The Belle II Experiment

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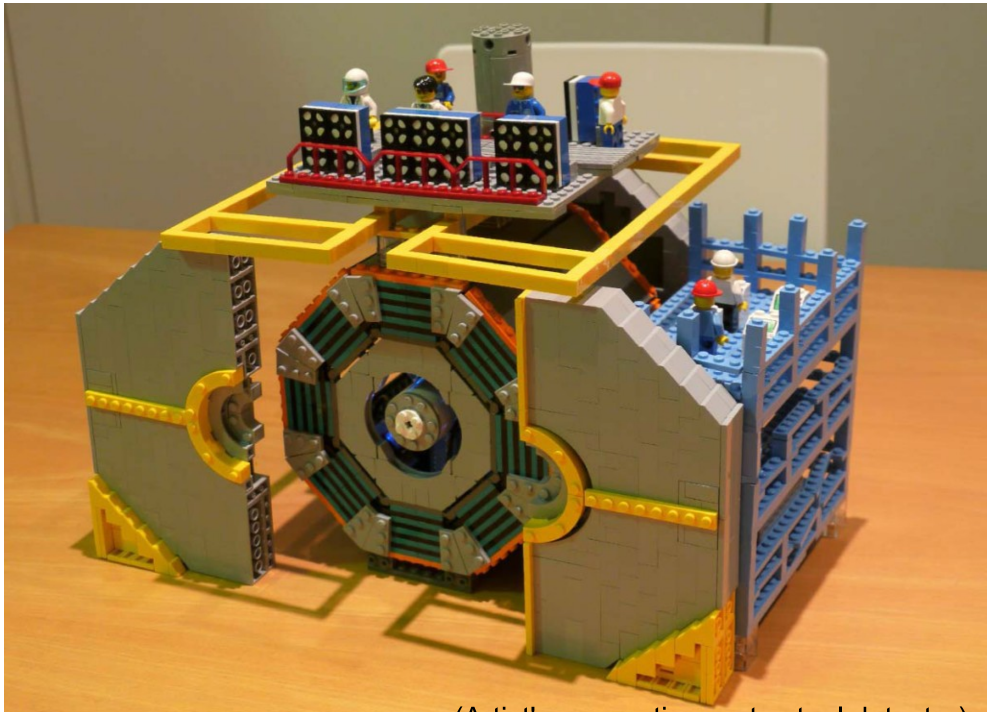
INSTITUTE OF PARTICLE PHYSICS

McGill

Outline

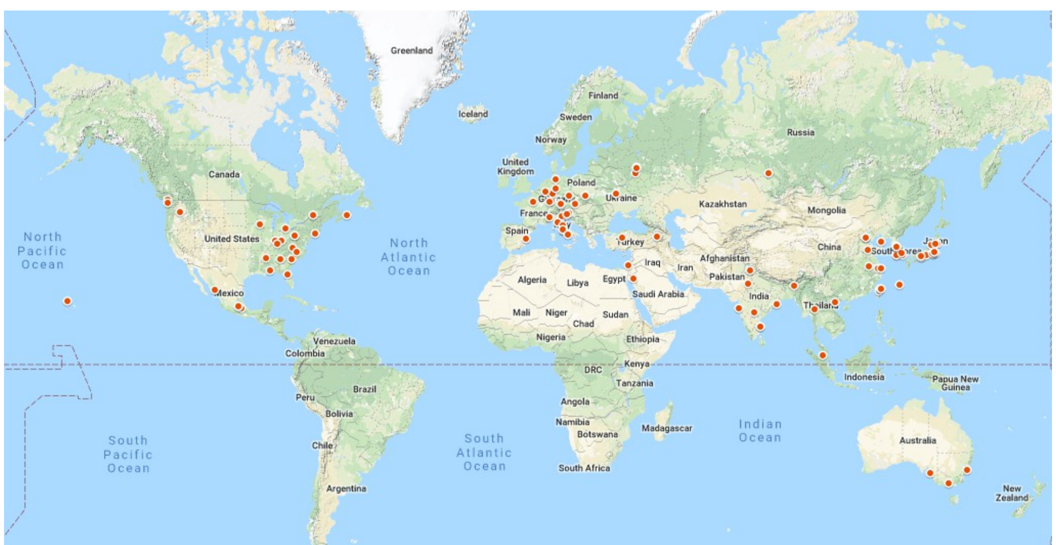
- B Factory overview
- Phase 3 operations and commissioning
- Performance validation
- Physics results
- Future prospects


(Artist's conception; not actual detector)

Belle II

Belle II is the successor of the Belle experiment at the KEK laboratory in Tsukuba, Japan

- Intensity frontier "Super B Factory" flavour physics experiment
- Target data set of ~30x the combined integrated luminosity of BABAR + Belle
- ~800 collaborators from 26 countries, including over 260 graduate students

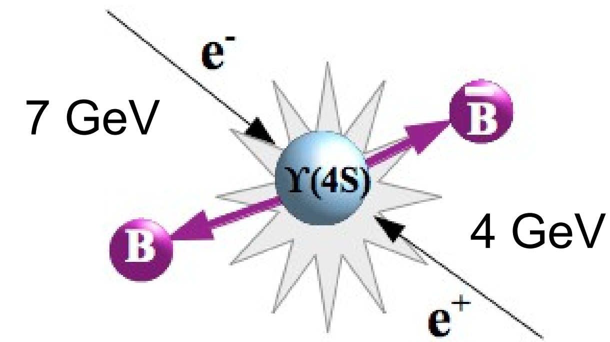


Canadian participation:

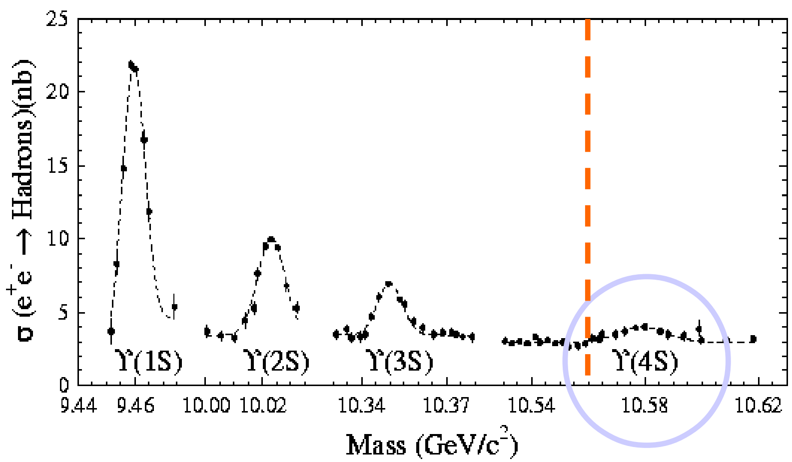
- UBC
- UVic
- McGill
- St Francis Xavier

B Factories

B Factories are e^+e^- colliders operating in the vicinity of the $\Upsilon(4S)$ resonance at ~10.5 GeV centre of mass energy



- Resonant production of $\Upsilon(4S) \rightarrow B\bar{B}$ along with continuum production of large samples of $e^+e^- \rightarrow l^+l^-$ ($l = e, \mu, \tau$) and $e^+e^- \rightarrow q\bar{q}$
- Asymmetric beam energies to create longitudinal boost of resulting $B\bar{B}$ mesons



Process	σ (nb)
$b\bar{b}$	1.1
$c\bar{c}$	1.3
Light quark $q\bar{q}$	~2.1
$\tau^+\tau^-$	0.9
e^+e^-	~40

Detectors optimized for B vertex separation and momentum measurement, K - π particle identification and precision calorimetry

Record ~ 1 billion each of charged and neutral B meson decays per ab^{-1} of data

Belle II

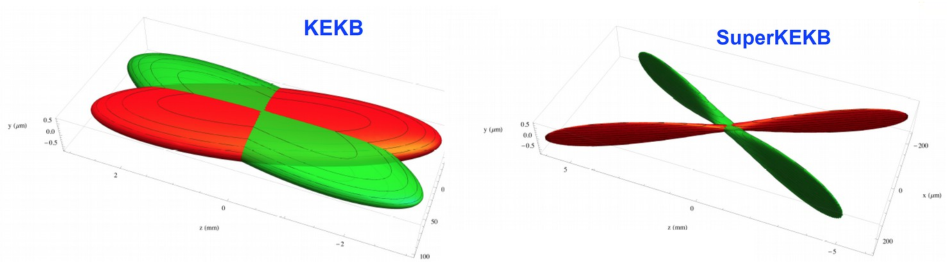
Belle II detector substantially upgraded from Belle experiment for improved performance in the high-luminosity Super B Factory environment

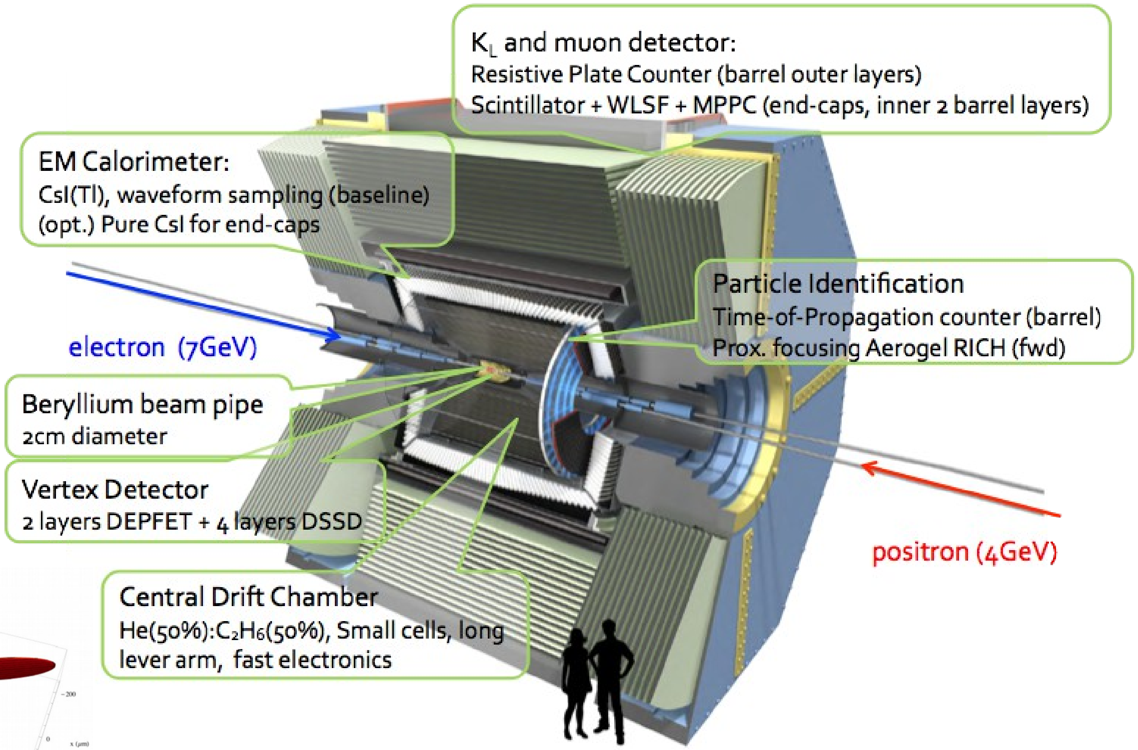
4 GeV on 7 GeV e^+e^- collisions at $8 \times 10^{35} cm^{-2}s^{-1}$

- Low-emittance "nanobeam" scheme exploiting ILC and light-source technologies
- Crossing angle at IP

SuperKEKB has now broken KEKB peak and daily integrated luminosity records (949 pb^{-1} in a 24 hour period)

- Typically integrating ~1fb^{-1} per day
- "Crab waist" scheme successfully commissioned

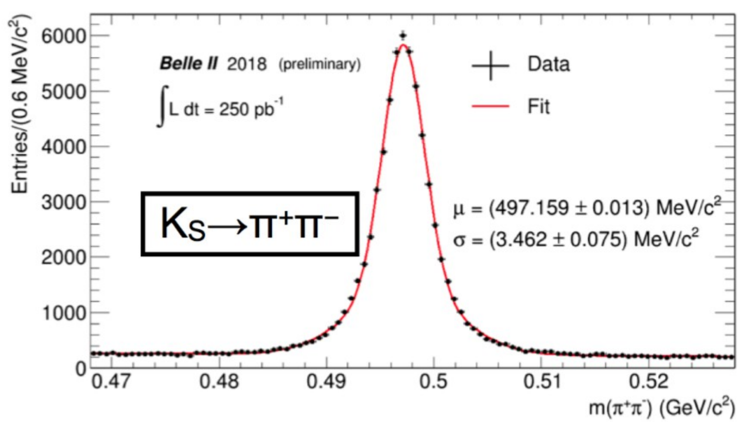


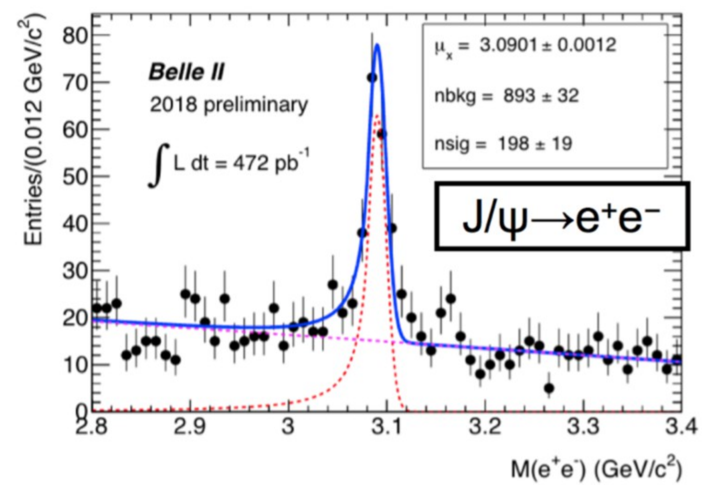


Belle II commissioning

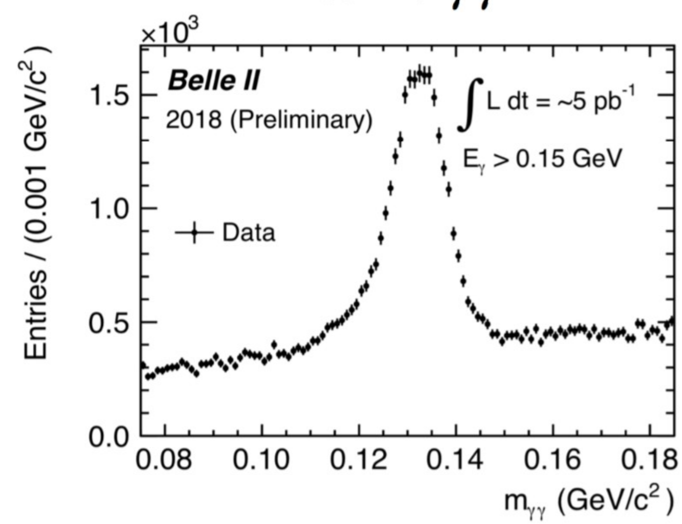
2018 SuperKEKB run provided opportunity to validate detector performance with colliding beams during accelerator commissioning run

- “Rediscovery” of various particle states:





$\pi^0 \rightarrow \gamma\gamma$



“Phase 3” commissioning began in 2019

- Colliding-beams data with full detector (minus one layer of pixel vertex detector)
- Instantaneous luminosity comparable to BABAR or Belle

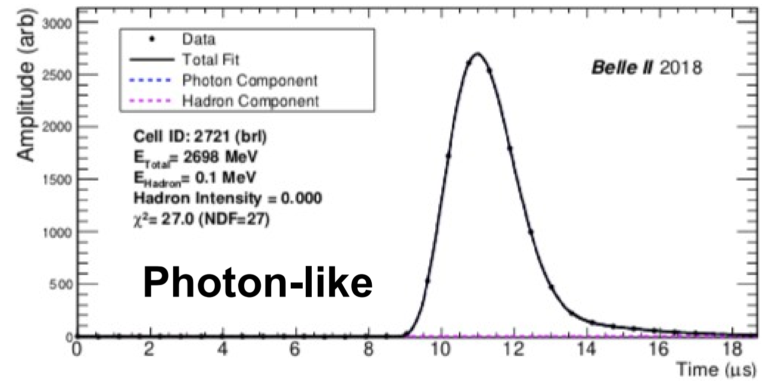
CsI(TI) Pulse Shape Discrimination

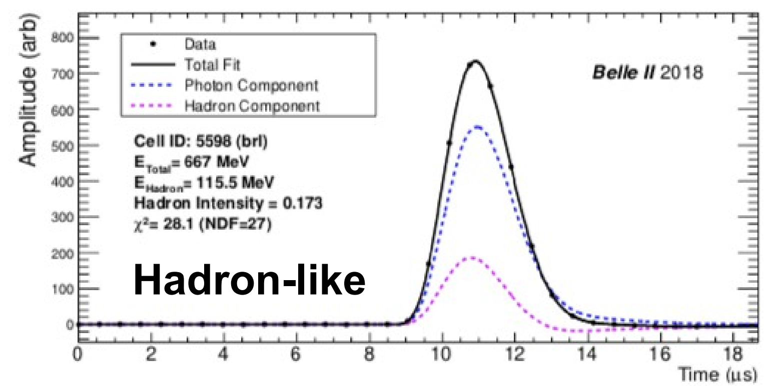
Reconstruction of neutral particles is an important capability of B-factories

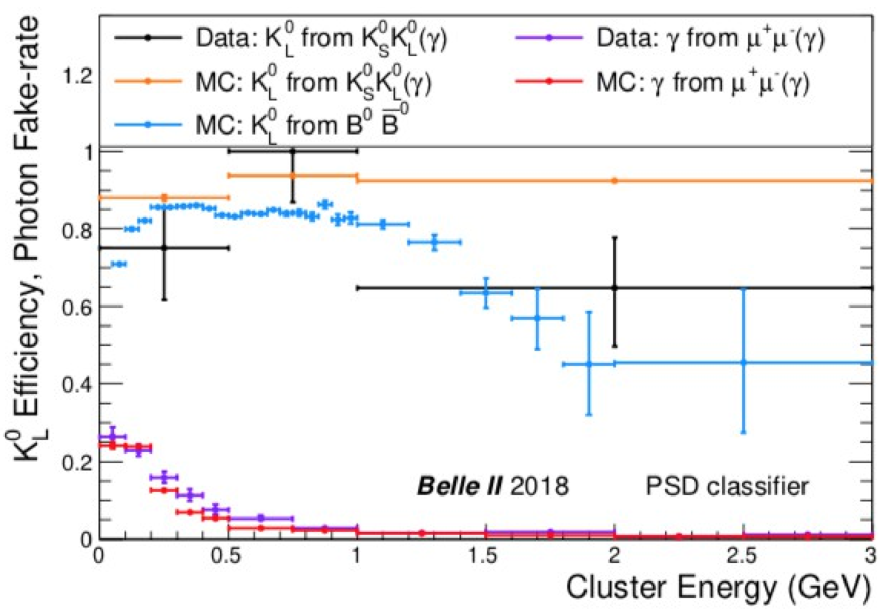
e.g. $B \rightarrow J/\psi\ K_L^0$ measurement of $\sin(2\beta)$

- Calorimeter-based neutral hadron discrimination exploits difference in time structure of scintillation light from hadrons compared to EM showers

PhD thesis work of Savino Longo (UVic)
NIM A paper in preparation

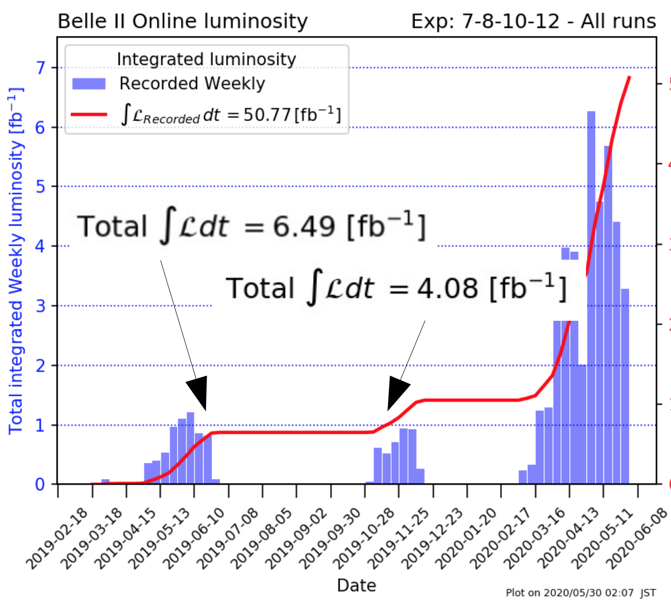


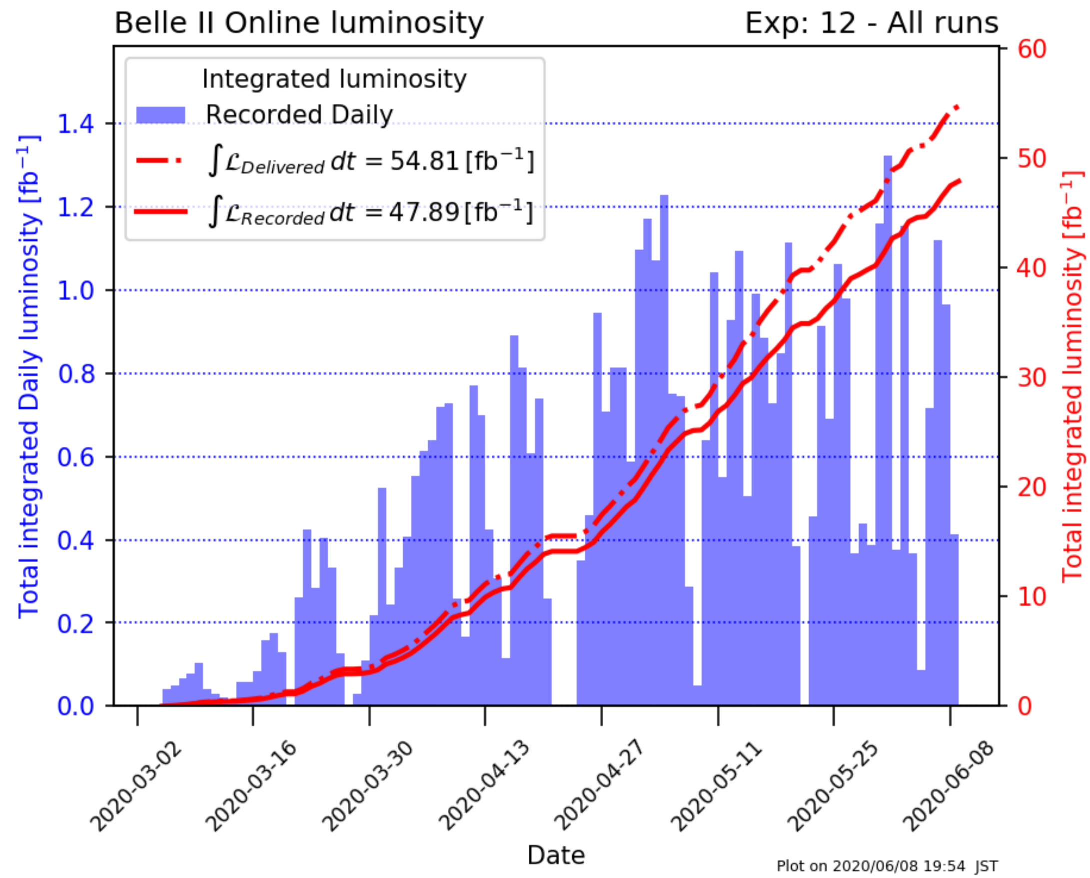




Fit ECL waveforms with templates for photon and hadron components to obtain “Hadron Intensity”

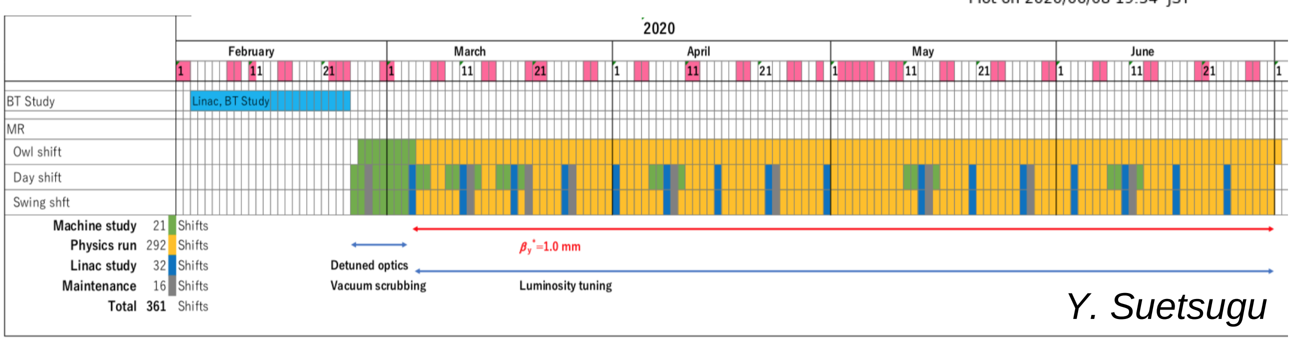
Phase 3 data taking





2020 Run plan:

- ~100 days of physics data taking in first half of 2020
- Summer shutdown due to power restrictions
- ~2 months of additional data taking anticipated for late fall



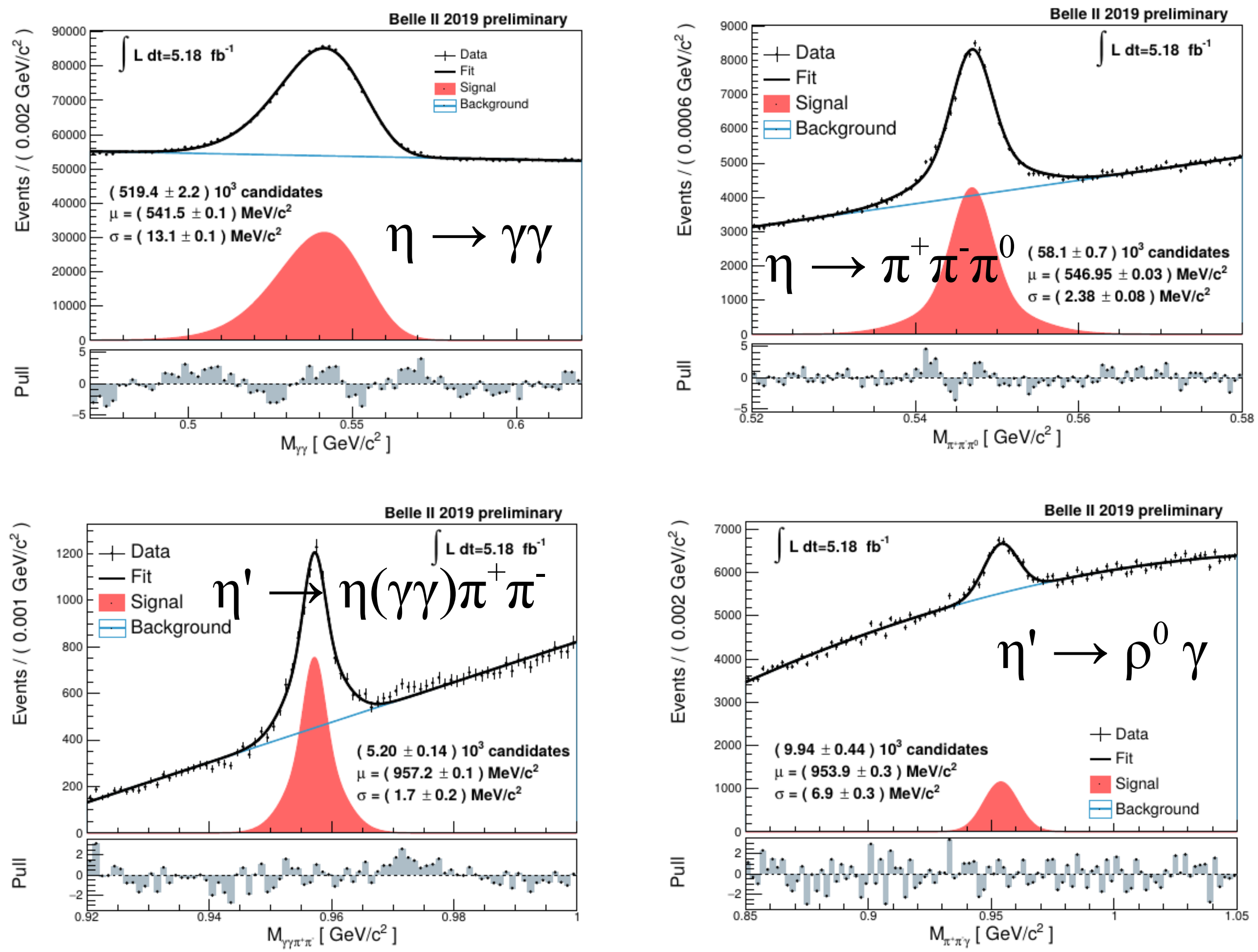
Y. Suetsugu

η and η' "rediscovery"

With accumulation of high-quality colliding-beam data, continued effort to characterize detector and commission data analysis tools

- Use track and neutral cluster objects for reconstruction of composite particles:

η and η' important for analyses such as time dependent CP violation of $B^0 \rightarrow K^0\eta'$

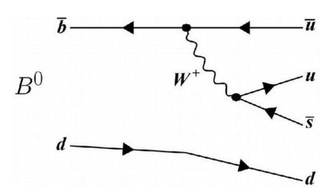


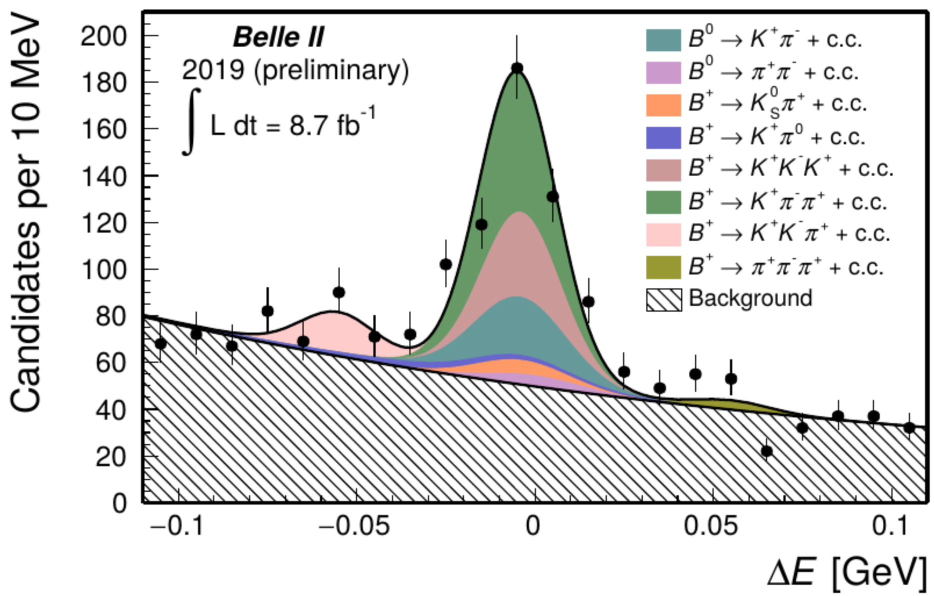
Charmless B decays

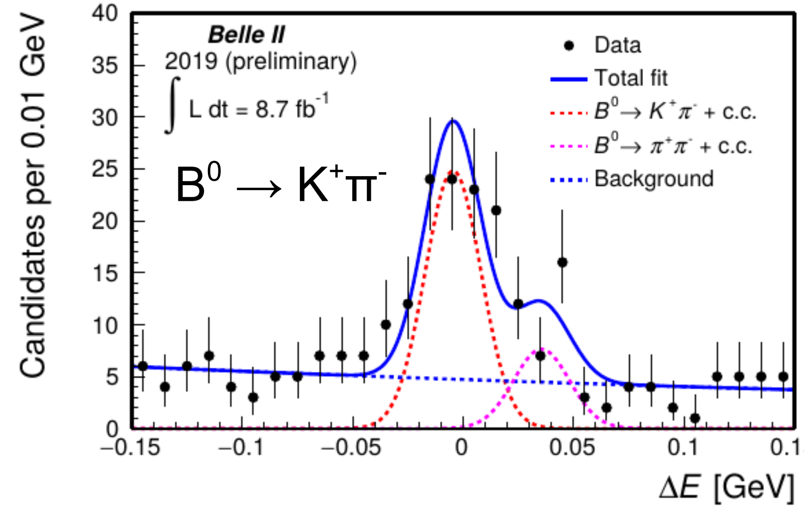
arXiv:2005.13559 [hep-ex]
BELLE2-CONF-PH-2020-001

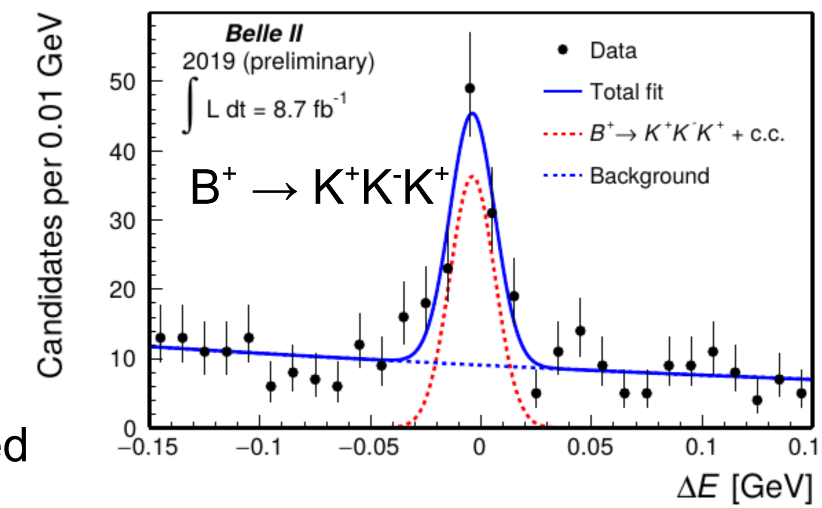
Decays of B mesons to charmless hadronic final states are essential to measure the quark-mixing parameter α/φ_2

- Small ($<10^{-5}$) branching fractions; very large continuum backgrounds
- Yields are consistent with expectation from simulation









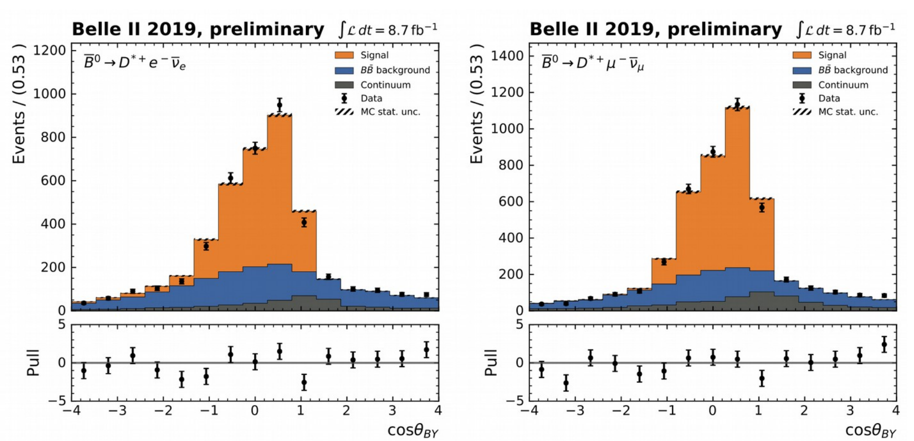
ΔE = difference between kinematically expected energy and reconstructed B meson energy

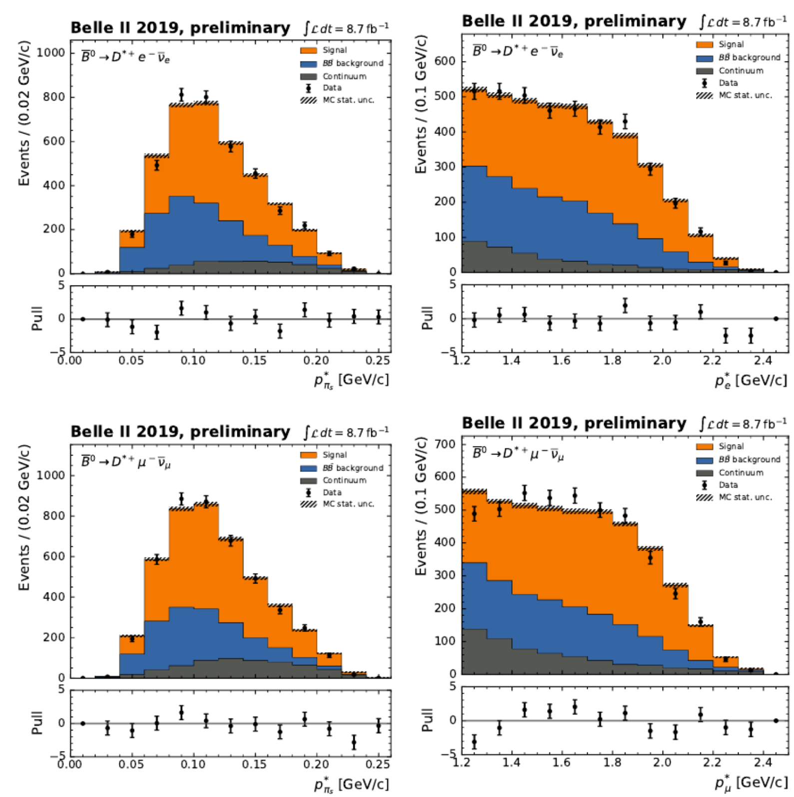
$\overline{B}^0 \rightarrow D^{*+} l\, \nu$

arXiv:2004.09066 [hep-ex]
BELLE2-CONF-PH-2020-002

Semileptonic B decay branching fractions needed for the determination of CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$

- $\overline{B}^0 \rightarrow D^{*0+} l\, \nu$ is the cleanest of the semileptonic B modes
- Also a major sources of backgrounds for measurements of $|V_{ub}|$ and of $B \rightarrow D^{(*)} \tau\, \nu$
- Reconstruct B decays by combining $D^{\pi+} \rightarrow D^0 \pi^+$ with $D^0 \rightarrow K^- \pi^+$, with an identified e or μ





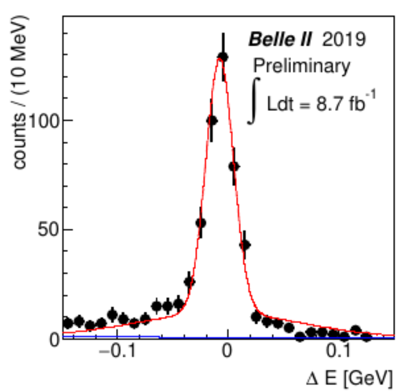
- Results consistent with world average of previous measurement

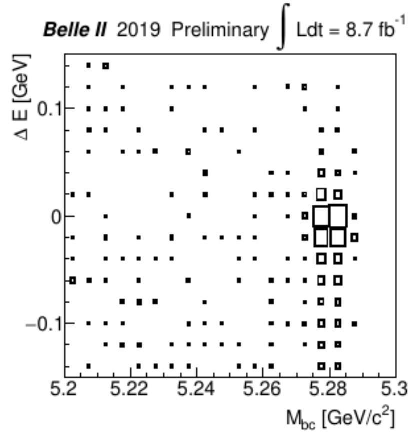
$B^0 \rightarrow J/\psi\, K_s^0$ and $B^+ \rightarrow J/\psi\, K^+$

"Golden modes" for B factories for the study of CP violation in time-dependent decays

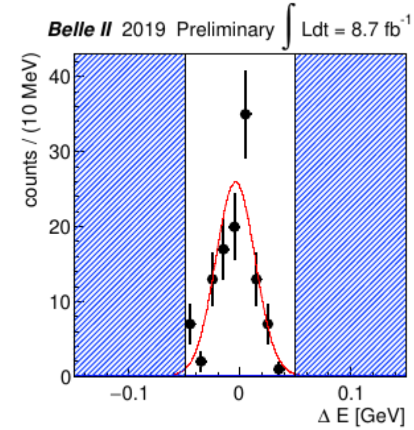
- $\sin2\Phi_1$ (or $\sin2\beta$) in the CKM Unitarity Triangle

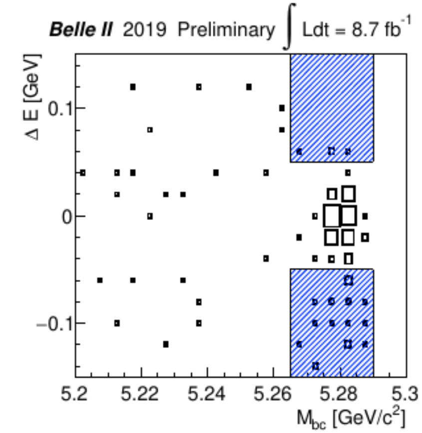
$B^0 \rightarrow J/\psi\, K_s^0$



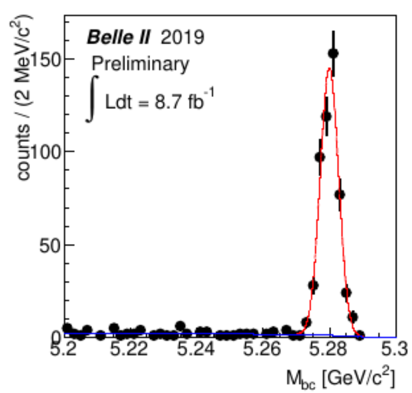


$B^+ \rightarrow J/\psi\, K^+$

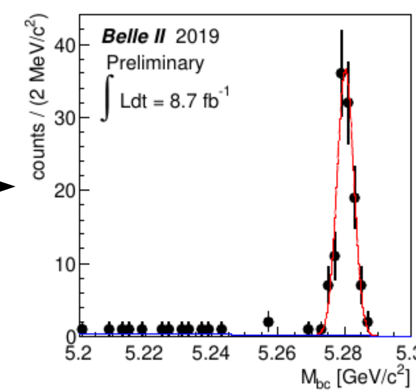




- Signal yields are consistent with expectations



Reconstructed B meson mass

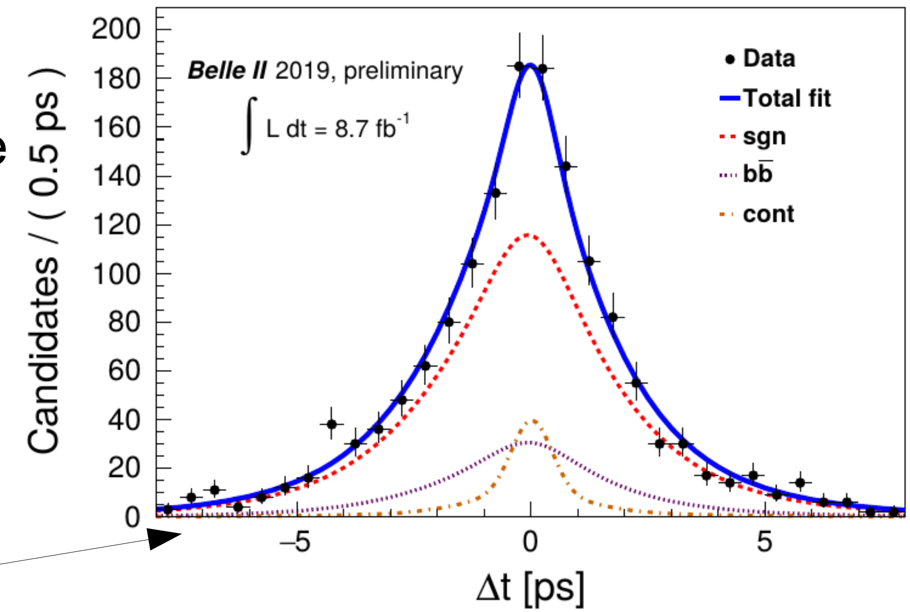


B lifetime

arXiv:2005.07507 [hep-ex]
BELLE2-CONF-PH-2020-003

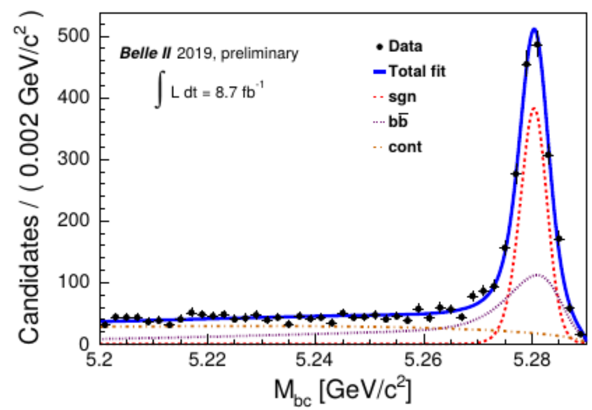
Asymmetric beam energy of SuperKEKB causes B mesons from $\Upsilon(4S) \rightarrow B\bar{B}$ to be (longitudinally) boosted relative to CM frame

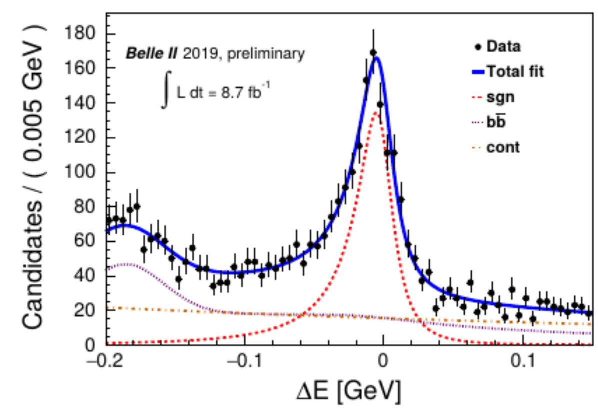
- B mesons have lifetime of ~1.5ps
- Reconstruction of B decay vertices permits measurement of Δt



Proper decay time difference between decays of the two B mesons in the event

- Lifetime consistent with experimental world average





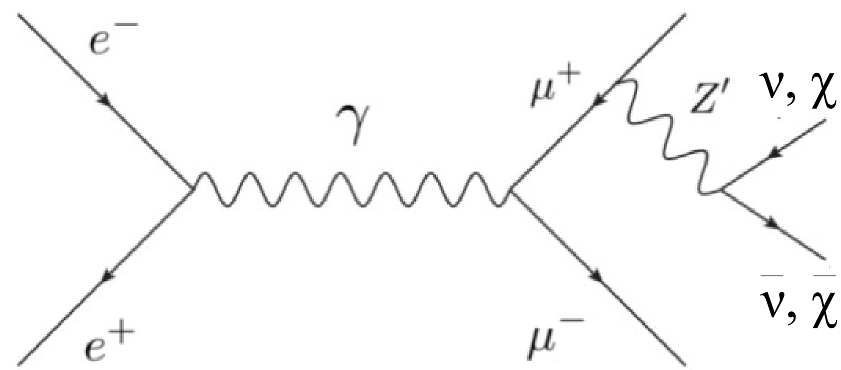
→ Crucial demonstration of vertexing capabilities for time dependent CP violation measurements

Invisible Z'

Not all physics studies require large data sets!

Search for invisibly decaying Z' in $e^+e^- \to \mu^+\mu^- \; Z'$

- Z' arises from gauging of difference of leptonic μ and τ number $L_\mu - L_\tau$
- Z' couples to SM only through μ and τ and their associated neutrinos with coupling constant g'



B. Shuve and I. Yavin, Phys. Rev. D 89, 113004 (2014).
W. Altmannshofer, S. Gori, S. Profumo, and F. S. Queiroz, JHEP 12, 106 (2016).

Z' is produced via radiation off of a final state μ

- If $m_{Z'} < 2m_\mu$ then Z' decays to neutrinos
- Alternatively, expect $B(Z' \to \chi\bar{\chi}) \sim 100\%$ if direct decays are possible

Consider also the LFV scenario of $e^+e^- \to e^+\mu^- \; Z'$

- Identical search methodology, but with PID criteria changed for one of the two leptons

I. Galon and J. Zupan, JHEP 05, 083 (2017).
I. Galon, A. Kwa, and P. Tanedo, JHEP 03, 064 (2017).

Invisible Z'

Phys. Rev. Lett. 124, 141801 (2020)
arXiv:1912.11276 [hep-ex]

Systematics evaluated by comparison of data control samples to simulation

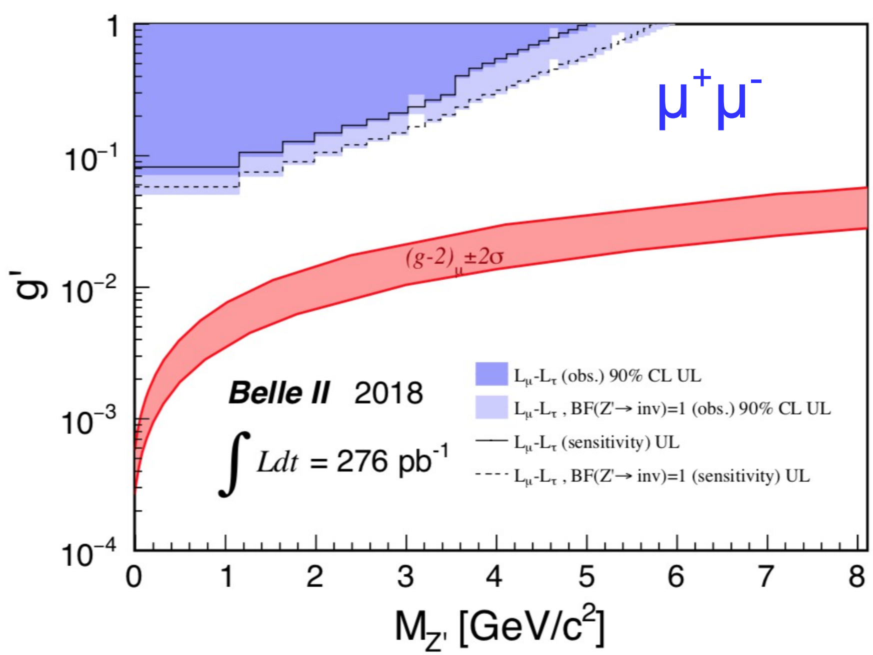
- Dominated by MC modelling of $\mu^+\mu^-$ yield in data

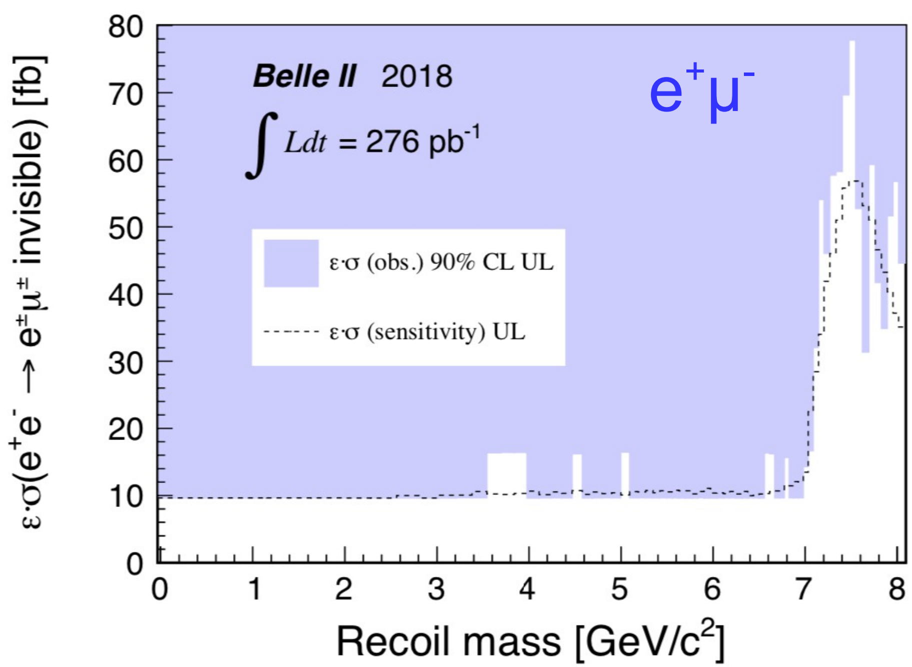
First Belle II physics publication!

Source	$\mu^+\mu^-$	$e^\pm\mu^\mp$
Trigger efficiency	6%	1%
Tracking efficiency	4%	4%
PID	4%	4%
Luminosity	0.7%	0.7%
τ suppression (background)	22%	22%
Background before τ suppression	2%	2%
Discrepancy in $\mu\mu$ yield (signal)	12.5%	-

Cross section limits on $e^+e^- \rightarrow \mu^+\mu^- Z'$ and $e^+\mu^- Z'$ for invisible Z' decays

- Interpreted as limit on coupling g' in context of $Z' \rightarrow \chi\bar{\chi}$

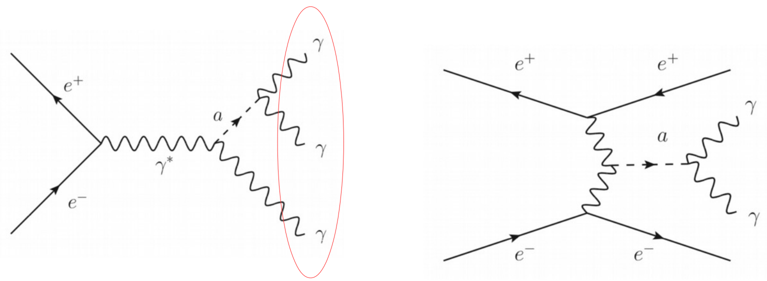


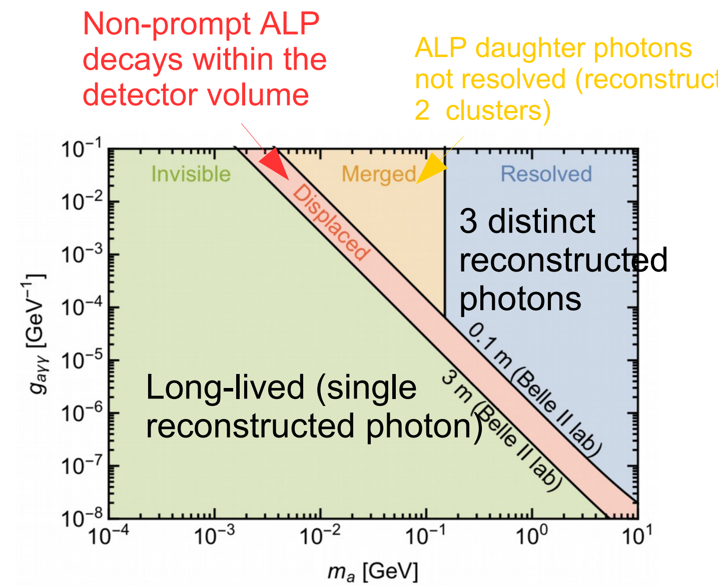


Axion-Like Particles

ALPs are pseudo-scalar particles that couple to bosons

- Unlike QCD axions, there is no specific relationship between coupling and mass
- For ALPs coupling to photon, production via “ALP-strahlung” and “photon fusion” processes

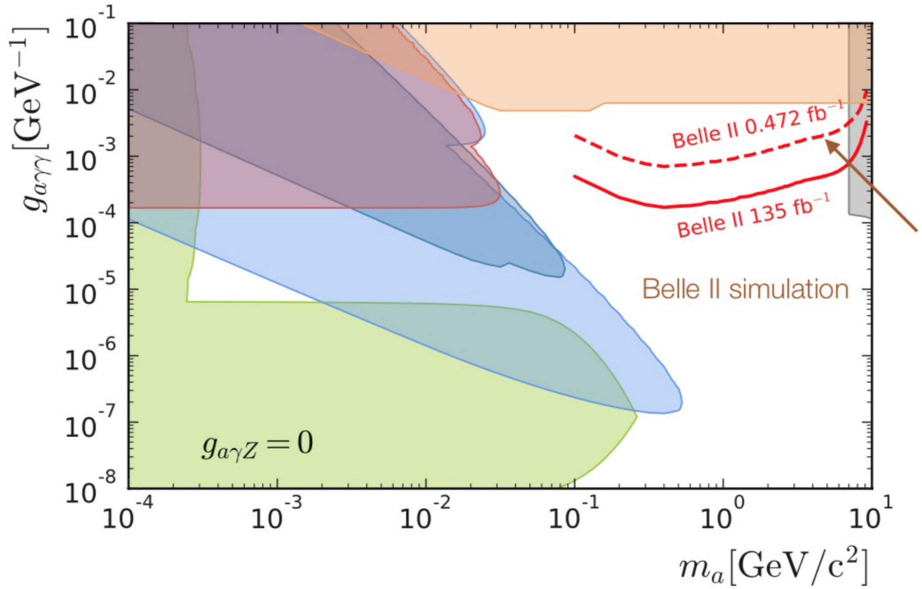




Lifetime depends on mass and coupling:

$$\tau \sim 1/m_a^3 g^2_{a\gamma\gamma}$$

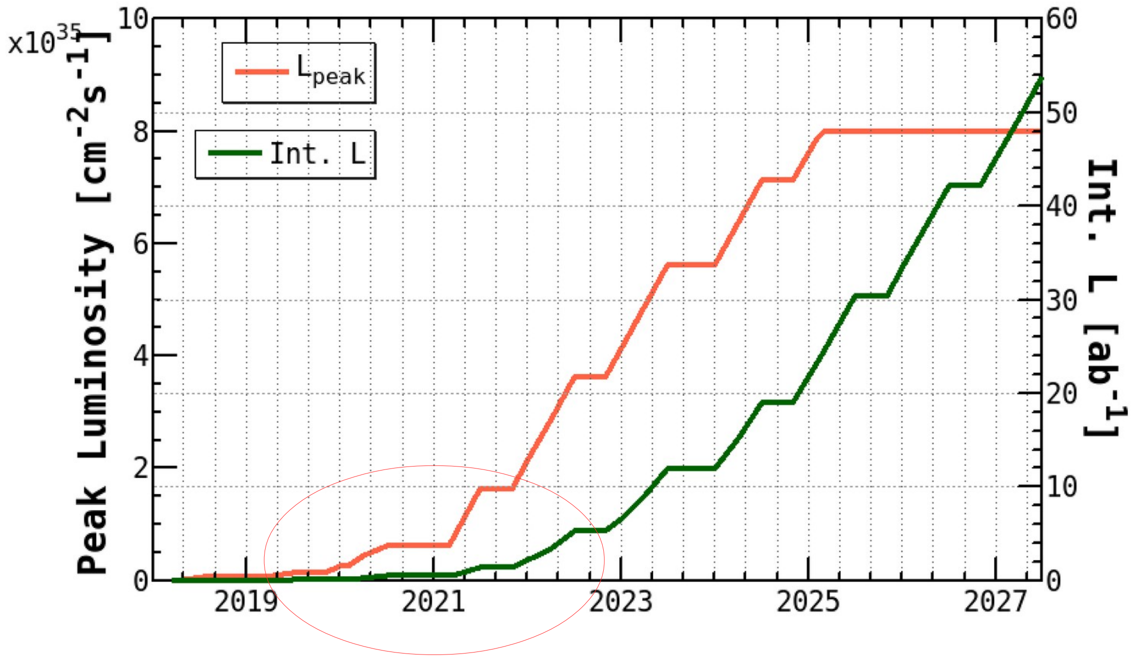
- Several distinct experimental signatures depending on value



JHEP 1712, 094 (2017)

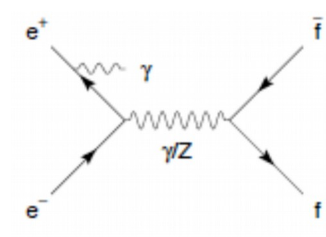
Luminosity prospects

- Anticipate ~100 fb^{-1} recorded during 2020
  - Beam currents presently limited by vacuum scrubbing and resulting beam backgrounds
- ~1ab^{-1} integrated luminosity by end of 2022 with instantaneous luminosity reaching $1x10^{35}$ $cm^{-2}s^{-1}$ during 2021
  - Includes ~9 month shutdown for pixel detector installation in 2021 or 2022; dates TBD



Chiral Belle

Polarized beam operation of SuperKEKB would permit measurement of $\sin^2\theta_W$ via left-right asymmetries in di-fermion final states



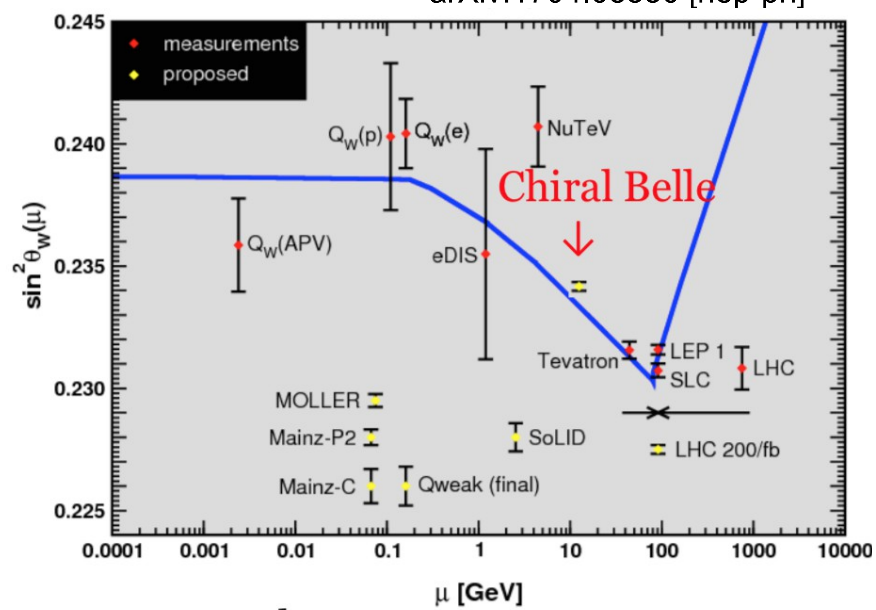
$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{4}{\sqrt{2}}\left(\frac{G_F s}{4\pi\alpha Q_f}\right) g_A^e g_V^f \langle Pol \rangle$$

$$\propto T_3^f - 2Q_f \sin^2\theta_W$$

At 10.58 GeV, polarized e^- beam yields product of the neutral axial-vector coupling of the electron and vector coupling of the final-state fermion via Z-γ interference:

- 70% polarized electron beam with 20 – 40 ab^{-1} would yield unprecedented precision for neutral current vector couplings

arXiv:1704.08330 [hep-ph]



Canadian effort in collaboration with physicists from KEK + Japan, Russia, US and France

  - physicists from UVic, U Manitoba, TRIUMF
- Requires:
  - Inject vertically polarized electrons
  - Spin-rotators to align polarization vector at IP
  - Compton polarimeter
  - Re-optimization of the machine lattice
- Aim for installation in mid-2020's

Same technique as SLD A_{LR} measurement at the Z-pole: $\sin^2\theta_{W\mathrm{eff}}^{\mathrm{lepton}} = 0.23098 \pm 0.00026$

Conclusion

Belle II physics program has begun, with ~100 fb^{-1} of data anticipated in 2020

- SuperKEKB has now exceeded B factory instantaneous luminosity records
- Physics results are starting to appear, including validation and “rediscovery” measurements, but also worlds-best sensitivity in dark-sector and other specialized data sets

The Super B Factory era has begun!

Publications and conference papers:

https://confluence.desy.de/display/BI/Belle+II+Publications

The Belle II Physics Book:

PTEP 2019, no. 12, 123C01 (2019). arXiv:1808.10567

Social media:

https://www.facebook.com/belle2collab/
https://twitter.com/belle2collab

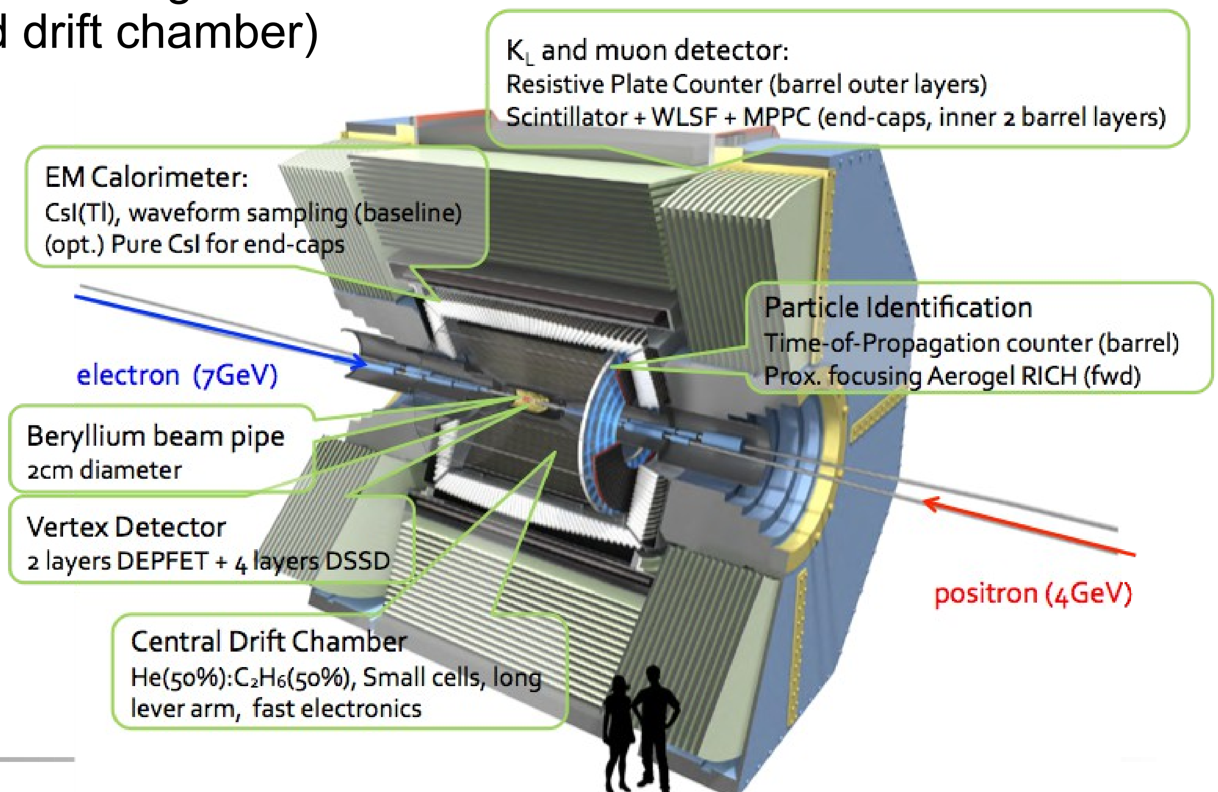
Backup slides

Belle II Experiment

- Target data sample of 50 ab^{-1}
- 4 GeV on 7 GeV e^+e^- collisions at $8 \times 10^{35} cm^{-2}s^{-1}$
- Low-emittance "nanobeam" scheme exploiting ILC and light-source technologies; crossing angle at IP

Very substantial "upgrades" to the original Belle detector:

- Replacement of beam pipe and redesign of entire inner detector (including vertex detectors and drift chamber)
- New quartz-bar Time-of-Propagation PID in barrel region
- Retain existing CsI(Tl) calorimeter crystals, but front-end electronics, feature extraction and reconstruction software entirely new
- Entirely new software framework and distributed computing environment



SuperKEKB

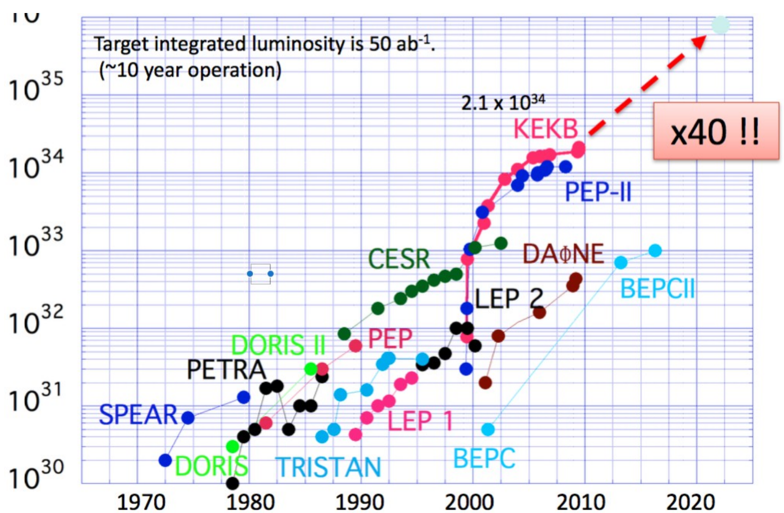
How to get to $8 \times 10^{35}\ cm^{-2}s^{-1}$:

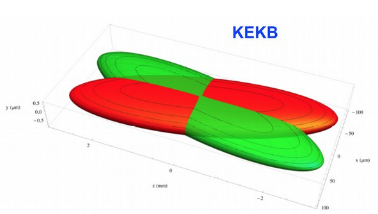
- Very high charge density bunches
- Bunch crossings every 6ns (~1.2m spacing)
- Low emittance beams
- Tiny beam spot at IP

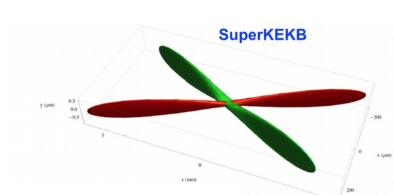
beam current **x2** beam-beam param. **x1**

$$L = \frac{\gamma_\pm}{2er_e}(1+a)\frac{R_L}{R_\xi}\left(\frac{I_\pm \xi_{y\pm}}{\beta^*_{y\pm}}\right)$$

vertical beta function **x20**



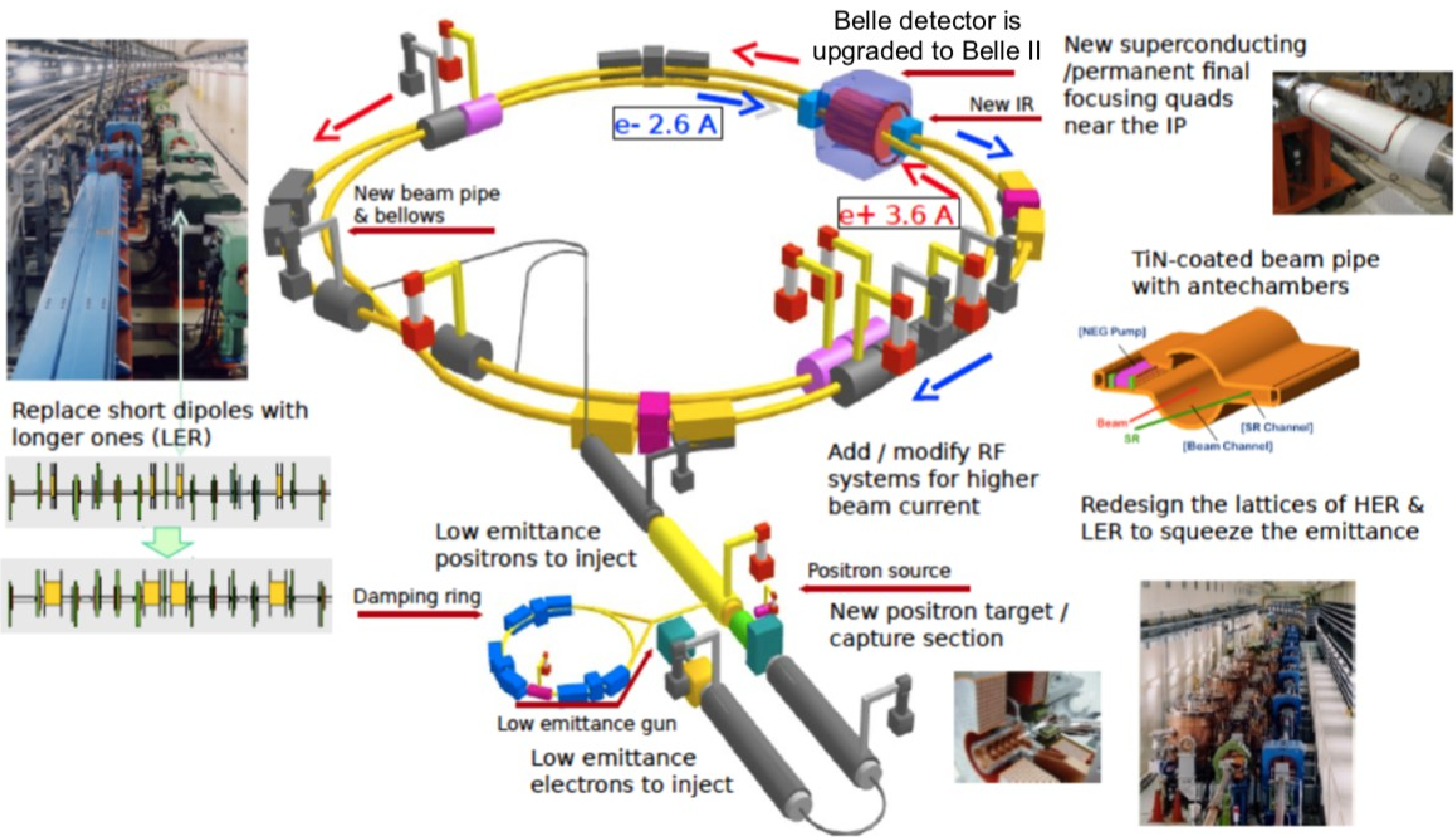




	KEKB Achieved LER	KEKB Achieved HER	SuperKEKB LER	SuperKEKB HER
RF frequency f [MHz]	508.9			
# of Bunches N	1584		**2500**	
Horizontal emittance εx [nm]	18	24	3.2	4.6
Beta at IP βx*/βy* [mm]	1200/5.9		32/**0.27**	25/**0.30**
beam-beam param. ξy	0.129	0.090	0.088	0.081
Bunch Length Sz [mm]	6.0	6.0	6.0	5.0
Horizontal Beam Size sx* [μm]	150	150	10	11
Vertical Beam Size sy* [nm]	0.94		48	62
Half crossing angle φ [mrad]	11		41.5	
Beam energy Eb [GeV]	3.5	8	4	7.007
Beam currents Ib [A]	1.64	1.19	**3.6**	**2.6**
Lifetime t [min]	133	200	**6**	**6**
Luminosity L [$cm^{-2}s^{-1}$]	**2.1×10^{34}**		**8×10^{35}**	

Short beam lifetime requires continuous ("trickle") injection during live data taking

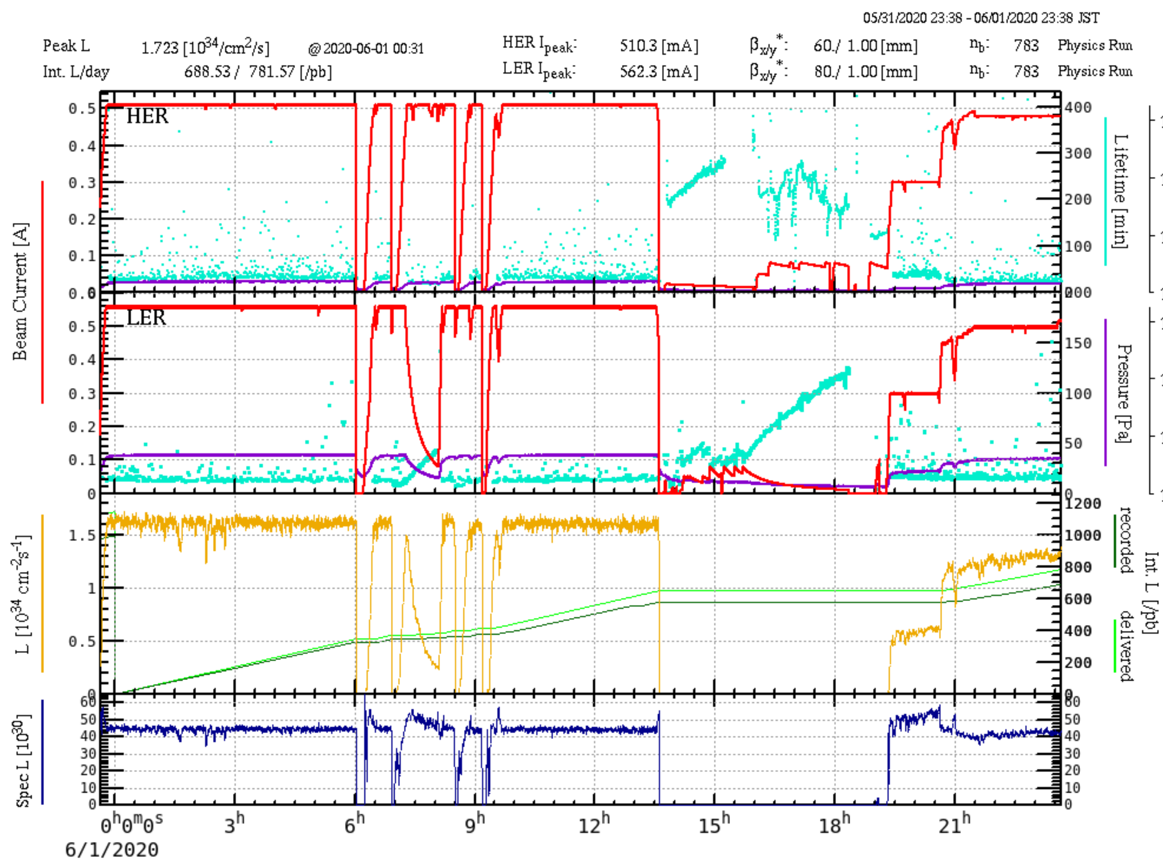
SuperKEKB


Belle detector is upgraded to Belle II
New superconducting /permanent final focusing quads near the IP
New IR
e- 2.6 A
e+ 3.6 A
New beam pipe & bellows
TiN-coated beam pipe with antechambers
[NEG Pump]
Beam
SR
[SR Channel]
[Beam Channel]
Replace short dipoles with longer ones (LER)
Add / modify RF systems for higher beam current
Redesign the lattices of HER & LER to squeeze the emittance
Low emittance positrons to inject
Damping ring
Positron source
New positron target / capture section
Low emittance gun
Low emittance electrons to inject

SuperKEKB performance

SuperKEKB has now exceeded KEKB peak and daily integrated luminosity records (949 pb^{-1} in a 24 hour period)

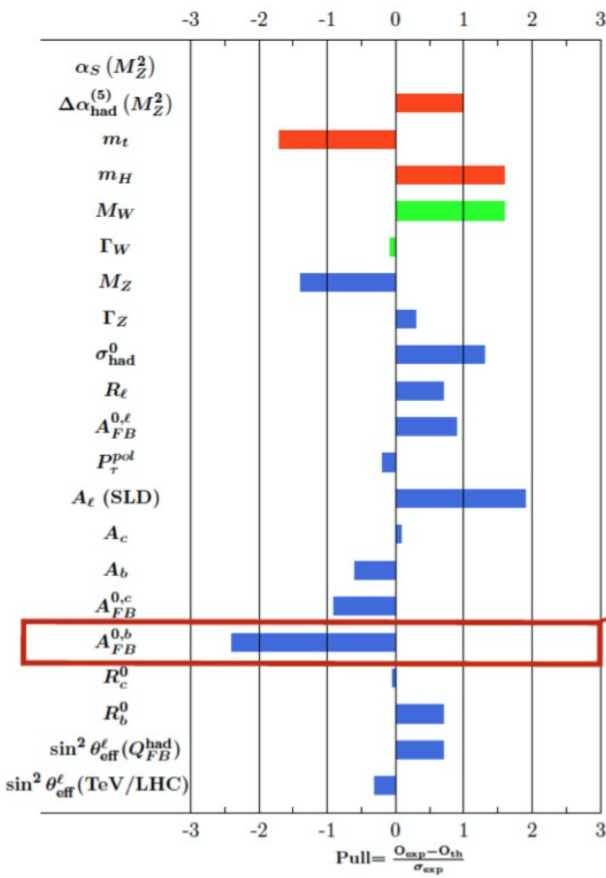
- HER and LER beam currents presently limited to ~0.5A due to beam backgrounds
- New LER beampipe requires integrated A-h for vacuum scrubbing
- Trickle injection (2 bunch) is commissioned, but has been a source of backgrounds
- "Crab waist" scheme successfully commissioned
- Typically integrating ~1fb^{-1} per day



The Standard Model Electroweak fit

SM fit results: Predictions for EWPO

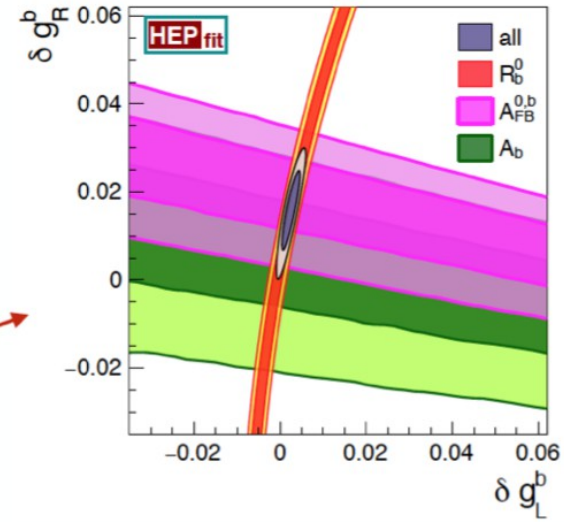
Also good agreement between indirect determination of EWPO and experimental measurements, **with one notable exception**



~2.5 σ discrepancy in forward-fackward asymmetry of the b quark

Requires modifications of (right-handed) *Zbb* couplings

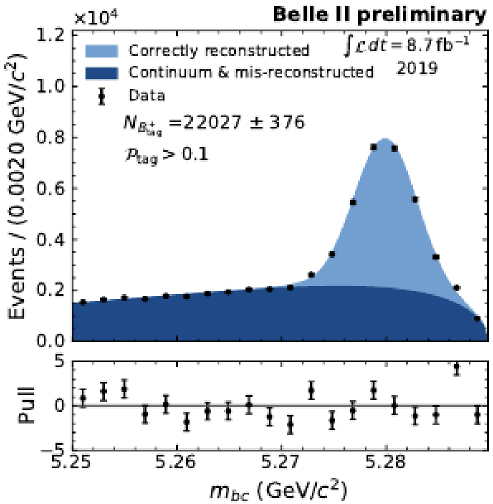
$$g^b_{L,R} = g^{b\,\rm SM}_{L,R} + \delta g^b_{L,R}$$

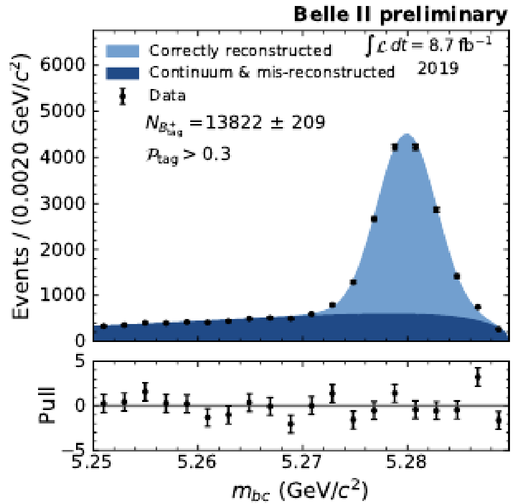


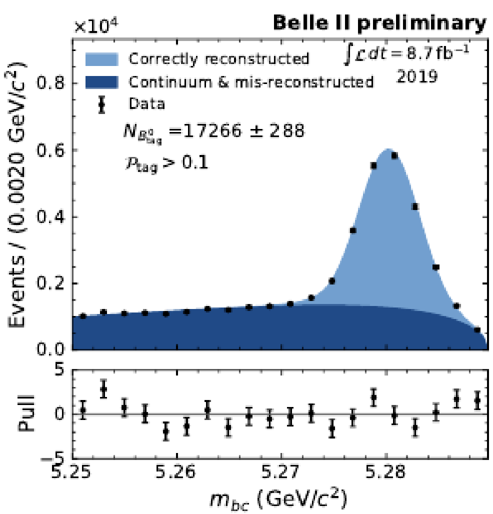
	Fit result	Correlations	
δg^b_R	0.017 ± 0.007	1.00	
δg^b_L	0.003 ± 0.001	0.89	1.00

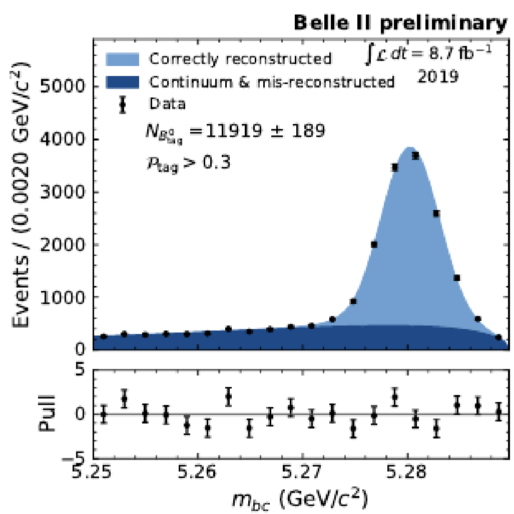
29th International Symposium on Lepton Photon Interactions at High Energies
Toronto, August 6, 2019 — 19 — Jorge de Blas, INFN - University of Padova

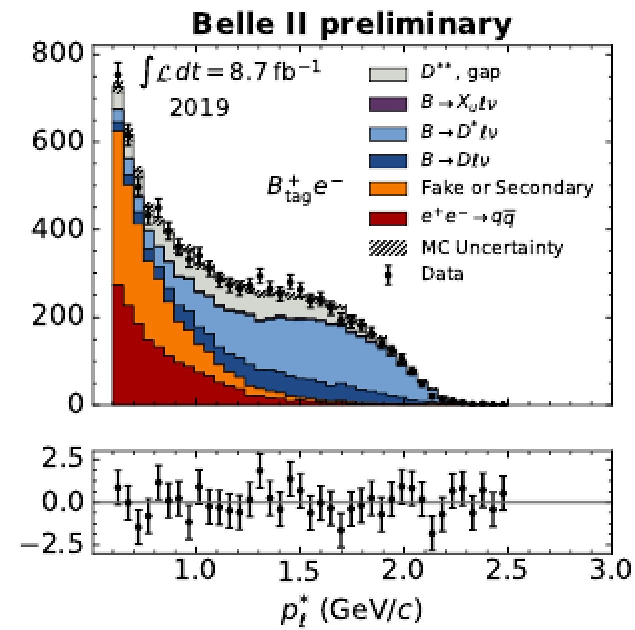
FEI

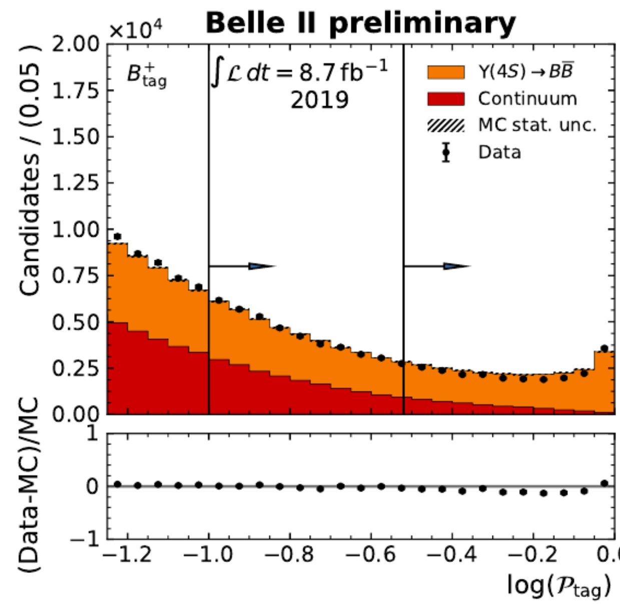

Belle II preliminary
×10^4
Correctly reconstructed
Continuum & mis-reconstructed
Data
∫ℒ dt = 8.7 fb^−1
2019
N_{B+tag} = 22027 ± 376
P_tag > 0.1
Events / (0.0020 GeV/c^2)
Pull
m_bc (GeV/c^2)


Belle II preliminary
Correctly reconstructed
Continuum & mis-reconstructed
Data
∫ℒ dt = 8.7 fb^−1
2019
N_{B+tag} = 13822 ± 209
P_tag > 0.3
Events / (0.0020 GeV/c^2)
Pull
m_bc (GeV/c^2)


Belle II preliminary
×10^4
Correctly reconstructed
Continuum & mis-reconstructed
Data
∫ℒ dt = 8.7 fb^−1
2019
N_{B0tag} = 17266 ± 288
P_tag > 0.1
Events / (0.0020 GeV/c^2)
Pull
m_bc (GeV/c^2)


Belle II preliminary
Correctly reconstructed
Continuum & mis-reconstructed
Data
∫ℒ dt = 8.7 fb^−1
2019
N_{B0tag} = 11919 ± 189
P_tag > 0.3
Events / (0.0020 GeV/c^2)
Pull
m_bc (GeV/c^2)


Belle II preliminary
∫ℒ dt = 8.7 fb^−1
2019
B+tag e−
D**, gap
B → X_u ℓ ν
B → D* ℓ ν
B → D ℓ ν
Fake or Secondary
e+e− → qq̄
MC Uncertainty
Data
p*_ℓ (GeV/c)


Belle II preliminary
×10^4
B+tag
∫ℒ dt = 8.7 fb^−1
2019
Υ(4S) → BB̄
Continuum
MC stat. unc.
Data
Candidates / (0.05)
(Data-MC)/MC
log(P_tag)

Covid-19 impact

KEK has not shut down, but imposed a mandatory 14-day quarantine period for travellers prior to lab entry

- No confirmed cases amongst lab staff or lab-based users
- SuperKEKB and Belle II have been able to continue operations with existing personnel; Belle II experiment has implemented a partially-virtual control room shift system system
- Ongoing Belle II experimental program has not to-date been significantly impacted

Previous Belle II collaboration meeting was in early Feb, prior to Covid lockdowns

- Operation plan through summer was defined at that point, but several scenarios for medium term (2021-2022) were still under discussion; timing of “long” shutdown(s) for detector upgrades contingent on KEK operating money, subsystem readiness, competition with LHCb etc.

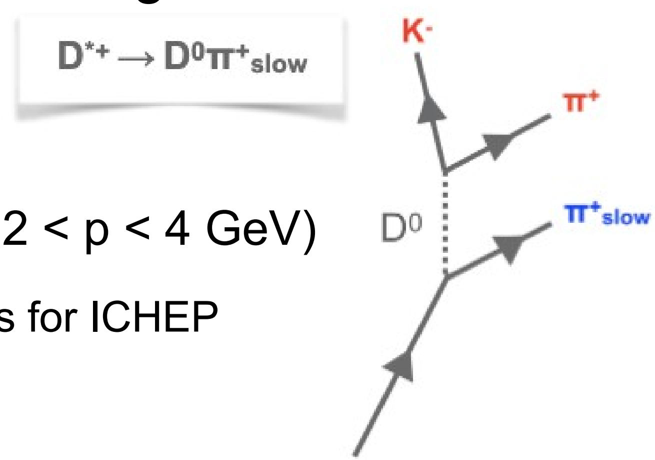
  → Not clear (to me) what the most likely luminosity accumulation scenario will end up being. Best guess is that Belle II will be “competitive with” BABAR data set through 2021.

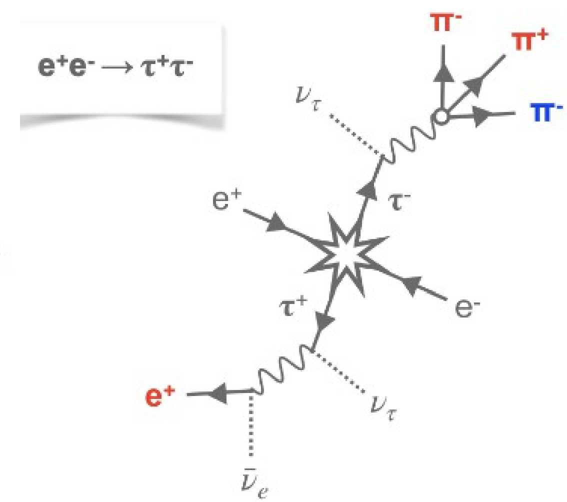
Tracking performance

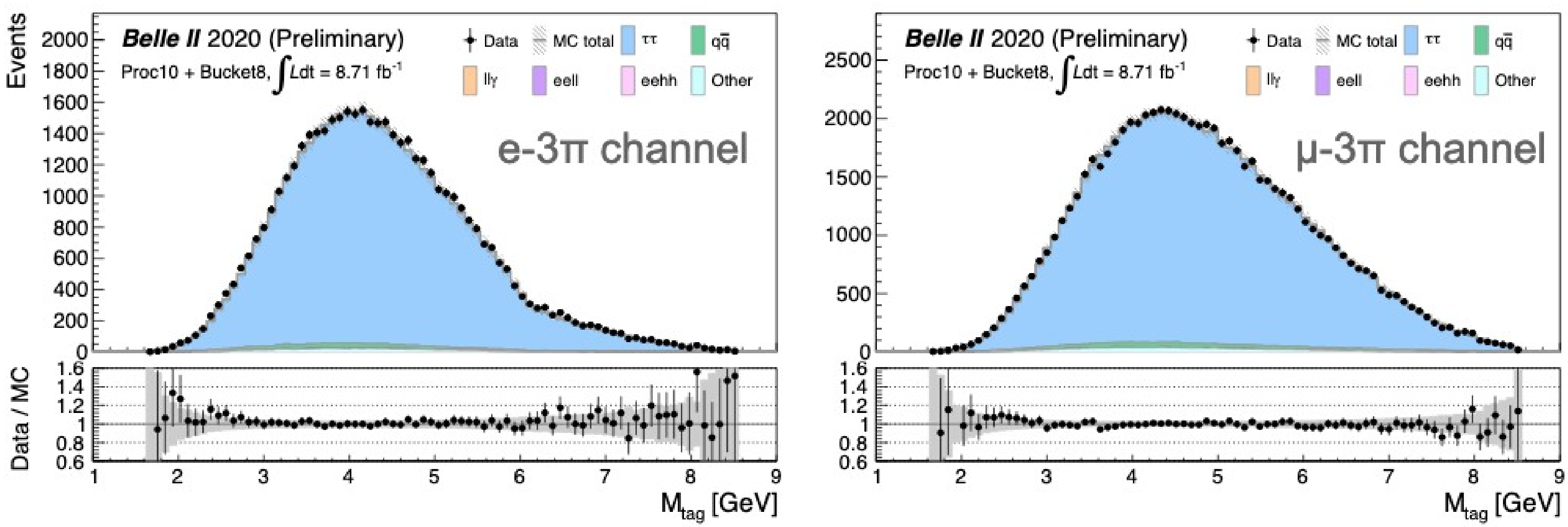
Tag and probe studies of tracking efficiency:

- $B \rightarrow D^* \pi/\rho$ ($p < 300$ MeV)
- $e^+e^- \rightarrow \tau^+\tau^-$ 1 vs 3 prong ($0.2 < p < 4$ GeV)

Efficiency corrections and systematics for ICHEP





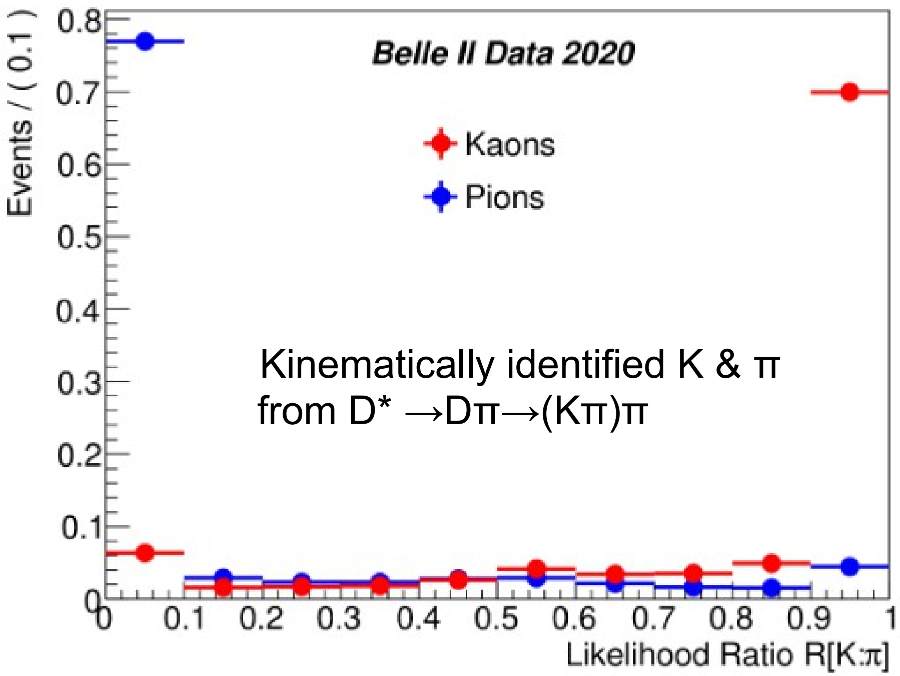


Particle Identification

Belle II particle ID provides a combination of "Global" and "Binary" likelihood ratios for each particle type, from a combination of likelihoods from individual detector subsystems

- Relevant variables accessible in the analysis framework
- Hypotheses: electron, muon, pion, kaon, proton, deuteron
- Performance dominated by different detectors in different kinematics ranges
- Analysts can use predefined values ("tight", "loose") or cut directly on the likelihoods
- MC modelling is not perfect, so of course performance needs to be validated in data and MC corrections derived

$$P(i|\mathbf{x}) = \frac{\mathcal{L}_i}{\sum_j \mathcal{L}_j}. \qquad P(i/j|\mathbf{x}) = \frac{\mathcal{L}_i}{\mathcal{L}_i + \mathcal{L}_j}.$$

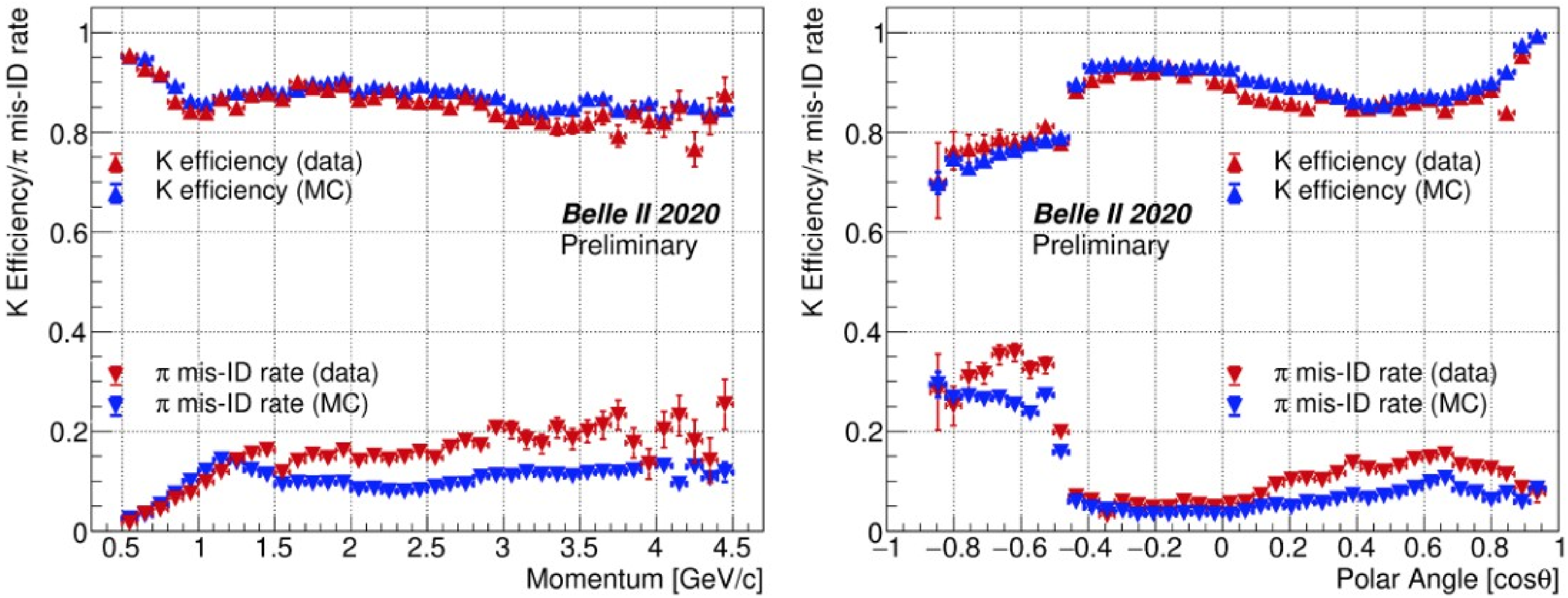


S. Sandilya

Hadron ID

Based on ionization energy loss dE/dx (CDC), Time of flight (TOP) and Cherenkov angle (TOP and ARICH)

R[K:π] > 0.5



Modelling is not perfect, but corrections available for summer conferences

Lepton ID

Similarly, lepton ID efficiencies and mis-ID rates determined from data control samples and compared with MC to derive correction tables

Electron ID efficiency:

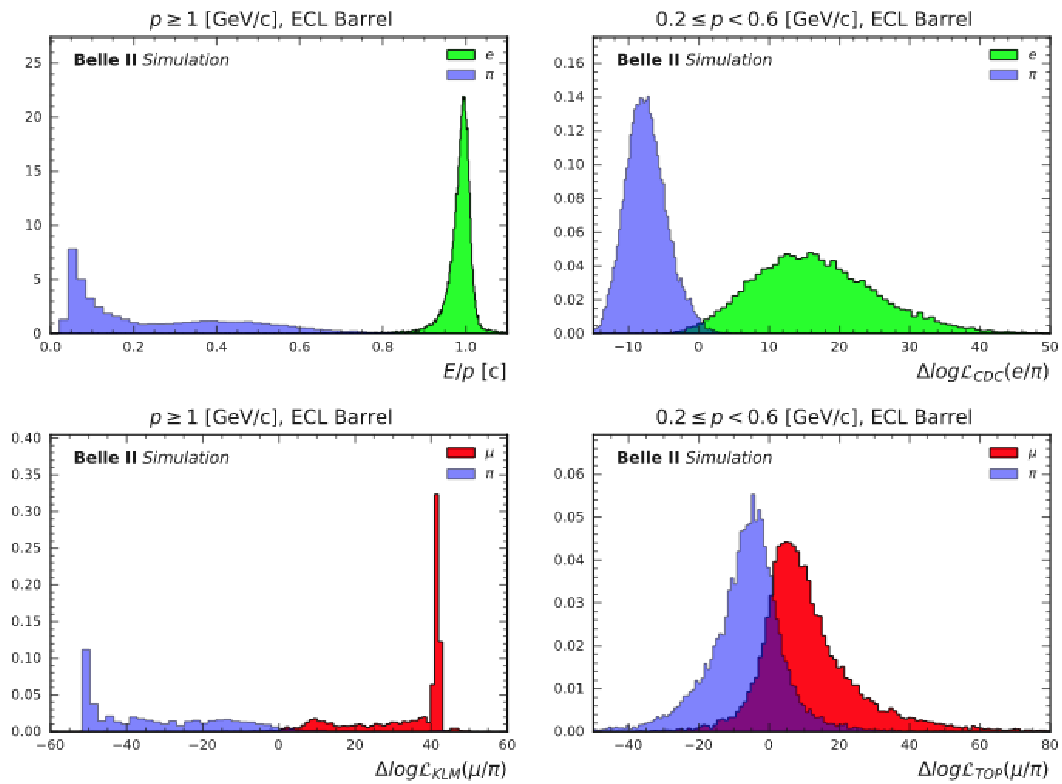
- $J/\psi \rightarrow e^+e^-$, (radiative) Bhabha, $(e^+e^-)e^+e^-$

Muon ID efficiency:

- $J/\psi \rightarrow \mu^+\mu^-$, $e^+e^- \rightarrow \mu^+\mu^-\gamma$, $(e^+e^-)\mu^+\mu^-$

Hadron-lepton mid-ID probability:

- Pions: $Ks^0 \rightarrow \mu^+\mu^-$, $D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+$, $e^+e^- \rightarrow \tau^+\tau^-$ (1 vs 3 prong)
- Kaons: $D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+$

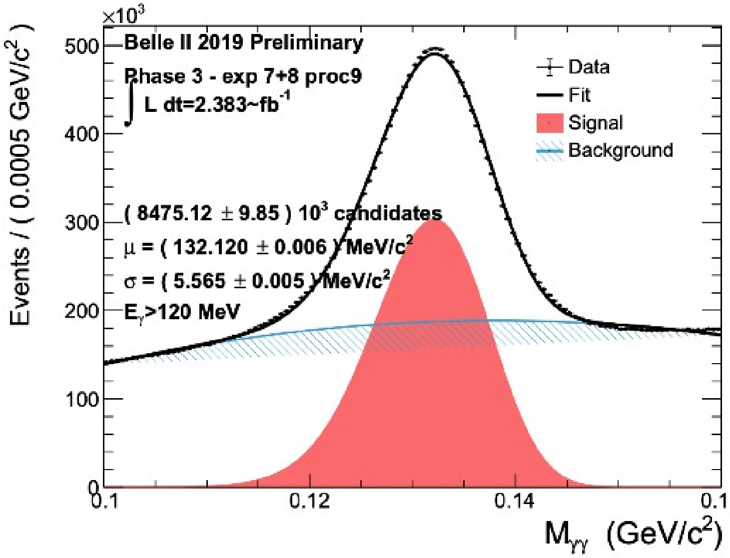


M. Milesi

Neutrals performance

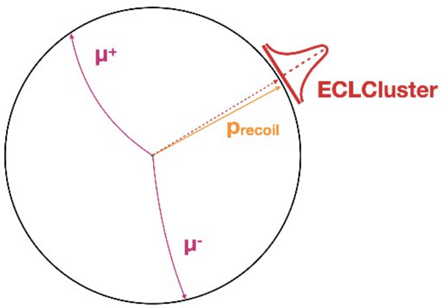
Neutrals performance likely to be a defining feature of Belle II

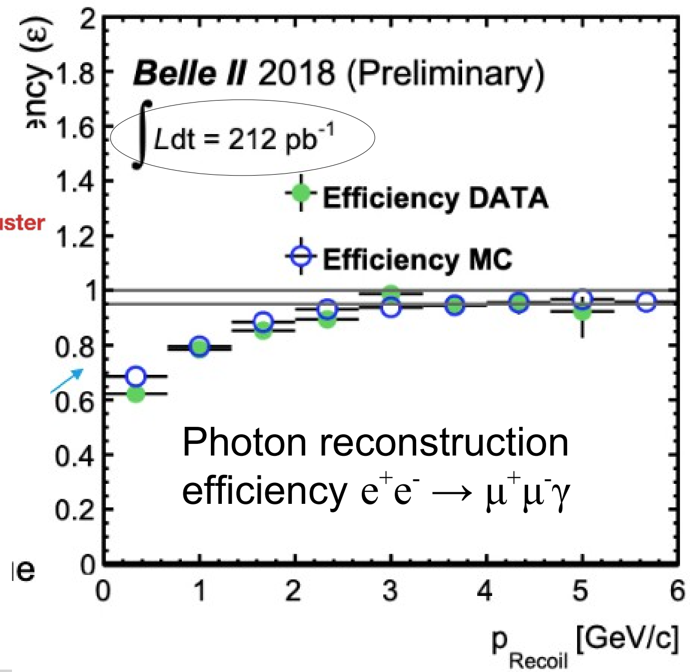
- Many high-profile analyses rely on missing energy or inclusive reconstruction
- LHCb advantage in all- (and mostly-) charged final states
- Potential for substantial beam and luminosity backgrounds in calorimeter
- Very different readout and reconstruction than Belle



Potential sources of systematics:

- MC efficiency modelling
- Energy and resolution biases
- Timing biases
- Beam background variation (run dependence)

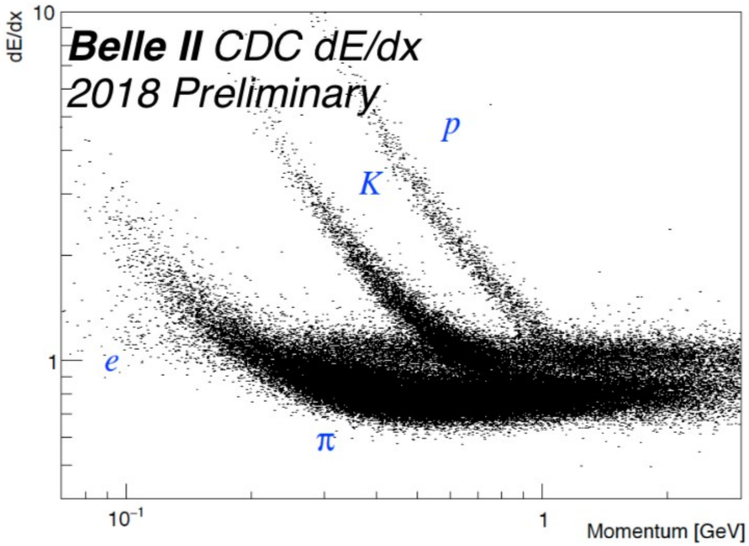




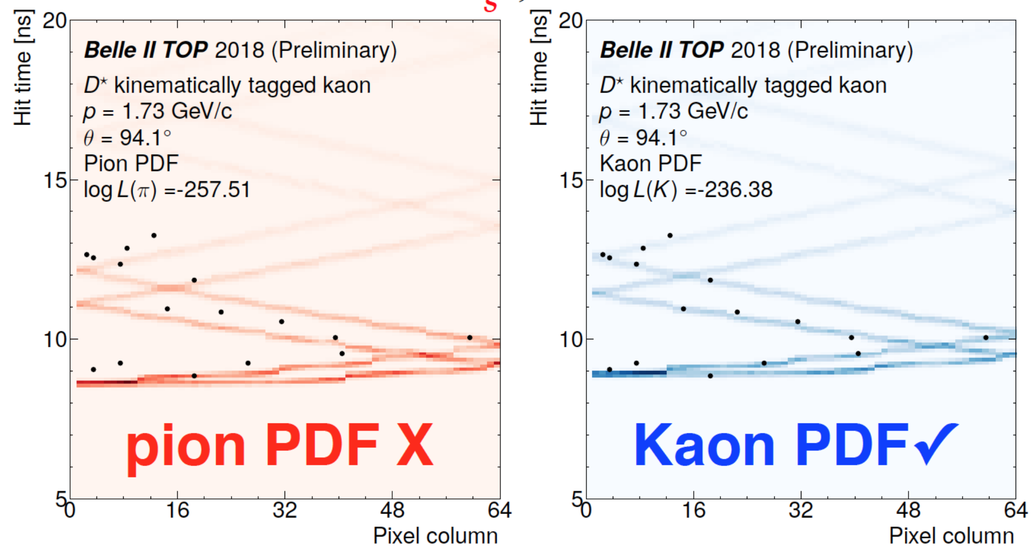
Very analysis specific; neutrals group providing recipes to help assess impact on individual analyses

Particle Identification

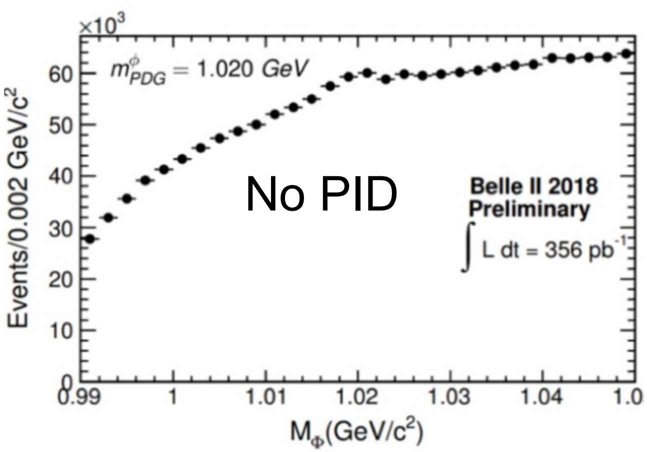
Central Drift Chamber (CDC)

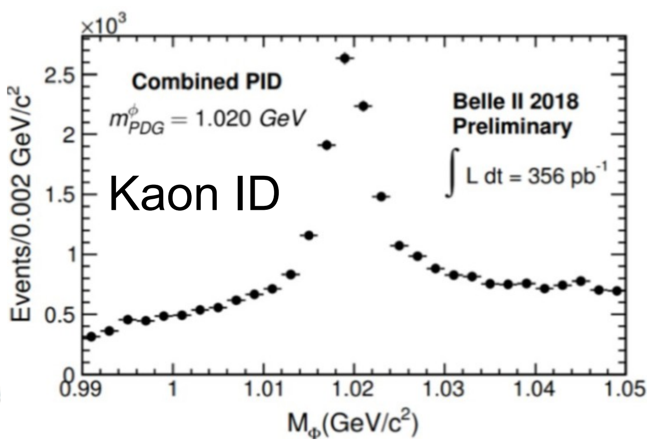


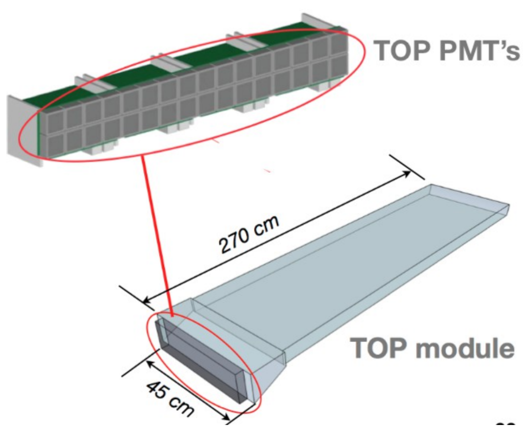
$D^{*+} \rightarrow D^0\pi_s^+ ; D^0 \rightarrow K^-\pi^+$



Time of Propagation (TOP) detector





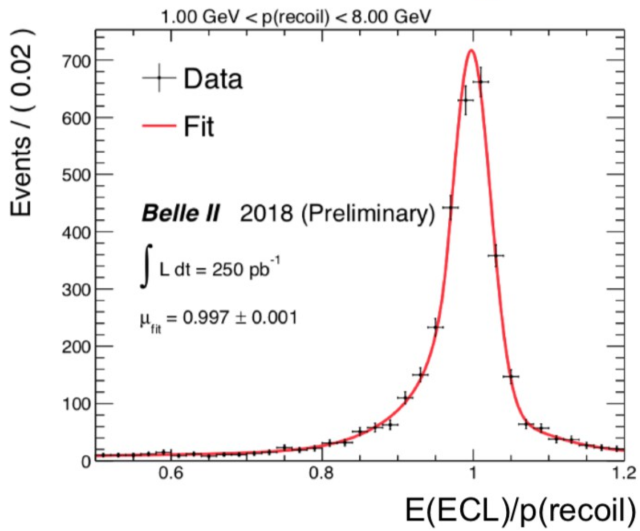


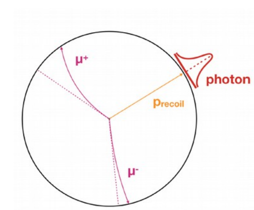
$\Phi \rightarrow K^+K^-$ reconstruction

Calorimetry

- Neutrals reconstruction using calorimeter clusters

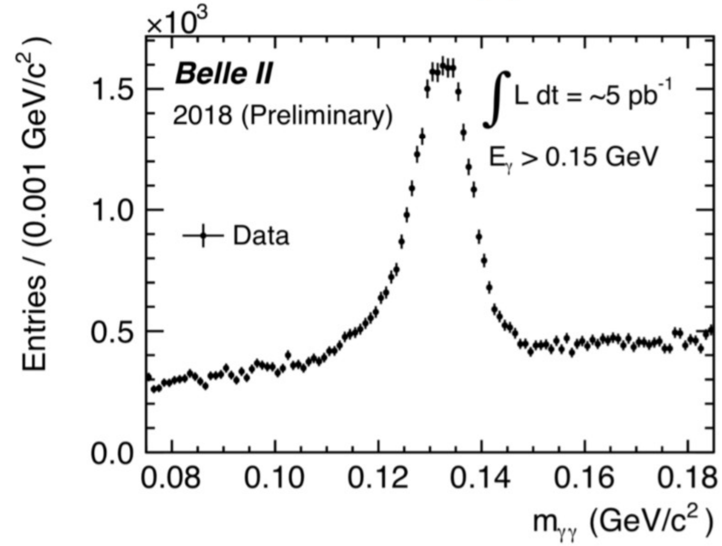
$e^+e^- \to \mu^+\mu^-\gamma$



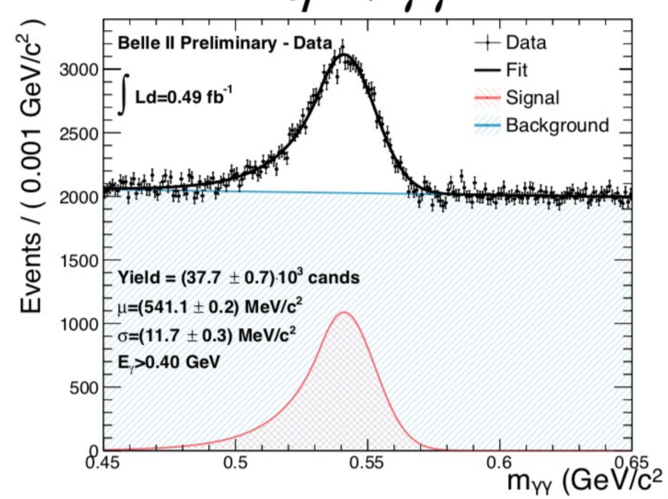


Single photon energy resolution based on $\mu^+\mu^-\gamma$ events

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



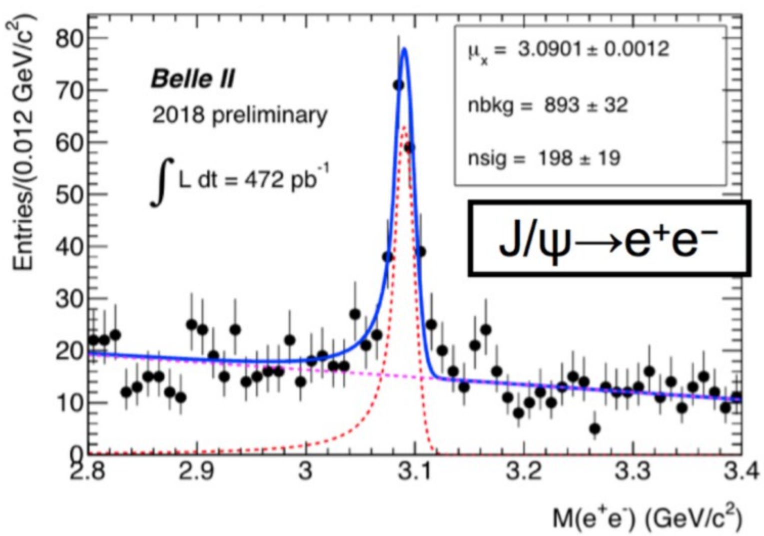
$\eta \to \gamma\gamma$

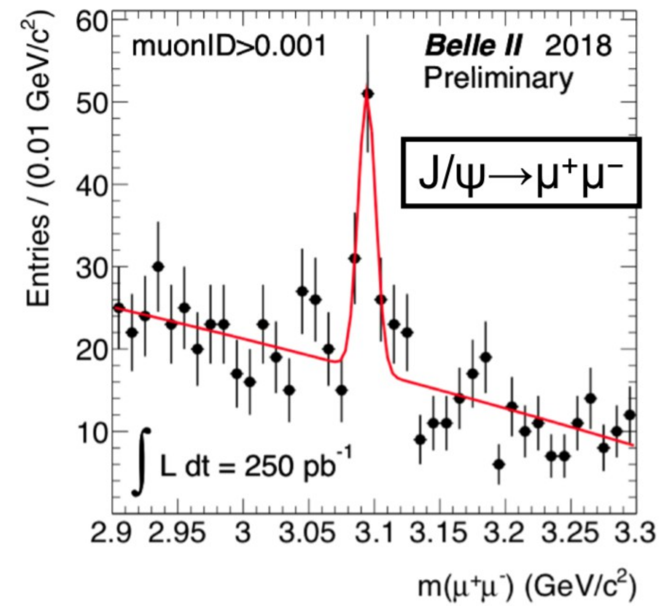


Belle II commissioning

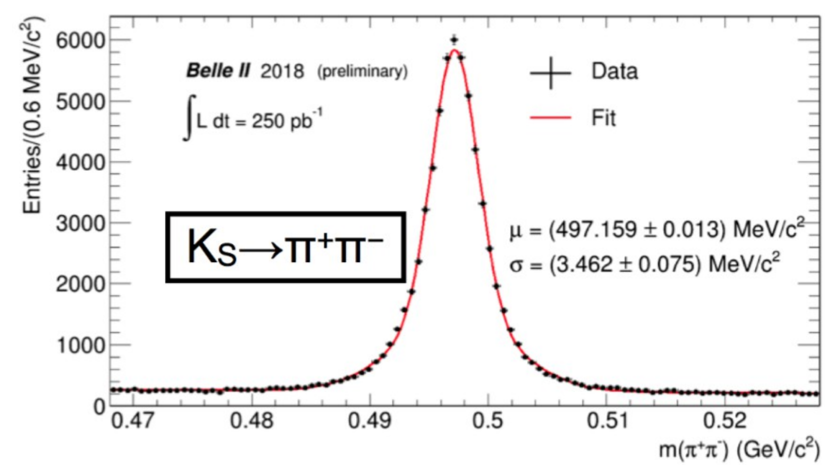
2018 SuperKEKB commissioning run provided opportunity to validate detector performance with colliding beams

- Achieved instantaneous luminosity of 5.5 x 10^{33} cm^{-2} s^{-1}
- Recorded 472 pb^{-1} integrated luminosity (~1 million B mesons)
- Only one sector of vertex detector installed



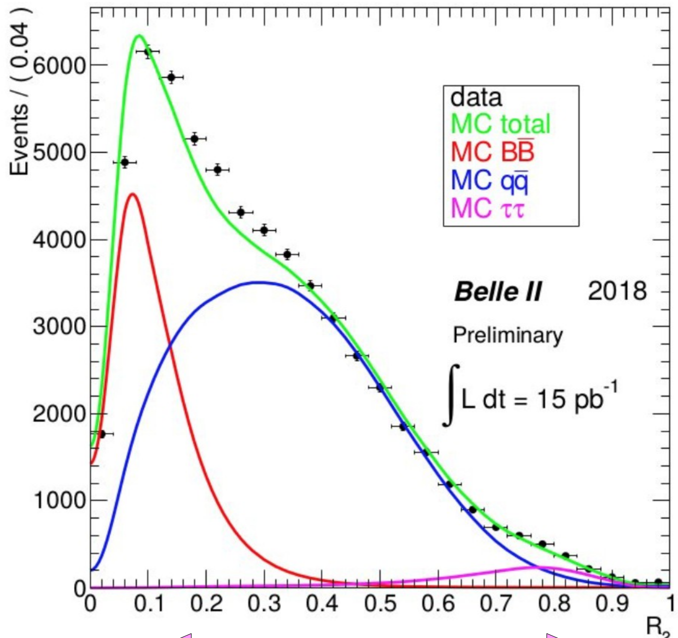


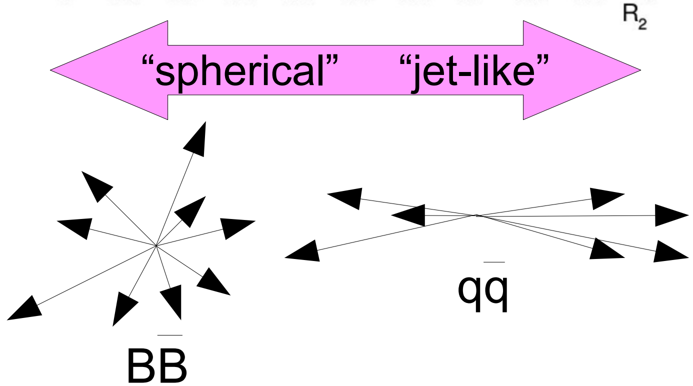
- Track reconstruction (using CDC and partial vertex detector)
- Alignment and solenoid B field are well understood

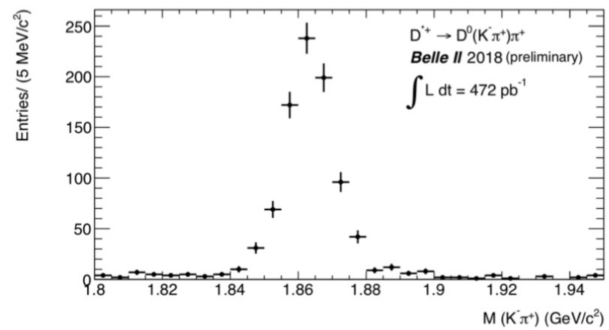


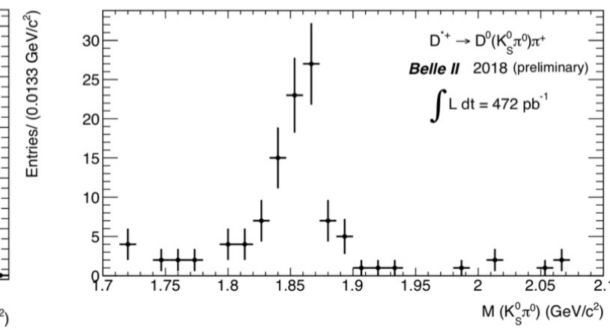
B reconstruction

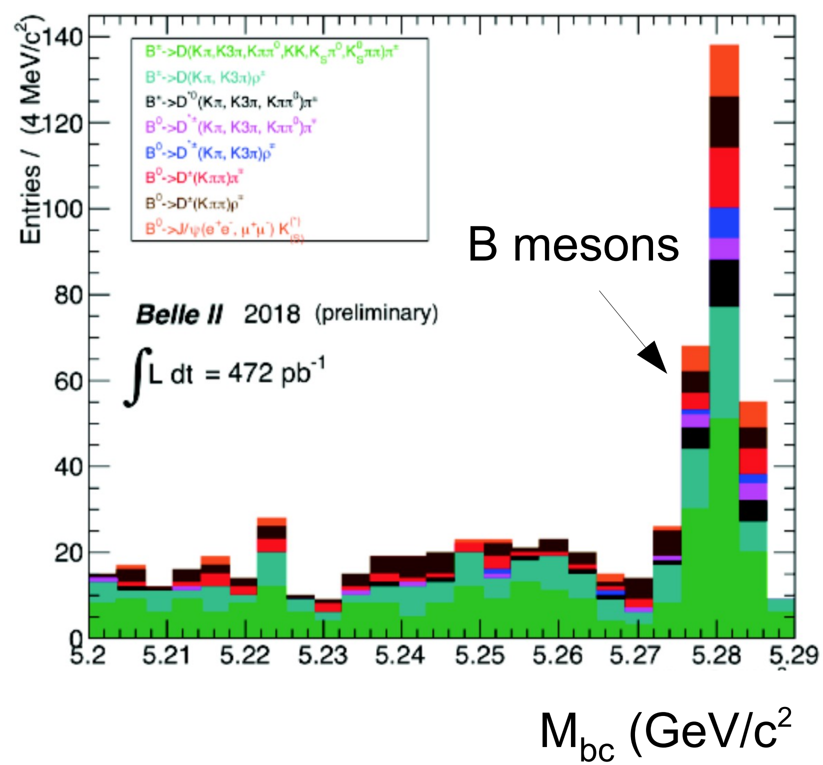
Topological event shapes:











Evidence that SuperKEKB was operating on the Υ(4S) resonance

Dark sectors

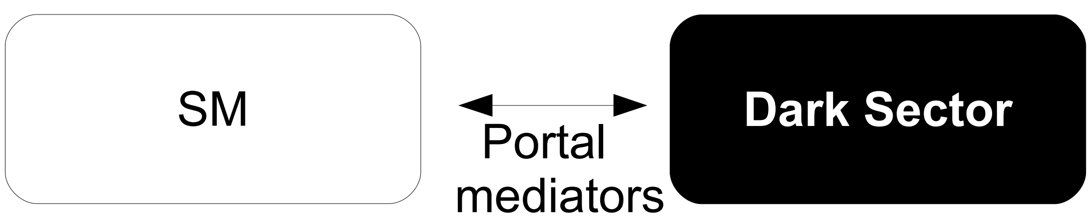
Maybe dark matter is not specifically related to solution to problems of the SM and is, in effect, a distinct "sector"

- Dark sector fermions which carry charges for non-SM gauge interactions, possibly acquiring mass via dark sector Higgs etc.
- EFT provides a number of "portals" to access this dark sector

$$\mathcal{L} = \sum_{n=k+l-4} \frac{c_n}{\Lambda^n} \mathcal{O}_k^{(\mathrm{SM})} \mathcal{O}_l^{(\mathrm{med})} = \mathcal{L}_{\mathrm{portals}} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

$$= -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

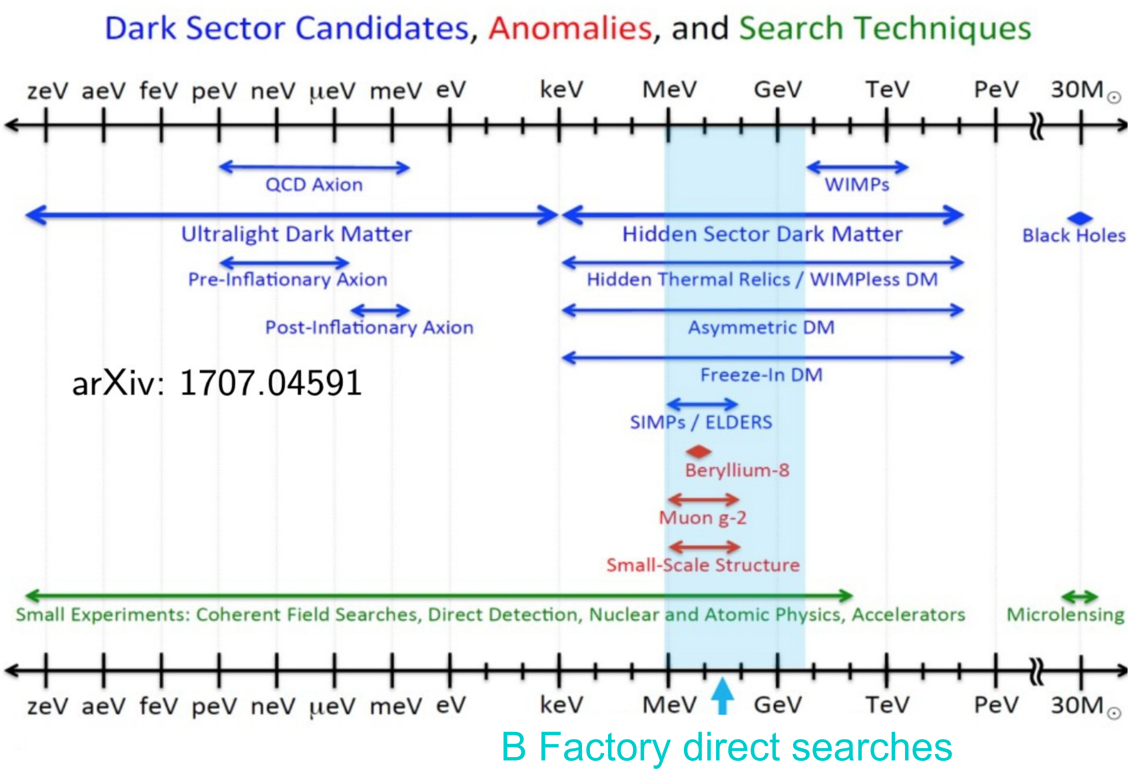
Vector portal · Higgs portal · Neutrino portal



Dark sector can be probed via mixing of the portal mediators with SM bosons

Dark Sector @ B Factories

- Clean e^+e^- environment with hermetic (near 4π) detector coverage; good missing energy reconstruction
- Potential to reconstruct displaced vertices in $\sim 1\text{mm} < c\tau < \sim 10\text{cm}$ ($\sim 100\text{cm}$), with $c\tau > \sim 3\text{m}$ being "missing energy"
- Production of on-shell bosons via "radiative" $e^+e^- \rightarrow \gamma Z'$ and $e^+e^- \rightarrow f \bar{f} Z'$ "-strahlung" processes
- Inclusive trigger for (N_{tracks}>3) hadronic events, but low-multiplicity searches require dedicated triggers



Invisible Z'

Experimental signature is a $\mu^+\mu^-$ pair (or $e^+\mu^-$ pair in LFV scenario) with a peak in the missing mass

- Backgrounds originate from QED processes which mimic the $\mu^+\mu^-$ + missing energy final state, typically due to detector acceptance

Background sources:

$e^+e^- \to \mu^+\mu^- \gamma(\gamma)$	undetected photon(s)
$e^+e^- \to \tau^+\tau^- \ (\gamma)$	muonic τ decays and mis-ID
$e^+e^- \to \mu^+\mu^- e^+e^-$	missing e^+e^-

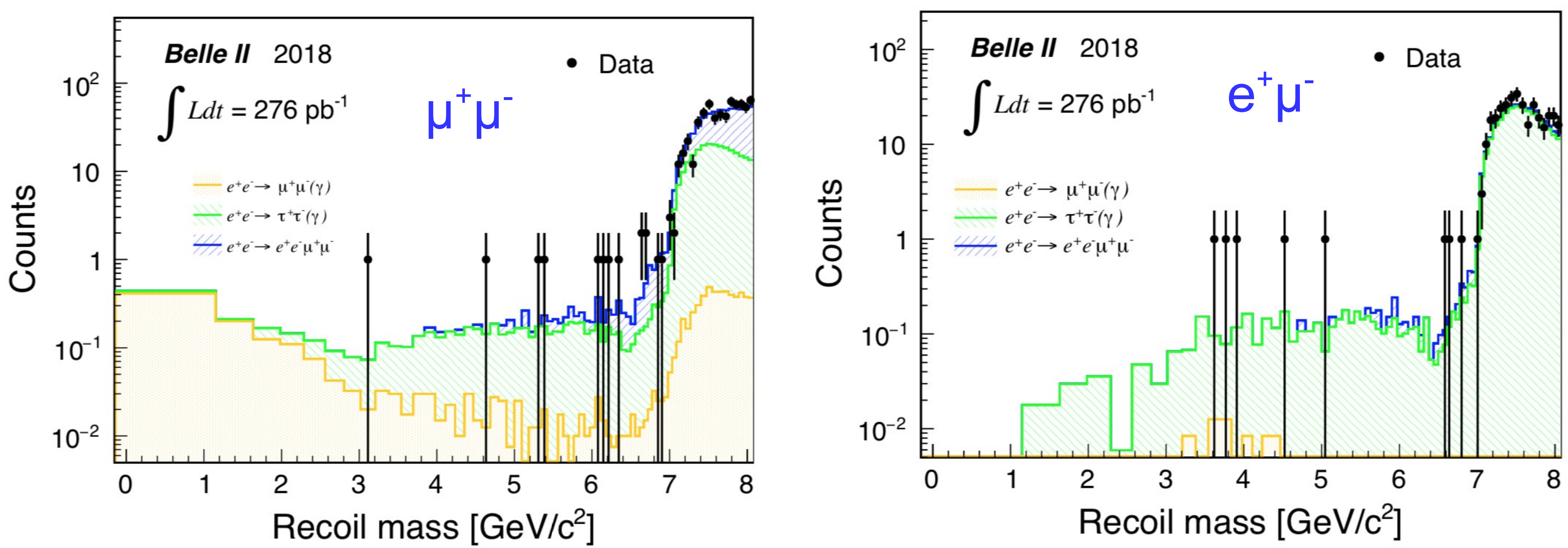
276 pb^{-1} of good-quality data from 2018 “Phase 2” commissioning running

- Require p_{miss} to point into calorimeter barrel region
- Calorimeter-based particle identification (E/p)
- Reject events with additional energy E >0.4 GeV or any π^0 candidates
- Exploit kinematics to reduce $\tau^+\tau^-$ backgrounds

Invisible Z'

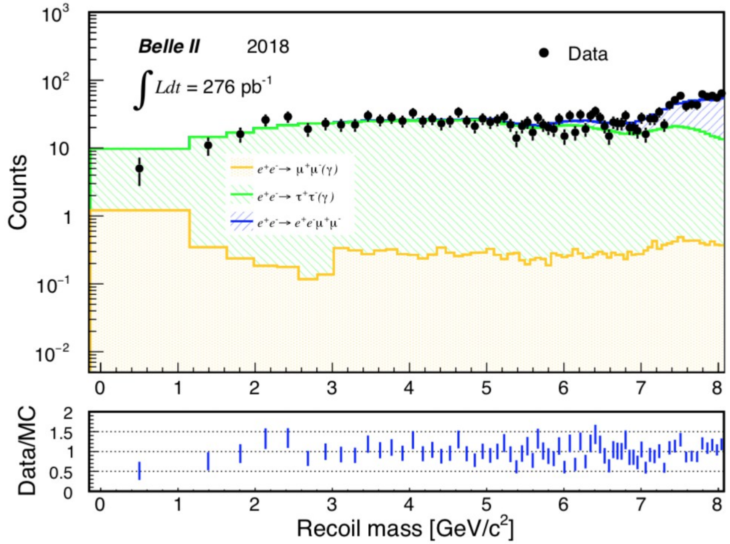
Signal extracted in 69 mass windows spanning the range
$m_{Z'} = 0.5 – 8\ GeV/c^2$

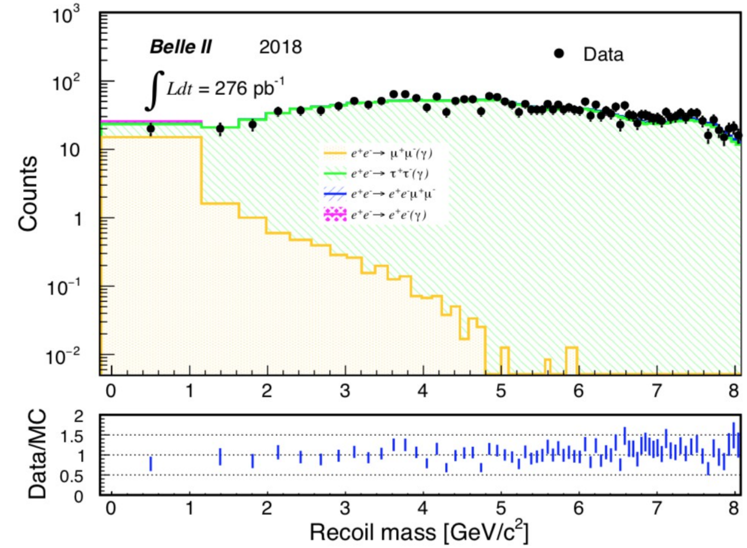
- Each window defined to be ±2σ of the expected signal width at that mass

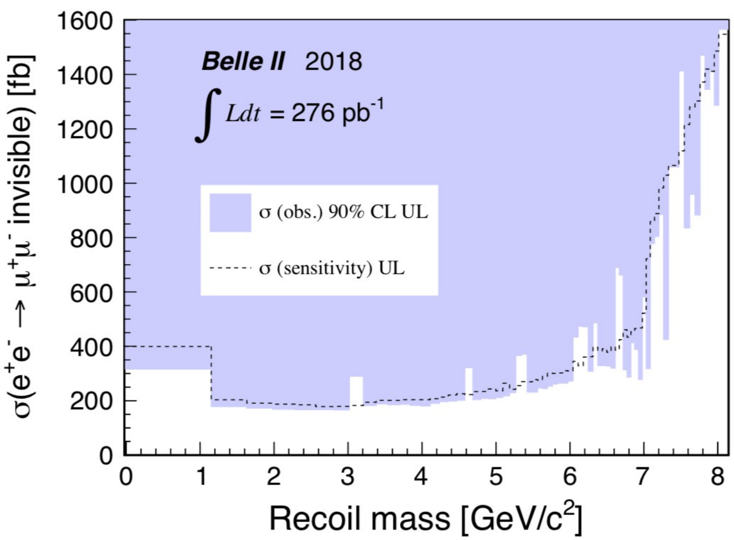


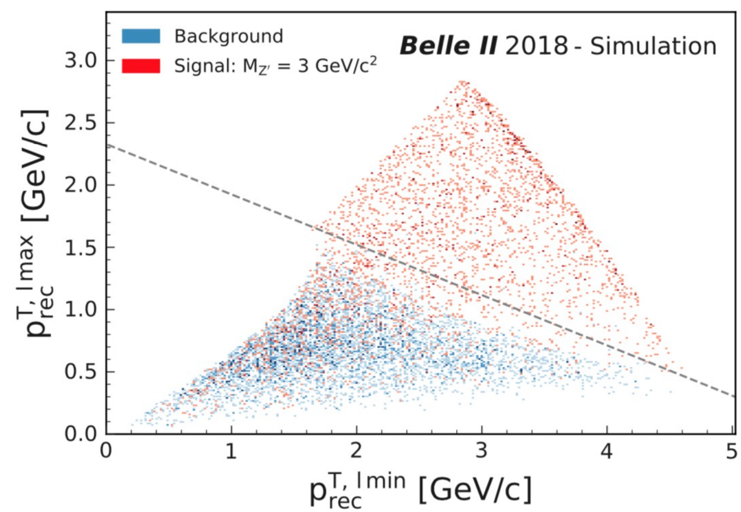
- No yield exceeds 3σ local significance in either nominal or LFV search

Invisible Z'



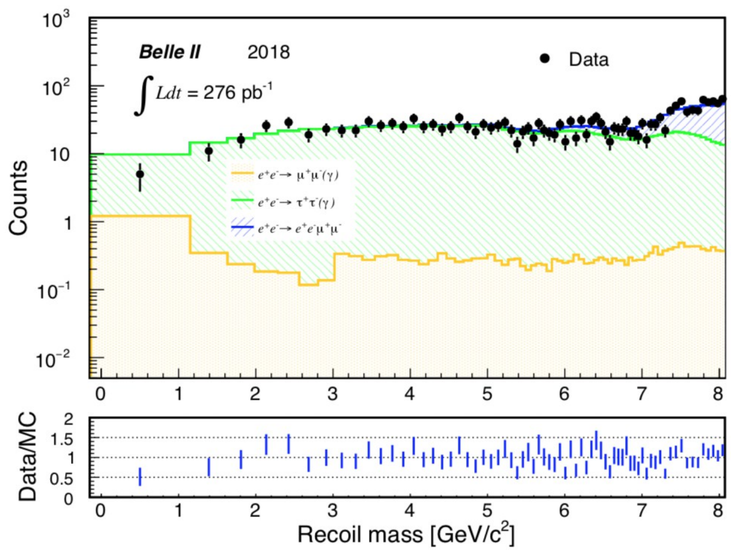




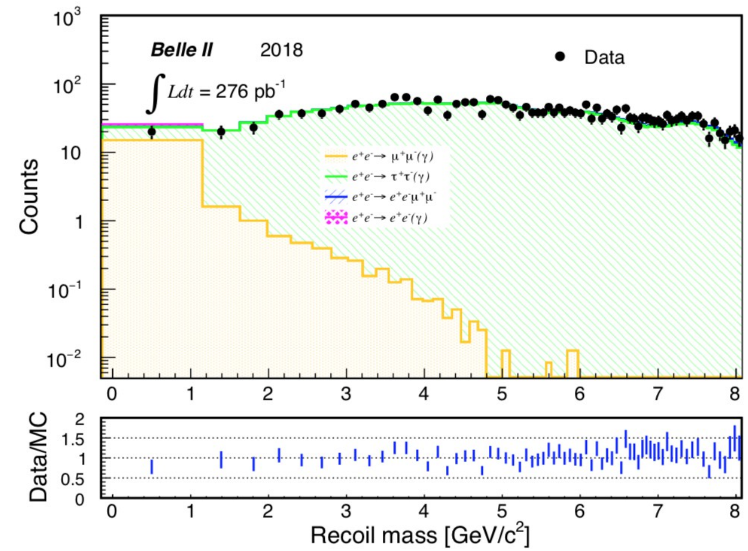


Transverse recoil momentum with respect to the lepton with higher (lmax) And lower (lmin) momentum

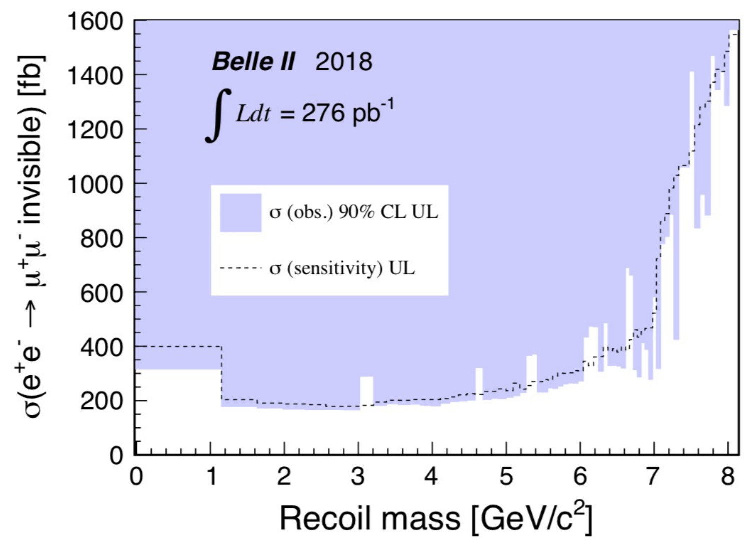
Invisible Z'



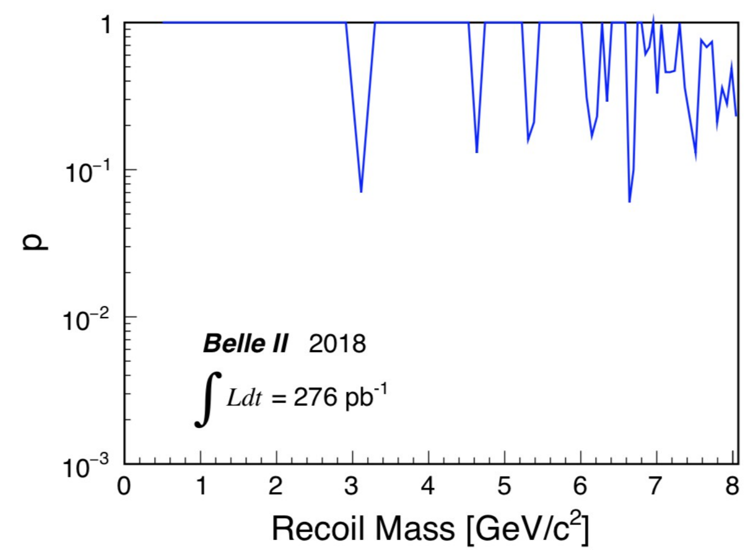
Belle II 2018
$\int Ldt$ = 276 pb^{-1}
Data
$e^+e^- \to \mu^+\mu^-(\gamma)$
$e^+e^- \to \tau^+\tau^-(\gamma)$
$e^+e^- \to e^+e^-\mu^+\mu^-$
Counts
Data/MC
Recoil mass [GeV/c^2]



Belle II 2018
$\int Ldt$ = 276 pb^{-1}
Data
$e^+e^- \to \mu^+\mu^-(\gamma)$
$e^+e^- \to \tau^+\tau^-(\gamma)$
$e^+e^- \to e^+e^-\mu^+\mu^-$
$e^+e^- \to e^+e^-(\gamma)$
Counts
Data/MC
Recoil mass [GeV/c^2]

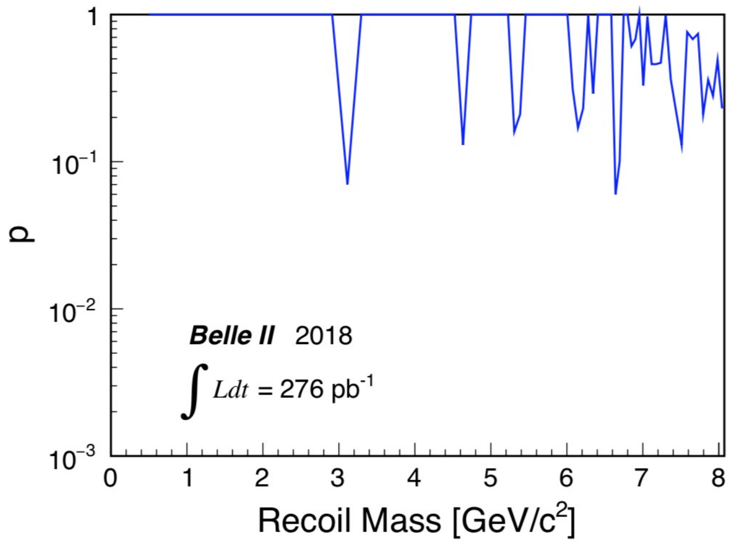


Belle II 2018
$\int Ldt$ = 276 pb^{-1}
σ (obs.) 90% CL UL
σ (sensitivity) UL
$\sigma(e^+e^- \to \mu^+\mu^-$ invisible) [fb]
Recoil mass [GeV/c^2]

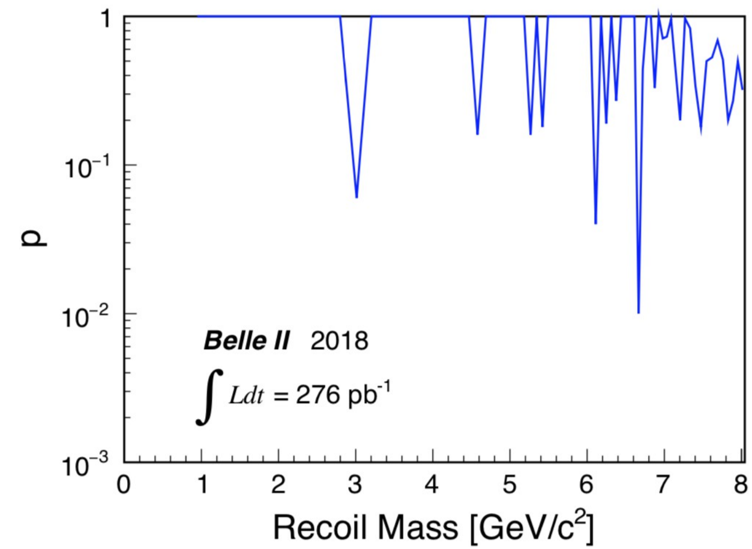


Belle II 2018
$\int Ldt$ = 276 pb^{-1}
p
Recoil Mass [GeV/c^2]

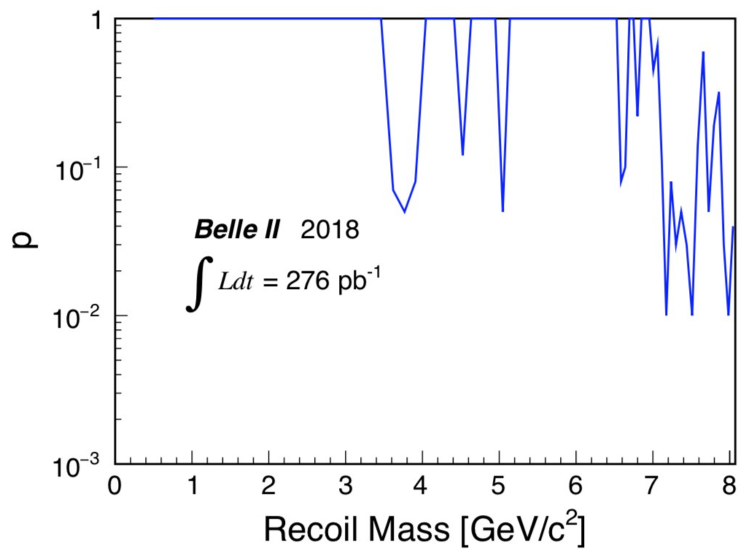
Invisible Z'



Belle II 2018
$\int Ldt$ = 276 pb^{-1}
p
Recoil Mass [GeV/c^2]



Belle II 2018
$\int Ldt$ = 276 pb^{-1}
p
Recoil Mass [GeV/c^2]



Belle II 2018
$\int Ldt$ = 276 pb^{-1}
p
Recoil Mass [GeV/c^2]

Invisible Dark Photon

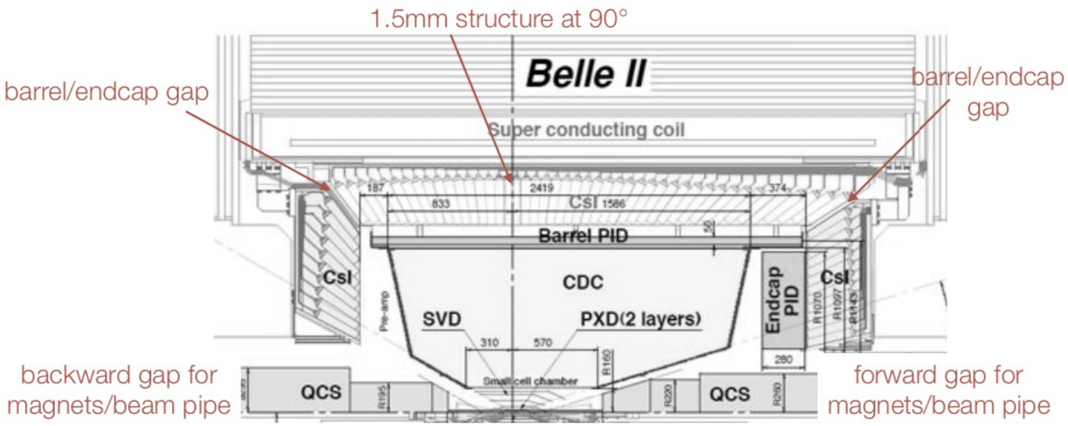
BABAR limits on VISIBLE dark photon based on 514 fb^{-1}

- Beyond reach of Belle II in 2020

However, INVISIBLE dark photon result only used 53 fb^{-1}

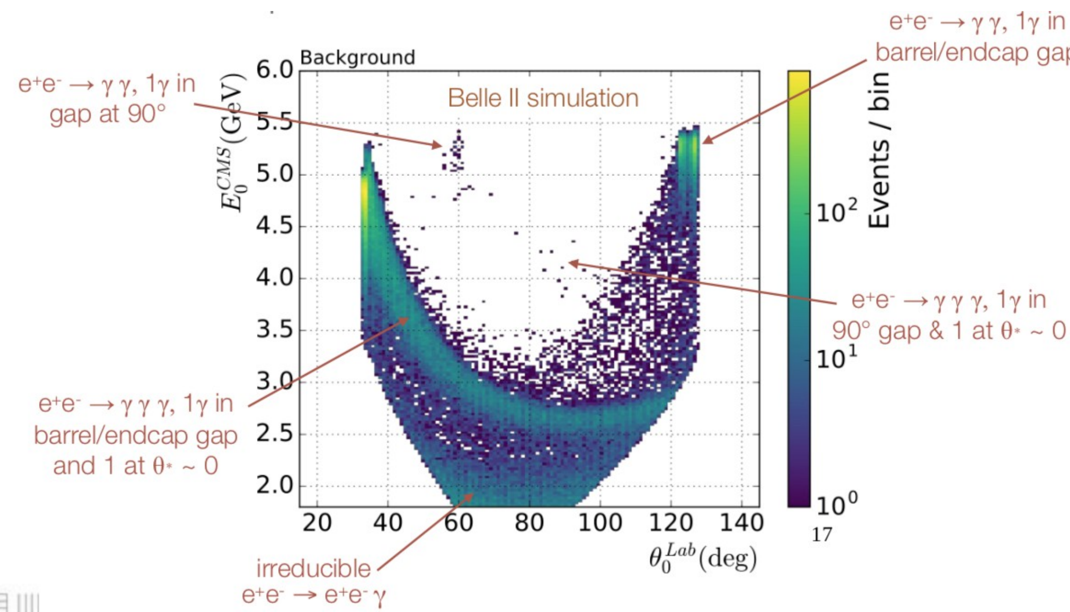
- Signal signature is a single photon; look for a peak in the recoil mass distribution:

$$E_\gamma = (s - m^2_{A'})/2\sqrt{s}$$



-0.94 < cosθ* < 0.96 Belle II
-0.92 < cosθ* < 0.89 BABAR

Backgrounds arise from QED sources with undetected particles; calorimeter hermeticity is the limiting factor:



Belle II has several advantages relative to BABAR analysis:

- Non-pointing cracks between crystals
- Greater solid-angle coverage (end caps and lower boost)
- Muon system can be used to detect particles missed by the calorimeter

Invisible Dark Photon

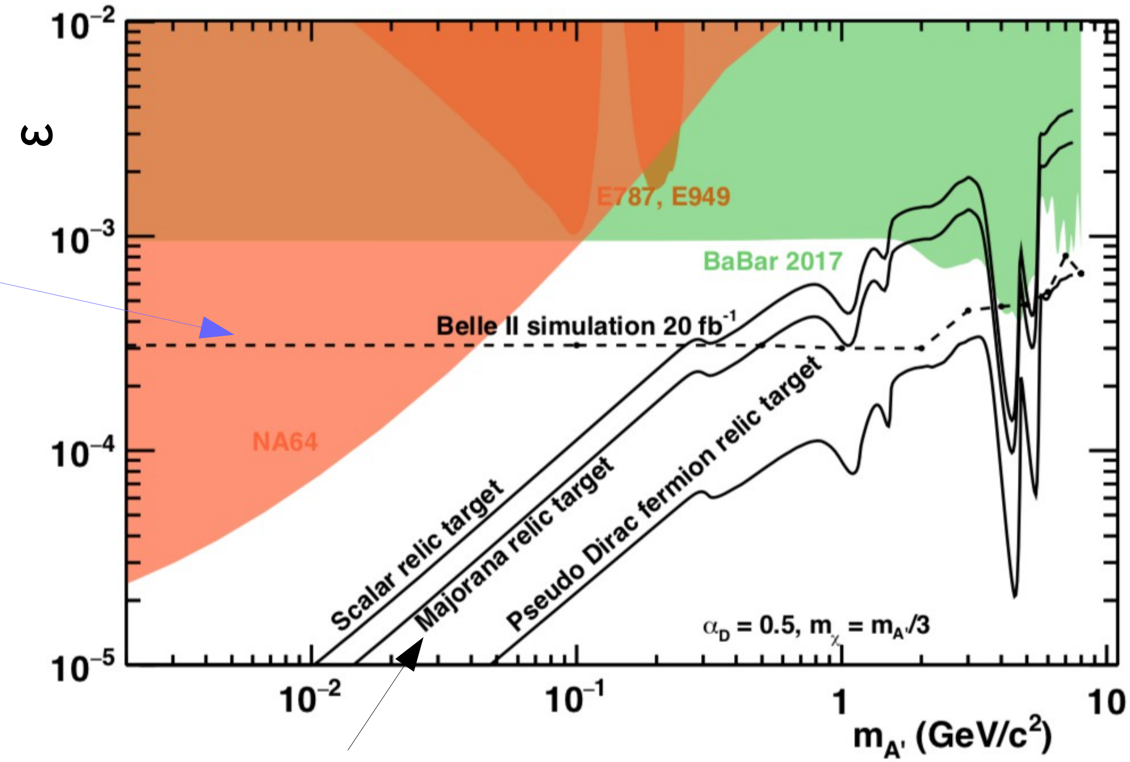
- Dedicated L1 trigger lines for more efficient candidate selection

Single photon trigger:
E_γ > 1GeV (veto events with additional clusters above 300 MeV)
E_γ > 2GeV (Bhabha and $\gamma\gamma$ vetos)

Invisible dark photon search anticipated to be competitive with relatively little data

- Studies still in progress; systematics still to be determined

Belle II projection (20 fb^{-1})
KEK-2018-27,
arXiv:1808.10567 [hep-ex]

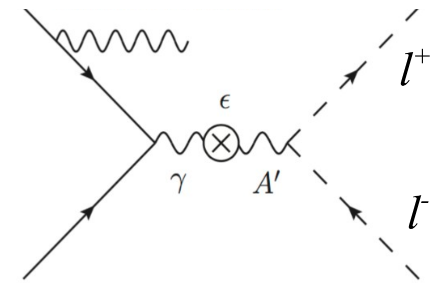


Astronomical dark matter predictions

Derived from E. Izaguirre, G. Krnjaic, P. Schuster, N. Toro, Phys. Rev. Lett. 115, 251301 (2015)

Visible Dark Photon

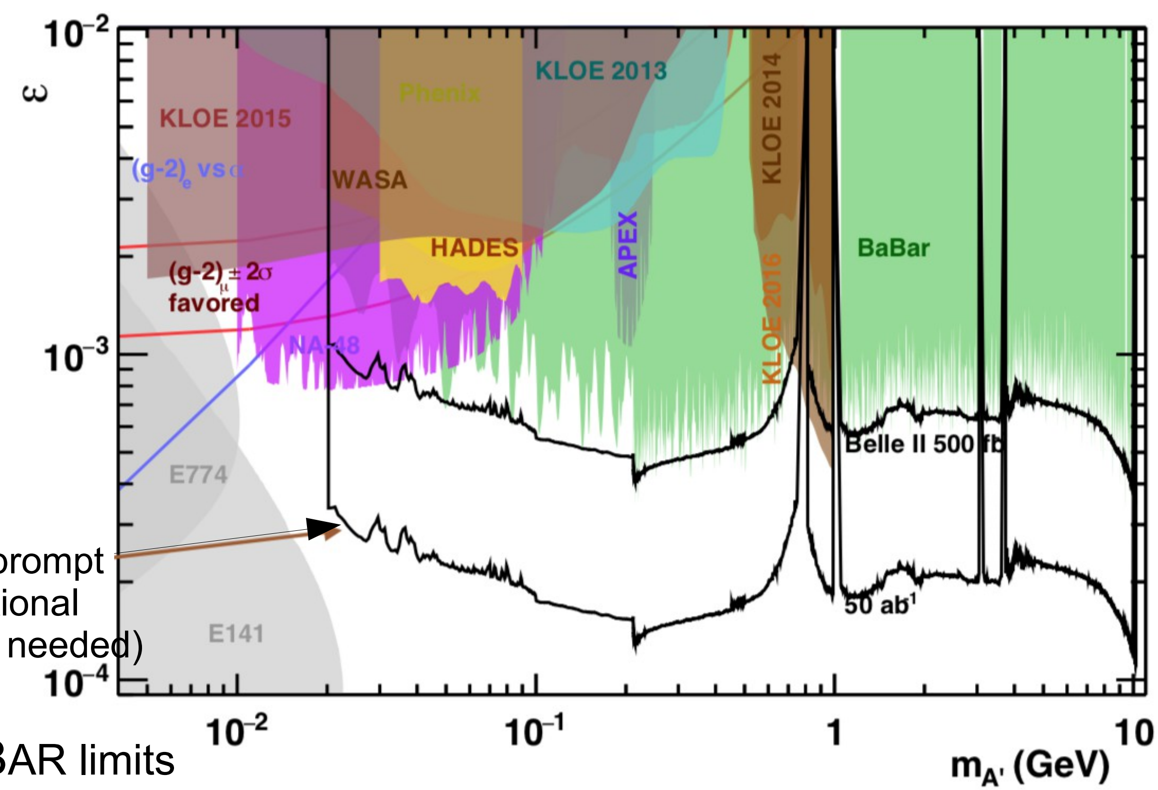
BABAR limits based on > 500 fb^{-1}; Belle II will require comparable data set to be competitive



- Final state is a photon, plus a lepton (or hadron) pair
- A' mass determined directly from decay daughters (not photon)
- Large SM backgrounds (particularly in electron mode); $\mu\mu\gamma$ is most sensitive mode above kinematic threshold

Some modest improvements possible relative to BABAR analysis:

- Trigger efficiency
- Improved mass resolution (better tracking/vertexing resolution of detector



Non-prompt (additional study needed)

Projections based on scaling from BABAR limits

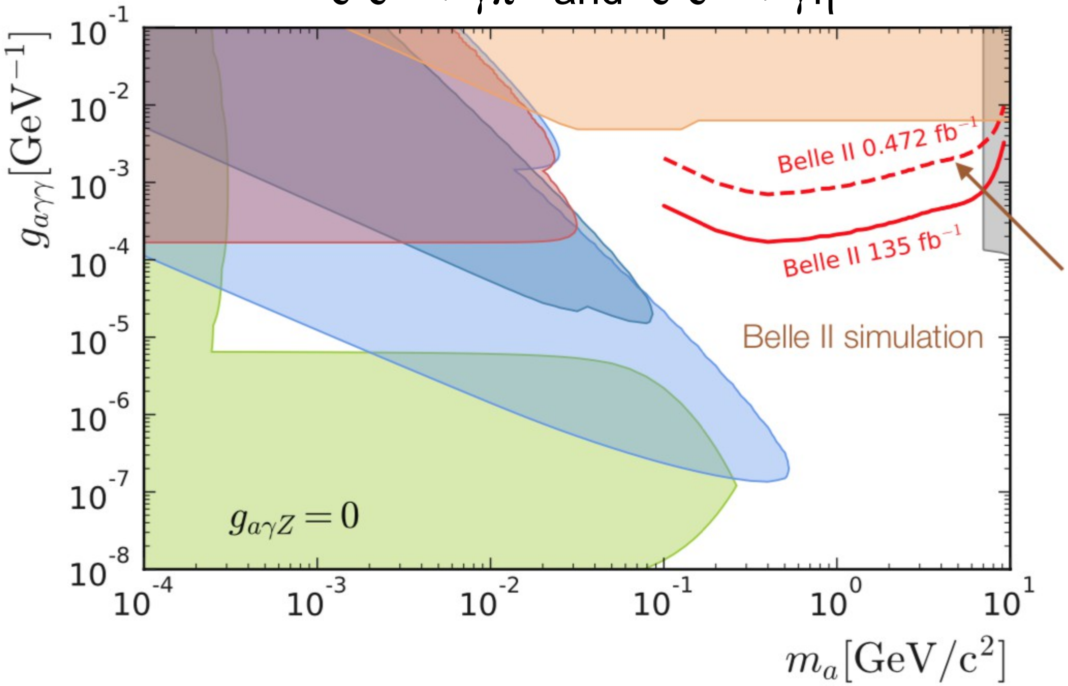
Axion-Like Particles

In 3γ analysis, signature is a bump in $m_{\gamma\gamma}$

- Non-peaking backgrounds from $e^+e^- \to \gamma\gamma(\gamma)$ and photon conversions $\gamma \to e^+e^-$ outside of tracking volume
- Peaking backgrounds from SM hadrons:

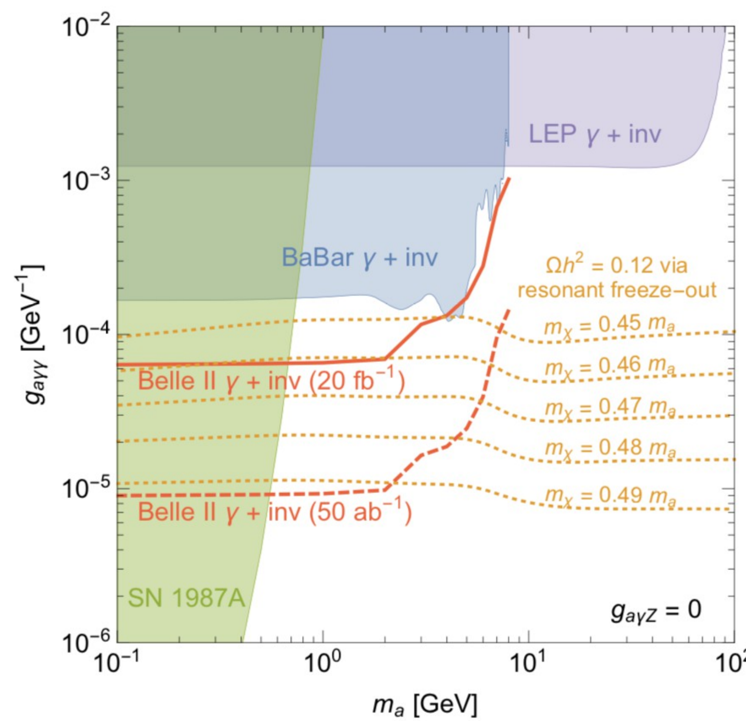
$$e^+e^- \to \gamma\omega,\ \omega \to \gamma\pi^0$$

$$e^+e^- \to \gamma\pi^0 \text{ and } e^+e^- \to \gamma\eta$$



Studies still ongoing, but competitive sensitivity expected already with existing data set

If ALP decays to dark matter, then single photon signature is relevant:



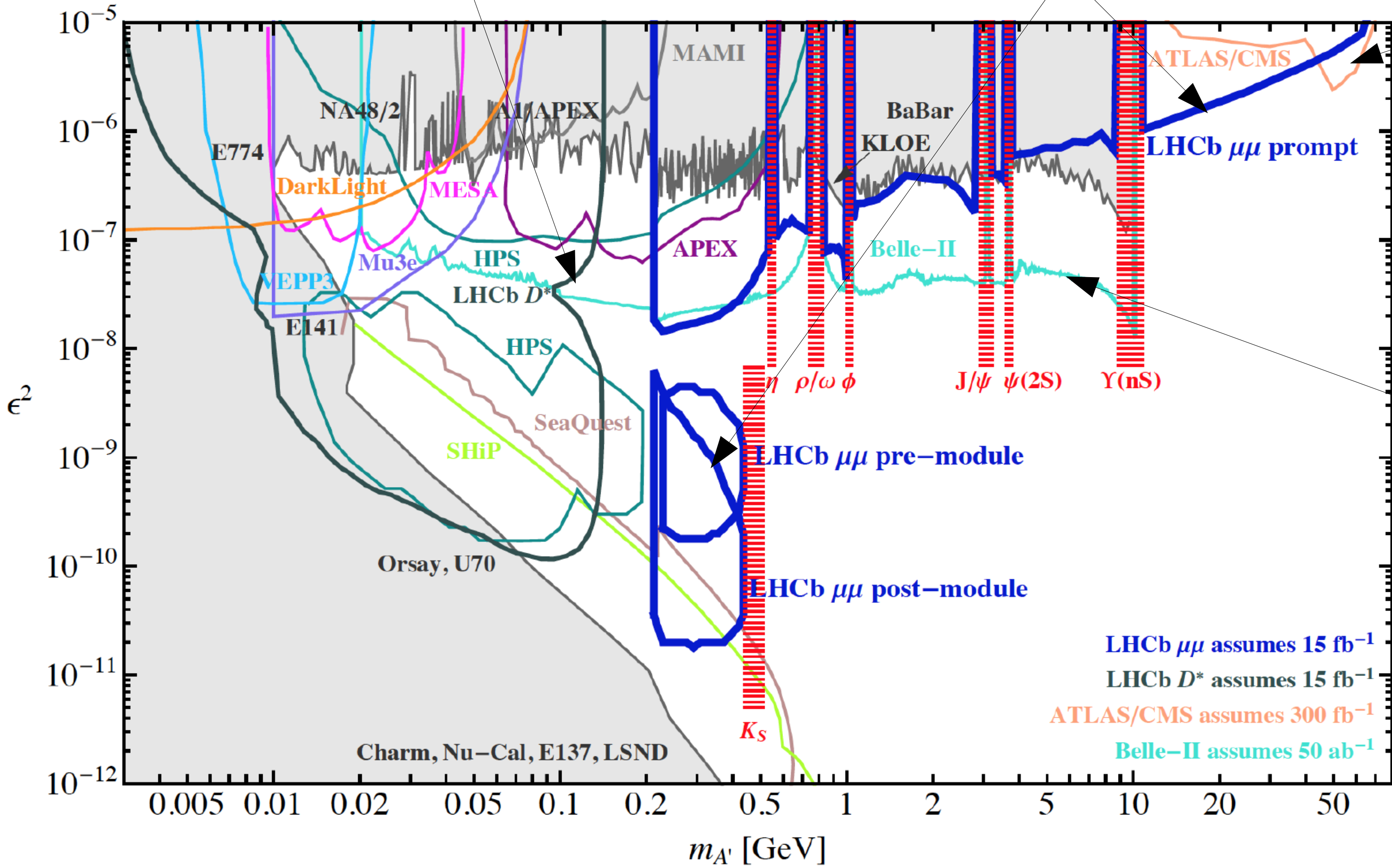
- ALP mediation of SM / dark matter interaction could explain observed abundance if $m_a \sim 2m_\chi$

Visible dark photon prospects

Phys. Rev. Lett. 116, 251803
arXiv:1603.08926 [hep-ex]

$D^{*0} \rightarrow D^0 e^+ e^-$
(prompt and displaced)

$A' \rightarrow \mu^+ \mu^-$



Similar methodology can be used by CMS and ATLAS (bump hunt in di-muon spectrum)

Belle II projection

Light meson Dalitz decays
$\pi^0,\ \eta \rightarrow e^+ e^- \gamma$