Status and latest results of the Belle II experiment at SuperKEKB e^+e^- Collider

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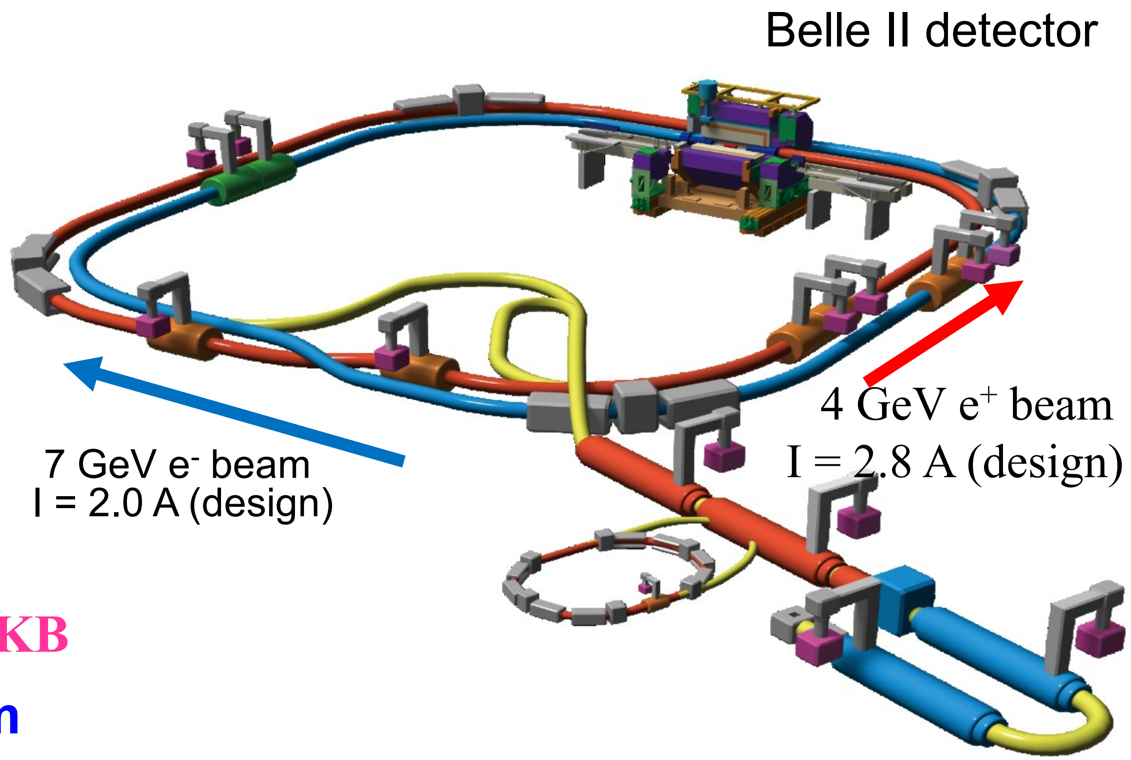
SuperKEKB collider

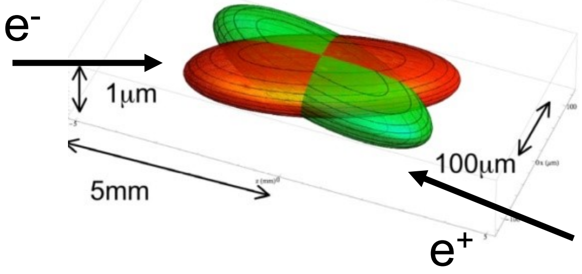
World record instantaneous luminosity: 5.1×10^{34} /cm²/s



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

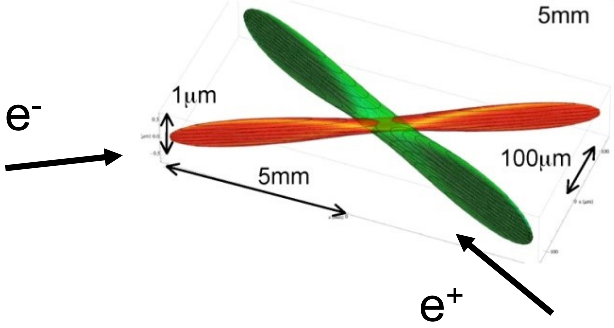
KEKB

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



Nano-Beam SuperKEKB

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



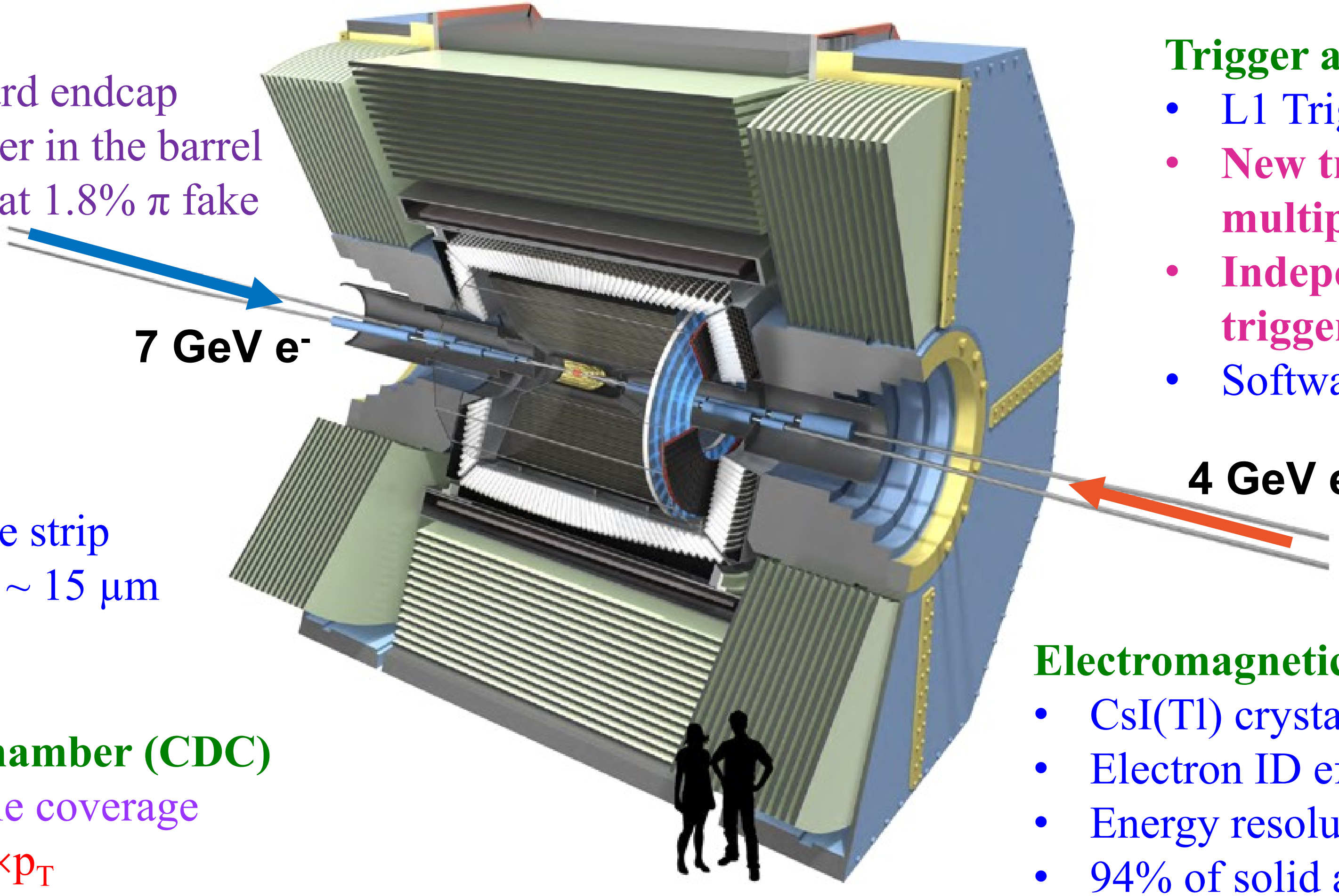
Belle II Detector

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



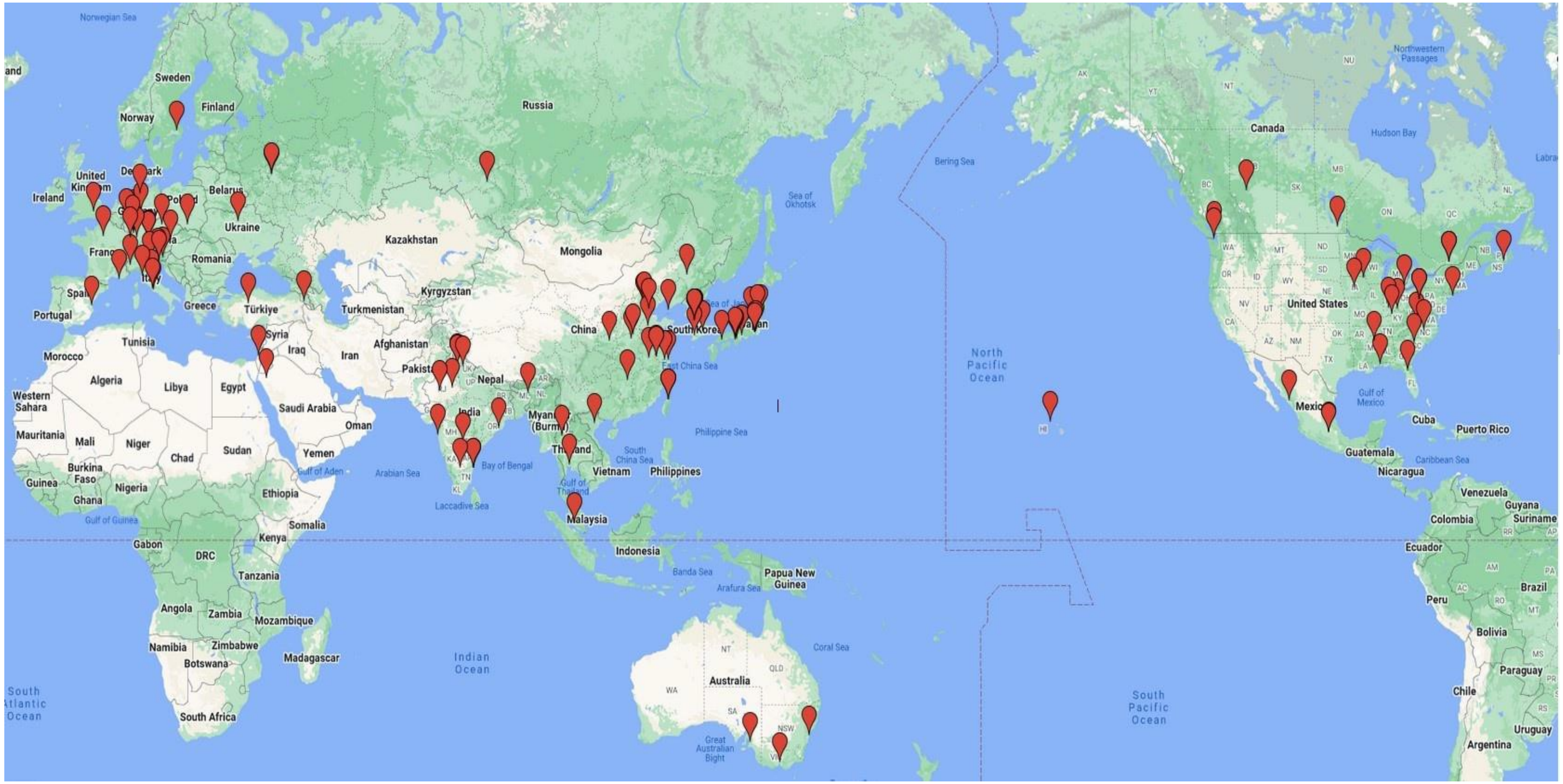
Trigger and DAQ
- L1 Trigger rate 30 kHz (design)
- **New trigger line for low-multiplicity events**
- **Independent CDC and ECL trigger modes**
- Software based HLT

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

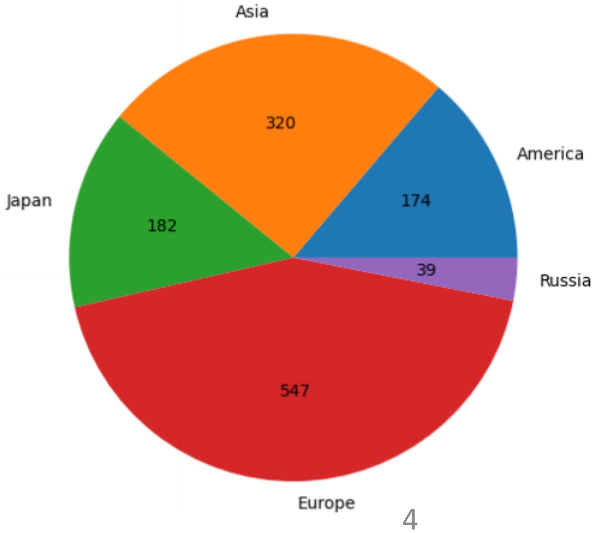
Electromagnetic Calorimeter (ECL)
- CsI(Tl) crystals + Waveform fit
- Electron ID eff. 90% at <0.1% fake
- Energy resolution 1.6-4%
- 94% of solid angle coverage

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)

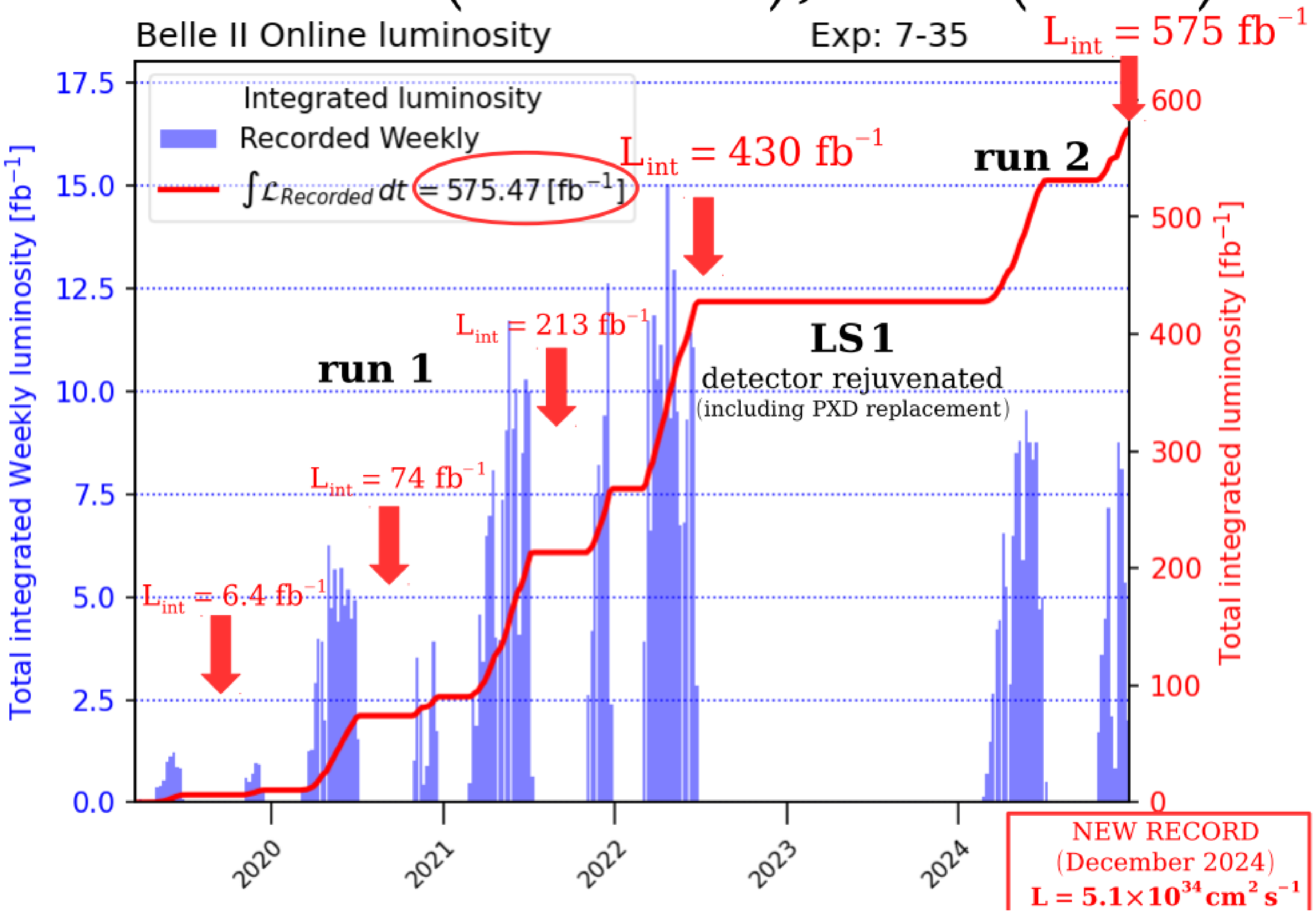
Belle II Collaboration



1208 members
124 institutions
28 countries



Belle II run 1 (2019 - 2022), run 2 (2024 -)



The Belle II experiment provides very wide field of researches

By now 82 results were published on various topics distributed (bit arbitrary):

CKM elements	**7**
CP violation and CKM unitarity-triangle phases	**16**
Direct searches for BSM particles in various scenarios	**8**
Search for lepton flavor violation	**9**
Bottomonium and charmonium physics, b and c hadron decays	**21**
Exotic hadrons	**1**
QCD, hadronic cross sections	**4**
Lepton flavor universality	**5**
Particle parameters	**6**
Detector, methodics	**5**

Some latest results

Measurement of the τ-lepton mass
Search for the lepton-flavor-violating $\tau^- \to e^\mp l^\pm l^-$, $l^- K_S^0$
Search for an Axion-Like Particle in $B \to K^{(*)} a(\to \gamma\gamma)$ decays
Determination of $|V_{cb}|$ using $B \to D l \nu_l$ decays
Evidence for $B^+ \to K^+ \nu\bar{\nu}$ decays
Measurement of $B^+ \to \tau^+ \nu_\tau$ branching fraction with a hadronic tagging method at Belle II
Measurement of the time-integrated CP asymmetry in $D^0 \to K_S^0 K_S^0$ decays using opposite-side flavor tagging
Test of lepton flavor universality with measurements of $R(D^+)$ and $R(D^{*+})$ using semileptonic tagging at the Belle II experiment
Measurement of the $e^+e^- \to \pi^+\pi^-\pi^0$ cross section in the energy range 0.62–3.50 GeV

In this talk we discuss only two different directions of studies – rare electroweak decays and precise measurements of the hadronic cross sections

$B^+ \to \tau^+\nu_\tau$ (2502.04885)

This is the purely leptonic B decay which can be easily calculated within SM:

$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left[1 - \frac{m_\tau^2}{m_B^2}\right]^2 f_B^2 |V_{ub}|^2 \tau_B$$

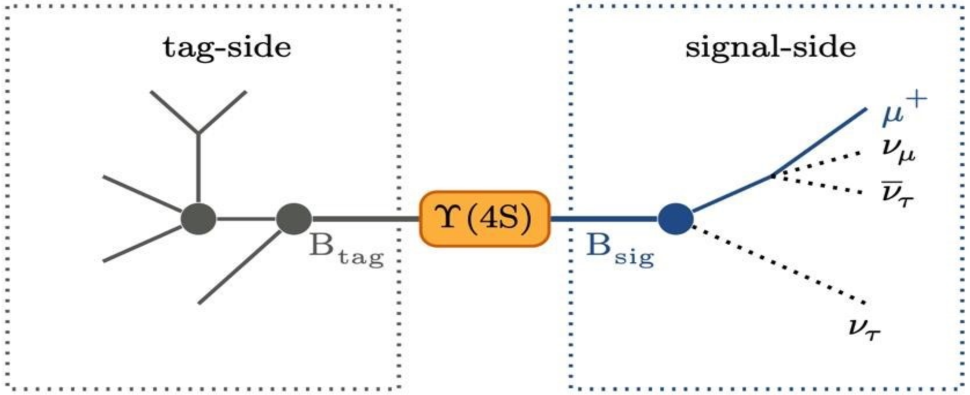
The experimental value of the B($B\to\tau\nu_\tau$) can be used for independent evaluation of the V_{ub} .
On the other hand, a difference of B($B\to\tau\nu_\tau$) from SM calculation would indicate a presense of NP.

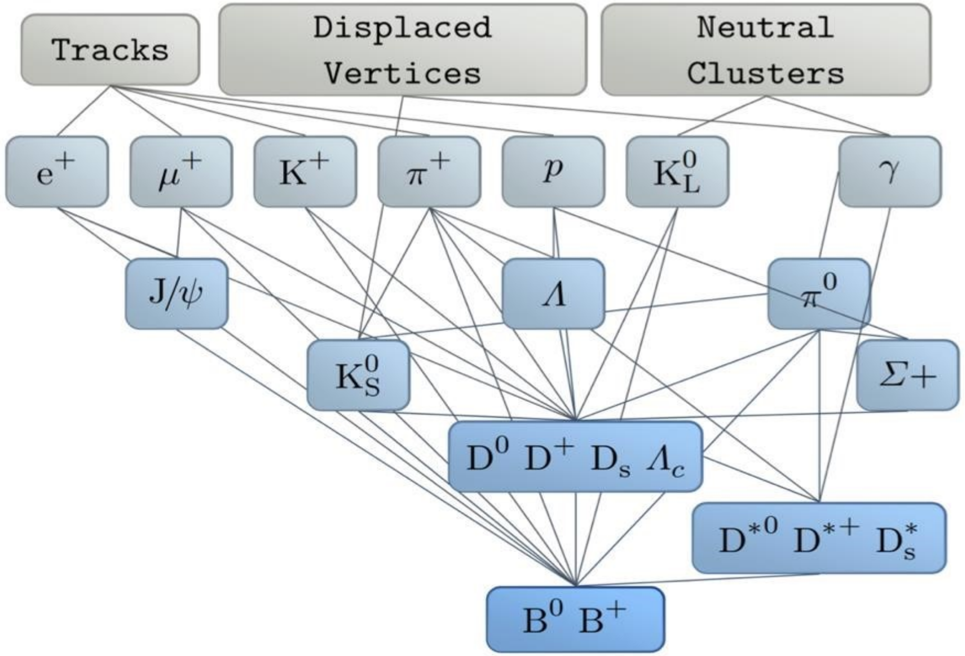
This analysis requires a reconstruction of both, tagging and signal, B mesons.

B_{tag} selection

B_{tag} is reconstructed in the hadronic final state (semileptonic also possible)
Fully reconstruct B_{tag} in thousands of hadronic decay modes using “Full Event Interpretation” (FEI)

Comput. Softw. Big Sci. 3, 6 (2019)

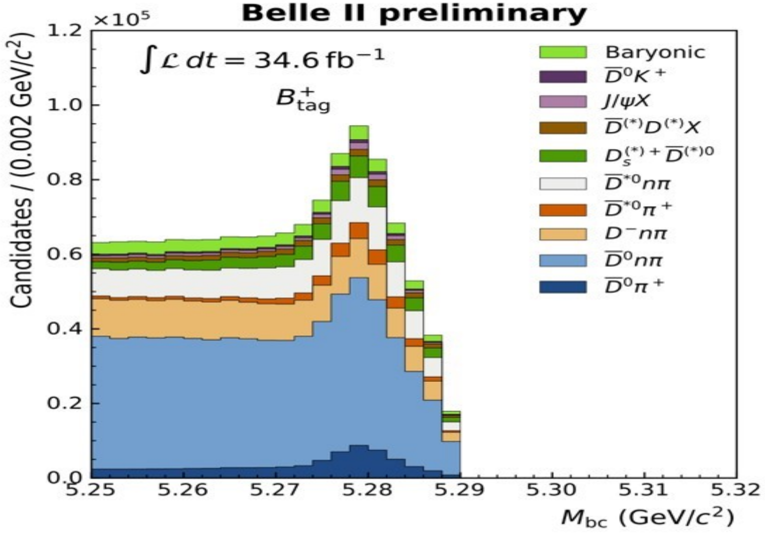




Further cuts on Btag

$$\Delta E = E^*_{B_{tag}} - s/2$$

$$M_{bc} = \sqrt{\frac{s}{4} - p^{*}_{B_{tag}}}$$



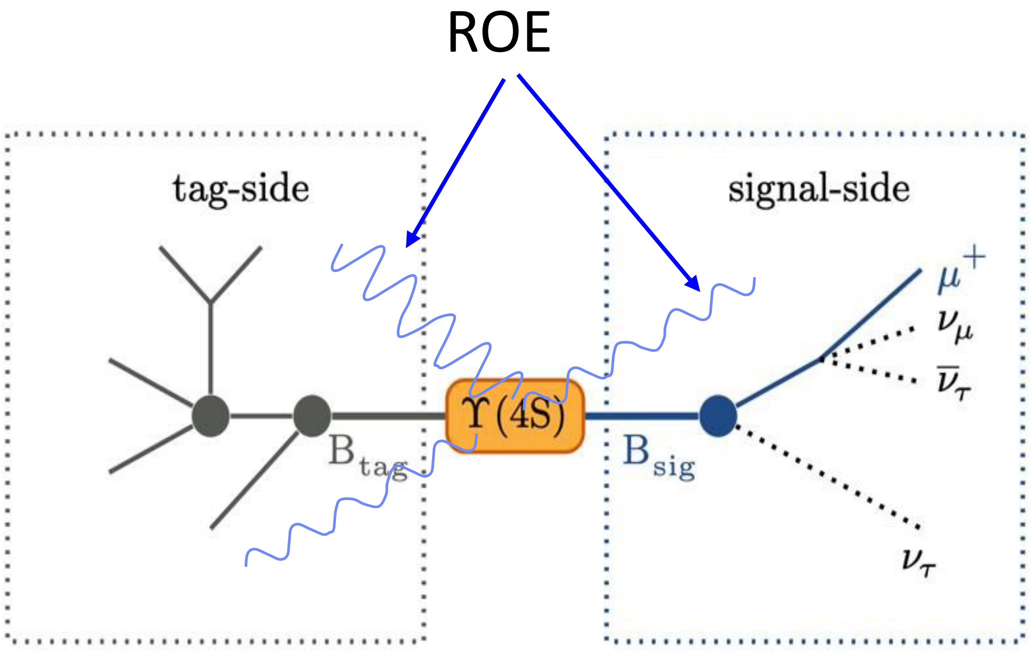
B_{sig} selection

Signal $B^+ \to \tau^+\nu_\tau$ decay reconstructed with an e^+, μ^+, π^+, or $\rho^+ \to \pi^+\pi^0$

- Veto events with additional tracks
- Assign all non-B_{tag} ECL (calorimeter) clusters (passing photon quality cuts), to the "rest of the event" (ROE).

The two most discriminating observables based on the ROE are the total residual energy from neutral clusters in the ECL (E_{ECL}^{extra}) , and the square of missing four-momentum (M_{miss}^2) calculated using the known beam energies and all the reconstructed objects:

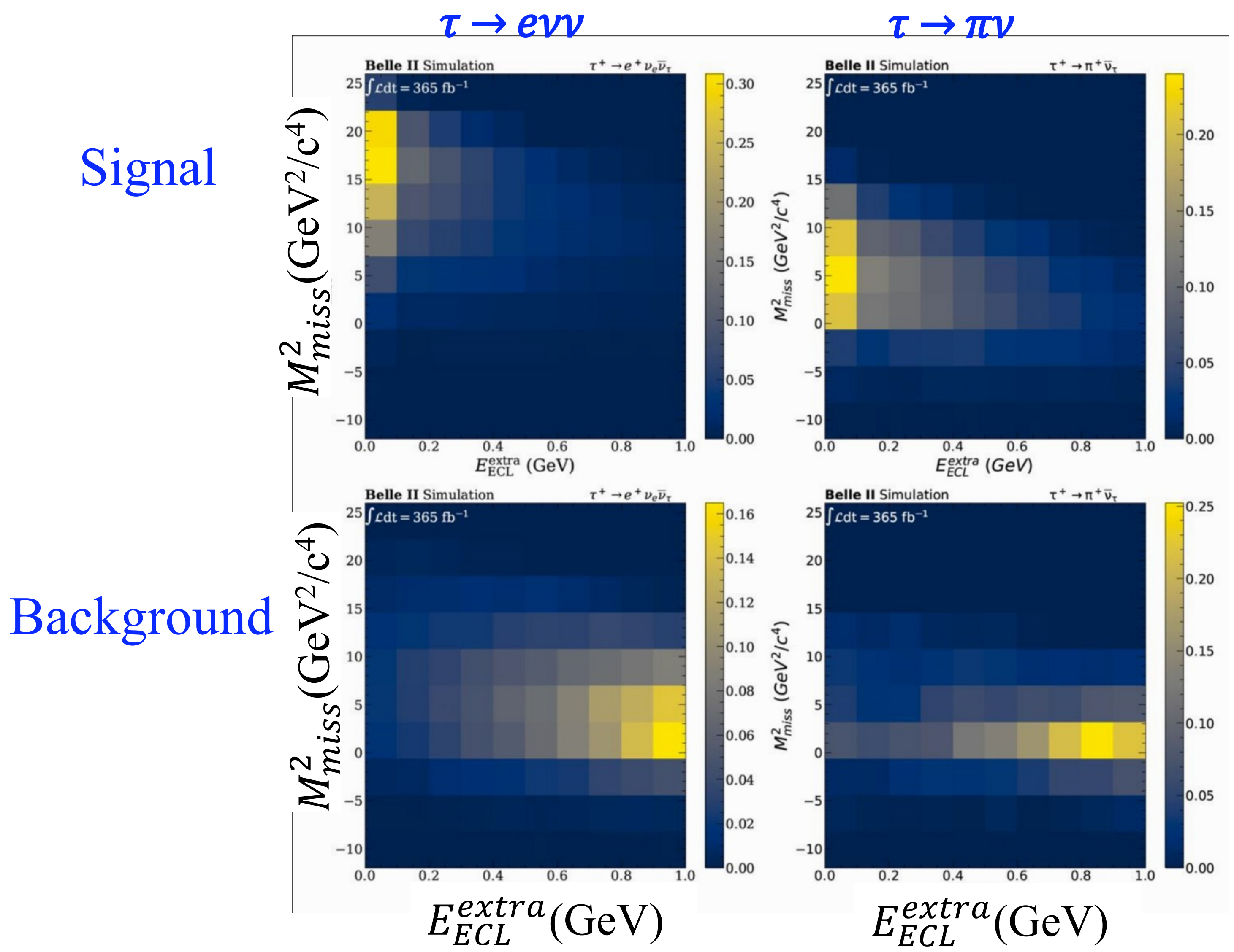
$$p_{miss}^* = (2E_{beam}^*,0,0,0) - p_{tag}^* - p_{sig}^* - p_{ROE}^*,$$
$$M_{miss}^2 = (p_{miss}^*)^2$$



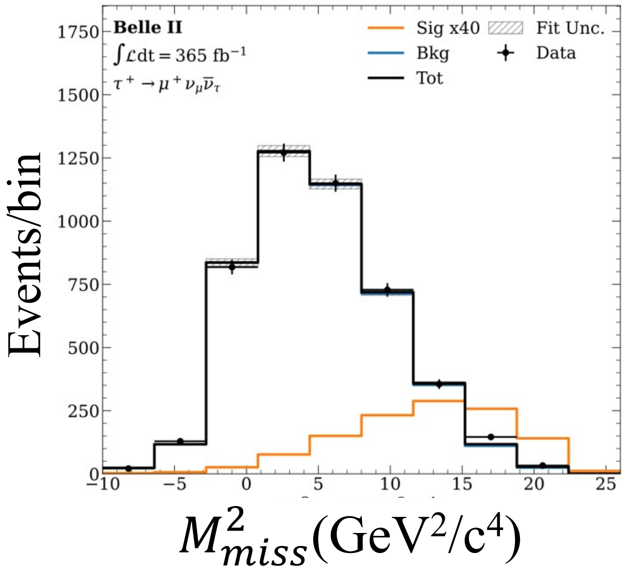
Signal extraction

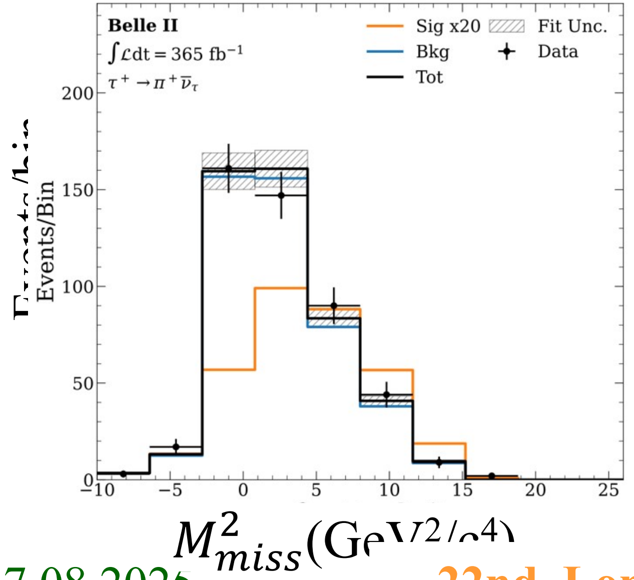
The branching fraction $B(B \to \tau \nu_\tau)$ is obtained from a simultaneous binned maximum likelihood fit to all of the four τ^+ categories. The PDFs are 2D histograms of M^2_{miss} and E^{extra}_{ECL} with 10×10 uniform binning, with $-10 < M^2_{miss} < 26\ \text{GeV}/c^4$ and $E^{extra}_{ECL} < 1$ GeV.

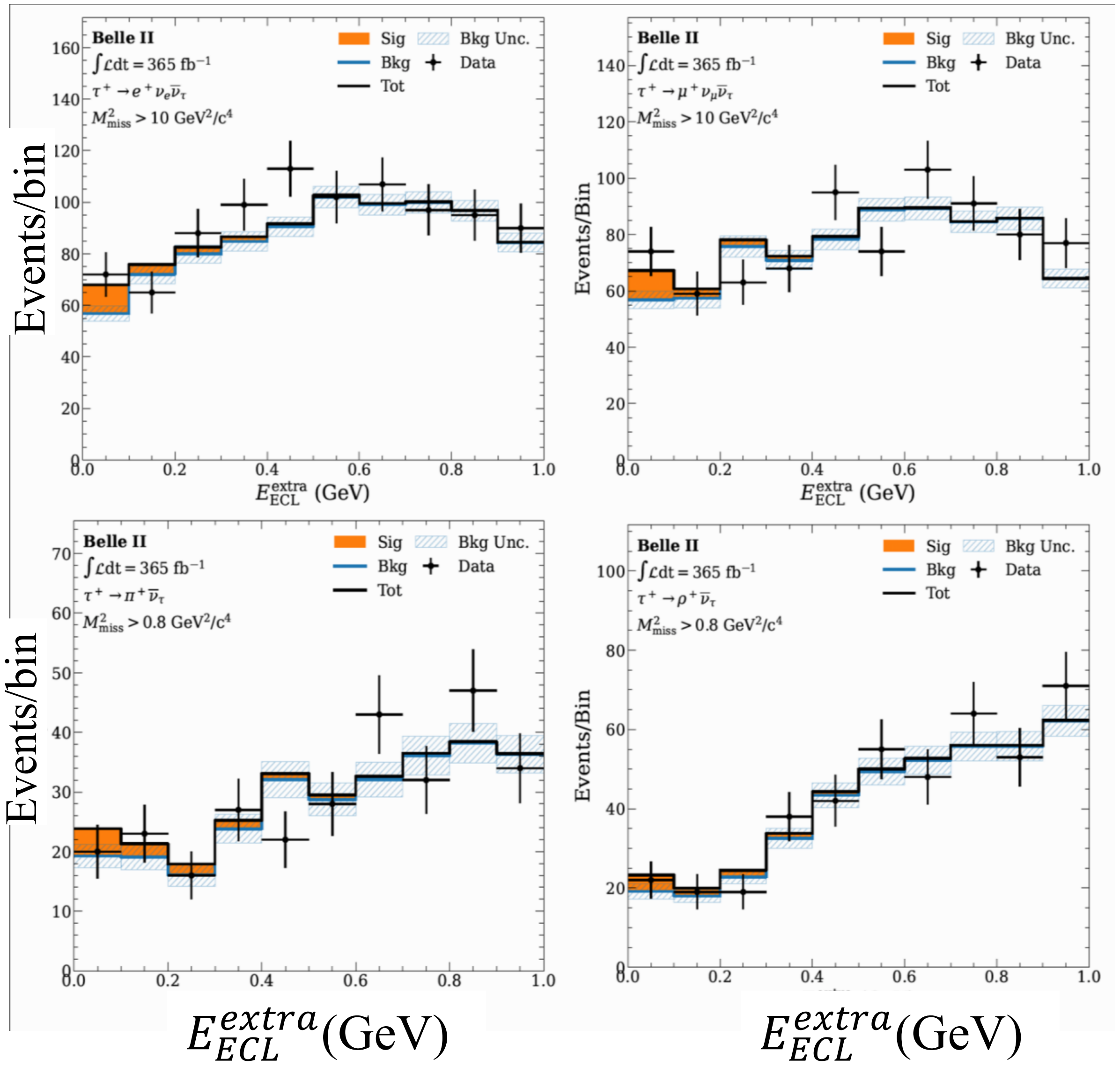
PDFs for the leptonic and hadronic modes (Simulation)



Fit 1D projections

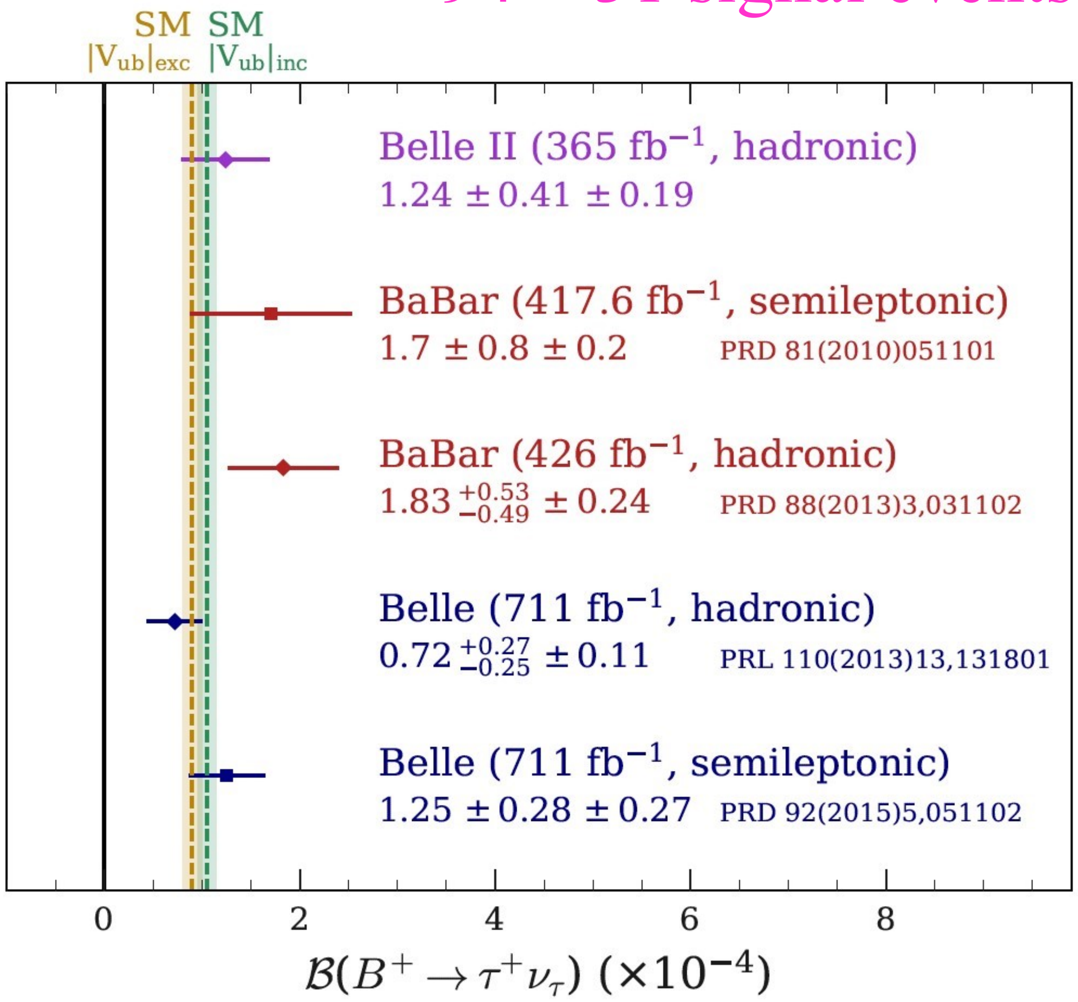






Results

94 ± 31 signal events



World average BR goes from
$1.09 \pm 0.24 \times 10^{-4}$ to
$1.12 \pm 0.21 \times 10^{-4}$

Leads to:

$$V_{ub}(\tau\nu) = 4.19^{+0.38}_{-0.41} \times 10^{-3}$$

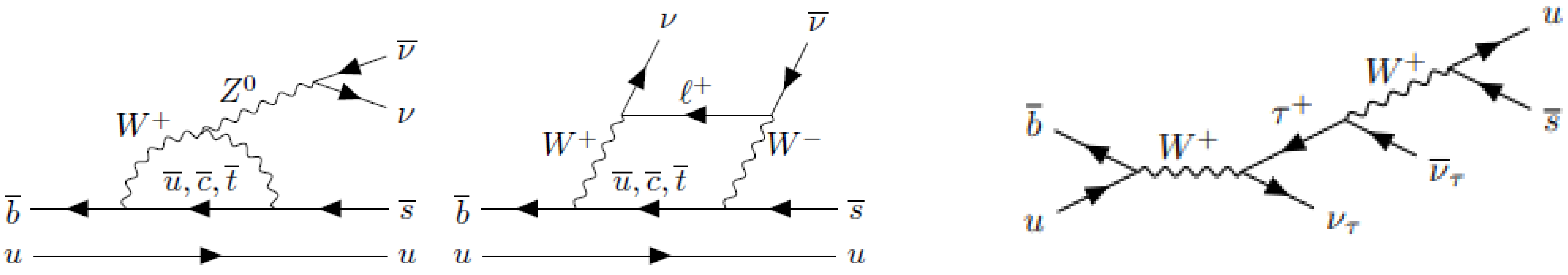
Relative uncertainty: +9% −10%

Compare [HFLAV]:

V_{ub} incl $= 4.06 \pm 0.12 \pm 0.11 \times 10^{-3}$

V_{ub} excl $= 3.76 \pm 0.06 \pm 0.19 \times 10^{-3}$

Rare B decay B→K $\nu\,\bar{\nu}$



Flavour-Changing Neutral Currents (FCNC),
are suppressed in the Standard Model (SM)

The branching fraction of B→K$\nu\bar{\nu}$ was calculated via SM with high accuracy (arXiv:2207.13371) B(B→K$\nu\bar{\nu}$)=$(5.6 \pm 0.4)\times 10^{-6}$
In case of a difference with experimental value this would indicate some extension of SM.
This is not observed yet due to low branching fraction, high background contributions and no peaking variables to separate signal

B→K ν ν̄ analysis

[arXiv :2311.14647]
PRD109, 112006 (2024)

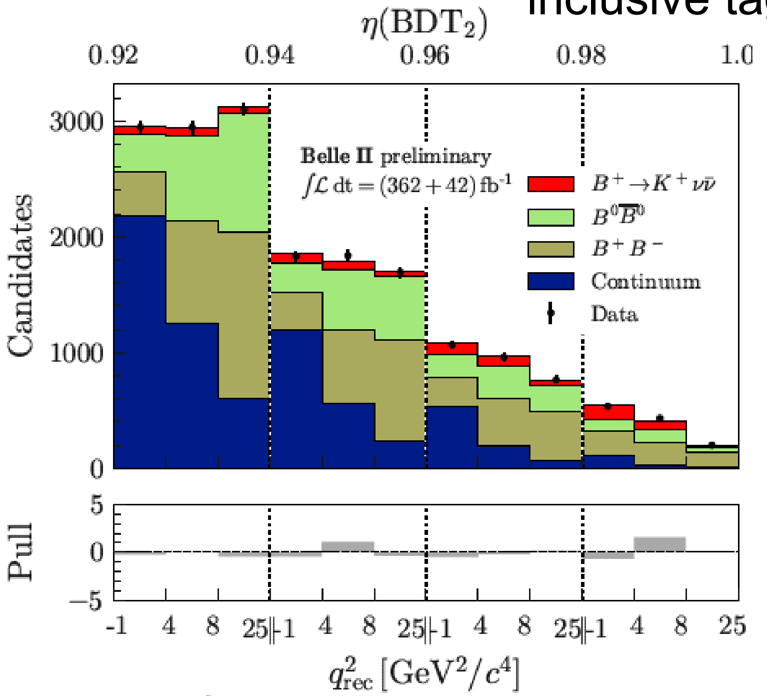
Two branches of the analysis : **inclusive tagging** (eff = 8%) conventional **hadronic** tagging (eff = 0.4%)

∘ background suppression is based on the events properties with multiple variables combined

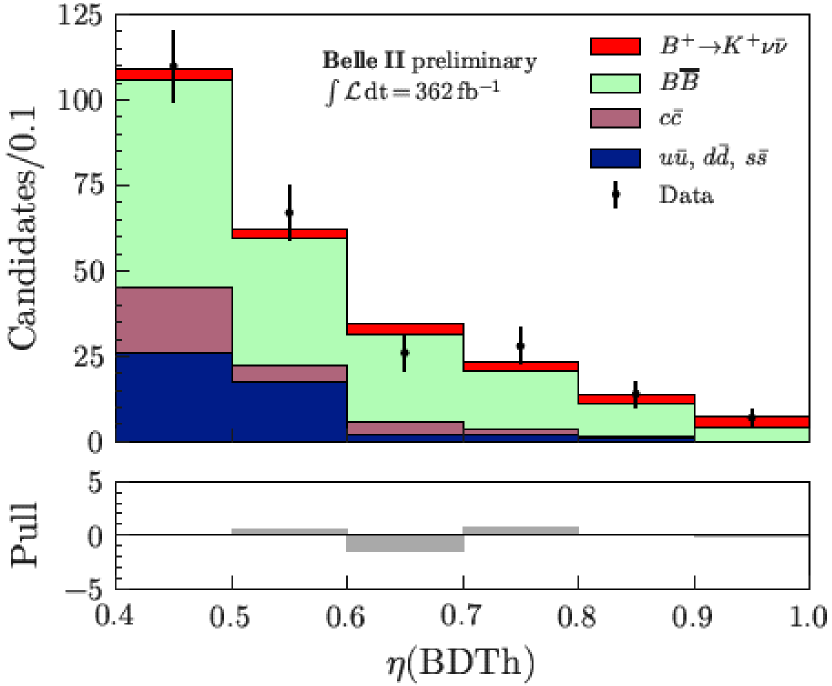
∘ classifier output is used as (one of) the fit variables, with signal and background templates from simulation

∘ Use multiple control channels to validate simulation with data

inclusive tag



hadronic tag



$$q^2_{rec} = \frac{s}{4c^4} + M_K^2 - \sqrt{s}E_K^*/c^4$$

Evidence of $B \to K \nu \bar{\nu}$

Max . likelihood fit to data using signal and bkg templates

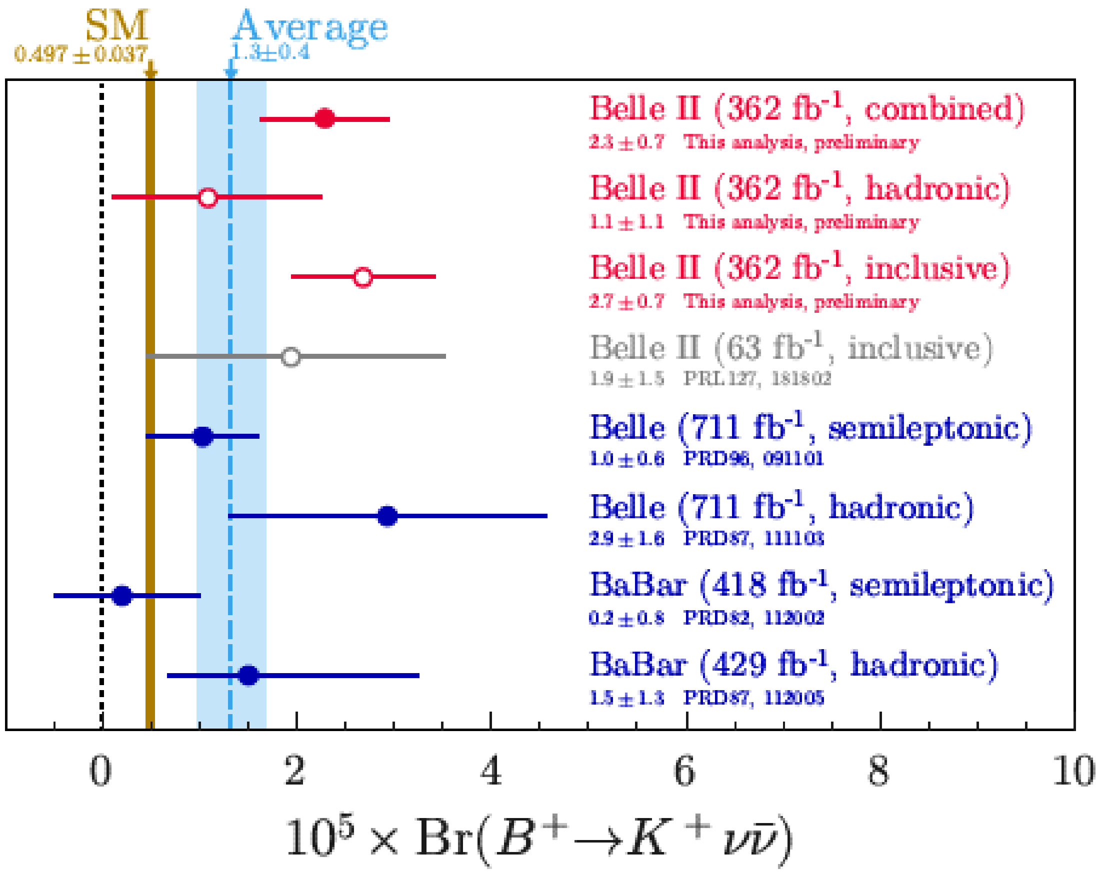
B_{incl} = (2.7 ± 0.5 (stat) ± 0.5 (syst)) × 10^{-5}

$B_{had} = (1.1^{+0.9}_{-0.8}(\text{stat})^{+0.8}_{-0.5}(\text{syst})) \times 10^{-5}$

∘ For inclusive analysis, evidence for $B \to K\nu\bar{\nu}$ branching fraction within 3.5σ and 3σ from SM

∘ For hadronic tag, the result is consistent with null hypothesis at 1.1σ and and 0.6σ from SM

⇒ Combination of two analyses provides first evidence of the decay at 2.7σ from SM



Search for $B \to X_s \nu \bar{\nu}$ decays

Flavour-Changing Neutral Currents (FCNC)

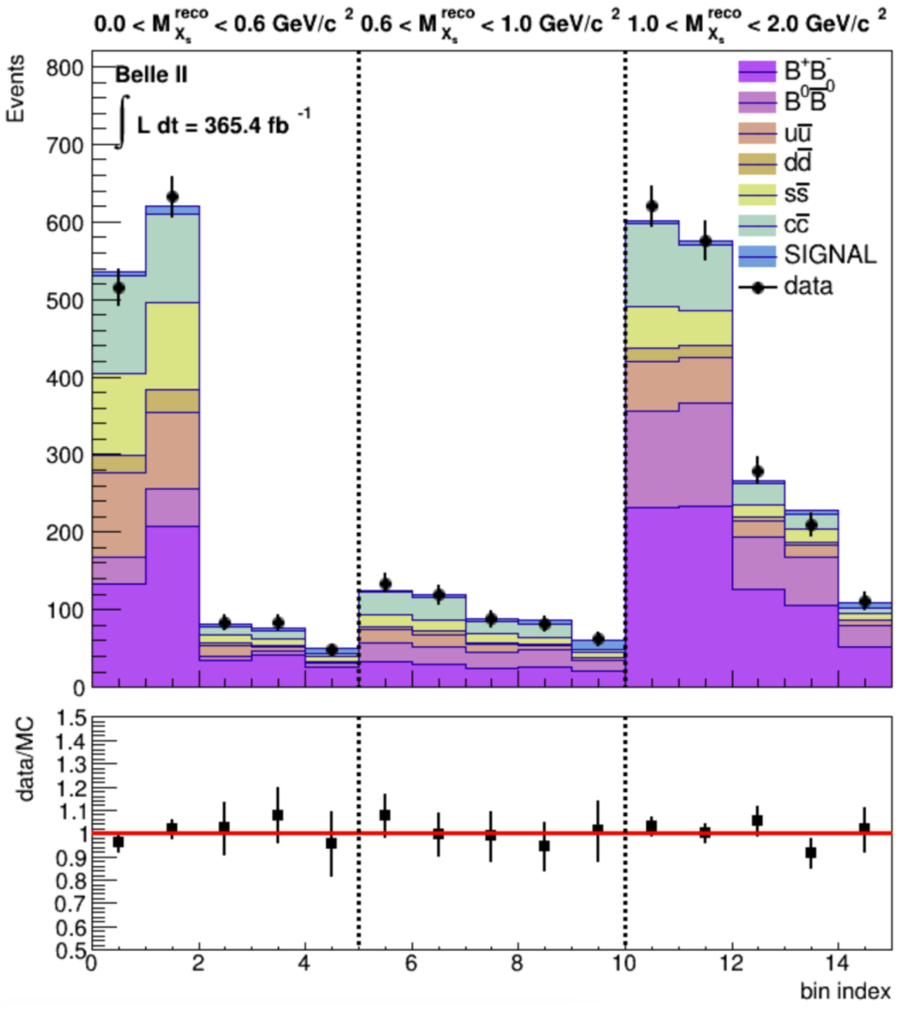
SM calculation: BSM =$(2.9 \pm 0.3)\times 10^{-5}$ [JHEP02 (2015) 184]

- B < 6.4×10^{-4} at 90% C.L. [ALEPH, EPJC 19 (2001) 213]

- using Belle II sample of 362 fb^{-1}
- Hadronic B- tagging
- Sum-of - exclusive from 30 decay modes (~90% of inclusive)

	$B^0\bar{B}^0$			$B^\pm$		
K	K_S^0			$K^\pm$		
$K\pi$	$K^\pm\pi^\mp$	$K_S^0\pi^0$		$K^\pm\pi^0$	$K_S^0\pi^\pm$	
$K2\pi$	$K^\pm\pi^\mp\pi^0$	$K_S^0\pi^\pm\pi^\mp$	$K_S^0\pi^0\pi^0$	$K^\pm\pi^\mp\pi^\pm$	$K_S^0\pi^\pm\pi^0$	$K^\pm\pi^0\pi^0$
$K3\pi$	$K^\pm\pi^\mp\pi^\pm\pi^\mp$	$K_S^0\pi^\pm\pi^\mp\pi^0$	$K^\pm\pi^\mp\pi^0\pi^0$	$K^\pm\pi^\mp\pi^\pm\pi^0$	$K_S^0\pi^\pm\pi^\mp\pi^\pm$	$K_S^0\pi^\pm\pi^0\pi^0$
$K4\pi$	$K^\pm\pi^\mp\pi^\pm\pi^\mp\pi^0$	$K_S^0\pi^\pm\pi^\mp\pi^\pm\pi^\mp$	$K_S^0\pi^\pm\pi^\mp\pi^0\pi^0$	$K^\pm\pi^\mp\pi^\pm\pi^\mp\pi^\pm$	$K_S^0\pi^\pm\pi^\mp\pi^\pm\pi^0$	$K^\pm\pi^\mp\pi^\pm\pi^0\pi^0$
$3K$	$K^\pm K^\mp K_S^0$			$K^\pm K^\mp K^\pm$		
$3K\pi$	$K^\pm K^\mp K^\pm\pi^\mp$	$K^\pm K^\mp K_S^0\pi^0$		$K^\pm K^\mp K^\pm\pi^0$	$K_S^0K^\pm K^\mp\pi^\pm$	

- Background suppression with a **BDT**
(include sum of remaining energy in ECL)
- Signal extraction: **template fit** to the
BDT output × M(Xs) plane
- Validation:
  - **off-resonance sample for qq background**
  - **Sideband in for BB background**
  - ***B* → *XsJ/ψ* control sample**



- Results: no significant signal observed

Upper Limit (90% CL): ⇒

$$UL(B \to X_s \nu\bar{\nu}) = \begin{cases} 2.5 \times 10^{-5} & (0.0 < M_{X_s} < 0.6\,\mathrm{GeV}/c^2) \\ 1.0 \times 10^{-4} & (0.6 < M_{X_s} < 1.0\,\mathrm{GeV}/c^2) \\ 3.5 \times 10^{-4} & (1.0\,\mathrm{GeV}/c^2 < M_{X_s}) \end{cases}$$

all mass region: $\mathcal{B}(B \to X_s \nu\bar{\nu}) < 3.6 \times 10^{-4}$

The most stringent upper limit on B→Xs ν ν decay

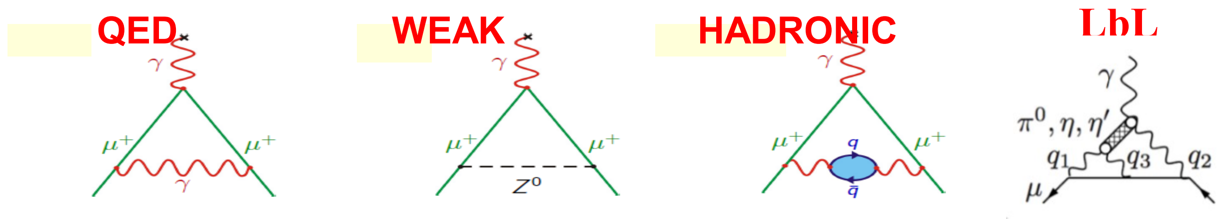
Precise hadronic cross sections - Muon anomaly, $a_\mu=(g-2)_\mu/2$

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

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

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

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

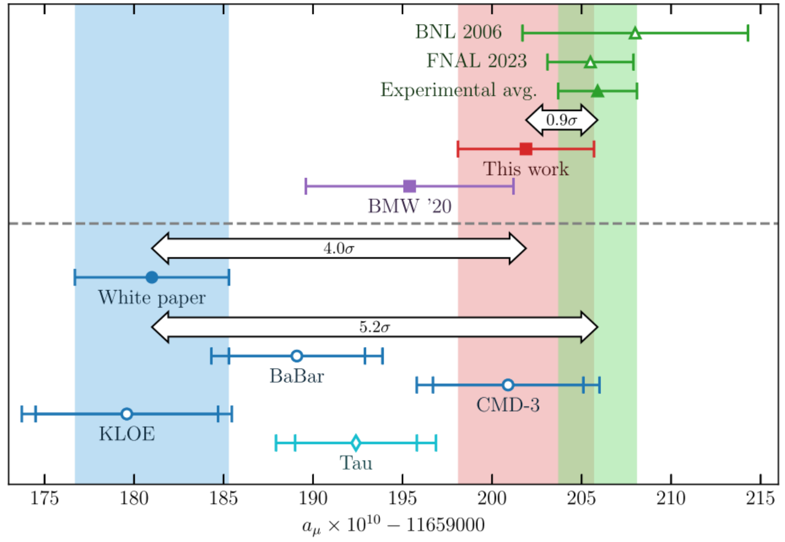


Contribution	Value $\times 10^{11}$
QED	116 584 718.931(104)
Electroweak	153.6(1.0)
HVP (e^+e^-, LO + NLO + NNLO)	6845(40)
HLbL (pheno + lattice + NLO)	92(18)
Total SM Value Section	116 591 810(43)
Exp. (E821) - SM	279(76)

$\pi^+\pi^- \sim 73$ %,
$\pi^+\pi^-\pi^0 \sim 7$%

FNAL 0.001 165 920 71.5 (14.5) (2025)

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

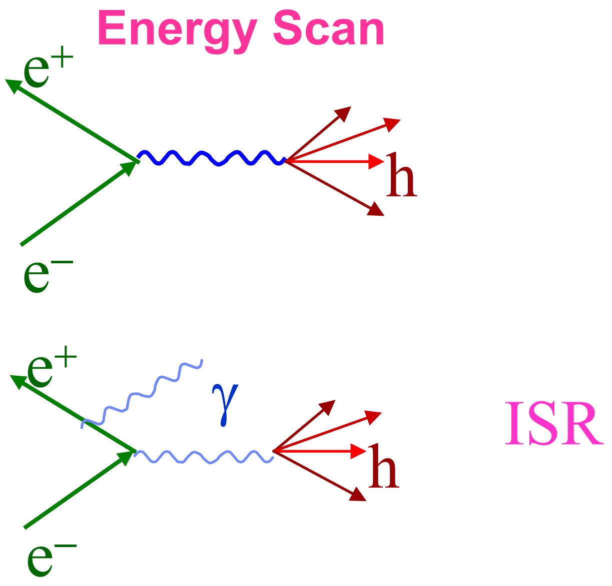


$e^+e^- \to \pi^+\pi^-$ PRD 109 112002 (2024)

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

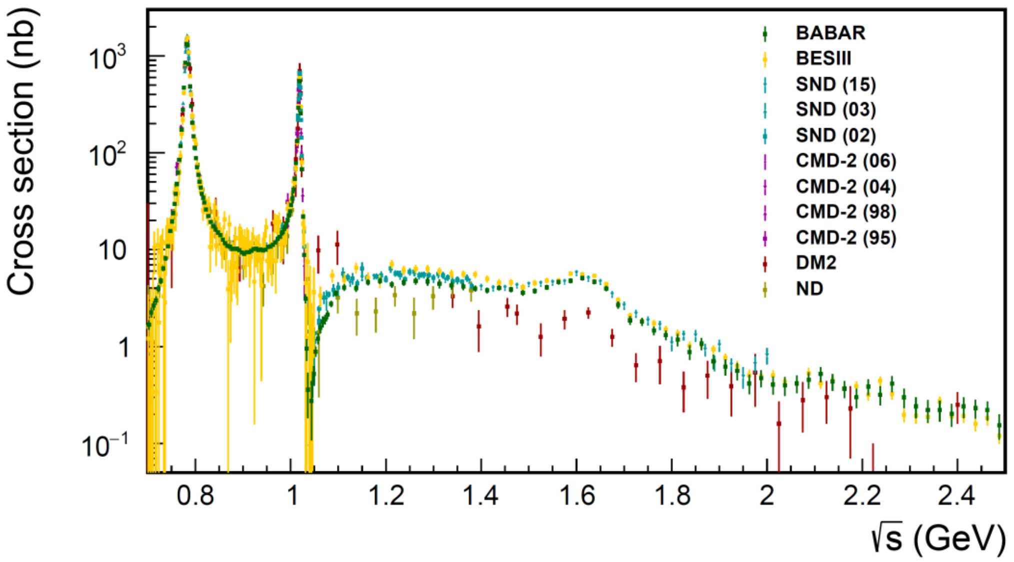
Try to following BaBar methods as a base line

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

Mass range : 0.6-3.5 GeV,

Target precision : $\delta a_\mu(3\pi) \sim 2\%$

At present the results is published in arXiv:2404.04915 and by PRD and accepted by PRD.



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

Dataset : 2019-2021 191 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

- Four-vector kinematic fit (4C-KFit)
- Fit to positions and momenta
- Constrain to initial e^+e^- four-momentum
- Select small $\chi 2$ to extract signal-like event

Event selection

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

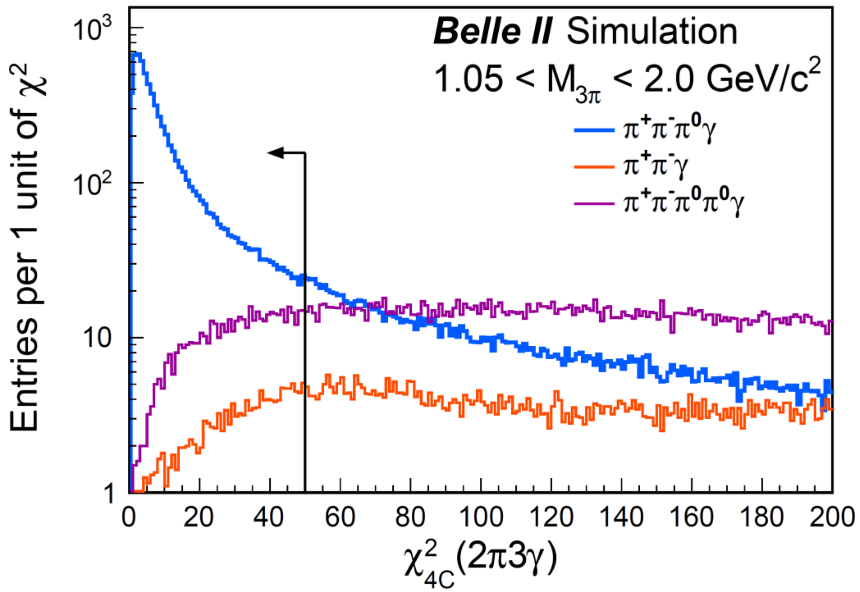
Tracks : dr < 0.5 cm and |dz| < 2 cm and p_T > 0.2 GeV/c

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

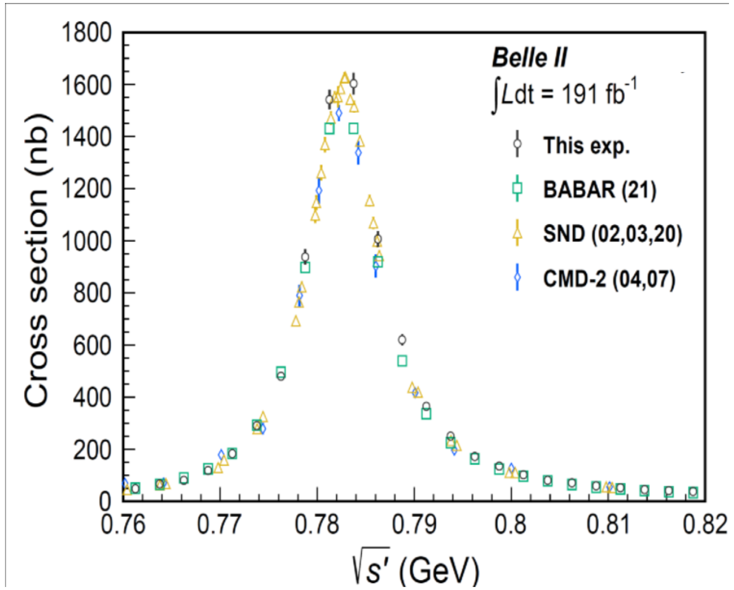
π^0 reconstruction

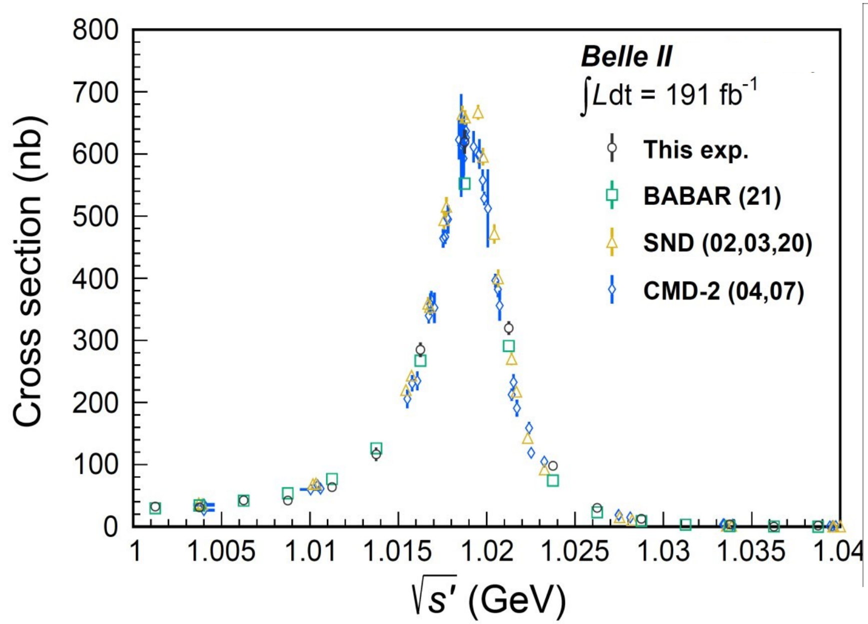
Invariant mass of two photons within 0.123-0.147 GeV/c^2

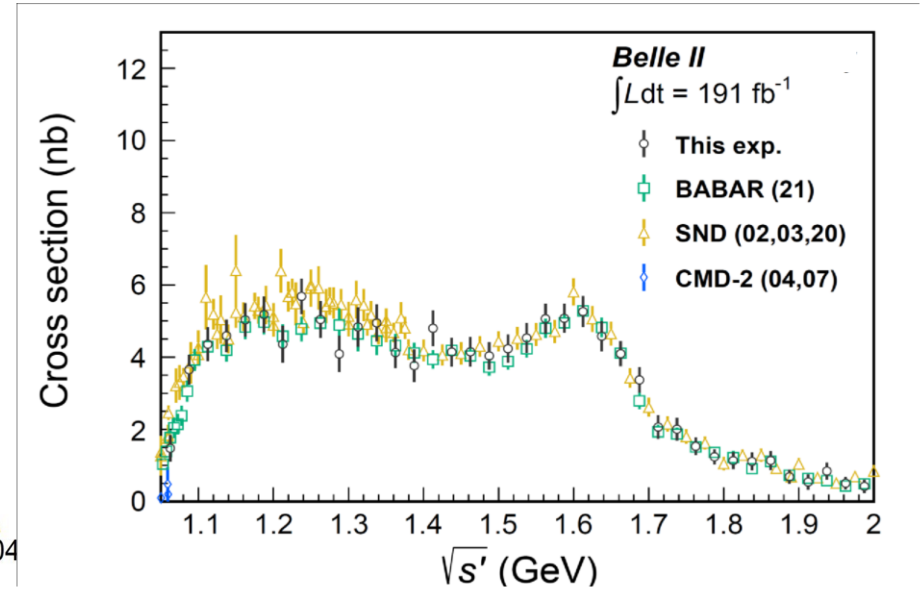
$\chi^2_{4C}(3\pi\gamma)$ < 50 is used for the cross section measurement

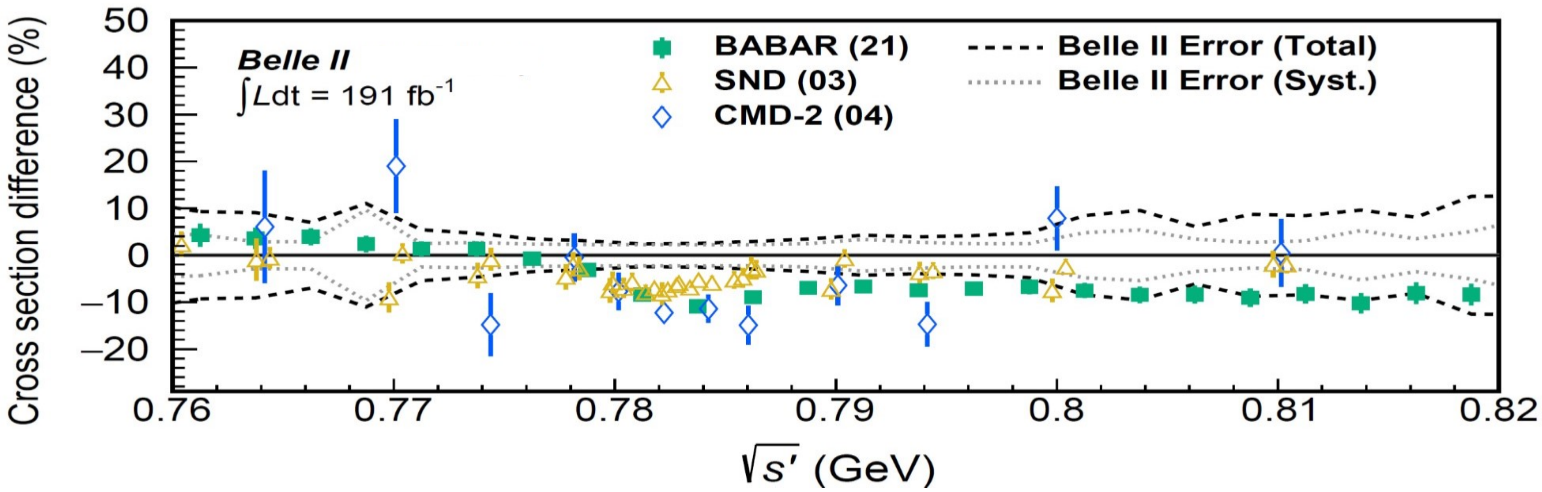


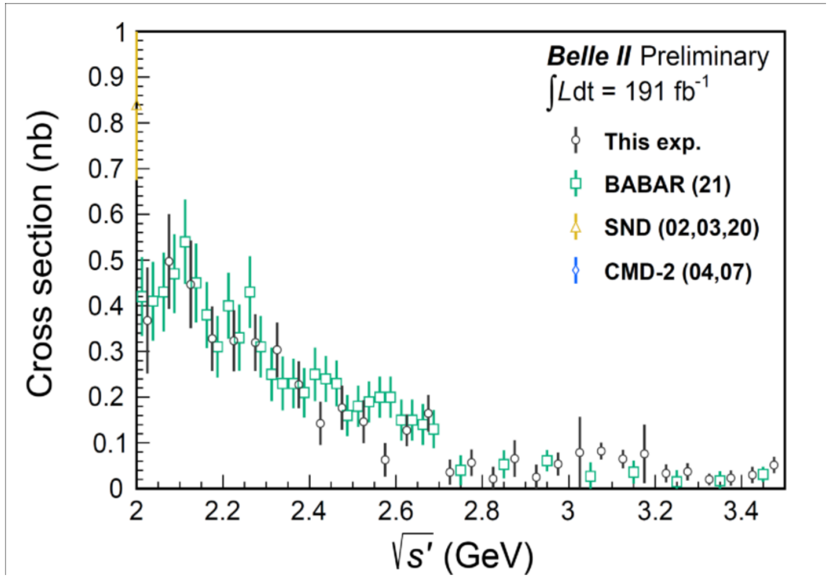
Result: cross section below 1.05 GeV











Results: 3π contribution to a_μHVP

a_μ(LO,HVP, 3π [0.62- 1.8 GeV]) = (48.91 ± 0.25stat ± 1.07syst) $\times 10^{-10}$

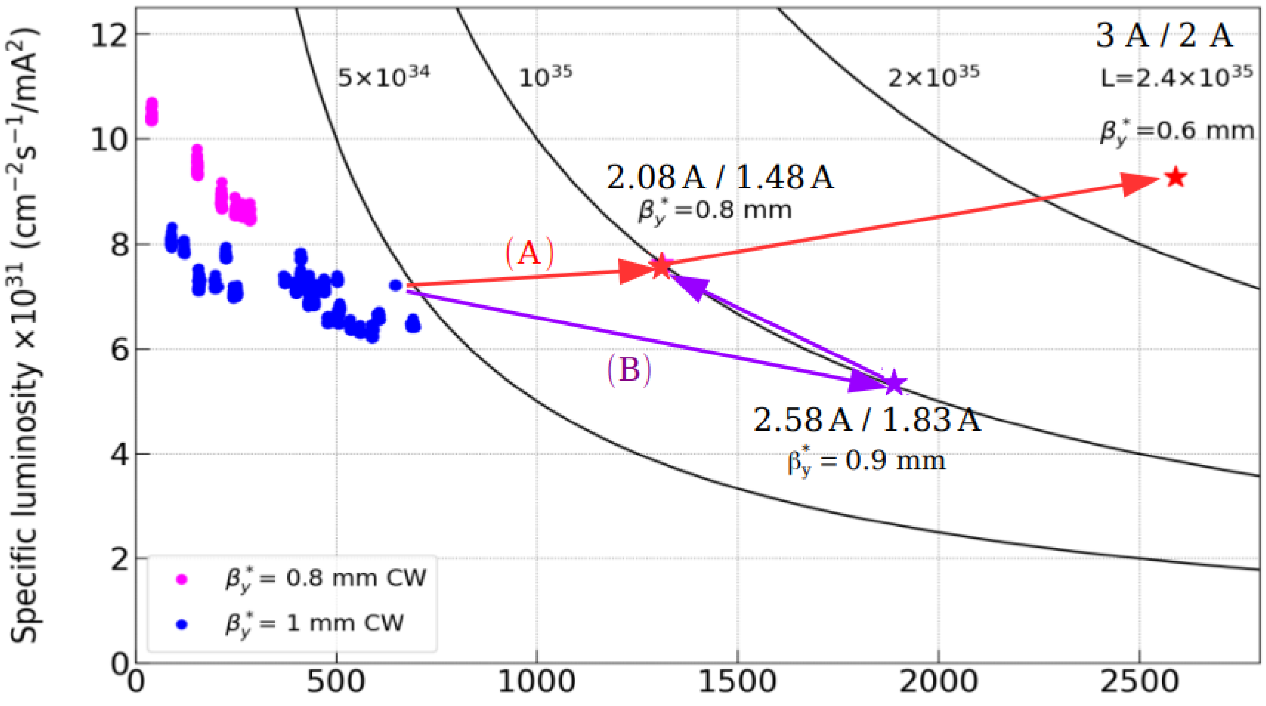
BABAR alone [PRD104 11 (2021)] 45.86±0.14±0.58 -3.2±1.3 (6.9%)
Global fit [JHEP08 208 (2023)] 45.91±0.37±0.38 -3.0±1.2 (6.5%)

Source	Systematic uncertainty (%)
Efficiency corrections	1.63
Monte Carlo generator	1.20
Integrated luminosity	0.64
Simulated sample size	0.15
Background subtraction	0.02
Unfolding	0.12
Radiative corrections	0.50
Vacuum polarization corrections	0.04
Total	2.19

6.5% higher than the global fit result with 2.5σ significance
This difference 3×10^{-10} corresponds 10% of $\Delta a_\mu = a_\mu(Exp) - a_\mu(SM) = 25 \times 10^{-10}$

Belle II near-term and and longer-term upgrades

The next run - Resume data taking in November 2025 for a long run of 7 months



$10^{35}cm^{-2}s^{-1}$ corresponds to ~$1ab^{-1}$/ year (for 8 months data taking period)

During Long Term shutdown 2 (LS2) (~2030)
New final focus
Upgrade or new subdetectors
Belle II near-term and and longer-term upgrades are reported in the Conceptual Design Report (CDR) published in June 2024: arXiv:2406.19421v2

Possible after LS2 upgrades:
– Higher energies→ Y 5*S* , Y 6*S* physics
– Beam polarization→ electroweak physics: sin2 θW, left-right asymmetries

Conclusion

- The Belle II experiment provides very wide field of researches including:
  - ❖ precise measurements of CKM elements, phases and CP violation
  - ❖ B mesons decays with missing energy $B \to K(*)\ \nu\ \nu$, $K(*)\ \tau\ \tau$, $K(*)\ \tau\ l$, $\tau\ \tau$, $\tau\ l$, $D(*)\ \tau\ \nu$, $\tau\ \nu$, $\mu\ \nu$...
  - ❖ Sudy of τ lepton decays and characteristics
  - ❖ Search for dark particles, ALP ets.
  - ❖ Precise measurement of the hadronic cross sections
  - ❖ Study of the exotic hadrons and many other opportunities
- By now Belle II collected 575 fb^{-1} and demonstrated high performance
- SuperKEKB reached the world highest luminosity $5\times10^{34} cm^{-2}s^{-1}$ and on the way to $10^{35} cm^{-2}s^{-1}$
- Many analyses of the Belle II data are ongoing
- Goal of Run 2: by LS2 (2032), accumulate > 5 ab^{-1}

Back up

Belle II physics program

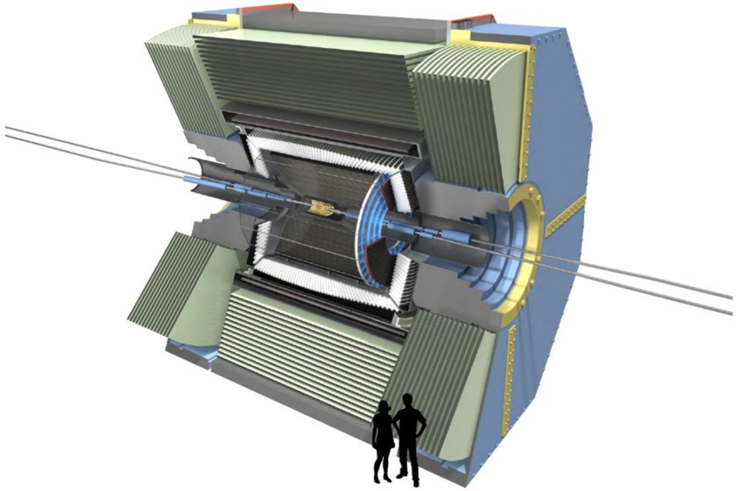
Snowmass White Paper arXiv:2207.06307v2 [hep-ex]

Collected data:

- ~ 375 fb^{-1} at Y(4S)
- 42 fb-1 off-resonance, 60 MeV below Y(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

Demands on the detector

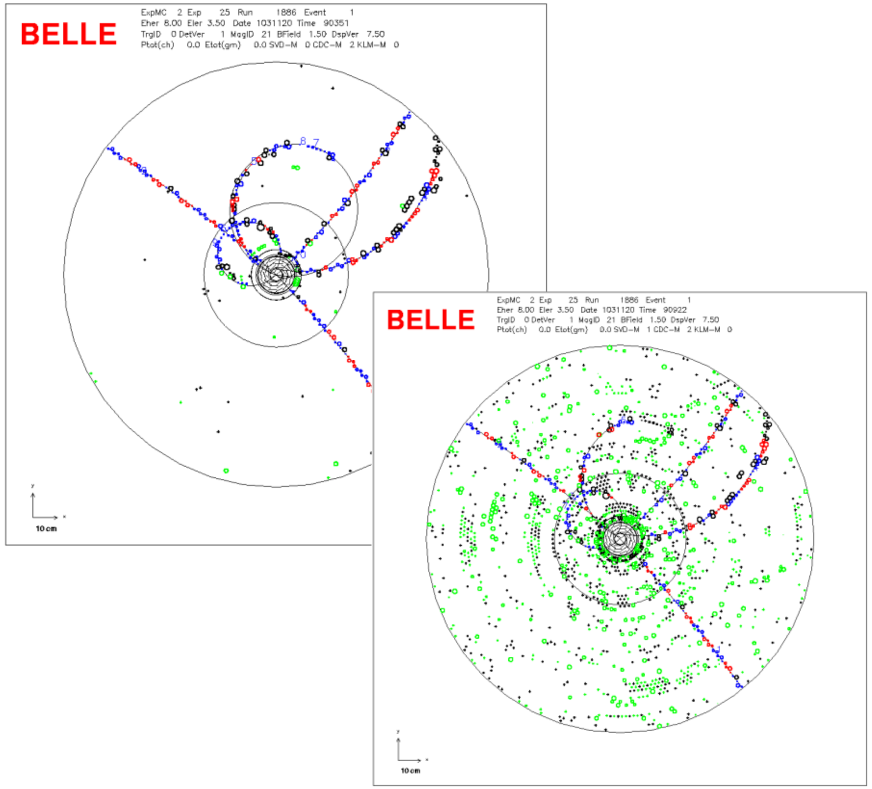
Total cross section and trigger rates with $L = 8\times10^{35}$ cm^{-2} s^{-1} from various physics processes at Υ(4S).

Physics process	Cross section (nb)	Rate (Hz)
Υ (4S) →BB	1.2	960
Hadron production from continuum	2.8	2200
$\mu^+\mu^-$	0.8	640
$\tau^+\tau^-$	0.8	640
Bhabha (θlab> 17°)	44	350[a]
γγ (θlab> 17°)	2.4	19 [a]
2γ processes (θlab> 17°, pt > 0.1GeV/c)	~80	~ 15000
Total	~130	~20000

(a) rate is pre-scaled by a factor of 1/100

The requirements for the trigger system are:

1. high efficiency for hadronic events;
2. maximum average trigger rate of 30 kHz;
3. fixed latency of about 5 μs;
4. timing precision of less than 10 ns;
5. minimum two-event separation of 200 ns;
6. trigger configuration that is flexible and robust.



Beam-related backgrounds are 10-20 x KEKB.
Radiative Bhabha, Touschek scattering, 2-photon

Fake hits, pile up, radiation damage!!

Efficiency and Systematic uncertainty

$$\sigma_{ee\to 3\pi} M_i = \frac{N_{i,unfolded}}{\varepsilon(M_i)\cdot L_{eff}(M_i)\cdot(1+\delta_{rad})}$$

Efficiency $\varepsilon = \varepsilon_{MK}\Pi(1+\delta_i)$ Data-MC correction $\delta_i \sim O(1)\%$

Source	Efficiency correction (%) 1.05 GeV/c2	M > 1.05 GeV/c2
Trigger	-0.1±0.1	-0.1±0.1
ISR photon detection	+0.2±0.7	+0.2±0.7
Tracking	-1.4±0.8	-1.7±0.8
π^0 detection	-1.4±1.0	-1.4±1.0
Background suppression	-1.9±0.2	-1.8±1.9
$\chi2$ distribution	0.0±0.6	0.3±0.3
MC generator	0.0±1.2	0.0±1.2
Total correction	-4.6±2.0	-4.6±2.0

Source	Systematic uncertainty (%) <1.05 GeV	>1.05GeV
Trigger efficiency	0.1	0.2
ISR photon efficiency	0.7	0.7
Tracking efficiency	0.8	0.8
$\Pi0$ efficiency	1.0	1.0
$\chi2$ criteria efficiency	0.6	0.3
Background suppression efficiency	0.2	1.9
MC generator	1.2	1.2
Radiative correction	0.5	0.5
Integrated luminosity	0.6	0.6
Total systematics	2.2	2.8