Second-Class Currents @ Belle II Pasado, Presente & Futuro.

Más anécdotas que ecuaciones, con física de por medio.

Michel Hernández Villanueva
DESY

El Sabor de la Física: celebración del 60 aniversario del Dr. Gabriel López Castro
07 de Abril del 2022

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

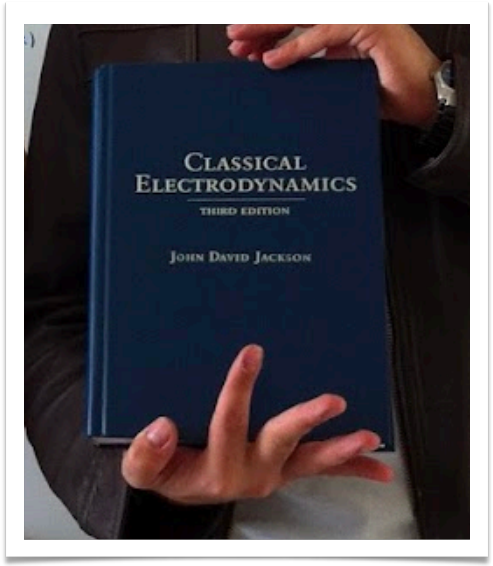
Belle II

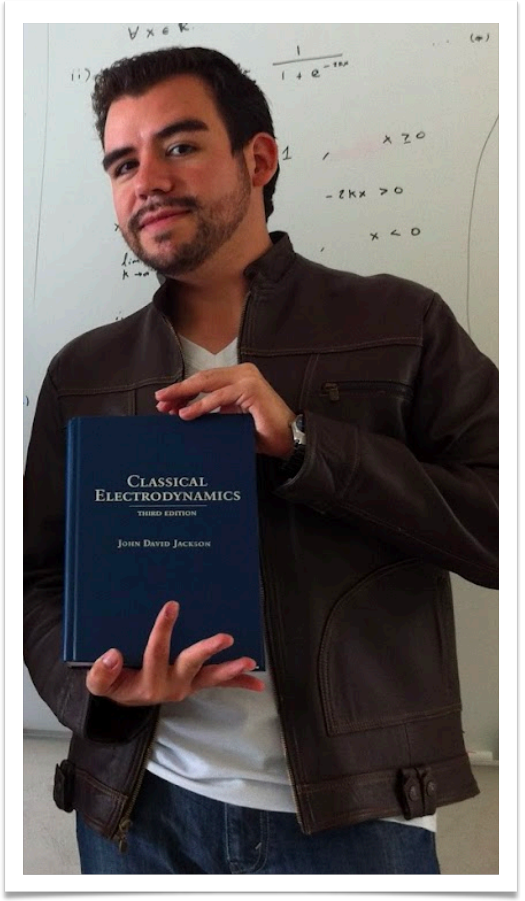
DESY.

My first steps in HEP

Or how I ended doing Tau lepton physics

- **I started the master program at Cinvestav in 2012.**
  - Survived the first semesters, and joined the course of QFT with the Dr. Gabriel López.



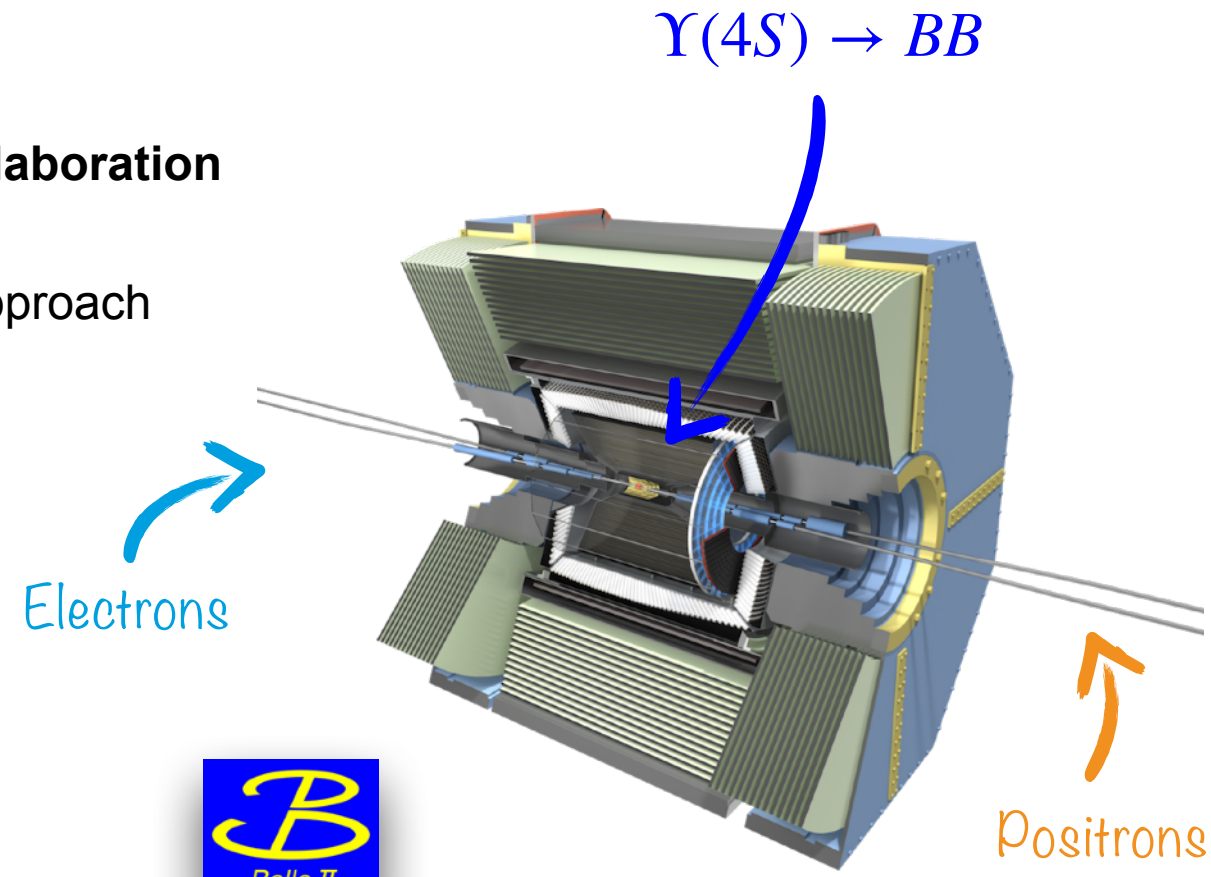


"Oh my sweet summer child..."

My first steps in HEP

Or how I ended doing Tau lepton physics

- I started the master program at Cinvestav in 2012.
  - Survived the first semesters, and joined the course of QFT with the Dr. Gabriel López.
- **He suggested me to join Belle II, a brand-new collaboration focused in Flavour Physics.**
  - Split the work in two parts: a phenomenological approach and the experimental study.



My first steps in HEP

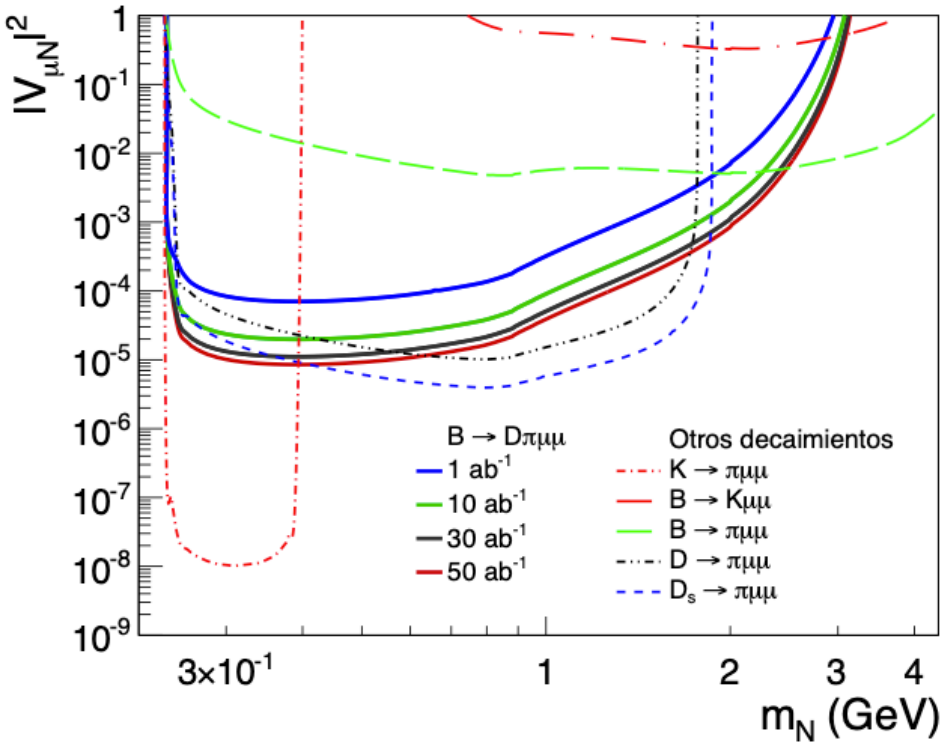
Or how I ended doing Tau lepton physics

- I started the master program at Cinvestav in 2012.
  - Survived the first semesters, and joined the course of QFT with the Dr. Gabriel López.

- He suggested me to join Belle II, a brand-new collaboration focused in Flavour Physics.
  - Split the work in two parts: a phenomenological approach and the experimental study.

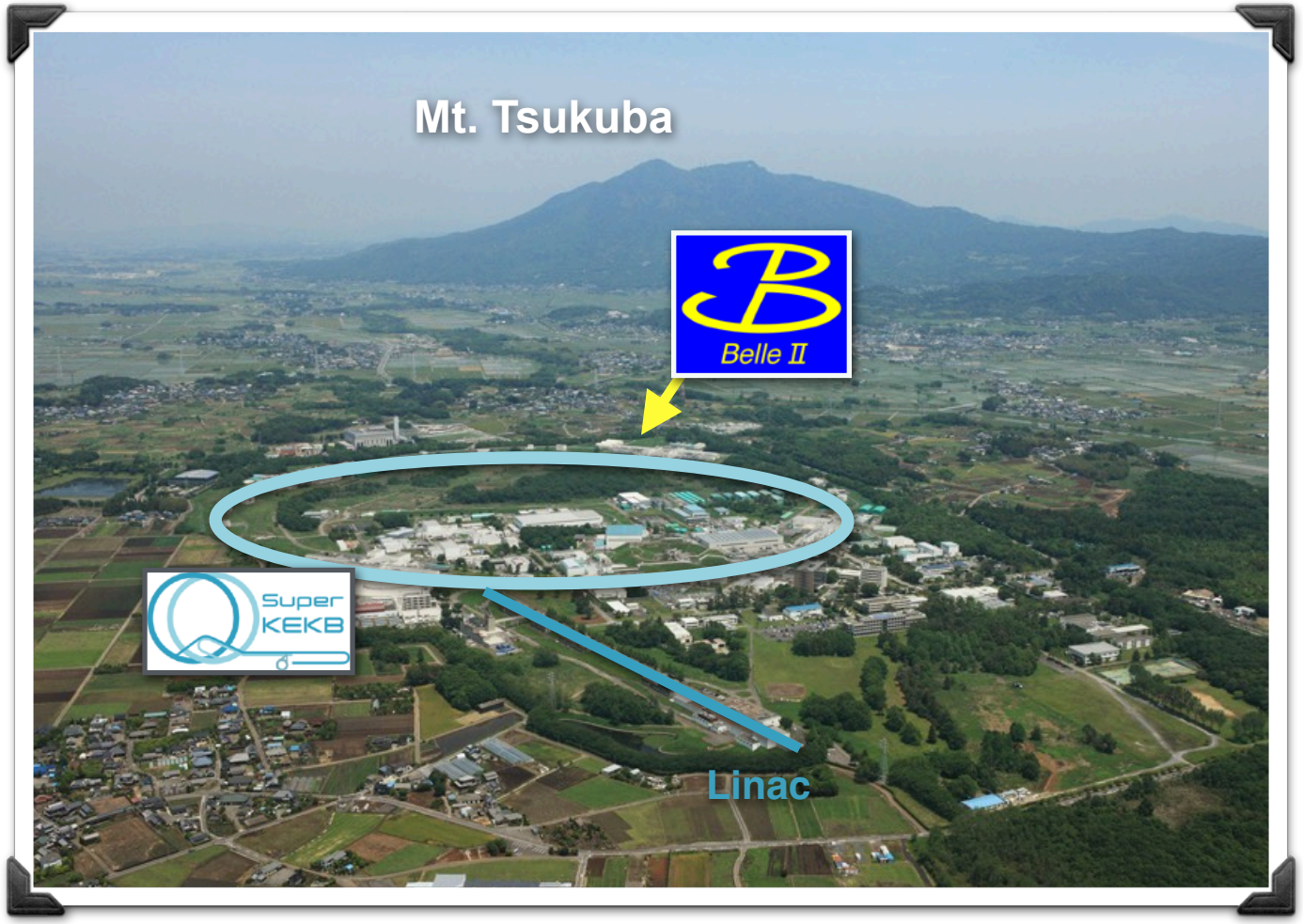
- **With Eduard as co-advisor, we developed a sensitivity study for Lepton Number Violation decays:**

Exclusion regions for Majorana-neutrino N:



The Belle II Collaboration

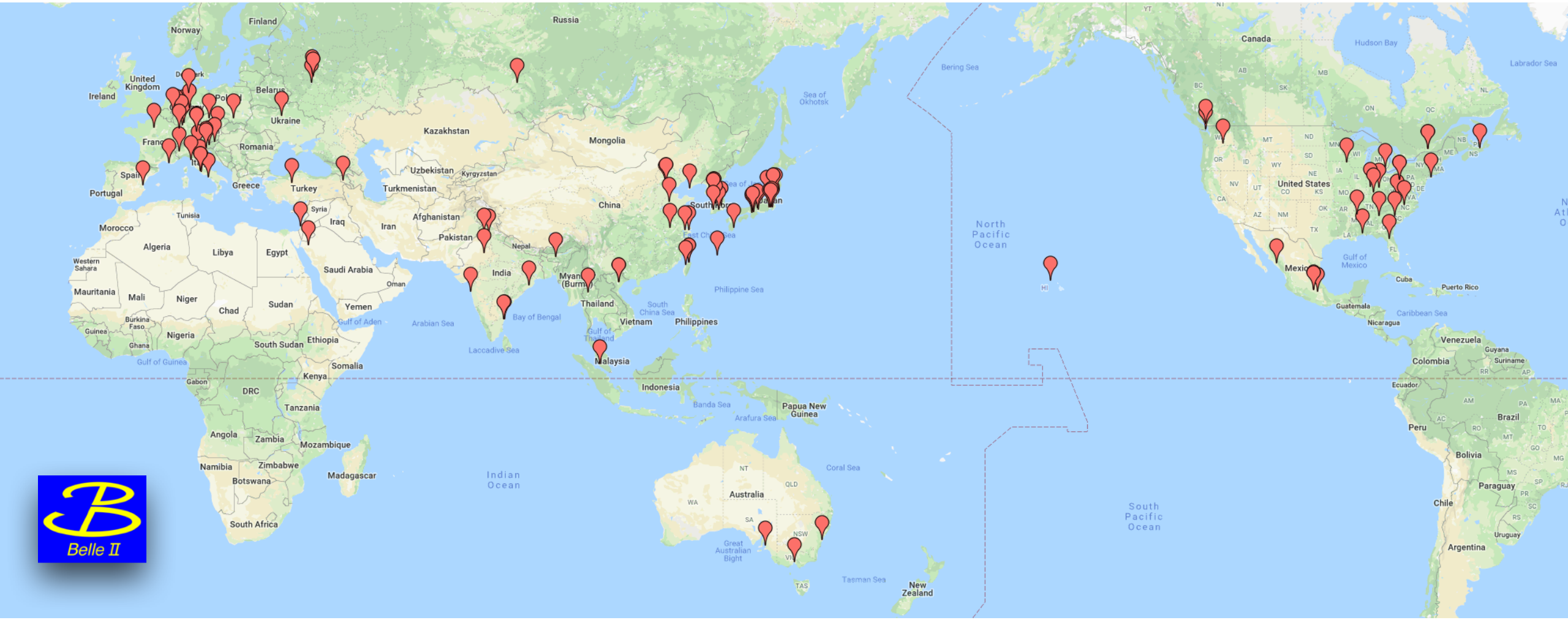
A B-Factory of next generation



The Belle II Collaboration

1100 members, 123 institutions, 26 countries

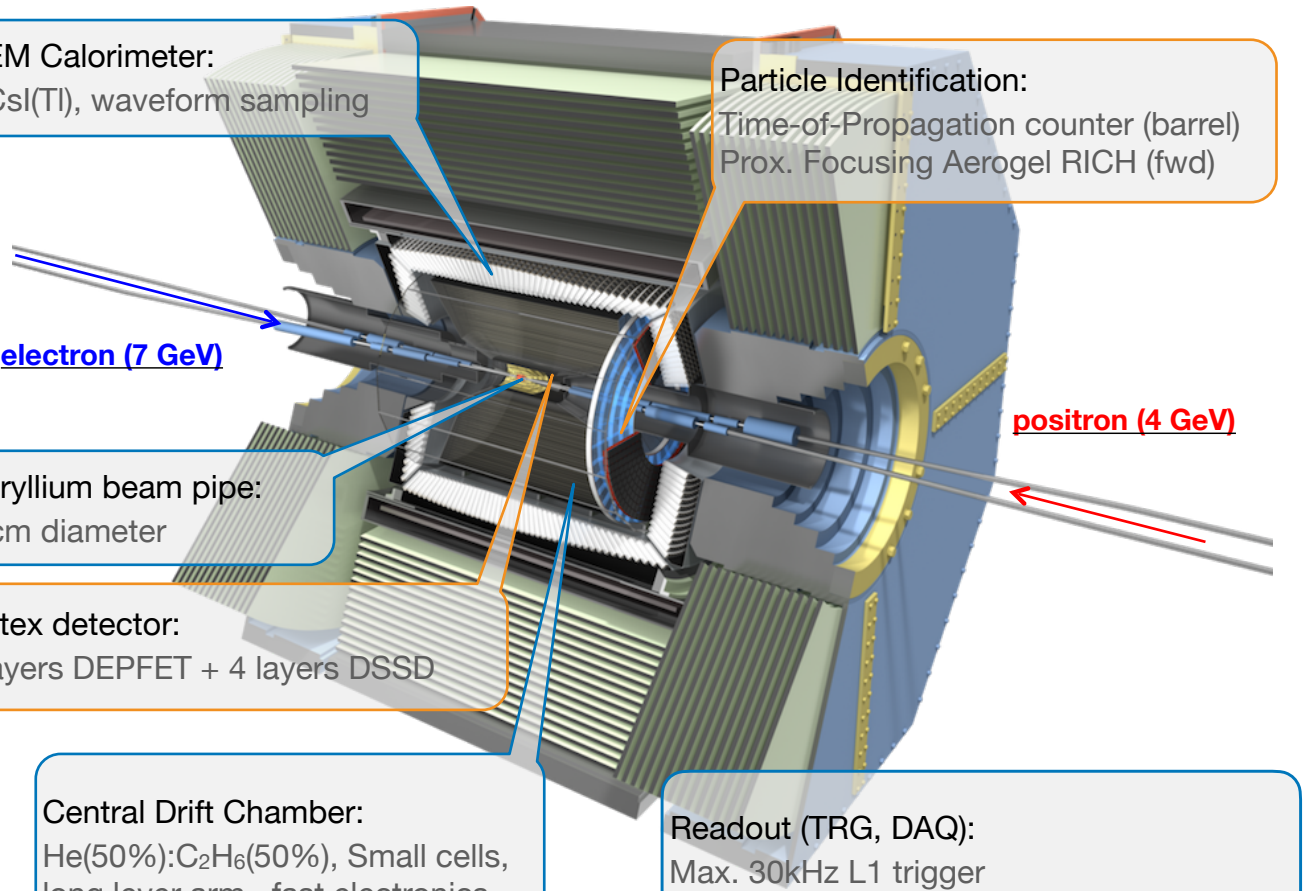
Belle II Experiment
@belle2collab



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

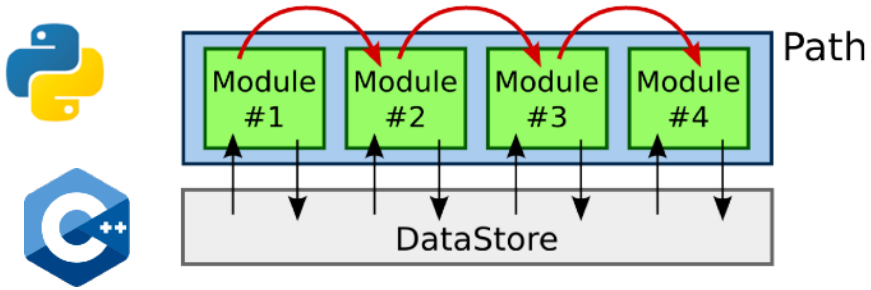
Vertex detector:
2 layers DEPFET + 4 layers DSSD

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

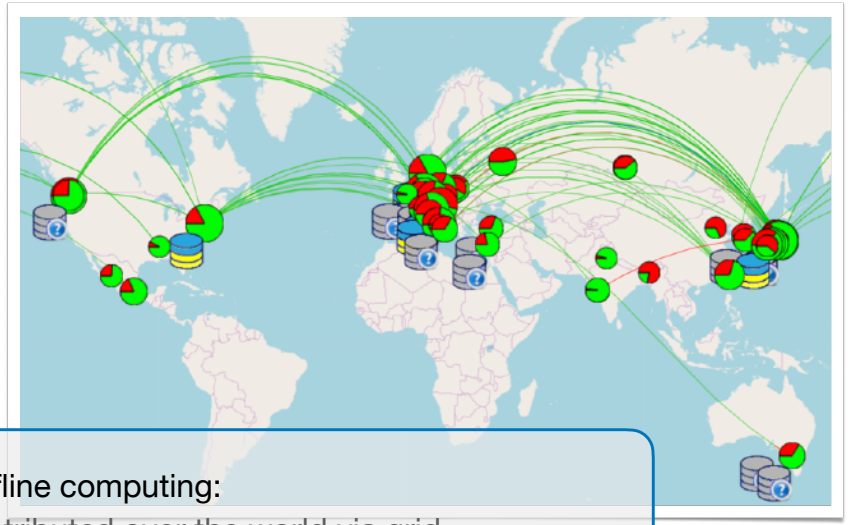
Readout (TRG, DAQ):
Max. 30kHz L1 trigger
~100% efficient for hadronic events.
1MB (PXD) + 100kB (others) per event
- over 30GB/sec to record

arXiv:1011.0352 [physics.ins-det]

Software:
Open-source sophisticated algorithms for simulation, reconstruction, visualization, and analysis.



Comput. Softw. Big Sci. 3 1 (2019)



Offline computing:
Distributed over the world via grid.

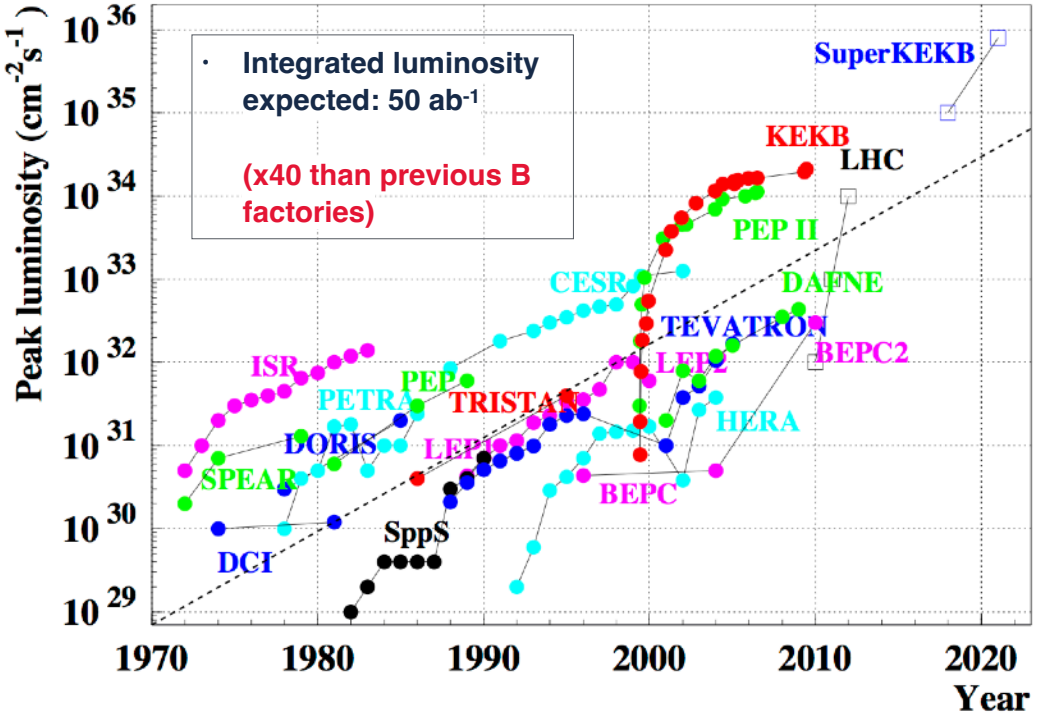
EPJ Web Conf., 245 (2020) 11007

Belle II

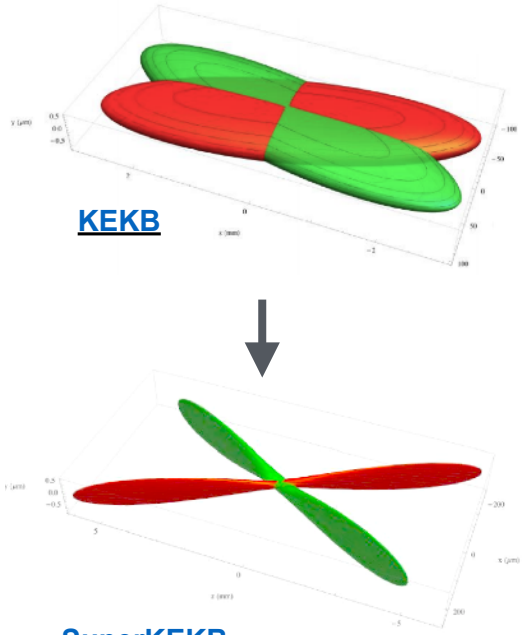
DESY.

Luminosity

Projections

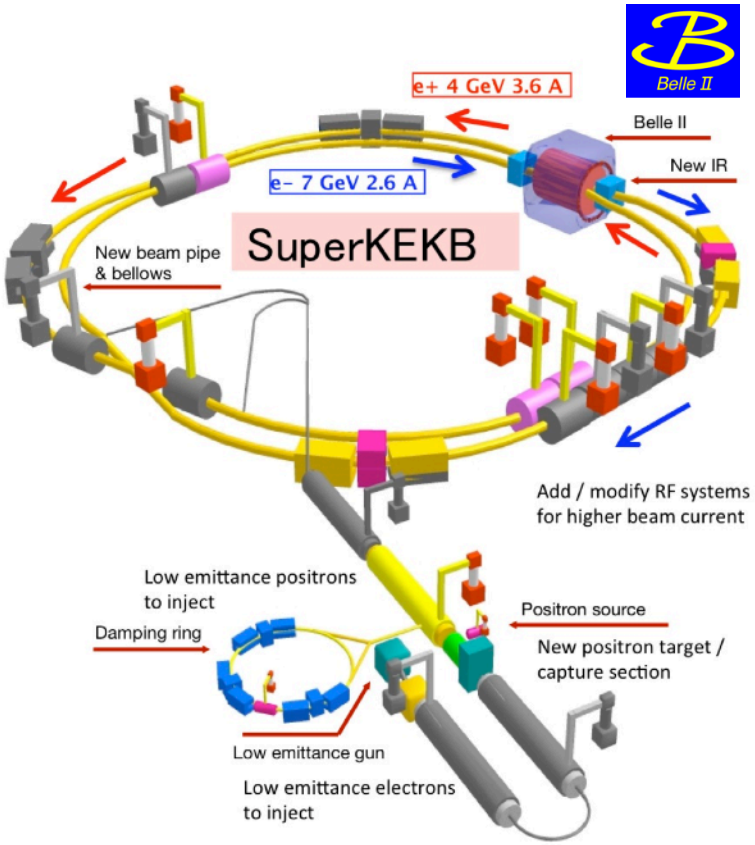


"Nano-beams": vertical beam size is 50nm at the IP.



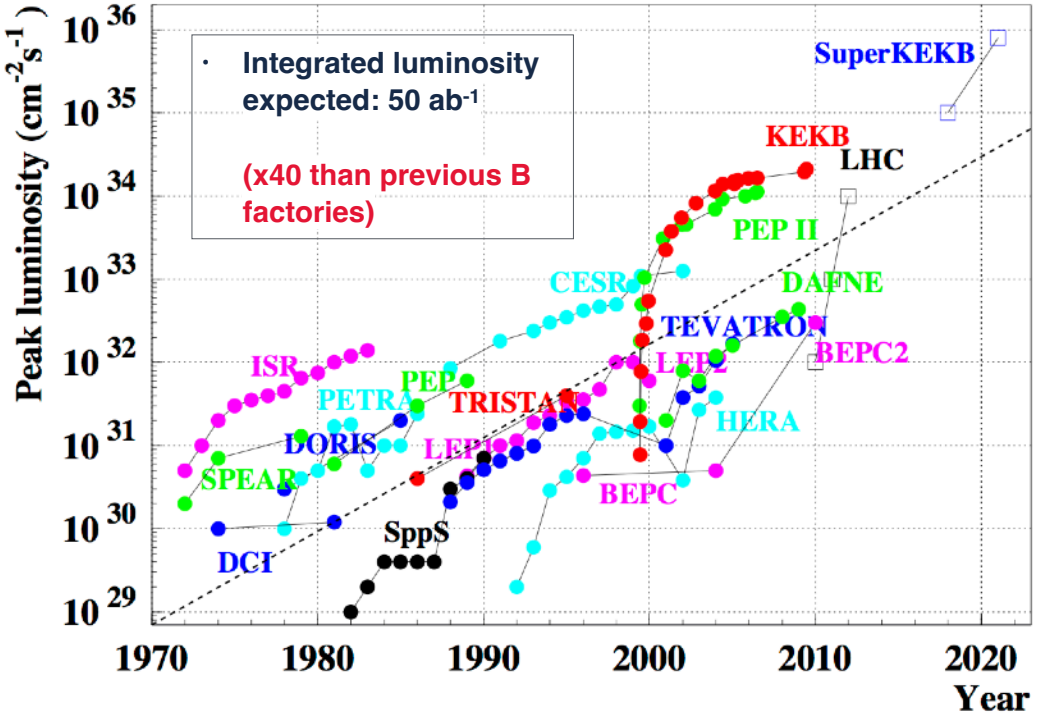
KEKB

SuperKEKB

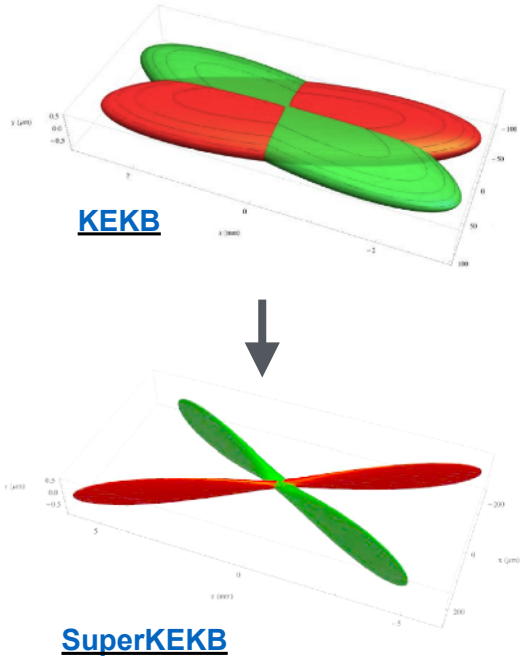


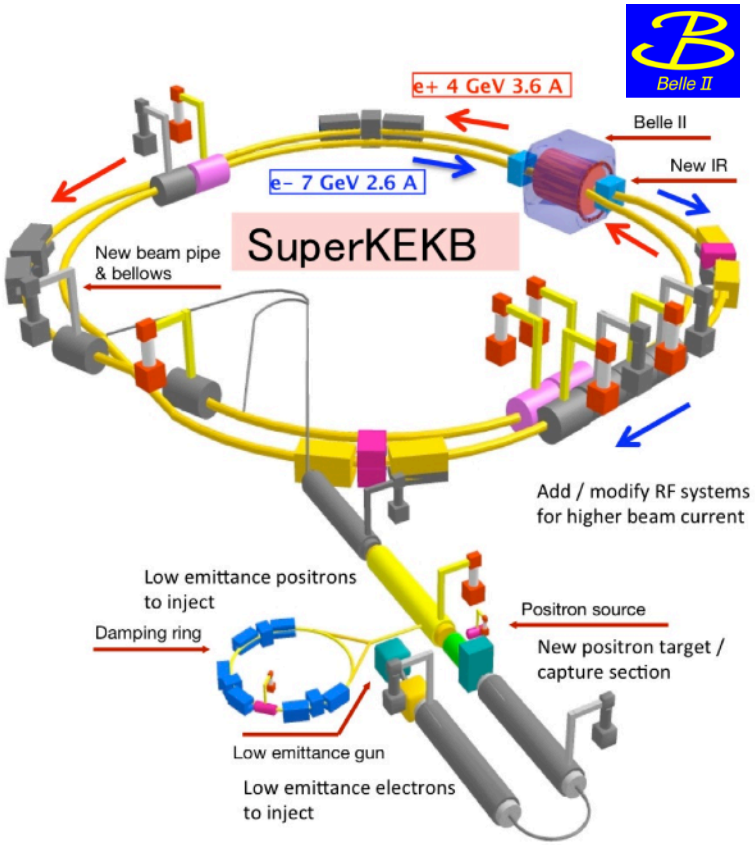
Luminosity

Projections



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

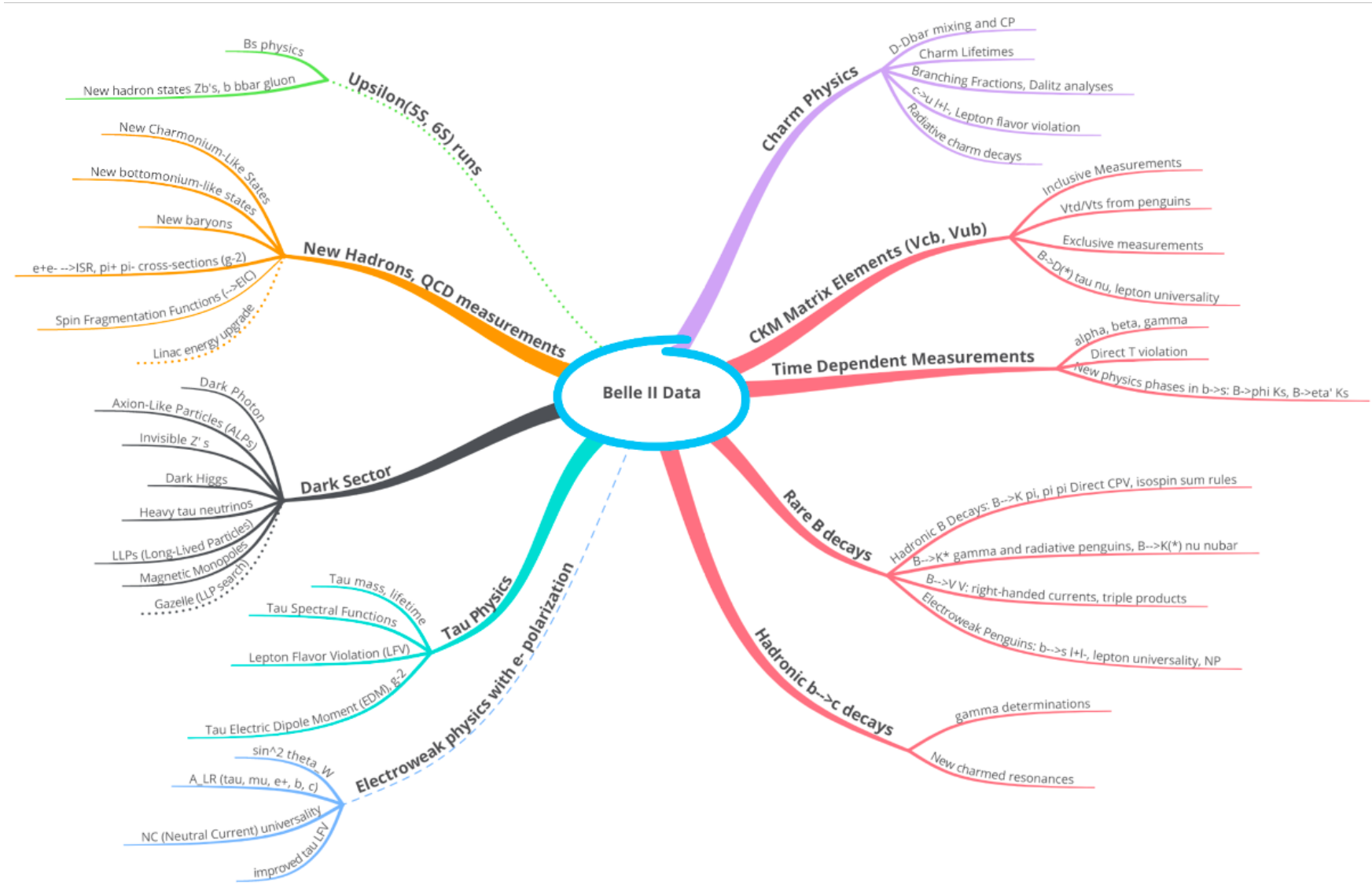




- Challenges at L=6.5x10^{35} cm^{-2} s^{-1}:
  - **Higher background** (Radiative Bhabha, Touschek, beam-gas scattering, etc.).
  - **Higher trigger rates** (High performance DAQ, computing).

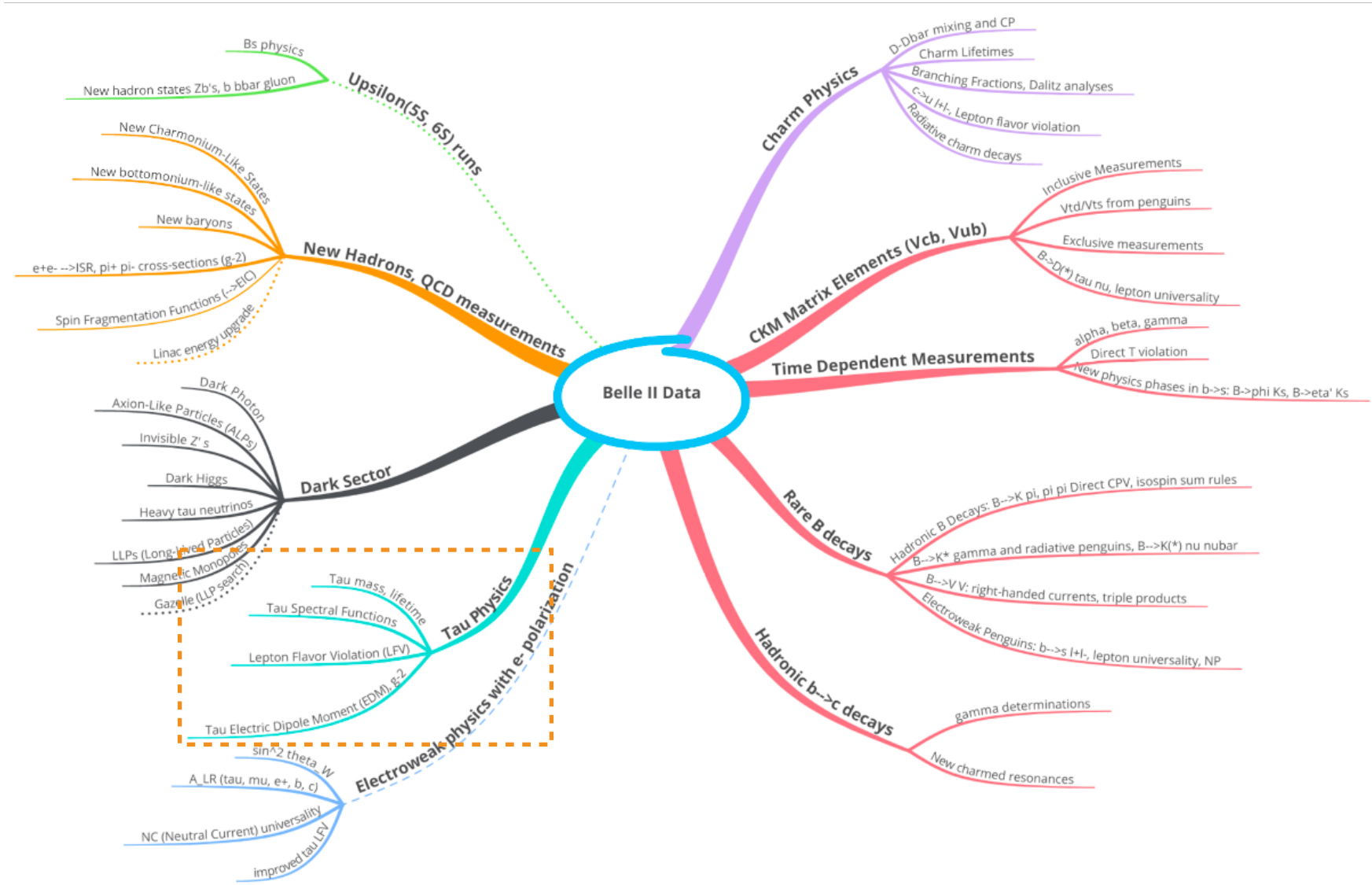
Belle II Physics Program

- The physics program of Belle II covers measurements in B decays, charm, dark sectors, exotic particles, etc.
- Further details can be found in “The Belle II Physics Book”: PTEP 2019 (2019) 12, 123C01
- The enormous number of e+e- collisions features a unique environment for the study of τ physics with high precision.



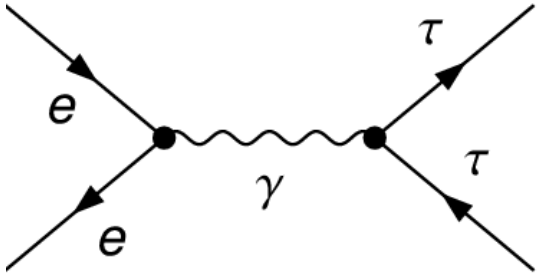
Belle II Physics Program

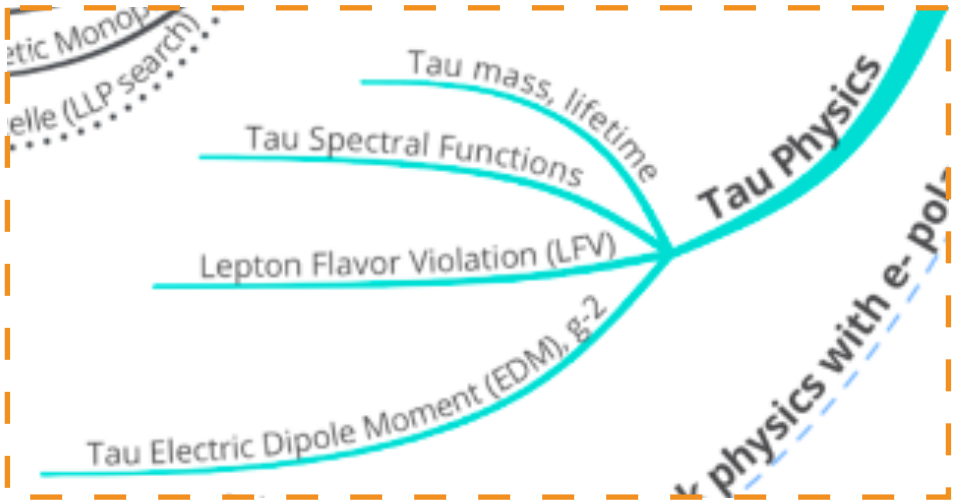
- The physics program of Belle II covers measurements in B decays, charm, dark sectors, exotic particles, etc.
- Further details can be found in “The Belle II Physics Book”: PTEP 2019 (2019) 12, 123C01
- The enormous number of e+e- collisions features a unique environment for the study of τ physics with high precision.



Tau leptons at the B factories

Let's talk about the tau





- At Y(4S):

  $\sigma(e^+e^- \dashrightarrow B\bar{B}) = 1.05$ nb

  $\sigma(e^+e^- \dashrightarrow \tau^+\tau^-) =$ **0.92 nb**

- Approximately 10^{10} tau pairs during Belle II lifetime.

- **B-Factories are also τ-factories**

Figure: The particle zoo.

- **Features of a B-Factory:**
  - Well-defined initial state.
  - High vertex resolution.
  - Excellent calorimetry.
  - Sophisticated particle ID.

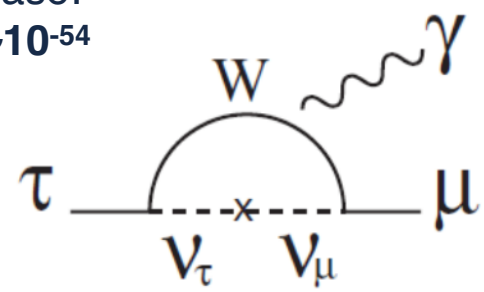
Tau leptons at the B factories

Why the tau?

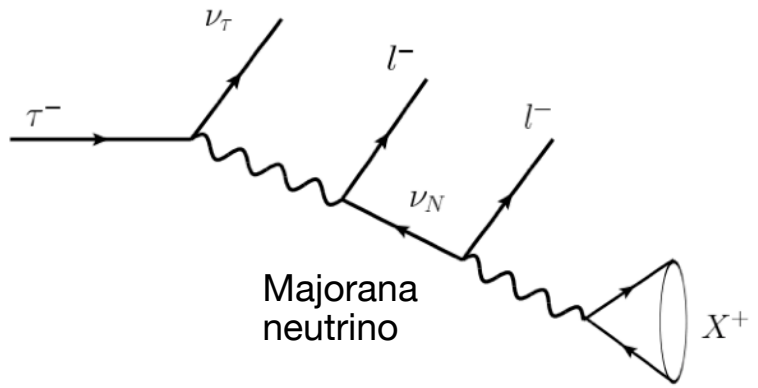
- The τ is the charged lepton of the third generation.
- **It is the only lepton massive enough to decay into hadrons.**
- Decay channels of the tau τ allow a clean theoretical analysis of the hadronization, determination of SM parameters and searches of new physics.
  - Standard Model parameters
    m_τ, α_s (m_τ), CKM parameter V_{us}.
  - CP violation.
  - **Lepton Number and Lepton Flavor Violation.**
  - etc…

$\tau^- \to \ell^- \gamma$ **LFV**

SM case:
BR ~10^{-54}



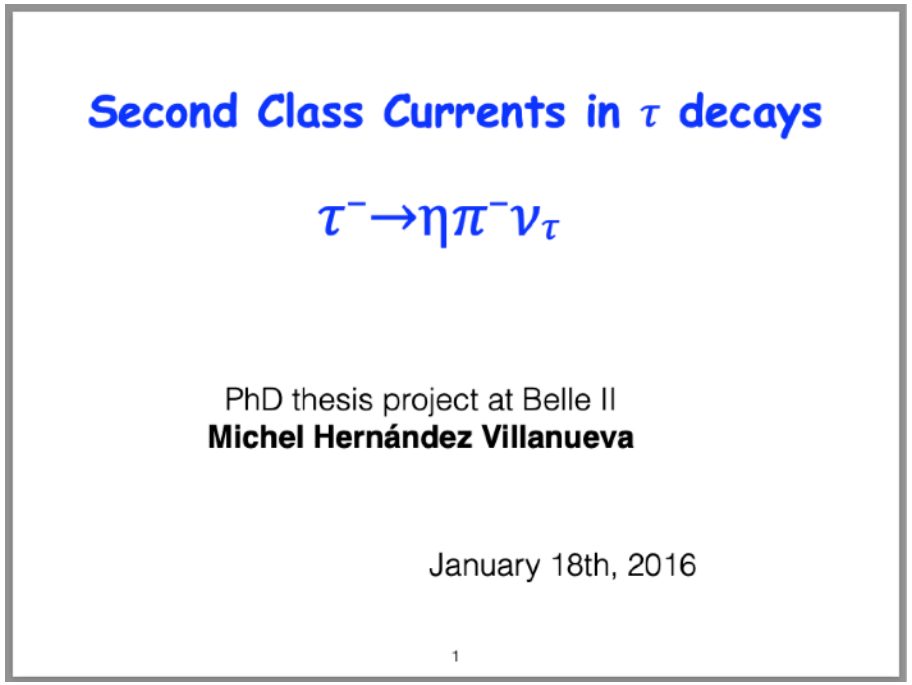
$\tau^- \to h^+ \ell^- \ell^- \nu_\tau$ **LNV (ΔL=2)**



Tau leptons at the B factories

Why the tau?

- The τ is the charged lepton of the third generation.
- It is the only lepton massive enough to decay into hadrons.
- Decay channels of the tau τ allow a clean theoretical analysis of the hadronization, determination of SM parameters and searches of new physics.
  - Standard Model parameters
    m_τ, α_s (m_τ), CKM parameter V_{us}.
  - CP violation.
  - Lepton Number and
    Lepton Flavor Violation.
  - etc…
- **We decided to continue our journey in Belle II joining the Tau working group.**



G. Lopez Castro

Second Class Currents

Classification of hadronic currents

- V-A currents can be classified by their transformation proprieties under G-parity [1].

$$G = Ce^{i\pi I_2}$$

  - First-class currents:

Standard Model

$$J^{PG} = 0^{++}, 0^{--}, 1^{-+}, 1^{+-}, \ldots$$

  - Second-class currents (SCC):

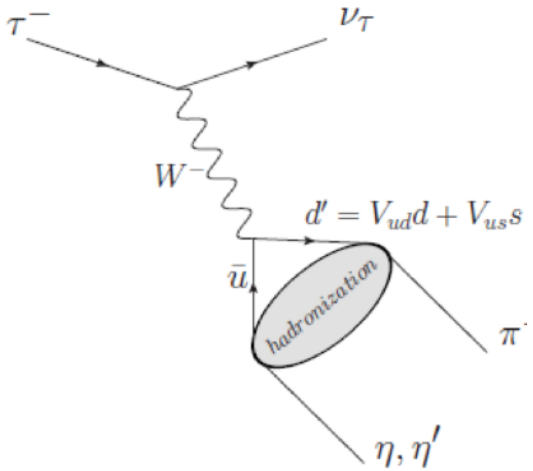
New Physics

$$J^{PG} = 0^{+-}, 0^{-+}, 1^{++}, 1^{--}, \ldots$$

[1]S. Weinberg. *Physical Review*, *112* (4), 1375 (1958).

- Unsuccessful searches of SCC in nuclear Physics.
- Another possibility: Search in tau decays[1]

$$\tau^- \rightarrow \eta\pi^-\nu_\tau$$



$$G|\bar{d}\gamma^\mu u\rangle = +|\bar{d}\gamma^\mu u\rangle$$

$$G|\pi\rangle = -|\pi\rangle$$
$$G|\eta\rangle = +|\eta\rangle$$

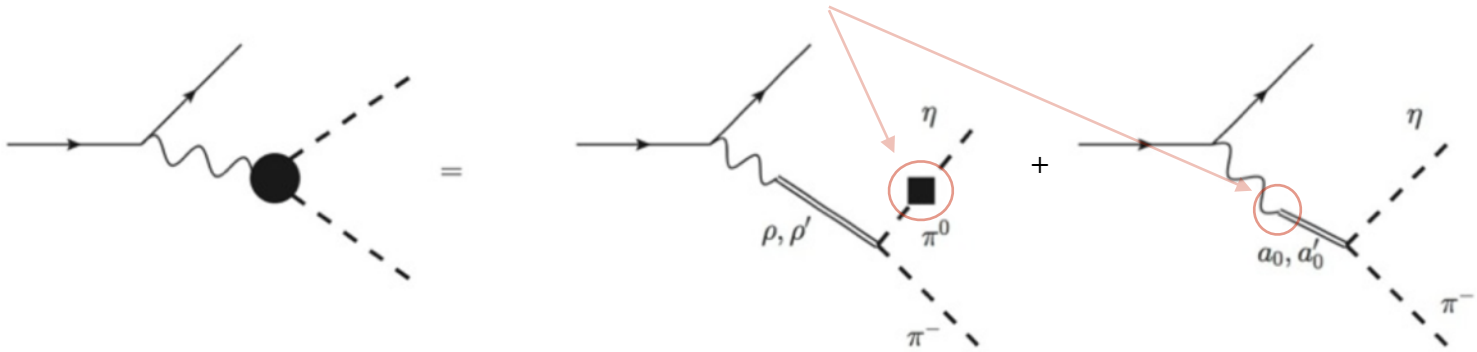
[1]Leroy, C., & **Pestieau, J.** (1978). Physics Letters B, 72(3), 398-399.

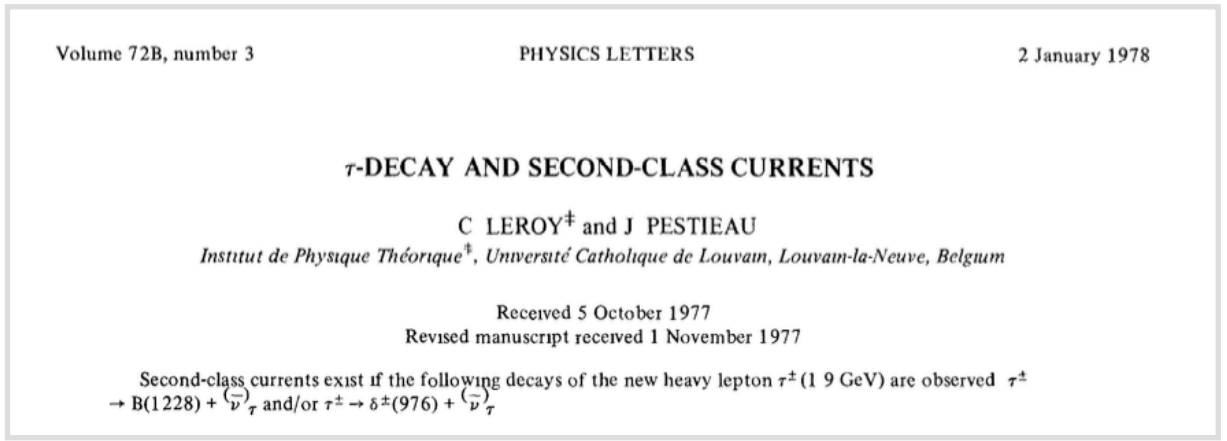
Second Class Current searches in $\tau \to \eta\pi\nu$

A quest of 44 years[1] and counting

- $\tau^- \to \eta\pi^-\nu_\tau$ in the SM: isospin violation

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





Volume 72B, number 3 PHYSICS LETTERS 2 January 1978

τ-DECAY AND SECOND-CLASS CURRENTS

C LEROY‡ and J PESTIEAU

Institut de Physique Théorique‡, Université Catholique de Louvain, Louvain-la-Neuve, Belgium

Received 5 October 1977
Revised manuscript received 1 November 1977

Second-class currents exist if the following decays of the new heavy lepton $\tau^\pm$ (1 9 GeV) are observed $\tau^\pm \to B(1228) + \overset{(-)}{\nu}_\tau$ and/or $\tau^\pm \to \delta^\pm(976) + \overset{(-)}{\nu}_\tau$

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

SM predictions: BR($\tau \to \eta\pi\nu$) ~ 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[2]

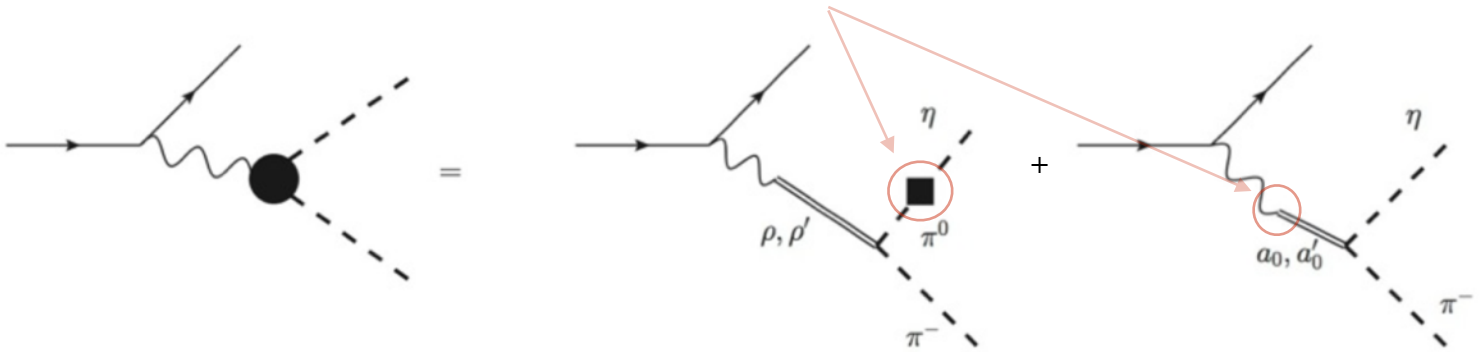
A measurement of the BR provides capability of testing QCD models

[2]Escribano, R. et. al. (2016). Phys. Rev. D **94**, 034008.

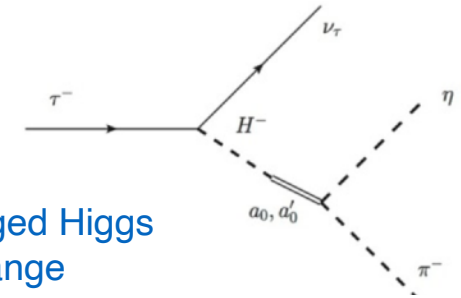
Second Class Current searches in $\tau \to \eta\pi\nu$

BSM searches

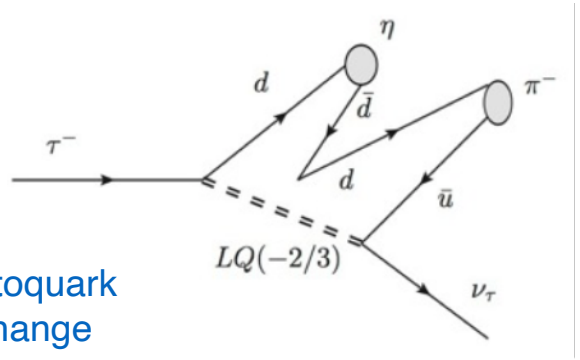
- $\tau^- \to \eta\pi^-\nu_\tau$ in the SM: isospin violation



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



Charged Higgs exchange

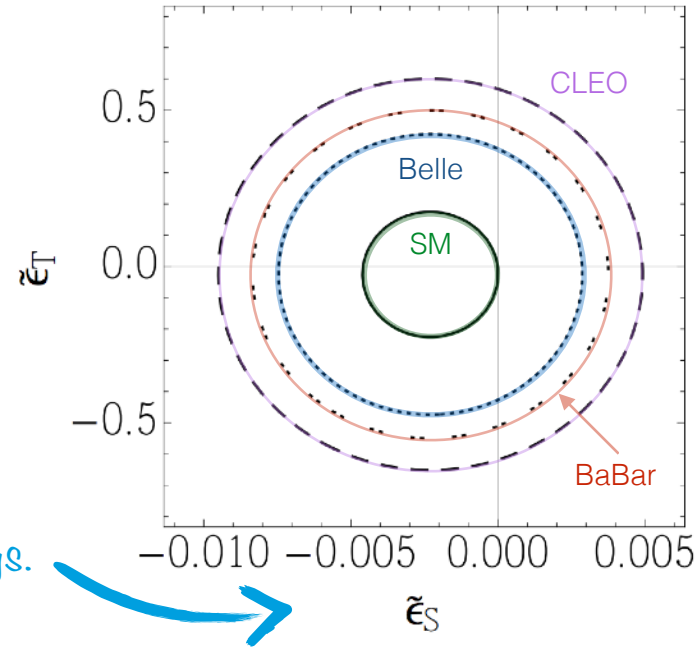


Leptoquark exchange

- Second paper during the PhD.

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

$$\begin{aligned}\mathcal{M} &= \mathcal{M}_V + \mathcal{M}_S + \mathcal{M}_T \\ &= \frac{G_F V_{ud}\sqrt{S_{EW}}}{\sqrt{2}}(1+\epsilon_L+\epsilon_R)\,\left[L_\mu H^\mu + \tilde{\epsilon}_S L H + 2\tilde{\epsilon}_T L_{\mu\nu} H^{\mu\nu}\right],\end{aligned}$$



Strongest constrains in scalar couplings.

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

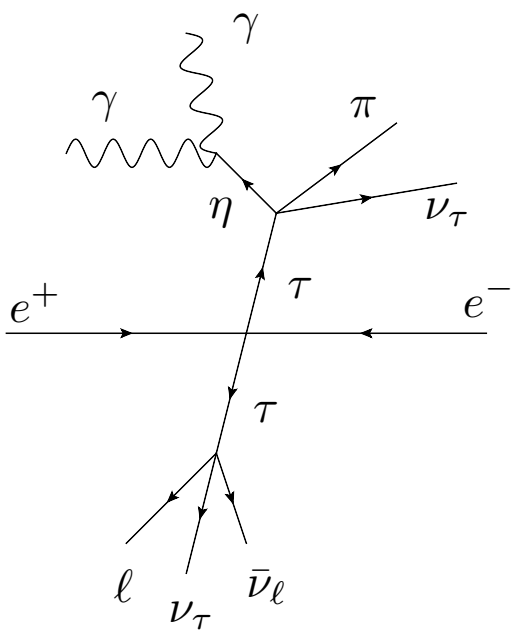
Second Class Current searches in $\tau \to \eta\pi\nu$

Experimental Results

- SM predictions: BR($\tau \to \eta\pi\nu$) ~ 10^{-5}
- B-Factories have produced 10^8 tau pairs. **Have we observed $\tau \to \eta\pi\nu$?**

1-prong

BR(η —> $\gamma\gamma$) = 39.41%

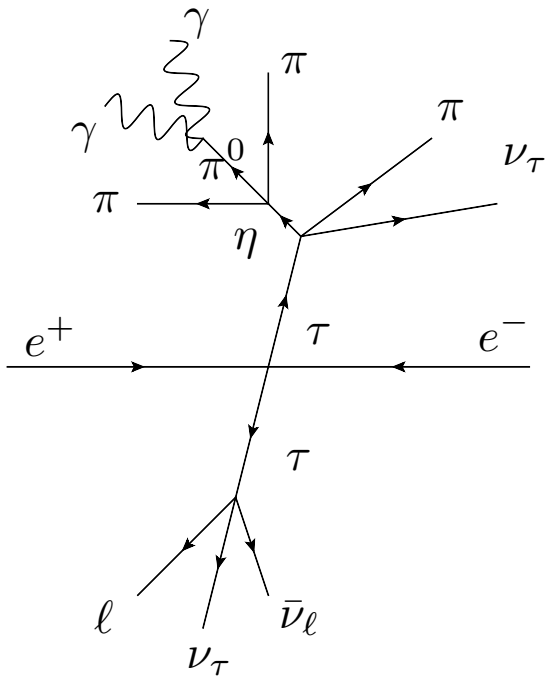


Signal side

Tag side

3-prong

BR(η —> $\pi\pi\pi^0$) = 22.92%

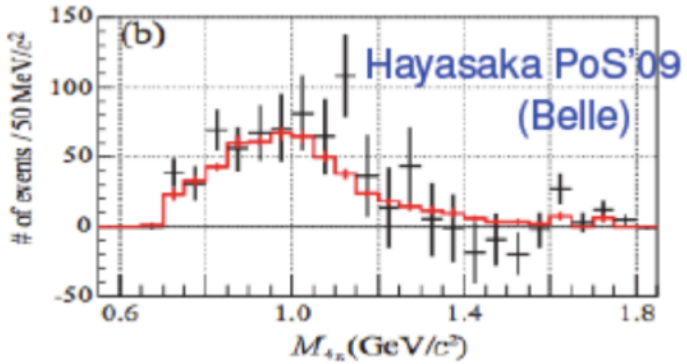


Second Class Current searches in $\tau \to \eta\pi\nu$

Experimental Results

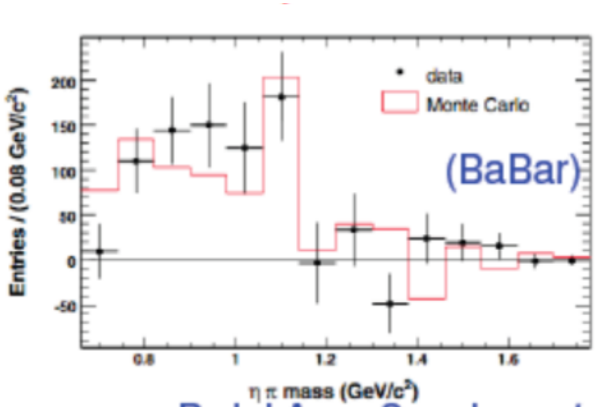
- SM predictions: BR($\tau \to \eta\pi\nu$) ~ 10^{-5}
- B-Factories have produced 10^8 tau pairs. Have we observed $\tau \to \eta\pi\nu$?
  - Well… no.

670 fb^{-1}



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

470 fb^{-1}



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

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

- Strong backgrounds: non-suppressed $\tau \to \eta + X$

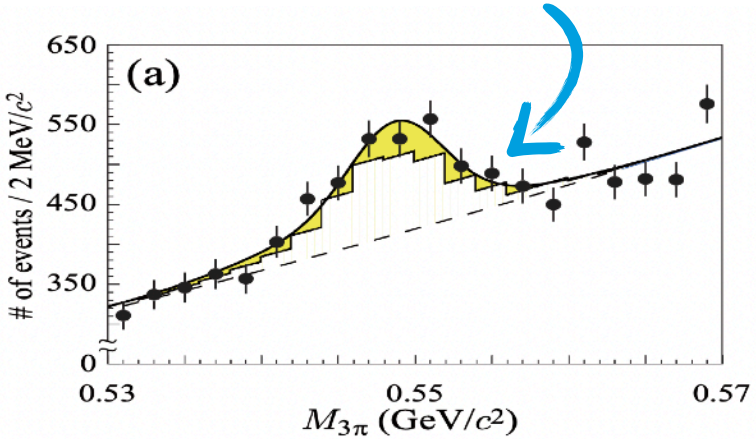


Figure: Hayasaka, *PoS* EPS-HEP2009 (2009) 374

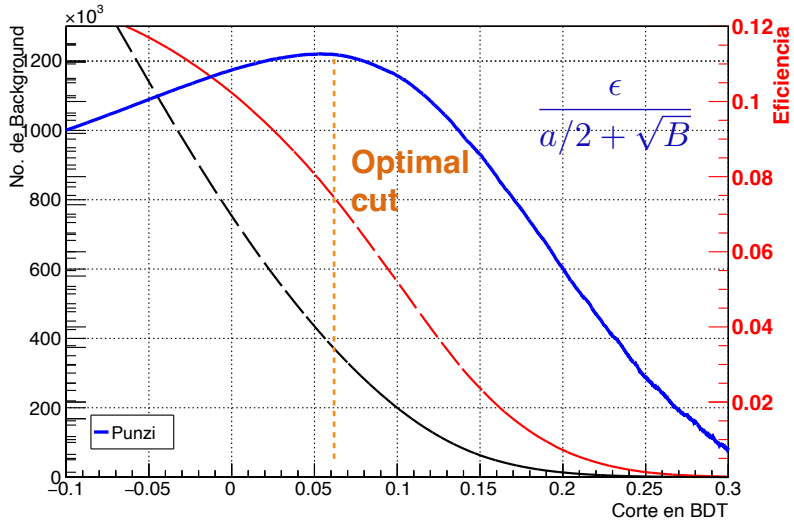
- **What about Belle II?**

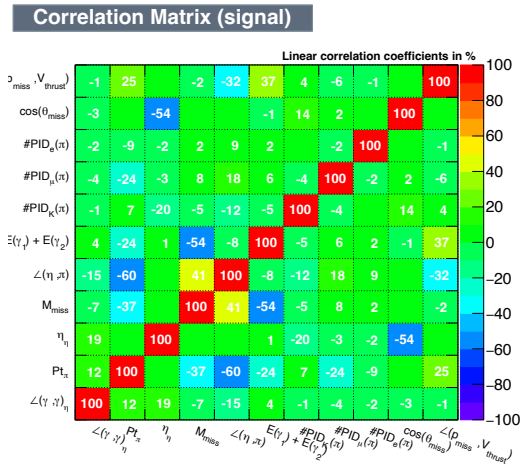
Second Class Current searches in $\tau \to \eta\pi\nu$

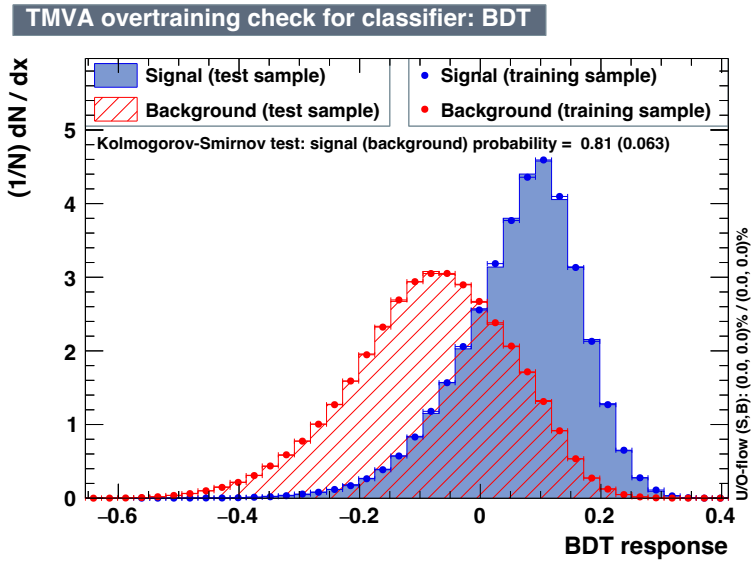
Experimental Results

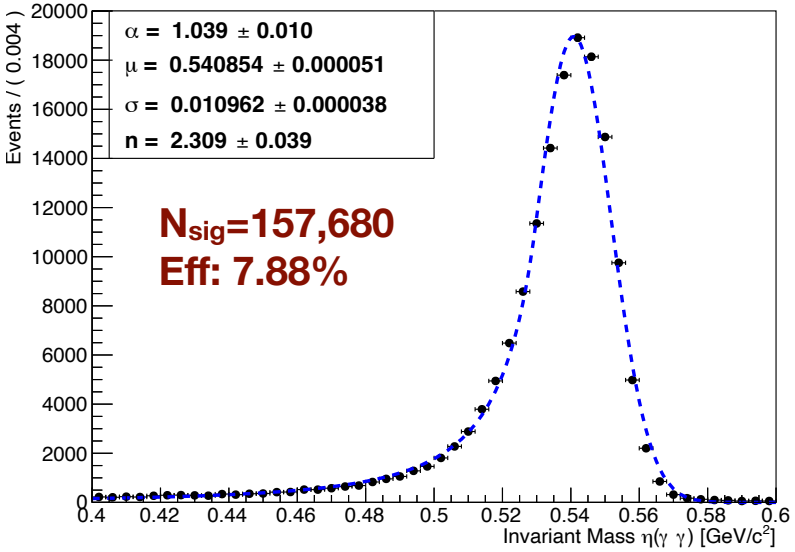
- $\angle(\eta,\pi)$
- $\angle(p_{miss}, V_{thrust})$
- M_{miss}
- $P_t(\pi)$
- $\eta(\eta)$
- $\angle(\gamma, \gamma)_\eta$
- $\cos(\theta_{miss})$
- $PID_e(\pi)$
- $PID_\mu(\pi)$
- $PID_K(\pi)$
- $E(\gamma)$

Optimization proposed by Punzi, G. at arXiv preprint physics/0308063



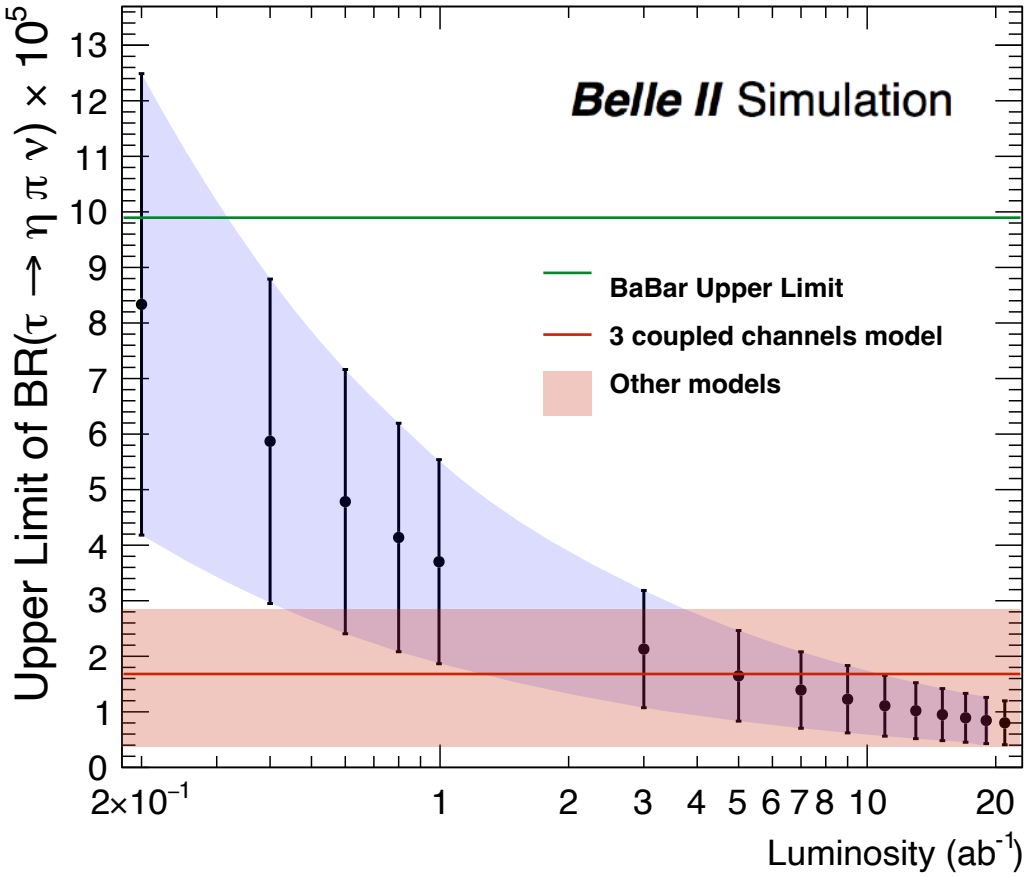






Sensitivity of $\tau \to \eta\pi\nu$ @ Belle II

Our PhD thesis result



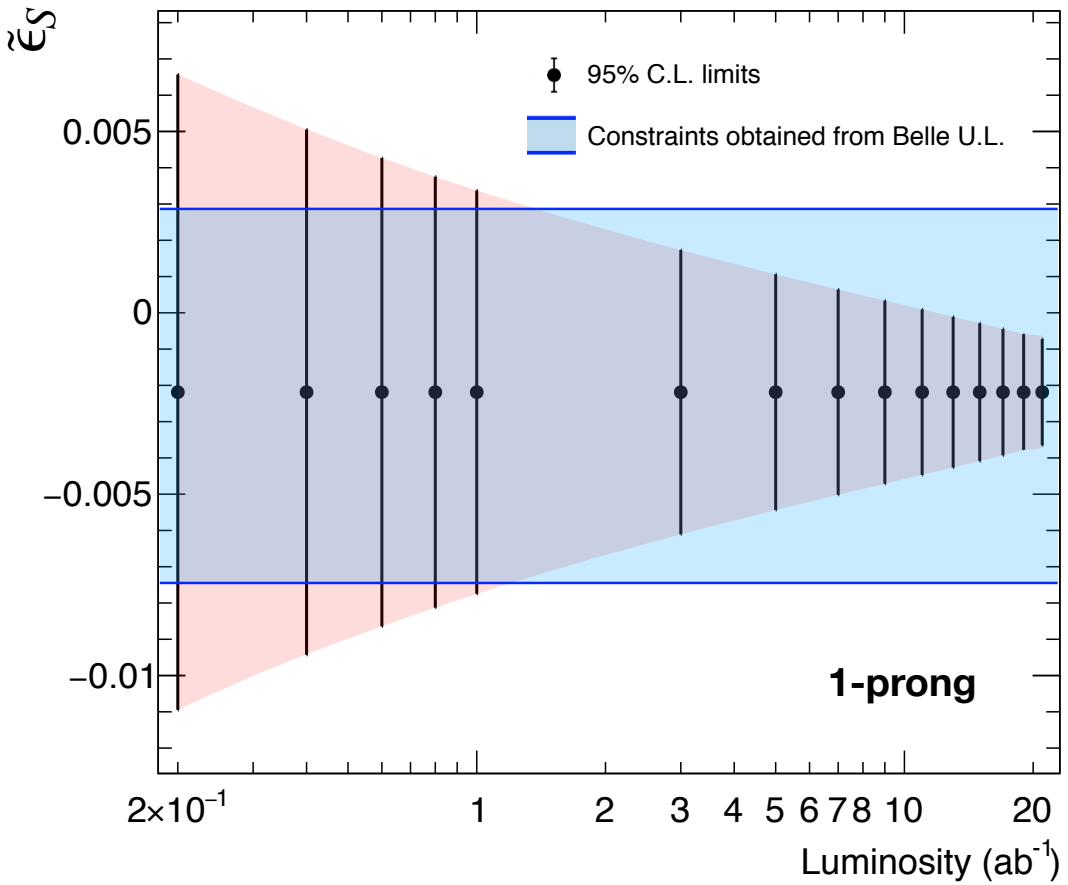
- At least ~1 ab^{-1} for testing SM predictions.

SM predictions: BR($\tau \to \eta\pi\nu$) ~ 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

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

Our PhD thesis result



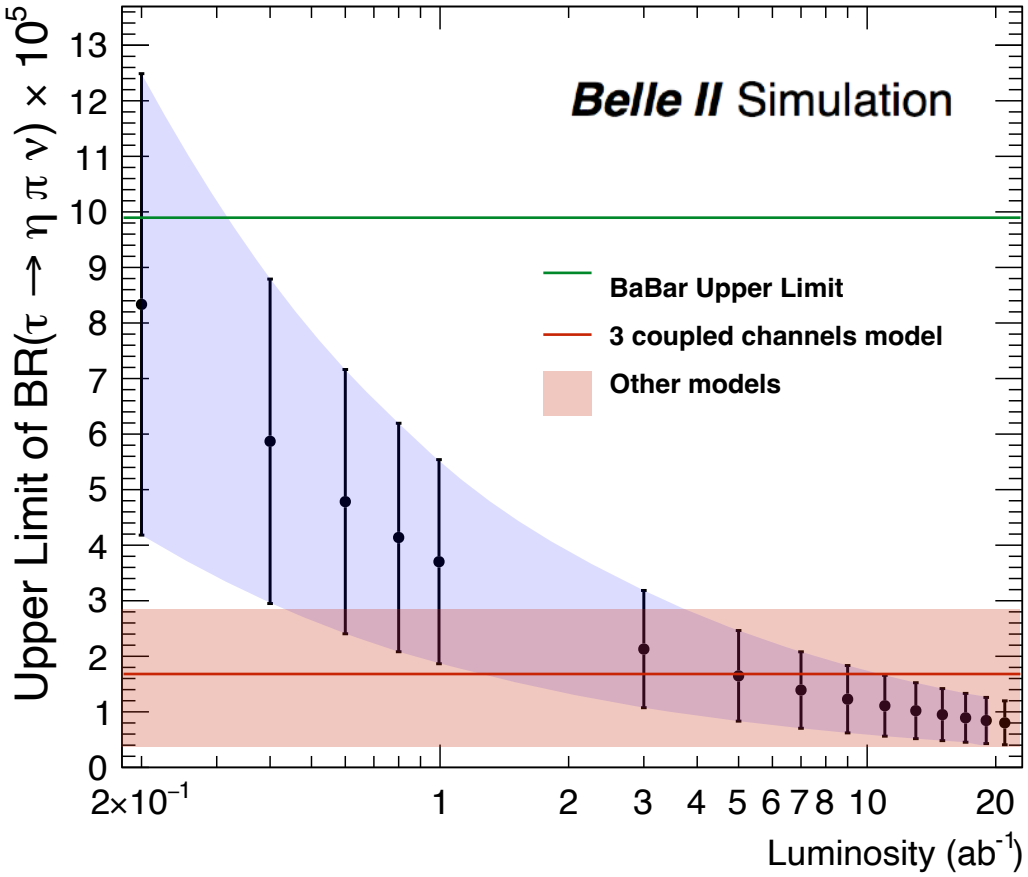
- At least ~1 ab^{-1} for testing SM predictions.

SM predictions: BR($\tau \to \eta\pi\nu$) ~ 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

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

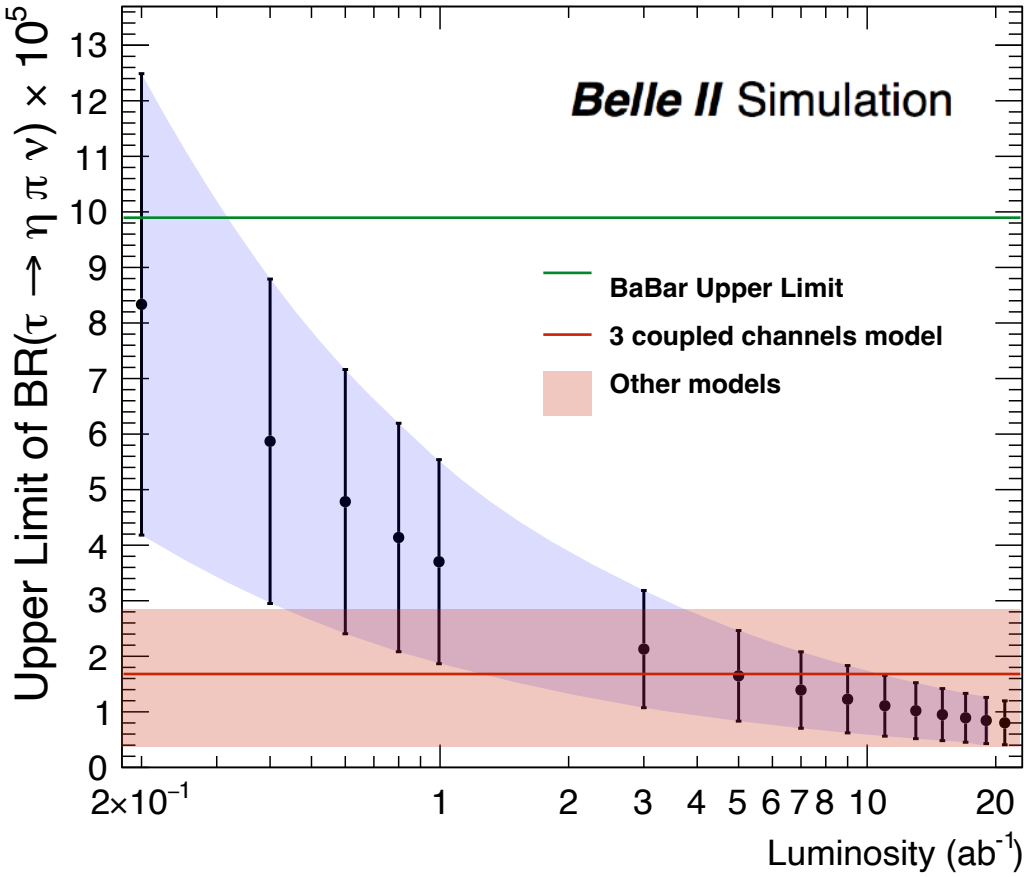
Our PhD thesis result



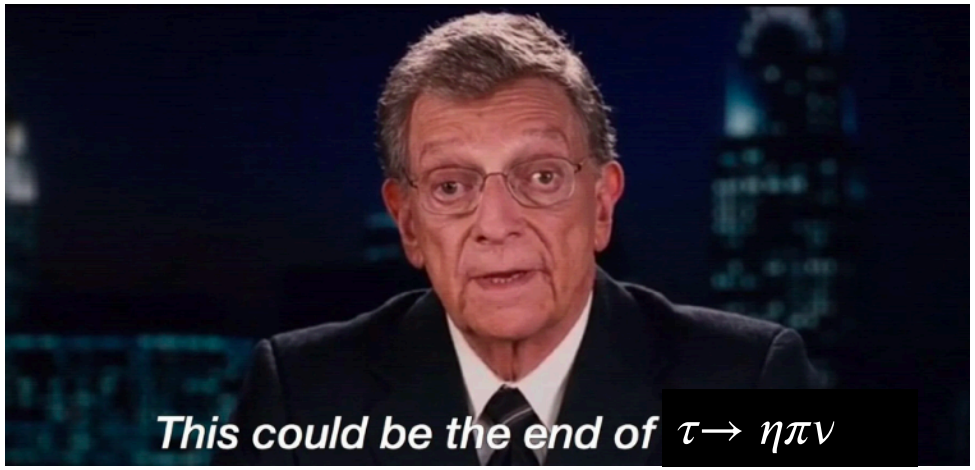
- At least ~1 ab^{-1} for testing SM predictions.
- **By summer 2022: 0.5 ab^{-1}**

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

Our PhD thesis result



- At least ~1 ab^{-1} for testing SM predictions.
- **By summer 2022: 0.5 ab^{-1}**

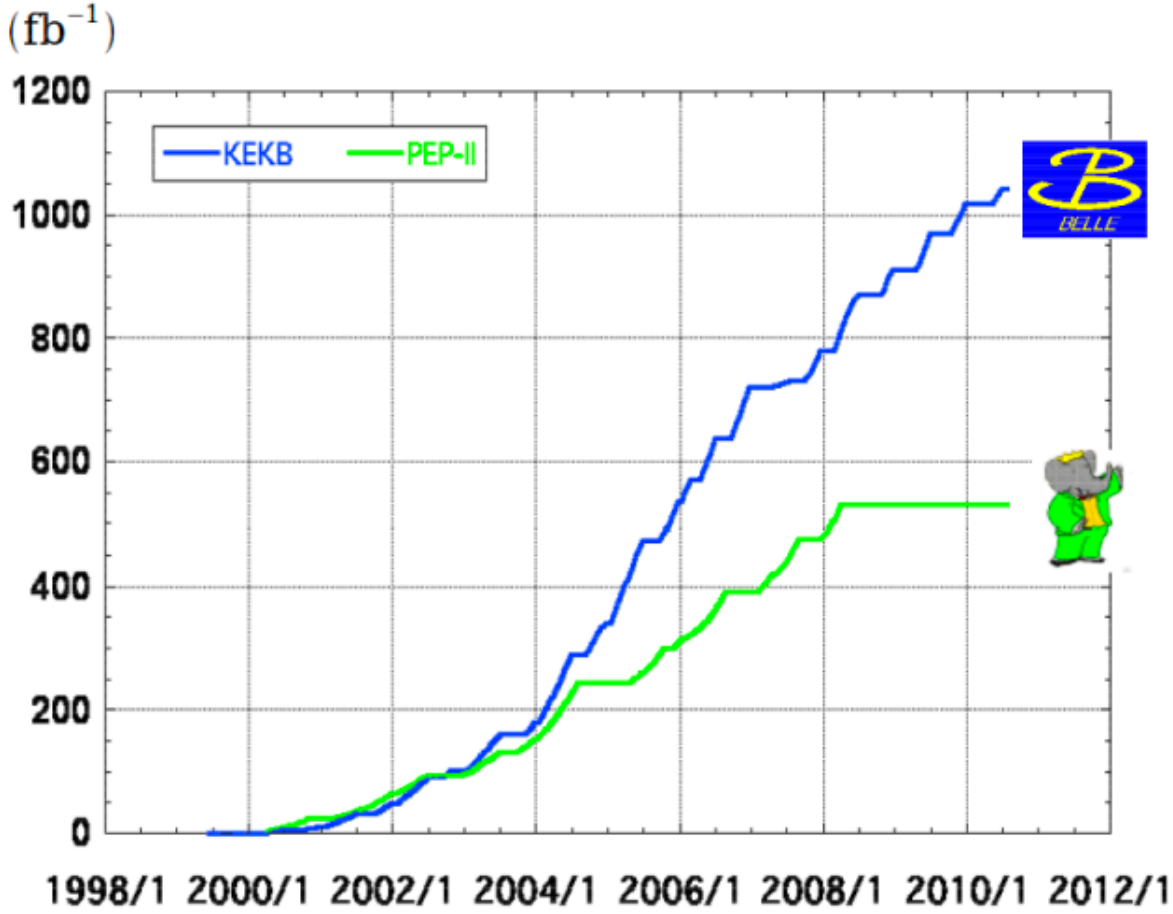


(At least for a while)

Integrated luminosity at the B factories

(… and tau Factories)

- We actually have 1 ab^{-1} of data waiting to be analysed!



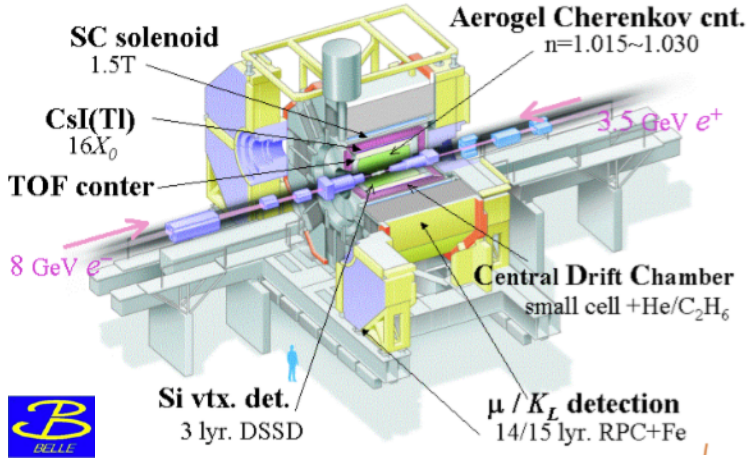
> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

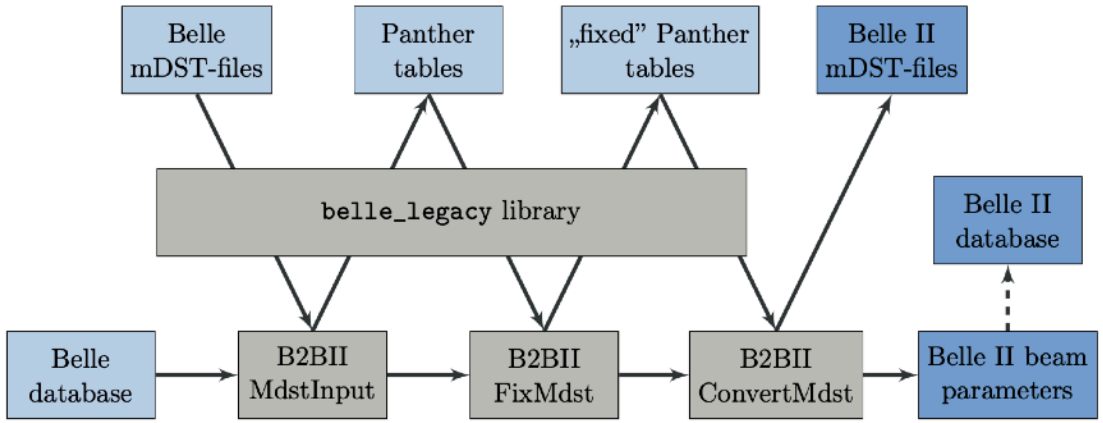
~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

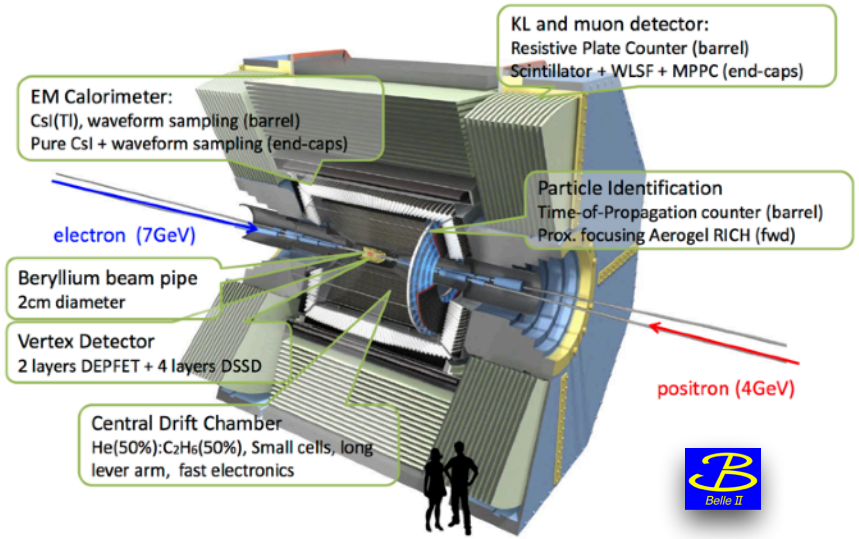
Conversion from Belle to Belle II

The B2BII package

- **The B2BII package is being developed to convert recorded Belle events to the Belle II format.**
- This allows to reproduce Belle results using BASF2, preserving the legacy of the Belle datasets.
  - Also, it allows new studies with Belle data using the advanced analysis tools provided at BASF2.







Conversion from Belle to Belle II

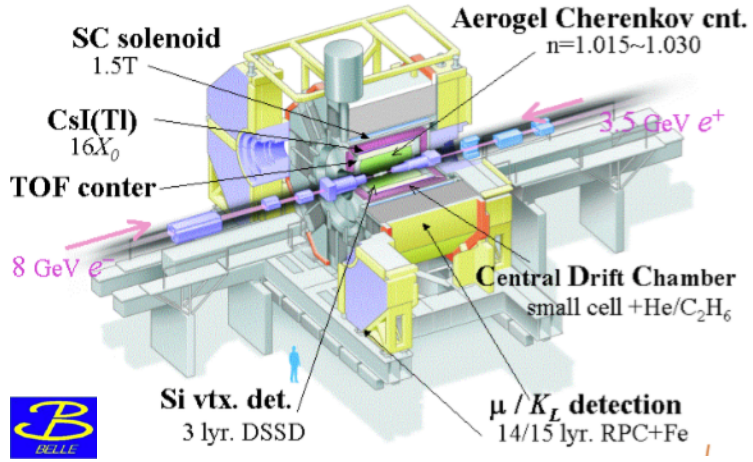
The B2BII package

- The conversion process has been validated for B decays, and several studies using B2BII are ongoing.

Combined analysis of Belle and Belle II data to determine the CKM angle ϕ_3 using $B^+ \to D(K^0_S h^+ h^-)h^+$ decays

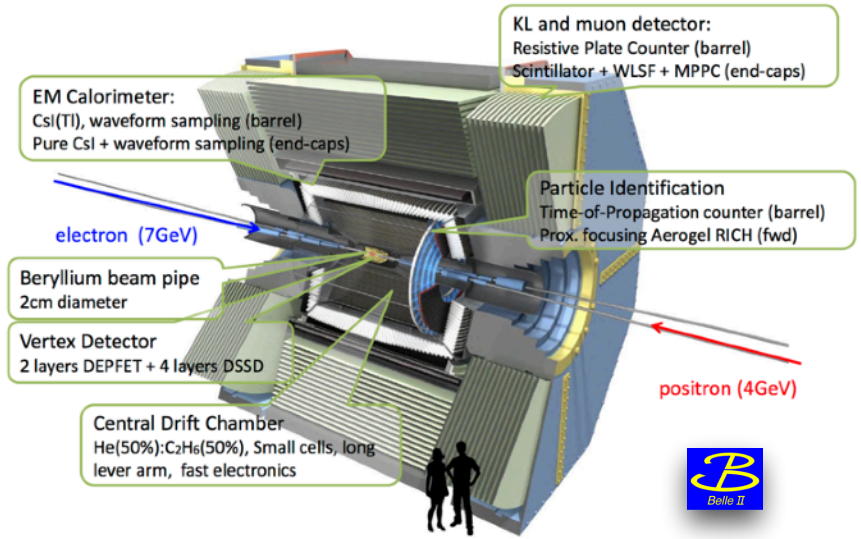
---

The Belle and Belle II collaborations



- I started trying to answer a "simple" question: **may we do the same for $\tau \to \eta\pi\nu$?**

?



Boosted Decision Trees

Boosted Decision Trees

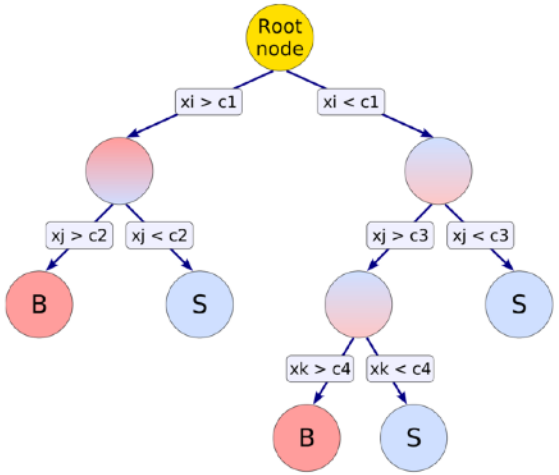
- To select $\tau \to \eta + X$ events, a BDT with 4 variables is trained using a FastBDT (part of Basf2 modules).
- As **signal**, samples of $\tau \to \eta$ from generic tau decays + signal MC are used.
- As **background**, non $\tau \to \eta$ decays from tau pair MC, qqbar and BBar.
- **Splitting samples** for training and testing in **50%** each.

Variables in training:

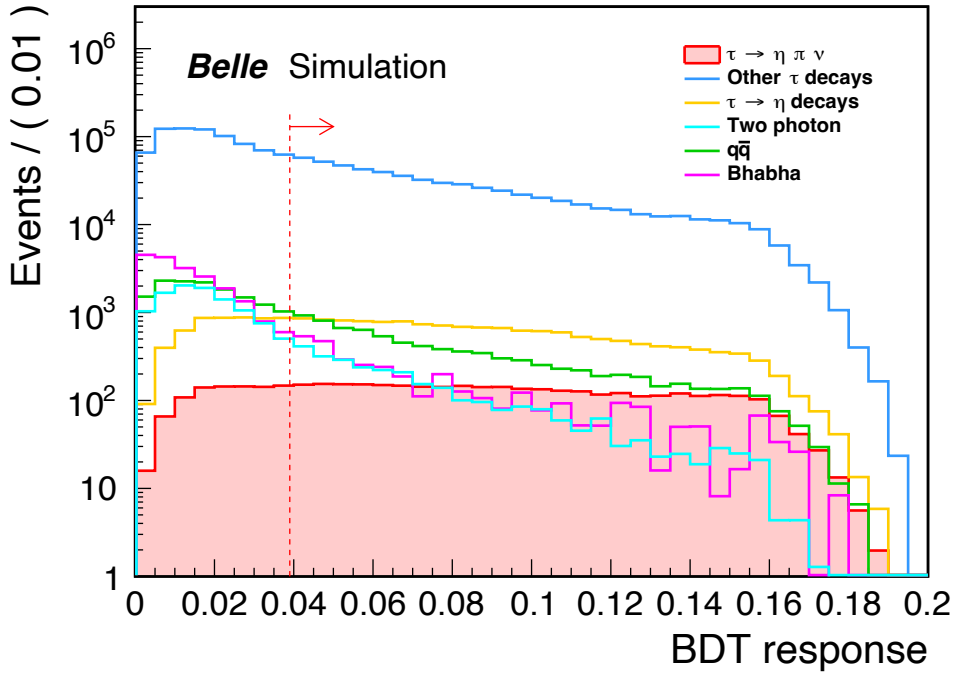
- A(γ's) = $|E_{\gamma_1} - E_{\gamma_2}|/(E_{\gamma_1} + E_{\gamma_2})$
- $\angle(\gamma_1, \gamma_2)$
- $\theta(\gamma)$'s

Selected to avoid any dependency to the dynamics of the $\tau \to \eta + X$ decays.

- A Random Forest is an ensemble method that combines different trees.
- Final output is determined by the majority vote of all the trees.



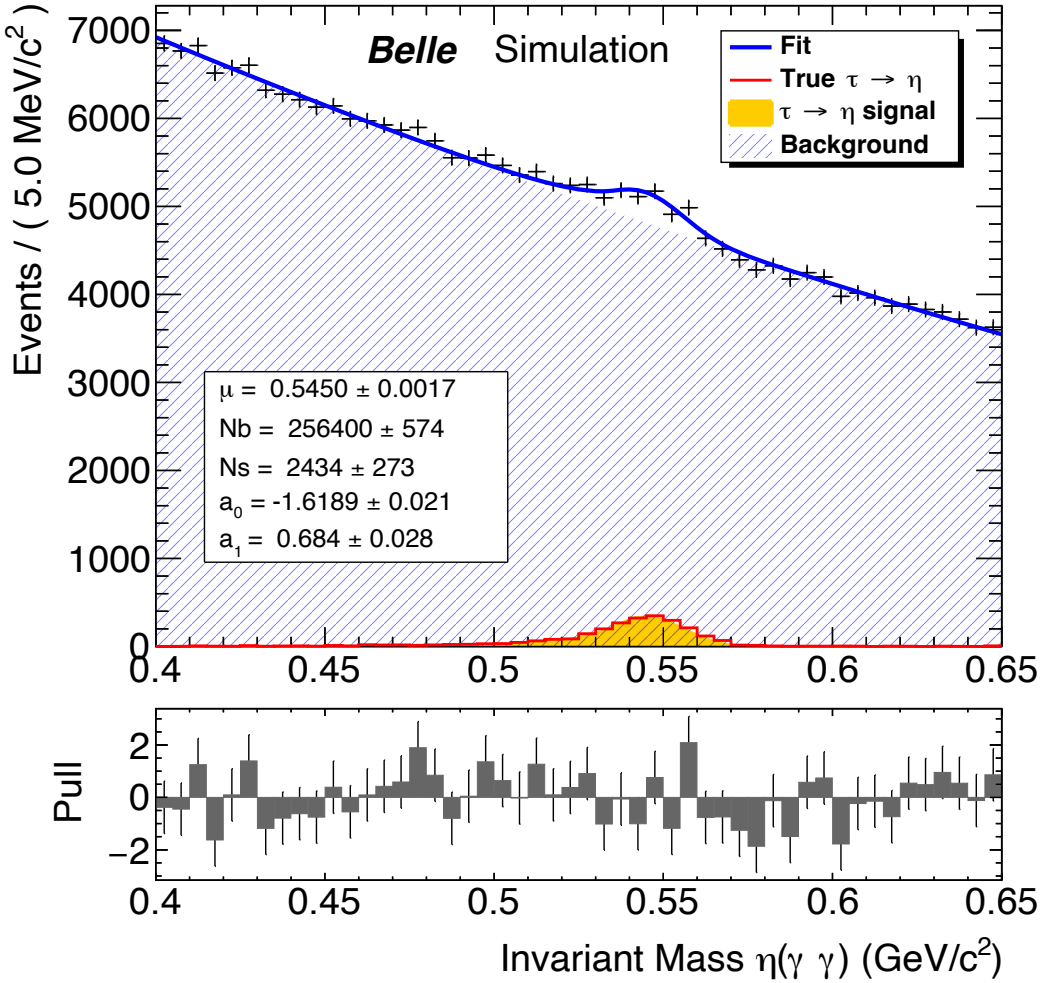
$$bdt = \frac{\sum_i w_i N_i}{\sum_i w_i}; \quad N_i = 0 \text{ or } 1$$



SM decays after BDT cut

Work under review

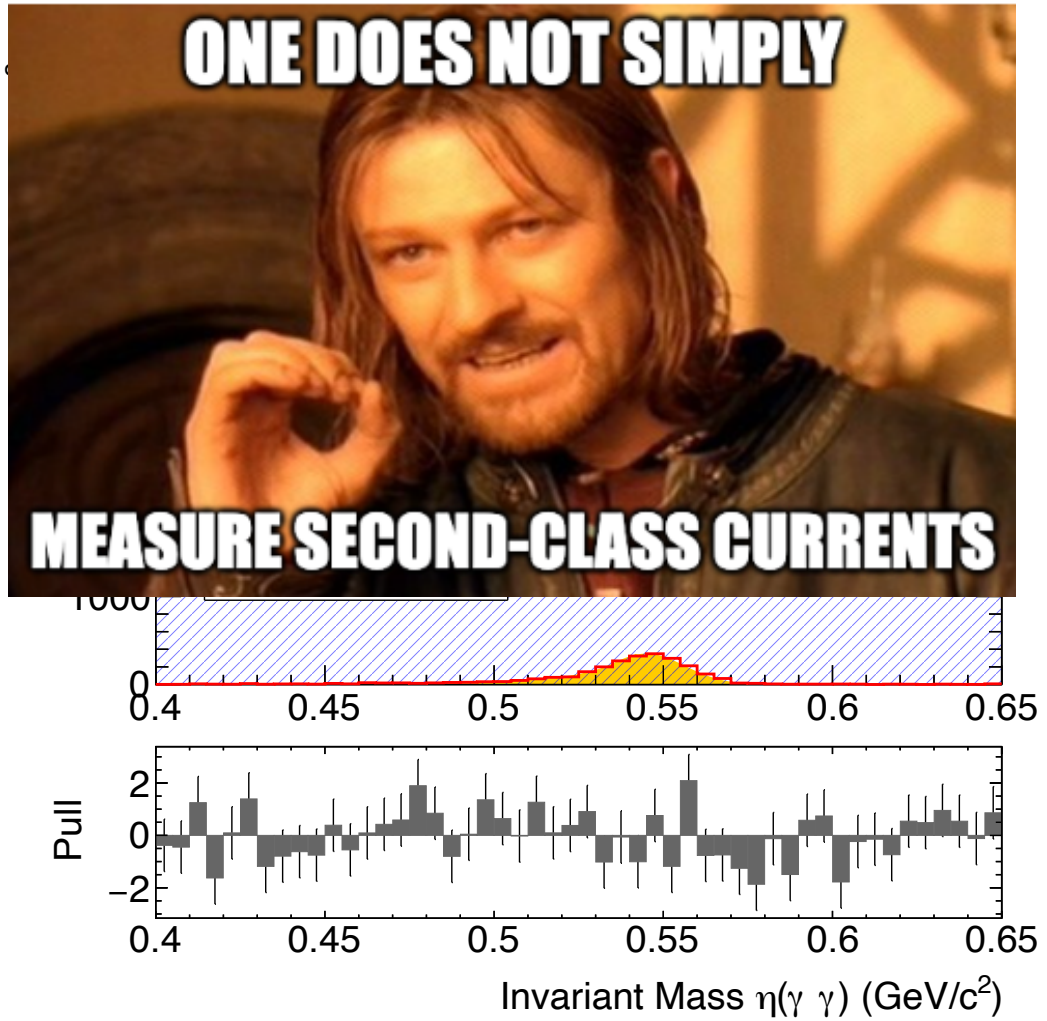
- This is the distribution of $\tau \to \eta$ SM decays + non $\tau \to \eta$ SM decays, scaled to the luminosity on data.
- Modelled using crystal ball + polynomial PDFs.
- Before the BDT cut, the η peak was not distinguishable for the fit. After the cut, there is a peak around the η mass.
- **This does NOT include the signal $\tau \to \eta\pi\nu$ MC sample.**
- **Removing the background coming from other $\tau \to \eta$ decays will be challenging**
  - $\tau \to \pi\pi^0\eta\nu$, $\tau \to \pi\pi^0\pi^0\eta\nu$,
  - $\tau \to K\eta\nu$, **etc**



SM decays after BDT cut

Work under review

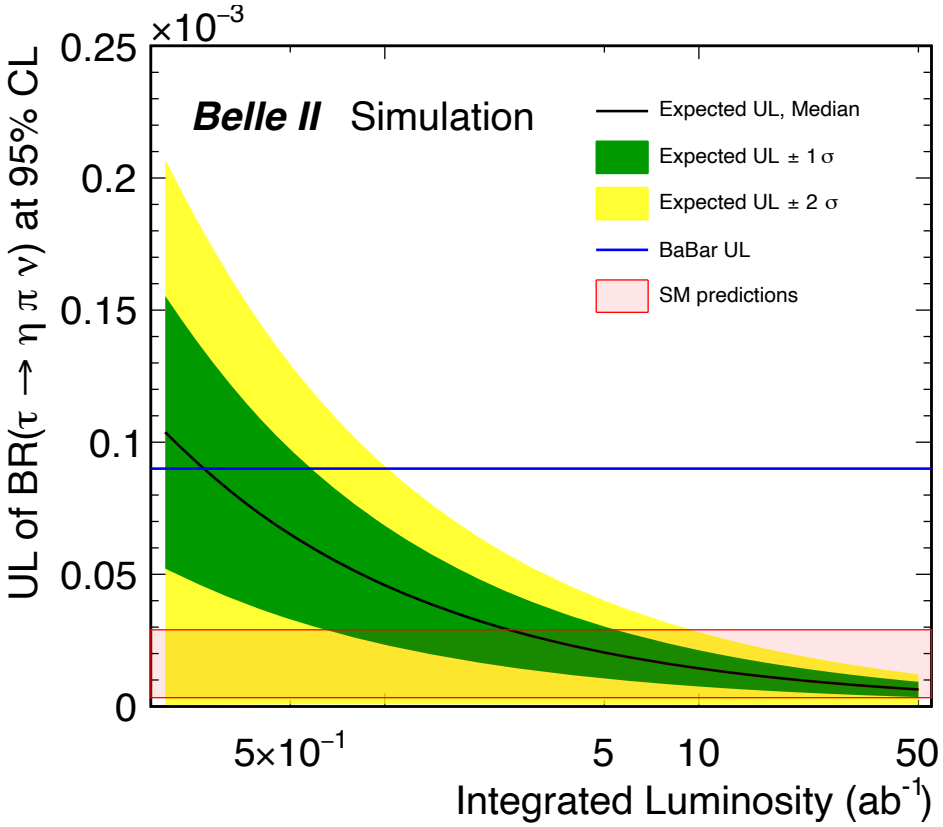
- This is the distribution of $\tau \to \eta$ SM decays + non $\tau \to \eta$ SM decays, scaled to the luminosity on data.
- Modelled using crystal ball + polynomial PDFs.
- Before the BDT cut, the η peak was not distinguishable for the fit. After the cut, there is a peak around the η mass.
- **This does NOT include the signal $\tau \to \eta\pi\nu$ MC sample.**
- **Removing the background coming from other $\tau \to \eta$ decays will be challenging**
  - $\tau \to \pi\pi^0\eta\nu$, $\tau \to \pi\pi^0\pi^0\eta\nu$,
  - $\tau \to K\eta\nu$, **etc**

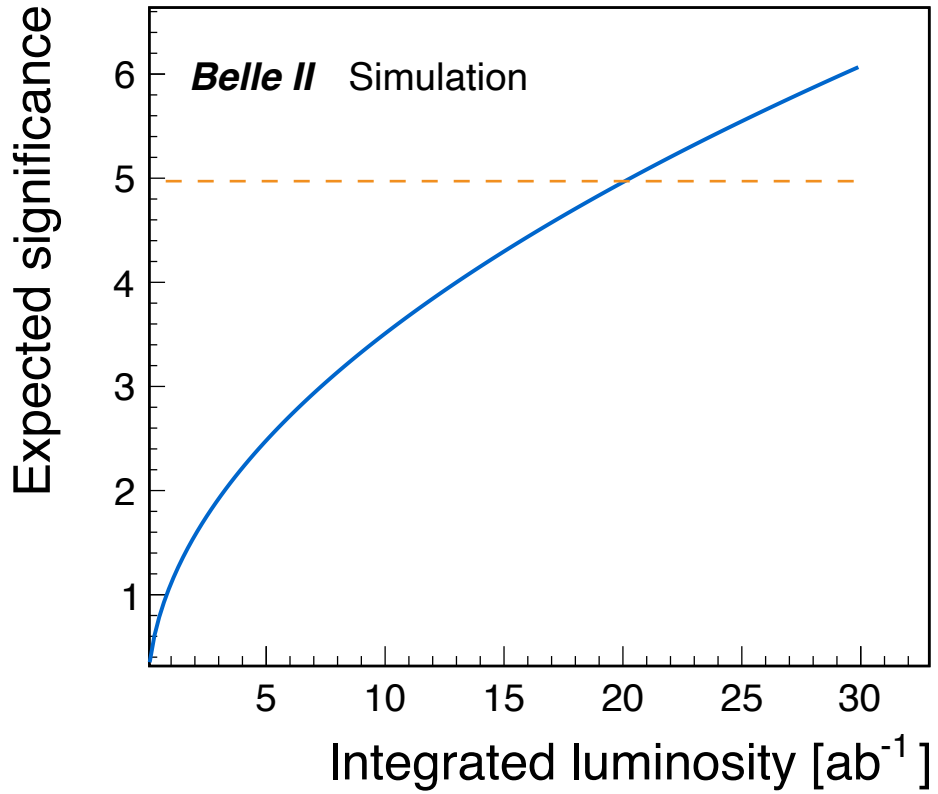


Belle II: Towards the high-luminosity scenario

The glass is half-empty

- Latest estimations with high-luminosity conditions @ Belle II.
- A large degradation of performance observed w.r.t. previous results, mainly coming from large number of photons from the beam.

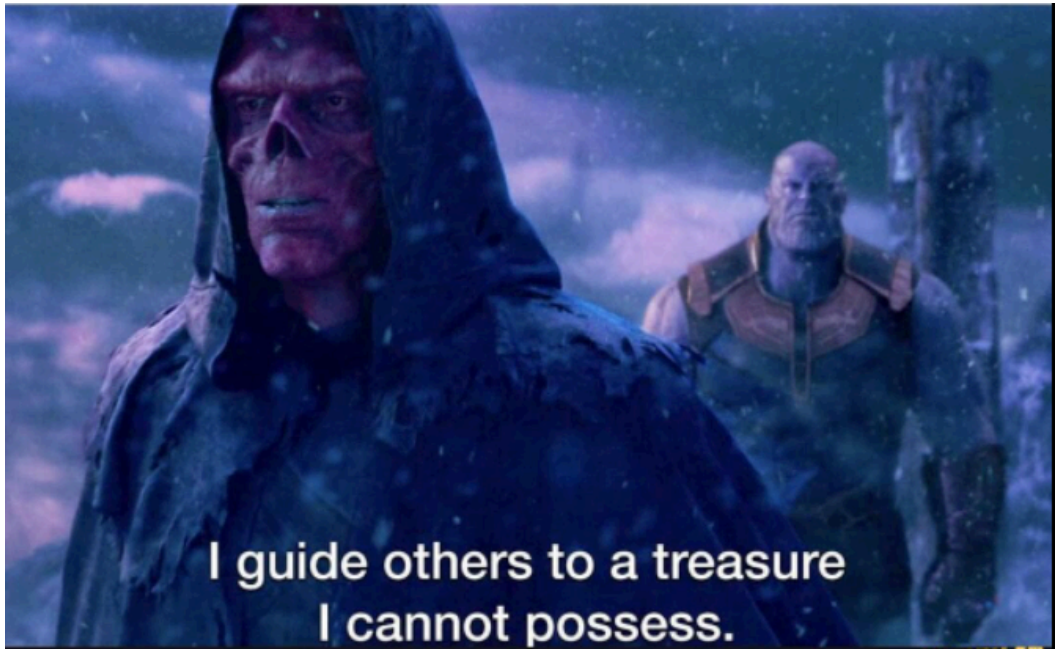




Discovery of $\tau \to \eta\pi\nu$ @ Belle II

Not “if”, but “when”

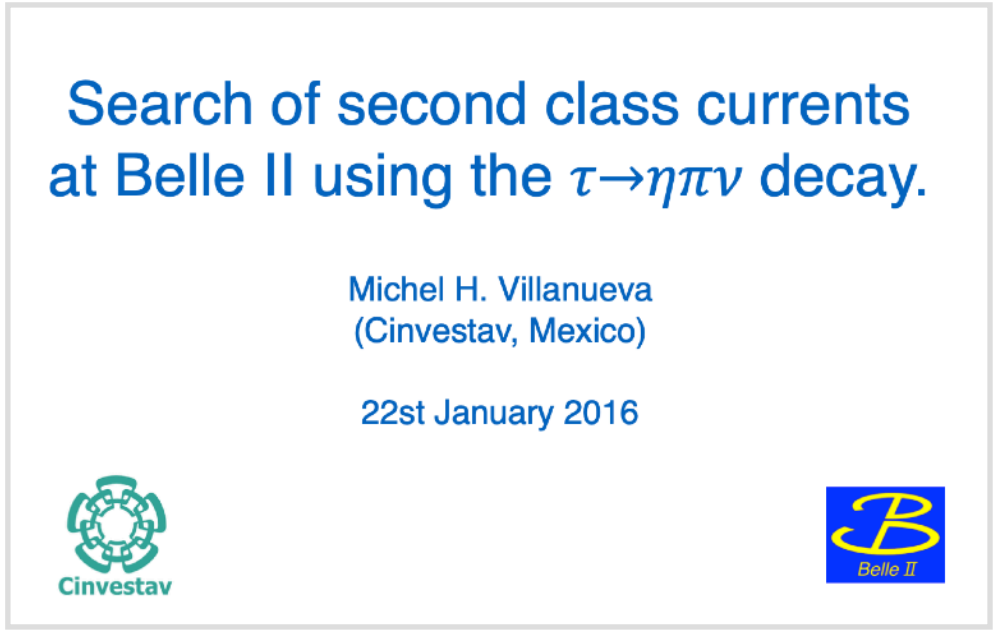
- We need a significant amount of data, but it is reachable within the lifetime of Belle II.
- I hope to the be there, but you never know…



Aftermath

The glass is half-full

- Despite the not positive results related to the discovery of $\tau \to \eta\pi\nu$, there is a lot that we have learned on the way.

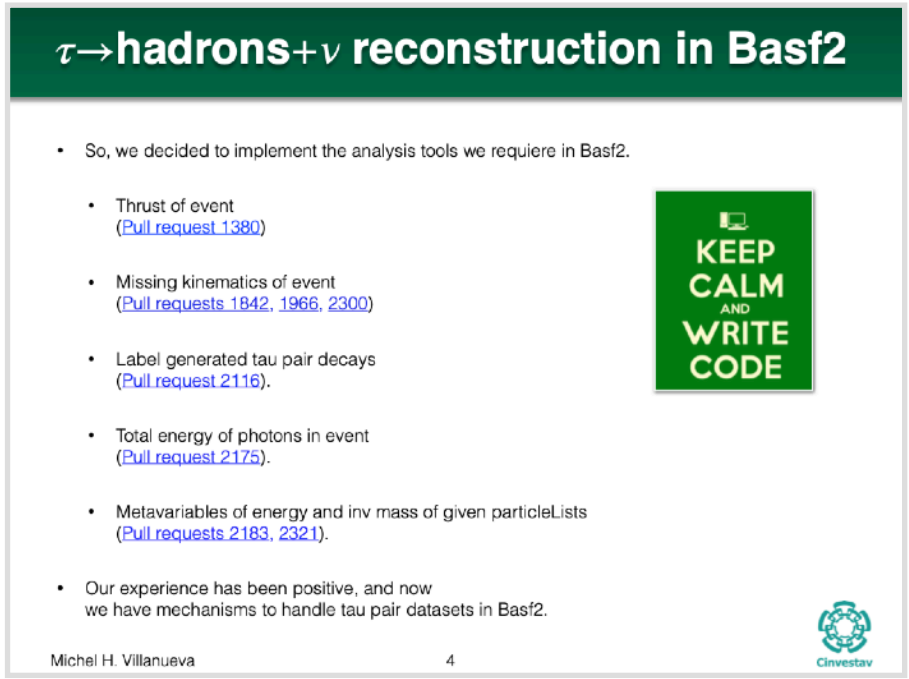


Aftermath

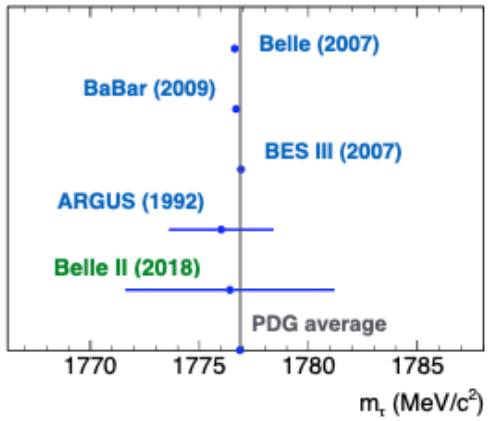
The glass is half-full

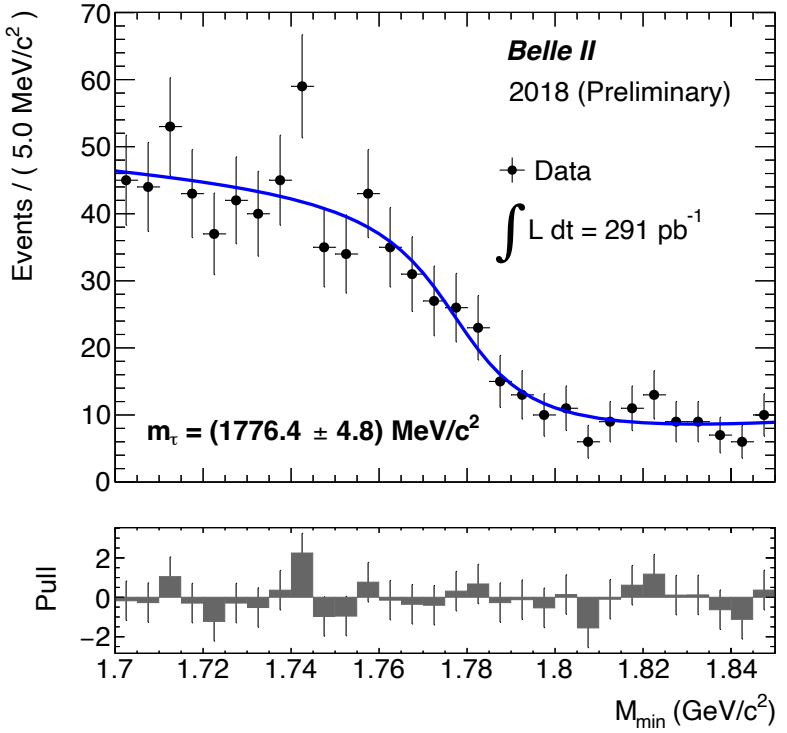
- Despite the not positive results related to the discovery of $\tau \to \eta\pi\nu$, there is a lot that we have learned on the way.

- We developed many of the tools used for tau physics at Belle II.

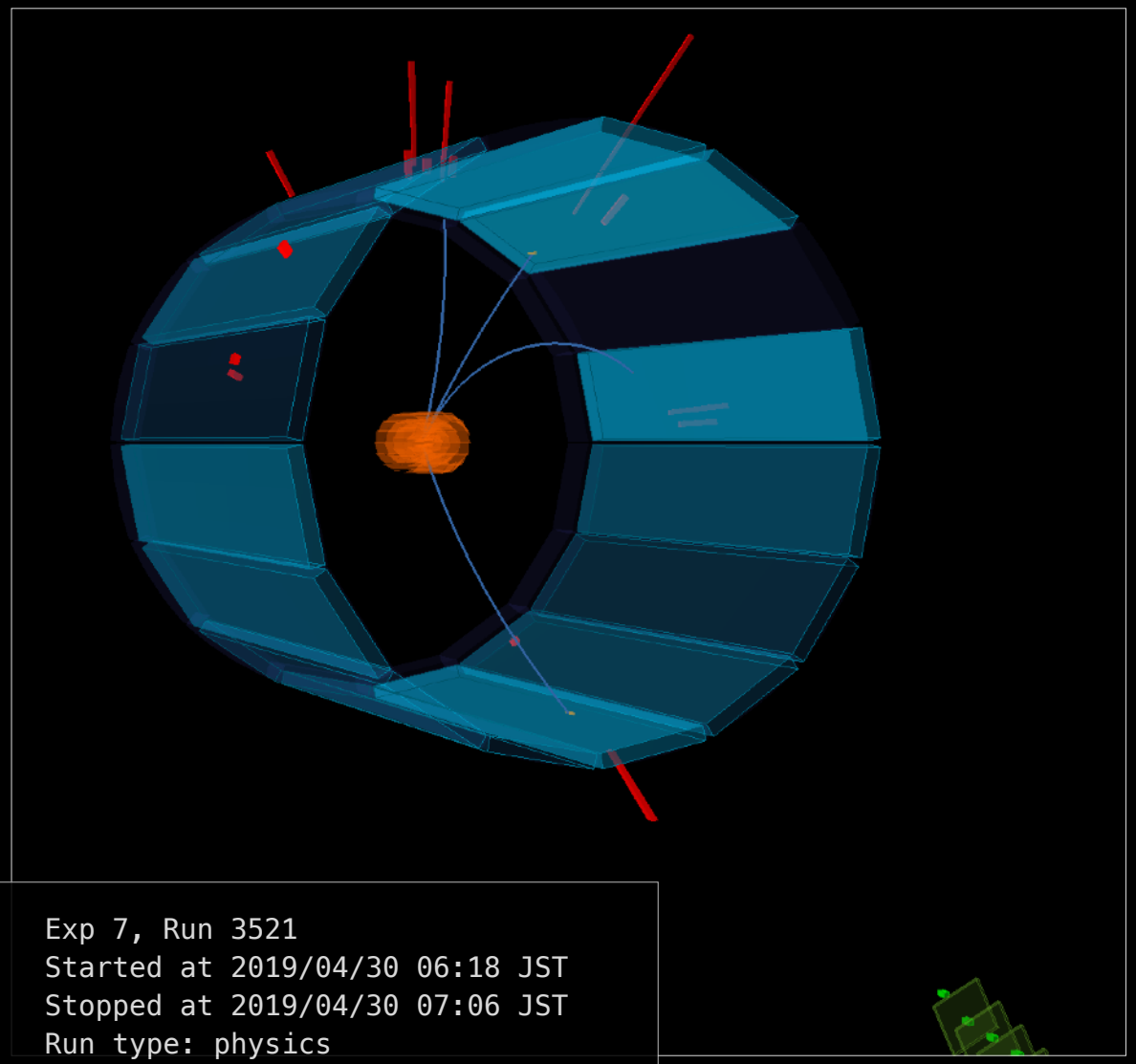


- We got the first measurement of the tau mass with (very) early data.

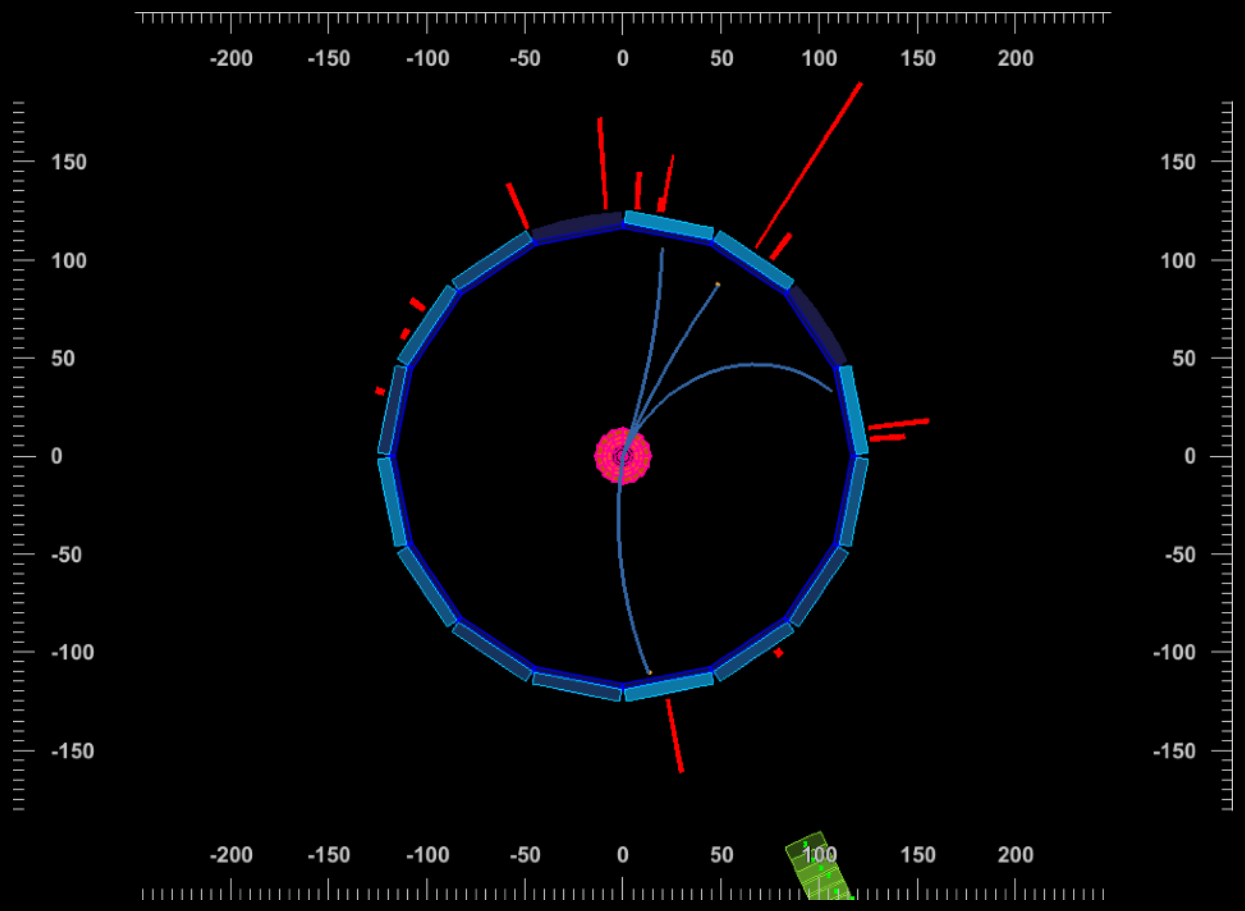




Tau decay event in early Belle II data



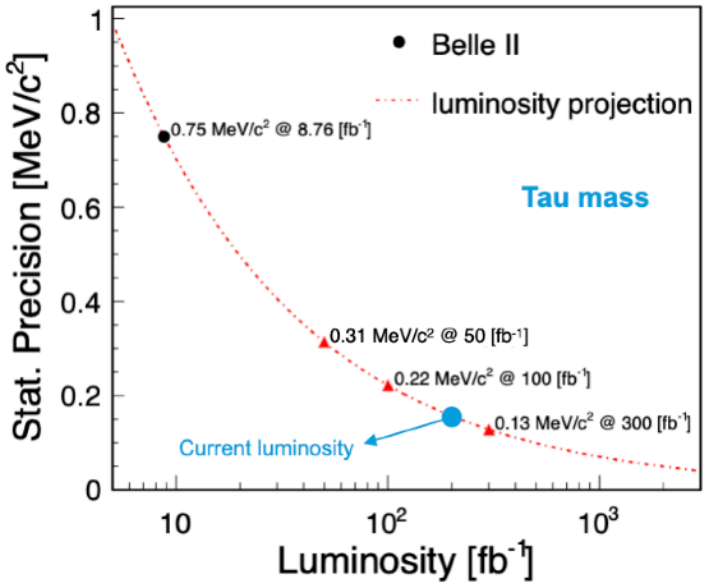
Exp 7, Run 3521
Started at 2019/04/30 06:18 JST
Stopped at 2019/04/30 07:06 JST
Run type: physics

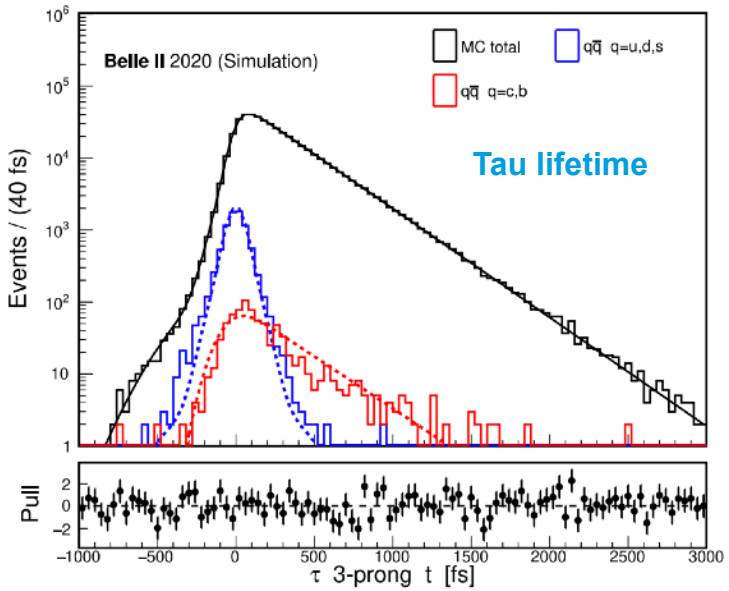


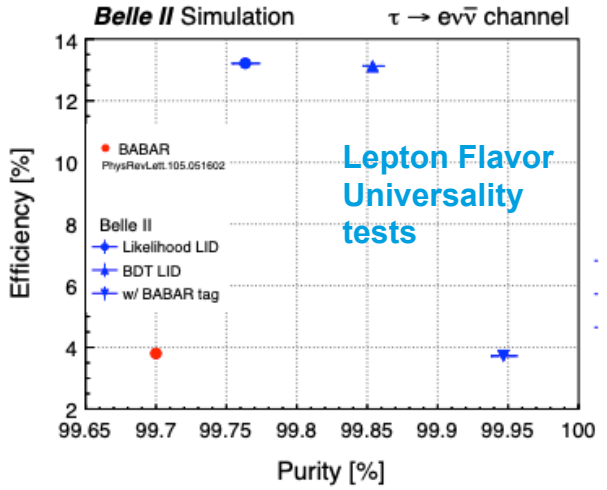
Aftermath

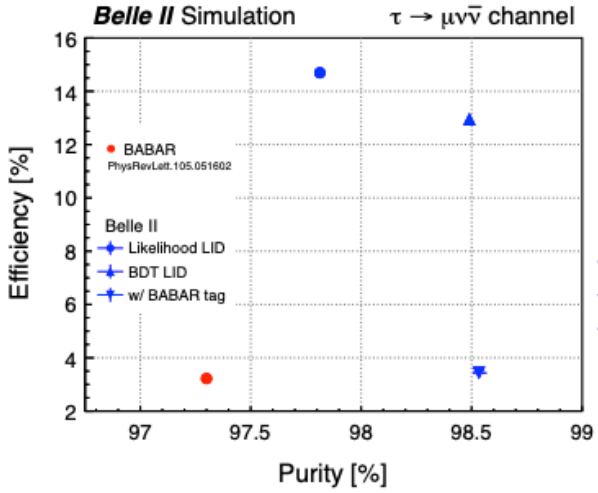
The glass is half-full

- Currently, I contribute as one of the conveners of the τ working group, with several results on the pipe:







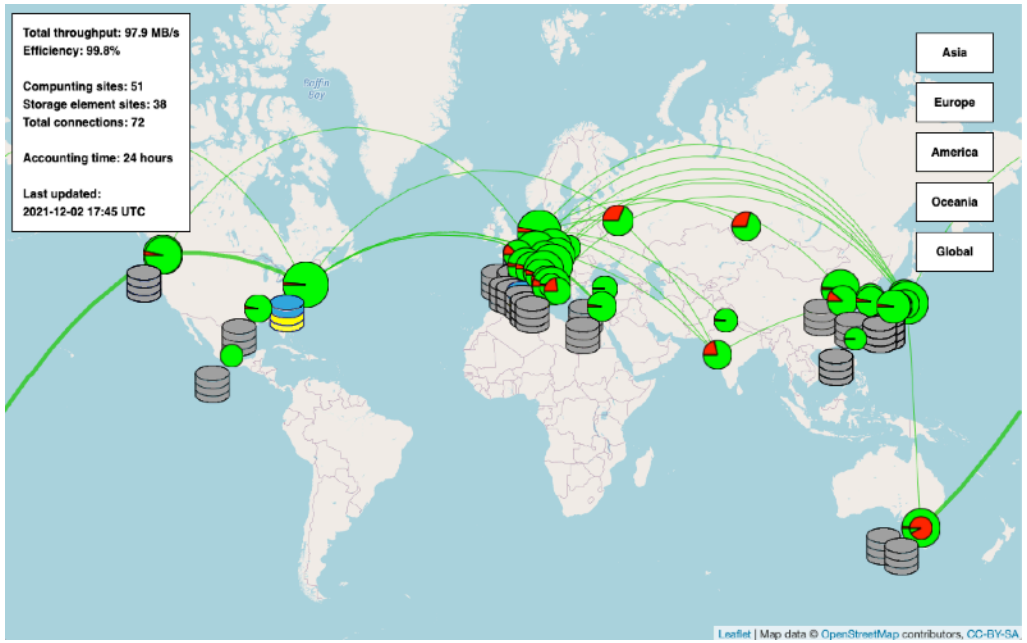


- All challenging systematic-dominated measurements.

Aftermath

A bit of extra-tau duties

- Deputy coordinator of the of Belle II computing
  https://belle2.jp/computing/



- Convener of the Training group in the HEP Software Foundation
  https://hepsoftwarefoundation.org/

HSF
HEP Software Foundation

The HEP Software Foundation facilitates cooperation and common efforts in High Energy Physics software and computing internationally.


Kilian Lieret


Michel Hernandez Villanueva


Sudhir Malik


Wouter Deconinck

Aftermath

The glass is half-full

- But always with $\tau \to \eta\pi\nu$ in mind.
  - TO-DO: η efficiency reconstruction and $\tau \to \eta\pi\pi^0\nu$, $\tau \to \eta K\pi^0\nu$, etc.
  - Close communication with Tauola/KKMC developers and experts.
  - **Keeping close communication with Gabriel on the potential in tau lepton measurements.**

- The knowledge that I got during my time at Cinvestav has been an unique and fundamental tool during my time at Belle II.
  - And I am deeply grateful for that.

TAU 2018

Thank you, Gabriel

Contact

DESY. Deutsches Elektronen-Synchrotron

www.desy.de

Michel Hernandez Villanueva
michel.hernandez.villanueva@desy.de
Orcid: 0000-0002-6322-5587