τ physics results and prospects at Belle II

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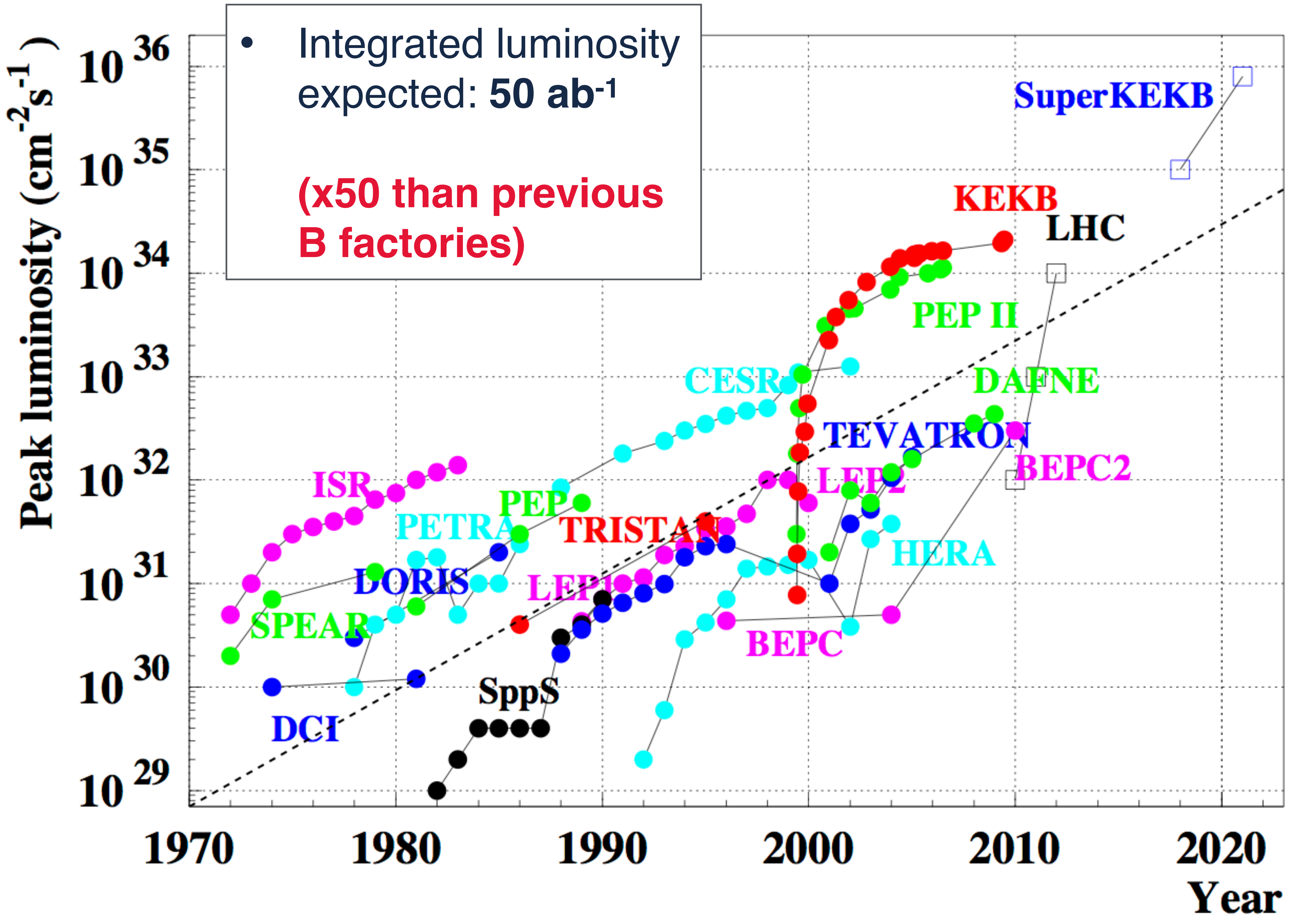
The University of Mississippi

On behalf of the Belle II collaboration

Conference on Flavour Physics and CP violation (FPCP) 2020

Jun 8, 2020

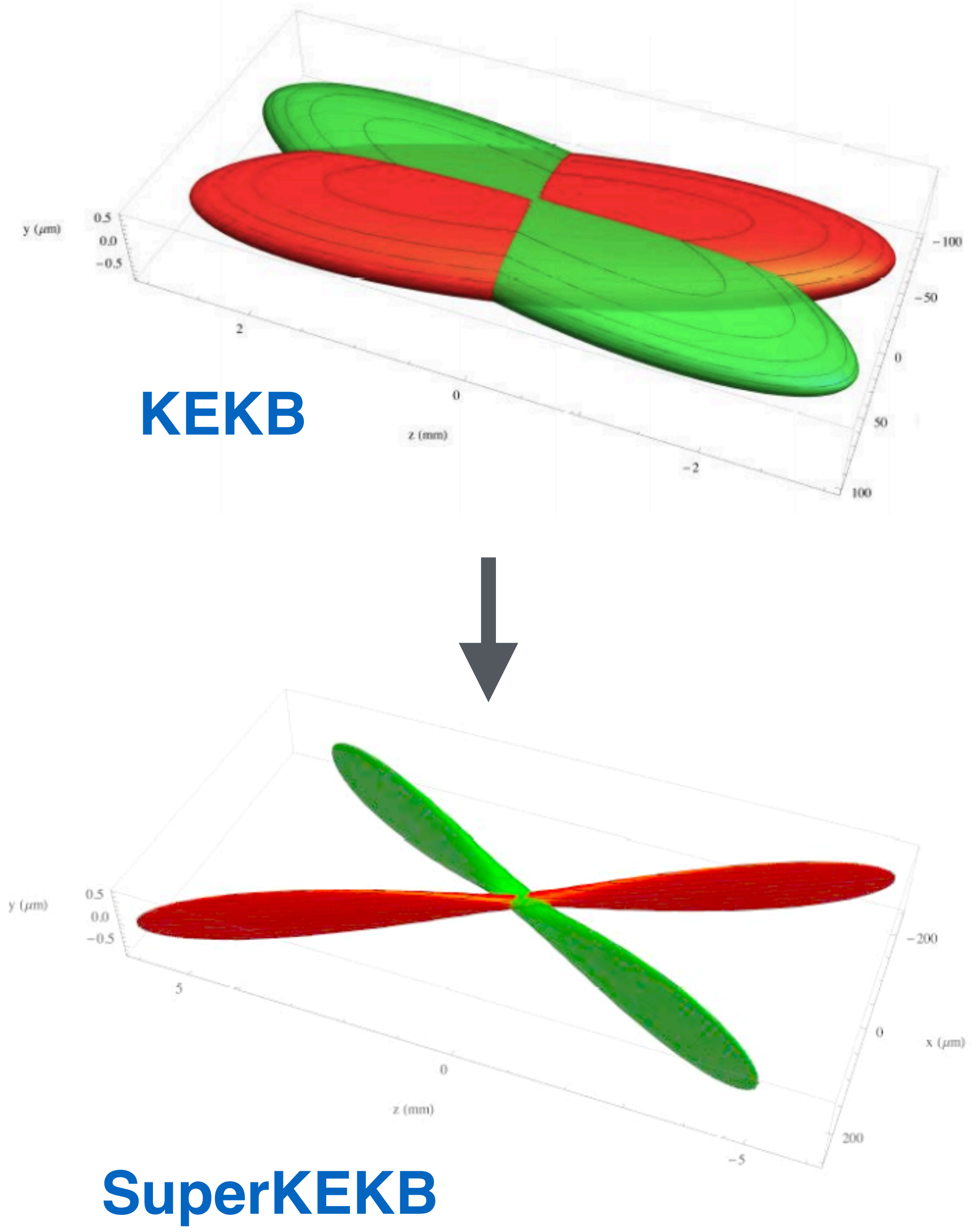
SuperKEKB and The Belle II experiment

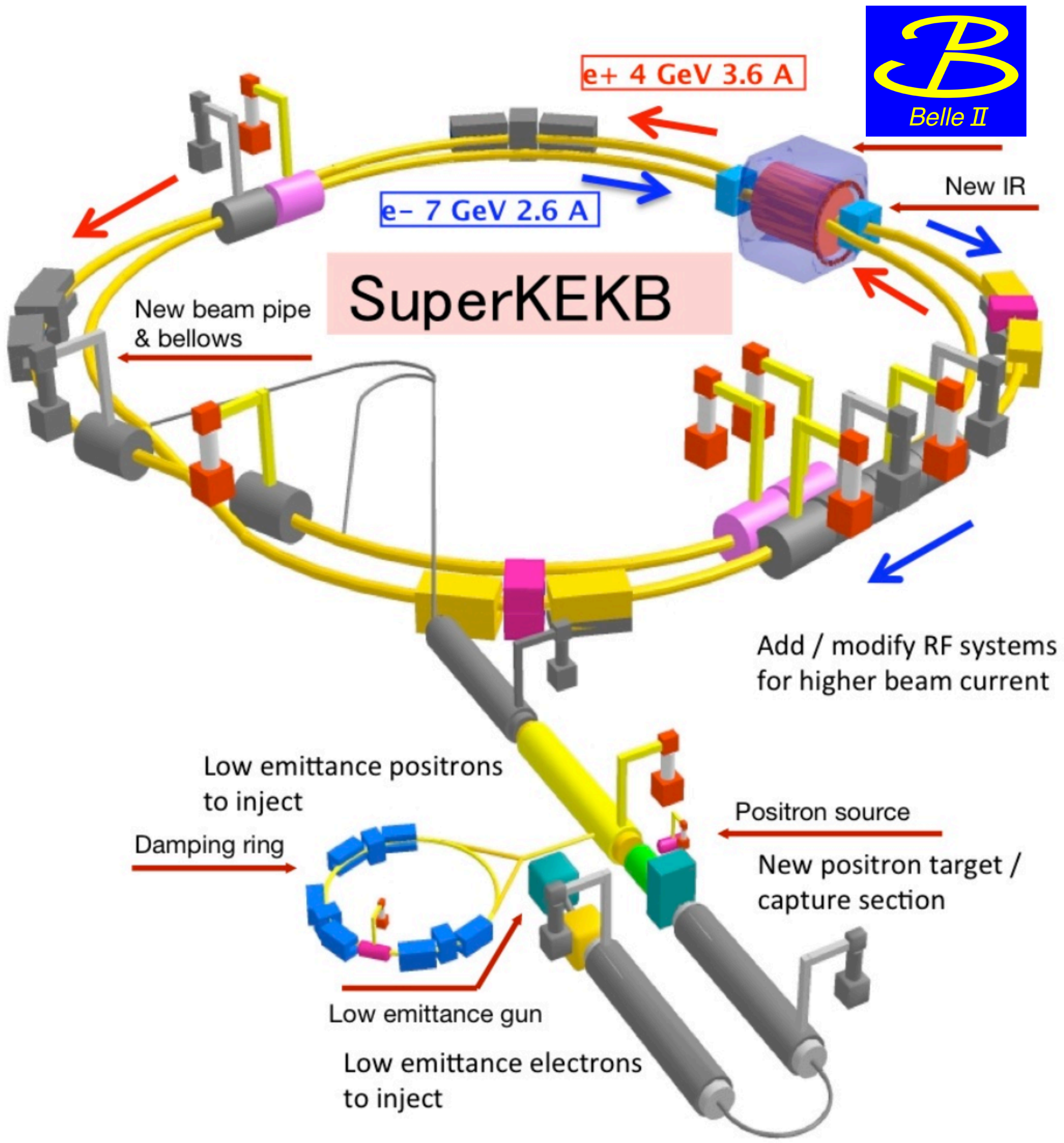


- Integrated luminosity expected: **50 ab^{-1}**

  (x50 than previous B factories)

"Nano-beams": vertical beam size is 50nm at the IP.



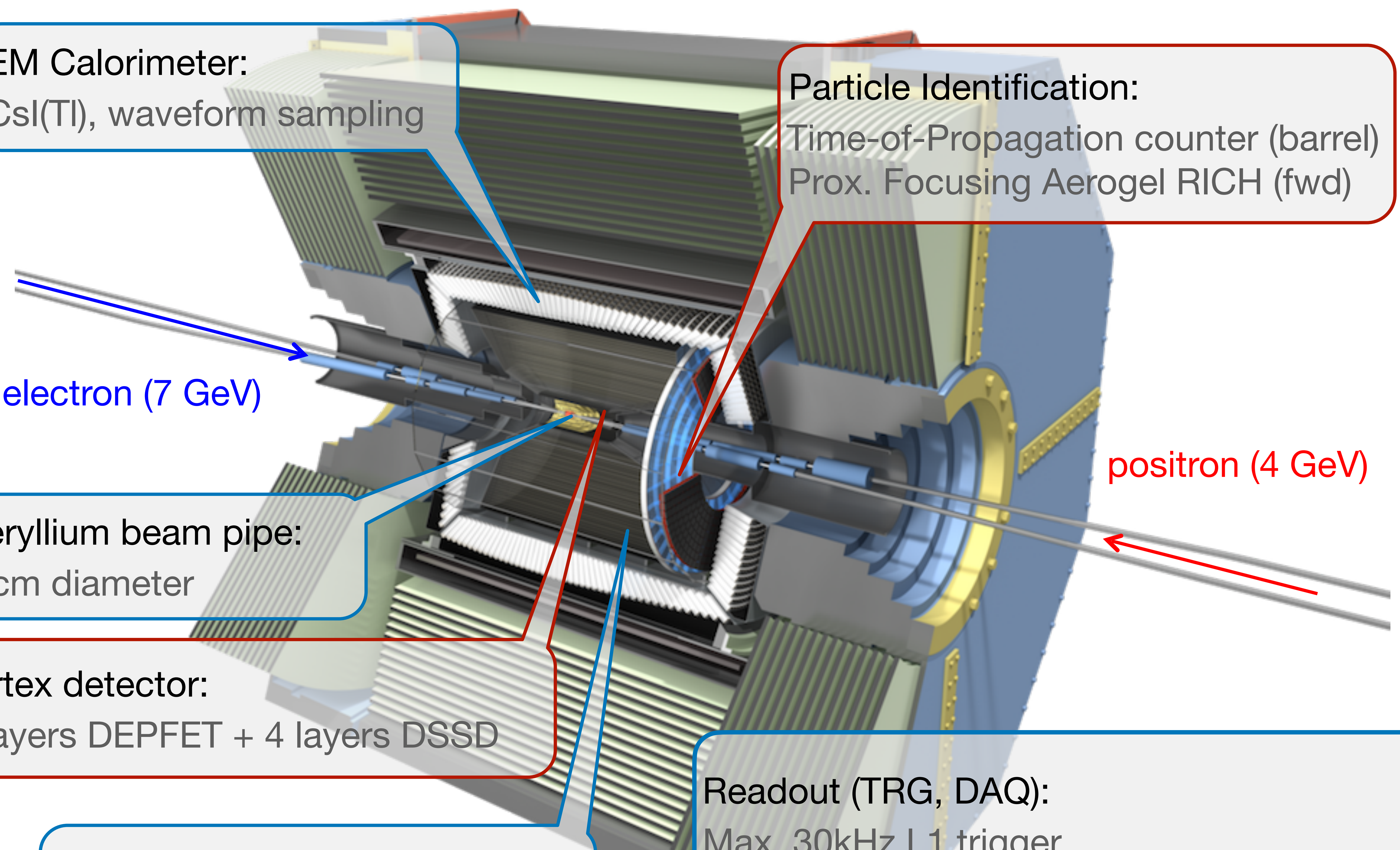


- **Challenges at L=8x10^{35} 1/cm^2/s:**

  - Higher background (Radiative Bhabha, Touschek, beam-gas scattering, etc.).

  - Higher trigger rates (High performance DAQ, computing).

The Belle II experiment



EM Calorimeter:
CsI(Tl), waveform sampling

Particle Identification:
Time-of-Propagation counter (barrel)
Prox. Focusing Aerogel RICH (fwd)

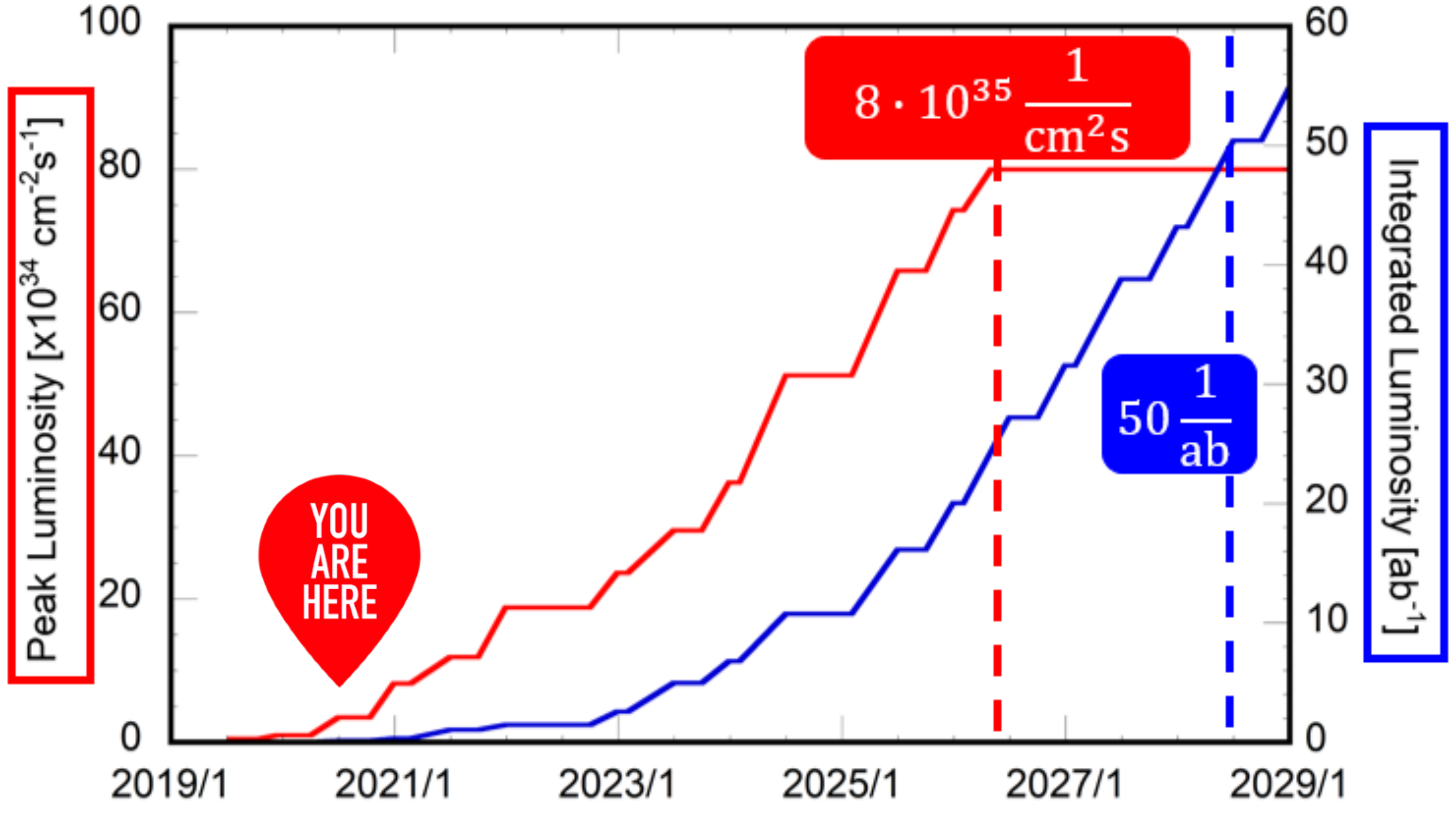
Beryllium beam pipe:
2 cm diameter

Vertex detector:
2 layers DEPFET + 4 layers DSSD

Central Drift Chamber:
He(50%):C_2H_6(50%), Small cells, long lever arm, fast electronics

Readout (TRG, DAQ):
Max. 30kHz L1 trigger
~100% efficient for hadronic events.
1MB (PXD) + 100kB (others) per event
- over 30GB/sec to record

Offline computing:
Distributed over the world via the GRID



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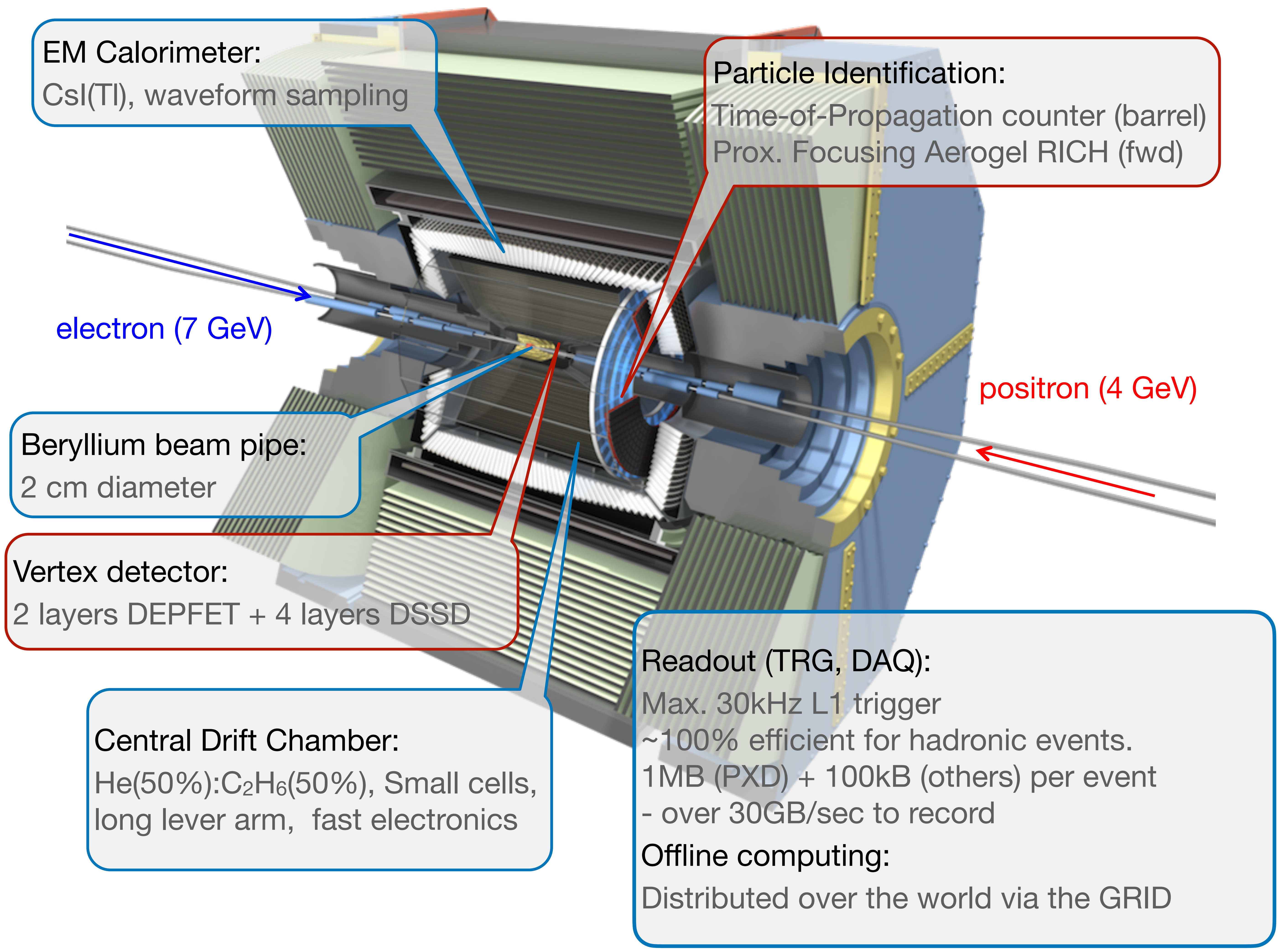
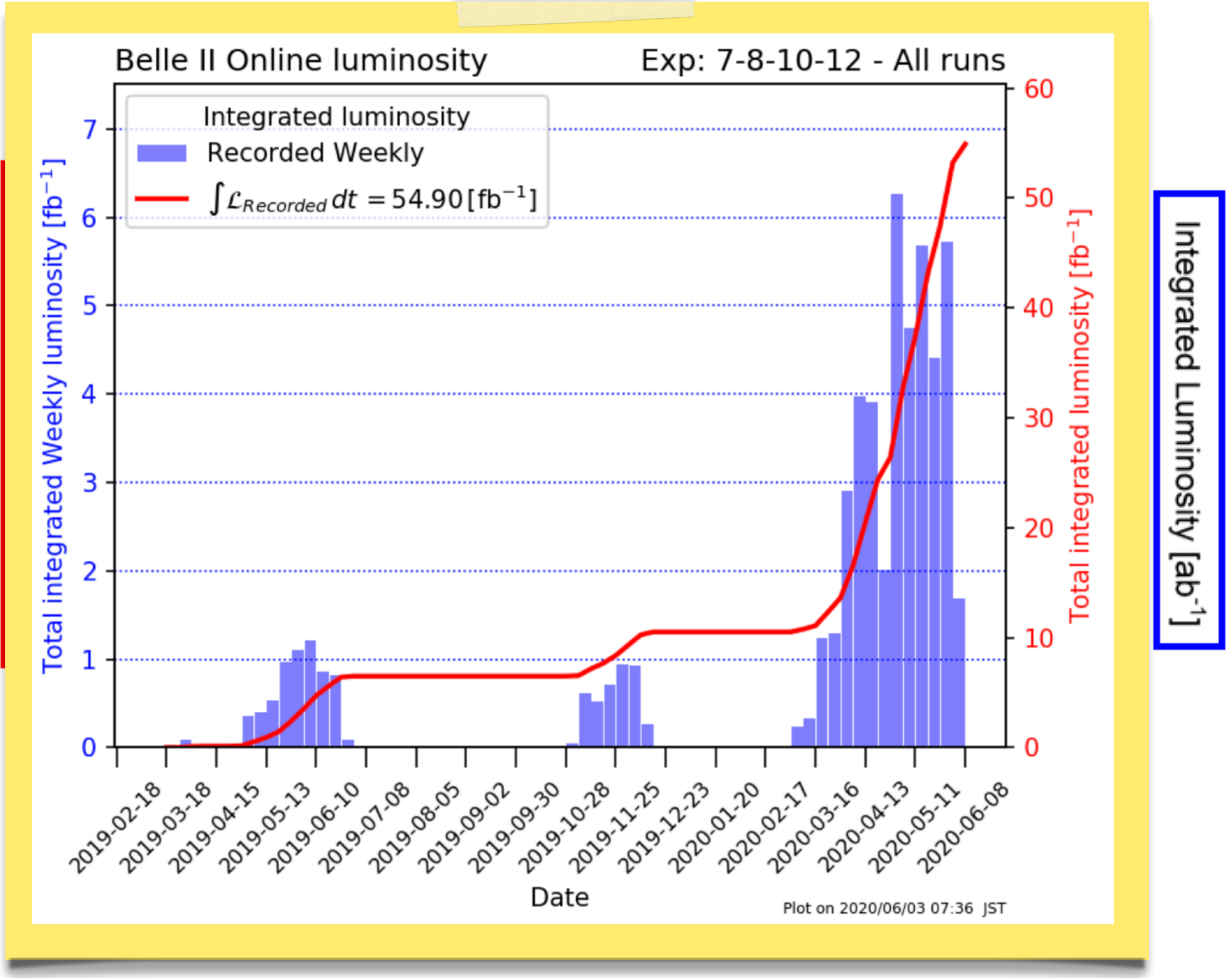
The Belle II experiment





(x50 than the previous B factories)

To the date, we have reached an integrated luminosity of 50 fb^{-1}

Belle II

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τ lepton physics on the B-Factories

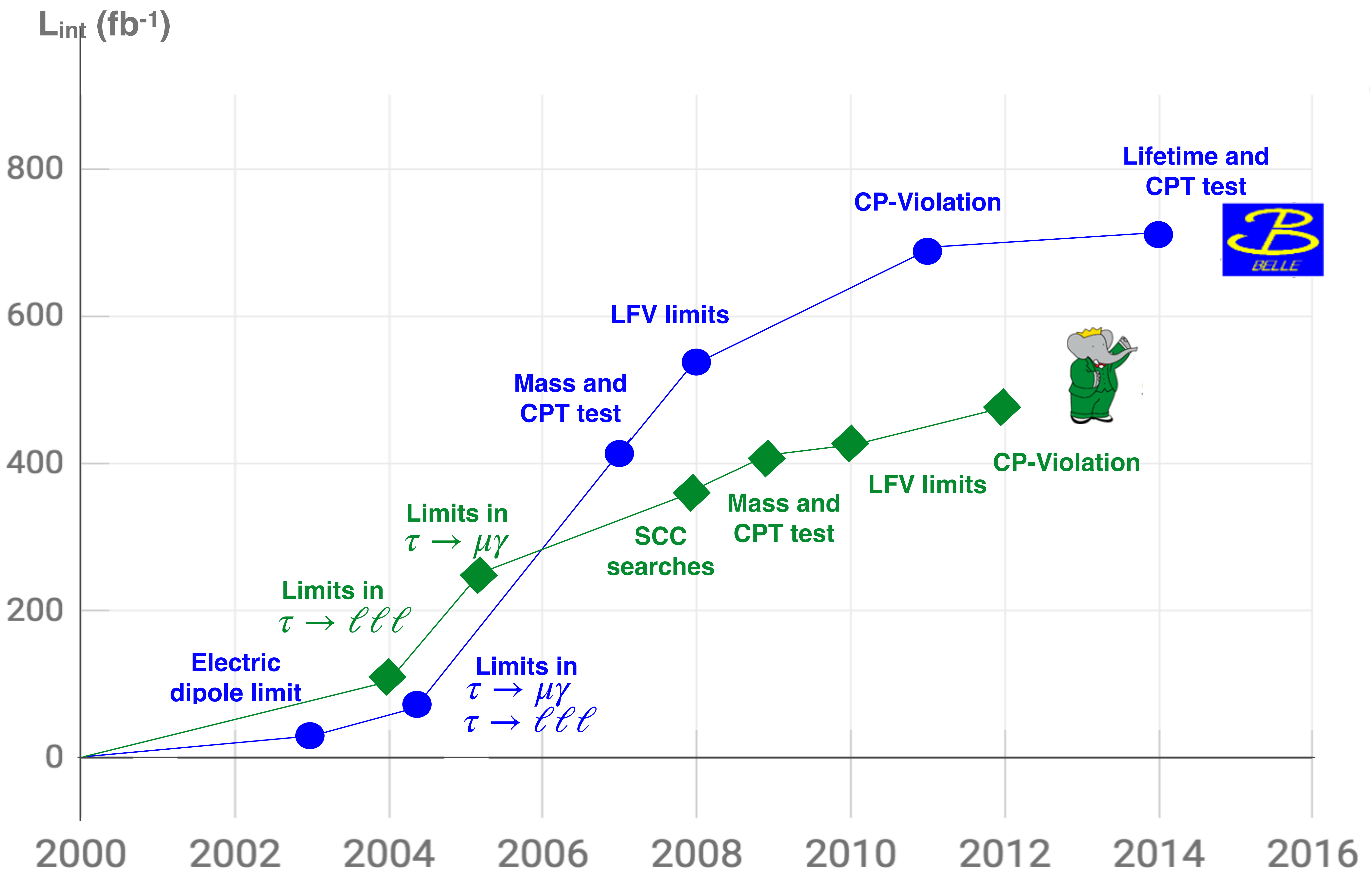
- B-Factories are also τ-factories!

  $\sigma(e^+e^- \longrightarrow BB) = 1.05$ nb

  $\sigma(e^+e^- \longrightarrow \tau\,\tau) = 0.92$ nb

- τ lepton decays allow a clean analysis of hadronization, determination of SM parameters, properties of weak currents and BSM searches.

- Belle and BaBar provided many interesting results in τ lepton physics along the last two decades.



- **Many of this results will be updated by Belle II**

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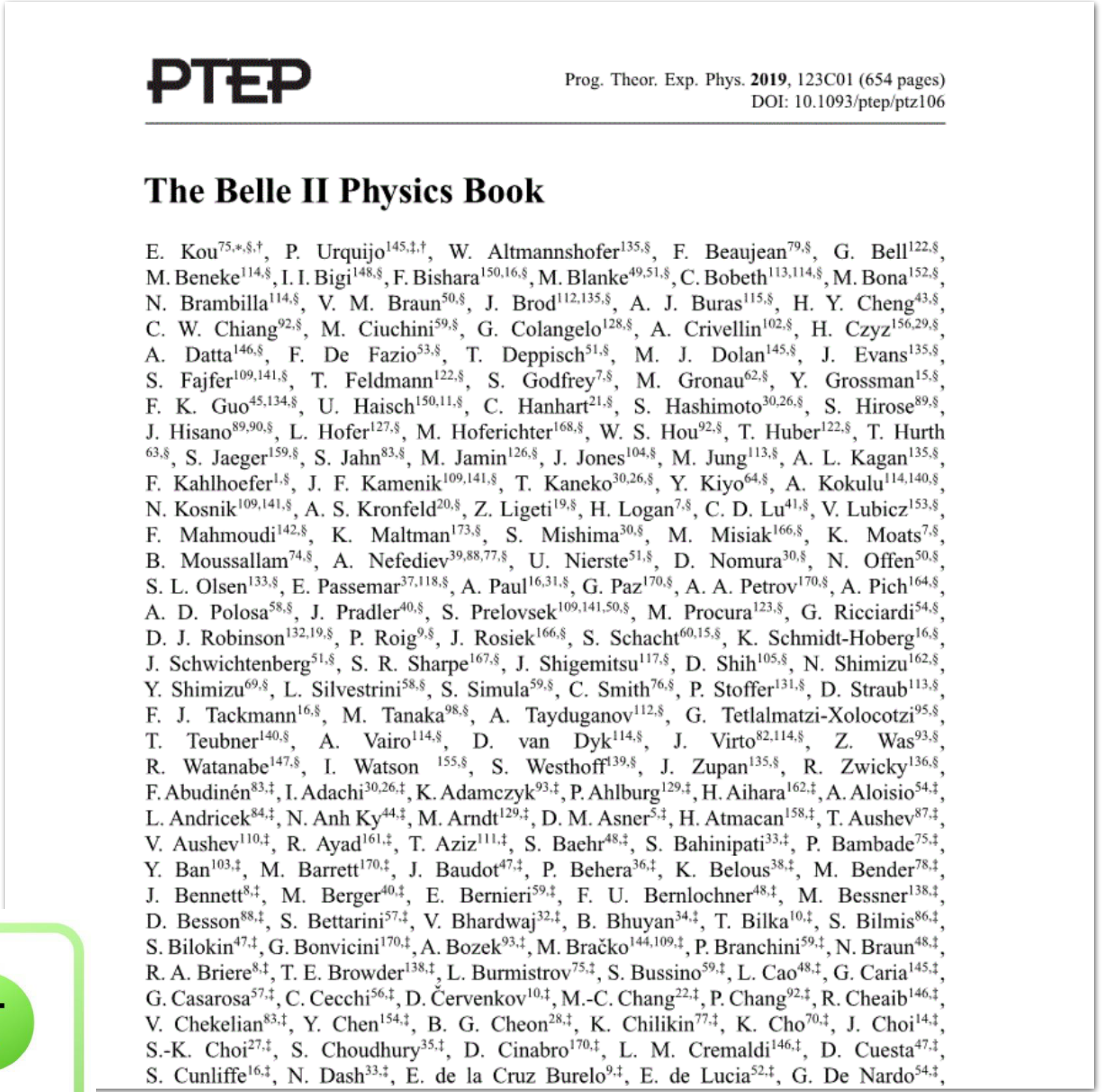
The physics program at Belle II

- The enormous number of e^+e^- collisions features a unique environment for the study of τ **physics** with high precision.

- Further details can be found in **"The Belle II Physics Book"**, which is now available at: PTEP 2019 (2019) 12, 123C01

- The physics program of the Belle II experiment covers also high precision measurements in B decays, charm, dark sectors, exotic particles, etc.

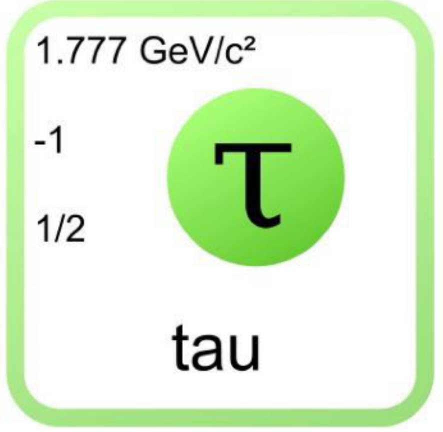
- See the Belle II talks during FPCP 2020:
  - Charm and charmonium
  - First B physics results
  - Radiative and electroweak penguin decays
  - CKM matrix
  - Full Event Interpretation algorithm
  - Belle II status and prospects



PTEP
Prog. Theor. Exp. Phys. **2019**, 123C01 (654 pages)
DOI: 10.1093/ptep/ptz106

The Belle II Physics Book

E. Kou[75,*,§,†], P. Urquijo[145,‡,†], W. Altmannshofer[135,§], F. Beaujean[79,§], G. Bell[122,§], M. Beneke[114,§], I. I. Bigi[148,§], F. Bishara[150,16,§], M. Blanke[49,51,§], C. Bobeth[113,114,§], M. Bona[152,§], N. Brambilla[114,§], V. M. Braun[50,§], J. Brod[112,135,§], A. J. Buras[115,§], H. Y. Cheng[43,§], C. W. Chiang[92,§], M. Ciuchini[59,§], G. Colangelo[128,§], A. Crivellin[102,§], H. Czyz[156,29,§], A. Datta[146,§], F. De Fazio[53,§], T. Deppisch[51,§], M. J. Dolan[145,§], J. Evans[135,§], S. Fajfer[109,141,§], T. Feldmann[122,§], S. Godfrey[7,§], M. Gronau[62,§], Y. Grossman[15,§], F. K. Guo[45,134,§], U. Haisch[150,11,§], C. Hanhart[21,§], S. Hashimoto[30,26,§], S. Hirose[89,§], J. Hisano[89,90,§], L. Hofer[127,§], M. Hoferichter[168,§], W. S. Hou[92,§], T. Huber[122,§], T. Hurth[63,§], S. Jaeger[159,§], S. Jahn[83,§], M. Jamin[126,§], J. Jones[104,§], M. Jung[113,§], A. L. Kagan[135,§], F. Kahlhoefer[1,§], J. F. Kamenik[109,141,§], T. Kaneko[30,26,§], Y. Kiyo[64,§], A. Kokulu[114,140,§], N. Kosnik[109,141,§], A. S. Kronfeld[20,§], Z. Ligeti[19,§], H. Logan[7,§], C. D. Lu[41,§], V. Lubicz[153,§], F. Mahmoudi[142,§], K. Maltman[173,§], S. Mishima[30,§], M. Misiak[166,§], K. Moats[7,§], B. Moussallam[74,§], A. Nefediev[39,88,77,§], U. Nierste[51,§], D. Nomura[30,§], N. Offen[50,§], S. L. Olsen[133,§], E. Passemar[37,118,§], A. Paul[16,31,§], G. Paz[170,§], A. A. Petrov[170,§], A. Pich[164,§], A. D. Polosa[58,§], J. Pradler[40,§], S. Prelovsek[109,141,50,§], M. Procura[123,§], G. Ricciardi[54,§], D. J. Robinson[132,19,§], P. Roig[9,§], J. Rosiek[166,§], S. Schacht[60,15,§], K. Schmidt-Hoberg[16,§], J. Schwichtenberg[51,§], S. R. Sharpe[167,§], J. Shigemitsu[117,§], D. Shih[105,§], N. Shimizu[162,§], Y. Shimizu[69,§], L. Silvestrini[58,§], S. Simula[59,§], C. Smith[76,§], P. Stoffer[131,§], D. Straub[113,§], F. J. Tackmann[16,§], M. Tanaka[98,§], A. Tayduganov[112,§], G. Tetlalmatzi-Xolocotzi[95,§], T. Teubner[140,§], A. Vairo[114,§], D. van Dyk[114,§], J. Virto[82,114,§], Z. Was[93,§], R. Watanabe[147,§], I. Watson [155,§], S. Westhoff[139,§], J. Zupan[135,§], R. Zwicky[136,§], F. Abudinén[83,‡], I. Adachi[30,26,‡], K. Adamczyk[93,‡], P. Ahlburg[129,‡], H. Aihara[162,‡], A. Aloisio[54,‡], L. Andricek[84,‡], N. Anh Ky[44,‡], M. Arndt[129,‡], D. M. Asner[5,‡], H. Atmacan[158,‡], T. Aushev[87,‡], V. Aushev[110,‡], R. Ayad[161,‡], T. Aziz[111,‡], S. Baehr[48,‡], S. Bahinipati[33,‡], P. Bambade[75,‡], Y. Ban[103,‡], M. Barrett[170,‡], J. Baudot[47,‡], P. Behera[36,‡], K. Belous[38,‡], M. Bender[78,‡], J. Bennett[8,‡], M. Berger[40,‡], E. Bernieri[59,‡], F. U. Bernlochner[48,‡], M. Bessner[138,‡], D. Besson[88,‡], S. Bettarini[57,‡], V. Bhardwaj[32,‡], B. Bhuyan[34,‡], T. Bilka[10,‡], S. Bilmis[86,‡], S. Bilokin[47,‡], G. Bonvicini[170,‡], A. Bozek[93,‡], M. Bračko[144,109,‡], P. Branchini[59,‡], N. Braun[48,‡], R. A. Briere[8,‡], T. E. Browder[138,‡], L. Burmistrov[75,‡], S. Bussino[59,‡], L. Cao[48,‡], G. Caria[145,‡], G. Casarosa[57,‡], C. Cecchi[56,‡], D. Červenkov[10,‡], M.-C. Chang[22,‡], P. Chang[92,‡], R. Cheaib[146,‡], V. Chekelian[83,‡], Y. Chen[154,‡], B. G. Cheon[28,‡], K. Chilikin[77,‡], K. Cho[70,‡], J. Choi[14,‡], S.-K. Choi[27,‡], S. Choudhury[35,‡], D. Cinabro[170,‡], L. M. Cremaldi[146,‡], D. Cuesta[47,‡], S. Cunliffe[16,‡], N. Dash[33,‡], E. de la Cruz Burelo[9,‡], E. de Lucia[52,‡], G. De Nardo[54,‡],



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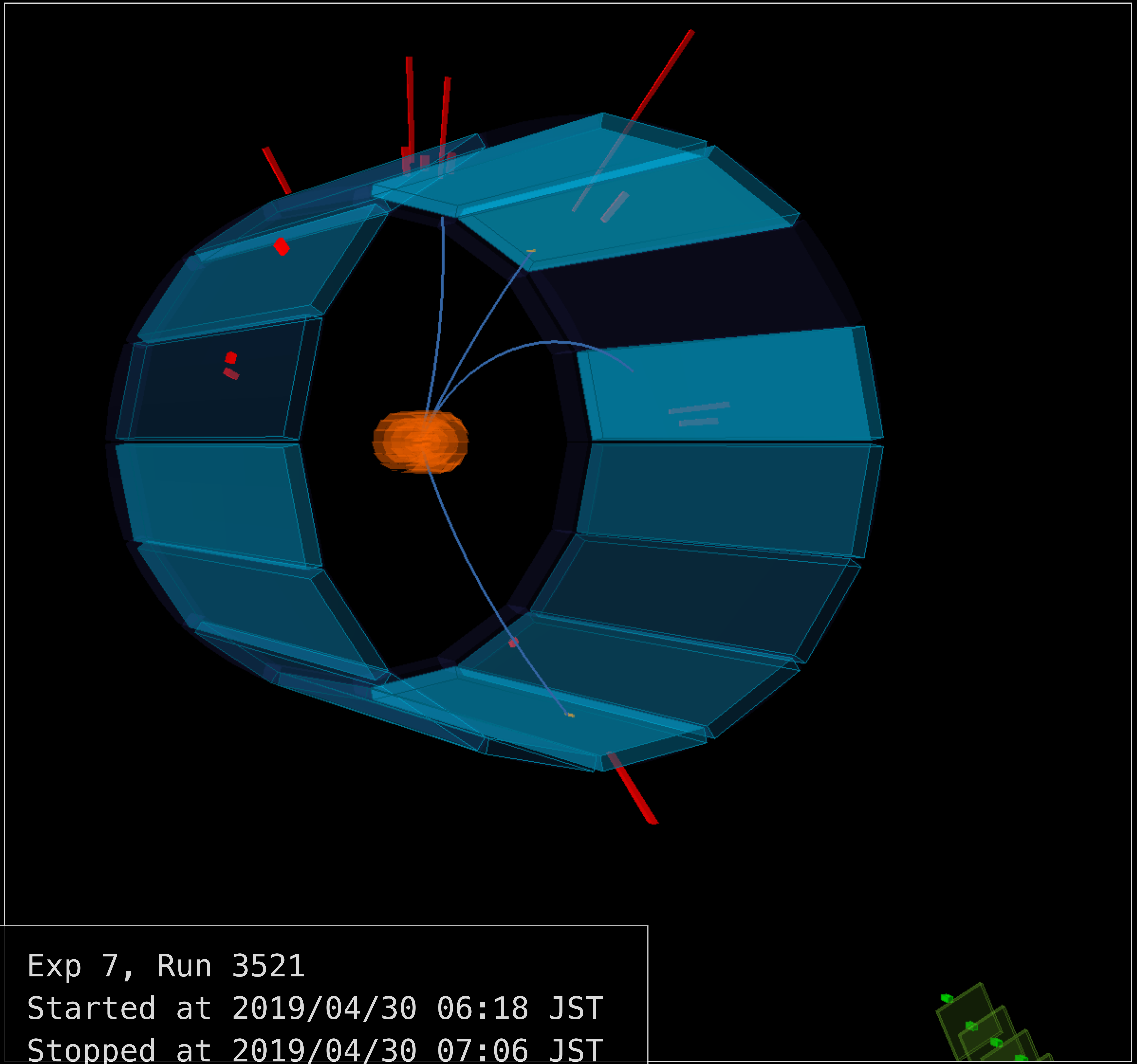
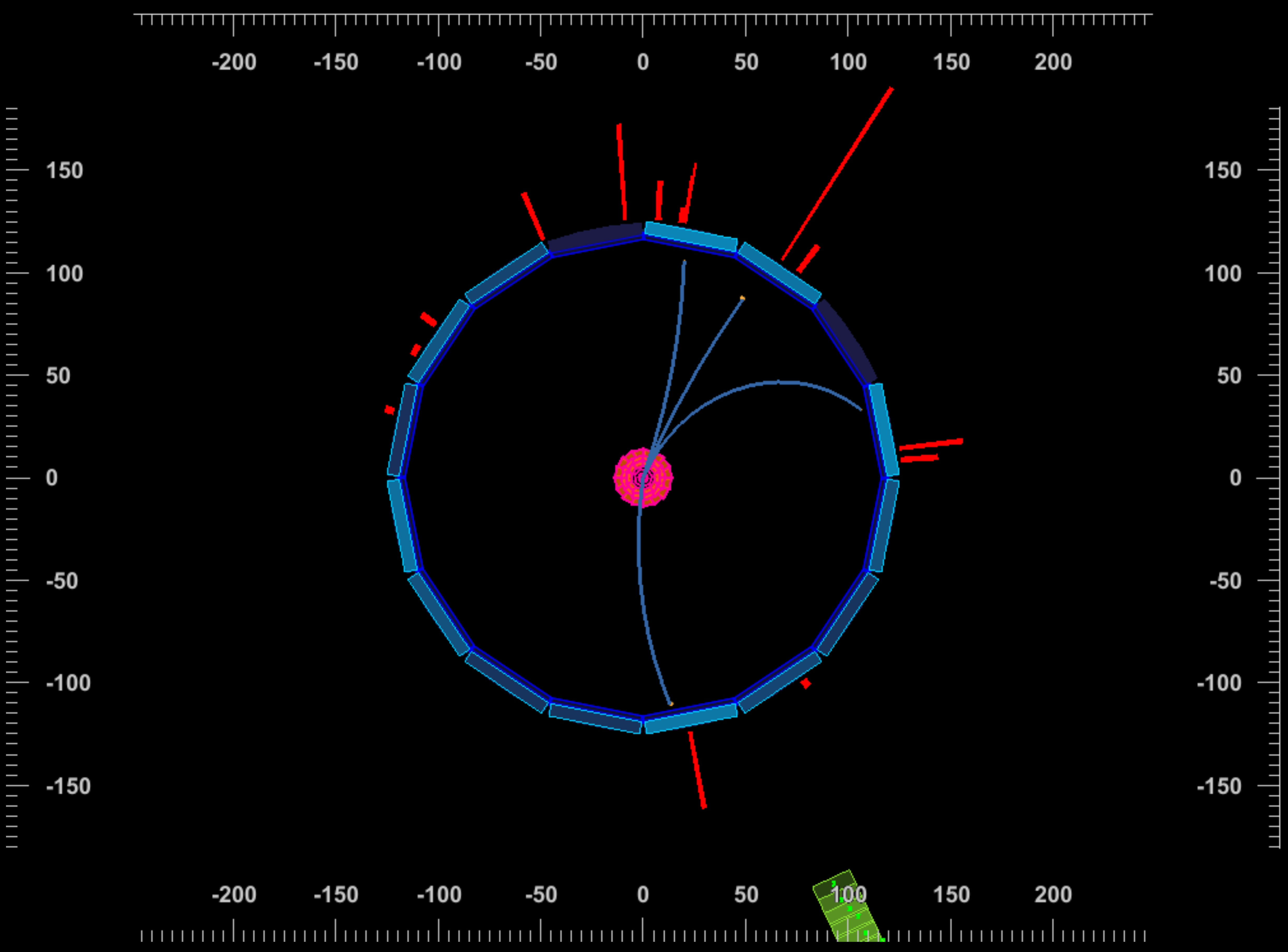
Tau decay event in early Belle II data





Exp 7, Run 3521
Started at 2019/04/30 06:18 JST
Stopped at 2019/04/30 07:06 JST
Run type: physics

Measurement of the τ lepton mass

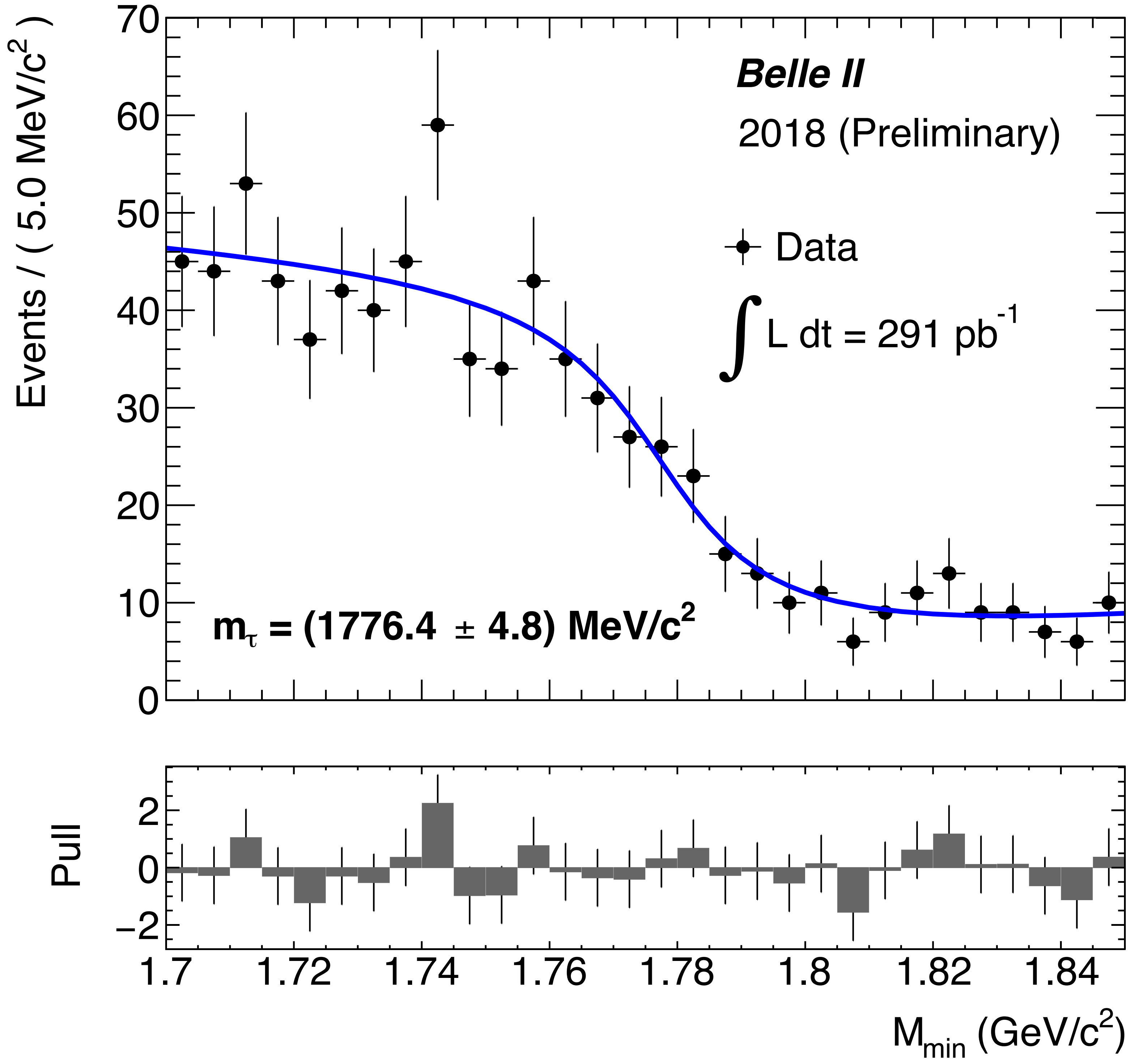
- Measured in the decay mode $\tau \to 3\pi\nu$, using a pseudomass technique developed by the ARGUS collaboration:
- $$M_{min} = \sqrt{M_{3\pi}^2 + 2(E_{beam} - E_{3\pi})(E_{3\pi} - P_{3\pi})}$$
- The distribution of the pseudomass is fitted to a empirical edge function.
- Current best fit from Belle [1]
  1776.61 ± 0.13 ± 0.35 MeV
  Dominated by syst.
- Not so good compared to the BES III mass measurement in the production threshold [2]
  1776.91 ± 0.12 ± 0.13 MeV

[1] K. Belous et al, Phys. Rev. Lett. 99, 011801 (2007)

[2] M. Ablikim et al, Phys. Rev. D 90 012001 (2014)

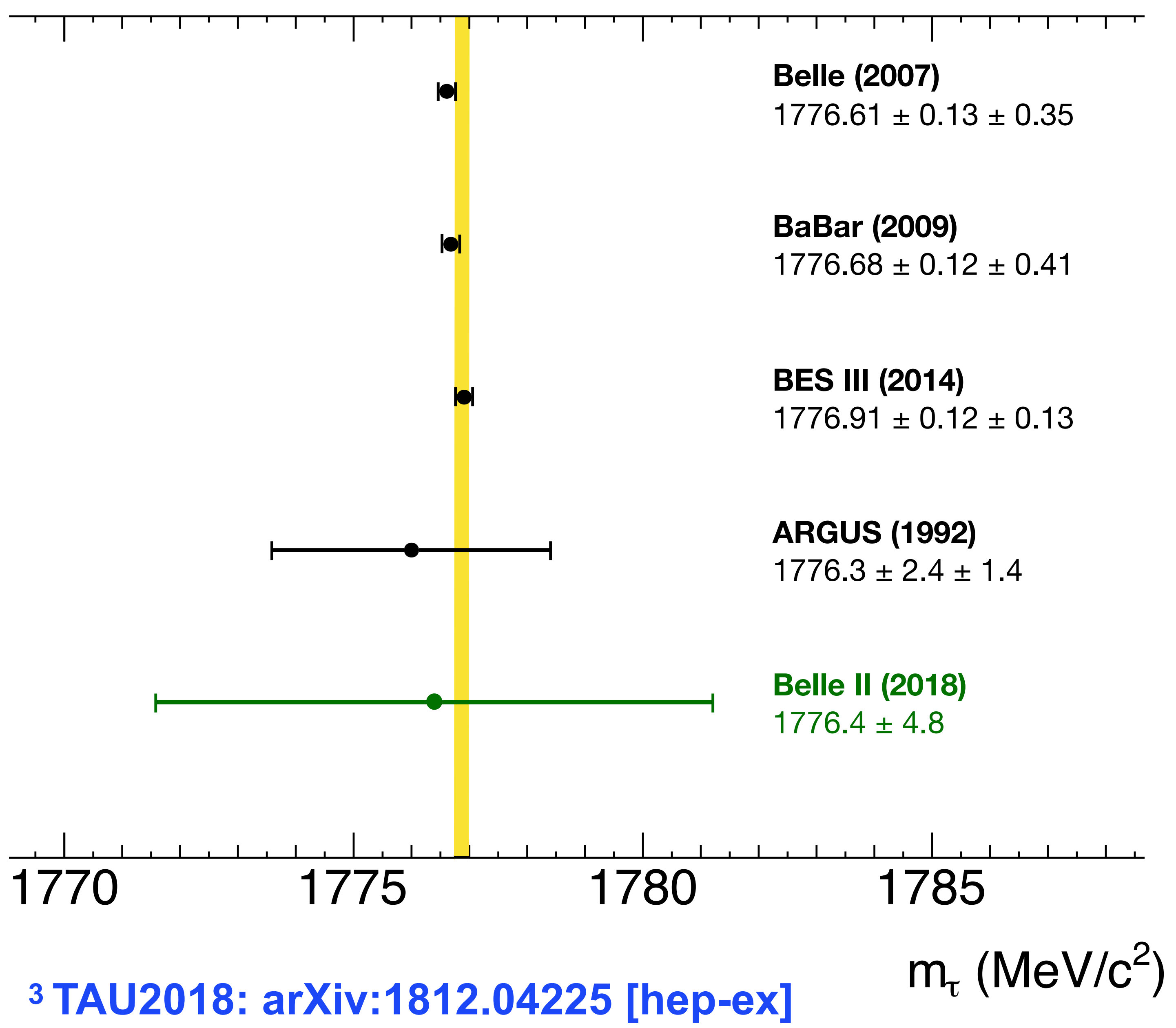
Uncertainty in the τ mass has important consequences the accuracy of lepton universality measurements:

$$\frac{\Gamma(\mu \to e\nu\bar{\nu})}{\Gamma(\tau \to e\nu\bar{\nu})} \sim \left(\frac{g_\mu}{g_\tau}\right)^2 \frac{m_\mu^5}{m_\tau^5}$$



Our result, obtained from Belle II early data [3]
m_τ = (1776.4 ± 4.8 (stat)) MeV/c²)
is consistent with previous experimental results.

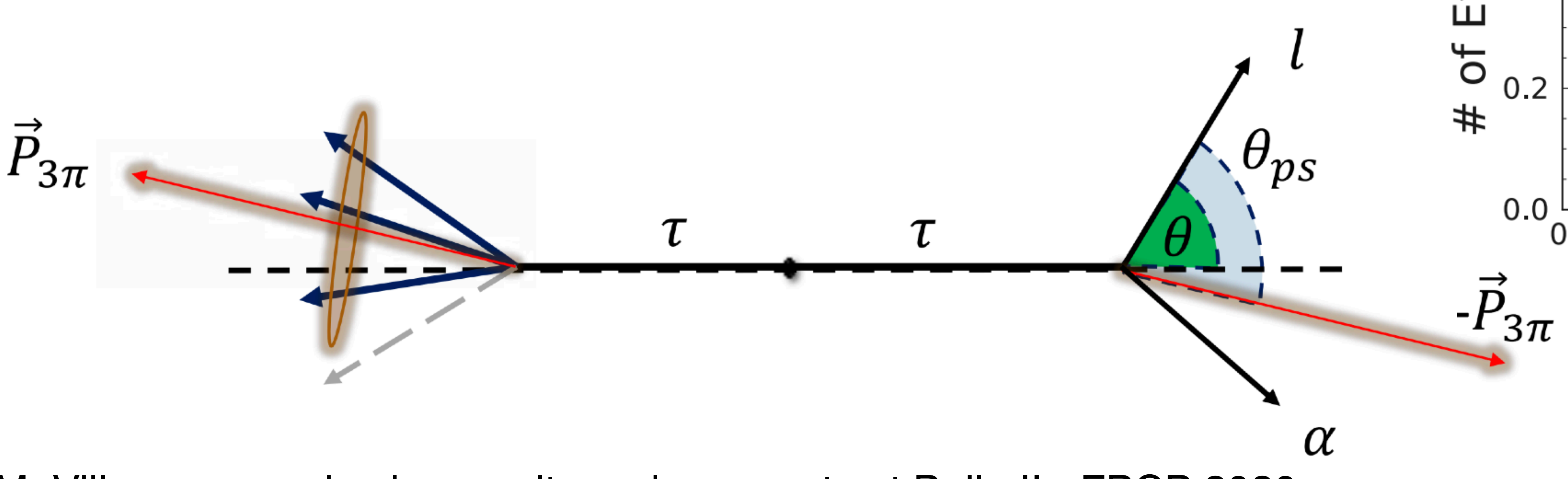
We are updating the result using the most recent data.



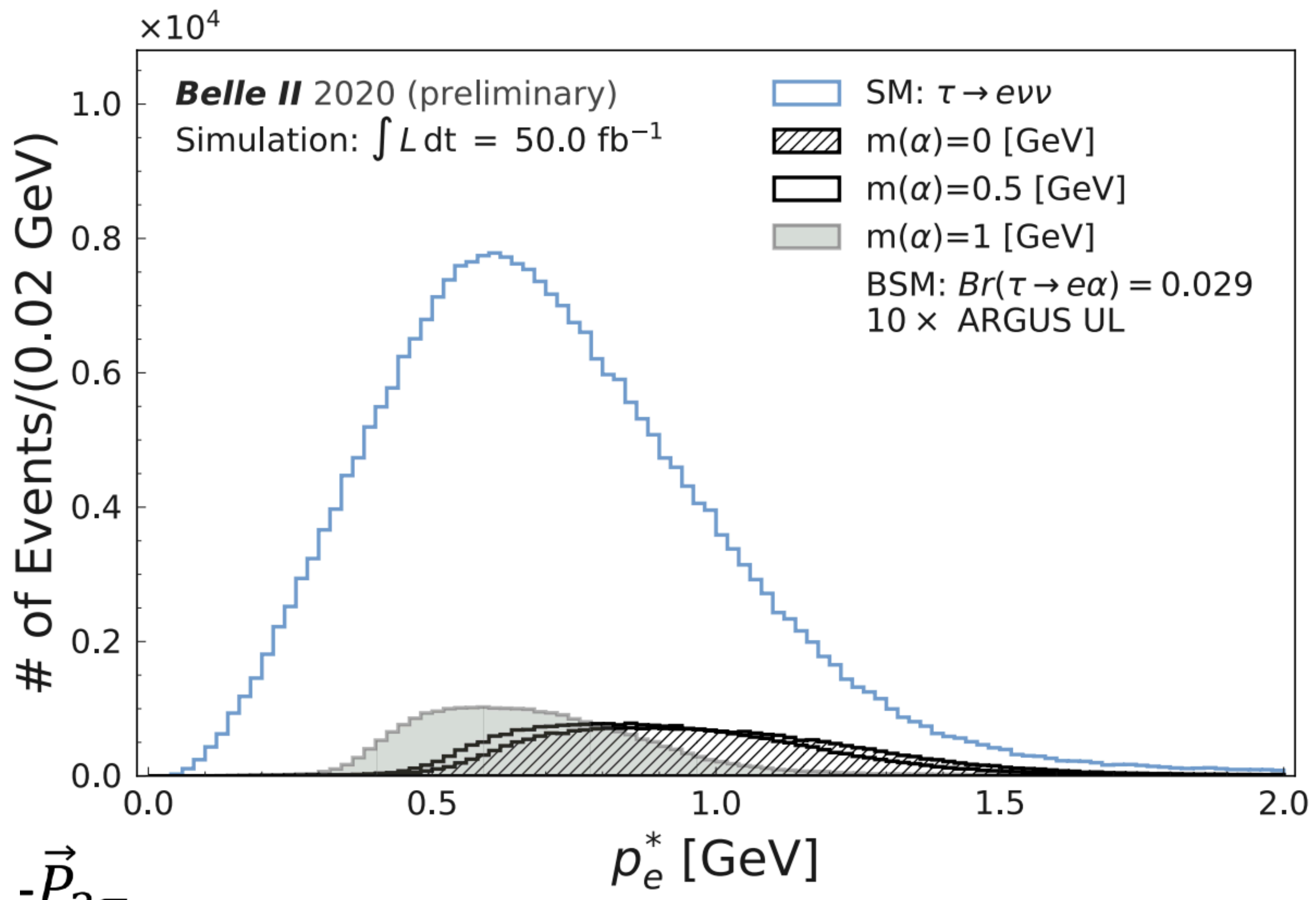
[3] TAU2018: arXiv:1812.04225 [hep-ex]

$\tau \to \ell + \alpha$ (invisible boson)

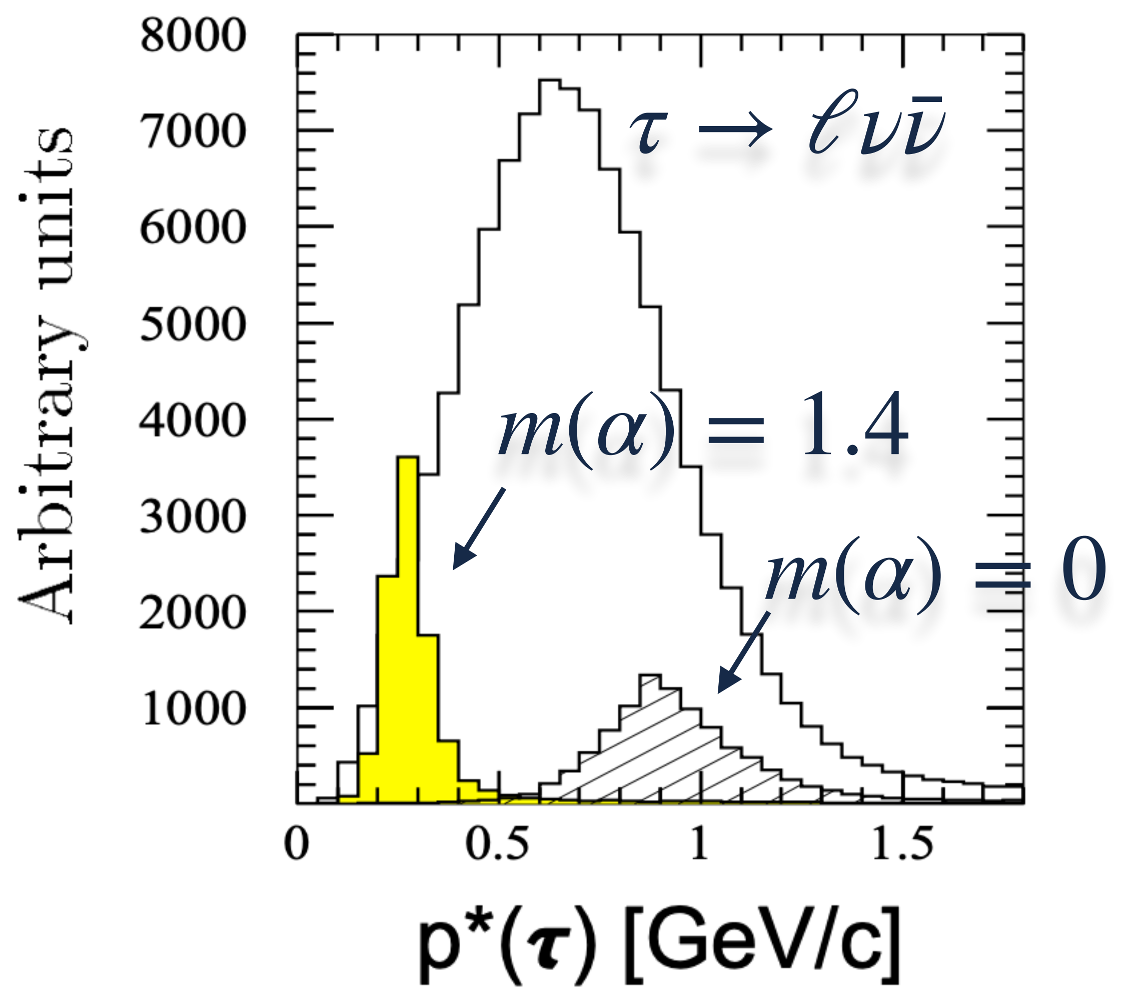
- It probes the existence of a long-lived BSM boson α.
- Peaking signal in a two-body decay spectrum in the τ lepton rest frame (TRF).
- Since we cannot access to the TRF due to the missing neutrino, a pseudo-TRF is built with the following assumptions:
  - $E_\tau \simeq E_{\text{cms}}/2, \quad \vec{p}_\tau \approx \vec{p}_{3\pi}$



- Fit full spectrum with:
  - SM expectation
  - SM + NP expectation and compare likelihood of the two models
- Large smearing due to imprecise boost direction (lost ν):



- Latests results from
  - ARGUS (472 pb^{-1}) *
  - MARK III (9.4 pb^{-1})



H. Albrecht et. al. (ARGUS) Z.Phys. C68 (1995) 25-28

* Belle II is competitive right now.

CP violation in $\tau \to K_S \pi \nu$

- The decay of the τ lepton to final states containing a K_S meson will have a nonzero decay-rate asymmetry due to CP violation in the kaon sector.

$$A_\tau = \frac{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_S^0 \bar{\nu}_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_S^0 \bar{\nu}_\tau)}$$

- The SM prediction[1,2] is

$$A_\tau^{SM} = (3.6 \pm 0.1) \times 10^{-3}$$

- BaBar measured:

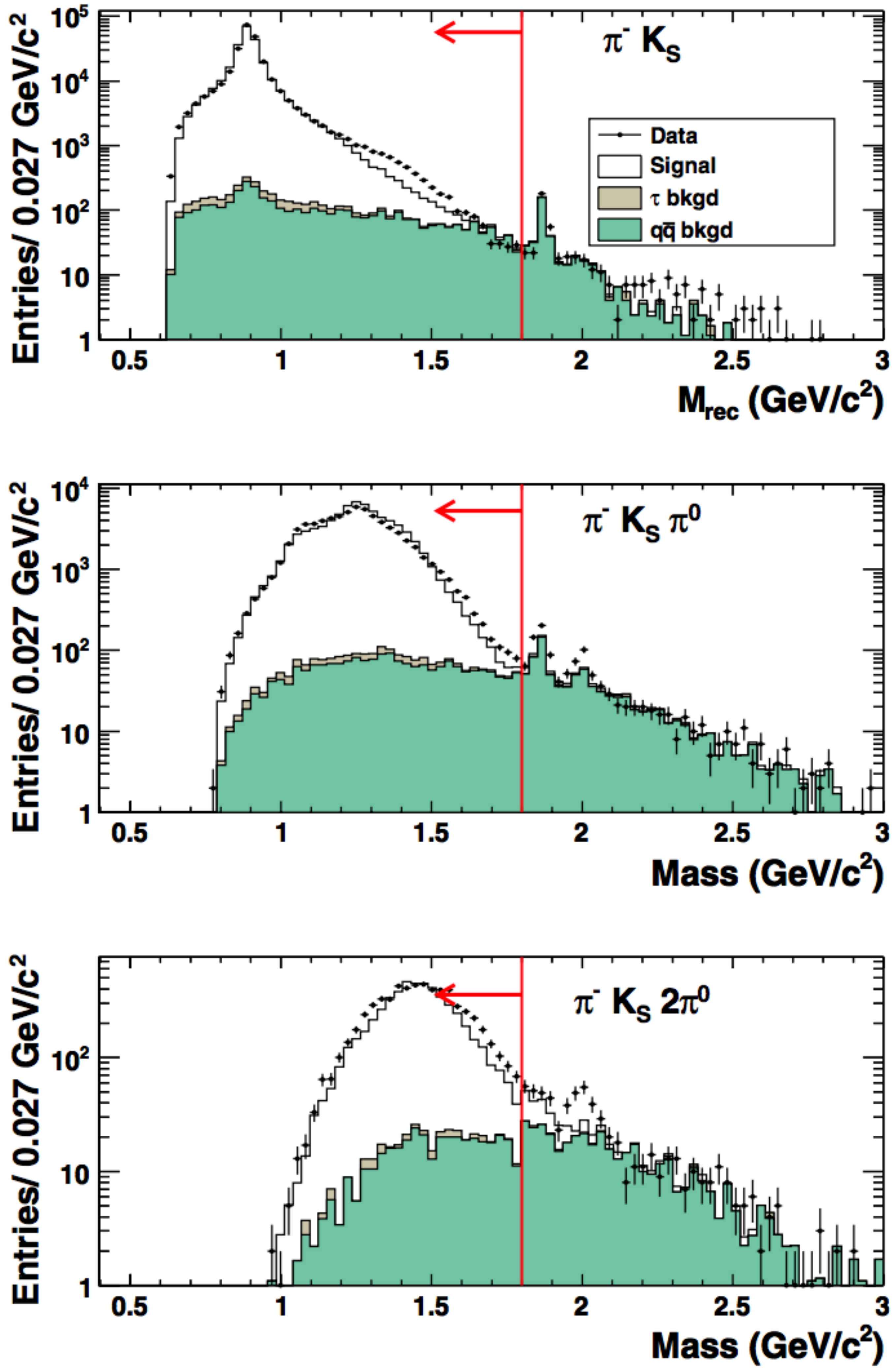
$$A_\tau^{BaBar} = (-3.6 \pm 2.3 \pm 1.1) \times 10^{-3}$$

2.8 σ away from SM

A measurement of A_τ is a priority at Belle II.

- **Improved vertexing and tracking algorithms play a key role.**

[1] I. I. Bigi and A. I. Sanda, Phys. Lett. B 625, 47 (2005).
[2] Y. Grossman and Y. Nir, JHEP 2012.4 (2012).

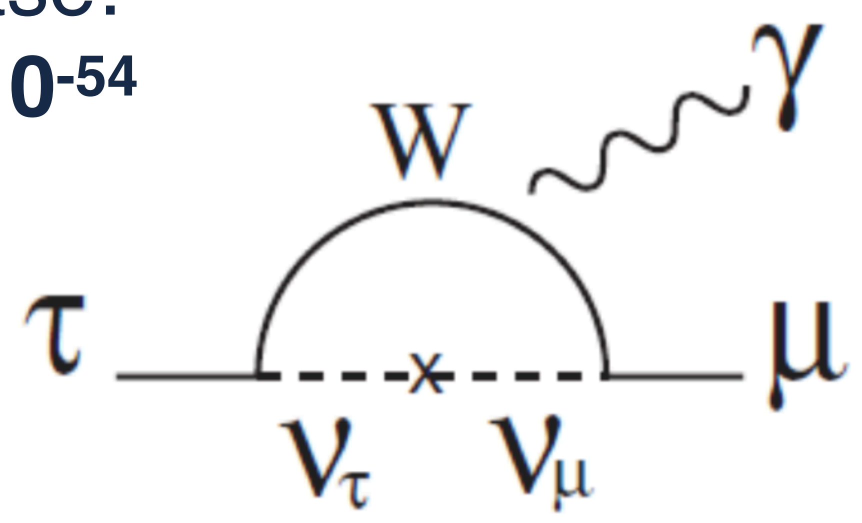


J.P. Lees et.al (BaBar)
Phys.Rev D85 (2012) 031102

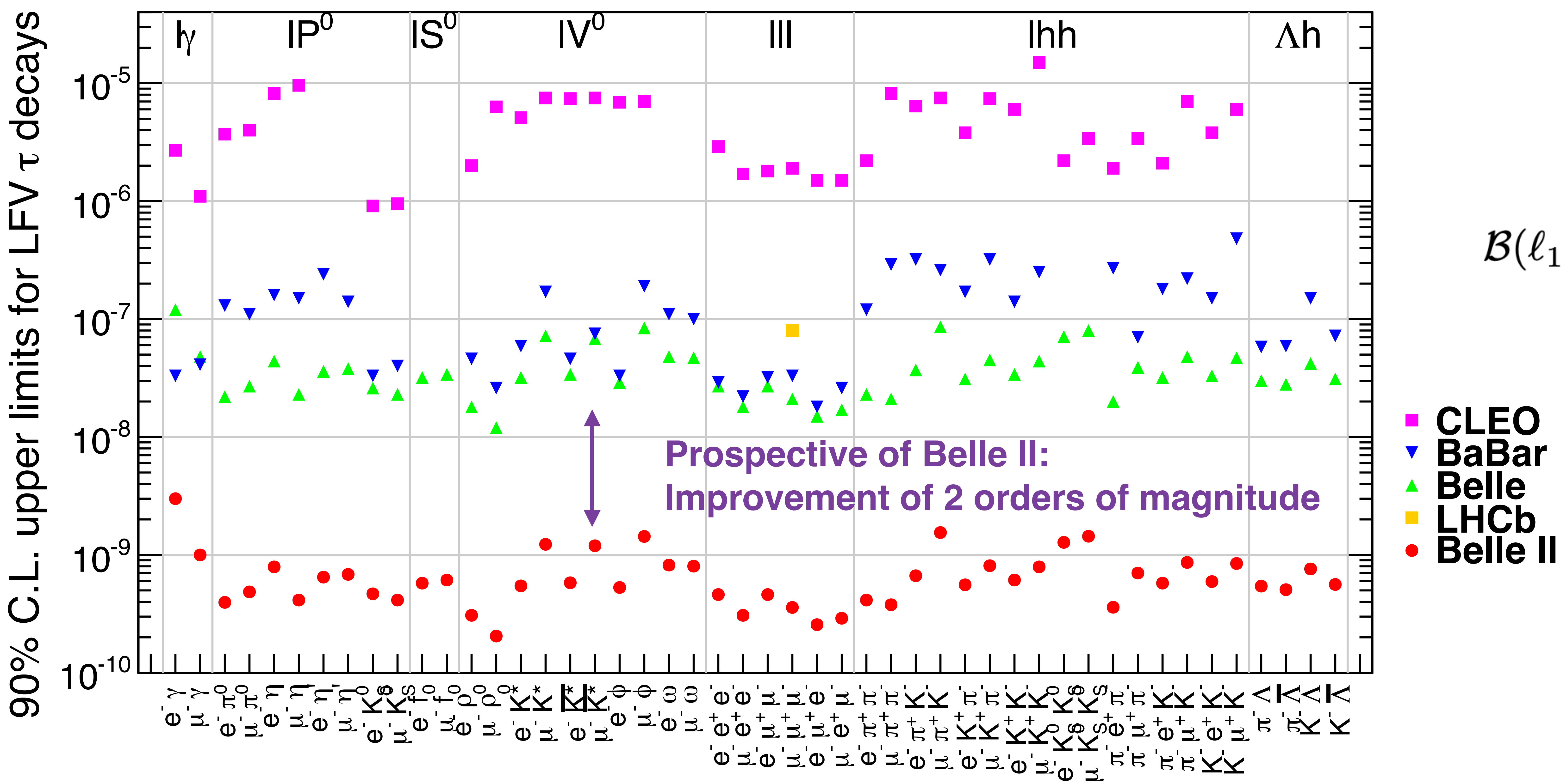
Lepton Flavor Violation

- $\tau^- \to \ell\gamma$, $\tau^- \to hhh$, etc. **(Almost) forbidden in the SM**

SM case:
BR ~10^{-54}



Assuming Belle II full dataset (50 ab^{-1}):



$$\mathcal{B}(\ell_1 \to \ell_2\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\ell_1 i}U_{\ell_2 i}\frac{\Delta m^2_{i1}}{M_W^2}\right|^2.$$

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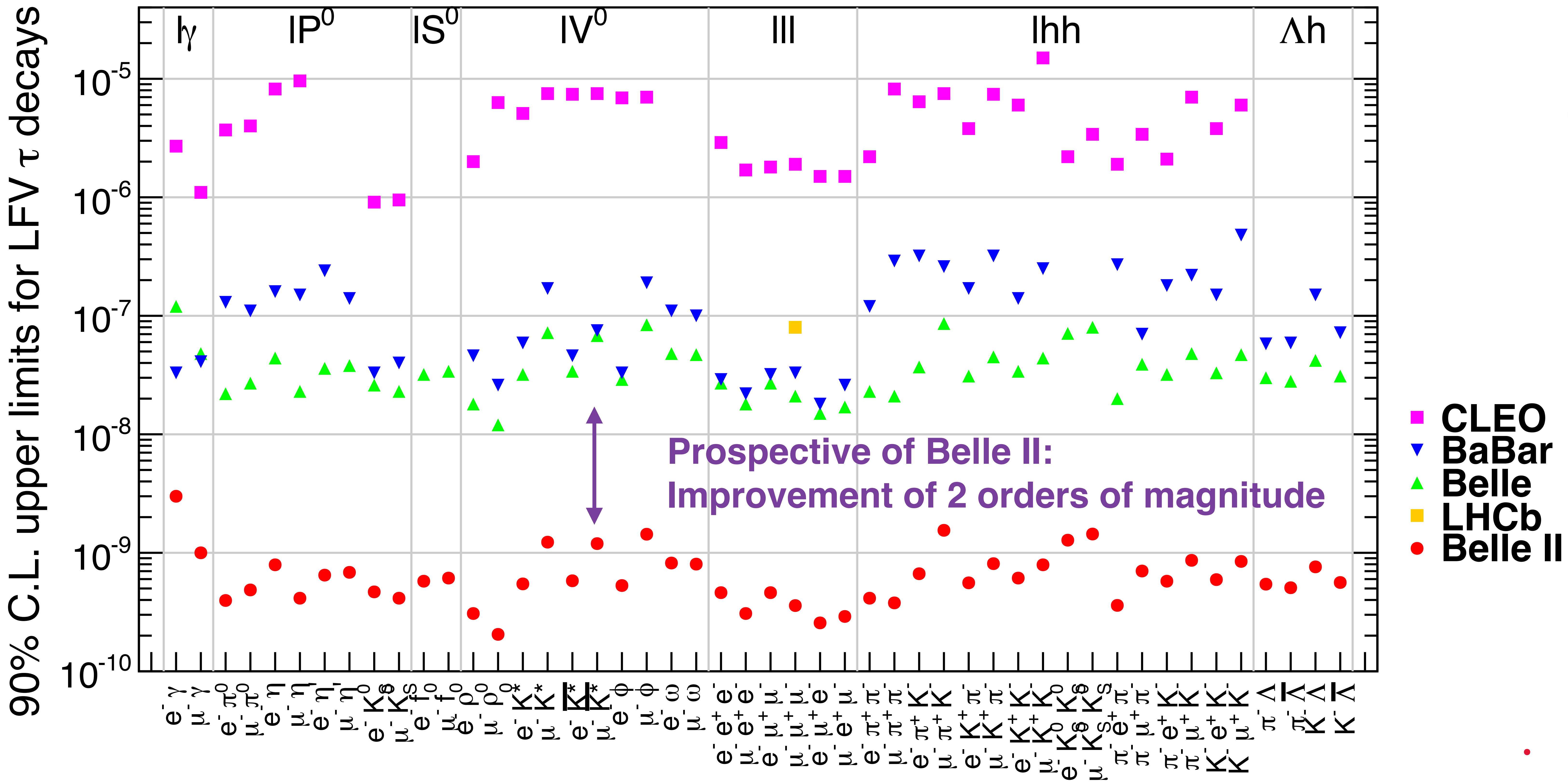

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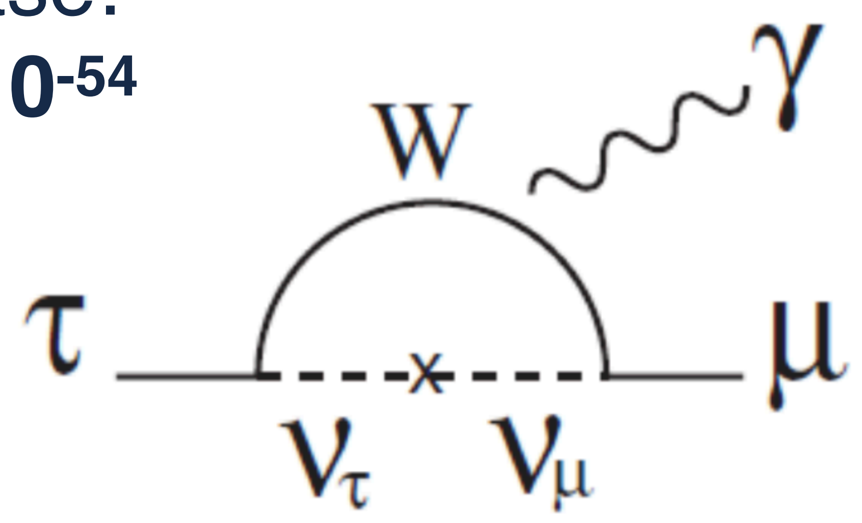
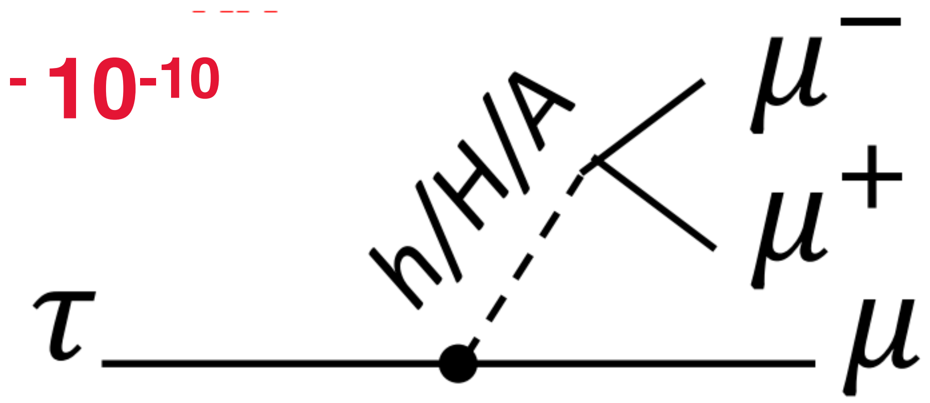
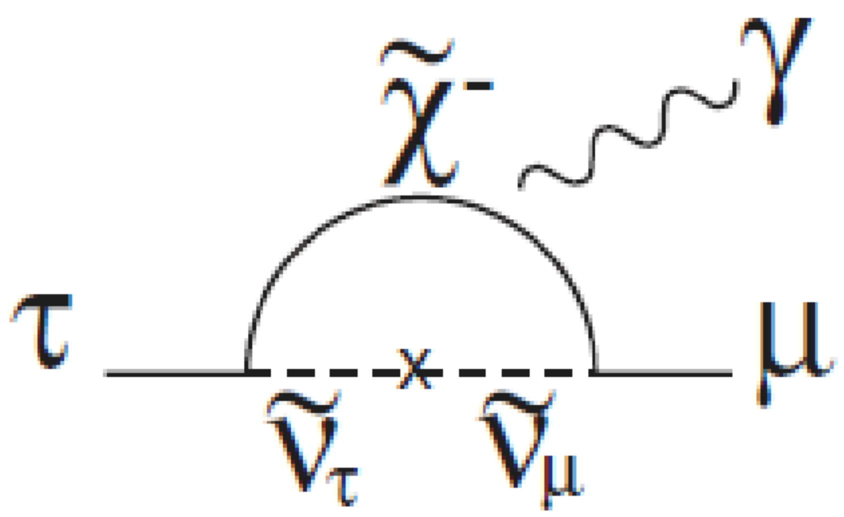


NP case:
BR ~10^{-7} - 10^{-10}





- **Observation of LFV is a clear signature of New Physics!**

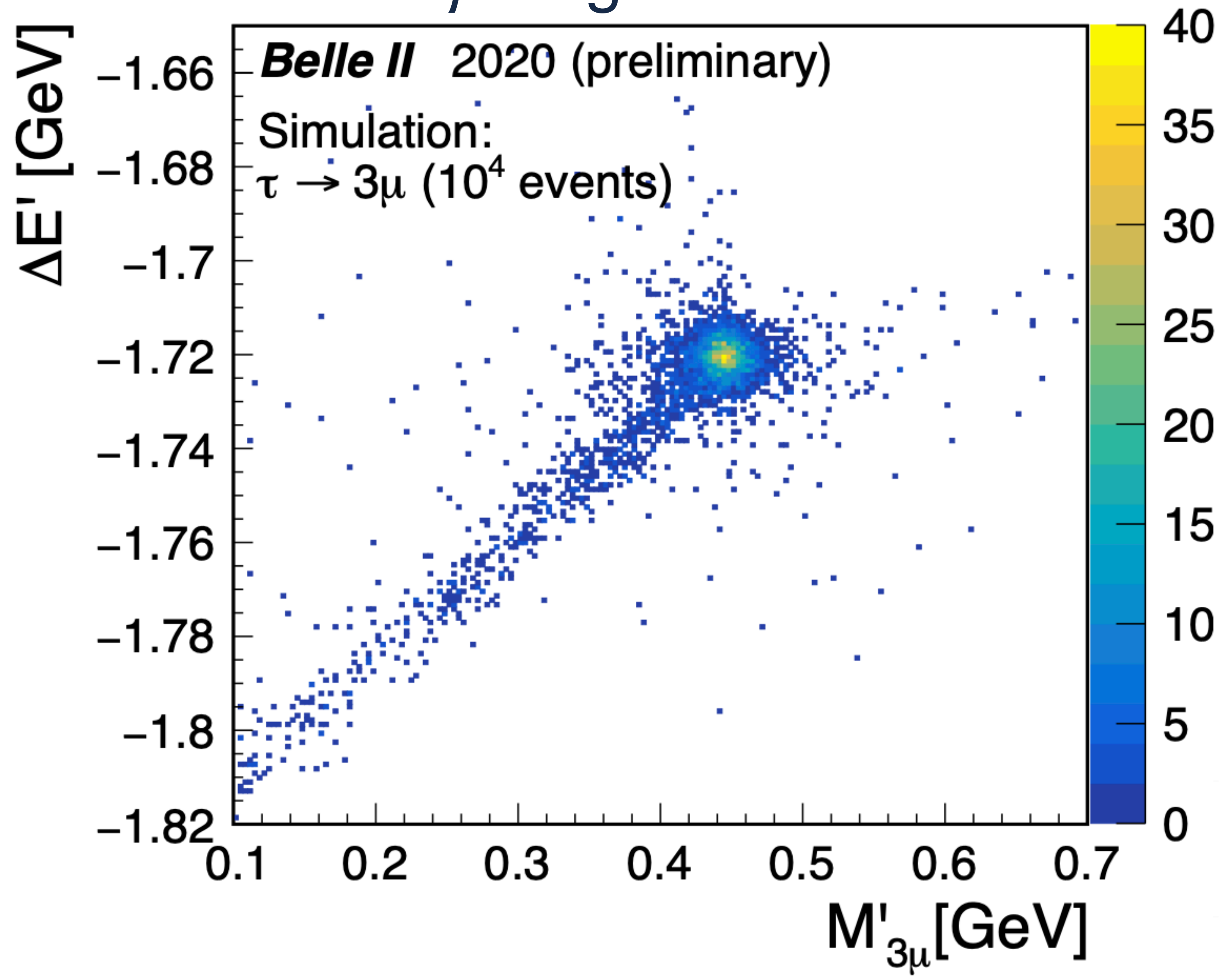
Lepton Flavor Violation

- Signal identification in LFV analysis is done using a defining a region in the M_τ vs ΔE (= $E_\tau - E_{beam}$) space.

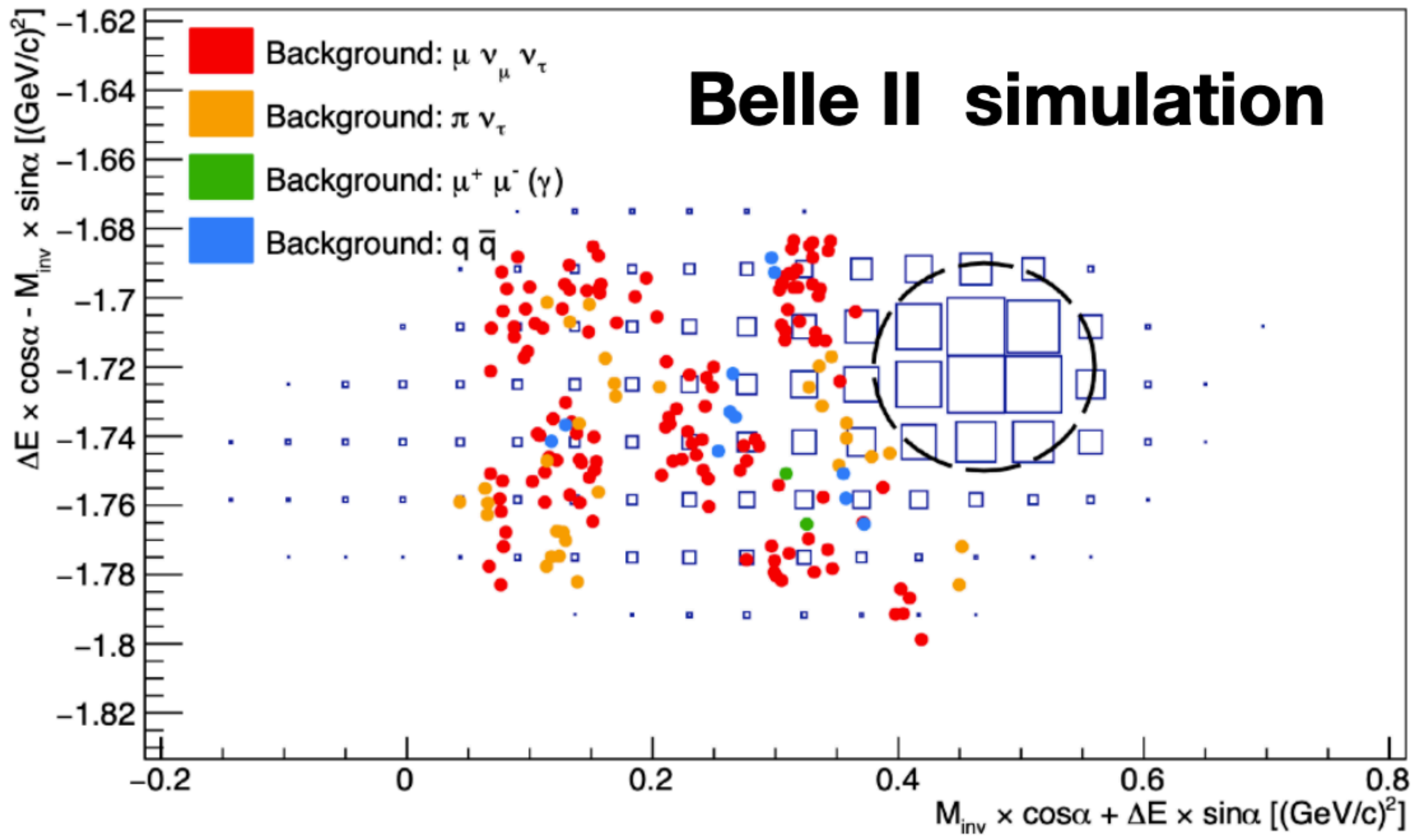
- Rotated signal region:

$$\begin{pmatrix} M'_{3\mu} \\ \Delta E' \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} M_{3\mu} \\ \Delta E \end{pmatrix}$$

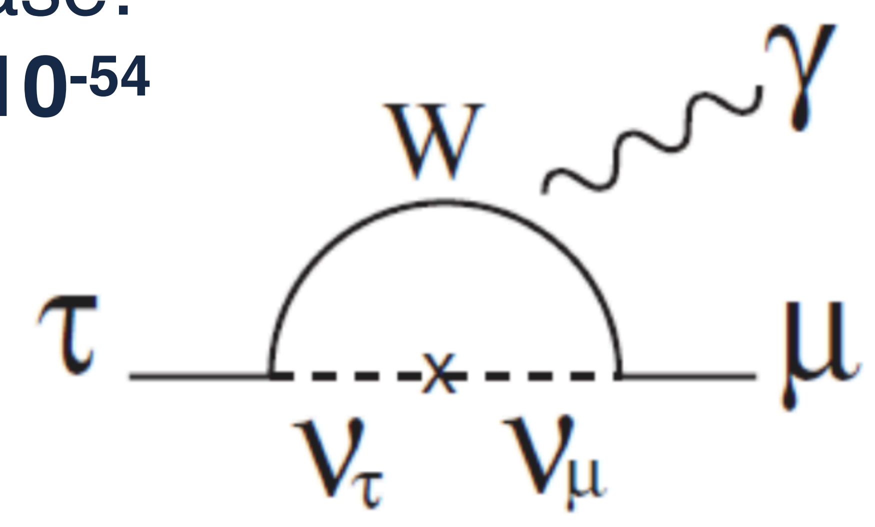
$\tau \to 3\mu$ Signal events



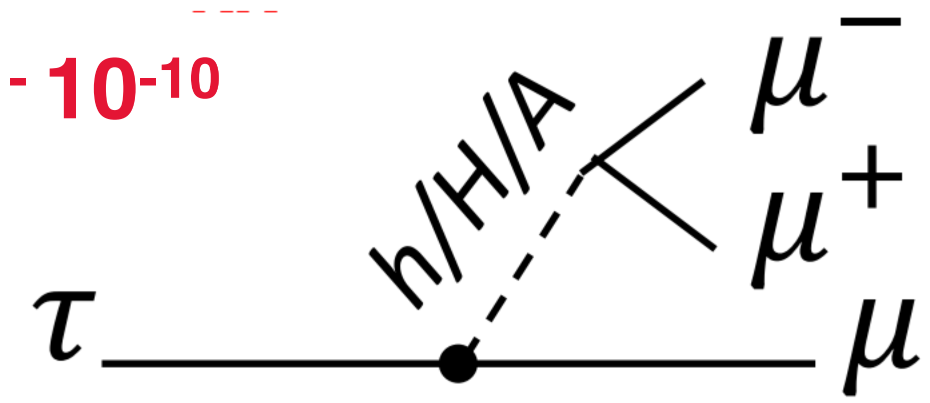
$\tau \to \ell\gamma$ w/background components

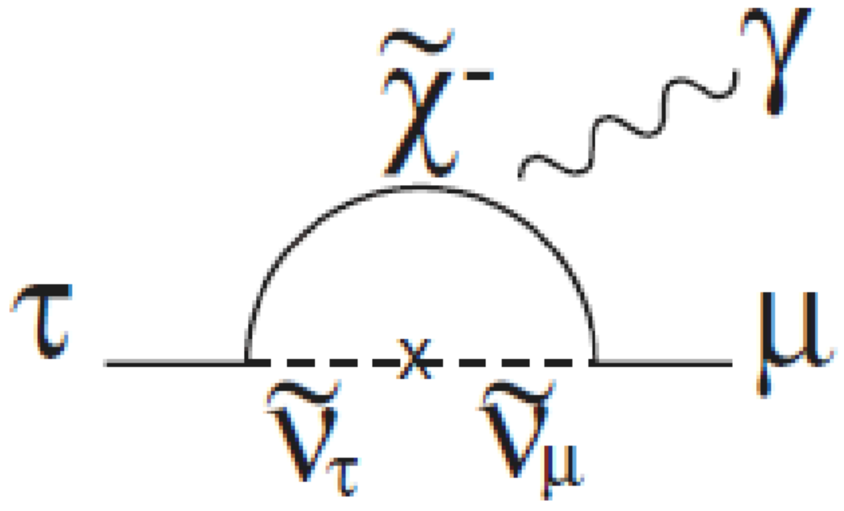


SM case:
BR ~10^-54



NP case:
BR ~10^-7 - 10^-10



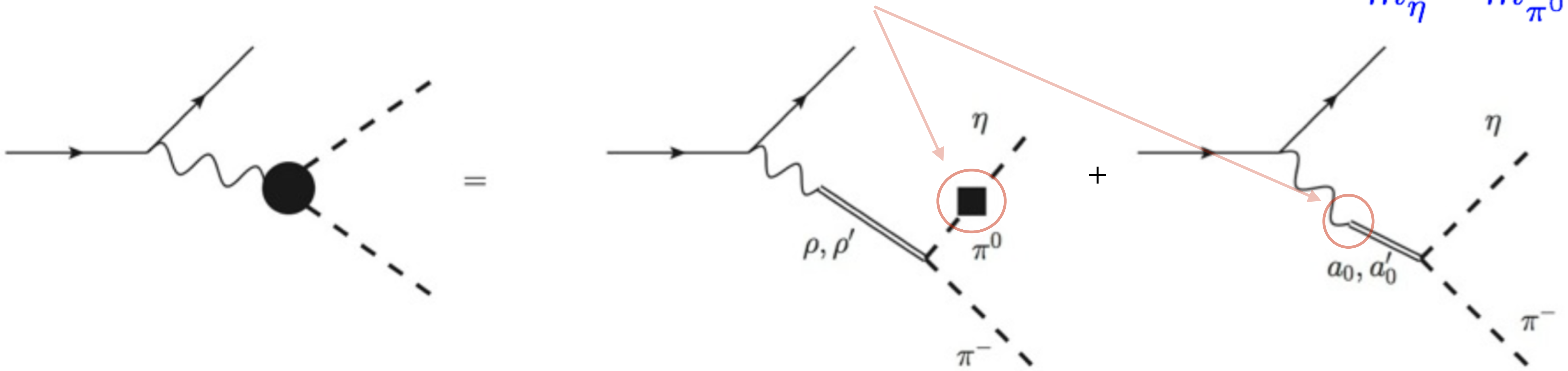


- **Belle II PID algorithms will be crucial for LFV studies.**

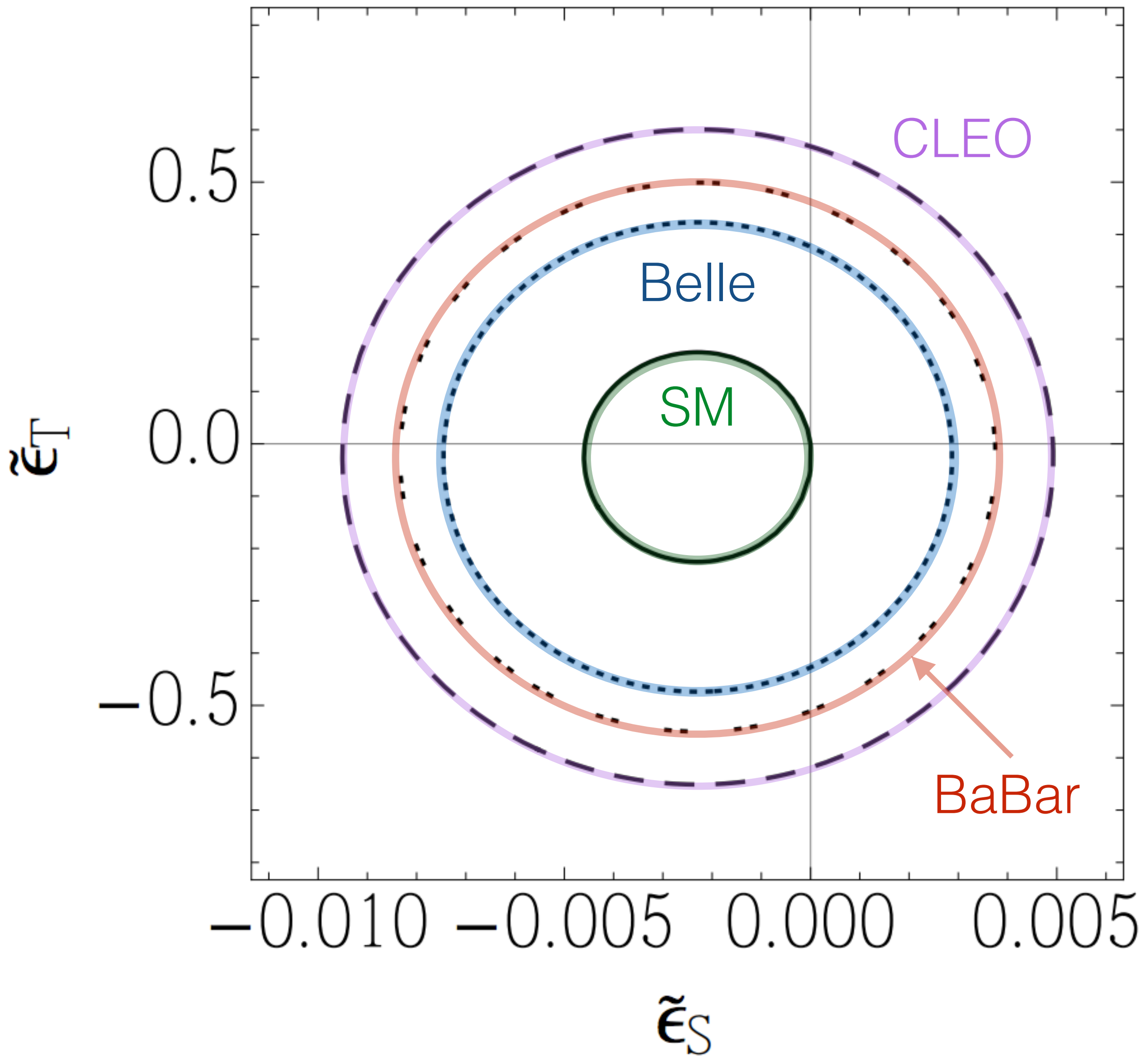
Searches of $\tau \to \eta\pi\nu$ [1]

- Mechanisms in the SM: isospin violation

$$\epsilon_{\eta\pi} = \frac{\langle \pi^0 | H | \eta \rangle}{m_\eta^2 - m_{\pi^0}^2} = \frac{\sqrt{3}}{4} \frac{m_d - m_u}{m_s - \bar{m}} \sim 1.5 \times 10^{-2}$$

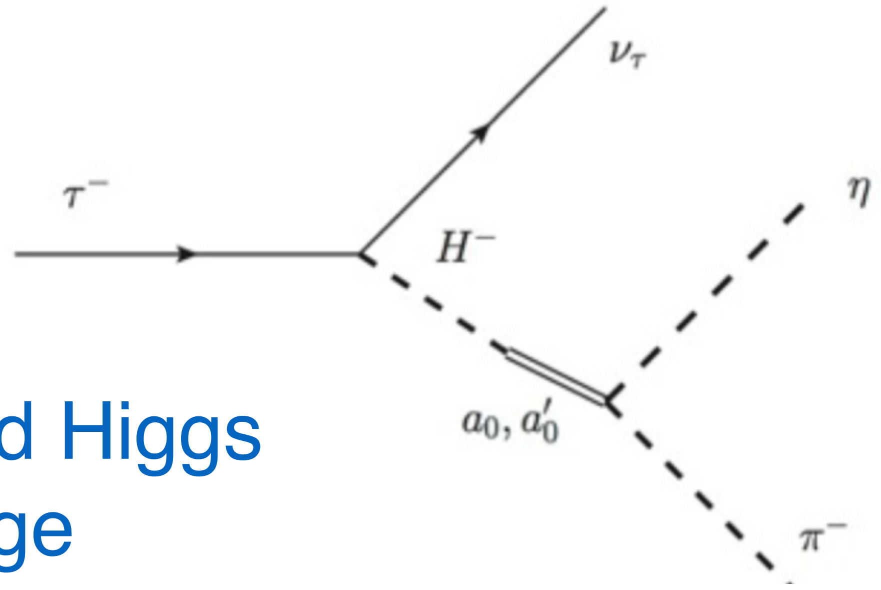


- Constraints on scalar and tensor couplings can be obtained from upper limits on BRs.[2]

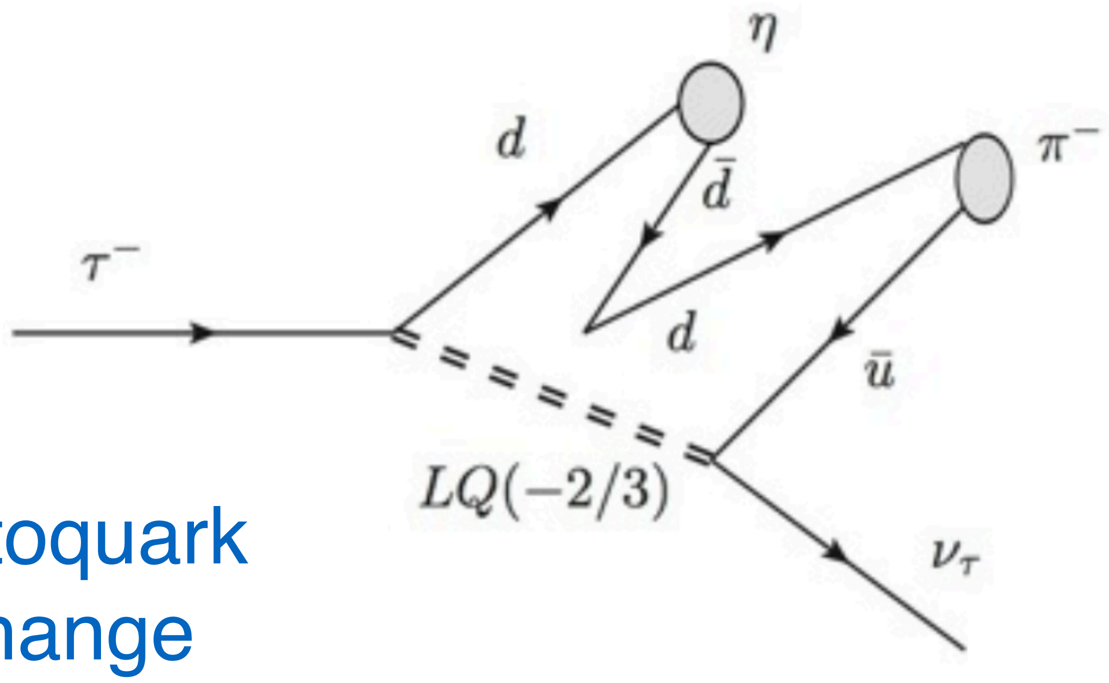


- The corresponding suppression of the SM contribution can make new physics visible.

Charged Higgs exchange



Leptoquark exchange



[2] E. A. Garcés, MHV, G. López Castro, P. Roig. JHEP, 2017(12), 27.

[1] Leroy, C., & Pestieau, J. (1978). Physics Letters B, 72(3), 398-399.

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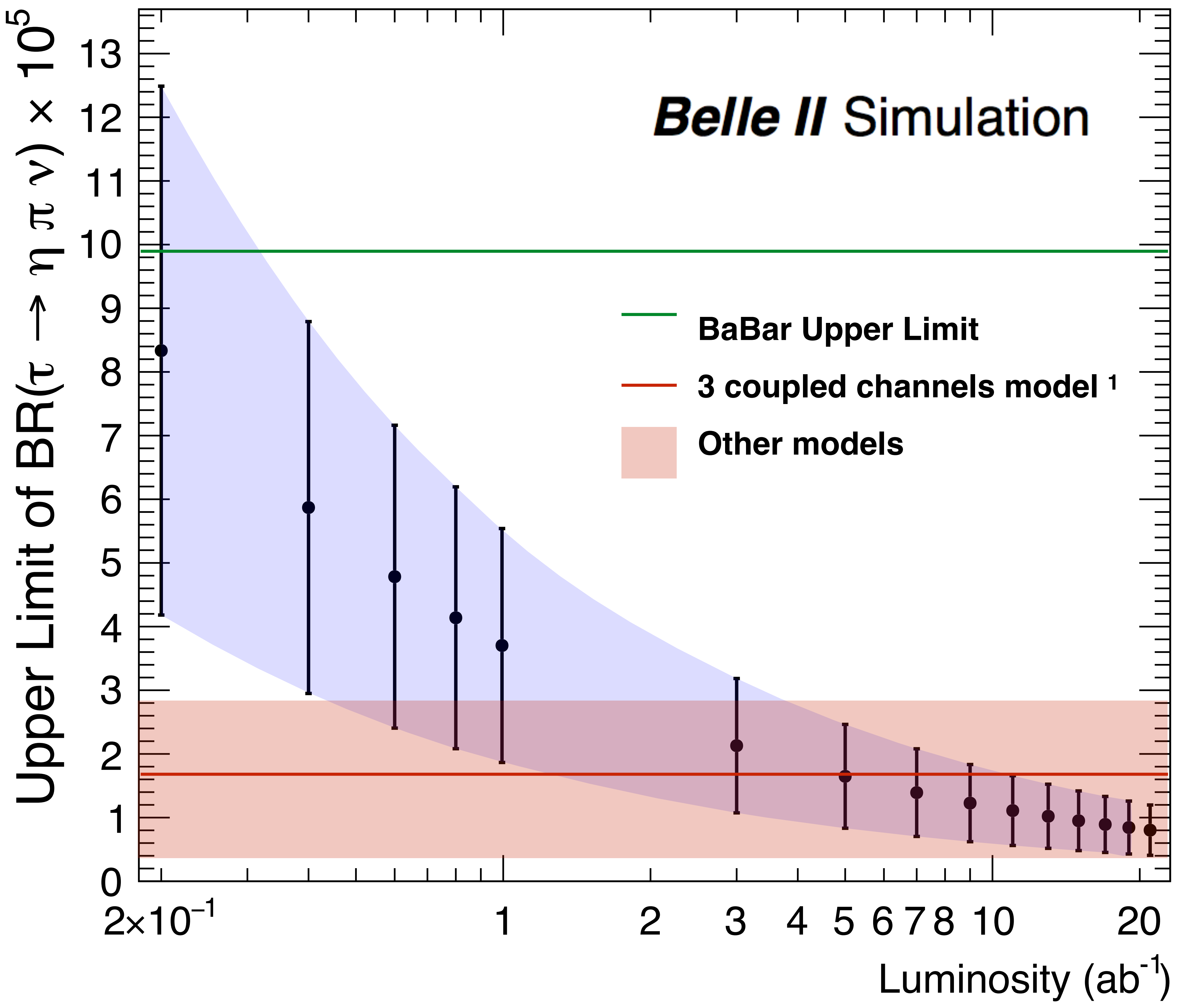
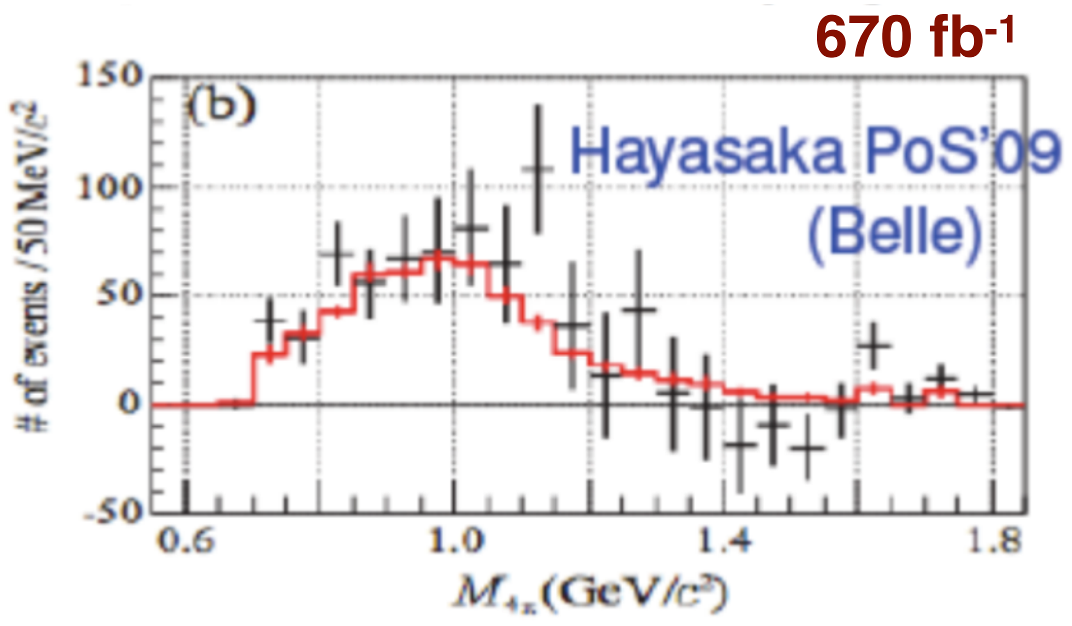
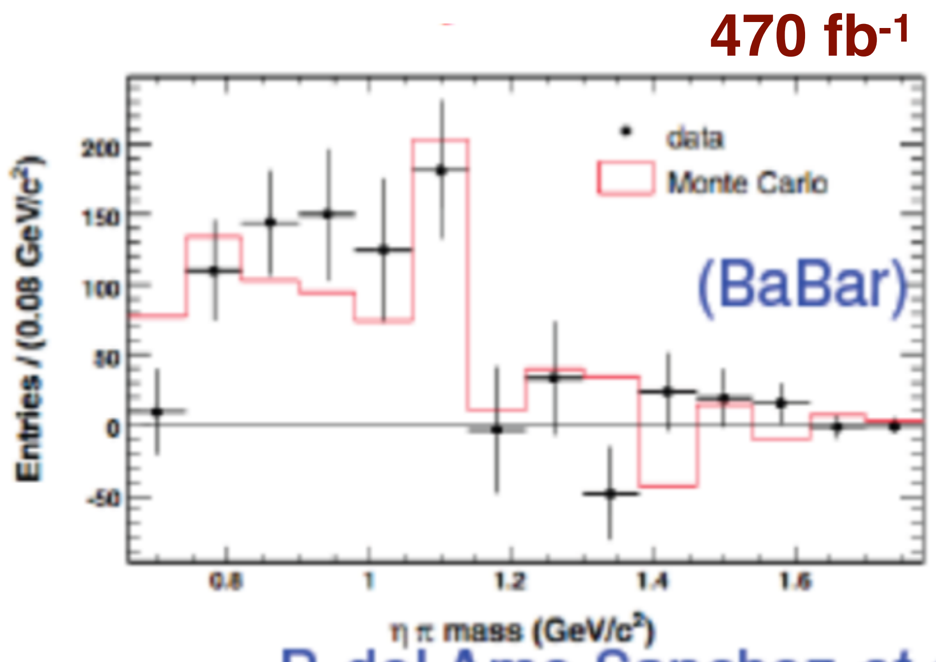
Sensitivity of $\tau \to \eta\pi\nu$ @ Belle II



- We have the capability of testing QCD models
- **Control of the background is fundamental**

- Previous results





P. del Amo Sanchez *et.al* (PRD 83 032002 '11)

$BR^{Belle}_{exp} < 7.3 \cdot 10^{-5}$ 90%CL

$BR^{BaBar}_{exp} < 9.9 \cdot 10^{-5}$ 95%CL

SM predictions: $BR(\tau\to\eta\pi\nu) \sim 10^{-5}$

BR_V (x10^5)	BR_S (x10^5)	BR_{V+S} (x10^5)	Model
0.36	1.0	1.36	MDM, 1 resonance
[0.2, 0.6]	[0.2, 2.3]	[0.4, 2.9]	MDM, 1 and 2 resonances
0.44	0.04	0.48	Nambu-Jona-Lasinio
0.13	0.20	0.33	Analiticity, Unitarity
0.26	1.41	1.67	3 coupled channels

[1] R Escribano, S Gonzalez-Solis, P Roig - Physical Review D, 2016

Summary

- SuperKEKB and Belle II will produce a sample of τ pairs 50 times larger than previous B-factories. Precision studies with τ leptons involved will be performed.
- The performance of the detector in the first months of data taking is good. Belle II is reconstructing $e^+e^- \rightarrow \tau^+\tau^-$ events. Performance studies on going.
- The τ lepton decays presented aim to study:
  - Searches of a long-lived BSM boson α and heavy neutrinos
  - CP violation
  - Lepton Flavor Violation decays.
  - Properties of vector, scalar and tensorial interactions, isospin symmetries.
- Belle II will provide a sort of very interesting results in the next decade.
  See "The Belle II Physics Book" at PTEP 2019 (2019) 12, 123C01

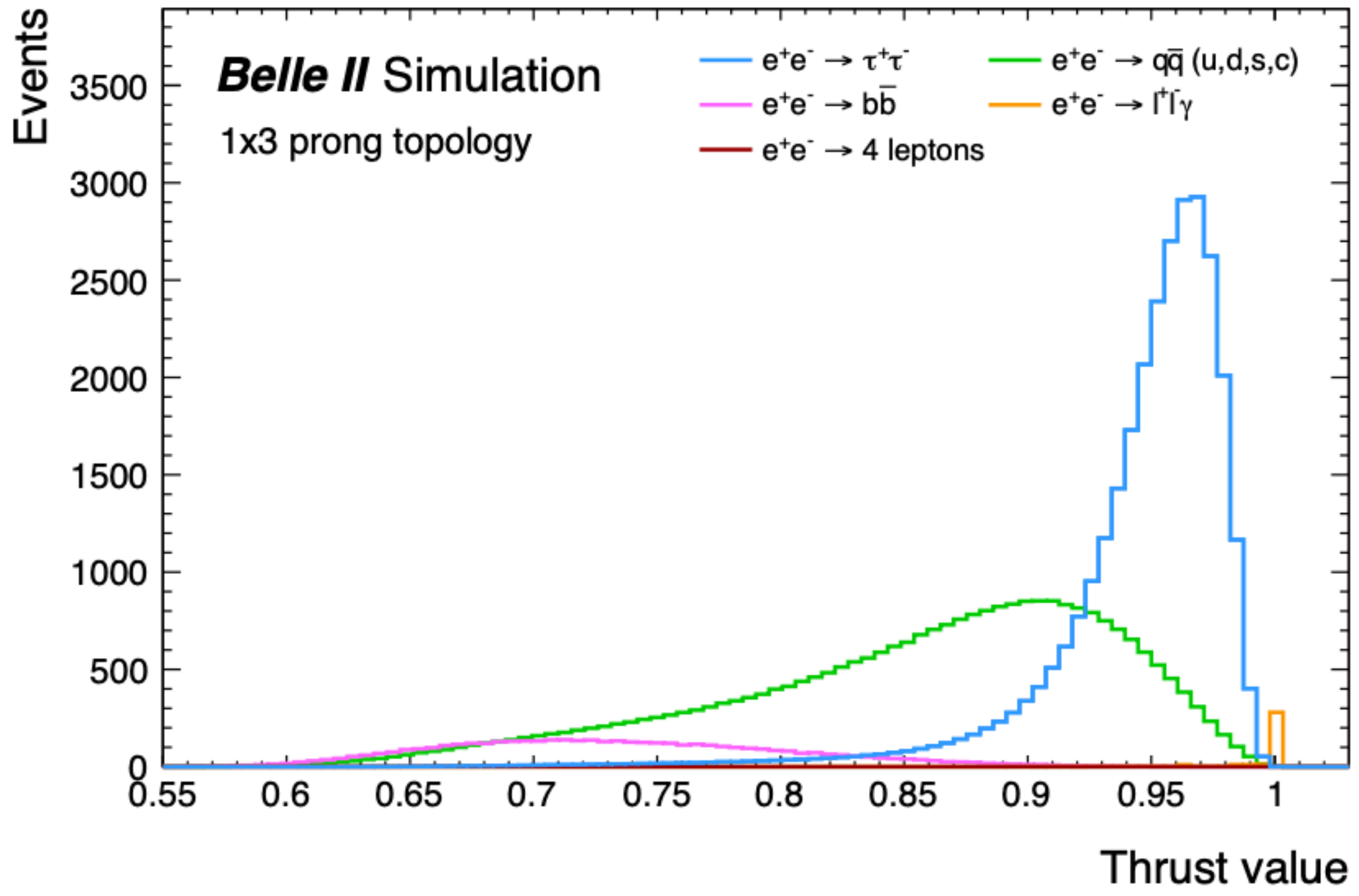
Thank you

Backup

Event selection strategy

- Event is divided in two sides (signal and tag) using a plane defined by a **thrust axis**, build with all the final state particles:

- $$V_{thrust} = \frac{\sum_i |\vec{p}_i{}^{cm} \cdot \hat{n}_{thrust}|}{\sum_i |\vec{p}_i{}^{cm}|}$$



- Thrust axis: $\hat{n}_{thrust}$ such that V_{thrust} is maximum.