Hot Topics at Belle II
(HVP prospects and bottomonium)

B.Shwartz, on behalf of BELLE II collaboration

Budker Institute of Nuclear Physics
Novosibirsk State University
Novosibirsk, Russia

Belle II Detector

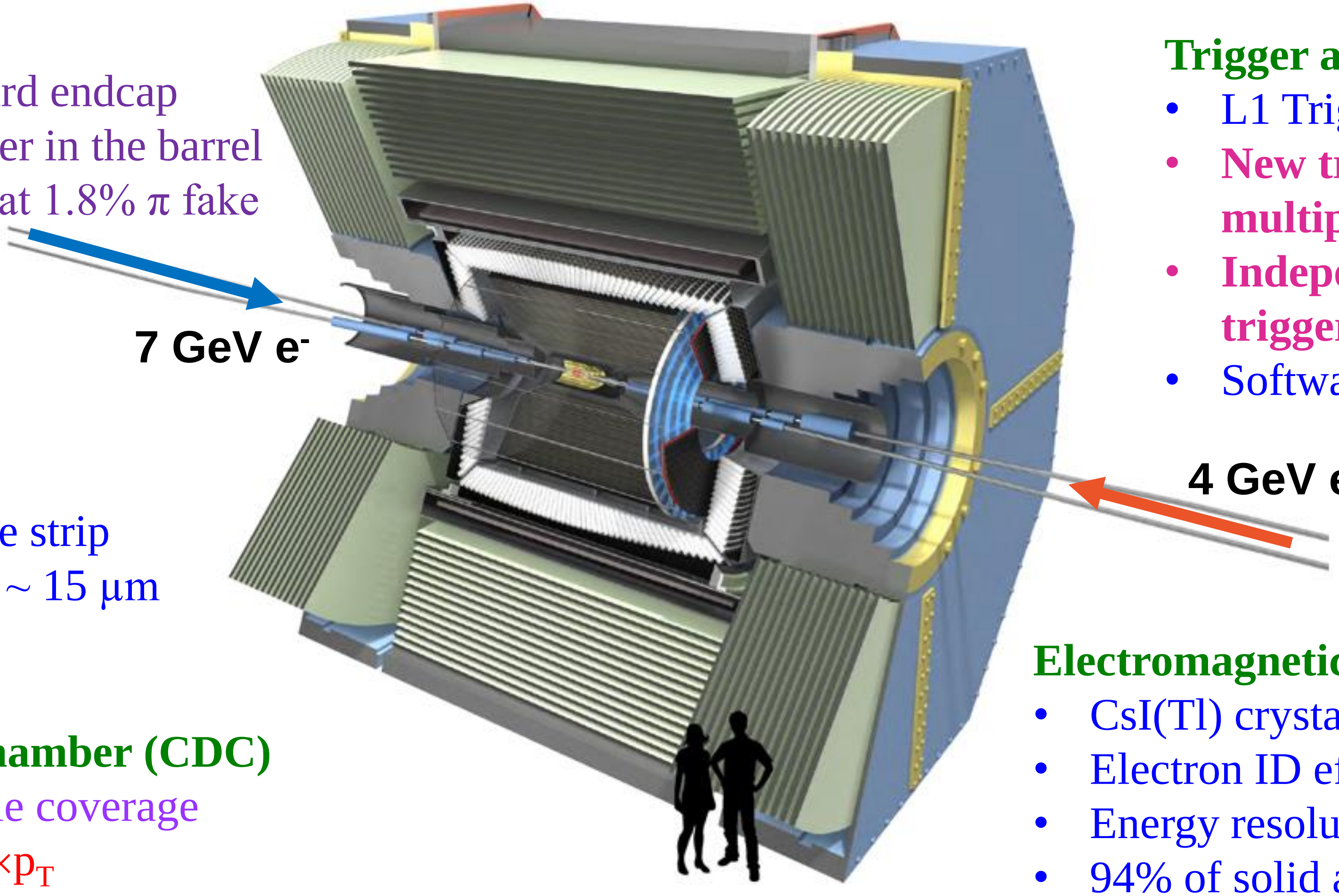
Near-hermetic multipurpose detector

At SuperKEKB collider

K-long and Muon Detector (KLM)
Alternating iron and detector plates
Scintillator / Resistive Plate Chamber
Muon ID efficiency 90% at 2% fake

Particle Identification
Aerogel RICH in the forward endcap
Time-of-Propagation counter in the barrel
K/π ID : K efficiency 90% at 1.8% π fake

Trigger and DAQ
- L1 Trigger rate 30 kHz (design)
- **New trigger line for low-multiplicity events**
- **Independent CDC and ECL trigger modes**
- Software based HLT



Vertex Detector (VXD)
Inner 2 layers : Pixel
Outer 4 layers : Double side strip
σ(Track impact parameter) ~ 15 μm

Electromagnetic Calorimeter (ECL)
- CsI(Tl) crystals + Waveform fit
- Electron ID eff. 90% at <0.1% fake
- Energy resolution 1.6-4%
- 94% of solid angle coverage

Central Drift Chamber (CDC)
91% of solid angle coverage
$\sigma(p_T)/p_T \sim 0.4\% \times p_T$
dE/dx resolution 5% (low-p PID)

Belle II physics program

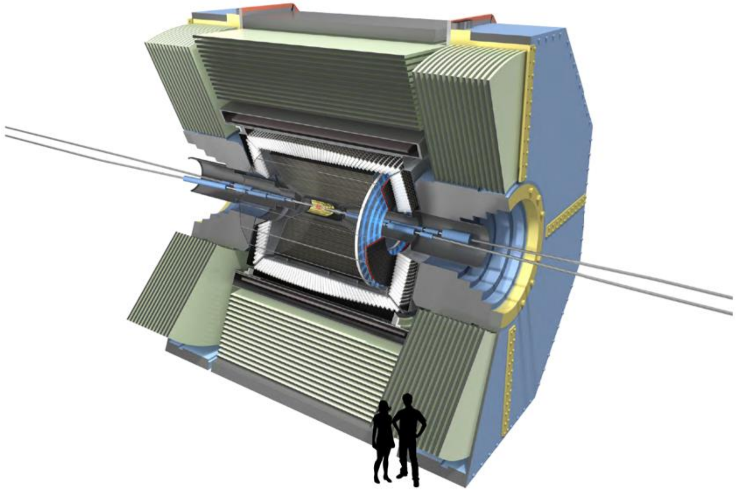
Snowmass White Paper arXiv:2207.06307v2 [hep-ex]

Collected data:

- ~ 362 fb^{-1} at Υ(4S)
- 42 fb-1 off-resonance, 60 MeV below Υ(4S).
- 19 fb-1 energy scan between 10.6 to 10.8 GeV for exotic hadron studies.

Precision CKM tests and searches for non-SM CP violation in B decays

Non-SM probes from semileptonic, radiative, and leptonic B decays



Precise particle metrology: Masses and lifetimes measurements

Charm physics

Direct searches for light non-SM physics and Dark Sector studies

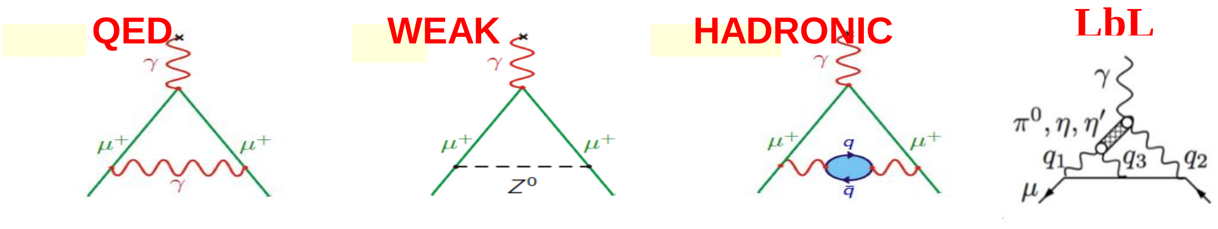
Tau lepton physics

Quarkonium, exotics, and hadron spectroscopy
High precision measurements of the hadronic cross section demanded by HVP in muon (g-2) and other precise QCD tests

Muon anomaly, $a_\mu=(g-2)_\mu/2$: SM calculations and experiment

$$a_\mu^{theory(SM)} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had}$$

Two approaches for estimating the HVP contribution:
Dispersion relations (w/ inputs from ee → hadrons data)
Lattice QCD

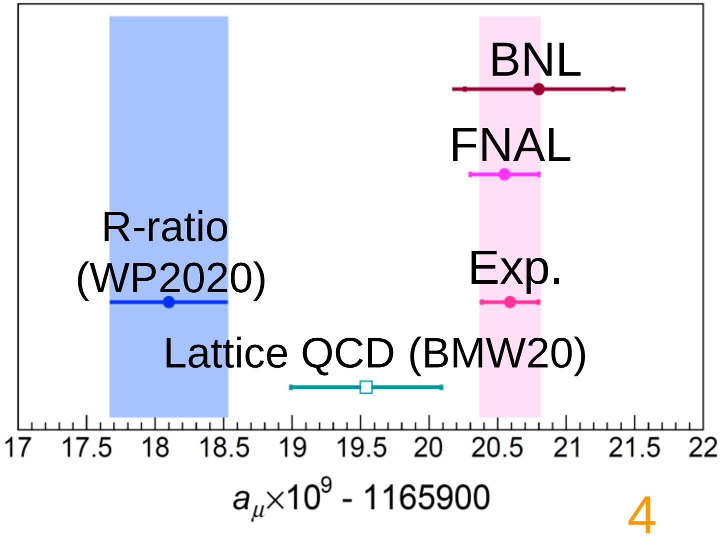


$$a_\mu^{had} = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty} ds\,\frac{K(s)}{s}R(s)$$

$$R(s) = \frac{\sigma(e^+e^- \to \gamma^* \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

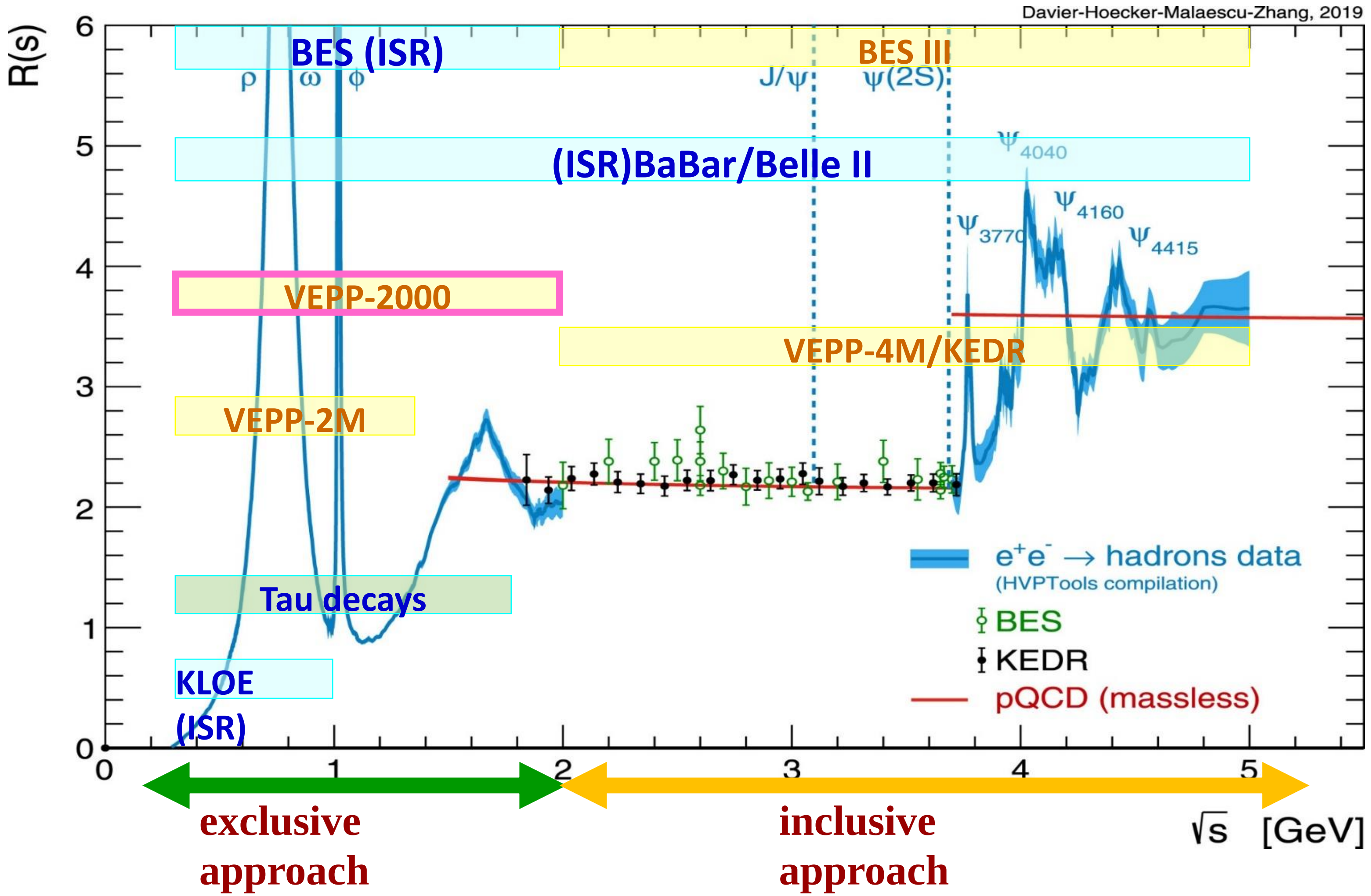
Contribution	Value $\times 10^{11}$
QED	116 584 718.931(104)
Electroweak	153.6(1.0)
HVP (e^+e^-, LO + NLO + NNLO)	6845(40)
HLbL (pheno + lattice + NLO)	92(18)
Total SM Value Section	116 591 810(43)
Exp. (E821) - SM	279(76)

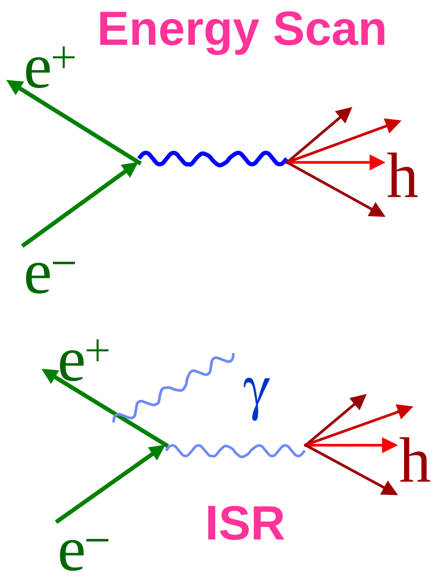
⇐ $\pi^+\pi^-$~ 73 %, $\pi^+\pi^-\pi^0$ ~7%

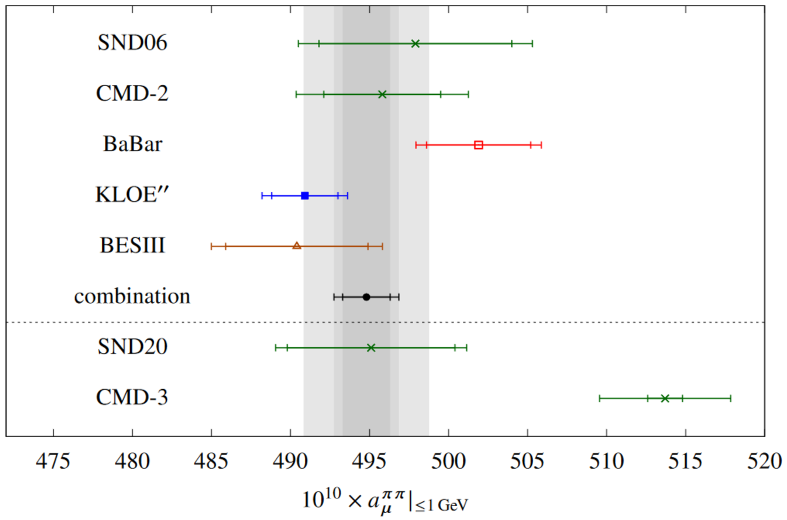


The table is from:
"The anomalous magnetic moment of the muon in the Standard Model",
T. Aoyama et al., Physics Reports 887 (2020) 1–166

R measurement – exclusive vs inclusive







The figure is from:

“The anomalous magnetic moment of the muon in the Standard Model”,
T. Aoyama et al., Physics Reports 887 (2020) 1–166.

$e^+e^- \to \pi^+\pi^-$ HVP contribution to muon g-2

arXiv:2308.04217

HVP measurements at Belle II

In comparison to Belle:

- New low-multiplicity trigger effectively distinguish ISR events from e^+e^- and $\gamma\gamma$ subjected to prescaling.
- Two independent triggers based on the Tracker and Calorimeter which provide efficiency estimation from the data
- Almost 100% efficiency for energetic ISR

Two channels are under study now.
$e^+e^- \to \pi^+\pi^-$
Target 0.5% precision using 363 fb^{-1}data
Try to following BaBar methods as a base line

$e^+e^- \to \pi^+\pi^-\pi^0$
Mass range : 0.6-3.5 GeV,
Target precision : $\delta a_\mu(3\pi) \sim 2\%$
Present status is reported in this talk.
No results on the cross section yet, the study is under internal review, results are expected in a few months

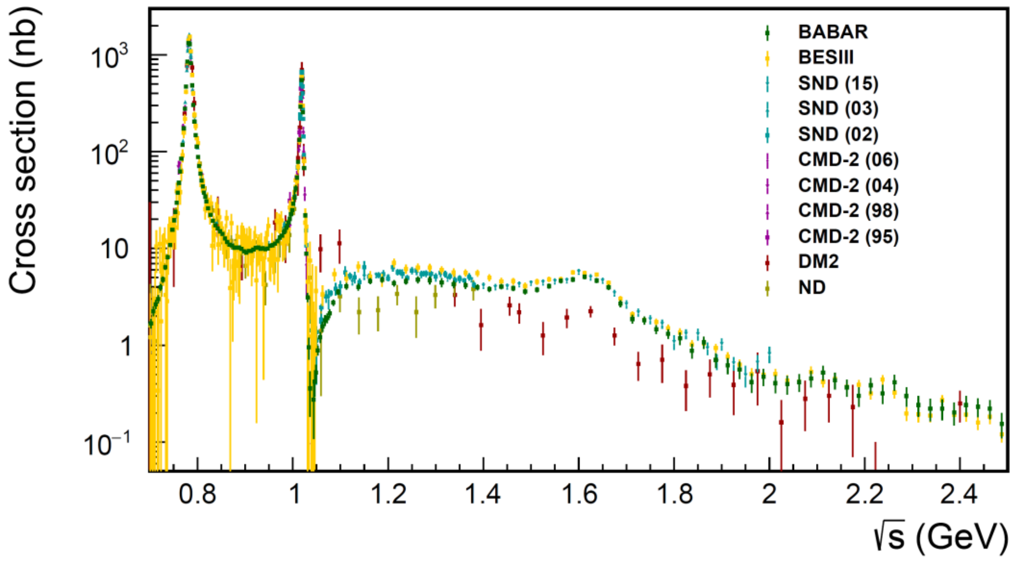
Previous measurements of $e^+e^- \to \pi^+\pi^-\pi^0$

Recent measurements:

- Preliminary result from BES III [arXiv:1912.11208]
- BABAR has updated its results with full data [Phys. Rev. D 104, 112003 (2021)]

As for the $e^+e^- \to \pi^+\pi^-\pi^0$ contribution $a_\mu(3\pi)$, the uncertainty of $a_\mu(3\pi)$ is 2-3% for combination and 1.3% for BABAR alone.

- The difference in the cross section between the experiments below 1.1 GeV produces the error.



$e^+e^- \to \pi^+\pi^-\pi^0$ analysis

Dataset : 2019-2021 Summer 190 fb^{-1}

- **Blind analysis**
  - Study of analysis methods using MC and validation using 10% data.
  - Final confirmation under way using full data set.
- **Key items**
  - Trigger
  - Background reduction and estimation
  - Efficiency corrections
  - Unfolding

A) Background not containing real π^0 : $e^+e^- \to e^+e^-\gamma, \pi^+\pi^-\gamma, \mu^+\mu^-\gamma$
   Pion/Electron ID : $L(\pi/e) > 0.1$, $M^2_{recoil}(\pi^+\pi^-) > 4\ GeV^2/c^4$

B) Charged kaon : $e^+e^- \to K^+K^-\pi^0\gamma$
   Pion/Kaon ID : $L(\pi/K) > 0.1$

C) $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\gamma$
   Reconstruct $\pi^+\pi^-\pi^0\pi^0\gamma$ (with additional π^0)
   4C kinematic fit under $\pi^+\pi^-\pi^0\pi^0\gamma$ hypothesis, and $\chi^2_{4C}(4\pi\gamma) > 30$

Event selection

Two tracks + three photons : $e^+e^- \to \pi^+\pi^-\pi^0\gamma_{ISR} \to \pi^+\pi^-\gamma\gamma\gamma_{ISR}$

Tracks : $dr < 0.5$ cm and $|dz| < 2$ cm and $p_T > 0.2$ GeV/c

Photons : $E > 100$ MeV + at least one photon must be energetic ISR ($E^{CMS} > 2$ GeV in barrel ECL)

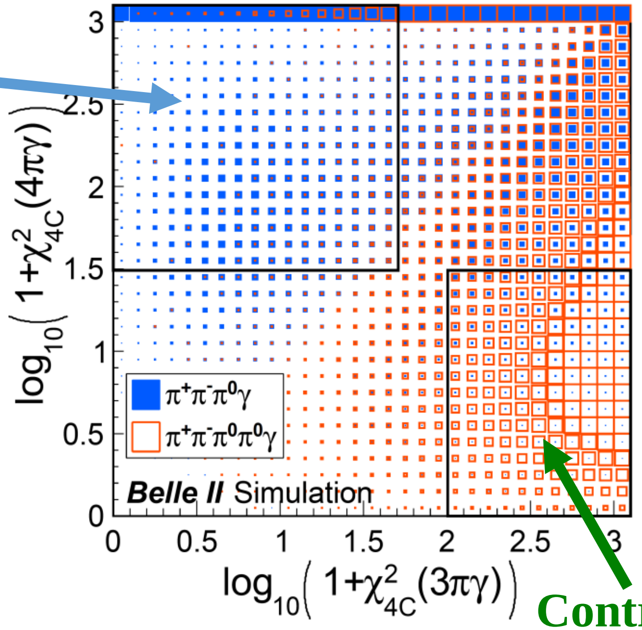
π^0 reconstruction

Invariant mass of two photons within 0.123-0.147 GeV/c^2

Select events using four-momentum kinematic fit (4C-Kfit) χ^2

$\chi^2_{4C}(3\pi\gamma) < 50$ is used for the cross section measurement

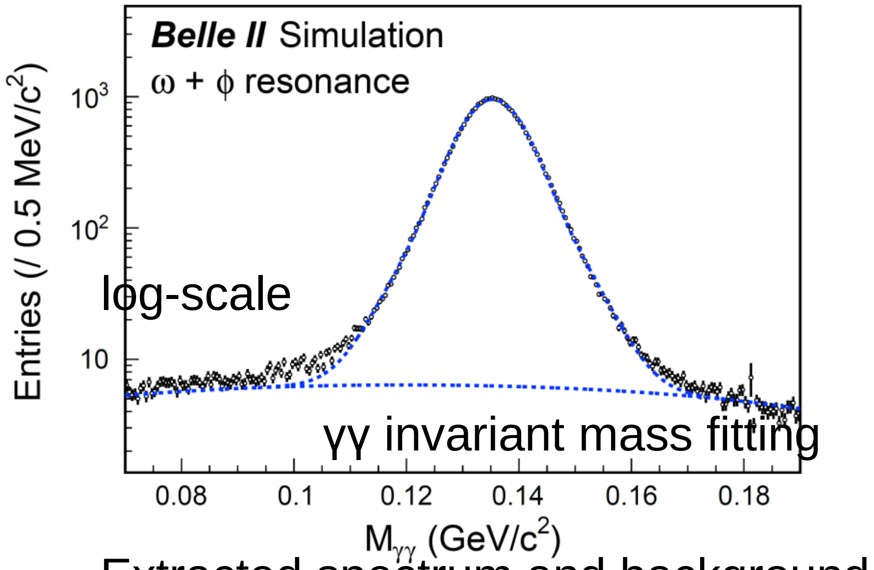
Signal region



Control region

Signal extraction after event selection

- The signal is estimated by fitting M(γγ) in each M(3π) bin, to remove the combinatorial background in γγ
  - Fit and integral over 0.123-0.147 GeV/c^2
- Estimated background is subtracted from the spectrum.



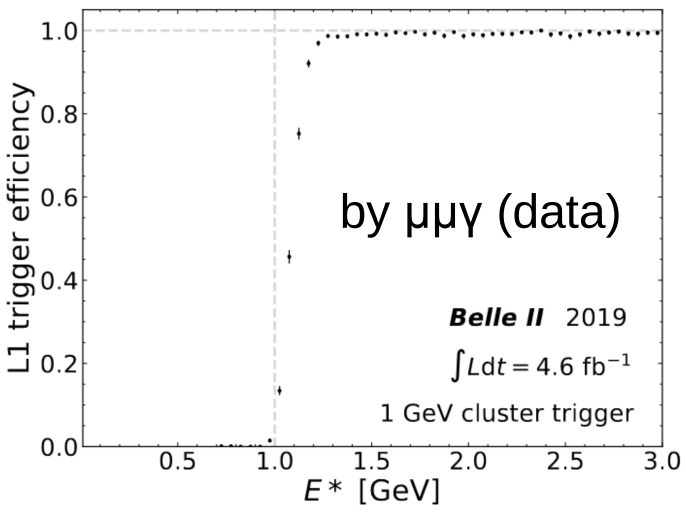
Extracted spectrum and background

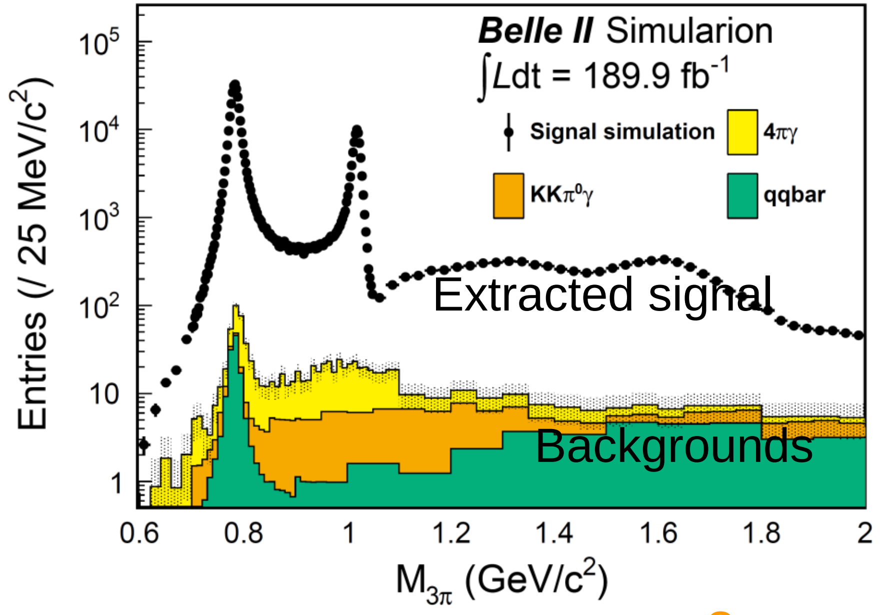
First, detection efficiency is estimated using MC of the x20 larger statistics.
Possible differences between data and MC are checked by data.

Main items important in this analysis:

- Trigger efficiency
- High energy photon detection efficiency
- Tracking efficiency
- π^0 efficiency
- χ^2 selection
- Background reduction cut efficiency

Unfolding





Systematic uncertainty and prospects

- Major systematic uncertainty comes from π^0 and tracking efficiencies.
  - In $M(3\pi) > 1.05$ GeV, the uncertainty of selection efficiency is dominant.
- For $a_\mu(3\pi)$, the total uncertainty is expected to be 2% including stat. uncertainty of 0.5%.
- **The results will be released within a few months.**

Systematic uncertainties for $e^+e^- \to \pi^+\pi^-\pi^0$ cross section (Preliminary)

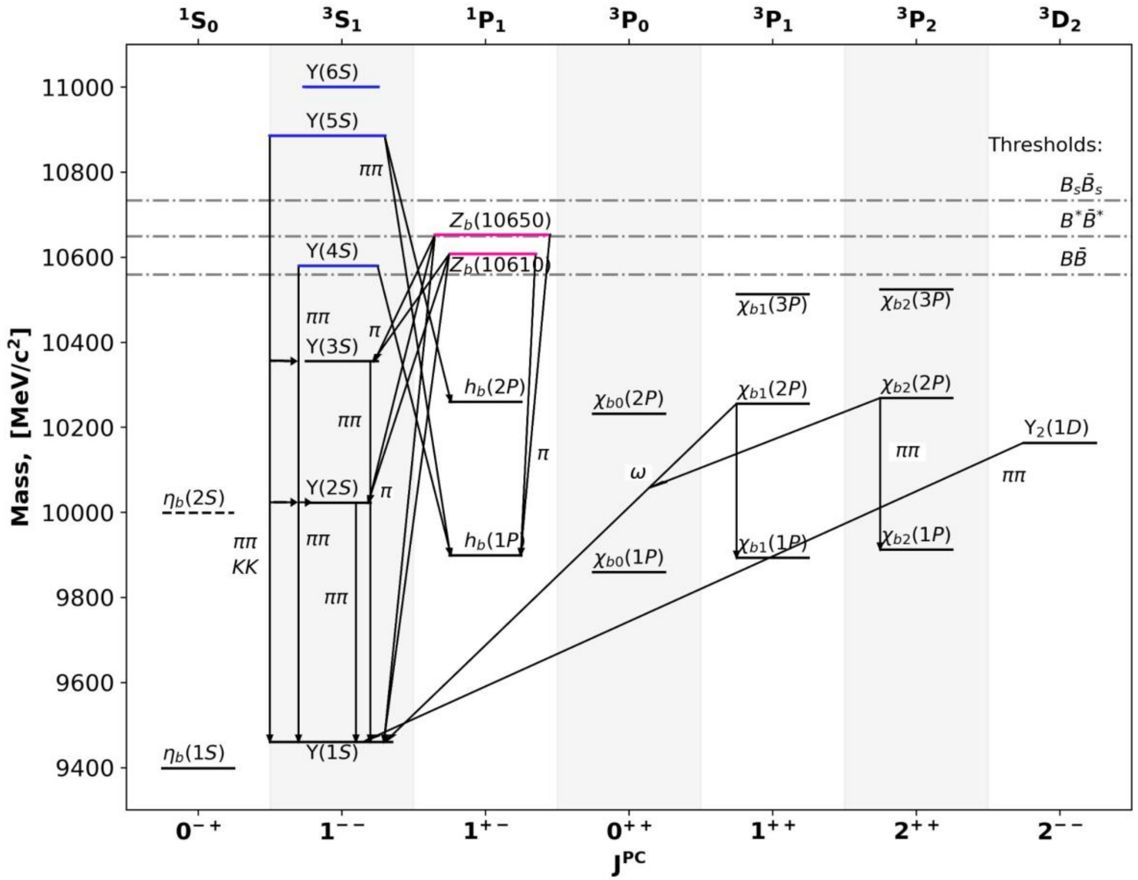
Source	Systematic uncertainty (%)	
	M < 1.05 GeV/c^2	M > 1.05 GeV/c^2
Trigger	0.2	0.2
ISR photon detection	0.7	0.7
Tracking	0.8	0.8
π^0 reconstruction	1.0	1.0
χ^2 distribution	0.3	0.3
Selection	0.2	**1.9***
Integrated luminosity	0.7	0.7
Radiative correction	0.5	0.5
Total systematics	1.8	2.6

* Statistical error dominant

Bottomonium

Below BB threshold states are well described by the potential models.
Above BB threshold states exhibit unexpected properties:

- The transitions to lower bottomonium with the emission of light hadrons are not suppressed (violate OZI);
- The η transitions are not suppressed compare to $\pi^+\pi^-$transitions (violate HQSS);
- Two charged Z_b^+ states are observed.



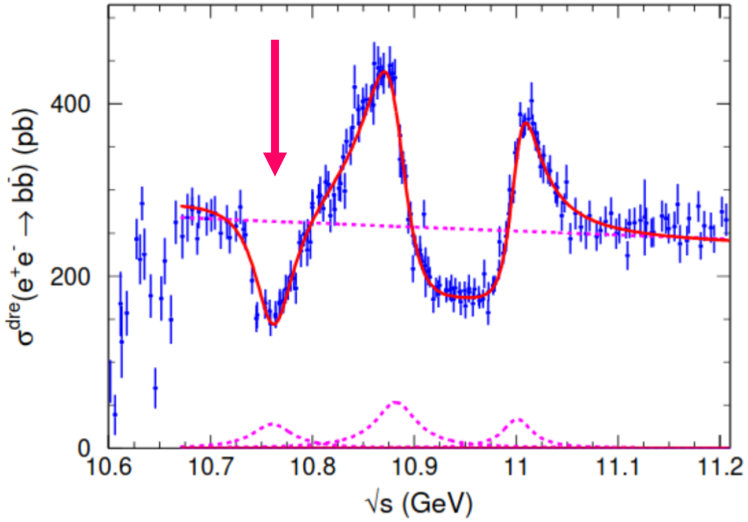
Exotic admixtures: molecule, compact tetraquark, hybrid?.

Z_b^+ **(10610)** and Z_b^+**(10650)**: observed near the $B^*\bar{B}$ thresholds, properties are consistent with $B^*\bar{B}$ molecules.

Discovery of Υ(10753)

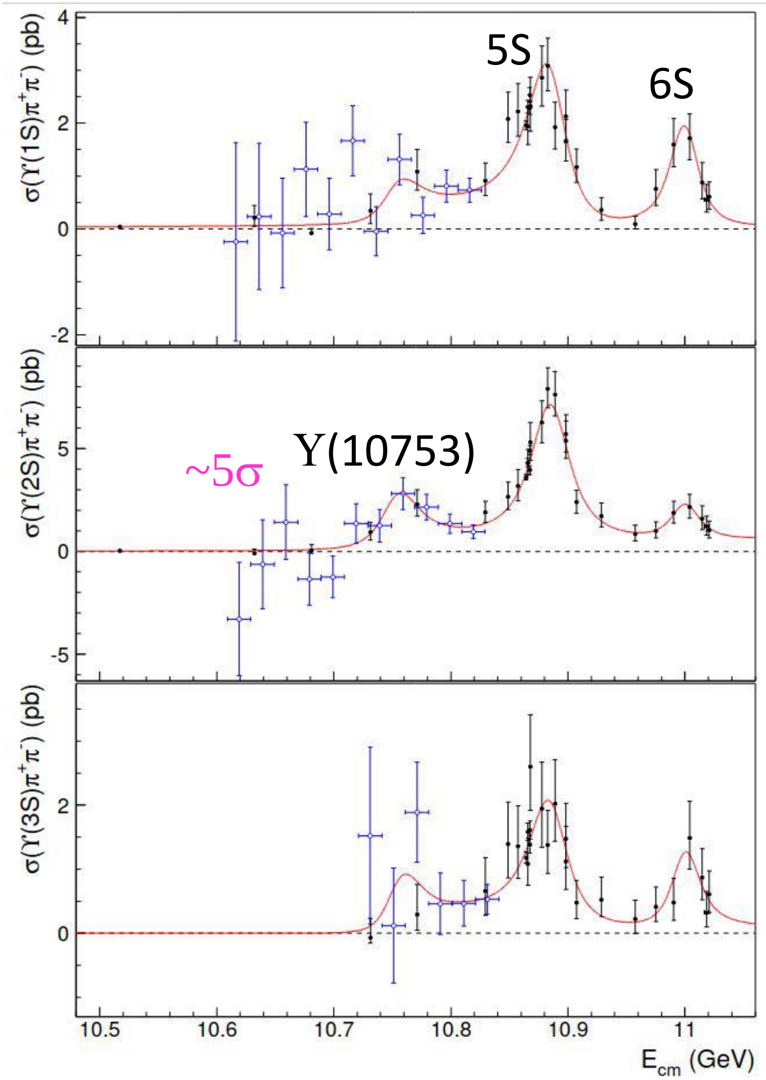
The Υ(10753) was observed in the energy dependence of $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$(n=1,2,3) cross sections by Belle.
Υ(10753) → $\pi^+\pi^-\Upsilon(1S)$, $\pi^+\pi^-\Upsilon(2S)$, $\pi^+\pi^-\Upsilon(3S)$
[JHEP 10,220(2019)]

	Υ(10860)	Υ(11020)	New structure
M (MeV/c²)	$10885.3 \pm 1.5 ^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}{}^{+1.0}_{-1.3}$	$10752.7 \pm 5.9 ^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5}_{-3.9}{}^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}{}^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}{}^{+3.9}_{-3.3}$



[CPC 44 (2020) 8, 083001]:

Interpretation: Υ(3D) or Υ(4D) state with S-D mixing enhanced due to hadron loops or exotic state.

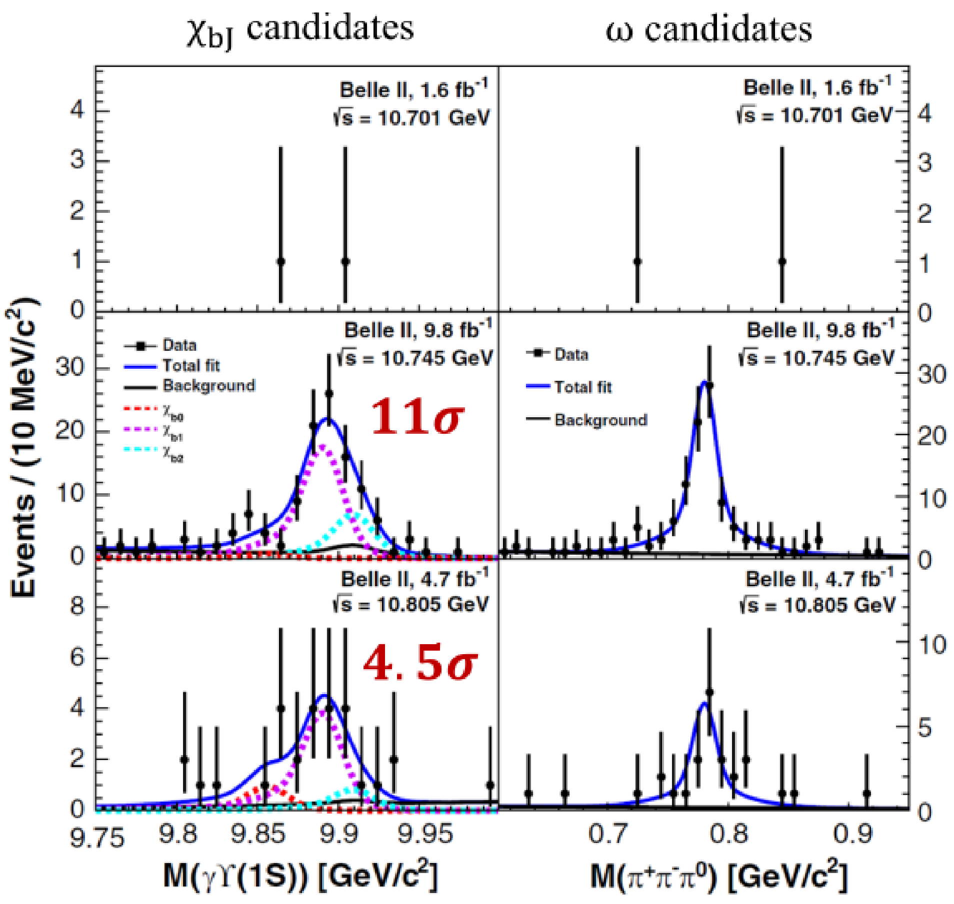


In November 2021, Belle II collected 19 fb^{-1} of scan data at four energy points: 10.653 (3.5 fb^{-1}), 10.704 (1.6 fb^{-1}), 10.745 (9.8 fb^{-1}), 10.805 (4.7 fb^{-1})

Observation of $\Upsilon(10753) \to \omega\chi_{bJ}(1P)$

Interpretations as an admixture of conventional 4S and 3D states predict comparable branching fractions of 10^{-3} for $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS)$ and $\Upsilon(10753) \to \omega\chi_{bJ}(1P)$. [PRD104, 034036 (2021), PRD 105, 074007 (2022)]

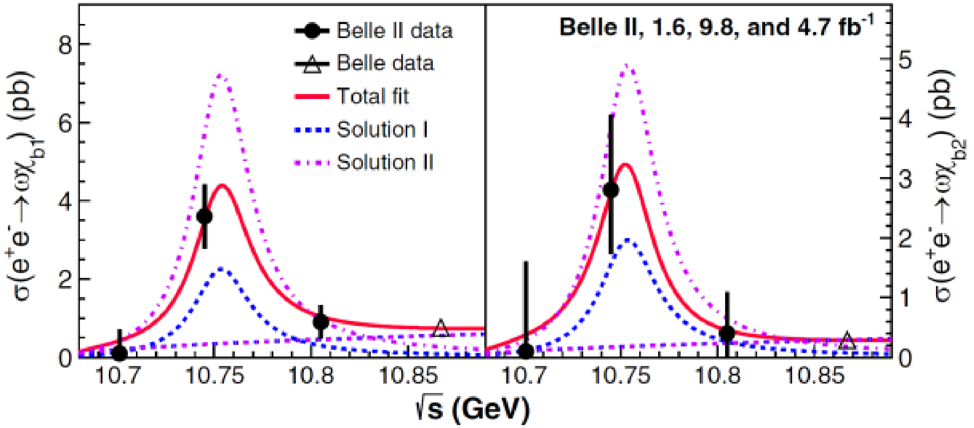
Channel	$\sqrt{s}$ (GeV)	$N^{\rm sig}$	$\Sigma(\sigma)$	σ_B (pb)
$e^+e^- \to \omega\chi_{b0}$	10.701	< 3.0	-	< 16.6
$e^+e^- \to \omega\chi_{b1}$		< 3.9	-	< 1.2
$e^+e^- \to \omega\chi_{b2}$		< 4.0	-	< 2.5
$e^+e^- \to \omega\chi_{b0}$	10.745	< 12.0	0.5	< 11.3
$e^+e^- \to \omega\chi_{b1}$		$68.9^{+13.7}_{-13.5}$	5.9	$3.6^{+0.7}_{-0.7} \pm 0.5$
$e^+e^- \to \omega\chi_{b2}$		$27.6^{+11.6}_{-10.0}$	3.1	$2.8^{+1.2}_{-1.0} \pm 0.4$
$e^+e^- \to \omega\chi_{b0}$	10.805	< 9.9	1.2	< 11.4
$e^+e^- \to \omega\chi_{b1}$		$15.0^{+6.8}_{-6.2}$	2.7	< 1.7
$e^+e^- \to \omega\chi_{b2}$		$3.3^{+5.3}_{-3.8}$	0.8	< 1.6



$$\frac{\sigma(e^+e^- \to \omega\chi_{bJ}(1P))}{\sigma(e^+e^- \to \pi^+\pi^-\Upsilon(nS))} \sim$$

~ 1.5 at $\sqrt{s} = 10.745$ GeV

~ 0.15 at $\sqrt{s} = 10.867$ GeV



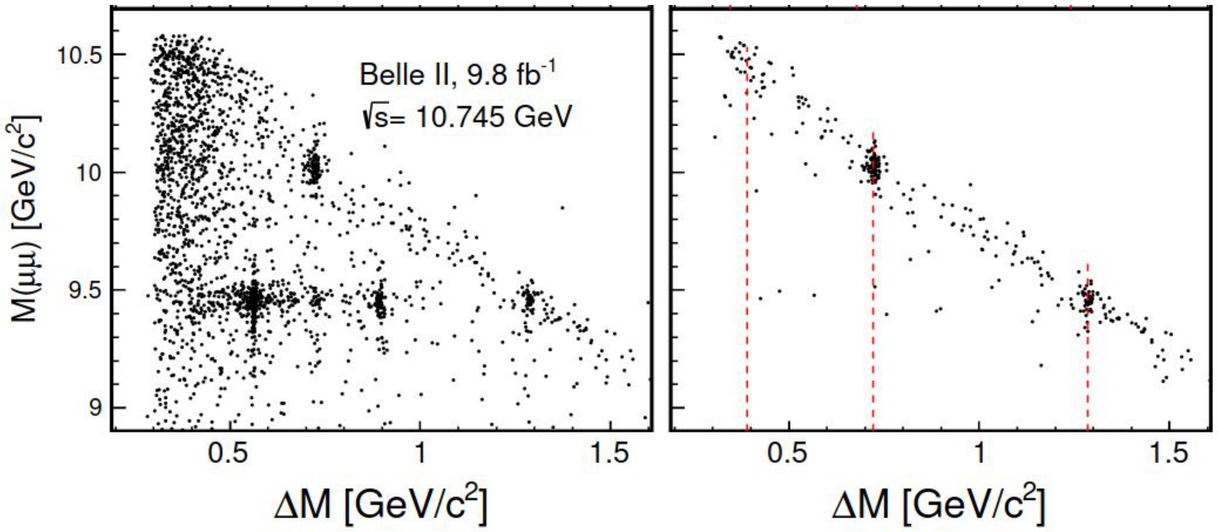
Diffrence in this ratio for Υ(5S) and Υ(10.745) can be an evidence of the different nature of resonanses

Di-pion transition of $\Upsilon(10753)$: Study of $e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$ (n = 1, 2, 3)

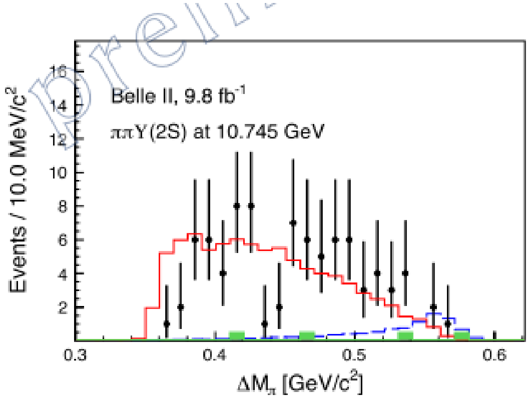
The full reconstruction is used:
$e^+e^- \to [\Upsilon(nS) \to \mu^+\mu^-]\,\pi^+\pi^-$.
N(Tracks) = 4 or 5, At least 2 tracks with P>2.5 GeV/c
Lepton and pion PID

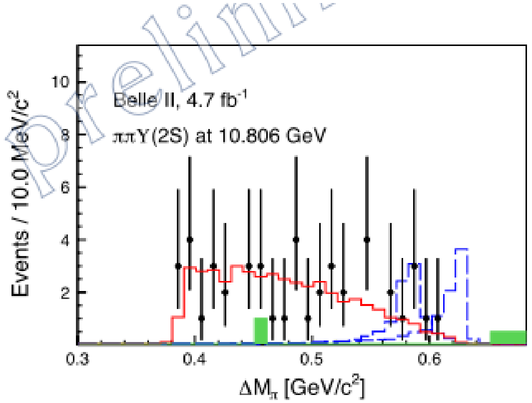
Plot $\Delta M = [M(\pi^+\pi^-\mu^+\mu^-) - M(\mu^+\mu^-)]$ vs. $M(\mu^+\mu^-)$:
clear signals of $\Upsilon(1S)\,\pi^+\pi^-$ and $\Upsilon(2S)\,\pi^+\pi^-$,
No signal of $\Upsilon(3S)\,\pi^+\pi^-$.

$p^*(\pi^+\pi^-\mu^+\mu^-) < 0.1$ **GeV**



Signal region defined: $\Delta M \in [\Delta m_0 - 30, \Delta m_0 + 21]$ MeV/c^2; $\Delta m_0 = s - m(\Upsilon(nS))$, unbinned fit in the signal regions.





No Evidence of $Z_b(10610/10650)$
Upper limits at 90% C.L. using Bayesian method.

	10.745 GeV		10. 805GeV	
Mode	$\pi\Upsilon(1S)$	$\pi\Upsilon(2S)$	$\pi\Upsilon(1S)$	$\pi\Upsilon(2S)$
$\sigma^B_{UL}(Z_{b1})$(pb)	<0.13	<0.14	<0.43	<0.35
$\sigma^B_{UL}(Z_{b2})$(pb)	-	-	<0.28	<0.20

Born cross sections and fit

$$\sigma^B = \frac{N_s(1-\Pi)^2}{\mathcal{L}\epsilon(1+\delta)\mathfrak{B}(\Upsilon(nS)\to\mu^+\mu^-)}$$

Fit with three coherent BW, convoluting a Gaussian modeling energy spread:

$$\sigma \propto \left|\sum_1^3 \frac{\sqrt{12\pi\Gamma_i\mathfrak{B}_i}}{s-M_i+iM_i\Gamma_i}\cdot e^{i\phi_i}\sqrt{\frac{f(\sqrt{s})}{f(M_i)}}\right|^2 \otimes G(0,\delta E)$$

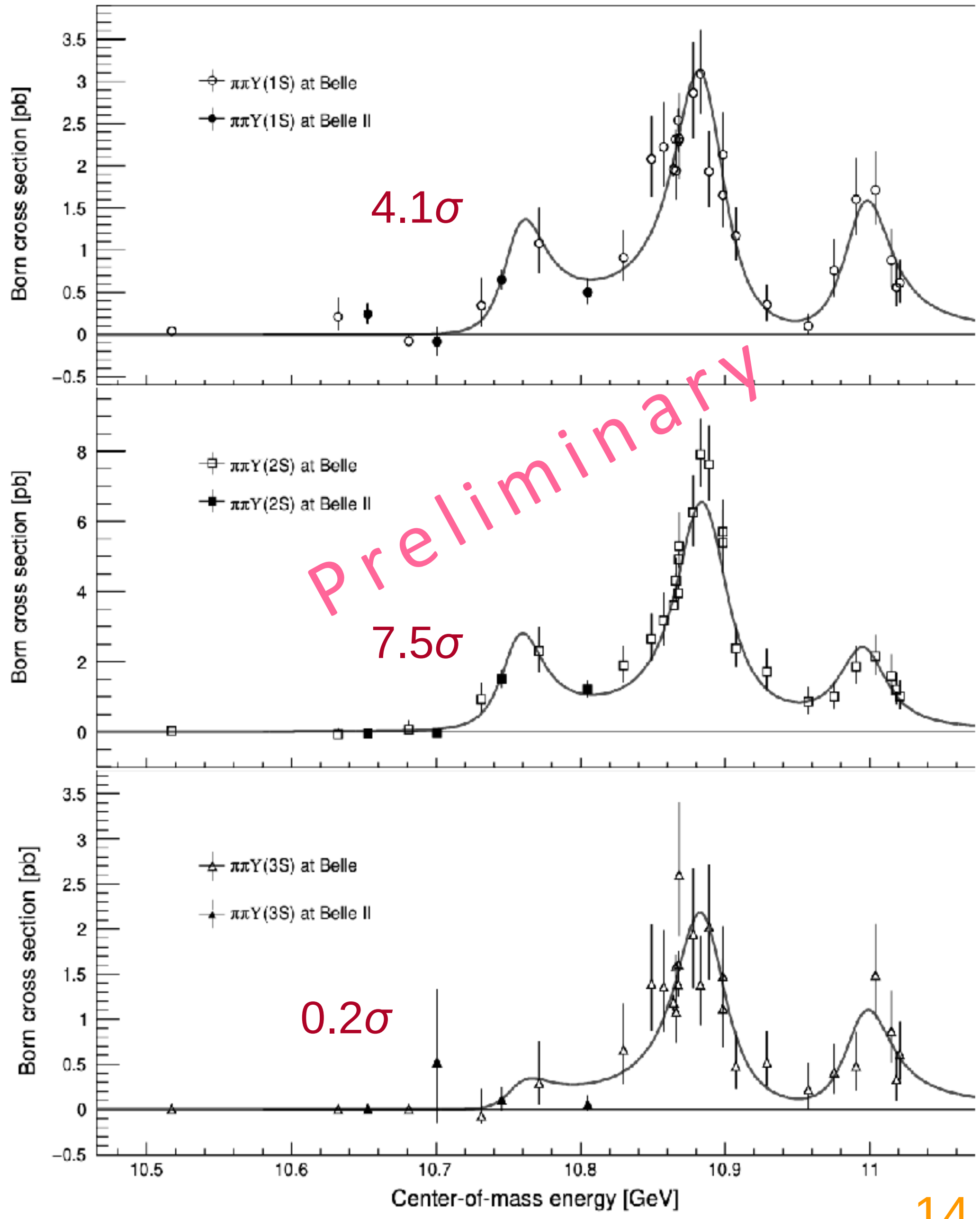
All parameters are free, except δE = 0.0056 GeV

Parameters of : Υ(10753)

M = 10756.3 ± 2.7(*stat.*) ± 0.6(*syst.*) MeV/c2

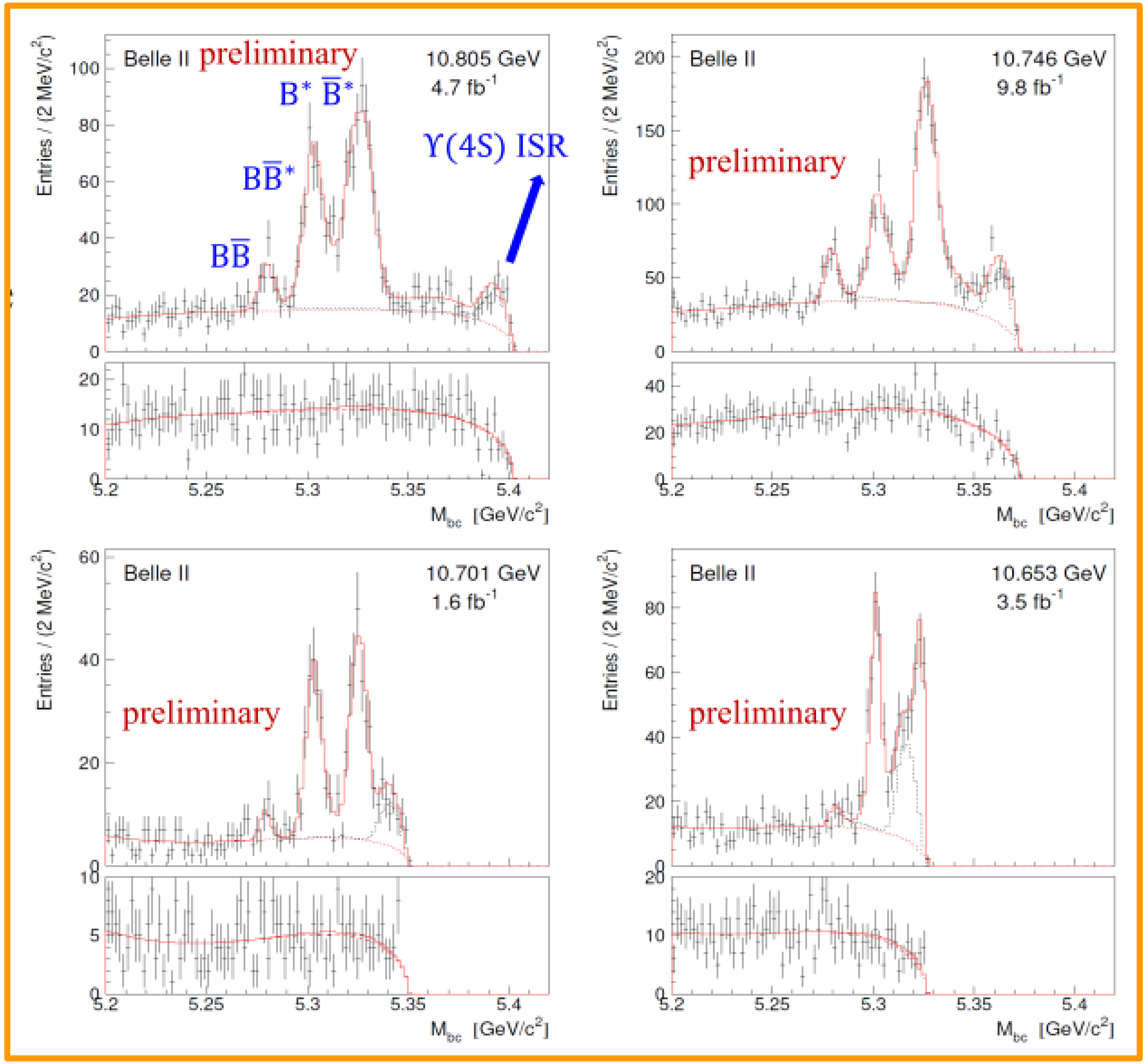
Γ = 29.7 ± 8.5(*stat.*) ± 1.1(*syst.*) MeV

phase space



$e^+e^- \to B^{(*)}\bar{B}^{(*)}$ cross sections

Precise measurement of the $B^{(*)}\bar{B}^{(*)}$ cross section provides valuable knowledge about hadrons with b-quarks spectroscopy and dynamics.
The $B^{(*)}\bar{B}^{(*)}$ are expected to be dominant decay channels for excited bottomonium-like states.



Selection method:

- Fully reconstruct one B in hadronic decays;
- Identify signals with Mbc:

$$M_{bc} = \sqrt{\frac{E_{CM}^2}{4} - p_B^2}\,,\ \Delta E = E_B - E_{CM}/2,$$

$$\Delta E' = \Delta E + M_{bc} - M_B$$

Contribution of Y 4S → BB production via ISR is visible, well described by the fit.

$e^+e^- \to B^{(*)}\overline{B}^{(*)}$ cross sections

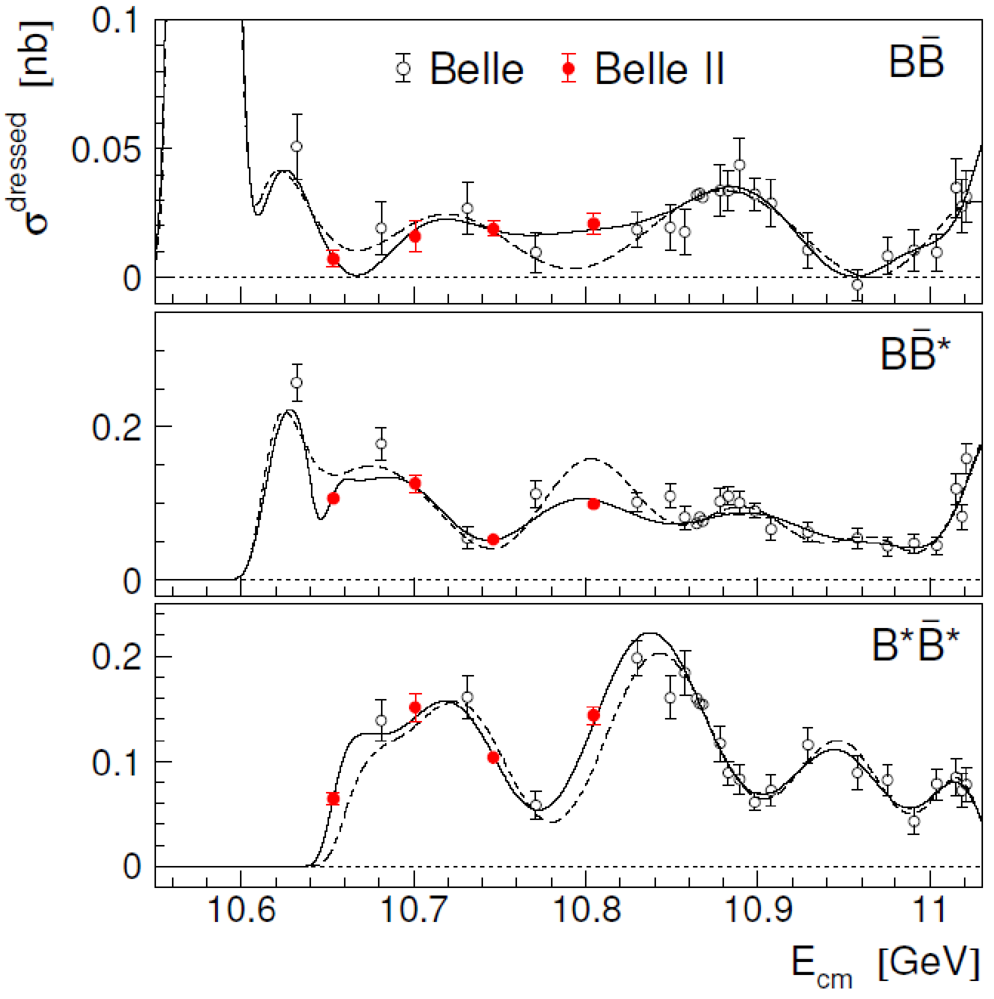
$e^+e^- \to B^*\bar{B}^*$ cross sections rises very rapidly above its threshold:

❑ Similar behaviour was seen for $D^*\bar{D}^*$ cross section; possible interpretation: P-wave $D^*\bar{D}^*$ molecule near threshold.

❑ There could be a $B^*\bar{B}^*$ molecule near the $B^*\bar{B}^*$ threshold?

❑ Also explains a narrow dip in $\sigma(e^+e^- \to B\bar{B}^*)$ near $B^*\bar{B}^*$ threshold by destructive interference between $e^+e^- \to B\bar{B}^*$ and $e^+e^- \to B^*\bar{B}^* \to B\bar{B}^*$.

[PRD 87, 094033 (2013)].



Solid curve –combined Belle + Belle II data fit
Dashed curve –Belle data fit only

Conclusion

Belle II has collected 424 fb^{-1} data.

Long shutdown 1 is finishing and new run will start from the end of 2023.

- Measurements related to muon g-2 are active and in progress at Belle II.
  The results on $e^+e^- \to \pi^+\pi^-\pi^0$ will be released within a few months.

Study of $\Upsilon(10753)$ state

- $\Upsilon(10753)$ signals are observed in $\Upsilon(1S,2S)\pi^+\pi^-$ channels.
- No signals of intermediate Z_b resonances are observed.
- Observation of $\Upsilon(10753) \to \omega\chi_{bJ}(1P)$

Energy dependence of $e^+e^- \to B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$

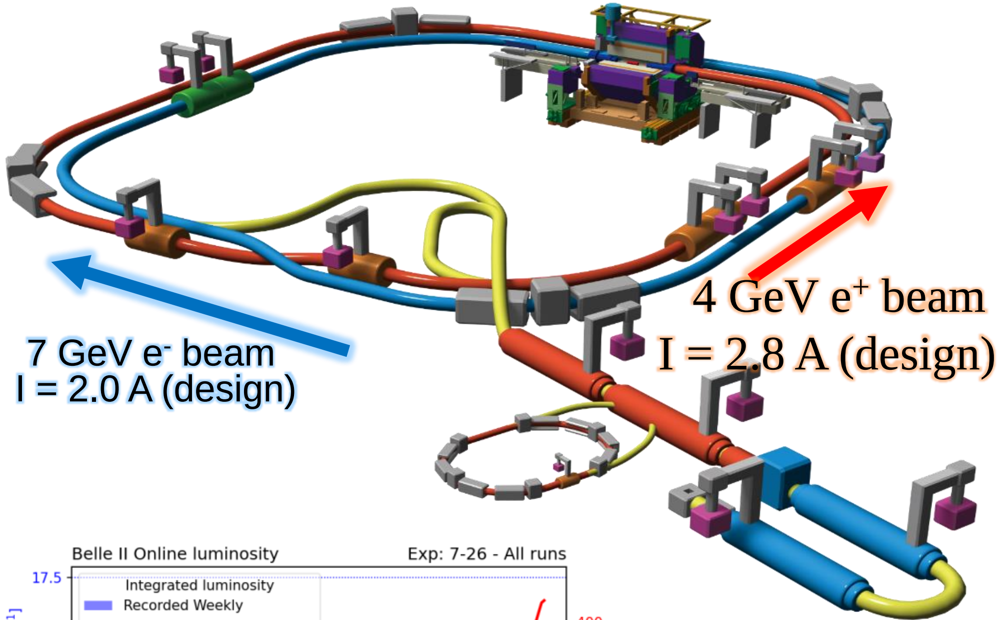
- Confirmation of “oscillatory” behavior, improvement of accuracy.
- Rapid rise of $\sigma(e^+e^- \to B^*\bar{B}^*)$ above threshold - signal of molecular $B^*\bar{B}^*$ state?

Back-up

SuperKEKB collider

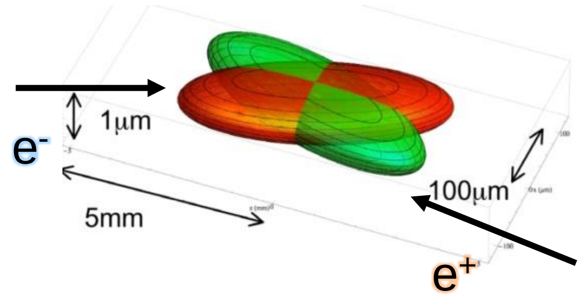
World record instantaneous luminosity: 4.7×10^{34} /cm^2/s

- Asymmetric e^+e^- collider
  - $\sqrt{s} = M(\Upsilon(4S)) = 10.58$ GeV
  - Design luminosity : 6×10^{35} cm^{-2}s^{-1}
- Improvements from KEKB
  - Nano beam scheme
  - Higher design beam currents



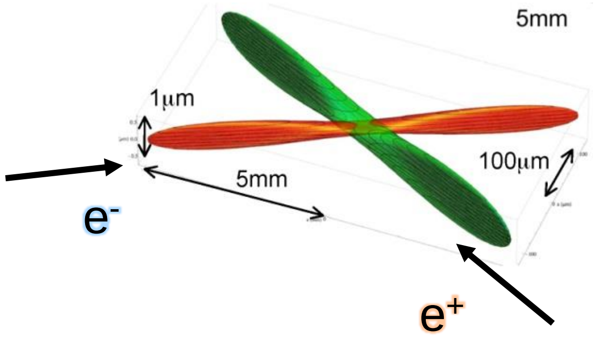
KEKB

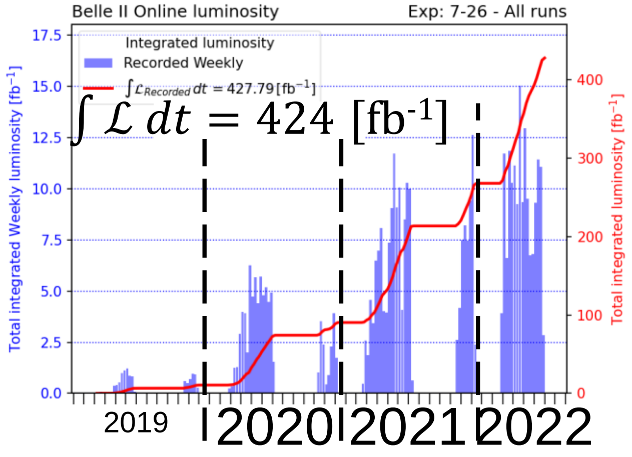
$\sigma_x \sim 100\mu m, \sigma_y \sim 2\mu m$



Nano-Beam SuperKEKB

$\sigma_x \sim 10\mu m, \sigma_y \sim 60nm$

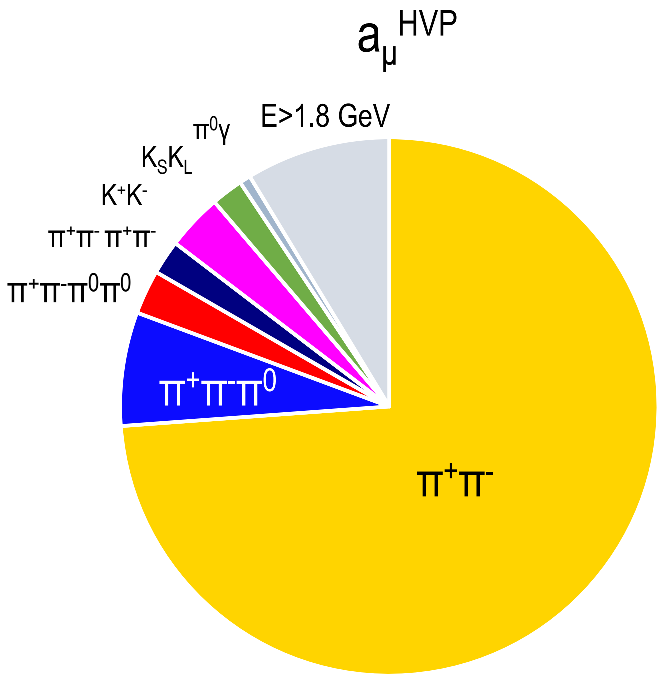


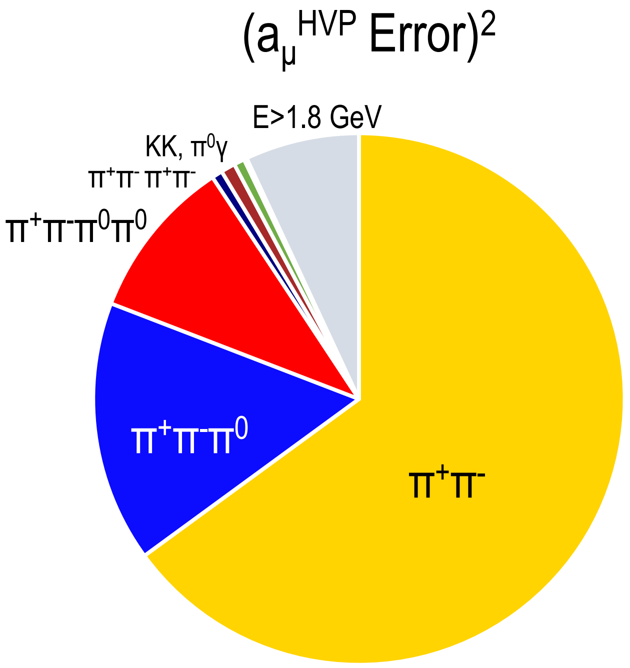


Long Shutdown-1 is finishing and new run will start at the end of 2023.

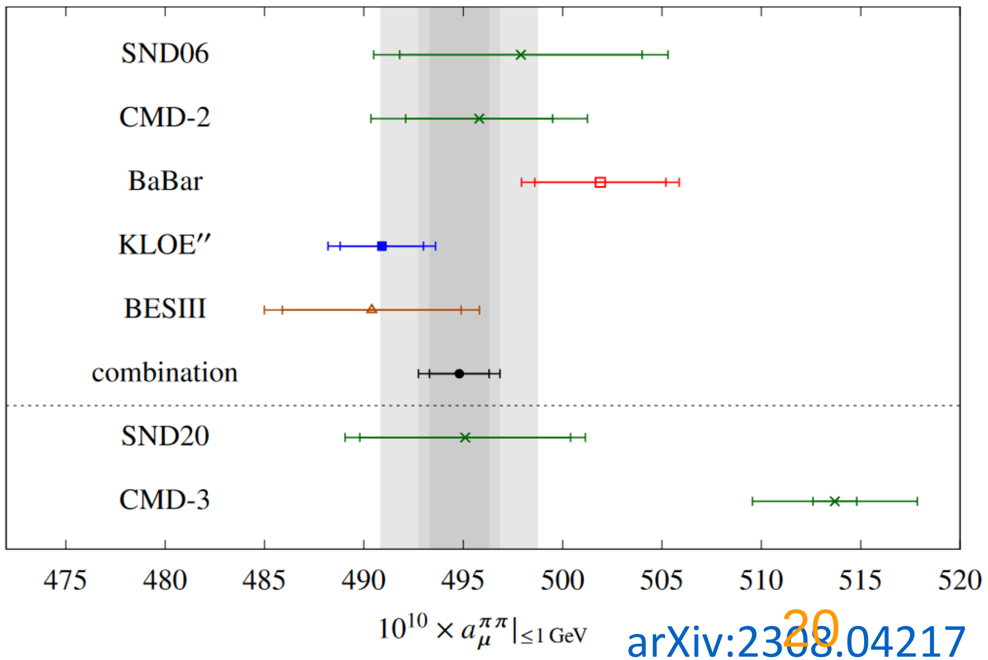
Muon g-2 and Hadronic Vacuum Polarization (HVP)

- HVP contributes to the largest uncertainty in the prediction of muon g-2.
- Two approaches for estimating the HVP contribution of SM predictions
  - Dispersion relations (w/ inputs from ee → hadrons data)
  - Lattice QCD
- Belle II can provide the cross section for $e^+e^- \rightarrow$ hadrons to improve the theoretical prediction.
- Follow-up verification by ongoing experiments would be very useful.





$e^+e^- \rightarrow \pi^+\pi^-$ HVP contribution to muon g-2

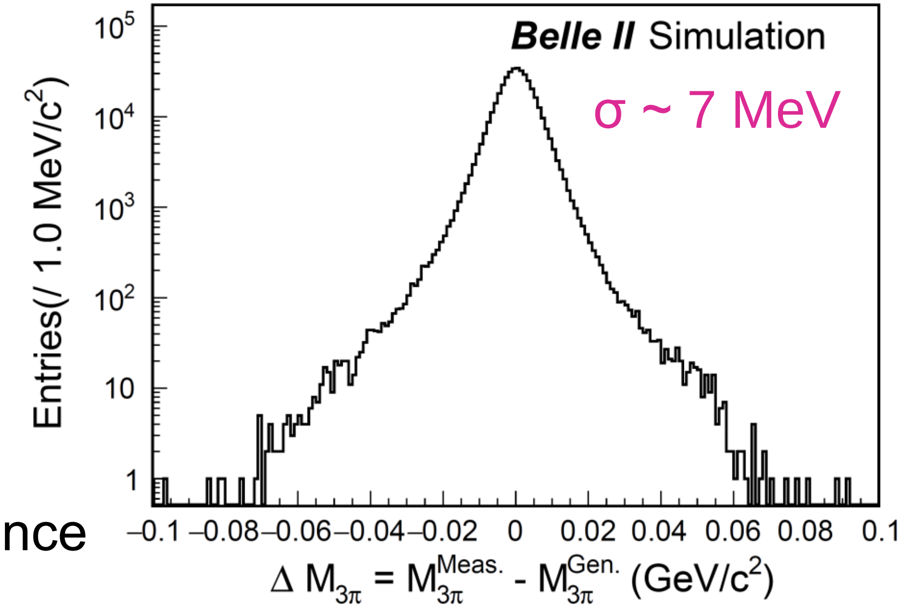


arXiv:2308.04217

Unfolding

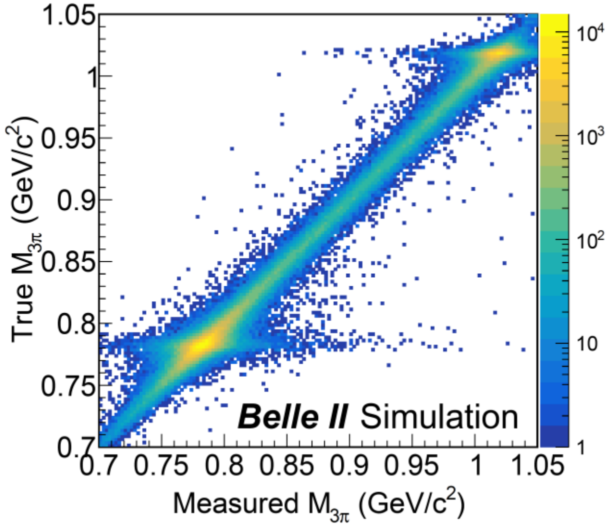
- The background-subtracted spectrum is unfolded to mitigate the effect of detector response and final-state radiation.
- The data-MC resolution difference is determined by a Gaussian convolution fit
  to the ω, Φ, and J/ψ resonances.
  - The agreement is good typically with a mass resolution around 7-10 MeV.

3π mass resolution



ω resonance

Response function



Di-pion transition of $\Upsilon(10753)$
Study of $e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$ (n = 1, 2, 3)

The full reconstruction is used: $e^+e^- \to [\Upsilon(nS) \to \mu^+\mu^-]\,\pi^+\pi^-$.
N(Tracks) = 4 or 5, At least 2 tracks with P>2.5 GeV/c
Lepton and pion PID

Plot $\Delta M = [M(\pi^+\pi^-\mu^+\mu^-) - M(\mu^+\mu^-)]$ vs. $M(\mu^+\mu^-)$:
clear signals of $\Upsilon(1S)\,\pi^+\pi^-$ and $\Upsilon(2S)\,\pi^+\pi^-$,
No signal of $\Upsilon(3S)\,\pi^+\pi^-$.

Signal region defined: $\Delta M \in [\Delta m_0 - 30, \Delta m_0 + 21]$ MeV/c^2
$\Delta m_0 = s - m(\Upsilon(nS))$

$p^*(\pi^+\pi^-\mu^+\mu^-) < 0.1$ GeV