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Master in Physics

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B τ D

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

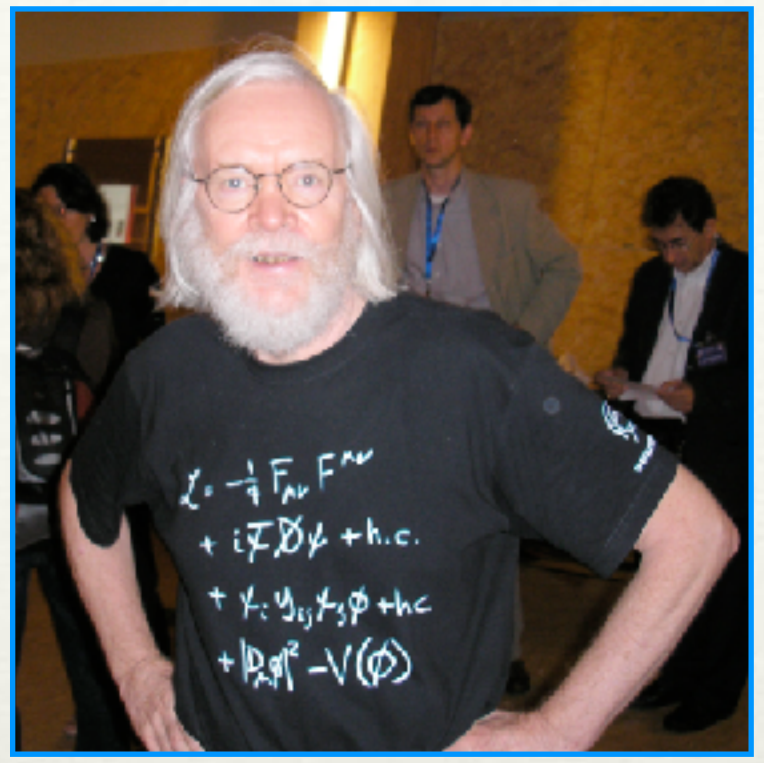
Outline:

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

09/10/2020

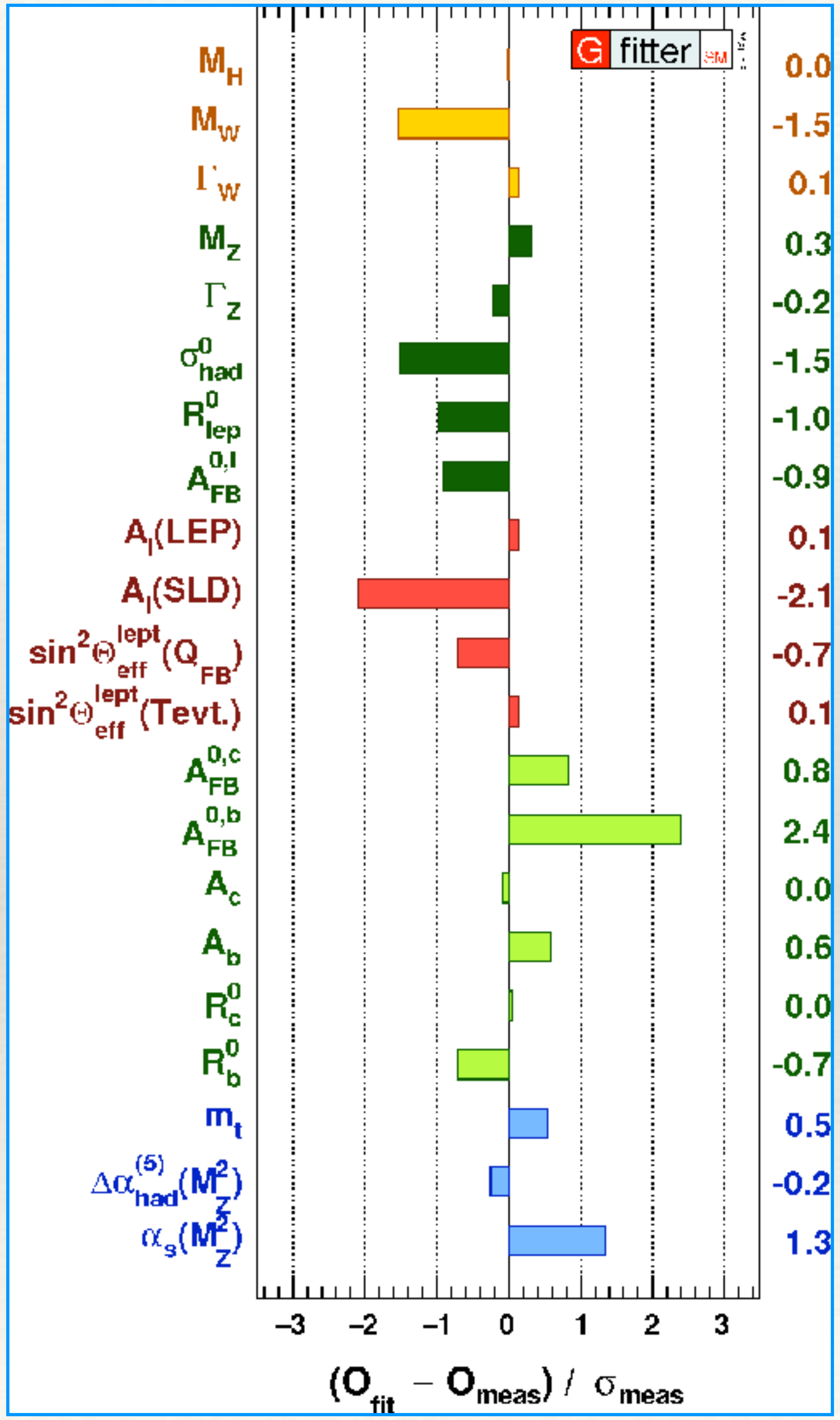
To Standard Model…

- The SM of particle physics was developed step by step:
  - Based on fundamental symmetries:
    CPT, E-p and spin conservation, gauge symmetries…
  - With *ad hoc* additives according to observation:
    chirality, Higgs boson, CKM matrix, …
  - In the end: 18 parameters remain free (25 with neutrino masses).



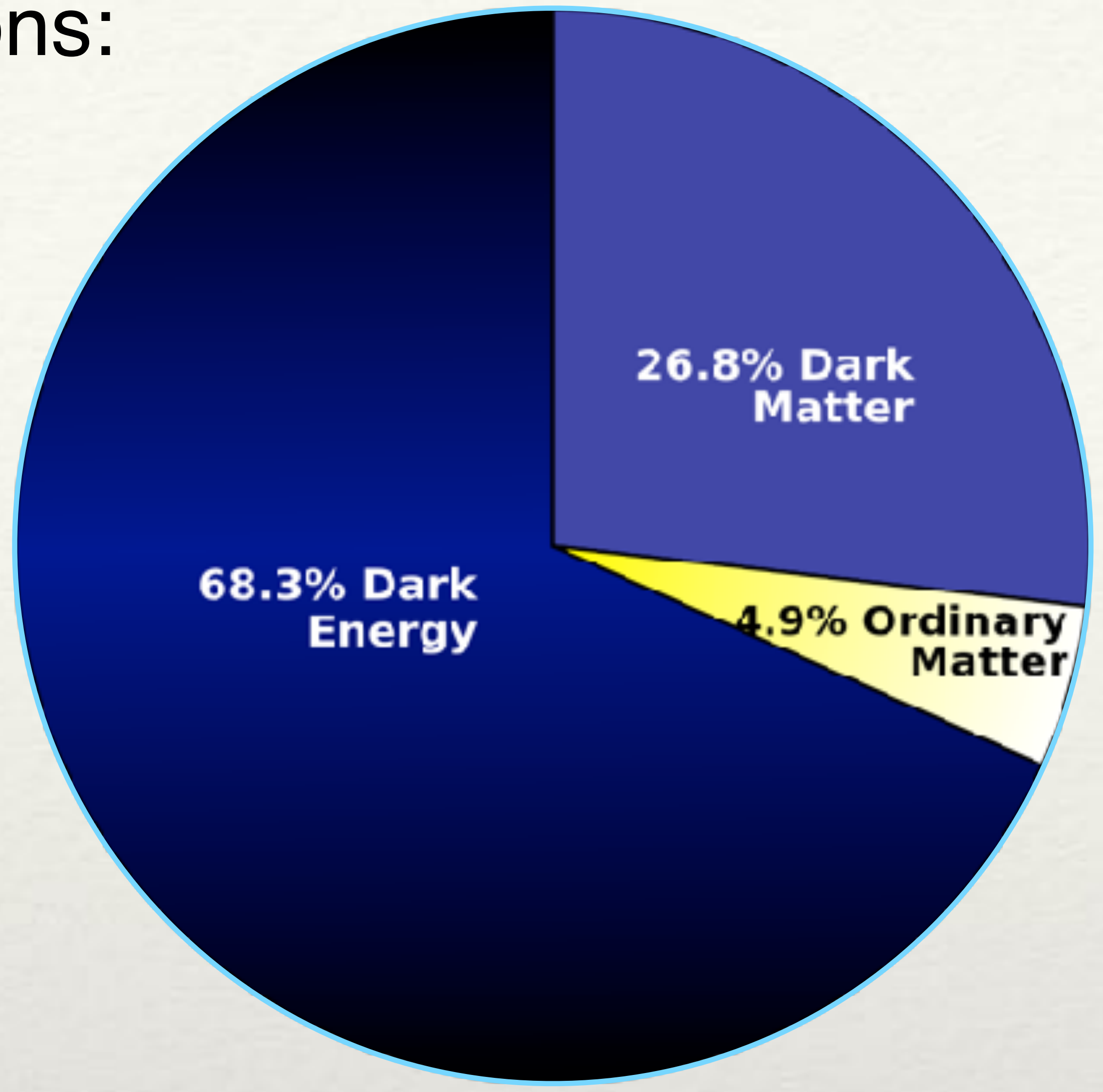
- The SM is a robust theory at the $\mathcal{O}$(100 GeV) scale:
  exhaustive and precise tests, up to ~TeV,
  mainly at colliders.

"Particles, particles, particles."

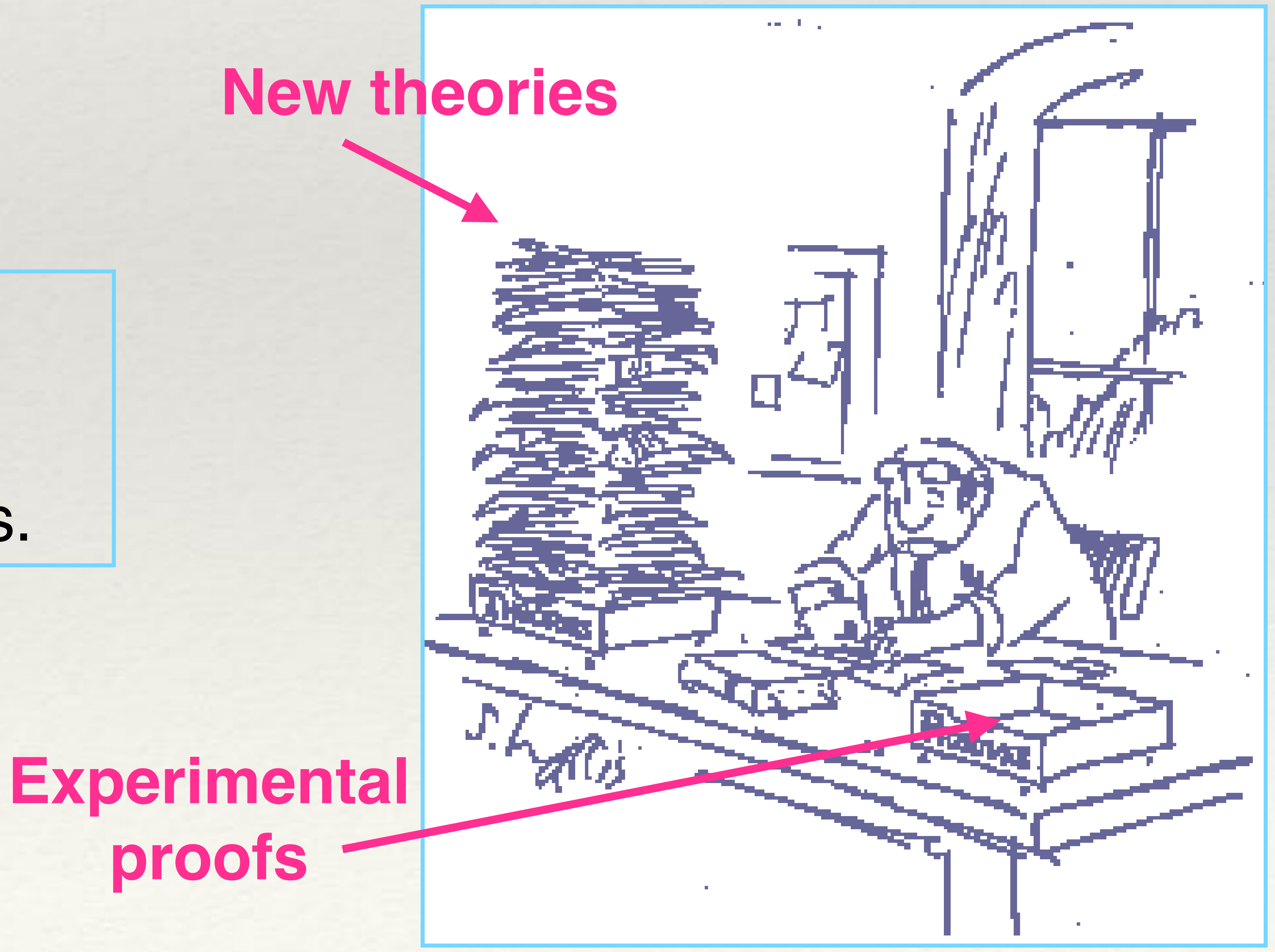


… and Beyond

- However still many unanswered questions:
  - Where is anti-matter?
  - Nature of the dark matter?
  - Nature of the dark energy?
  - …



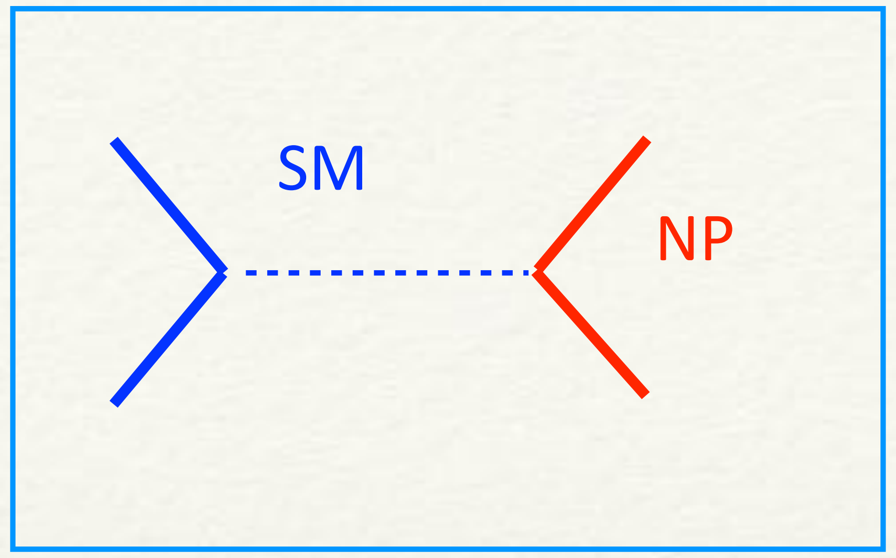
- And other annoying aspects:
  - How to include gravitation at higher energies?
  - Unnatural fine-tuning necessary.
  - Why 3 families of fermions,
    where does the mass hierarchy come from?
  - …



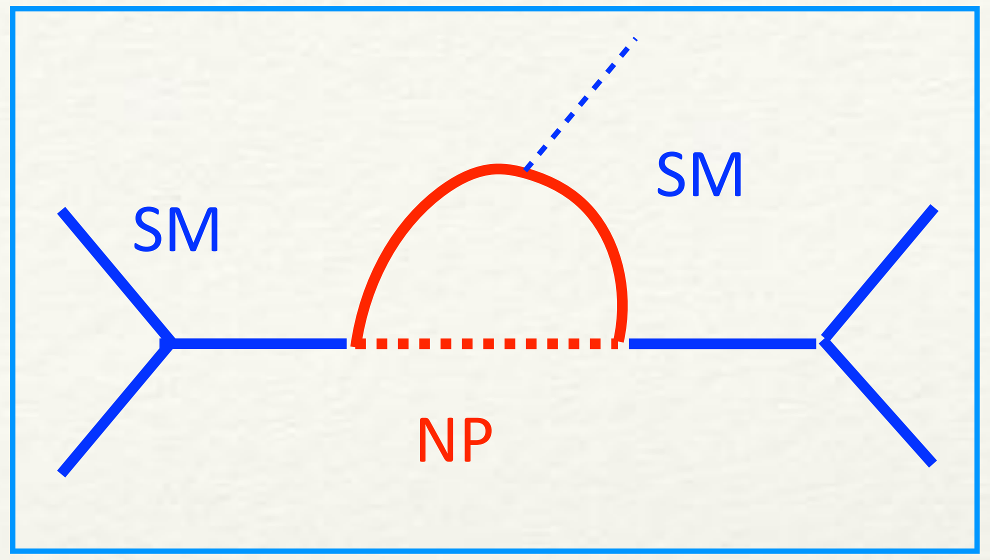
➛ The SM is an effective theory,
not valid anymore at higher energy and in earlier universe.
Particle physicists look now for Beyond-SM-physics, a.k.a. New Physics.

The quest for New Physics

- The relativistic path:
  - Produce new unknown particles in the final state.
  - Need high energy: LHC.



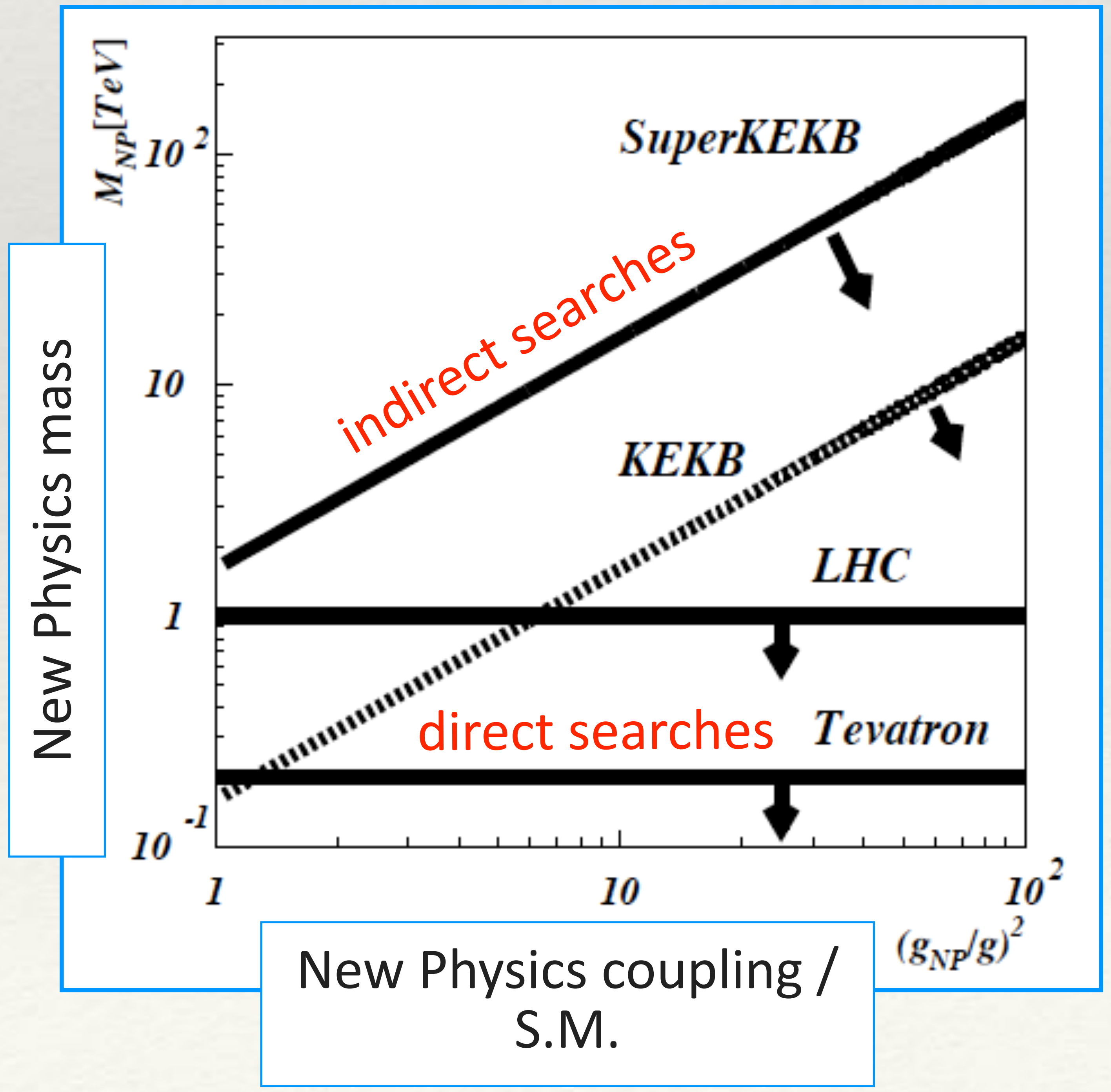
direct search of NP



indirect search of NP

- The quantum path:
  - Sensitive to quantum manifestation on NP by comparing very precise measurements to very precise predictions.
  - Need clean environment (small systematic uncertainty) & intense beams (small statistic uncertainty): SuperKEKB.

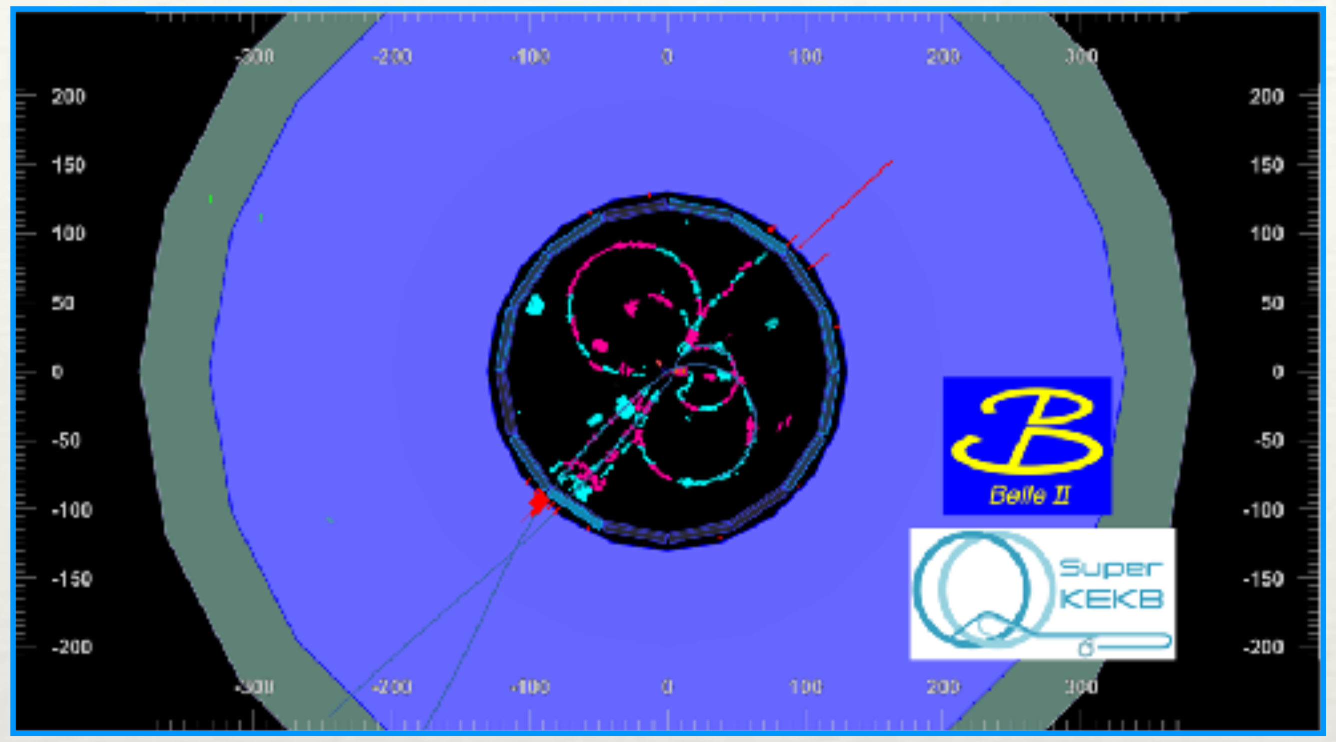
New Physics discovery potential



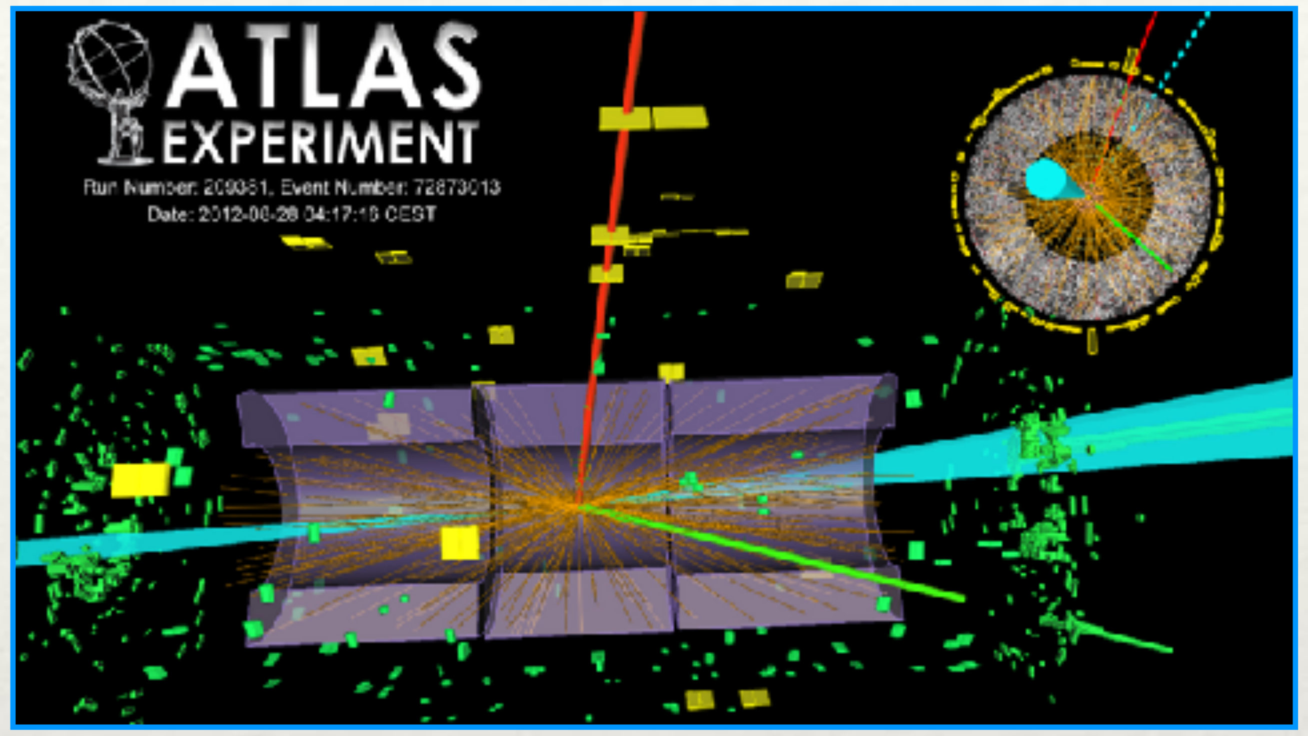
➛ The indirect search is potentially sensitive to higher New Physics masses than the direct search at LHC (cf. Higgs mass, top mass, charm quark, …).

The Belle II experiment at the intensity frontier

- Target utmost experimental precision:
    - $e^+ e^-$ collisions: known initial state governed by QED, clean final state.

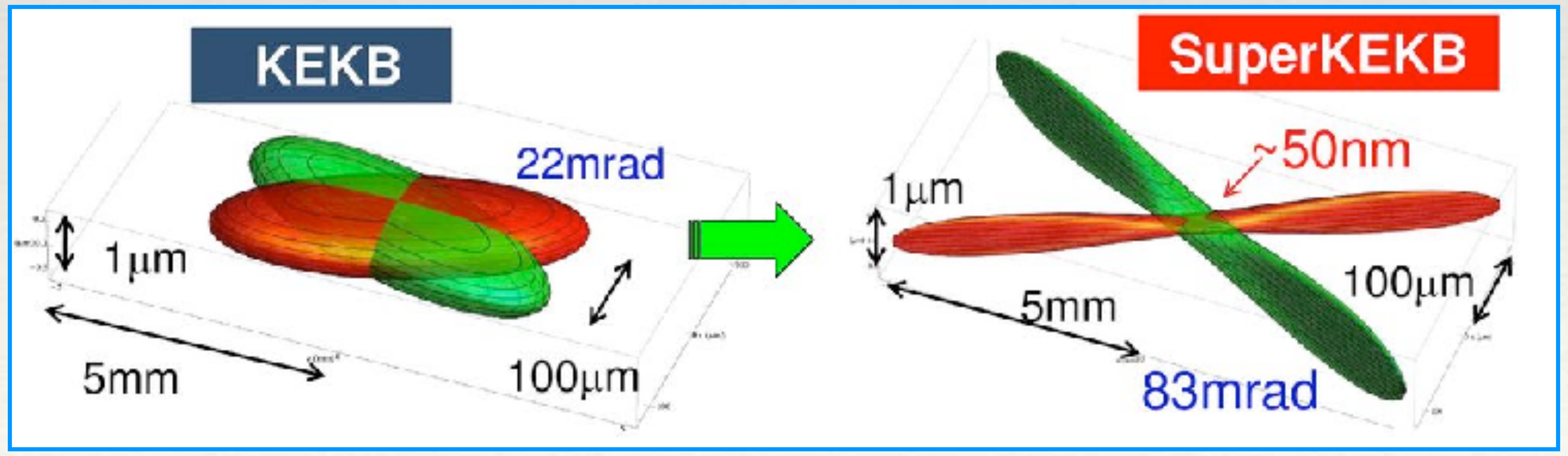


to be compared to, e.g.

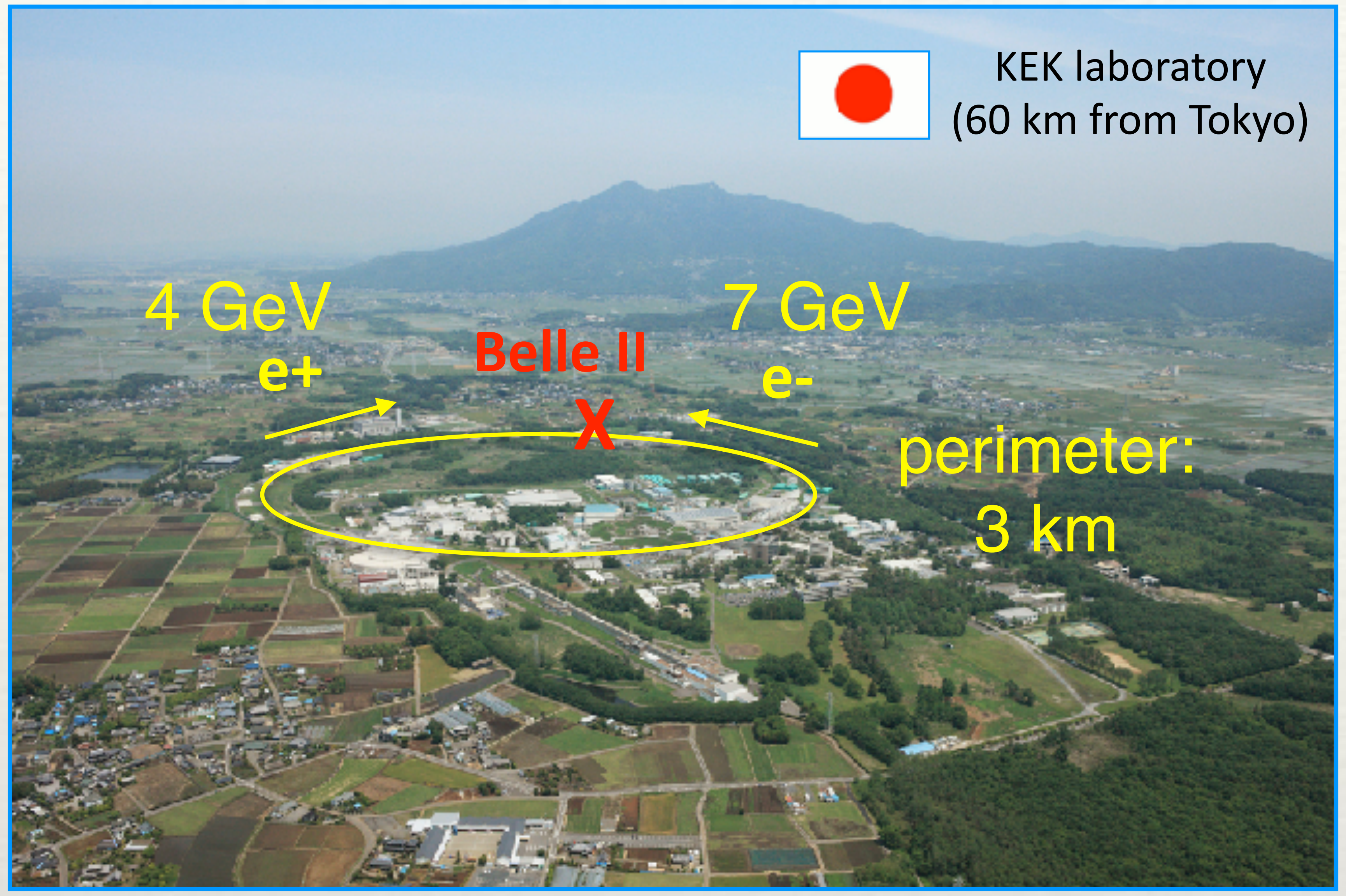


- Relying on excellent legacy of B-Factories:
  10 years of success of BaBar (US) and Belle (Japan) experiments 1998-2010.
  Precise measurement of CP violation in quark sector.
  Nobel prize 2008 to Kobayashi and Maskawa.

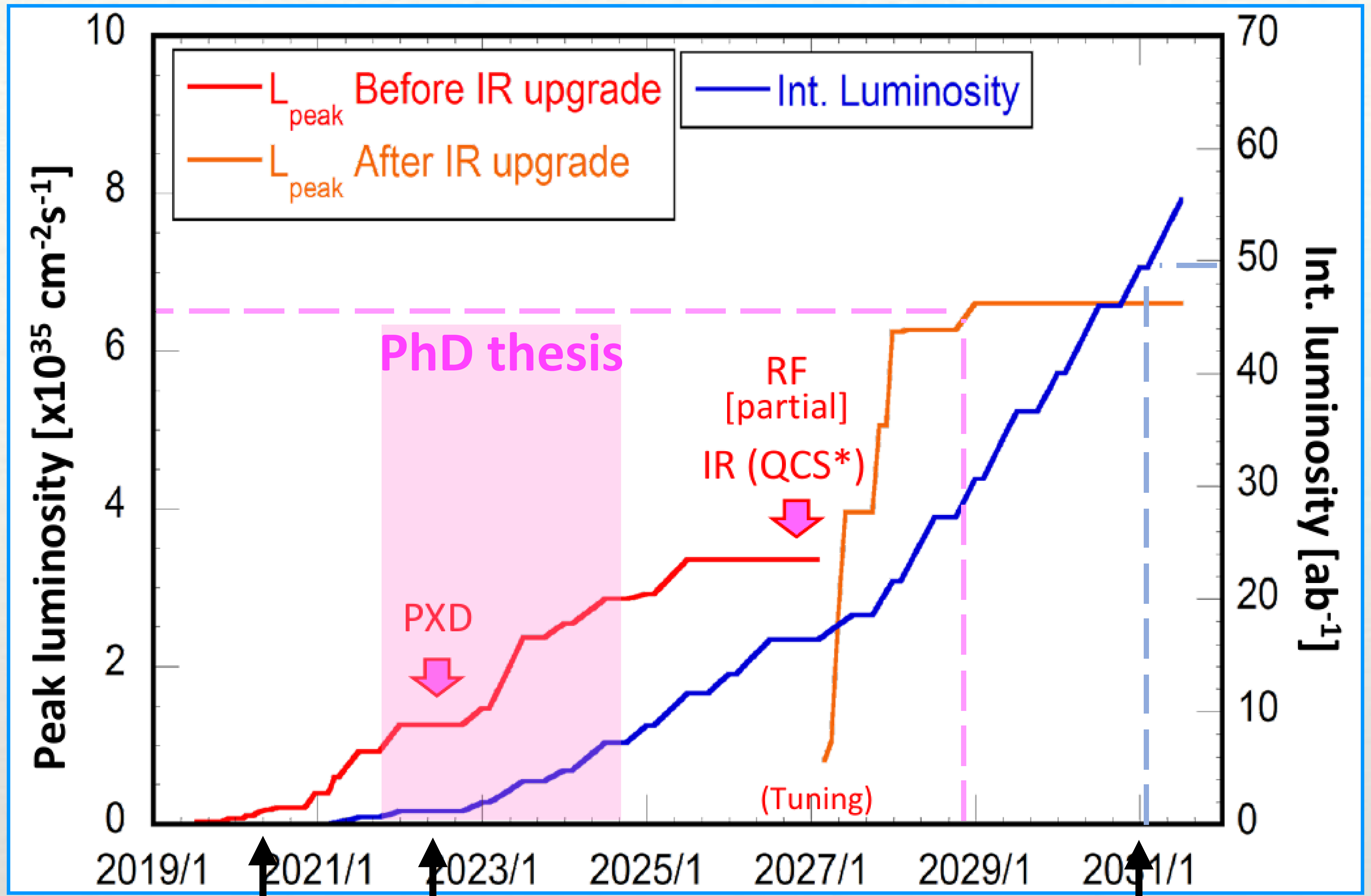
- Breakthrough in accelerator physics, first collider using Nano-beams: current world data-sample ×50.



The SuperKEKB collider



SuperKEKB luminosity projections



Instantaneous luminosity world record in 2020

2.4×10^{34} cm^{-2} s^{-1}

Largest current existing dataset in the world

50× existing dataset

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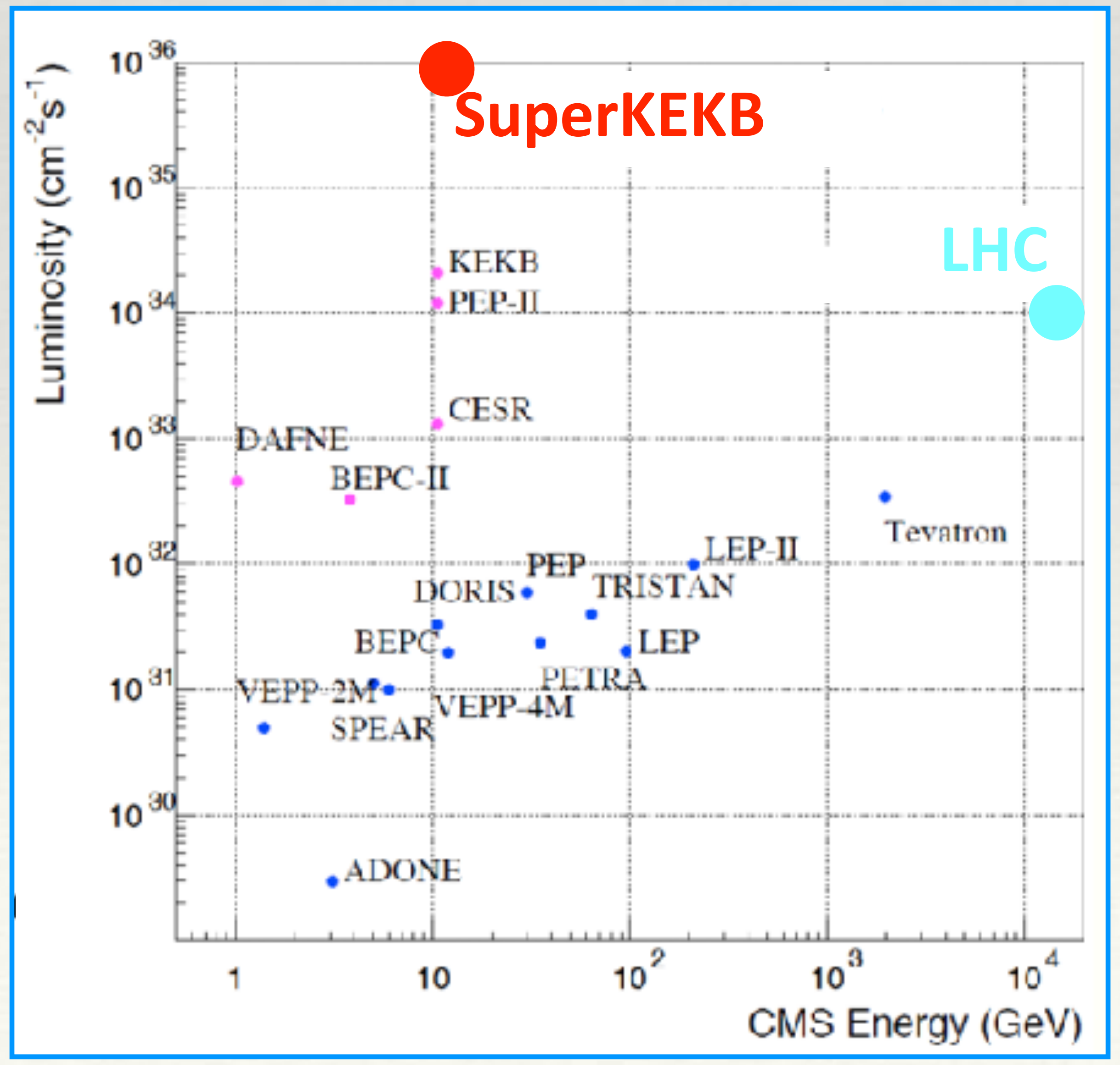
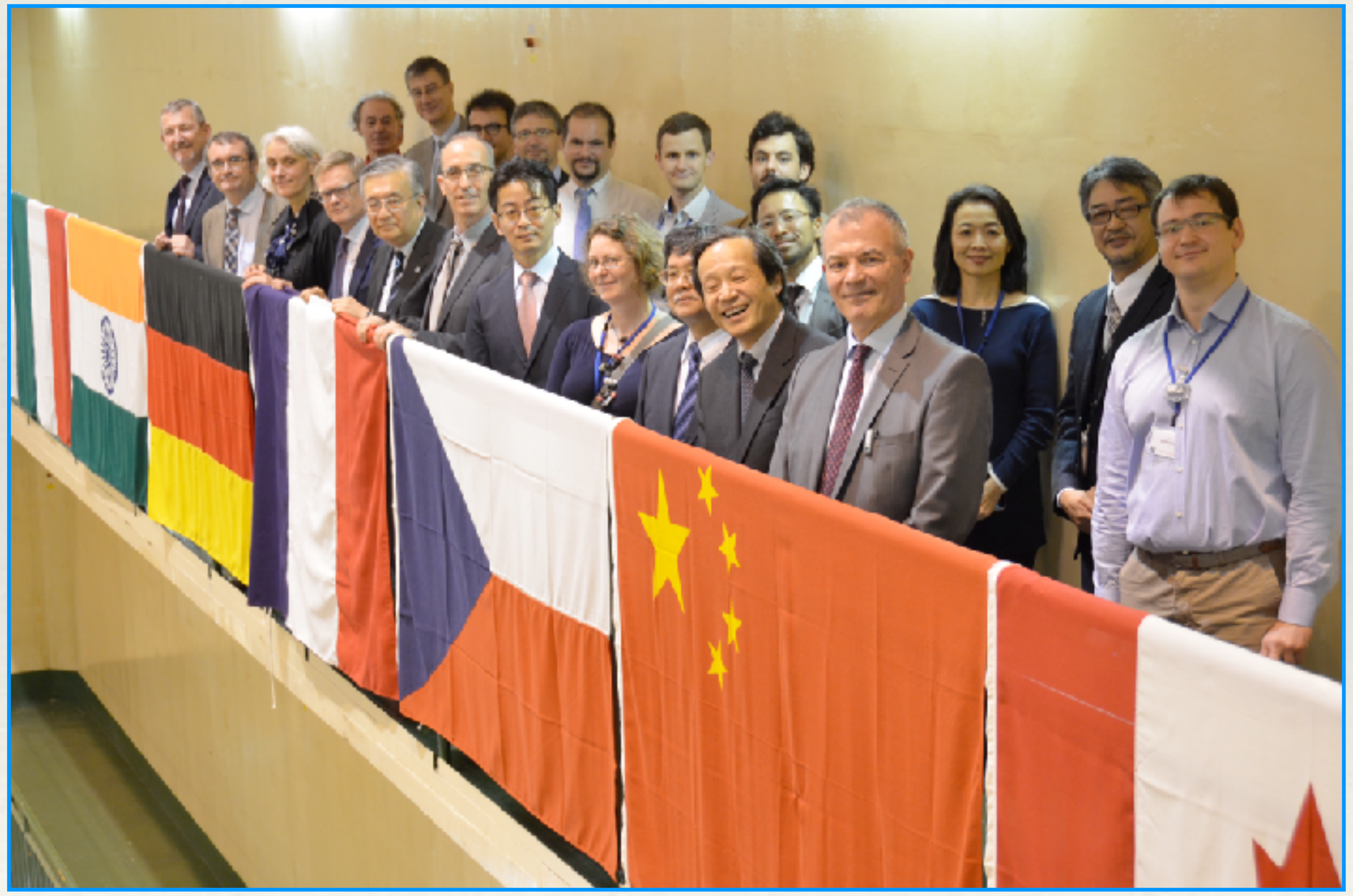


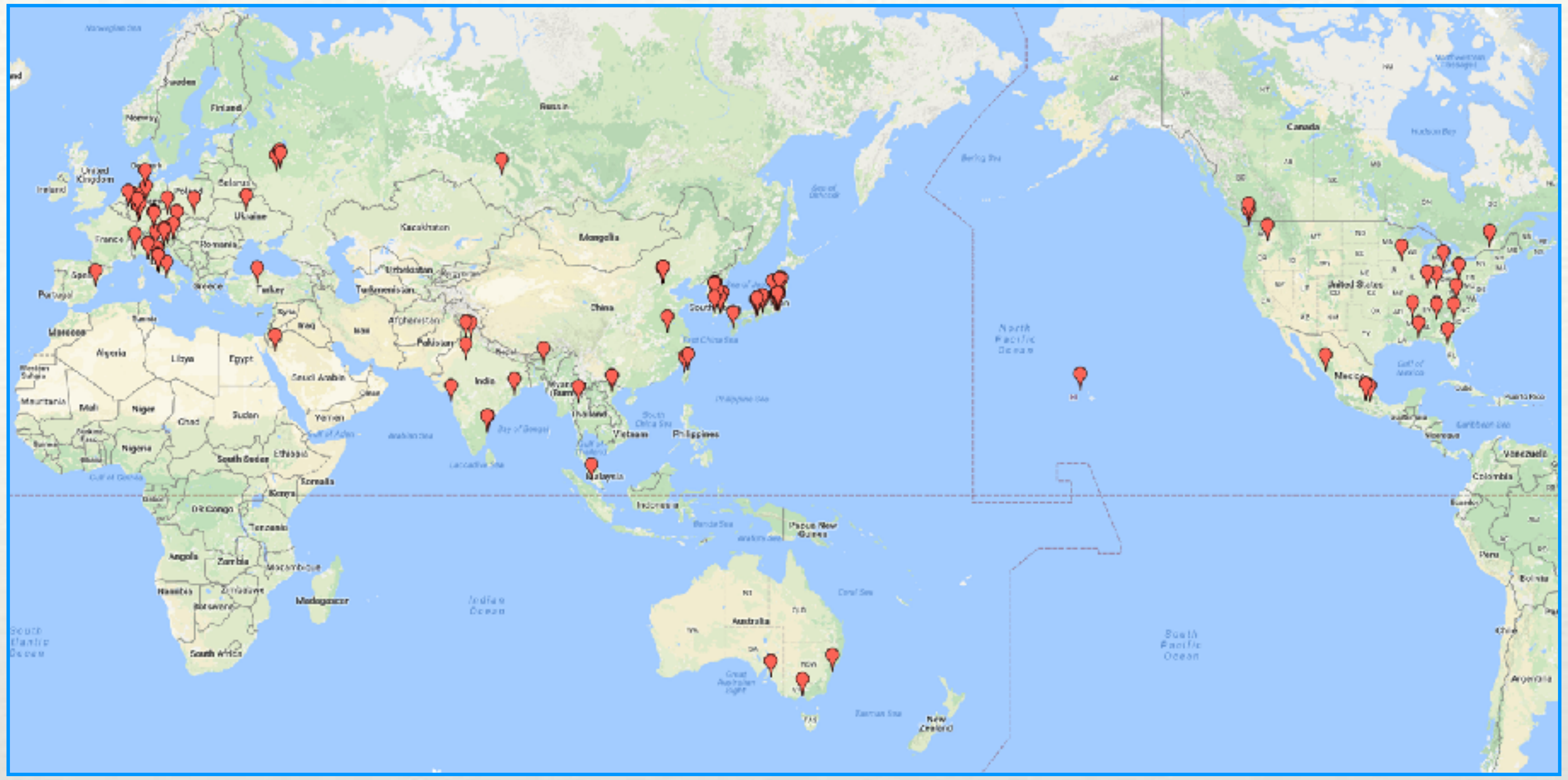
➛ Excellent potential of discoveries and of original publications during the thesis.

National and international context

- International Belle II collaboration:
  ~ 800 participants from 26 countries.
- France joined officially in 2016:
  other French labs are CPPM Marseille & IJCLab Orsay.



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, Nara, Nagoya.
  - South Korea: Daegu.
  - Slovenia: Ljubljana.

The Belle II group @IPHC in 2021

Jérôme Baudot
professor
@ Unistra

Giulio Dujany
junior researcher
@ CNRS

Christian Finck
senior researcher
@ CNRS

Isabelle Ripp-Baudot
research director
@ CNRS

Reem Rascheed
Unistra PhD student
→ 01/2021

Tristan Fillinger
CNRS PhD student
→ 09/2022

Lucas Martel
Unistra PhD student
→ 09/2023

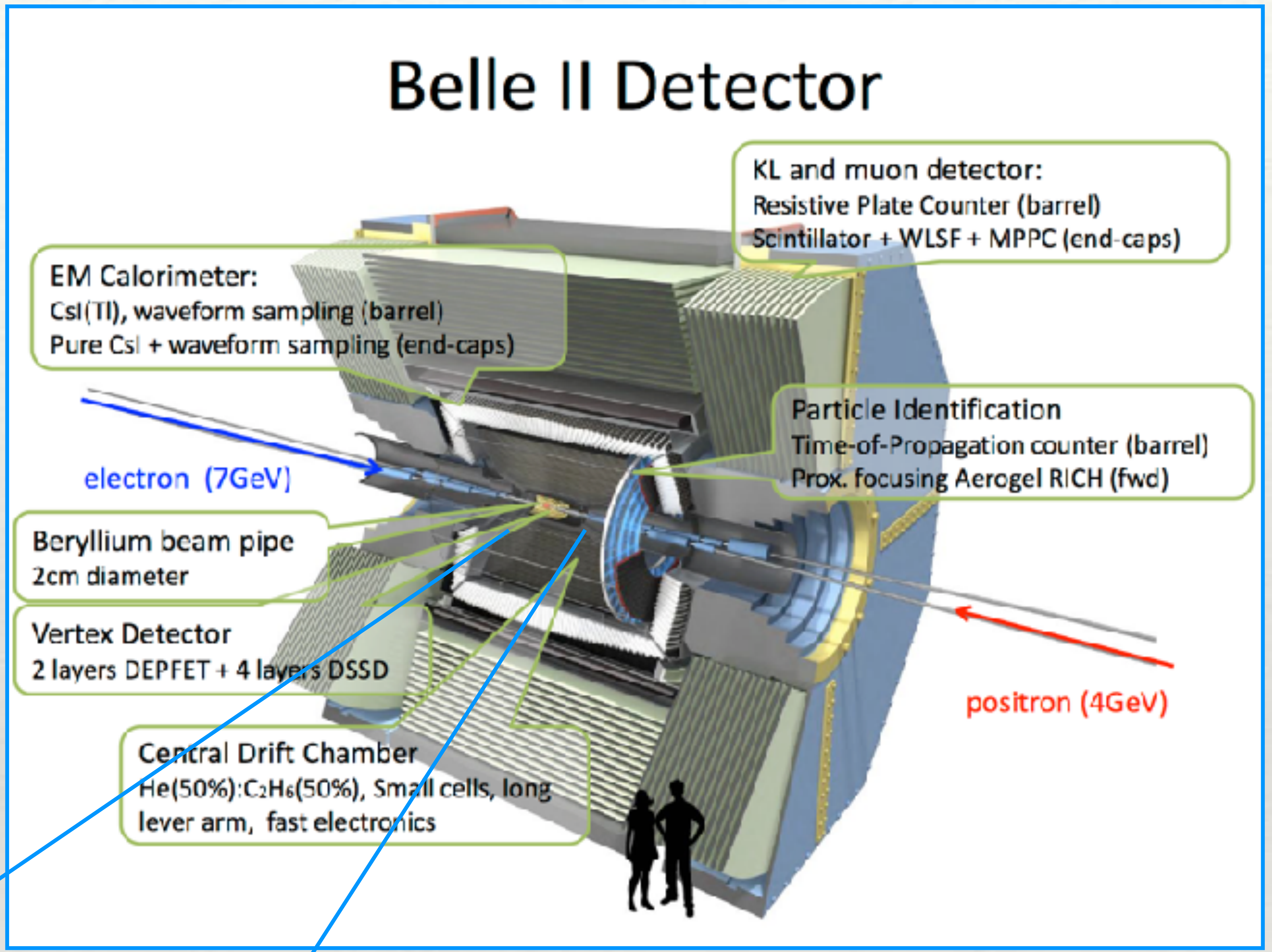
YOU
M2 / PhD student
→ 09/2024

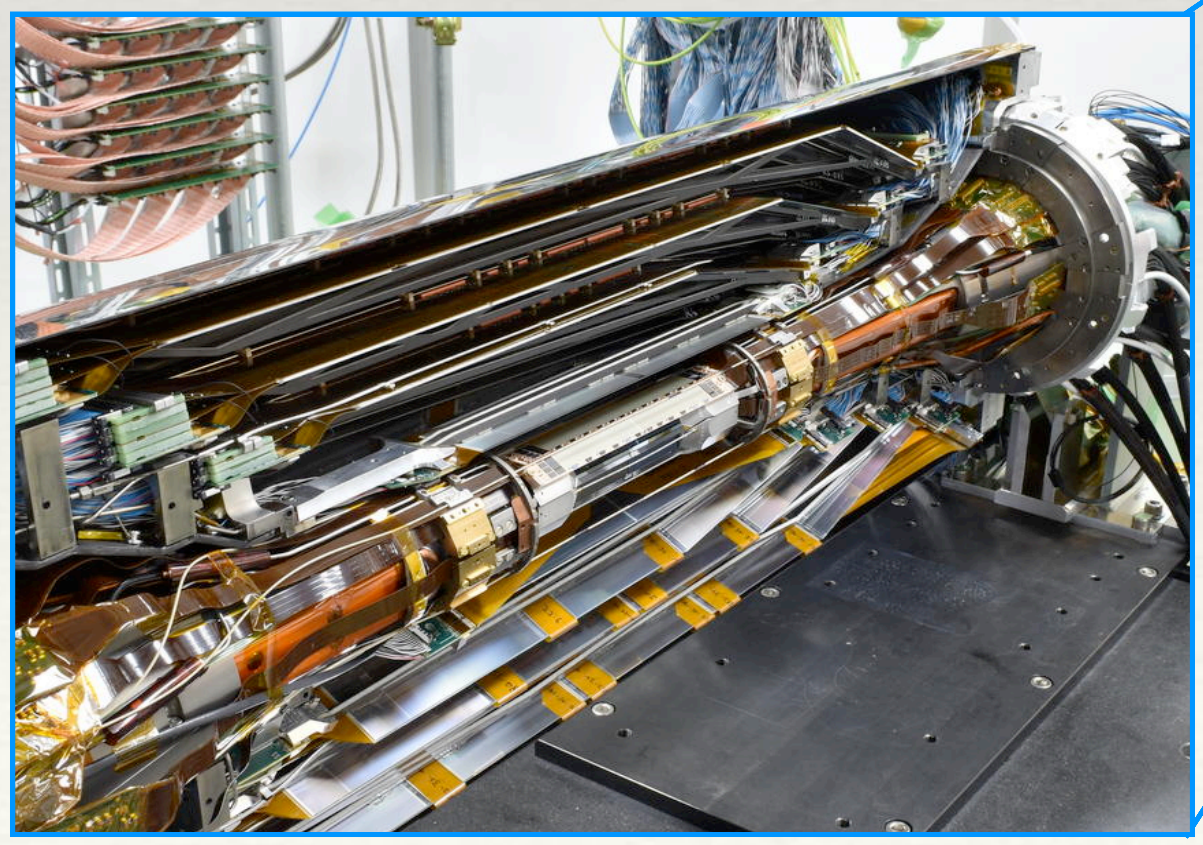
+ several engineers : slow control of the Vertex detector, upgrade of the vertex det., computing.

+ potential L and M students.

IPHC-Belle II group activities

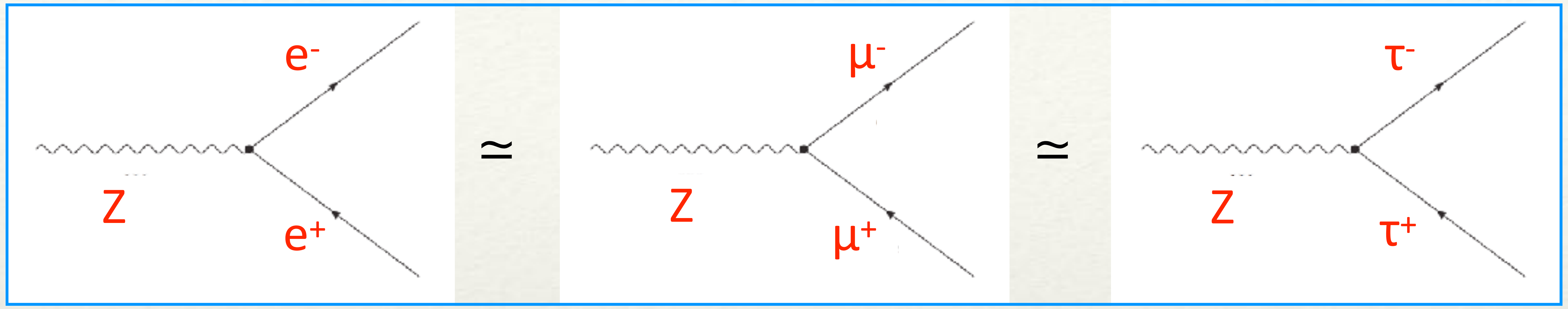
- Search for new physics beyond the Standard Model:
  - Measurement of the CP asymmetry as a function of time of $b \to s\gamma$ processes.
  - First observation of $b \to s\nu\bar{\nu}$ processes.
- Operate the Belle II detector:
  - Development of the vertex detector slow-control.
  - Development of the calibration database.
  - Shifts.
- Design the next generation vertex detector:
  - Define the detector specifications.
  - Simulation and tracking with new detector.
  - R&D and beam test of a CMOS sensor.





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: $$-i \frac{g}{\cos\theta_W} \gamma^\mu \frac{g_v - g_a \gamma^5}{2}$$

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:

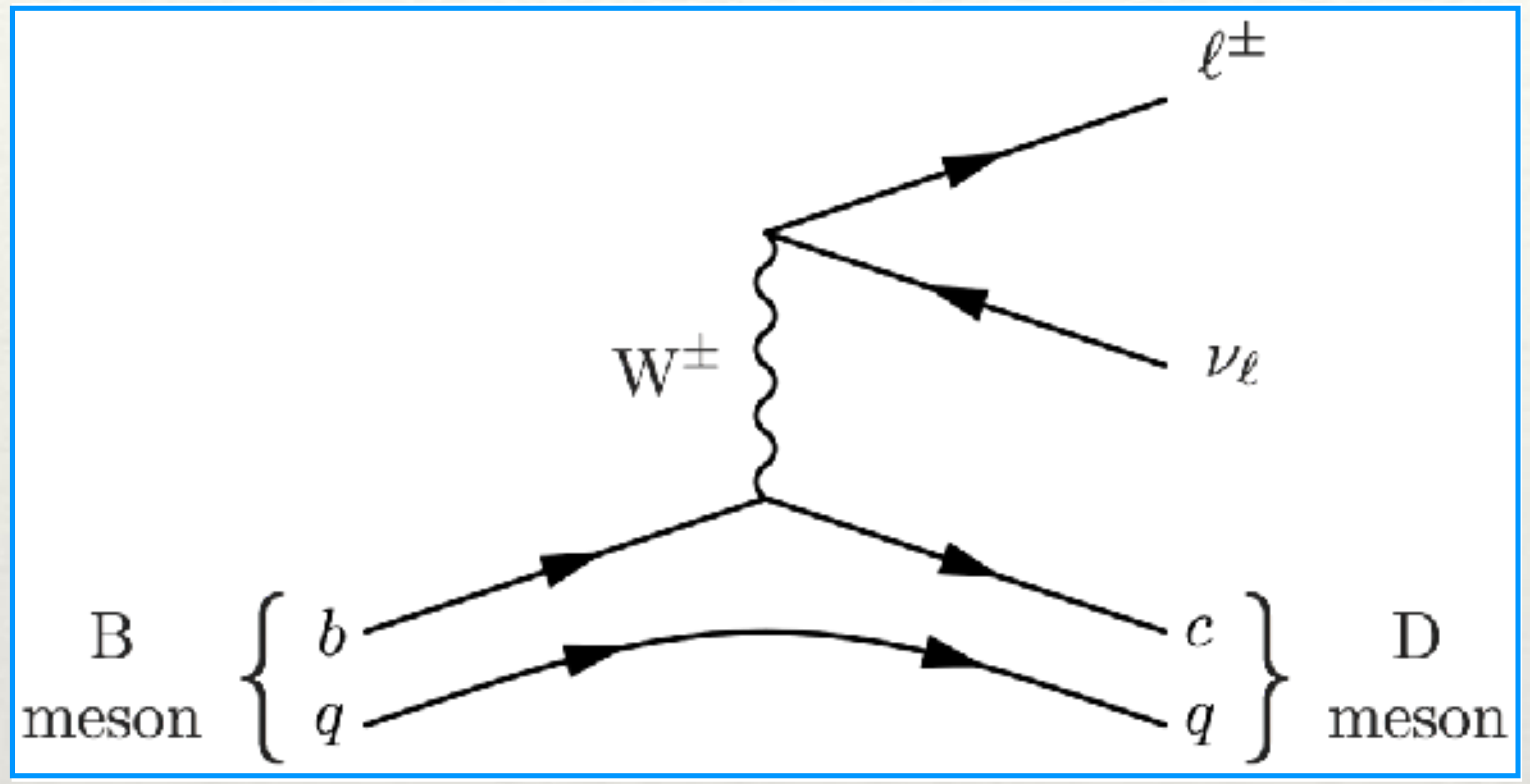
$$\frac{\Gamma_{Z\to\mu\mu}}{\Gamma_{Z\to ee}} = 1.0009 \pm 0.0028 \qquad \frac{\Gamma_{Z\to\tau\tau}}{\Gamma_{Z\to ee}} = 1.0019 \pm 0.0032 \qquad \frac{\mathcal{B}(W\to e\nu_e)}{\mathcal{B}(W\to\mu\nu_\mu)} = 1.004 \pm 0.008$$

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

Measured lepton universality anomalies (1)

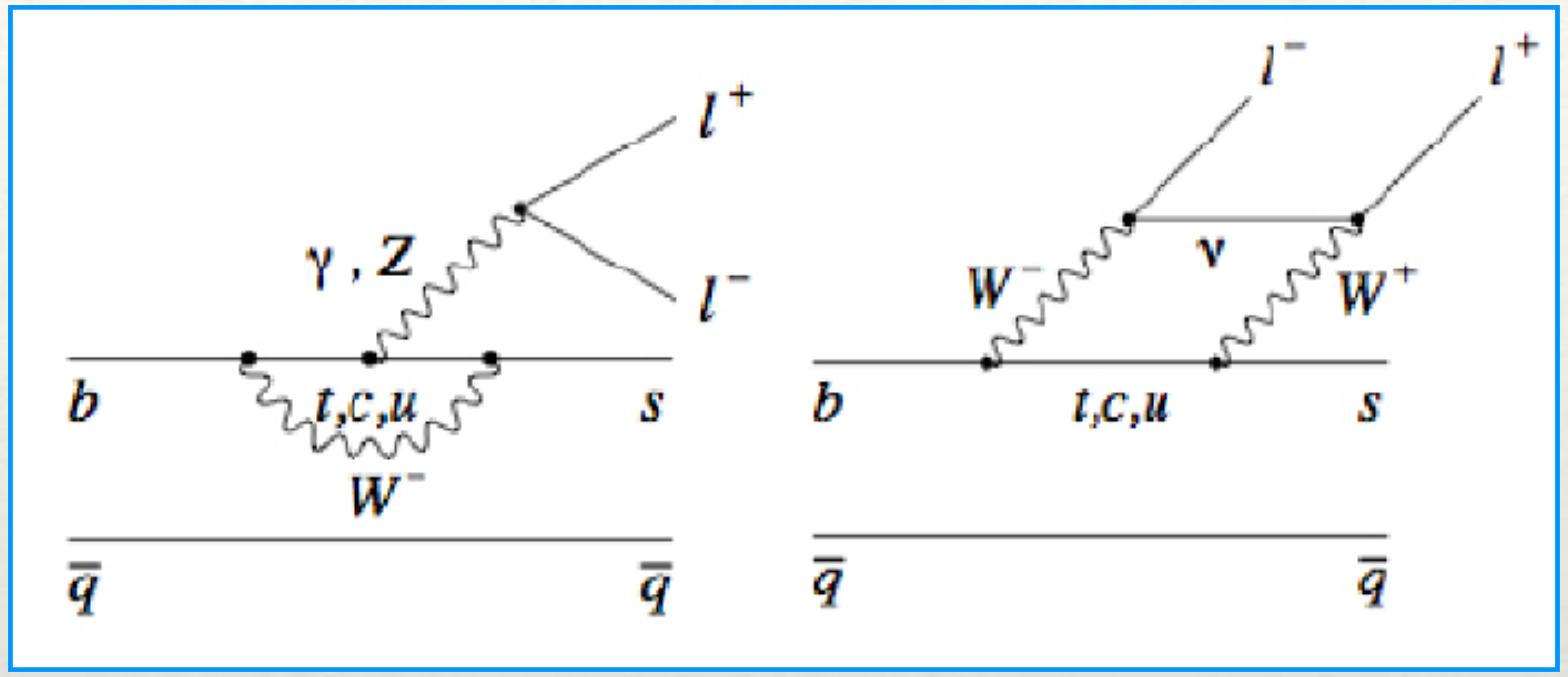
- Actually, several discrepancies are observed in the flavour sector:

  - b → c ℓ ν



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

  - b → s ℓ ℓ



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

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

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

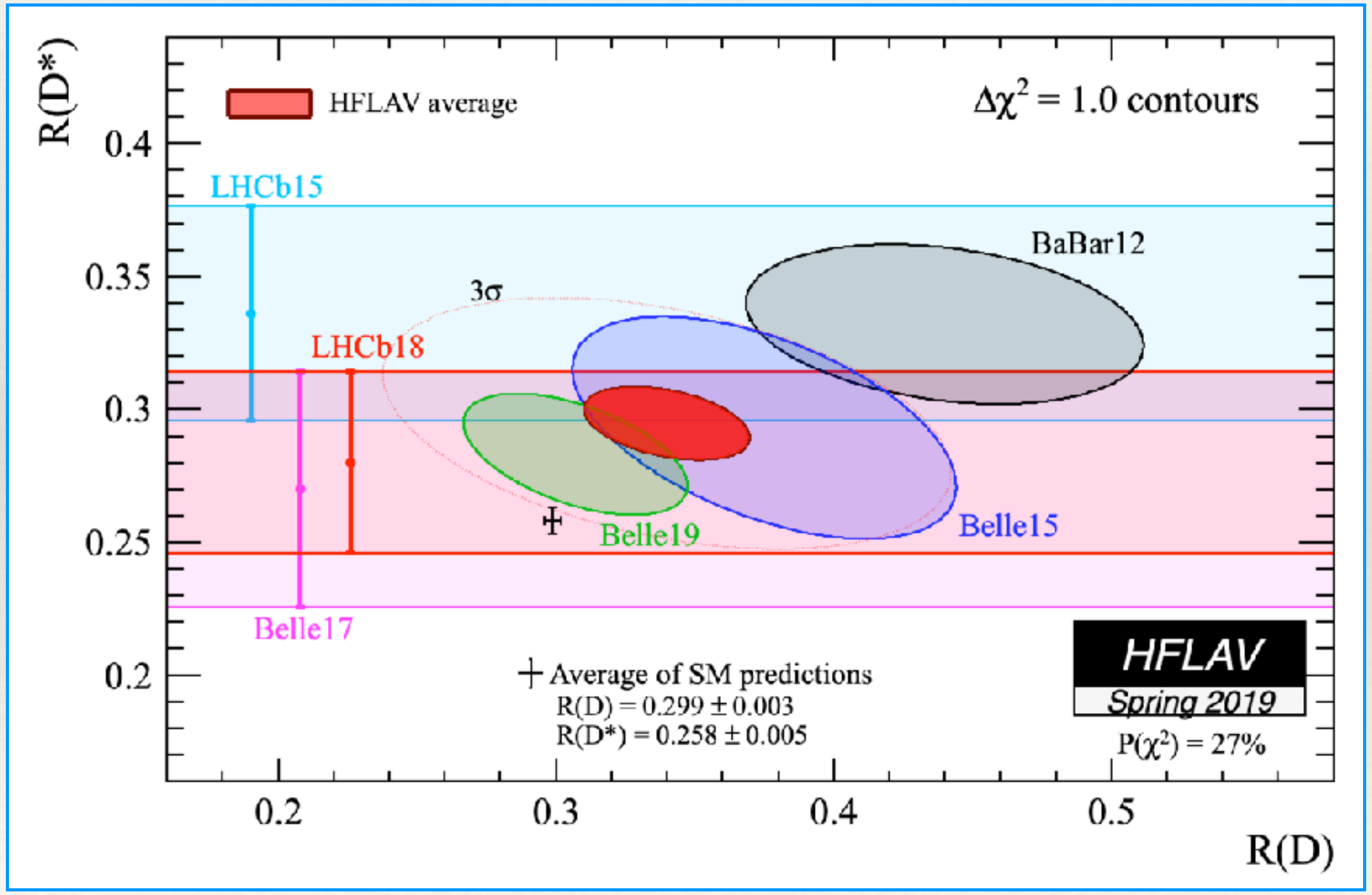
$$R^{SM}_{K^{*0}} = \frac{BR(B^0 \rightarrow K^{*0}\mu^+\mu^-)}{BR(B^+ \rightarrow K^{*0}e^+e^-)} = 1 \pm \mathcal{O}(10^{-3})$$

Measured lepton universality anomalies (2)

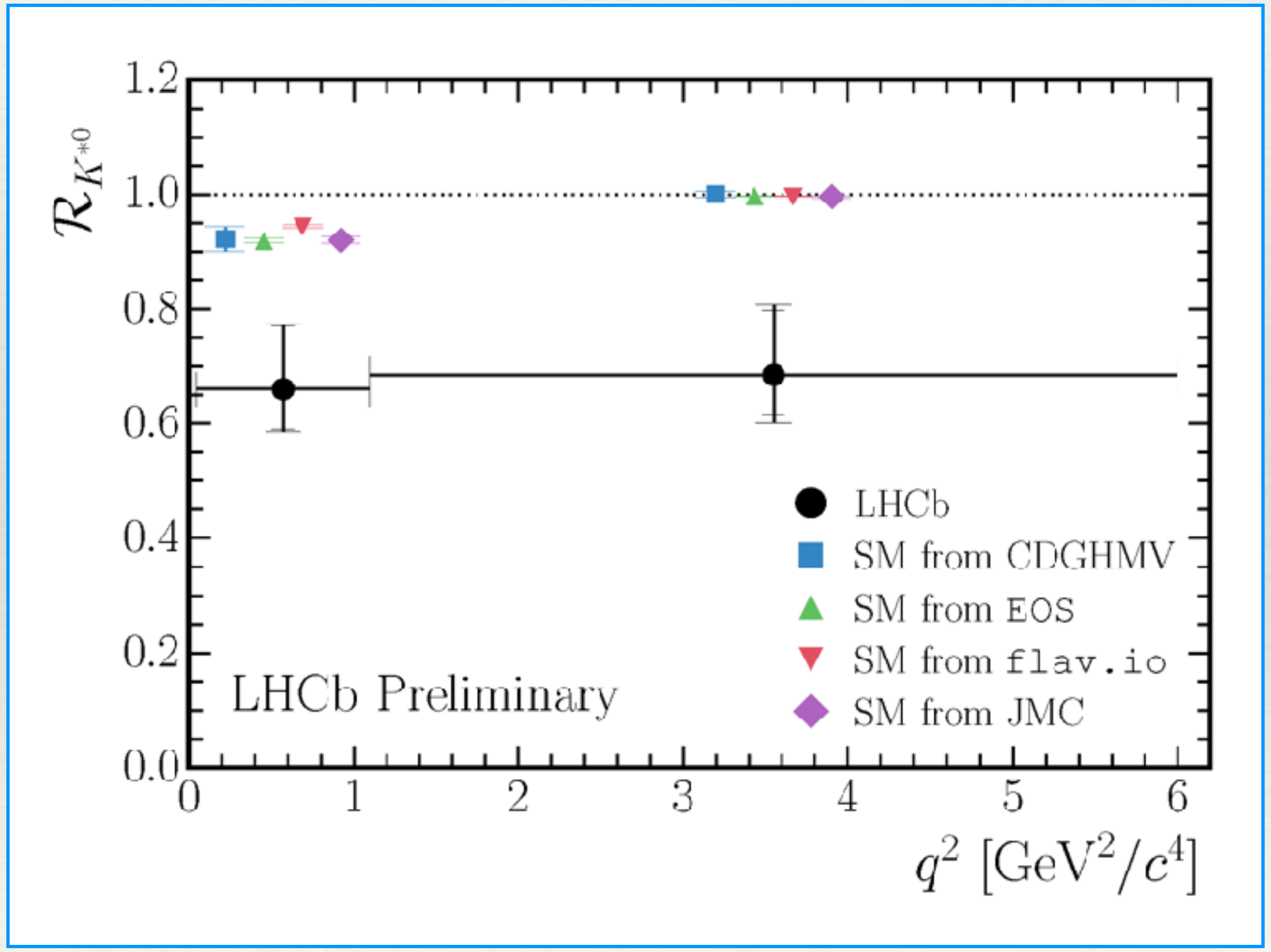
- 3 different experiments agree and measure 3 to 4σ-discrepancies with S.M. prediction:

  BaBar and Belle (at e^+e^- colliders closed in 2010), and LHCb (at pp collider running at CERN)

- $b \to c \ \ell \ \nu$



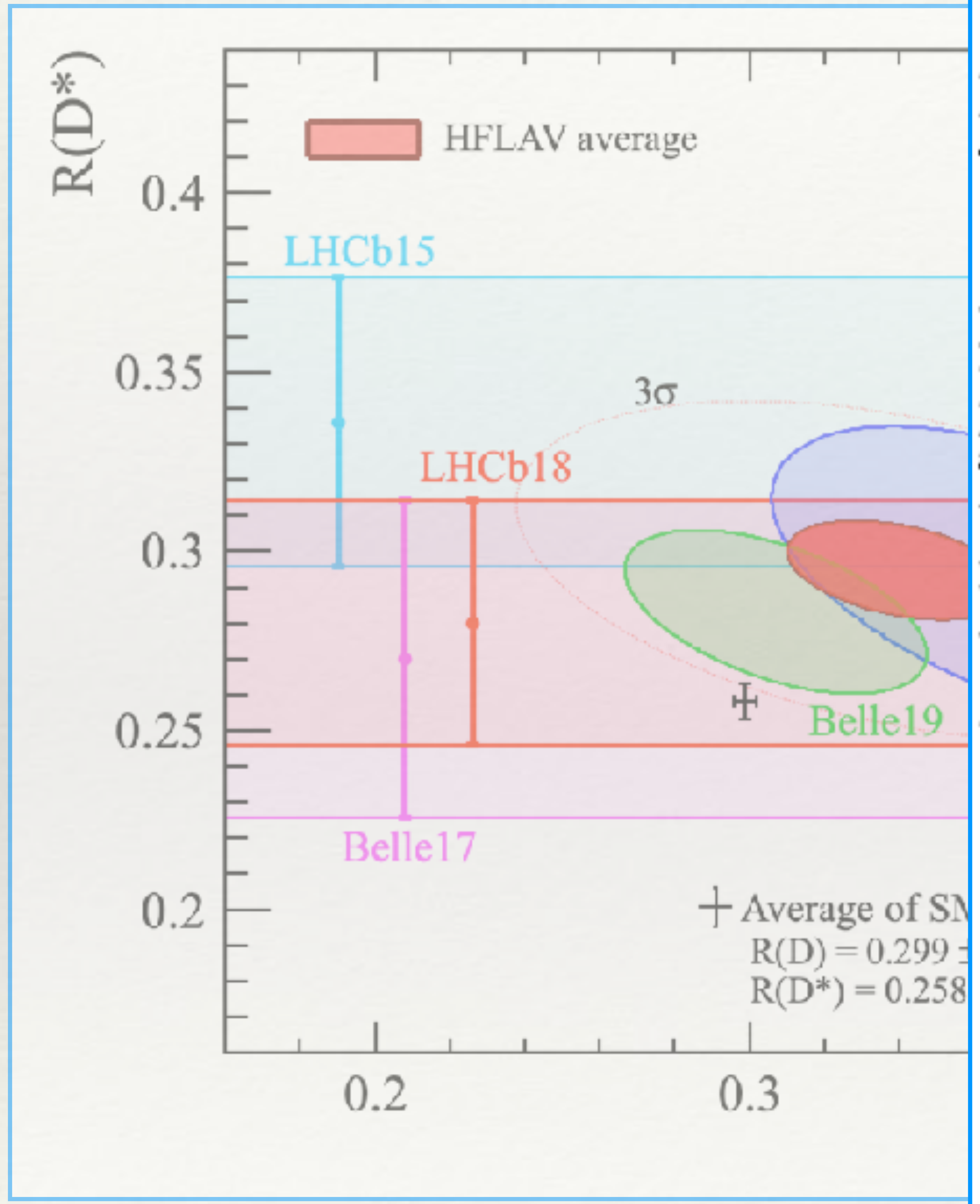
- $b \to s \ \ell \ \ell$

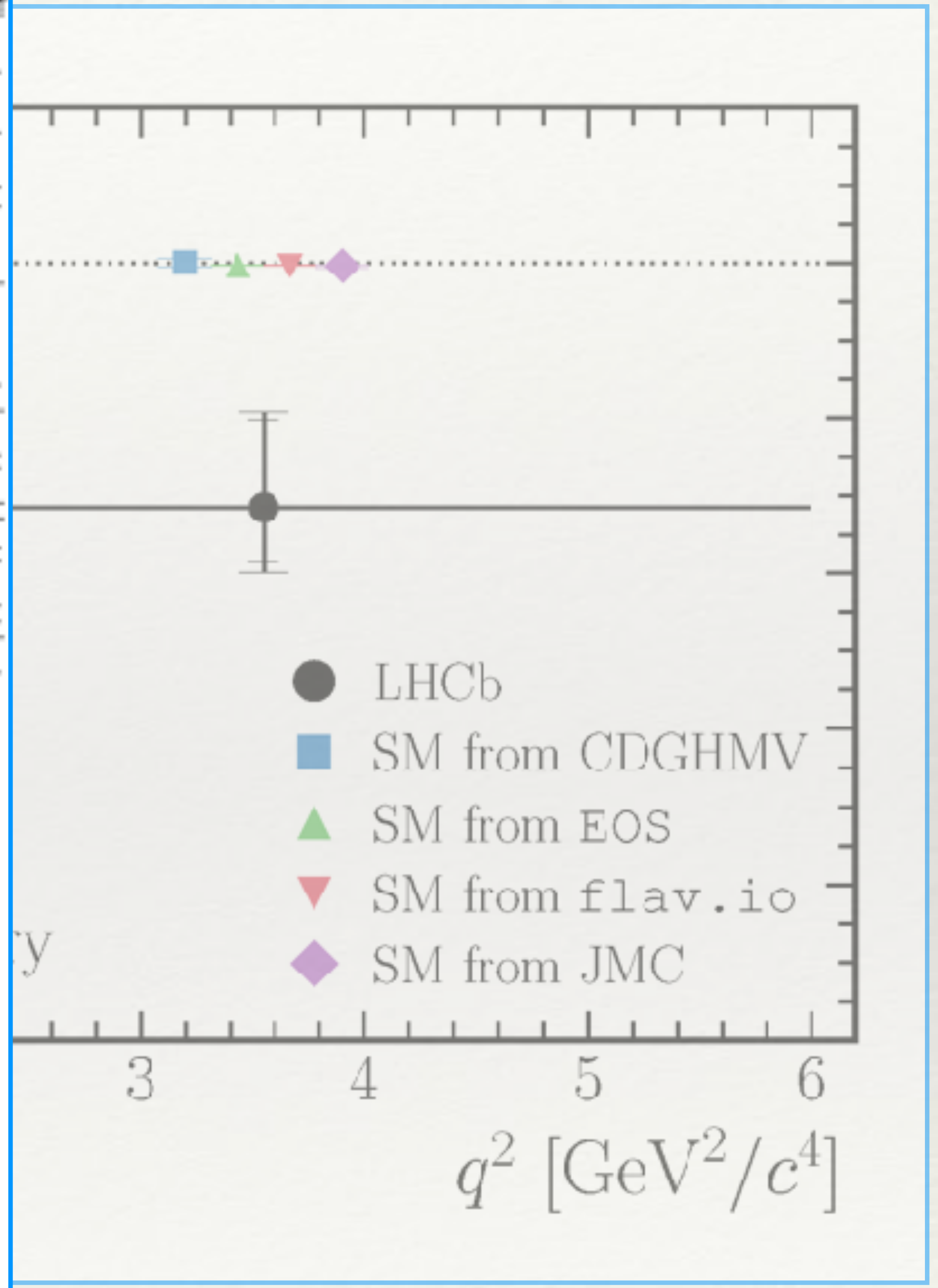


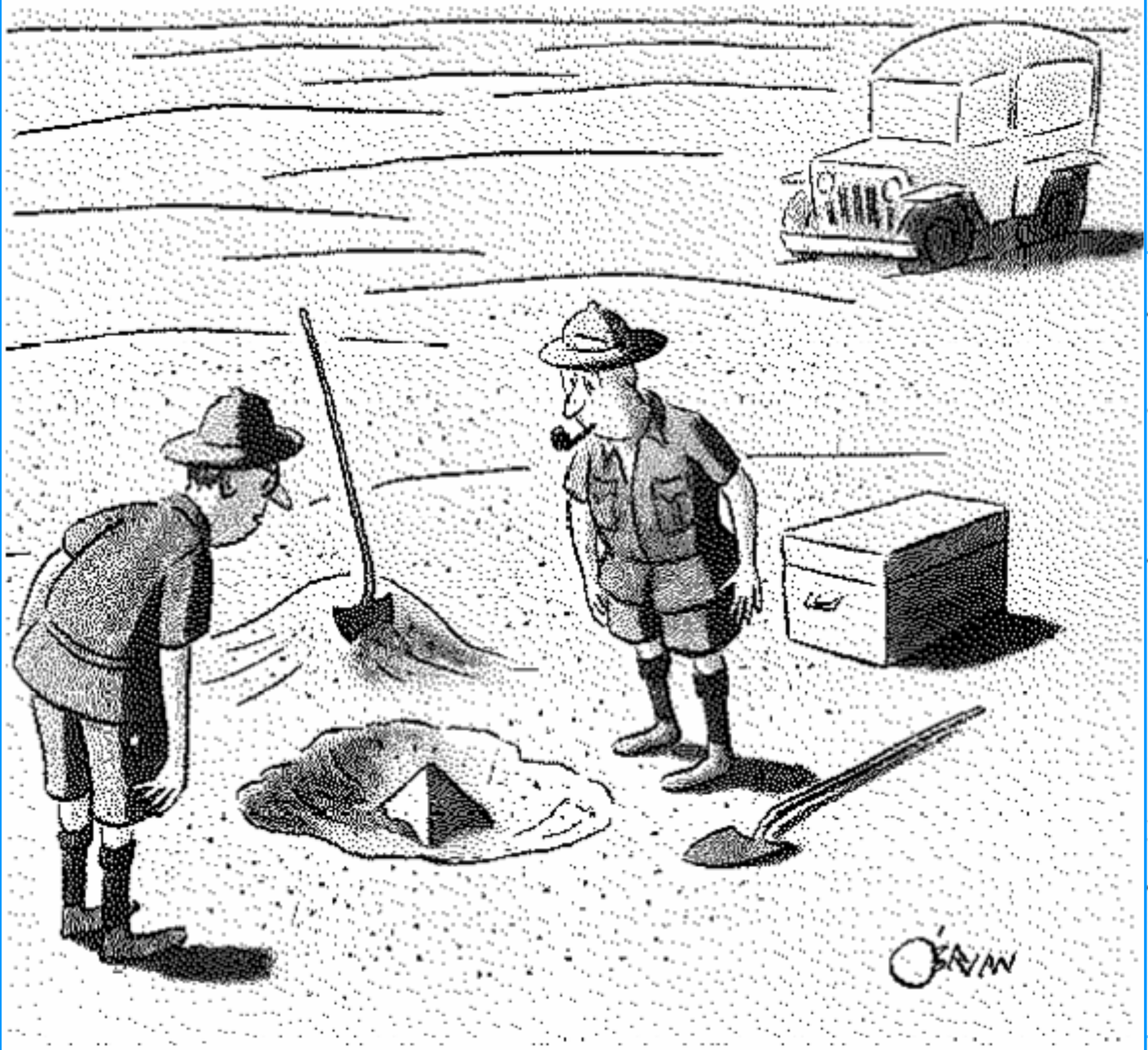
Measured lepton universality anomalies (2)

- 3 different experiments agree an

  BaBar and Belle (at e^+e^- colliders c



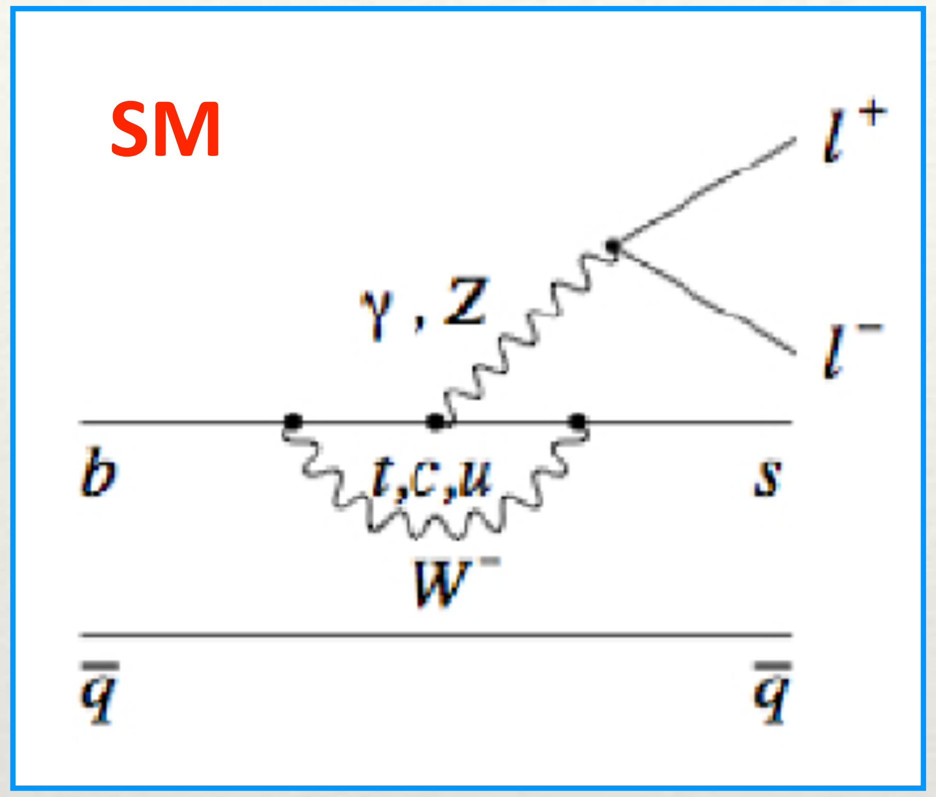




"This could be the discovery of the century. Depending, of course, on how far down it goes."

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, …



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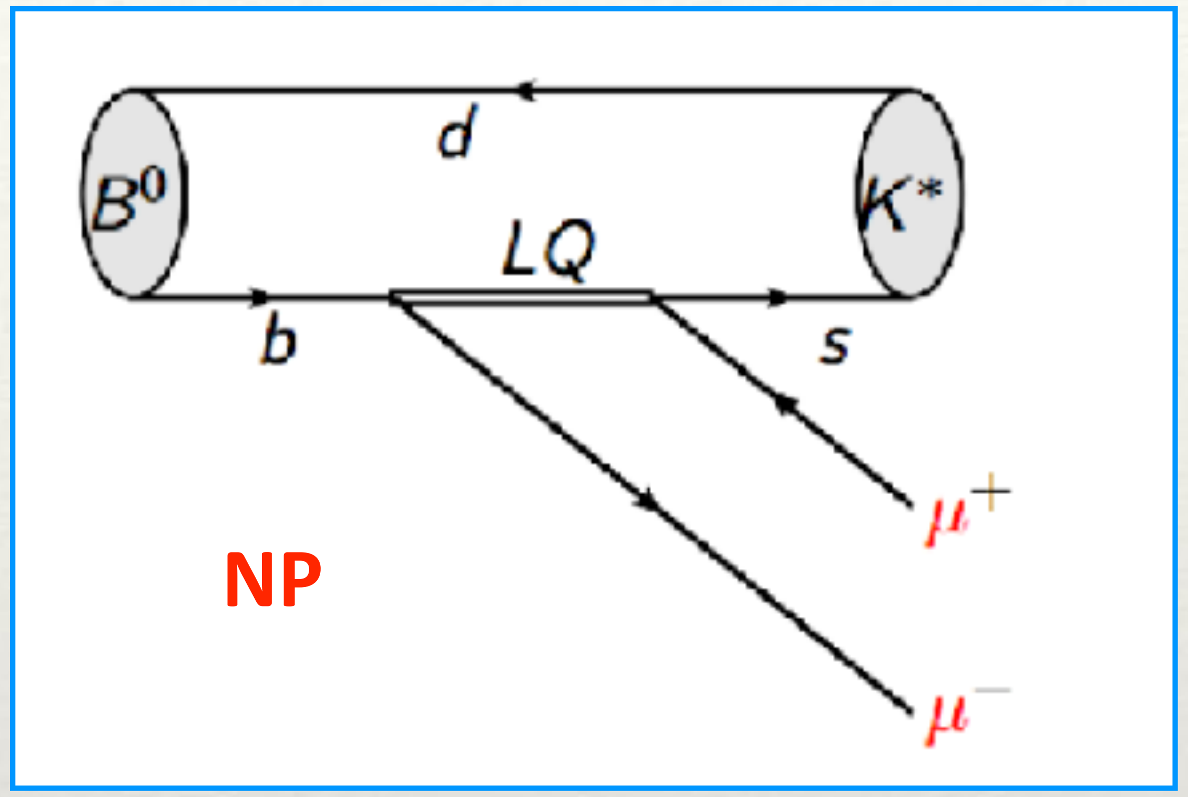
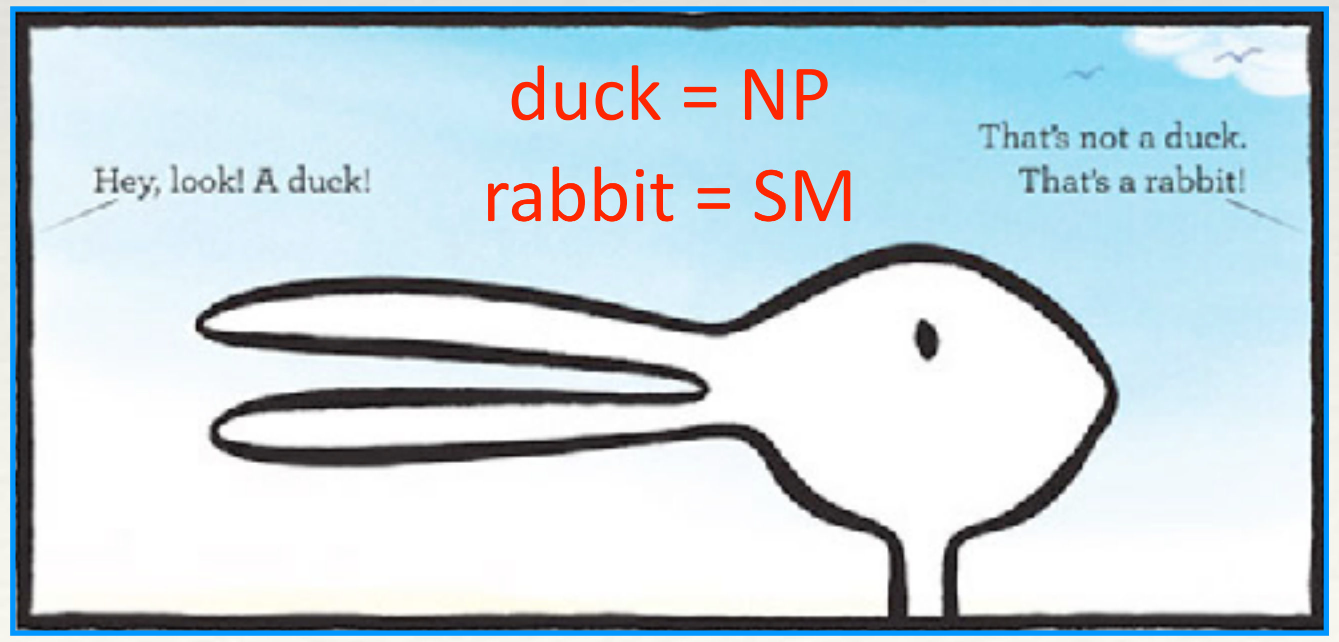
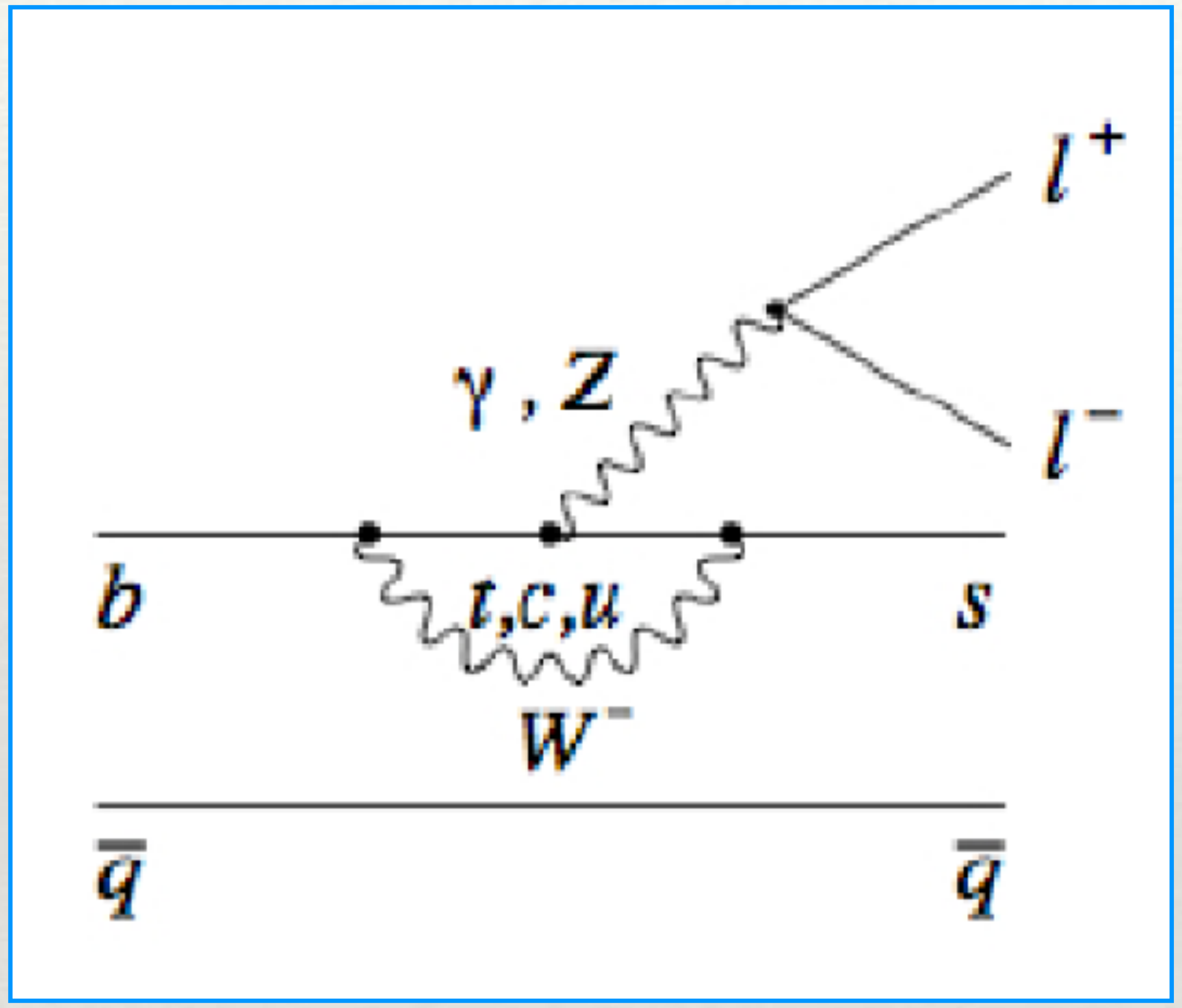


- However we must make sure that the discrepancy is actual:
  - Get rid of possible experimental errors or forgetting in the interpretation.
  - Investigate carefully the significance of the discrepancy.



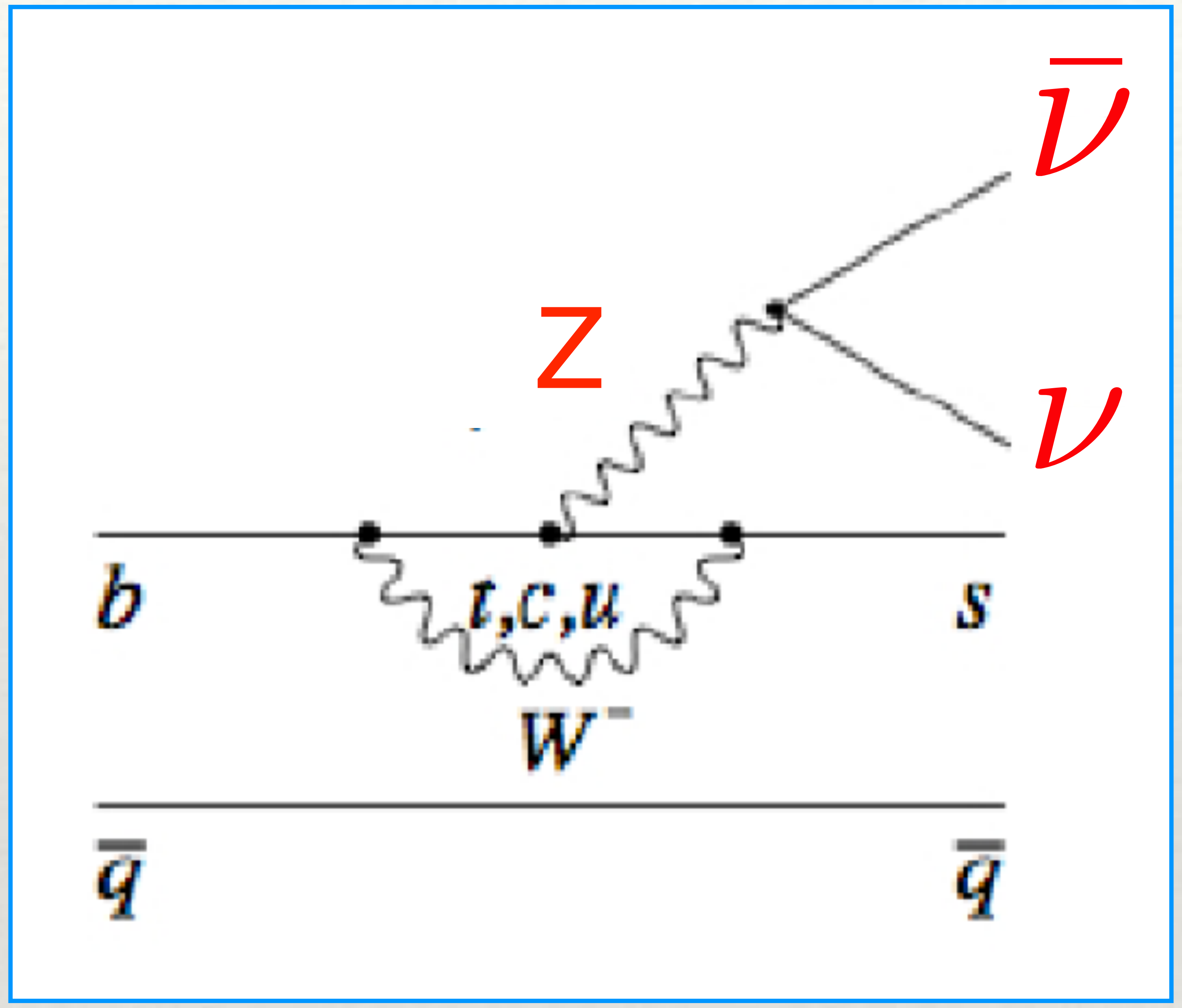
$b \to s \ell \ell$, $b \to s \gamma$ and $b \to s \nu \nu$ processes

$b \to s \ell \ell$



Observed anomalies.

$b \to s \nu \nu$

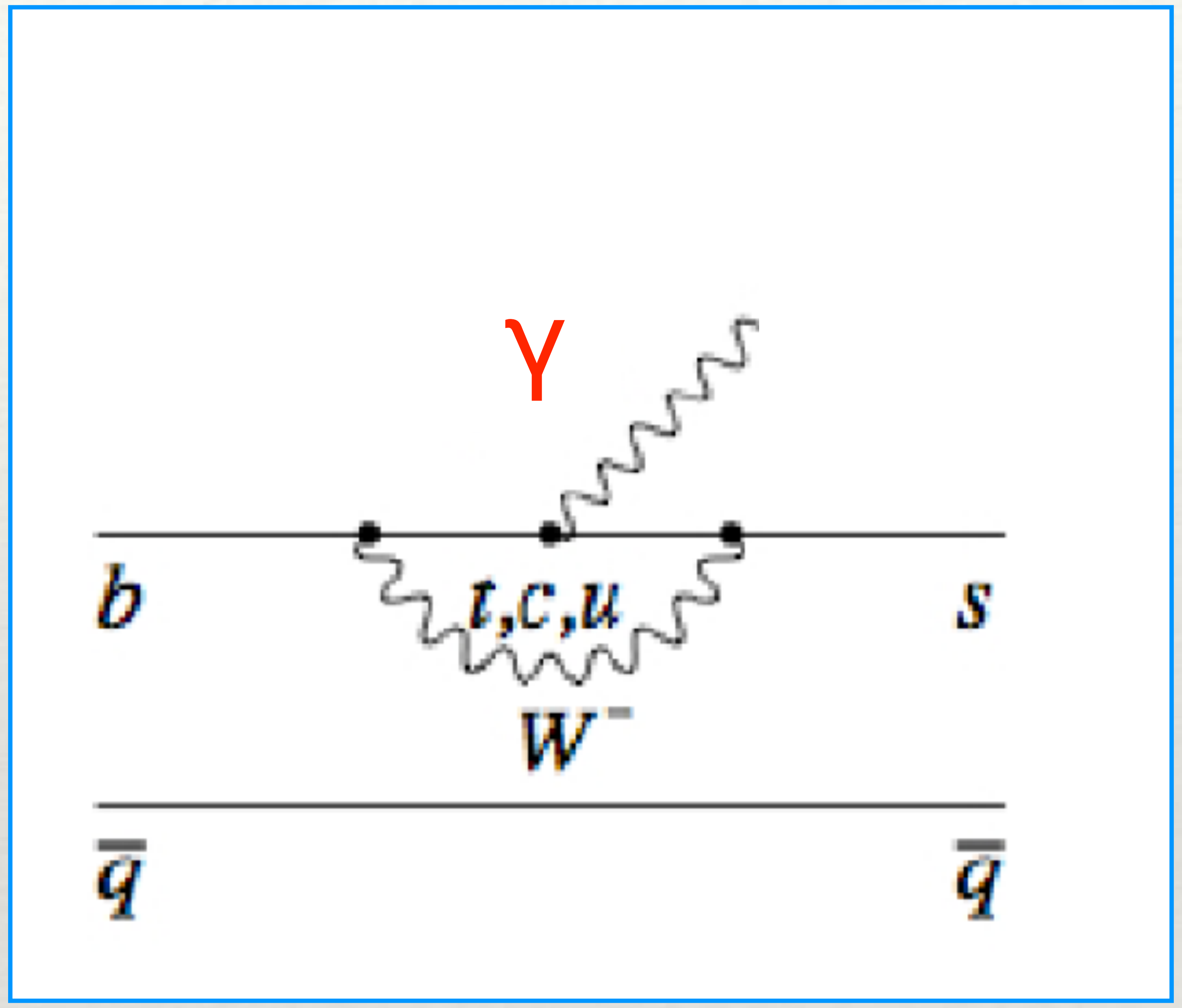


Only Z involved.

Also sensitive to Dark Matter in final state.

@IPHC

$b \to s \gamma$



Only γ involved.

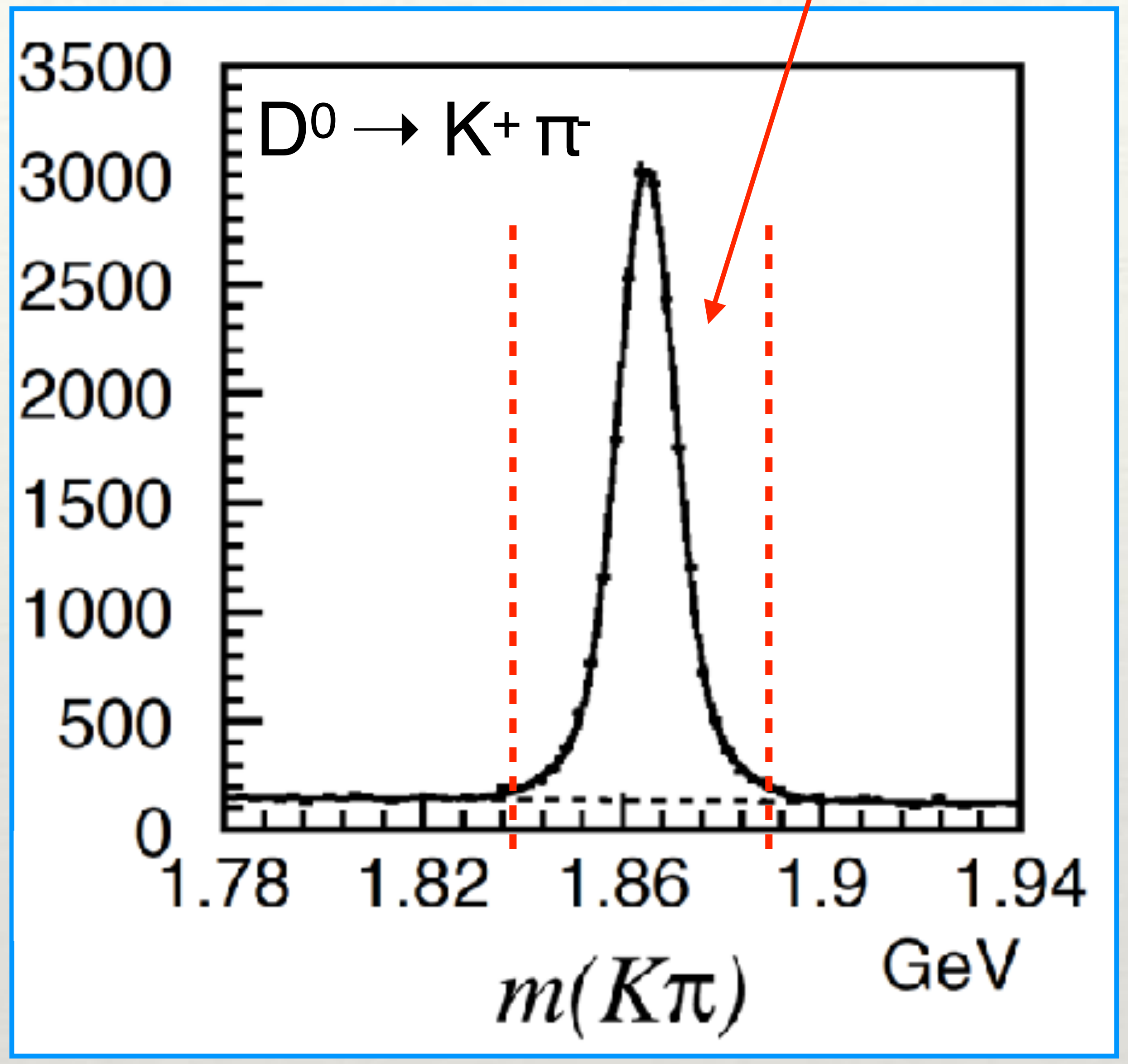
Very sensitive to left-right chiral structure.

@IPHC

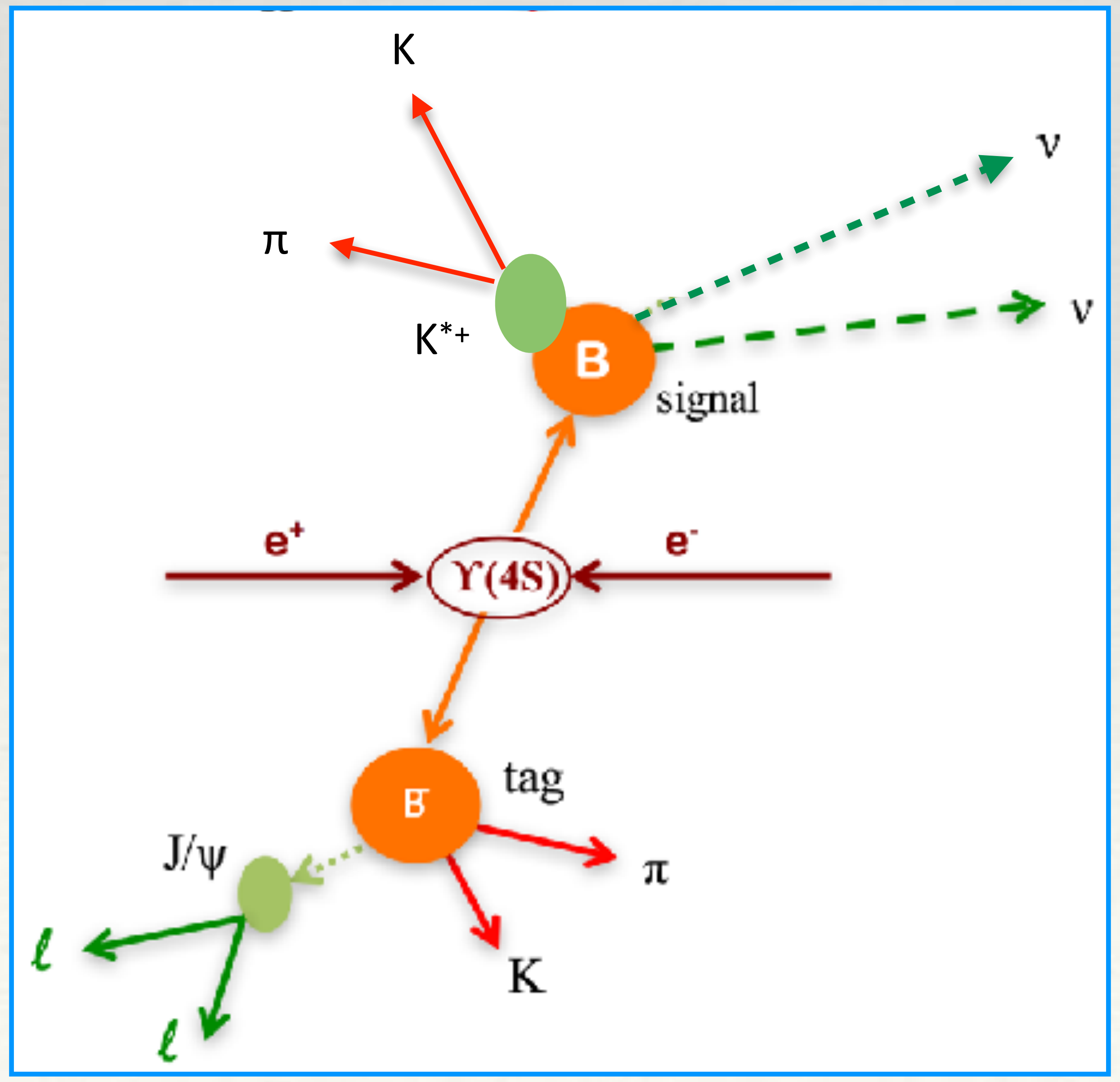
$b \to s \nu \nu$ process

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

region with good Signal/Background ratio



- $B \to K^{(*)} \nu \nu$ decays yet un-observed. Very rare decay & signal is K + nothing.



- The trick: reconstruct companion B, then search for additional K & missing energy.

- Many different B_{Tag} final states possible (see PDG), each one with total B.R. ~ O(‰).
  Key point is to reconstruct as many B_{Tag} as possible ➛ Full Event Interpretation.

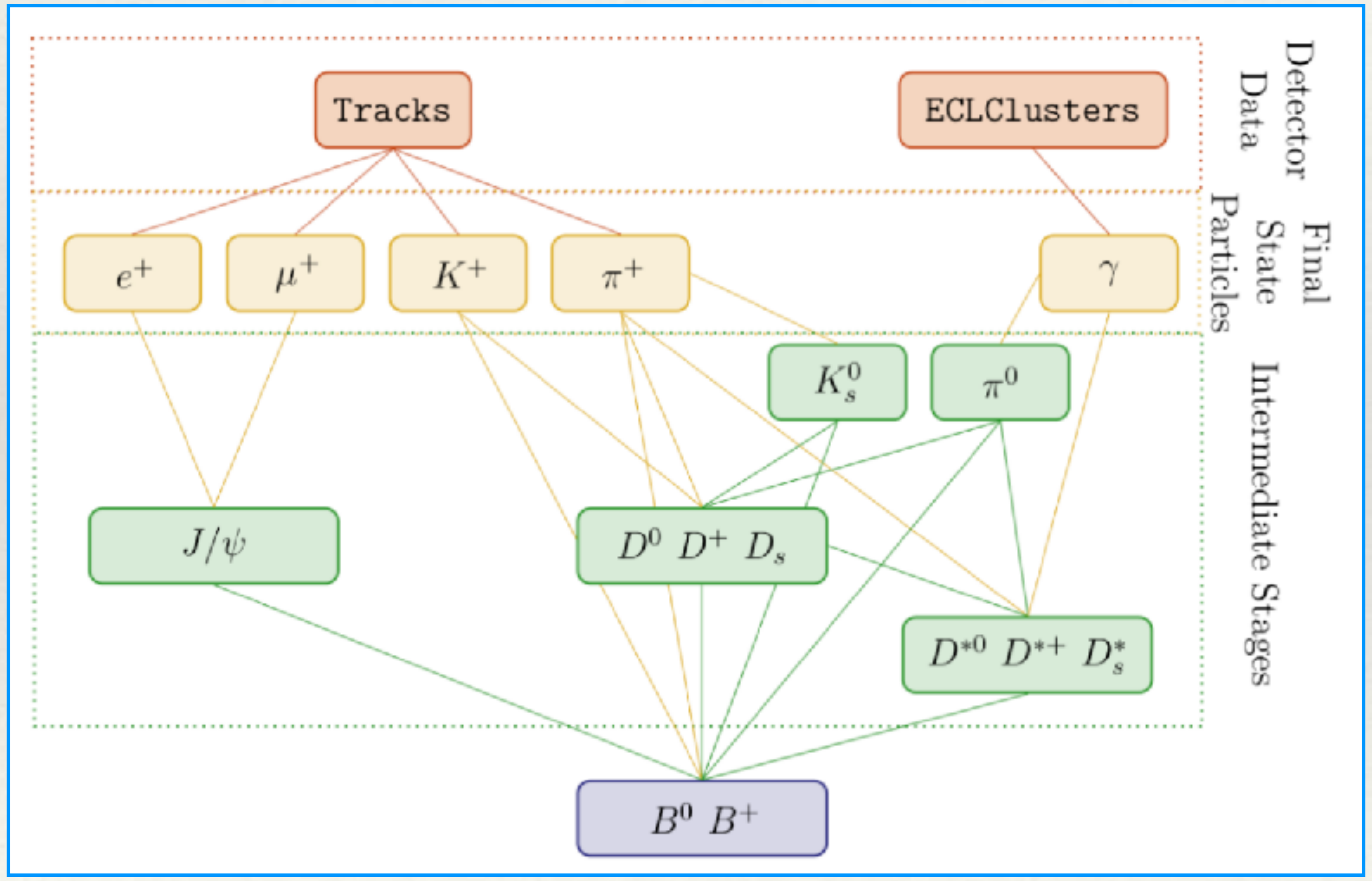
Full Event Interpretation

- Why a dedicated multivariate algorithm?

Example: try to reconstruct $D^0 \to K^- \pi^+ \pi^+ \pi^-$ 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 $B^+_{Tag} \to D^0 (\to K^- \pi^+ \pi^+ \pi^-) \pi^+$.

➛ impossible to do for 10 000 different final states.



- Each step reconstructed with a dedicated Boosted Decision Tree:

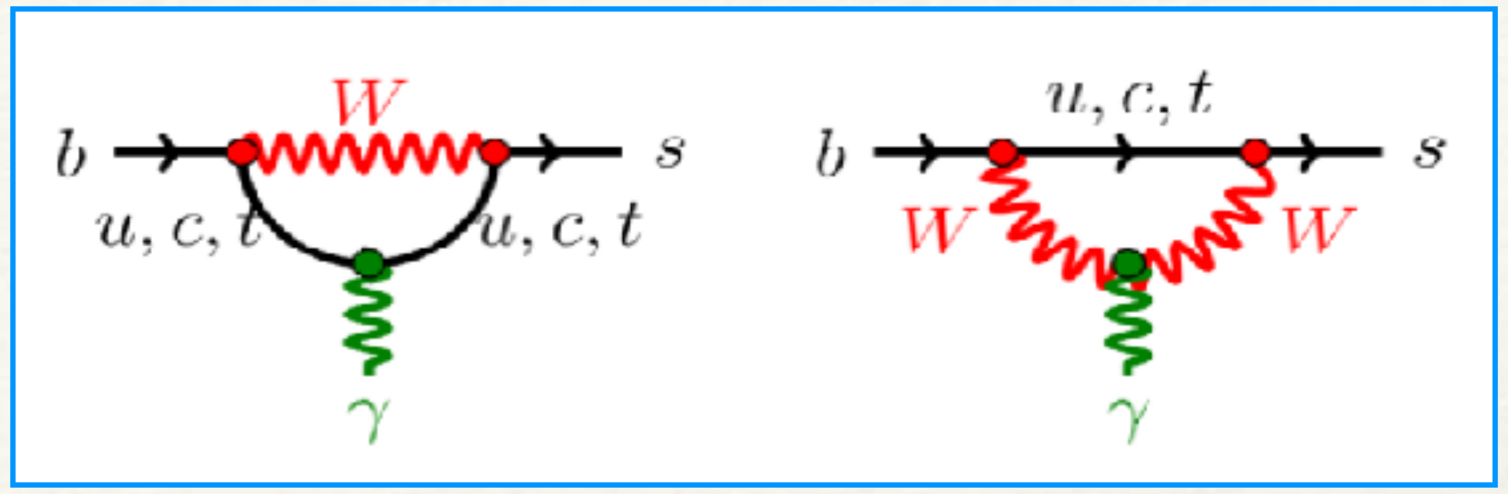
detector objects → final state particles → intermediate particles → one B_{Tag} decay channel.

Final efficiency ~ %.

- To improve B_{Tag} reconstruction efficiency: development of a new algorithm based on Deep Learning, @IPHC.

➛ Thesis work of Lucas Martel (2020-2023) **+ M2 internship proposed in 2021.**

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



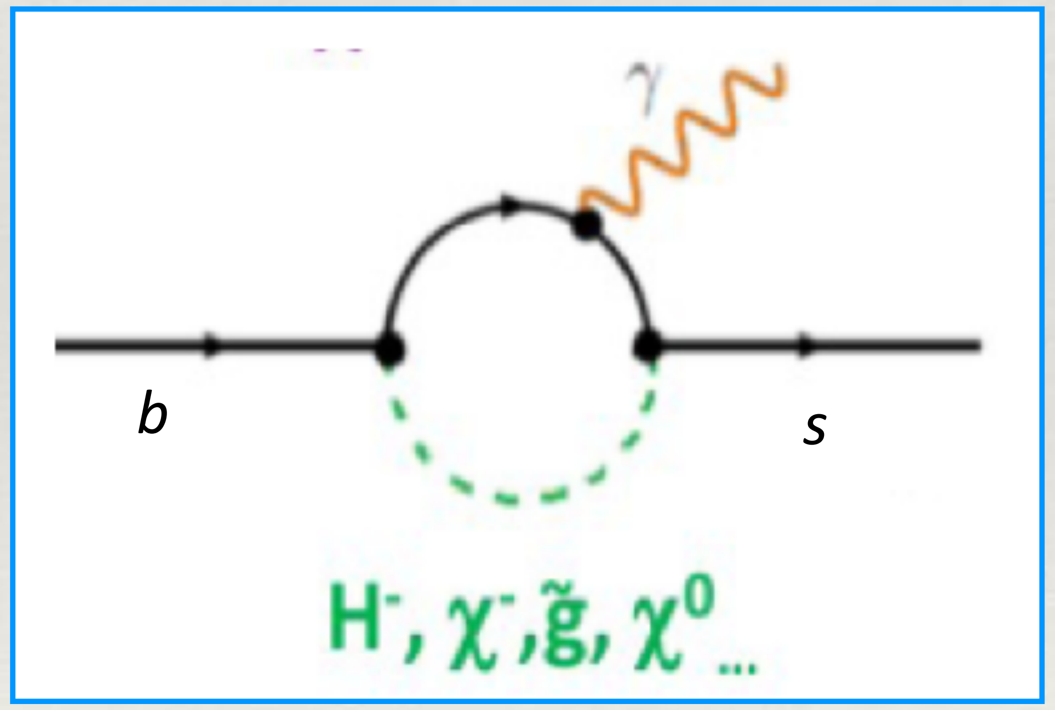
- V-A coupling in the SM: photons produced mainly with a left-handed polarisation in $b \to s\gamma$ transitions.

- Time-dependent CP asymmetry:

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

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

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



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

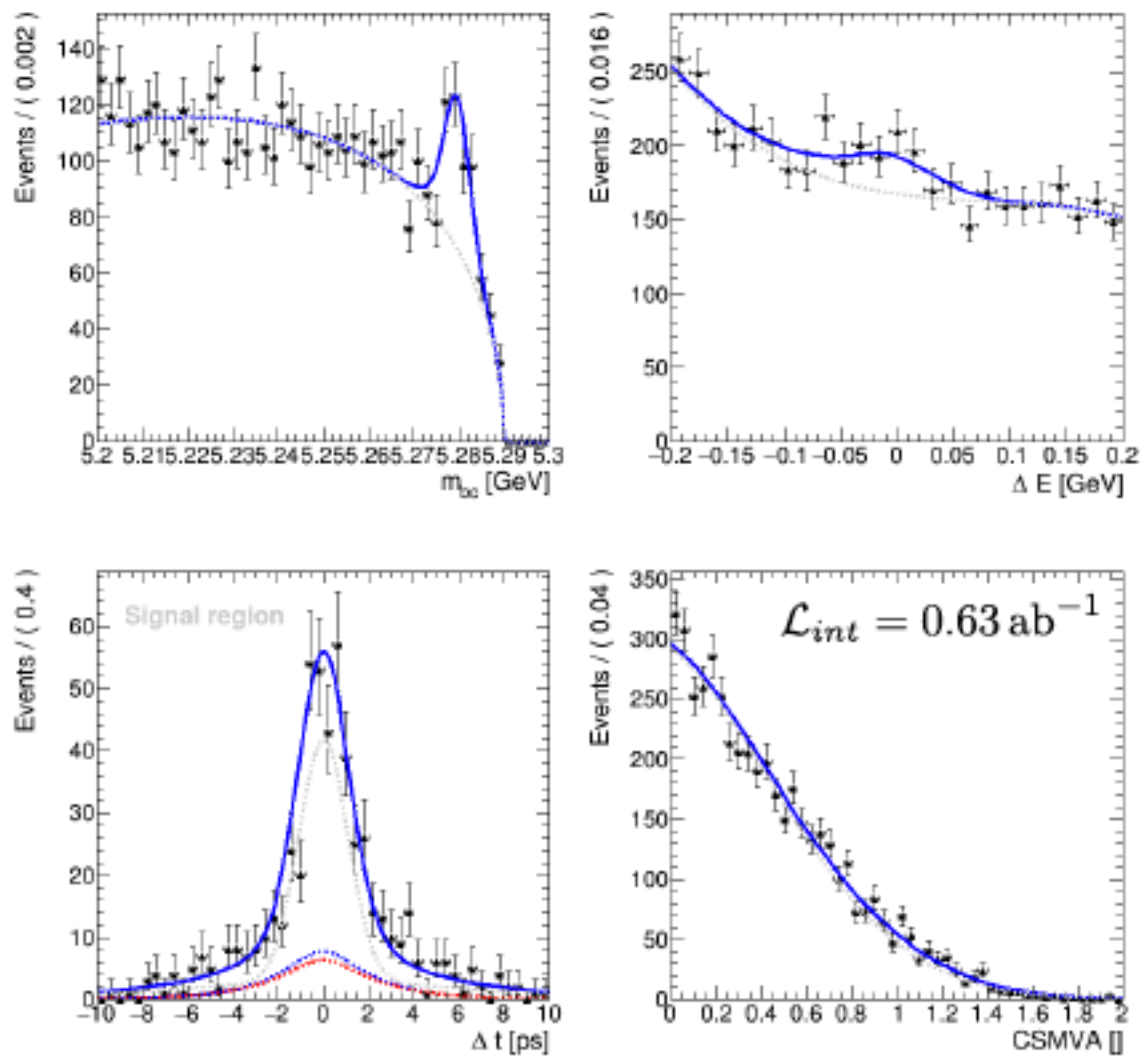
- Experimentally: measurement of A_{CP} with $B^0 \to K_S{}^0 \pi^+ \pi^- \gamma$ and $B^0 \to K_S{}^0 \pi^0 \pi \gamma$ decays.

➛ Thesis work of Reem Rasheed (2017-2020) and Tristan Fillinger (2019-2022) **+ new thesis proposed 2021-2024.**

b → s γ 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:

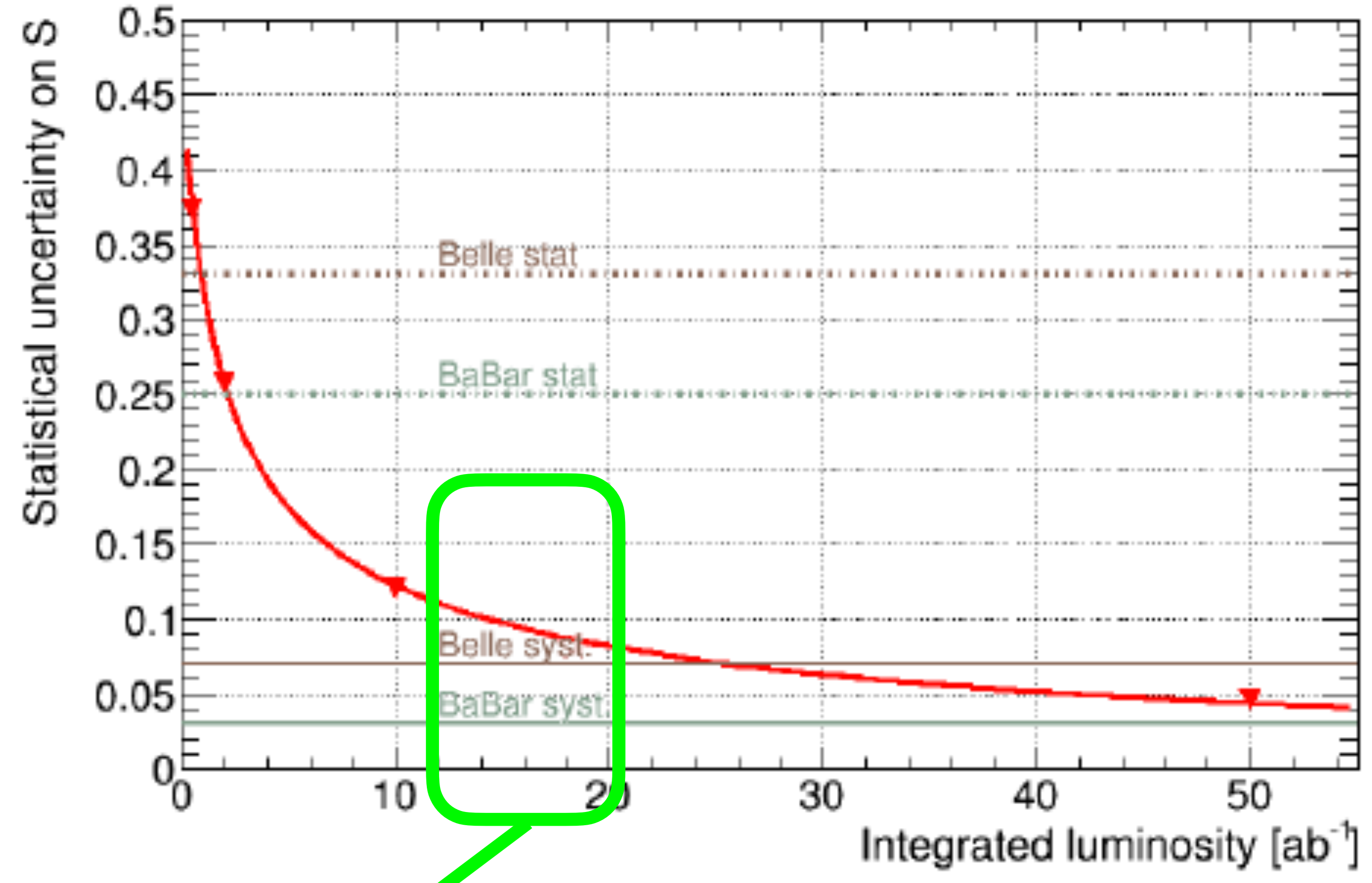
$$A = -0.2 \pm 0.26$$
$$S = \quad 0.01 \pm 0.37$$

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**

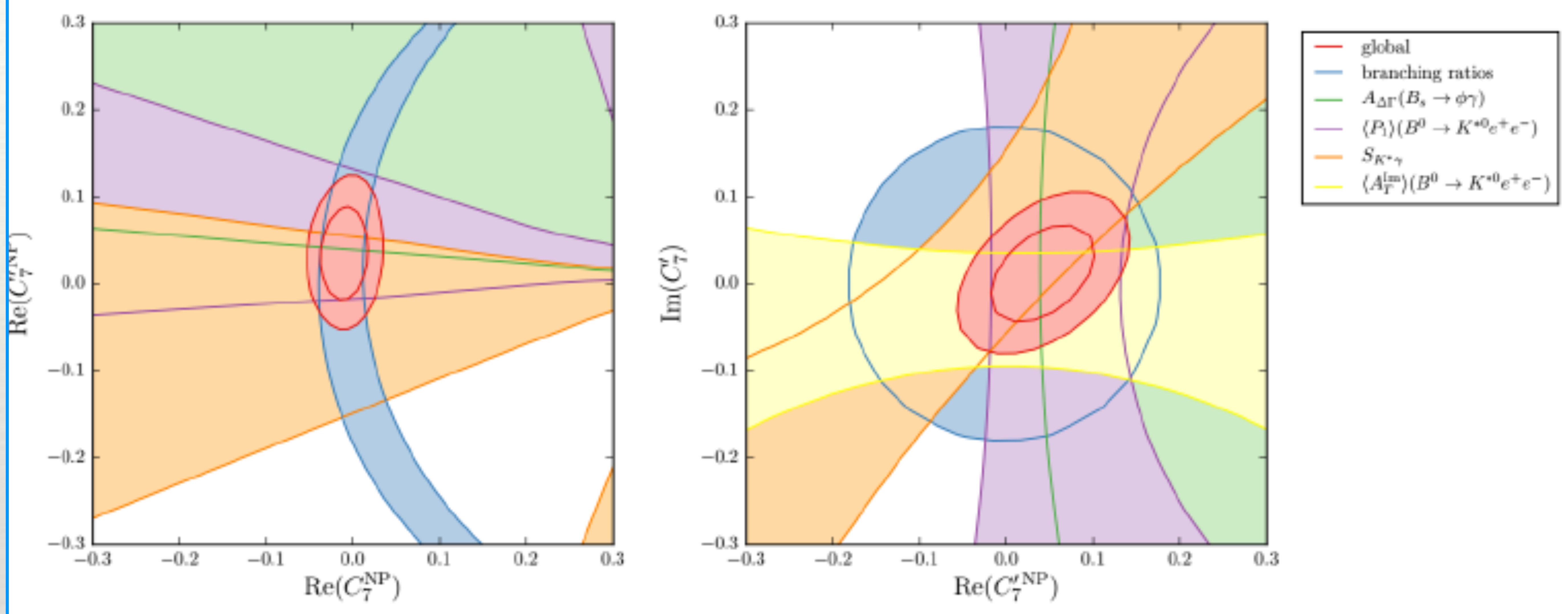
Bilokin S. ALPS 2018 7

Proposed thesis

b → s γ process: photon helicity (3)

- This measurement constrains Wilson coefficients C_i of the effective Hamiltonian of New Physics:

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

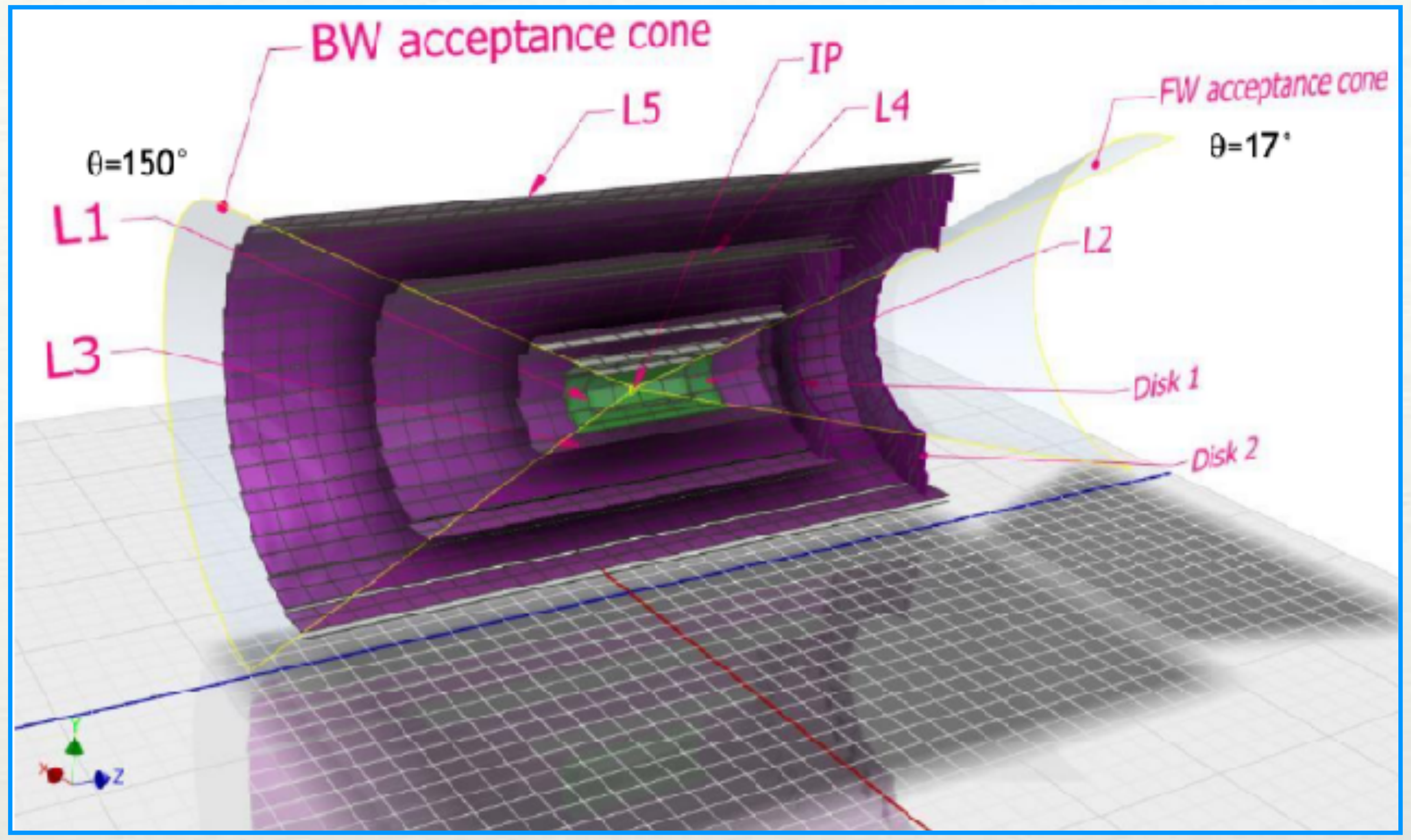


Paul, Straub: arXiv:1608.02556

➛ also some work possible with theorists during the thesis.

Upgrade of the Vertex detector

- Upgrade of the SuperKEKB collider and the Belle II detector scheduled in 2026.

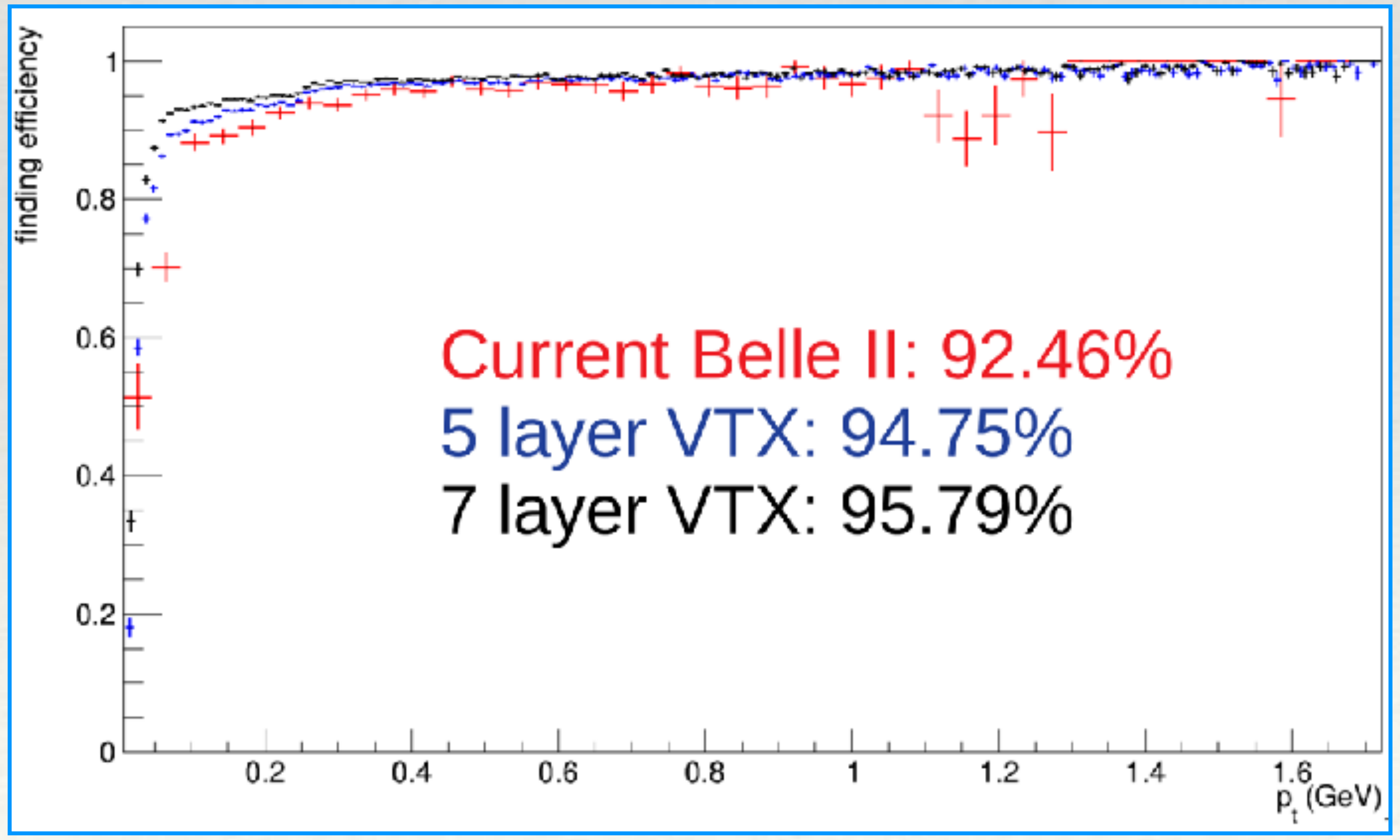


- Performance studies for the upgrade of the Vertex detector:

1. Preliminary studies based on fast simulation (parametrised perfomances).
2. Development of the full simulation of the upgraded vertex detector and of its use for track reconstruction.
3. Tracking and vertexing performance studies based on full simulation.

   ➛ Thesis work of Tristan Fillinger (2019-2022)

4. Study of performances in a benchmark physics channel:
   - Is tracking efficiency more important than pointing precision?
   - Can we decrease track fake rate?



➛ NEXT STEPS: during M2 internship & thesis 2021-2024.

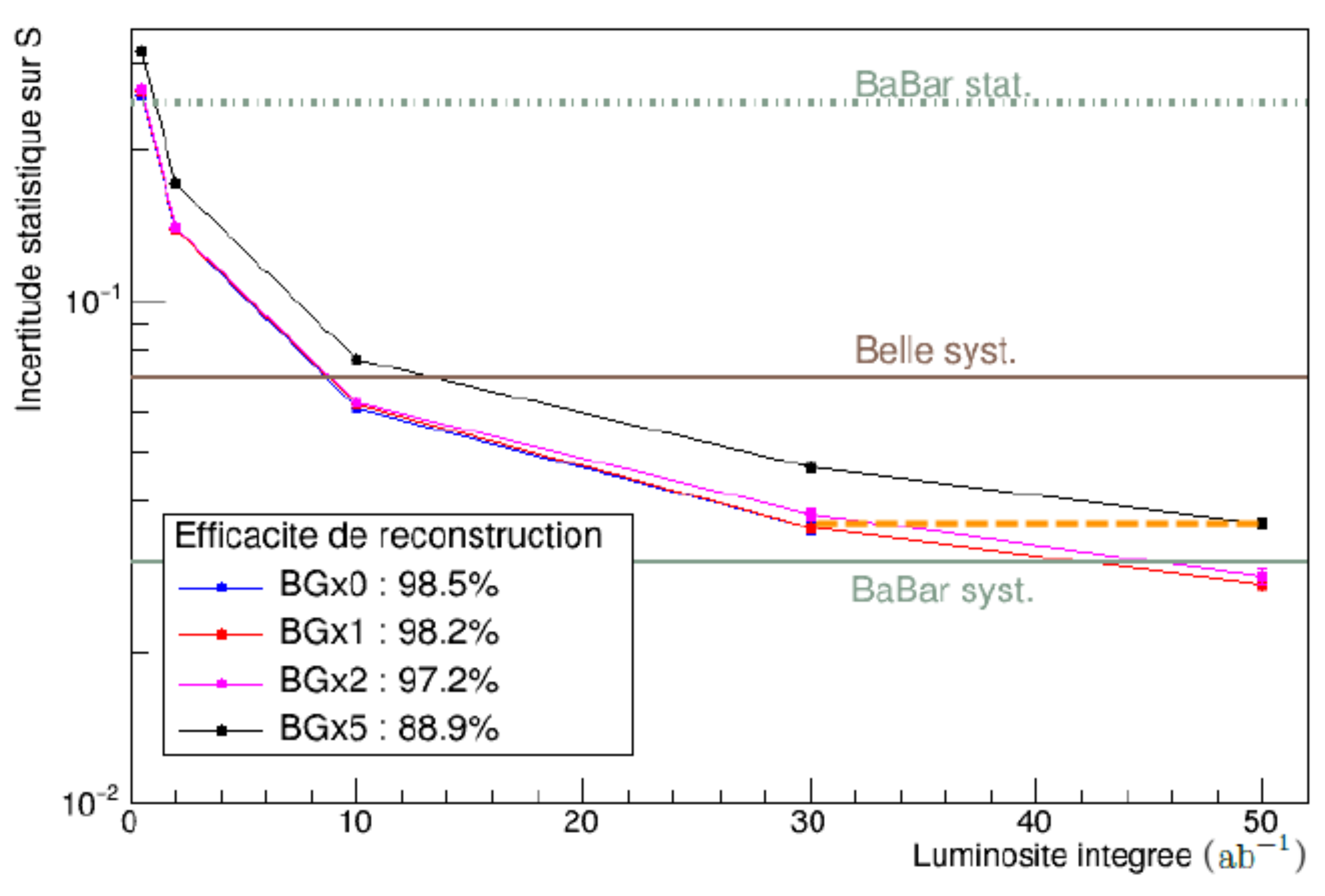
M2 internship and PhD thesis projects in Belle II at IPHC

- M2 internship subject #1: **Improvement of the precision on the measured time-dependent CP asymmetry of $B \rightarrow K_S \pi^+ \pi^- \gamma$ decays in Belle II with an upgraded fully pixelated vertex detector.**

- Thesis subject: **Measurement of time-dependent CP asymmetries of $B \rightarrow K_{res} \gamma$ decays in the Belle II experiment and study of the performance of an upgraded fully pixelated vertex detector.**

- Supervisor: **Christian Finck**

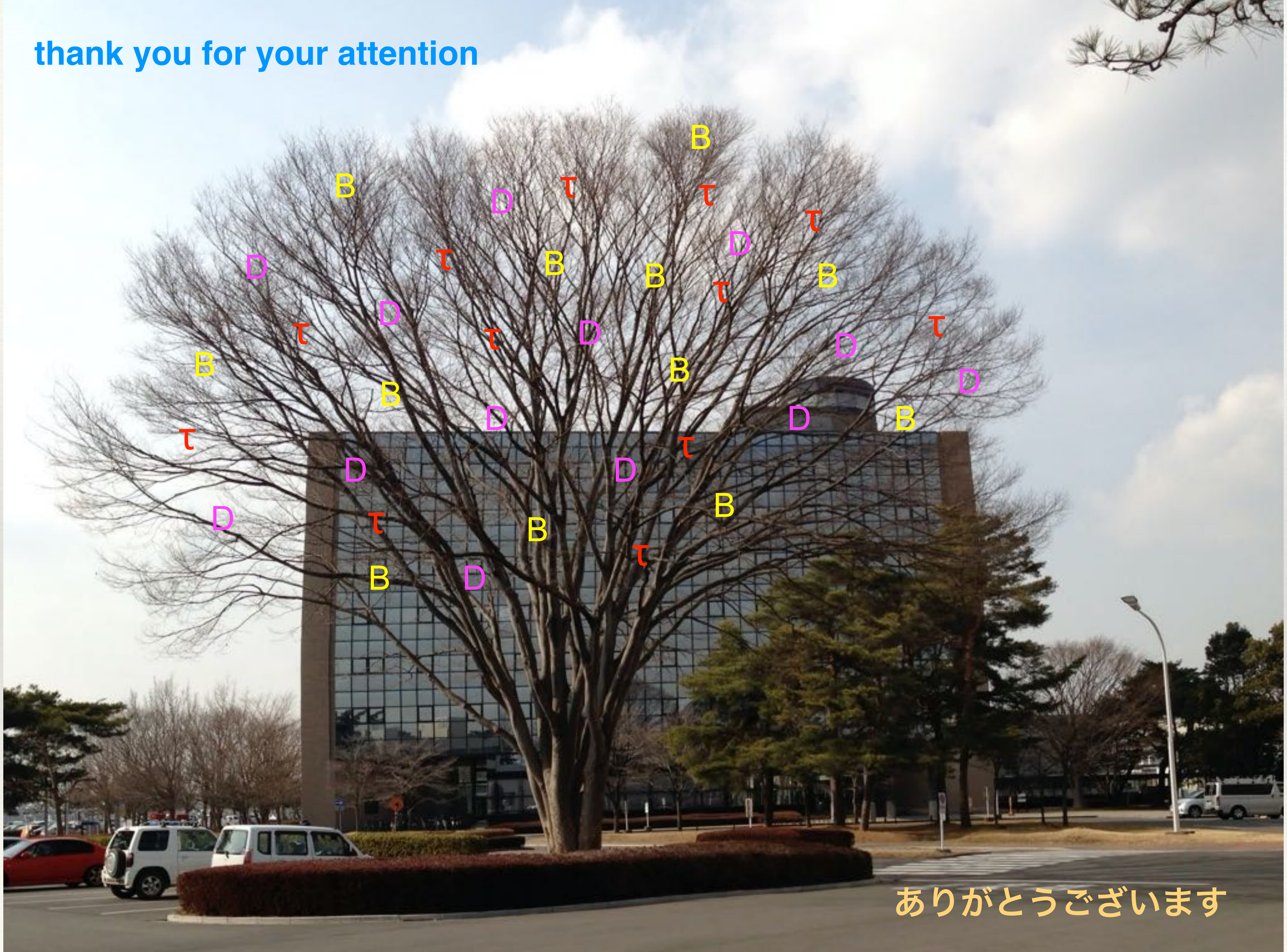
  christian.finck@iphc.cnrs.fr.



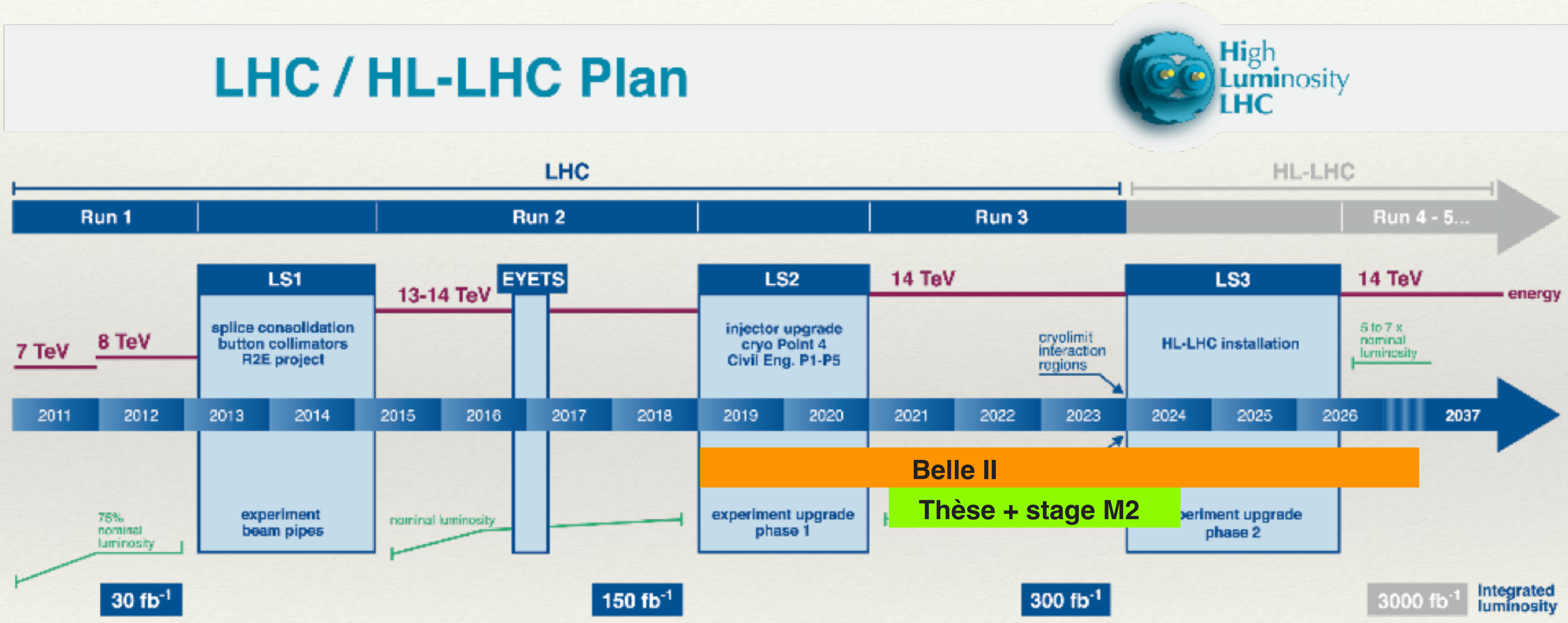
- M2 internship subject #2: **Development of a Full Event Interpretation algorithm based on Deep Learning.**

- Supervisor: **Giulio Dujany**

  giulio.dujany@iphc.cnrs.fr


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

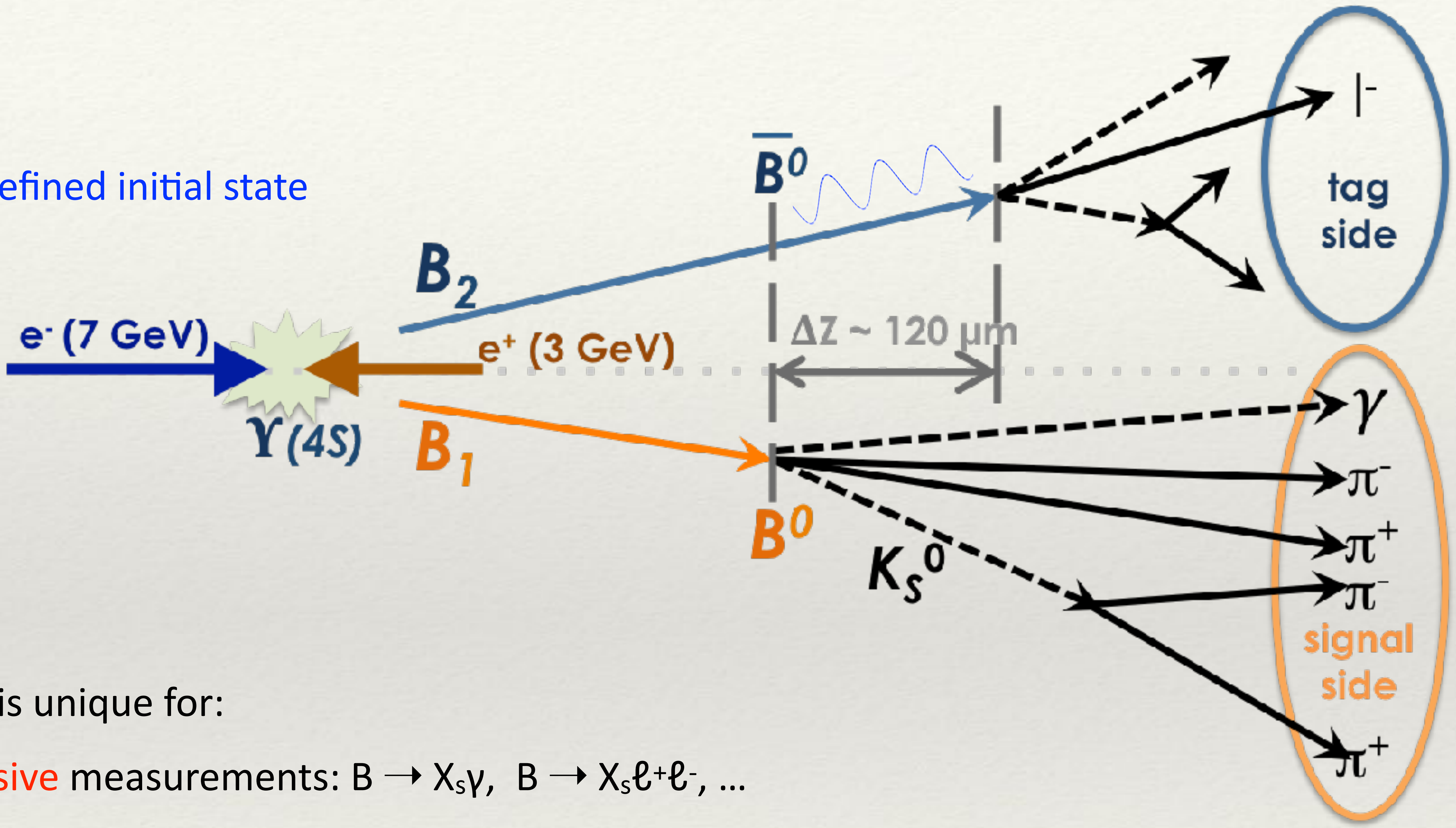
Collider runs



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.