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Master in Physics

B τ D

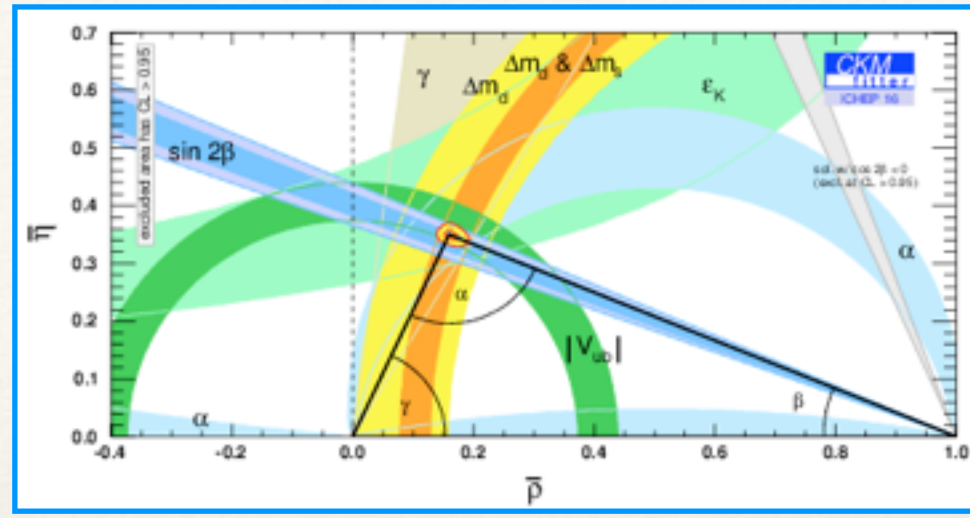
Search for quantum manifestation of new physics with the Belle II experiment

Outline:

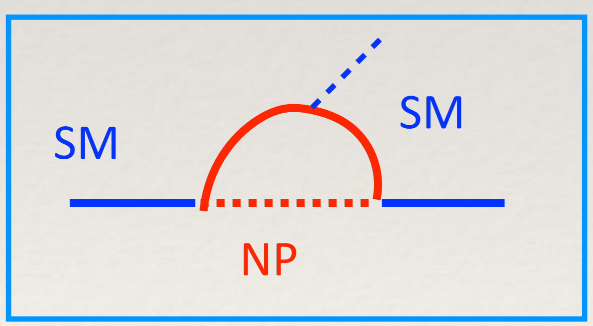
- The Belle II experiment at the Intensity Frontier
- Belle II schedule
- The Belle II group at IPHC
- M2 internship and PhD project

The Belle II experiment

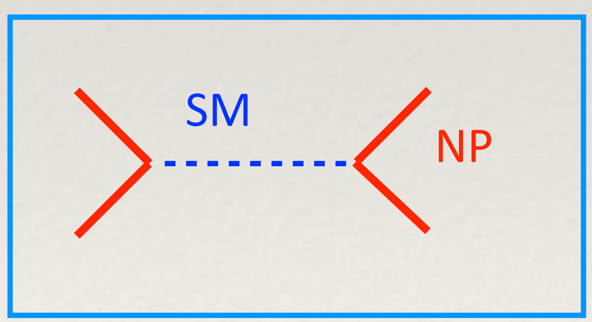
- Legacy of B-Factories:
  - BaBar at PEP-II (US) 1999-2008.
    and Belle at KEKB (Japan), 1998-2010.
  - Precise measurement of CP violation in quark sector.
  - Nobel Prize 2008 to Kobayashi and Maskawa.



- Belle II is a Super-B-Factory, building on the excellent accumulated skill :
  - Goal: discovery of physics beyond the SM.
  - Search for quantum manifestation of New Physics: sensitive to higher masses than direct searches at LHC.

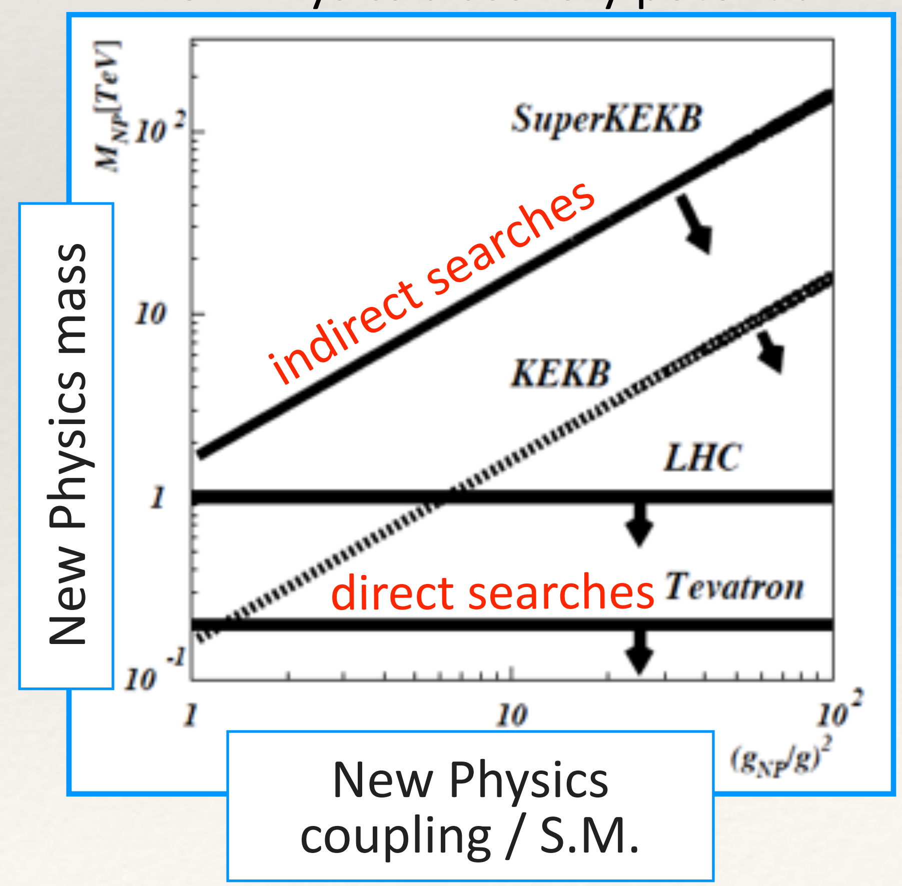


indirect search of NP



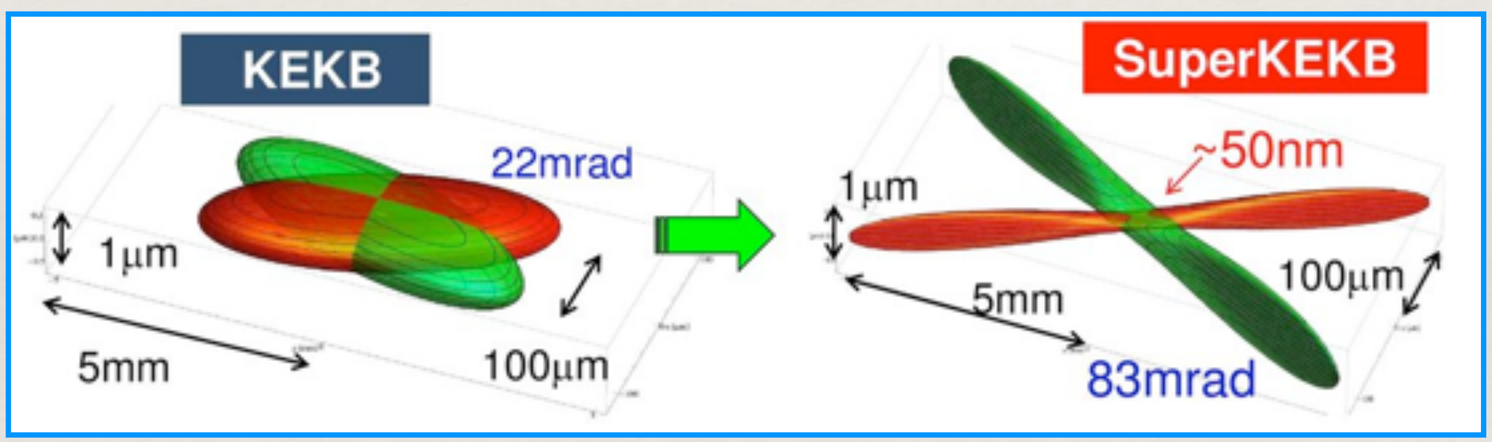
direct search of NP

New Physics discovery potential



The intensity frontier

- How to search for quantum manifestation of New Physics:
  - Compare very precise measurement to very precise theoretical prediction.
  - Experimental precision: statistical and systematical uncertainty:
    - e^+e^- collisions: known initial state governed by QED, clean final state ➛ good for syst.
    - Current data-sample ×50 ➛ good for stat.
      Needs a breakthrough in accelerator physics: SuperKEKB is the first collider of nano-beams (P. Raimundi, 2007).



Current luminosity world record (KEKB):
2.1×10^{34} cm^{-2} s^{-1}

Beam transverse size: ~ 1 μm

SuperKEKB targeted luminosity is
40 × the world record:
0.8×10^{36} cm^{-2} s^{-1}

Beam transverse size: ~ 50 nm

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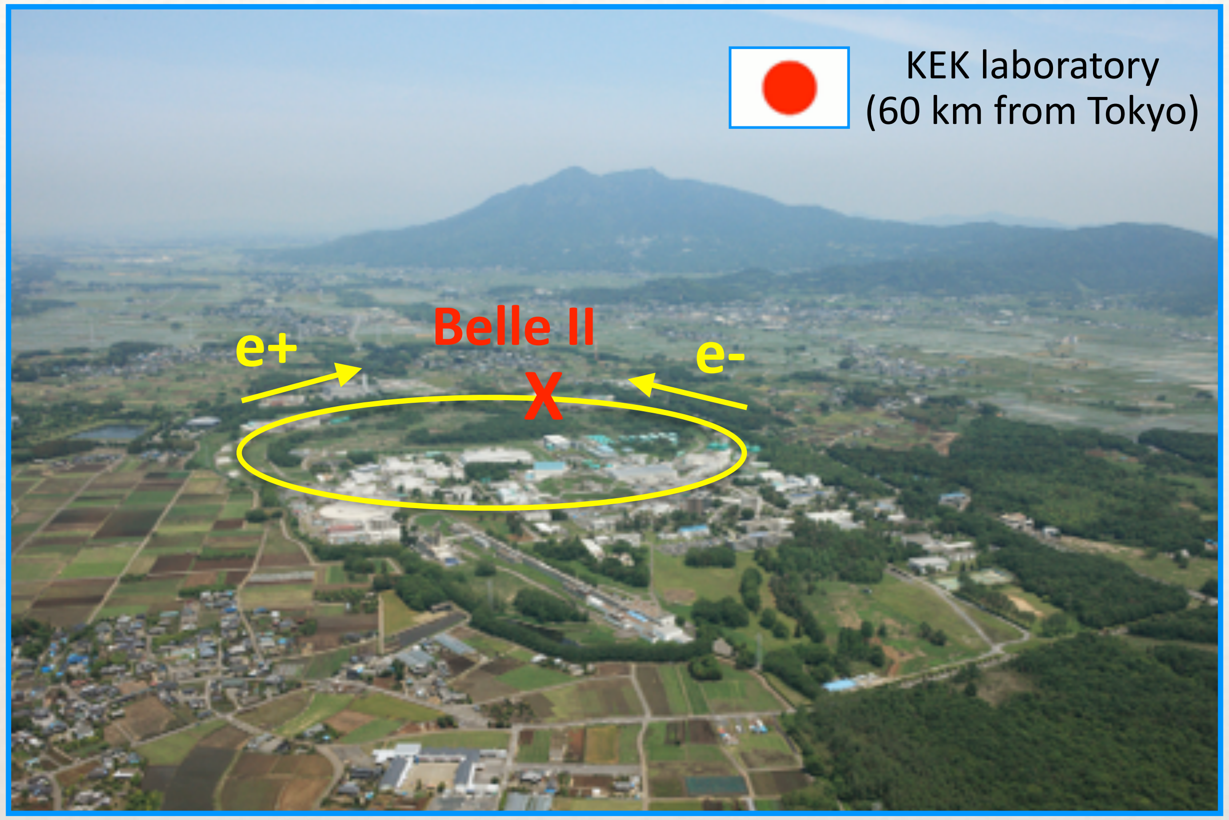
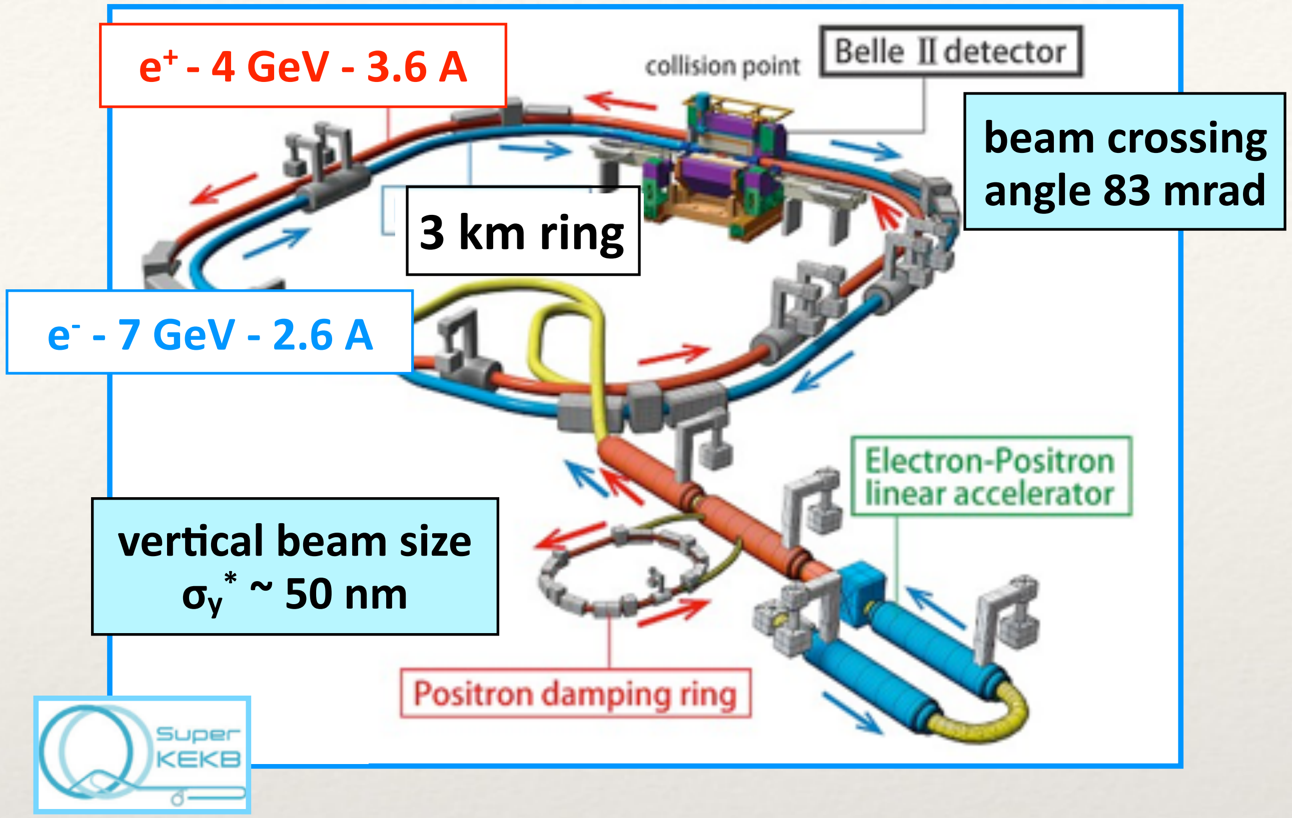
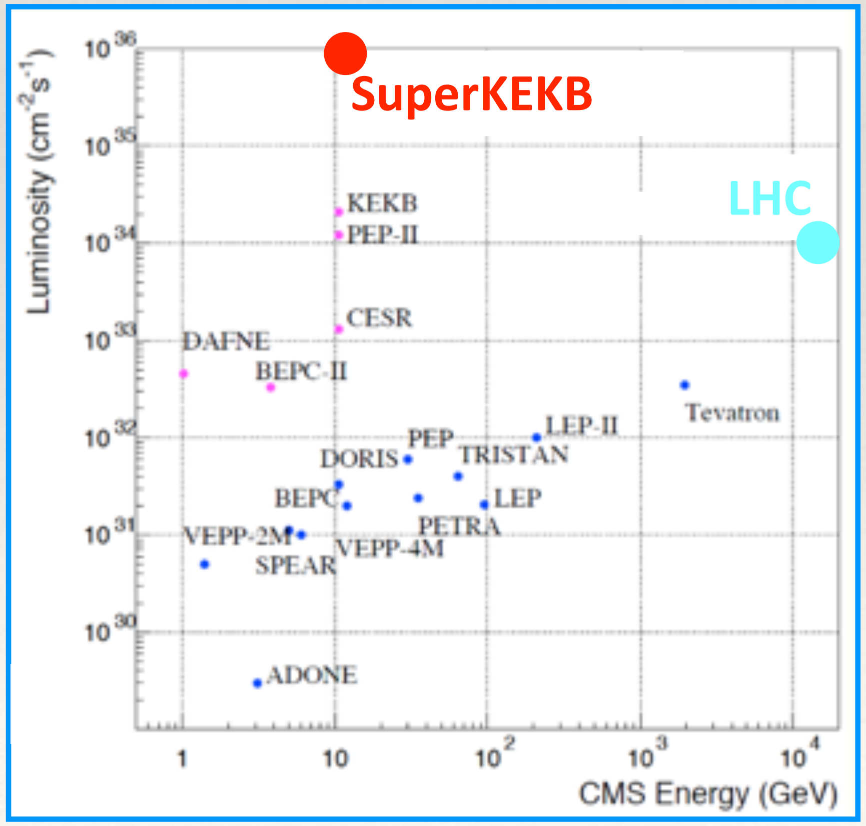
The SuperKEKB collider





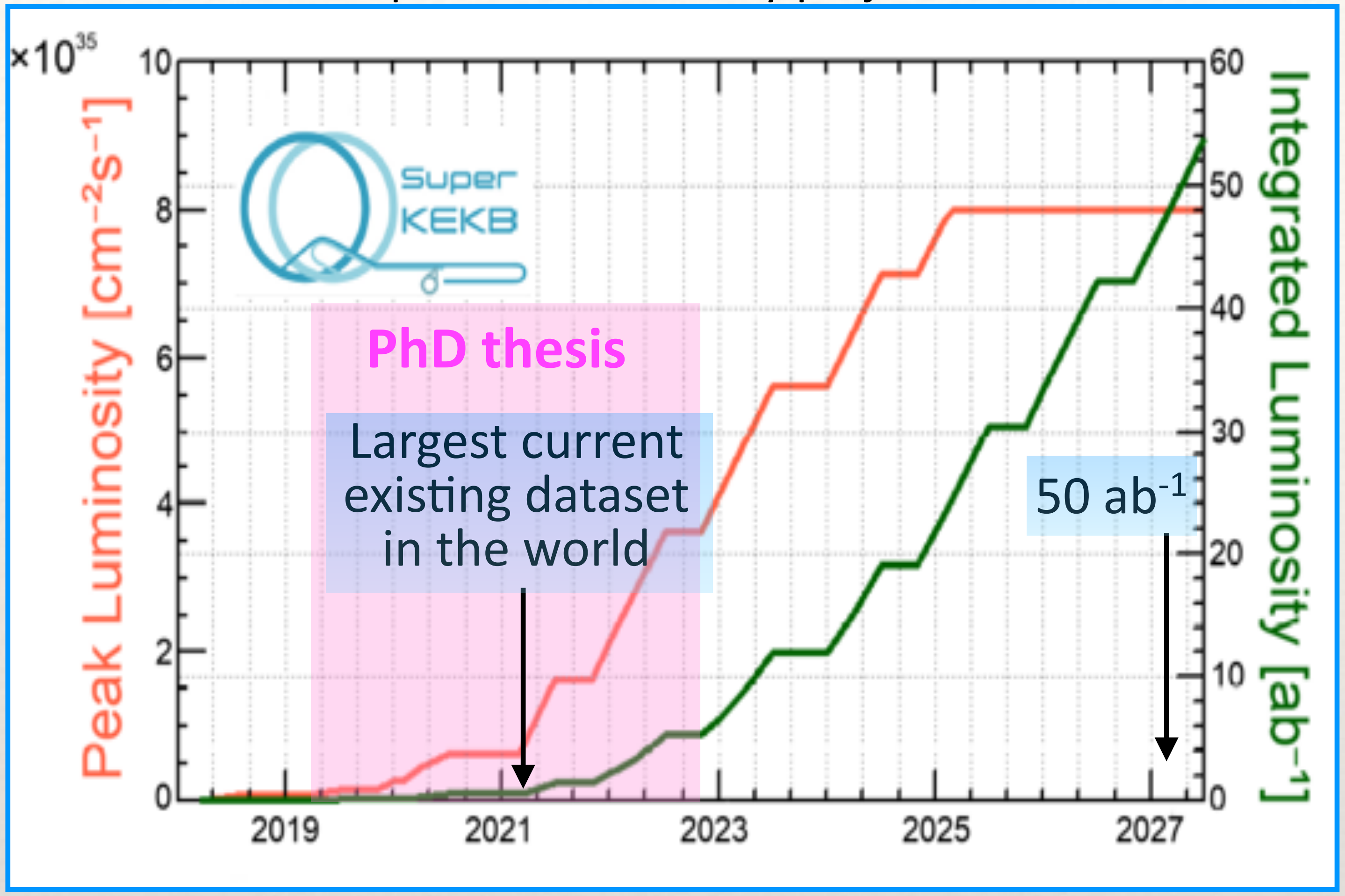


SuperKEKB will produce:

- 55×10^9 of $b\bar{b}$
- 65×10^9 of $c\bar{c}$
- 45×10^9 of $\tau^+ \tau^-$

Belle II schedule

SuperKEKB luminosity projections

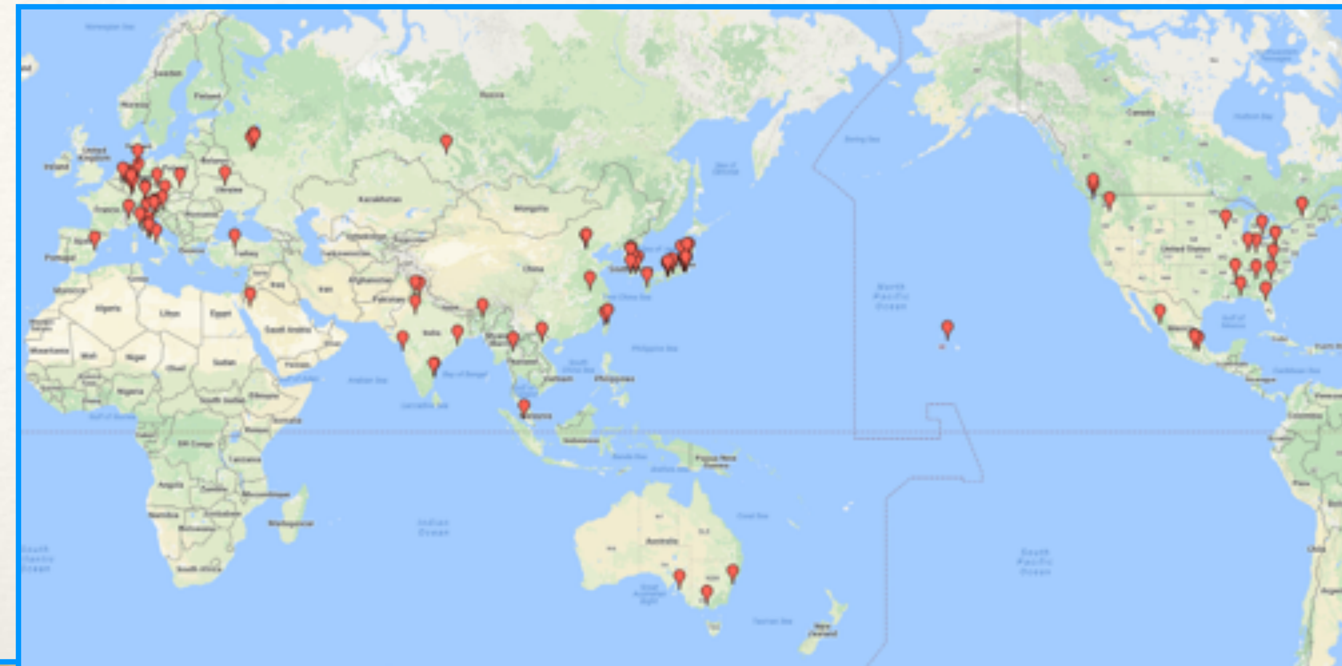


- Experiment commissioning in Spring 2018.
- Belle II Physics run started in Spring 2019.
- Current particle collisions dataset existing in the world will be overpassed within 1 year.

➛ PhD thesis in Belle II: **publications**
with > 5× currently available dataset in the world

National and international context

- International Belle II collaboration:
  ~ 800 participants from 26 countries.
- France joined officially in 2016.



Ceremony of French Flag Raising with French Embassy

- Belle II-IPHC main collaborators
  - Germany: KIT (Karlsruhe), DESY (Hamburg), Bonn and München.
  - Italy: Pisa, Perugia, Trieste.
  - Japan: KEK, Nagoya.
  - South Korea: Daegu
  - Slovenia: Ljubljana

The Belle II group @IPHC in 2020

Jérôme Baudot
professor
@ Unistra

Giulio Dujany
junior researcher
@ CNRS

Isabelle Ripp-Baudot
research director
@ CNRS

Tristan Fillinger
CNRS PhD student
→ 09/2022

Reem Rascheed
Unistra PhD student
→ 09/2020

YOU
M2 / PhD student
→ 09/2023

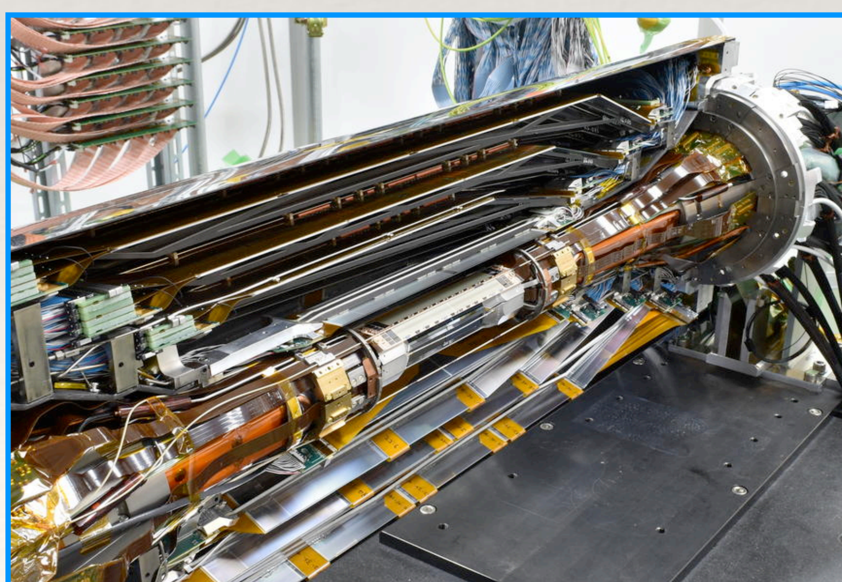
M2 physics project Jan. 2020
M2 internship March-July 2020
PhD student Oct. 2020-2023

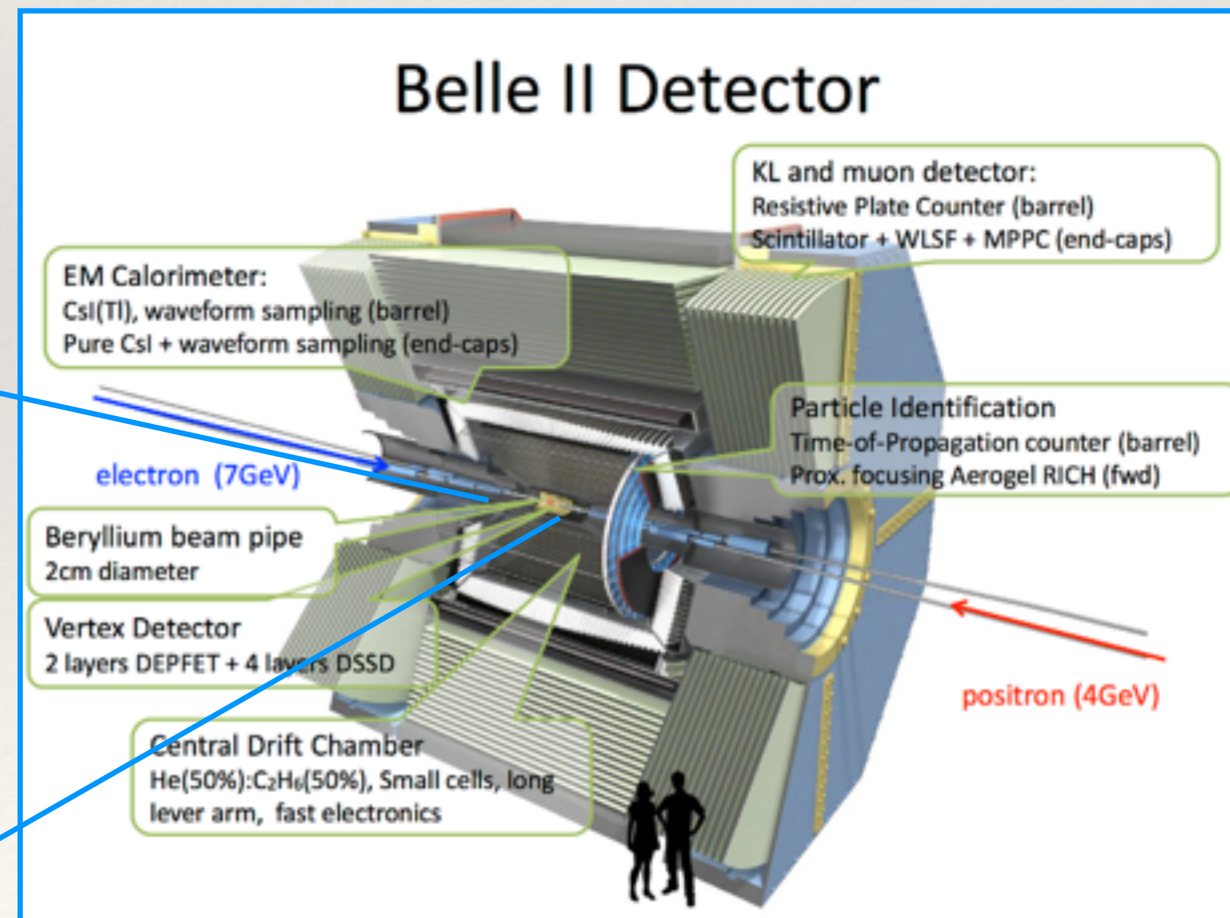
+ several engineers : slow control of the Vertex detector, upgrade of the vertex det., computing.

+ potential M1 students

IPHC-Belle II group activities

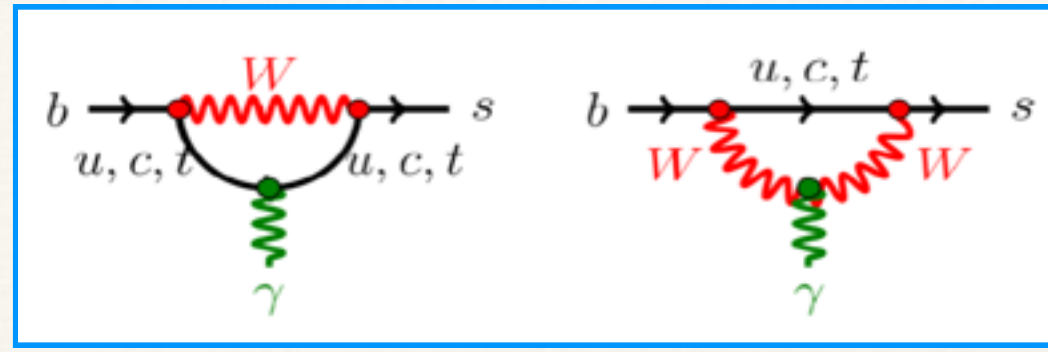
- Search for new physics beyond the Standard Model:
  - Measurement of the CP asymmetry as a function of time of b → s γ processes.
  - Search for b → s ν ν̄ processes.
  - Participation to the Physics Statistic Advisory committee.
- Operate the Belle II detector:
  - Development of the vertex detector slow-control.
  - Development of the calibration database.
  - Shifts (on-site and remote: Belle II, vertex detector, computing, machine-detector interface).
- Design the next generation vertex detector:
  - Define the detector specifications.
  - Simulation and tracking with the new detect.
  - R&D of a sensor prototype.





$b \to s\,\gamma$ process: photon helicity (1)

- V-A coupling in the SM: B mesons produce mainly right-handed photons in $\bar{b} \to \bar{s}\,\gamma$ transitions.



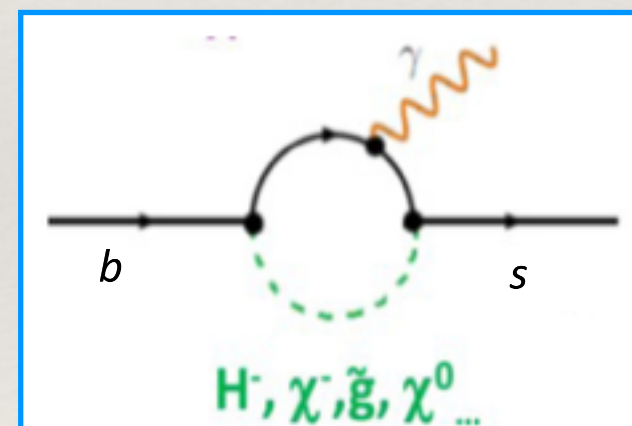
- Time-dependent CP asymmetry:

$$\mathcal{A}_{CP}(t) = \frac{\Gamma(B^0(t) \to f_{CP}) \;-\; \bar{\Gamma}(\bar{B}^0(t) \to f_{CP})}{\text{''} \;+\; \text{''}}$$

- In SM with a pure left-handed (V-A) coupling to fermions, we have:

$$\mathcal{A}_{CP}(t) \sim \frac{2m_s}{m_b} \sin 2\beta\ \sin \Delta m t = S_{CP} \sin \Delta m t + A_{CP} \cos \Delta m t \ \simeq 0$$

- However, if New Physics with right-handed coupling exists: the photon is not fully polarised and $A_{CP} \neq 0$.



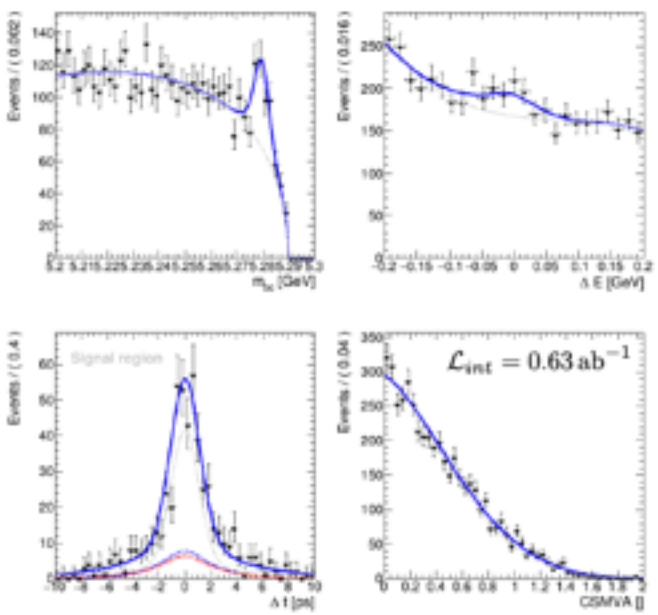
- Experimentally: measurement of A_{CP} with $B^0 \to K_S^0 \pi^+ \pi^- \gamma$ et $B^0 \to K_S^0 \pi^0 \pi\, \gamma$ decays.

➛ Thesis work of Reem Rasheed (2017-2020) and Tristan Fillinger (2019-2022).

$b \to s\,\gamma$ process: photon helicity (2)

Full simulation extended likelihood fit

- Multidimensional fit of the full simulation:



- Main observables:
  - M_{bc} – beam-constrained mass
  - ΔE – energy difference
  - Δt – temporal distance
  - Continuum Suppression MVA against the $e^+e^- \to q\bar{q}$ processes
- Extended likelihood fitting is applied to 4-dimensional dataset

First results on the full MC:

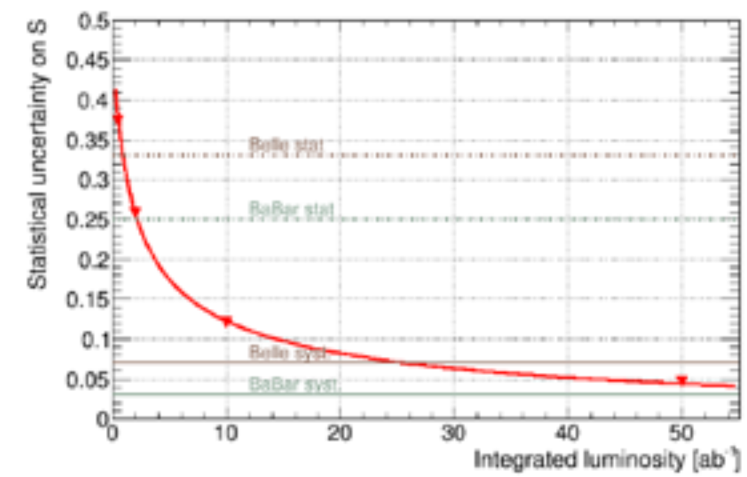
$$A = -0.2 \pm 0.26$$
$$S = \;\; 0.01 \pm 0.37$$

Full analysis on simulation matches precision obtained at Belle and there is a room for improvement

Bilokin S. ALPS 2018 6

Sensitivity study

- The Toy MC studies will provide statistical and systematics prospects
- Results of 1000 Toy MC experiments:

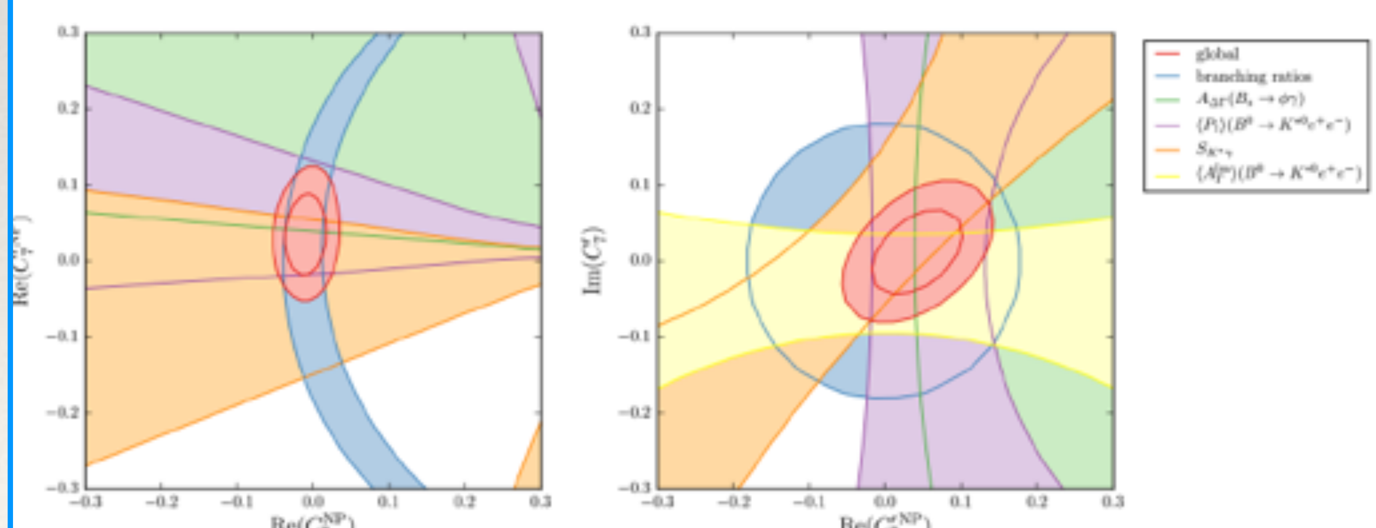


- **The expected statistical uncertainty at full Belle II luminosity will be comparable to the BaBar systematics**

Bilokin S. ALPS 2018 7

➢ This measurement constrains Wilson coefficients C_i of the effective Hamiltonien of New Physics :

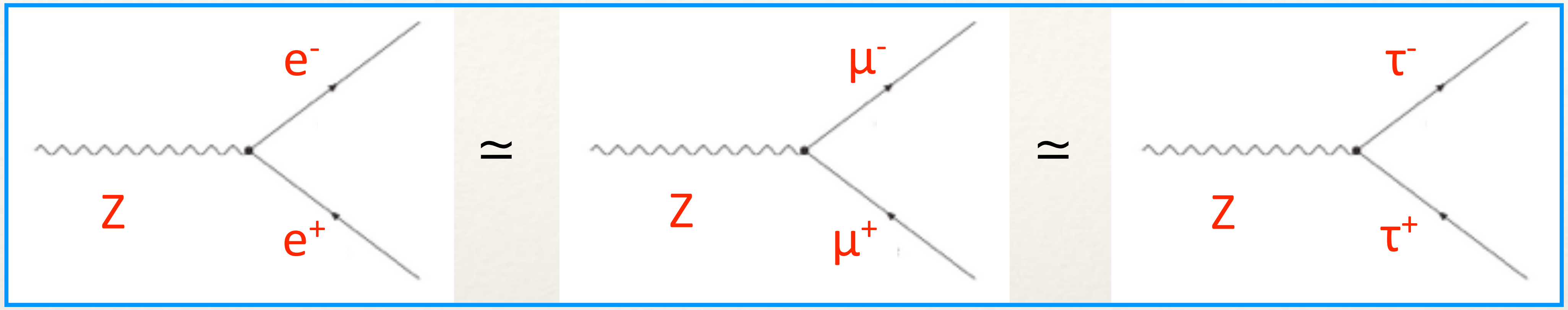
$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i \left(C_i\mathcal{O}_i + C_i'\mathcal{O}_i'\right)$$



Paul, Straub: arXiv:1608.02556

Lepton universality in the S.M.

- S.M. electroweak coupling with leptons is universal:
  (i.e. the same, but small corrections due to different lepton masses)



Z coupling with fermions: $-i \dfrac{g}{\cos\theta_W} \gamma^\mu \dfrac{g_v - g_a\gamma^5}{2}$

With: $g_v = T_3 - 2\,Q\,\sin^2\theta_W$

And: $g_a = T_3$

For electron, muon, tau : Q = -1 , T_3 = -1/2 , g_v = -0.04

- Experimental measurements agree with this prediction:

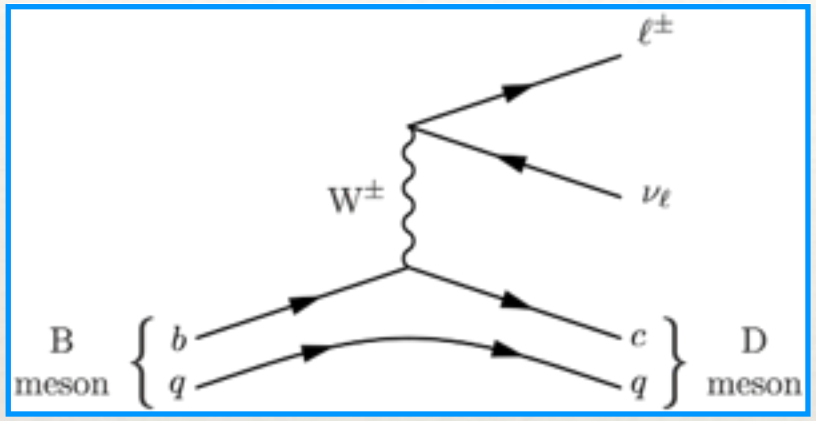
$$\frac{\Gamma_{Z\to\mu\mu}}{\Gamma_{Z\to ee}} = 1.0009 \pm 0.0028 \qquad \frac{\Gamma_{Z\to\tau\tau}}{\Gamma_{Z\to ee}} = 1.0019 \pm 0.0032 \qquad \frac{\mathcal{B}(W\to e\nu_e)}{\mathcal{B}(W\to \mu\nu_\mu)} = 1.004 \pm 0.008$$

However, this equality is accidental, there is no theoretical ground

Measured lepton universality anomalies (1)

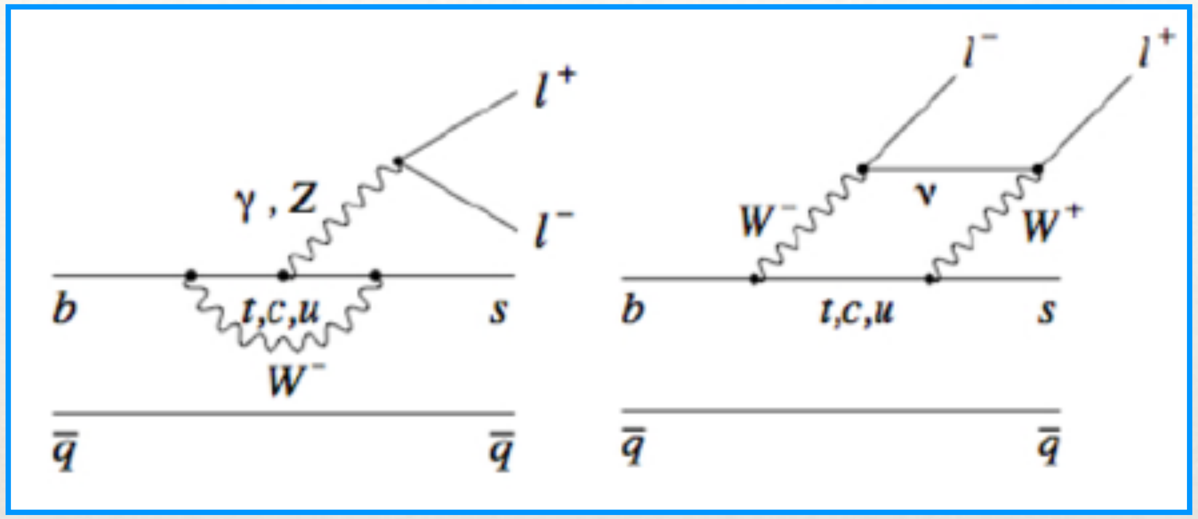
- Actually, several discrepancies are observed in the flavour sector:

  - b → c ℓ ν



B^0 or $B^+ \to D^{(*)} \ell^+ \nu$

  - b → s ℓ ℓ



B^0 or $B^+ \to K^{(*)} \ell^+ \ell^-$

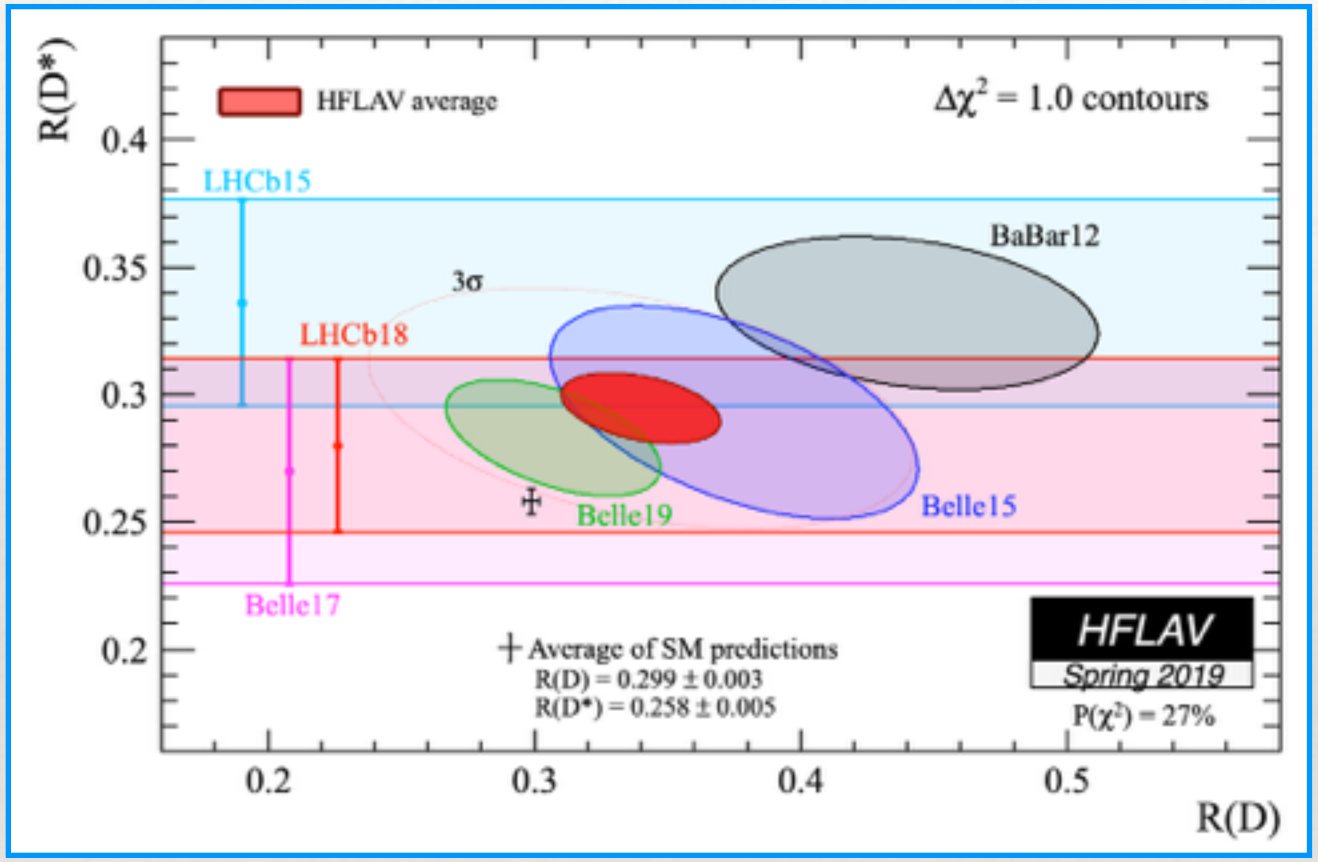
- Measured observable: a ratio of Branching Ratios (many uncertainties cancel in the ratio)

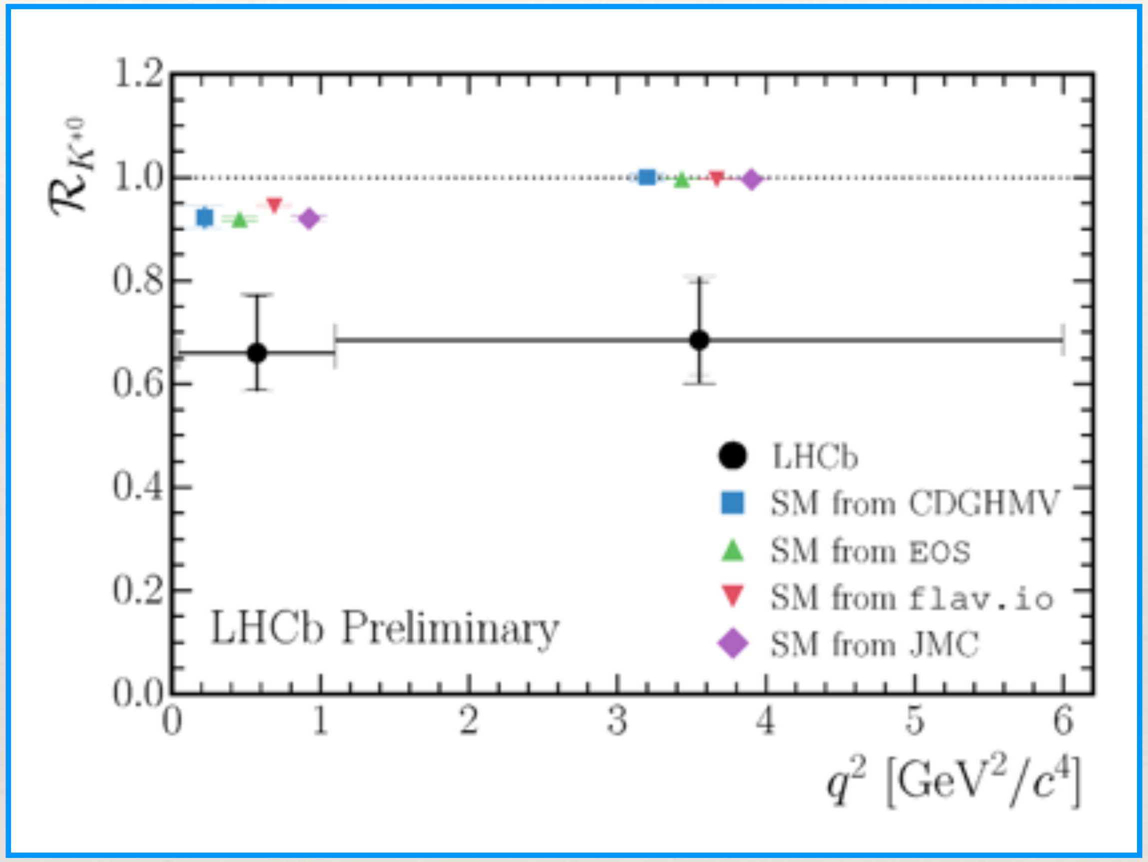
$$R(D^*)^{SM} = \frac{BR(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{BR(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)} = 0.252 \pm 0.003$$

$$R_{K^{*0}}^{SM} = \frac{BR(B^0 \to K^{*0}\mu^+\mu^-)}{BR(B^+ \to K^{*0}e^+e^-)} = 1 \pm \mathcal{O}(10^{-3})$$

Measured lepton universality anomalies (2)

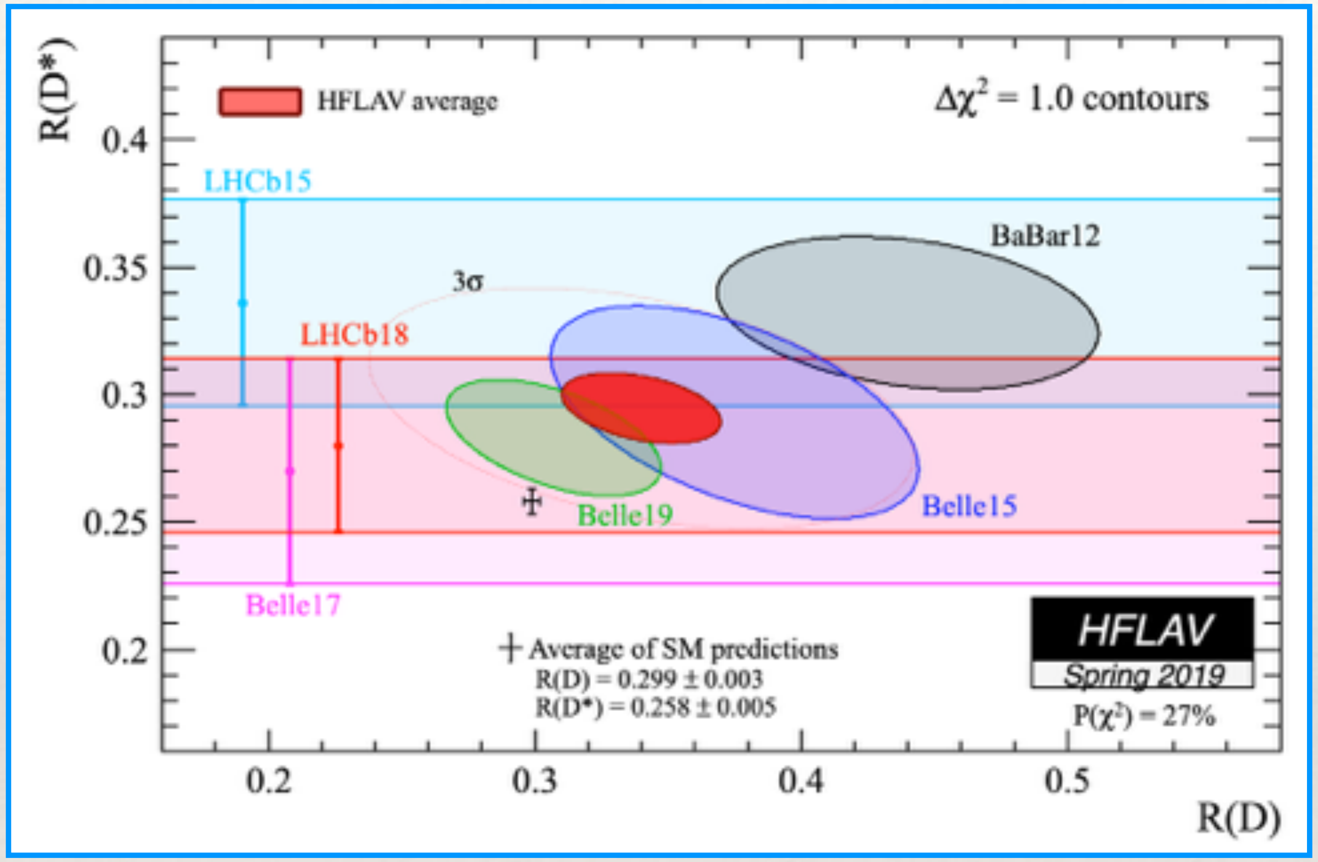
- 3 different experiments, BaBar and Belle (at e^+e^- colliders closed in 2010), and LHCb (at pp collider running at CERN) agree and measure 3 to 4σ-discrepancies with S.M. prediction.

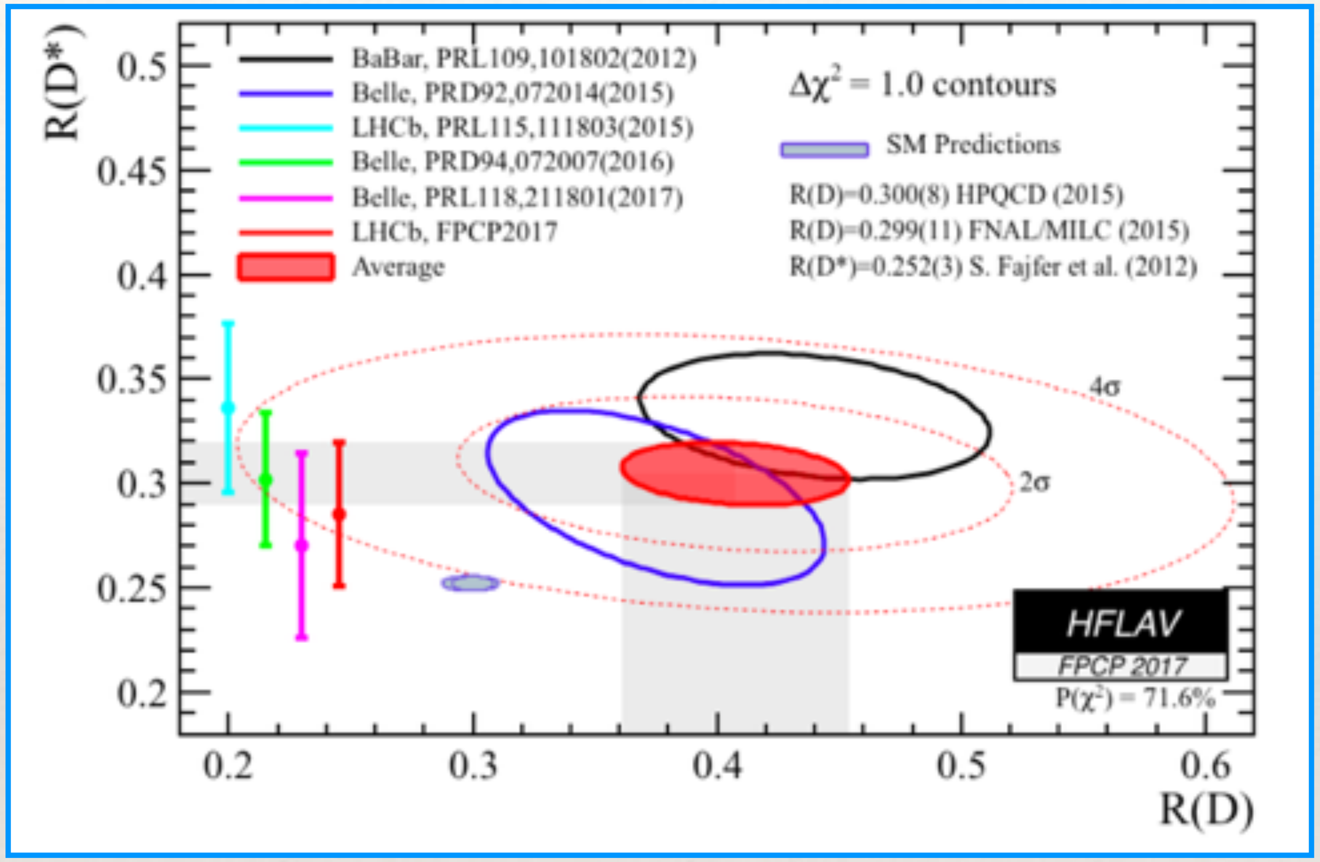




Measured lepton universality anomalies (3)

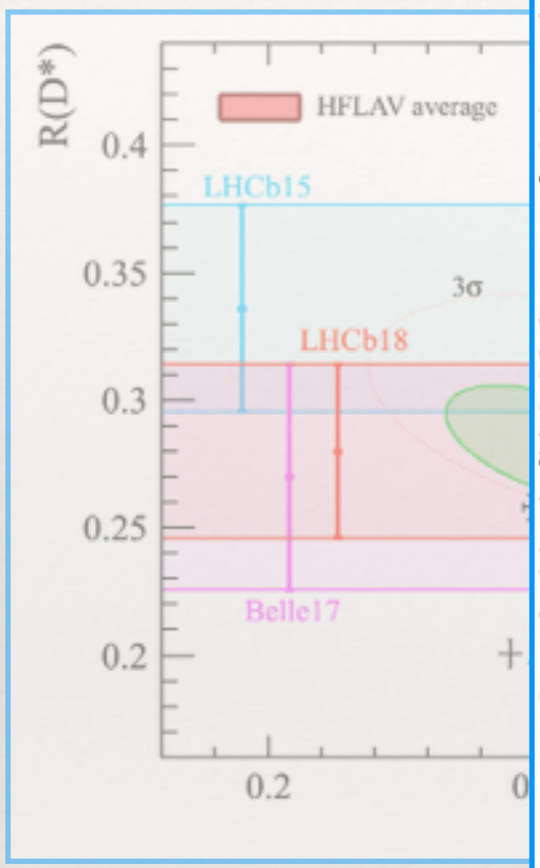
- 2017: almost 5σ-discrepancy with S.M. prediction!



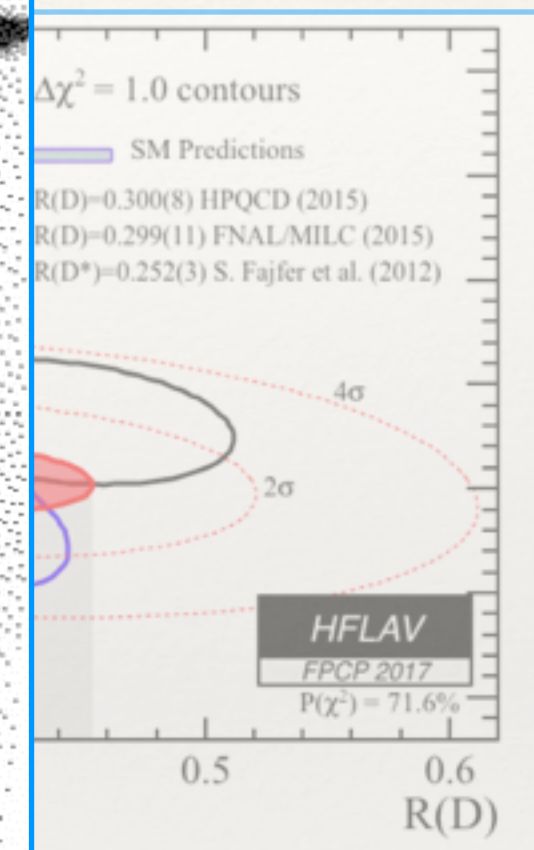


Measured lepton universality anomalies (3)

- 2017: almost 5

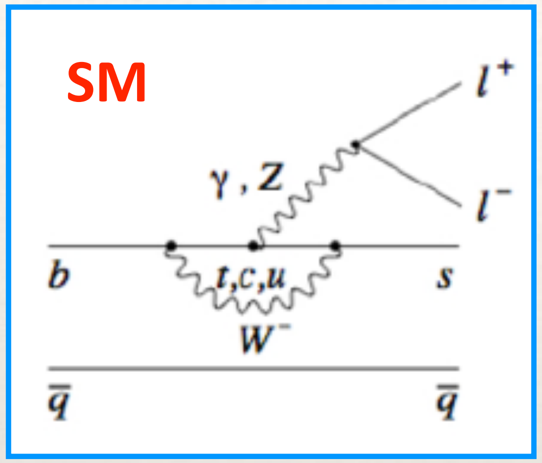


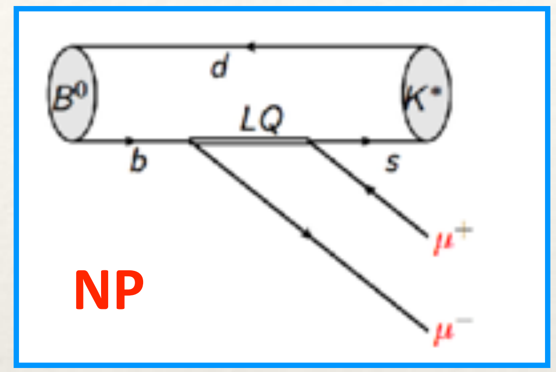
“This could be the discovery of the century. Depending, of course, on how far down it goes.”



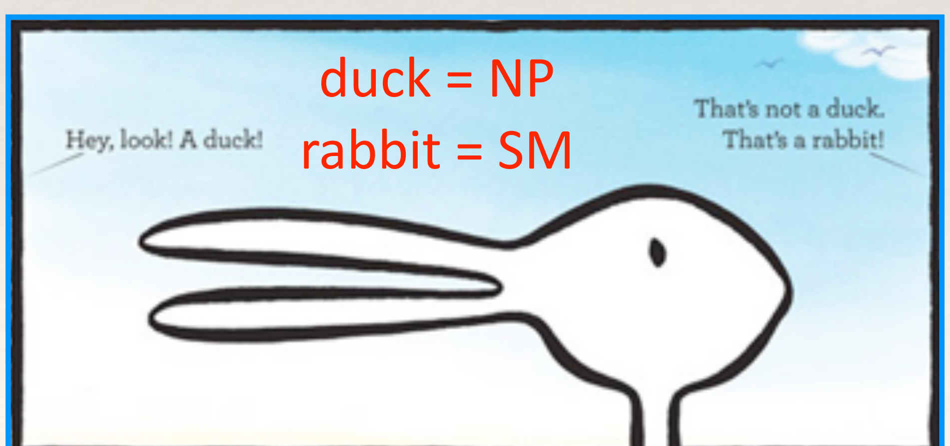
What could explain these anomalies?

- Introduction of new particles with couplings to leptons dependent on the lepton flavour: neutralinos, leptoquarks, additional Z’ vector bosons, additional H^+ Higgs bosons, …



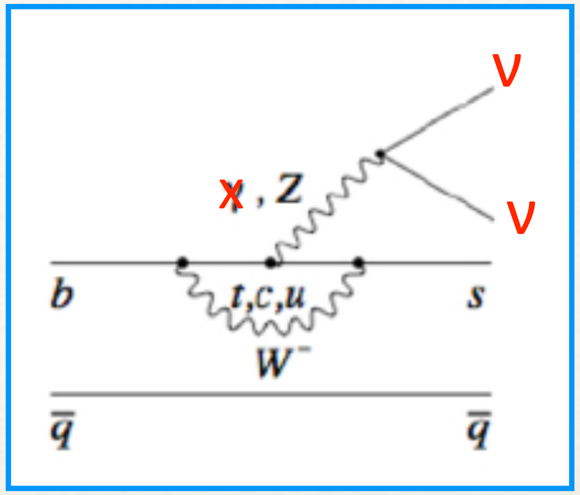


- However we must make sure that the discrepancy is actual:
  - Get rid of possible experimental errors or forgetting in the interpretation.
  - Investigate carefully the significance of the discrepancy.



PhD thesis project in Belle II at IPHC

- Thesis title: **Search for rare $B \rightarrow K^{(*)} \nu \bar{\nu}$ decays**



- Supervisor: Isabelle Ripp-Baudot (ripp@in2p3.fr)
  co-supervisor: Giulio Dujany.

- Motivation:
  - Yet un-observed ➛ discovery.
    Current experimental upper limits are put by BaBar and Belle: $\mathcal{B} <$ few$\times 10^{-5}$.
  - Sensitive to indirect New Physics contribution and to direct Dark Matter production.
  - Very precise SM prediction: $\mathcal{B}(B^+ \rightarrow K^{*+} \nu \nu) = 9.2\times 10^{-6}$
    Contribution to the understanding of Lepton Universality observed anomaly:
    important input to check theoretical prediction of $b \rightarrow s \ell \ell$ value.

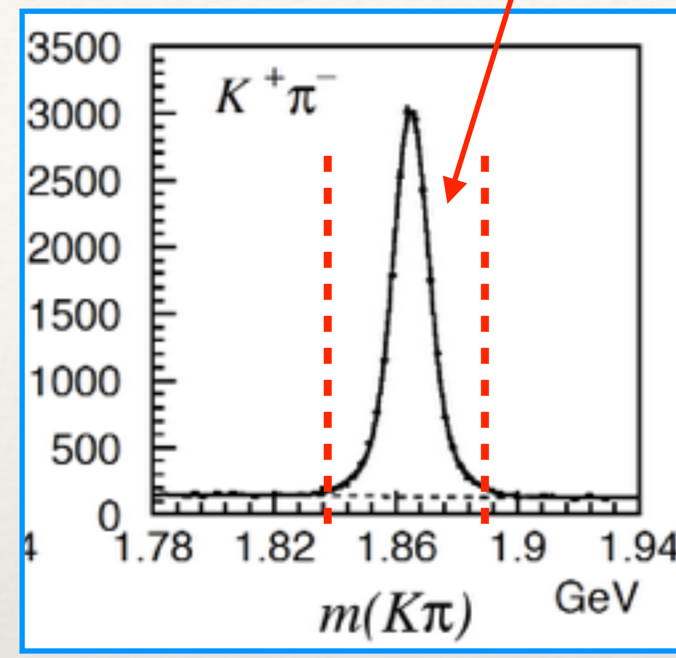
- Belle II assets:
  - Observation possible only in Belle II, particularly well adapted to final states involving ν.
  - Experiment at the most luminous collider.

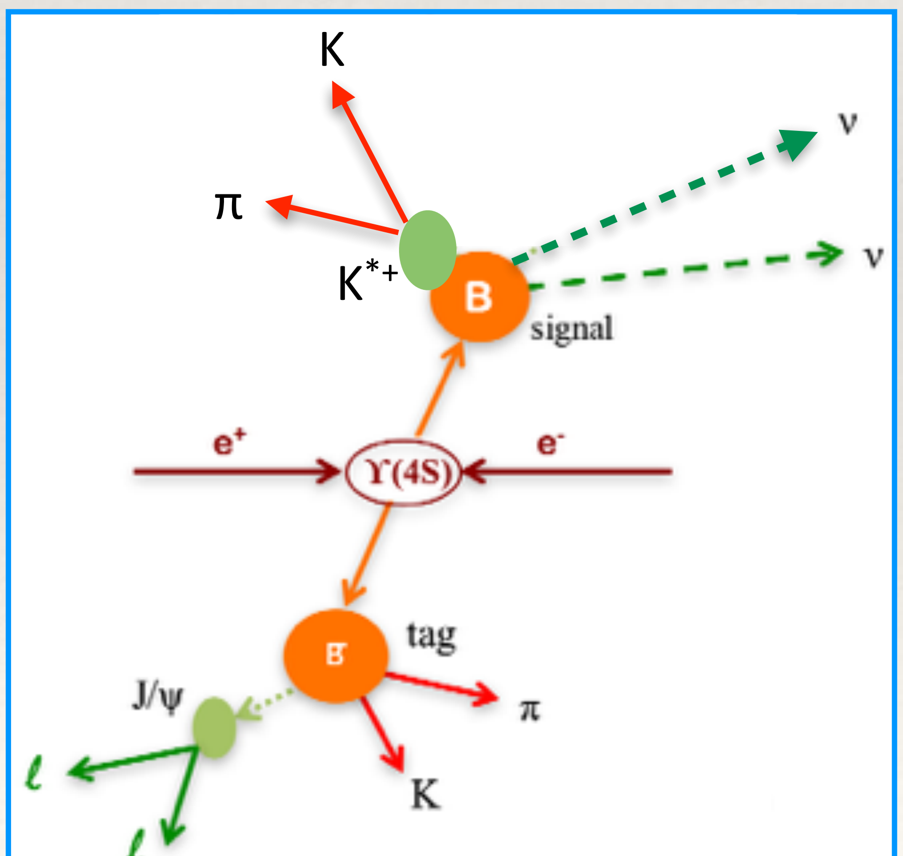
- Particularities:
  - Travels to Japan: 3 collaboration weeks/year + shifts + 1 possible mid-term stay.

Selection of $B^+ \to K^{*+} \nu \nu$ events (1)

- For simple cases a signal selection is done like that:
  - Particles identified (dE/dx, Čerenkov angle, Time of Flight): mass known.
  - Momentum measured from reconstructed bent particle track in silicon detectors with magnetic field.
  - Energy measured in the calorimeter.
    ➛ 4-momentum reconstructed and nice mass peak:
    invariant mass = $\sqrt{(\sum E^2 - \sum p^2)}$.

region with good Signal/Background ratio





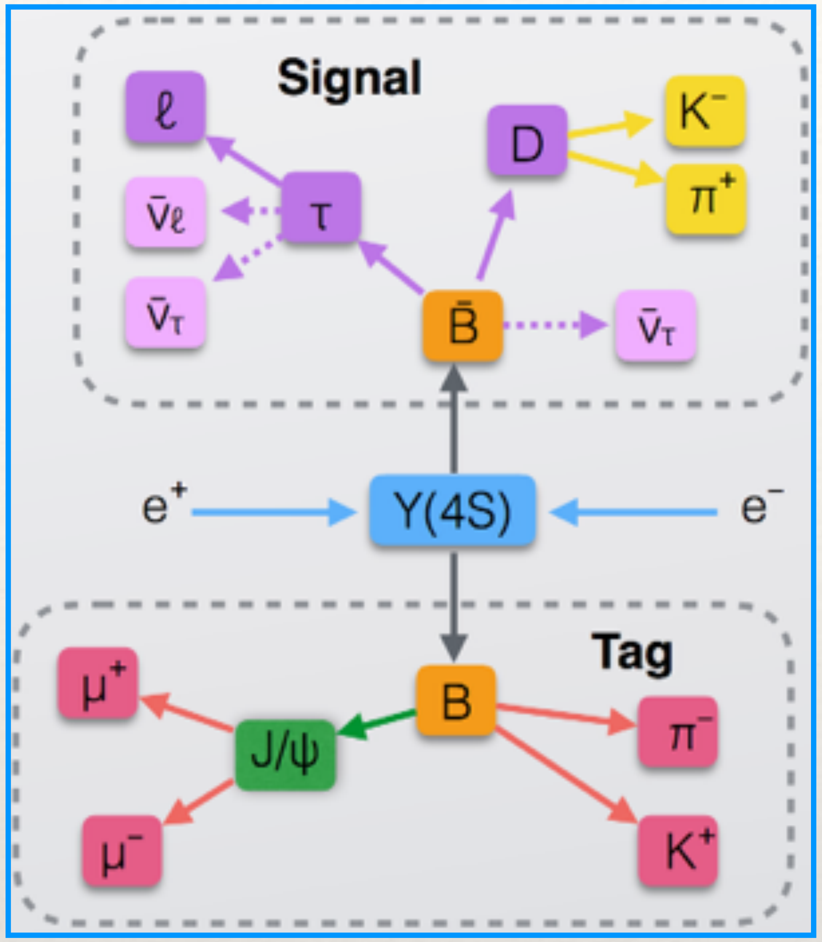
- But here: presence of several undetected neutrinos in final state, signal consists only of a $K^{*+} \to K^+ \pi^-$
  ➛ and there are many K^{*+}, very few originating in $B^+ \to K^{*+} \nu \nu$.
- The trick is: reconstruct the companion B, then search for an additional K^{*+} & missing energy.
- Many different final states can be considered to reconstruct B_{Tag} (see PDG), each one with total B.R. ~ or < $\mathcal{O}$(‰): the cornerstone of the analysis is to be able to reconstruct as many B_{Tag} as possible ➛ Full Event Interpretation.

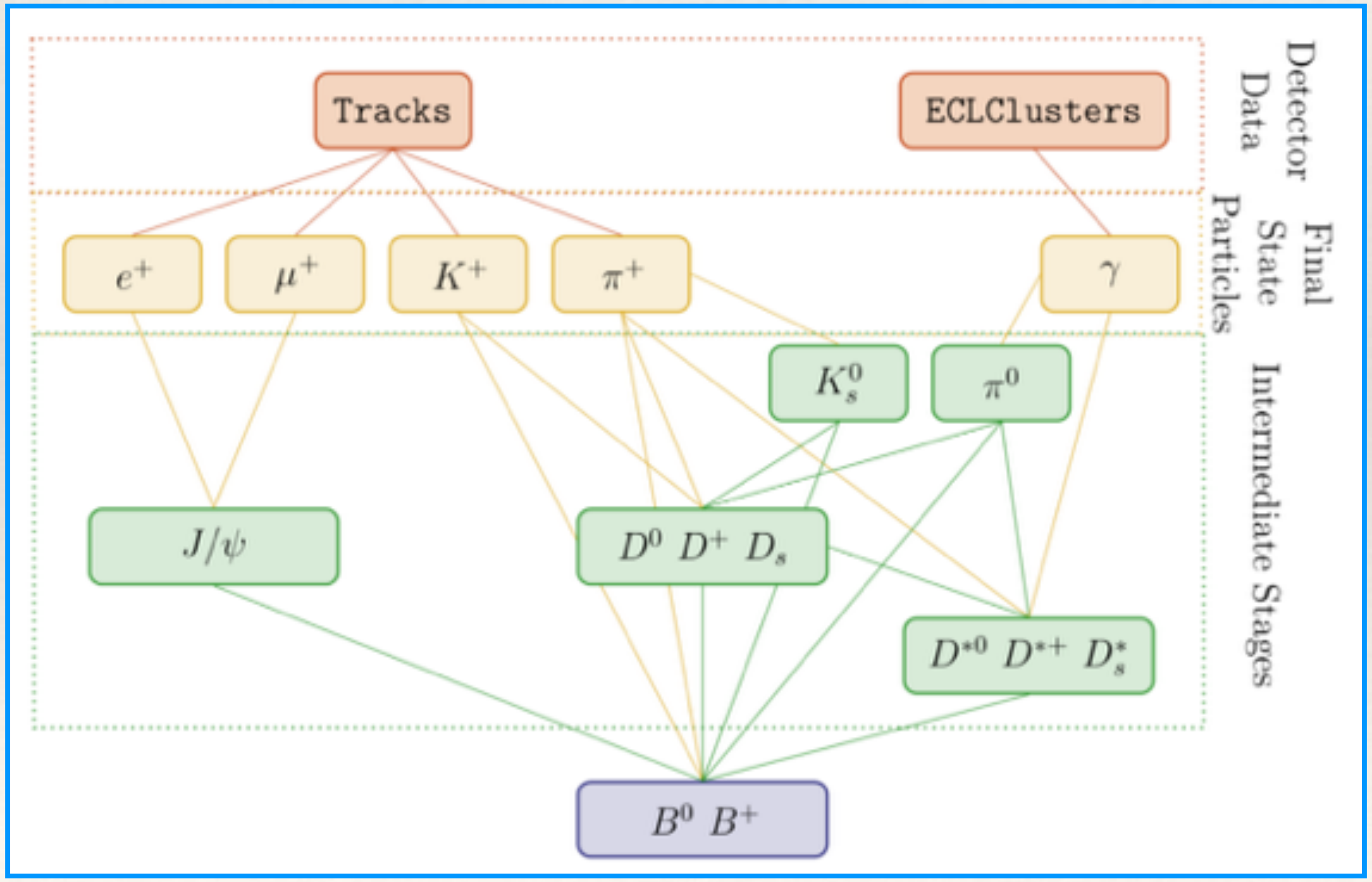
Full Event Interpretation

- Why a dedicated multivariate algorithm?
  Example: try to reconstruct $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$ in a collision with 10 tracks in final state: 5 with q>0 and 5 with q<0

  ➛ 100 possible combinations of the 10 tracks
  and 300 combinations to reconstruct $B^+_{Tag} \rightarrow D^0 (\rightarrow K^- \pi^+ \pi^+ \pi^-)\ \pi^+$.

  ➛ impossible to do for 10 000 different final states.





- Each step is reconstructed with a dedicated Boosted Decision Tree (BDT).
- Each B_{Tag} decay channel is reconstructed with a dedicated Boosted Decision Tree.

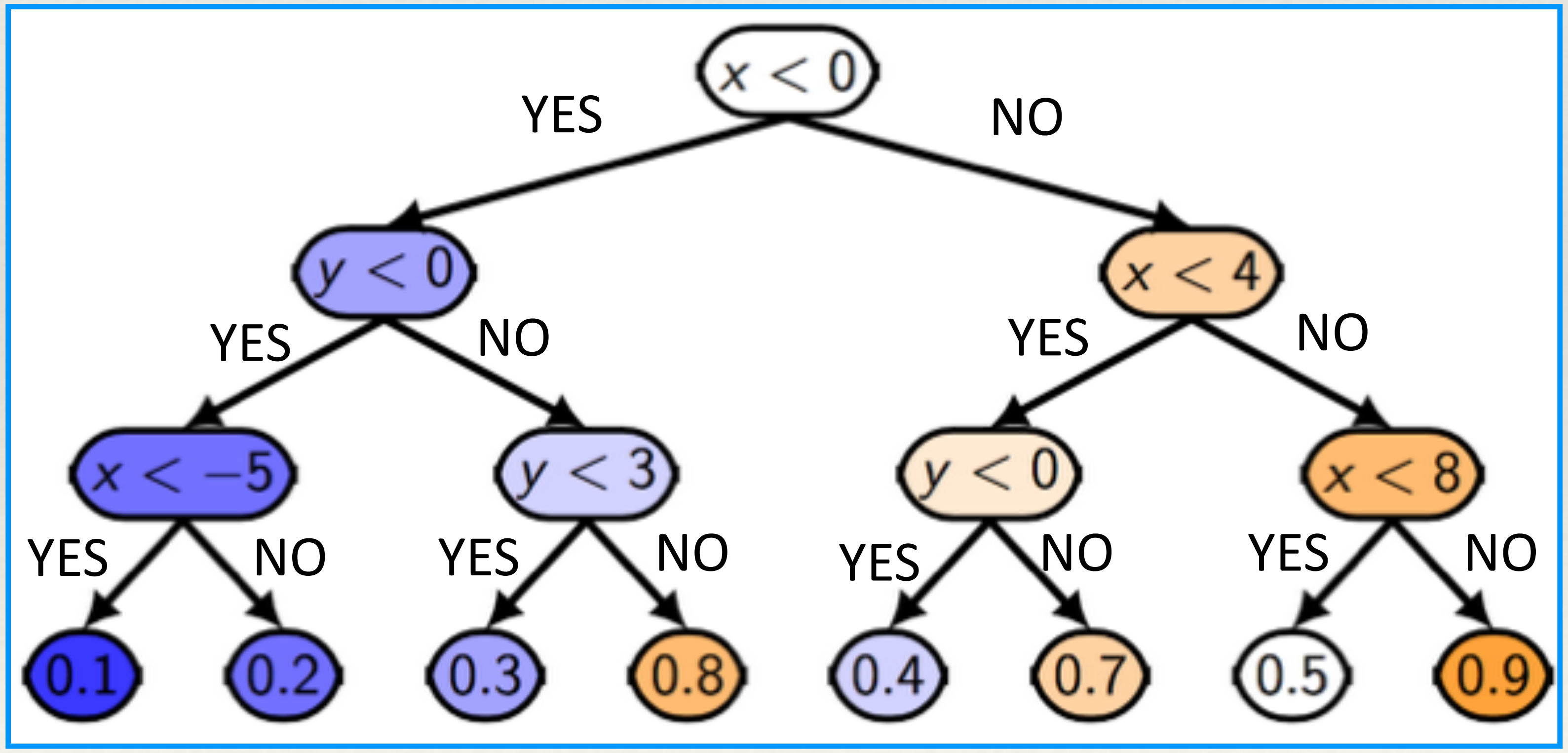
Decision Trees

- Simple selection: one combination of sequential cuts on variables.
  Example: select events if $p < 2$ GeV and particle is identified as a Kaon.
  A purity can be determined for these selection criteria, example: 33 % of the selected candidates will be Kaons originating from $D^0 \rightarrow K^- \pi^+$.

- Decision tree: all combinations of sequential cuts are used, each one has a given purity.

- Building of DT: machine learning process with Signal data and Background data.

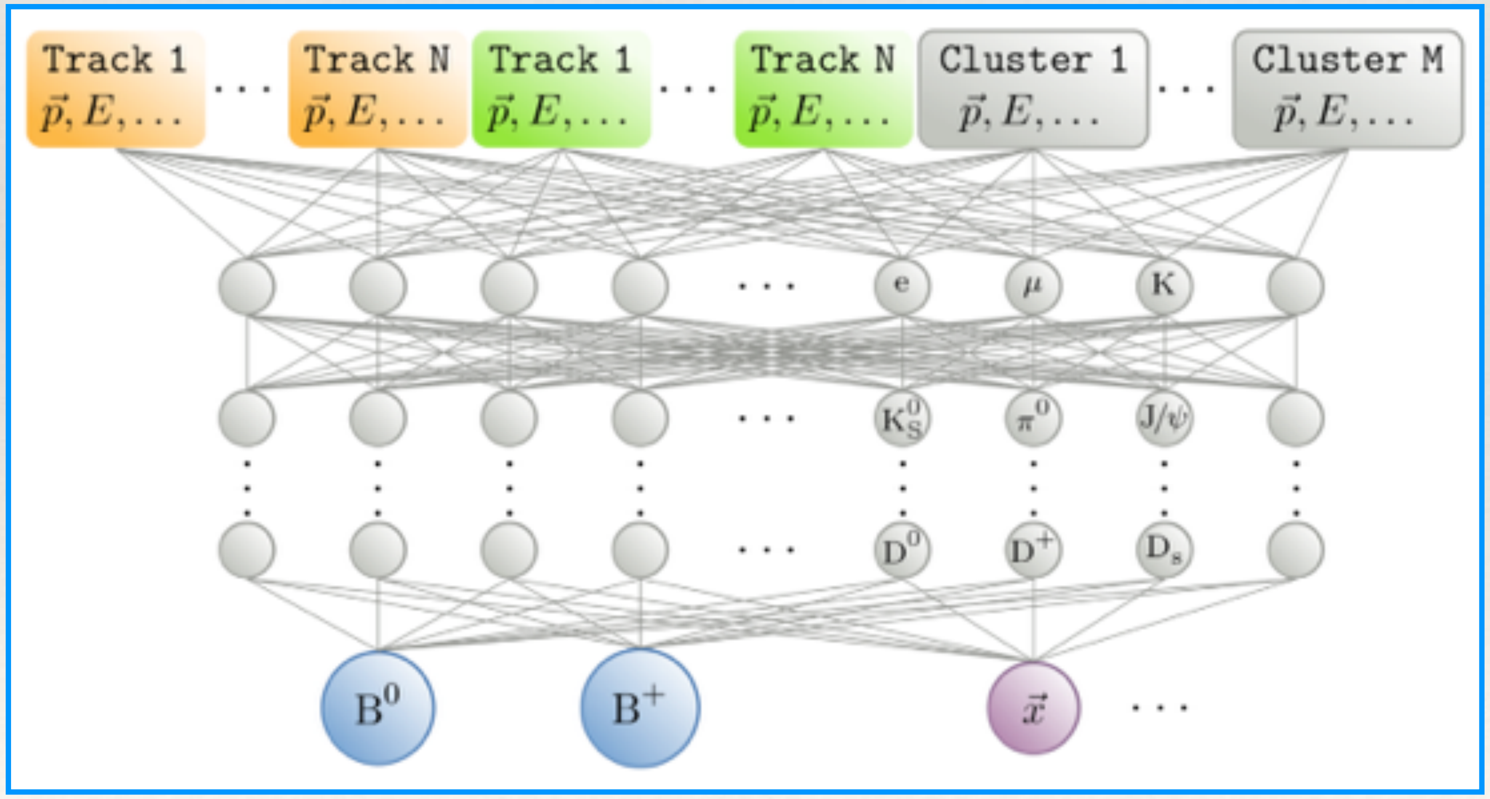
  ➛ needs a lot of CPU.

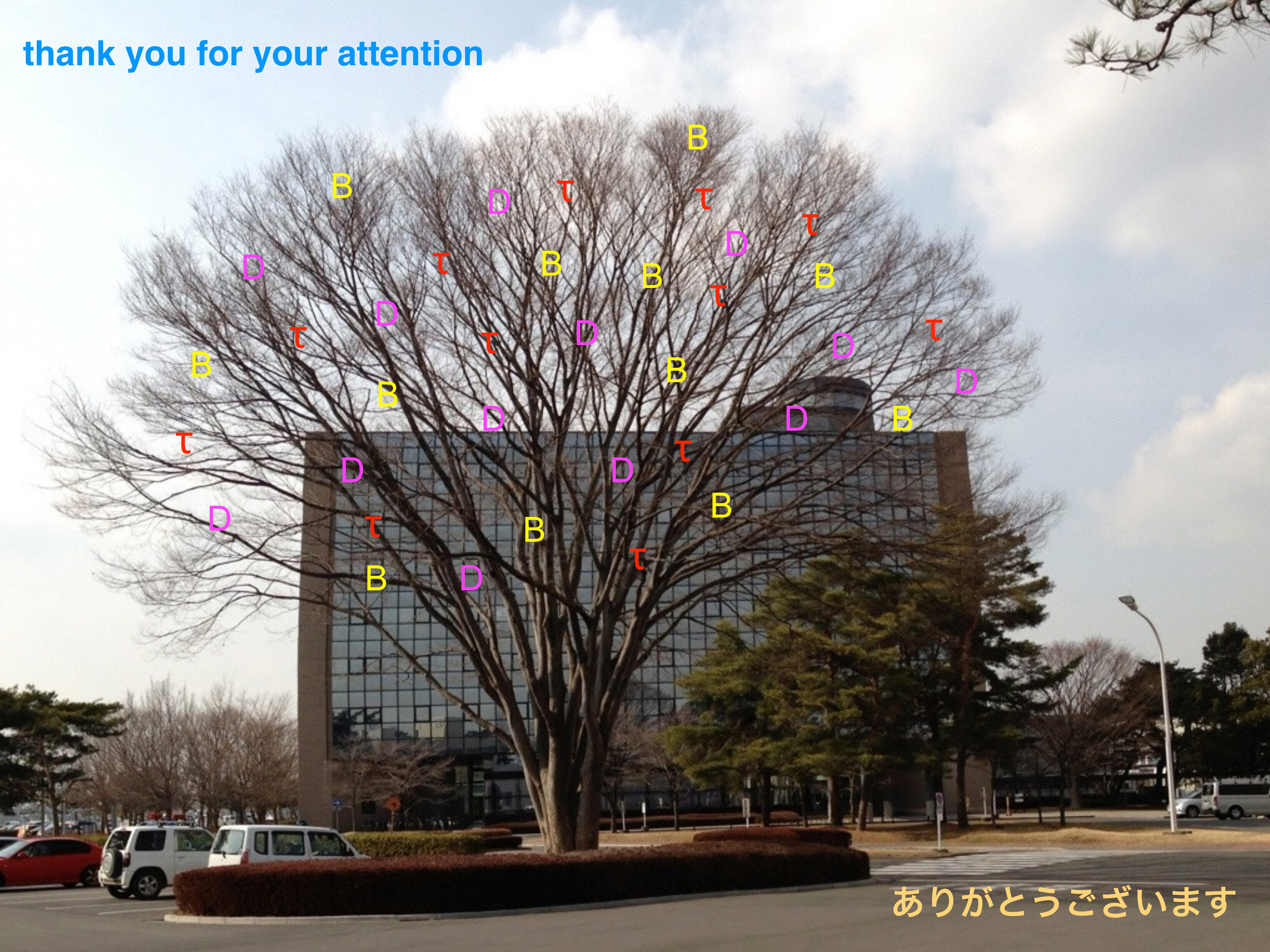


Boosted Decision Tree: many BDT are built,
and combined into a better one, reducing biases.

Deep learning

- The Full Event Interpretation is a key algorithm to discover new physics beyond the S.M. with the Belle II experiment, and in particular $B \rightarrow K^{(*)} \nu \nu$ decays.
- At IPHC, the Belle II group will work on its improvement, in particular in the framework of the proposed PhD thesis:
  - Careful study to understand where inefficiencies come from.
  - Build a new FEI based on Deep Learning techniques.



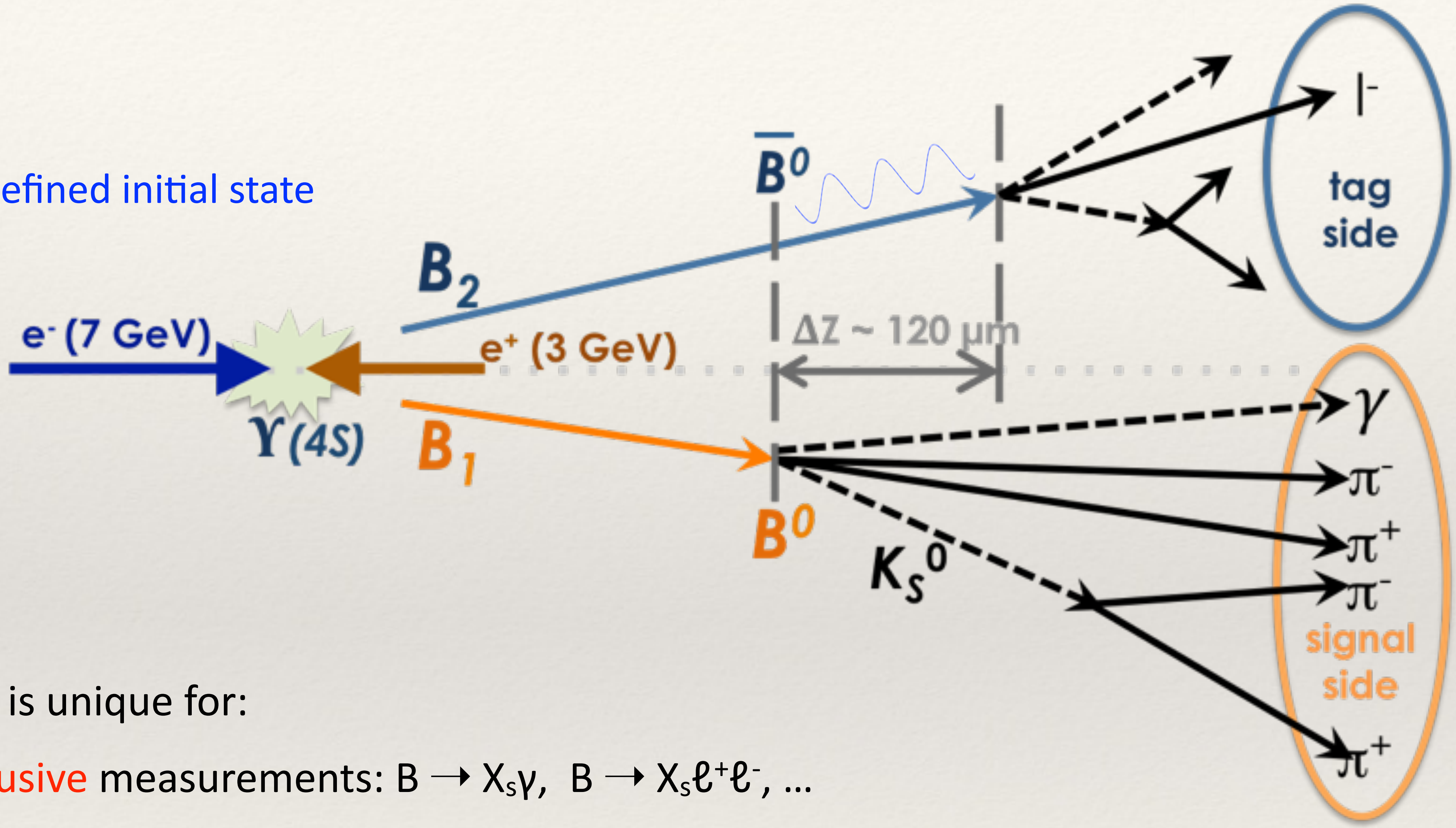

thank you for your attention
ありがとうございます

Collider runs

Belle II event

clean final state: only 2 B mesons, quantum correlated

well defined initial state



- Belle II is unique for:
  - inclusive measurements: $B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$, …
  - events with missing energy: $B^+ \to \tau^+\nu$, $B \to D^{(*)}\tau\nu$, $B \to K^{(*)}\nu\nu$…
  - events with neutrals: $B^0 \to \gamma\gamma$, $B^0 \to K_S^0\pi^0\gamma$, $B^0 \to K_S^0K_S^0K_S^0$, …
    - ➛ interesting complementary with LHCb.