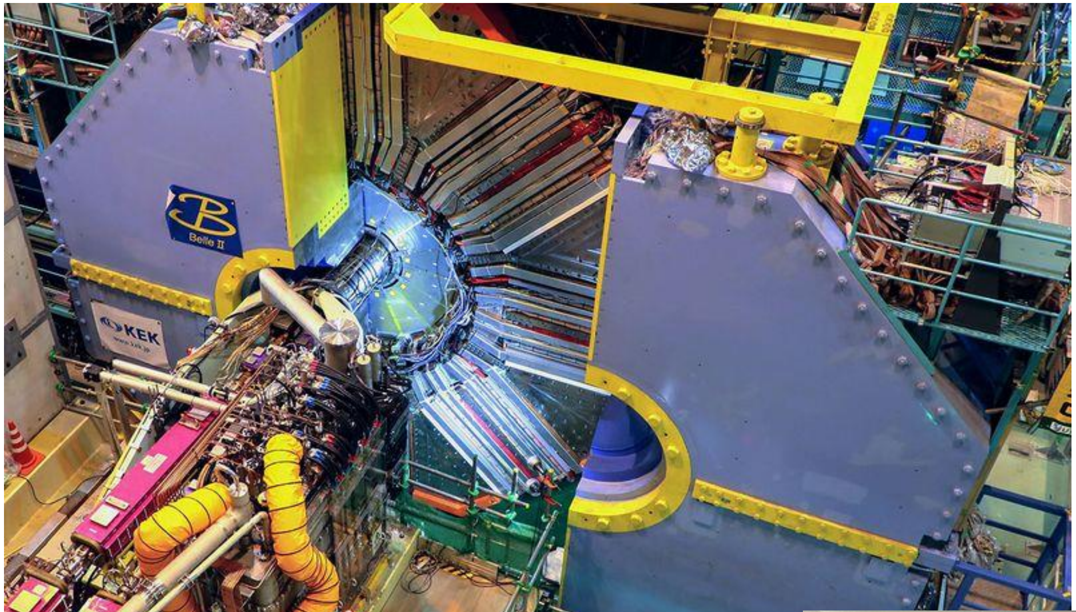
Belle II/SuperKEKB Status and Outlook

Tom Browder, University of Hawai’i at Manoa



The complex superconducting final focus is partially visible here (before closing the endcap).

Some Highlights from First Collisions and the Phase 2 Belle II Pilot Run.

Physics and the Road Ahead to Phase 3

The Geography of the International Belle II collaboration

Belle II now has grown to ~800 researchers from 25 countries

This is <u>rather unique</u> in Japan and Asia. The only comparable example is the T2K experiment at JPARC, which is also an <u>international collaboration</u>

Youth and potential: There are ~267 graduate students in the collaboration

Belle II India

Indian Institute of Science Education and Research (IISER) Mohali
(Prof. V. Bhardwaj)
Indian Institute of Technology, Bhubaneswar
(Prof. S. Bahinipati)
Indian Institute of Technology, Guwahati
(Prof. B. Bhuyan, D. Kalita)
Indian Institute of Technology, Hyderabad
(Prof. A. Giri)
Indian Institute of Technology, Madras
(Prof. P. Behera, Prof. J. Libby)
Institute of Mathematical and Sciences, Chennai
(Prof. R. Sinha)
Panjab Univ. Chandigarh + Panjab Agricultural Univ.
(Prof. S. Bansal, Prof. J.B. Singh+ R. Kumar)
Tata Institute of Fundamental Research, Mumbai
(Prof. T. Aziz, Prof. G. Mohanty, Dr. P. Krishnan, K. Rao, S. Mayakar, P. Shingade))
MNIT Jaipur
(Prof. K. Lalwani)

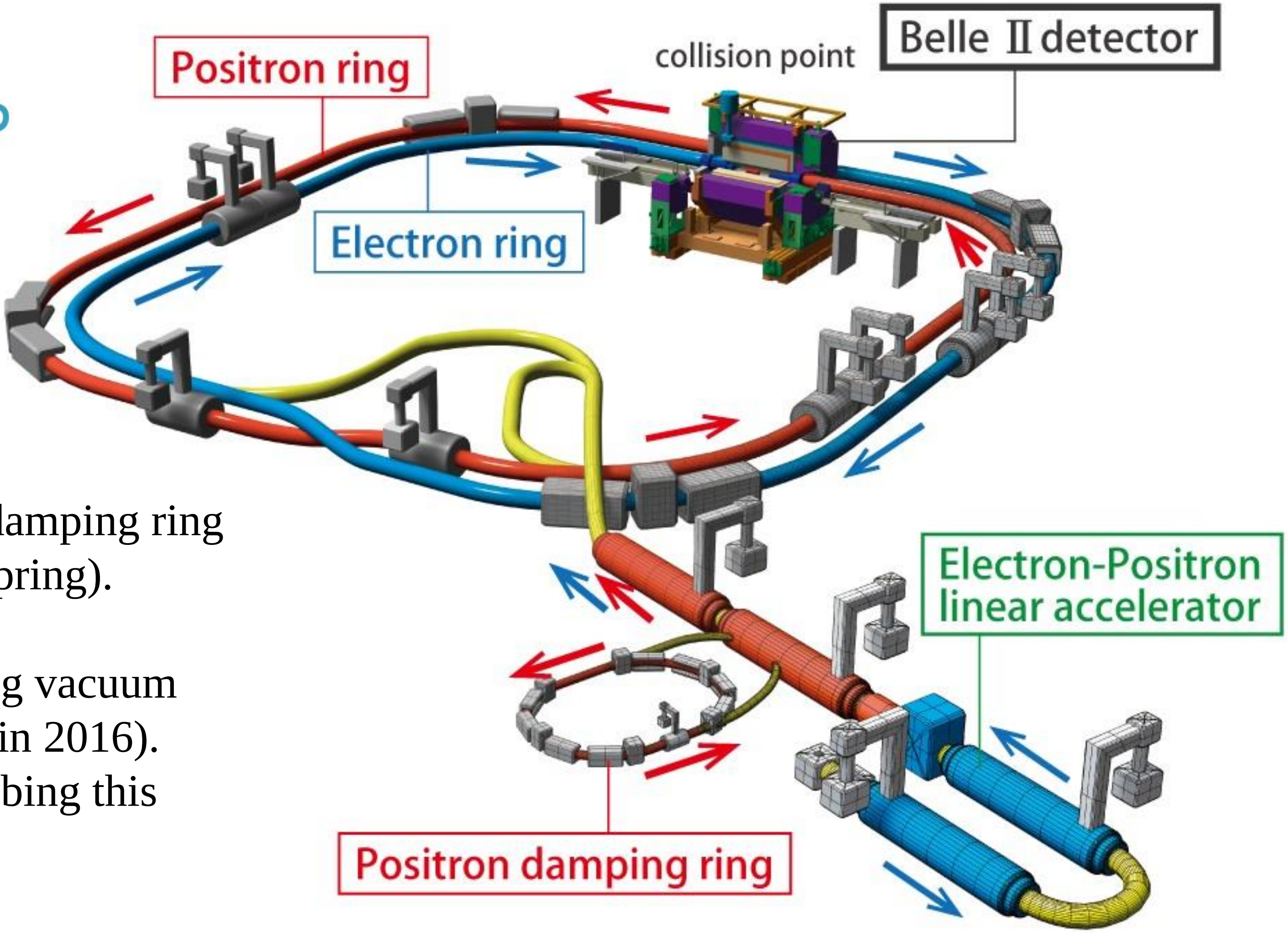
+ 15 graduate students

Indian contributions to rare B decays, γ / ϕ_3 measurements and charm physics on Belle + *major impact in Belle II first physics*

Clean room for SVD assembly with Indian team at IPMU in Japan

India *built* layer 4 of the Belle II silicon vertex detector. Major GRID computing planned.

SuperKEKB, the first new collider in particle physics since the LHC in 2008 (electron-positron (e^+e^-) rather than proton-proton (pp))



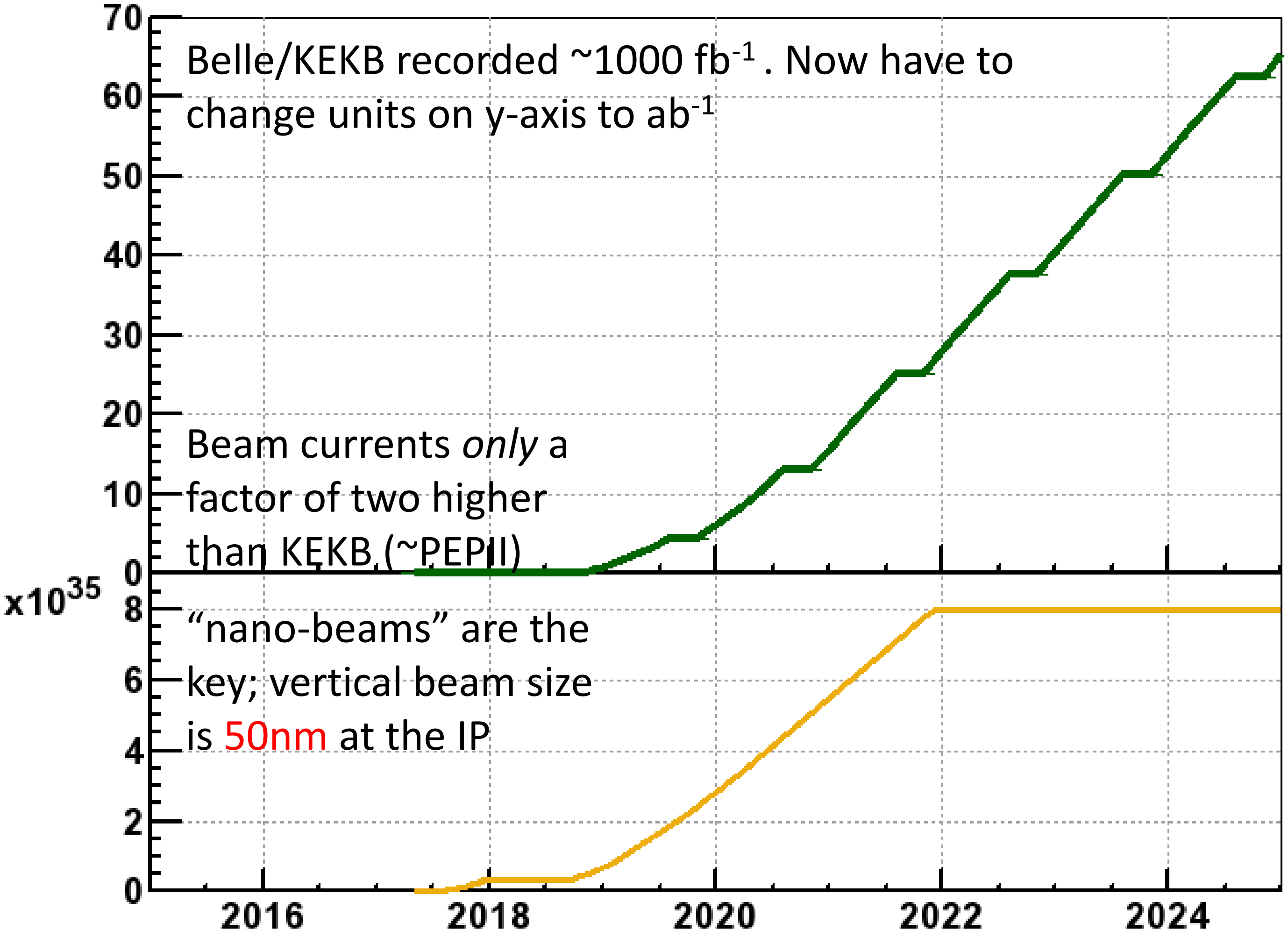
Some items to note:

1) Brand-new positron damping ring (commissioned this spring).

2) New 3 km positron ring vacuum chamber (commissioned in 2016). Optics and vacuum scrubbing this spring.

3) New complex superconducting final focus (commissioned this spring).

SuperKEKB/Belle II Luminosity Profile

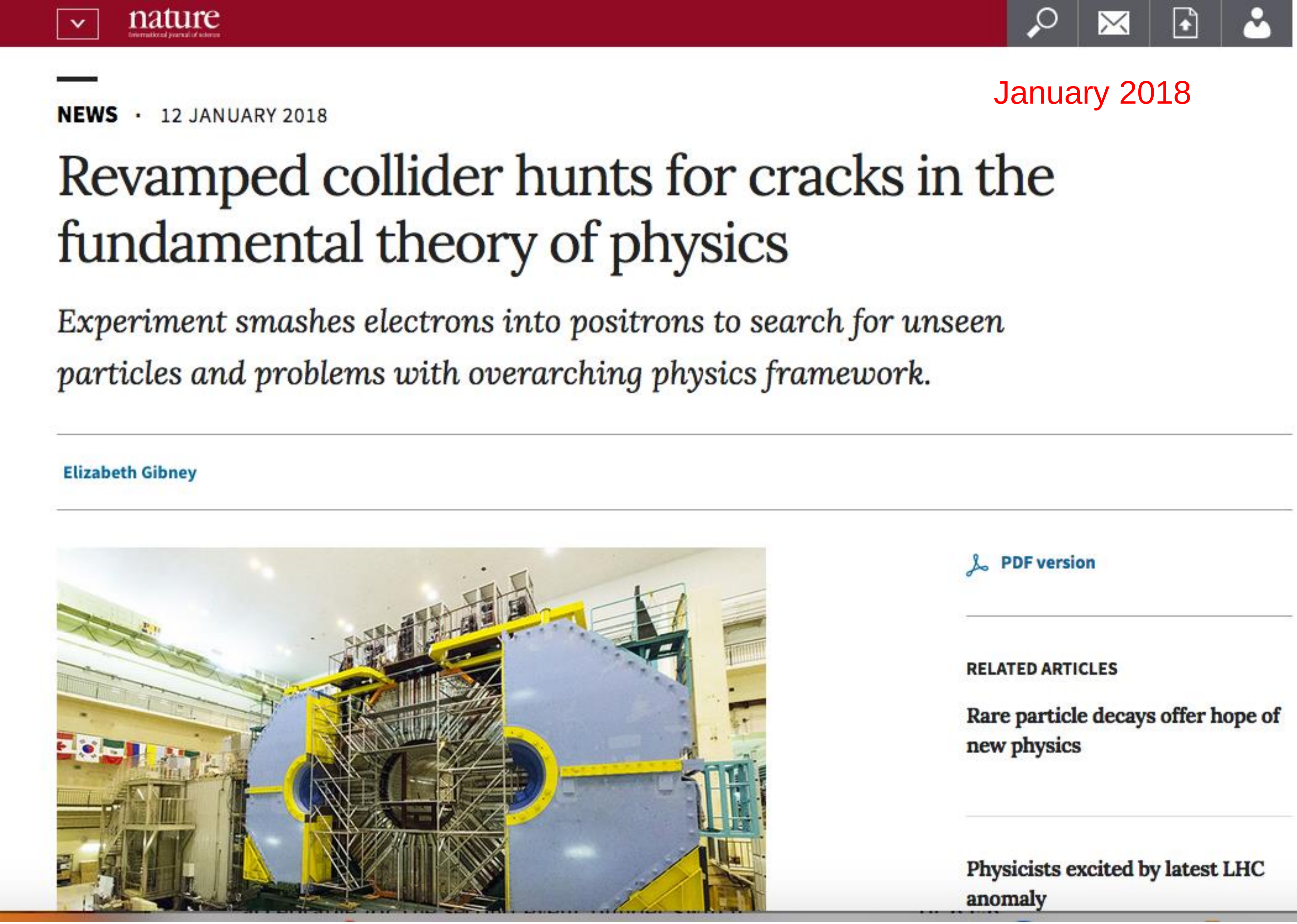


Belle/KEKB recorded ~1000 fb^{-1}. Now have to change units on y-axis to ab^{-1}

Beam currents *only* a factor of two higher than KEKB (~PEPII)

“nano-beams” are the key; vertical beam size is 50nm at the IP

N.B. To realize this steep turn-on, requires close cooperation between Belle II and SuperKEKB [and some *international collaboration* on the accelerator].



January 2018

nature

NEWS · 12 JANUARY 2018

Revamped collider hunts for cracks in the fundamental theory of physics

Experiment smashes electrons into positrons to search for unseen particles and problems with overarching physics framework.

Elizabeth Gibney

PDF version

RELATED ARTICLES

Rare particle decays offer hope of new physics

Physicists excited by latest LHC anomaly

https://www.nature.com/articles/d41586-018-00162-x

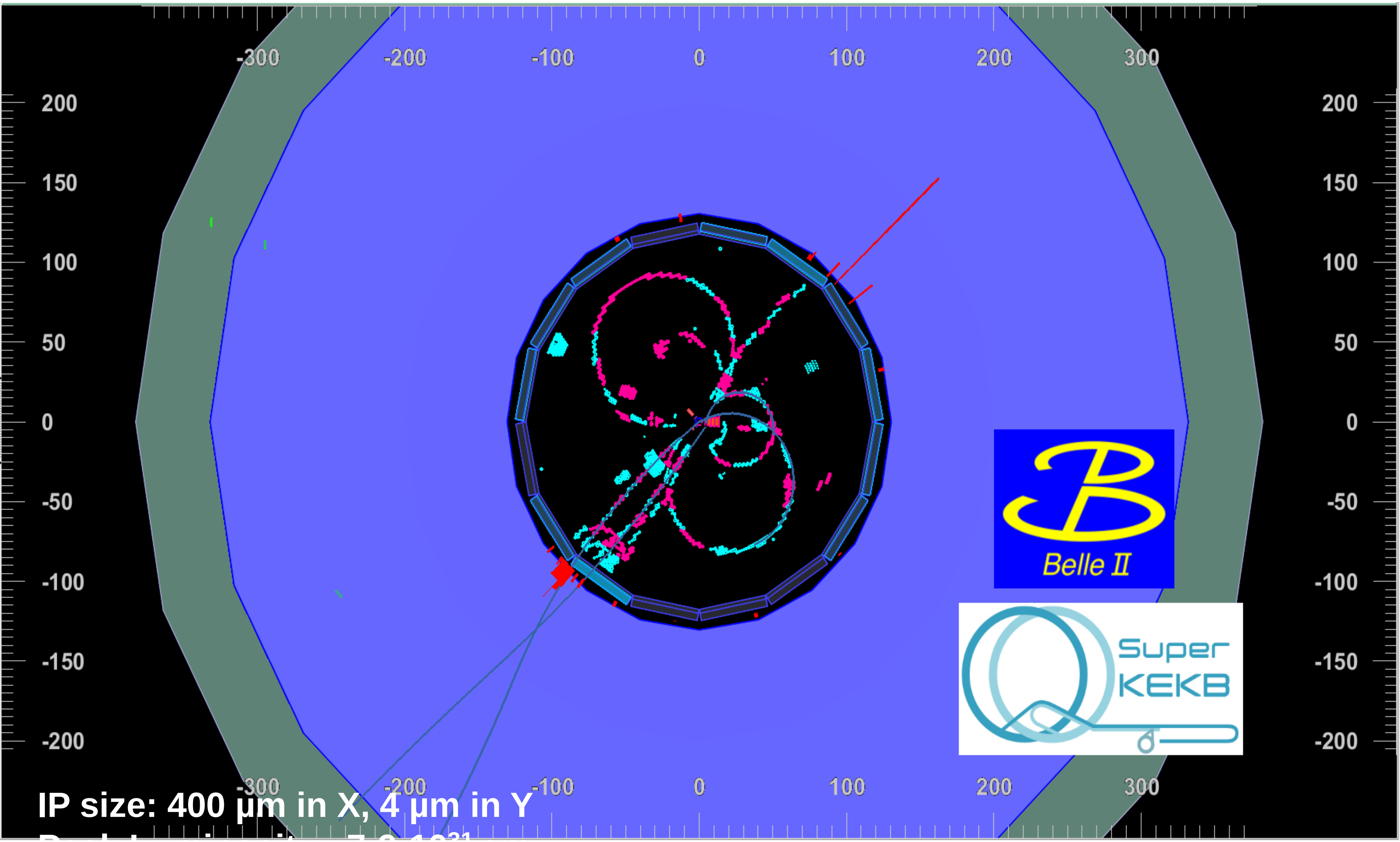
Some Belle II jargon

PHASE 1: Simple background commissioning detector (diodes, diamonds TPCs, crystals…). No final focus. Only *single* beam background studies possible [started in Feb 2016 and completed in June 2016.

SuperKEKB Commissioning Detector
BEAST II
獣
Belle II Collaboration

PHASE 2: More elaborate inner background commissioning detector (VXD samples). Full Belle II outer detector. Full superconducting final focus. *No vertex detectors. Collisions !* *[Phase 2 collisions: April 26-July 17, 2018]*

Antimatter-matter annihilation in Tsukuba, Japan



IP size: 400 µm in X, 4 µm in Y

Probably $e^+e^- \rightarrow g^* \rightarrow q\bar{q}$

The scene at the experimental control room in Tsukuba Hall B3

This is scientific history in the making: SuperKEKB/Belle II joins DORIS/ARGUS, CESR/CLEO, and PEP-II/BaBar and KEKB/Belle

Welcome to the world of large crossing angle nano-beams !

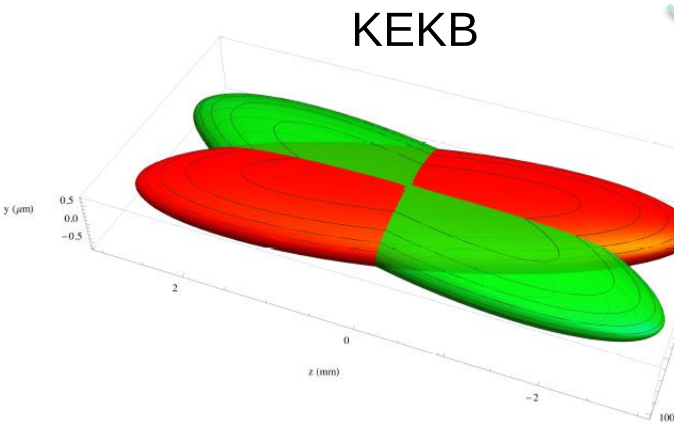
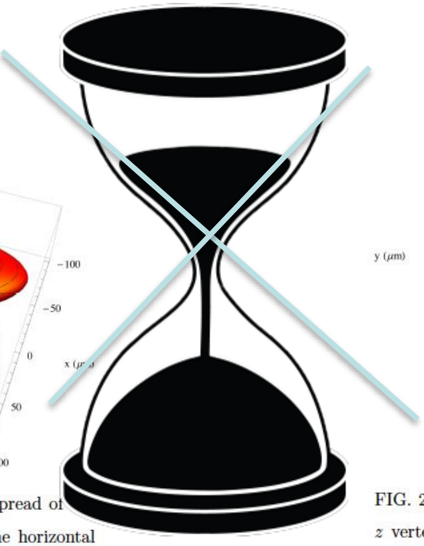


FIG. 1: Schematic view of Belle-I beam crossing at the interaction region. The spread of the z vertex distribution can be estimated as $\sigma_z = \frac{\sqrt{\epsilon_x \beta_x^*}}{\sqrt{2}\phi_x}$ where for Belle-I optics the horizontal emittance $\epsilon_x = 20 \times 10^{-6}$ mm, $\beta_x^* = 1200$ mm, and the crossing angle $\phi_x = 11$ mrad leading to expected $\sigma_z = 1$ cm.



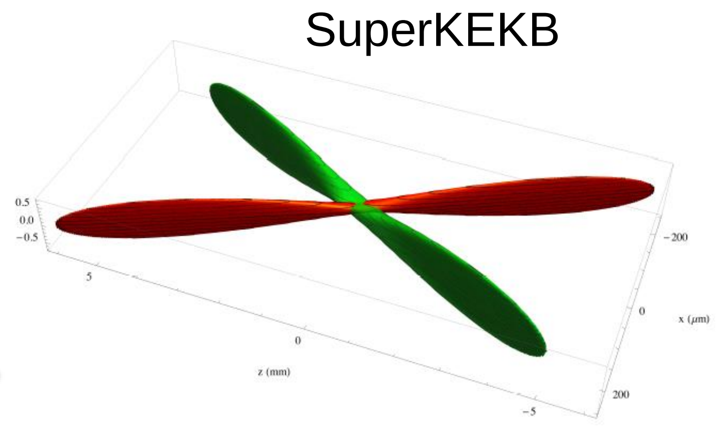
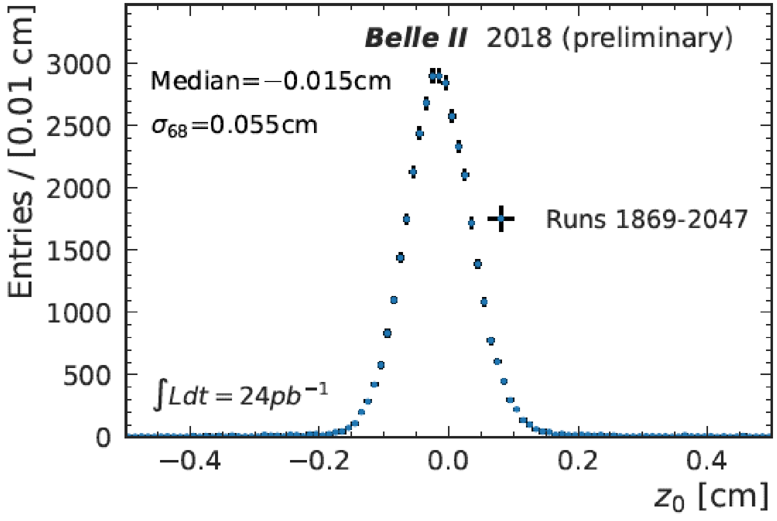


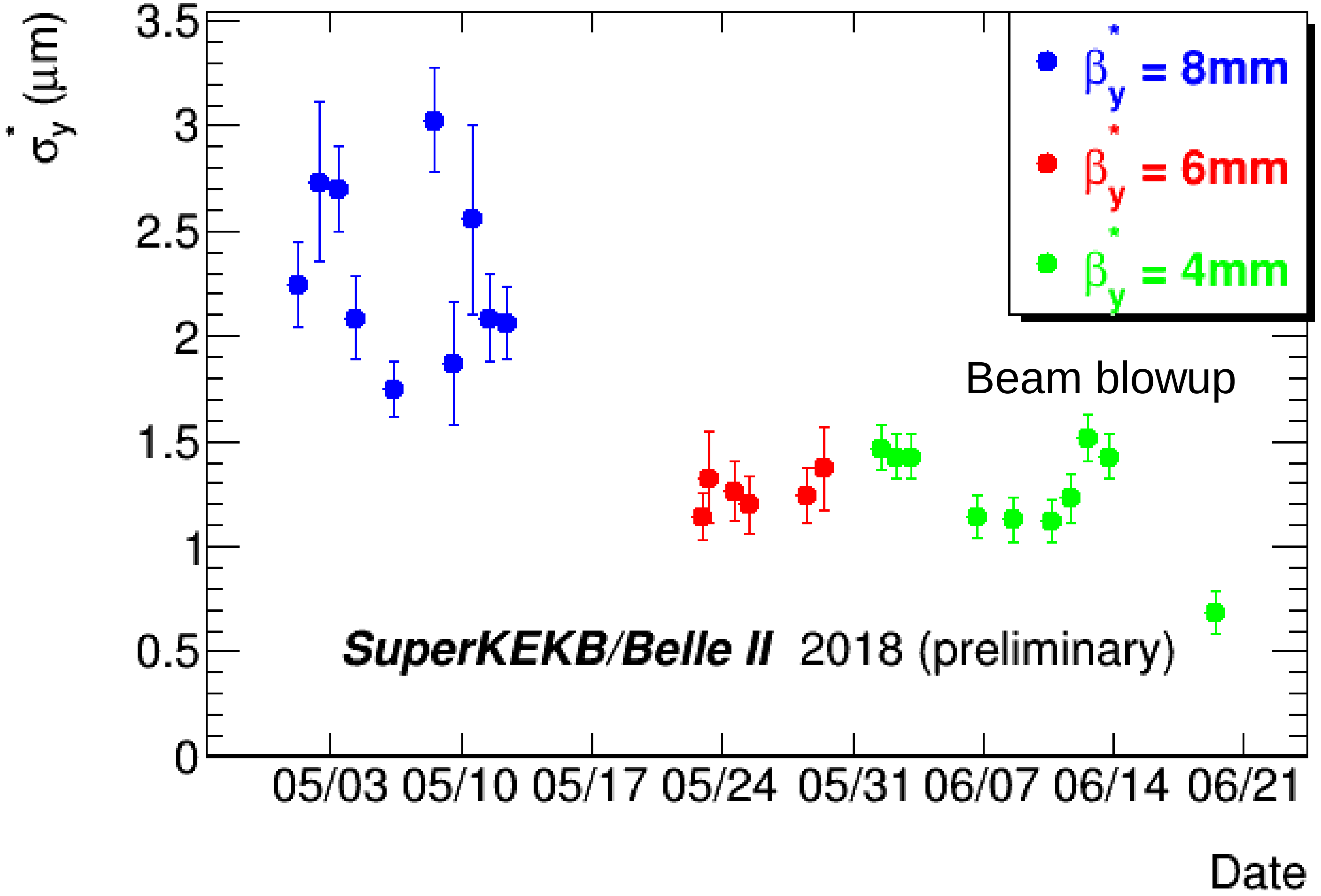
FIG. 2: Schematic view of Belle-II beam crossing at the interaction region. The spread of the z vertex distribution can be estimated as $\sigma_z = \frac{\sqrt{\epsilon_x \beta_x^*}}{\sqrt{2}\phi_x}$ where for Belle-II optics in phase 2 the horizontal emittance $\epsilon_x = 4 \times 10^{-6}$ mm, $\beta_x^* = 200$ mm, and the crossing angle $\phi_x = 41$ mrad leading to expected $\sigma_z = 0.049$ cm.

As expected, the effective bunch length is *reduced* from ~10 mm (KEKB) to 0.5 mm (SuperKEKB)

We measure this in two track events in Belle II data.



How do we measure the vertical height of nanobeams ?
Ans: Width of Luminosity scans with diamond detectors

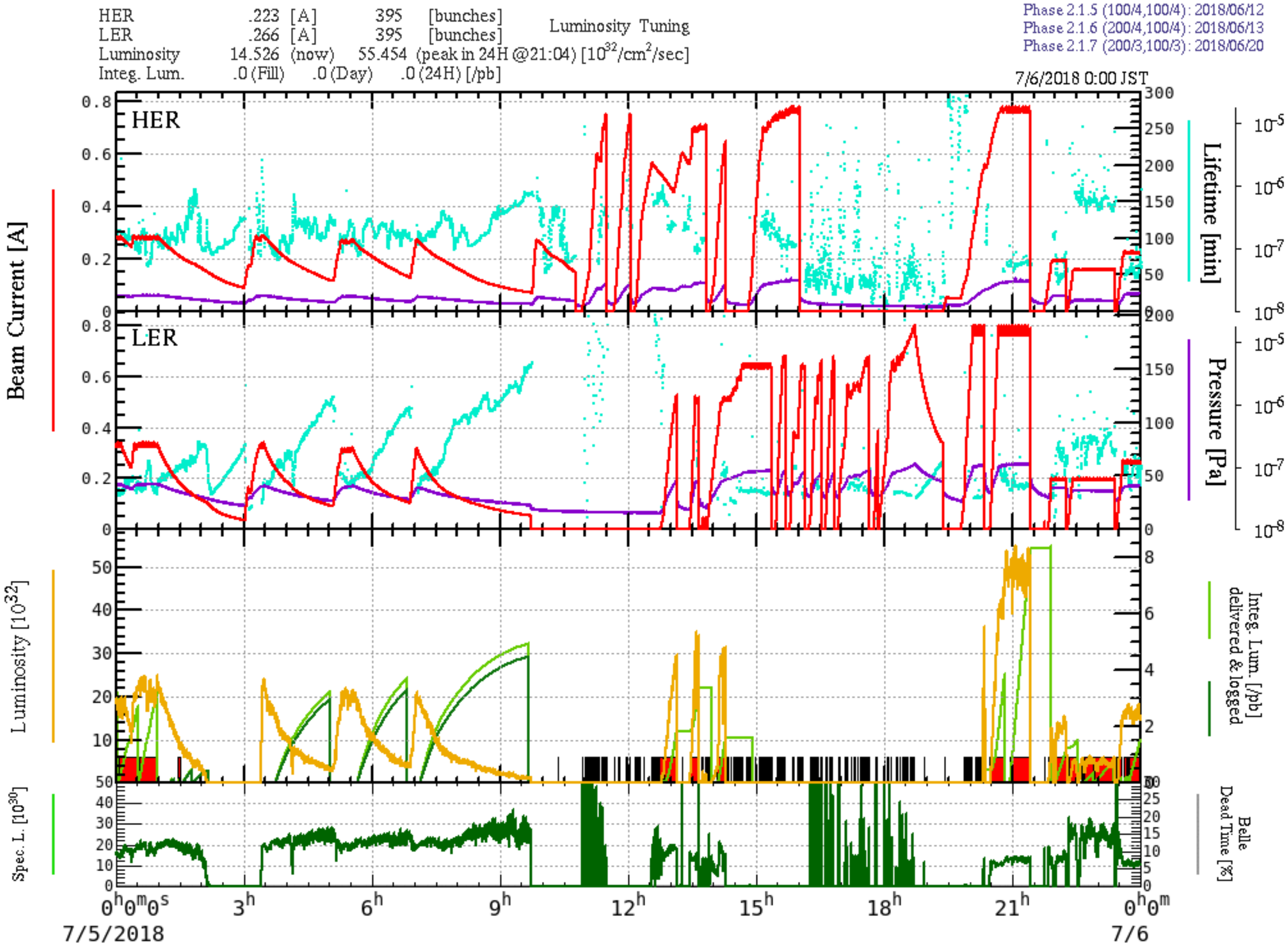


At Phase 2 peak luminosity of 5 x 10^{33}/cm^2/sec , the vertical spot is ~700nm high. There is still beam-beam blowup at high currents. At low currents, the vertical spot size is 330 nm high (the final goal is O(50nm) with full capability of the QCS system).

Keep on squeezing the two beams with the superconducting final focus β_y^*=3mm, making sure that the two “thin pancakes” are well aligned. One then adds beam current…..

$$L_{peak} = 5.5 \times 10^{33} / cm^2 / \sec$$

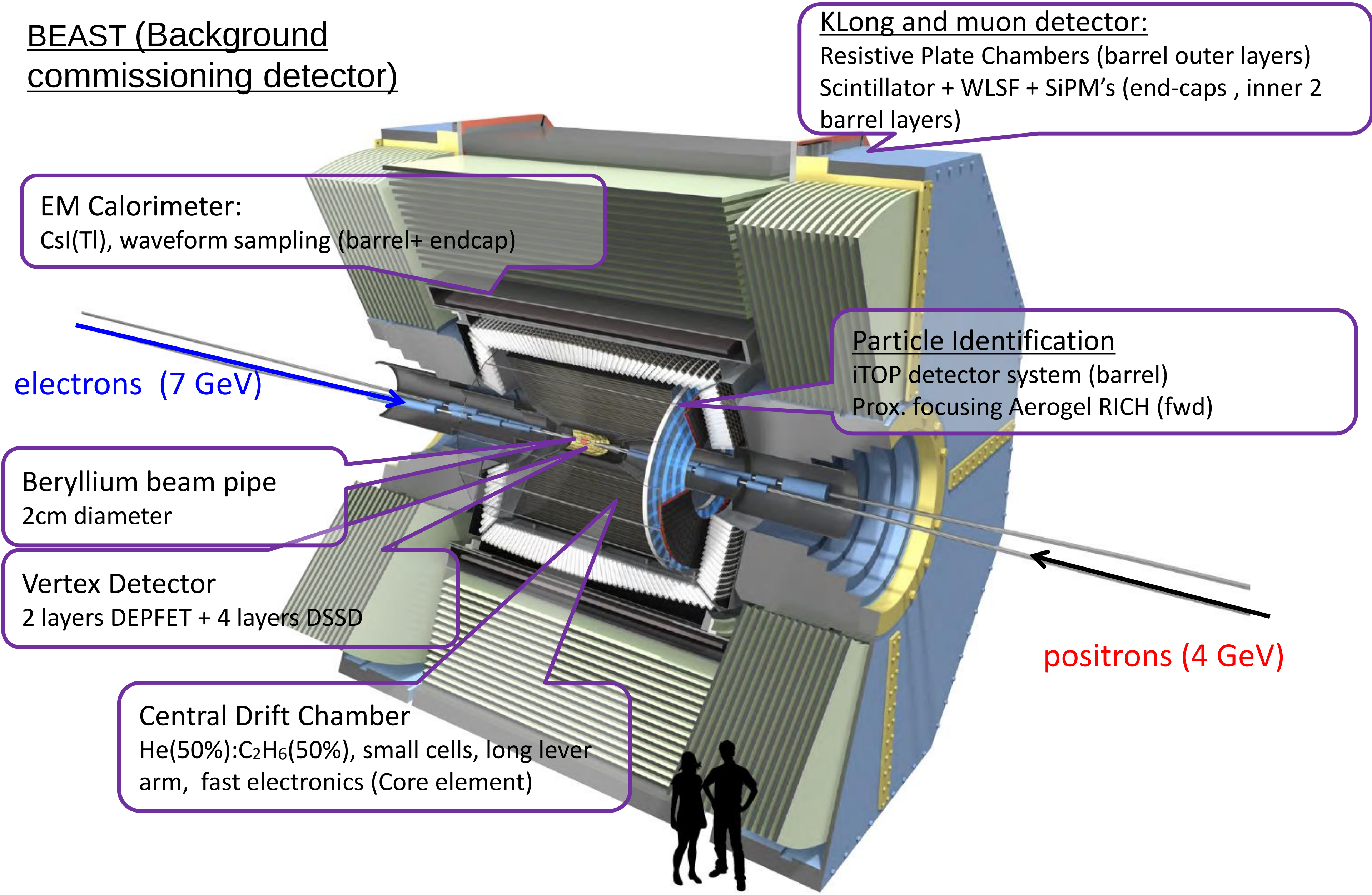
Phase 2,
July 2018



N.B. Still a long way to go with the superconducting final focus (one order of magnitude in β_y^*)

Luminosity tuning has priority. When accelerator physicists become tired, Belle II takes data (usually owl shift). Only able to record 0.5 fb^{-1}.

Belle II Detector



BEAST (Background commissioning detector)

KLong and muon detector:
Resistive Plate Chambers (barrel outer layers)
Scintillator + WLSF + SiPM’s (end-caps , inner 2 barrel layers)

EM Calorimeter:
CsI(Tl), waveform sampling (barrel+ endcap)

electrons (7 GeV)

Particle Identification
iTOP detector system (barrel)
Prox. focusing Aerogel RICH (fwd)

Beryllium beam pipe
2cm diameter

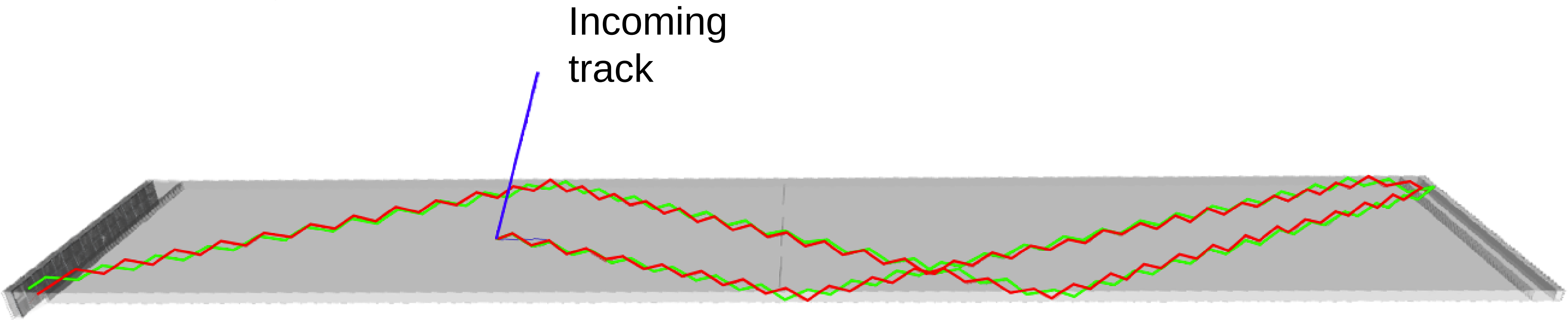
Vertex Detector
2 layers DEPFET + 4 layers DSSD

positrons (4 GeV)

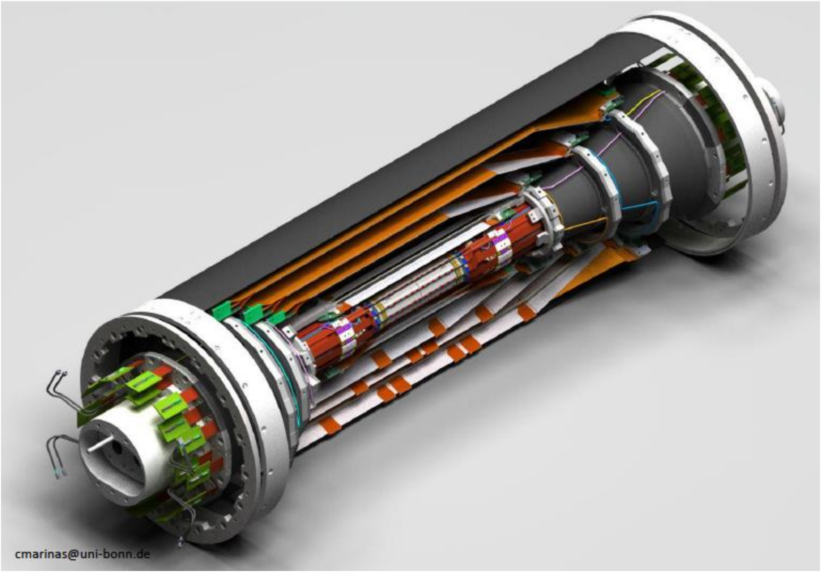
Central Drift Chamber
He(50%):C_2H_6(50%), small cells, long lever arm, fast electronics (Core element)

Barrel Particle Identification (uses Cherenkov radiation)

The paths of Cherenkov photons from a 2 GeV pion and kaon interacting in a TOP quartz bar. (Japan, US, Slovenia, Italy)



Vertexing/Inner Tracking

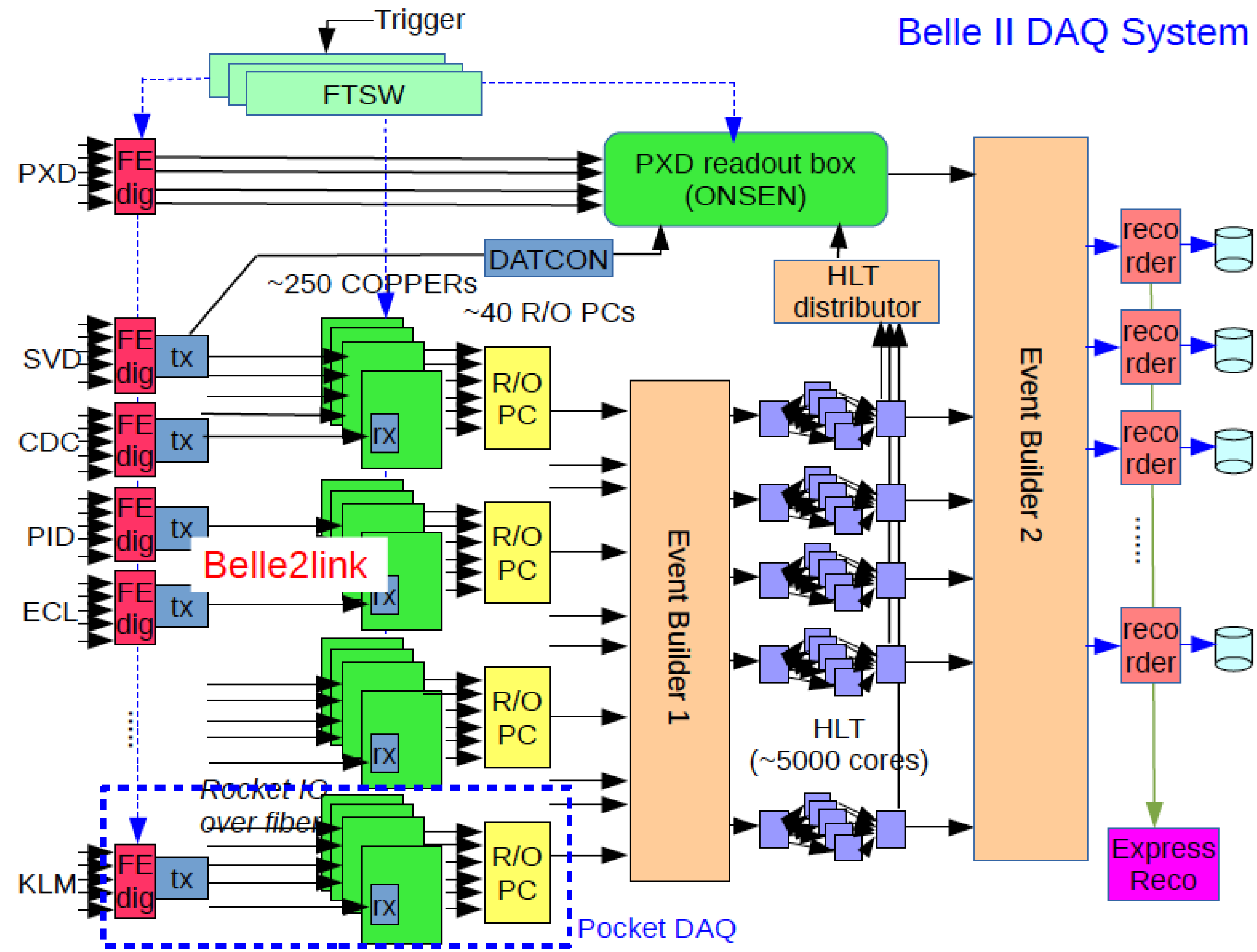

cmarinas@uni-bonn.de

Beampipe r= 10 mm
DEPFET pixels (Germany, Czech Republic…)
    Layer 1 r=14 mm
    Layer 2 r= 22 mm
DSSD (double sided silicon detectors)
    Layer 3 r=38 mm (Australia)
    Layer 4 r=80 mm (India)
    Layer 5 r=115 mm (Austria)
    Layer 6 r=140 mm (Japan)

FWD/BWD
Italy

+Poland, Korea

Belle II has a modern DAQ and readout system



Item to note: Front-end readout electronics and Gb fiber optic link(Belle2link) to the back-end.

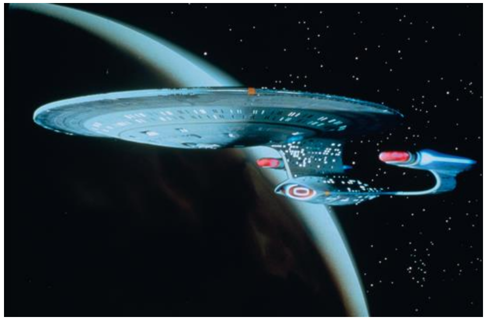
Item to note: Note ROI(Region of Interest) for PXD data volume.

Advanced & Innovative Technologies used in Belle II

Pixelated photo-sensors play a central role

MCP-PMTs in the iTOP
HAPDs in the ARICH
SiPMs in the KLM

Collaboration with Industry



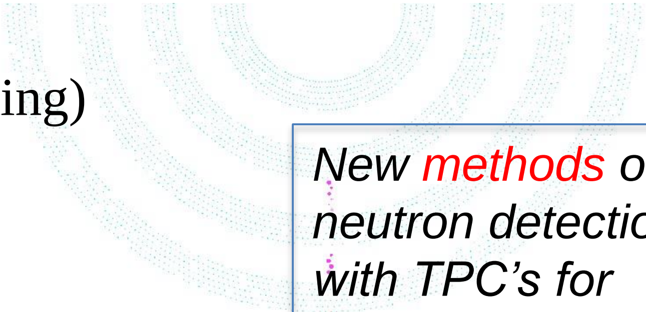
DEPFET pixel sensors

Waveform sampling with precise timing is “saving our butts”.

Front-end custom ASICs (Application Specific Integrated Circuits) for all subsystems
→ DAQ with high performance network switches, large HLT software trigger farm

→ a 21st century HEP experiment.

KLM (*TARGETX* ASIC)
ECL (New waveform sampling backend with good timing)
TOP (*IRSX* ASIC)
ARICH (KEK custom ASIC)
CDC (KEK custom ASIC)
SVD (APV2.5 readout chip adapted from CMS)



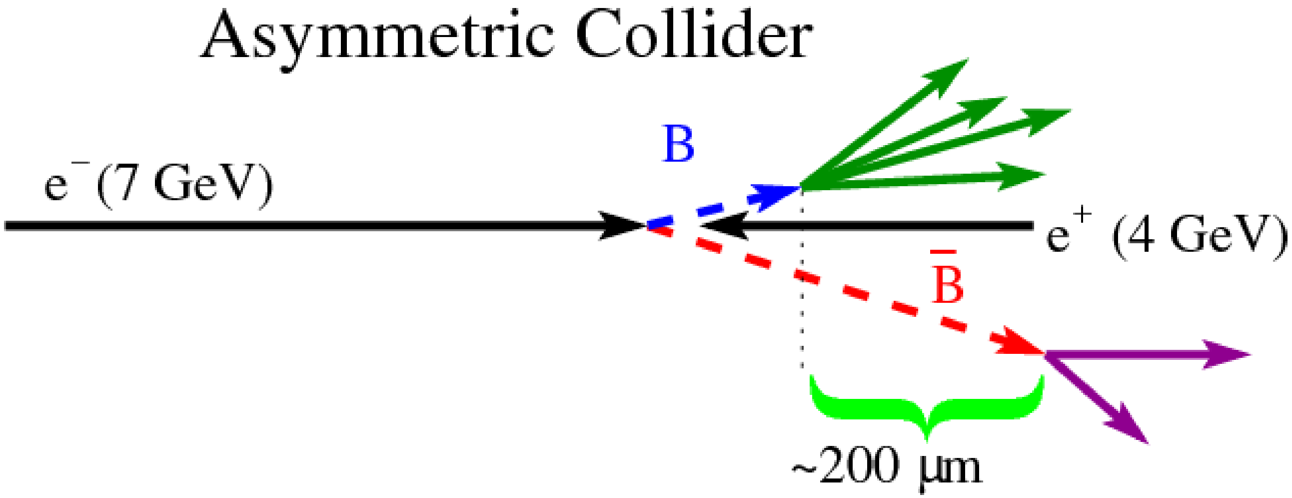
New methods of neutron detection with TPC’s for the background. Directions !

The B-anti B meson pairs at the Upsilon(4S) are produced in a coherent, *entangled* **quantum mechanical state**.

$$|Y\rangle = |B^0(t_1, f_1)\overline{B^0}(t_2, f_2)\rangle - |B^0(t_2, f_2)\overline{B^0}(t_1, f_1)\rangle$$

Need to measure decay times to observe CP violation (particle-antiparticle asymmetry).

One B decays →collapses the flavor wavefunction of the other anti-B. (Exercise: Also one B must decay before the other can mix)



Not to scale

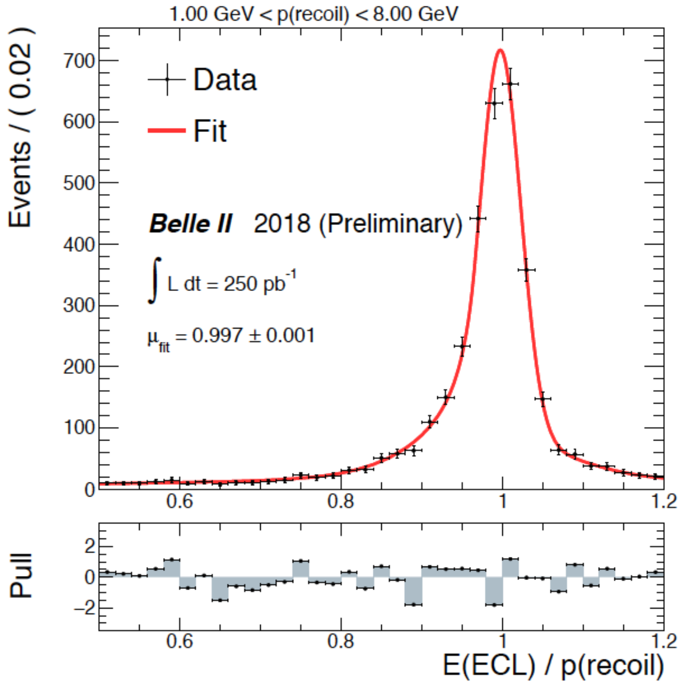
The beam energies are asymmetric (7 on 4 GeV)

The decay distance is increased by around a factor ~7

Most of the Belle II detector subsystems are working well.

Some nice examples of *signals* involving photons.

$e^+e^- \to \mu^+\mu^-\gamma$

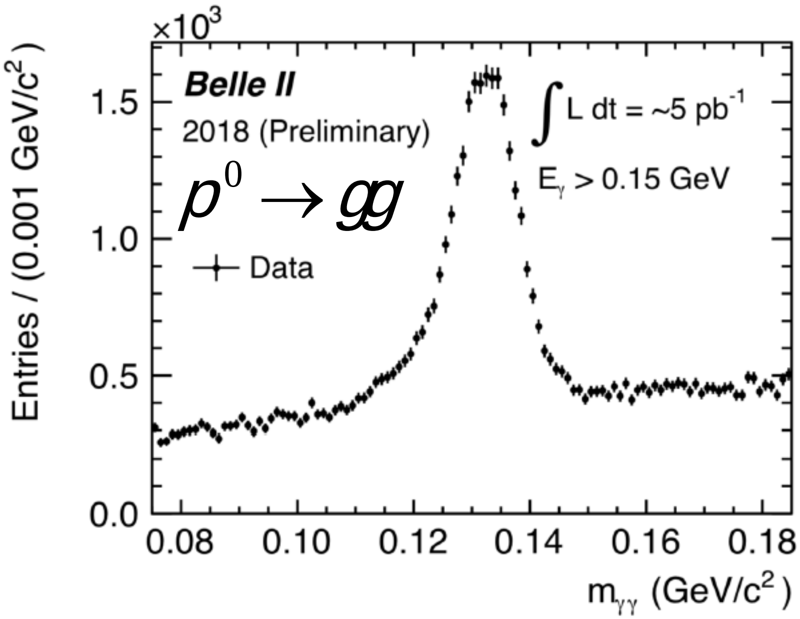


Single Photon Lines

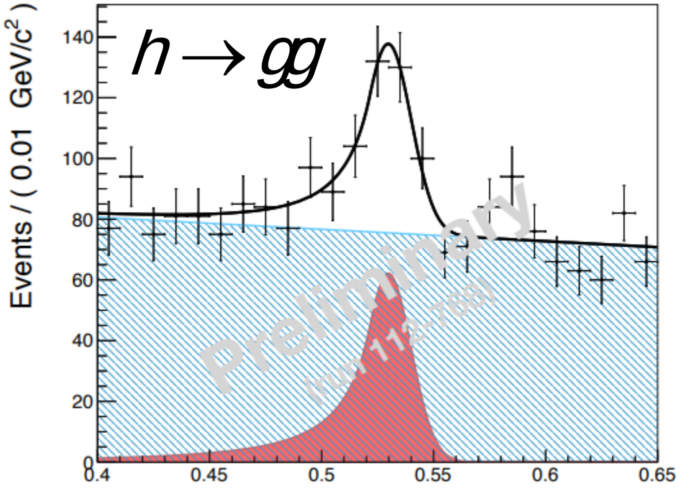
Ready for the dark sector !

$e^+e^- \to \gamma X$

$e^+e^- \to \gamma ALPS \to \gamma(\gamma\gamma)$

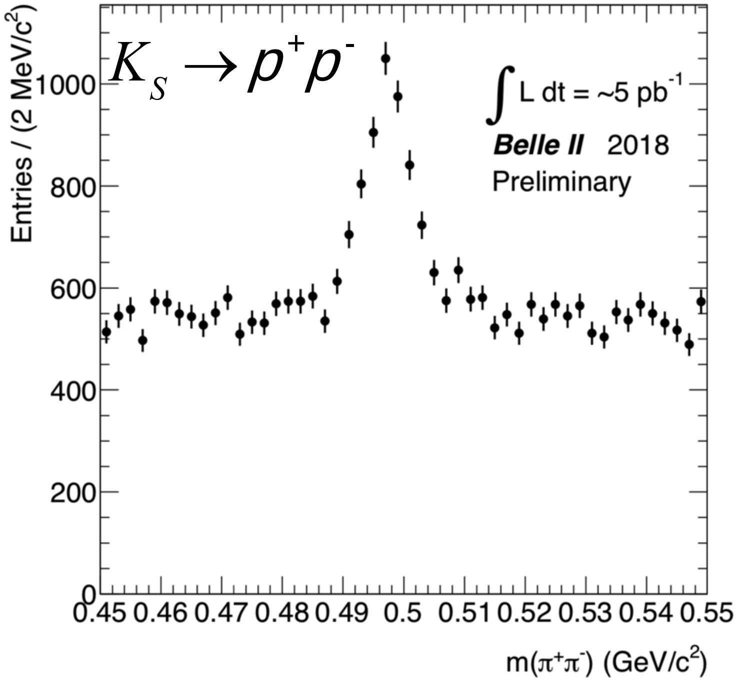


$\pi^0 \to \gamma\gamma$

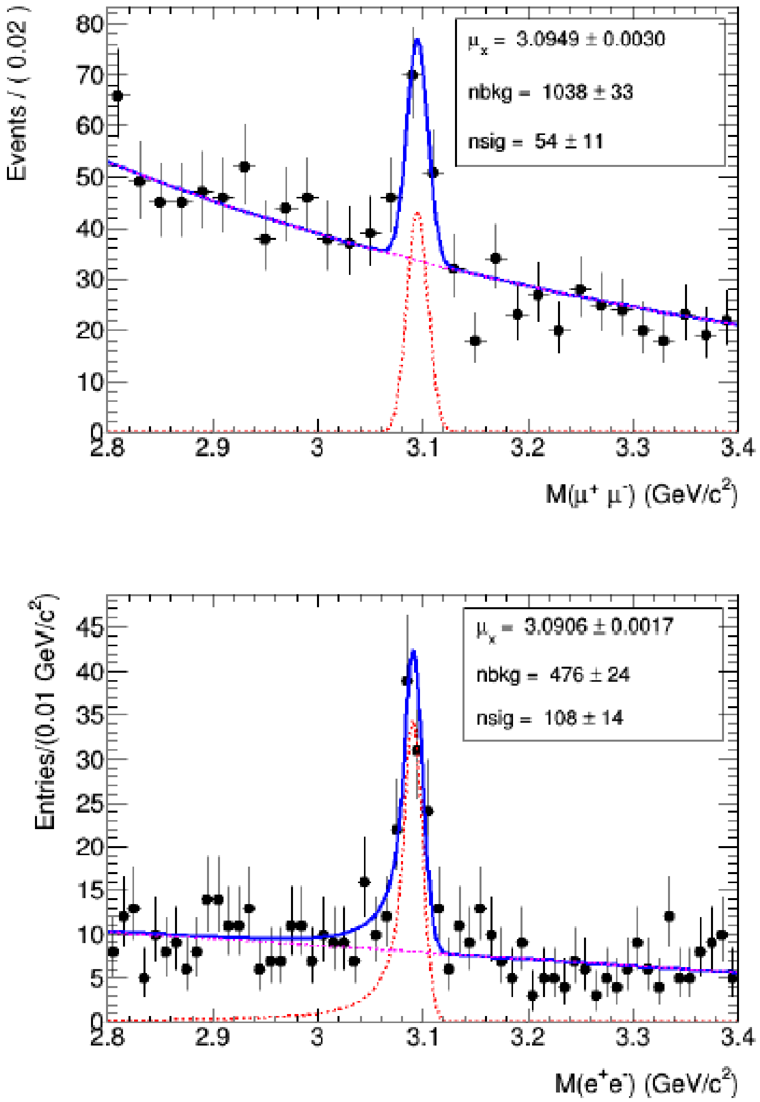


$h \to \gamma\gamma$

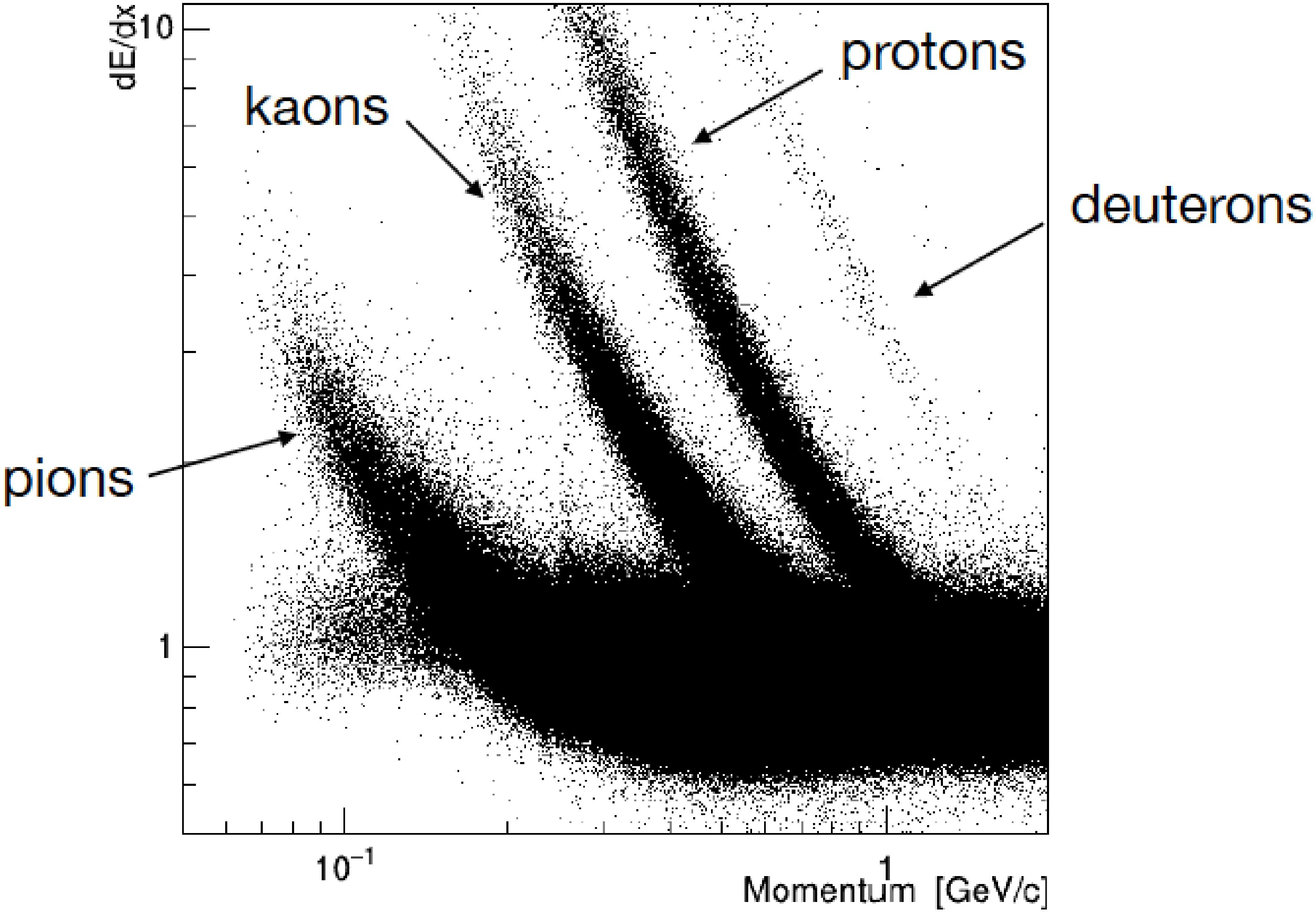
Most of the Belle II detector subsystems are working well.
Here are some *signals* involving charged tracks.



$J/\psi \to \mu^+\mu^-$, $J/\psi \to e^+e^-$



Performance of CDC dE/dx particle identification with early calibrations in the hadronic event sample.



Extra cuts:

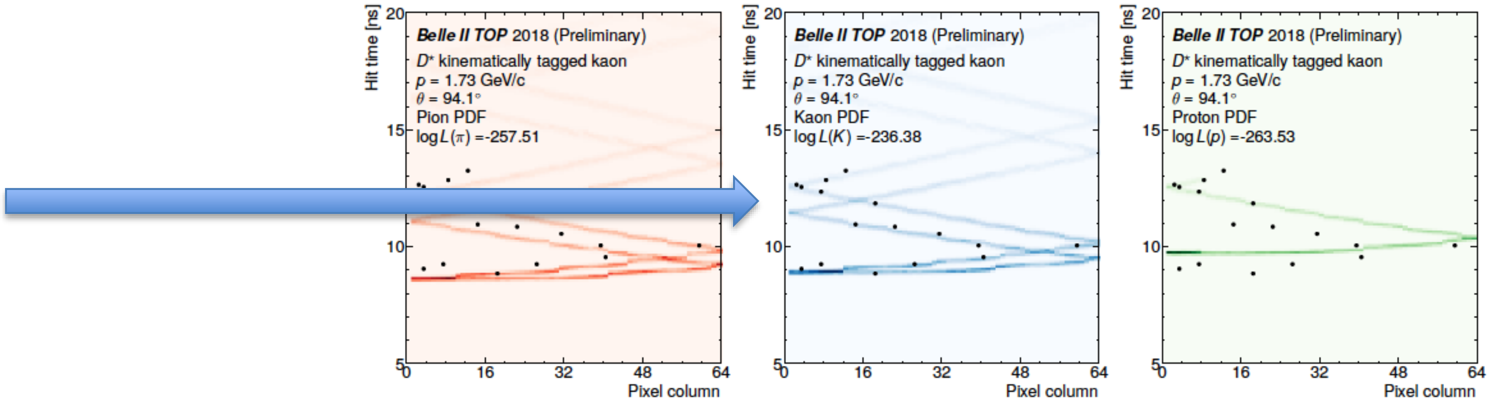
- |d0| < 1
- |dz| < 3
- # layers hit > 20

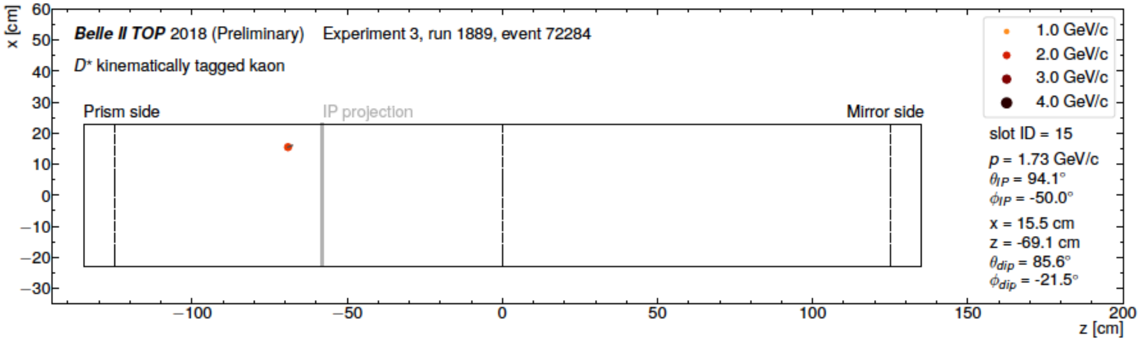
TOP Particle Identification.

$$D^{*+} \rightarrow D^0 \pi_s^+ ; D^0 \rightarrow K^- \pi^+$$

N.B. The charge correlation with the slow pion determines which track is the kaon (or pion)

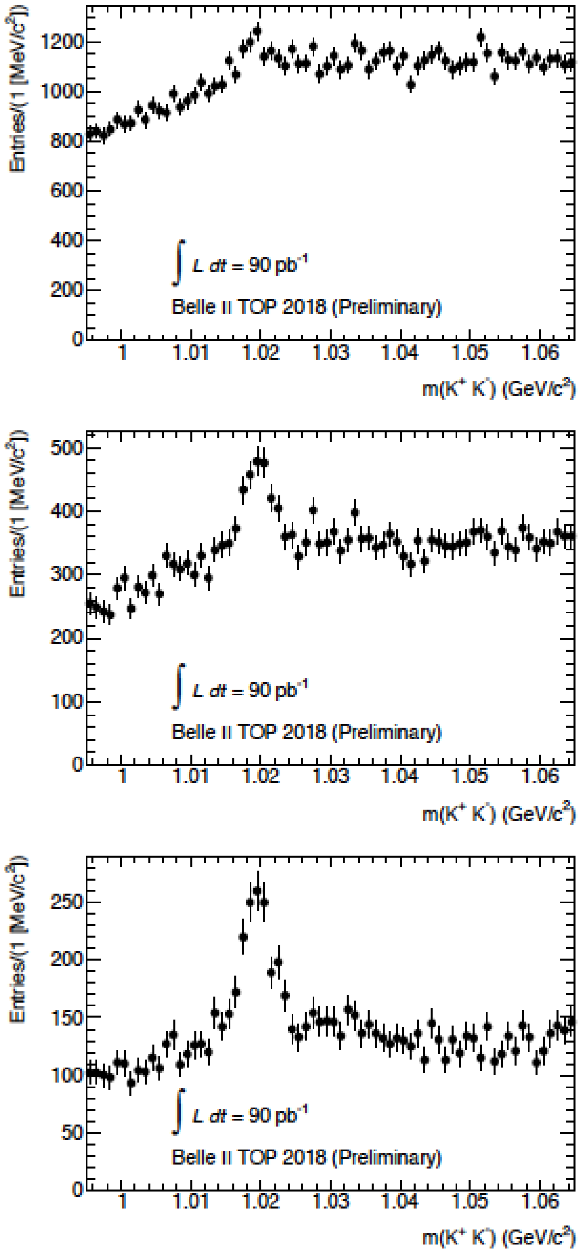
Kinematically identified kaon from a D^{*+} in the TOP; Cherenkov x vs t pattern (mapping of the Cherenkov ring)





$f \to K^- K^+$ inclusive

Another example of TOP particle identification with early calibration and alignment.



No kaons identified

One kaon identified in the TOP.

Both kaons identified in the TOP.

FIG. 7: $m(K^+K^-)$ distributions for runs with TOP calibration (run number up to 2531). Tracks are required to be in the TOP acceptance. Top: No PID requirement. Middle: $LL(K)^{TOP} > LL(\pi)^{TOP}$ for one of the tracks. Bottom: $LL(K)^{TOP} > LL(\pi)^{TOP}$ for both tracks.

Rediscovery of Ds$\rightarrow\phi\pi^+$,
with $\phi\rightarrow K^+ K^-$

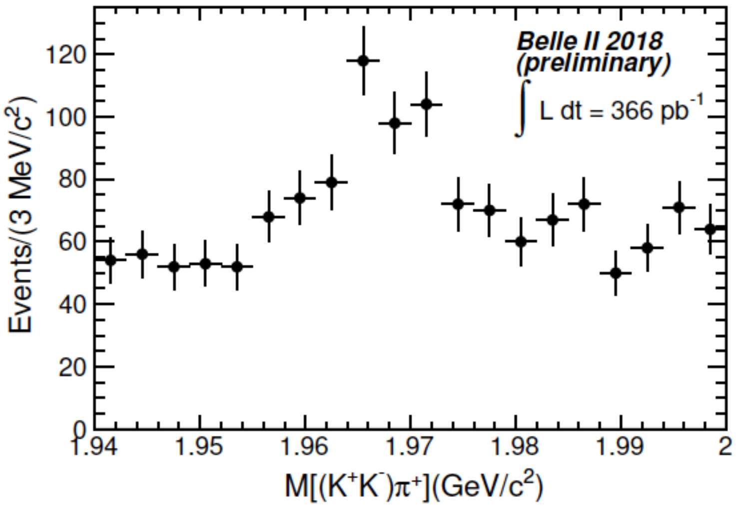


FIG. 1: This figure shows M$[(K^+K^-)\pi^+]$ distribution, which was produced using phase-II 366 pb^{-1} hadron skim data. No PID criteria are applied to any of the charged tracks ($K^\pm\pi^+$). Selection criteria and further details are described in the internal note BELLE2-NOTE-PH-2018-026.

No PID

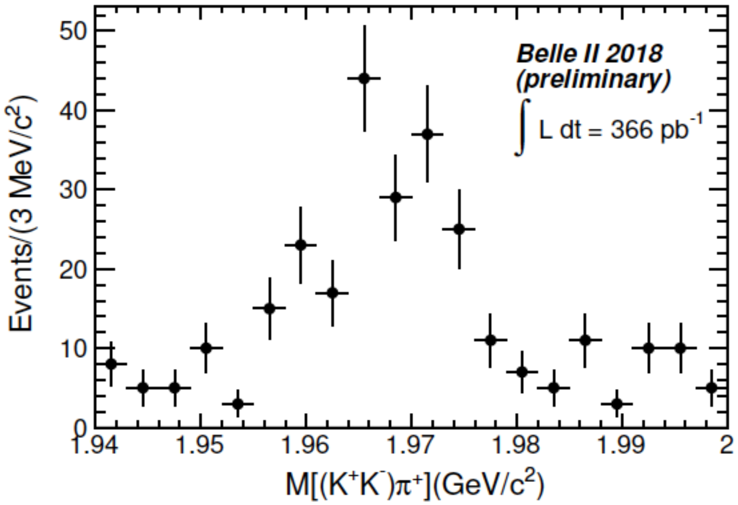
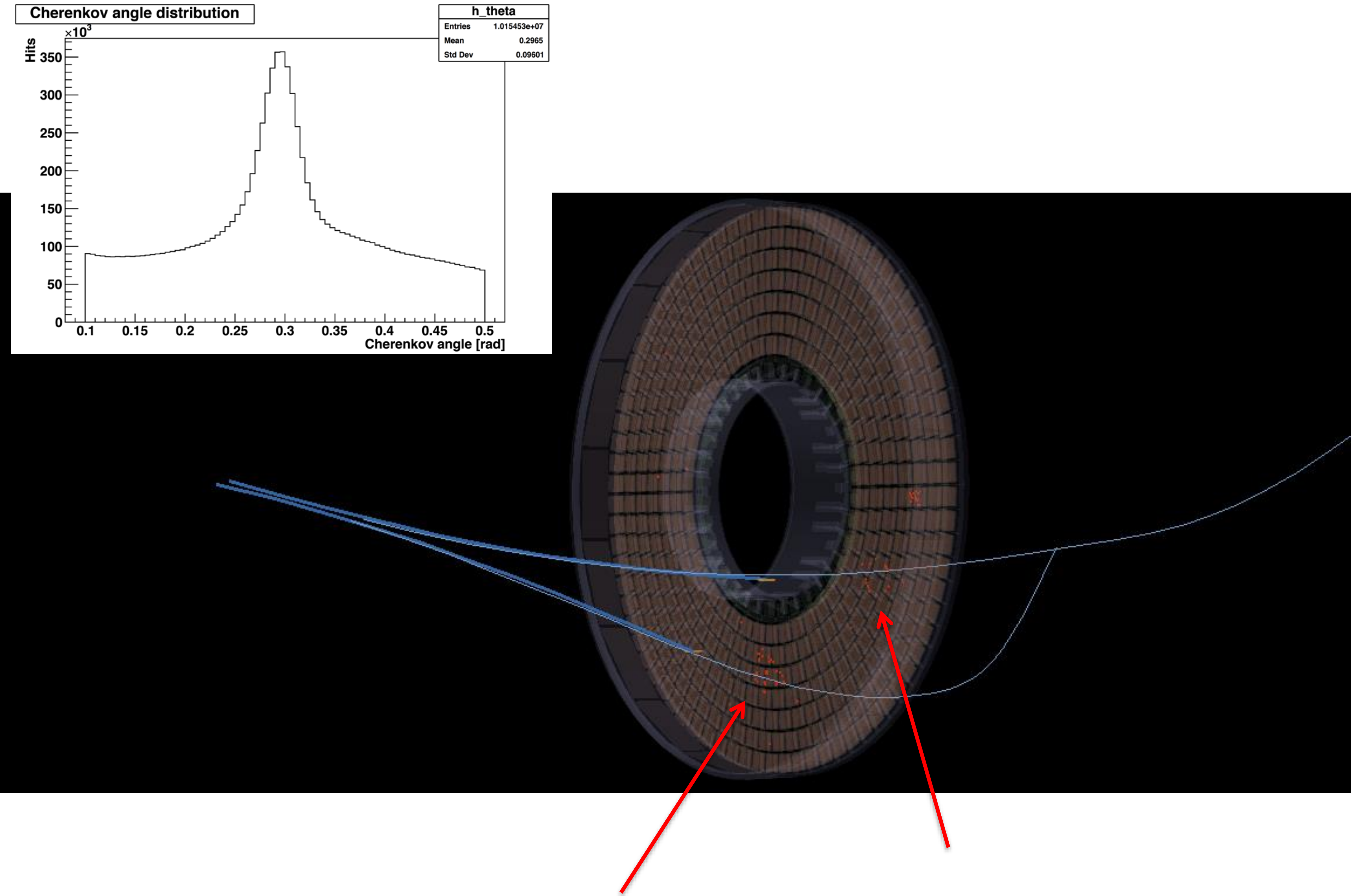


FIG. 2: This figure shows M$[(K^+K^-)\pi^+]$ distribution, which was produced using phase-II 366 pb^{-1} hadron skim data. Combined PID criteria, Prob(K:π) >0.5 for $K^\pm$ tracks and Prob(π:K) >0.5 for π^+ tracks are applied. Selection criteria and further details are described in the internal note BELLE2-NOTE-PH-2018-026.

Two identified charged kaons.

Endcap particle identification via Aerogel RICH (ARICH)

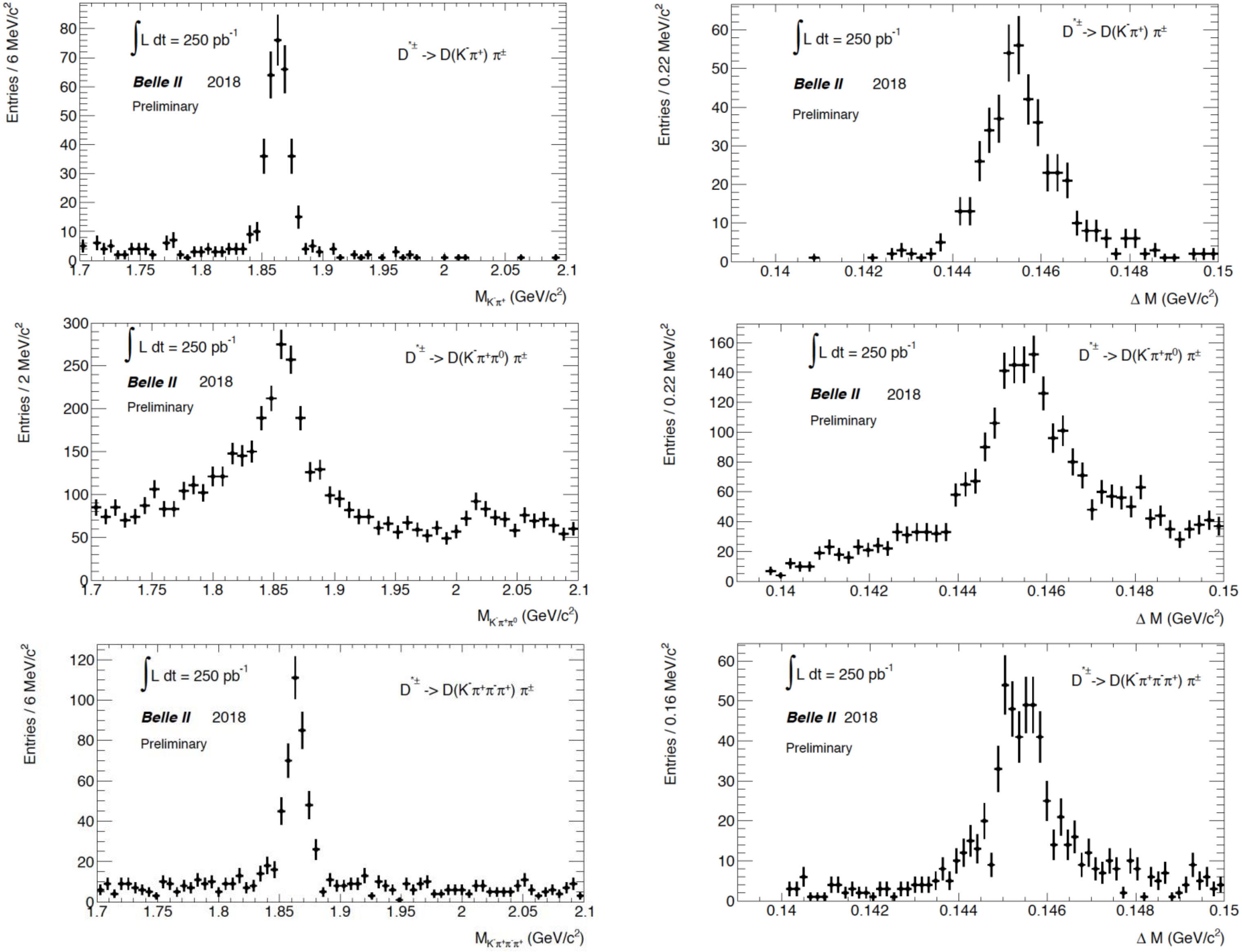


$$e^+e^- \rightarrow c\bar{c}$$

$$D^{*+} \rightarrow D^0\pi^+,$$

$$D^0 \rightarrow K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^-\pi^+$$

The signal peaks are charm in continuum not B's



Clearly illustrates the capabilities of Belle II and the potential for charm physics and the building blocks of B mesons.

CP Eigenstate: $D^0 \rightarrow K_S \rho^0$

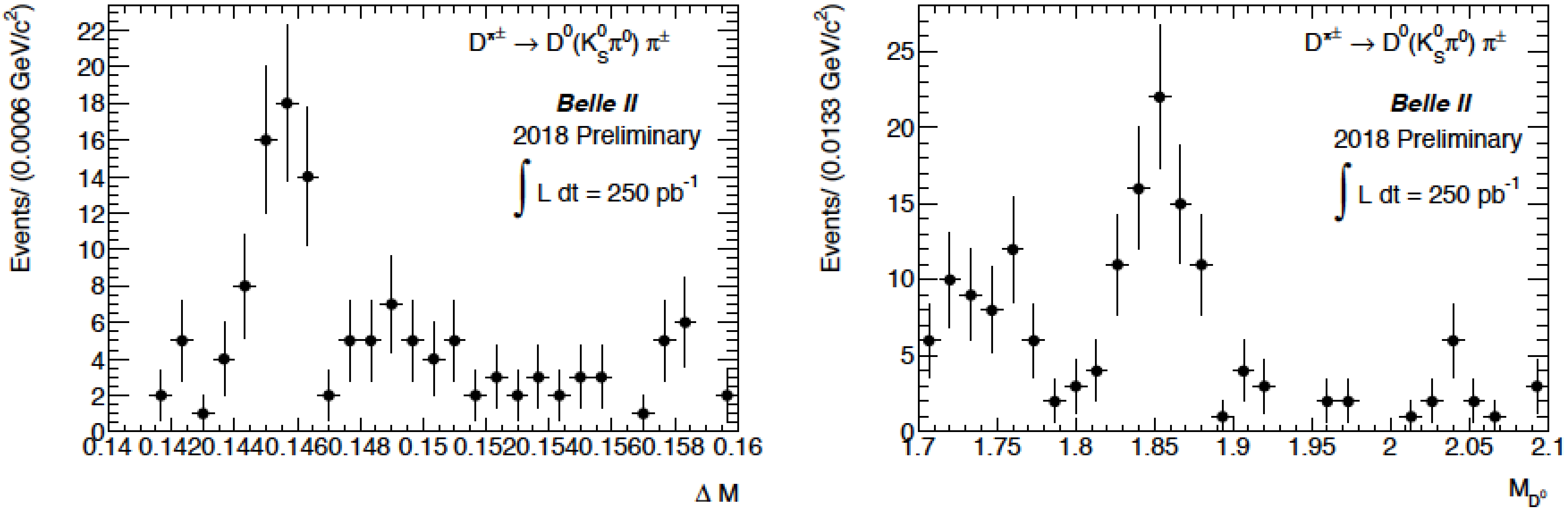
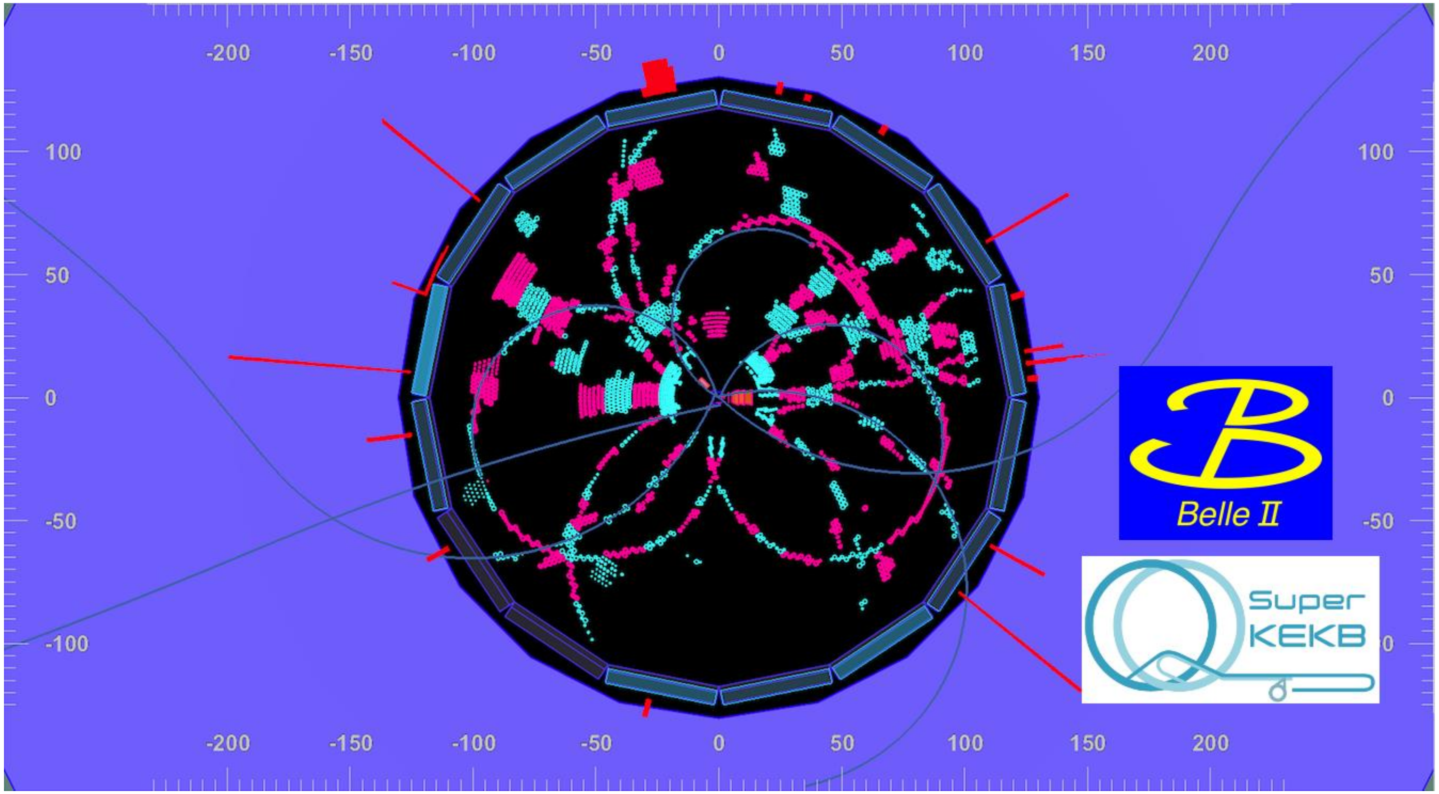


FIG. 36: ΔM (left) and M_D (right) signal-enhanced projections in 250 pb^{-1} prod4 data sample for $D \rightarrow K_S^0\pi^0$ final state.

Also illustrates some of the important capabilities of Belle II.

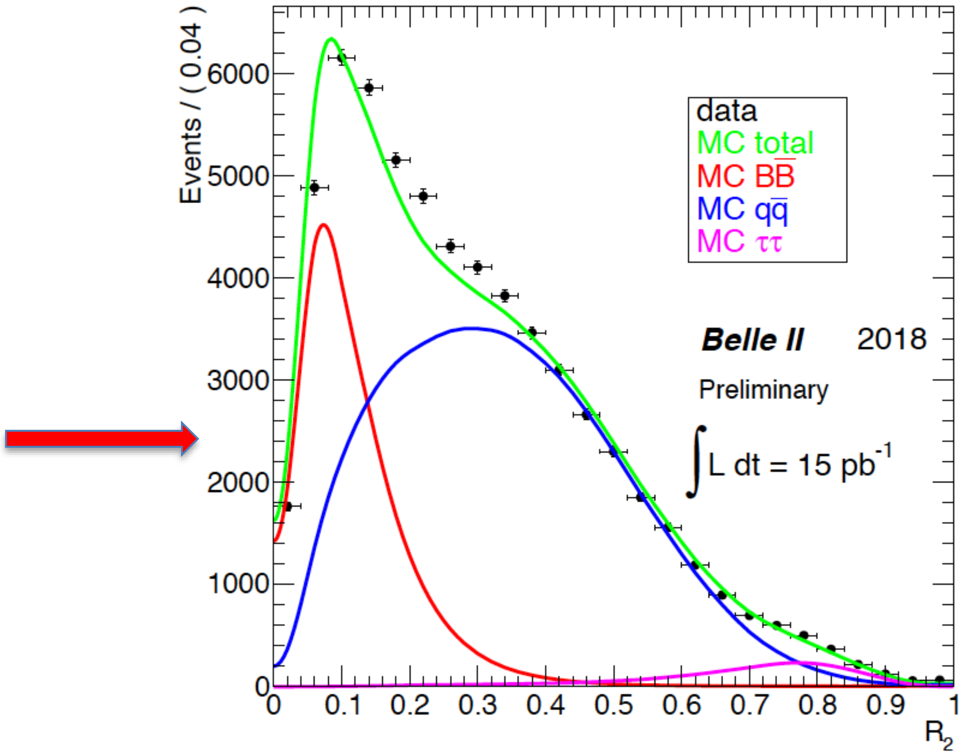
More matter-antimatter annihilation in Tsukuba: Another event from Belle II's first evening

$$e^+e^- \to g^* \to B\overline{B}$$

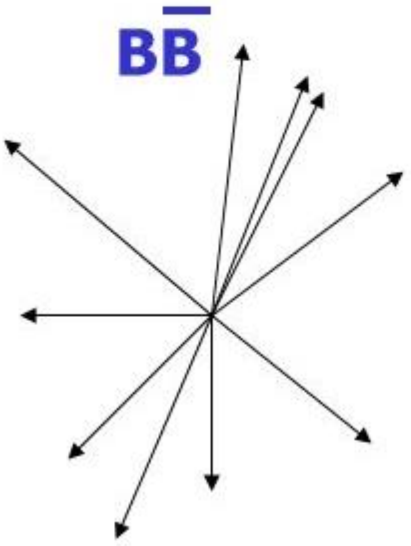


A potential e+ e- →B anti-B candidate

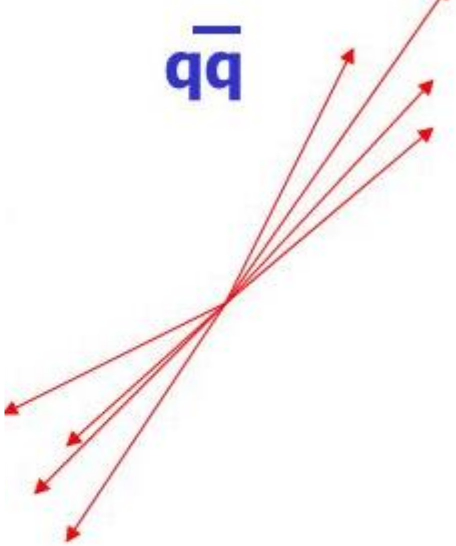
Event Topology tells us we are seeing B's



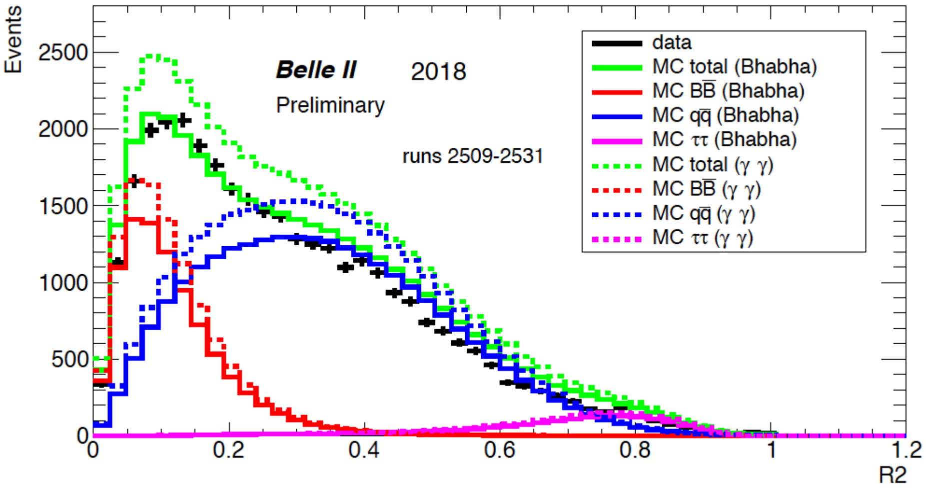
Spherical R_2 Jet-like

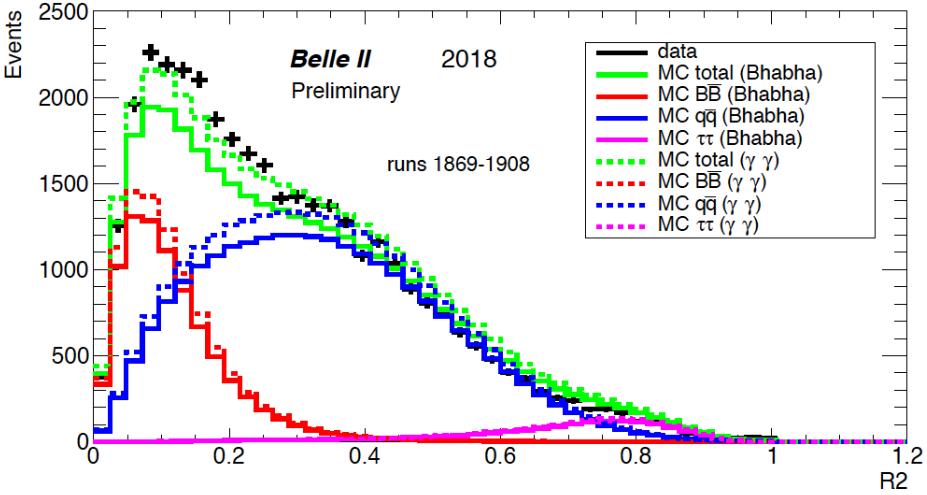


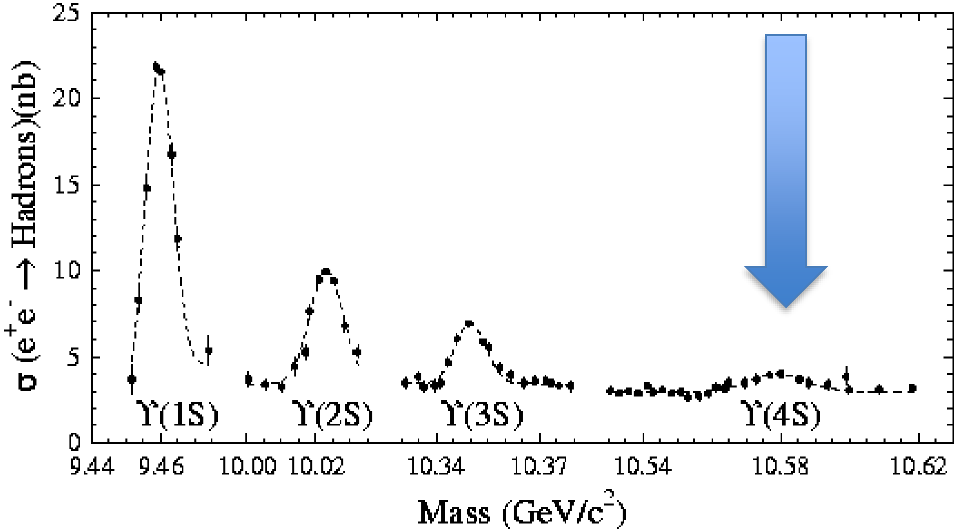
B pairs produced at rest in the CM with no extra particles



We are on the Y(4S) resonance and recording B anti-B pairs with ~99% efficiency.



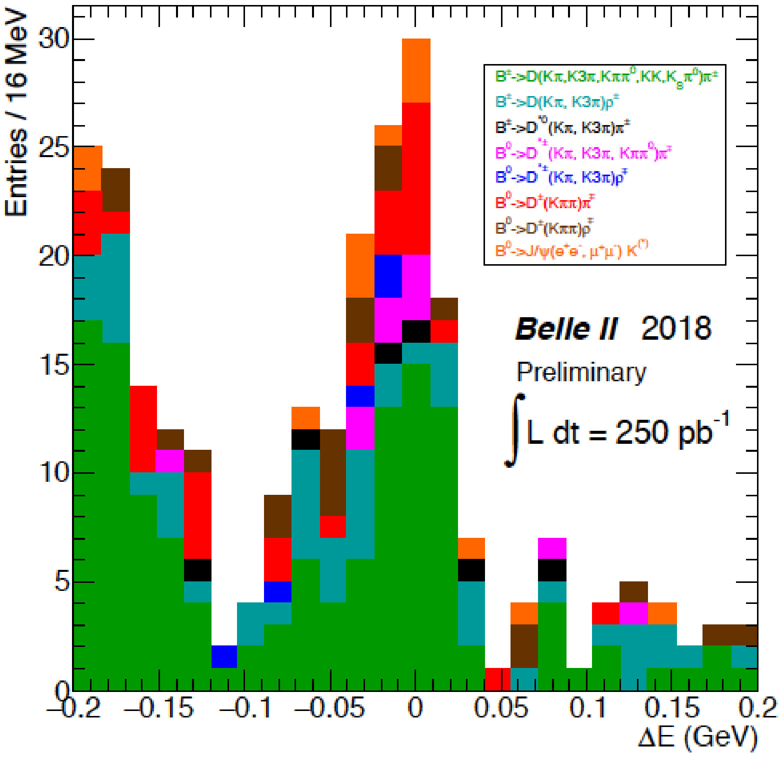


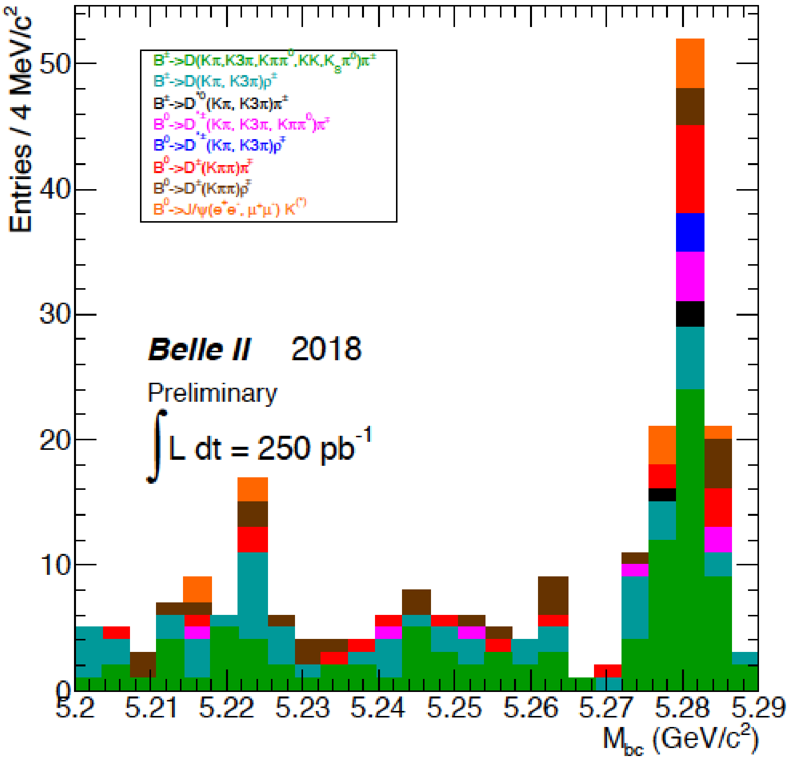


Event Topology (fits to R_2) tells us we are seeing B's

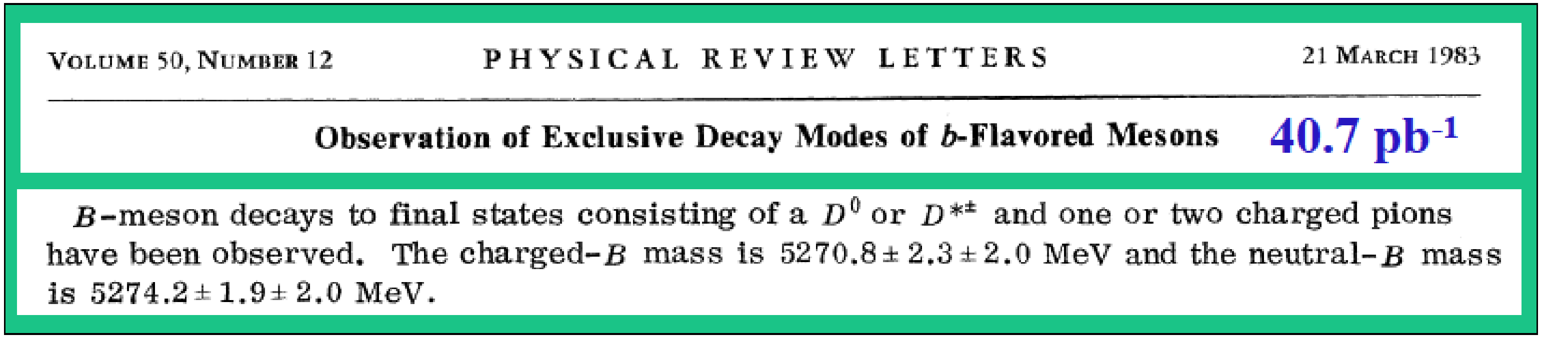
Not so obvious: When we change accelerator optics, we remain on the Upsilon(4S).

We have *rediscovered* the B meson !





History 1983:



VOLUME 50, NUMBER 12 PHYSICAL REVIEW LETTERS 21 MARCH 1983

Observation of Exclusive Decay Modes of *b*-Flavored Mesons 40.7 pb^{-1}

B-meson decays to final states consisting of a D^0 or $D^{*\pm}$ and one or two charged pions have been observed. The charged-B mass is $5270.8 \pm 2.3 \pm 2.0$ MeV and the neutral-B mass is $5274.2 \pm 1.9 \pm 2.0$ MeV.

Onwards to Phase 3 and the Physics Run

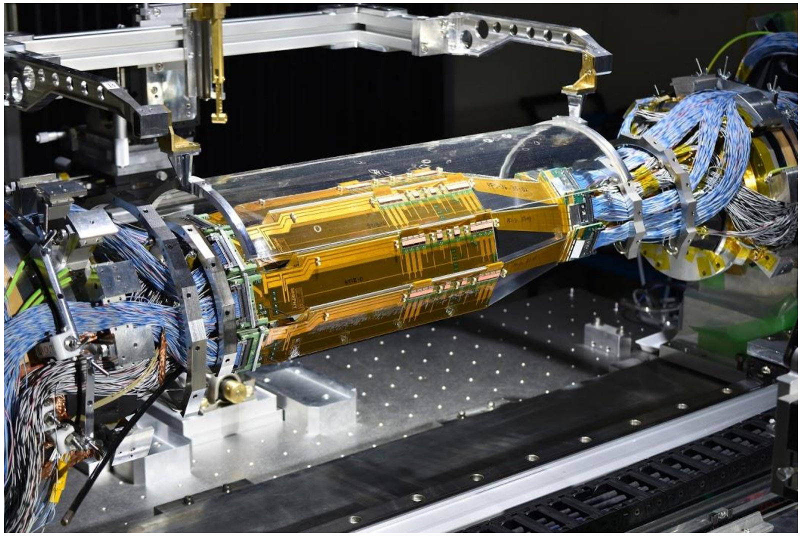
The VXD will be installed in Phase 3.
Restart Belle II data taking in February 2019.

PXD layer 1 ladders

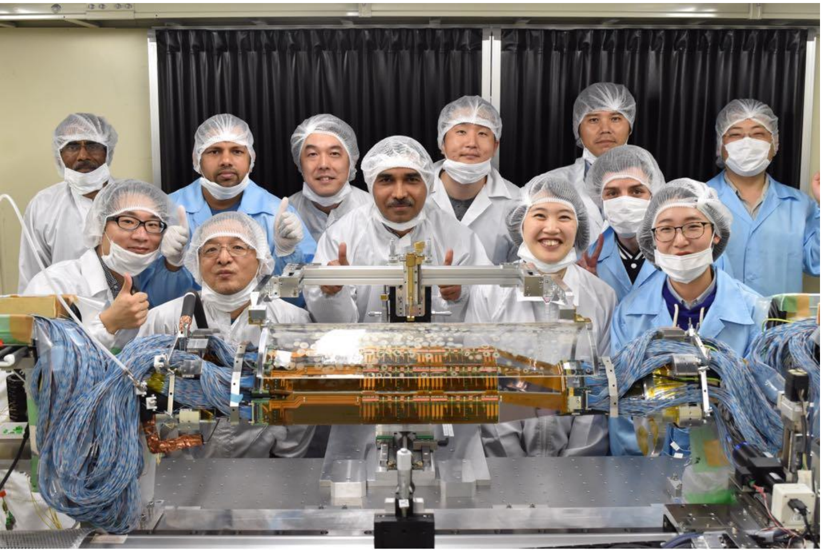
First PXD half-shell
being tested at DESY

SVD +x half-shell, Jan 2018

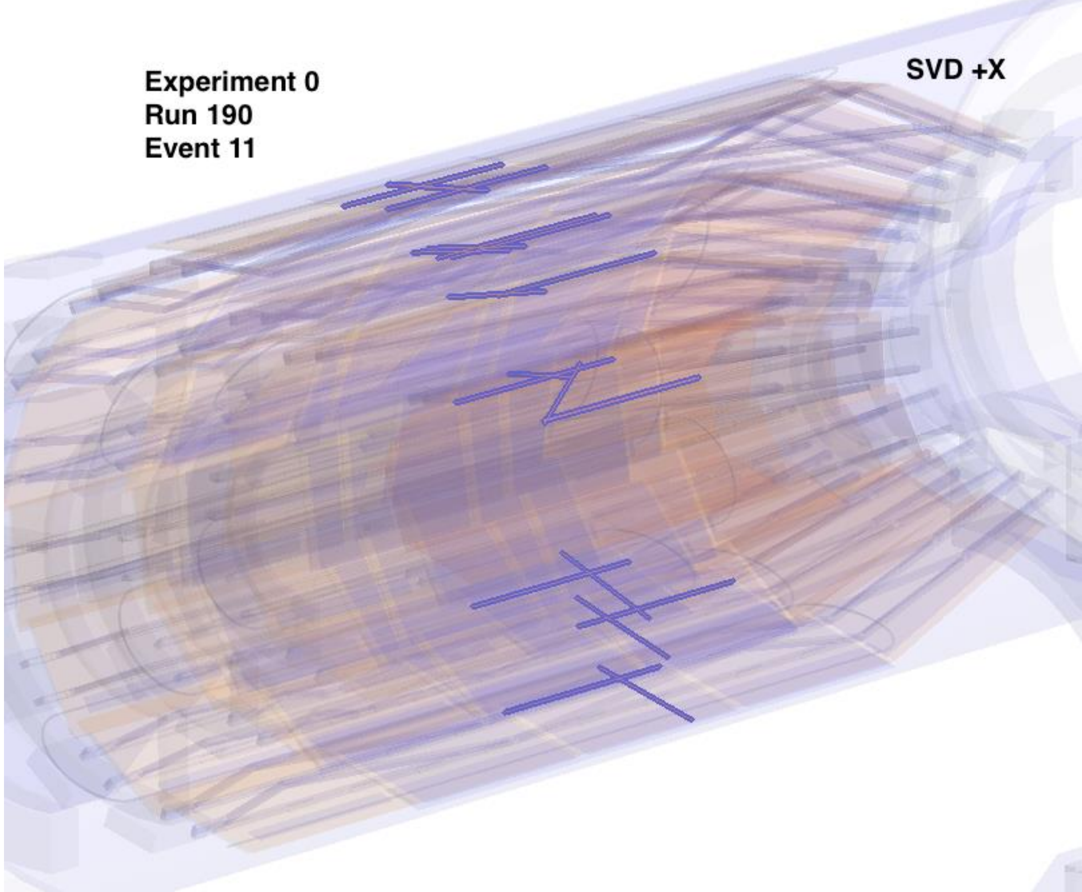
SVD -x half-shell, July 2018



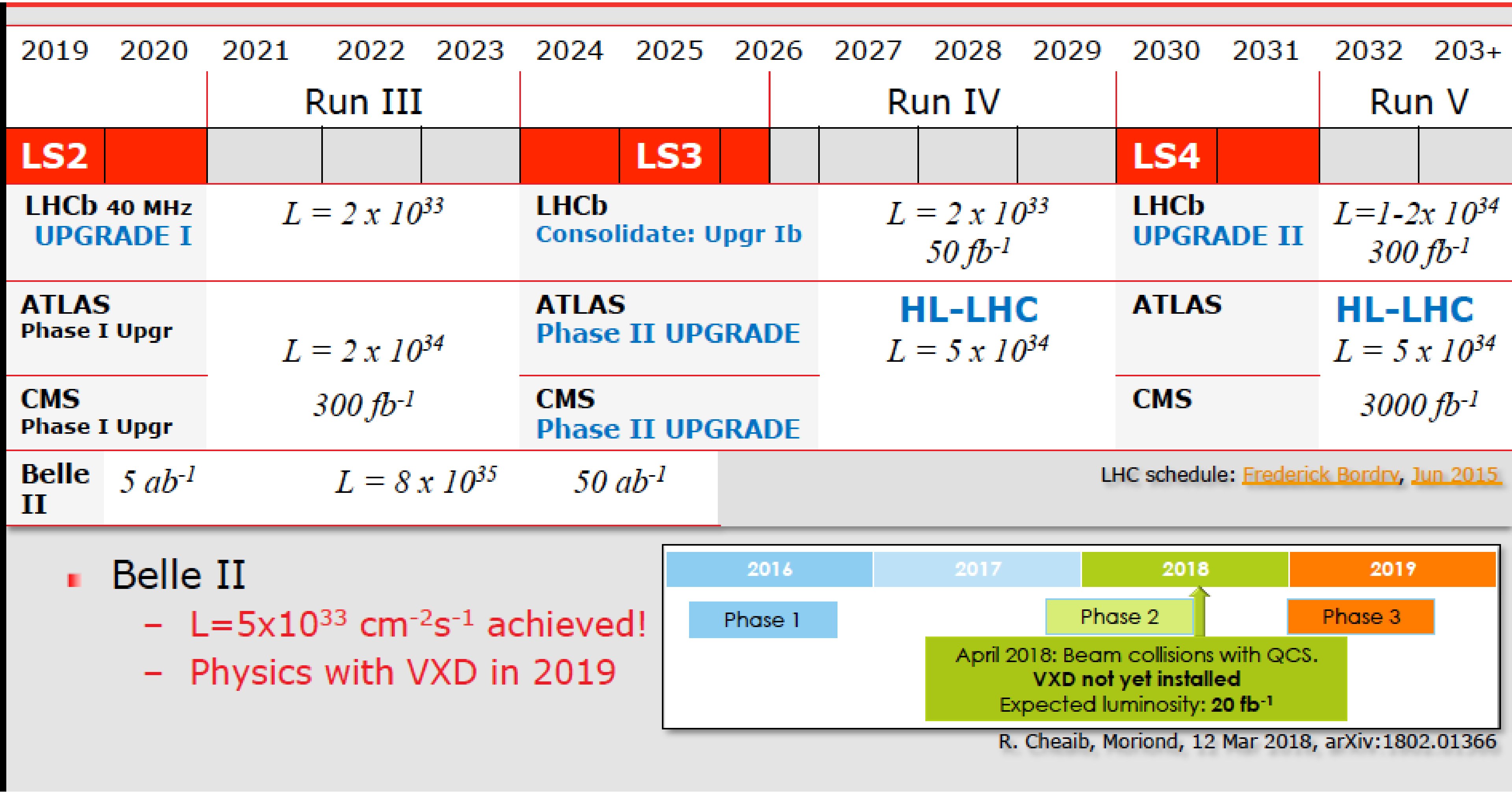
Completed L4 (India)



First Cosmic in the +x SVD clam shell at KEK, July 2018



Physics Competition and Complementarity



2019 2020	2021 2022 2023	2024 2025	2026 2027 2028 2029	2030 2031	2032 203+
	Run III		Run IV		Run V
LS2		**LS3**		**LS4**	
LHCb 40 MHz **UPGRADE I**	$L = 2 x 10^{33}$	**LHCb** **Consolidate: Upgr Ib**	$L = 2 x 10^{33}$ $50 fb^{-1}$	**LHCb** **UPGRADE II**	$L=1\text{-}2x 10^{34}$ $300 fb^{-1}$
ATLAS **Phase I Upgr**	$L = 2 x 10^{34}$	**ATLAS** **Phase II UPGRADE**	**HL-LHC** $L = 5 x 10^{34}$	**ATLAS**	**HL-LHC** $L = 5 x 10^{34}$
CMS **Phase I Upgr**	$300 fb^{-1}$	**CMS** **Phase II UPGRADE**		**CMS**	$3000 fb^{-1}$
Belle II $5 ab^{-1}$	$L = 8 x 10^{35}$	$50 ab^{-1}$			

LHC schedule: Frederick Bordry, Jun 2015

- Belle II
  - $L=5x10^{33}$ $cm^{-2}s^{-1}$ achieved!
  - Physics with VXD in 2019

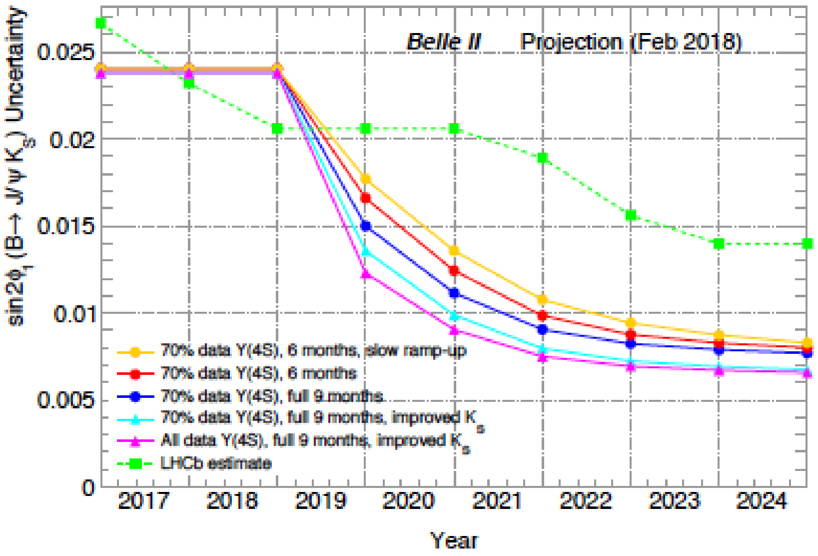
2016	2017	2018	2019
Phase 1		Phase 2	Phase 3

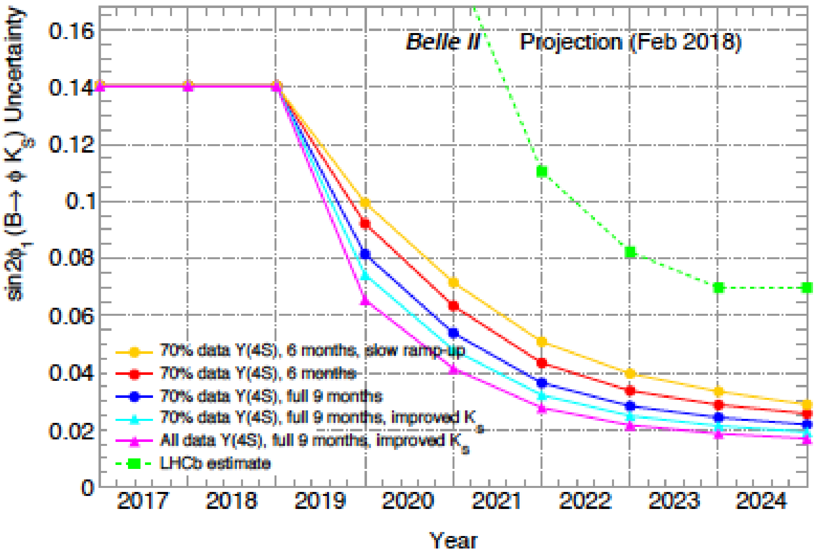
April 2018: Beam collisions with QCS.
VXD not yet installed
Expected luminosity: **20 fb^{-1}**

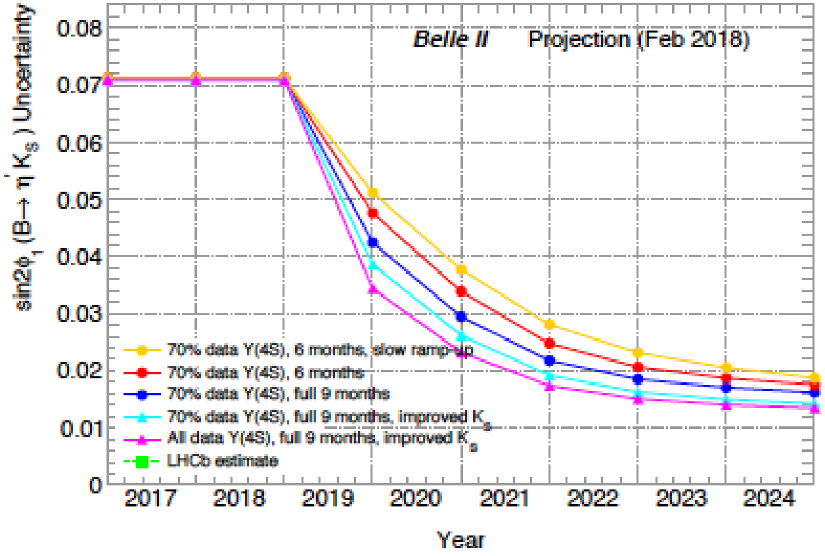
R. Cheaib, Moriond, 12 Mar 2018, arXiv:1802.01366

Outside perspective:
Plenary talk by Niels Tuning, ICHEP 2018 in Seoul, Korea

Examples of Physics Competition and Complementarity







Use
publicly
available
LHCb
projections.

How can we establish NP in $B \rightarrow K^* l^- l^+$?

Ans: Observe and measure the rate for $B \rightarrow s n\bar{n}$ and thus isolate the Z penguin (C_9) at *Belle II*

Answer from Buras et al.

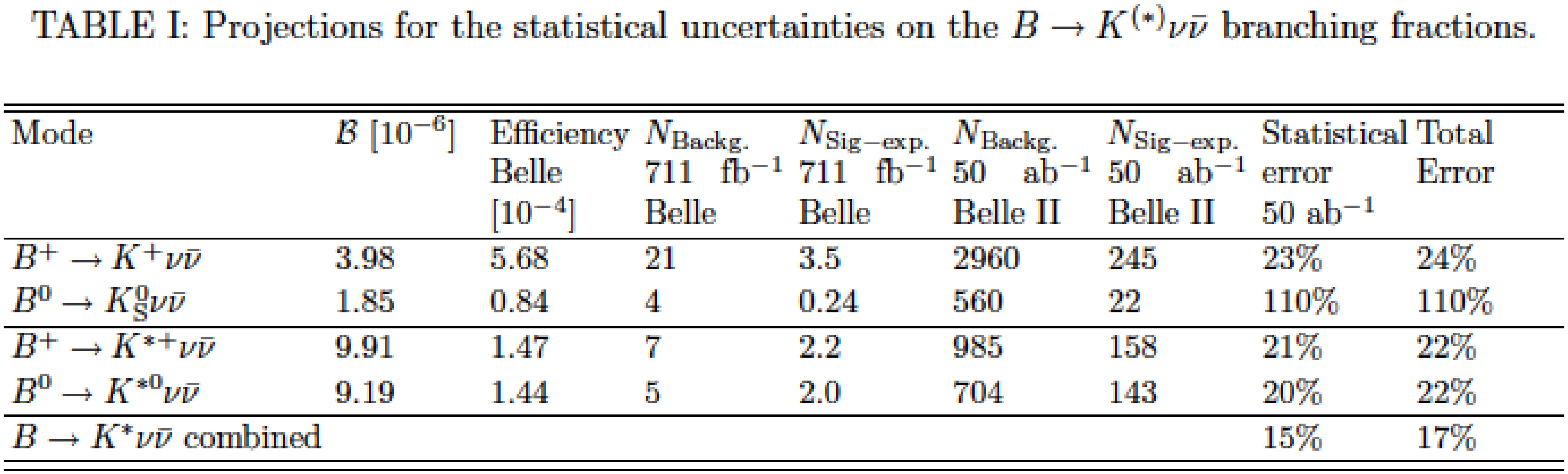


TABLE I: Projections for the statistical uncertainties on the $B \to K^{(*)}\nu\bar{\nu}$ branching fractions.

Mode	$\mathcal{B}$ $[10^{-6}]$	Efficiency Belle $[10^{-4}]$	$N_{\text{Backg.}}$ 711 fb^{-1} Belle	$N_{\text{Sig-exp.}}$ 711 fb^{-1} Belle	$N_{\text{Backg.}}$ 50 ab^{-1} Belle II	$N_{\text{Sig-exp.}}$ 50 ab^{-1} Belle II	Statistical error 50 ab^{-1}	Total Error
$B^+ \to K^+\nu\bar{\nu}$	3.98	5.68	21	3.5	2960	245	23%	24%
$B^0 \to K^0_S\nu\bar{\nu}$	1.85	0.84	4	0.24	560	22	110%	110%
$B^+ \to K^{*+}\nu\bar{\nu}$	9.91	1.47	7	2.2	985	158	21%	22%
$B^0 \to K^{*0}\nu\bar{\nu}$	9.19	1.44	5	2.0	704	143	20%	22%
$B \to K^*\nu\bar{\nu}$ combined							15%	17%

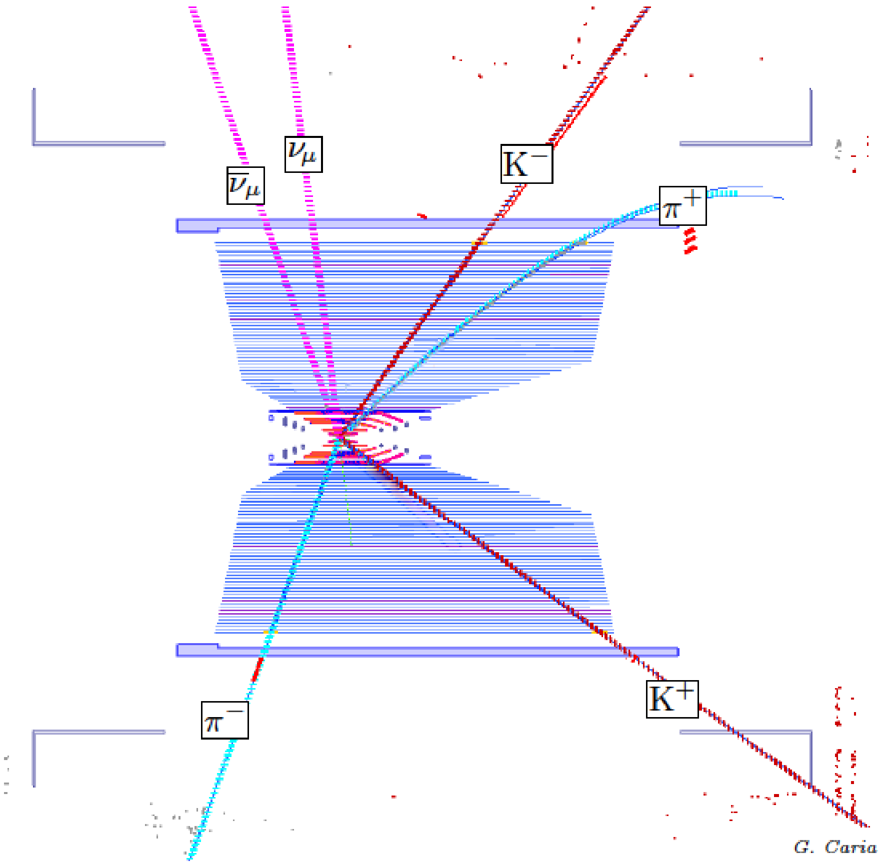
What’s Ahead ?

“Missing Energy Decay” in a Belle II GEANT4 MC simulation

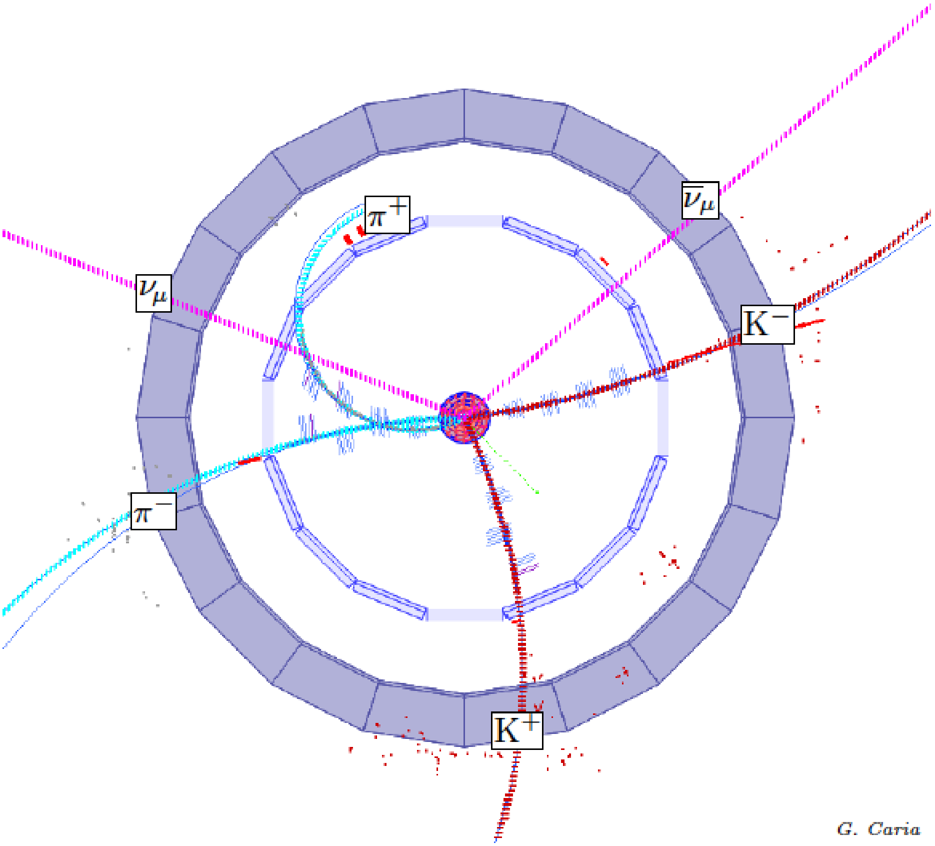
Signal: B→K ν ν

tag mode: B→Dπ; D→Kπ

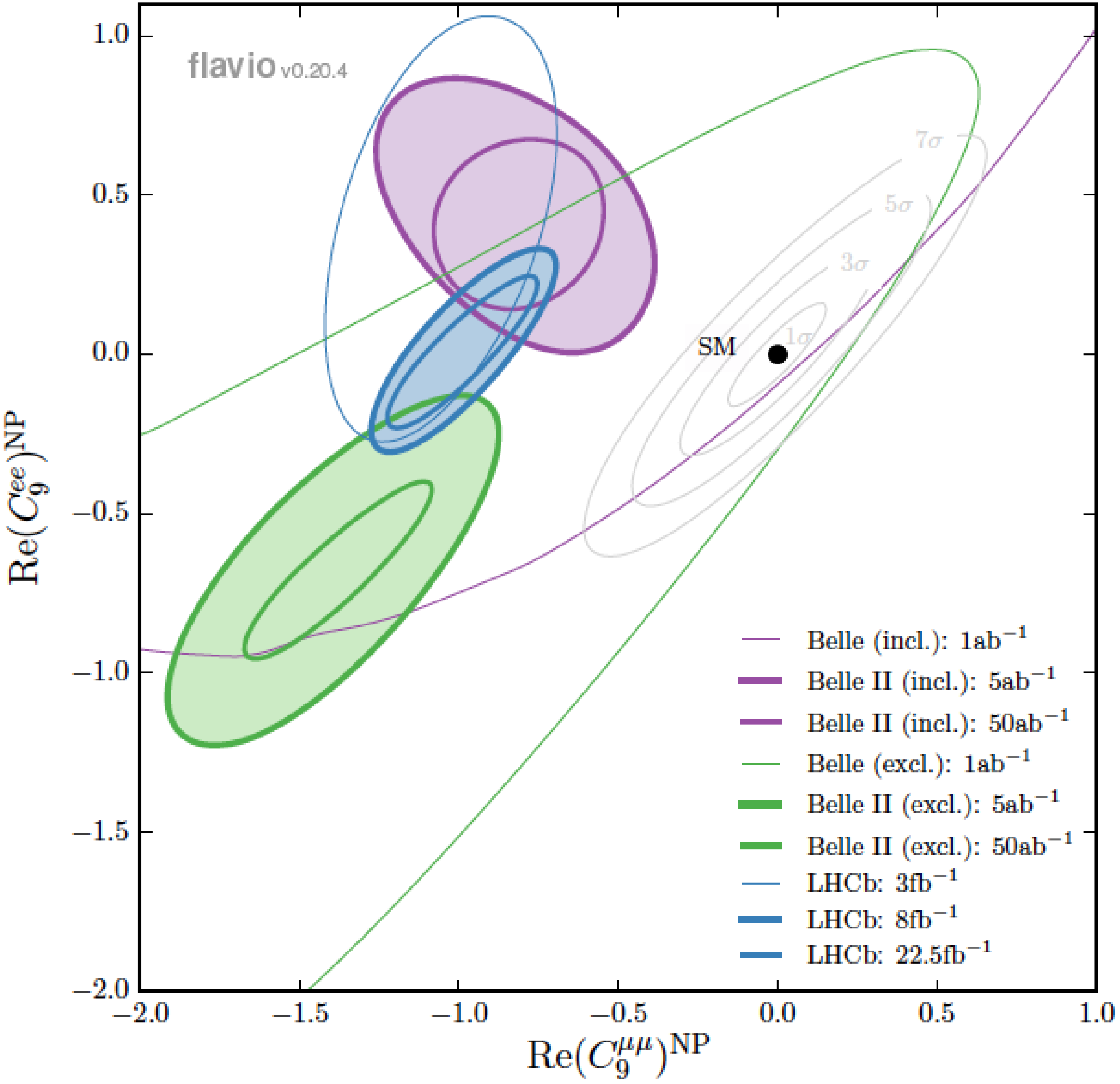
View in r-z



Zoomed view of the vertex region in r--phi



NP in $b \to s\, l^+ l^-$



Prepared by D. Straub et al. for the Belle II Physics Book (edited by P. Urquijo and E. Kou)

Belle II can do both <u>inclusive</u> and exclusive. Equally strong capabilities for electrons and muons.

Conclusions

- Belle II will explore New Physics on the Luminosity or Intensity Frontier. This is different and complementary to the LHC high p_T experiments, which operate on the Energy Frontier.

- There is competition and complementarity with LHCb

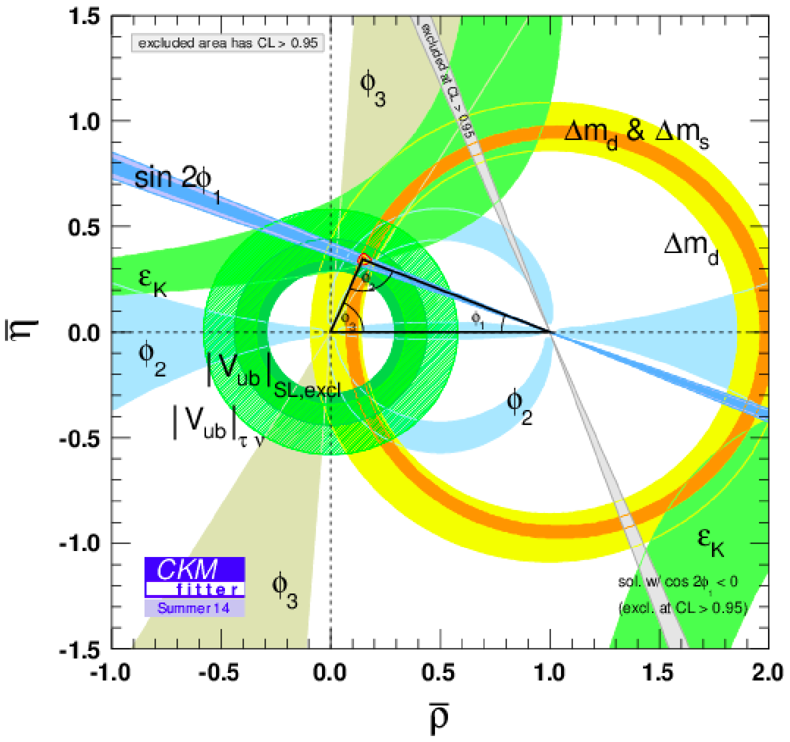
- We are ready to start a long physics run in the Super Factory mode. This requires *high-efficiency* data-taking by Belle II and *extensive running* by Super KEK-B, soon to be the world’s highest luminosity accelerator.

- The world is waiting for our results.

Backup Slides

Results from Global Fits to Data (CKMFitter Group)

Great progress on φ_3 or γ (first from B factories and now in the last four years from LHCb). *These measure the phase of V_{ub}*

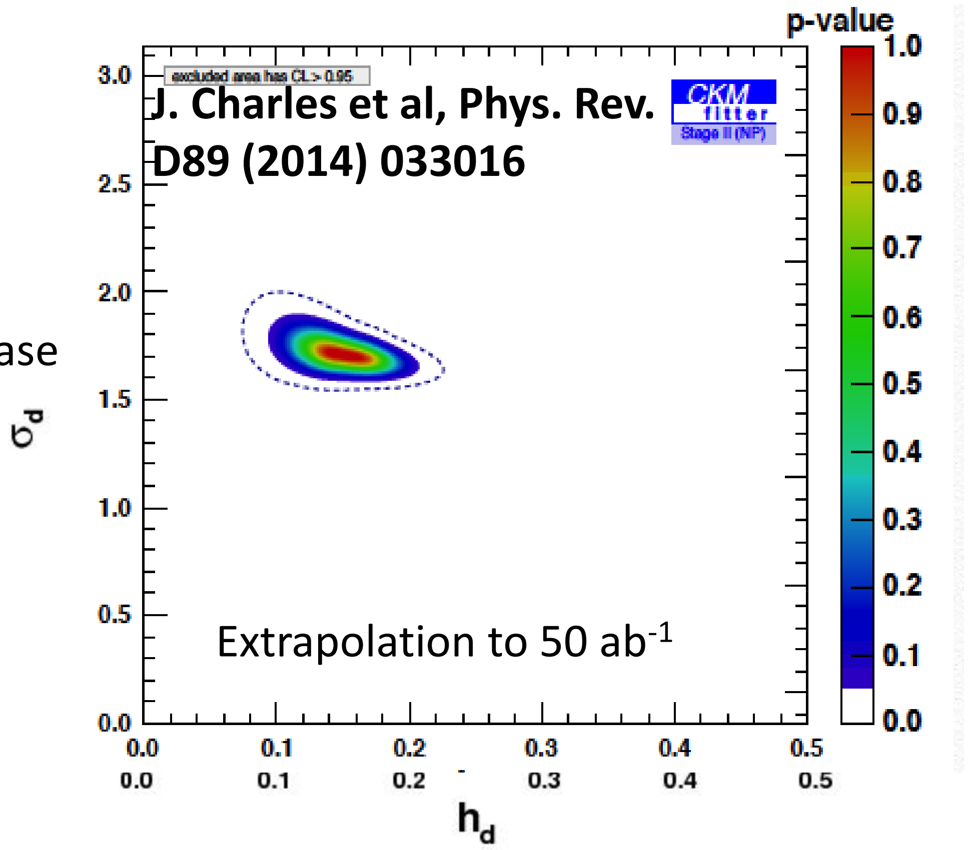


Looks good

(except for an issue with $|V_{ub}|$)

Similar results from UTFIT

NP Phase



J. Charles et al, Phys. Rev. D89 (2014) 033016

Extrapolation to 50 ab^{-1}

NP/SM amplitude ratio

But a 10-20% NP amplitude in B_d mixing is perfectly compatible with all current data.

More examples of Physics Competition and Complementarity

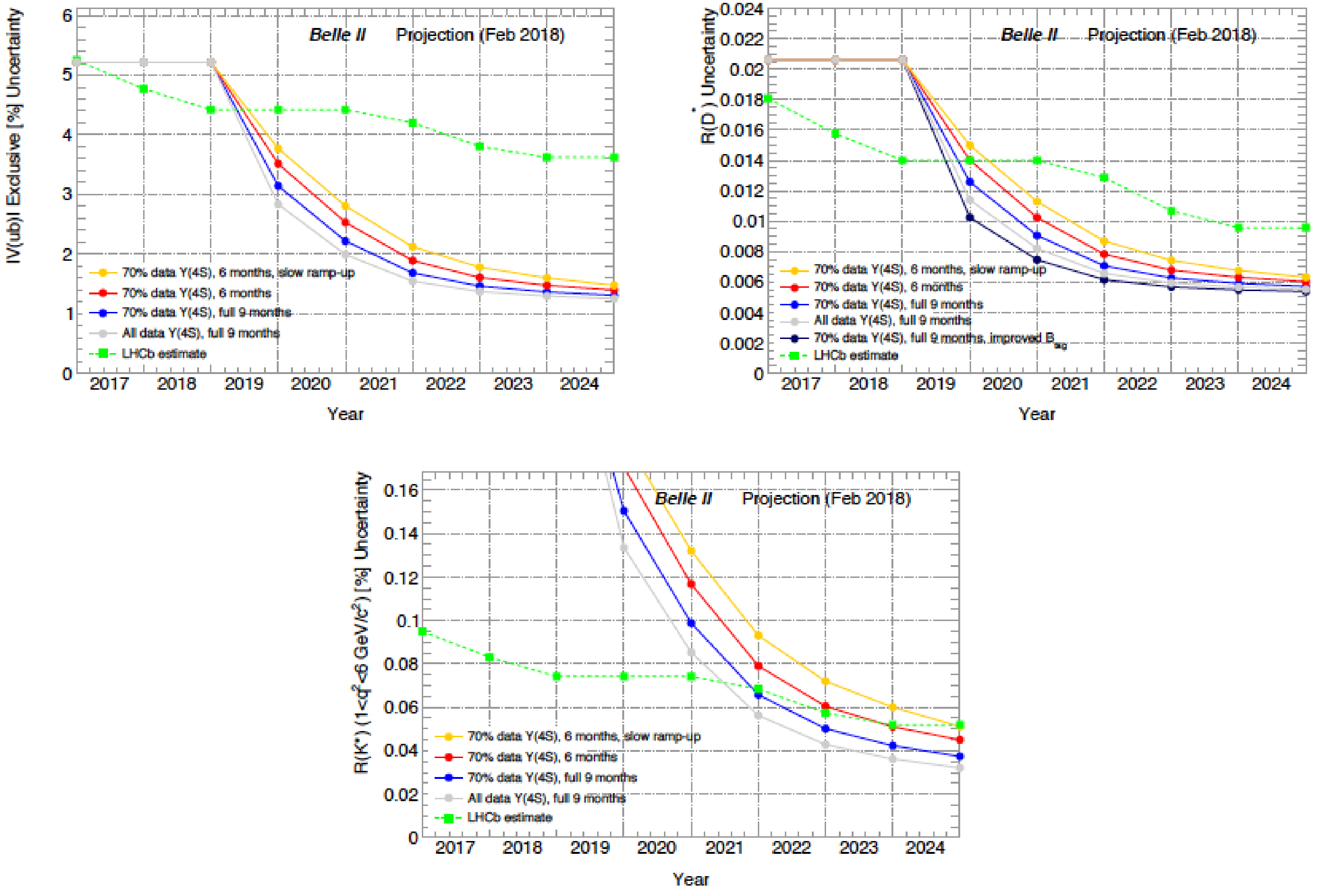
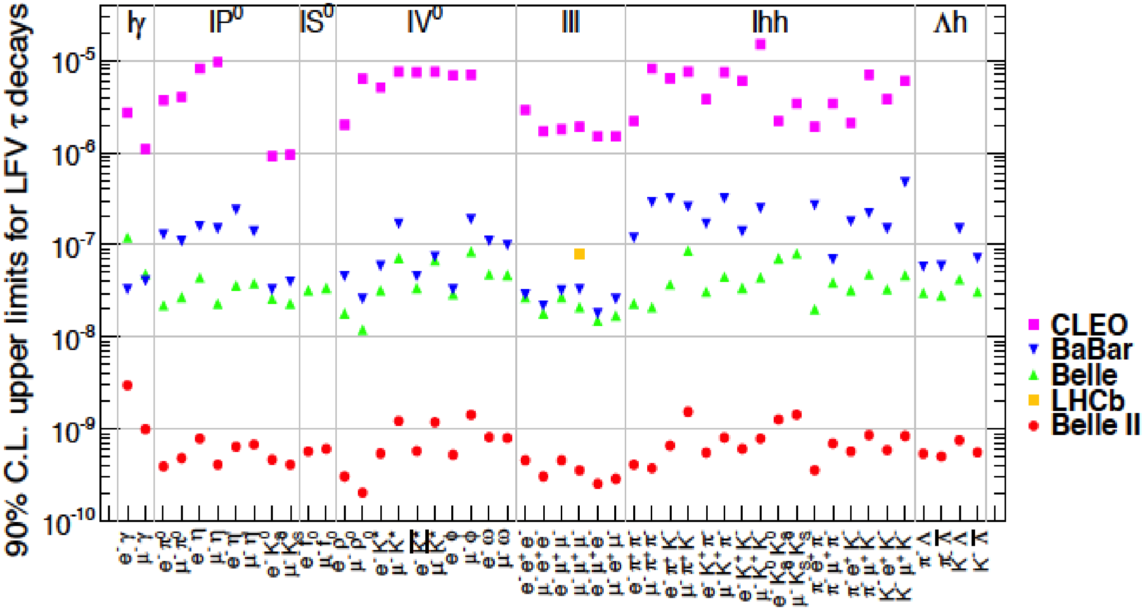


FIG. 6: Projected precision for various measurements of semileptonic B decays.

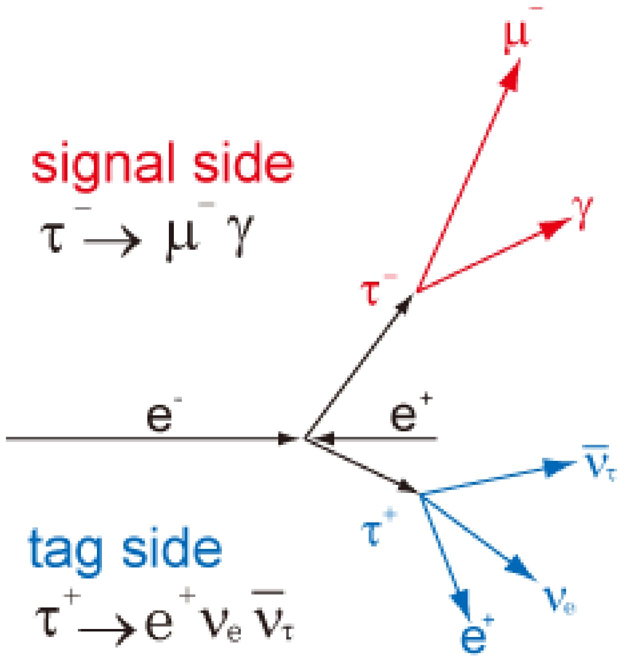
Use publicly available LHCb projections.

τ Lepton Flavor Violation



Note vertical log-scale (50 ab^{-1} assumed for Belle II; 3 fb^{-1} result for LHCb

Example of the decay topology



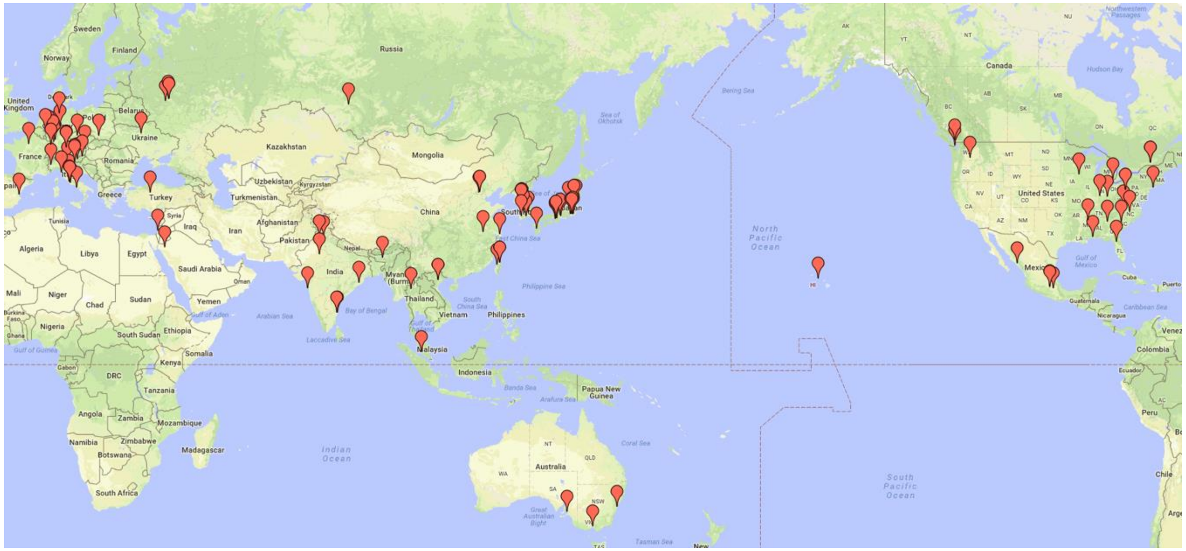
__Belle II will push many limits below 10^{-9}__;
LHCb, CMS and ATLAS have very *limited* capabilities.

LHC high pt: The modes τ→μγ and τ →μ h+ h- provide important constraints on H→μτ

Acknowledgements

We thank the dedicated and talented Belle II students, postdocs, engineers and professors as well as the funding agencies of:

Australia
Austria
Canada
China
Czechia
France
Germany
India
Israel
Italy
Japan
Malaysia
Mexico
Poland
Russia
Saudi Arabia
Slovenia
South Korea
Spain
Taiwan
Thailand
Turkey
Ukraine
USA
Vietnam



Early physics within two months of first collisions was made possible by the extensive preparations of the software, computing and data production teams.

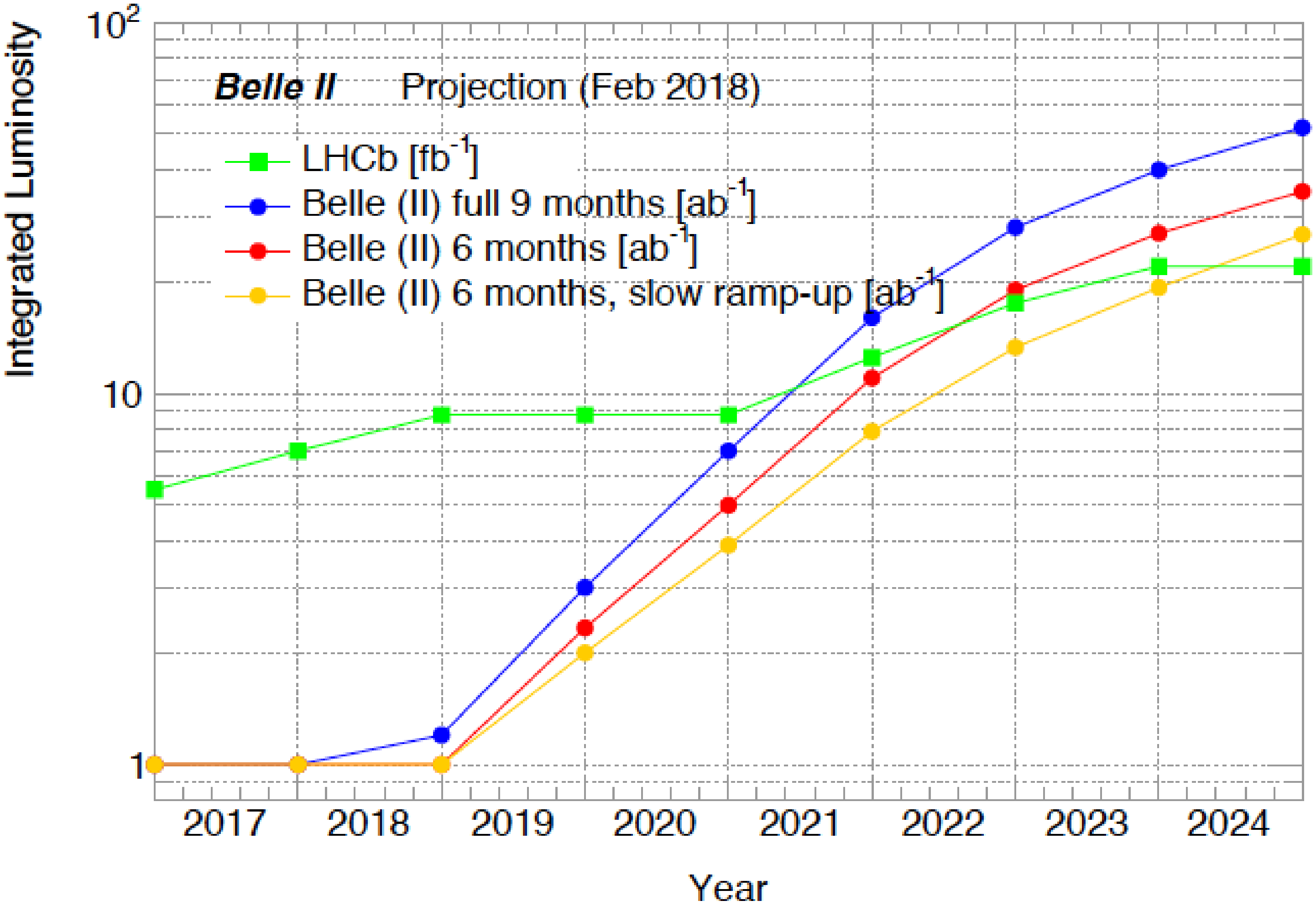


FIG. 2: SuperKEKB and LHCb integrated luminosity projections in fb^{-1} and ab^{-1} respectively.

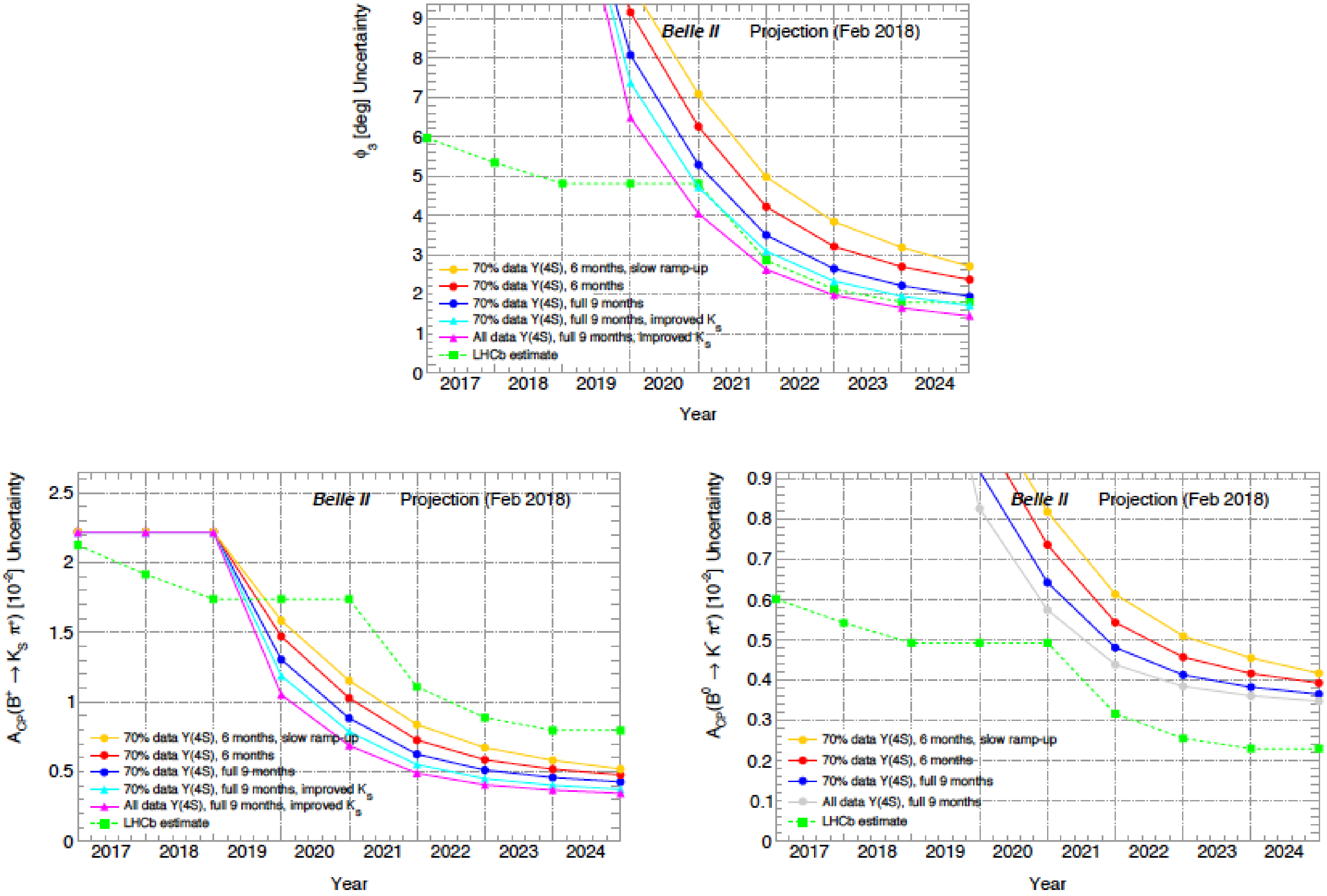


FIG. 5: Projected precision for various measurements of direct CP violation.

“Tsukuba, we have a Problem”

(apologies to Tom Hanks, Apollo 13)

WMAP
data

$$\boxed{\eta \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.21 \pm 0.16) \times 10^{-10}}$$

KM Theoretical
prediction

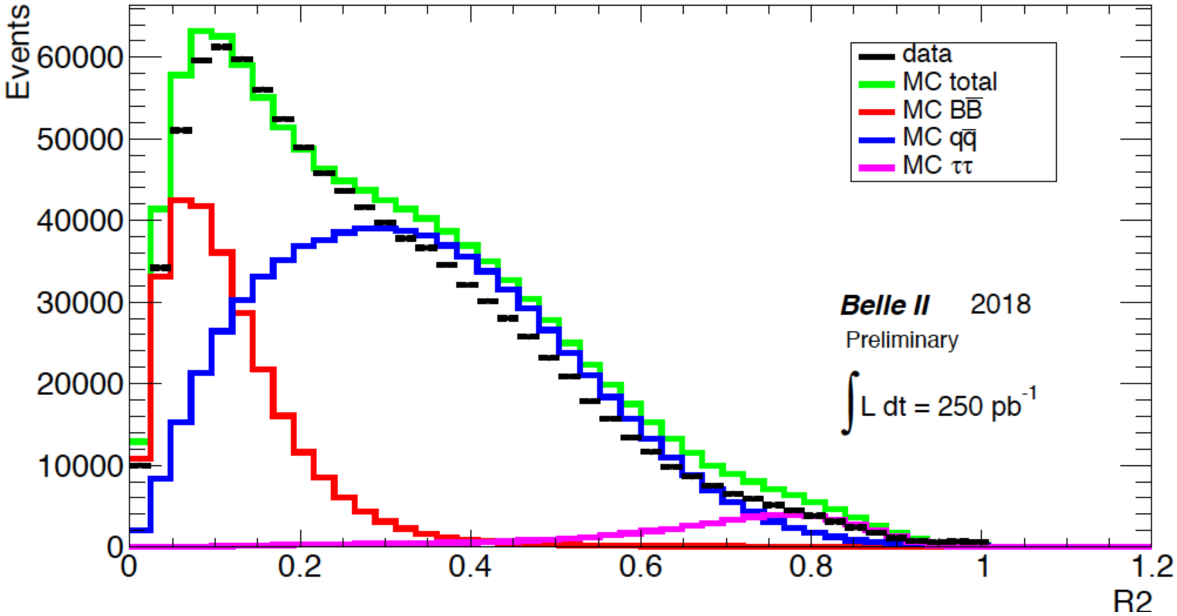
$$\left(\frac{n_b}{n_\gamma}\right)^{\mathrm{SM}} \propto \frac{J_{CP}}{T_c^{12}} \sim 10^{-20}$$

The CP Violation predicted by Kobayashi and Maskawa is too small by *~10 orders of magnitude* in the Standard Model.

What does this
mean ?

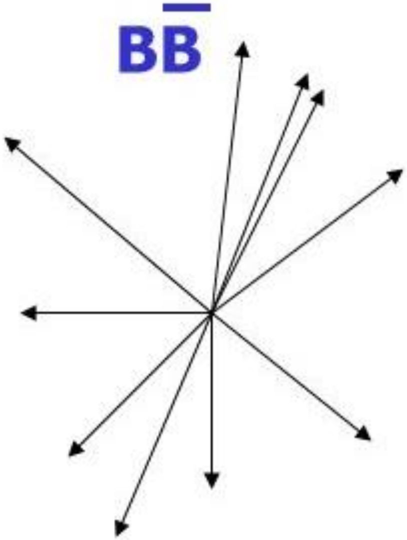
New
Physics

Event Topology tells us we are seeing B's

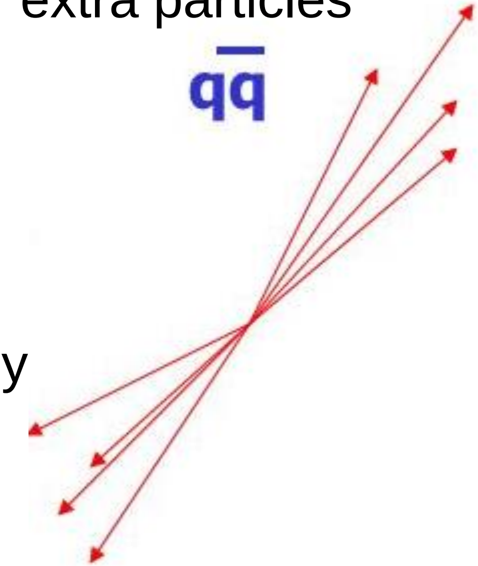


Spherical

Jet-like



B pairs produced at rest in the CM with no extra particles



We are on the Y(4S) resonance and recording B-anti B pairs with ~99% efficiency

Phase III:

Milestone: Completion of +X clam-shell of the SVD on Jan 18, 2018

Machine Parameters

2017/September/1	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	():zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	$3.20\text{x}10^{-4}$	$4.55\text{x}10^{-4}$		
σ_δ	$7.92(7.53)\text{x}10^{-4}$	$6.37(6.30)\text{x}10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6(4.7)	5(4.9)	mm	():zero current
ν_s	-0.0245	-0.0280		
ν_x/ν_y	44.53/46.57	45.53/43.57		
U_0	1.76	2.43	MeV	
$\tau_{x,y}/\tau_s$	45.7/22.8	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	$8\text{x}10^{35}$		$cm^{-2}s^{-1}$	