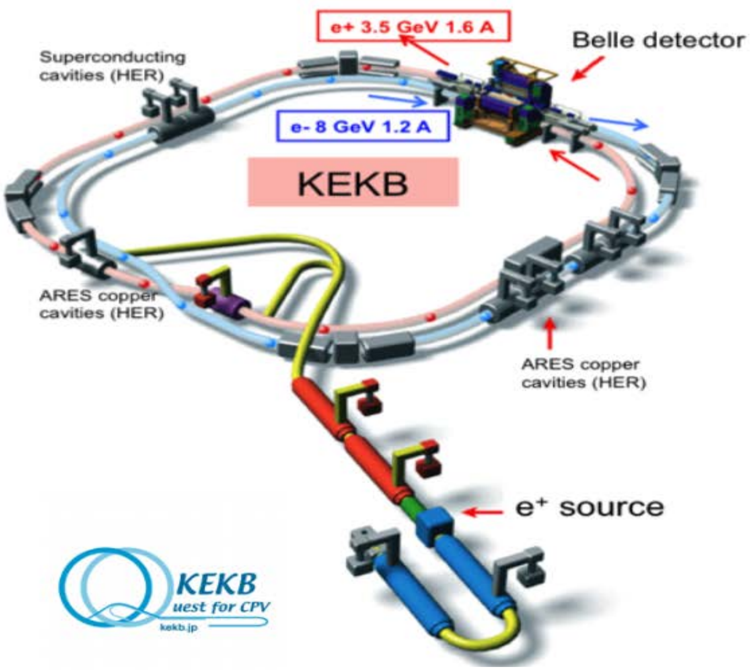
Belle II status and prospects on XYZ states

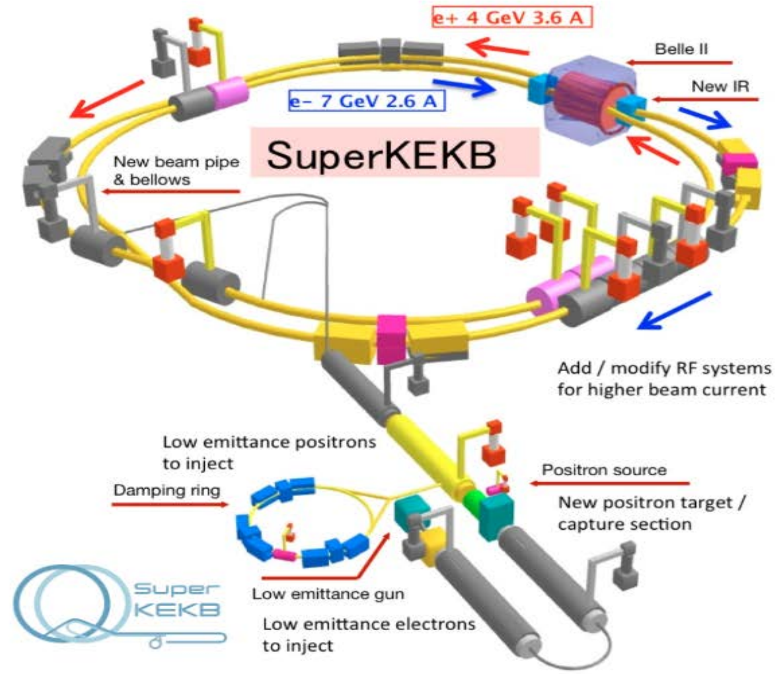
Yubo Li
Peking University

6th workshop on the XYZ particles

2020/01/13

SuperKEKB: First new collider in particle physics since the LHC



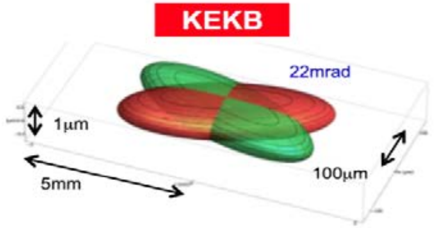


$$\int^{\text{goal}} \mathcal{L}\, dt = 50\ \text{ab}^{-1} = 50 \times \mathcal{L}^{\text{int}}_{\text{Belle}}$$

luminosity

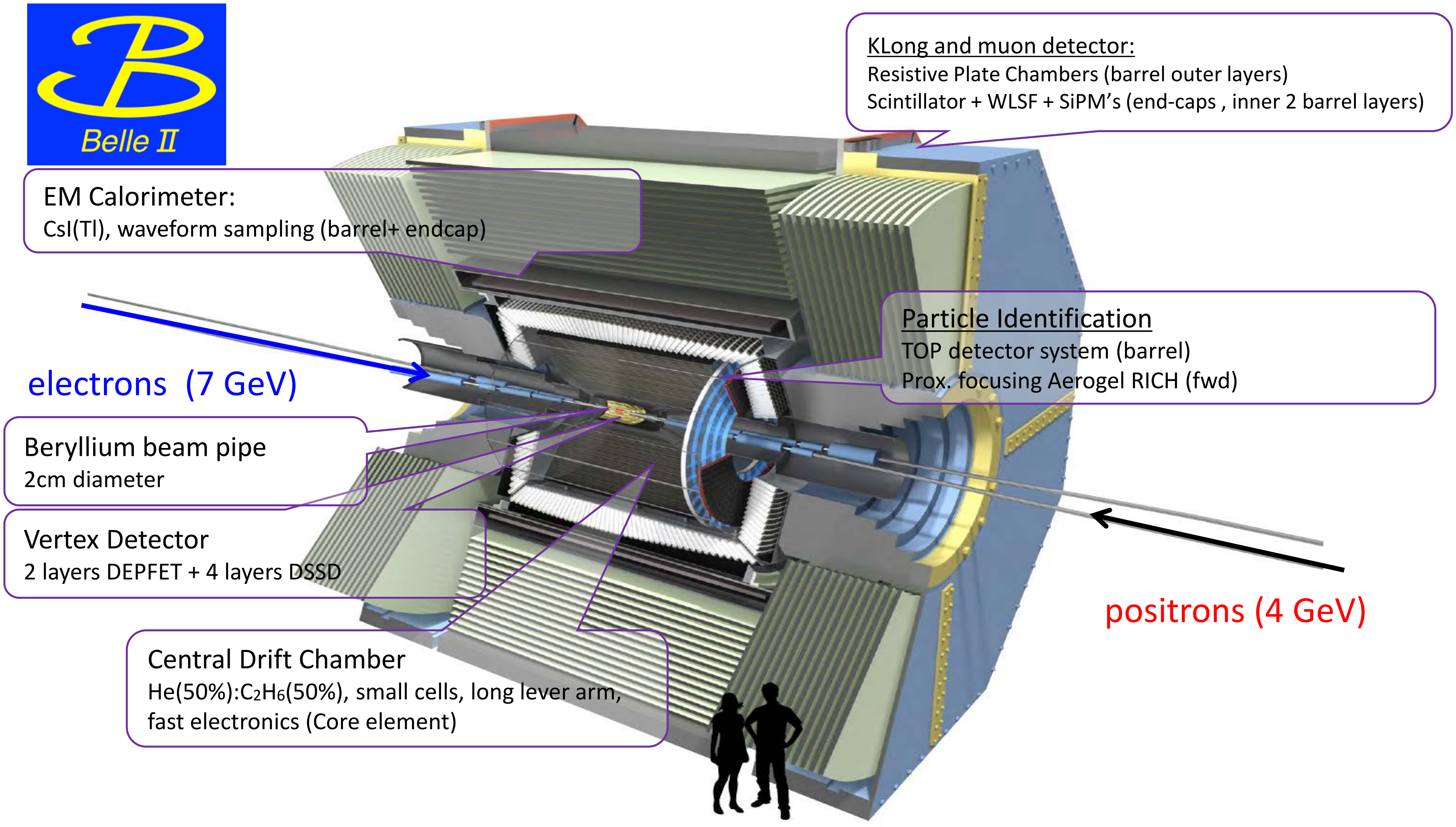
$$\mathcal{L} = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

beam size: σ^*, beam-beam par.: $\xi_\pm$,
beam current: $I_\pm$, beta function: β^*

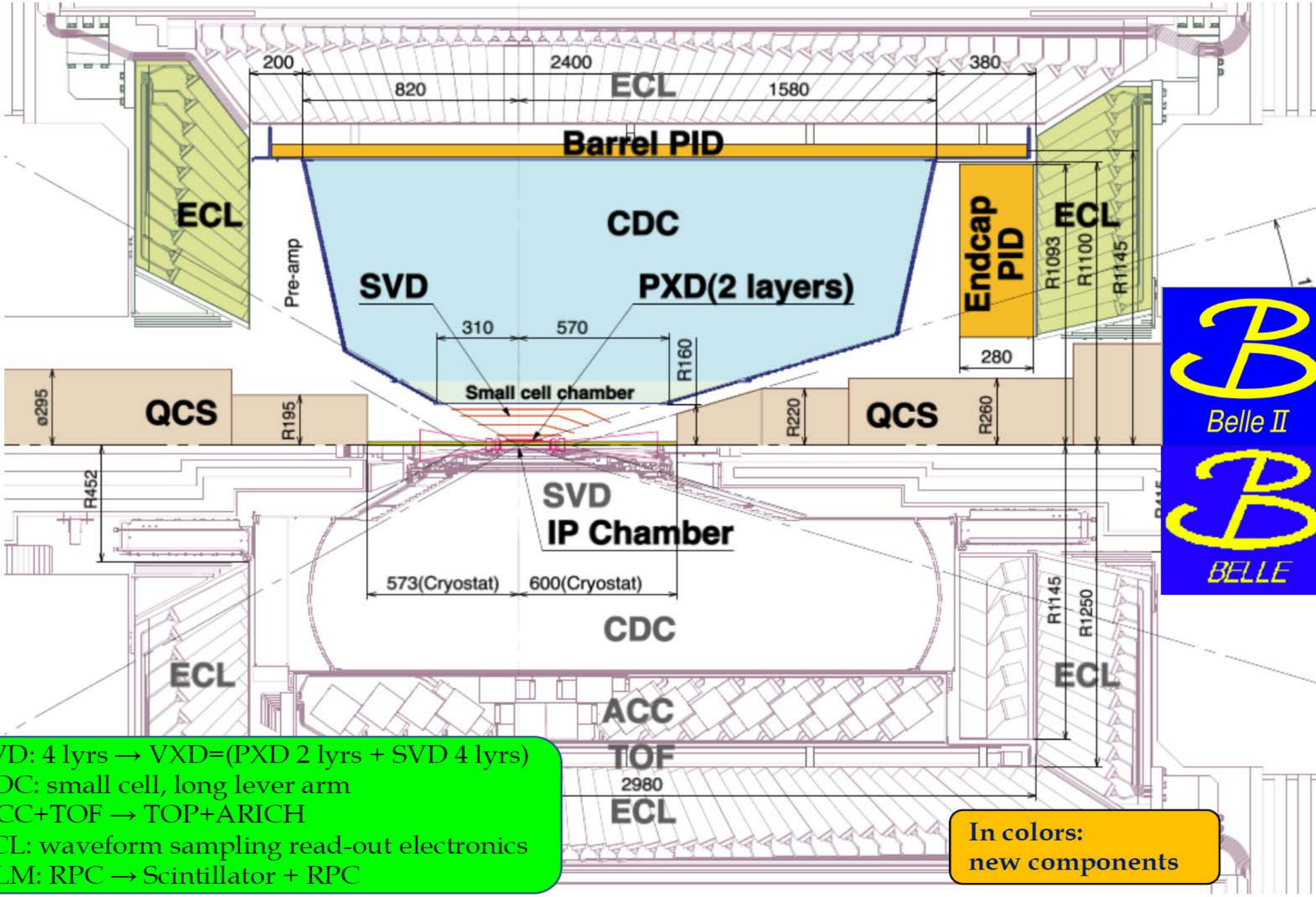


	$E_\pm$ (GeV) LER/HER	Cross Angle (mrad)	$I_\pm$ (A) LER/HER	β_y^* (mm) LER/HER	$\mathcal{L}$ $(cm^{-2}s^{-1})$
KEKB	3.5/8.0	22	1.64/1.19	5.9/5.9	2.1×10^{34}
SuperKEKB	4.0/7.0	83	3.60/2.60	0.27/0.31	80×10^{34}
	$\beta\gamma \sim 2/3$		×2	×20	×40

Belle II Detector



Belle II Detector vs. Belle



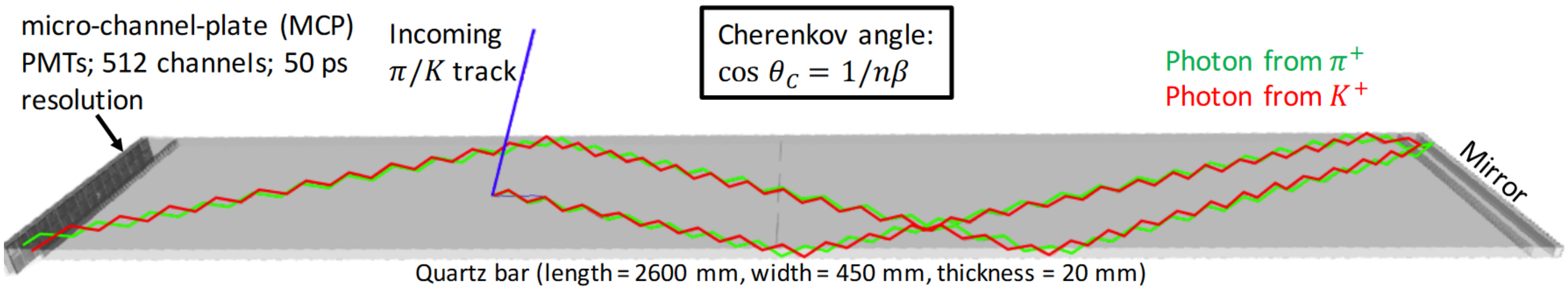
SVD: 4 lyrs → VXD=(PXD 2 lyrs + SVD 4 lyrs)
CDC: small cell, long lever arm
ACC+TOF → TOP+ARICH
ECL: waveform sampling read-out electronics
KLM: RPC → Scintillator + RPC

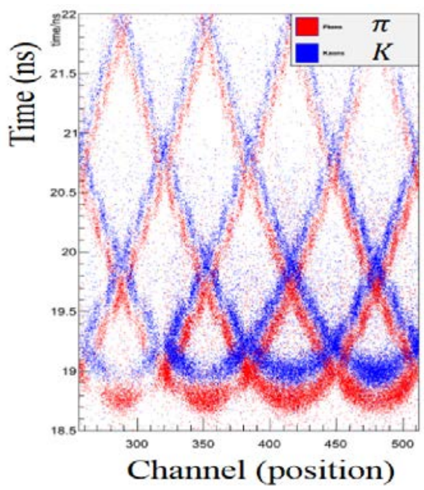
In colors:
new components

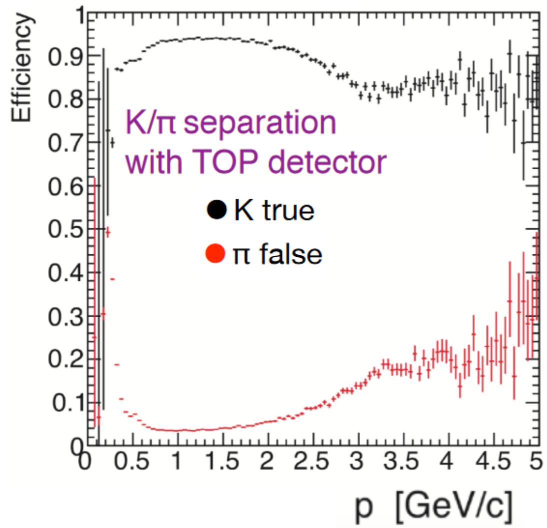
Advanced & Innovative Technologies used in Belle II

Barrel hadron ID: Time of Propagation(TOP)

Example of Cherenkov-photon paths for 2 GeV pion and kaon traversing in a TOP quartz bar





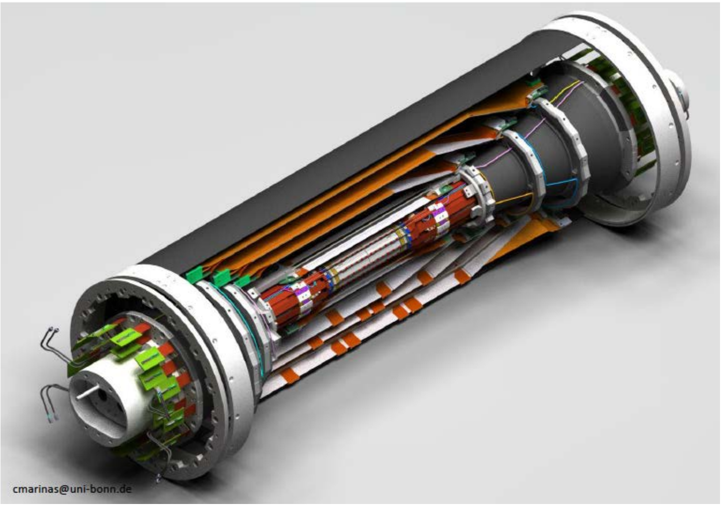


Improvements with respect to Belle:

- Signal readout speed and waveform sampling in the e.m. calorimeter (to reduce pileup);
- K_S reconstruction efficiency (+30%);
- **K/π separation** (wrong ID probability reduced by a factor ~2.5);
- Primary and secondary vertices reconstruction (resolution x2).

Advanced & Innovative Technologies used in Belle II

Vertex Detector



Beam pipe r= 10 mm

DEPFET pixels (Germany, Czech Republic…)

Layer 1 r=14 mm

Layer 2 r= 22 mm

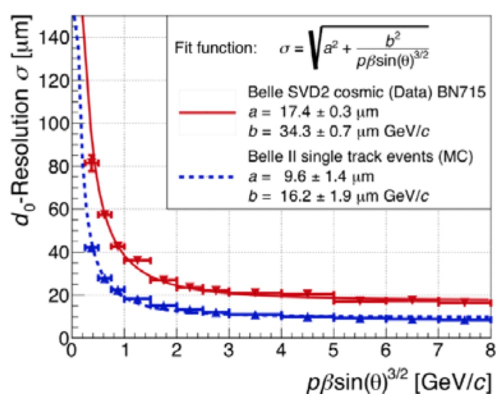
DSSD (double sided silicon detectors)

Layer 3 r=38 mm (Australia)

Layer 4 r=80 mm (India)

Layer 5 r=115 mm (Austria)

Layer 6 r=140 mm (Japan)



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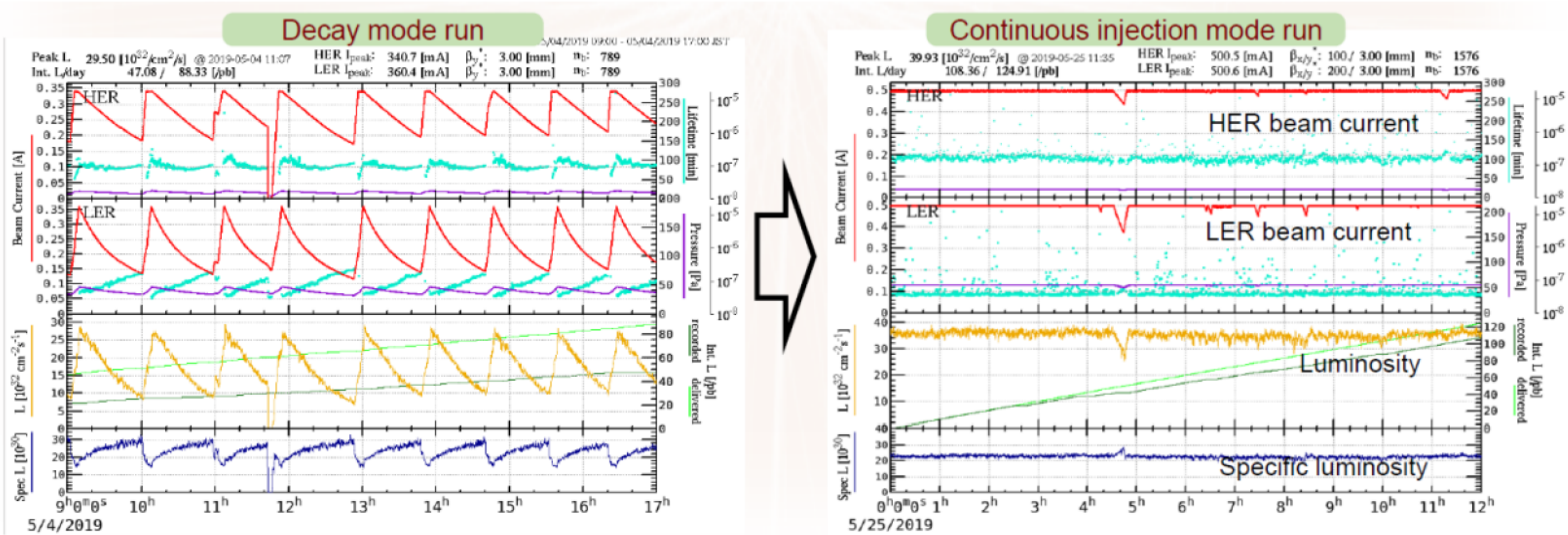
Belle II detector timeline:

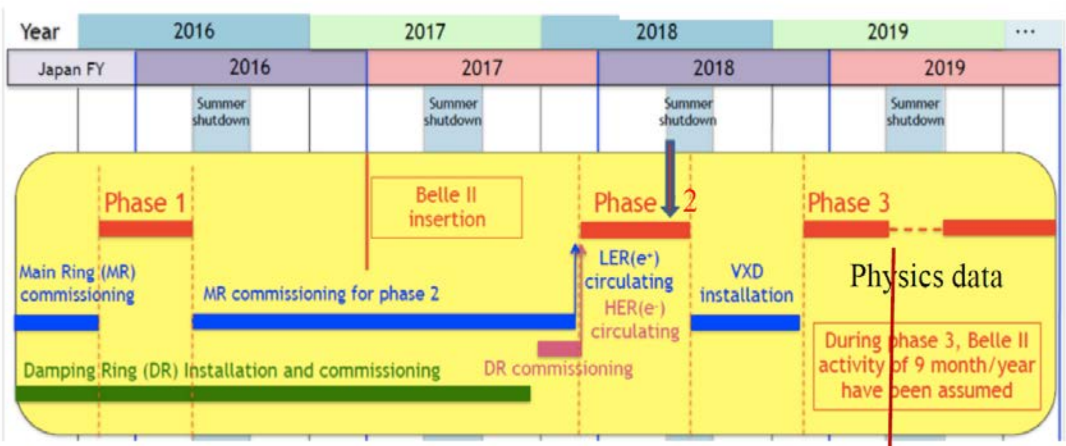
Milestone: continuous injection

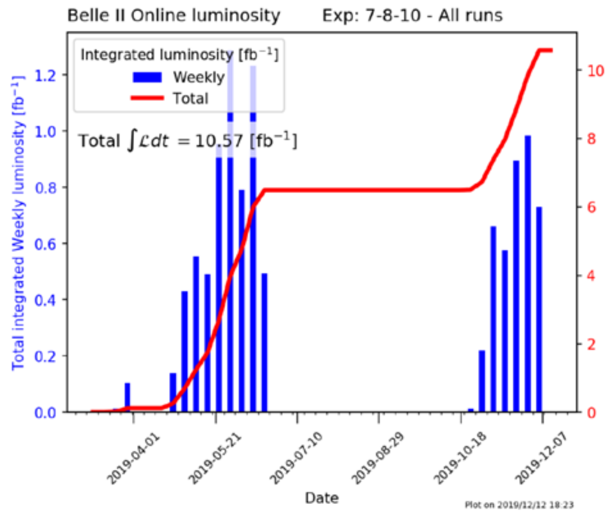


4 May, 2019 25 May, 2019

- Employed at PEP-II and KEKB to increase integrated luminosity
- Challenges: high injection background while detector HV is on
- A necessity at SuperKEKB, where beam lifetime is minutes, due to collisions

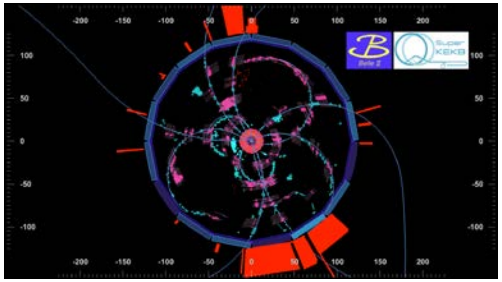
Start-up schedule:





First collisions, 26 April, 2018

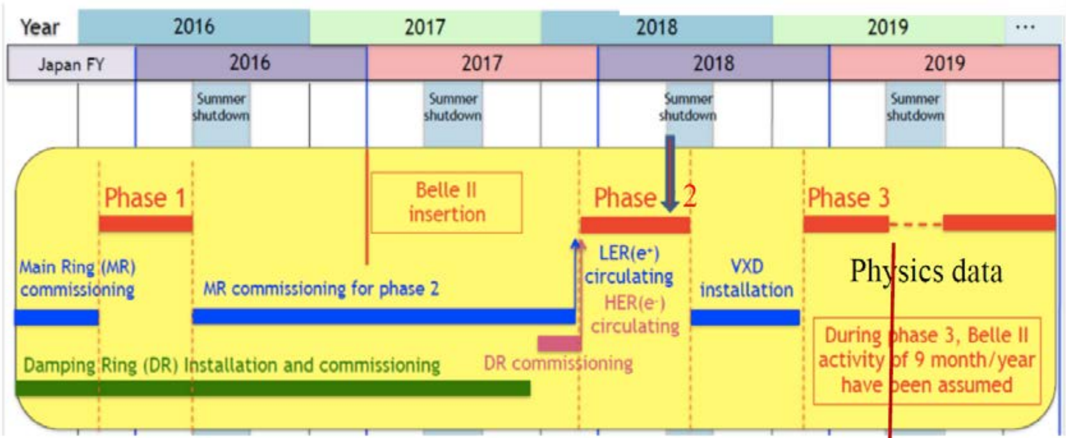
- Collected ~ 5 fb^{-1}
  - 0.5% of Belle
- Mostly at L ~ 0.5×10^{34} cm^2s^{-1}
  - 25% of KEKB
- Reached L ~ 1.2×10^{34} cm^2s^{-1}
  - With high background
  - Ongoing work on background

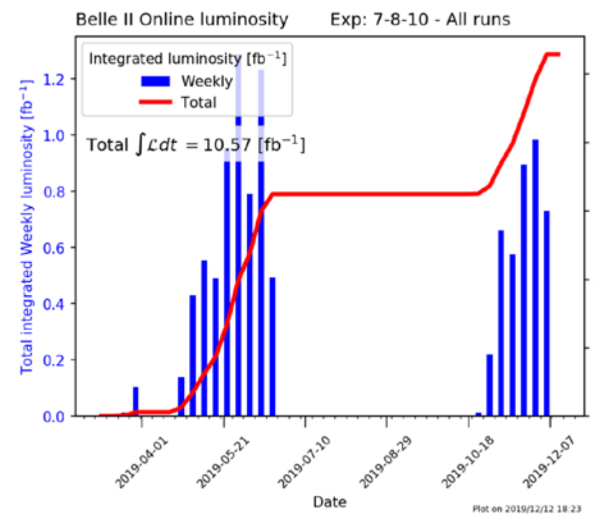


2019: First Collisions in Phase 3, the Physics Run

2019: First Collisions in the Phase 3 (the VXD is installed in Belle II)

Start-up schedule:





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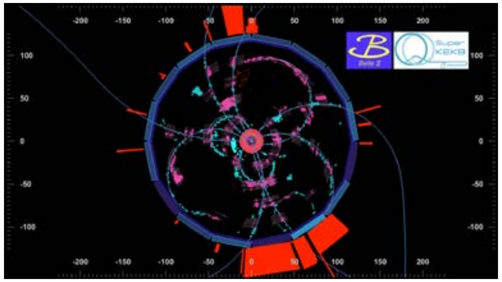
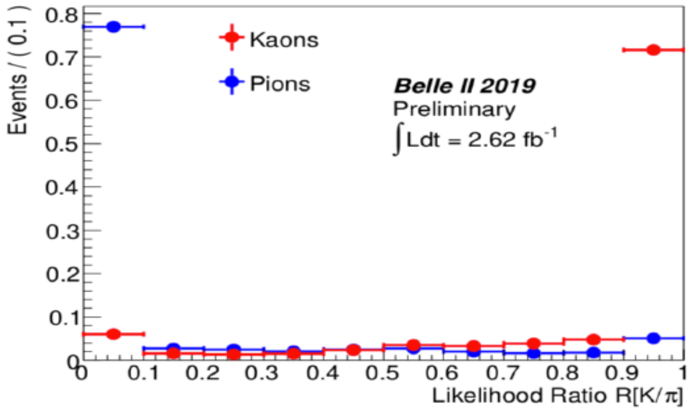
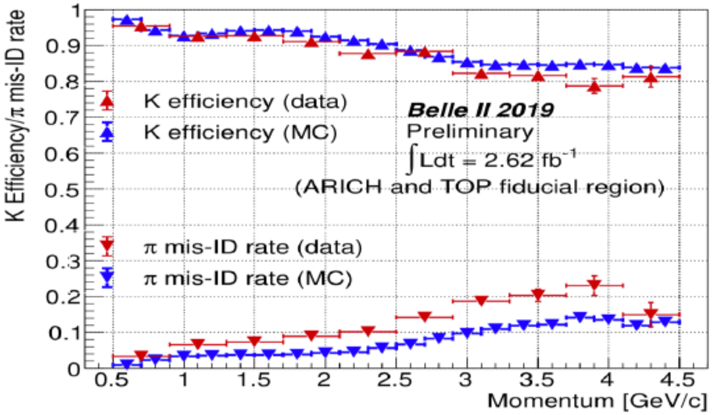


2019: First Collisions in the Phase 3 (the VXD is installed in Belle II)

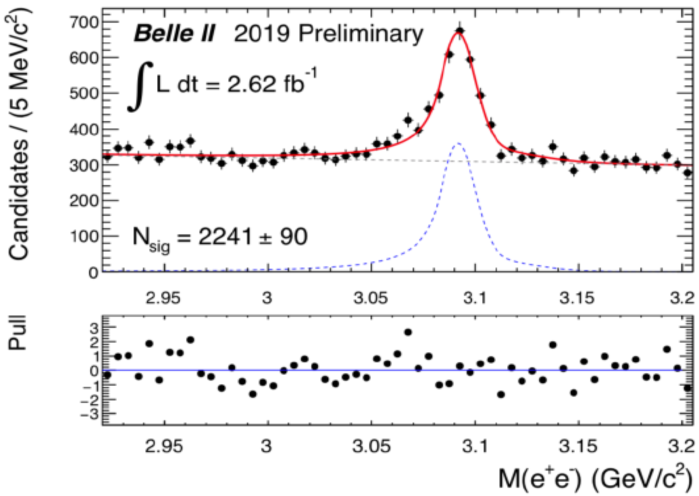
Detector performance: track and PID

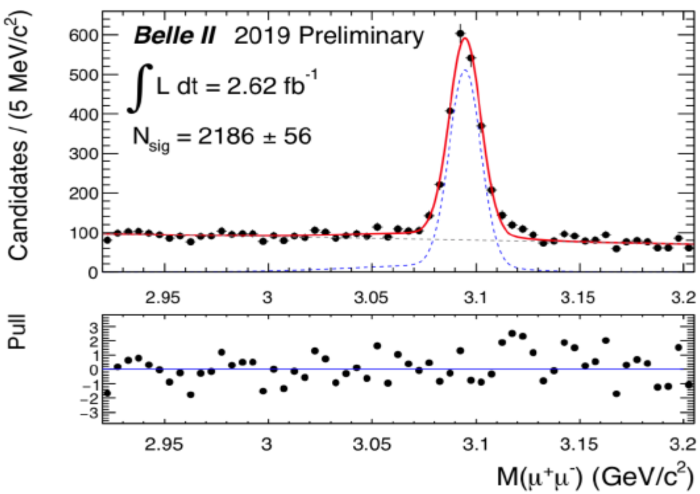
hadron ID: Kaon and pion identification using $D^{*+} \to D^0[\to K^-\pi^+]\pi^+$





lepton ID: using $J/\psi \to \ell^+\ell^-$ ($\ell = e,\ \mu$) with electron or muon ID (>0.95).

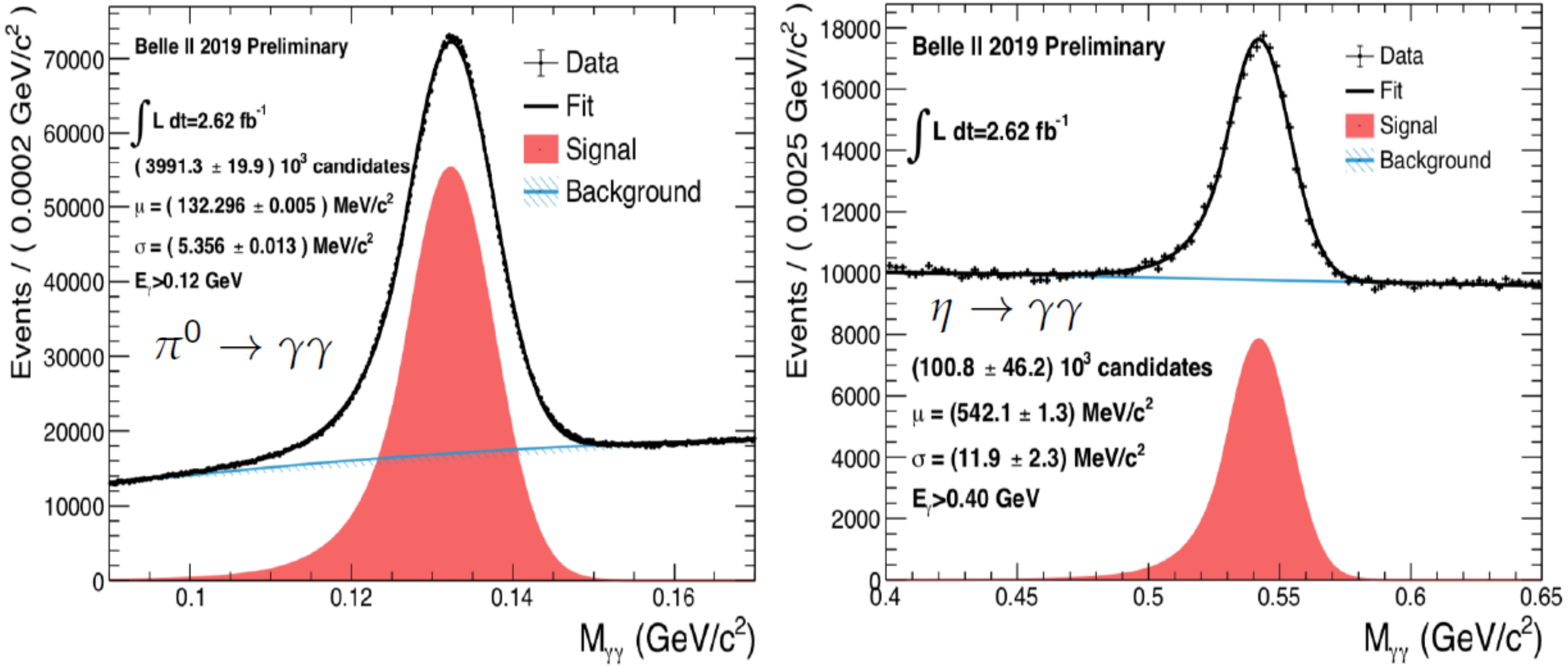




Detector performance: gamma

$E_\gamma >$120 (400) MeV; with good energy deposit in ECL crystals: $E_9 / E_{25} > 0.9$, $N_{hits} > 1.5$ for π^0 (η) channel.

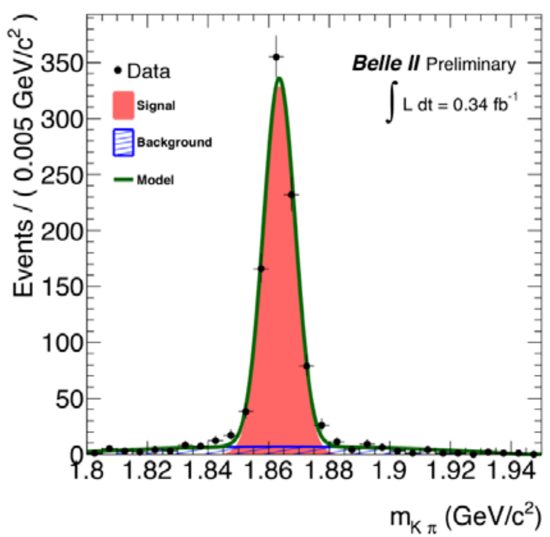
The mass resolution is comparable with Belle as expected.



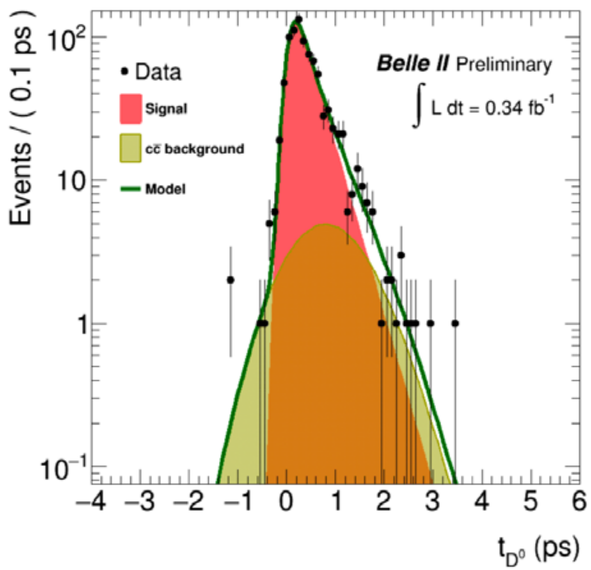
Detector performance: vertex

- Reconstruct $D^{*+} \to D^0[\to K^-\pi^+]\pi_s^+$ to obtain a clear D^0 sample using 0.34 fb^{-1}.
- D^0 lifetime, $\tau = 370 \pm 40$ fs is consistent with PDG value.
- Compared with Belle, D^0 lifetime resolution is much improved as expected due to a better detector performance, i.e. PXD, CDC with smaller cell, etc.

BELLE2-NOTE-PL-2019-003



With D^0 produced in $D^{*+} \to D^0\pi^+$



parameter	extracted value
N_{sig}^1	$(81 \pm 6) \cdot 10$
μ_1 (fs)	31 ± 16
σ_1 (fs)	127 ± 15
N_{sig}^2	$(10 \pm 5) \cdot 10$
μ_2 (ps)	(0.48 ± 0.17)
σ_2 (ps)	(0.73 ± 0.13)
τ (fs)	(370 ± 40)

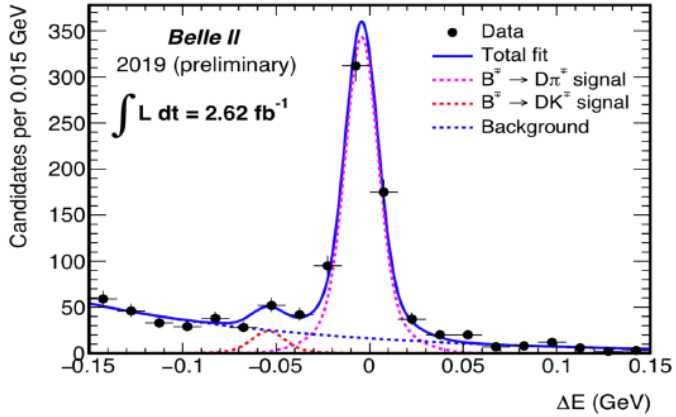
PDG: 410.1 ± 1.5 fs

$$T_{PDF}(t) = N_{sig}^1 \times Gauss(t|\mu_1,\sigma_1) * Exp(t|\tau) + N_{sig}^2 \times Gauss(t|\mu_2,\sigma_2) * Exp(t|\tau)$$

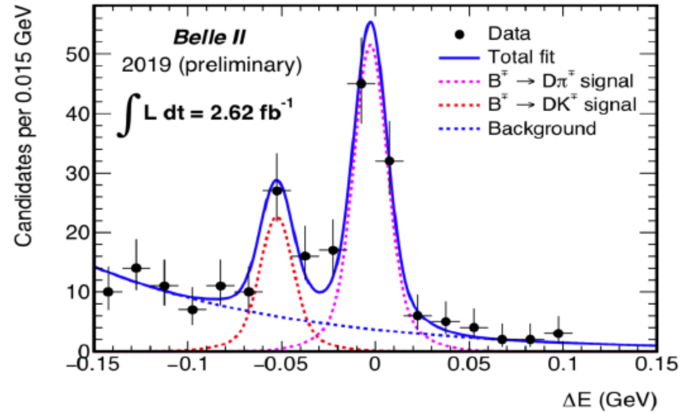
Detector performance: B

- Observation of $B^- \to D^0K^-$ with $D^0 \to K\pi/K\pi\pi^0/K3\pi$: $N = 38 \pm 8$ (6σ)

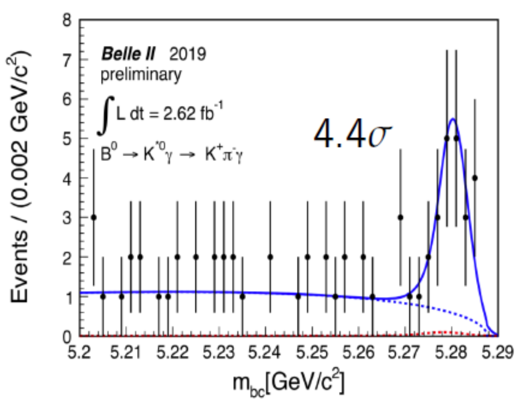
No PID requirement

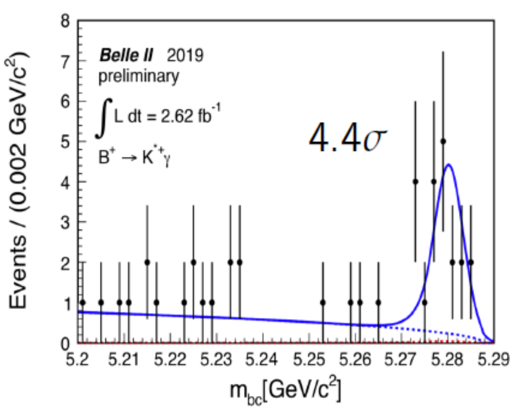


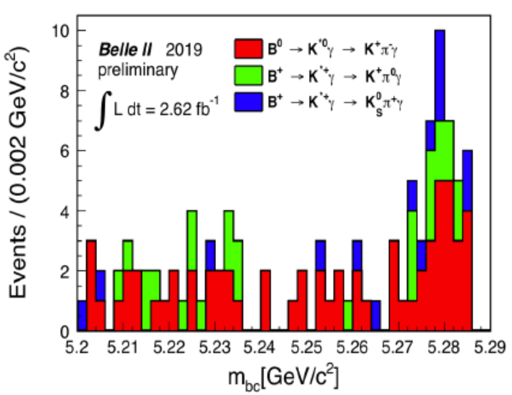
With high momentum PID



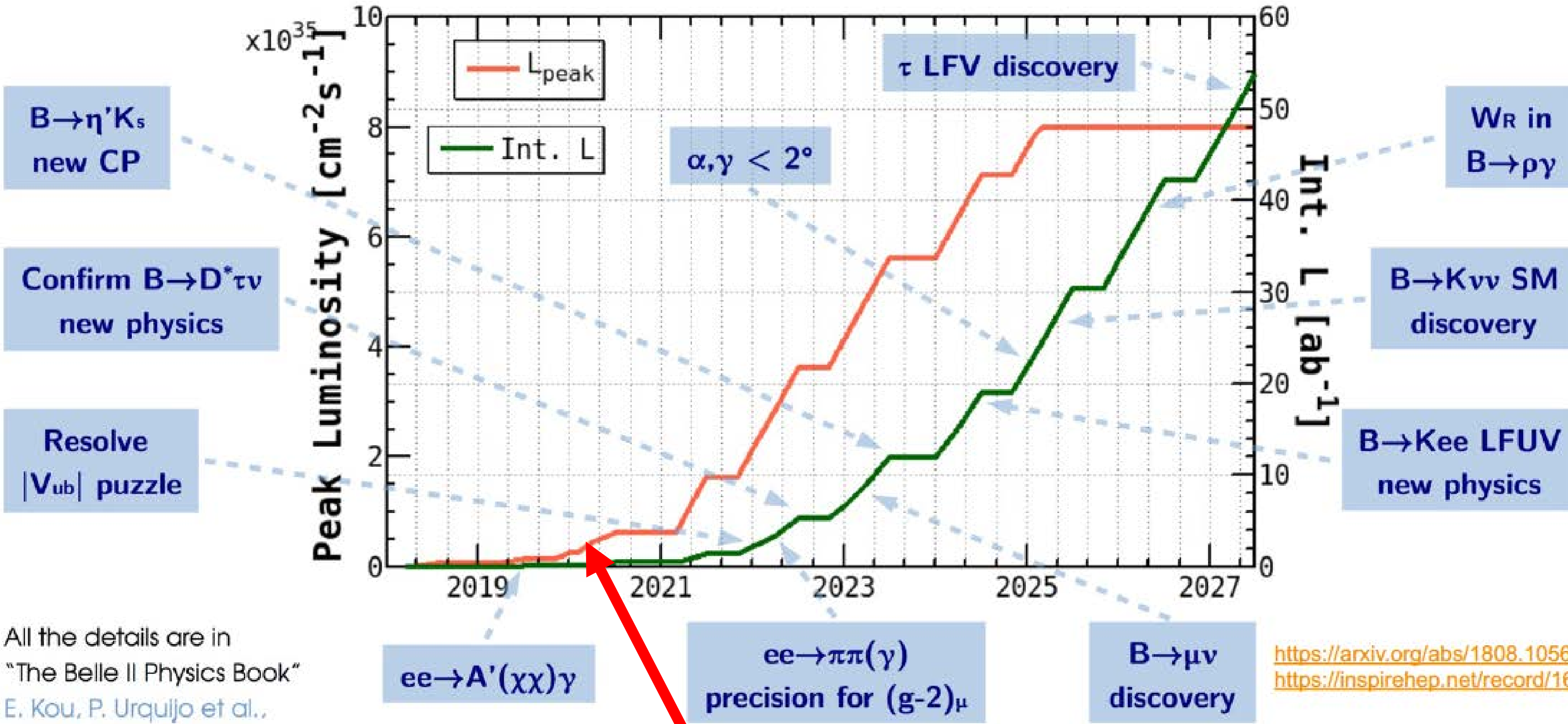
- re-discovery of $K^{*0}\gamma$ and $K^{*+}\gamma$ channels with 2.62 fb^{-1} (1/2 of the initial Phase III dataset). Yields $N_{sig} = 35.5 \pm 6.9$, consistent with W.A. branching fraction.







Long term prospects of Belle II



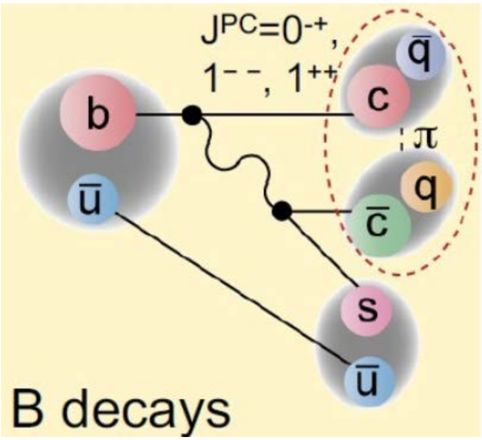
All the details are in
"The Belle II Physics Book"
E. Kou, P. Urquijo et al.,

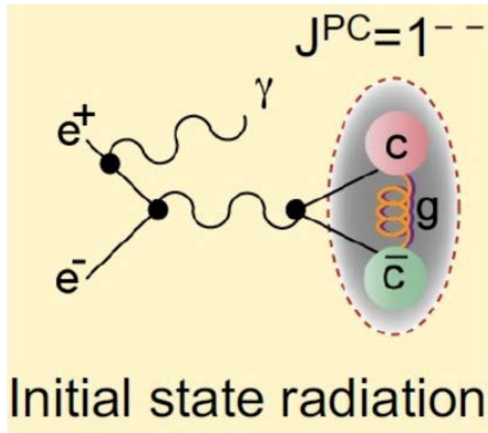
https://arxiv.org/abs/1808.10567
https://inspirehep.net/record/1692393/

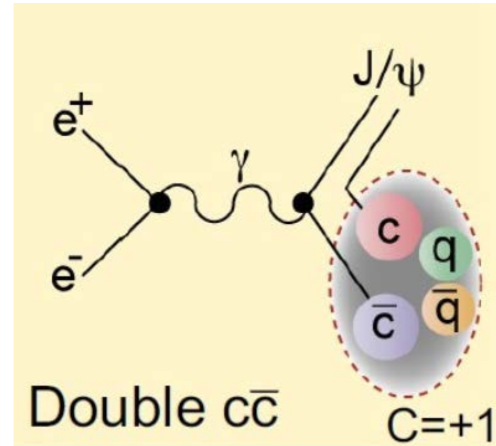
We are ready!

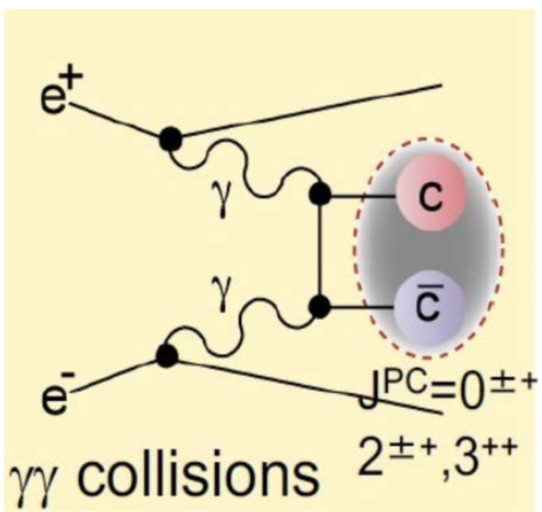
Prospects on XYZ states @ Belle II

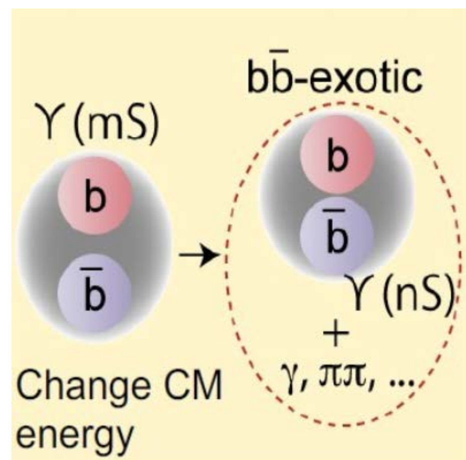
XYZ production mechanism @B factory:











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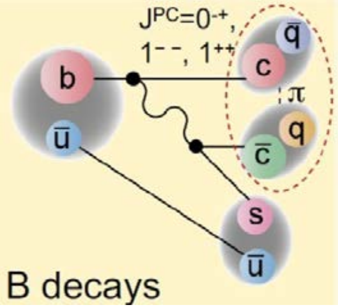
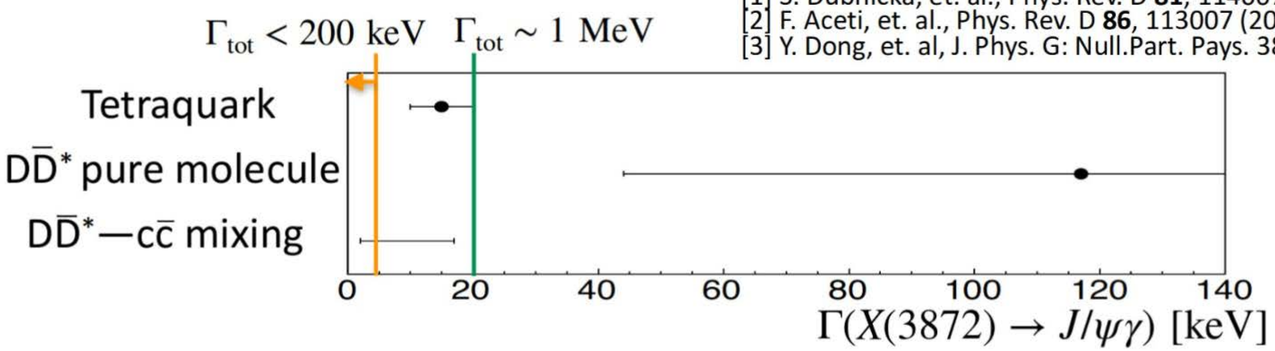
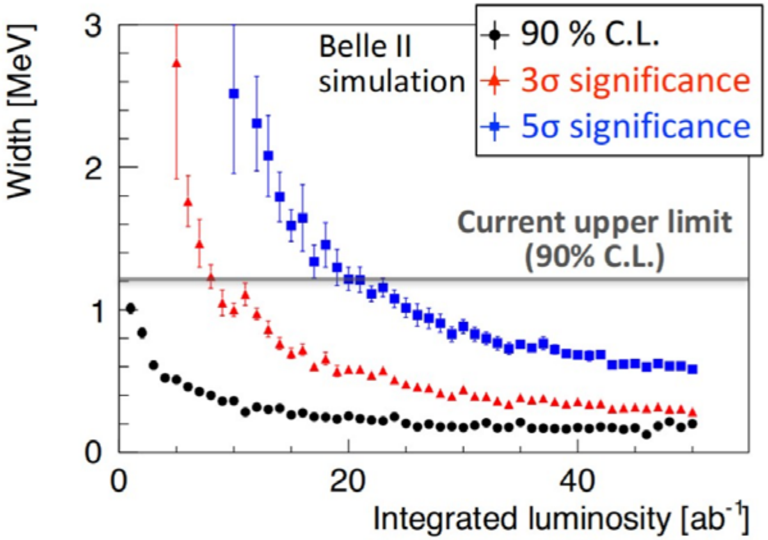


X(3872) Width

[1] S. Dubnicka, et. al., Phys. Rev. D **81**, 114007 (2010)
[2] F. Aceti, et. al., Phys. Rev. D **86**, 113007 (2012)
[3] Y. Dong, et. al, J. Phys. G: Null.Part. Pays. 38, 015001 (2011)





- With the full data sample of Belle II (50 ab^{-1}), total width with values up to

  [90% C.L.] ~ 180 keV

  [3σ significance] ~ 280 keV

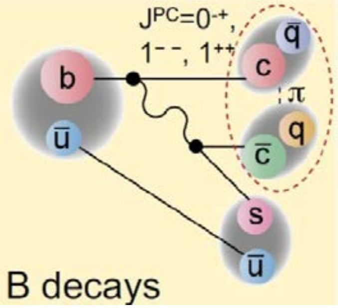
  [5σ significance] ~ 570 keV

  can be measured.

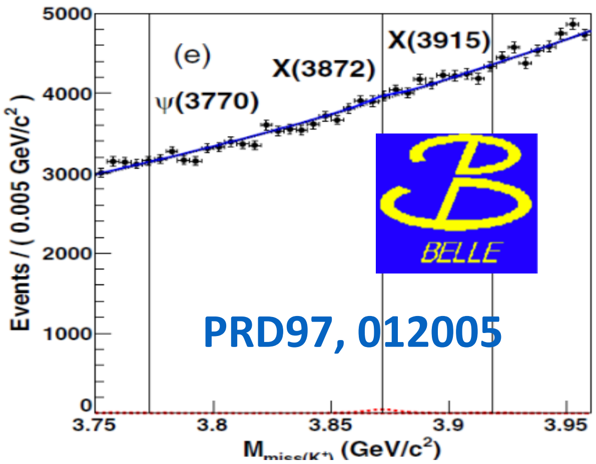
Assuming a Breit-Wigner shape

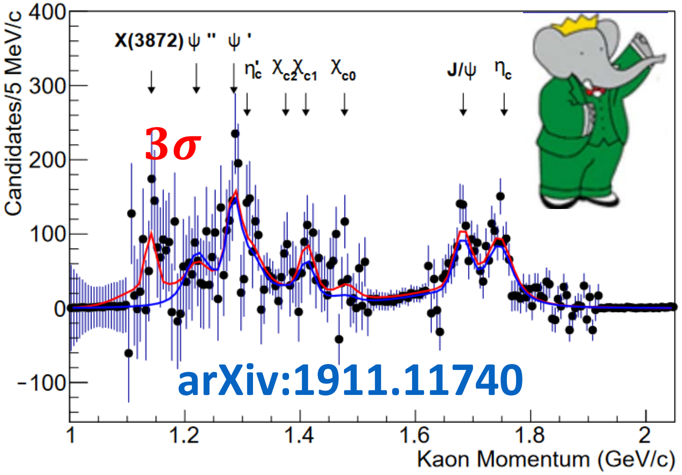
Hikari Hirata, Master thesis 2019

Prospects on XYZ states @ Belle II



X(3872) decay branching fraction





$\mathcal{B}(B \to K\, X(3872)) < 2.6 \times 10^{-4}$
@90%C.L.

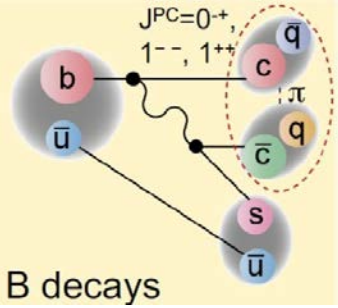
$\mathcal{B}(B \to K\, X(3872)) = (2.1 \pm 0.7) \times 10^{-4}$

$\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) \sim 50\%$ tetraquark PRD71, 014028

$\lesssim 10\%$ molecular model PRD72, 054022;
PRD69, 054008

Belle II: reliable results can be achieved.

Prospects on XYZ states @ Belle II



Other highlights:

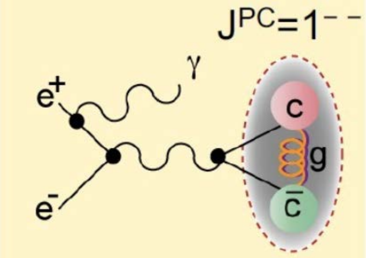
- $X(3872) \to D^0\bar{D}^{*0}$ has been seen,
  - other open flavor decays of other states?
    $B \to KD\bar{D}, KD\bar{D}^*, KD^*\bar{D}^*, KD^{(*)}\bar{D}^{(*)};$
    $KD\bar{D}^{(**)}, KD^{(*)}\bar{D}^{(**)}$

Belle II

- Full amplitude analysis to $B \to K\omega J/\psi$ and $B \to K\pi\chi_{c1}$
  - determine the spin-parities of the X(3915), Z(4050), Z(4250)..

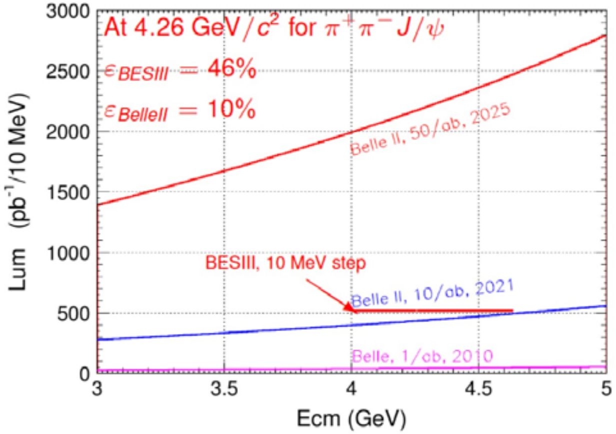
- $B \to K\ X$, to discover missing states?

Prospects on XYZ states @ Belle II



Initial state radiation

ISR

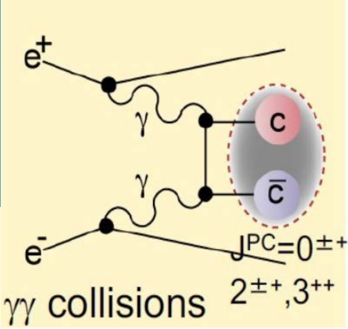


- BelleII 50ab^{-1}==BESIII 500 pb^{-1}, 10 MeV scan
- Line shape of the resonance and fine structures can be investigated.

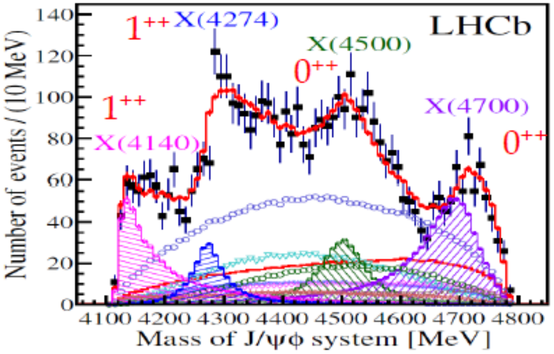
Golden channels	E_{cm} (GeV)	Statistical error (%)	Related XYZ states
$\pi^+\pi^- J/\psi$	4.23	7.5 (3.0)	$Y(4008)$, $Y(4260)$, $Z_c(3900)$
$\pi^+\pi^-\psi(2S)$	4.36	12 (5.0)	$Y(4260)$, $Y(4360)$, $Y(4660)$, $Z_c(4050)$
$K^+K^- J/\psi$	4.53	15 (6.5)	Z_{cs}
$\pi^+\pi^- h_c$	4.23	15 (6.5)	$Y(4220)$, $Y(4390)$, $Z_c(4020)$, $Z_c(4025)$
$\omega\chi_{c0}$	4.23	35 (15)	$Y(4220)$

10 ab^{-1} **(50 ab^{-1})**

Prospects on XYZ states @ Belle II



PRL118, 022003

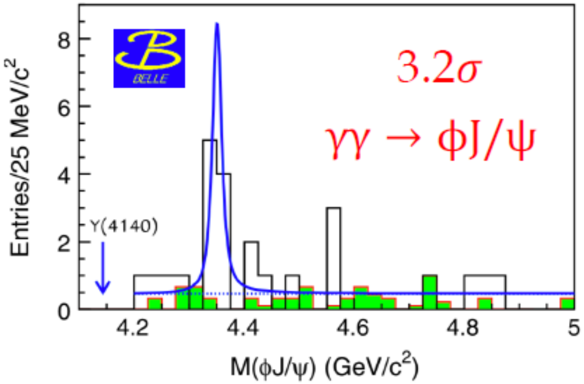


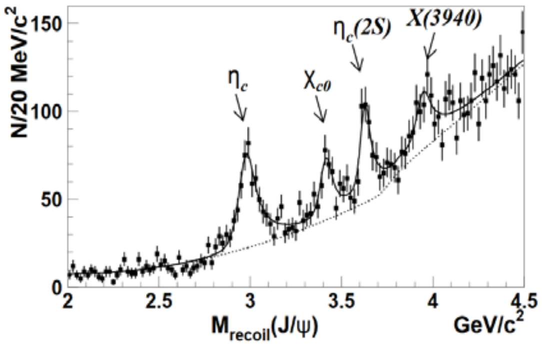
smaller boost in Belle II :
-> higher efficiency

$B^+ \to K^+ \phi J/\psi$

- Could decouple two of the four states seen by LHCb in $\phi J/\psi$
- Need > 10 ab-1 data
- Existence of the X(4350)?
- $X(3915) \to \omega J/\psi$ $\boldsymbol{J^P}$**???**
- ……………

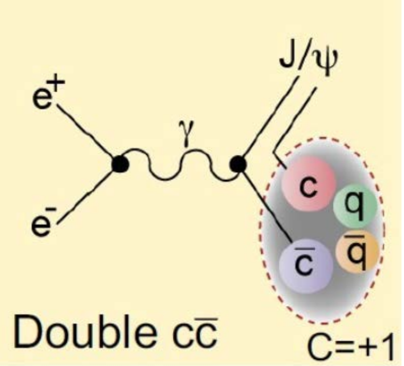
PRL104, 112004



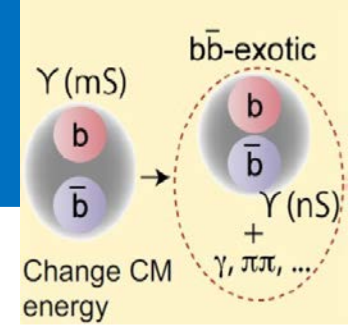


[Belle, PRL 98, 082001 (2007)]

- ❑ Absolute *BR* and cross sections
- ❑ Study of angular distributions:
  - ❑ to decouple overlapping states
  - ❑ to do cross checks on J^{PC}
- ❑ $e^+e^- \to c\bar{c}(0^{\pm})\, c\bar{c}(1^- \text{ or } 1^+)$
  - ❑ η_c or χ_{c0} recoils

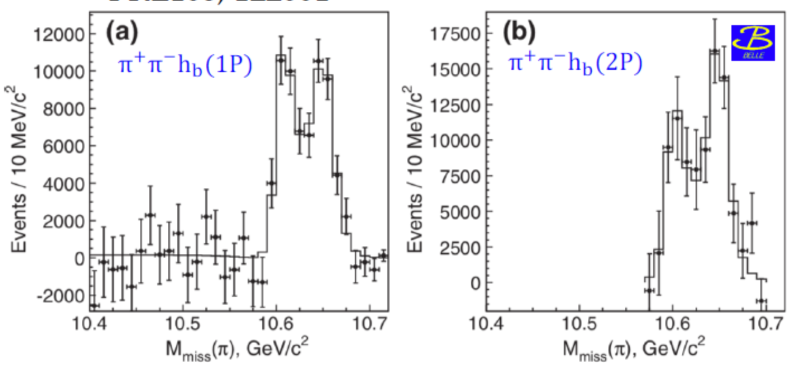


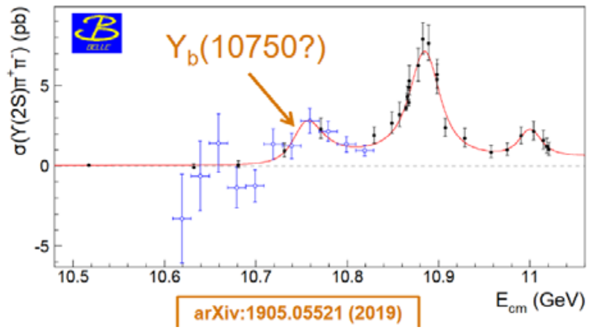
Prospects on XYZ states @ Belle II



- Z_b masses below or above $B^{(*)}B^*$ thresholds?

PRL108, 122001

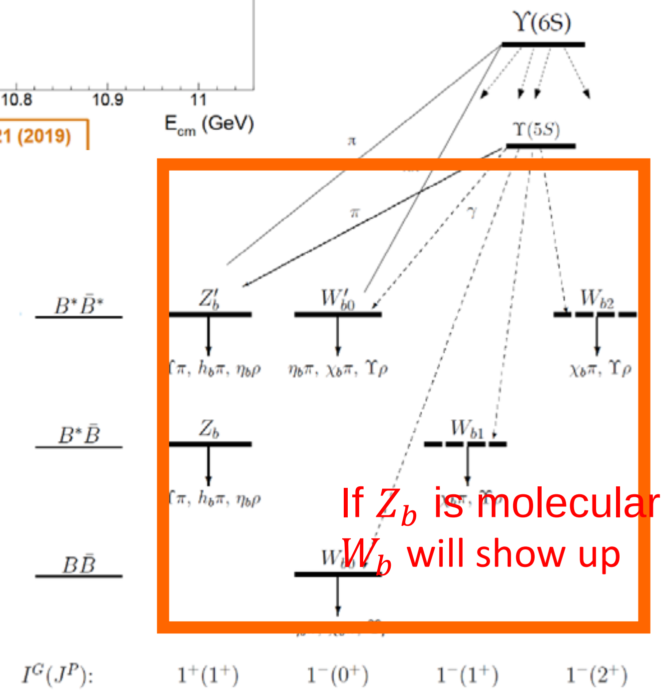




- Confirm $Y_b(10750)$. Other structure?
- Exotica discovery??
- More Z_b from $\Upsilon(6S)$ di-π transition?

Υ(6S) → π+ π- h_b(1P,2P)

Υ(6S) → π+ π- Υ(1S,2S,3S)



If Z_b is molecular W_b will show up

Belle II will collect 1ab^{-1} $\Upsilon(5S)$ data

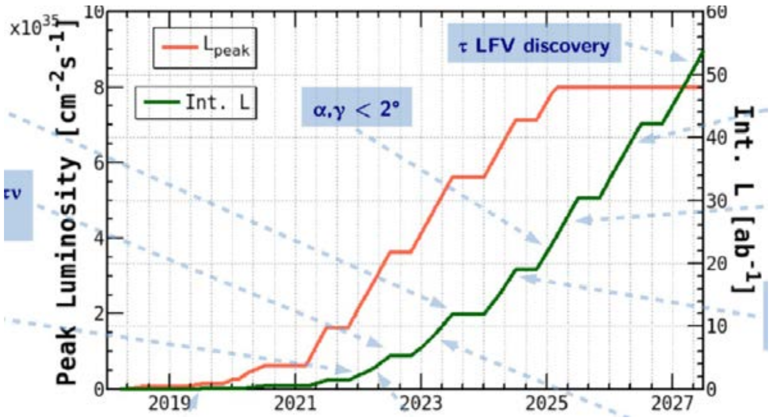
100fb^{-1} $\Upsilon(5S)$ + 400fb^{-1} scan data

Summary

The Belle II experiment has finally started the data taking

The Belle II quarkonium program includes

- $\rightarrow$ 50 ab^{-1} for charmonium ISR, double charmonium, $B \rightarrow c\bar{c}\,X$ ...
- $\rightarrow$ 500 fb^{-1} of scan above $\Upsilon(5S)$
- $\rightarrow$ 300 fb^{-1} of $\Upsilon(3S)$
- $\rightarrow$ 100 fb^{-1} of $\Upsilon(6S)$
- $\rightarrow$ 1 ab^{-1} of $\Upsilon(5S)$



Searching for explanation of families of exotic particle

The results of XYZ are on the way!!!

Thank you!

The 1st generation B factories

- B factory: High-luminosity, asymmetric-energy e^+e^- collider @ $\sqrt{s} = 10.58$ GeV to produce $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
- Such as: ARGUS, CLEO, CUSB

1999-2010
$\sim 1000\ \mathrm{fb}^{-1} = 1\mathrm{ab}^{-1}$

1999-2008
$\sim 500\ \mathrm{fb}^{-1} = 0.5\ \mathrm{ab}^{-1}$

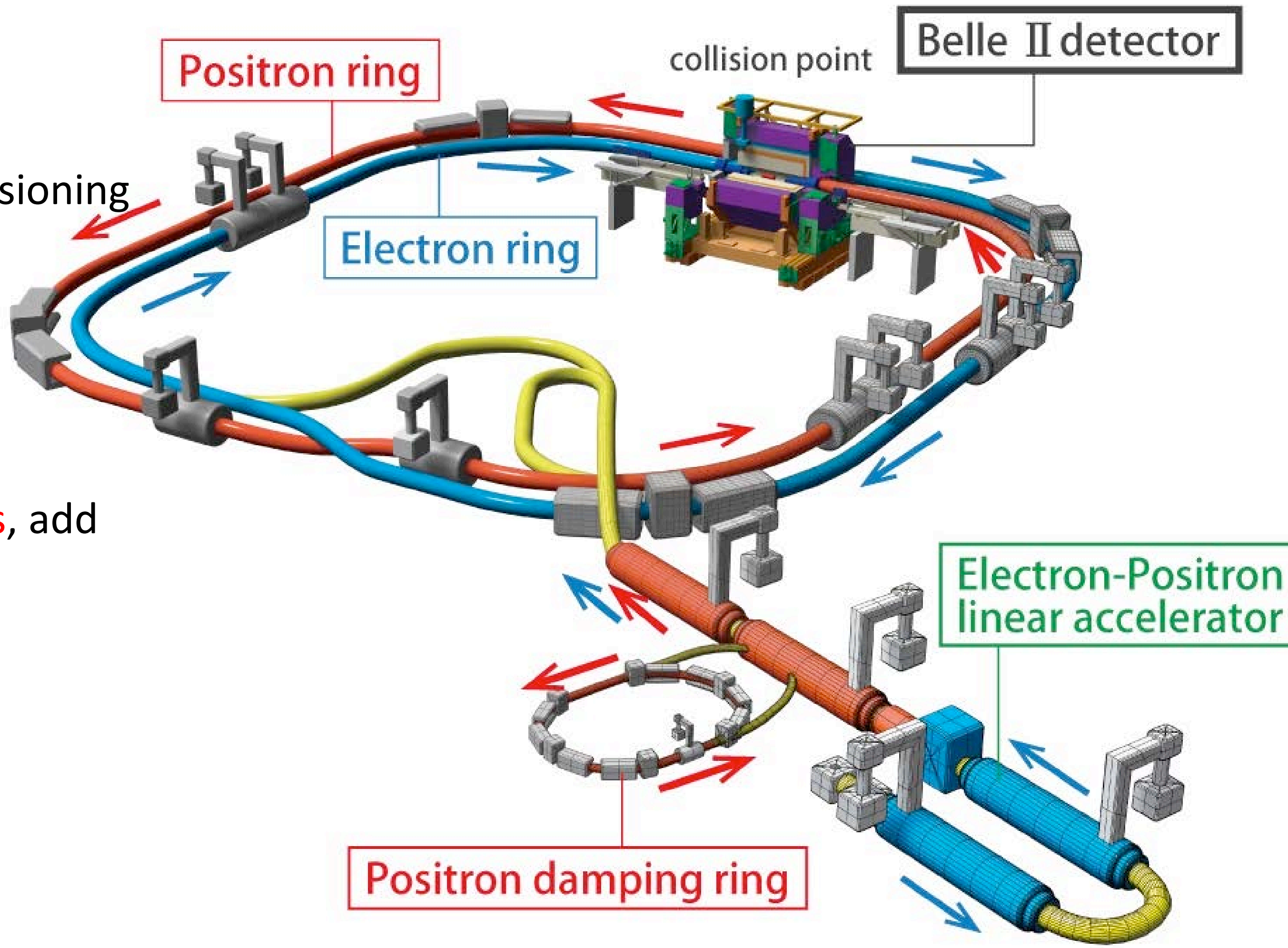
Back Up

- The first new collider in particle physics since the LHC in 2008

Phase 1:
Background, Optics Commissioning
Feb-June 2016.
Brand new
3 km positron ring.

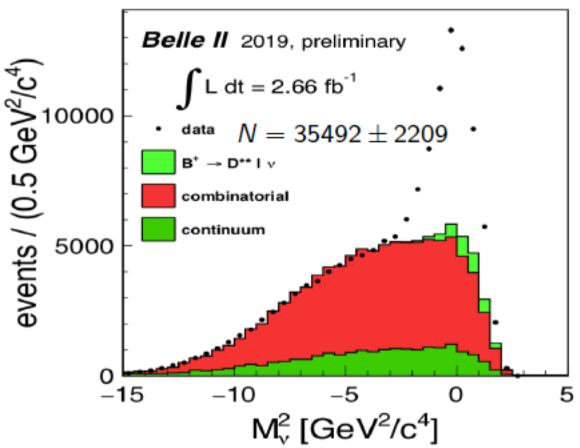
Phase 2: Pilot run
Superconducting Final Focus, add positron damping ring,
First Collisions (0.5 fb^{-1}).
April 27-July 17, 2018

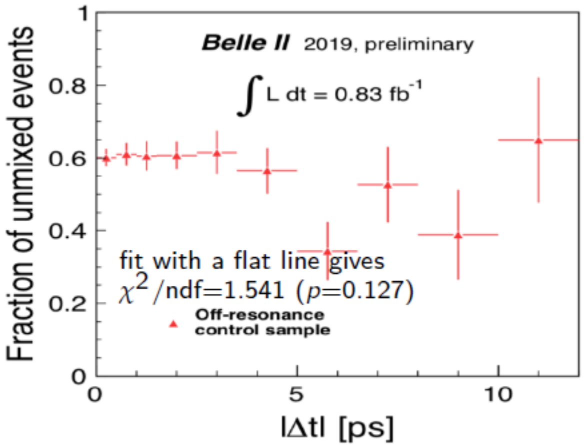
Phase 3: → Physics run

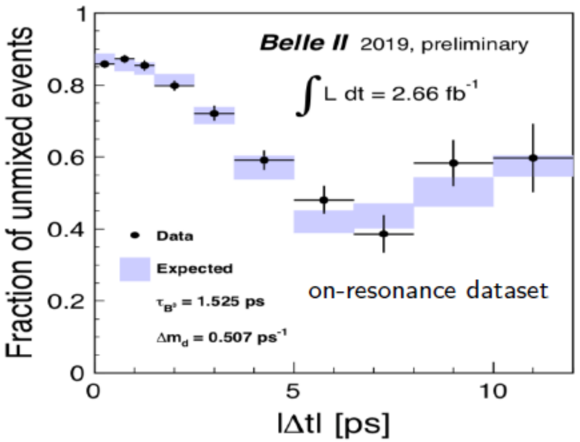


Back Up

- using partially reconstructed $B^0 \to D^{*-}\ell^+\nu$ (ℓ=e, μ) decays: obtained yields 18514 ± 1128 for e channel and 16625 ± 1111 for μ channel.
- Meaurement of the mixed-unmixed yield asymmetry a function of $|\Delta t|$. (Total $N_U = 1642 \pm 133$, $N_M = 253 \pm 45$ with correction factor $\epsilon_U/\epsilon_M = 1.35 \pm 0.10$)
- $|\Delta t|$ dependent fraction of unmixed event for on-resonance data.
- Good agreement is seen between the data and the expectations, proving that the physics capabilities of Belle II detector are sufficient to observe the expected pattern of B^0-$\bar{B}^0$ oscillations.



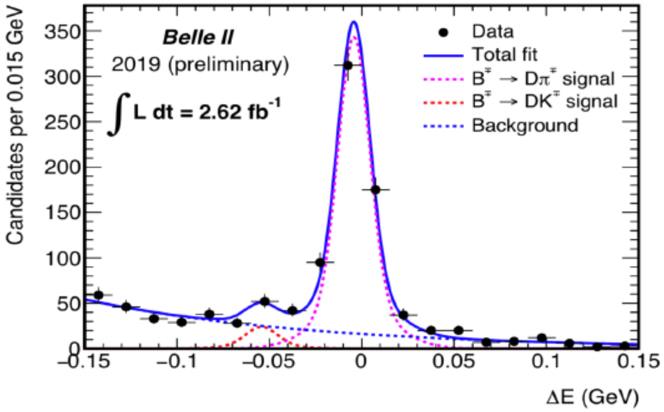




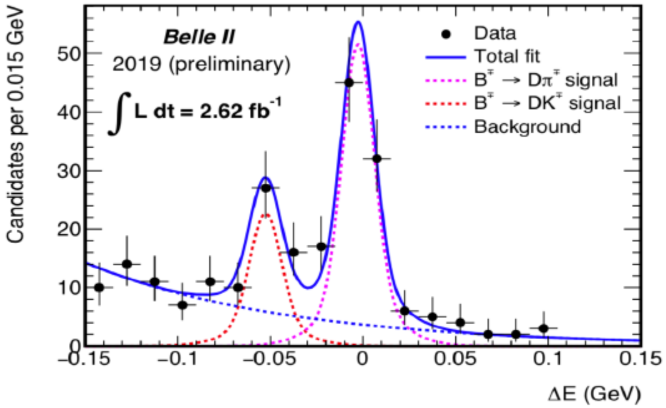
Back Up

- Observation of $B^- \to D^0 K^-$ with $D^0 \to K\pi / K\pi\pi^0 / K3\pi$: $N = 38 \pm 8$ (6σ)

No PID requirement

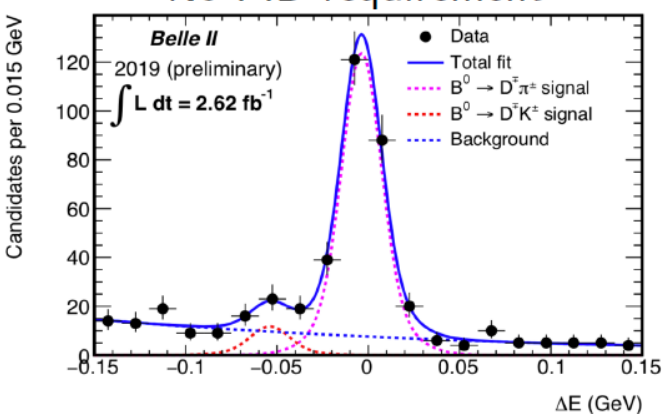


With high momentum PID

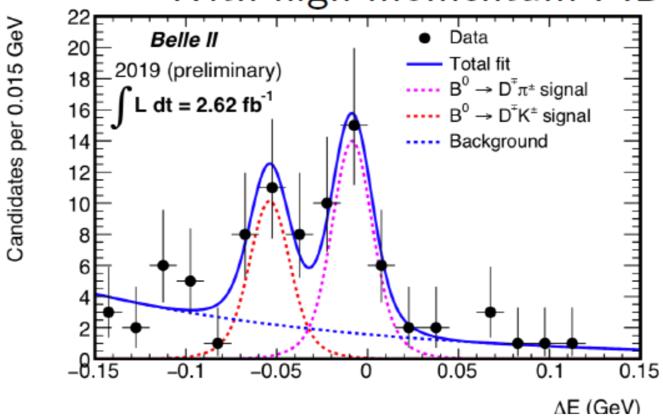


- Evidence of $B^0 \to D^- K^+$ with $D^- \to K\pi\pi / K^0_S\pi$: $N = 20 \pm 6$ (3.3σ)

No PID requirement

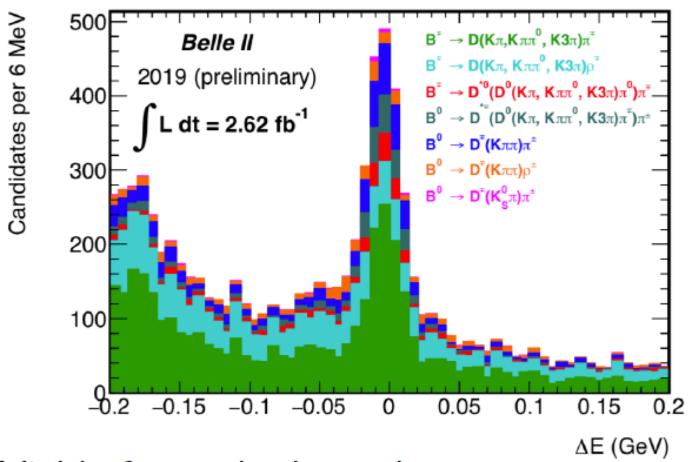


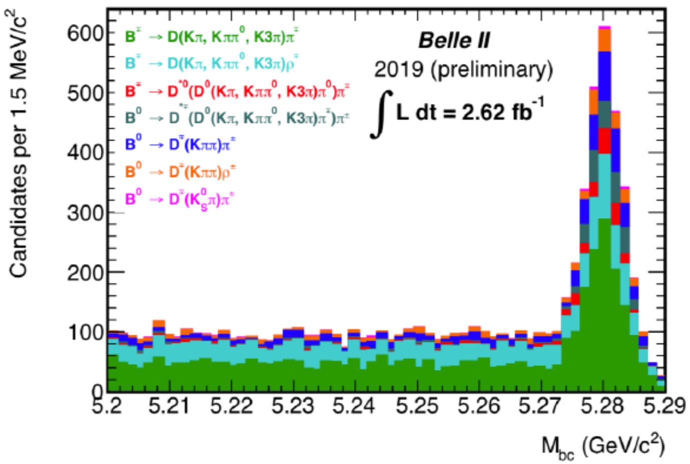
With high momentum PID



Back Up

- rediscovery of $B^{+,0} \to D^{(*)}\pi^{+}$, reconstructed in 2.62 fb^{-1}





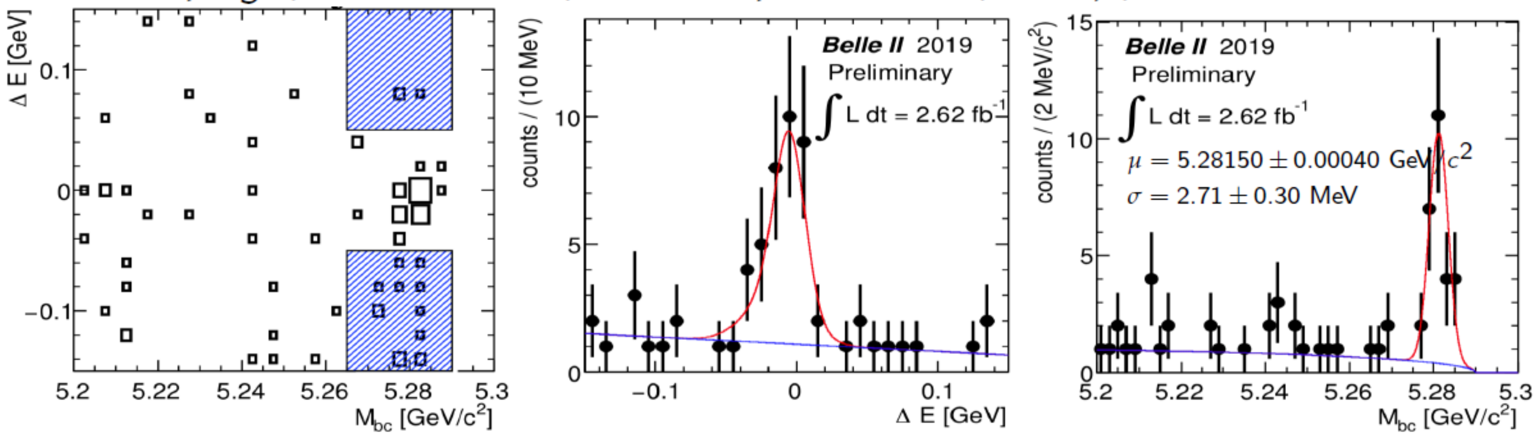
- Yields for each channel:

Decay	Yield
$B^- \to D^0(\to K\pi, K\pi\pi^0, K\pi\pi\pi)\pi^-$	944 ± 35
$B^- \to D^0(\to K\pi, K\pi\pi^0, K\pi\pi\pi)\rho^-$	369 ± 28
$B^- \to D^{*0}(\to D^0(\to K\pi, K\pi\pi^0, K\pi\pi\pi)\pi^0)\pi^-$	140 ± 13
$B^0 \to D^{*-}(\to D^0(\to K\pi, K\pi\pi^0, K\pi\pi\pi)\pi^-)\pi^+$	236 ± 16
$B^0 \to D^-(\to K\pi\pi)\pi^+$	351 ± 21
$B^0 \to D^-(\to K\pi\pi)\rho^+$	156 ± 17
$B^0 \to D^-(\to K_S^0\pi)\pi^+$	21 ± 5

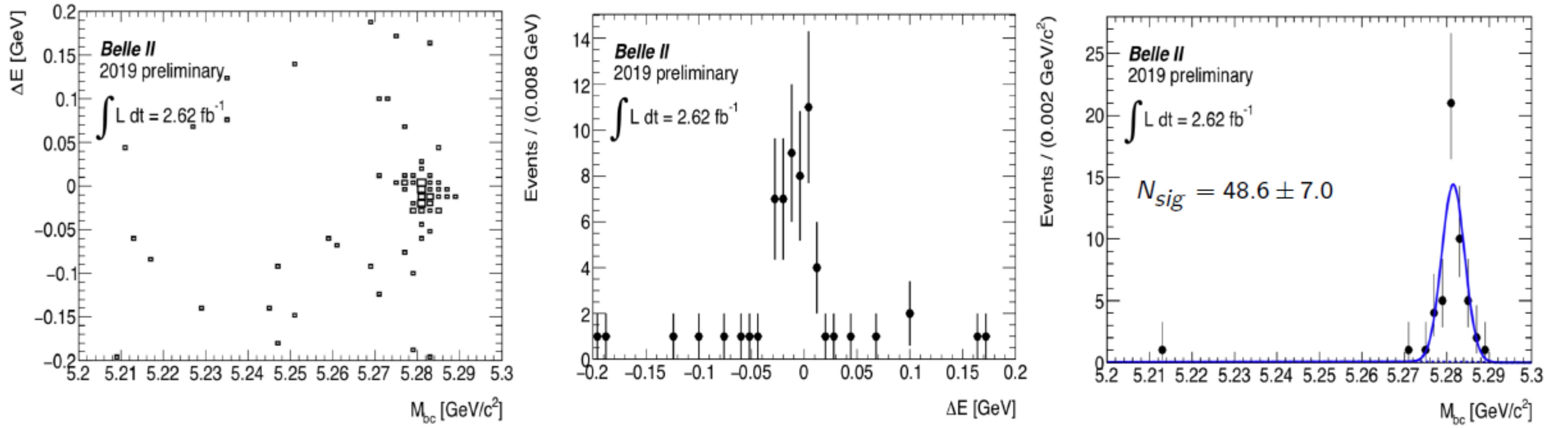
- Modes with neutrals mesons are efficiently reconstructed along with all-charged final states containing kaons and pions.

Back Up

- $B^0 \to J/\psi K_S^0$ (CP eigenstate) with $J/\psi \to \ell^+\ell^-$ (ℓ=e, μ)

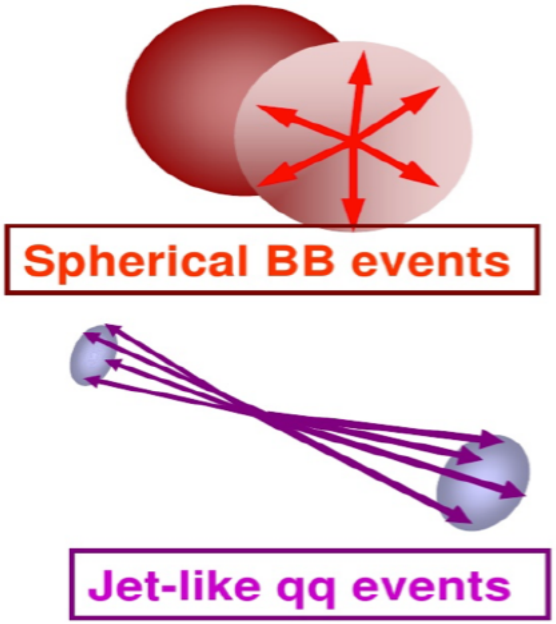


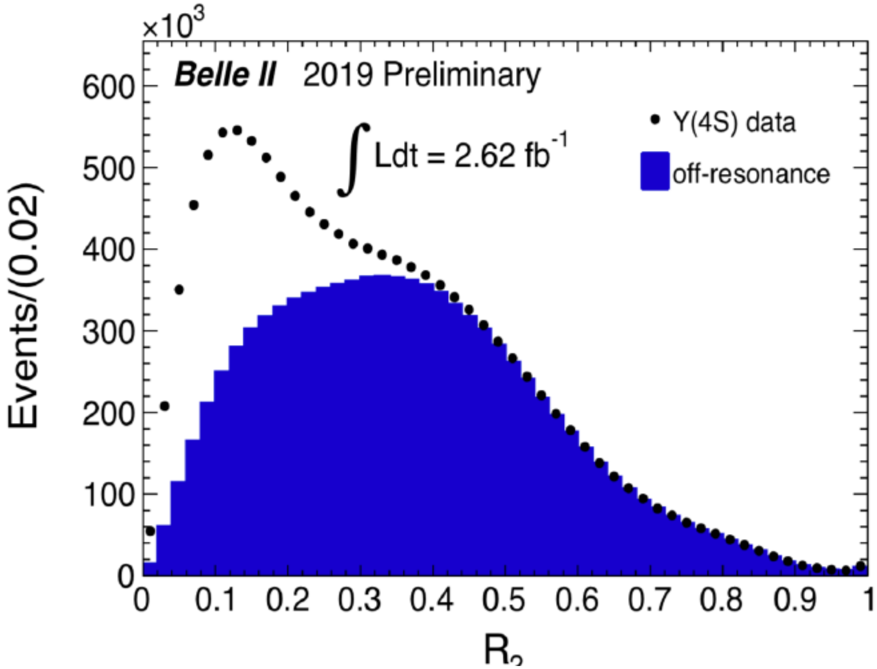
- $B^0 \to J/\psi K^{*0}$ with $K^{*0} \to K^+\pi^-$ (also study B decay vertex resolution)



Back Up

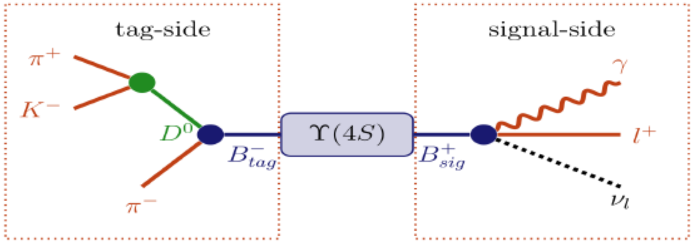
- Event shape $R_2 = H_2/H_0$ with Fox-Wolfram moments $H_l = \sum_{i,j} \frac{|P_i||P_j|}{E_j^{vis}} P_l(\cos\theta_{ij})$ where θ_{ij} is the opening angle between charged tracks or photons i and j.
- $B\bar{B}$ (continuum) event is spherical (jet-like) shape, $\Rightarrow$ $R_2 \to 0$ (1).
- The overall selection efficiency on the $B\bar{B}$ sample is 98.8%.
- The off-res. contribution is normalized to the luminosity of the on-res. data.

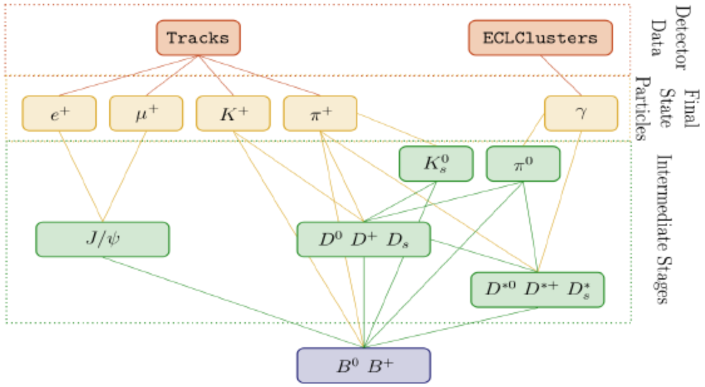


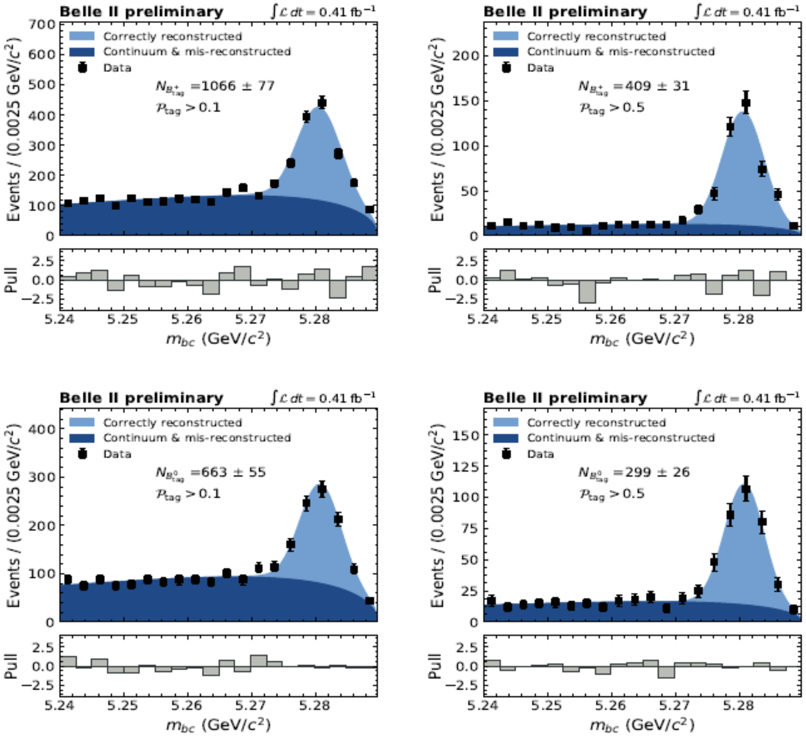


Back Up

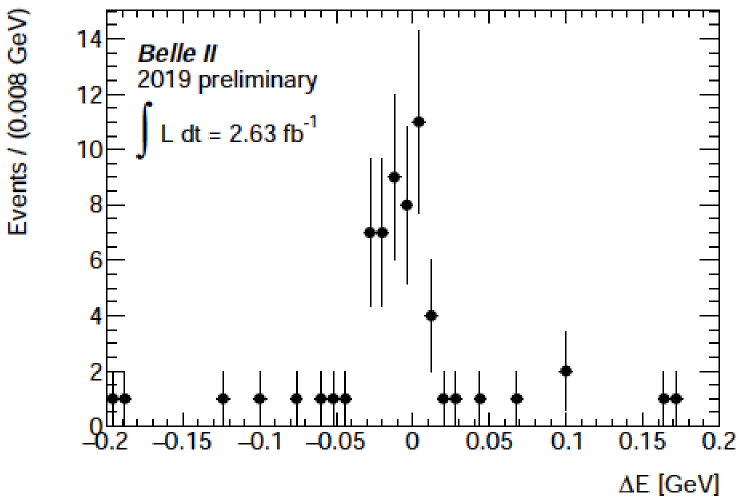
- FEI: Fast BDT-based algorithm fully reconstructs B decays with more than thousands B decay modes
- useful for channels with weak signature, e.g., missing momentum (vs in final state)
- performance on early data shows improvement compared to predecessor algorithm.

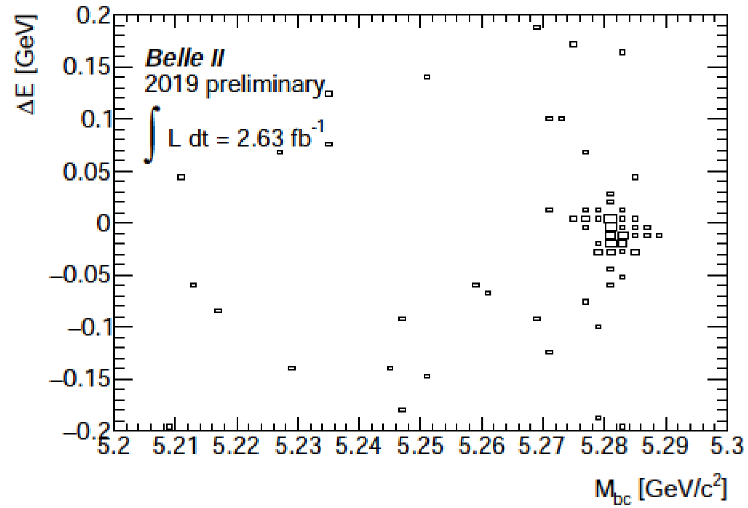






Observation of $B \to J/\psi\ K^{*0}$





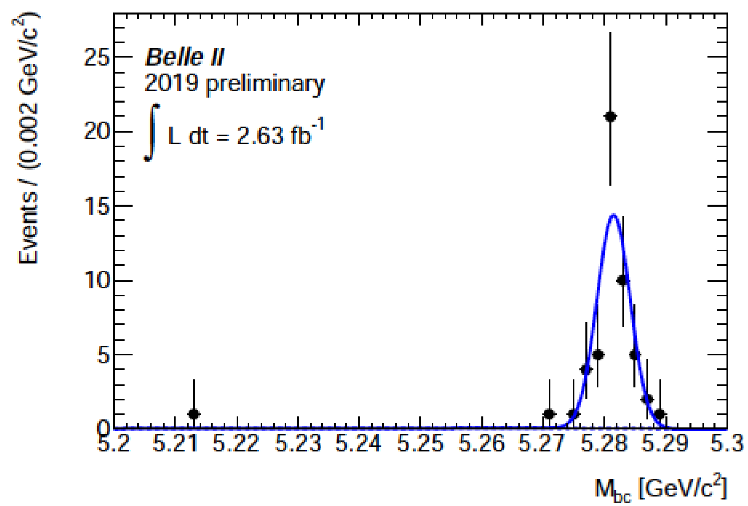
About ½ of the initial Phase 3 data sample

Note:

$$B \to J/\psi K^{*0} \to J/\psi\ K^- \pi^+$$

is not a CP eigenstate. Need

$$B \to J/\psi K^{*0} \to J/\psi\ K_S^0 \pi^0$$



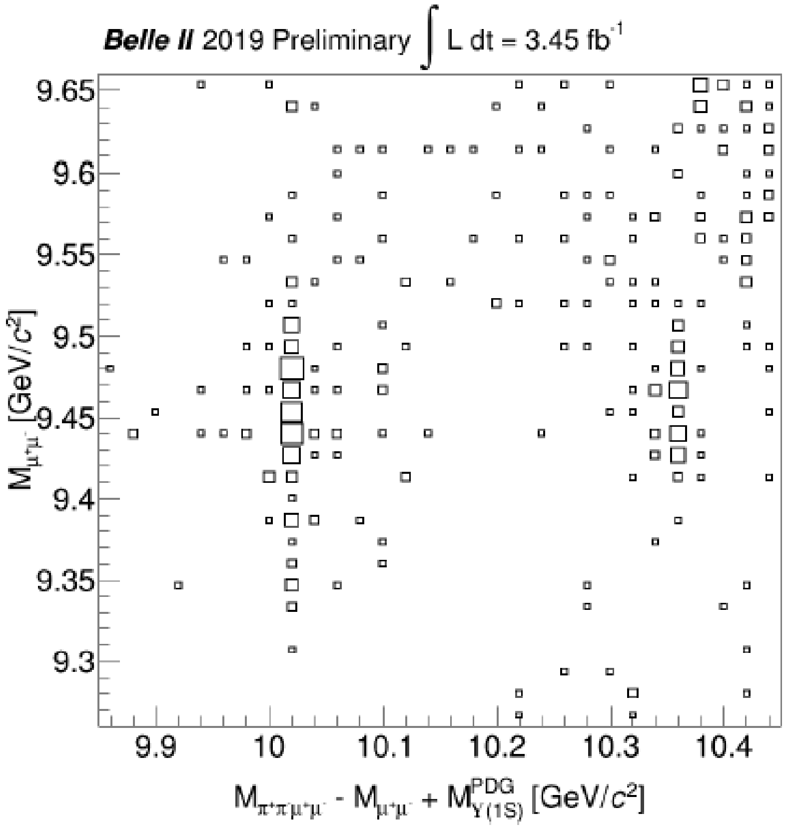
$$N(B \to J/\psi K^{*0} \to J/\psi\ K^- \pi^+) = 48.6 \pm 7.0$$

ISR

$$e^+e^- \to \gamma\ \Upsilon(3S,2S)$$

$$\Upsilon(3S,2S) \to \pi^+\pi^-\Upsilon(1S) \to \mu^+\mu^-$$

Upsilon(2S), Upsilon(3S) via Initial State Radiation (ISR)



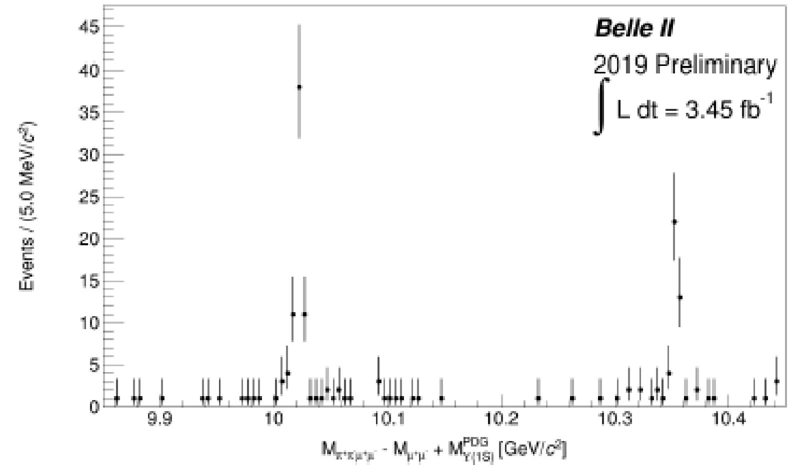
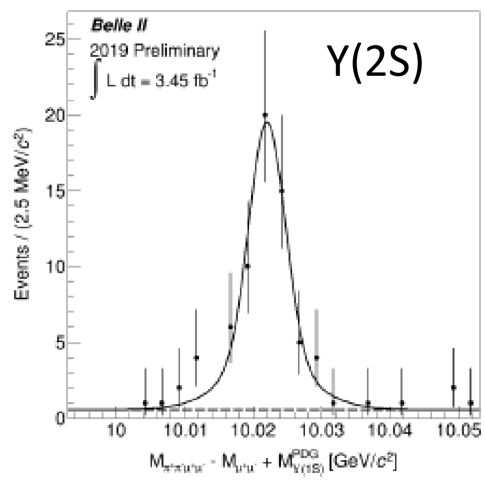
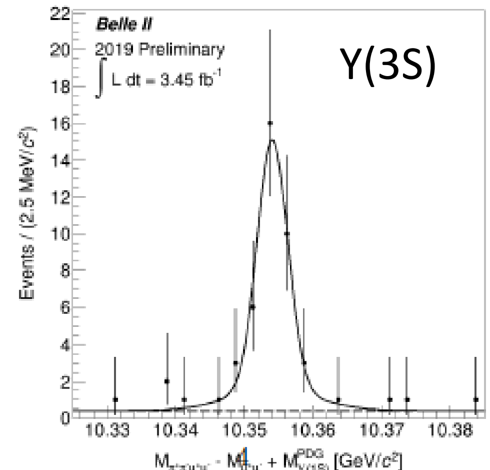


FIG. 2: Plot of $M_{\pi^+\pi^-\mu^+\mu^-} - M_{\mu^+\mu^-} + M^{PDG}_{\Upsilon(1S)}$ with a requirement of $|M_{\mu\mu} - M^{PDG}_{\Upsilon(1S)}| < 50$ MeV. The peaks indicate $\Upsilon(2S)$ and $\Upsilon(3S)$ dipion decay signals.



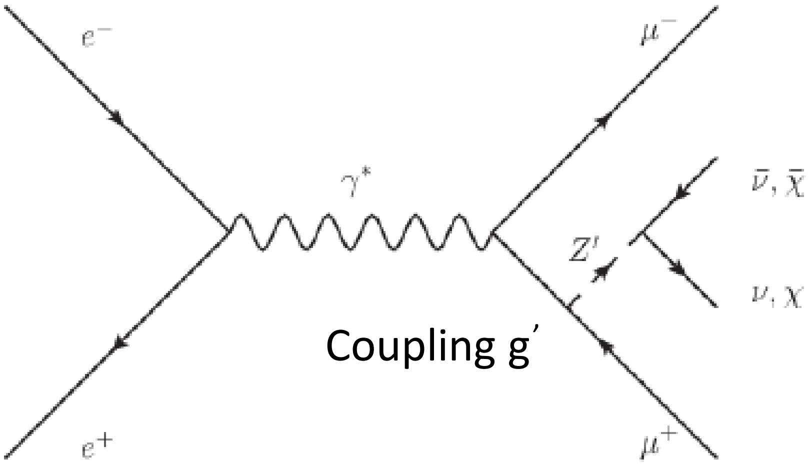


In Belle and BaBar, ISR was an important tool for finding new particles.

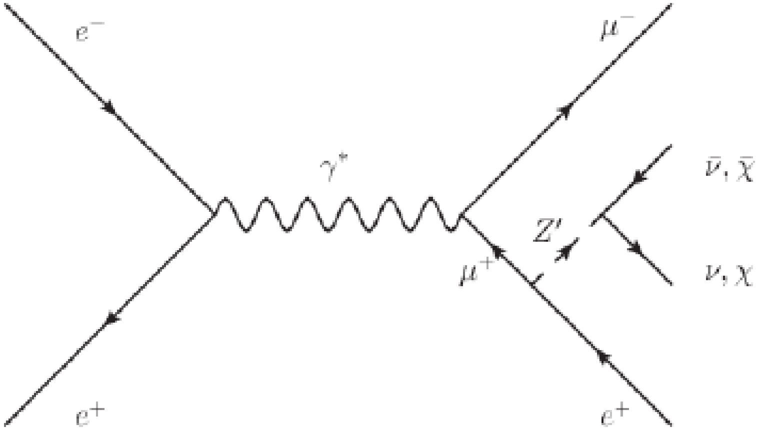
Dark Sector:

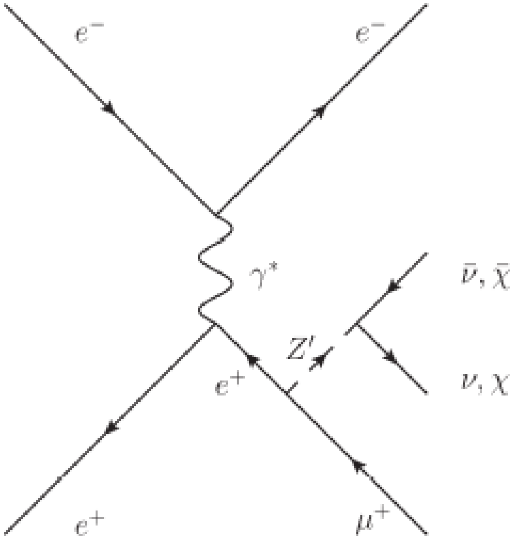
Previously limited by Triggering, QED backgrounds and theoretical imagination. *Now new possibilities of triggering, more bandwidth.*

Belle II First Physics. A novel result on the dark sector (Z’ →nothing) recoiling against di-muons *or* an electron-muon pair. *Both possibilities are poorly constrained at low Z’ mass and in the first case, could explain the muon g-2 anomaly.*



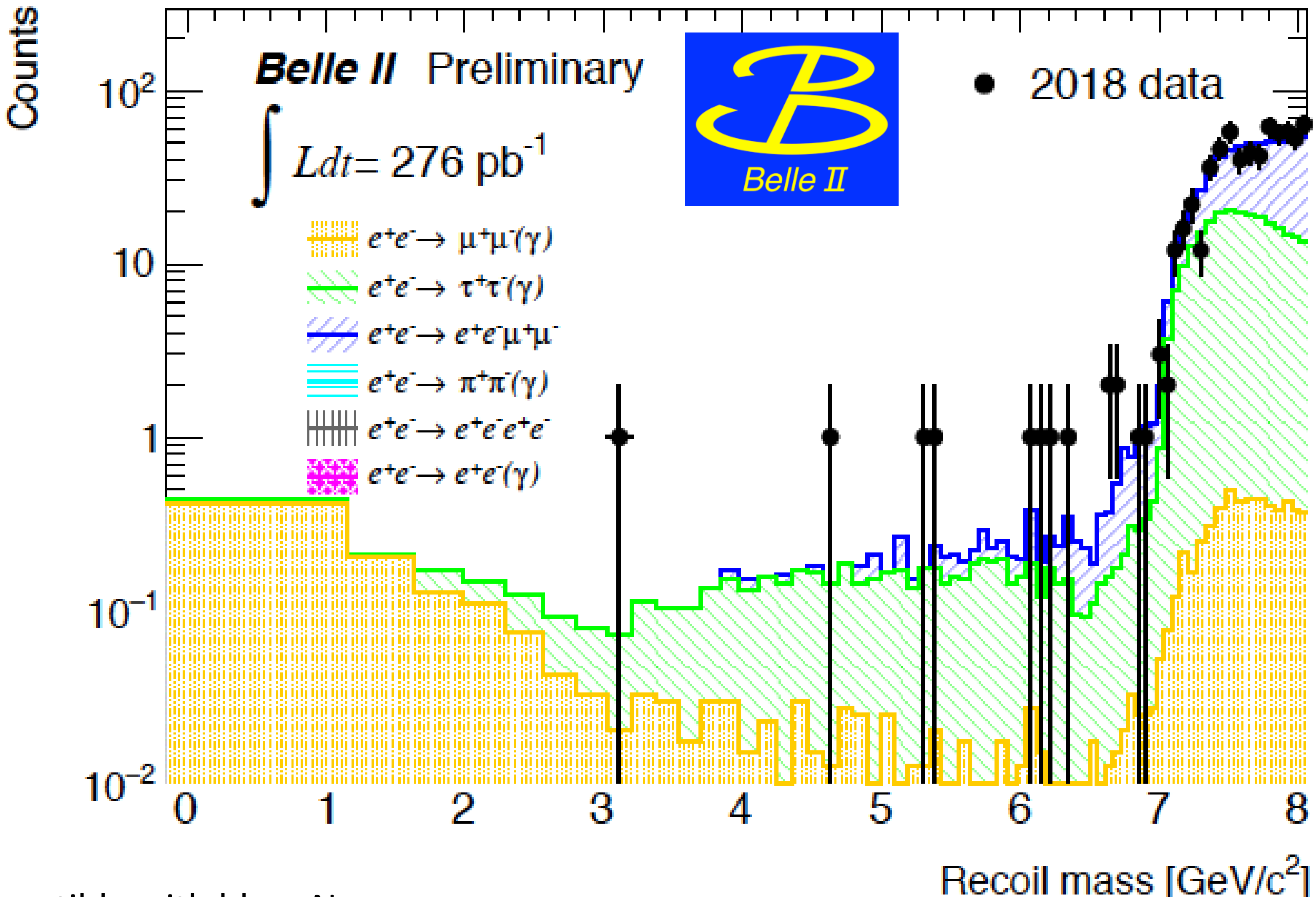
Also examine a lepton flavor violating NP signature in the dark sector





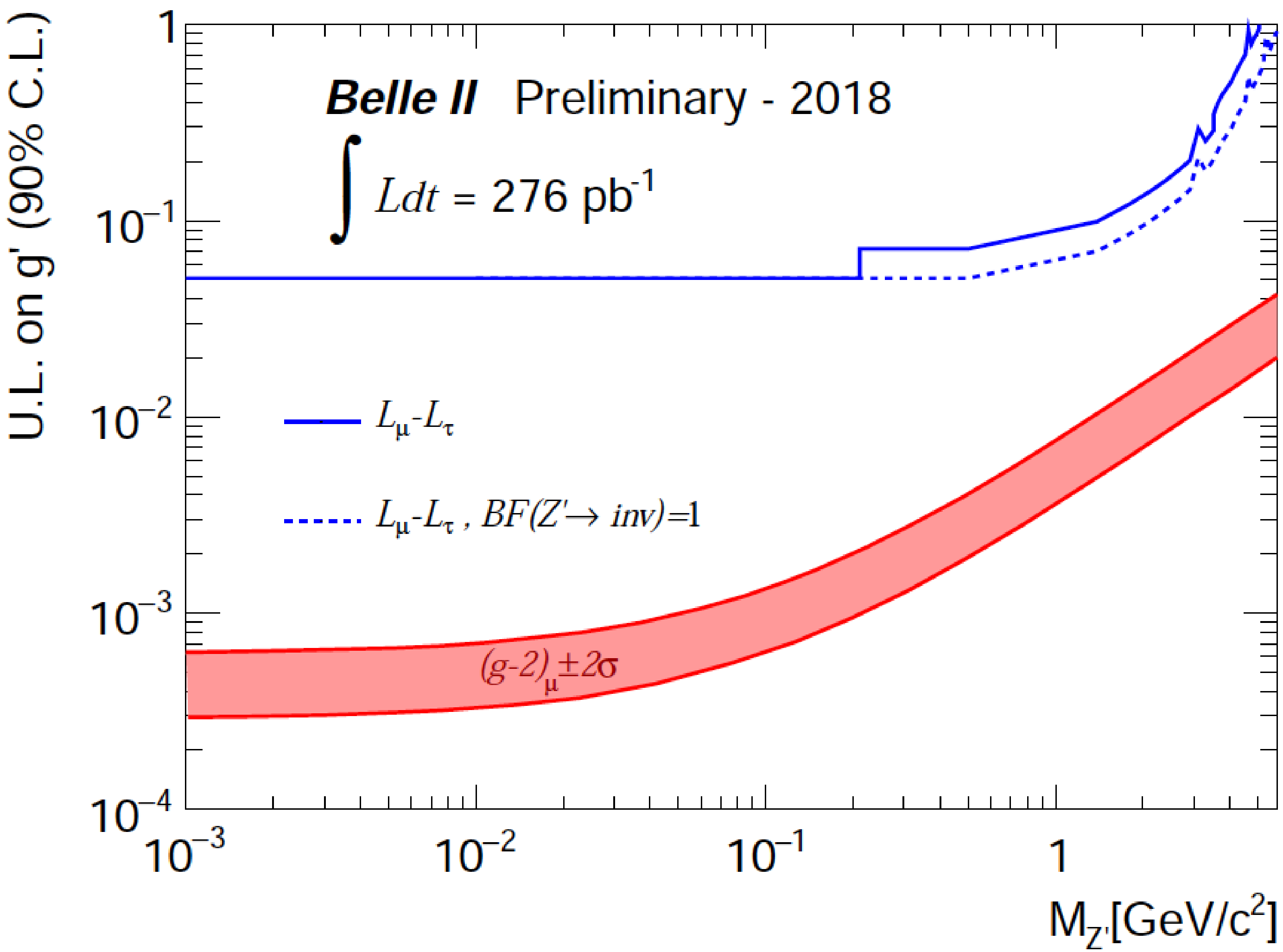
After tau suppression cuts and unblinding.

Search for $e^+e^- \rightarrow \mu^+\mu^- Z', Z' \rightarrow nothing$

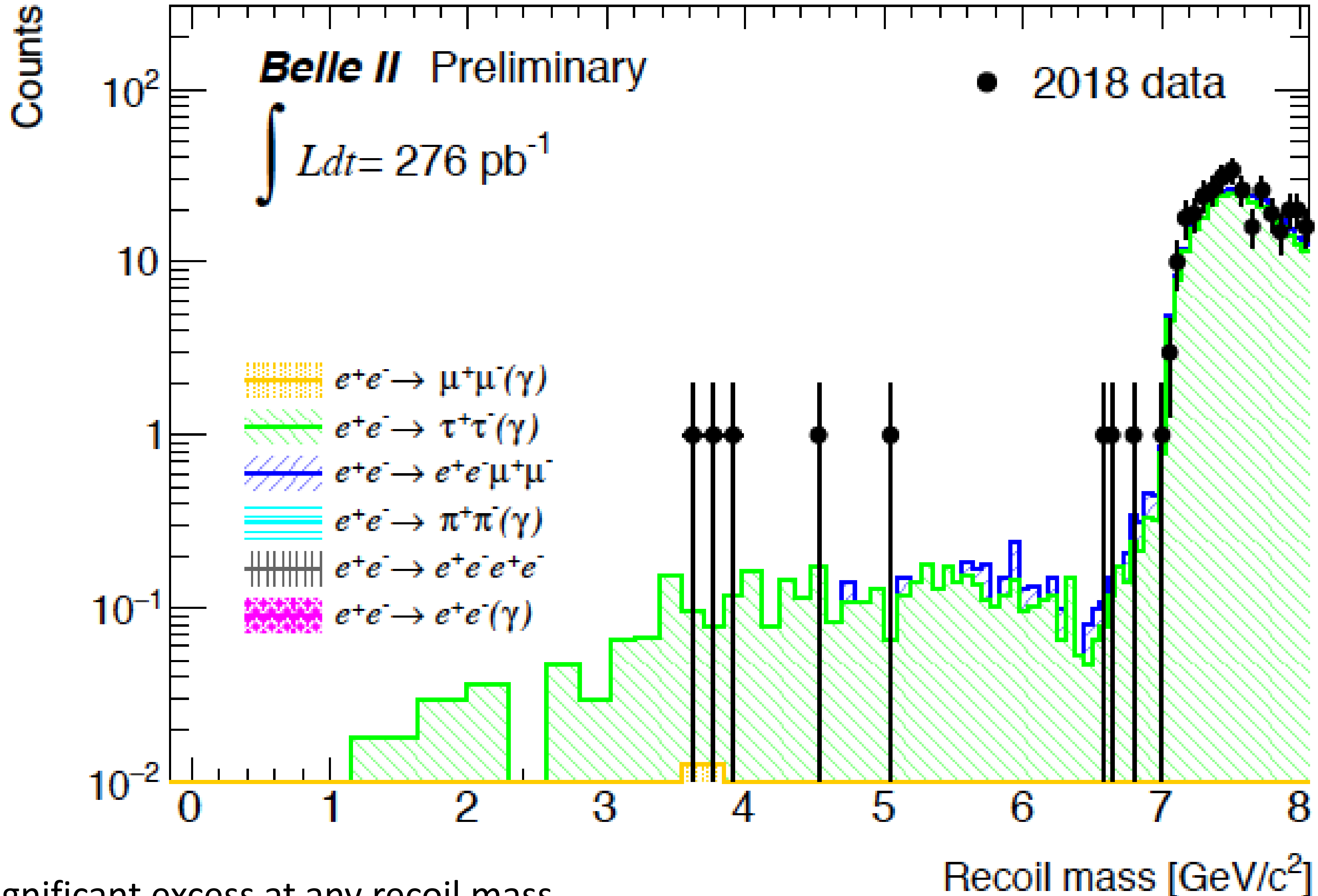


Compatible with bkgs, No excess above 3σ

Search for $e^+e^- \to \mu^+\mu^- Z', Z' \to nothing$

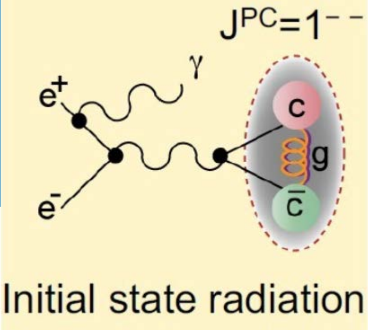


Search for $e^+e^- \to \mu^\pm e\ Z'_{LFV}, Z'_{LFV} \to nothing$



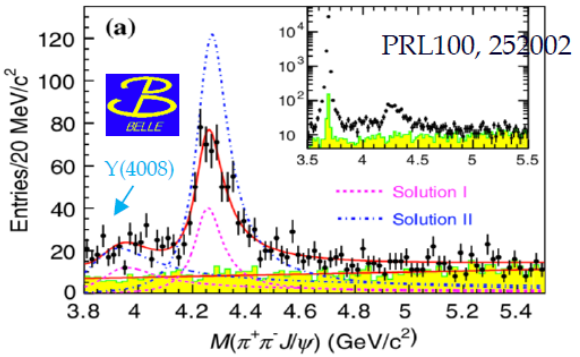
No significant excess at any recoil mass

Prospects on XYZ states @ Belle II

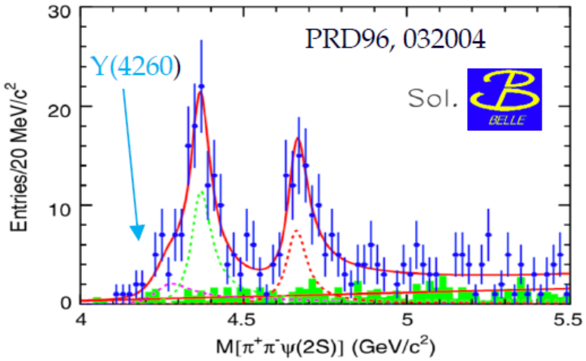


ISR

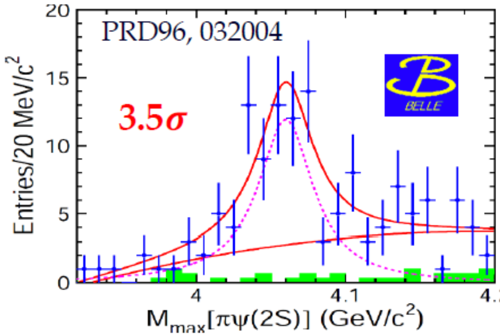
Q1: existence of the Y(4008)?



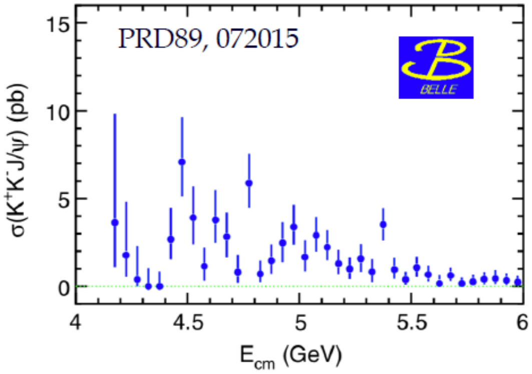
Q2: existence of the Y(4260)?



Q3: existence of the $Z_c(4050)$?

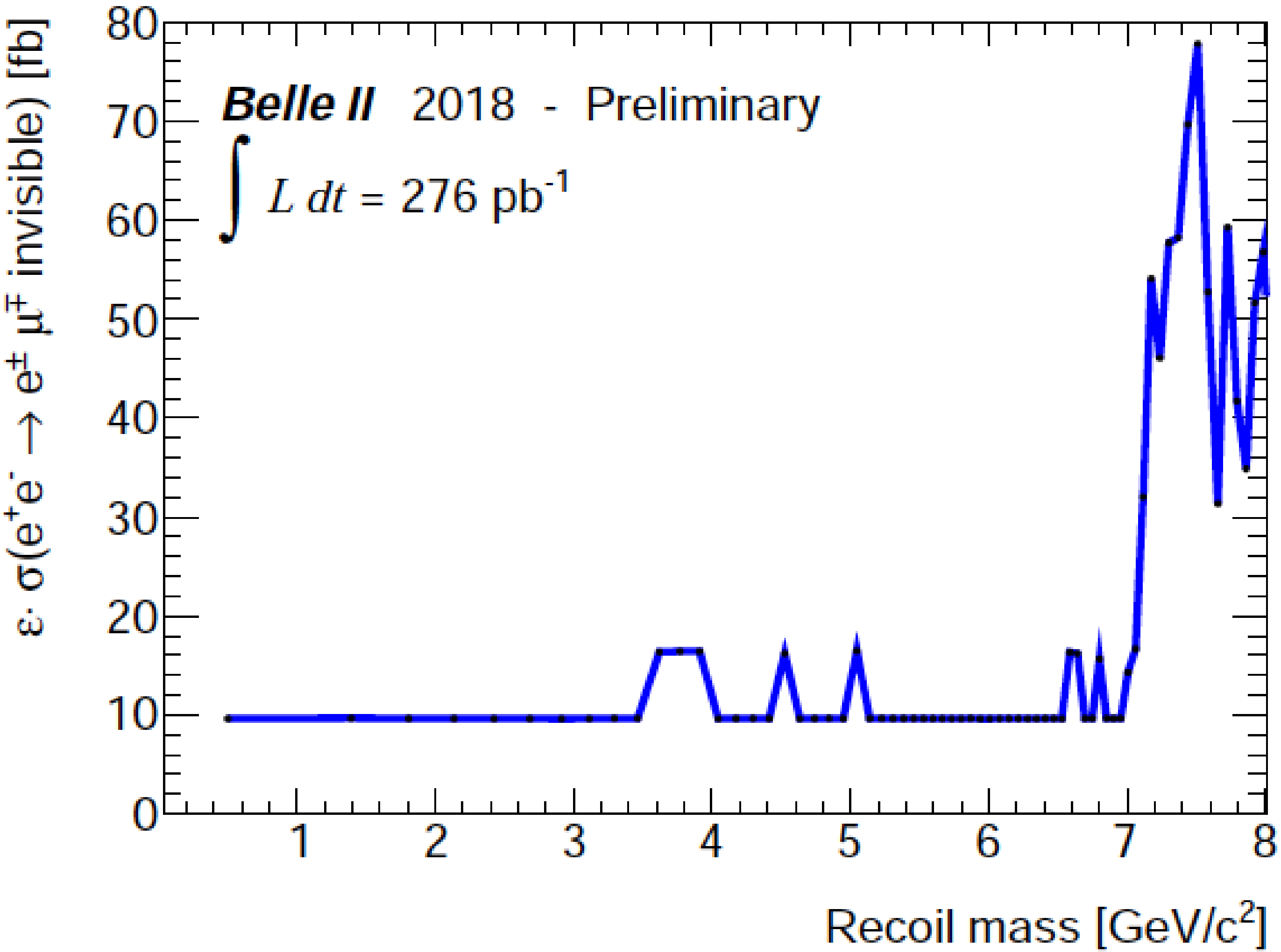


Q4: more structures in $M(K^+K^-J/\psi)$?



- Perform the analysis of $e^+e^- \to \pi^+\pi^- h_c$, $\omega\chi_{c0}$, and $(D^*\bar{D}^*)^{\pm}\pi^{\mp}$ to confirm the results with BESIII.
- Study the processes $e^+e^- \to \pi^+\pi^-\psi_2(1D)$, $K^+K^-\psi(2S)$, $\phi\chi_{cJ}$, $\eta J/\psi$, $\eta' J/\psi$, $\eta\psi(2S)$, $\omega\chi_{cJ}$, etc to search for more charmonium-like states and new decay modes.

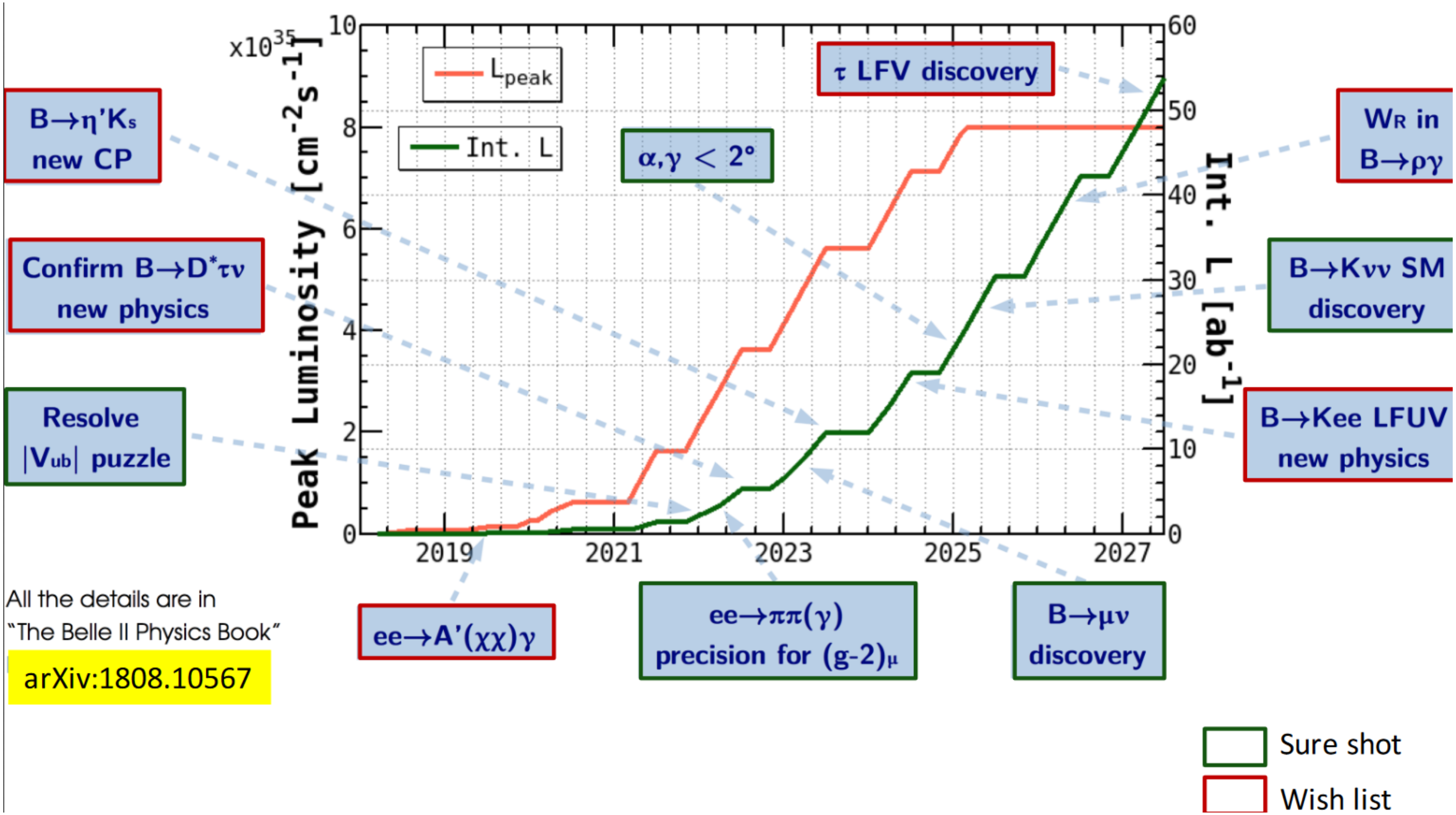
Search for $e^+e^- \to \mu^{\pm}e\ Z'_{LFV}, Z'_{LFV} \to nothing$



Some theory work on the MC needed to extract cross-section result

FIG. 75: 90% CL upper limits to $\epsilon \times \sigma[e^+e^- \to e^{\pm}\mu^{\mp}\text{invisible}]$.

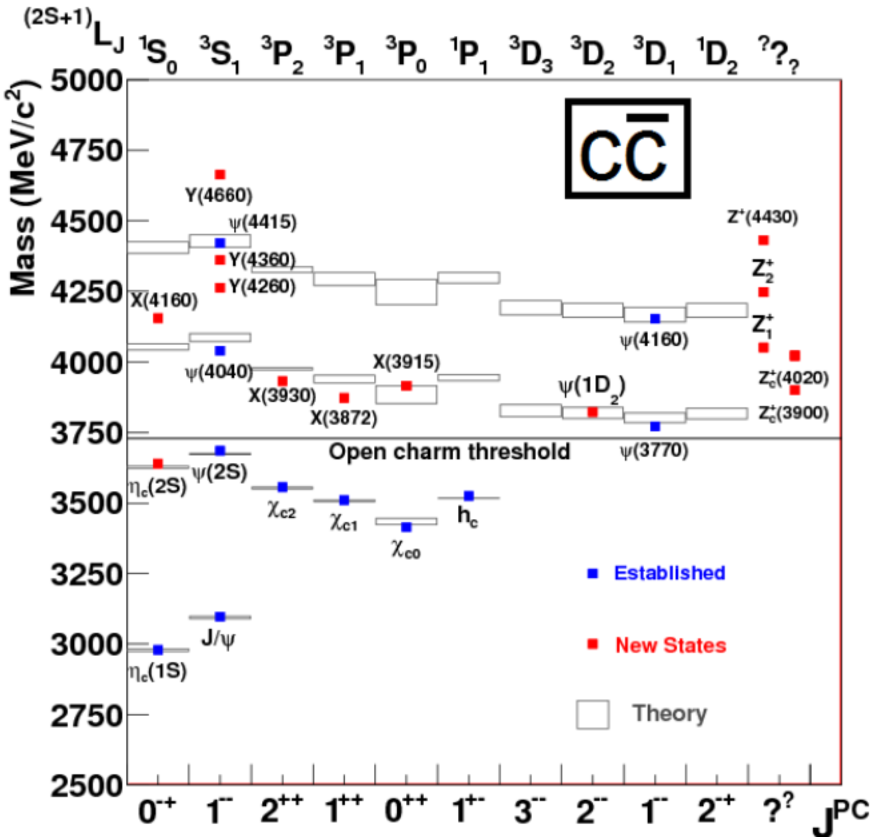
Back Up

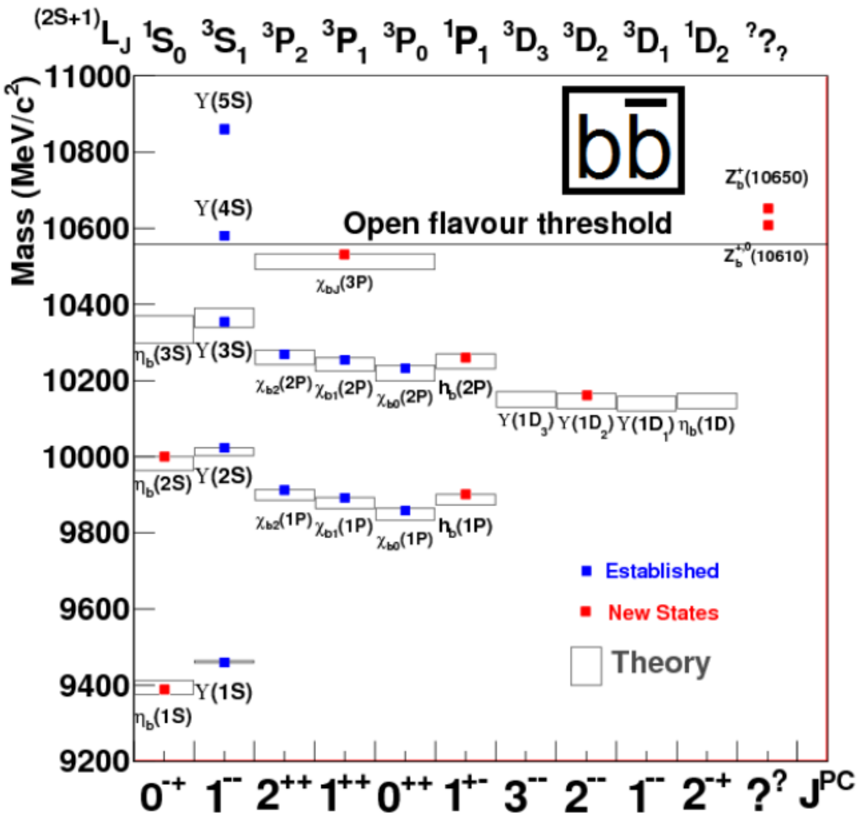


All the details are in
"The Belle II Physics Book"

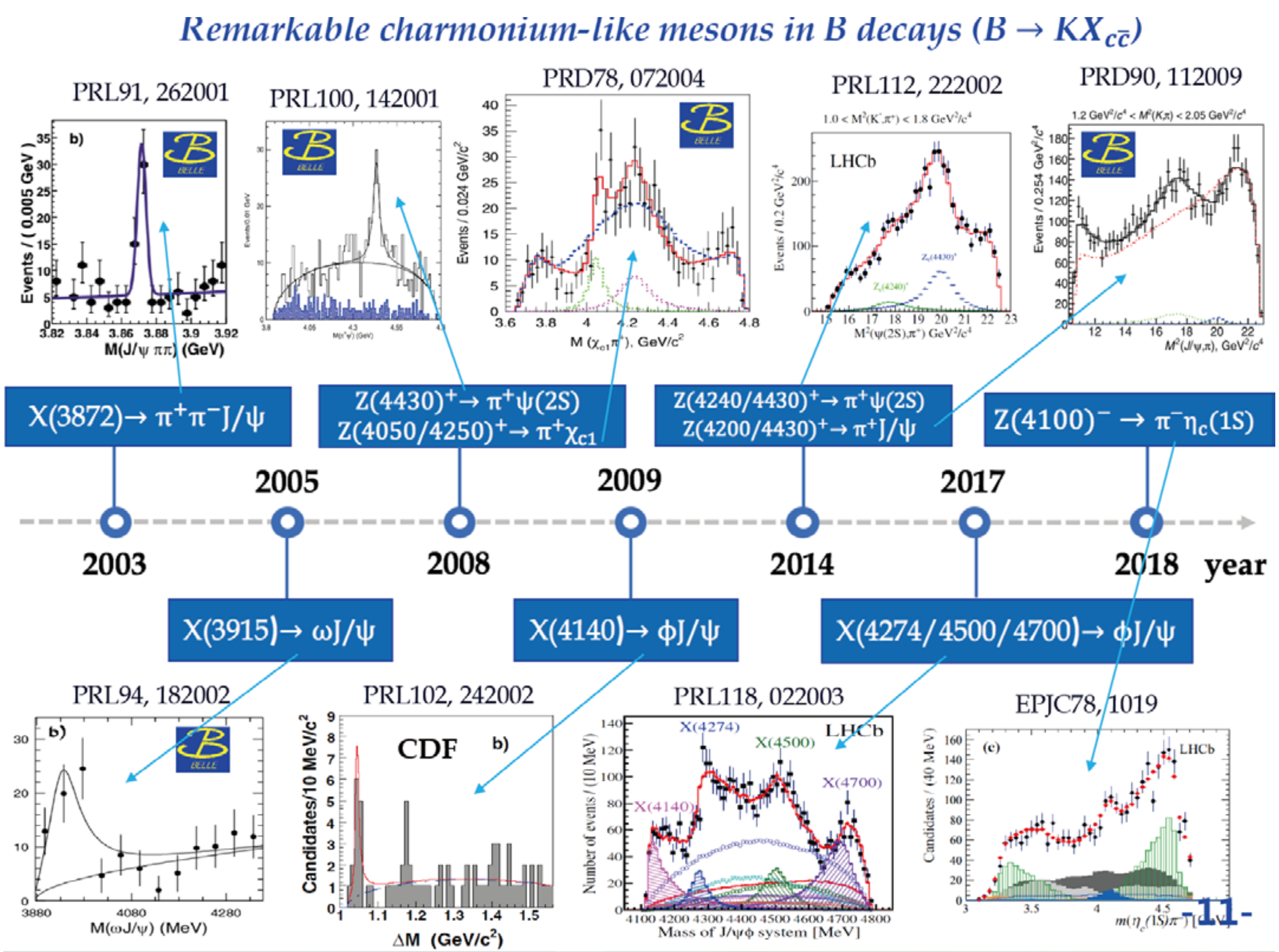
arXiv:1808.10567

Prospects on XYZ states @ Belle II

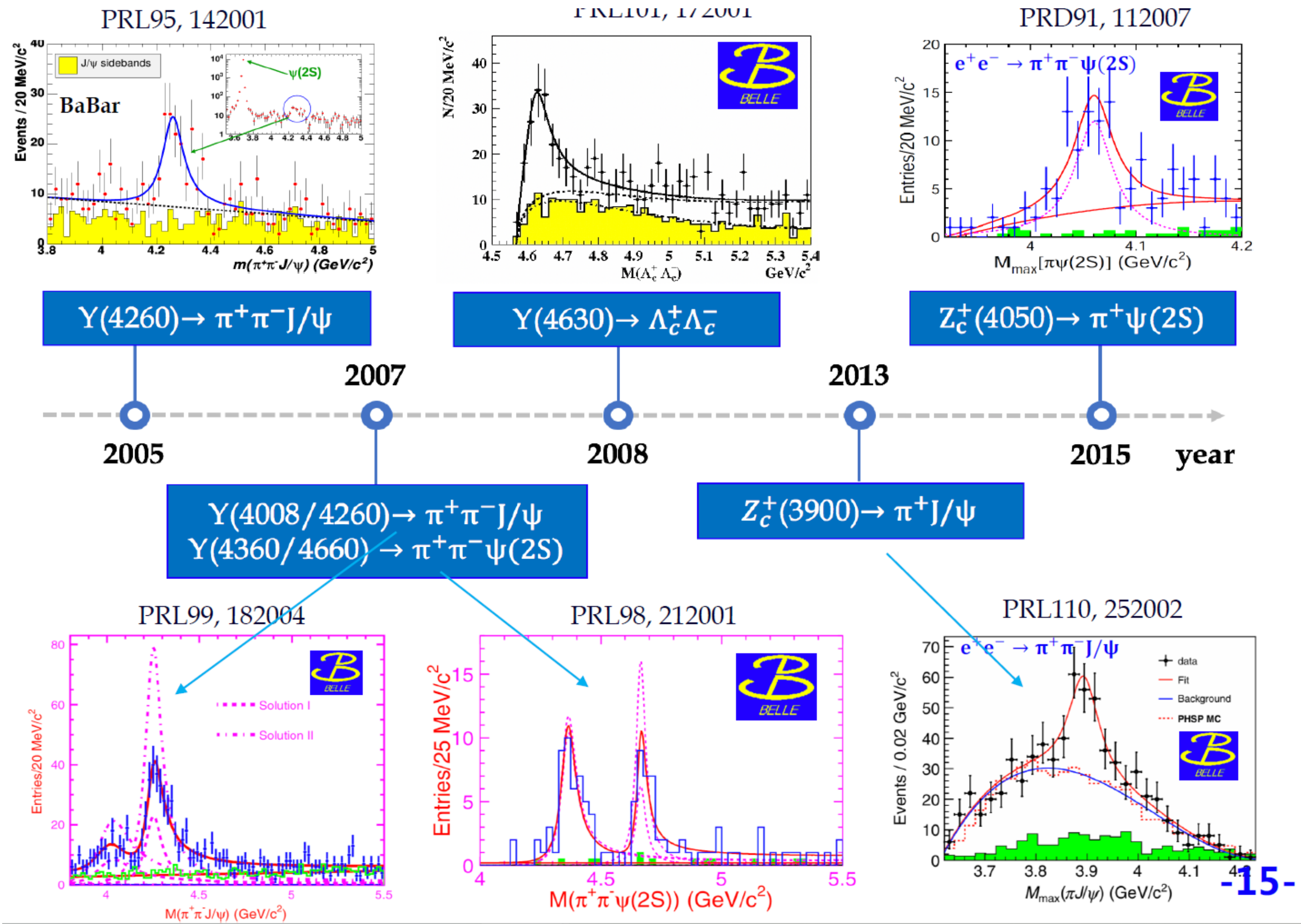




Back Up


Remarkable charmonium-like mesons in B decays (B → KX$_{c\bar{c}}$)
PRL91, 262001
PRL100, 142001
PRD78, 072004
PRL112, 222002
PRD90, 112009
X(3872)→ π⁺π⁻J/ψ
Z(4430)⁺→ π⁺ψ(2S)
Z(4050/4250)⁺→ π⁺χc1
Z(4240/4430)⁺→ π⁺ψ(2S)
Z(4200/4430)⁺→ π⁺J/ψ
Z(4100)⁻ → π⁻ηc(1S)
2003
2005
2008
2009
2014
2017
2018
year
X(3915)→ ωJ/ψ
X(4140)→ φJ/ψ
X(4274/4500/4700)→ φJ/ψ
PRL94, 182002
PRL102, 242002
PRL118, 022003
EPJC78, 1019
CDF
LHCb

Back Up



PRL95, 142001
BaBar
J/ψ sidebands
ψ(2S)
Events / 20 MeV/c²
m(π⁺π⁻J/ψ) (GeV/c²)
N/20 MeV/c²
M(Λc⁺Λc⁻) GeV/c²
PRD91, 112007
e⁺e⁻ → π⁺π⁻ψ(2S)
Entries/20 MeV/c²
Mmax[πψ(2S)] (GeV/c²)
Y(4260)→ π⁺π⁻J/ψ
Y(4630)→ Λc⁺Λc⁻
Zc⁺(4050)→ π⁺ψ(2S)
2005
2007
2008
2013
2015
year
Y(4008/4260)→ π⁺π⁻J/ψ
Y(4360/4660) → π⁺π⁻ψ(2S)
Zc⁺(3900)→ π⁺J/ψ
PRL99, 182004
Solution I
Solution II
Entries/20 MeV/c²
M(π⁺π⁻J/ψ) (GeV/c²)
PRL98, 212001
Entries/25 MeV/c²
M(π⁺π⁻ψ(2S)) (GeV/c²)
PRL110, 252002
e⁺e⁻ → π⁺π⁻J/ψ
data
Fit
Background
PHSP MC
Events / 0.02 GeV/c²
Mmax(πJ/ψ) (GeV/c²)
-15-

Back Up

Back Up