Belle II: Commissioning, First Results, Future Prospects

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University of Hawaii

Aspen 2019 Winter Conference

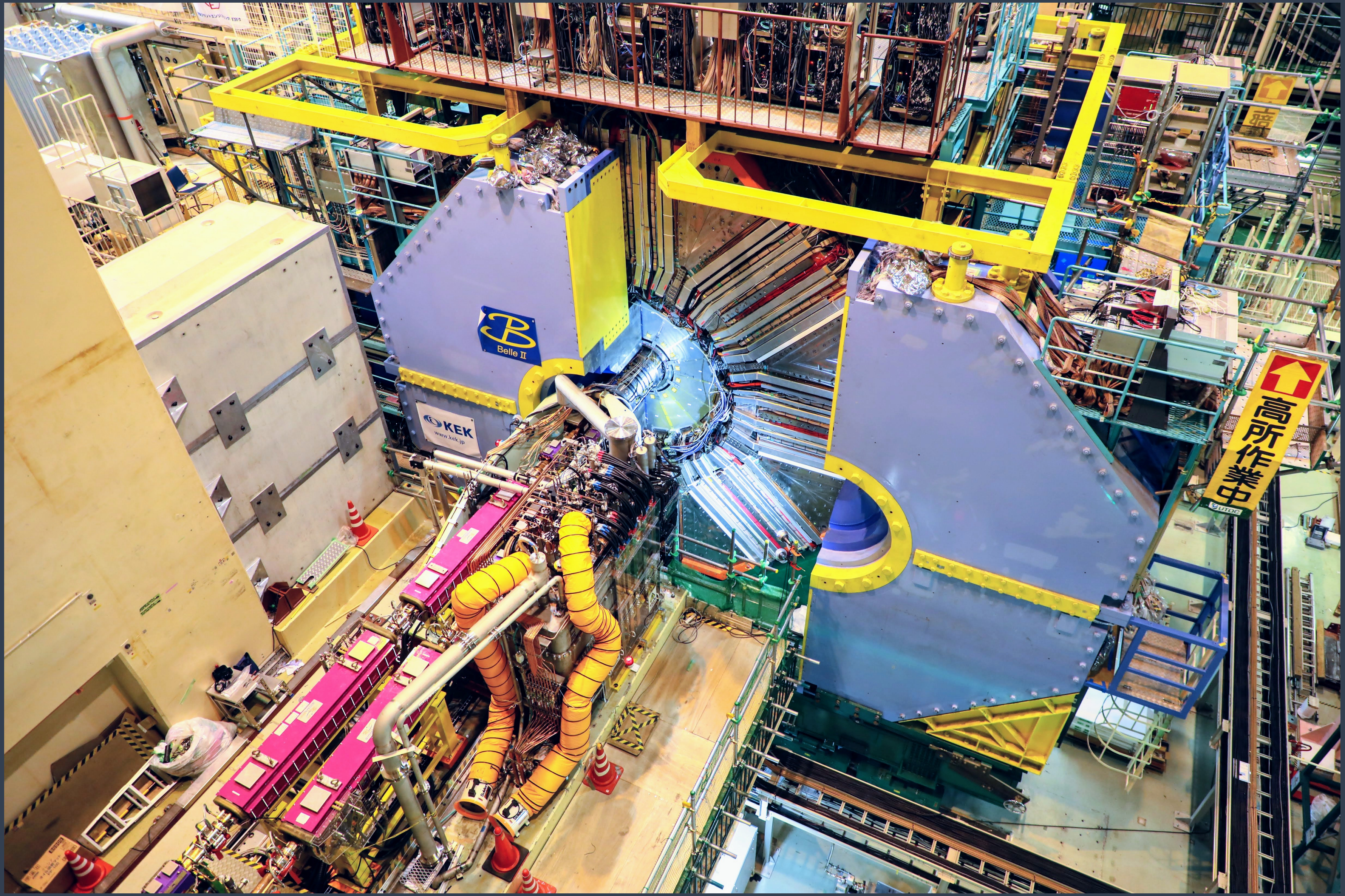
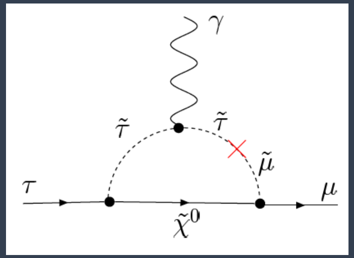
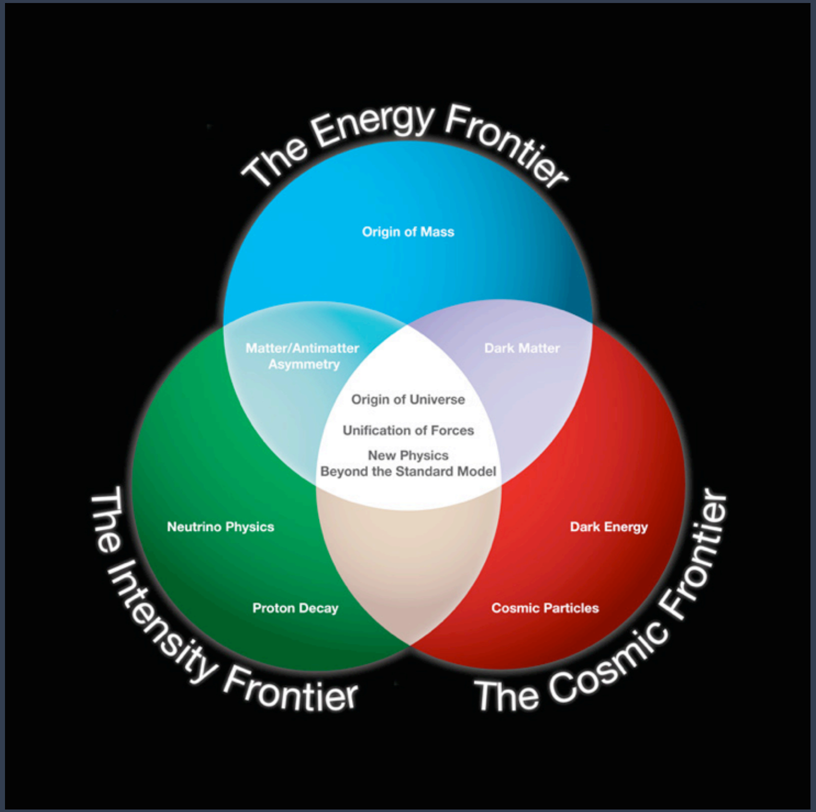
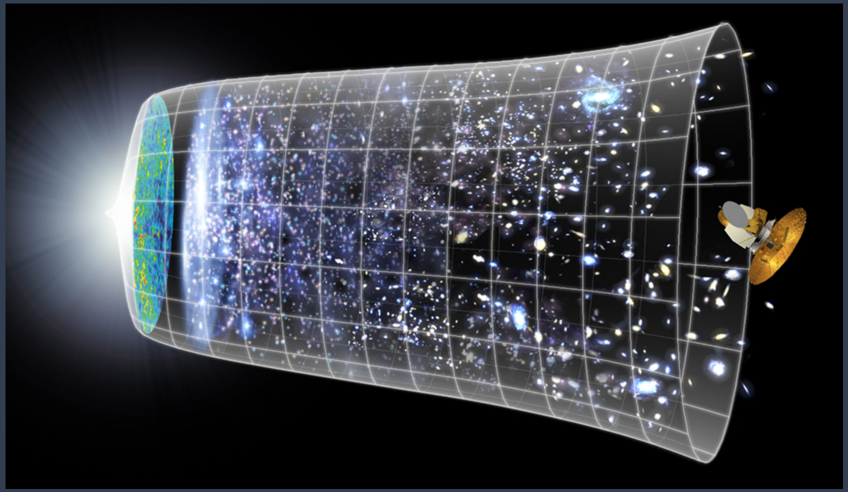


Photo Credit: Shota Takahashi of KEK



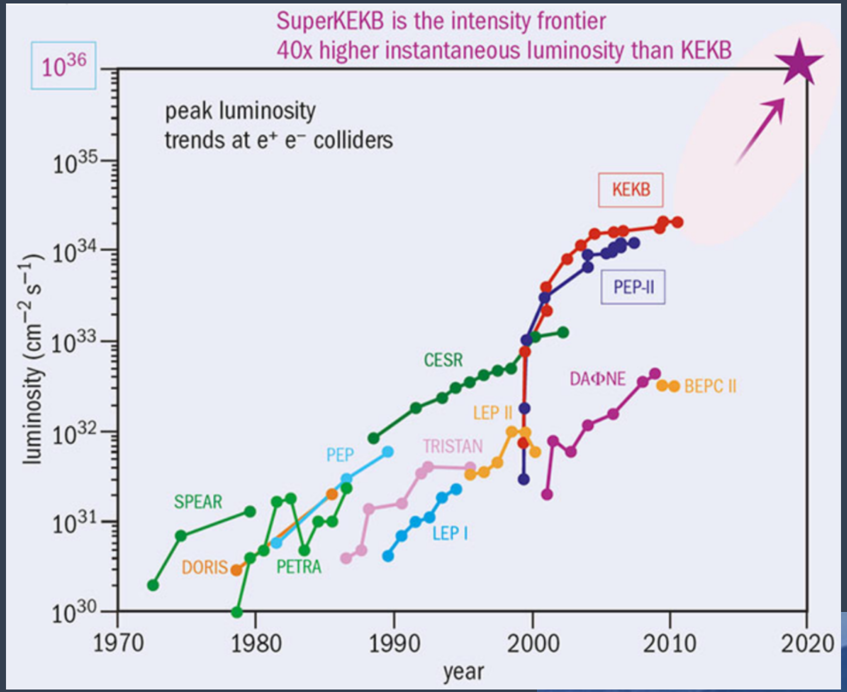


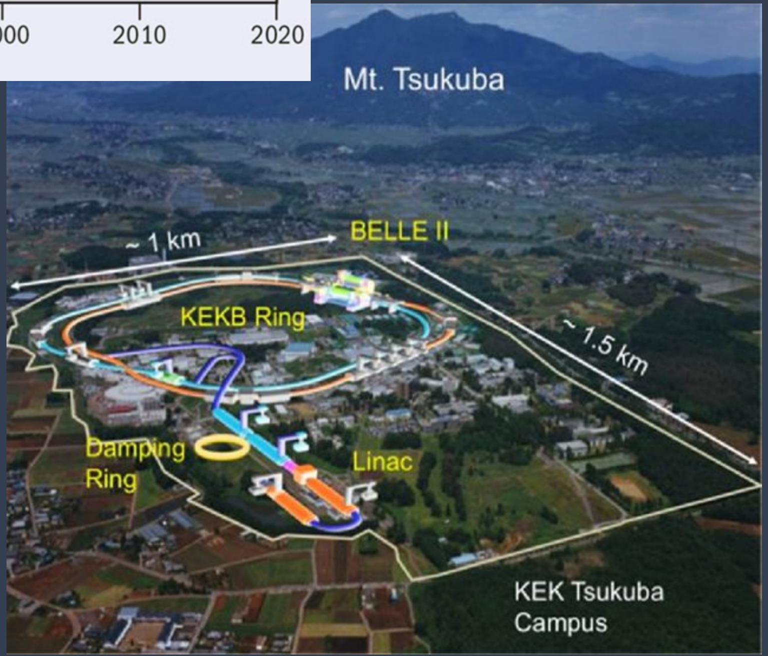


The Intensity Frontier: "Quantum Mechanical Finesse versus Brute Force"

Belle II @ SuperKEKB

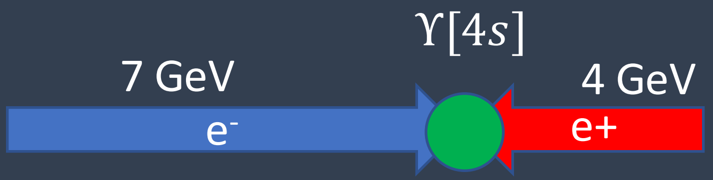
- Super B Factory experiment at world's highest luminosity electron-positron collider
- Precision measurements in a clean event environment
- Broad physics program
- Investigation of tantalizing, existing BSM hints

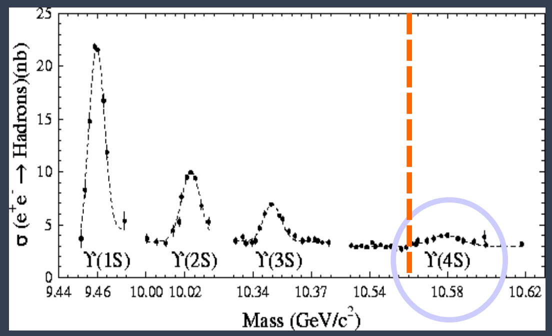




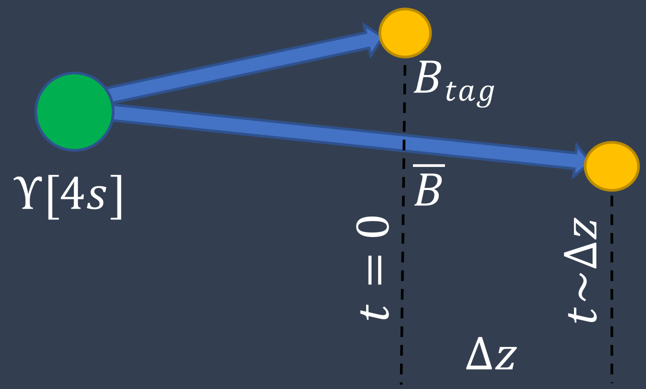
Belle II physics run has started!
Belle *still* producing new results – a hot one in this talk!

The B-factory idea in a nutshell





- Electron-positron collisions
- $E_{CM} \approx m_{\Upsilon(4s)}$
- $\Upsilon(4s) \to \overline{B}B$ ---- quantum-entangled!
- Asymmetric beam energies
  - B-decay-time distributions via $\Delta z \approx 200\ \mu\text{m}$
  - precision studies of B-meson mixing, mixing-induced CPV, quantum-decoherence, etc.

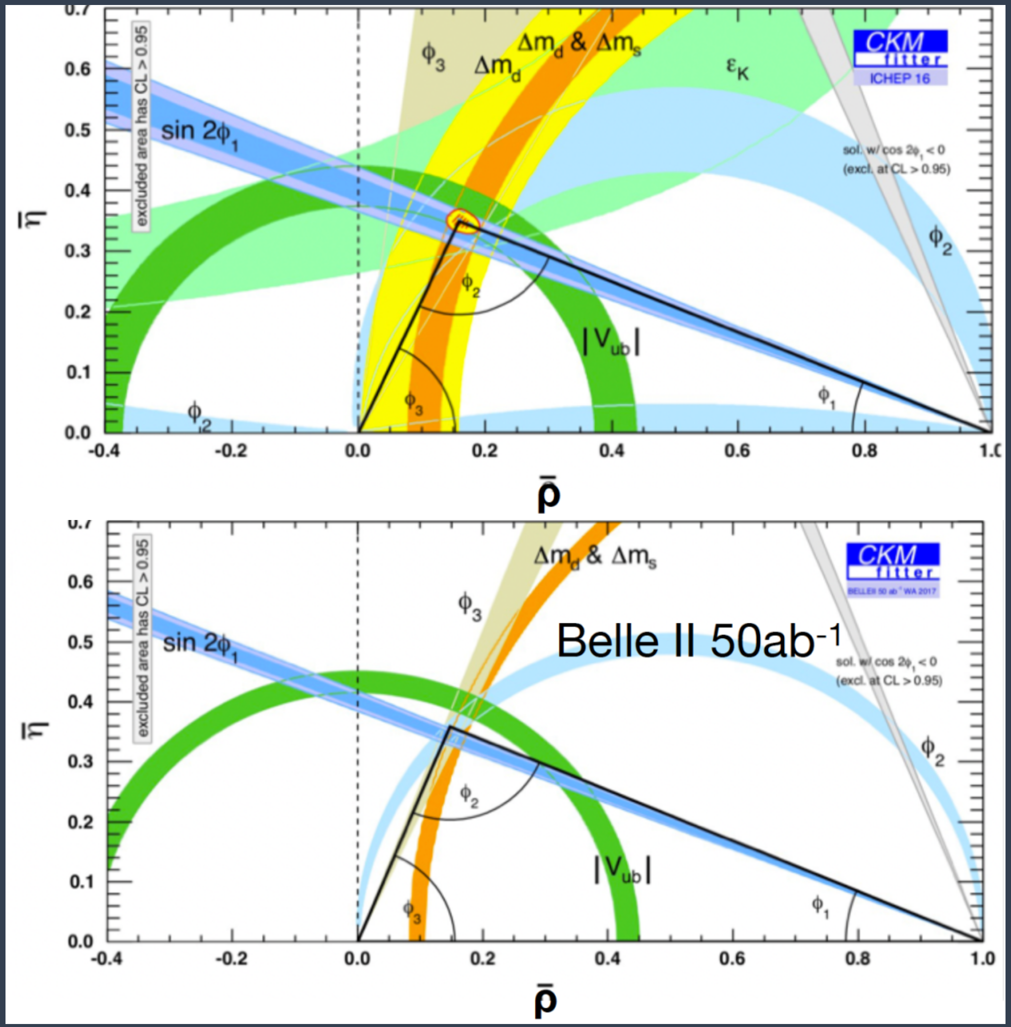


55 billion B-meson pairs in target data sample
Analysis sensitivity in B, τ and charm to $O(10^{-9})$ branching fractions

Process	σ (nb)
bb	1.1
cc	1.3
Light quark qq	~2.1
$\tau^+\tau^-$	0.9
e^+e^-	~40

Belle II Physics Program

- The original B factory experiments BaBar and Belle confirmed the Kobayashi-Maskawa Mechanism
- A single, irreducible, complex CKM phase can explain all CPV observed in the quark sector to date
- This is now a validated part of the SM
- Belle II will look for deviations from this picture to provide evidence of BSM physics
- Question: How does the newly observed CPV in D's (LHCb) fit into the figure to the right?



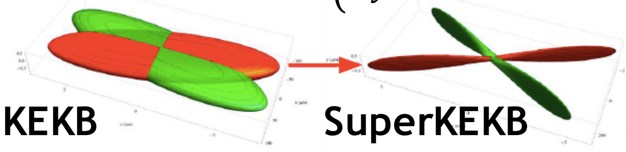
But the Belle II physics scope extends far beyond B physics and CPV
Charm, tau, precision EW, quarkonium physics, dark sector searches, and more
See *The Belle II Physics Book*, arXiv:1808.10567, 689 pages

SuperKEKB Accelerator

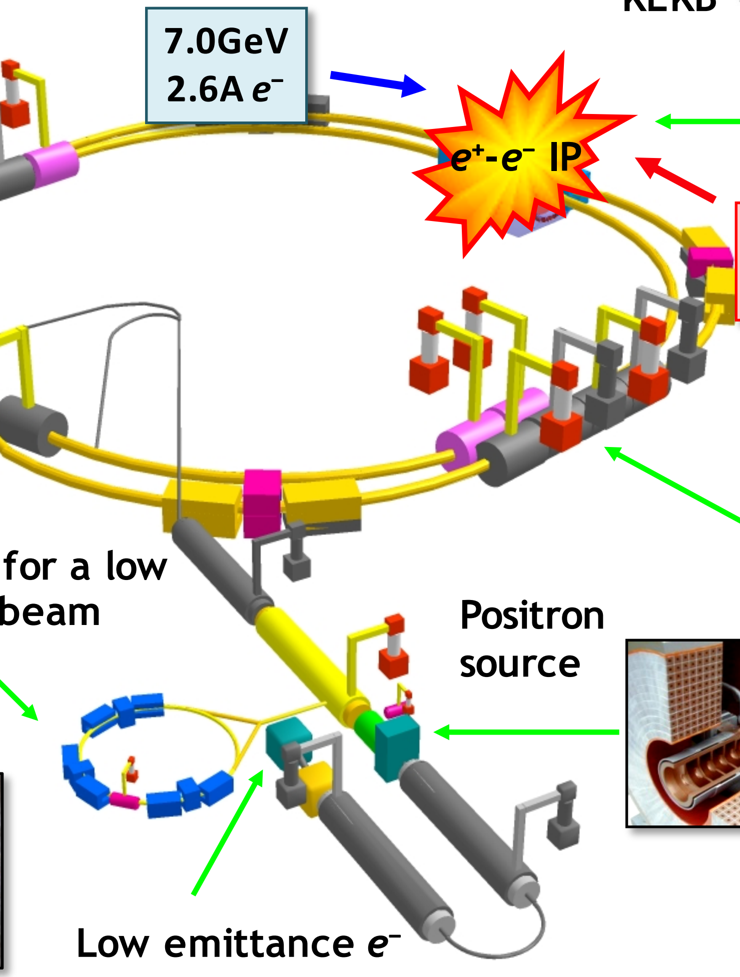
Change of the collision energy to increase beam lifetime

$\sigma_y = 940\text{nm}$

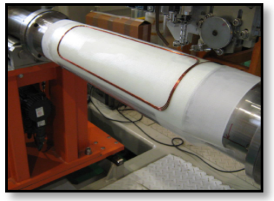
$\begin{cases} \sigma_y = 62\text{nm (HER)} \\ \sigma_y = 48\text{nm (LER)} \end{cases}$



Nano-beam scheme



Longer magnets (LER) than KEKB by 4m

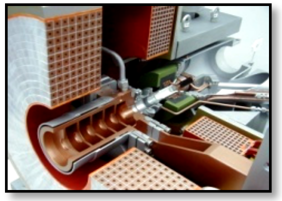


New final focusing magnets

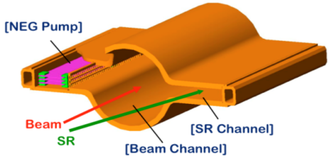
More RF cavities to increase the beam currents

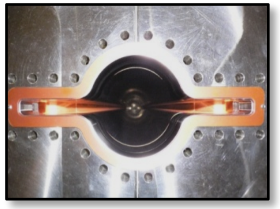
Damping ring for a low emittance e^+ beam

Positron source



New beam pipe design to reduce the SR

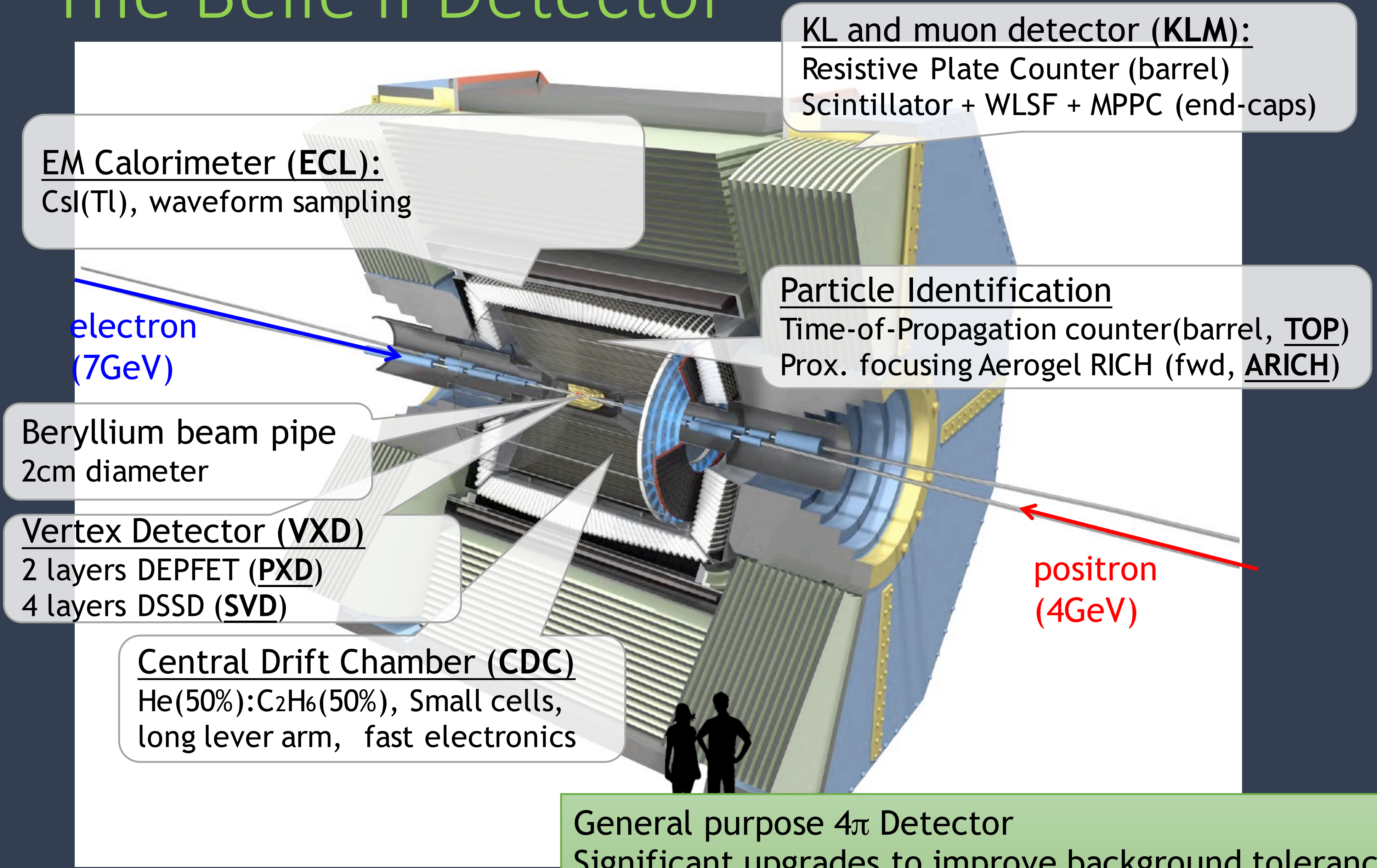




Low emittance e^-

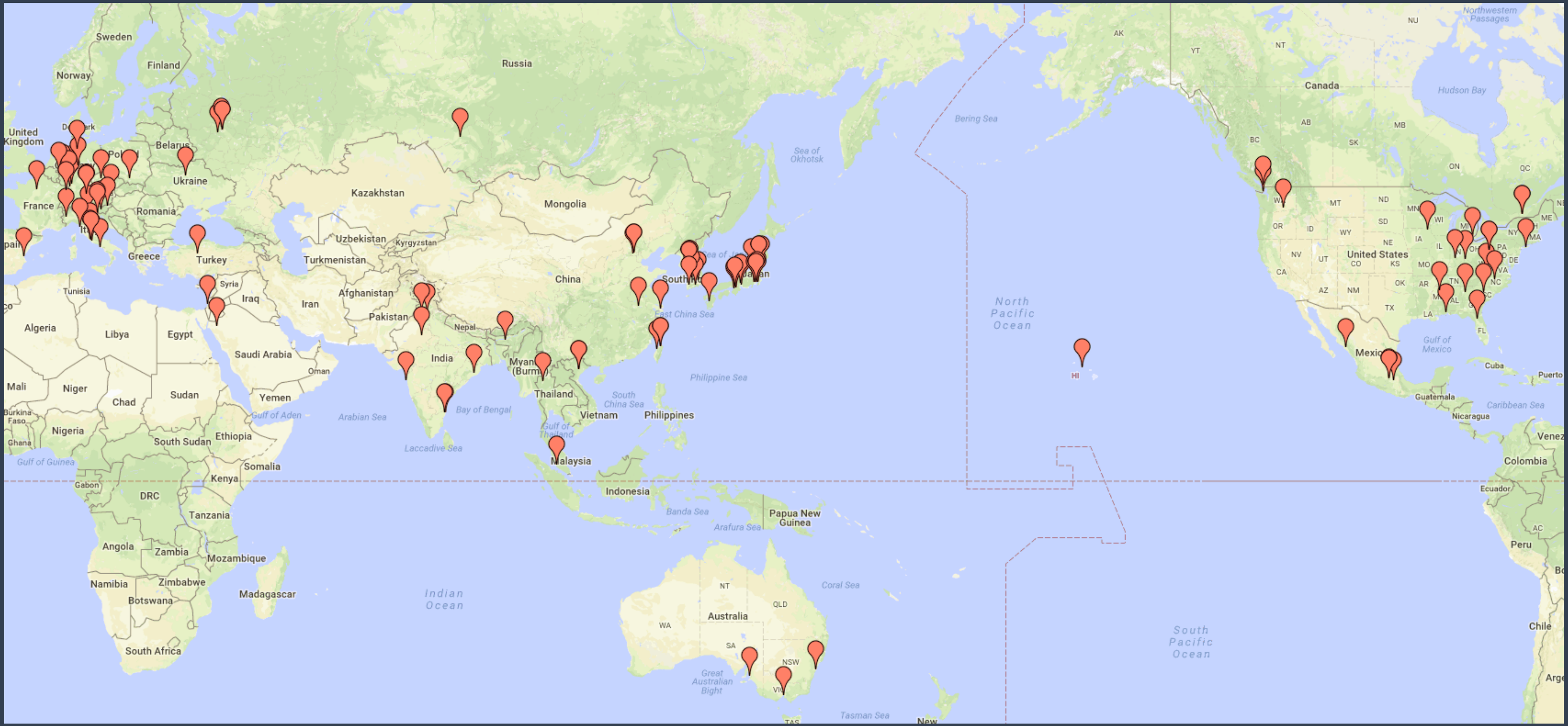
- 40 x higher instantaneous luminosity than KEKB by
  - doubling $I_{HER/LER}$
  - Extreme focusing of the beams – a.k.a. *nanobeam scheme*
- Note: this also strongly increases beam backgrounds [beam-gas and Touschek scattering]
- Background mitigation at the machine, detector, and reconstruction level are important ingredients for success

The Belle II Detector



General purpose 4π Detector
Significant upgrades to improve background tolerance
New PID systems, Vertex detector

The Geography of the International Belle II collaboration



- Belle II has grown substantially in recent years, to ~800 researchers from 26 countries
- Youth and potential: There are ~267 graduate students in the collaboration

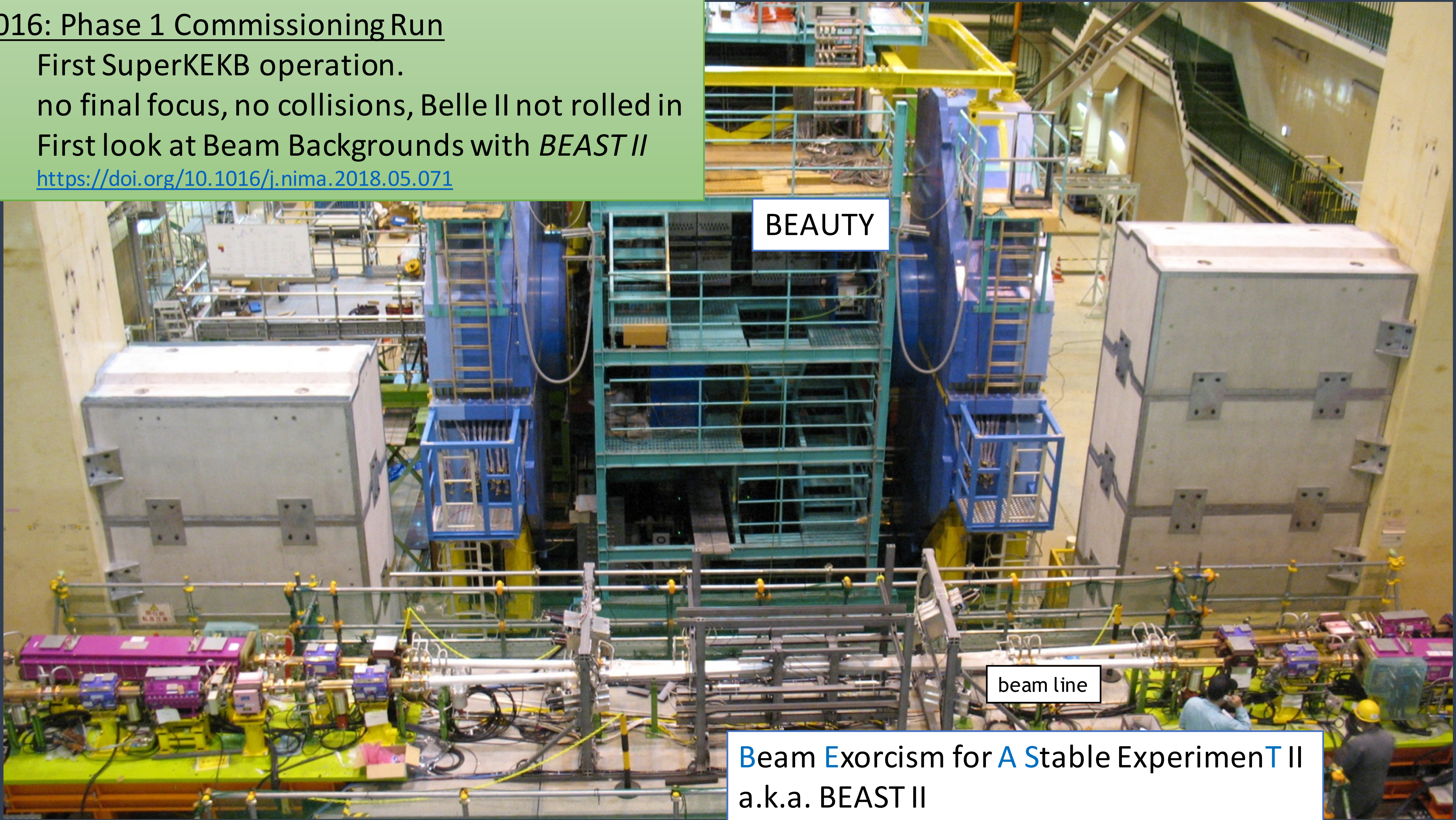
2016: Phase 1 Commissioning Run

First SuperKEKB operation.

no final focus, no collisions, Belle II not rolled in

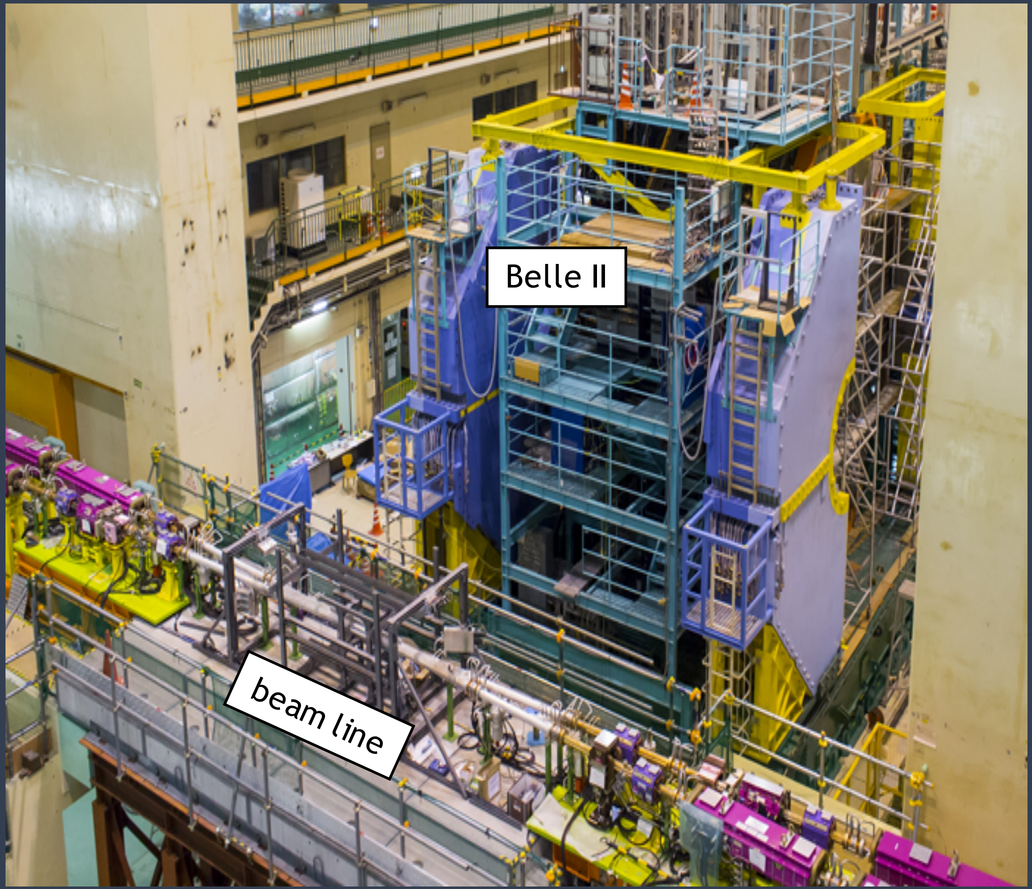
First look at Beam Backgrounds with *BEAST II*

https://doi.org/10.1016/j.nima.2018.05.071

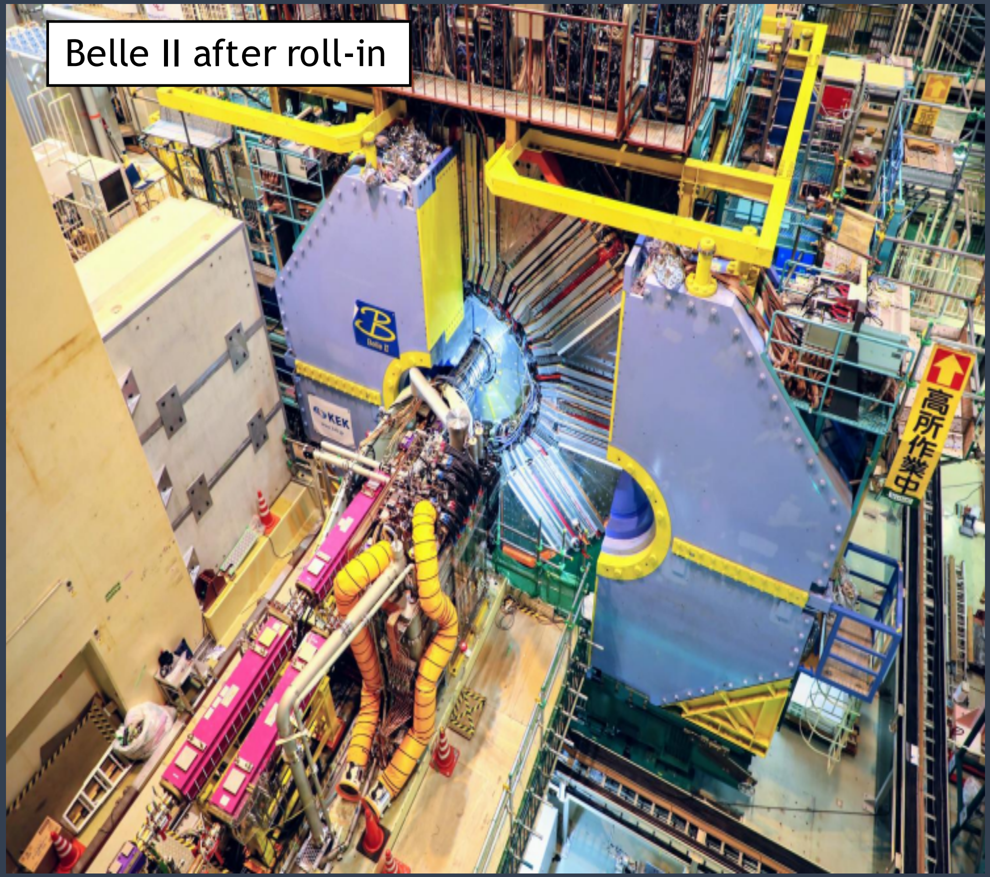


Beam Exorcism for A Stable ExperimenT II
a.k.a. BEAST II

2017: Belle II Detector rolled into the beam line, final beam-focusing magnets installed

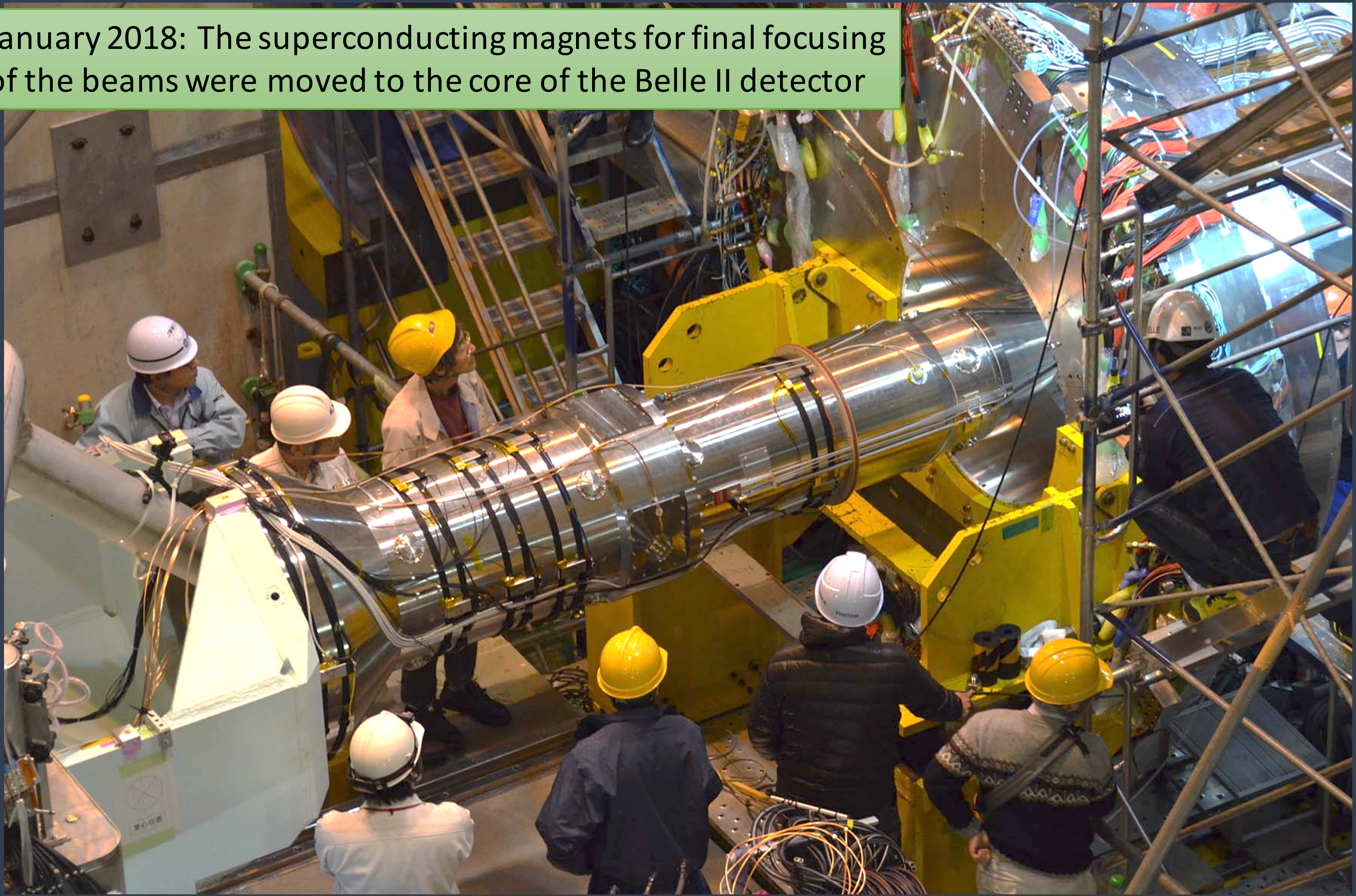


2016

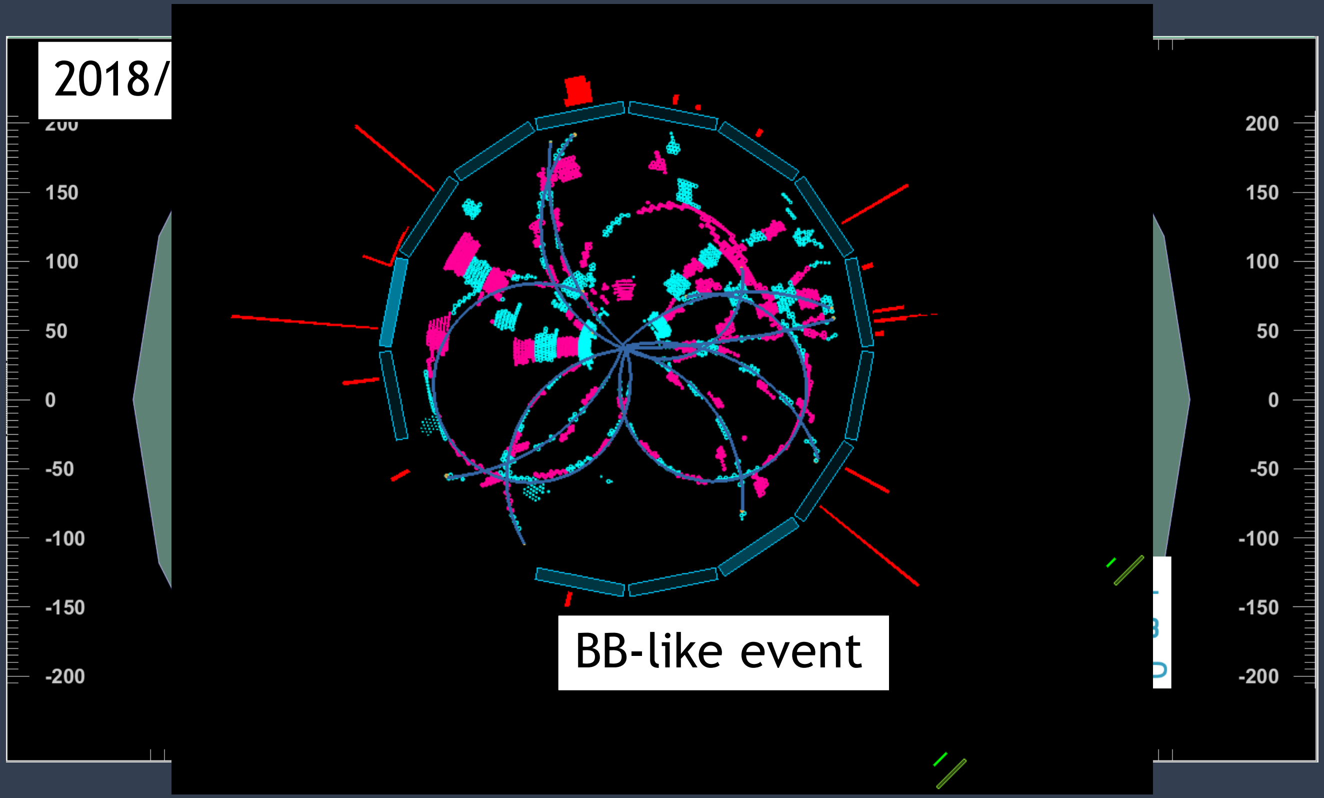


2017

January 2018: The superconducting magnets for final focusing of the beams were moved to the core of the Belle II detector



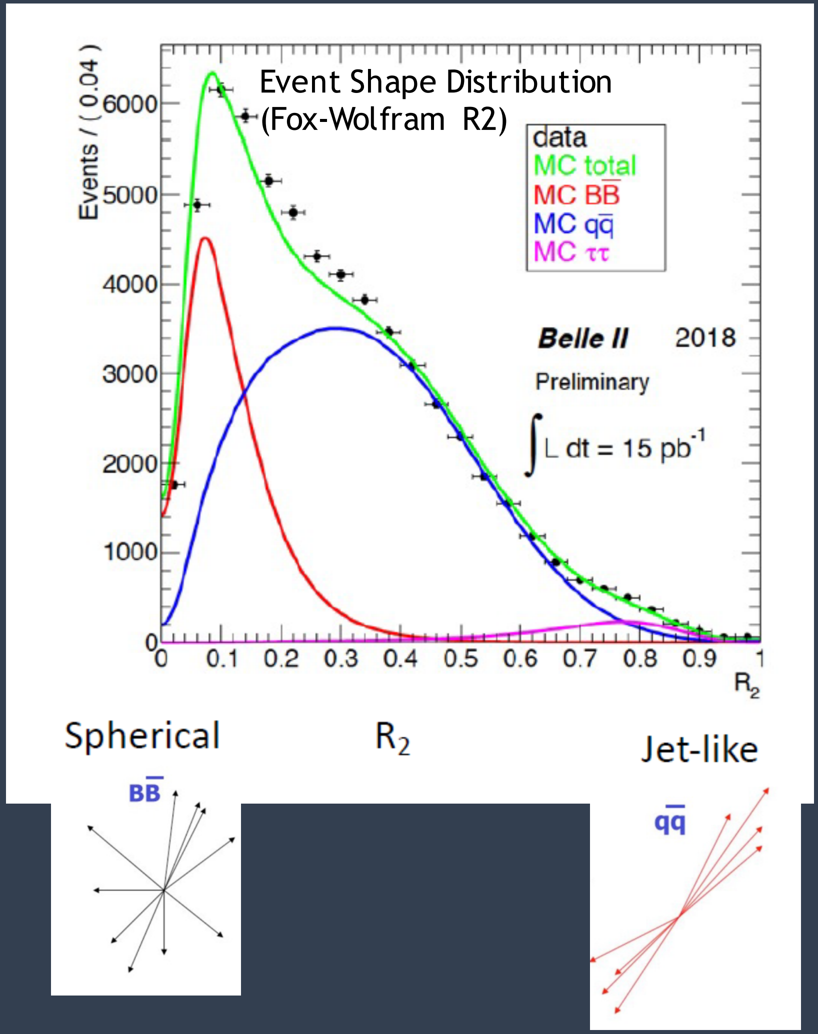
2018 March-July "Phase 2" Commissioning Run

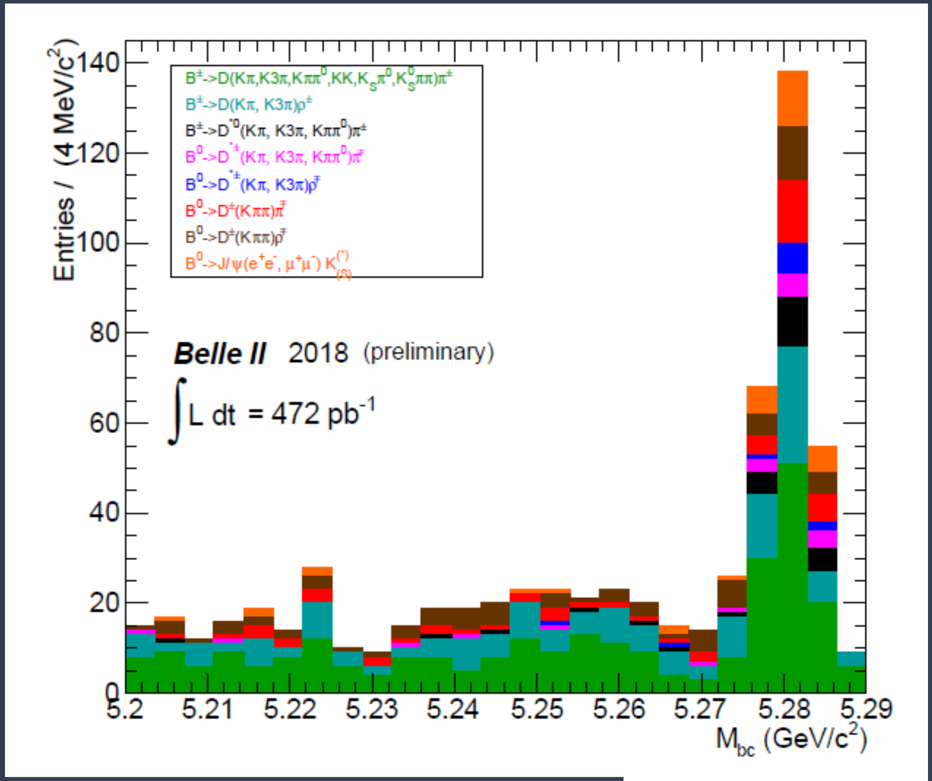


- First e^+e^- collisions achieved
- Data taking with Belle II minus VXD (vertex detector) - a safety conscious approach
- Beam backgrounds are high but tolerable
  - Synchrotron radiation (VXD background) observed for first time

→ All goals achieved. Safe to proceed and install full VXD

Rediscovery of B mesons

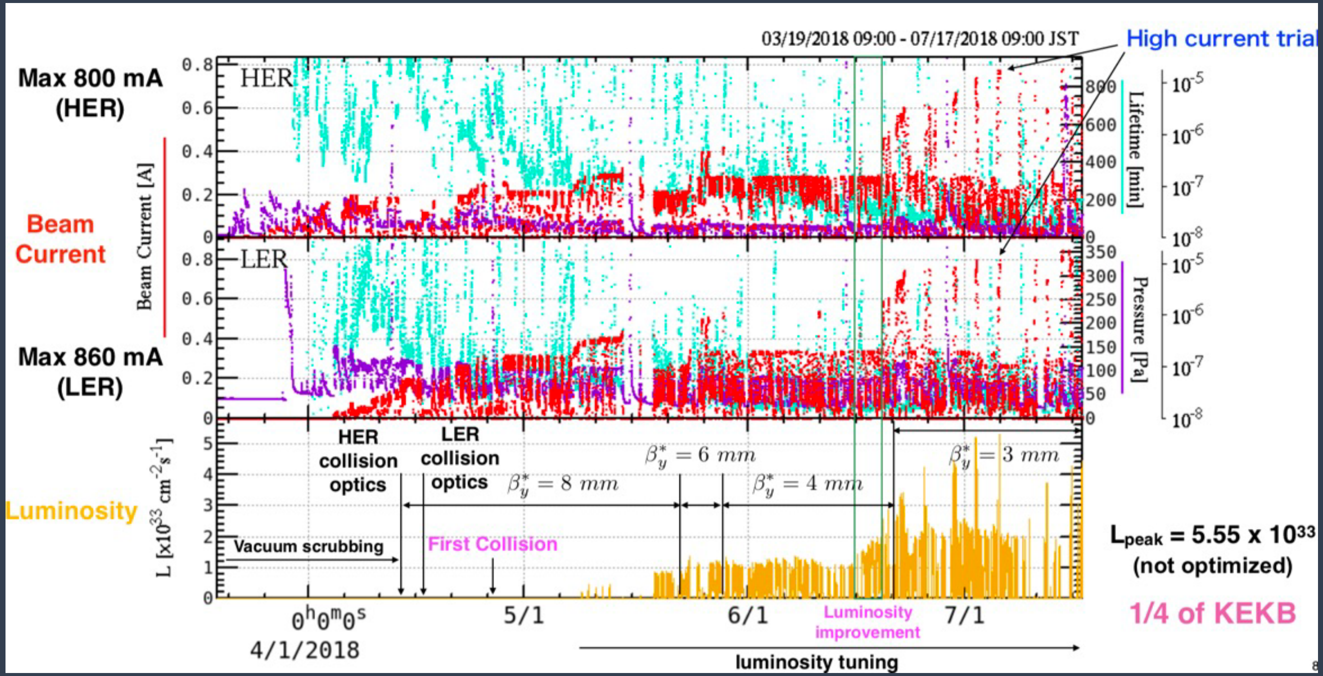




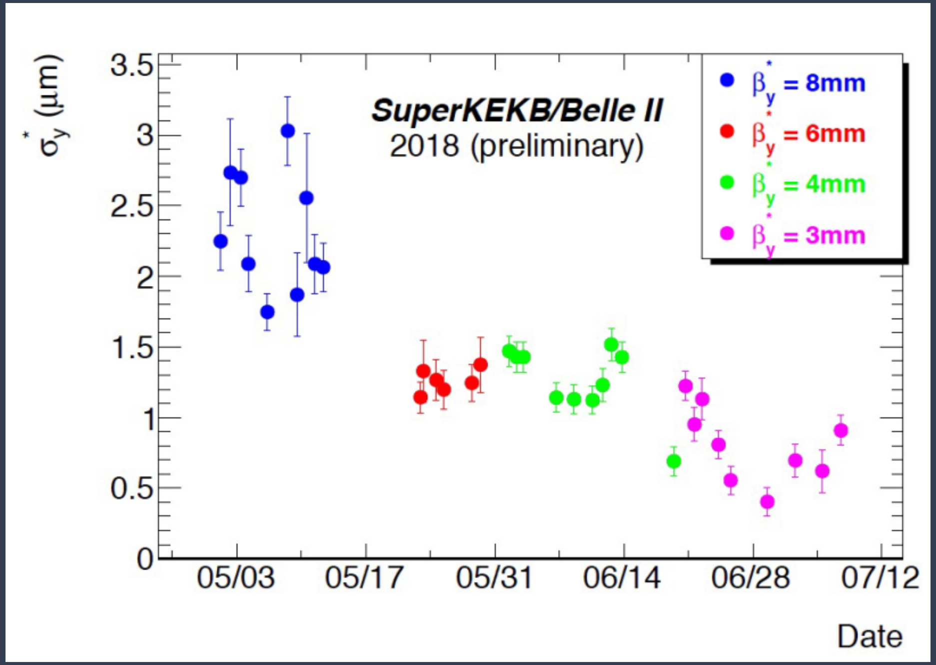
$$M_{bc} = \sqrt{(E_{cm}/2)^2 - p^2_{recon}}$$

- Clearly observed an excess of BB events
- Detector and full reconstruction analysis chain working well.

SuperKEKB in Phase2



Ramping up the beam currents

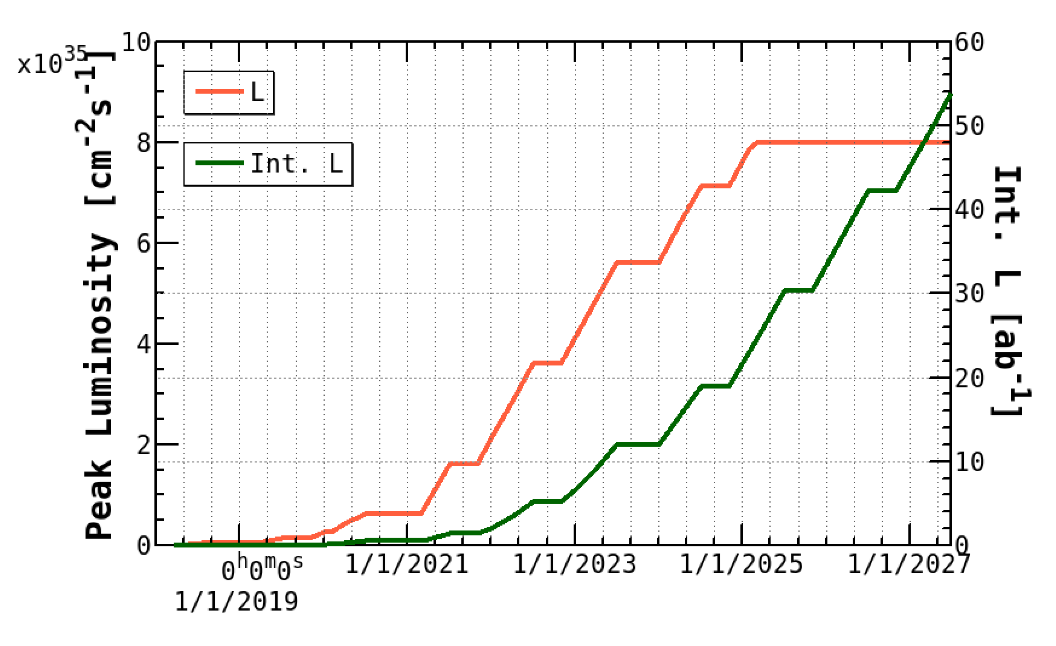


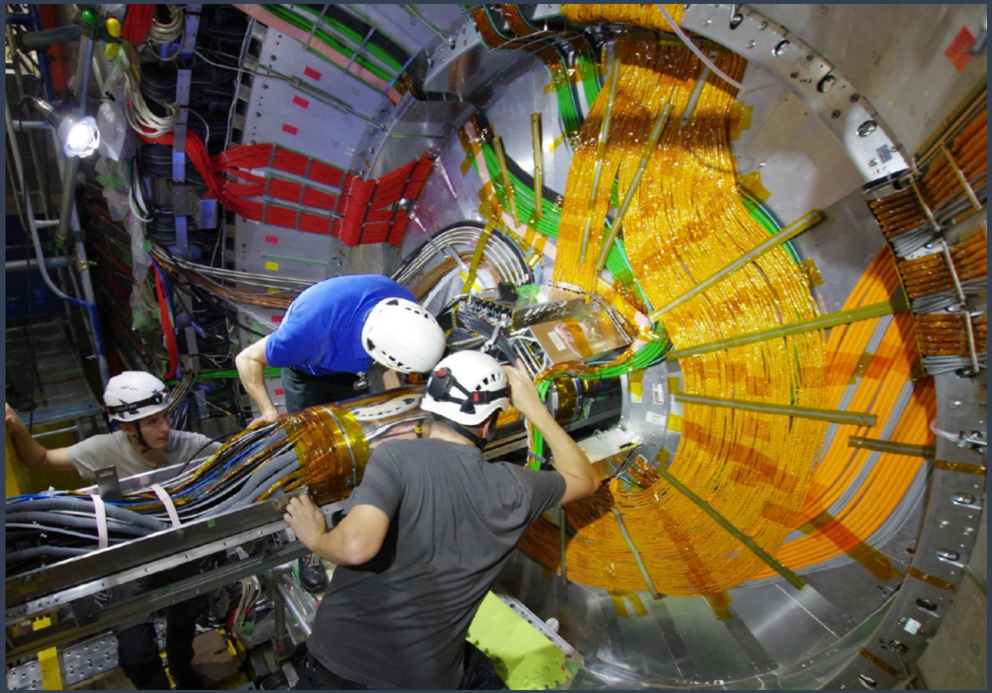
Squeezing the beams at the interaction point

- Achieved
  - L_{peak} = 5.55 x 10^{33} cm^2/s
  - Belle II recorded ~ 500 pb^{-1}
- Confirmed the nano-beam scheme
- Reduced β_y^* to 3 mm, σ_y^* ~ 400 nm (Final target β_y^* = 0.3 mm σ_y^* ~ 50 nm)

Phase 3: Physics Run

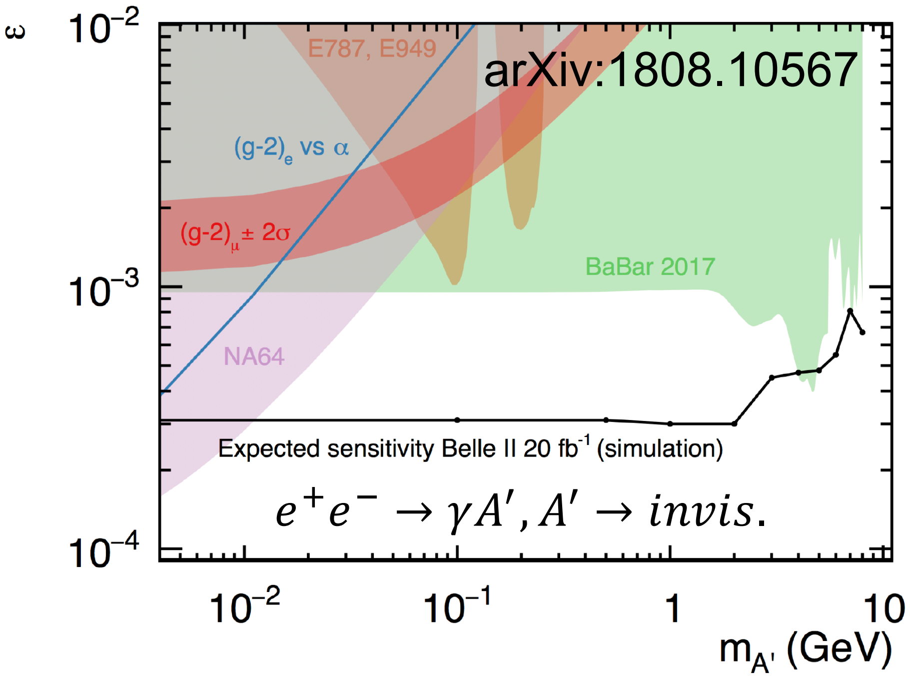
- Currently preparing for "factory mode" data taking
- Full vertex detector has been installed
- Phase 3 run began March 2019; planning ~8 months of operation this year
- All going smoothly so far!



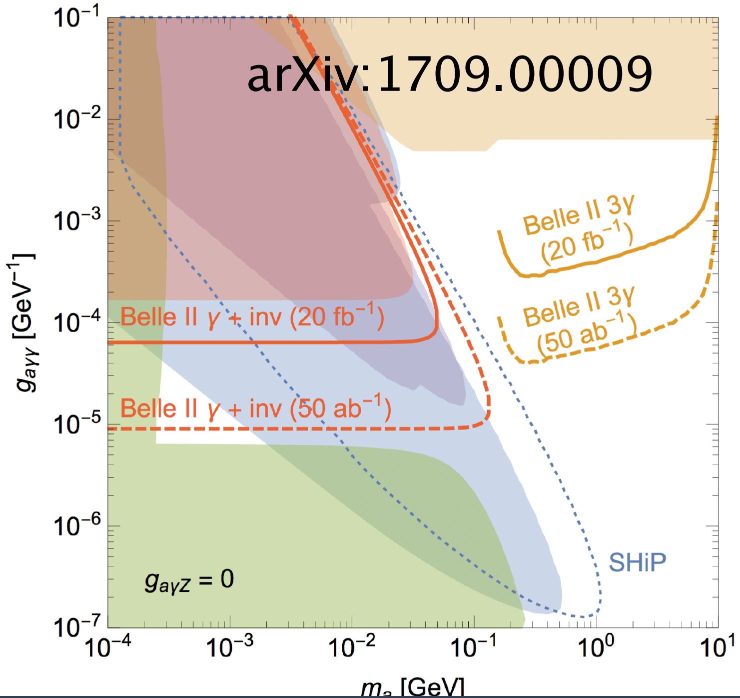


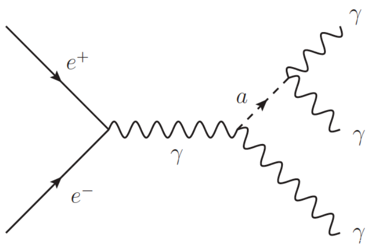
- Exceed existing world $e^+e^- \to \Upsilon(4S)$ dataset by 2021
- Target of 50 ab^{-1} recorded by 2027

Early Physics Target: Dark Sector



Dark Photon + Light Dark Matter





ALPs

Belle lacked dedicated single-photon trigger required for such searches
BaBar sensitivity reduced due to lack of hermiticity of projective crystals in calorimeter
Belle II has world-leading sensitivity with only 20fb^{-1}, expected in first year of running

Light Higgs (A^0) and low-mass DM via *Upsilon-tagging*

$\Upsilon(2S)\rightarrow\Upsilon(1S)\ \pi^+\pi^-$

Phys. Rev. Lett. 122, 011801 (2019)

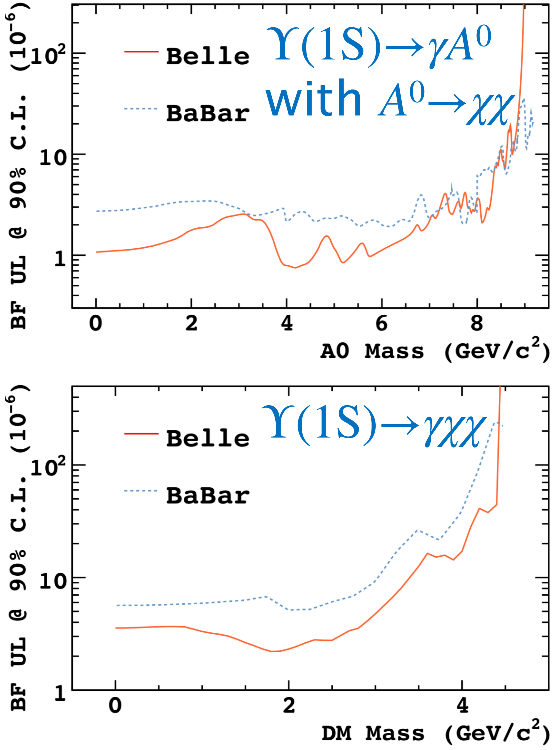


FIG. 2. 90% C.L. upper limits on the BFs of the on-shell process $\Upsilon(1S)\rightarrow\gamma A^0$ with $A^0\rightarrow\chi\chi$ (top) and the off-shell process $\Upsilon(1S)\rightarrow\gamma\chi\chi$ (bottom). The orange solid curves are the Belle limits and the blue dashed curves are the BaBar limits.

arXiv:1511.03728

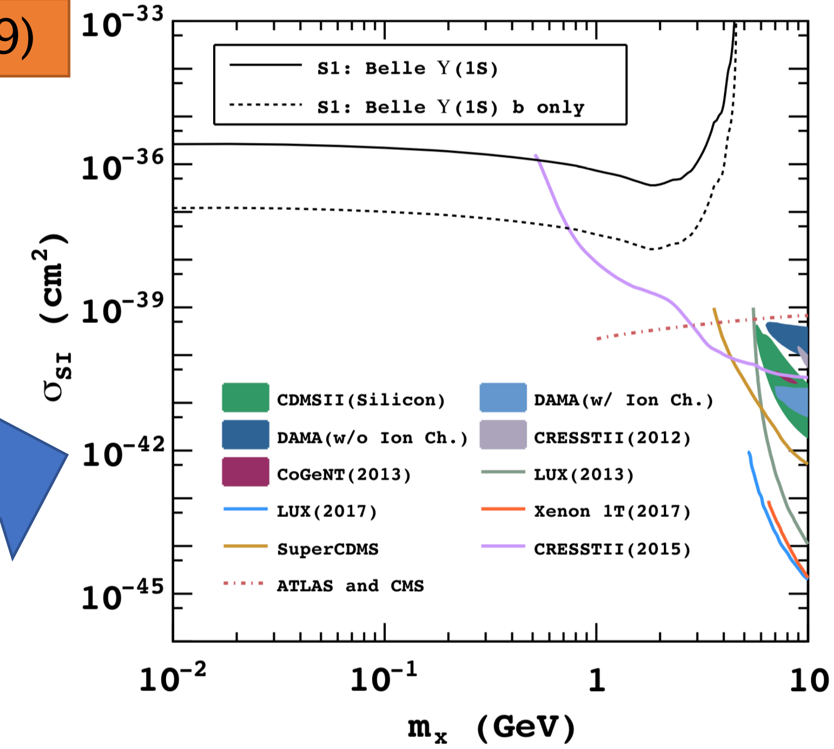
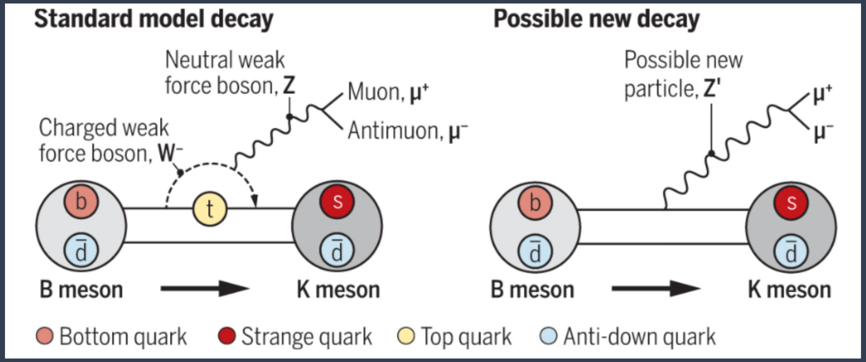


FIG. 3. WIMP-nucleon spin-independent scattering cross-section limits at 90% C.L. The black solid and dashed curves are the upper limits obtained by assuming the WIMP couples to all quarks and only b-quarks, respectively. The 90% C.L. exclusion limits of LUX [18], CRESST II [19], SuperCDMS [20], and ATLAS [21, 22] and CMS [23, 24] are shown for reference; and the 90% C.L. signal regions of CRESST II [25], Co- ... [28]

Highly competitive, though somewhat model-dependent limits on low-mass Dark Matter from Belle
Straightforward to extend and improve with Belle II

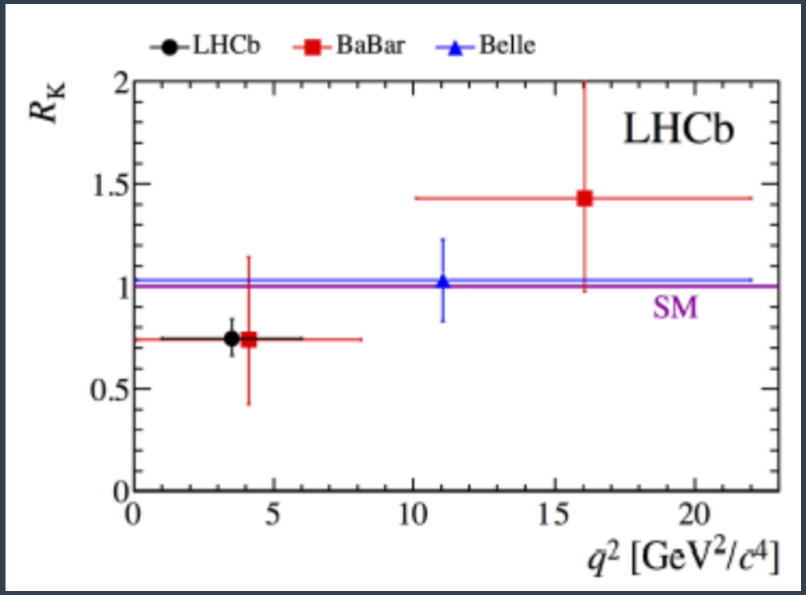
Hot Topic: test of flavor universality in $B \to K^{(*)} l^+ l^-$

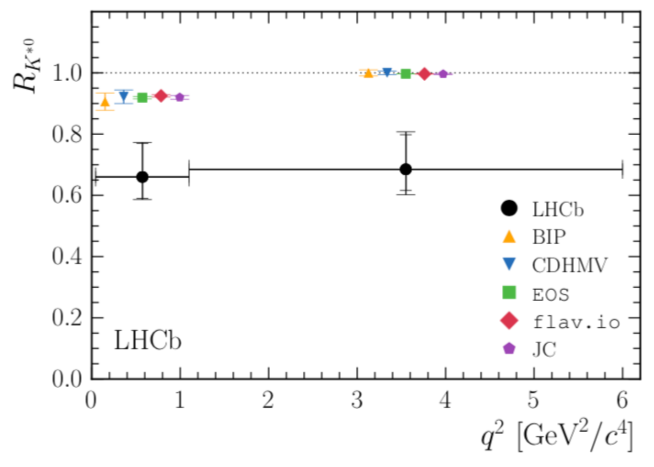


$B \to K^{(*)}\mu^+\mu^-$

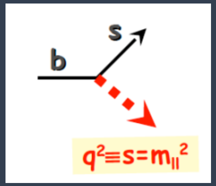
$B \to K^{(*)}e^+e^-$

$$R_{K^{(*)}}(q^2) = \frac{BF(B \to K^{(*)}\mu^+\mu^-)}{BF(B \to K^{(*)}e^+e^-)}$$

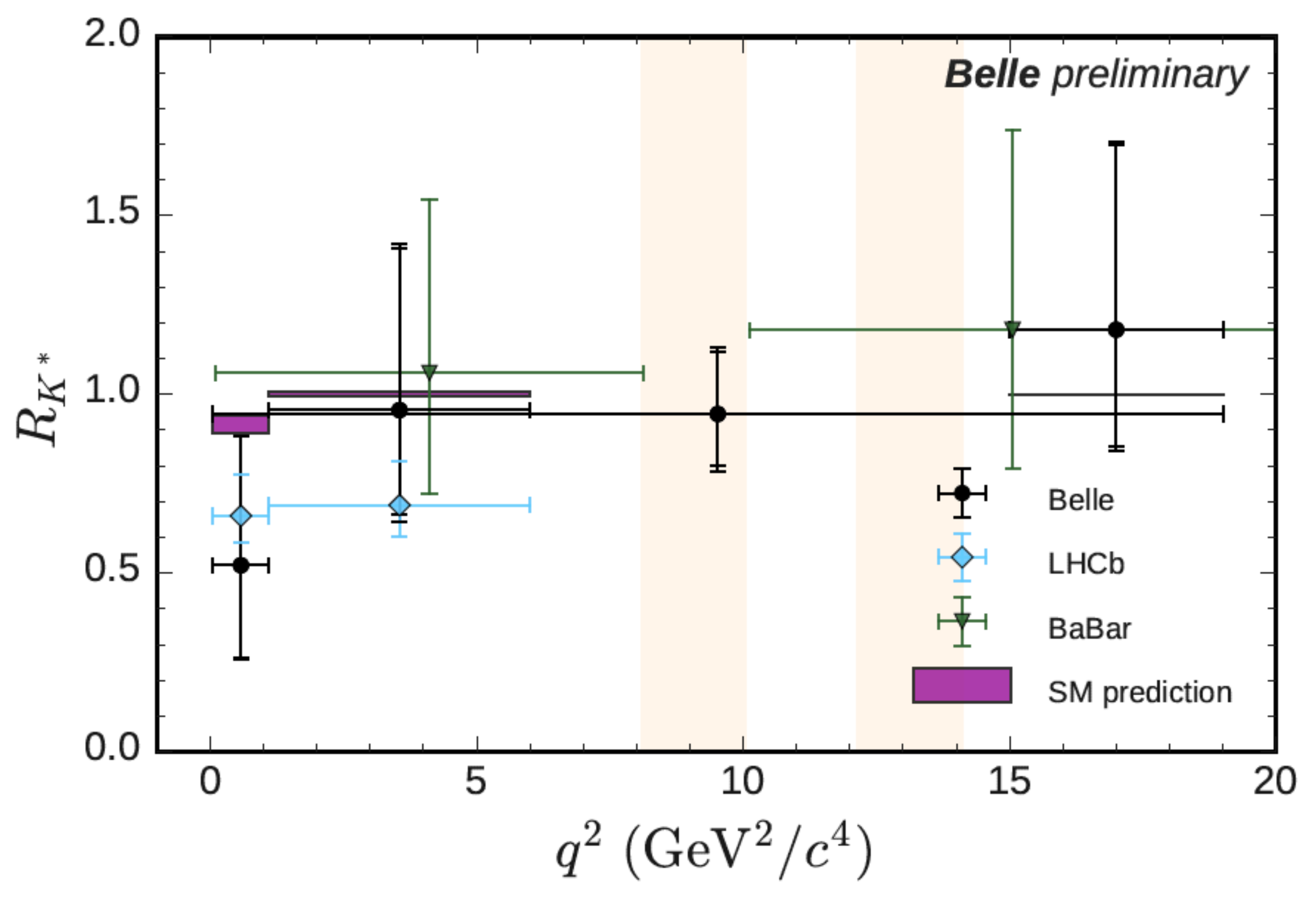




$R_{K^{*0}}$ vs q^2 for Run 1, LHCb Collaboration



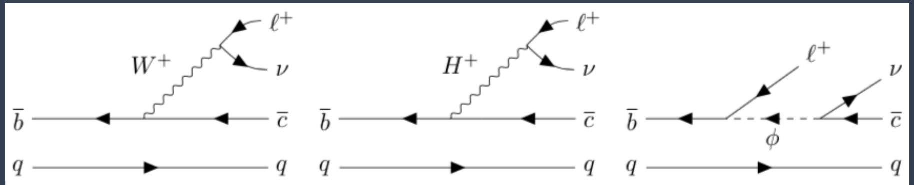
- SM couplings flavor independent, predict $R_{K(*)}$ close to 1
- LHCb measurements in tension with SM expectations at low q^2



New Belle result – four days old. Preprint coming soon.
Belle result includes first measurement of charged mode RK_{*+}.
Belle strongly statistics limited. Belle II will clarify.

Hot Topic: $B \to D^{(*)}\tau\nu$

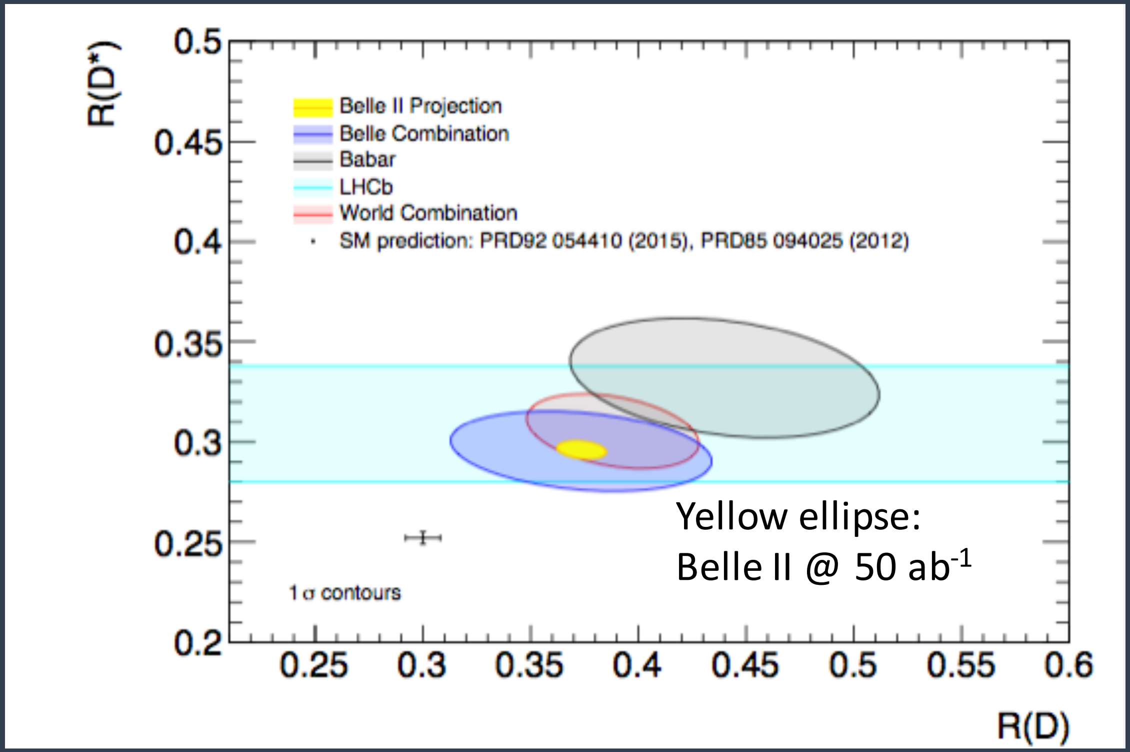
- $B \to D\tau\nu$ and $B \to D^*\tau\nu$ are tree-level SM decays containing 3rd generation quarks and leptons



- Ratio of heavy-to-light lepton modes provides robust theoretical prediction

$$R = \frac{\mathcal{B}(b \to q\,\tau\,\bar{\nu}_\tau)}{\mathcal{B}(b \to q\,\ell\,\bar{\nu}_\ell)} \qquad \ell = e, \mu$$

- Measurements from BaBar, Belle and LHCb all independently deviate from SM (combined ~4σ)



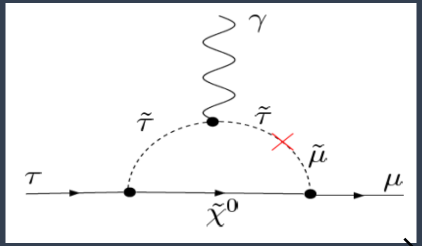
- Belle II can precisely measure R(D) and R(D*) to constrain or identify BSM physics
- Both charged and neutral B and various final states

Rare and forbidden decays

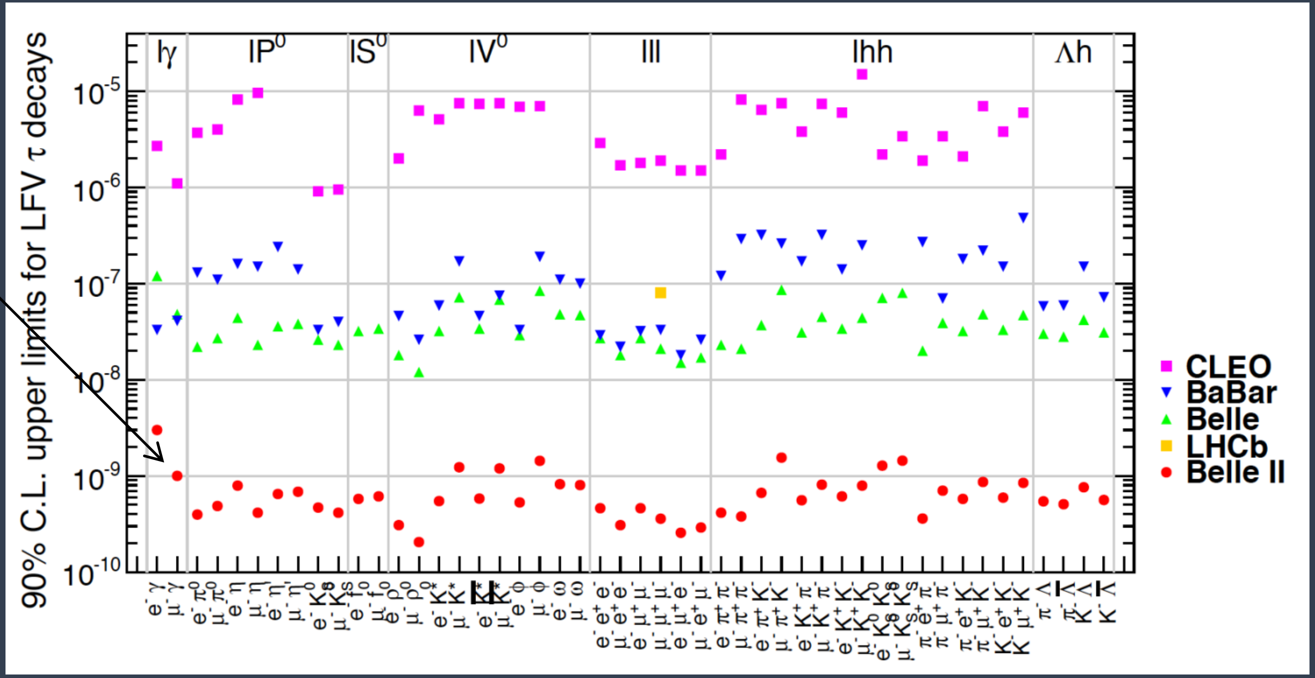
Processes that are suppressed or forbidden within the SM can potentially be dramatically enhanced by new physics contributions

e.g. Lepton flavour violation in τ decays:

“forbidden” in SM, but many new physics models saturate existing limits



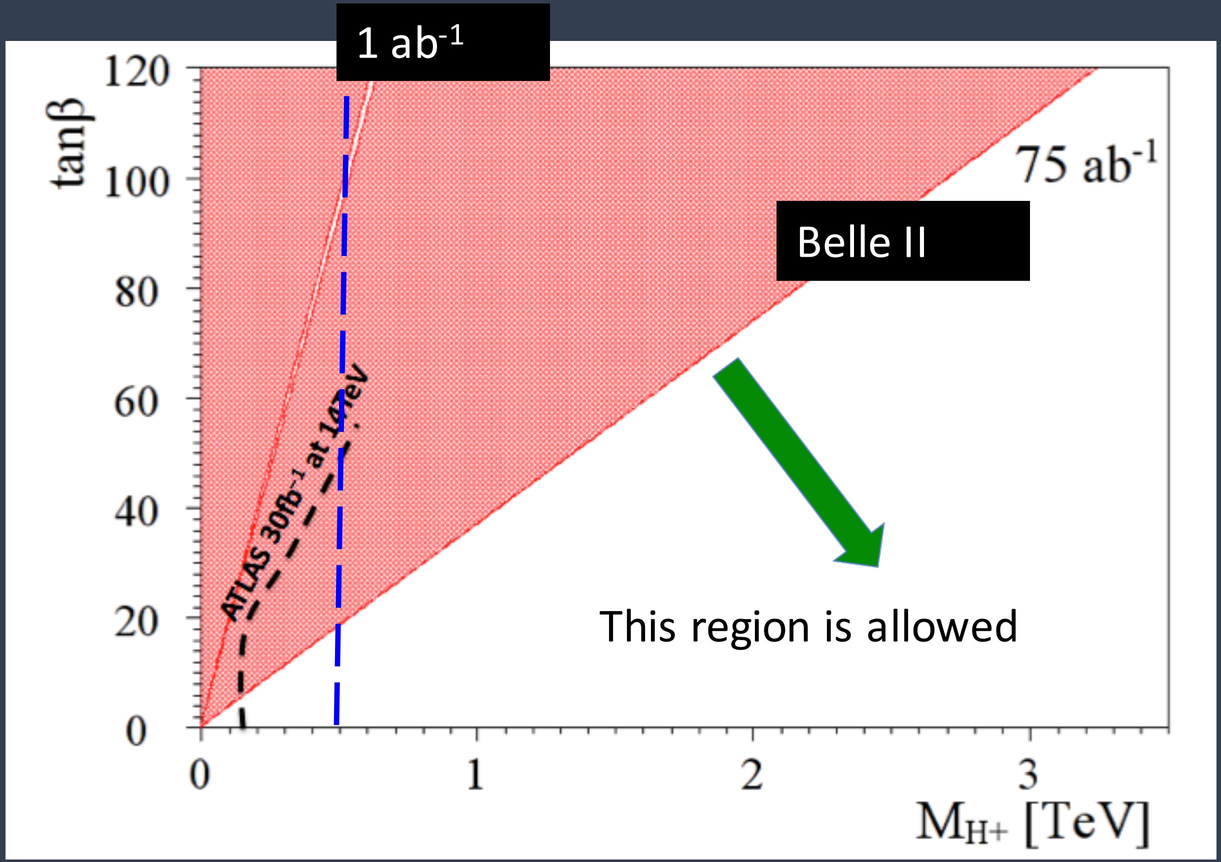
Expected Belle II sensitivity with full data sample

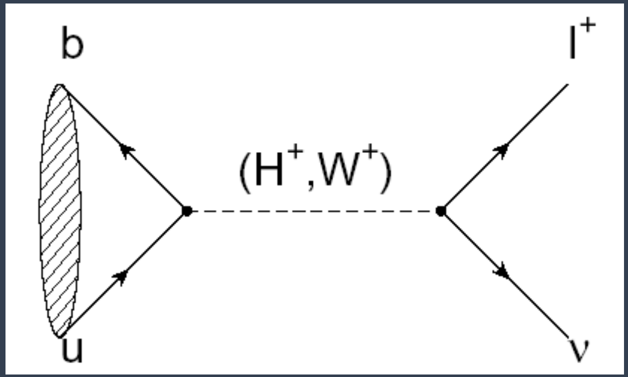


Very clean searches at B factories and unambiguous signal of new physics

Complementarity of e^+e^- and LHC: Charged Higgs Search

The current combined B→τυ limit places a stronger constraint than direct searches from LHC exps. for the next few years.





Currently inclusive b→sγ rules out m_{H+} below ~480 GeV/c² range at 95% CL (independent of tanβ), M. Misiak et al. (assuming no other NP)

http://arxiv.org/abs/1503.01789

Summary

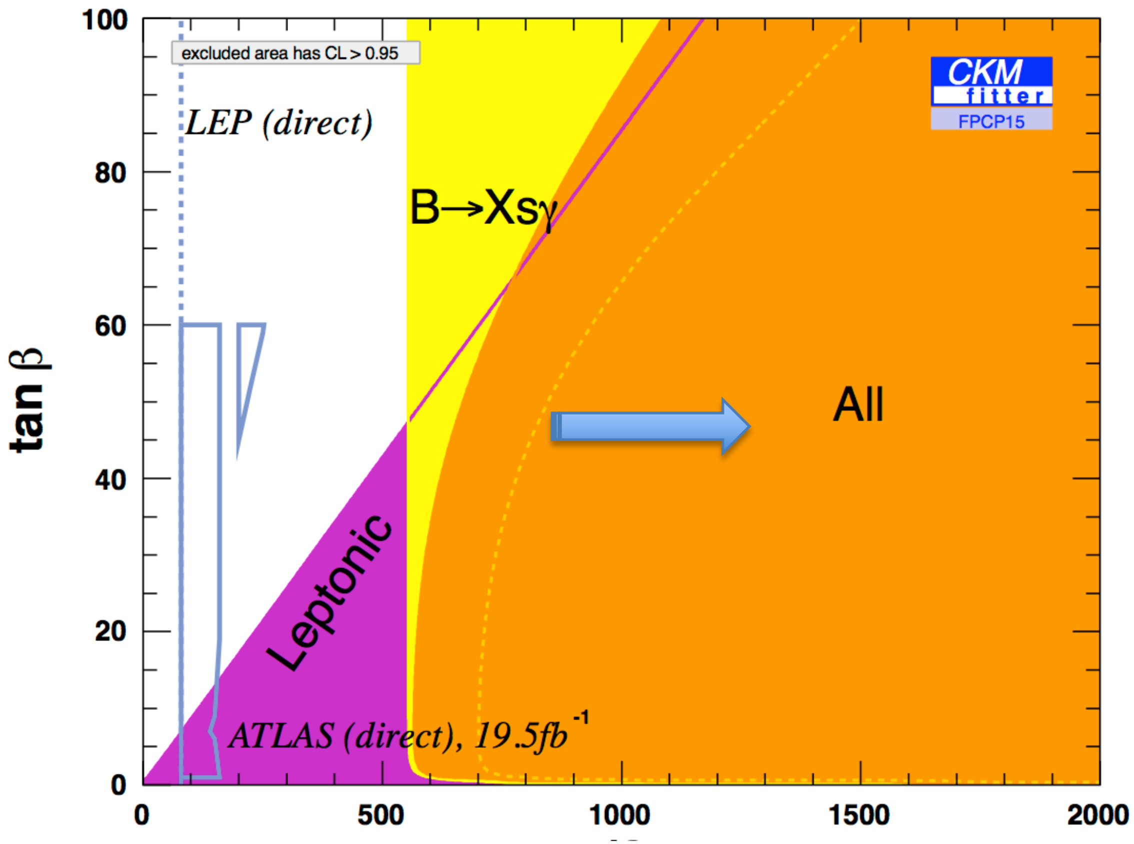
- The upgrade from Belle/KEKB to Belle II/SuperKEKB started in 2010, proceeded in three phases, and is now essentially complete
- The Belle II flavor factory experiment will
  - perform precision measurements of CPV and
  - investigate existing flavor physics anomalies
  - carry out broad searches for physics BSM
- SuperKEKB has achieved first collisions and verified the nano-beam scheme
- The Belle II detector performance has been confirmed with the Phase 2 data
- VXD has been assembled and installed in Belle II
- The "Phase 3" main physics run has started

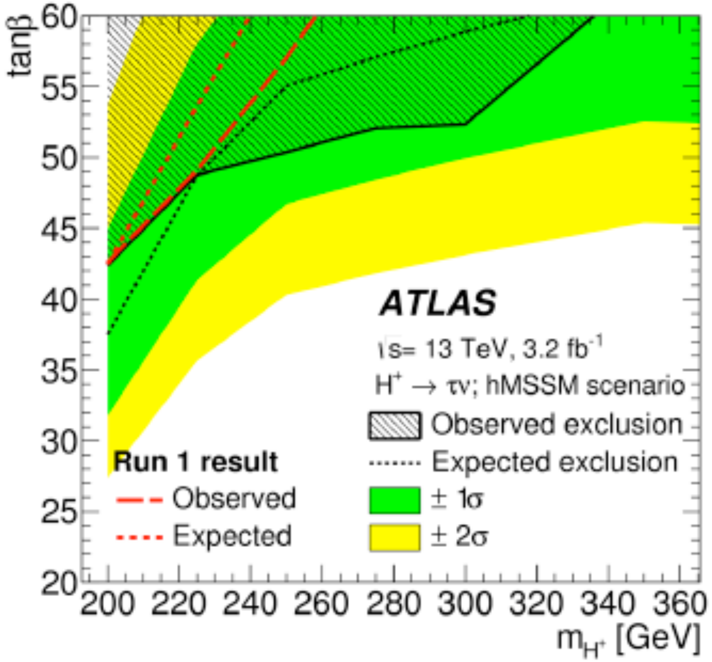
Backup

Complementarity of e+ e- factories and LHC

Thanks to Luis Pesantez and Phil Urquijo

The current combined B→τυ limit places a stronger constraint than direct searches from LHC exps. for the next few years.





$$r_H = \left(1 - \frac{m_B}{m_H^2} \tan^2 \beta\right)$$

Currently inclusive b→sγ rules out m_{H+} below ~480 GeV/c^2 range at 95% CL (independent of tanβ), M. Misiak et al. (assuming no other NP)

http://arxiv.org/abs/1503.01789

arXiv:1709.00009

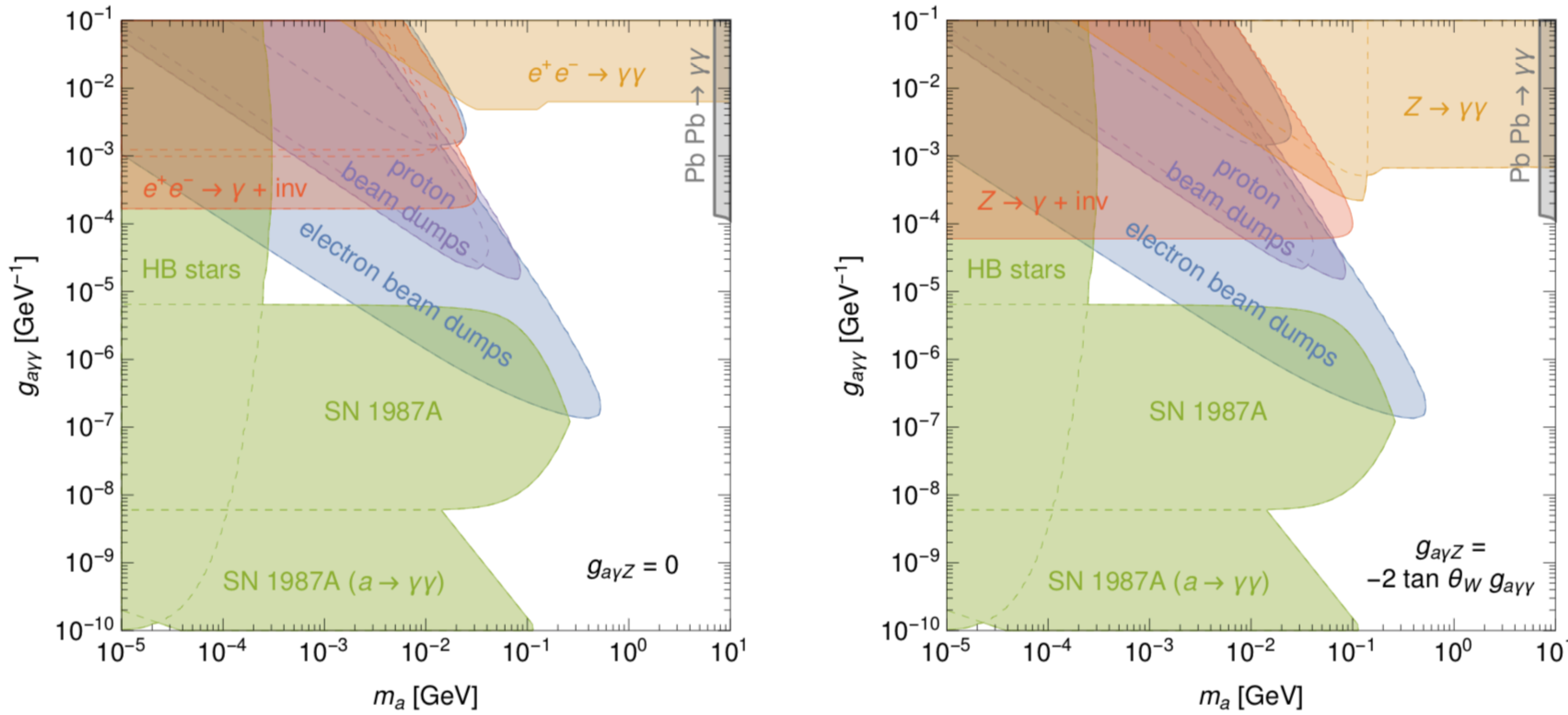


Figure 2: Existing constraints on ALPs with photon coupling (left) and hypercharge coupling (right). Proton beam dump constraints are taken from ref. [22], LEP constraints on $e^+e^- \to \gamma\gamma$ from ref. [21], CDF constraints on $Z \to \gamma\gamma$ from ref. [28], bounds from horizontal branch stars from ref. [11], bounds from visible decays of ALPs produced in SN 1987A from ref [50] and bounds from heavy-ion collisions from ref. [51]. All other constraints have been revisited and updated in the present work.

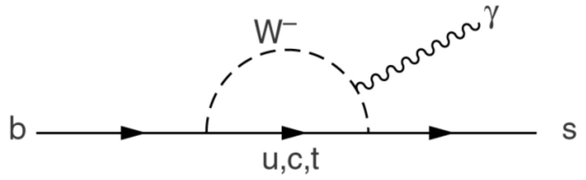
Electroweak FCNCs

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu)\, O_i(\mu)$$

Products of field operators
(non-perturbative hadronic matrix elements; Heavy quark expansion in inverse powers of m_b)

Wilson coefficients
(calculated perturbatively; encode short-distance physics)

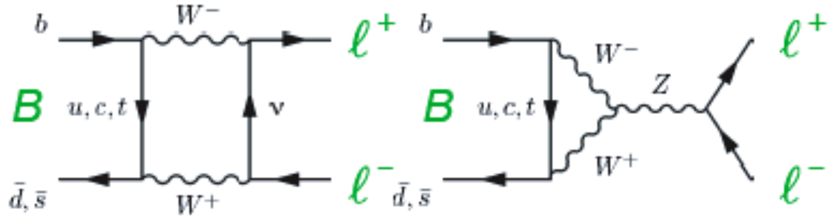
$B \to X_{s/d}\, \gamma$



C7 (Photon penguin)

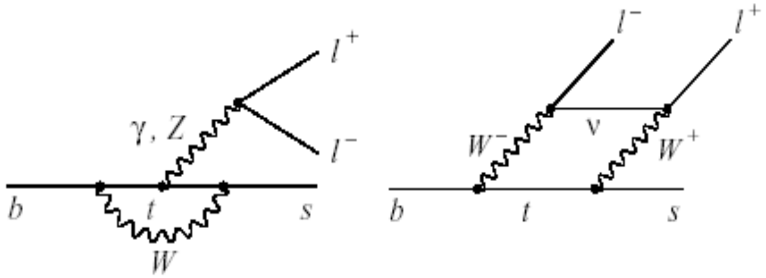
New physics could result in a distinctive pattern of deviations in observables across a variety of related FCNC modes

$B^0_{s/d} \to l^+ l^-$



C10 (Axial vector EW)

$B \to X_{s/d}\, l^+ l^-$



C7 ,C9 (Vector EW) and C10

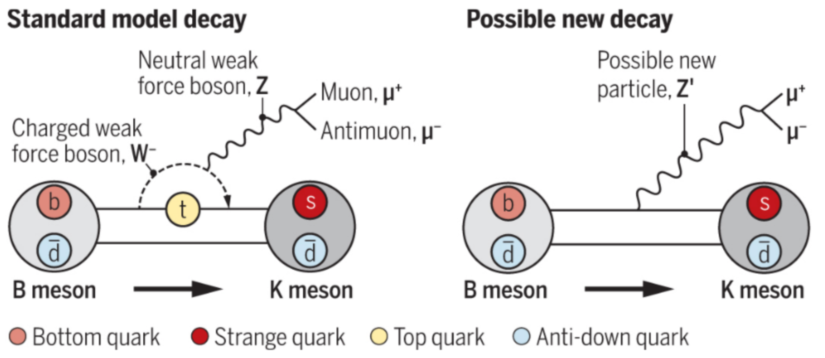
Potentially many observables:

- Branching fractions, CP asymmetries, kinematic distributions, angular distributions and asymmetries

$B \to K^{(*)} l^+ l^-$ and $R_{K^{(*)}}$

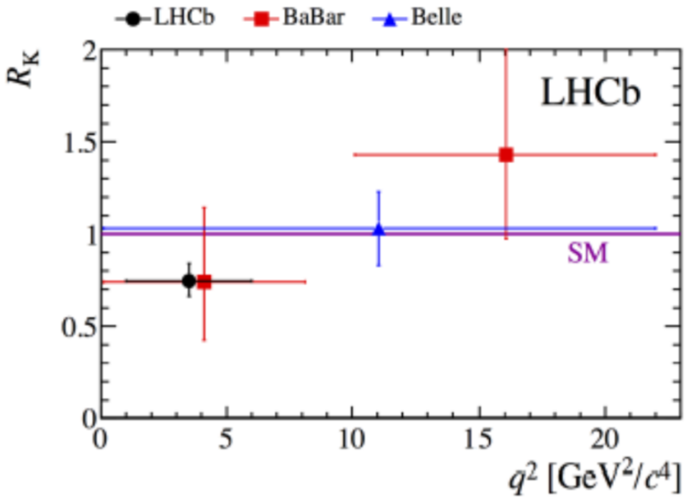
$B \to K^{(*)} \mu^+ \mu^-$

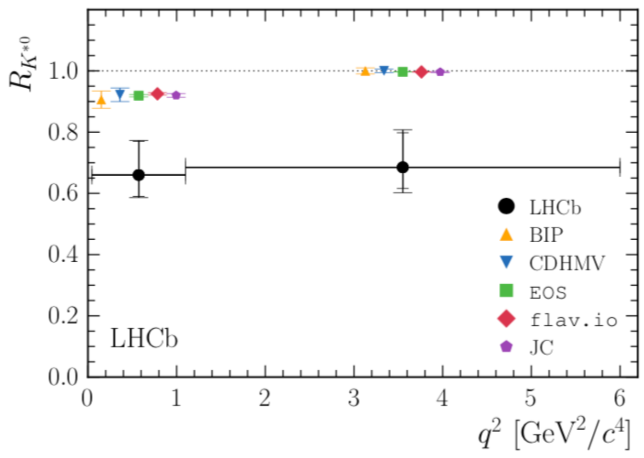
$B \to K^{(*)} e^+ e^-$



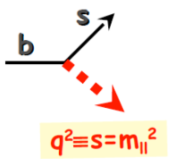
LHCb measurements in tension with SM expectations for ratio of muon and electronic final states:

$$R_{K^{(*)}}(q^2) = \frac{BF(B \to K^{(*)} \mu^+ \mu^-)}{BF(B \to K^{(*)} e^+ e^-)}$$





$R_{K^{*0}}$ vs q^2 for Run 1, LHCb Collaboration



$B \to K^{(*)} l^+ l^-$ and $R_{K(*)}$

$B \to K^{(*)} \mu^+ \mu^-$

$B \to K^{(*)} e^+ e^-$

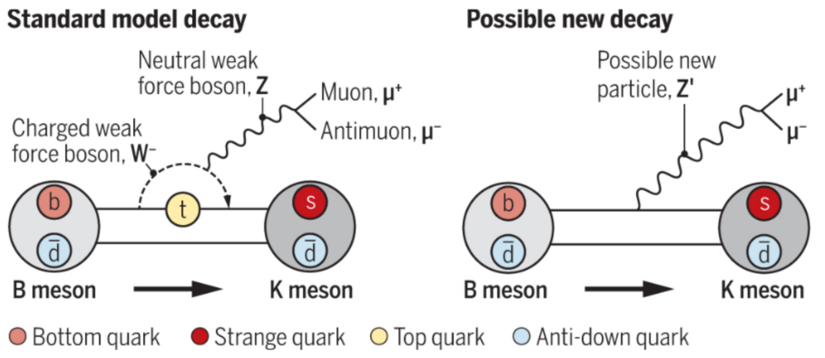
$B^0 \to K^{(*)0} l^+ l^-$

$B^+ \to K^{(*)+} l^+ l^-$

$B \to \pi\, l^+ l^-$

$B \to X_{s/d}\, l^+ l^-$

Belle II can measure absolute branching fractions, and has symmetric e/μ PID performance



... but there are also two distinct B charge/flavour states

...and two different final-state quark flavours (s,d)

... and also "inclusive" $X_{s/d}$ hadronic systems vs exclusive π, K, K* reconstruction

$B \to K^{(*)} l^+ l^-$ and $R_{K(*)}$

$B \to K^{(*)}\mu^+\mu^-$

$B \to K^{(*)}e^+e^-$

$B^0 \to K^{(*)0} l^+ l^-$

$B^+ \to K^{(*)+} l^+ l^-$

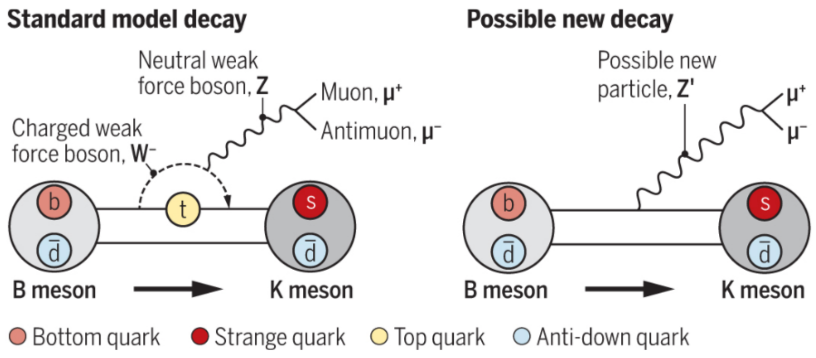
$B \to \pi\, l^+ l^-$

$B \to X_{s/d}\, l^+ l^-$

$B \to K^{(*)}\tau^+\tau^-$

$B \to K^{(*)}\nu\bar{\nu}$

$B \to K^{(*)}\tau^+ l^-$



...also two additional lepton species (τ,ν) which can be studied

...and of course lepton flavour violating modes.

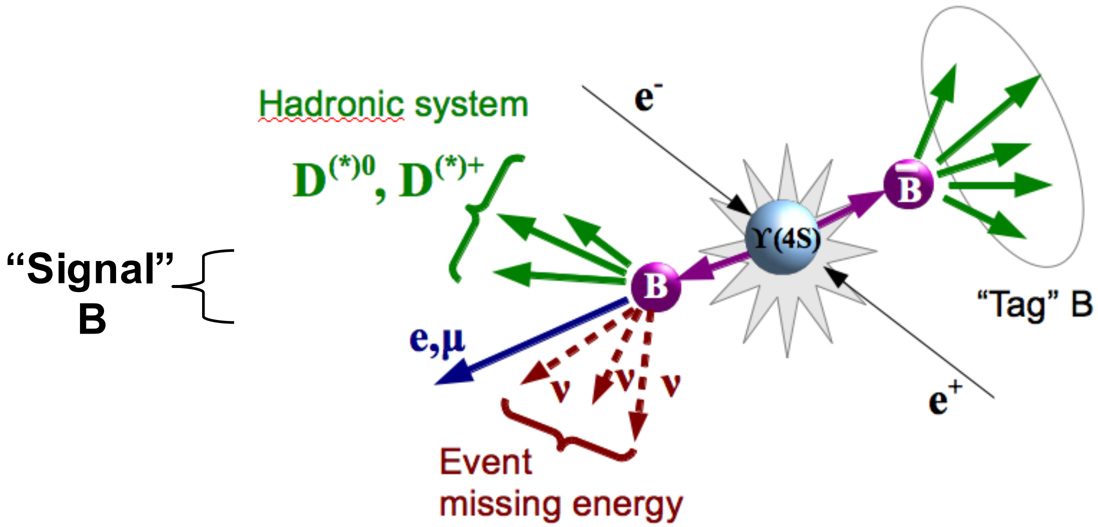
All with distinct experimental sensitivities and systematics, and theoretical sensitivities to various new physics scenarios

Missing energy decays

Unique capability to study B decay modes with missing energy:

- FCNC modes such as $B\to K^{(*)}\nu\nu$, $B^0\to\nu\nu$, $B\to K^{(*)}\tau^+\tau^-$ etc.
- Semileptonic B decays such as $B\to D^{(*)}\tau^+\nu$, $B^+\to\mu^+\nu$, and $B^+\to\tau^+\nu$

Precisely known CM energy, combined with exclusive hadronic reconstruction of the accompanying B, permit the decay daughters of missing energy decays to be uniquely identified:



$$m_{BC} \equiv \sqrt{E^{*2}_{\rm beam} - p^{*2}_B}$$
$$\Delta E^* \equiv E^*_B - E^*_{\rm beam}$$

Similar methodology exists for reconstructing semileptonic B tags

Expected Beam Backgrounds in Phase 3

Table 59: Belle II detectors most vulnerable to beam backgrounds in SuperKEKB Phase 3. Upper limits and safety factors assume ten years of SuperKEKB operation at full luminosity. Only detectors with safety factors less than five are included. Although all limits have been converted into rates, in several cases the detector degradation is a cumulative, rather than rate-dependent effect. Neutrons flux numbers are in units of $10^{11}/\text{cm}^2/\text{yr}$ and NIEL-damage weighted. See text for further explanation and discussion.

15^{th} campaign

Belle II detector	quantity	expected value	upper limit value	safety factor	dominant process(es)
PXD	occupancy	1.1%	3 %	3	two-photon, synchrotron radiation
CDC	wire hit rate	400 kHz	200 Hz	0.5	radiative Bhabha, two-photon
CDC	electr. neutron flux	2.5	1	0.3	radiative Bhabha, Touschek
CDC	electr. dose rate	250 Gy/yr	100	0.3	radiative Bhabha, two-photon
TOP	PMT hit rate	5-8 MHz	1 MHz	0.2	radiative Bhabha, two-photon
TOP	PCB neutron flux	0.35	0.5	3	radiative Bhabha, Touschek
ARICH	HAPD neutron flux	0.3	1.0	3	radiative Bhabha
ECL	crystal dose rate	6 Gy/yr in BWD	10 Gy/yr	2	radiative Bhabha, two-photon

- dangerously high
- *predictions,* based purely on simulation
- assume perfect collimators, with ideal settings

Goal of beam background group: achieve comprehensive understanding: *measure* all beam background components, and their scaling with beam conditions, in Phases 1,2

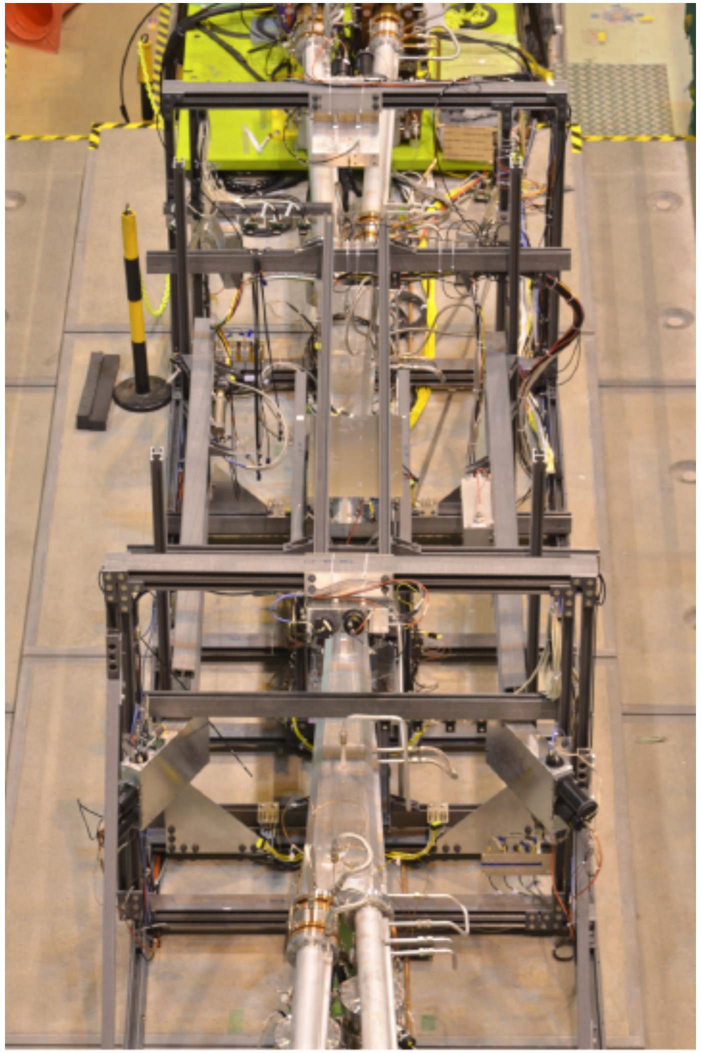
Phase 1

- Phase 1 results: https://arxiv.org/abs/1802.01366
- 1.5 years of work. 101 pages, 127 figures.
- *Accepted by NIMA May 30th 2018*

BEAST II Phase 1

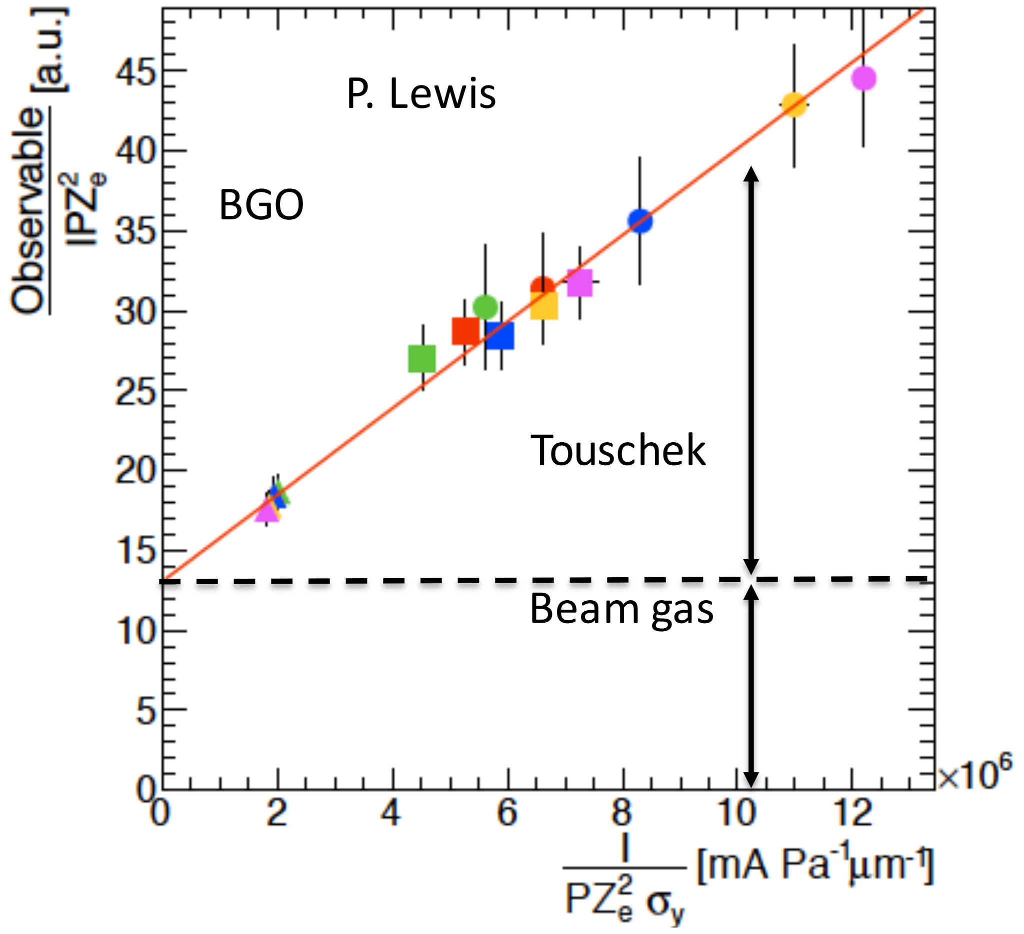
- Collection of detectors aimed at studying beam backgrounds
- Independent detectors, no global event building

System	Detectors Installed	Unique Measurement
PIN Diodes	64/64	neutral vs charged radiation dose
Diamonds	4/4	ionizing radiation dose
Micro-TPCs	4/4	directional fast neutron flux
He-3 tubes	4/4	thermal neutron rate
Crystals	6/6 Csi(Tl) 6/6 Csi 6/6/ LYSO	EM energy spectrum
BGO	8/8	EM dose rate
"CLAWS"	8/8	Inj. BG
Scintillator	4/4	EM particle rate



Beam size scans

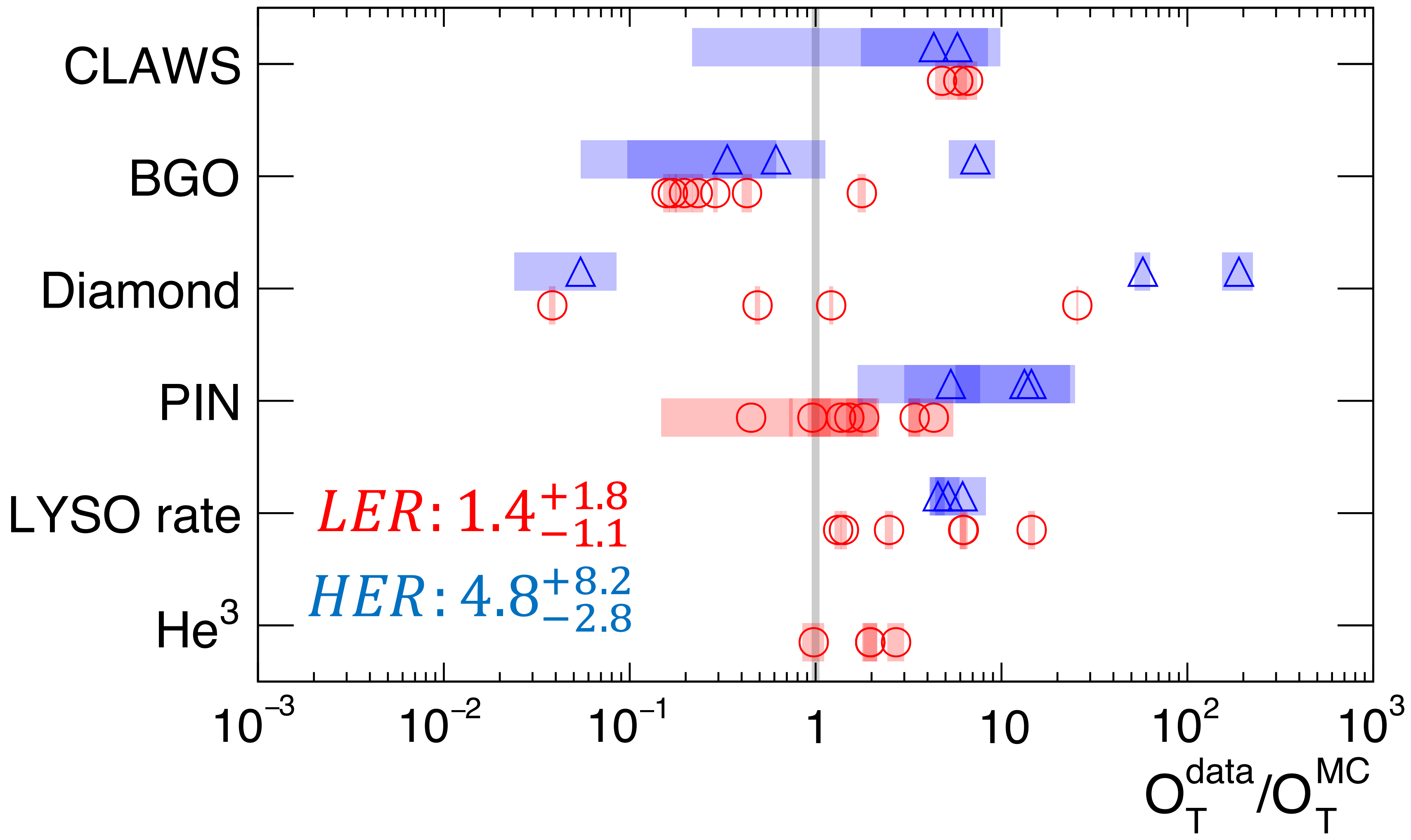
- Allowed us to separate beam-gas & Touschek contributions
- Allows validation of simulation
- Then use simulation to extrapolate to Phase 3
- *We think separating backgrounds into components and then extrapolating is the only reliable way to extrapolate backgrounds to Phase 3*



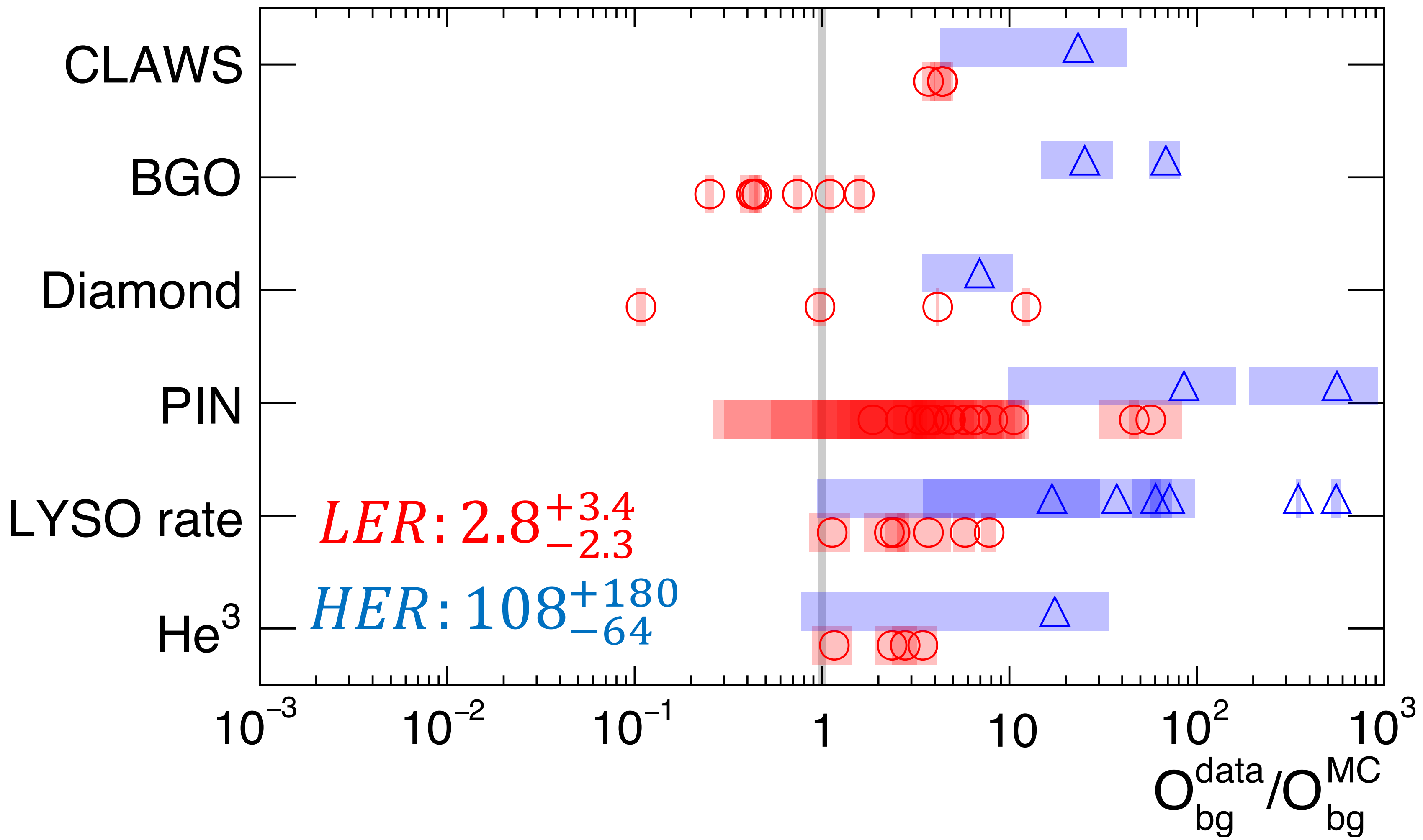
$$\frac{\text{Observable}}{IPZ_e^2} = A + B \cdot \frac{I}{PZ_e^2\sigma_y}$$

Touschek Experiment/Simulation ratios

Lewis, Jaegle, and all detector groups

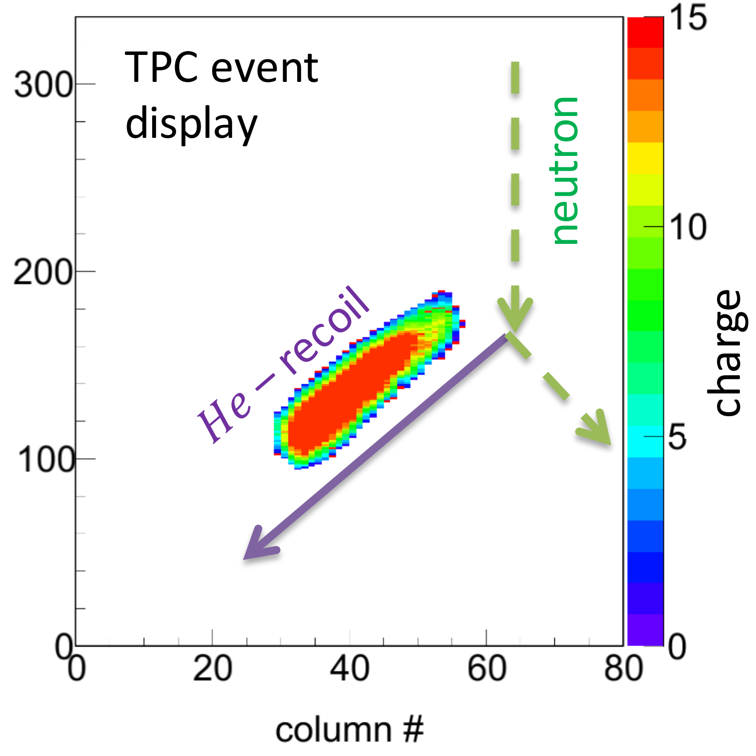


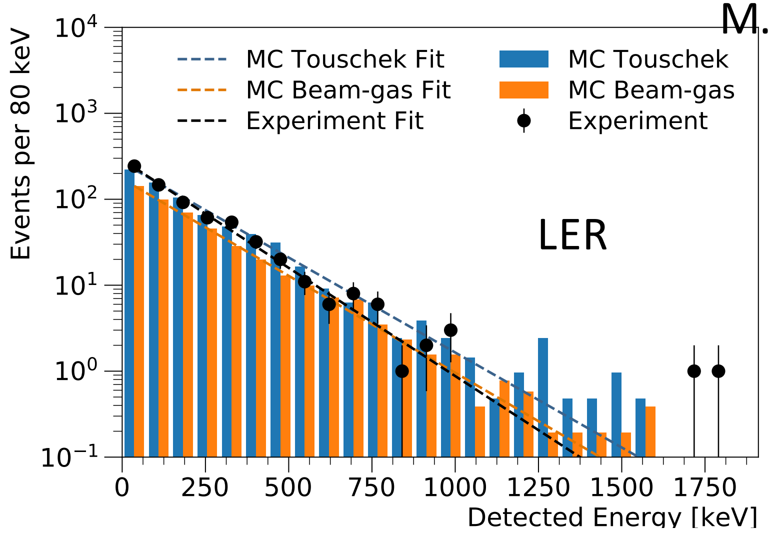
Beam-gas Experiment/Simulation ratios

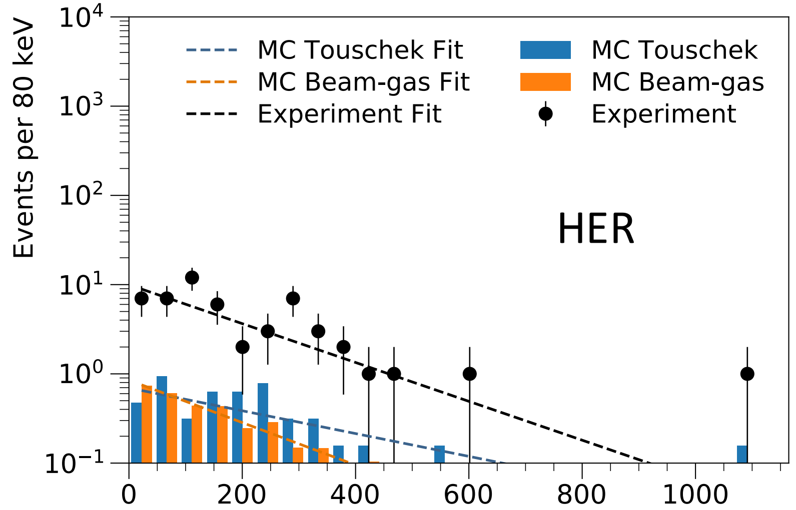


Fast Neutrons: Recoils

M. Hedges

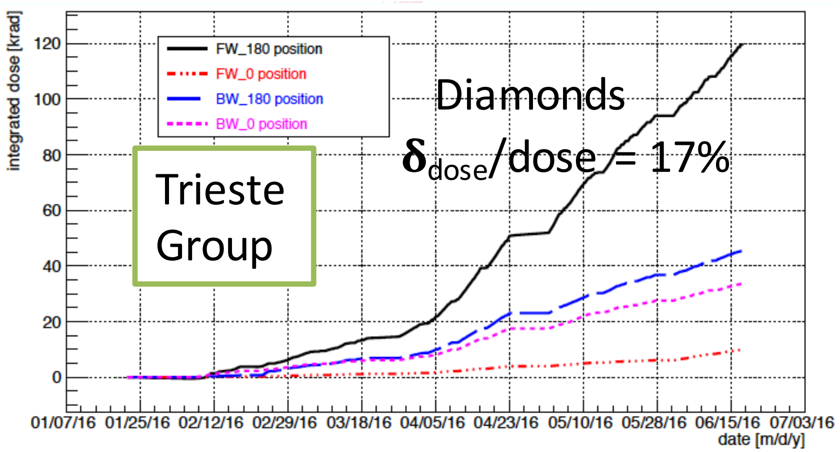


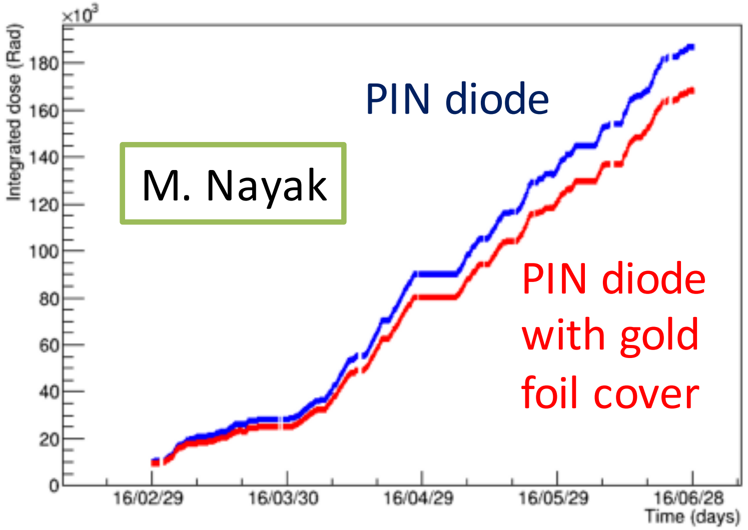


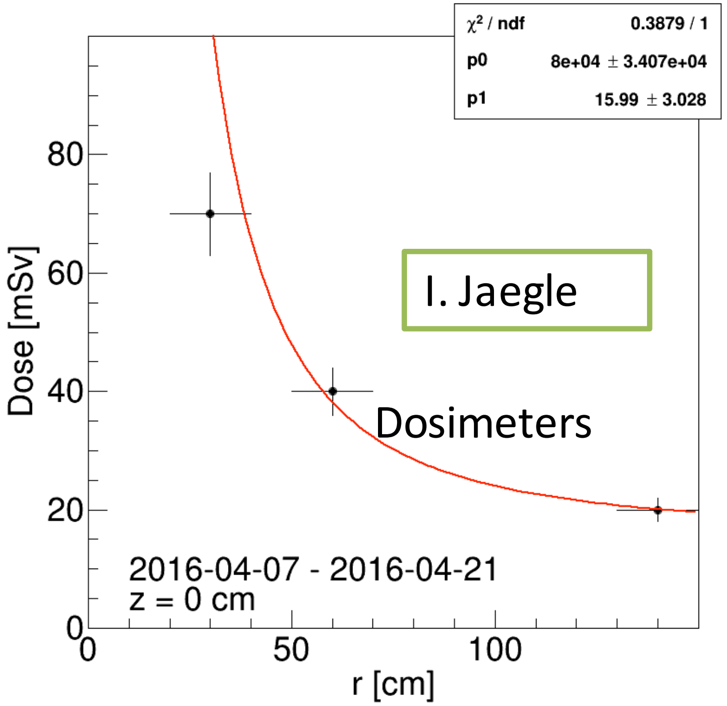


- Recoil energy *spectrum* (=negative derivative of neutron spectrum) agrees quite well with simulation
- Validates simulation of neutron production, propagation, and material description
- LER *rate* agrees fairly well with simulation. *5 x higher fast neutron rate from HER than predicted.*

Phase 1 Dosimetry







- Total phase 1 dose on surface of beam pipe ~ 100-200 kRad.
- PINs, diamond sensors, and dosimeters roughly consistent *within uncertainties*.
- No significant dose from Synchrotron Radiation (preliminary limit: < 1.7 krad)

Status at end of Phase 1

Background Type	Simulation Method
Touschek	SAD generates scattered particles and tracks them. Particles lost in IR are passed to GEANT4 fullsim.
Beam-gas Coulomb	
Beam-gas Brems	
Radiative Bhabha	BBBrem/BHWide → GEANT4
QED 2-photon	Aafh → GEANT4
Synchrotron Radiation	SR generation in GEANT4
Injection BG	Injection particles provided by accelerator group→ SAD →GEANT4
Beam dust	-
neutrons	

Touschek, Beam-gas Coulomb, Beam-gas Brems: measured in phase 1

Radiative Bhabha, QED 2-photon, Synchrotron Radiation: to be measured in phase 2

Injection BG, Beam dust, neutrons: measured in phase 1

- Beam gas: appears elevated w.r.t. simulation, but subdominant BG → level still safe
- Touschek: agrees fairly well with simulation, appears safe.
- Neutrons: elevated and should be checked further in Phase 2
- Radiative Bhaba, two-photon, and SR most dangerous and not yet measured
  → major goal for Phase 2 to measure these