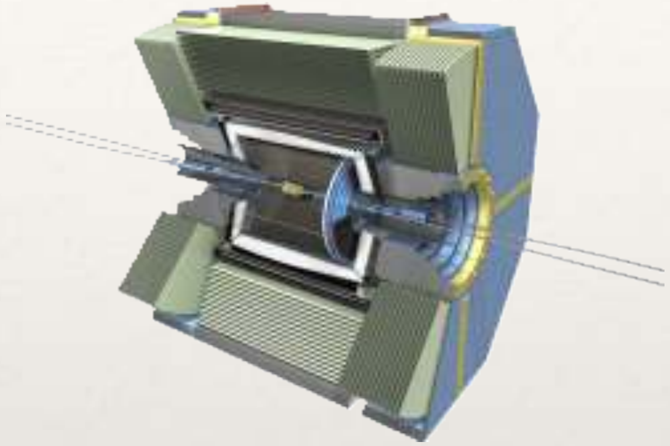
Ivan Heredia de la Cruz
CINVESTAV/CONACyT
Octubre 2021, Seminario ICN-UNAM & IF-UNAM

The Belle II experiment



Status and results

Overview

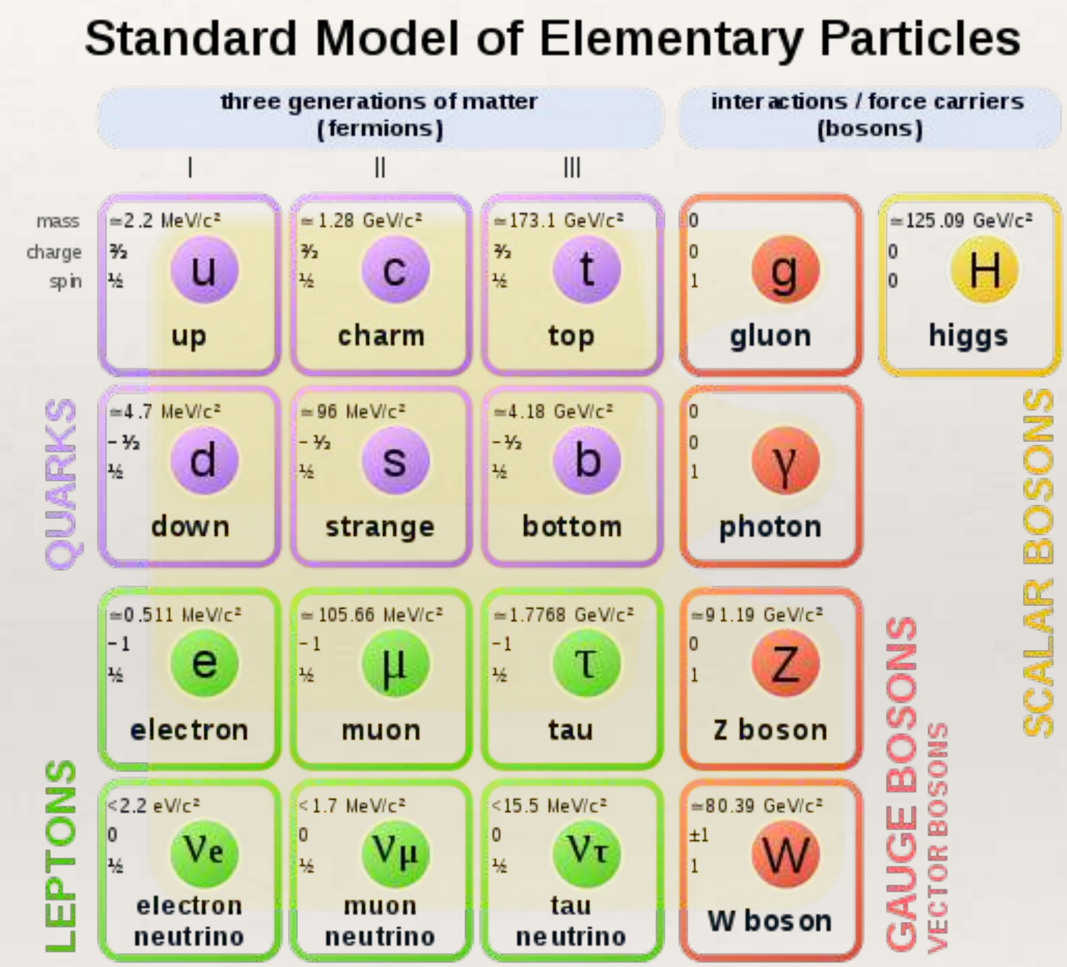
- Search for NP in B factories
- SuperKEKB & Belle II
- Tau preliminary results
- Summary

#CienciaBajoProtesta
#BuscoTrabajo
#SomosPuebloHaciendoCiencia

Searching for new physics

- **SM: best tested theory of nature at a fundamental level.**

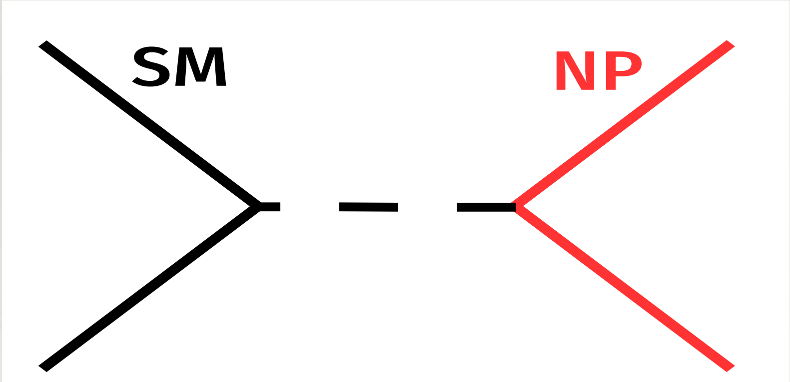
- However, **SM does not explain**:
  - Neutrino masses (can the Higgs account for it?)
  - Matter-antimatter asymmetry in the universe (implies undiscovered sources of CPV).
  - Only 3 generations of fermions and mass hierarchy.
  - CKM matrix ~diagonal (underlying flavor symmetry?)
  - Single Higgs (or more elaborate Higgs sector?)
  - Dark matter, etc.

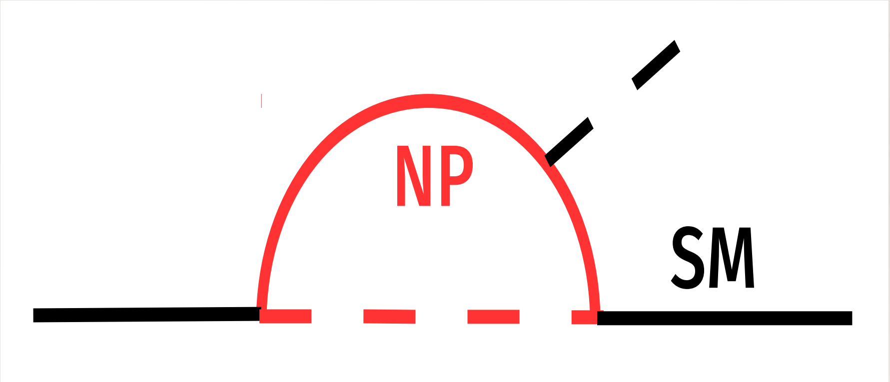


- ⇒ Present theory (SM) is only a phenomenological description of processes at energy scales up to $\mathcal{O}(1\ \text{TeV})$. **New physics scenarios are required to explain these issues.**

Searching for New Physics at colliders

- *Two approaches* at colliders:
  - Energy frontier: direct production of new particles, limited by beam energy (CMS & ATLAS @LHC).
  - Intensity (flavor) frontier: rare processes, reveal NP particles in loops, could test up to $\mathcal{O}$(100 TeV) ⇒ **high intensity colliders: B-Factories, LHCb,** …

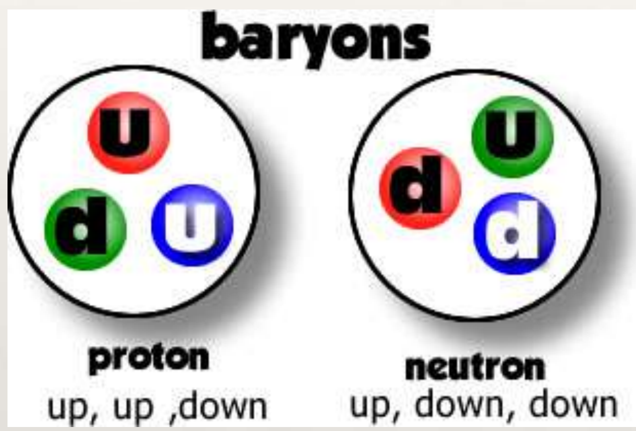


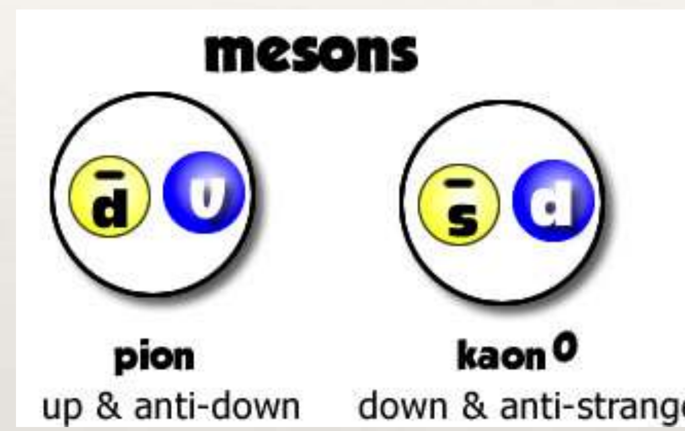


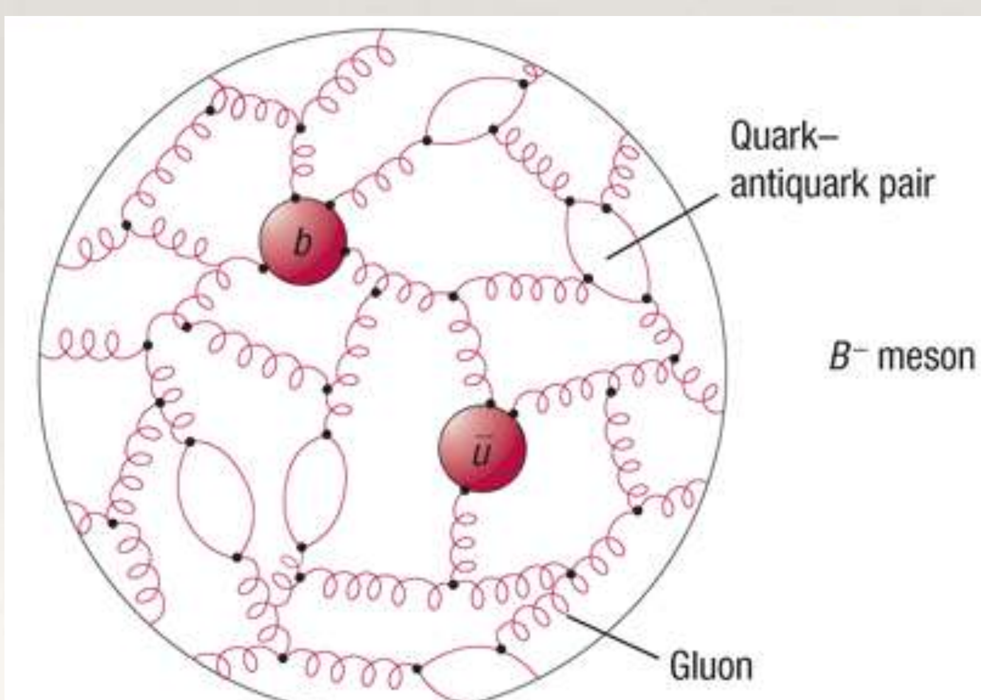
- *Complementarity*:
  - If NP at LHC, (measurable) effects will emerge in B, D, K & τ decays.
  - If not, measurements at **B-factories** will provide unique ways to find NP.

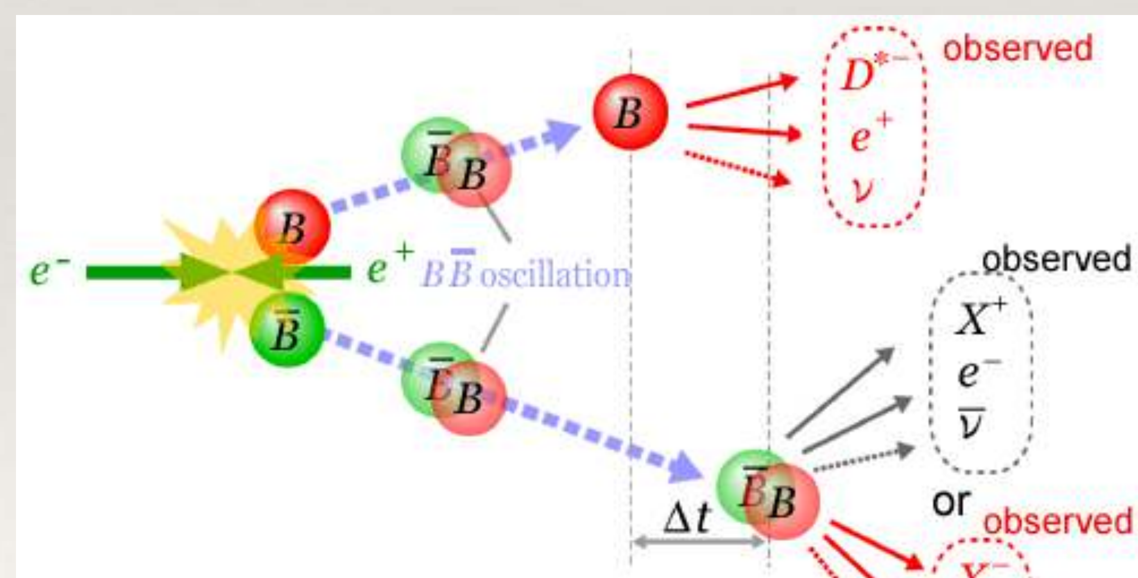
B mesons

- Hadrons are particles composed of quarks: baryons (3Q) & mesons (2Q).







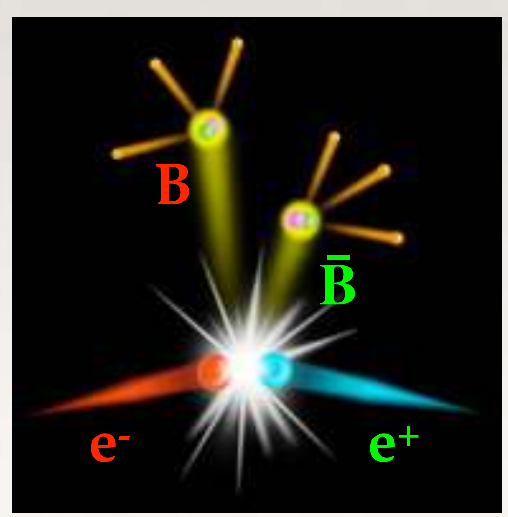


Entangled 1^{--} state

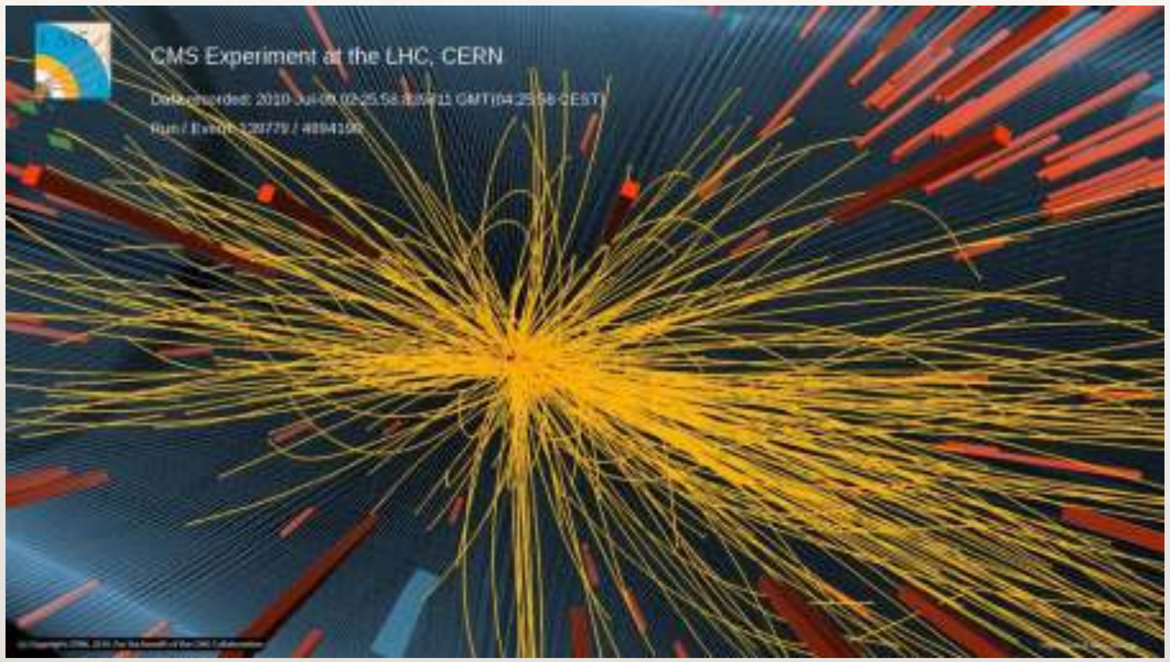
$$|\Upsilon\rangle = \frac{1}{\sqrt{2}}\left[|B^0(t_1)\rangle|\overline{B}^0(t_2)\rangle - |\overline{B}^0(t_1)\rangle|B^0(t_2)\rangle\right]$$

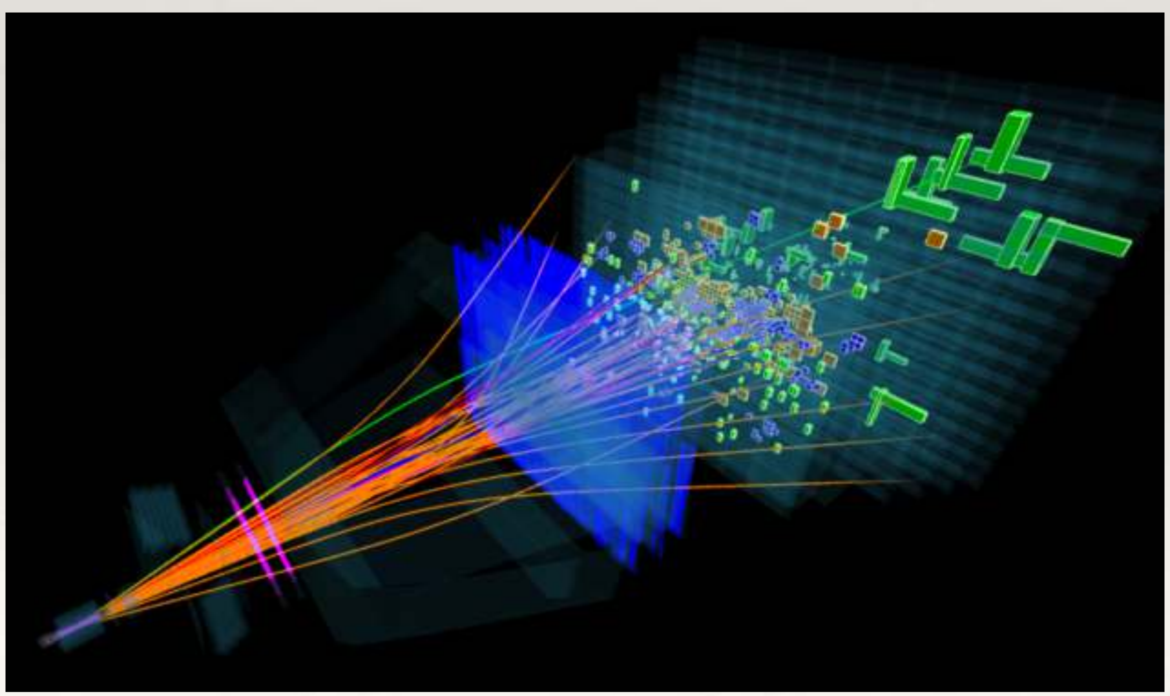
B-factories

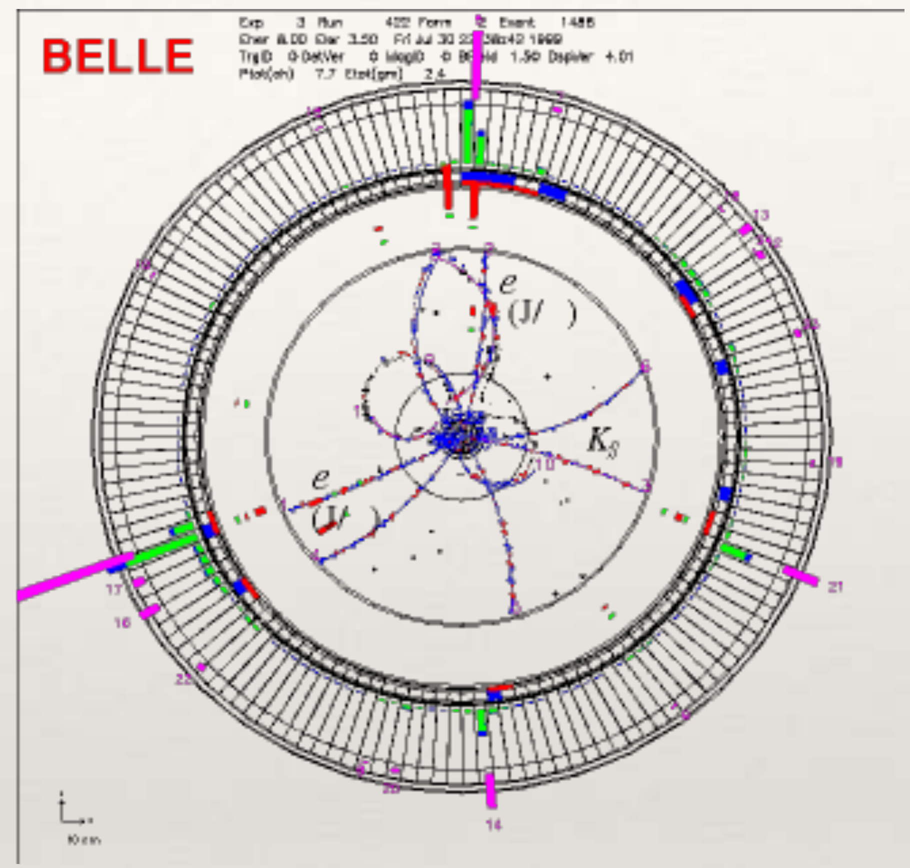
- PEP-II@SLAC & KEKB@KEK:
  - e^+e^- collisions at BaBar (99-08) & Belle (99-10).
- KEKB reached world highest luminosity (dN/dt/A), ~$2\text{x}10^{34}$ $cm^{-2}s^{-1}$.
- Collisions at $E_{CM} = m(Y(nS))c^2$:
  - Mainly at Y(4S), 10.58 GeV.
  - L ~ 1 ab^{-1} **Belle: ~800M $B\bar{B}$**.
- @ Belle ~ 500 papers.



Hadron colliders vs B factories



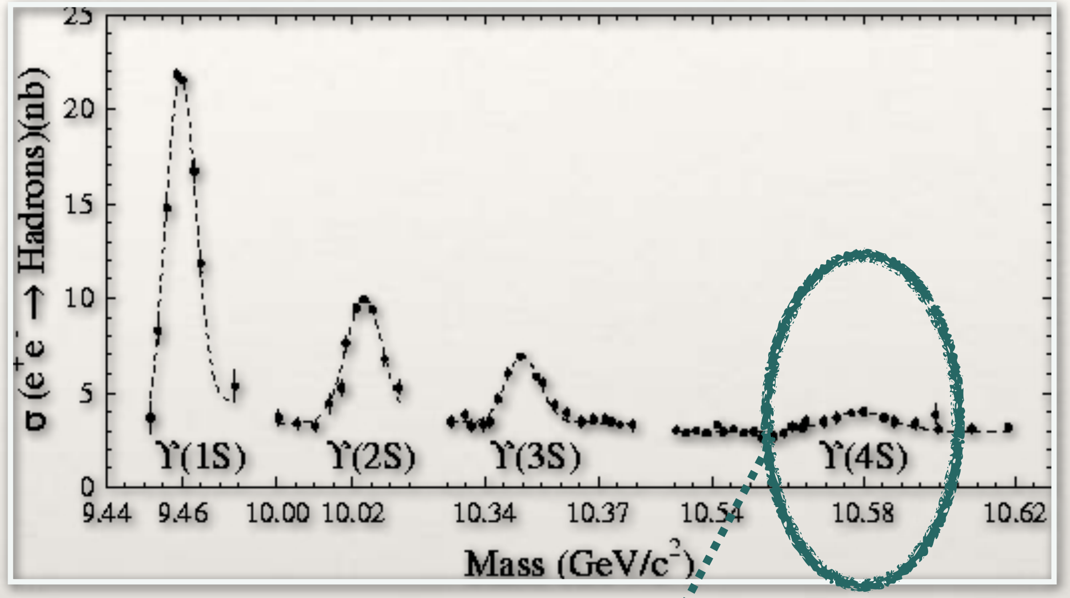


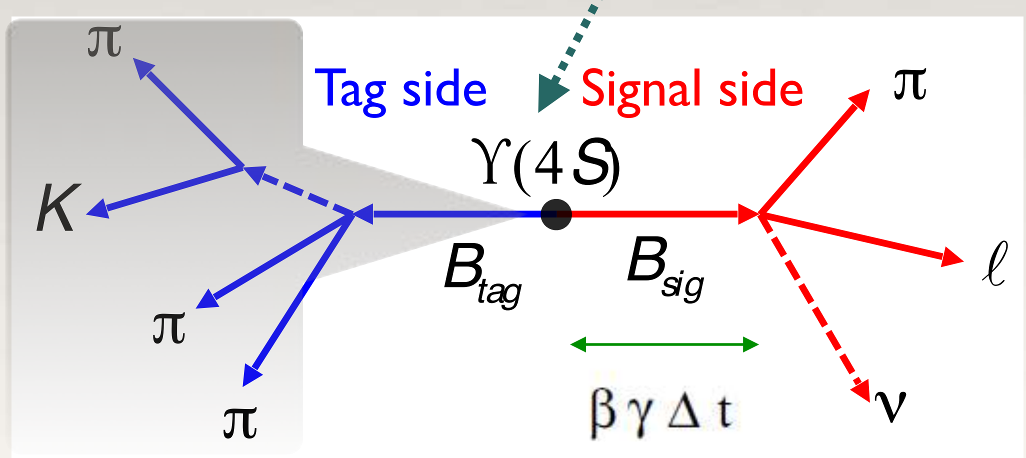


- Low background, few tracks (~10):
  - Easier detection of neutrals.
  - High reconstruction efficiency (B,D,τ).
  - Low trigger bias → small corrections/ syst.

Unique features in B factory

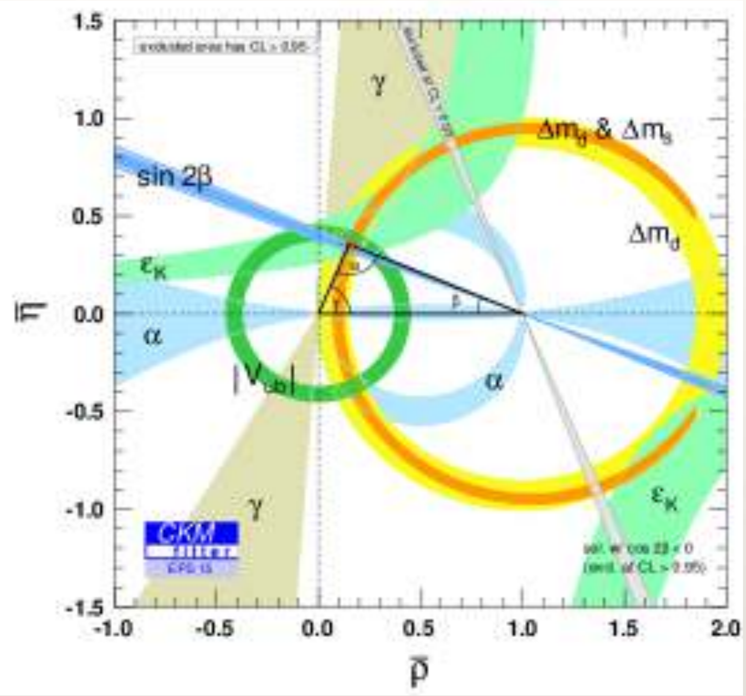
- E_{CM} can be adjusted:
  - $b\bar{b}$ spectroscopy, B_s @ $\Upsilon(5S)$, etc.
- Reconstruction of a B (B_{tag}) constrains flavor of the other (B_{sig}) & $\mathbf{p}(B_{sig}) = -\mathbf{p}(B_{tag})$.
- Particles not from B_{tag} must come from B_{sig}:
  - Inclusive measurements (absolute BR).
  - Missing energy channels, e.g. $B \to (D^*)\tau\nu$.
  - Tagging power > 30% (LHCb is 2%).
- Asymmetric beams → boosted $B\bar{B}$ → time dep. measurements (CPV).





B-factories achievements

- Observation and precise measurements of CPV in B decays.
- Observation of mixing in charm.
- Studies on rare B and τ decays.
- Discovery of many states (+exotics).
- Direct searches for light non-SM particles.
- Constrains on new physics.
- **Measurement of the Unitary Triangle (UT) parameters**.
    - Experimental confirmation of KM-mechanism (NP in Physics 2008).



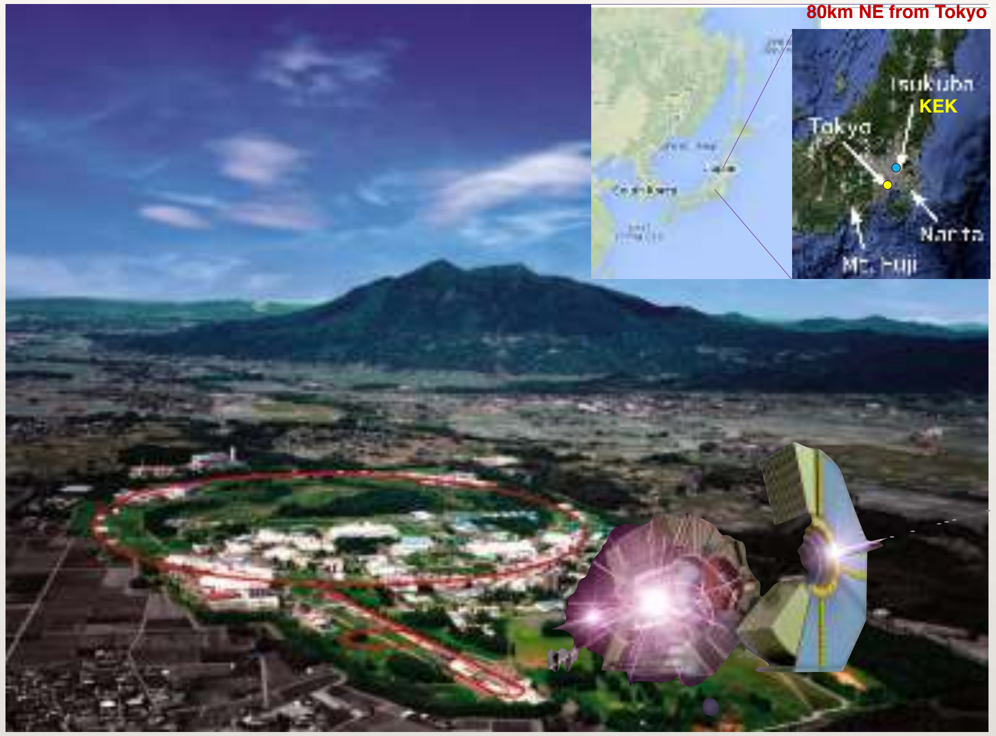
Makoto Kobayashi **Toshihide Maskawa**

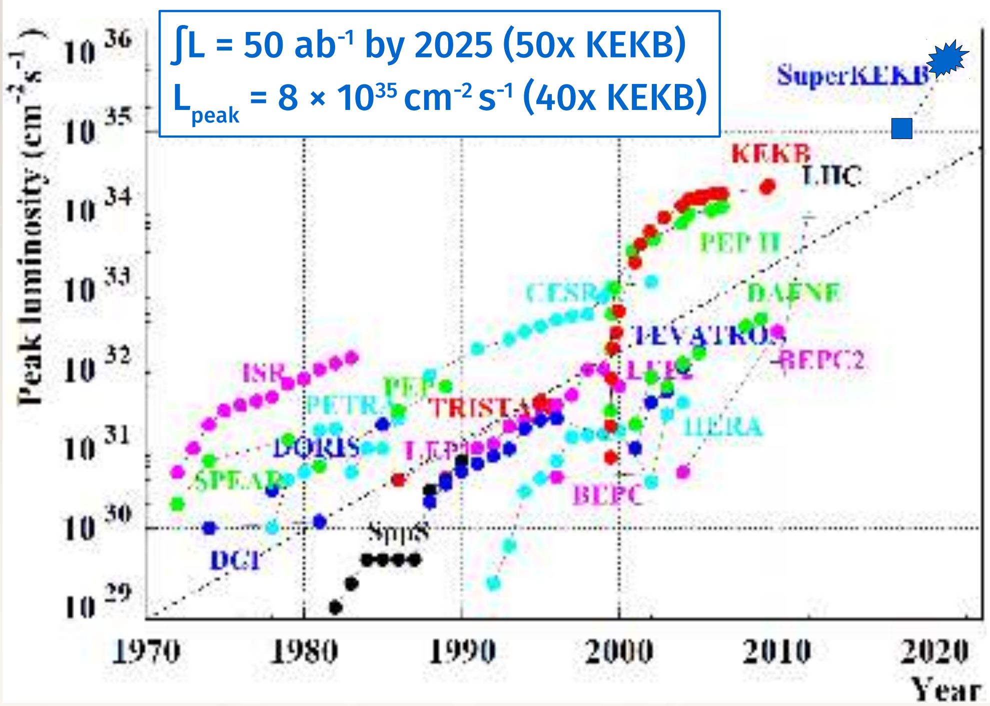
"For the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

SuperKEKB

- Located at KEK (High Energy Accelerator Research Organization), Tsukuba, Japan.
- Last generation B factory:
  - Major upgrade to KEKB.
- $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ mainly.
- Will deliver 50 ab^{-1} to Belle-II (50x KEKB).
- Peak lumi: 8 x 10^{35} cm^{-2} s^{-1} (40x KEKB).

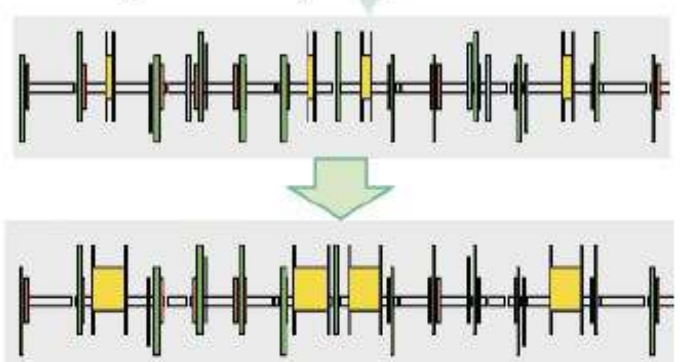
Channel	Belle	BaBar	Belle II (per year)
$B\bar{B}$	7.7×10^8	4.8×10^8	1.1×10^{10}
$B_s^{(*)}\bar{B}_s^{(*)}$	7.0×10^6	–	6.0×10^8
$\Upsilon(1S)$	1.0×10^8		1.8×10^{11}
$\Upsilon(2S)$	1.7×10^8	0.9×10^7	7.0×10^{10}
$\Upsilon(3S)$	1.0×10^7	1.0×10^8	3.7×10^{10}
$\Upsilon(5S)$	3.6×10^7	–	3.0×10^9
$\tau\tau$	1.0×10^9	0.6×10^9	1.0×10^{10}



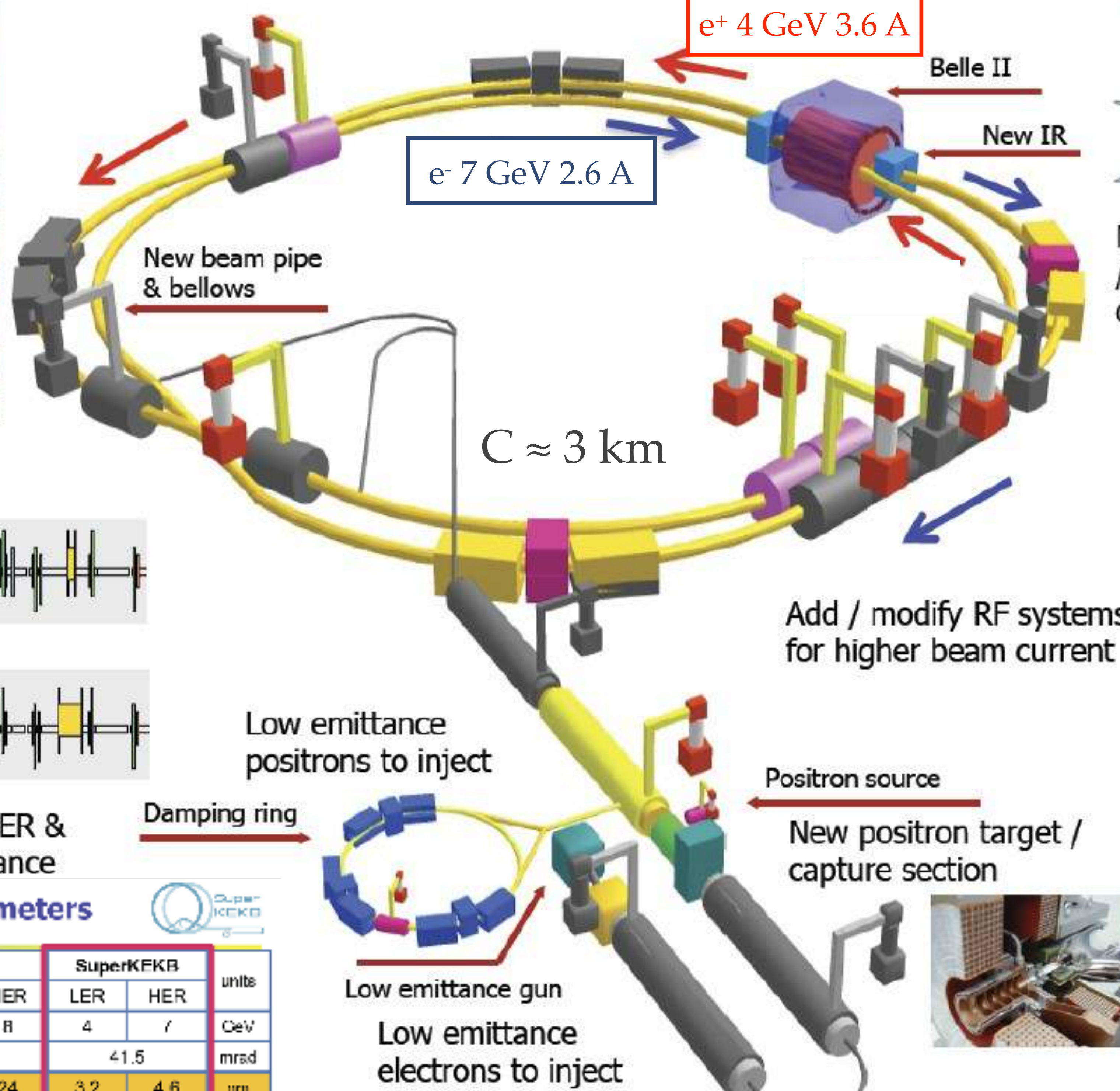


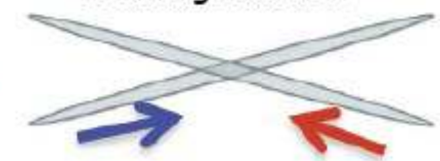
KEKB to SuperKEKB

Replace short dipoles with longer ones (LER)



Redesign the lattices of HER & LER to squeeze the emittance





Machine design parameters

parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
Beam energy	E_b	3.5	8	4	7	GeV
Half crossing angle	φ	11		41.5		mrad
Horizontal emittance	ε_x	18	24	3.2	4.6	nm
Emittance ratio	κ	0.88	0.66	0.37	0.40	%
Beta functions at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.30	mm
Beam currents	I_b	1.64	1.19	3.60	2.60	A
beam-beam parameter	ξ_y	0.129	0.090	0.0881	0.0807	
Luminosity	L	2.1×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$

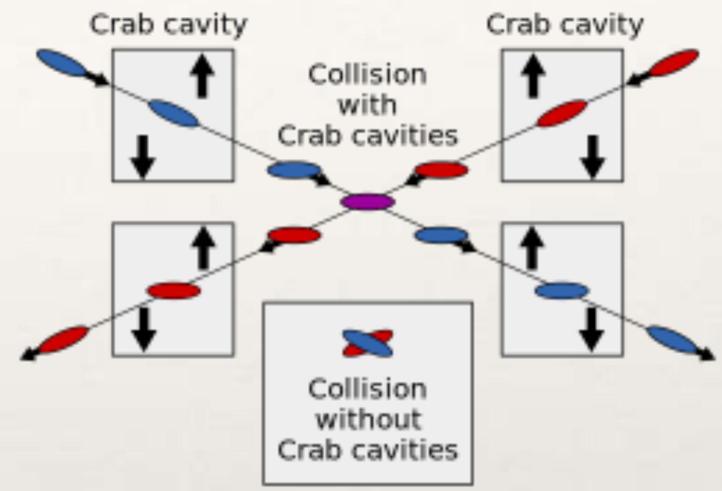
40x luminosity increase!

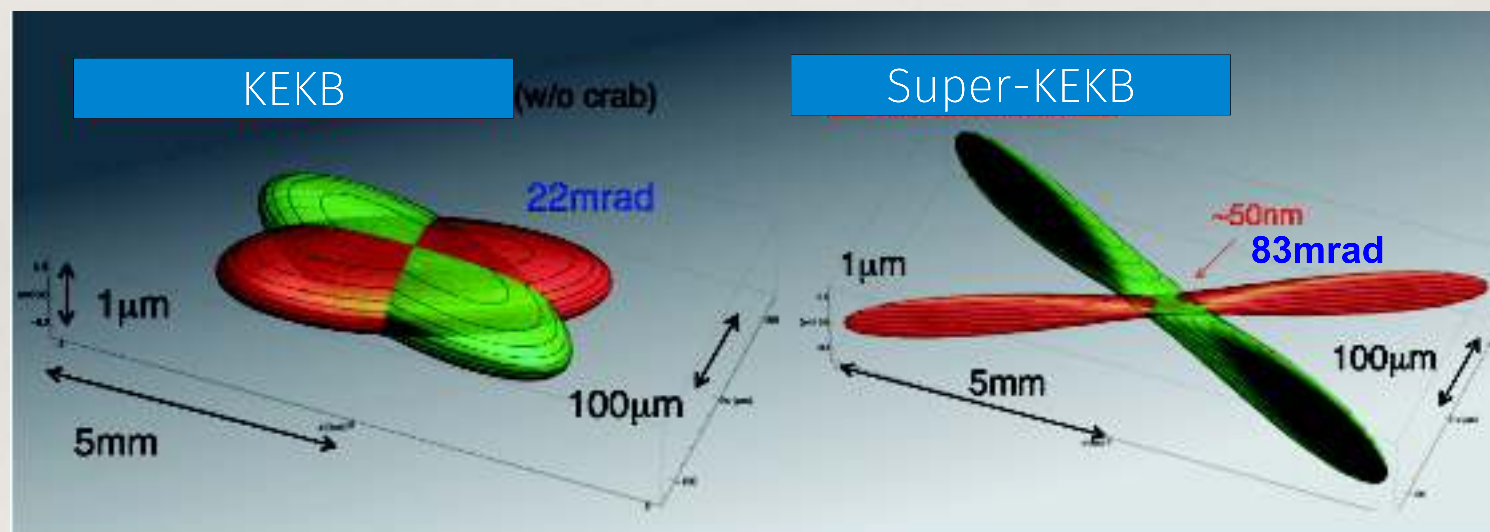
Luminosity increase

- Reduced beam size (1/20) by using nano-beams:
  - SC focusing quads near IP.
- Currents increased by 2-3.
- Larger crossing angle (~4x).
  - Avoids long-range beam-beam collisions.
  - Crab cavities restore head-on collisions.
- Higher energy of positron beam (LER) increases its lifetime.

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

Lorentz factor; Beam current; Beam-Beam parameter; Geometrical reduction factors (crossing angle, hourglass effect); Vertical beta function at IP; Beam aspect ratio at IP



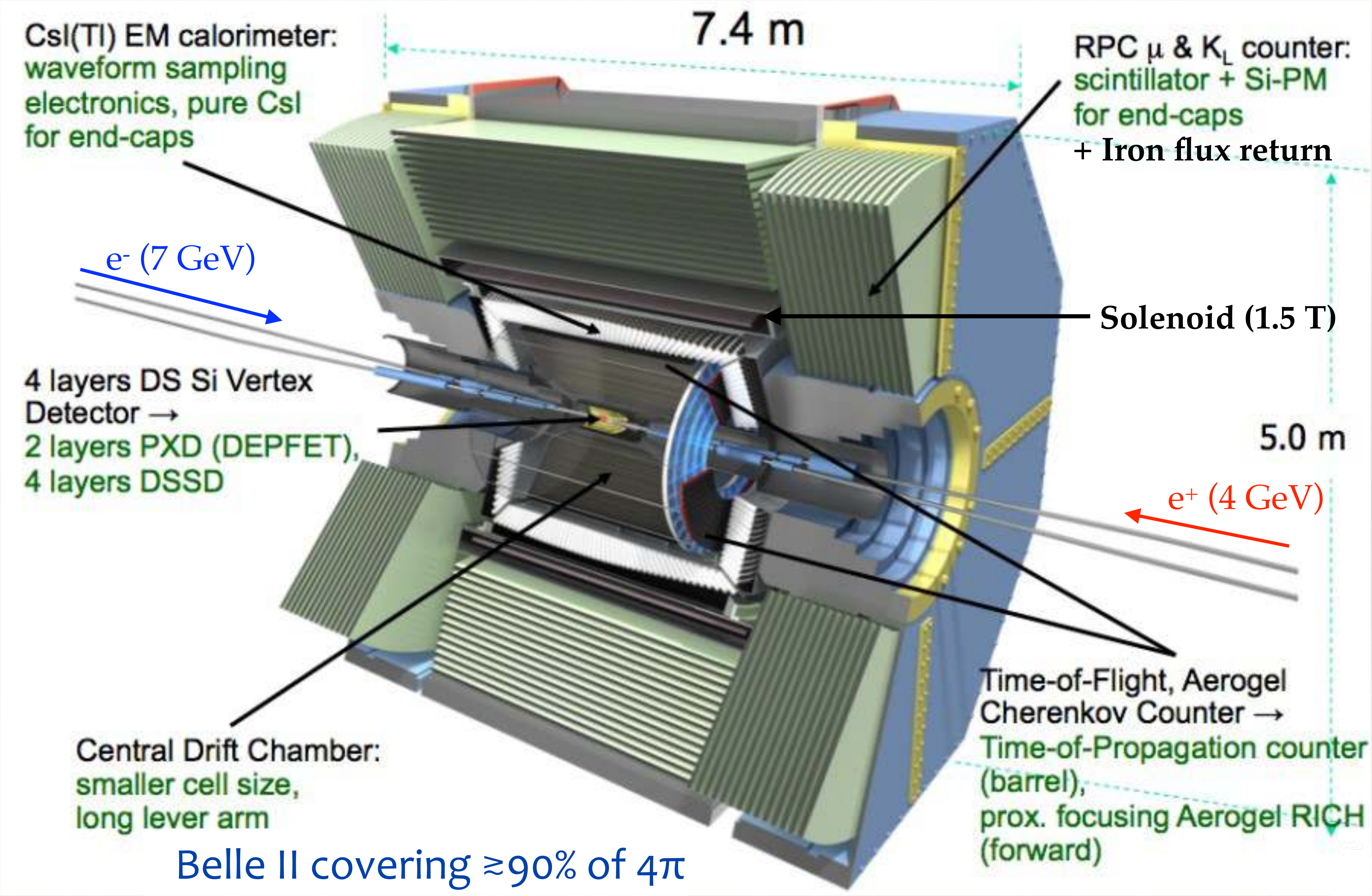


	E (GeV) LER/HER	β*y (mm) LER/HER	β*x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L (cm⁻²s⁻¹)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80×10^{34}

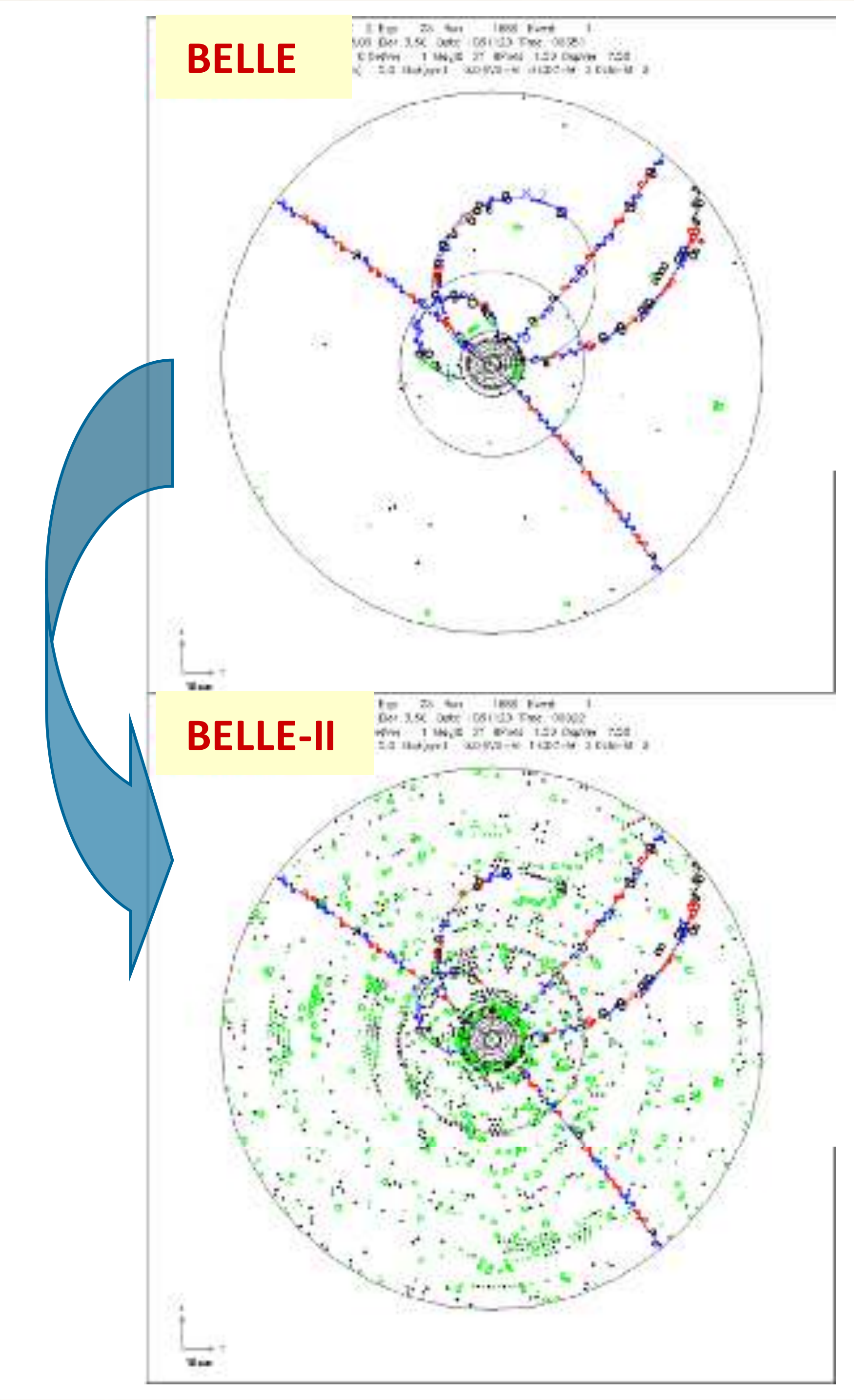
factor 20   factor 2-3

The Belle-II detector at SuperKEKB

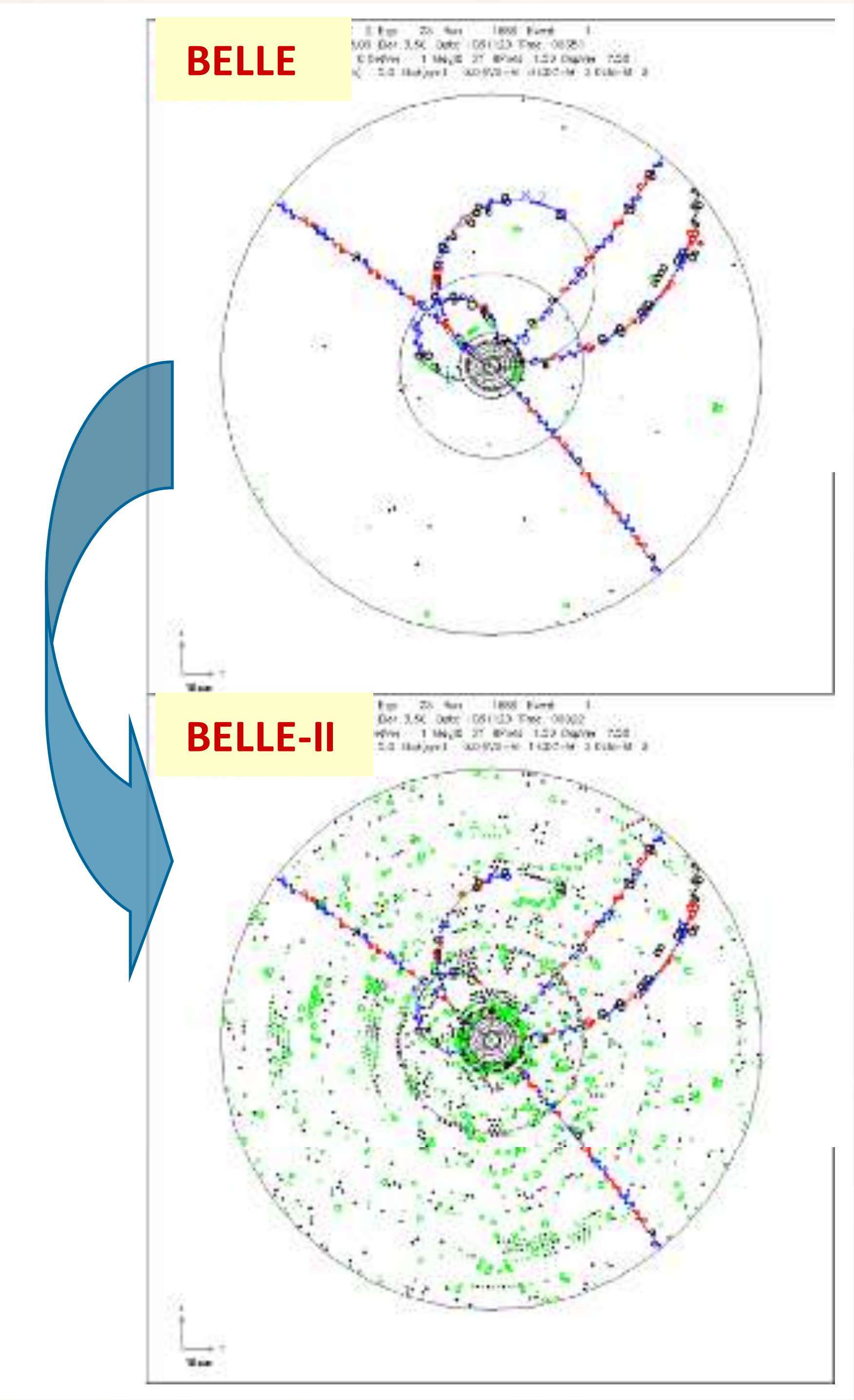
The Belle-II detector



From Belle to Belle-II

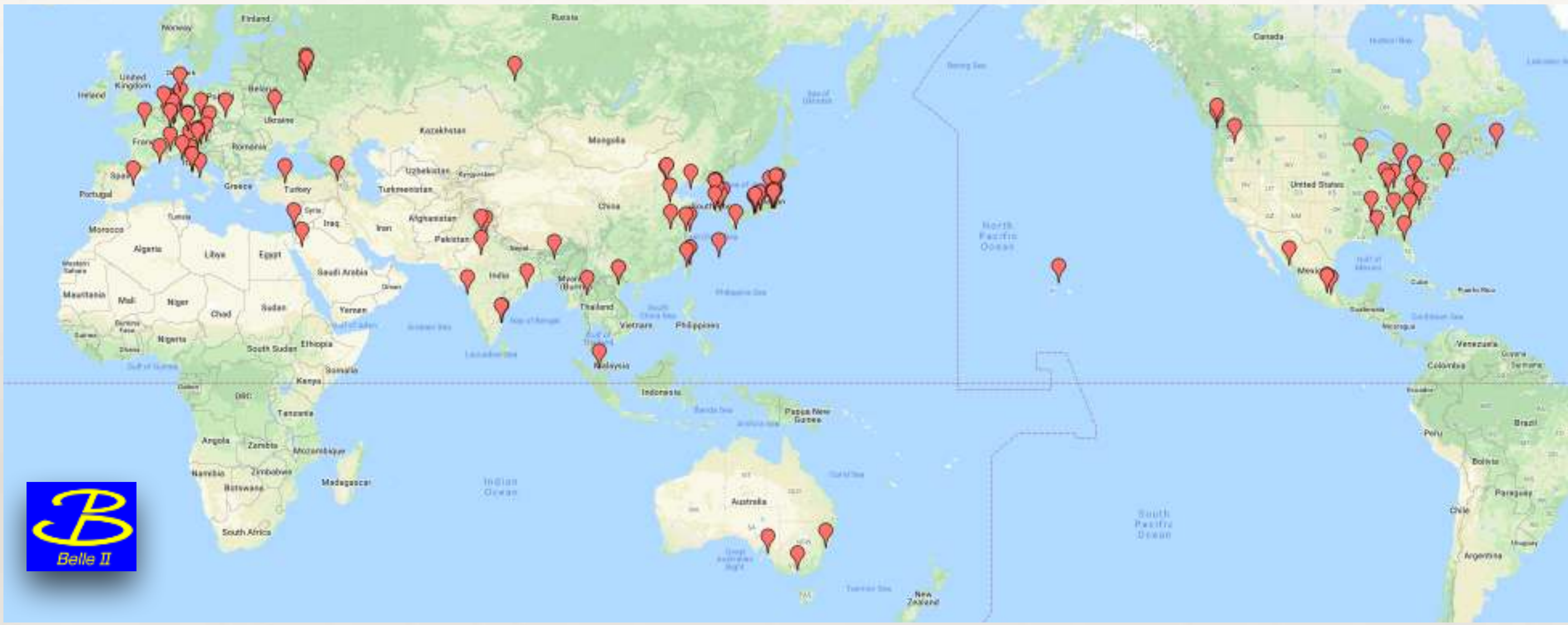


From Belle to Belle-II



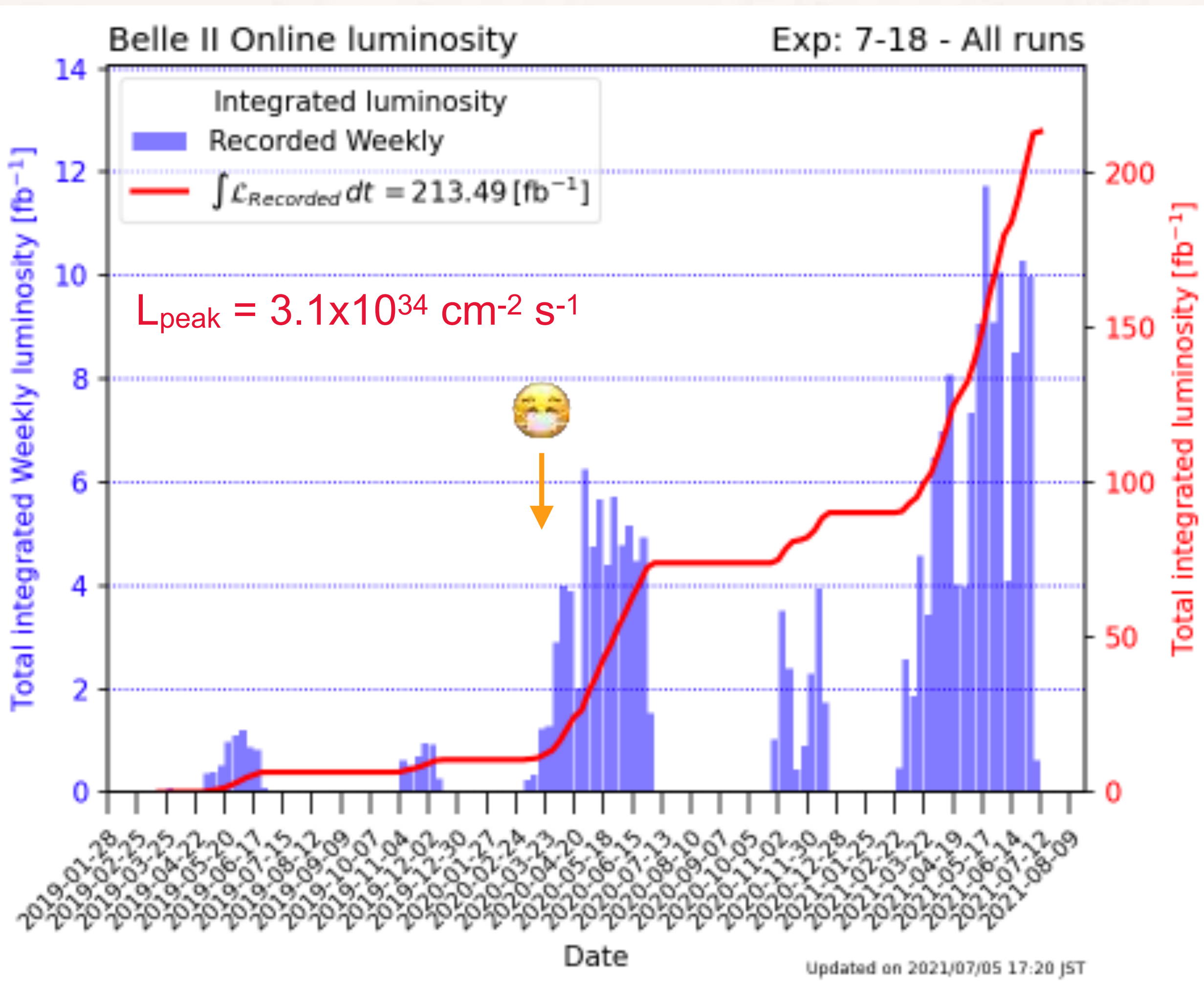
- **Several sub detectors upgraded or replaced** for improved performance at higher luminosity:
  - Higher beam bkg ⇒ higher occupancy, fake hits, rad. damage.
  - Event rates (0.5 → 30 KHz).
- **Larger tracker** (SVD & CDC):
  - Improve vertex resolution, K^0_S (+30%) & π^0 reco, …
- **Smaller beam pipe** (1.5 → 1.0 cm), PXD closer to IP:
  - Improve IP_z resolution (~60 → ~20 μm).
- **Upgraded TOP & ARICH**:
  - Better K/π/p separation, bkg rejection, …
- **Improved hermeticity** (PID & μ-ID in endcaps).
- **Improved trigger, DAQ, computing, algorithms**.

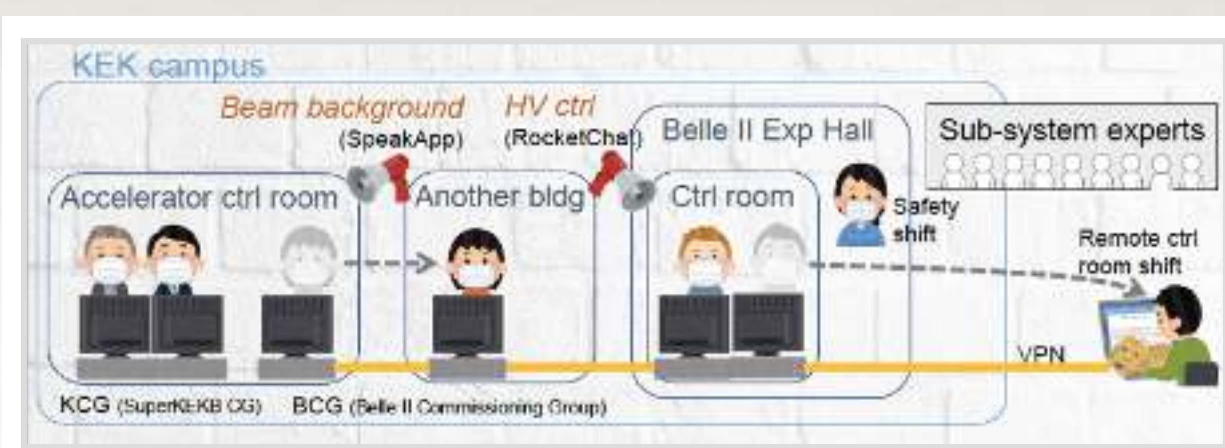
The Belle II Collaboration



1100 colleagues, 26 countries, 123 institutions

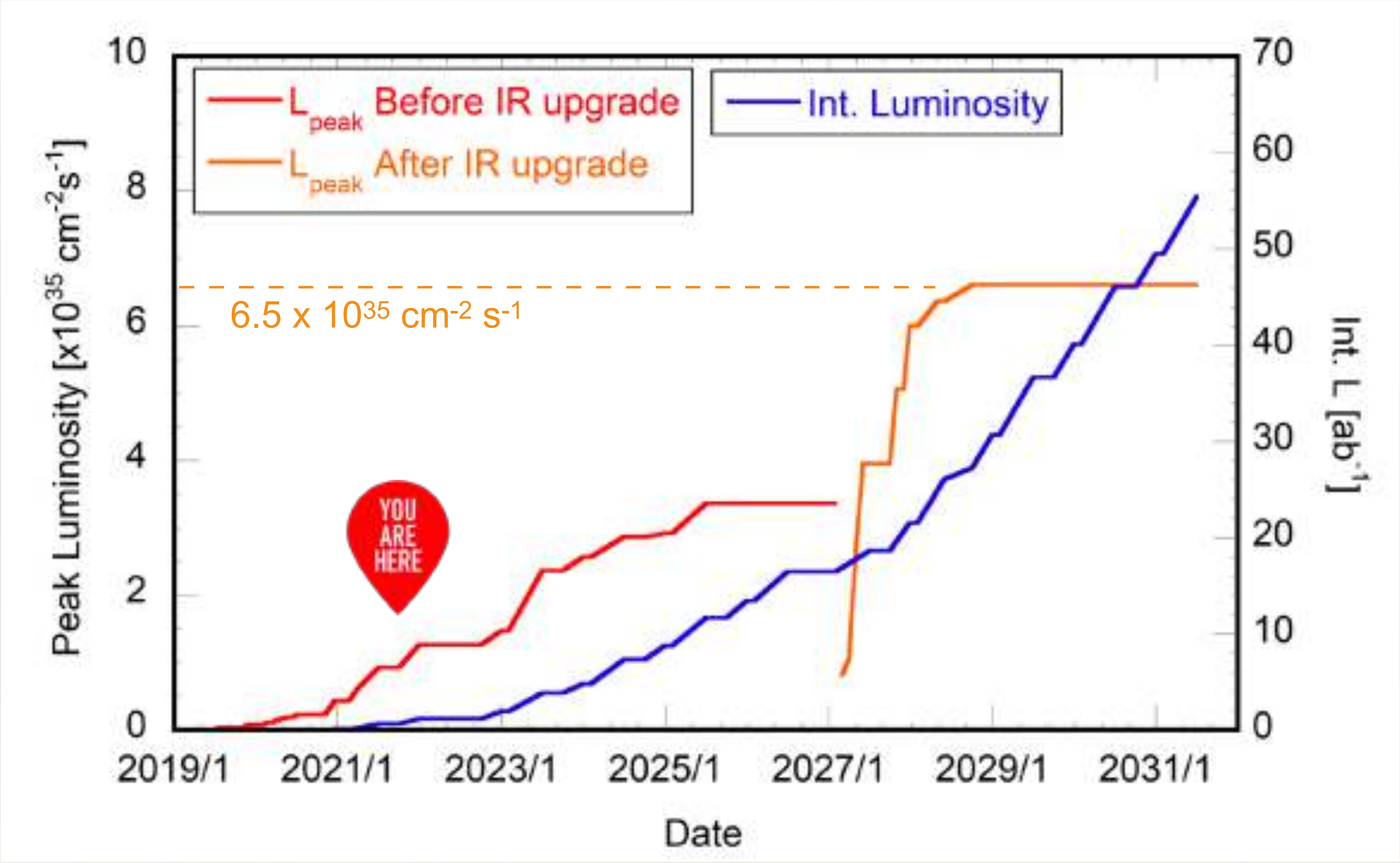
Belle-II in the COVID-19 era





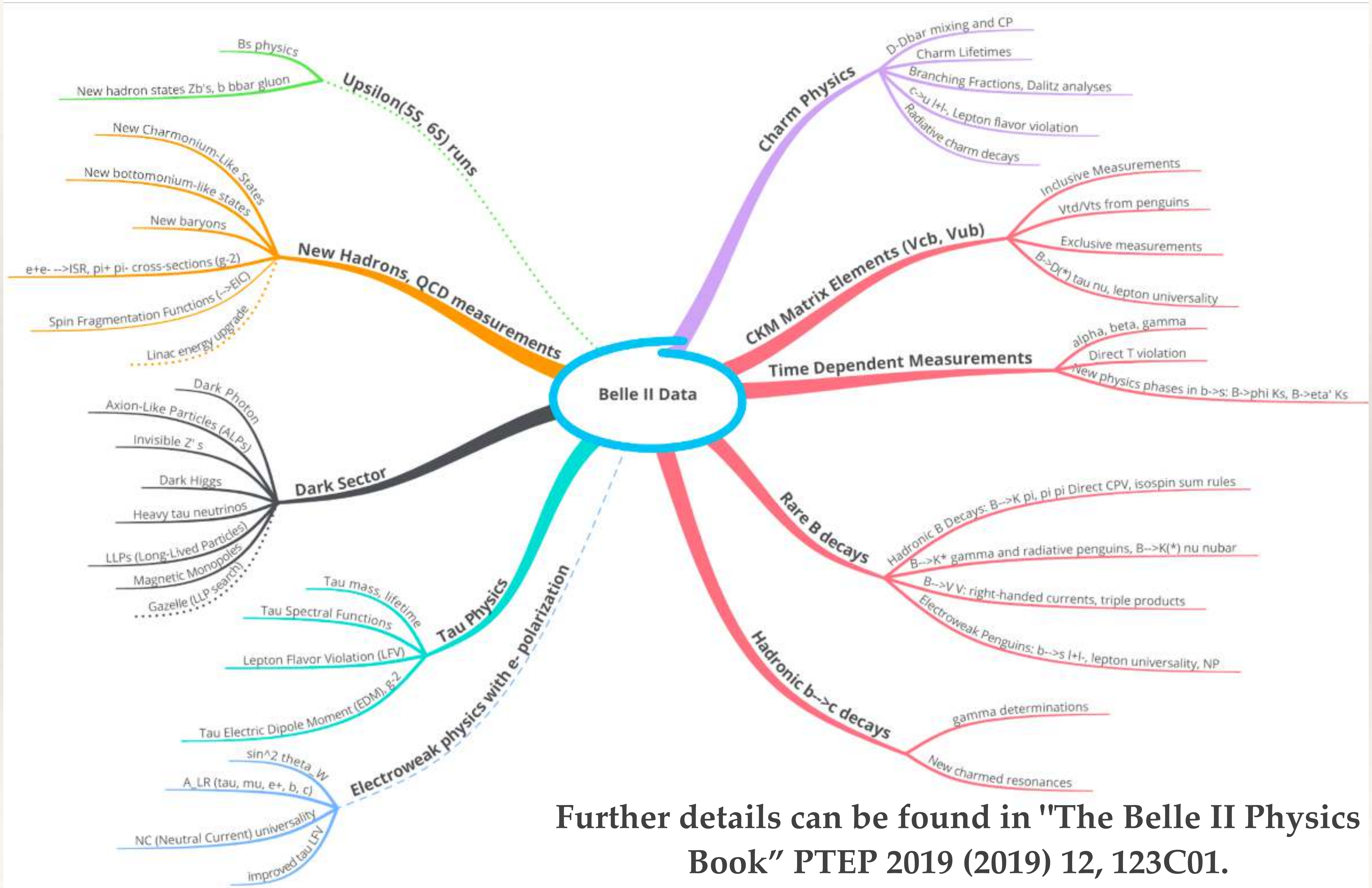
- Super B-factory performance levels, despite a global pandemic.
- World records:
  - 1.96 fb^{-1}/day, 12 fb^{-1}/week, 40 fb^{-1}/month.
- Luminosity above the B factories and LHC, with a product of beam currents 3.5 times lower than KEKB. World highest inst. lumi. 3.1 x 10^{34} cm^{-2} s^{-1} on 22 June 2021.
- “Social distancing” scheme for on-site shifts, and mobilized remote shifters around the world.

Projections



- Target: x40 the integrated luminosity collected by previous B-factories.
- ~500 fb^{-1} by next summer (2022).
- O(10 ab^{-1}) by the upgrade of the IR (2026).
- 50 ab^{-1} after the upgrade, by 2030.

Belle II Physics Program

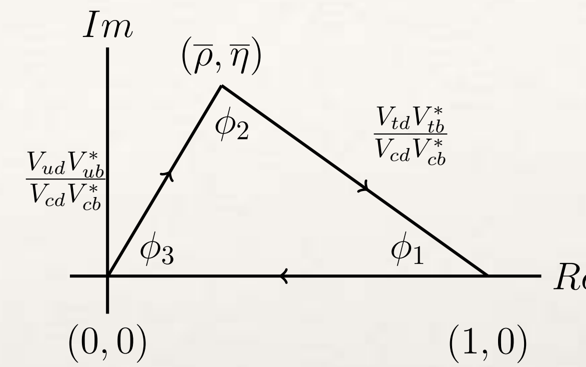


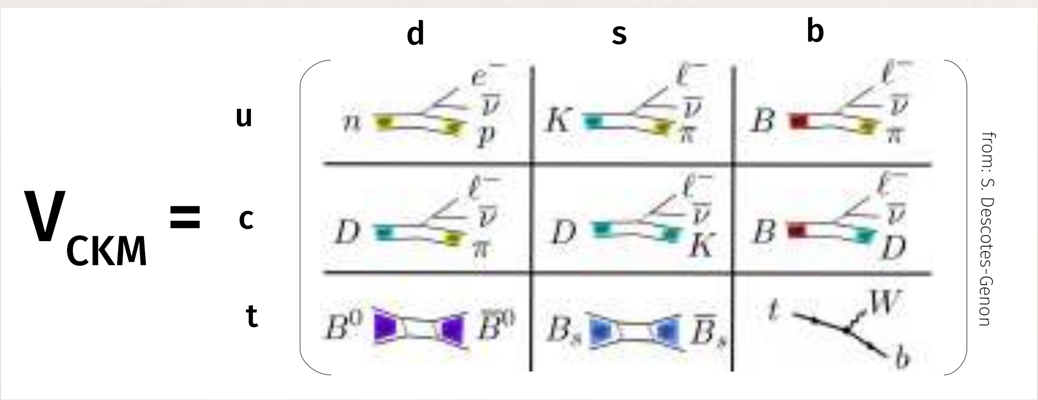
Further details can be found in "The Belle II Physics Book" PTEP 2019 (2019) 12, 123C01.

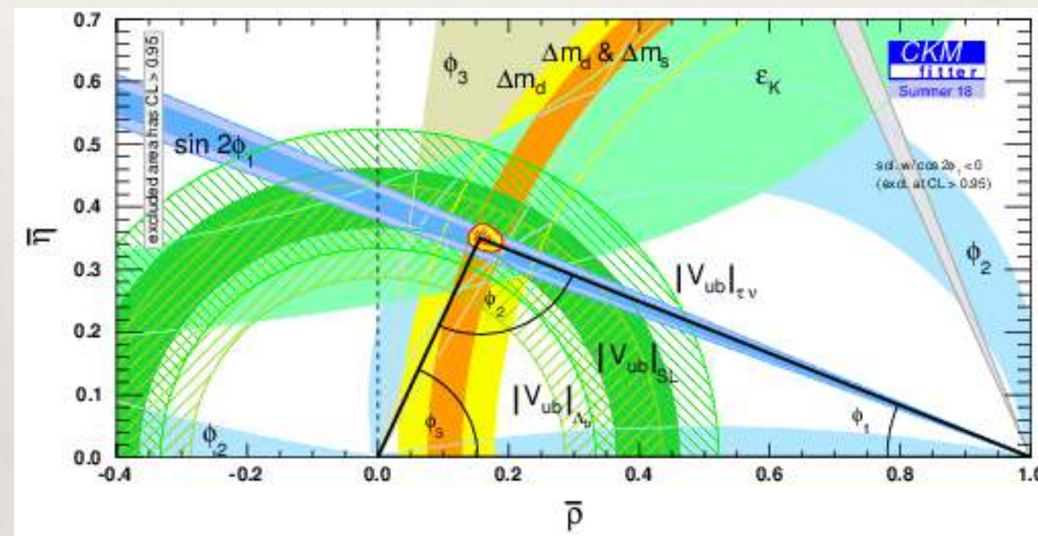
E.g. CKM Tests

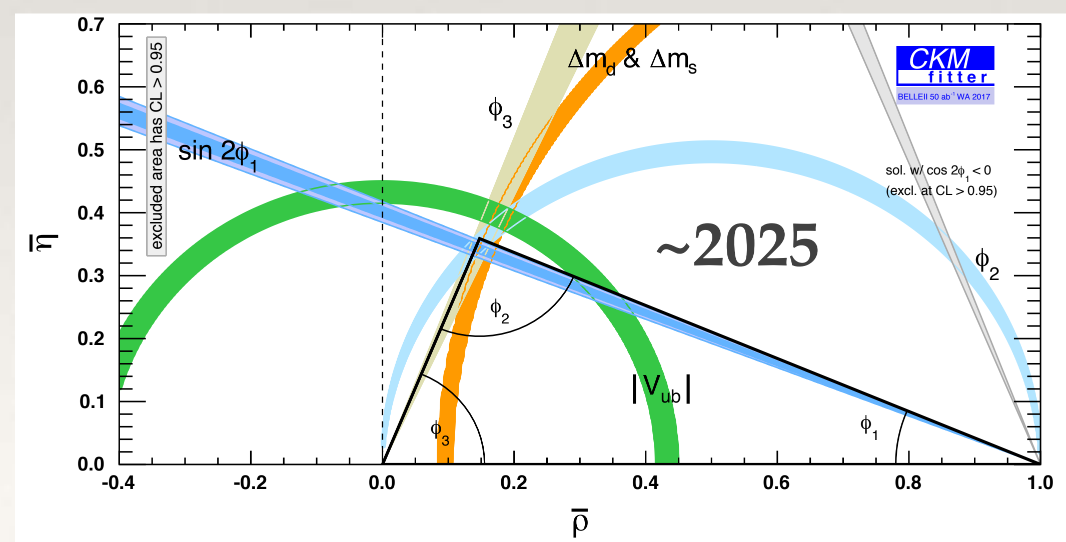
Unitary triangle: $1 + \frac{V_{ud}^* V_{ub}}{V_{cd} V_{cb}^*} + \frac{V_{td}^* V_{tb}}{V_{cd} V_{cb}^*} = 0$

$$\phi_1 \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right], \quad \phi_2 \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right], \quad \phi_3 \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$









Goal is to (over-)constrain UT with several measurements., e.g., $|V_{ub}|$ from $\mathbf{B^0 \to \pi^- l^+ \nu}$, $\mathbf{B^+ \to \tau^+ \nu}$ & $\Lambda_b \to p\mu^- \bar\nu$ BRs.

Belle II will be able to test CKM at ~1% level (and explore tensions e.g. btw sin2ϕ_1 & $|V_{ub}|$)

Summary of key flavor observables

Observables	Expected the. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	LHCb/Belle II
$\|V_{cb}\|$ incl.	***	1%	Belle II
$\|V_{cb}\|$ excl.	***	1.5%	Belle II
$\|V_{ub}\|$ incl.	**	3%	Belle II
$\|V_{ub}\|$ excl.	**	2%	Belle II/LHCb
CP Violation			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb
Radiative & EW Penguins			
$\mathcal{B}(B \to X_s\gamma)$	**	4%	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***	0.005	Belle II
$S(B \to K_S^0\pi^0\gamma)$	***	0.03	Belle II
$S(B \to \rho\gamma)$	**	0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**	0.3	Belle II
$\mathcal{B}(B \to K^*\nu\overline{\nu})$ $[10^{-6}]$	***	15%	Belle II
$\mathcal{B}(B \to K\nu\overline{\nu})$ $[10^{-6}]$	***	20%	Belle II
$R(B \to K^*\ell\ell)$	***	0.03	Belle II/LHCb
Charm			
$\mathcal{B}(D_s \to \mu\nu)$	***	0.9%	Belle II
$\mathcal{B}(D_s \to \tau\nu)$	***	2%	Belle II
$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	**	0.03	Belle II
$\|q/p\|(D^0 \to K_S^0\pi^+\pi^-)$	***	0.03	Belle II
$\phi(D^0 \to K_S^0\pi^+\pi^-)$ [°]	***	4	Belle II
Tau			
$\tau \to \mu\gamma$ $[10^{-10}]$	***	< 50	Belle II
$\tau \to e\gamma$ $[10^{-10}]$	***	< 100	Belle II
$\tau \to \mu\mu\mu$ $[10^{-10}]$	***	< 3	Belle II/LHCb

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ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	LHCb/Belle II
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$\|V_{cb}\|$ excl.	***	1.5%	Belle II
$\|V_{ub}\|$ incl.	**	3%	Belle II
$\|V_{ub}\|$ excl.	**	2%	Belle II/LHCb
CP Violation			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
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$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb
Radiative & EW Penguins			
$\mathcal{B}(B \to X_s\gamma)$	**	4%	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***	0.005	Belle II
$S(B \to K_S^0\pi^0\gamma)$	***	0.03	Belle II
$S(B \to \rho\gamma)$	**	0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**	0.3	Belle II
$\mathcal{B}(B \to K^*\nu\overline{\nu})$ $[10^{-6}]$	***	15%	Belle II
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$\phi(D^0 \to K_S^0\pi^+\pi^-)$ [°]	***	4	Belle II
Tau			
$\tau \to \mu\gamma$ $[10^{-10}]$	***	< 50	Belle II
$\tau \to e\gamma$ $[10^{-10}]$	***	< 100	Belle II
$\tau \to \mu\mu\mu$ $[10^{-10}]$	***	< 3	Belle II/LHCb

We can also explore the τ sector

Cross sections at 10.58 GeV

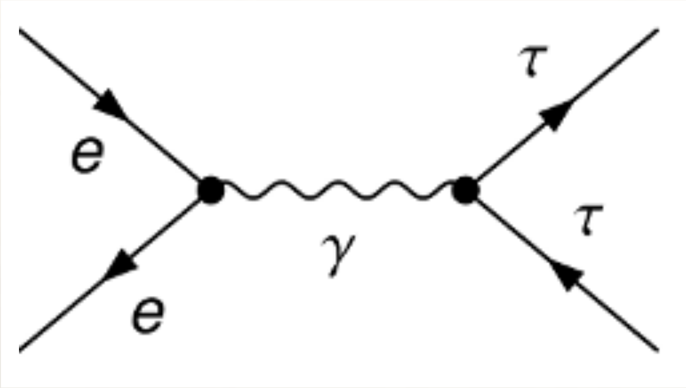
Table 18: Total production cross section from various physics processes from collisions at $\sqrt{s} = 10.58\,\text{GeV}$. $W_{\ell\ell}$ is the minimum invariant secondary fermion pair mass.

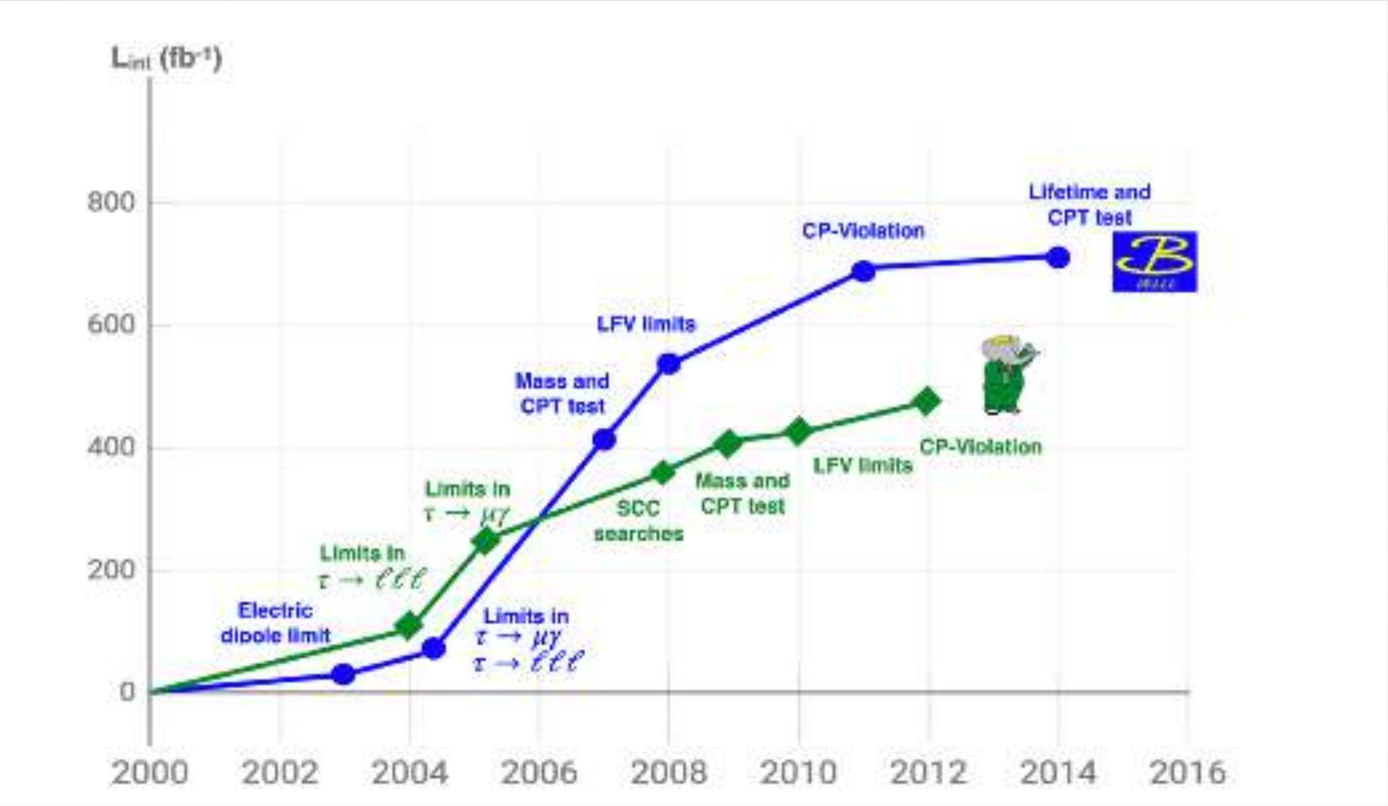
Physics process	Cross section [nb]	Selection Criteria	Reference
$\Upsilon(4S)$	1.110 ± 0.008	-	[2]
$u\bar{u}(\gamma)$	1.61	-	KKMC
$d\bar{d}(\gamma)$	0.40	-	KKMC
$s\bar{s}(\gamma)$	0.38	-	KKMC
$c\bar{c}(\gamma)$	1.30	-	KKMC
$e^+e^-(\gamma)$	300 ± 3 (MC stat.)	$10° < \theta_e^* < 170°$, $E_e^* > 0.15\,\text{GeV}$	BABAYAGA.NLO
$e^+e^-(\gamma)$	74.4	$p_e > 0.5\,\text{GeV}/c$ and e in ECL	-
$\gamma\gamma(\gamma)$	4.99 ± 0.05 (MC stat.)	$10° < \theta_\gamma^* < 170°$, $E_\gamma^* > 0.15\,\text{GeV}$	BABAYAGA.NLO
$\gamma\gamma(\gamma)$	3.30	$E_\gamma > 0.5\,\text{GeV}$ in ECL	-
$\mu^+\mu^-(\gamma)$	1.148	-	KKMC
$\mu^+\mu^-(\gamma)$	0.831	$p_\mu > 0.5\,\text{GeV}/c$ in CDC	-
$\mu^+\mu^-\gamma(\gamma)$	0.242	$p_\mu > 0.5\,\text{GeV}$ in CDC, $\geq 1\ \gamma\ (E_\gamma > 0.5\,\text{GeV})$ in ECL	-
$\tau^+\tau^-(\gamma)$	0.919	-	KKMC
$\nu\bar{\nu}(\gamma)$	0.25×10^{-3}	-	KKMC
$e^+e^-e^+e^-$	39.7 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5\,\text{GeV}/c^2$	AAFH
$e^+e^-\mu^+\mu^-$	18.9 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5\,\text{GeV}/c^2$	AAFH

21

τ Factory

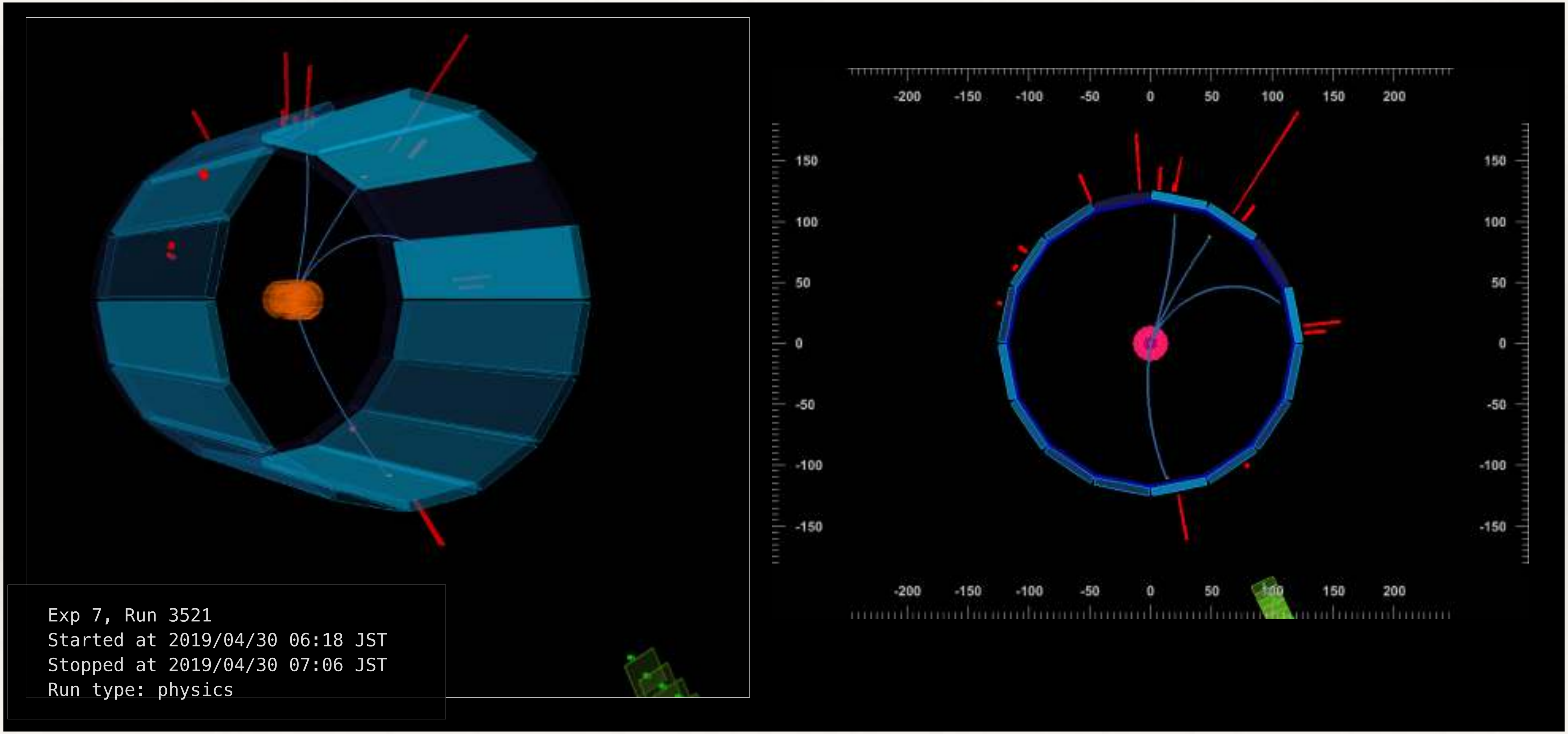
Tau leptons at the B factories

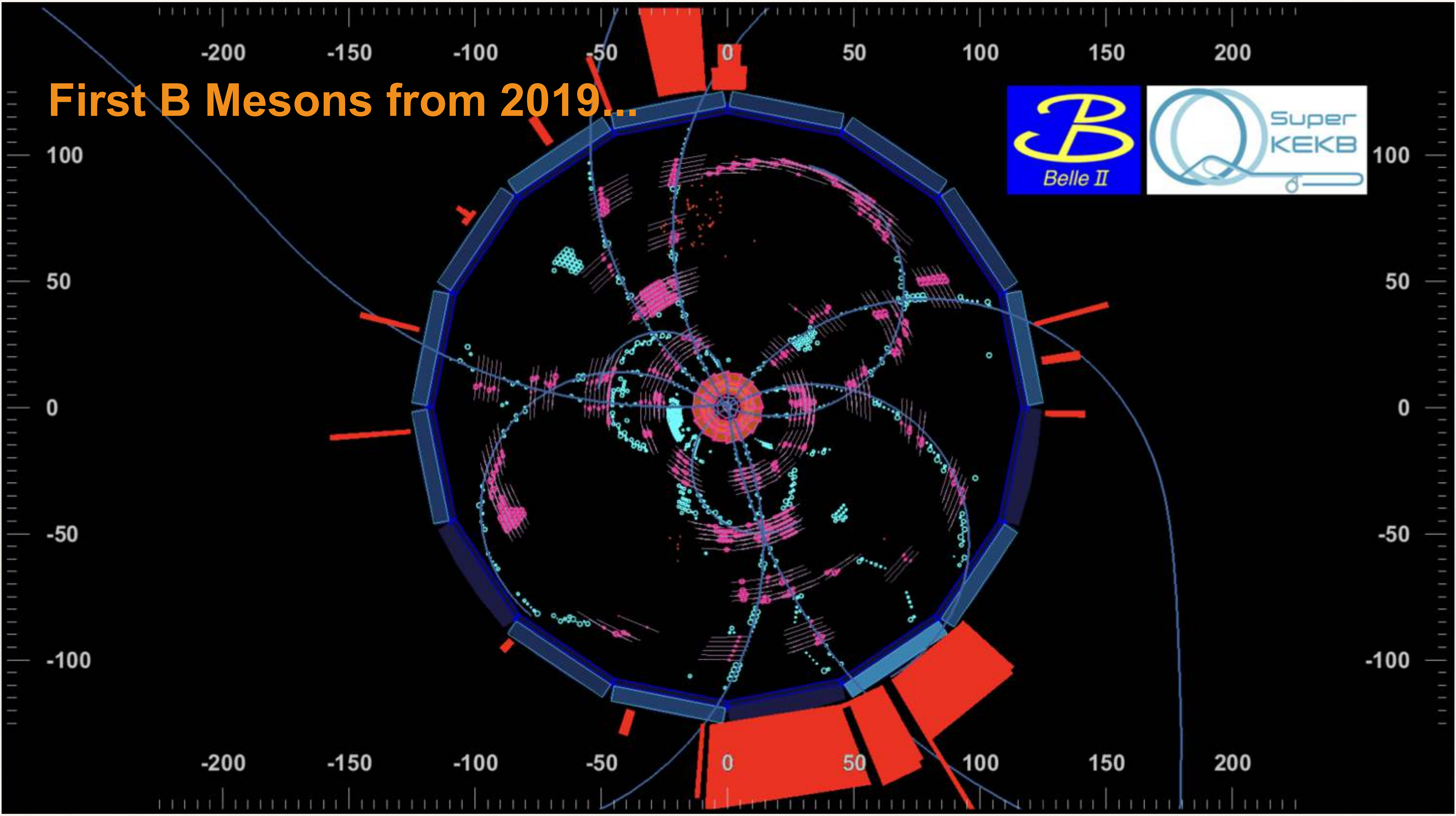




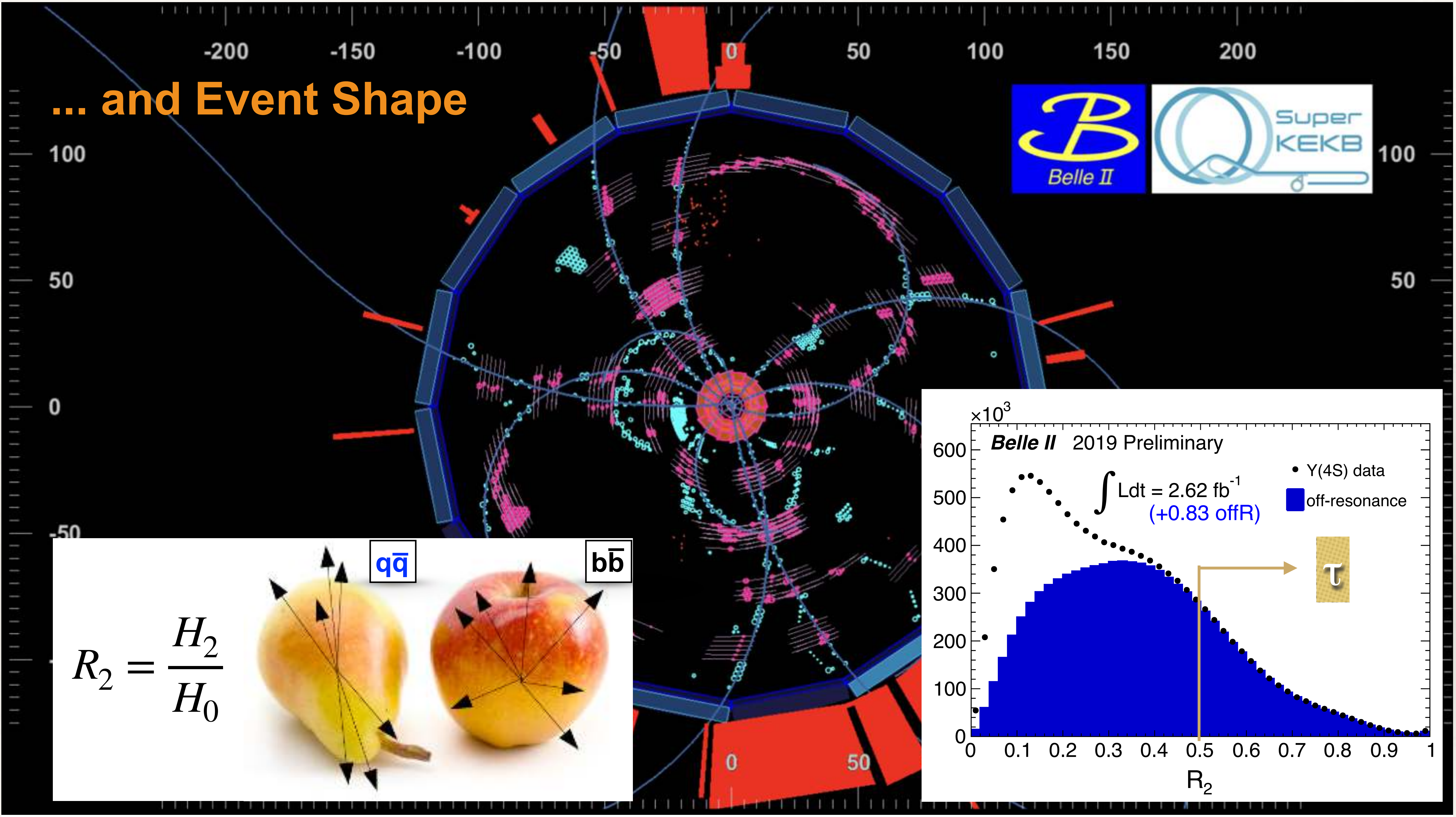
- B factories are also τ factories.
- Great environment for the study of tau lepton decays due to:
  - Well-defined initial state.
  - High vertex resolution.
  - Excelent calorimetry.
  - Sophisticated particle ID.
- Previous B factories provided many interesting results to be updated with Belle II.

Tau decay event in 3x1-prong topology




First B Mesons from 2019...
Belle II
Super KEKB
-200
-150
-100
-50
0
50
100
150
200
100
50
0
-50
-100

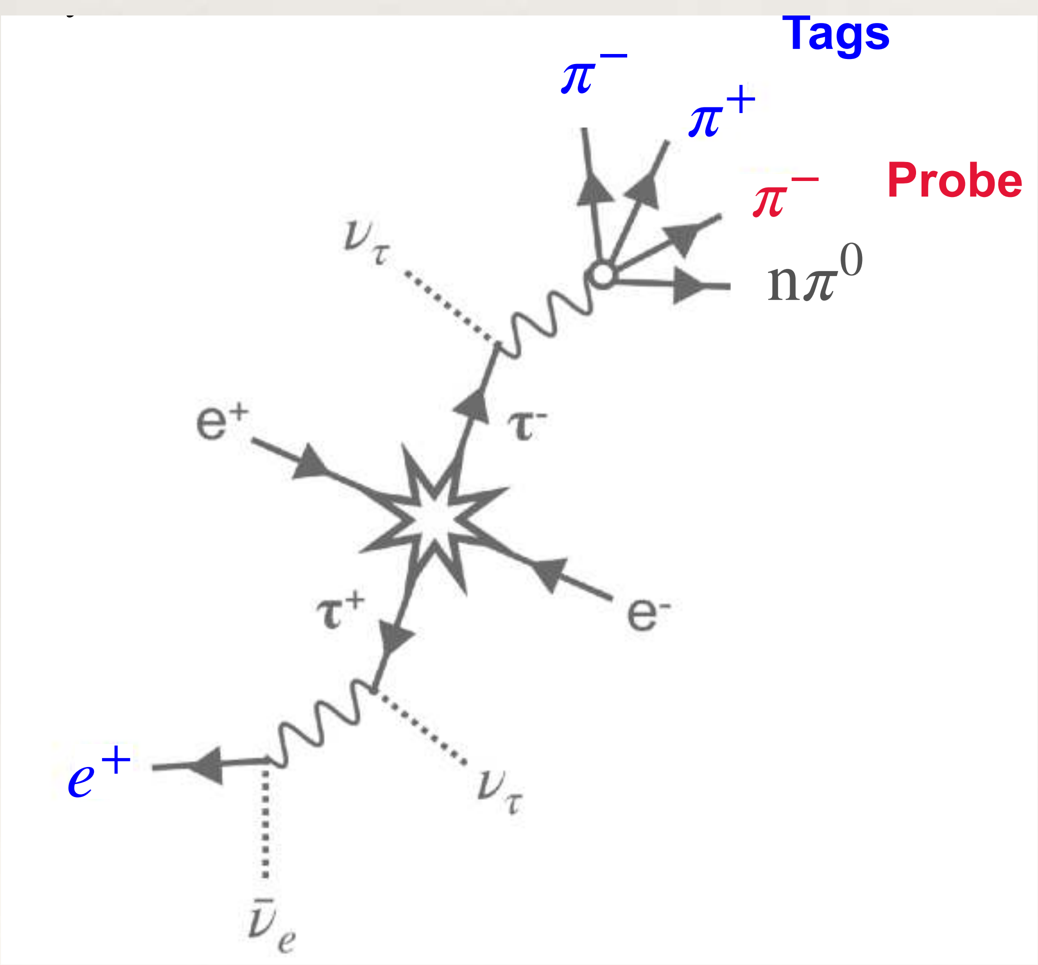
... and Event Shape

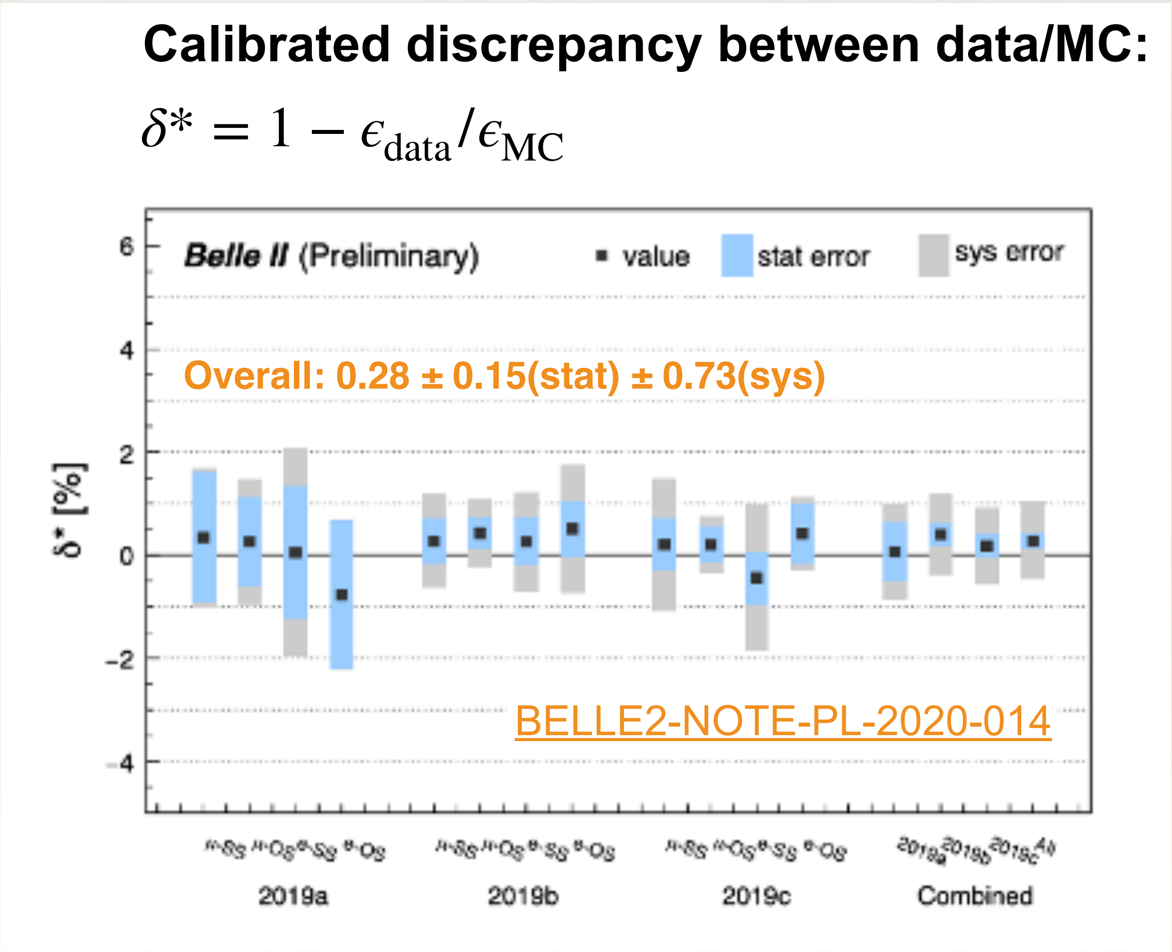


$$R_2 = \frac{H_2}{H_0}$$

Detector performance: tracking efficiency

- Tracking efficiency and fake rates have been measured using ττ events using a tag-and-probe approach and $\tau^- \to 3\pi^\pm \nu_\tau + n\pi^0$.

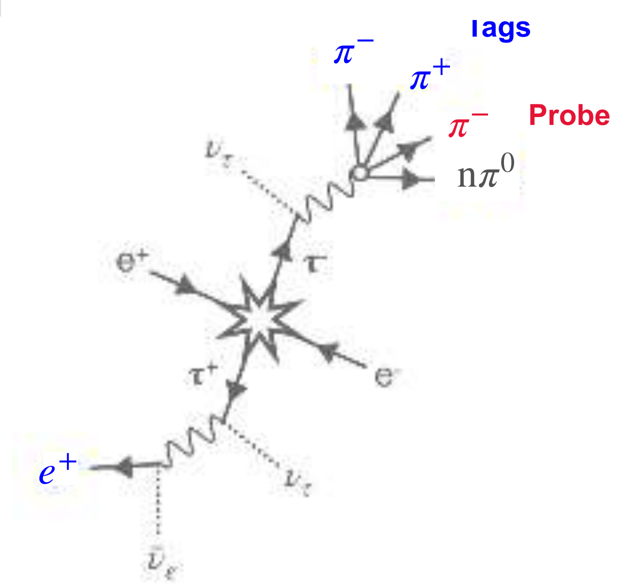


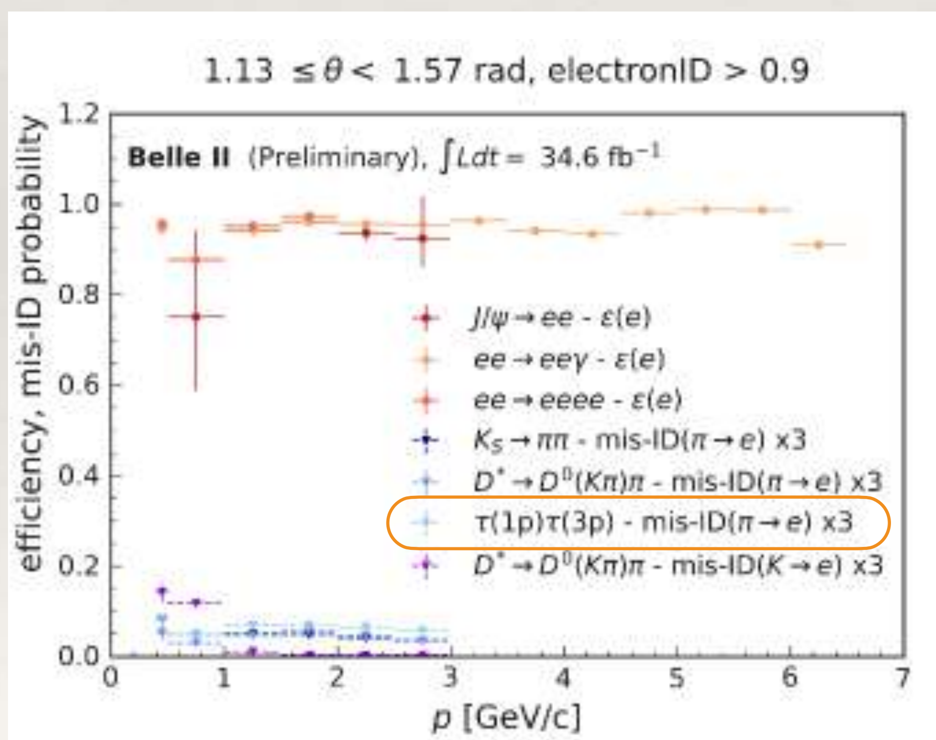


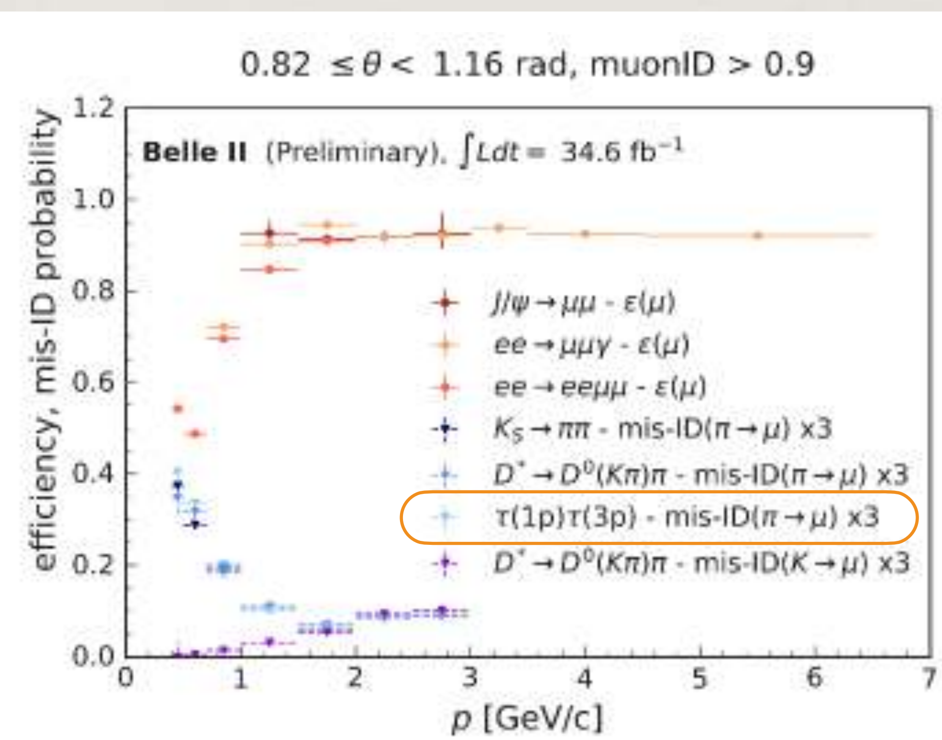
Detector performance: Lepton ID

- Particle ID is based on the global likelihood ratio from all subdetectors.
- With T&P approach, lepton efficiency and misidentification rates are calculated with pions from the 3-prong decay $\tau^- \rightarrow 3\pi^\pm \nu_\tau + n\pi^0$.

$$\ell \text{ ID} = \frac{\mathcal{L}_\ell}{\mathcal{L}_e + \mathcal{L}_\mu + \mathcal{L}_\pi + \mathcal{L}_K + \mathcal{L}_p}$$



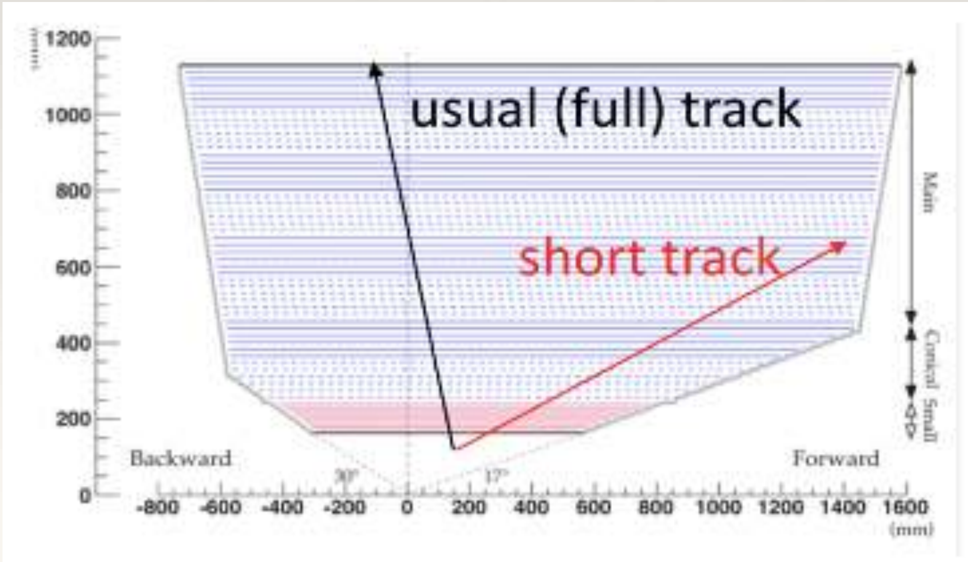


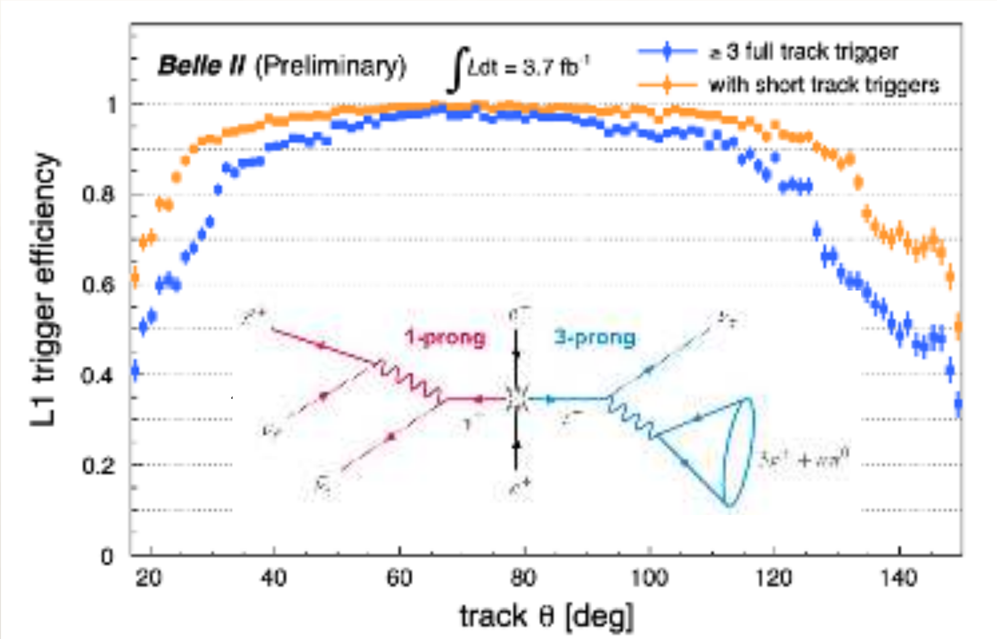


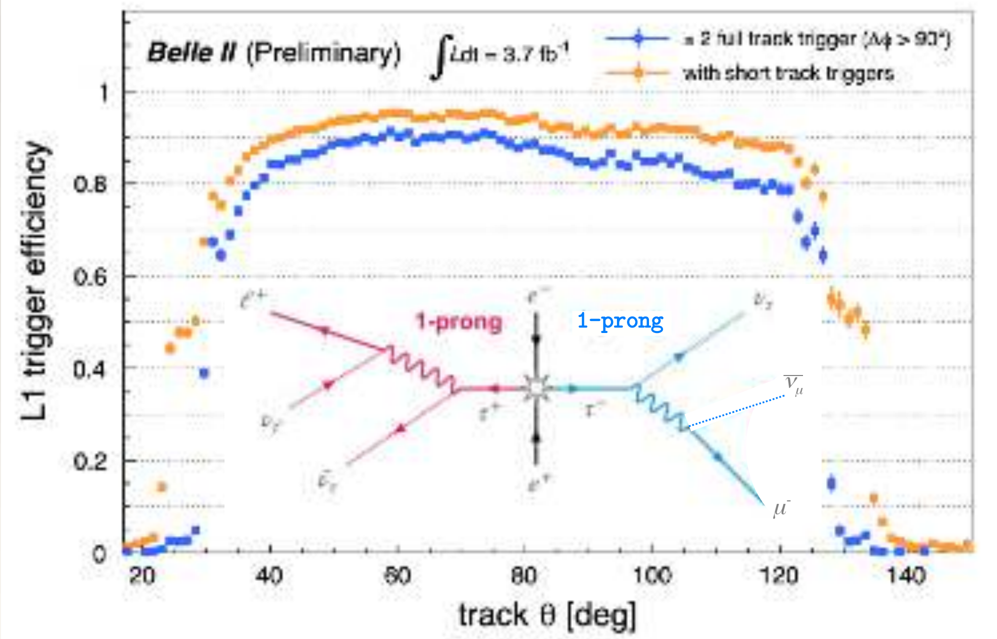
BELLE2-NOTE-PL-2020-027

Detector performance: triggering

- The L1 trigger efficiency studied with 1x1 and 3x1 tau topologies.
- Track triggers present low efficiency in endcaps.
- To compensate, the CDC trigger also searches for short tracks.
- Identification of the 1x1 topology is challenging.







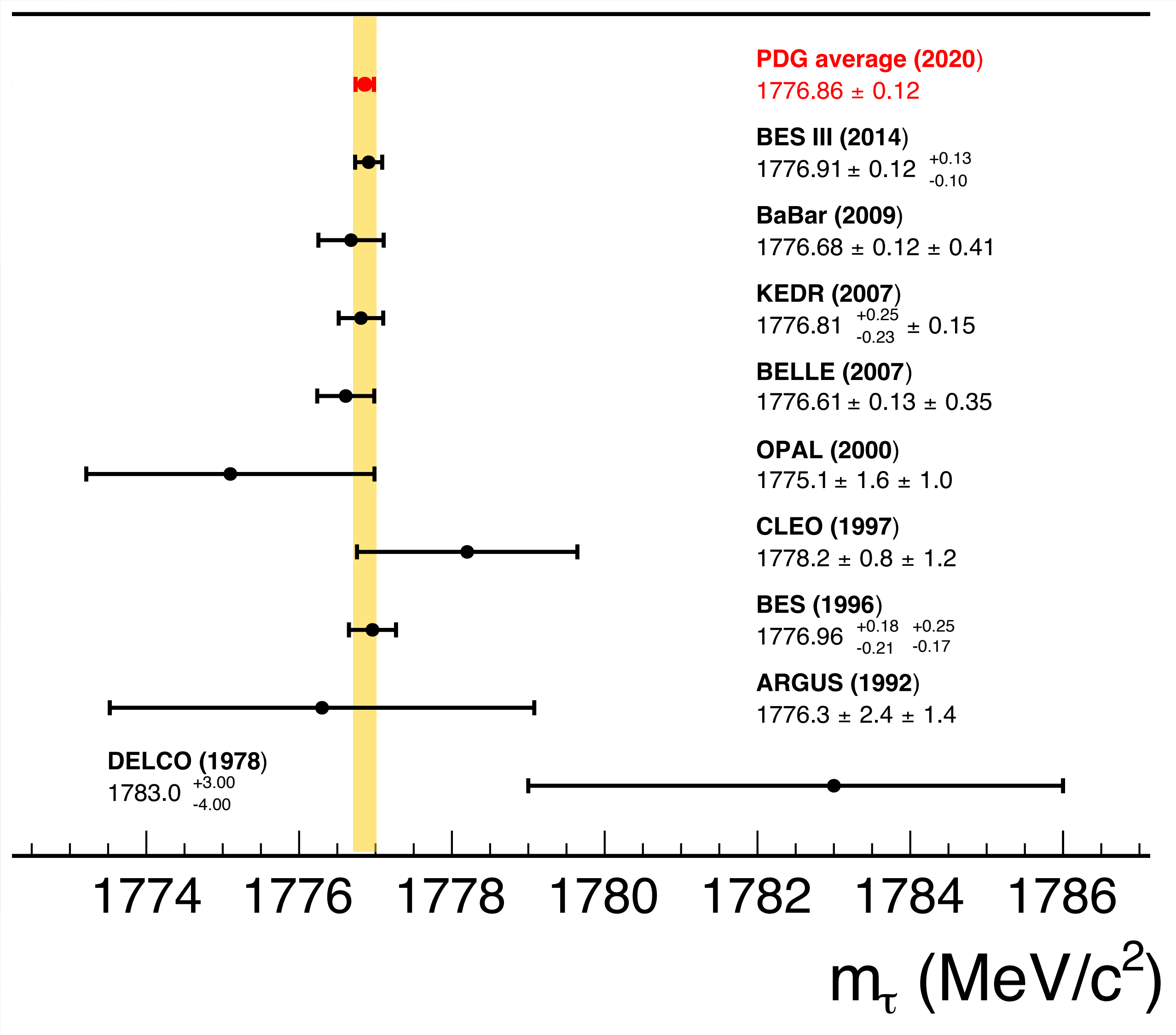
BELLE2-NOTE-PL-2020-015

Measurement of τ properties: mass

- Lepton masses are fundamental parameters of the SM:

$m_e = (0.5109989461 \pm 0.0000000031)$ MeV,
$m_\mu = (105.6583745 \pm 0.0000024)$ MeV,
$m_\tau = (1776.86 \pm 0.12)$ MeV.

- Two methods for measuring m_τ:
  - Production threshold (DELCO, BES, KEDR, **BES-III**).
  - Pseudomass distribution (ARGUS, OPAL, BaBar, **Belle**).



Pseudo-mass strategy

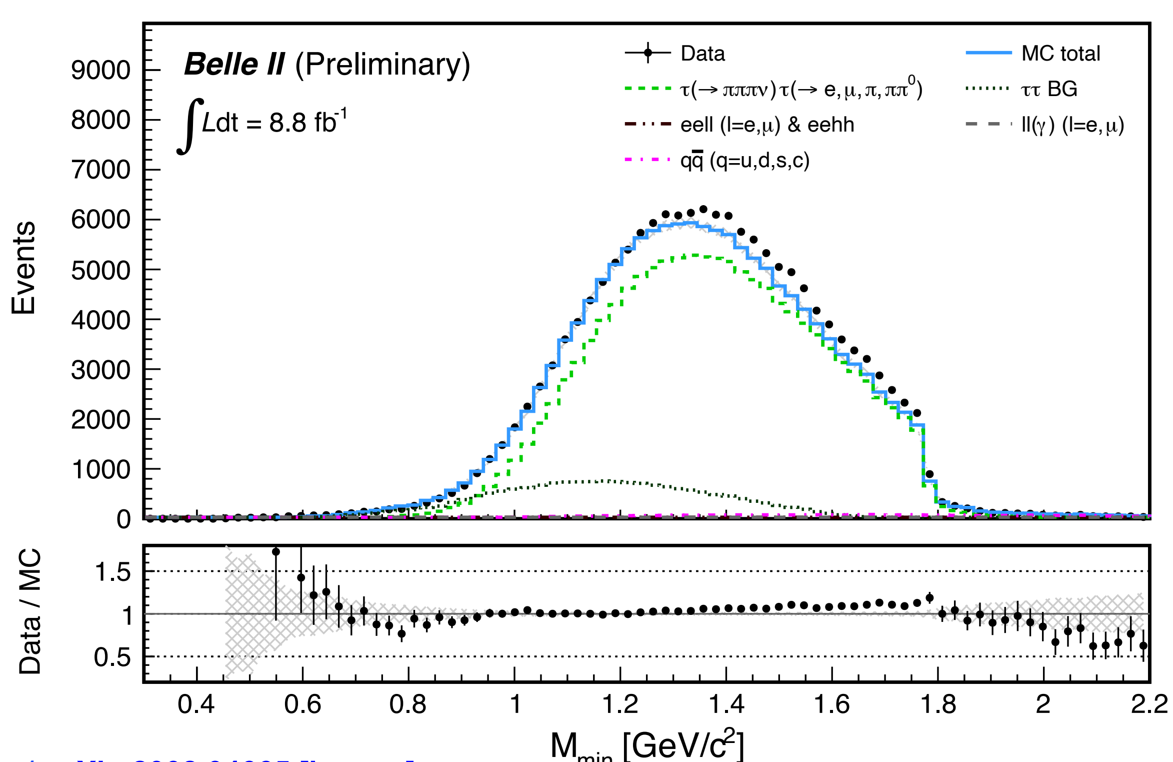
- Technique developed by ARGUS using $\tau^- \to 3\pi^\pm \nu_\tau$:

$$m_\tau^2 = (p_h + p_\nu)^2$$
$$= 2E_h(E_\tau - E_h) + m_h^2 - 2|\vec{p}_h|(E_\tau - E_h)\cos(\vec{p}_h, \vec{p}_\nu)$$

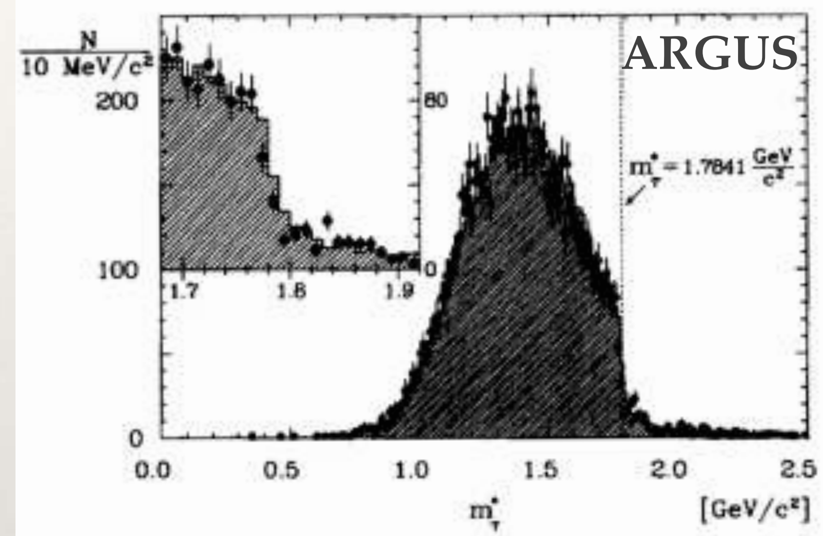
≈ 1 (not known)

$$M_{\rm min}^2 = 2E_h(E_\tau - E_h) + m_h^2 - 2|\vec{p}_h|(E_\tau - E_h) < m_\tau^2$$

Pseudomass distribution, data vs MC



[1] arXiv:2008.04665 [hep-ex]

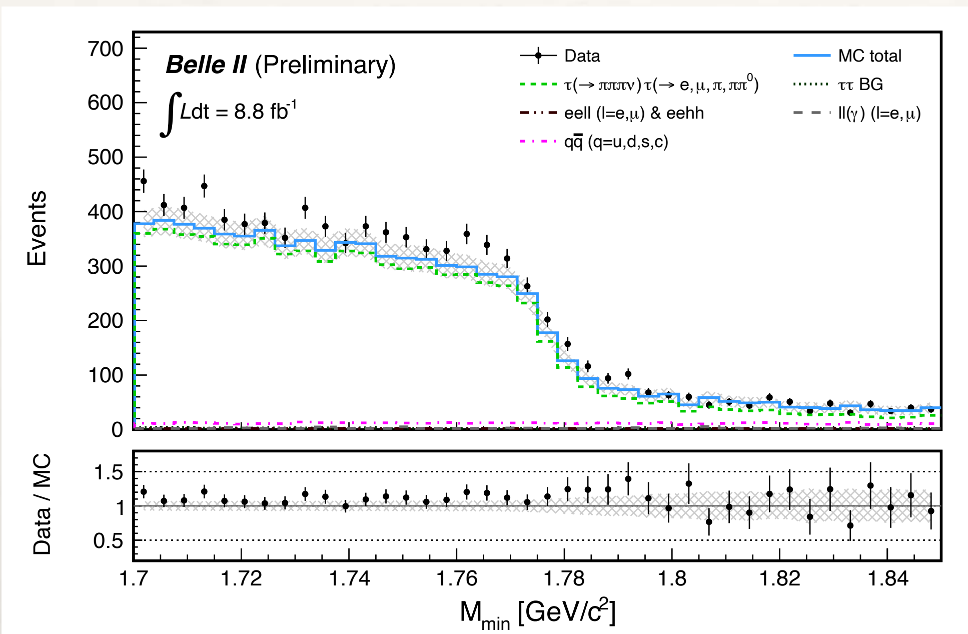


Phys. Lett. B 292 (1992) 221-228

- **Tau rediscovery.** Ongoing work to include missing background sources (4π) in the MC.
- Distribution fitted to an empirical edge function, **cut-off indicates the value of m_τ.**

τ-mass measurement

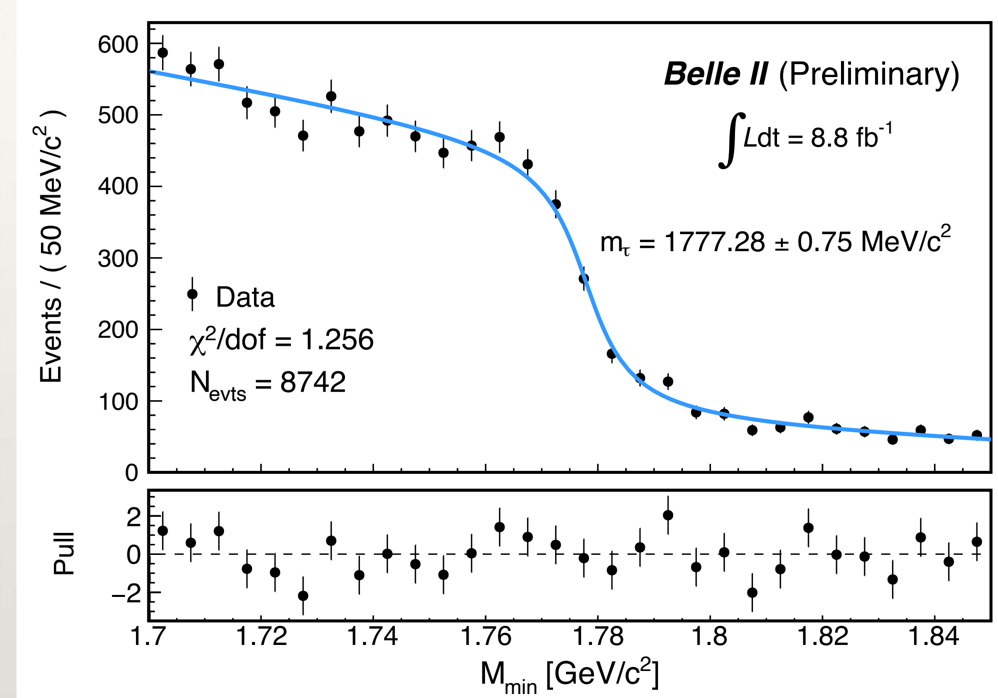
Zoom to cut-off region

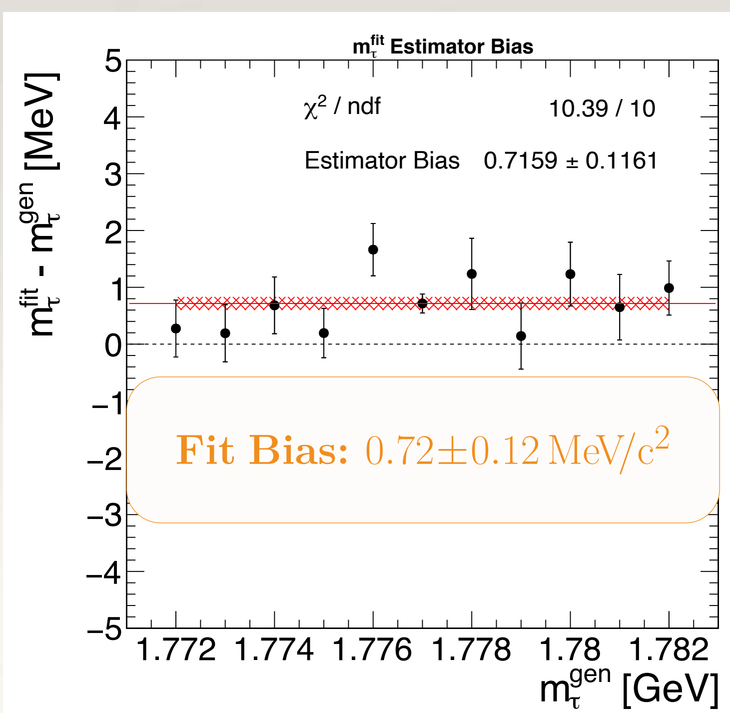


Fit

P₁ estimator of m_τ

$$F(M_{min}, \vec{P}) = (P_3 + P_4 M_{min}) \cdot \tan^{-1}[(M_{min} - P_1)/P_2] + P_5 M_{min} + 1$$





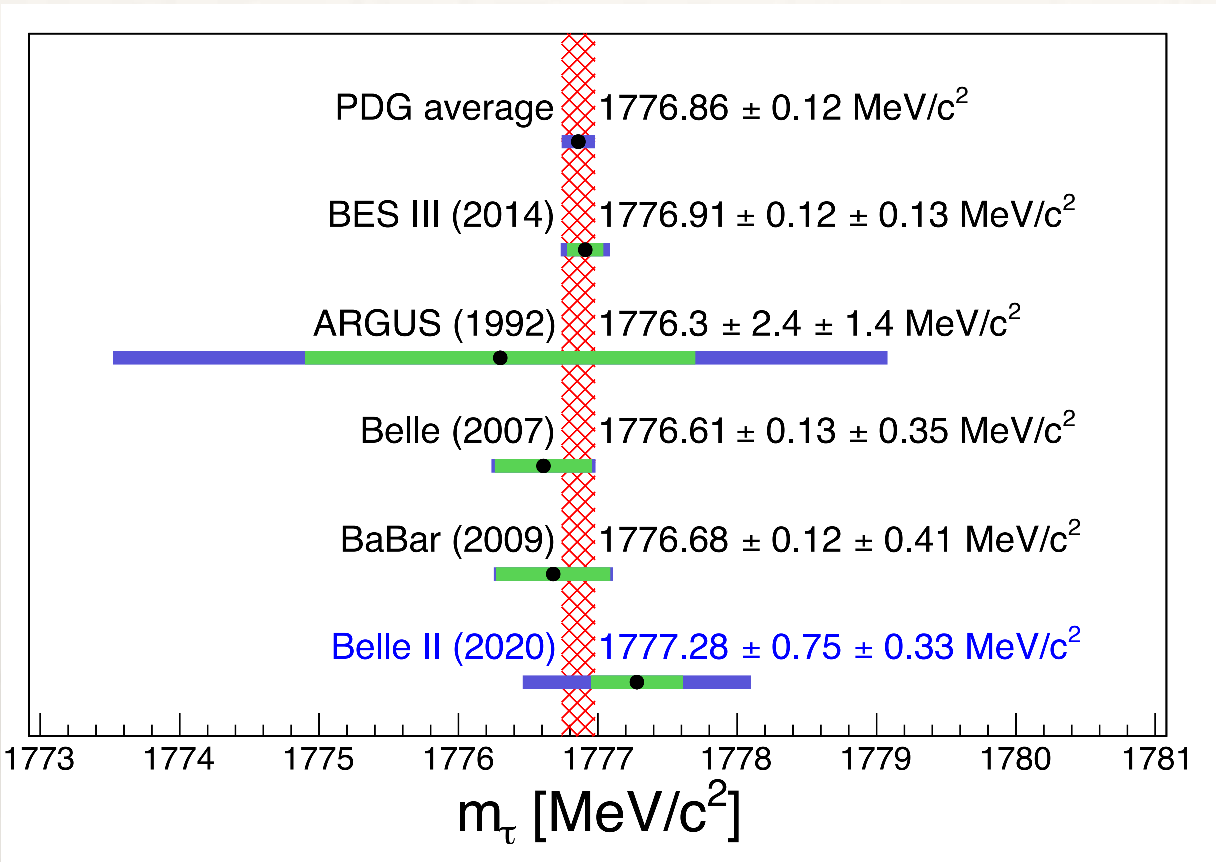
Systematic uncertainty	MeV/c^2
Momentum shift (B-field map)	0.29
Estimator bias	0.12
Choice of p.d.f.	0.08
Fit window	0.04
Beam energy shifts	0.03
Mass dependence of bias	0.02
Trigger efficiency	≤ 0.01
Initial parameters	≤ 0.01
Background processes	≤ 0.01
Tracking efficiency	≤ 0.01

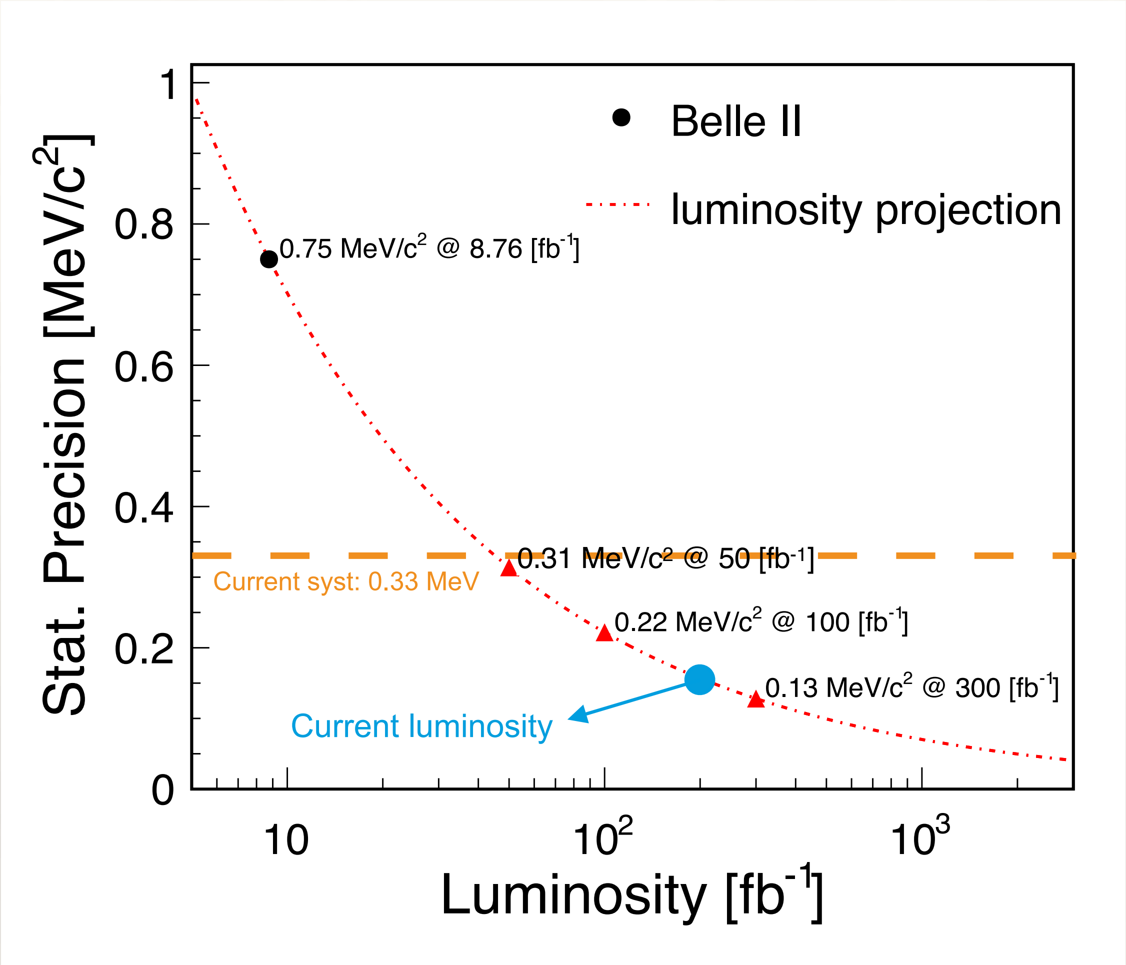
Belle II preliminary:

$1777.28 \pm 0.75 \pm 0.33$ MeV/c^2

arXiv:2008.04665 [hep-ex]

τ-mass measurement prospects

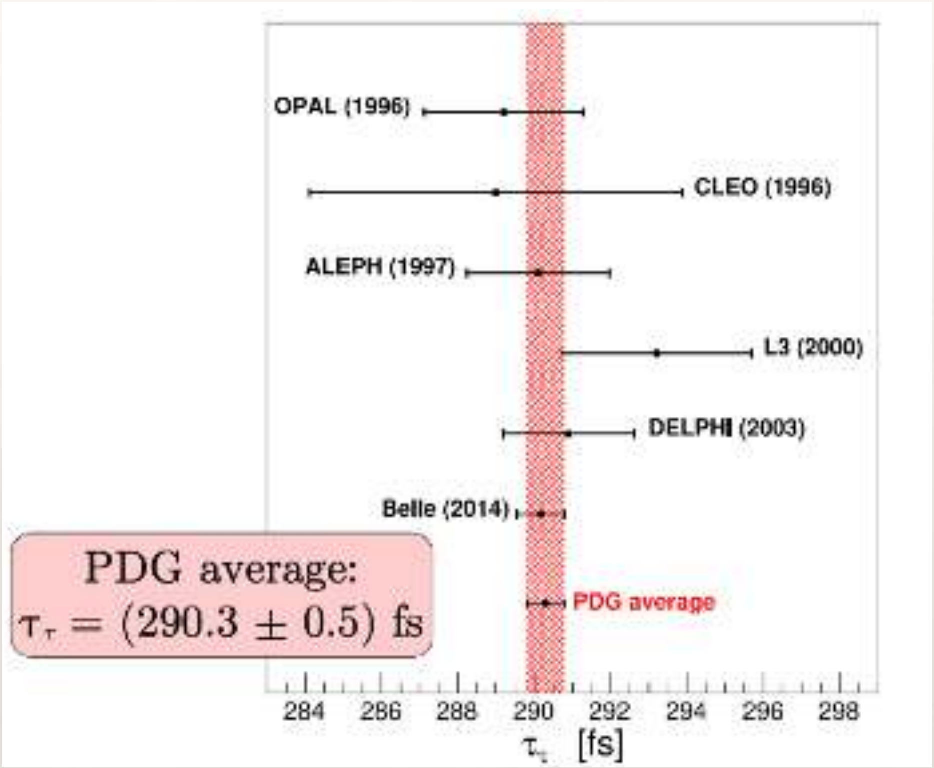


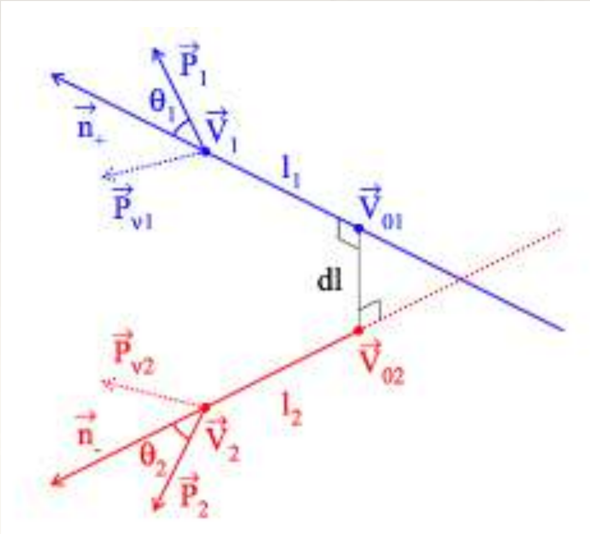


- Belle-II (8.76 fb^{-1}) preliminary result is still dominated by statistical uncertainty. Result will be improved with current luminosity.
- Precision of the momentum scale factor can be improved with more precise B-field map.

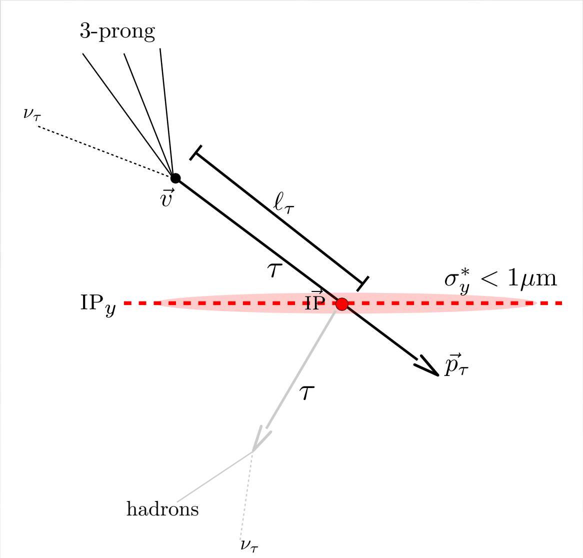
Tau lifetime measurement strategy

- Best measurement by Belle (PRL 112, 031801 (2014)):
  - Uses a 3x3 topology, with **both tau leptons decaying to $3\pi\nu_\tau$**, 711 fb^{-1}.
  - In CM frame, direction of positive tau, $\mathbf{n}^{+*} = -\mathbf{n}^{-*}$, can be solved using the 3-prong momenta. Its momentum is then boosted to the lab frame.
  - Require $\tau\tau$ coming (more or less) from the same point: 3D distance $|\mathbf{dl}| < 0.03$ cm.
  - $\tau_\tau = 290.17 \pm 0.53$ (stat) ± 0.33 (syst) fs.



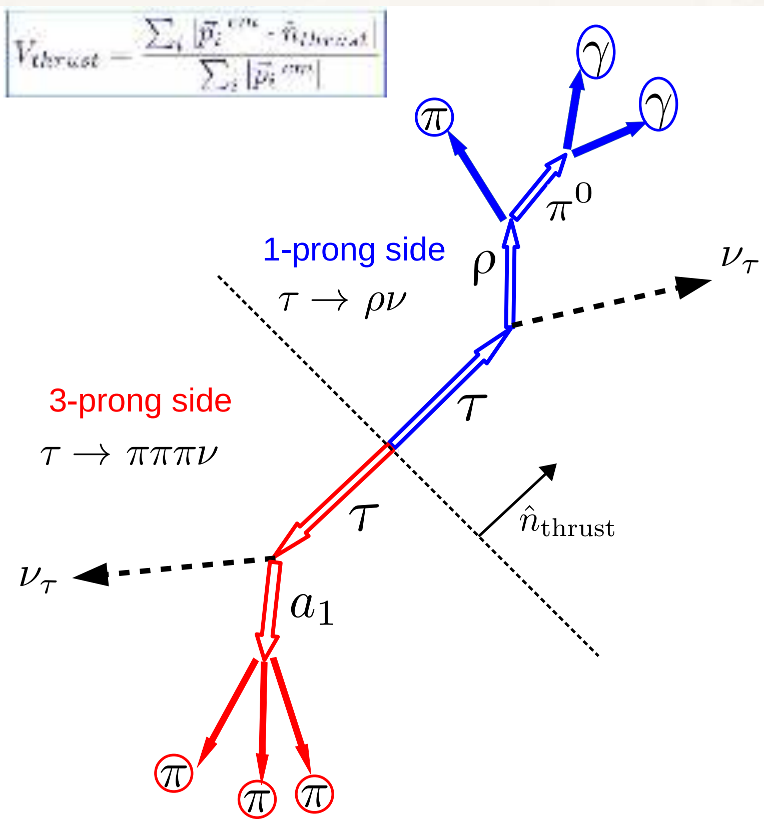


- Belle II strategy:
  - Exploit nano beam scheme ⇒ use beamspot constraint (don't need $\tau\tau$ vertex constraint).
  - Use 3x1 topology ⇒ higher statistics (**x5**).



Tau lifetime measurement sensitivity at Belle II

M. Hernadez Villanueva, TAU2021

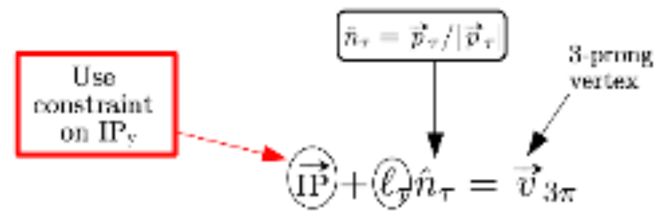


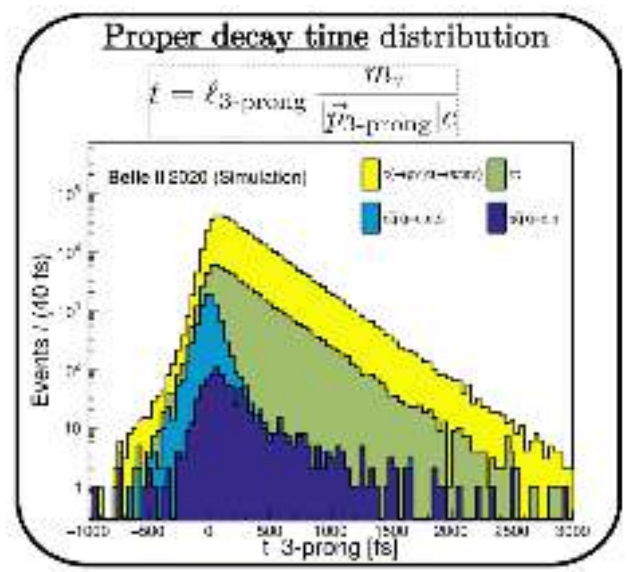
Advantages of $\tau \to \rho\nu$ respect to $\tau \to \pi\nu$:

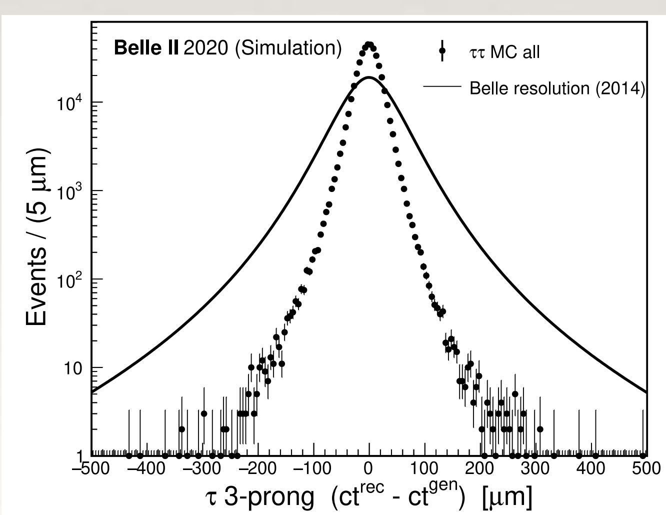
- BR($\tau \to \rho\nu$)≃25% > BR($\tau \to \pi\nu$)≃10%
- Better signature (ρ-peak)

- τ_τ presents ≃ 3 fs bias. (Generated lifetime: 290.57 fs)
  - ISR/FSR losses = underestimation of the proper time.
  - And intrinsic bias in the measurement.
- Further studies to estimate systematics:

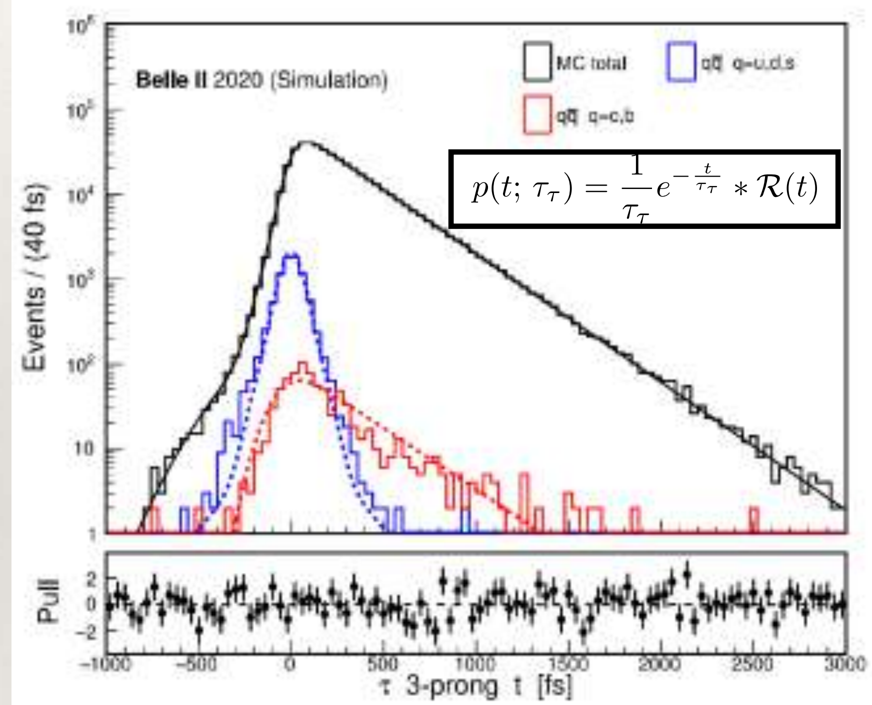
- ℓ_τ reconstruction and IP constrain:







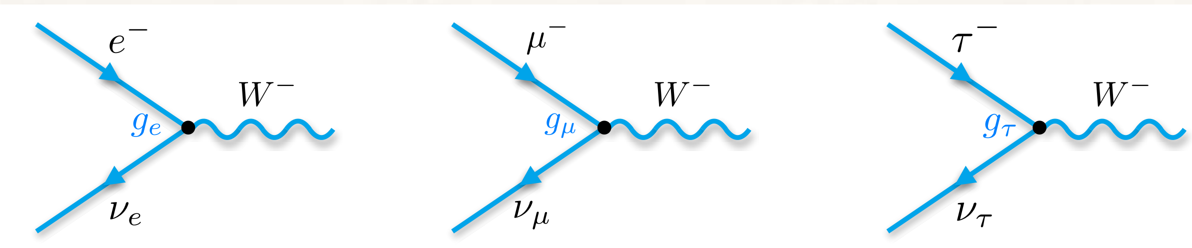
- Lifetime extraction:
  - τ_τ = 287.2 ± 0.5 (stat) fs
  - Same statistical uncertainty of Belle. (200 fb^{-1} vs 711 fb^{-1})



➡ the resolution @Belle II is nearly x2 narrower than @Belle

Competitive statistical precision can already be reached with 200 fb^{-1}

Lepton flavor universality



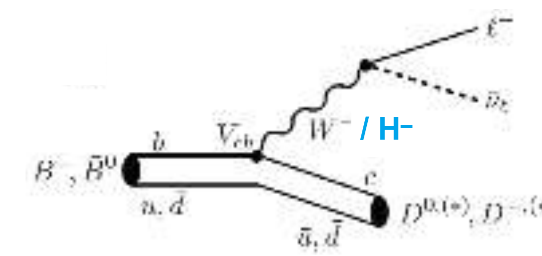
$g_e = g_\mu = g_\tau$ (SM)

Are flavor sector anomalies hints of new fundamental interactions that violate LFU?

Anomalies in quark sector

- R(D)-R(D*) plane (~3.1σ)
- R(K) (3.1σ), also P_5' in $B \to K^* \mu\mu$ (~3.4σ)
- and more…

$$R(D^*) = \frac{\mathcal{BR}(B \to D^* \tau \nu)}{\mathcal{BR}(B \to D^* \ell \nu)} \quad \text{with } \ell = e, \mu$$



Significant tensions in lepton sector

- anomalous magnetic moment of μ (4.2σ) and e (~2.5σ)

- Most precise tests in the tau sector by BaBar:

Test of e–μ universality

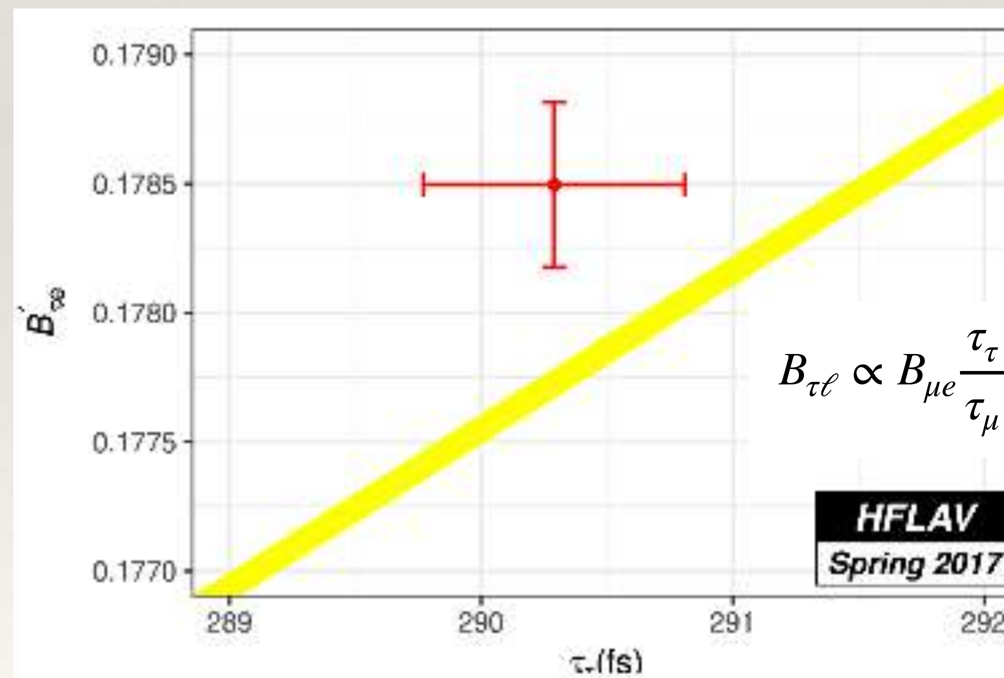
$$\left(\frac{g_\mu}{g_e}\right)^2_\tau \propto \frac{B(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{B(\tau^- \to e^- \bar{\nu}_e \nu_\tau)}$$

Phys.Rev.Lett.105:051602 (2010)

$$\left(\frac{g_\mu}{g_e}\right)_\tau = 1.0036 \pm 0.0020$$

- in agreement with SM

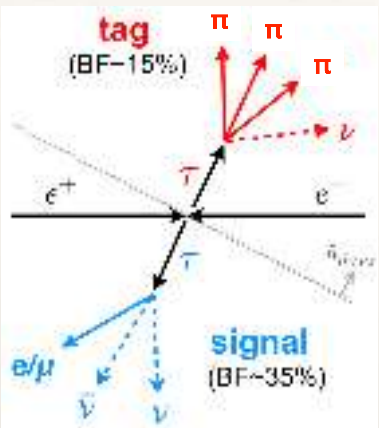
- The BR measurements dominated by systematic uncertainty
  - μ: PID due limited size of data and MC samples



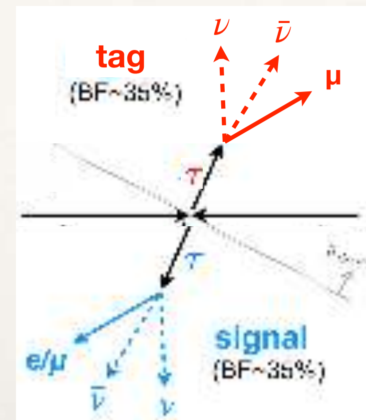
$$B_{\tau\ell} \propto B_{\mu e} \frac{\tau_\tau}{\tau_\mu} \frac{m_\tau^5}{m_\mu^5}$$

Figure: EPJ Web Conf., 218 (2019) 05002

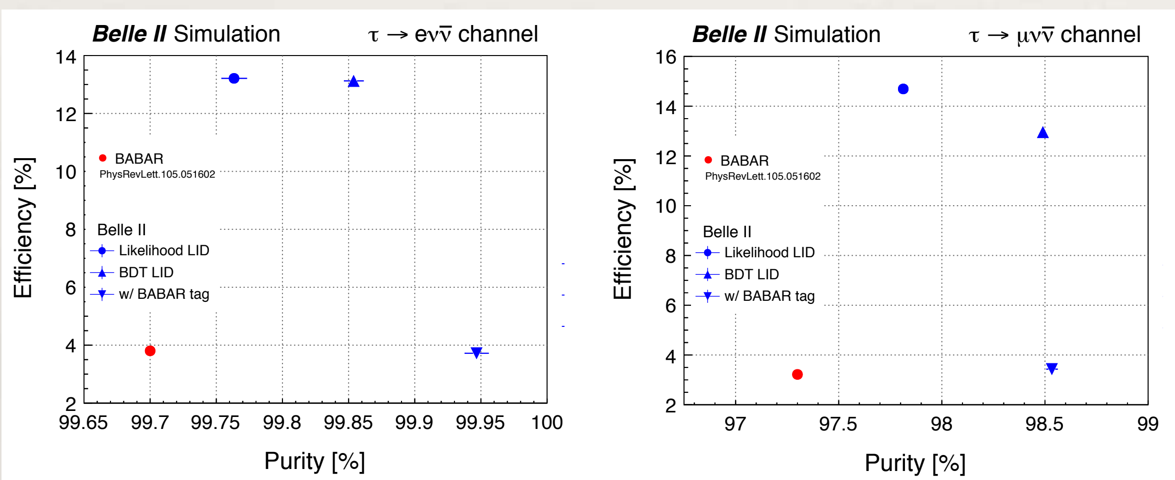
LFU measurement sensitivity

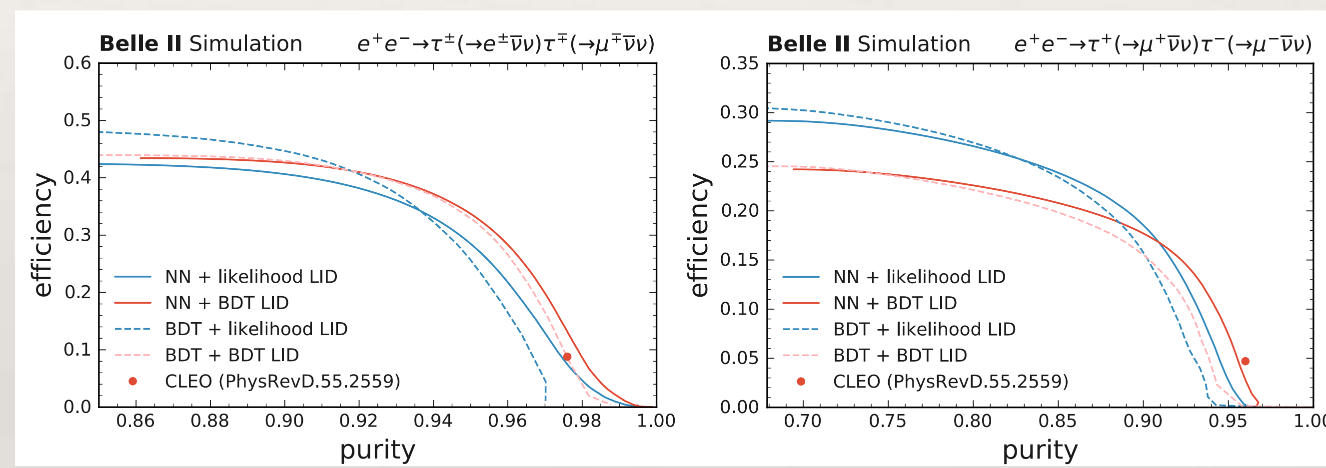


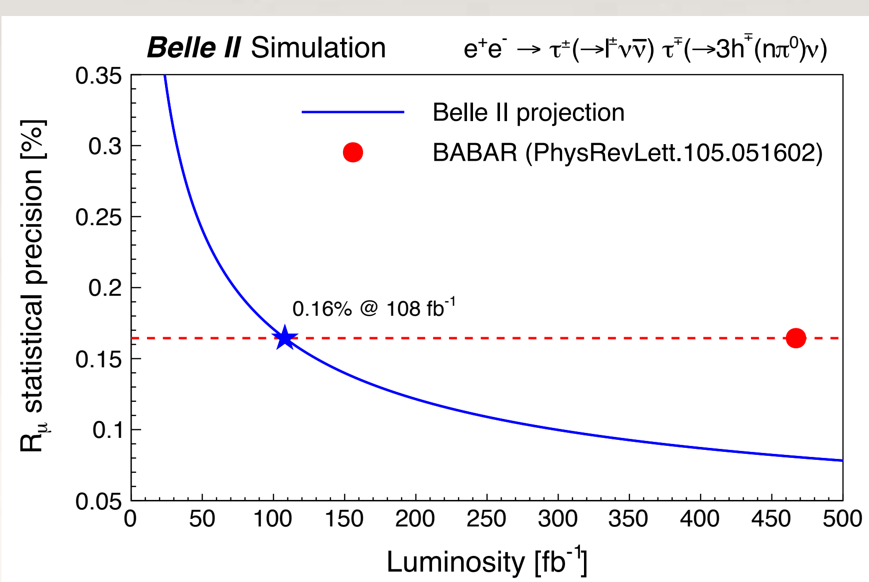
- 3x1: ~4x higher efficiency with better purity compared to BaBar.
  - No pionID cut required in contrast to BaBar, instead E/p to reject electrons + pt cuts.



- 1x1: similar performance compared to CLEO.
  - Room for improvements in LID and BDT/NN selection.







- Belle II can already exceed BaBar and CLEO on statistical precision for BR ratio.
- Goal is to achieve better systematic precision:
  - **lepton ID uncertainties** should scale well with luminosity & higher MC statistics .

LFV decay $\tau \to \ell\ \alpha$

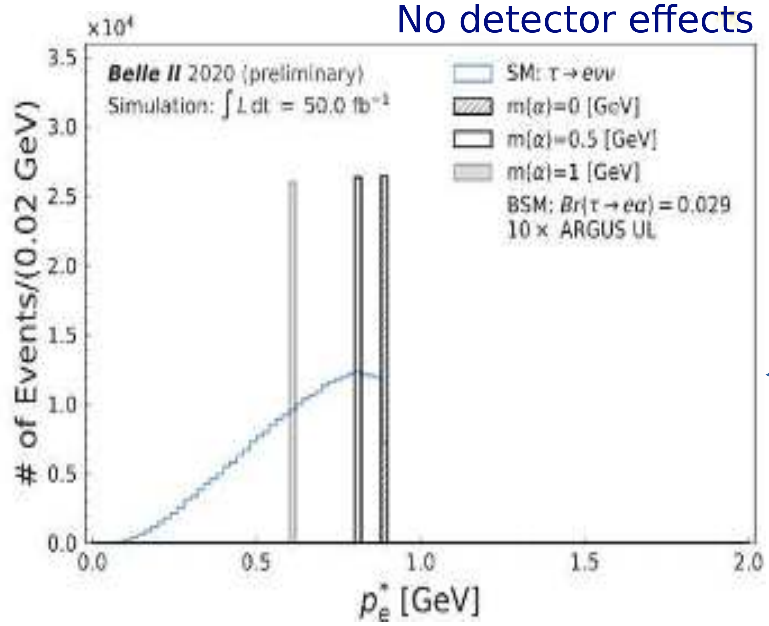
- Search for the LFV decay channels:
  $\tau \to e\alpha$ and $\tau \to \mu\alpha$
  being α a BSM invisible particle.

- This decay appears in several NP models: Axion-like particles, Z' gauge boson, etc.

- **Idea**: Search for a two body decay.

  The momentum spectrum of the signal lepton will manifest as a peak in the τ rest frame with a position depending on the α mass.

No detector effects

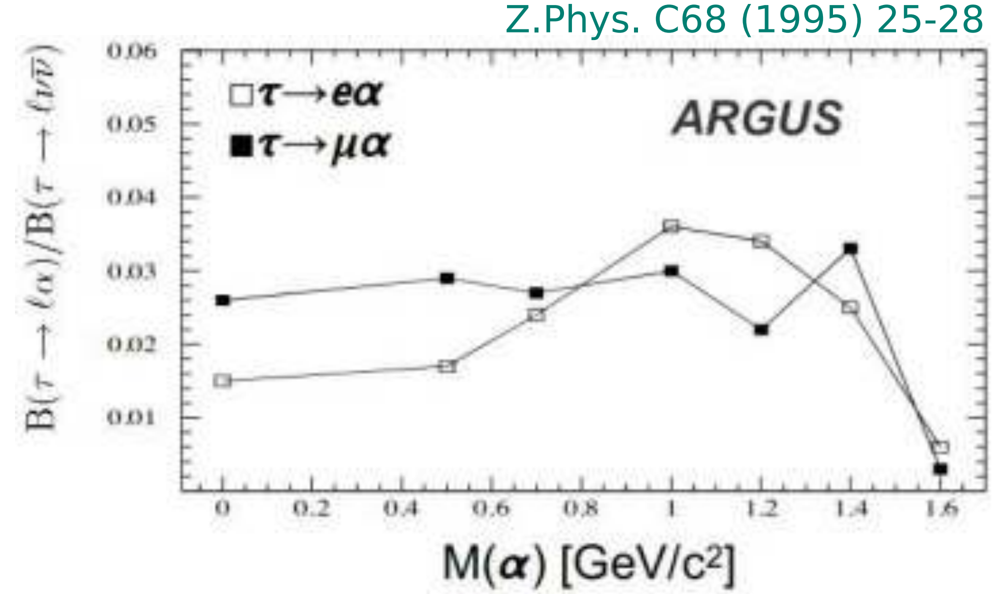


Signal vs Bkg
- Same final state
- Different kinematics

Previous searches

- Mark III (1985, 9.4 pb^{-1})
- ARGUS (1995, 472 pb^{-1})

Z.Phys. C68 (1995) 25-28



A. de Yta, TAU2021

$\tau \to \ell\, \alpha$: background suppression

A. de Yta, TAU2021

- Vertex fit
  - 3-prong side (reject failed fits)
- Neutrals

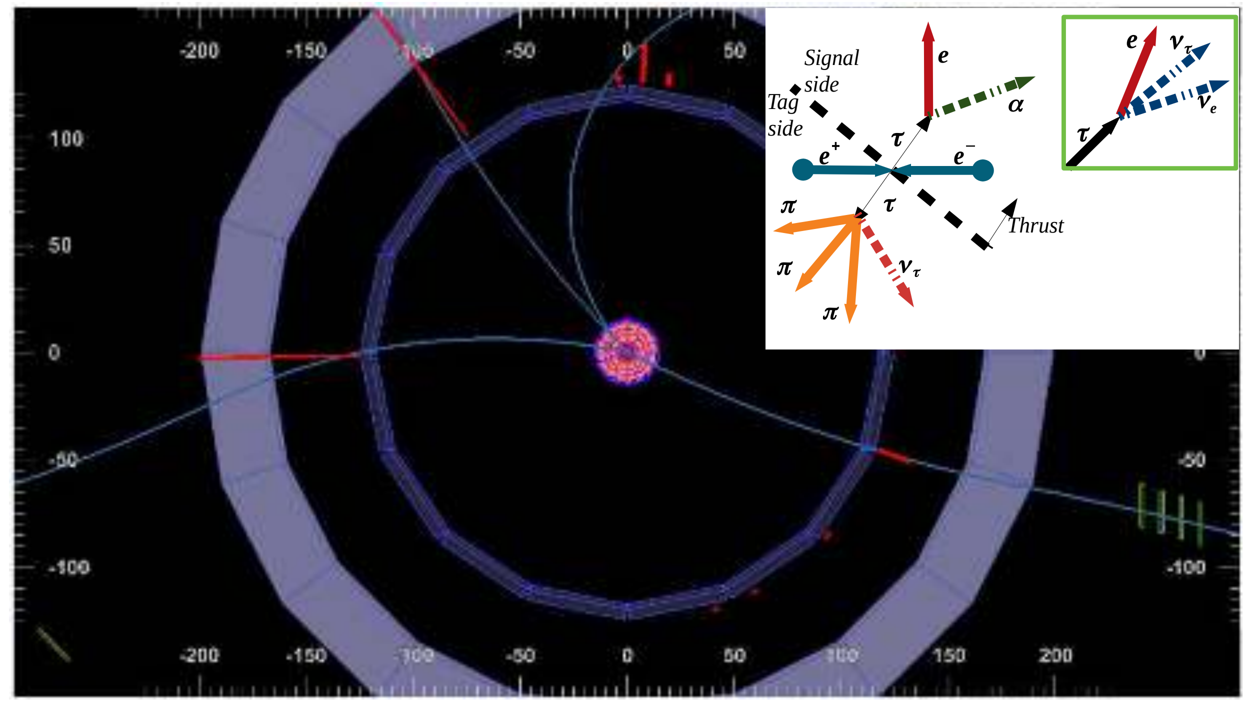
Lepton ID

Pion ID

  - $\#\gamma_{1prong} = \#\gamma_{3prong} = 0$
  - $\#\pi^0_{1prong} = \#\pi^0_{3prong} = 0$
- 3-prong tracks with asymmetric p_t cuts
  - Ranking the p_t (leading, sub-leading, third)
  - Optimal cuts based on the figure of merit

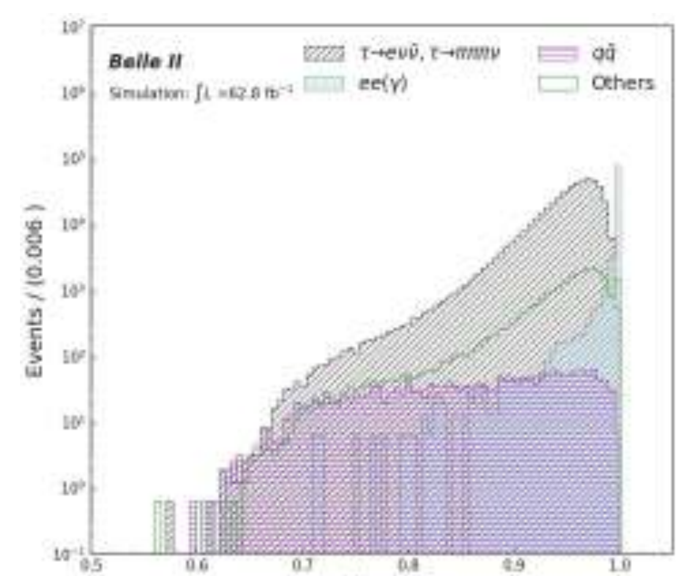
$$FOM = \frac{S}{\sqrt{S+B}}$$

- We optimize for $e^+e^- \to \tau(3\pi\nu)\tau(l\nu\bar{\nu})$



- Electron channel
  - Leading p_t > 0.69 GeV/c
  - Sub-leading p_t > 0.29 GeV/c
  - Third p_t > 0.08 GeV/c
- Muon channel
  - Leading p_t > 0.47 GeV/c
  - Sub-leading p_t > 0.17 GeV/c
  - Third p_t > 0.04 GeV/c

- Electron channel
  - 0.9 < thrust < 0.99
  - 0.5 < Inv M(3-prong) < 1.7 GeV/c^2
  - 1.2 < E_{CMS}(3-prong) < 5.3 GeV
- Muon channel
  - 0.9 < thrust < 1.0
  - 0.4 < Inv M(3-prong) < 1.7 GeV/c^2
  - 1.1 < E_{CMS}(3-prong) < 5.3 GeV

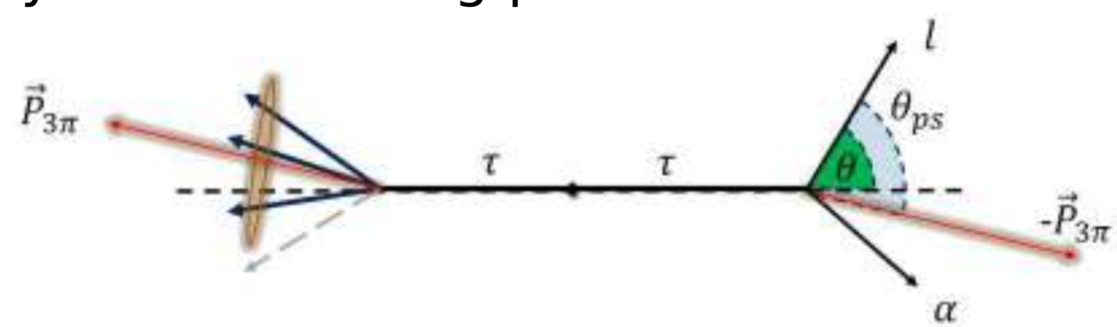


τ → ℓ α: τ-"pseudorest" frame

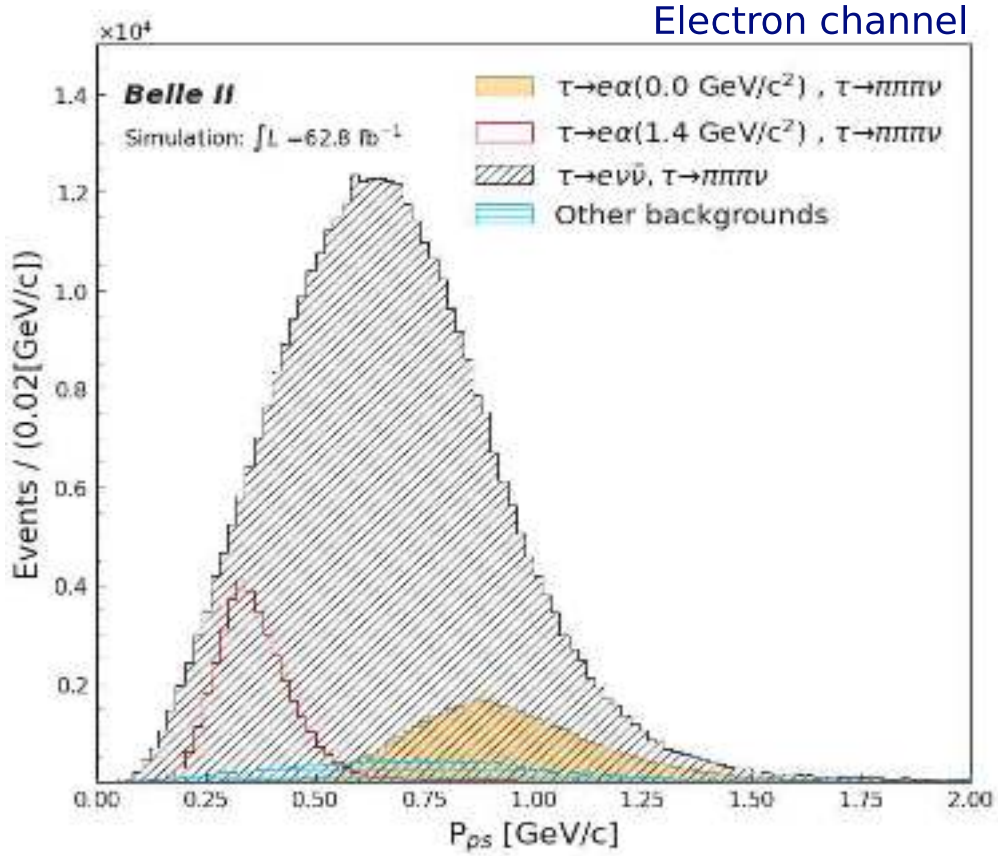
A. de Yta, TAU2021

- In the signal τ rest frame, the momentum of the lepton will be a monoenergetic peak with position depending on the α mass.

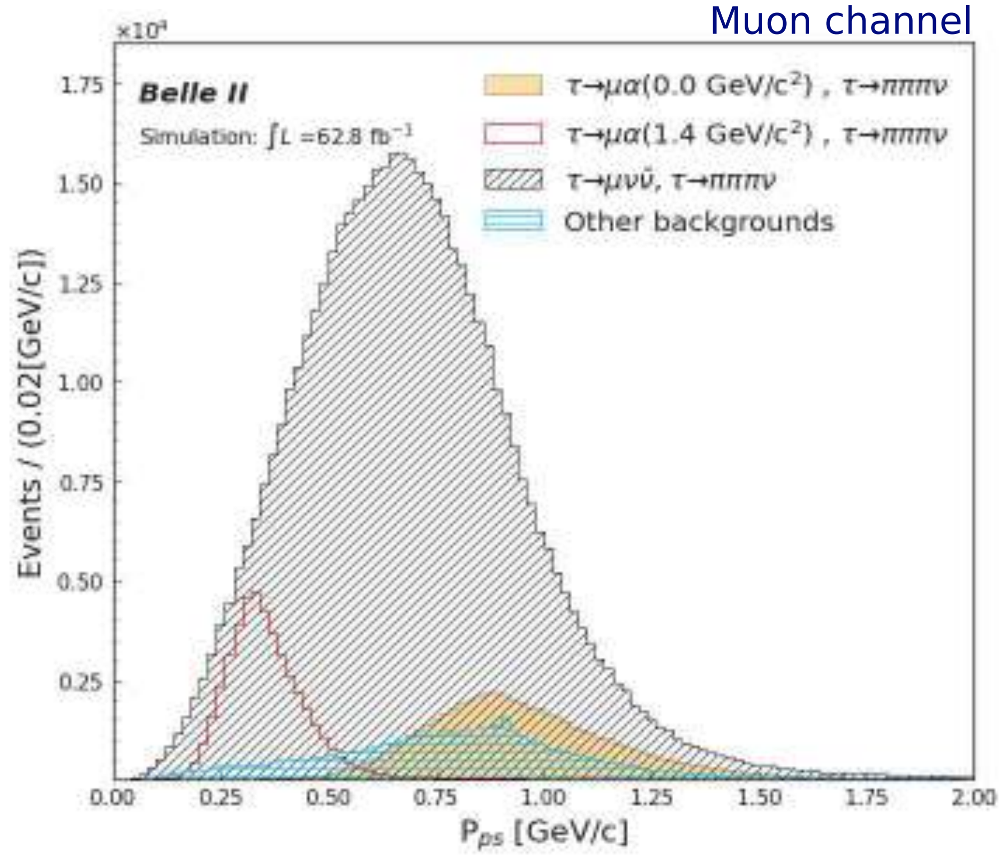
- We cannot access the τ rest frame directly due to missing particles
  - Use ARGUS method
    - $E_\tau = \sqrt{s}/2$
    - Approximation: τ flight direction given by the momentum of the 3-prong system



Electron channel



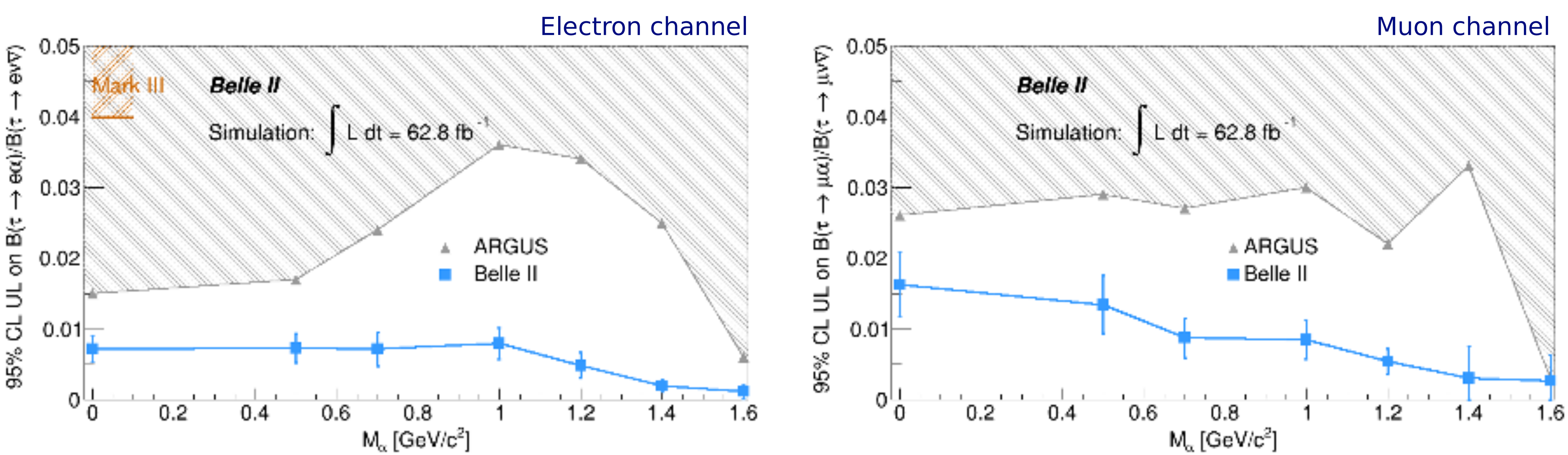
Muon channel



$\tau \to \ell\ \alpha$: expected sensitivity

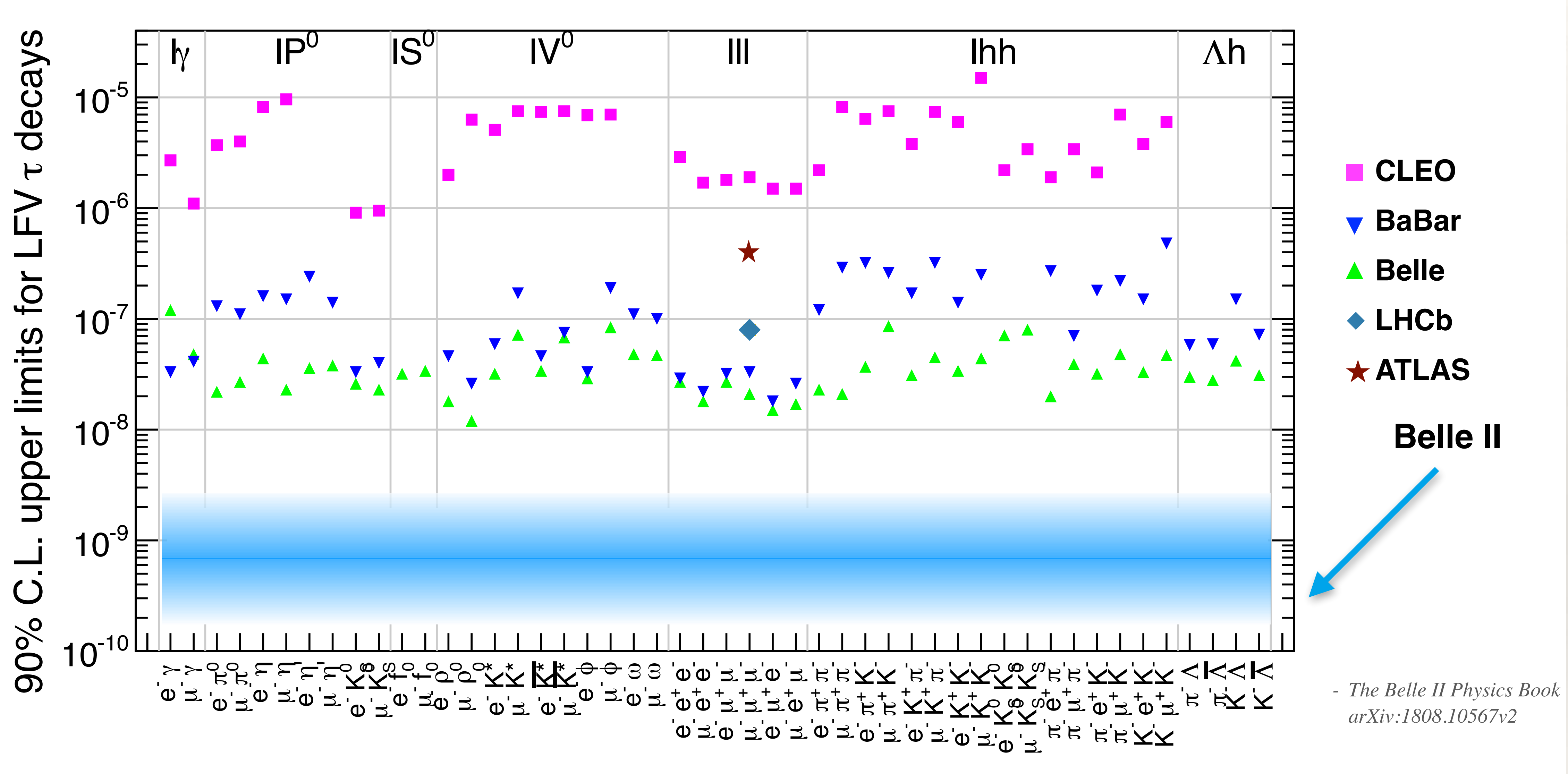
A. de Yta, TAU2021

- We provide the UL sensitivity for Br($\tau \to l\alpha$)/Br($\tau \to l\nu\nu$) at 95% CL for L_{int} = 62.8 fb^{-1}
- We have identified the sources of dominant systematic uncertainties
  - LID
  - Trigger



- A scenario with reduced systematic effects is expected.
- This is a closed box analysis
  - Data-MC validation procedure is ongoing
  - We aim to open the box in the near future

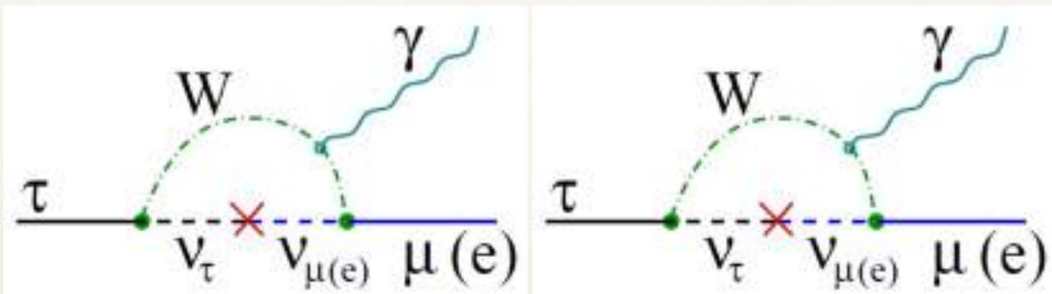
LFV in τ decays



- The Belle II Physics Book arXiv:1808.10567v2

> 48 modes searched at B-factories, but more integrated luminosity (and improvements in signal efficiency) is needed to improve current limits with Belle II.

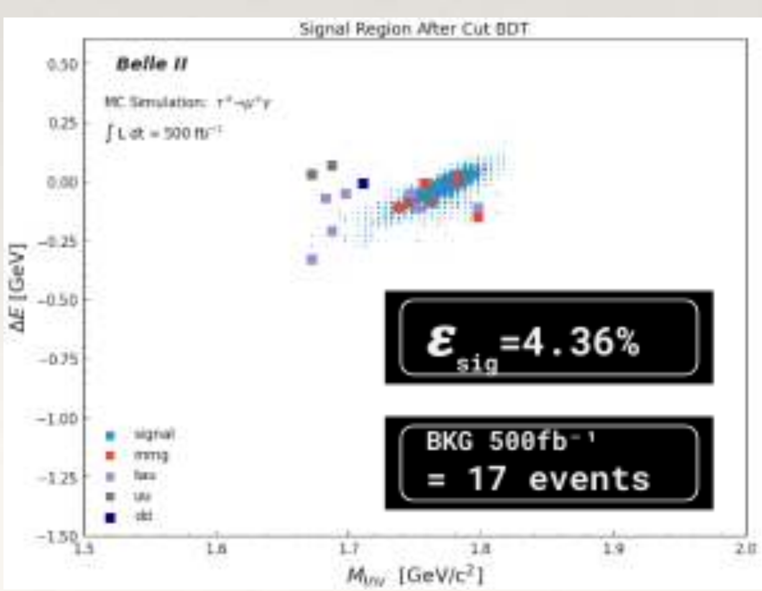
τ→μγ (Marcela G.) and τ→μμμ (Norman M.)



$$\mathcal{B}(\tau \to \mu\gamma) = \frac{3\alpha}{32\pi} \,|\, \Sigma U^*_{\tau i} U_{\mu i} \frac{\Delta m^2_{3i}}{m^2_W} \,|^2 \sim 10^{-45}$$

	reference	τ→μγ	τ→μμμ
SM + heavy Maj ν_R	PRD 66(2002)034008	10^{-9}	10^{-10}
Non-universal Z'	PLB 547(2002)252	10^{-9}	10^{-8}
SUSY SO(10)	PRD 68(2003)033012	10^{-8}	10^{-10}
mSUGRA+seesaw	PRD 66(2002)115013	10^{-7}	10^{-9}
SUSY Higgs	PLB 566(2003)217	10^{-10}	10^{-7}

BELLE II (Book 2018)	MC	$< 2.726 \times 10^{-8}$
BELLE2-NOTE-PH-2019-001	MC9 (1 ab^{-1})	$< 2.883 \times 10^{-8}$
Current analysis	MC10 (1 ab^{-1}) opt 2	$< 3.737 \times 10^{-8}$

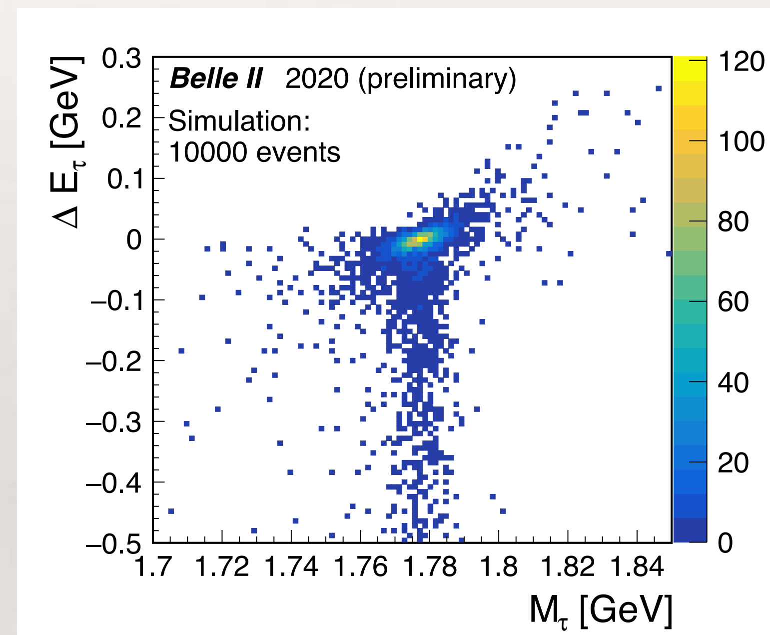


Two independent variables:

$$M_\tau = \sqrt{E^2_{\mu\mu\mu} - P^2_{\mu\mu\mu}}$$

$$\Delta E = E^{CMS}_{\mu\mu\mu} - E^{CMS}_{\text{beam}}$$

➡ For signal → ΔE close to 0 and $M_{\mu\mu\mu}$ close to τ mass



- For τ→μγ (1x1 topology), similar sensitivity to Belle. Plan to include 1x3 topology.
- For τ→μμμ (3x1 topology), Belle II can avoid μ veto in tag and almost double sensitivity.

Summary

- Rich and successful physics program at the B-factories.
- Hints of new physics will need both, Belle II and the LHC experiments, to investigate them.
  - Many flavor anomalies can be only resolved at Belle II.
- Belle II is more than Belle with higher luminosity; there are also many improvements in detector, trigger, reconstruction, analysis techniques, computing algorithms, etc. to reach beyond.
- Belle II is just ramping up, expect much more results in next few years, 4 publications so far (ALP, Z′, $B \to K\nu\nu$, luminosity, D lifetime).
- Cinvestav actively working on **properties of τ's and cLFV.** **We expect first Belle II publications on tau physics early next year (mass, $\tau \to \ell\, \alpha$).**