LHC Days in Split

Belle II

status and physics prospects

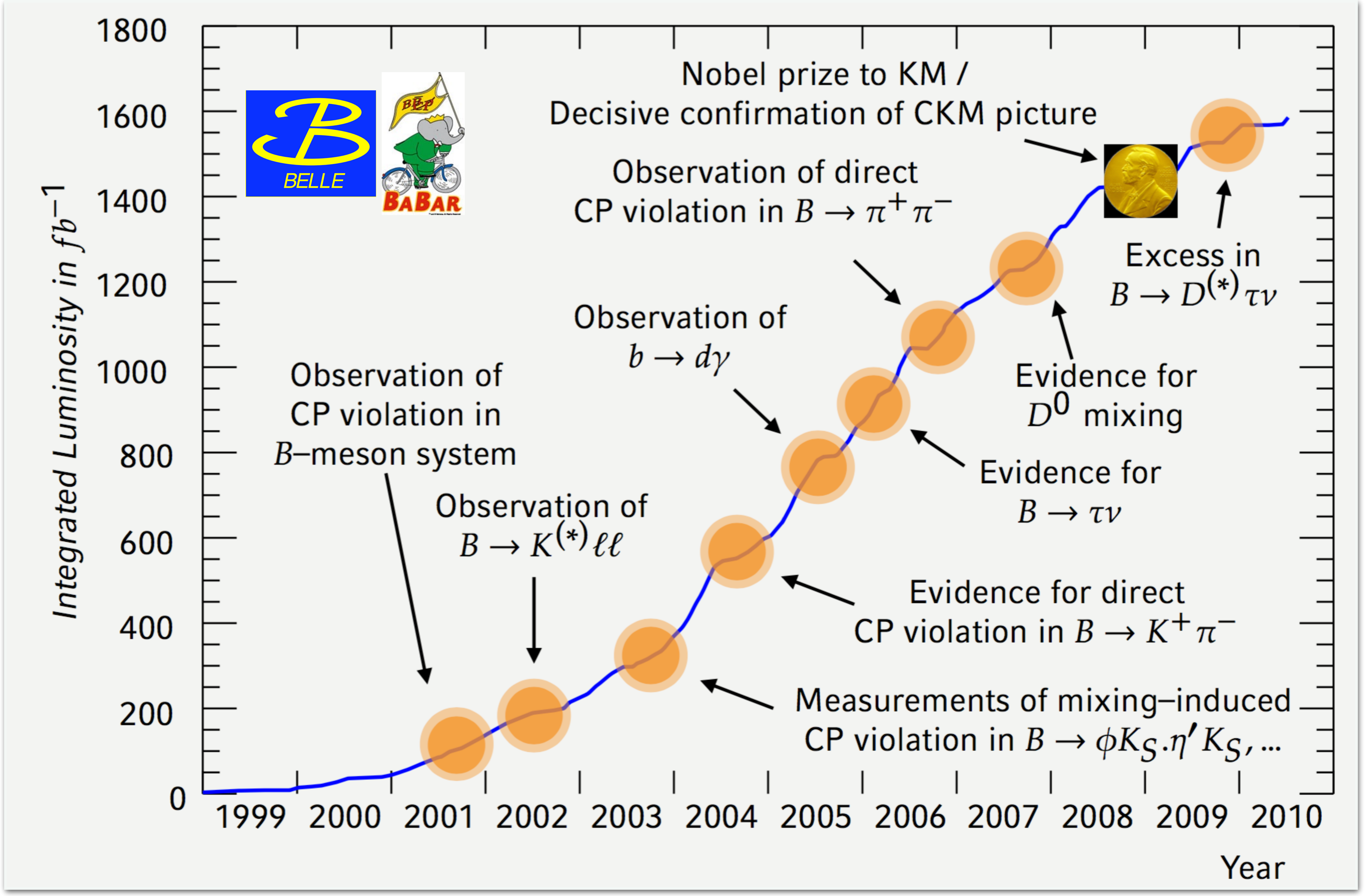
Anže Zupanc
Jožef Stefan Institute and University of Ljubljana
on behalf of the Belle II Collaboration

Outline

- ***B factories***
- *Accelerator*
- *Detector*
- *Physics*

B-factories 1st gen.: ***Test of the Flavour Sector of the SM***

BaBar (PEPII@SLAC) and **Belle** (KEKB@KEK)



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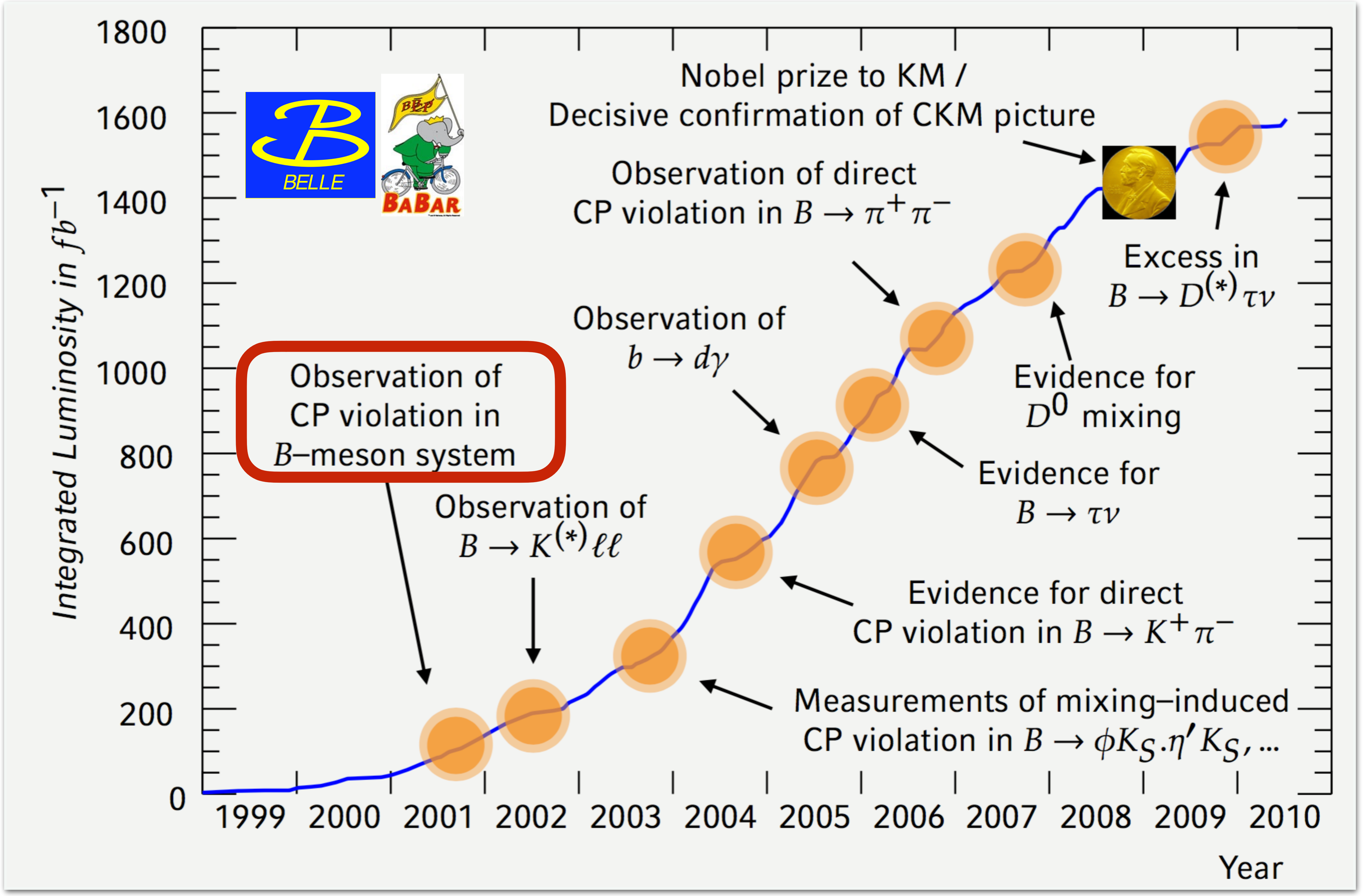

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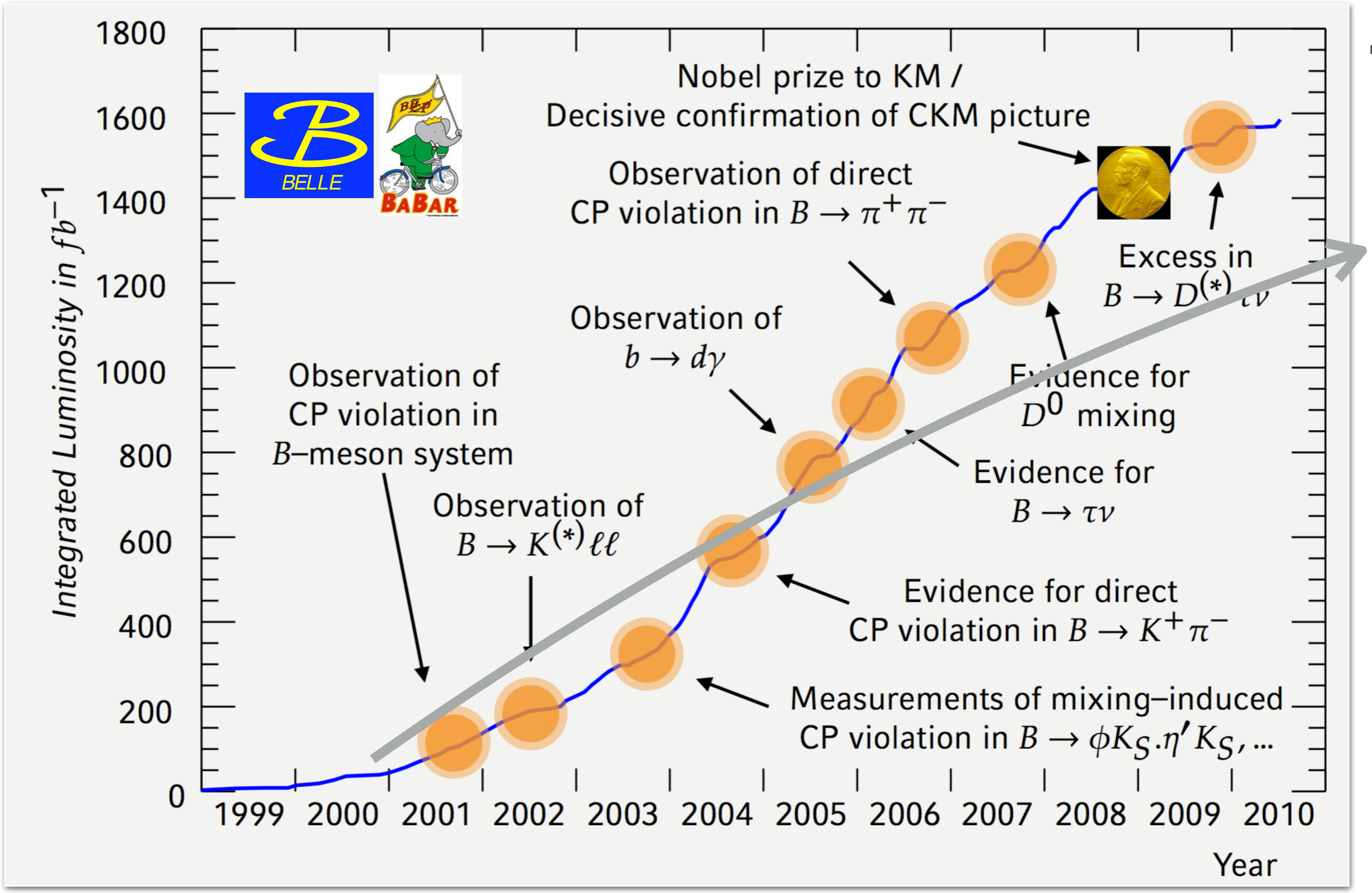
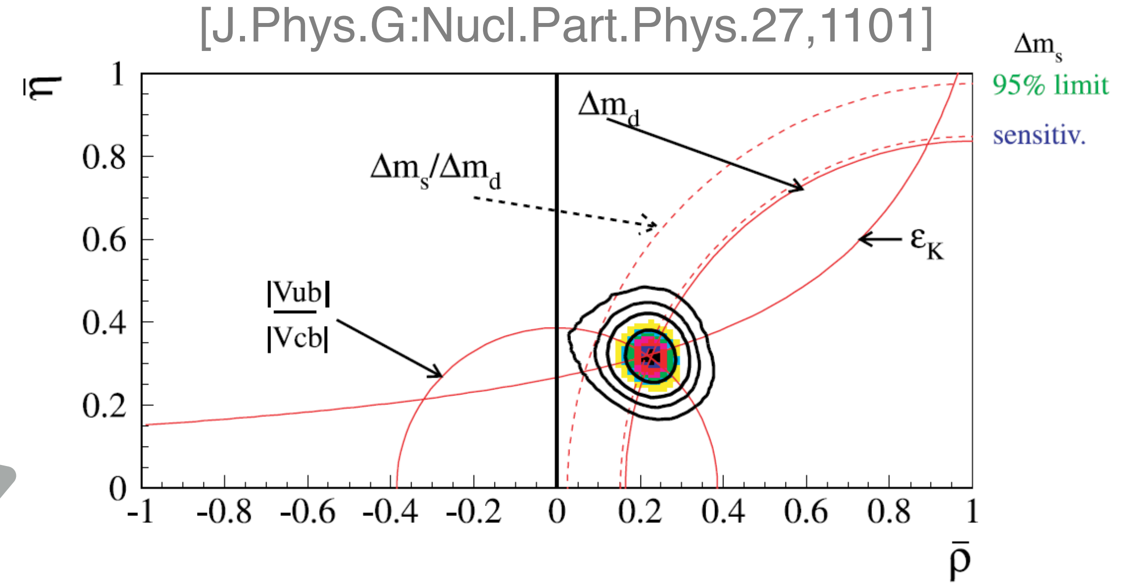


Unitarity Triangle @ 2000



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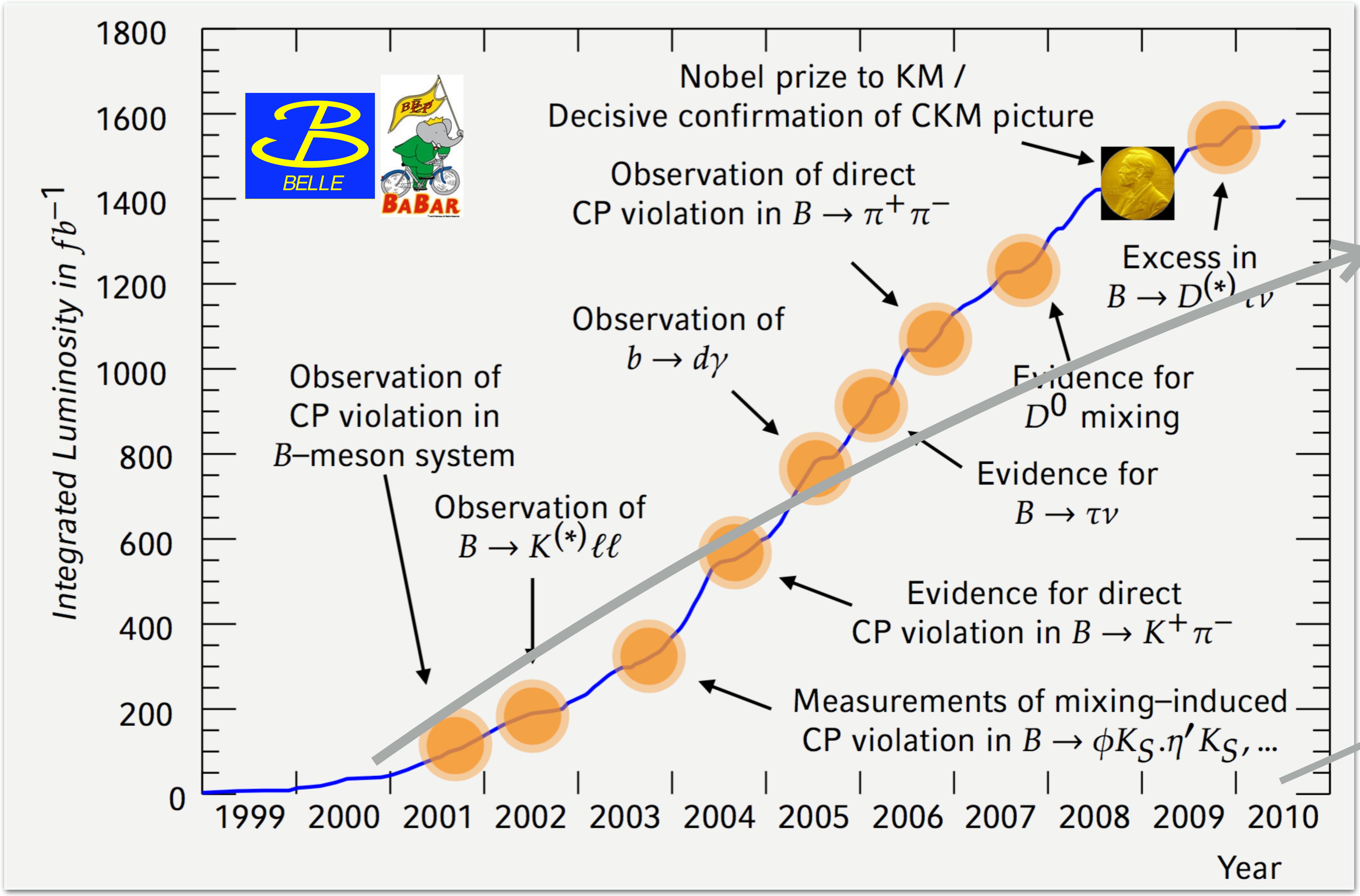

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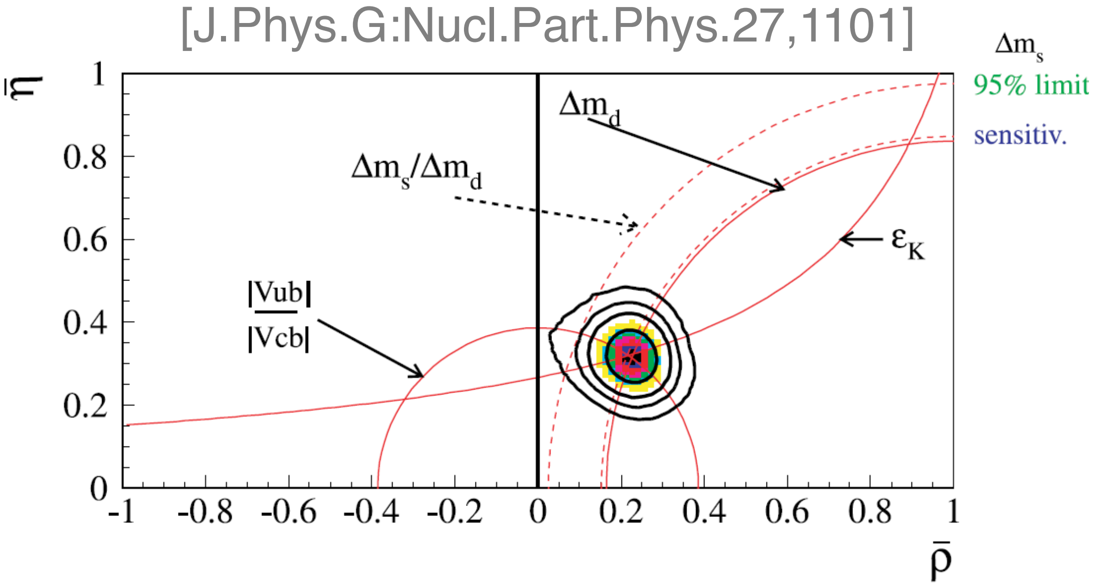
[J.Phys.G:Nucl.Part.Phys.27,1101]



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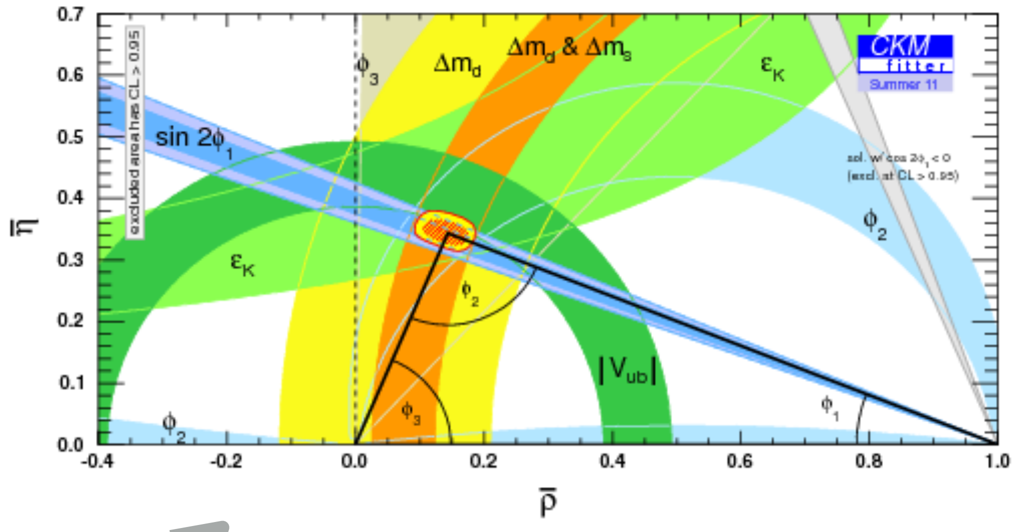
[CKM fitter]



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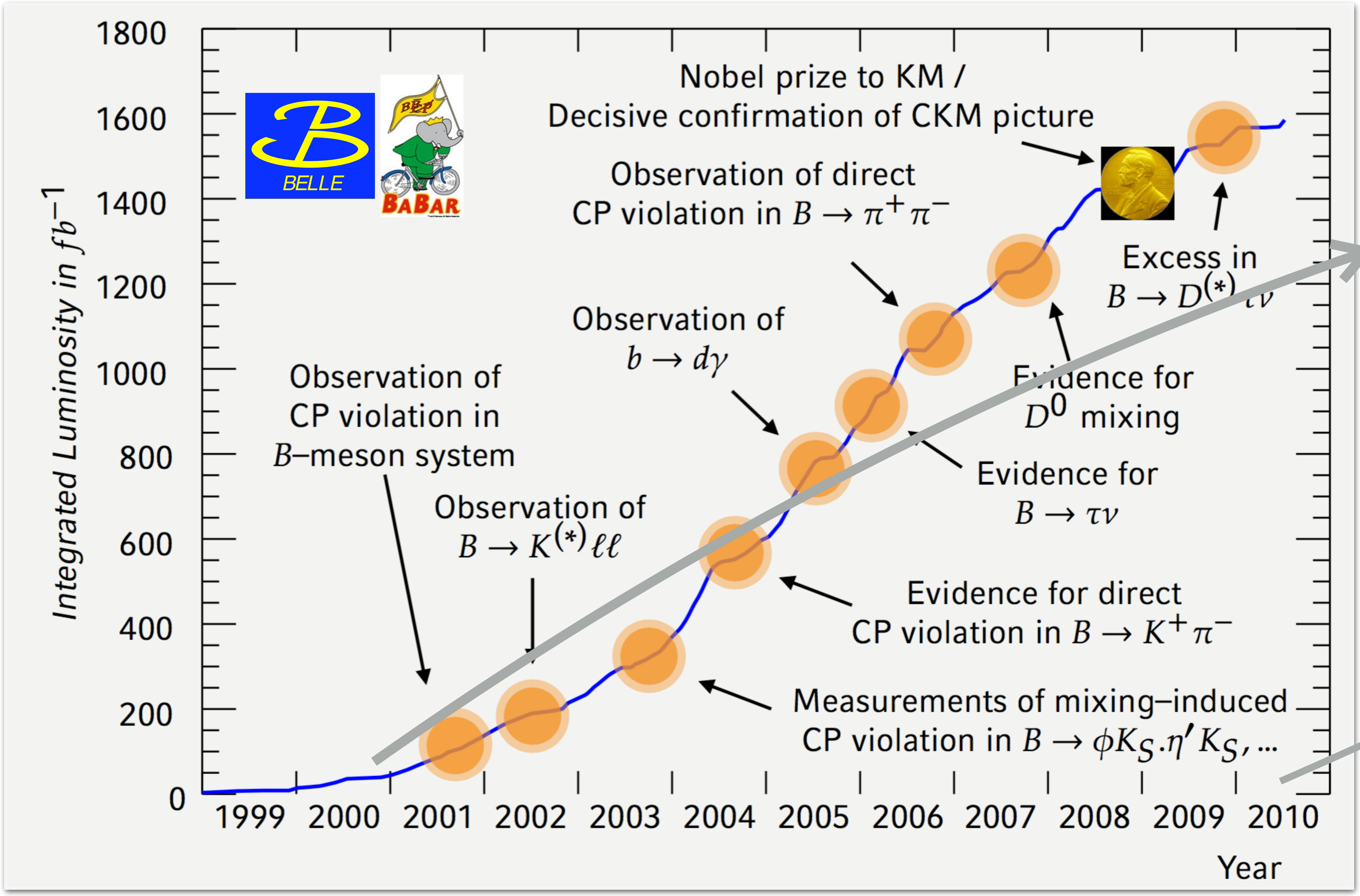

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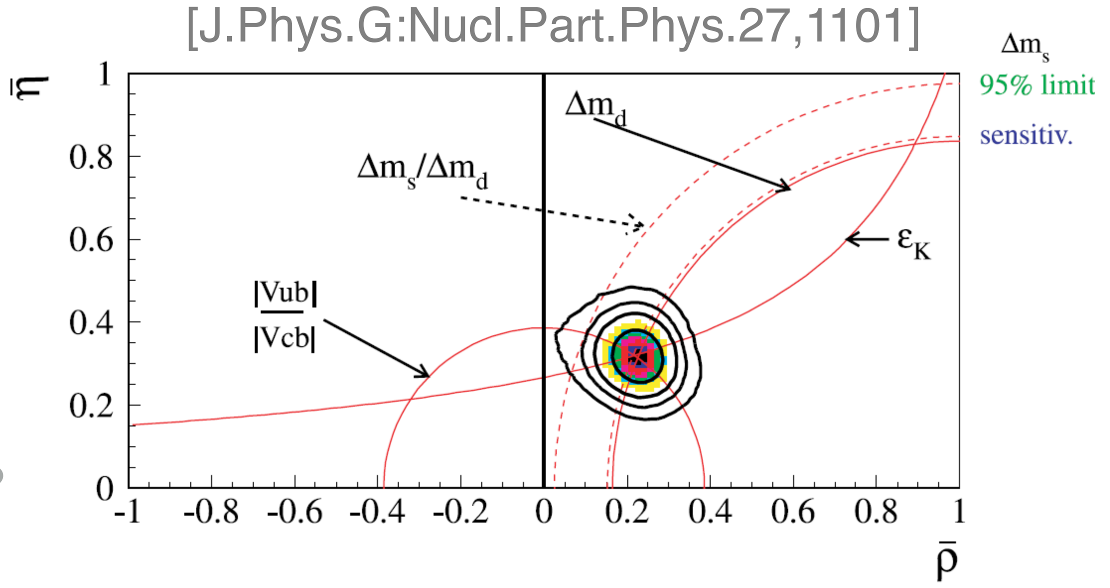

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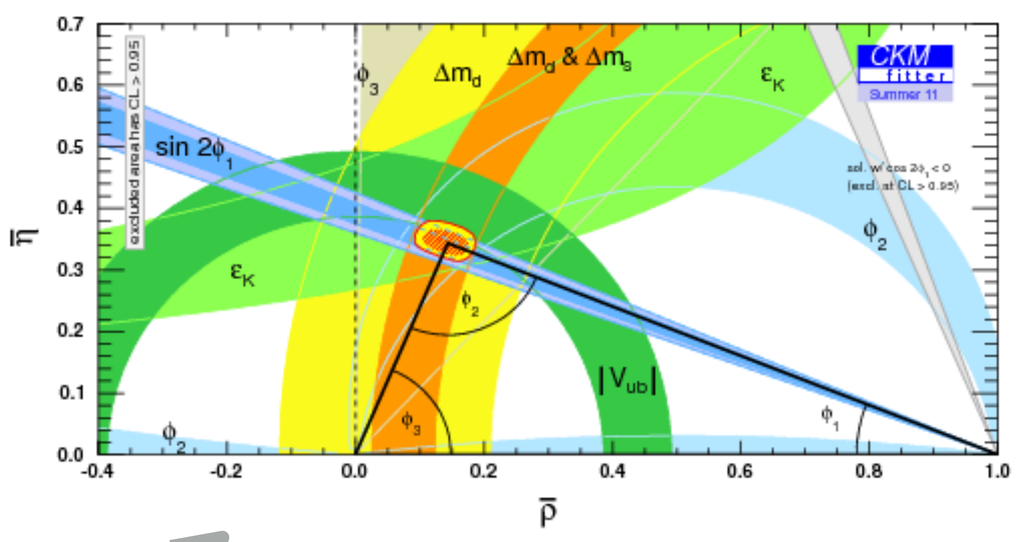

Confirmation of the Kobayashi-Maskawa mechanism of CPV.

B-factories 2nd gen.: ***Quest for New Physics***

Belle II at SuperKEKB (KEK):

- an intensity frontier experiment being built in Tsukuba, Japan
- aims to collect 50x larger data sample compared to Belle+BaBar in the next decade to reveal new physics through precision studies of rare or suppressed decays

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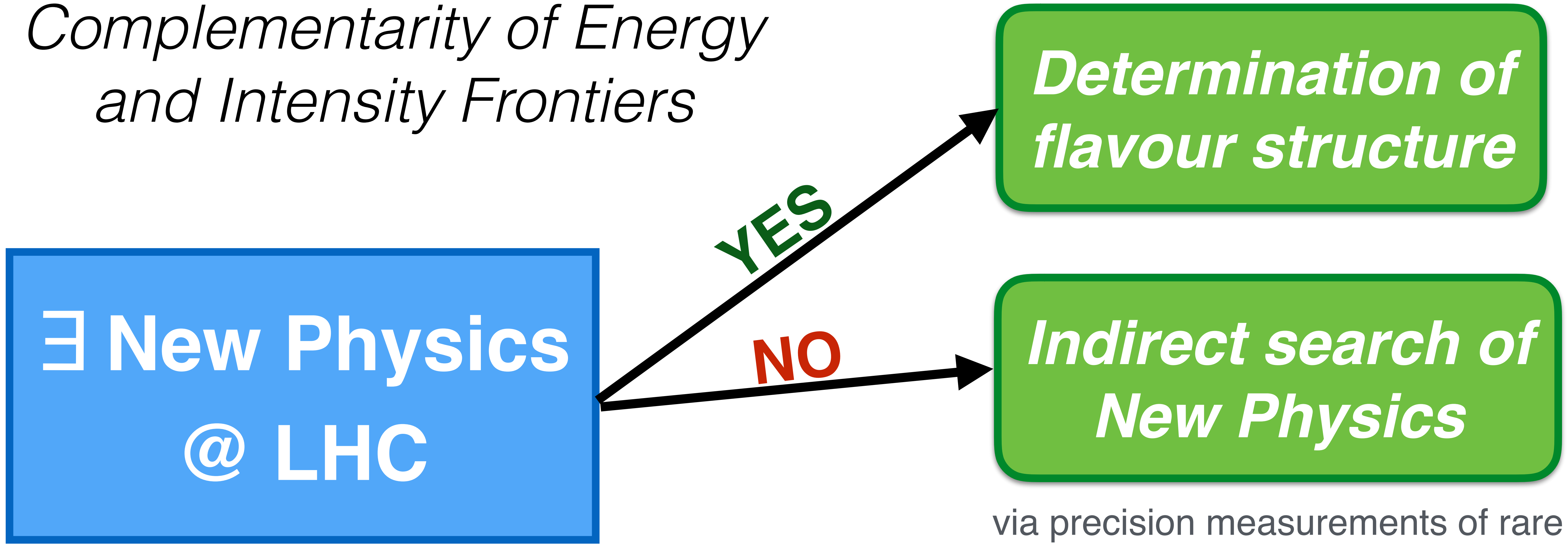
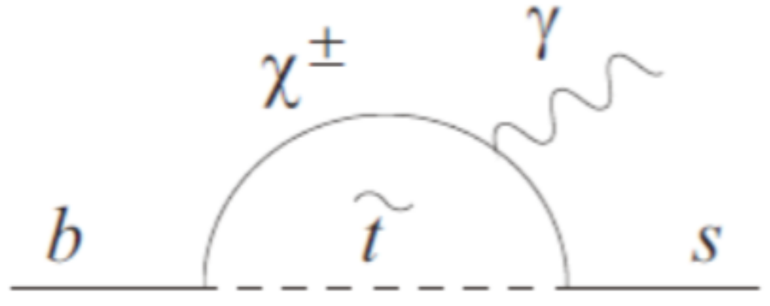


via precision measurements of rare days and forbidden processes



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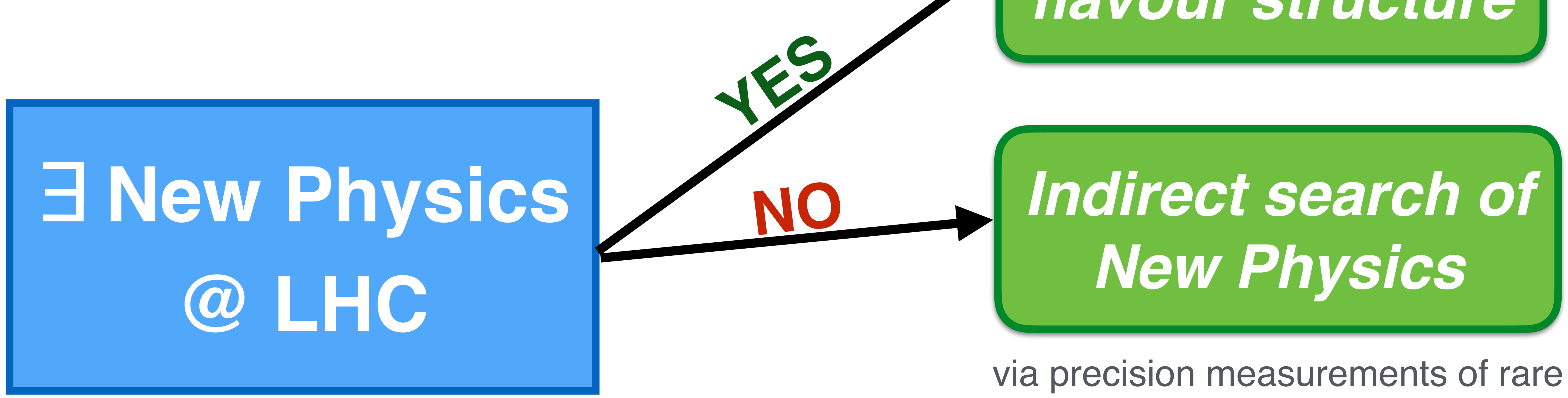

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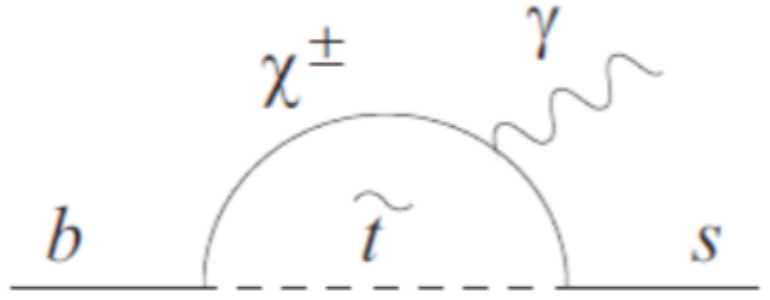
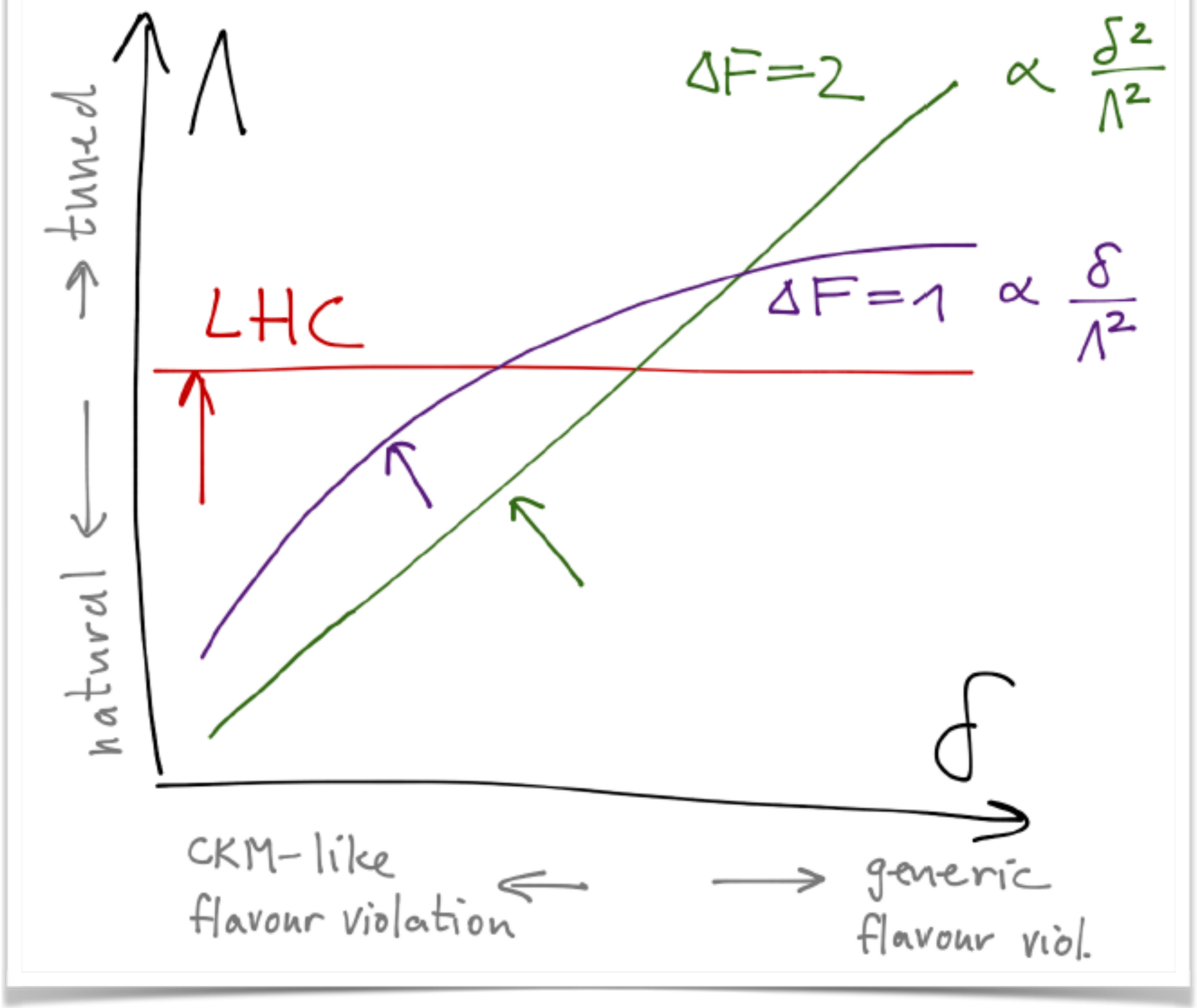


Courtesy of David Straub



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Spectacular examples from history:

1. $\Gamma(K_L^0 \to \mu\mu) \ll \Gamma(K \to \mu\nu_\mu)$

   $\Longrightarrow$ *charm quark [GIM,1970]*

2. *Neutral kaon mixing (Δm_K)*

   $\Longrightarrow$ *charm mass [Gaillard-Lee,1974]*

3. *CP Violation in kaon system (ϵ_K)*

   $\Longrightarrow$ *3 generations [KM,1973]*

4. *B meson mixing (Δm_B)*

   $\Longrightarrow$ *top mass [various,1973]*

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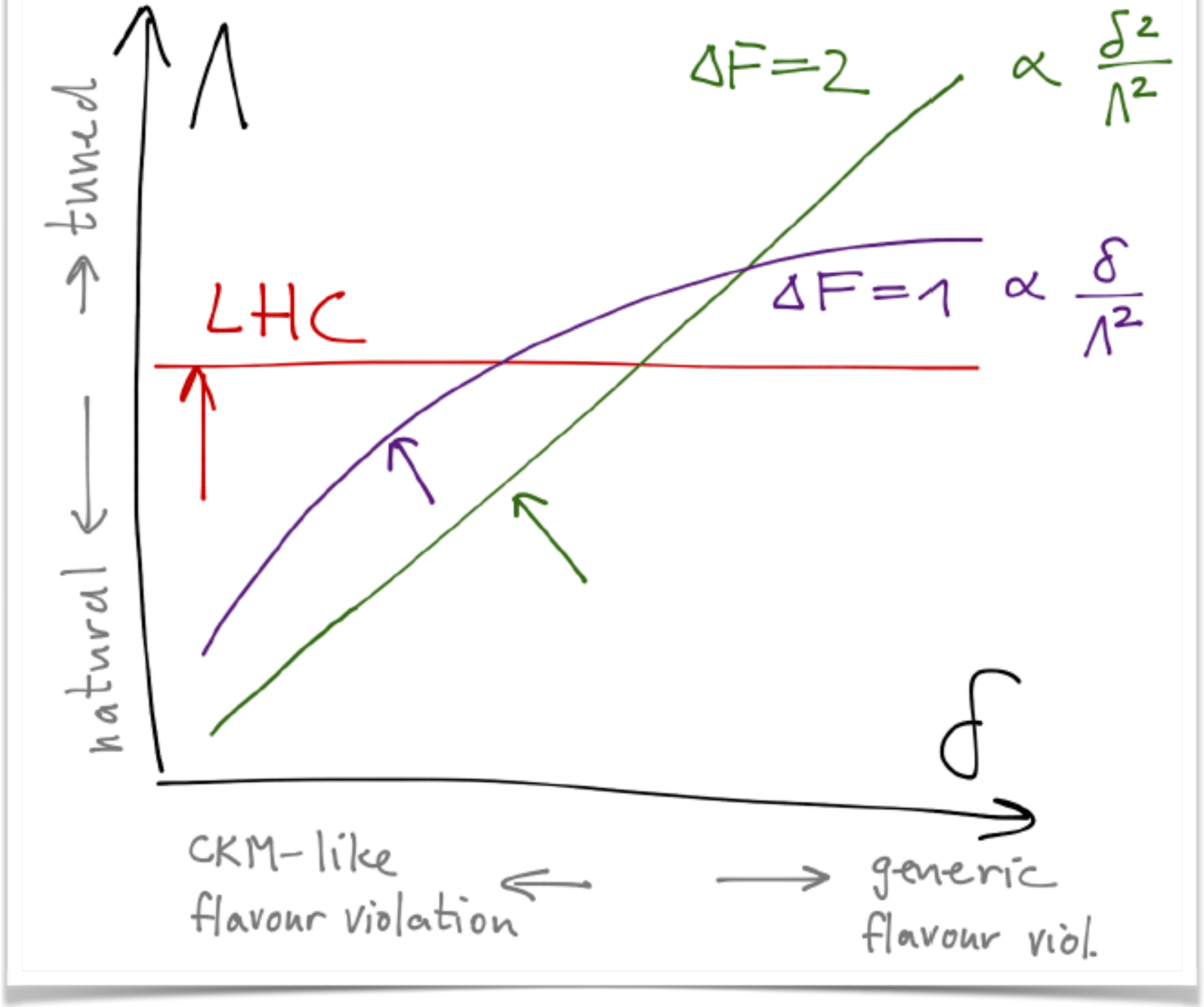

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Advantages of e^+e^- environment:

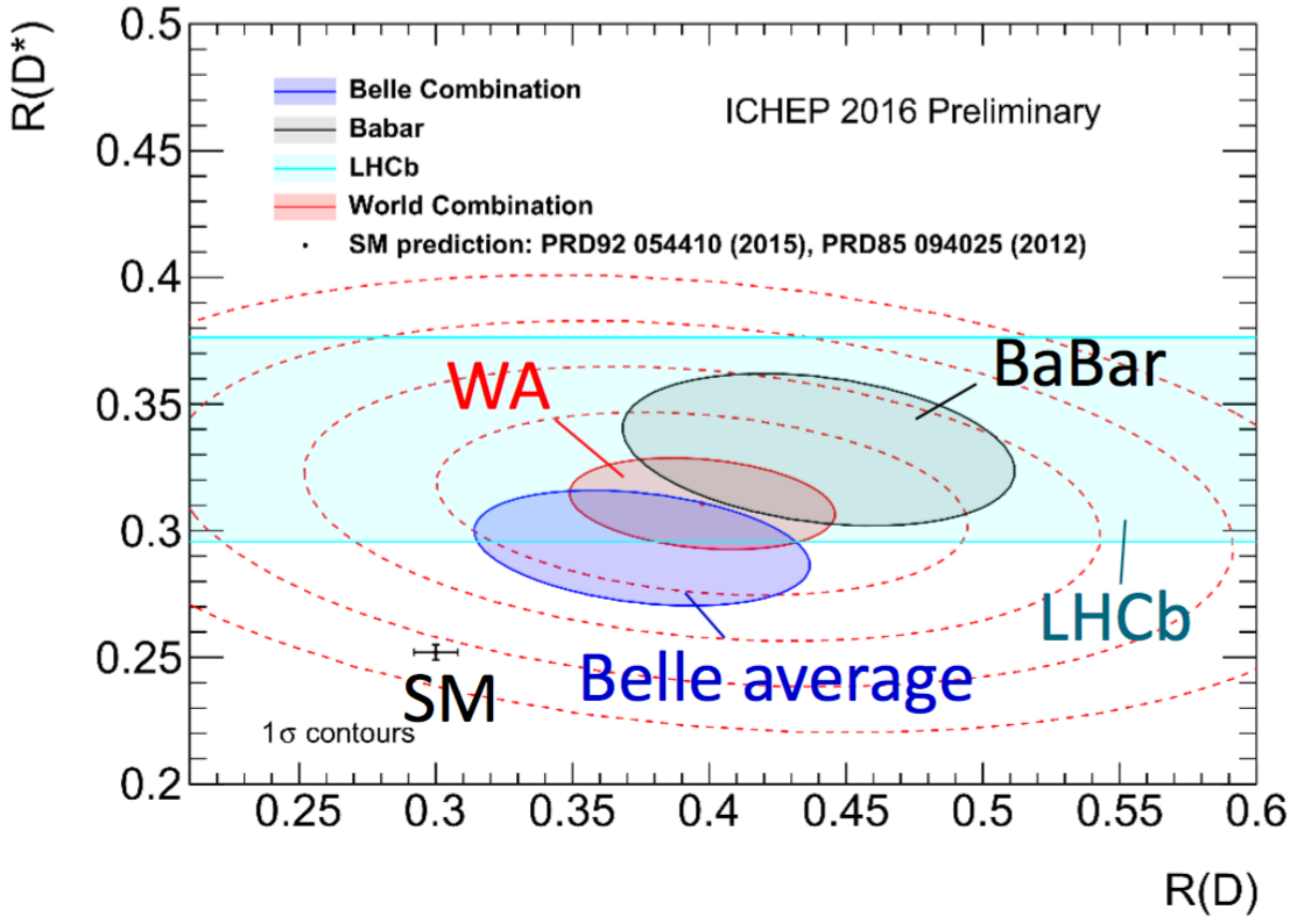
- *full solid angle detector; clean event environment; well defined initial state;*
- *Missing Energy decays*
  - $B \to \tau\nu \quad B \to D^{(*)}\tau\nu \quad B \to \pi\ell\nu$
- *Inclusive Measurements*
  - $B \to X_s\gamma \quad B \to X_s\ell\ell$
- *Good and Efficient reconstruction of decays with neutrals (γ, π^0, K_S, ...)*
  - $b \to s$ *penguins, various modes with neutrals*

Existing Anomalies in B Decays

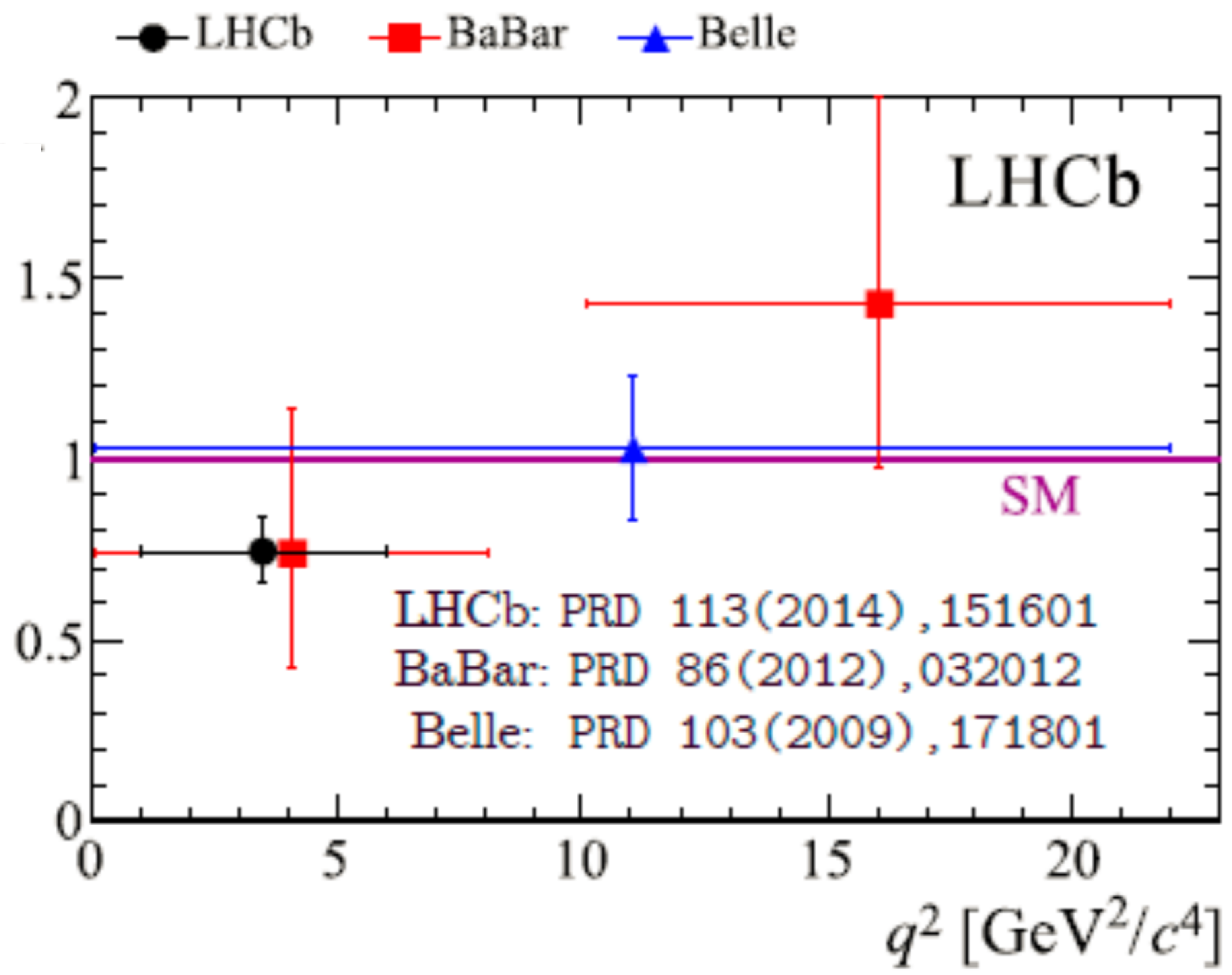
3σ anomalies from **Belle**, **BaBar**, and **LHCb**:

- Ratio of $B \to D^{(*)}\tau\nu$ to $B \to D^{(*)}\ell\nu$
- Ratio of $B \to K\mu\mu$ to $B \to Kee$
- Angular distribution of $B \to K^*\ell\ell$
- $|V_{ub}|$ from exclusive and inclusive decays
- …

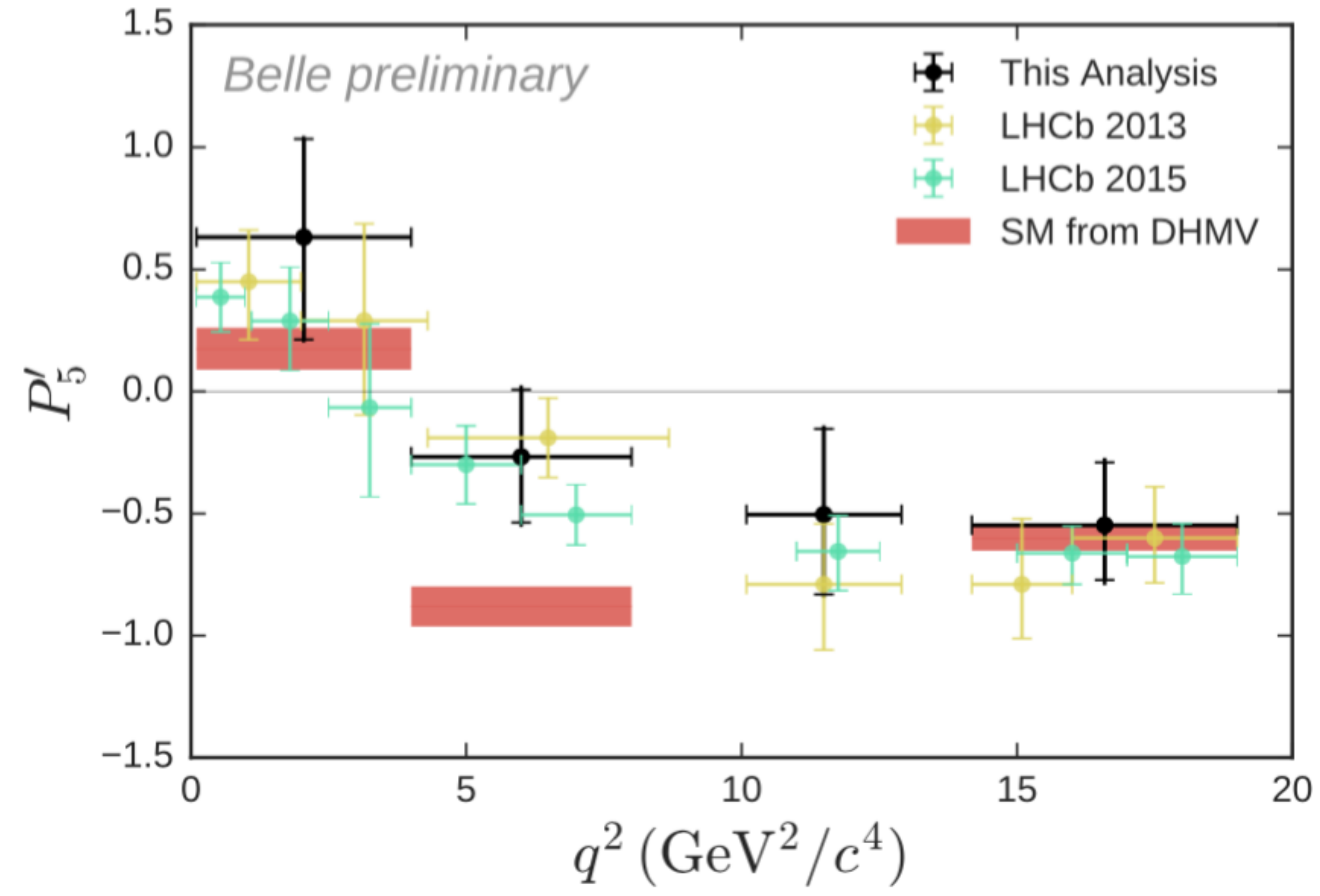
$B \to D^{(*)}\tau\nu$



$B \to K\mu\mu / B \to Kee$



$B \to K^*\ell\ell$



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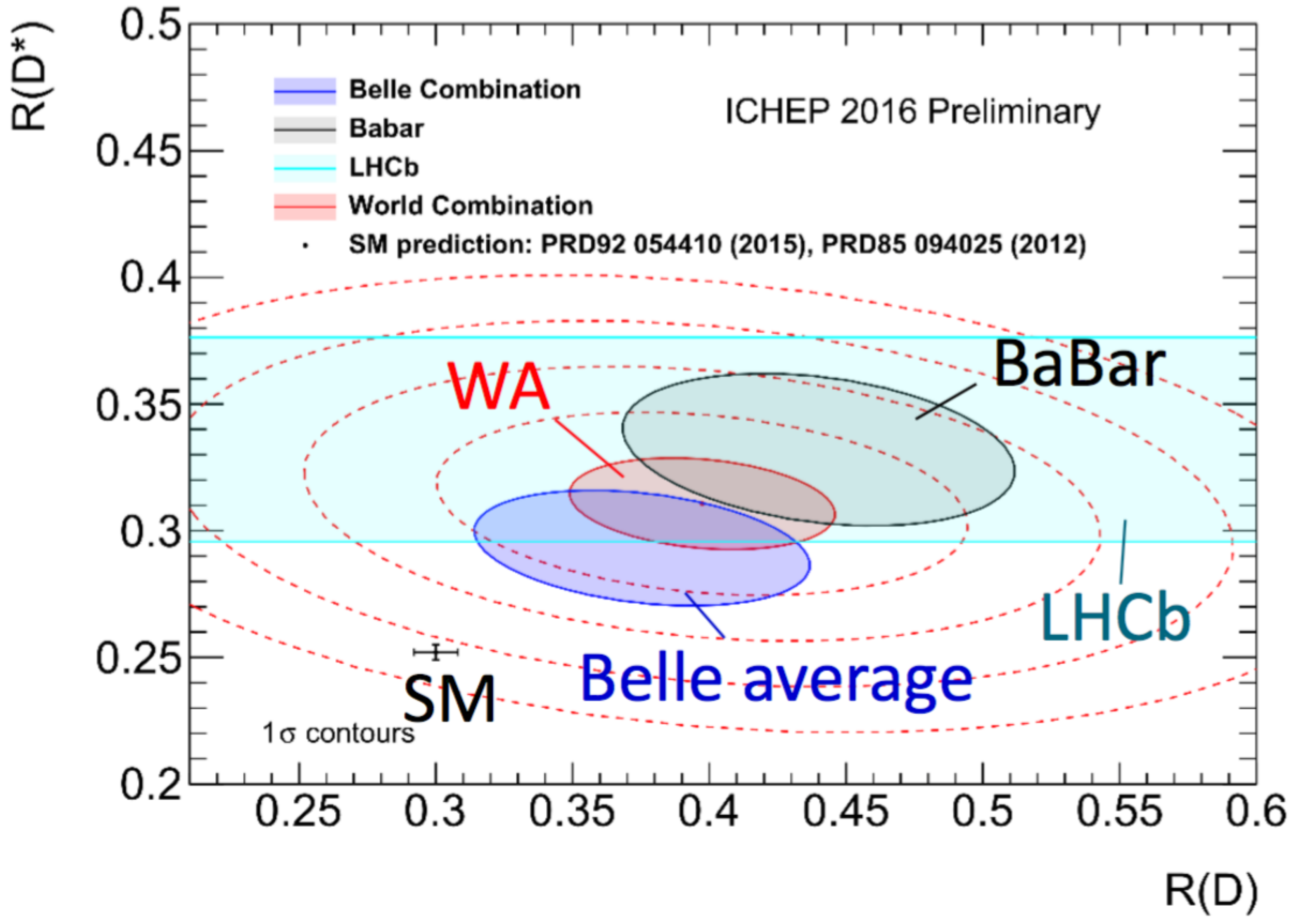
Signatures of New Physics?
Need more data!

$B \to D^{(*)}\tau\nu$



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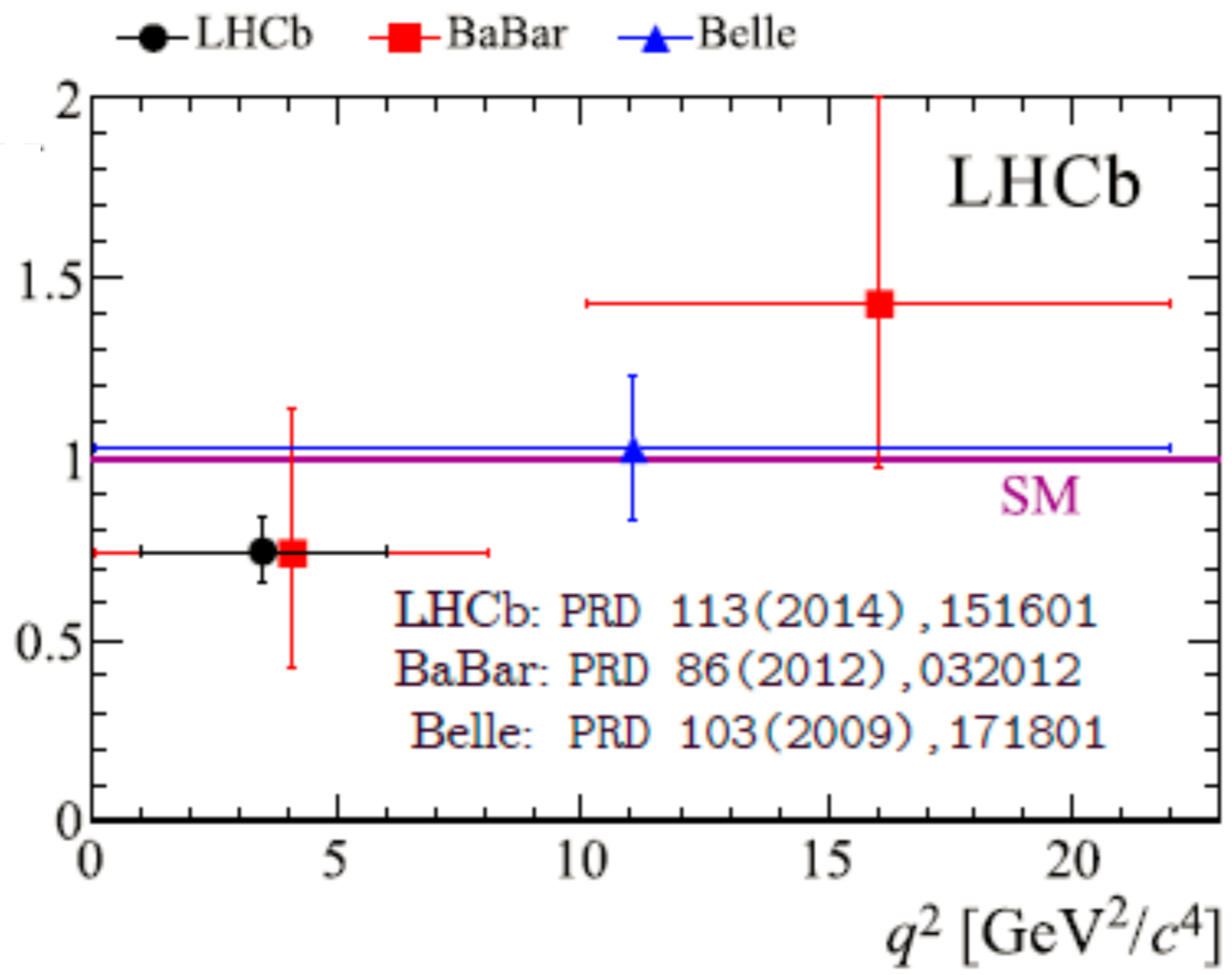

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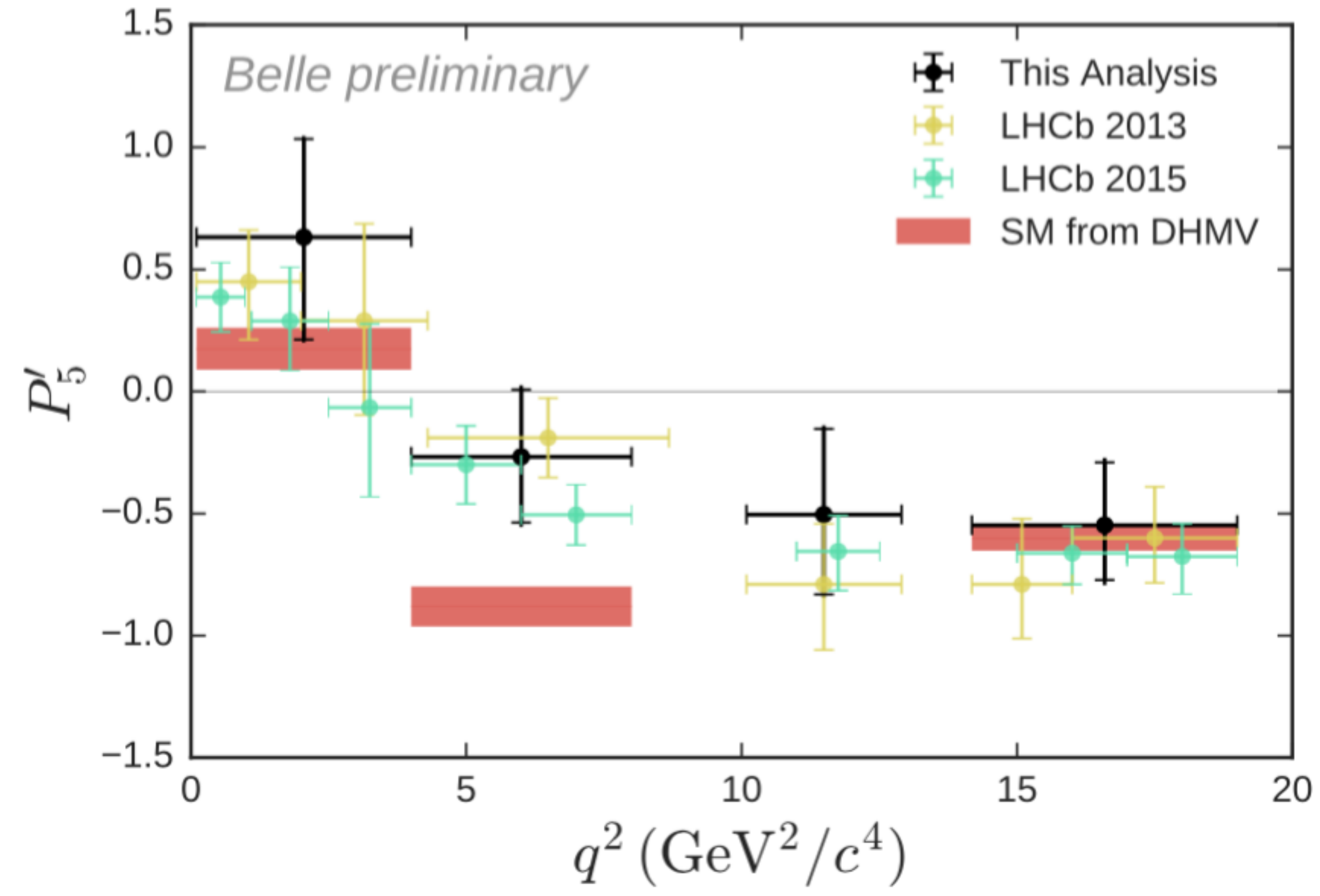

Outline

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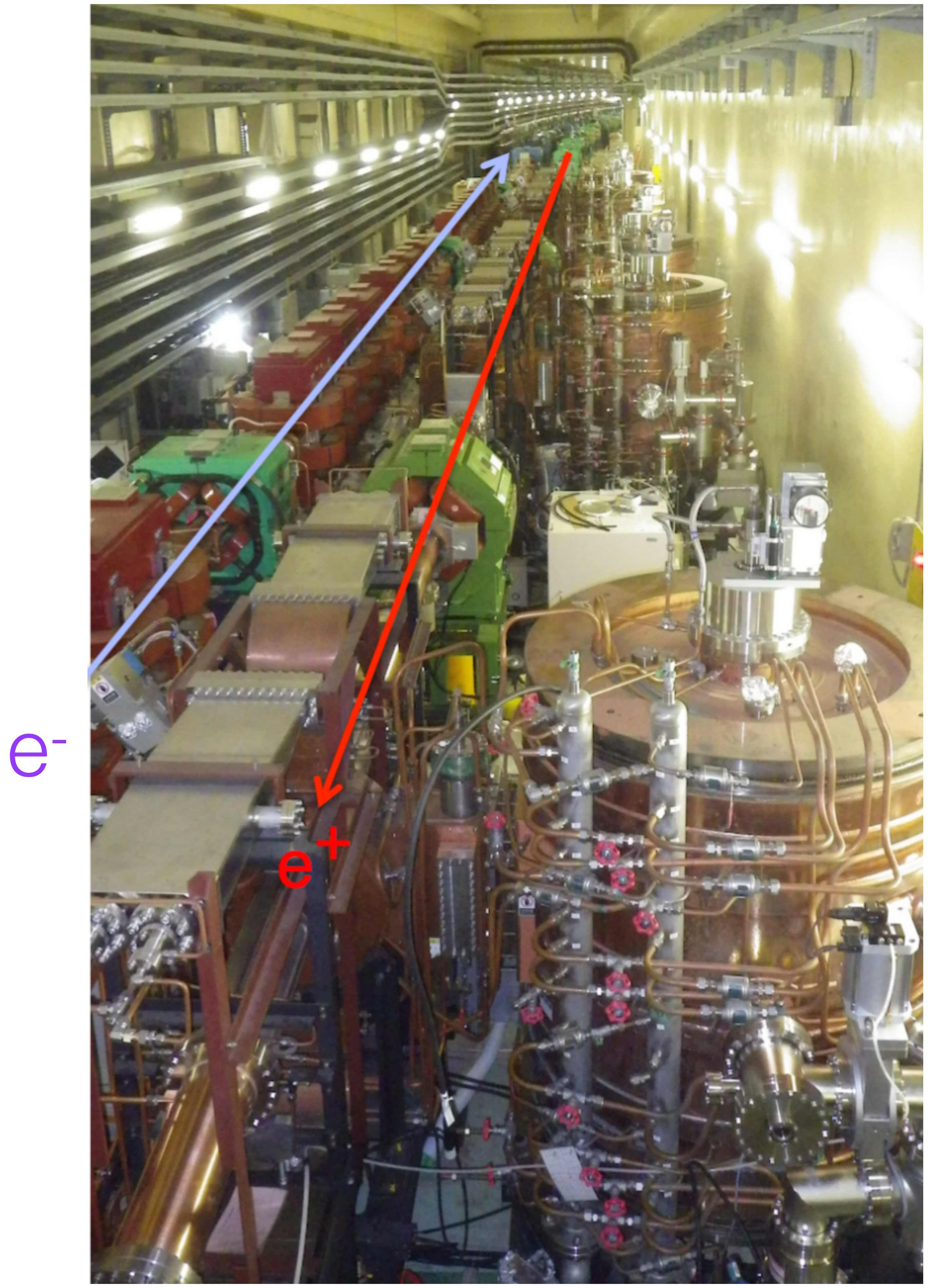
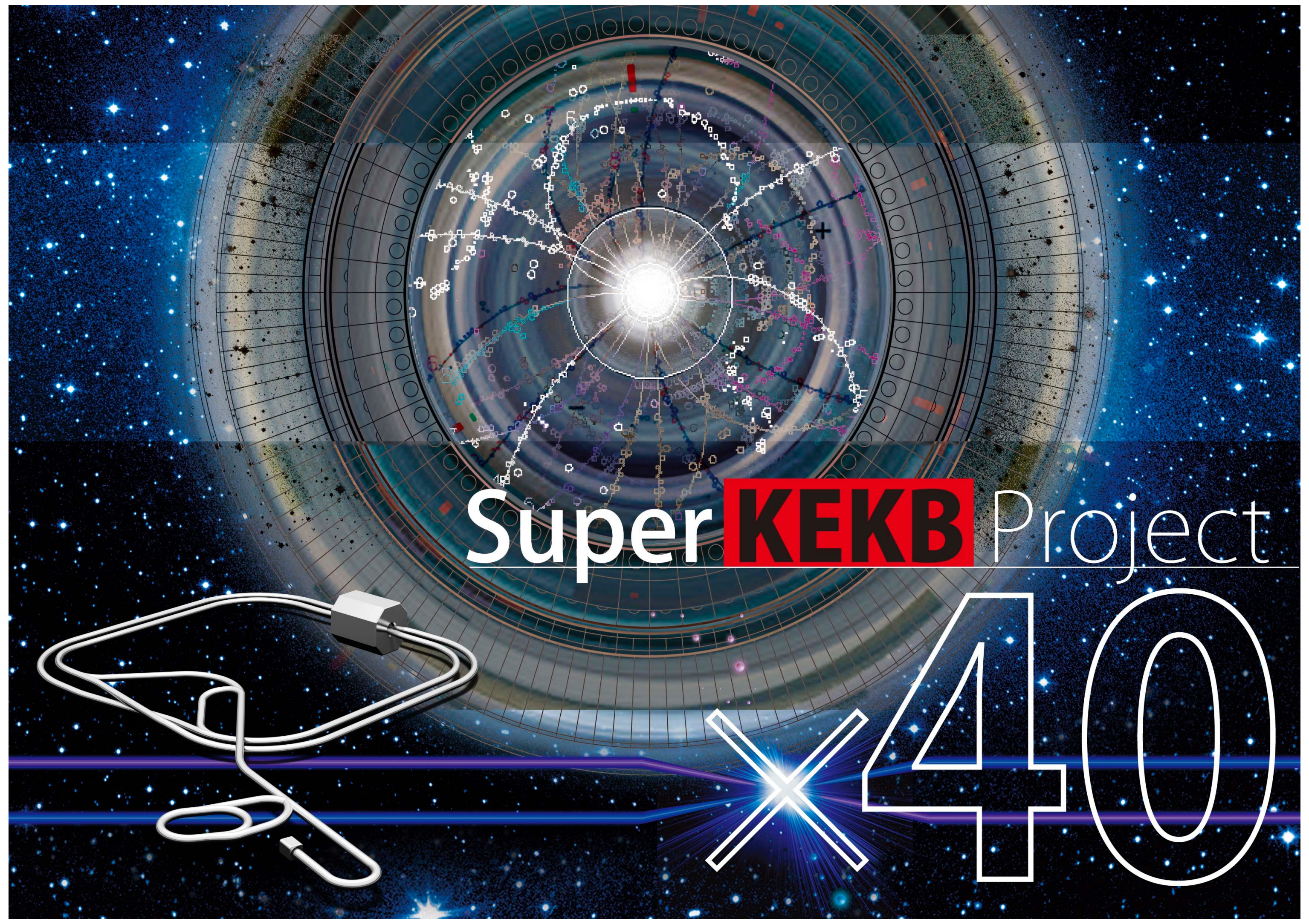
- ***Accelerator***
- *Detector*
- *Physics*





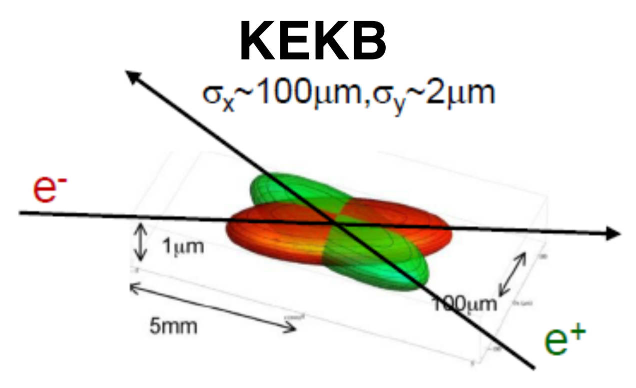
SuperKEKB

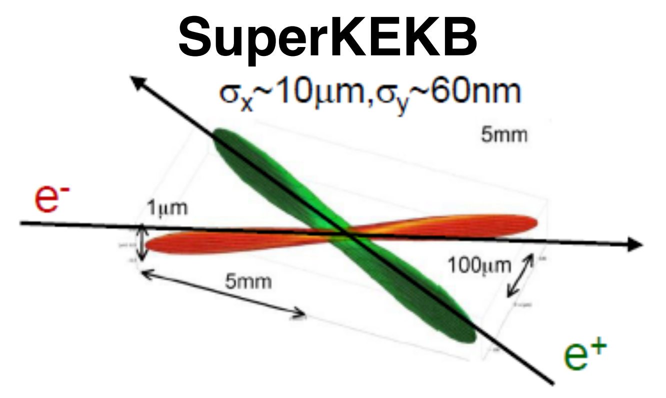
The Super **B** factory at KEK:

- a planned 40-fold increase in luminosity over KEKB achieved by:
  - squeezing the beams at the IP (x 1/20)
  - doubling the beam currents (x 2)

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

(Nano-beam design by P. Raimondi for SuperB)





	E(GEV) HER/LER	β^*_y(mm) HER/LER	β^*_x(mm) HER/LER	2φ (mrad)	I(A) HER/LER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	22	1.6/1.2	$2.1x10^{34}$
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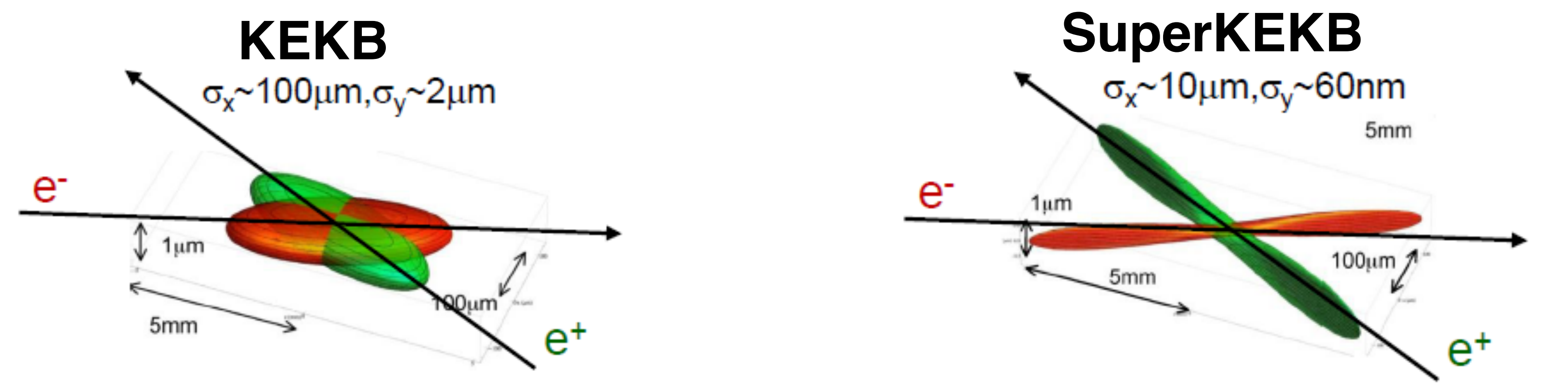

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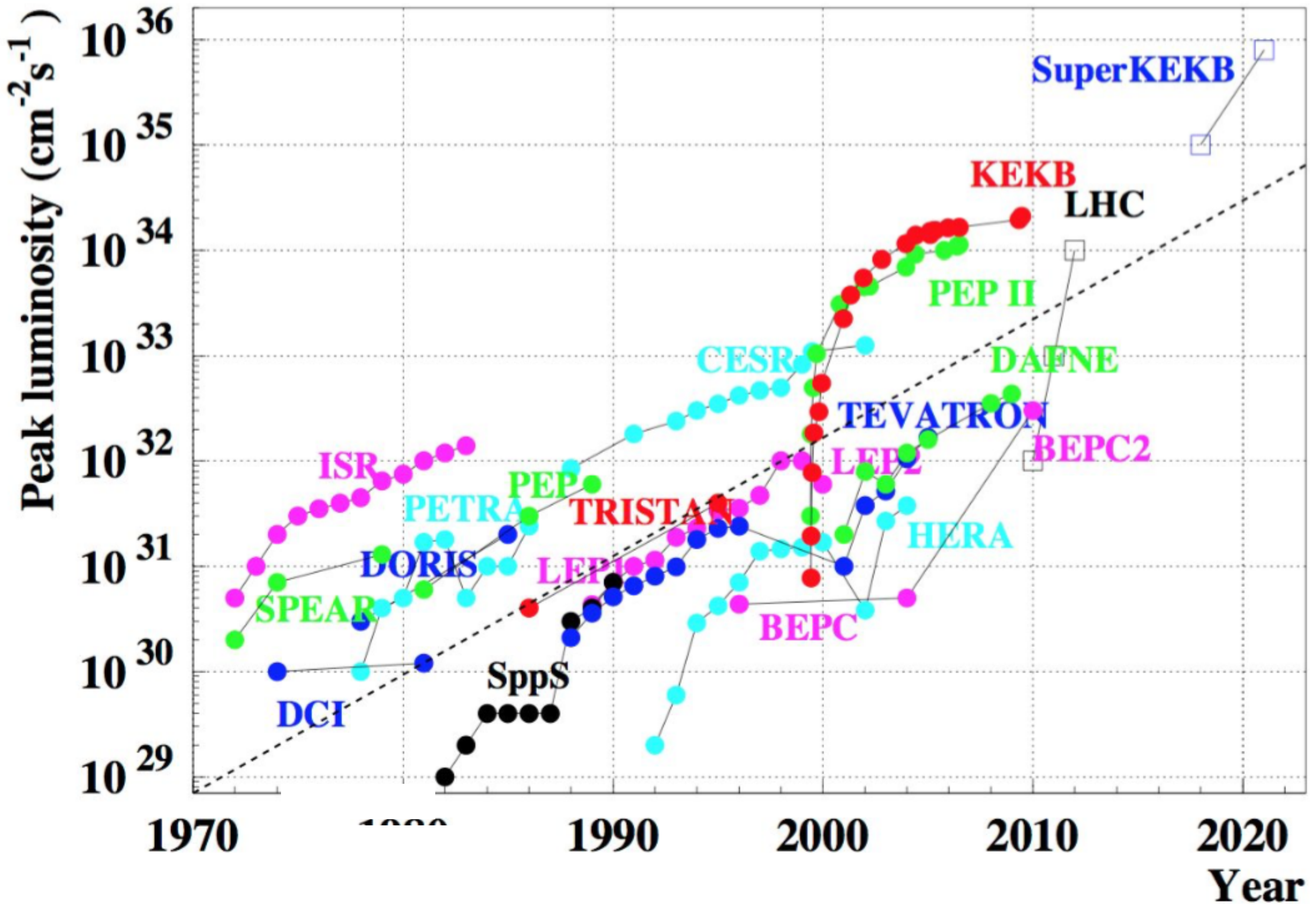

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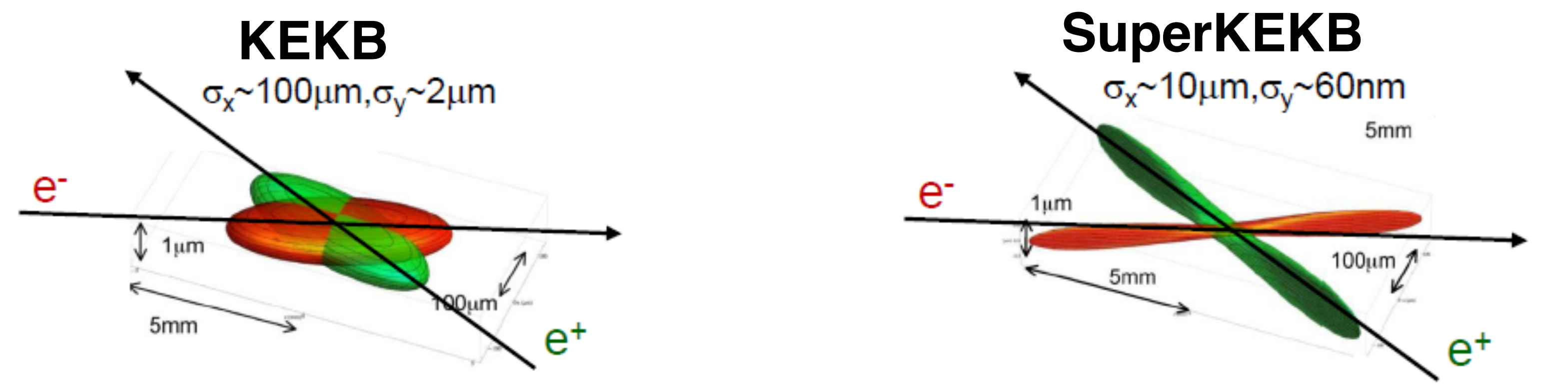

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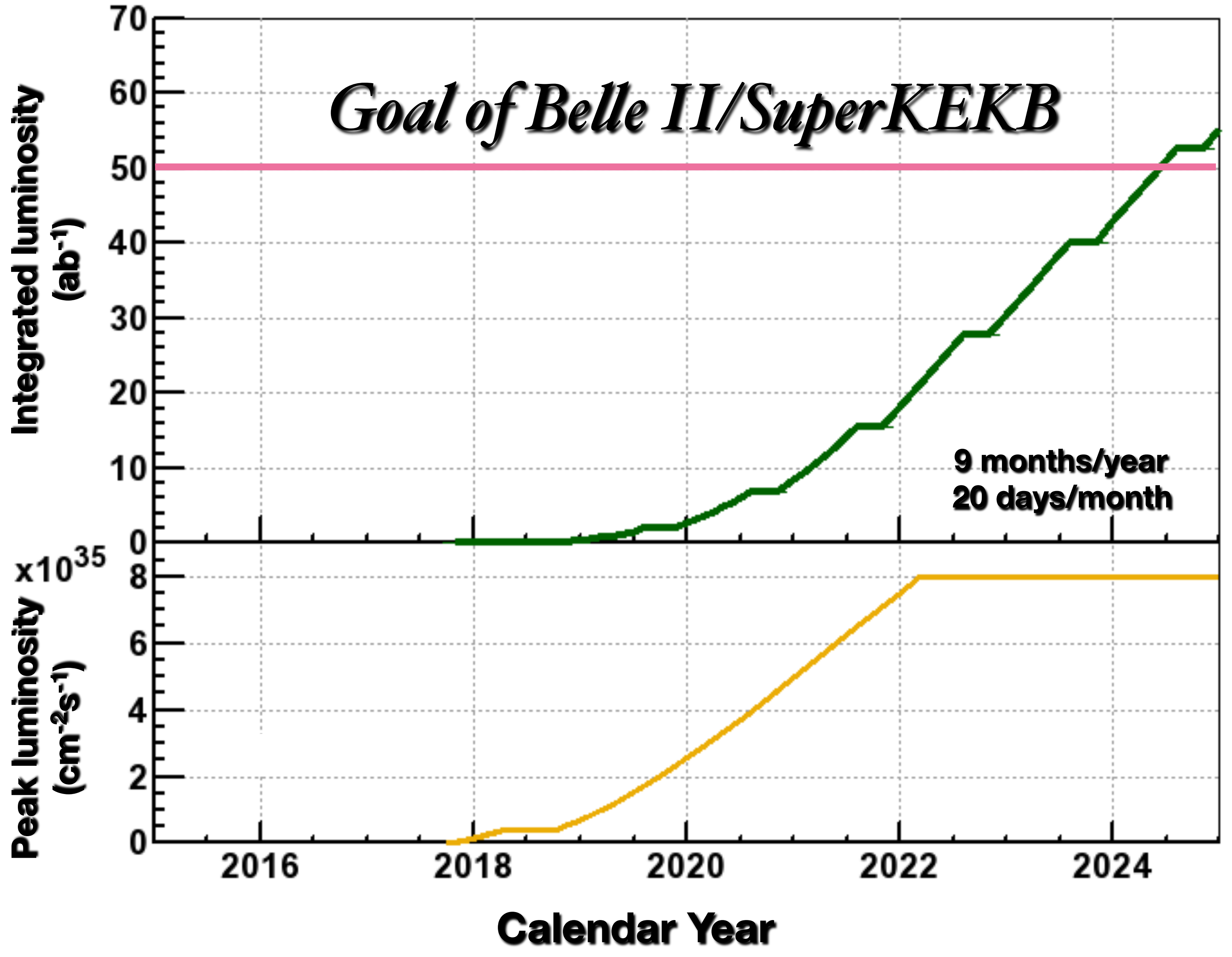
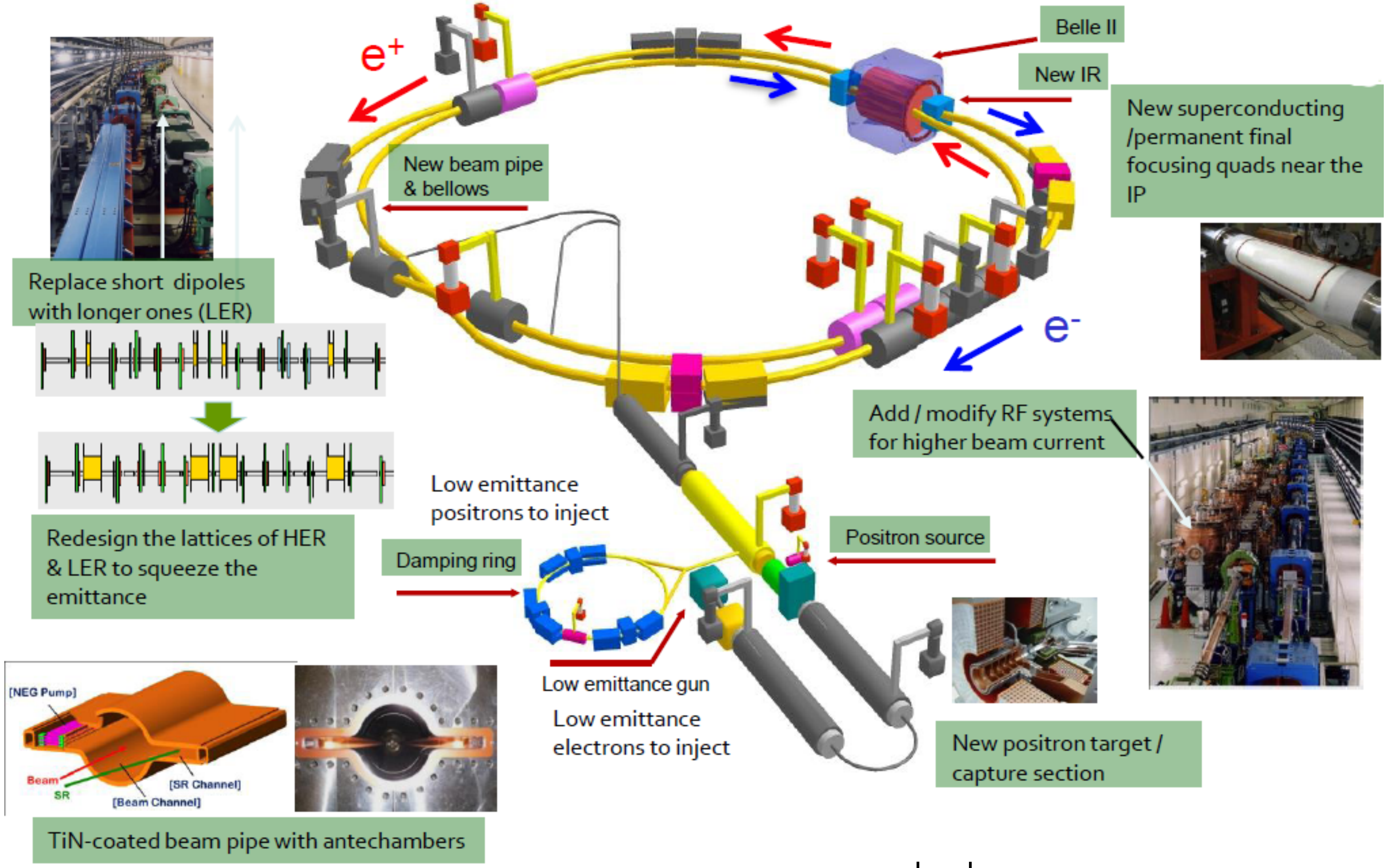
SuperKEKB luminosity projection



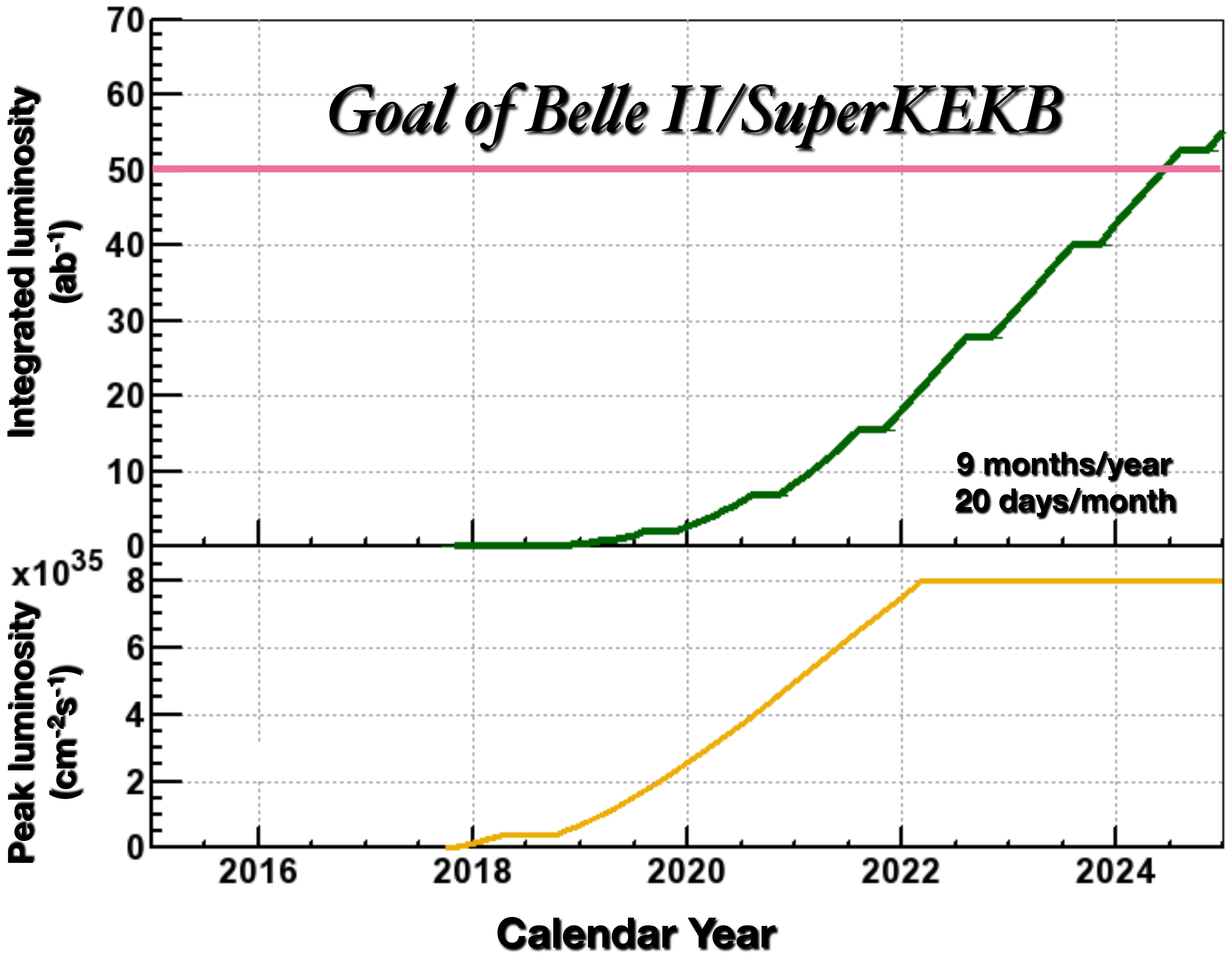
SuperKEKB

A lot of modifications all around the accelerator.



grey = recycled
colour = new

SuperKEKB Status and Schedule



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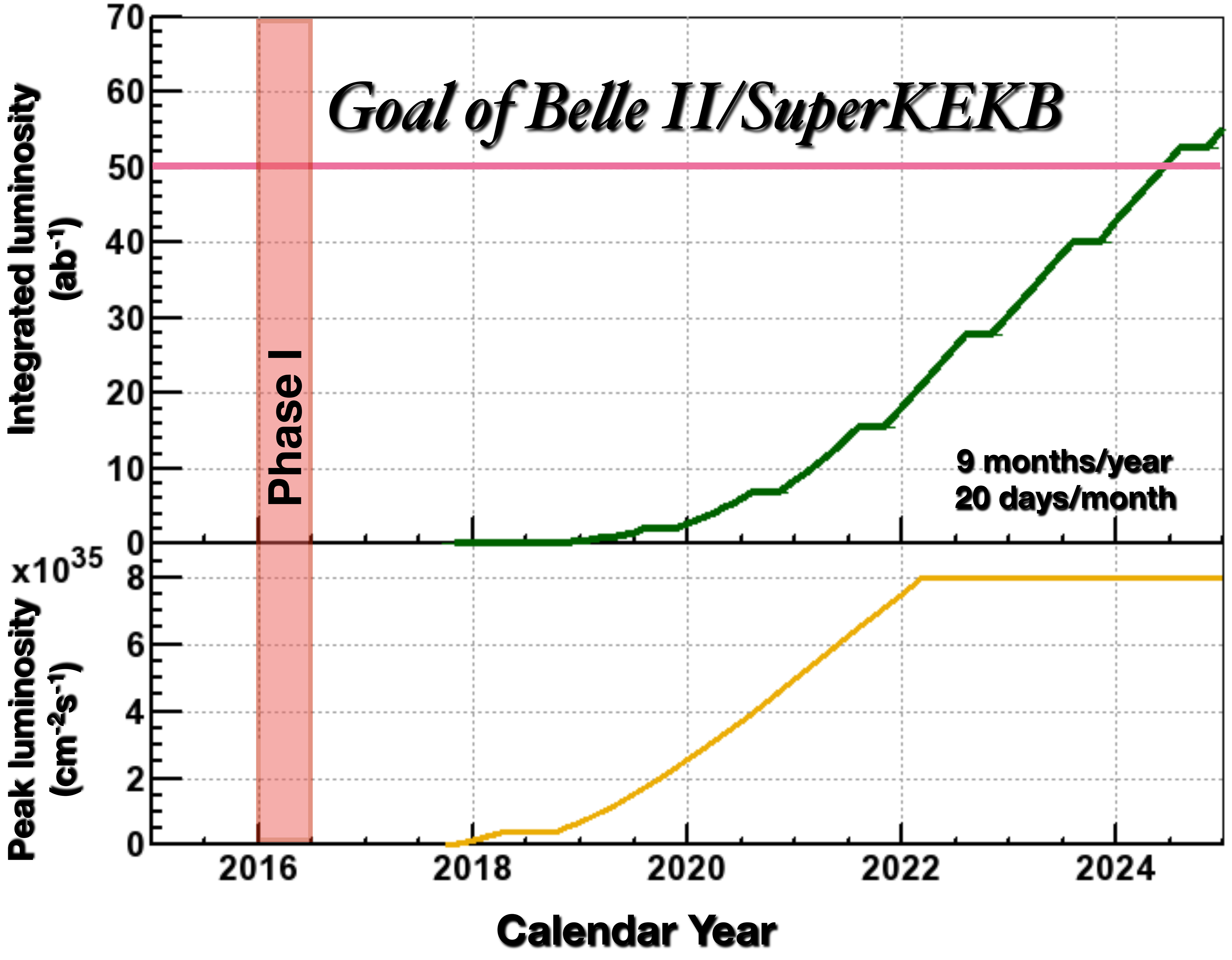
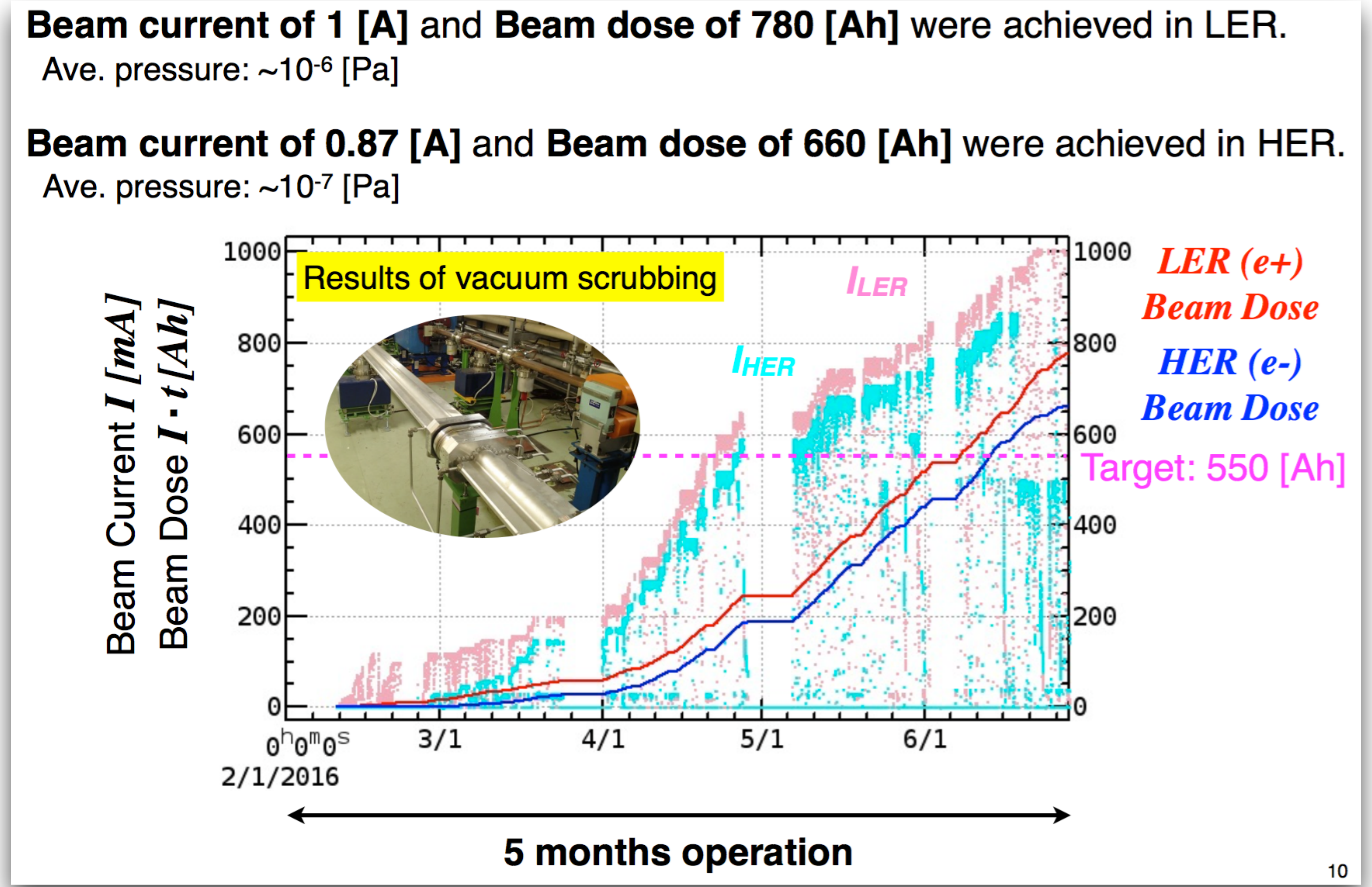


Phase I (completed)

- Circulated both beams; no collisions;
- Tune accelerator optics, etc.
- Vacuum scrubbing
- Beam Background studies with **BEAST II**

SuperKEKB Status and Schedule



Very successful start of SuperKEKB!

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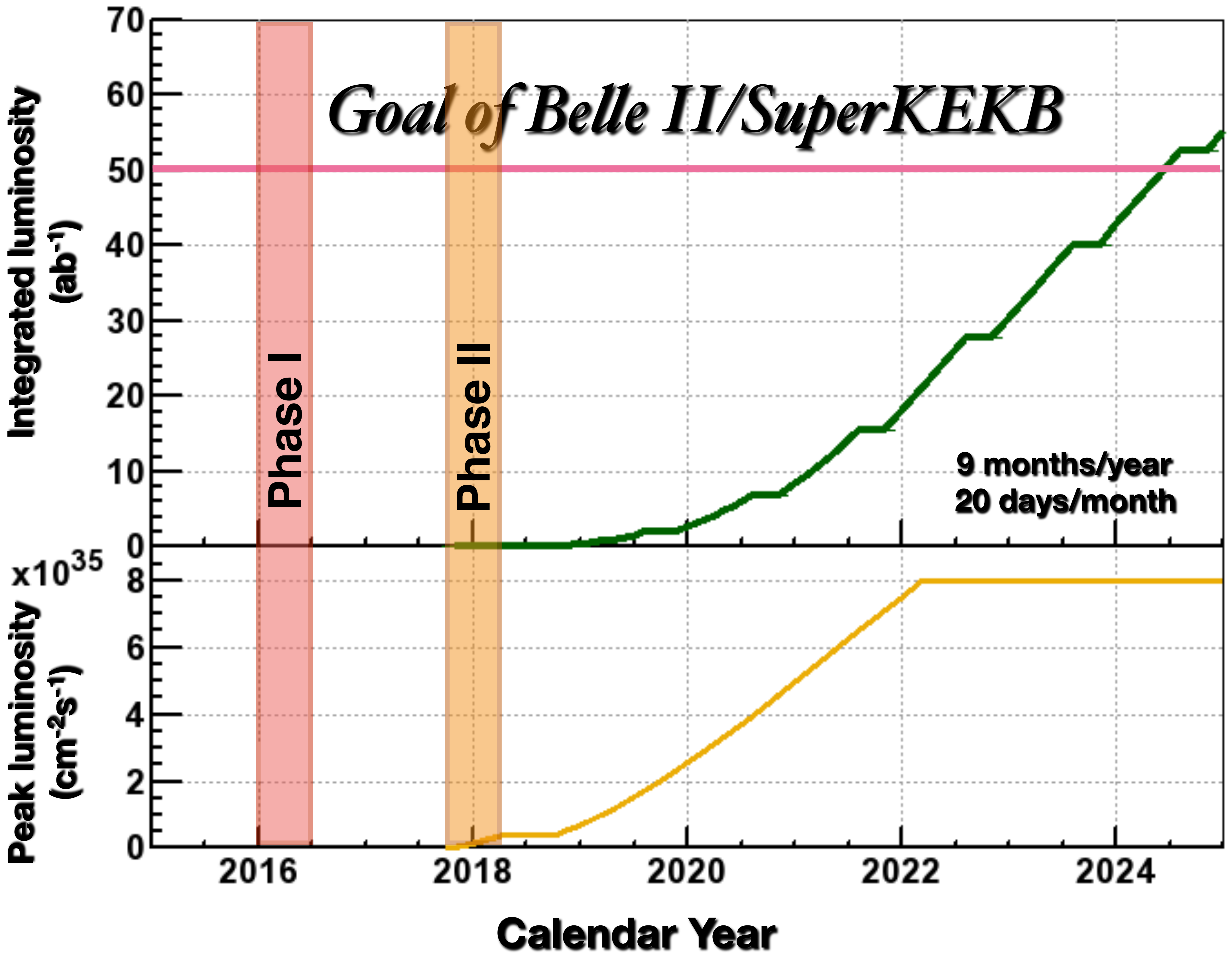
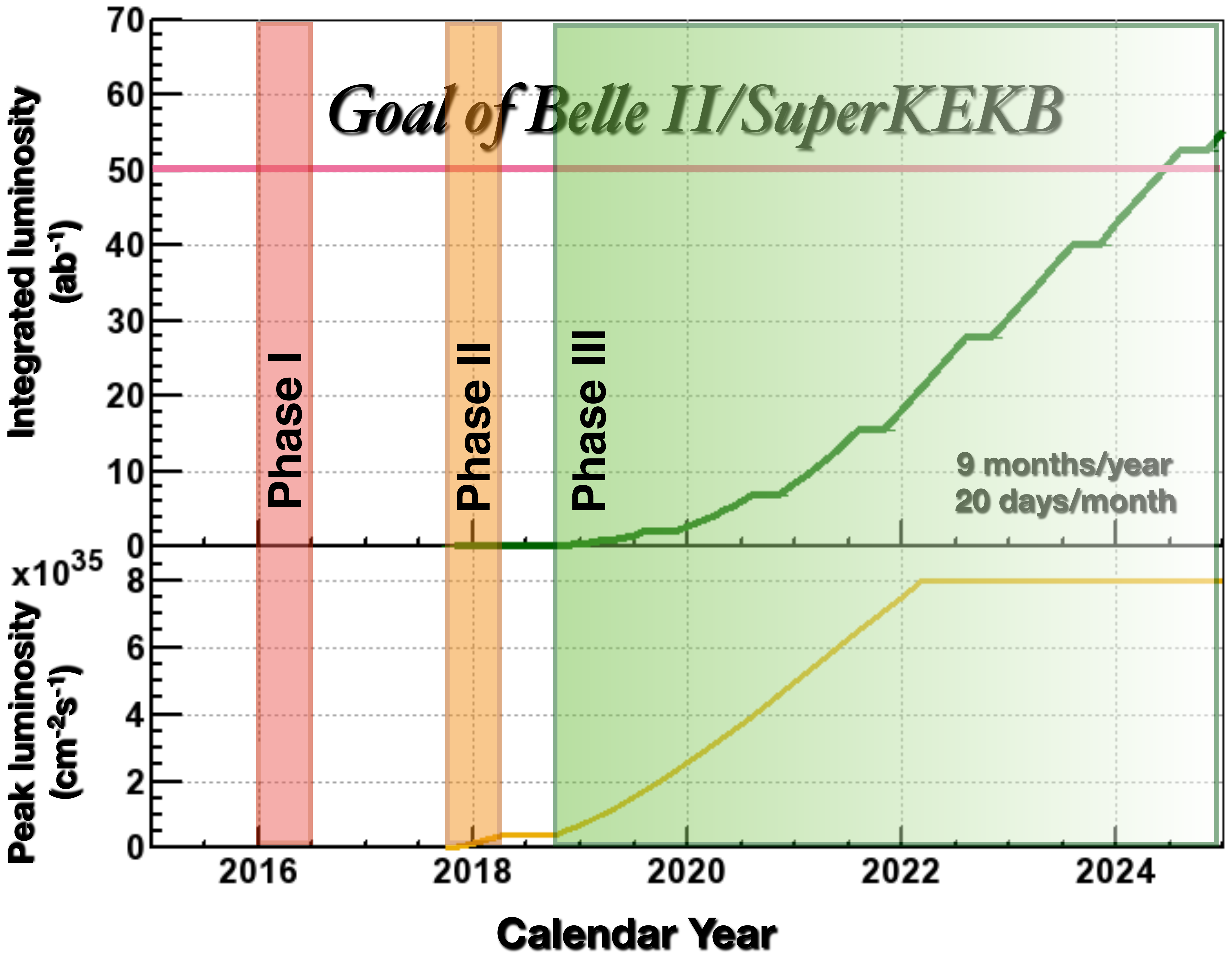


Phase II (2017-2018)

- First collisions
- Beam Commissioning
- Physics run with **Belle II w/o VTX**
  - on Y(4S) and Y(6S)

SuperKEKB Status and Schedule



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Phase III (2018 -)

- Luminosity tuning
- Physics run with full **Belle II**

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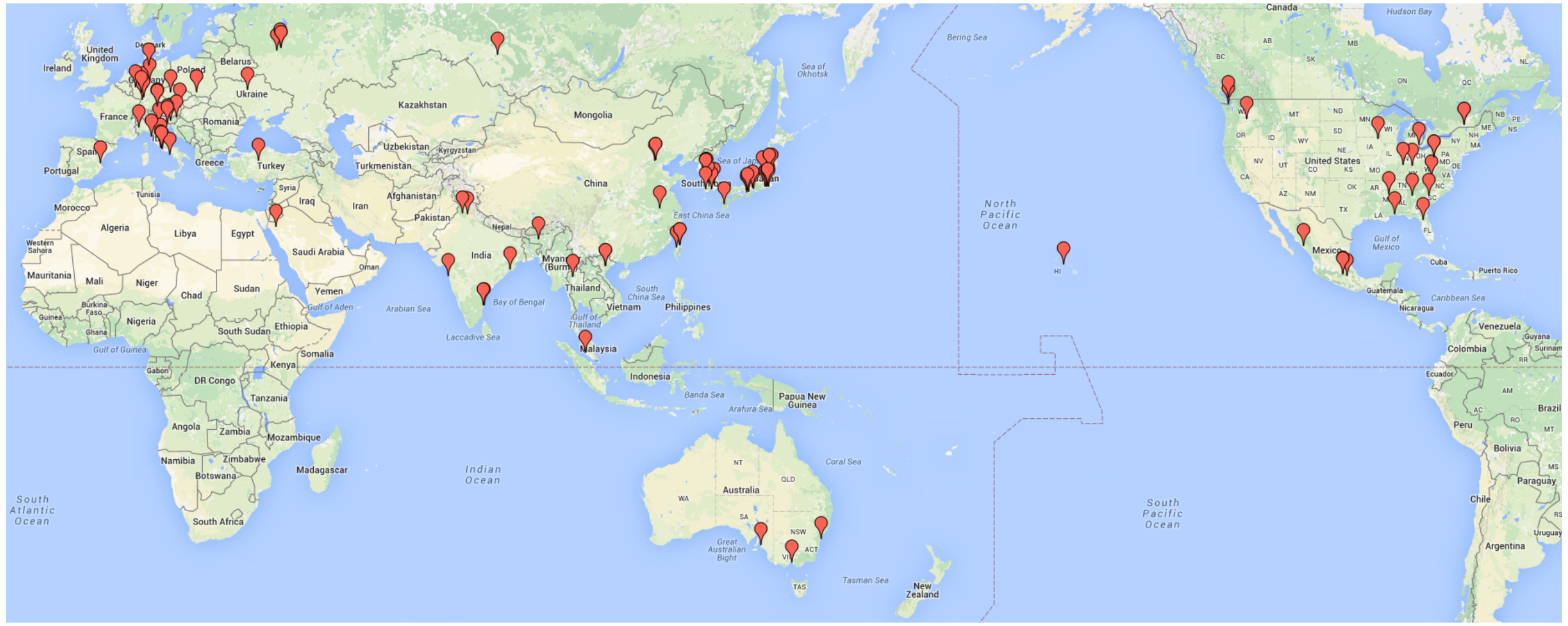
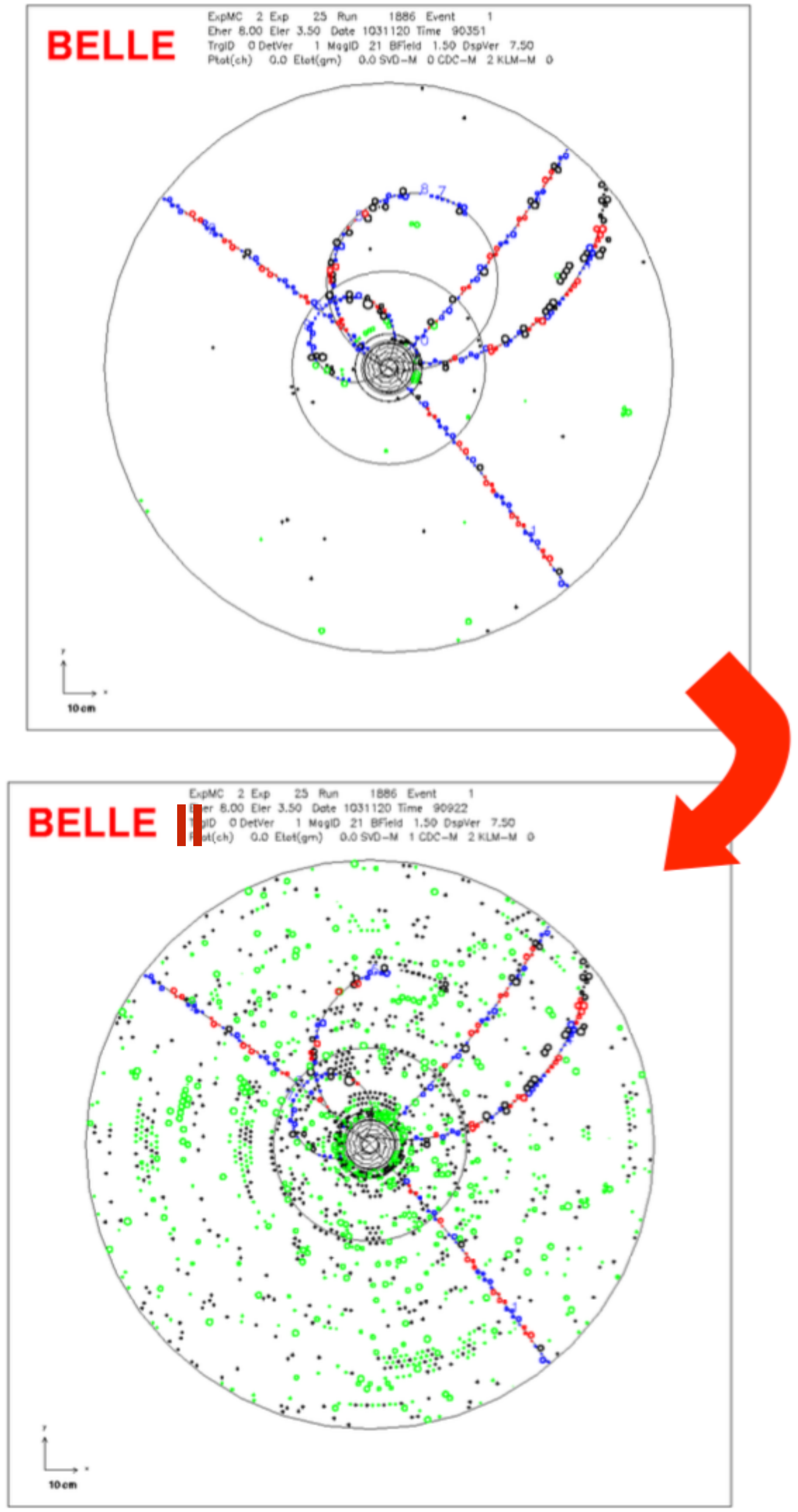
- ***Detector***
- *Physics*

660 members
100 institutions
23 countries/regions



Detector Requirements

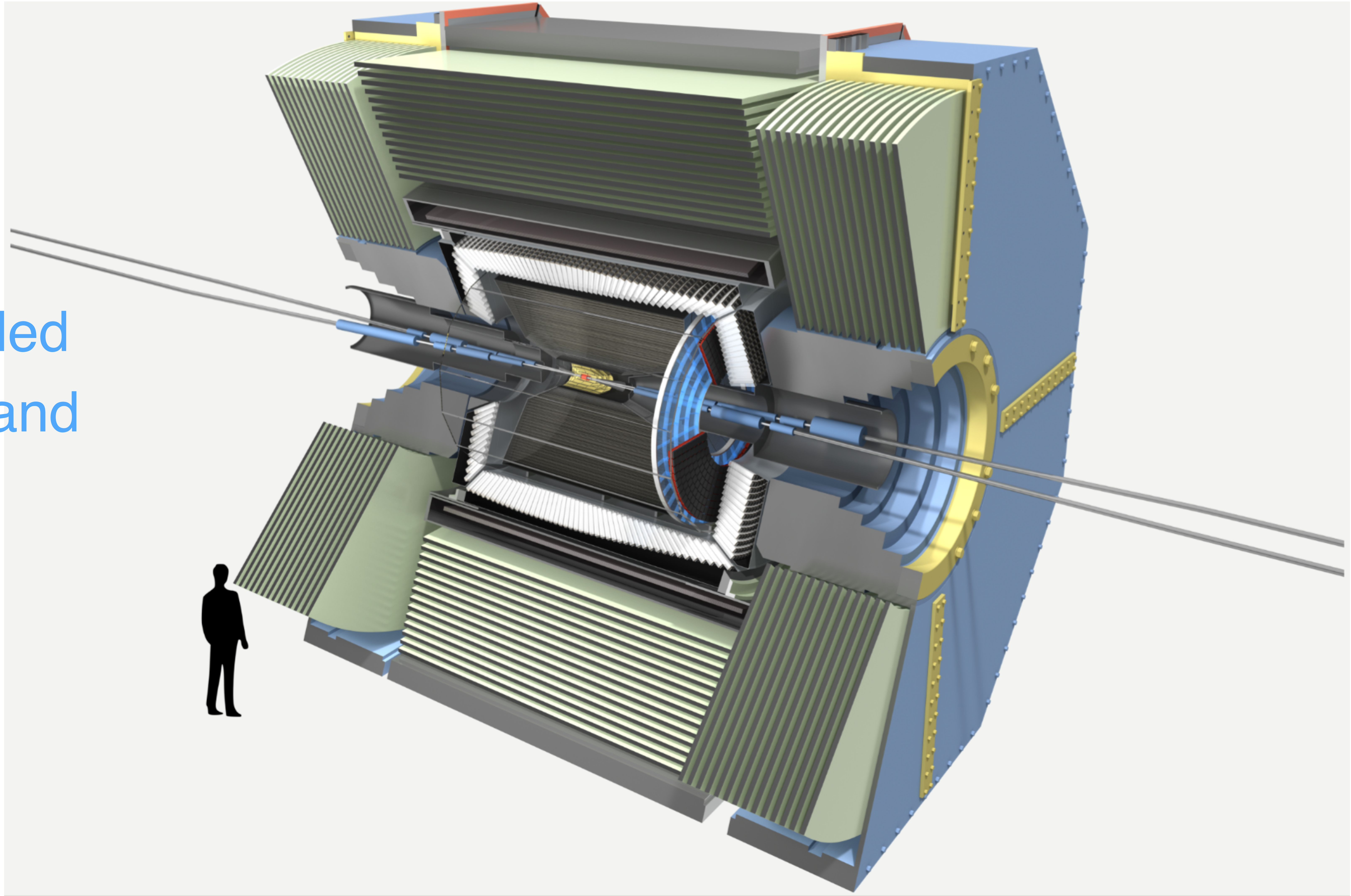
- Higher beam-related and QED background
- L1 trigger rate 30kHz vs 500 Hz at Belle
  - Stability against higher background
  - Faster readout
  - Improved performance
    - *vertex resolution*
    - *tracking*
    - *particle identification (K/pi separation)*
  - Less material in front of ECL for better performance



Not a simulation, just a naive illustration

Detector Upgrade

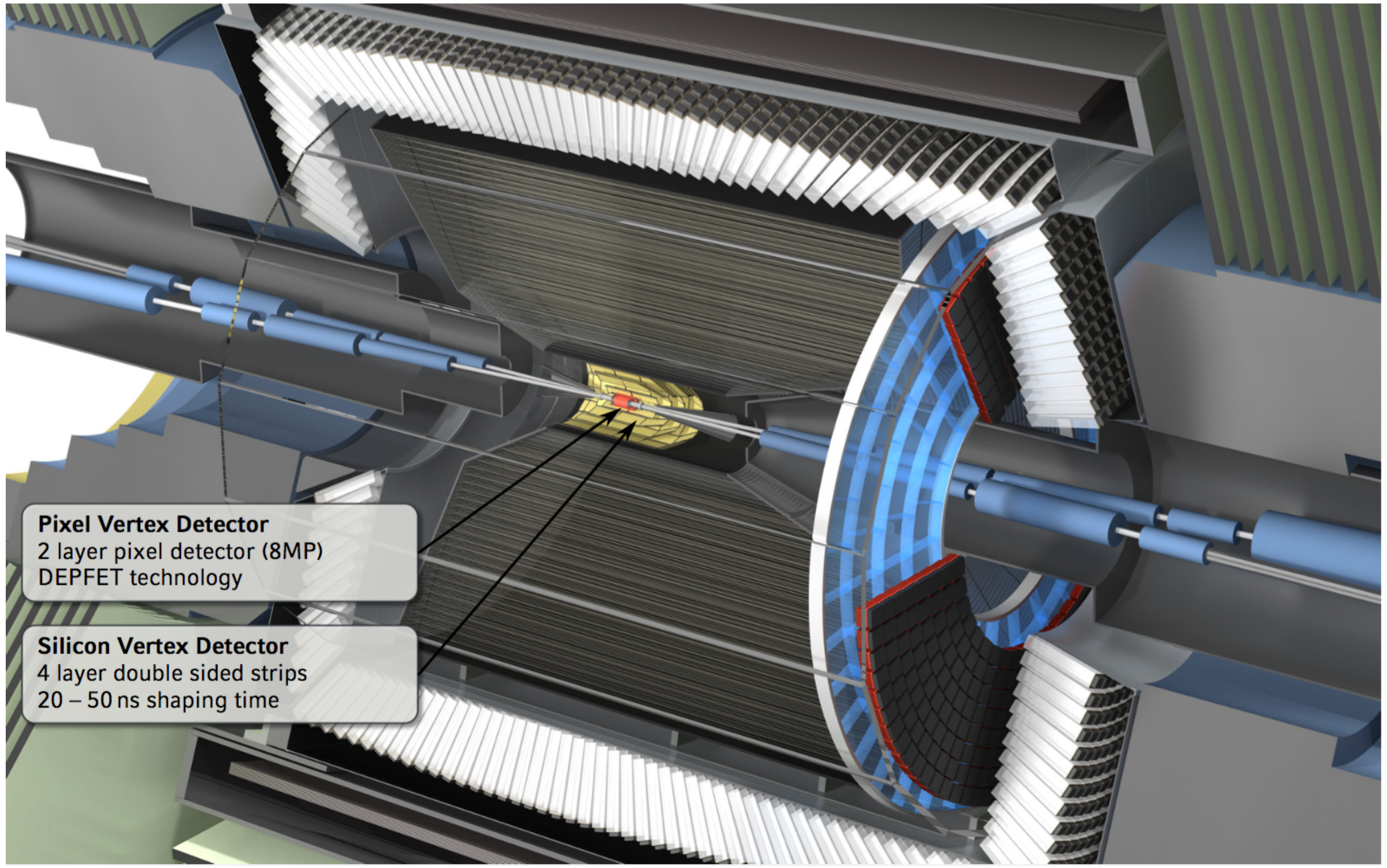
All sub-detectors are upgraded except for the ECL crystals and part of the barrel KLM.



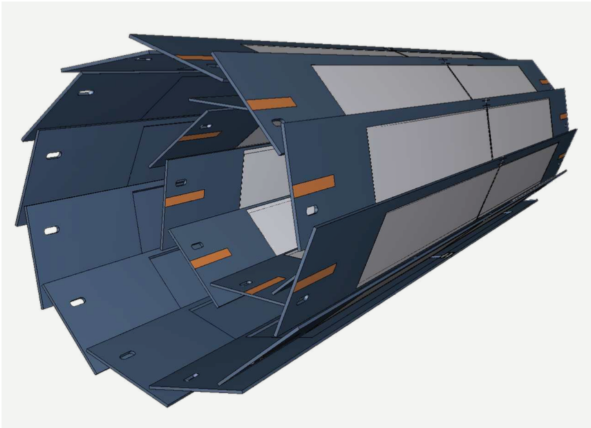
Detector Upgrade *- Vertex detectors*

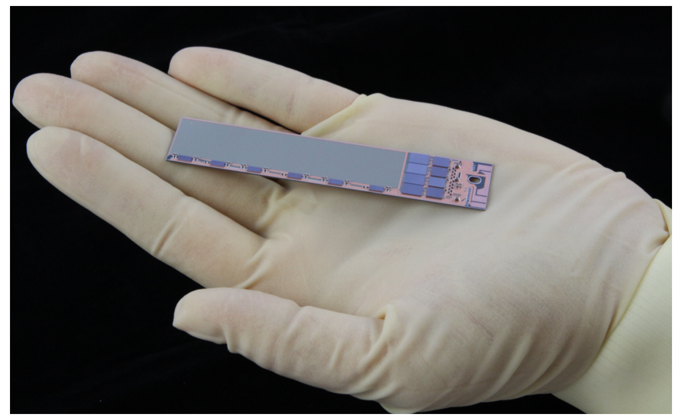
Si Pixel (2 layers) and Si strip (4 layers):

- smaller beam pipe allows placement of 1st pixel layer close to the IP (r = 14 mm)
  [Belle's first SVD layer at r = 20 mm]
  - *improves vertex resolution along z axis*
- larger SVD (outer layer at r = 135 mm)
  [Belle's outer SVD layer at r = 88 mm]
  - *higher fraction of Ks' with vertex hits improves vertex resolution in t-dep. CPV studies*

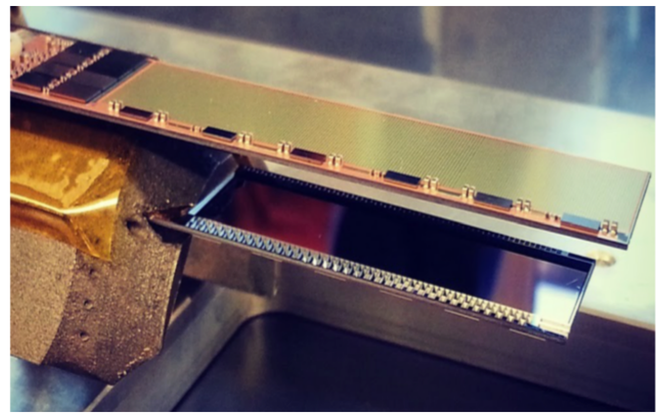


Pixel Detector

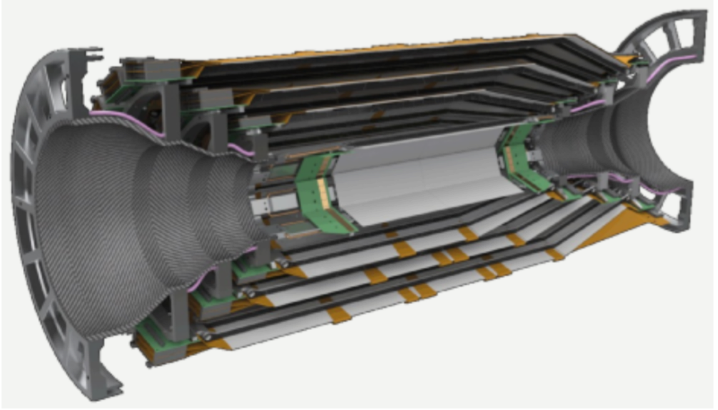




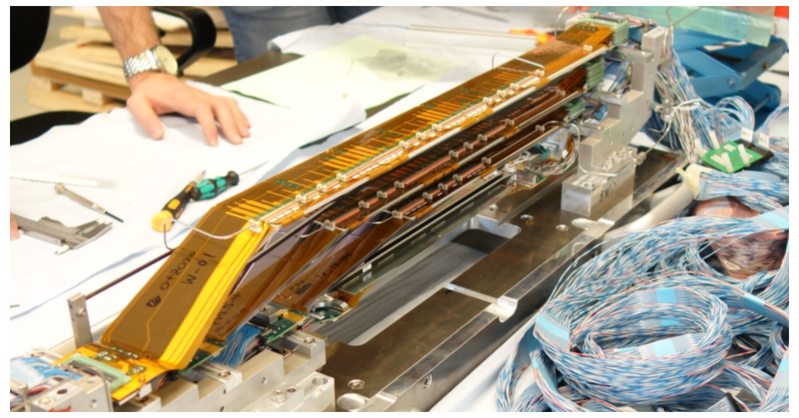
2 Pixel Half-Ladders



Strip Detector



4 strip ladders



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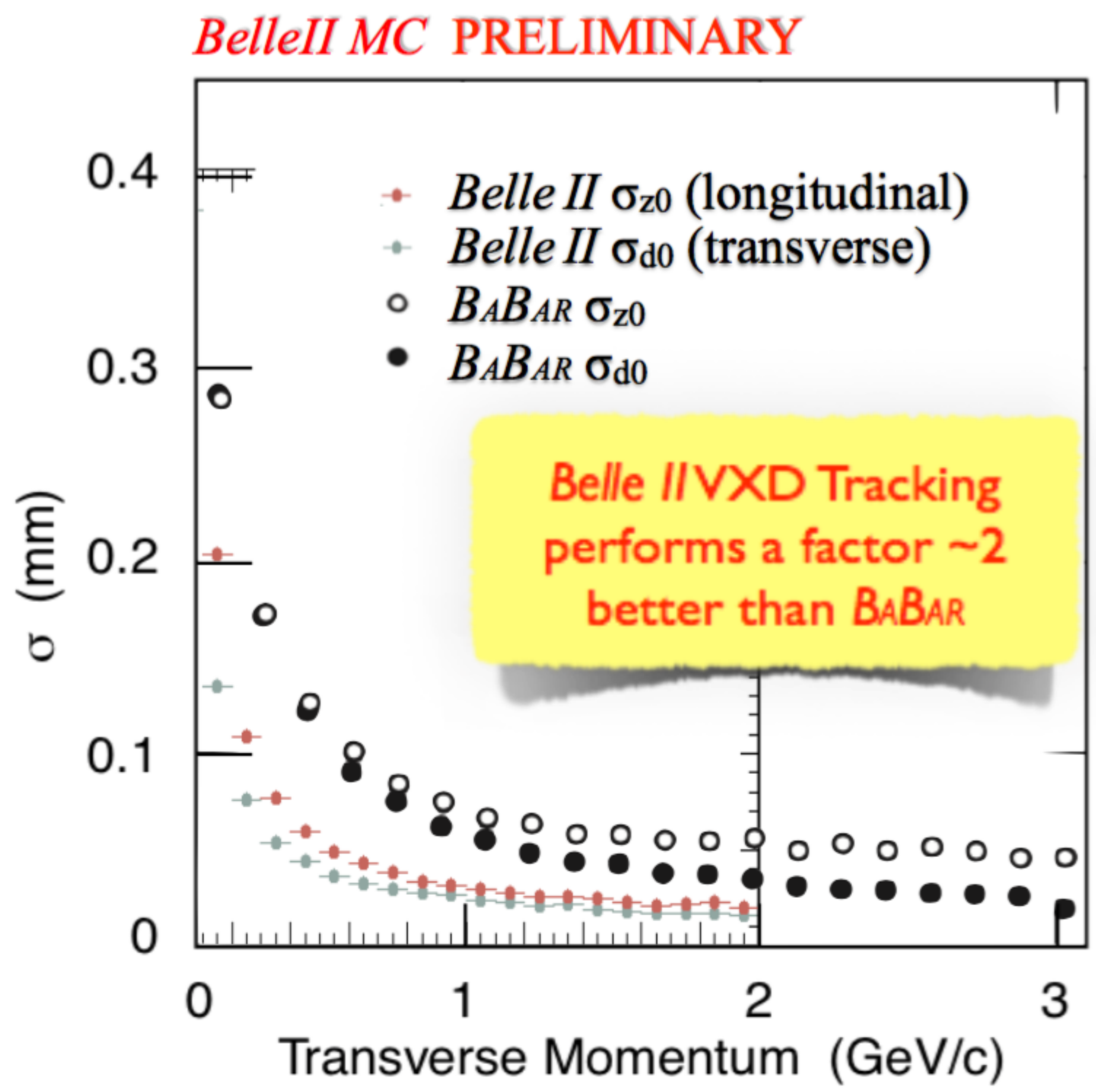
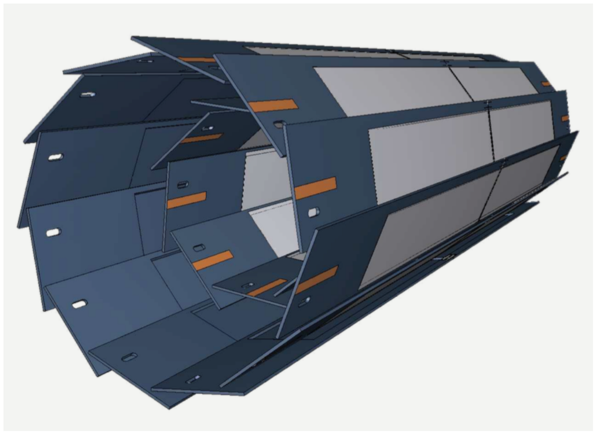
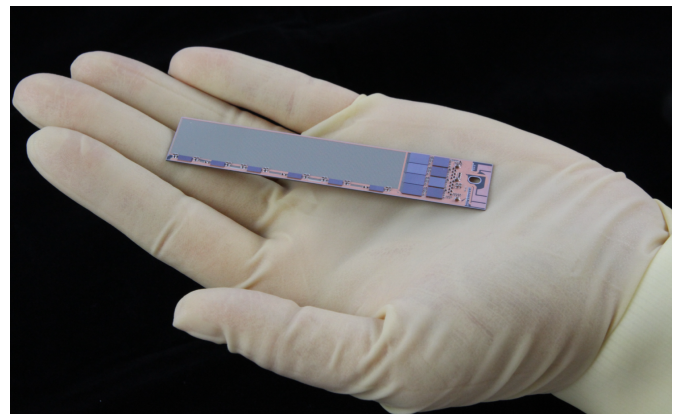
- larger SVD (outer layer at r = 135 mm)
  [Belle's outer SVD layer at r = 88 mm]
  - *higher fraction of Ks' with vertex hits improves vertex resolution in t-dep. CPV studies*

Impact parameter (d0, z0) resolution

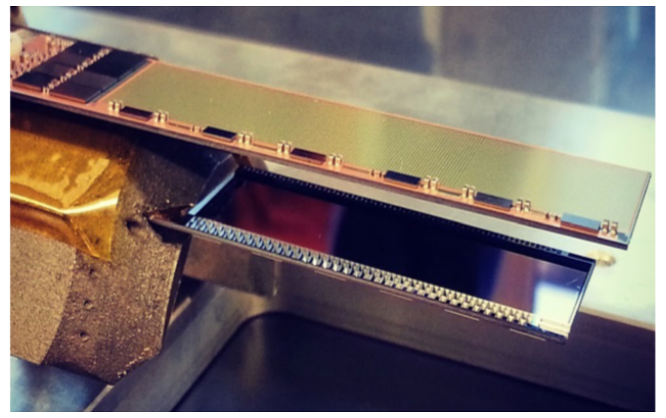


Pixel Detector

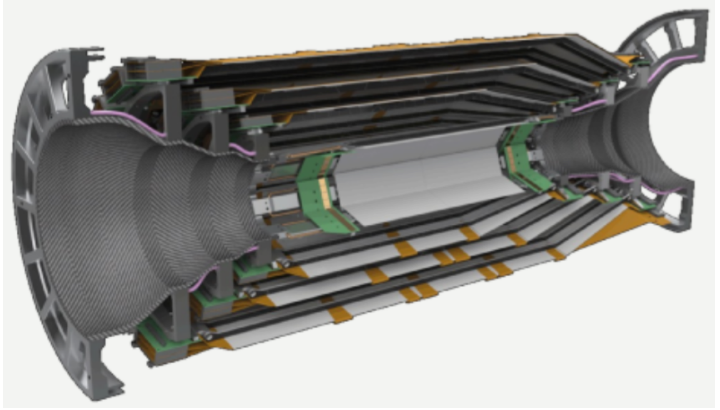




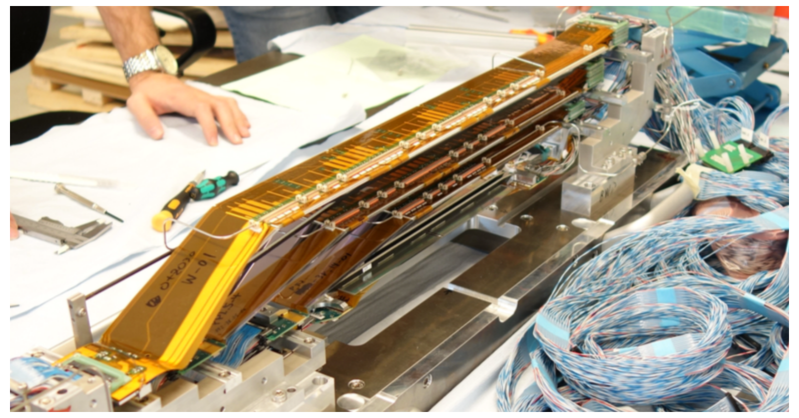
2 Pixel Half-Ladders



Strip Detector



4 strip ladders



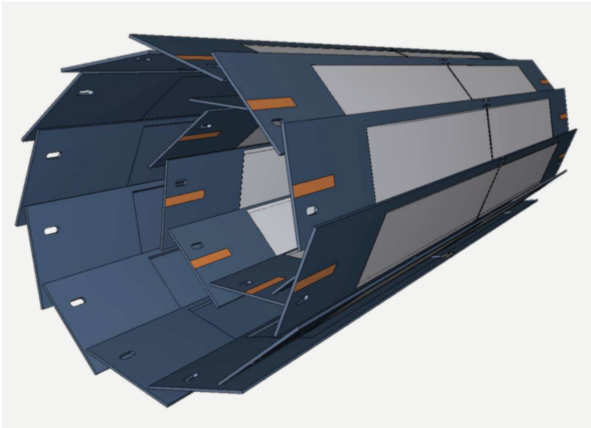
Detector Upgrade - *Vertex detectors*

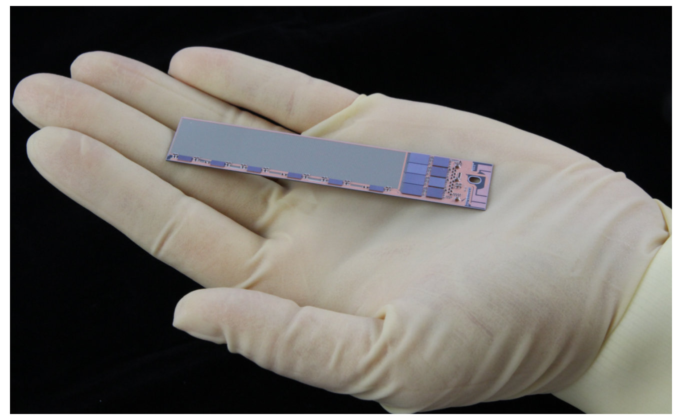
Si Pixel (2 layers) and Si strip (4 layers):

- smaller beam pipe allows placement of 1st pixel layer close to the IP (r = 14 mm)
  [Belle's first SVD layer at r = 20 mm]
  - *improves vertex resolution along z axis*
- larger SVD (outer layer at r = 135 mm)
  [Belle's outer SVD layer at r = 88 mm]
  - *higher fraction of Ks' with vertex hits improves vertex resolution in t-dep. CPV studies*

Combined Pixel and Strip detectors beam test at DESY
(with DAQ, software, database, CO_2 cooling, slow control, environmental control)
successful

Pixel Detector





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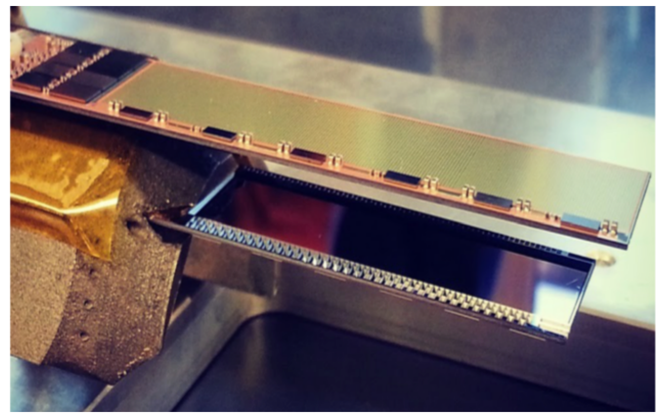
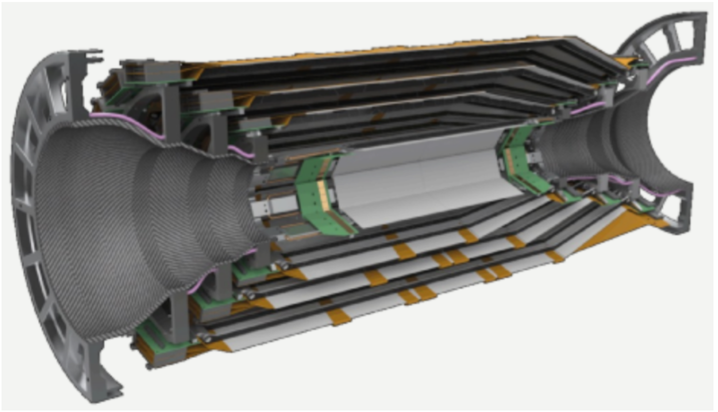
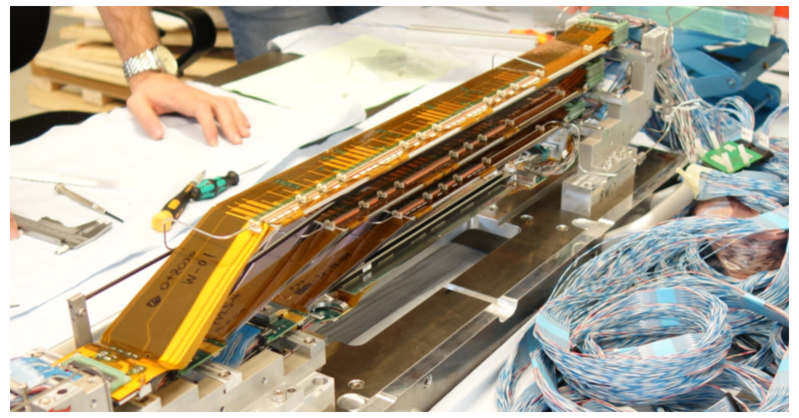


Strip Detector



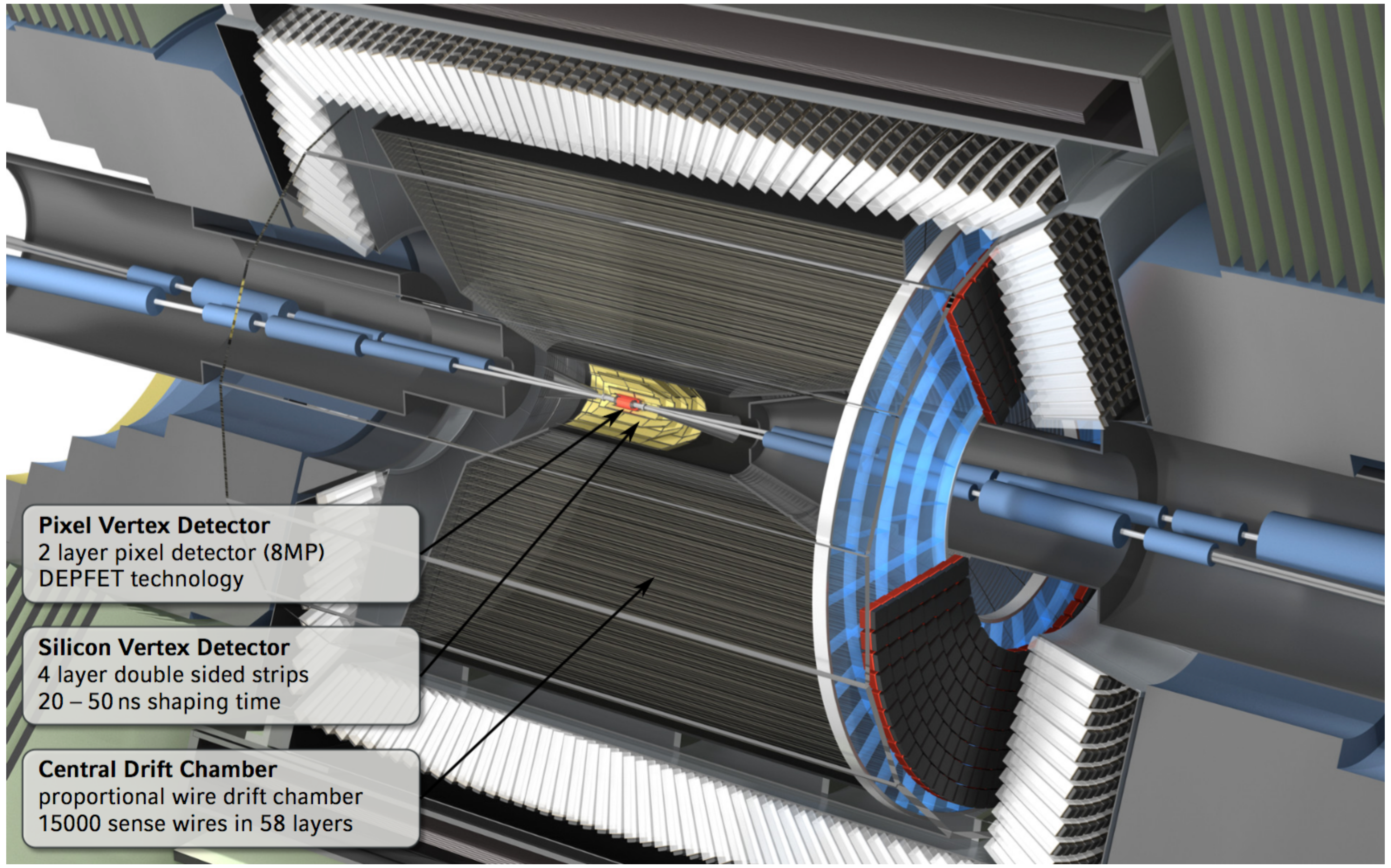
4 strip ladders



Detector Upgrade *- Tracking detector*

Central Drift Chamber

- larger compared to Belle
- smaller drift with sense wires and more layers allow better charged track reconstruction and dE/dx measurement compared to Belle
- Faster readout electronics



Detector Upgrade - *Tracking detector*

Central Drift Chamber

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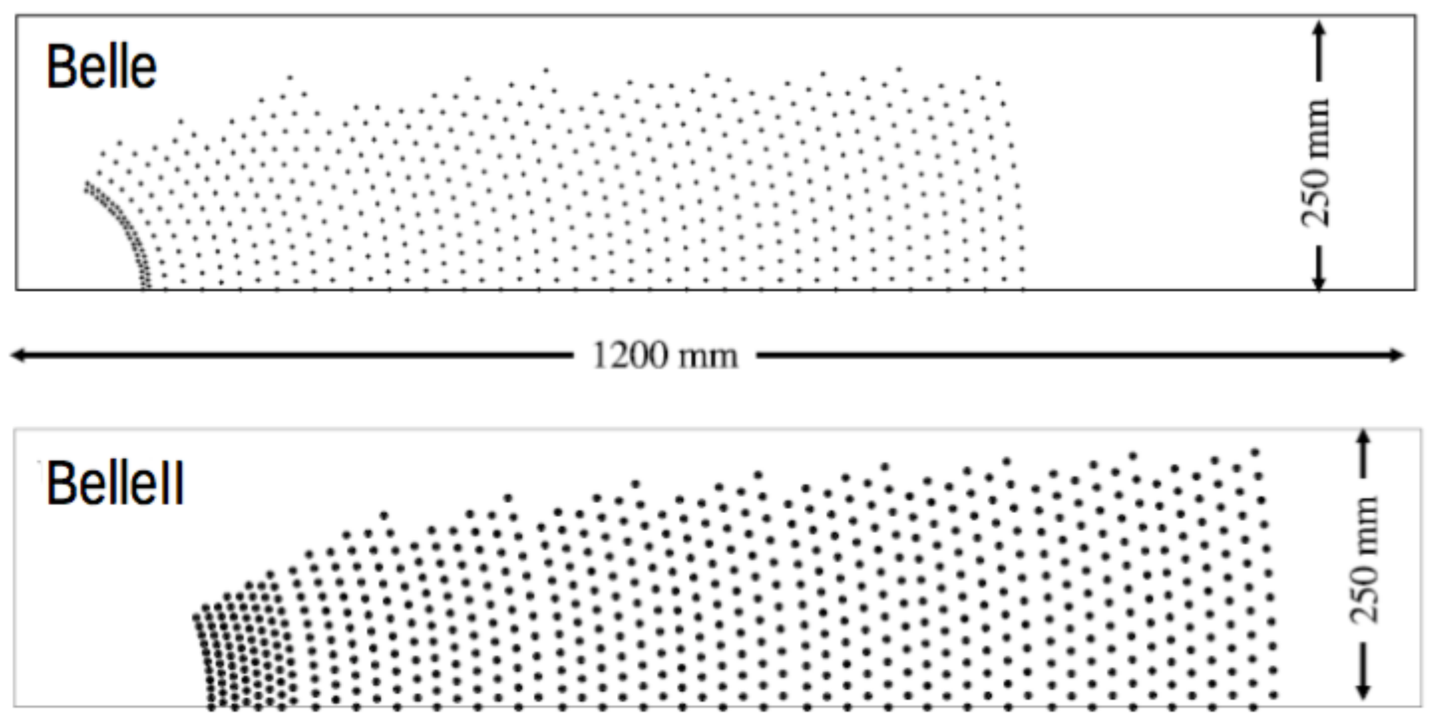
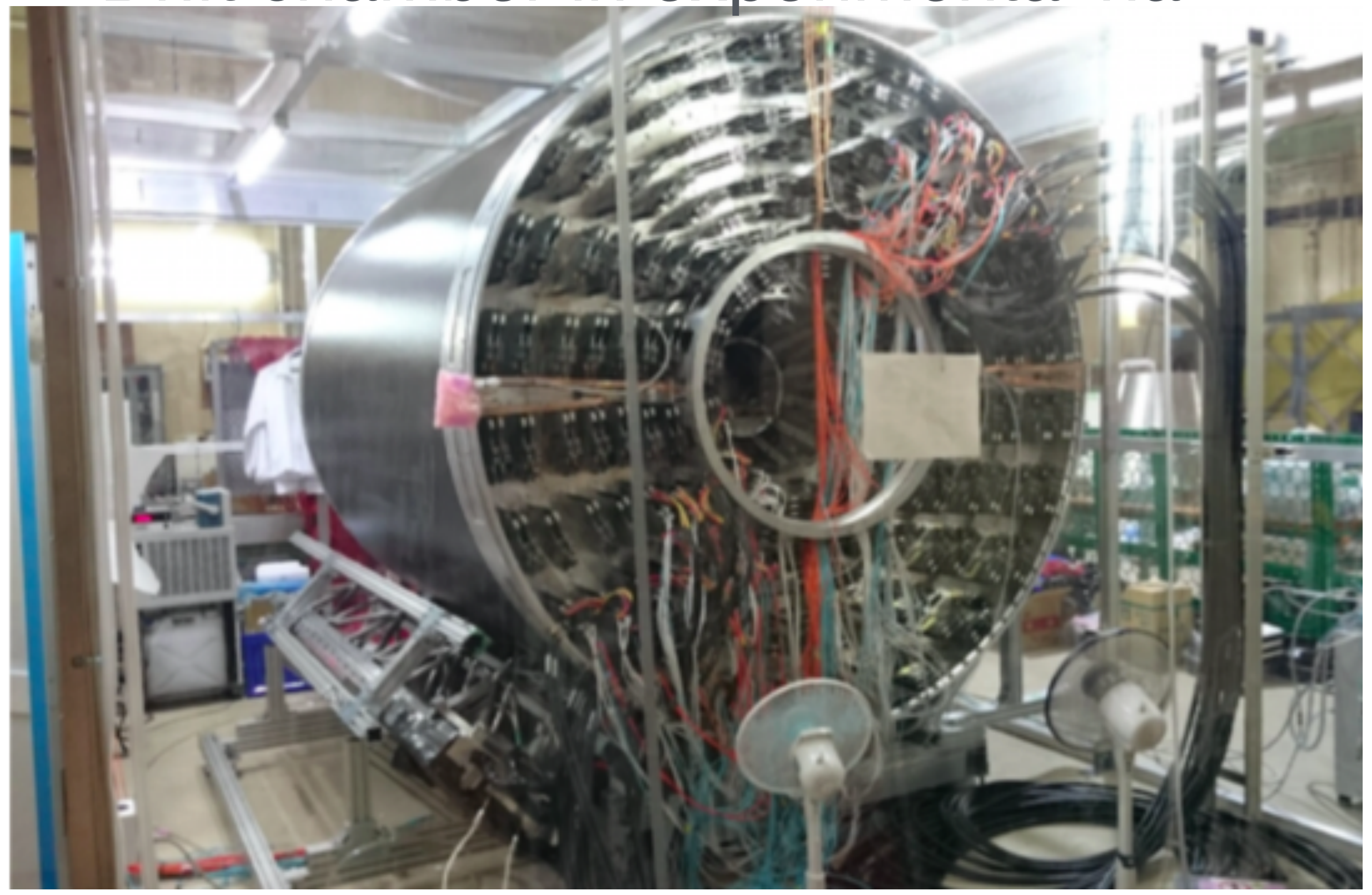
	Belle	Belle II
Radius of inner boundary (mm)	88	168
Radius of outer boundary (mm)	863	1111
Number of layers	50	56
Number of sense wires	8400	14336
Gas	HeC_2H_6	HeC_2H_6
Diameter of a sense wire (μm)	30	30

Wire Configuration



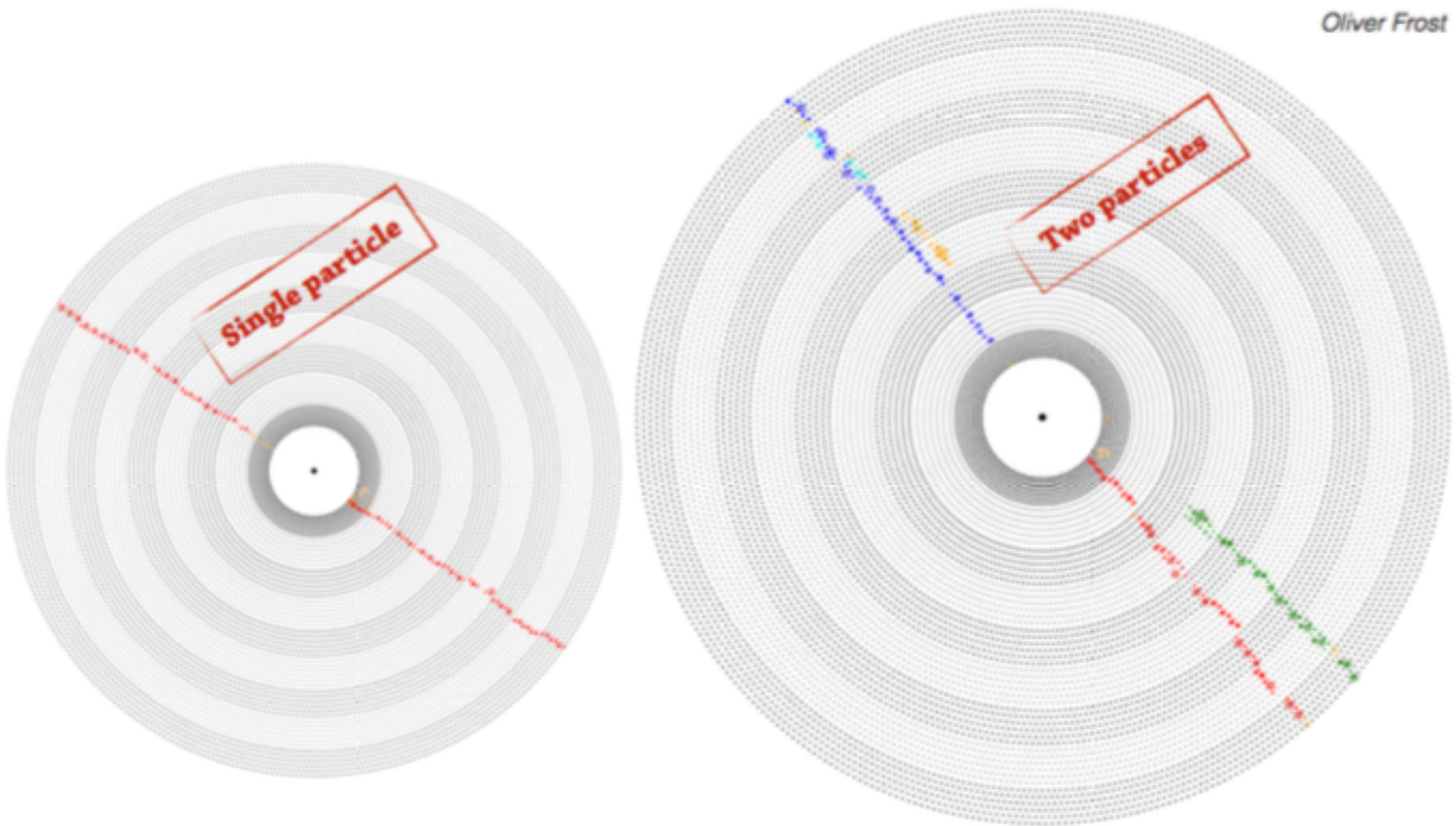
Detector Upgrade *- Tracking detector*

Drift chamber in experimental hall



Central Drift Chamber

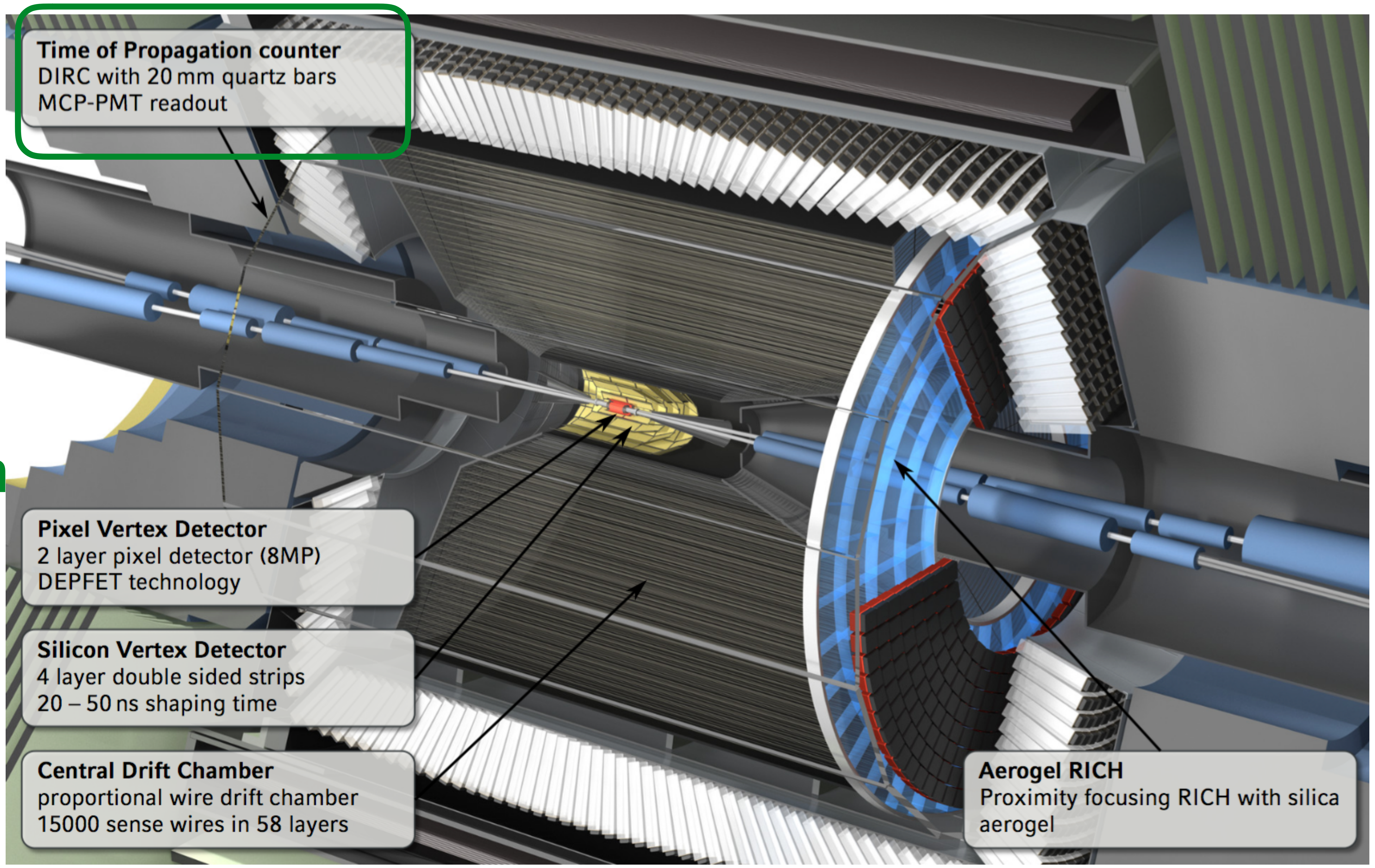
- larger compared to Belle
- smaller drift with sense wires and more layers allow better charged track reconstruction and dE/dx measurement compared to Belle
- Faster readout electronics
- Construction complete
- Cosmic ray test ongoing
  - track finder efficiency close to 100%



***Detector Upgrade** - Particle Identification*

Two Čerenkov detectors (K/π separation):

- Barel: Time Of Propagation
  - measures x-y position (5 mm) of Čerenkov photons and their arrival time (40 ps)
  - Time Of Flight from IP works additively
  - All modules installed and commissioning with cosmics ongoing



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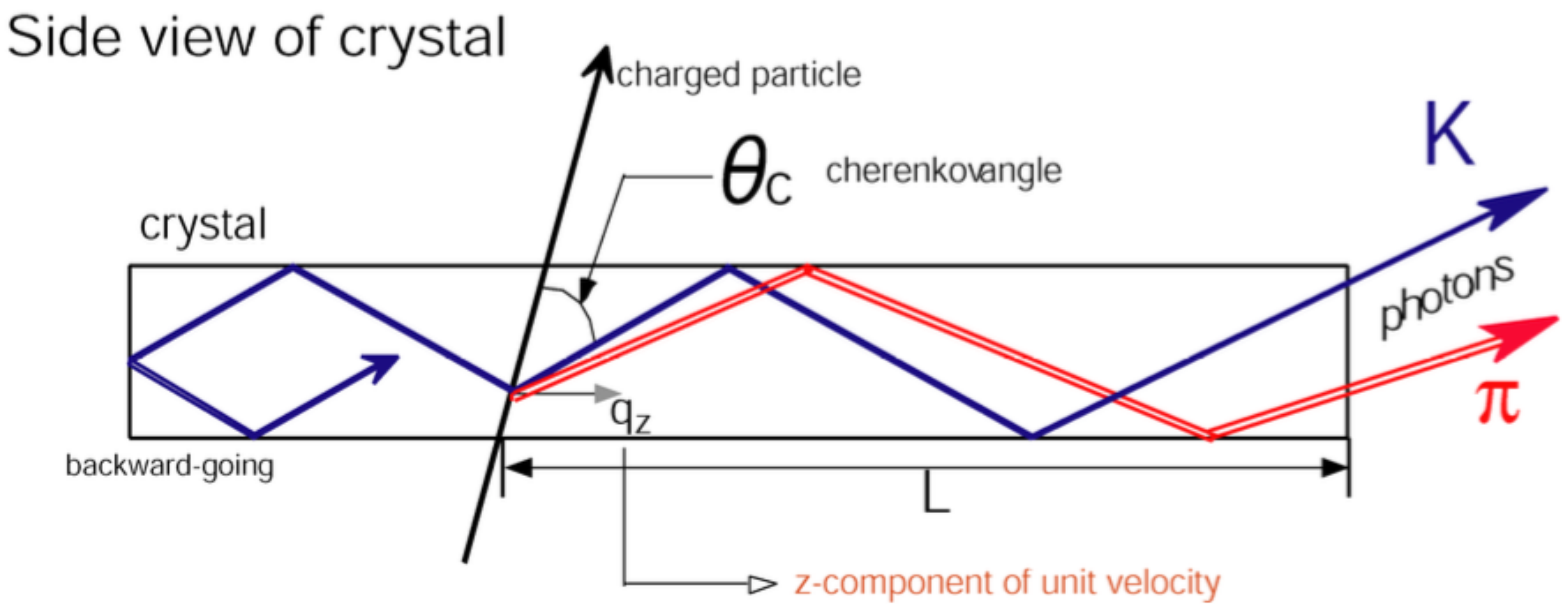
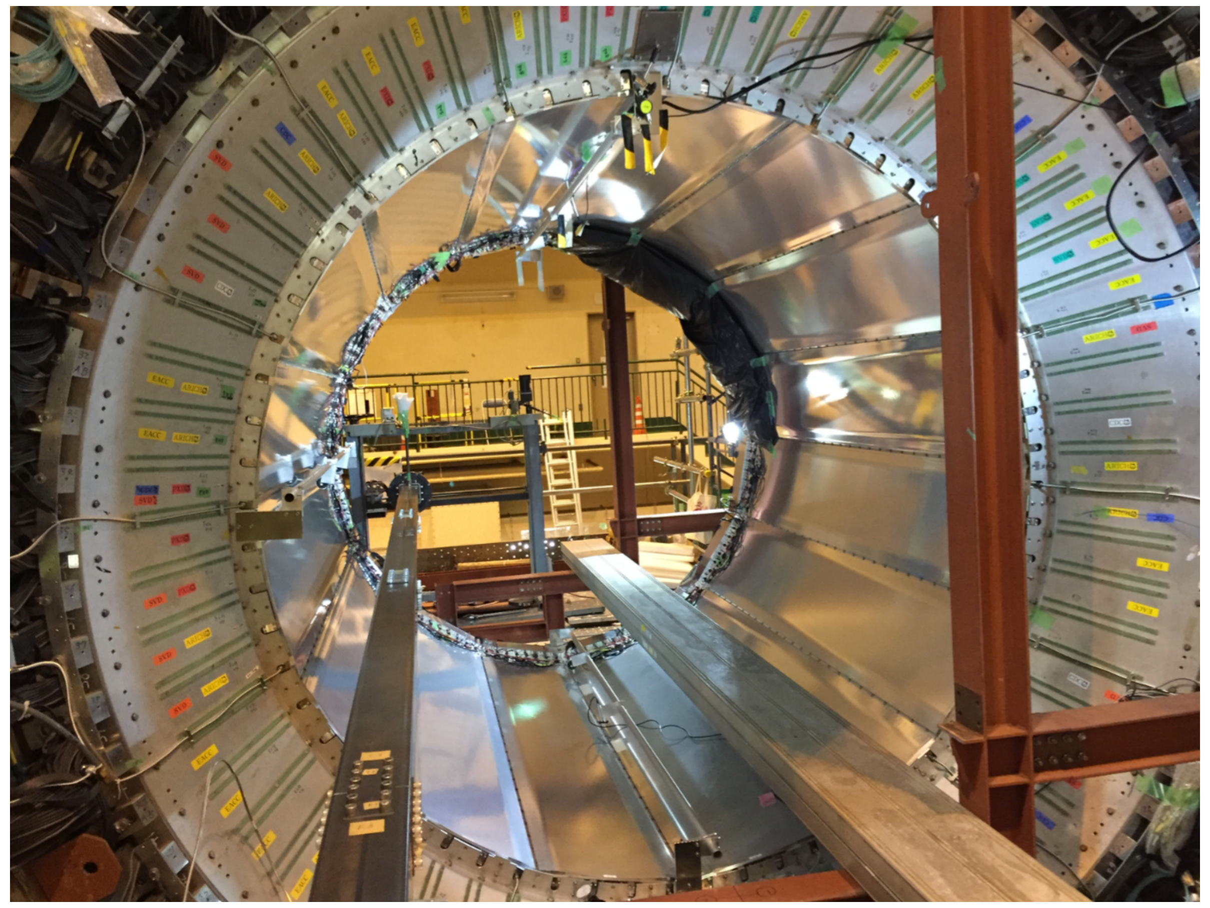
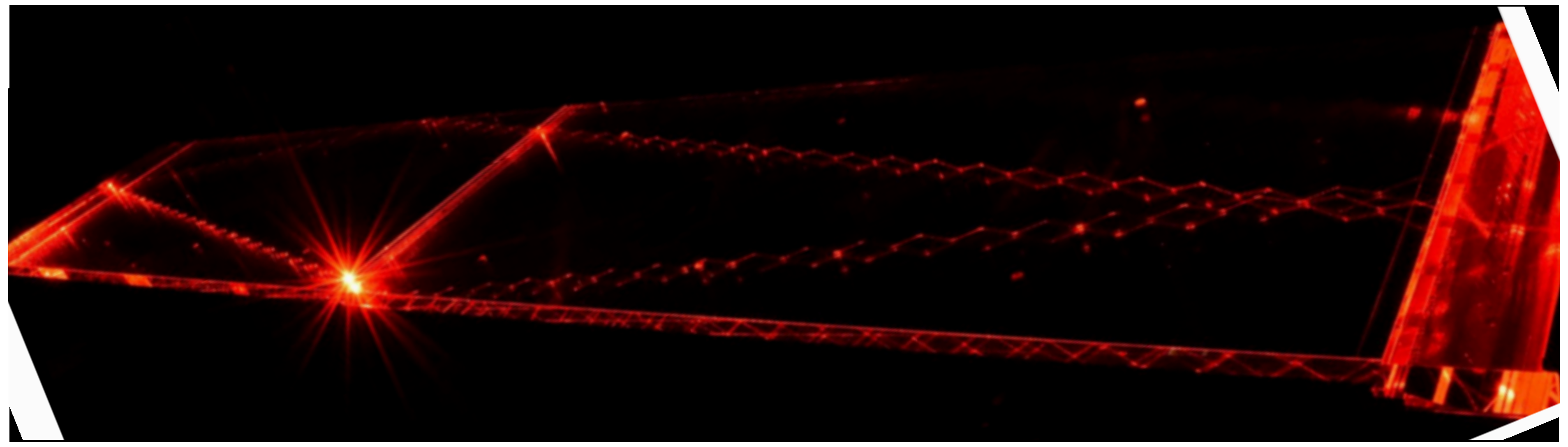
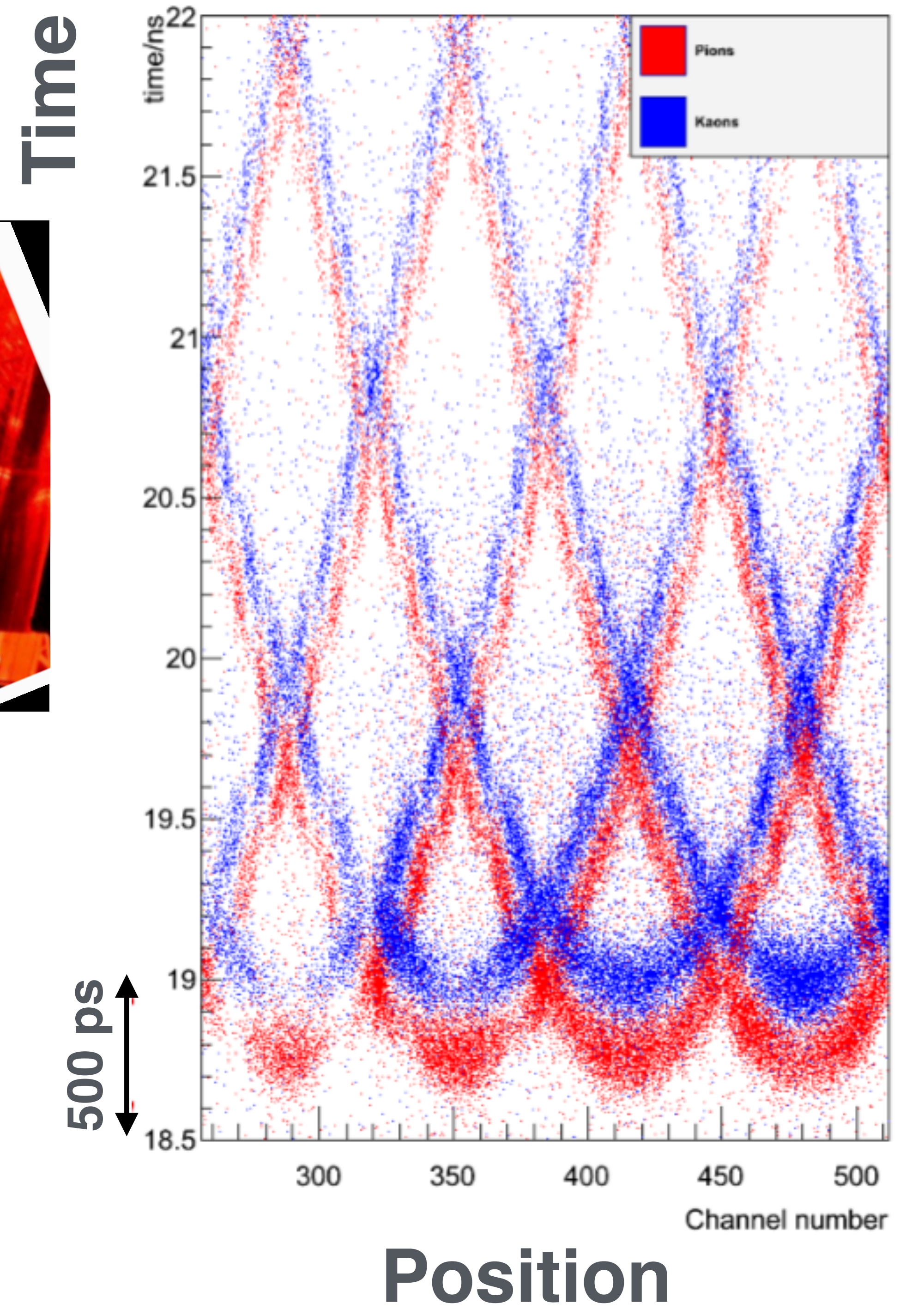




Total internal reflections of laser beam inside one quartz module





Detector Upgrade - *Particle Identification*

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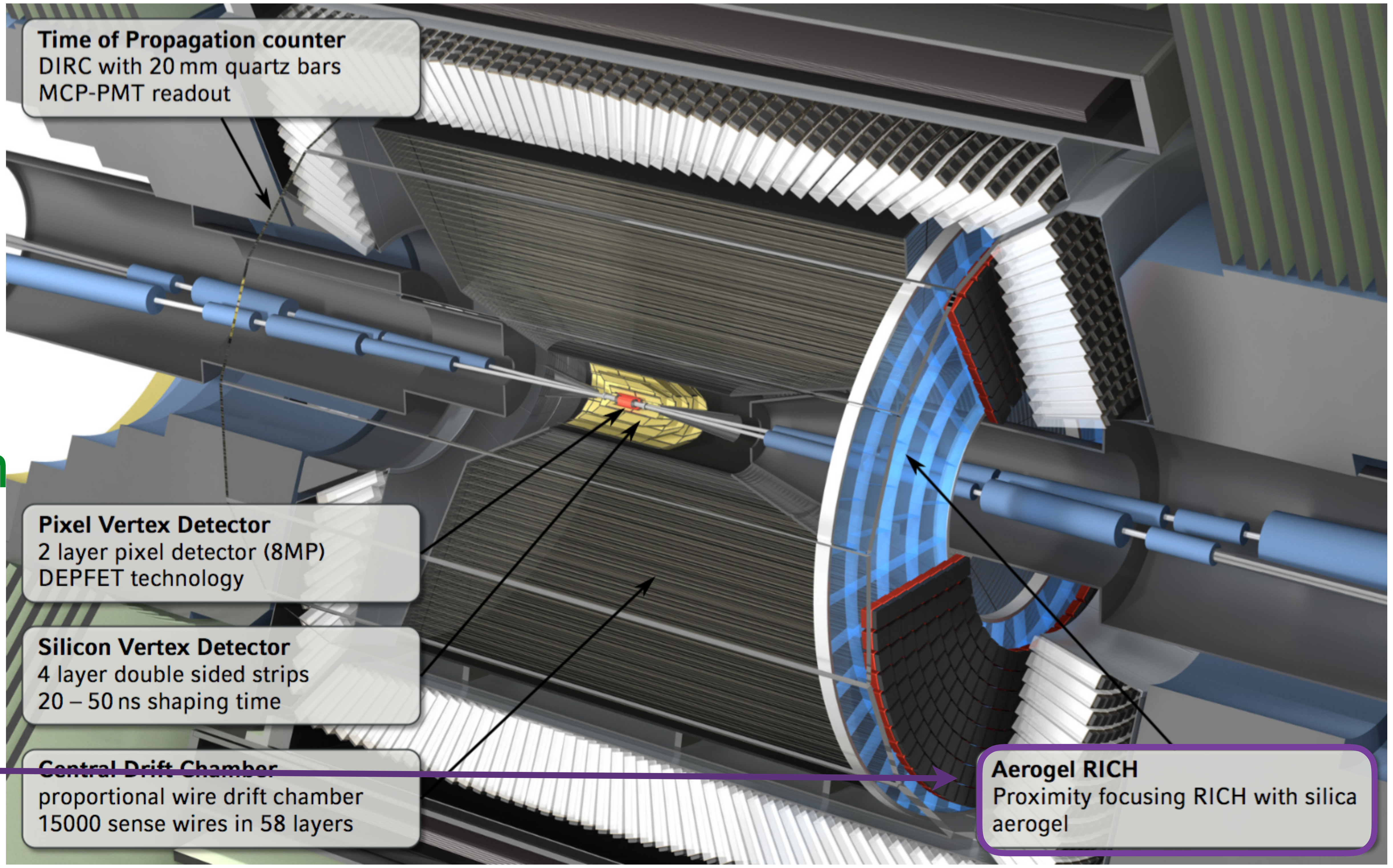
- Aerogel Ring-Imaging Čerenkov
  - Proximity focusing with silica aerogel
  - 4σ K/π separation at 1 - 3.5 GeV/c



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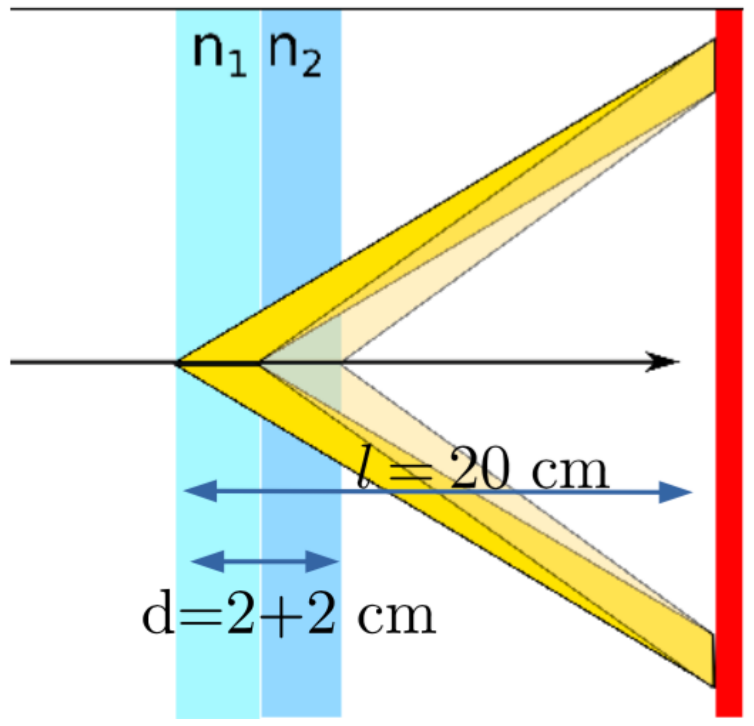
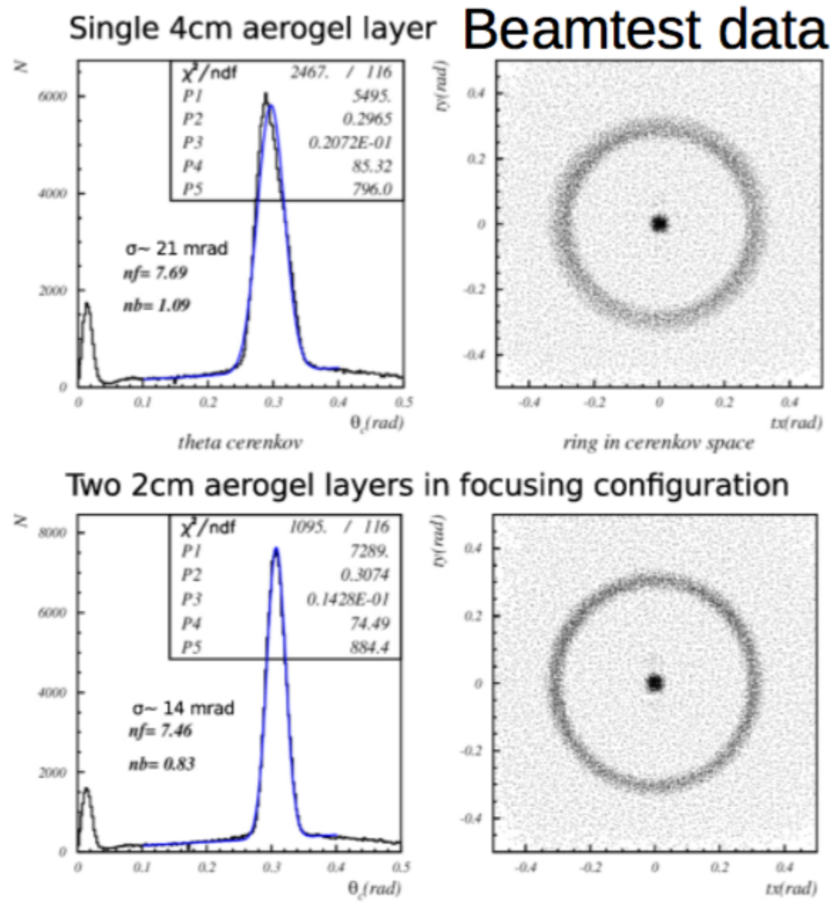
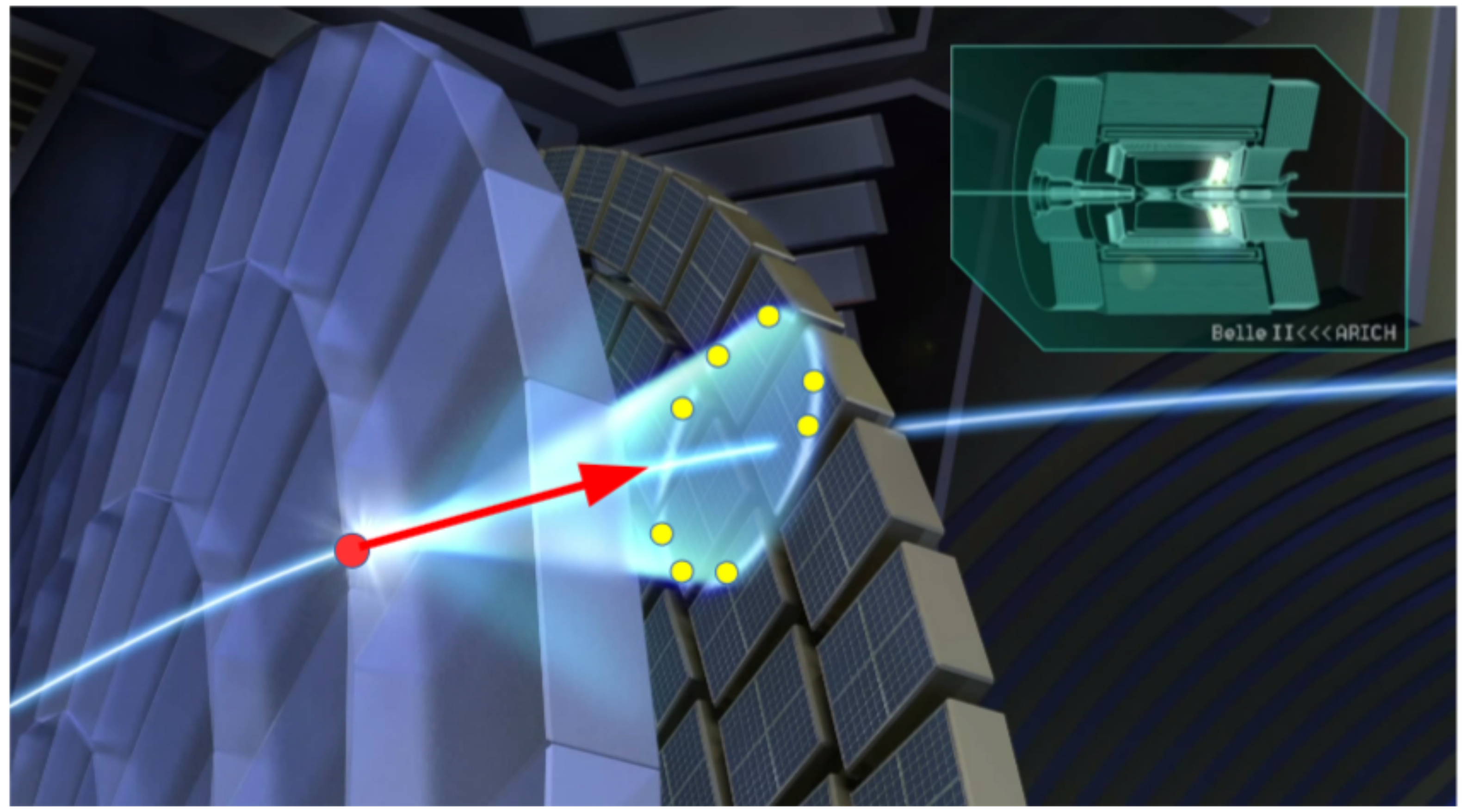
  - Proximity focusing with silica aerogel
  - 4σ K/π separation at 1 - 3.5 GeV/c

Novel technique of two aerogel layers in focusing configuration

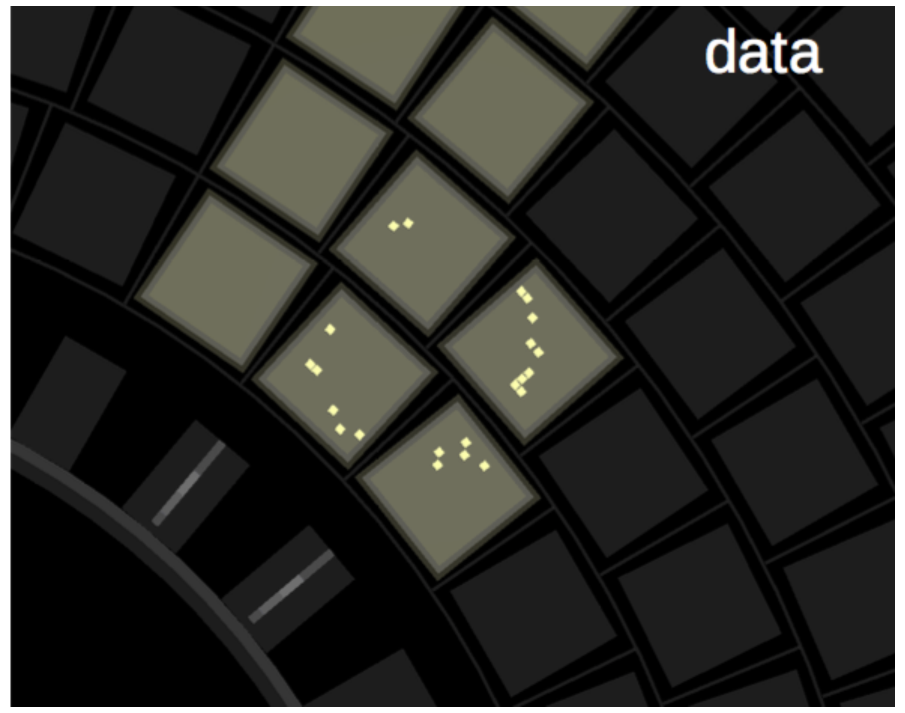


Almost doubling number of Cherenkov photons, without angle resolution degradation!



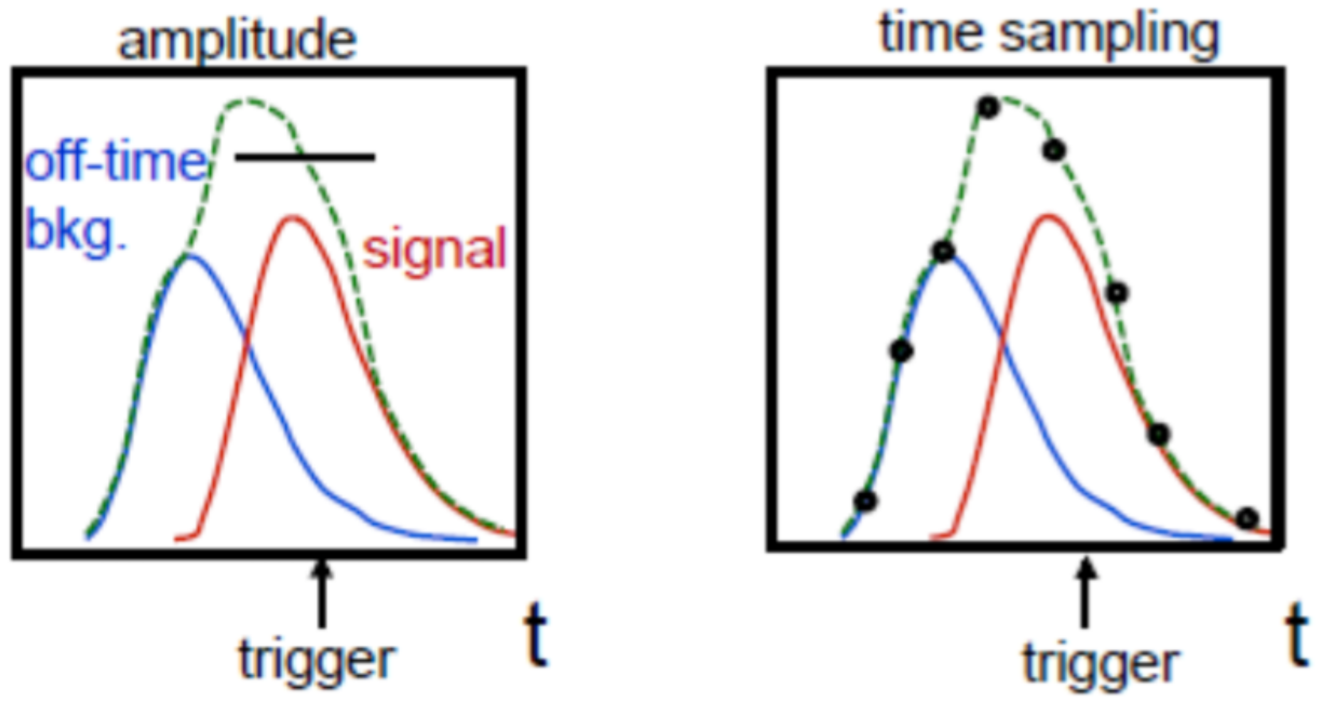


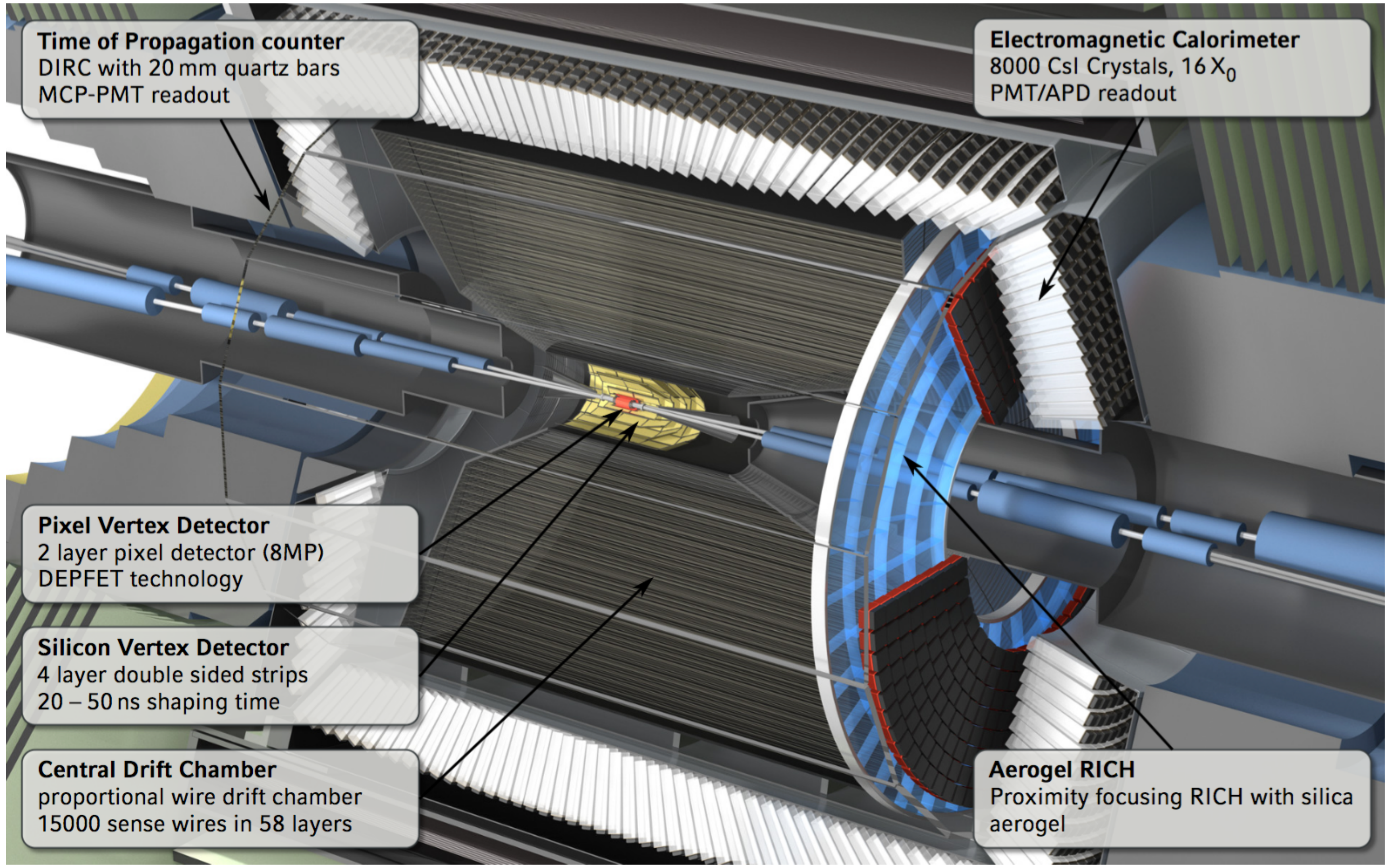
First rings from cosmics on partially instrumented detector



Detector Upgrade *- Electromagnetic Calorimeter*

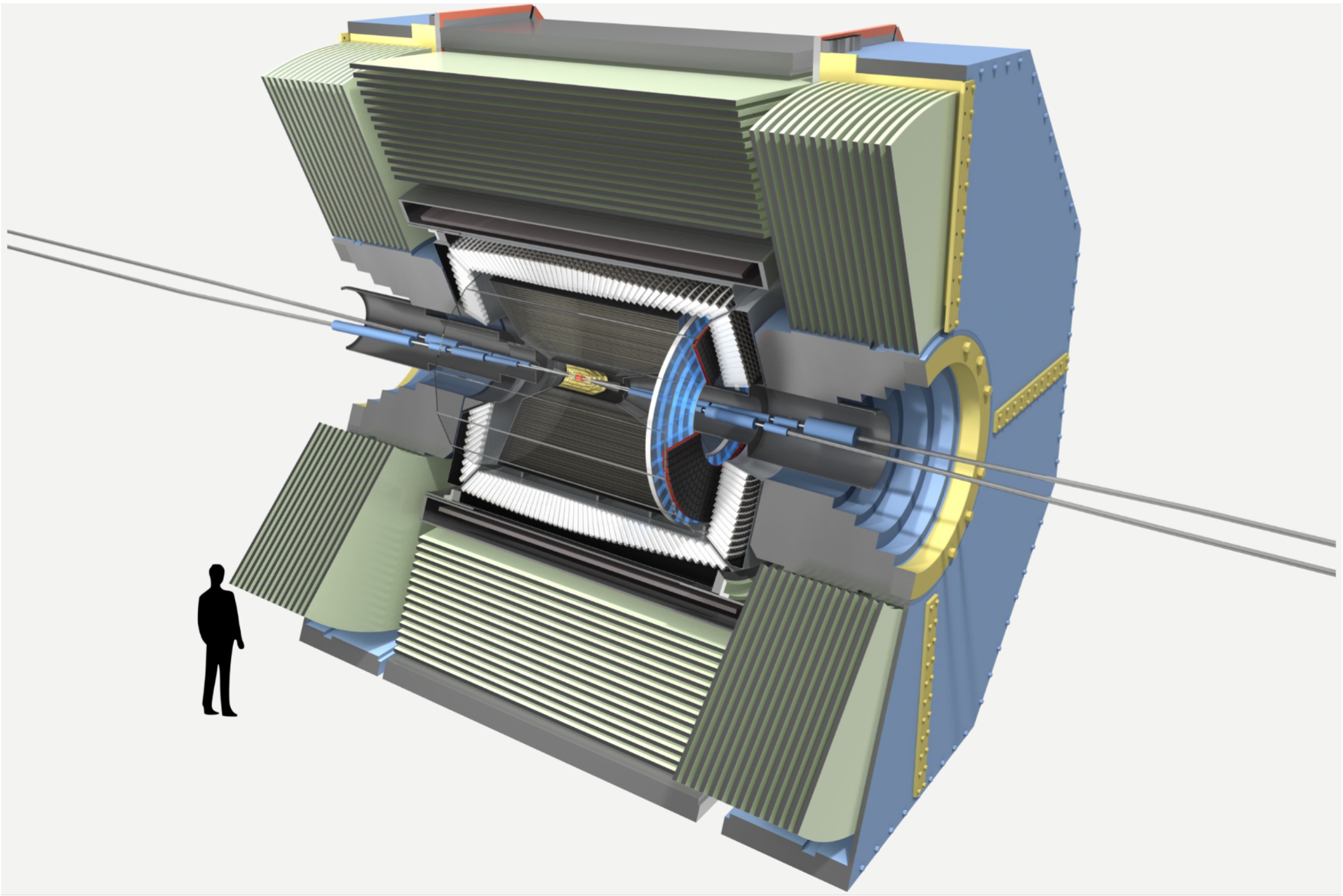
- Re-uses Belle's CsI(Tl) crystal calorimeter but with improved readout electronics with waveform sampling to compensate for higher beam background
- R&D to replace in future endcap crystals with pure CsI with faster light emission and smaller light yield
- ECL readout electronics was installed and DAQ integration tests are going on

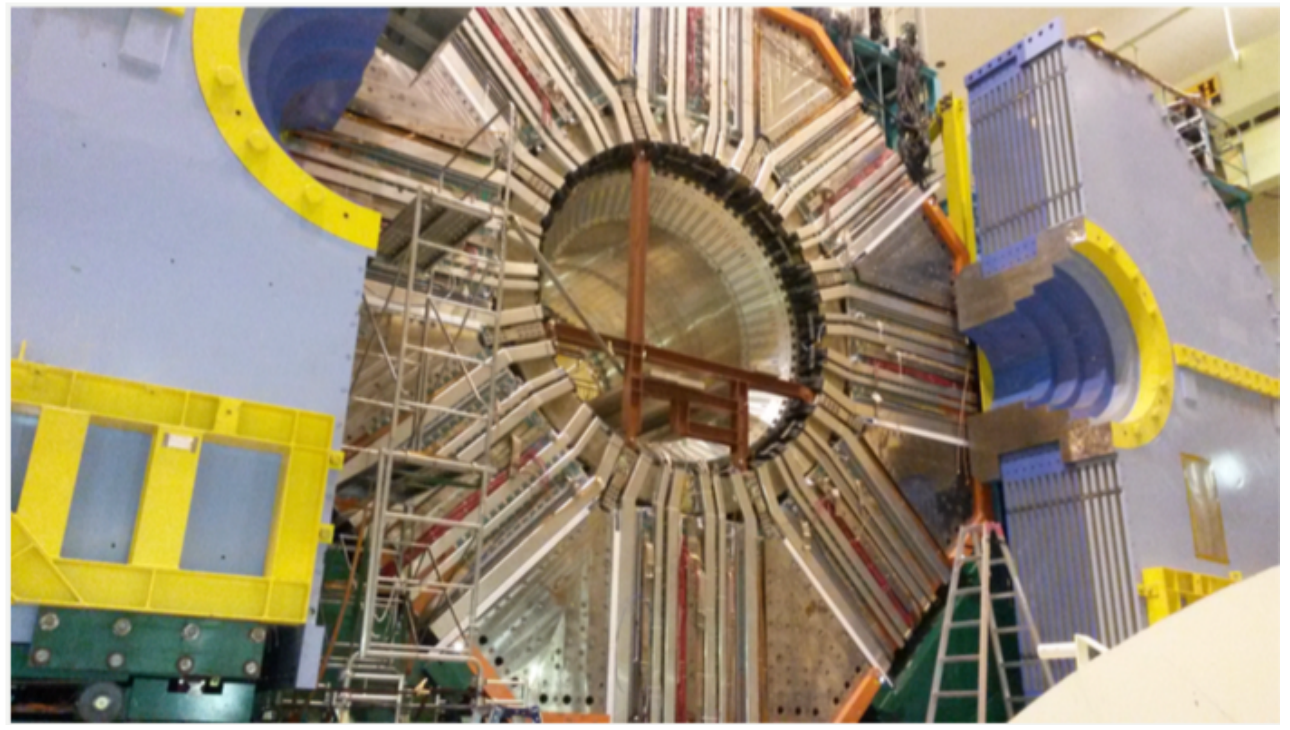


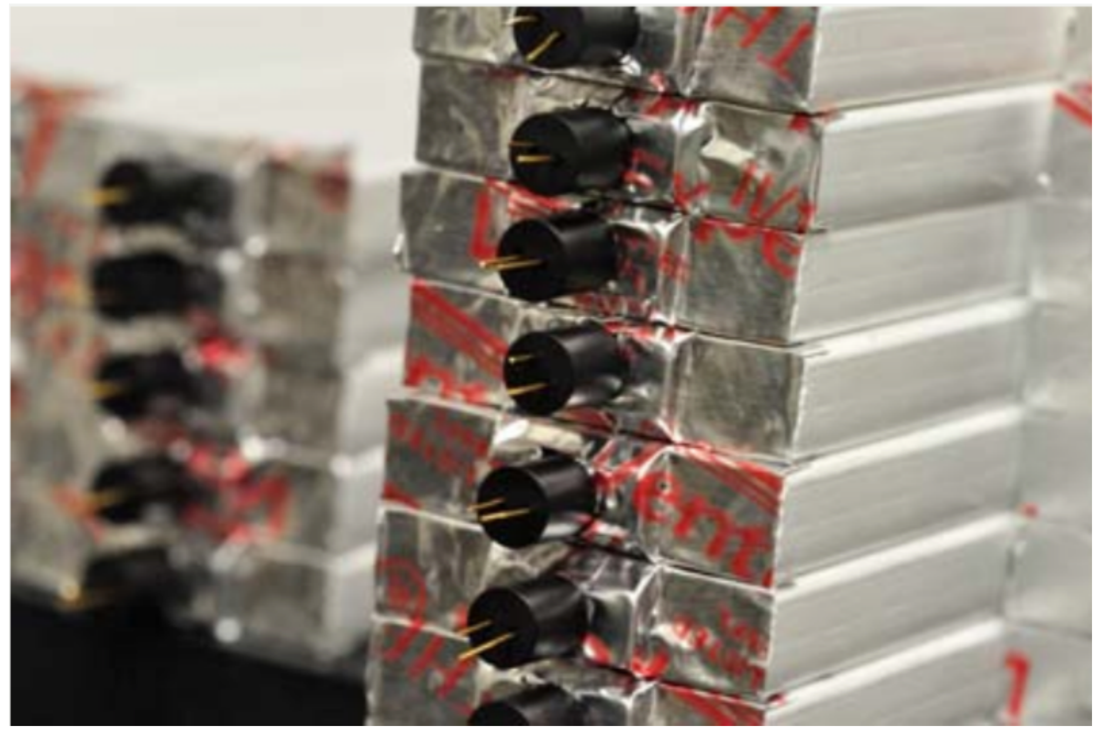


Detector Upgrade - *K_L and μ detector*

- Endcap and two layers of the barrel Resistive Plate Chambers have been replaced with scintillators to handle higher backgrounds (mainly from neutrons)
- Installation complete

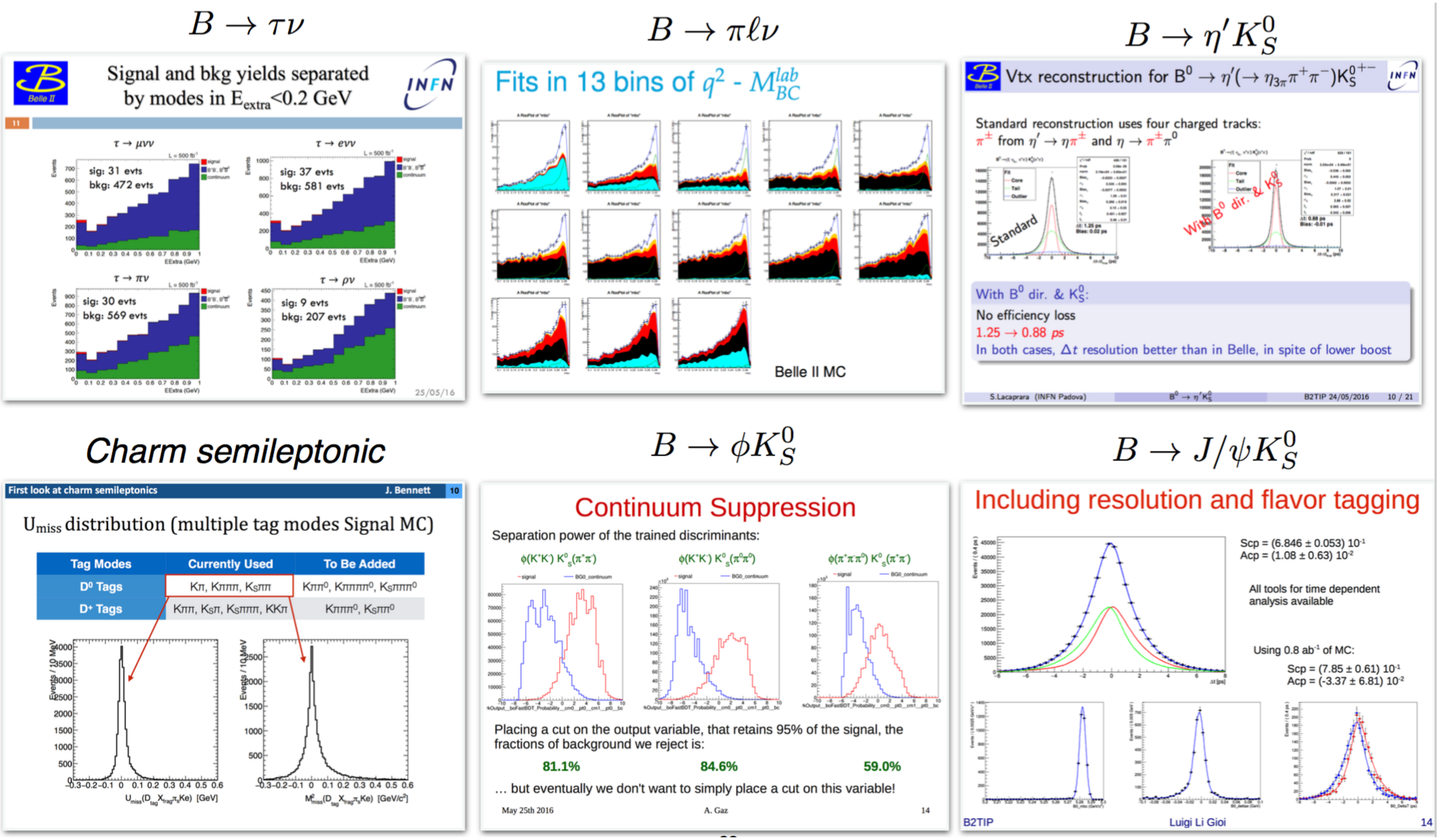






Outline

- *B factories*
- *Accelerator*
- *Detector*
- ***Physics***



Snapshot of physics sensitivity studies presented at B2TIP in Pittsburg (May'16) using Belle II Analysis Tools

Physics program at Belle II

Wide and Rich Physics Program:

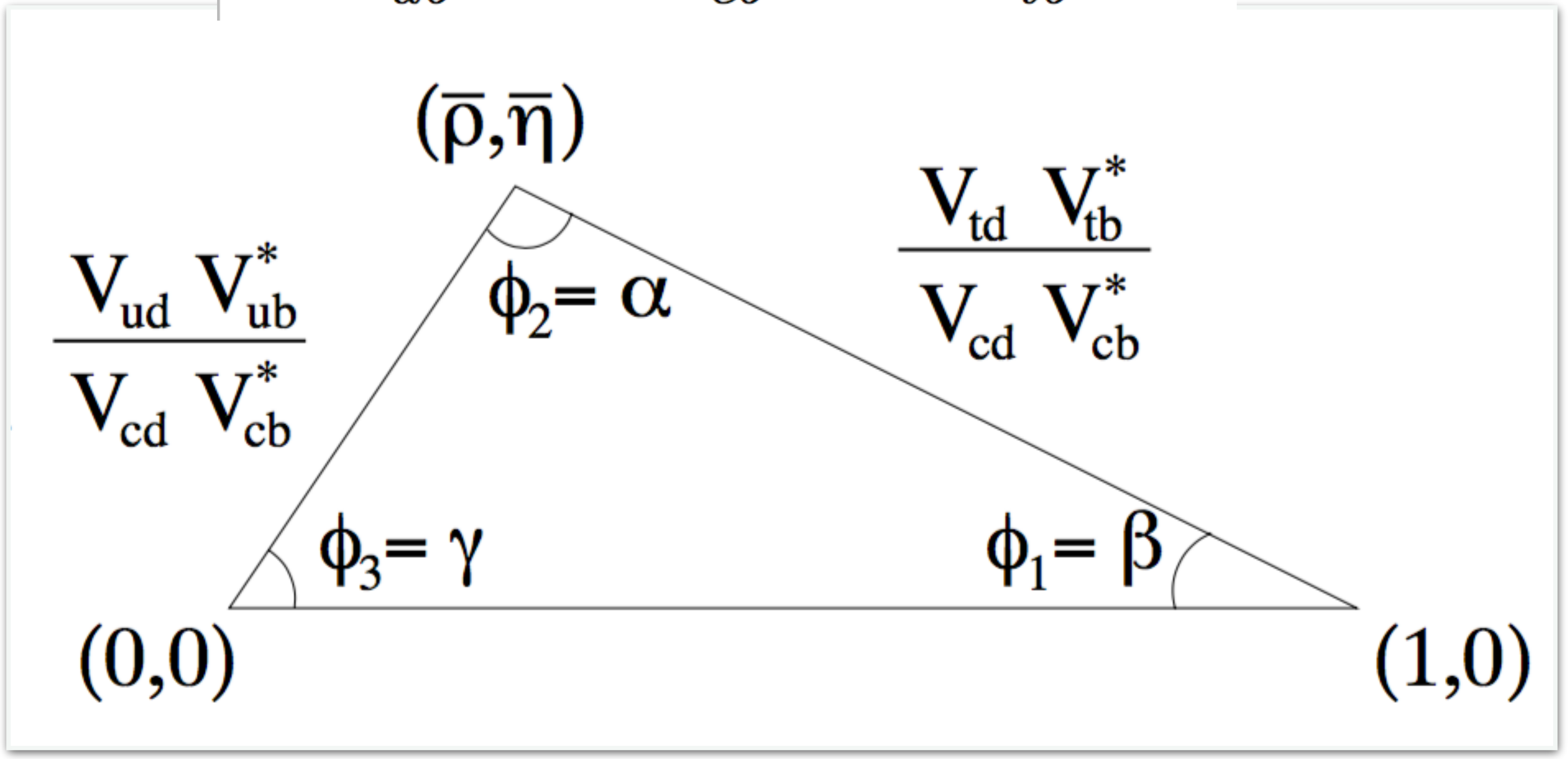
- Flavour physics
  - *$\Delta B=2$ loop processes: Neutral B meson mixing*
  - *$\Delta B=1$ loop processes: Penguin B meson decays*
  - *(Semi-)Leptonic B decays*
  - *Charm and τ lepton decays*
- Direct searches of New Physics
  - *dark photon, Higgs, etc.*
- Electroweak measurements
- Exotic hadron and hadron spectroscopy

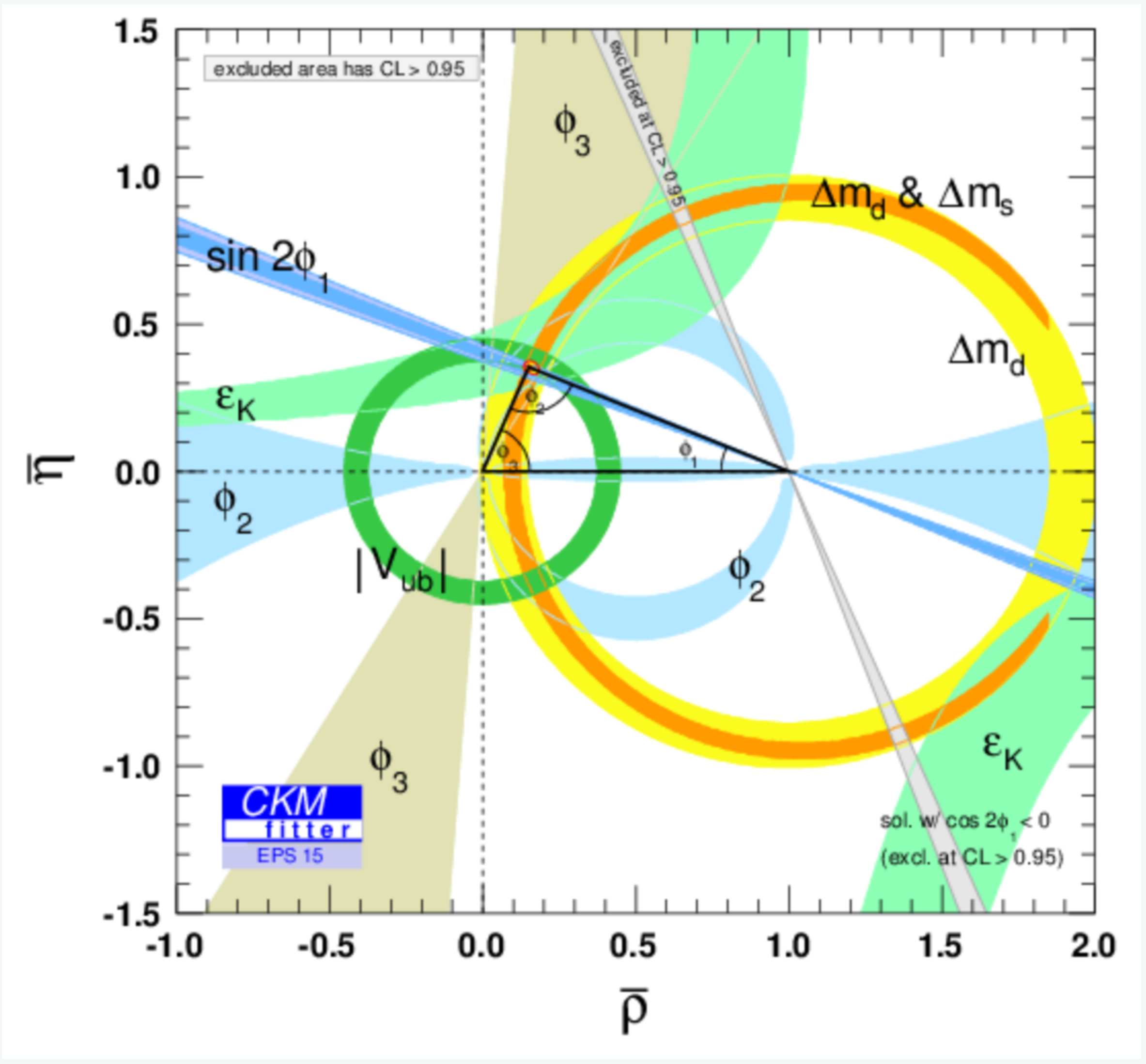
Flavour Physics at Belle II - *Unitarity Triangle*

SM allows for precise quantitative predictions:

- wide variety of weak processes including flavour depend only on handful of free parameters of the theory
  - Are measurements of wide variety of processes consistent with each other?
  - If not, presence of physics beyond SM is required.

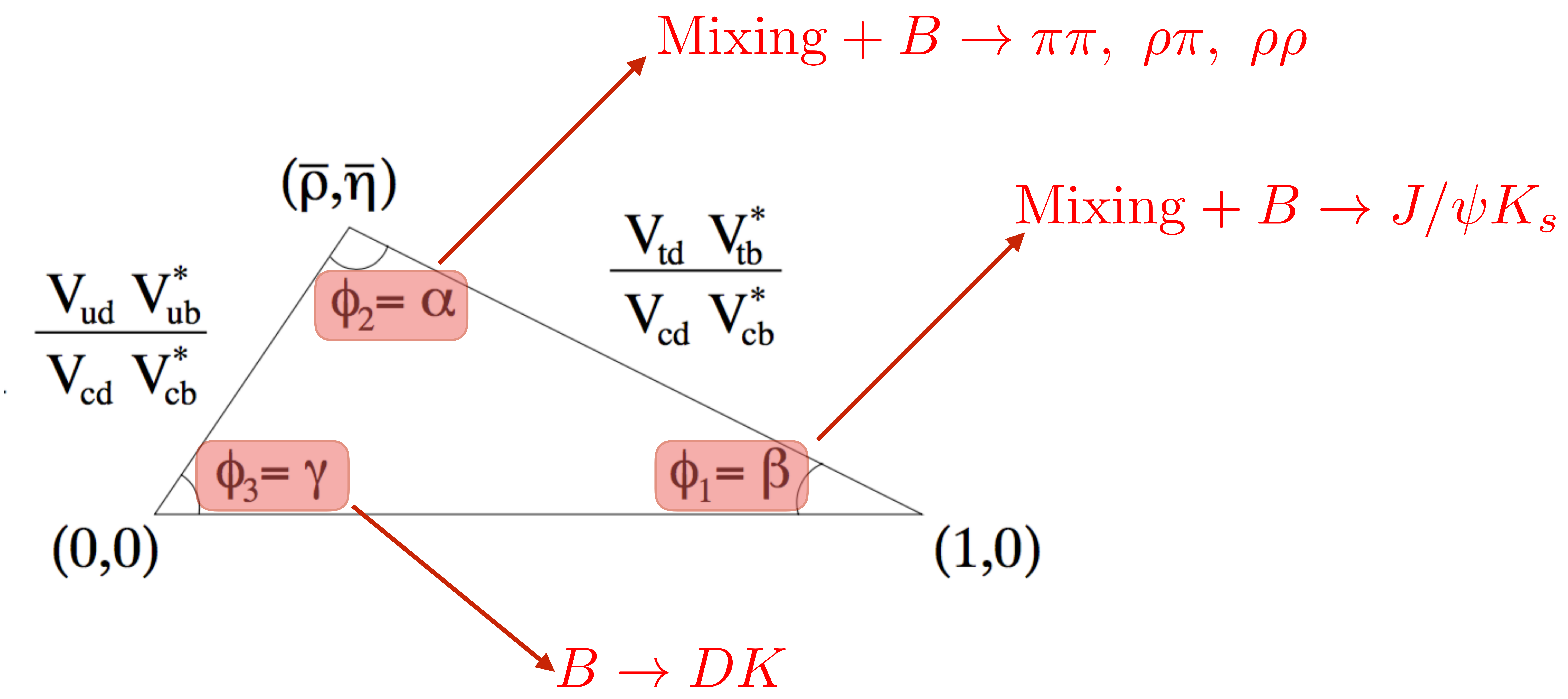
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



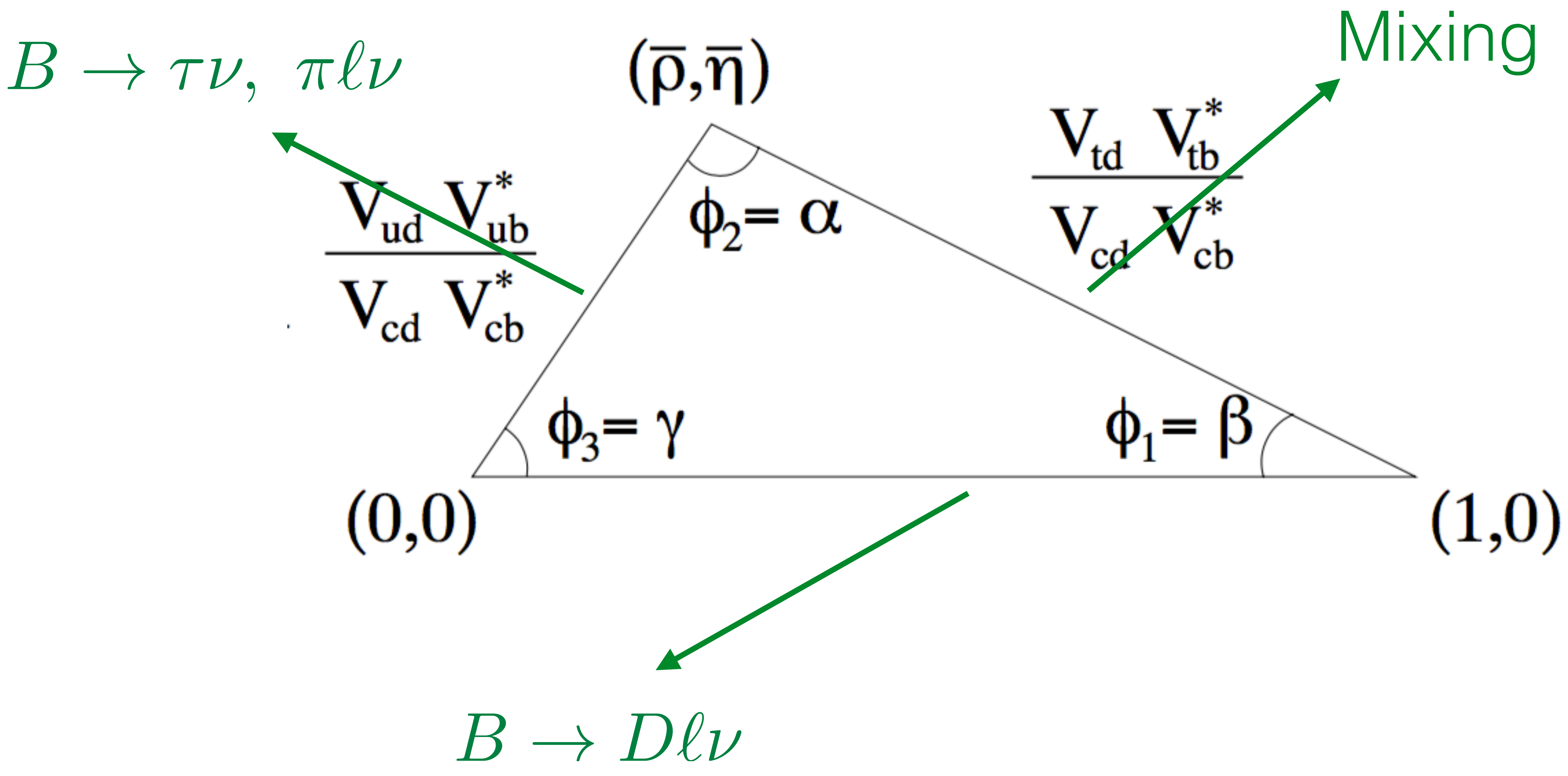


In the flavour sector the consistency of measurements can be visually presented in form of the Unitarity Triangle (stemming from unitarity of CKM matrix)

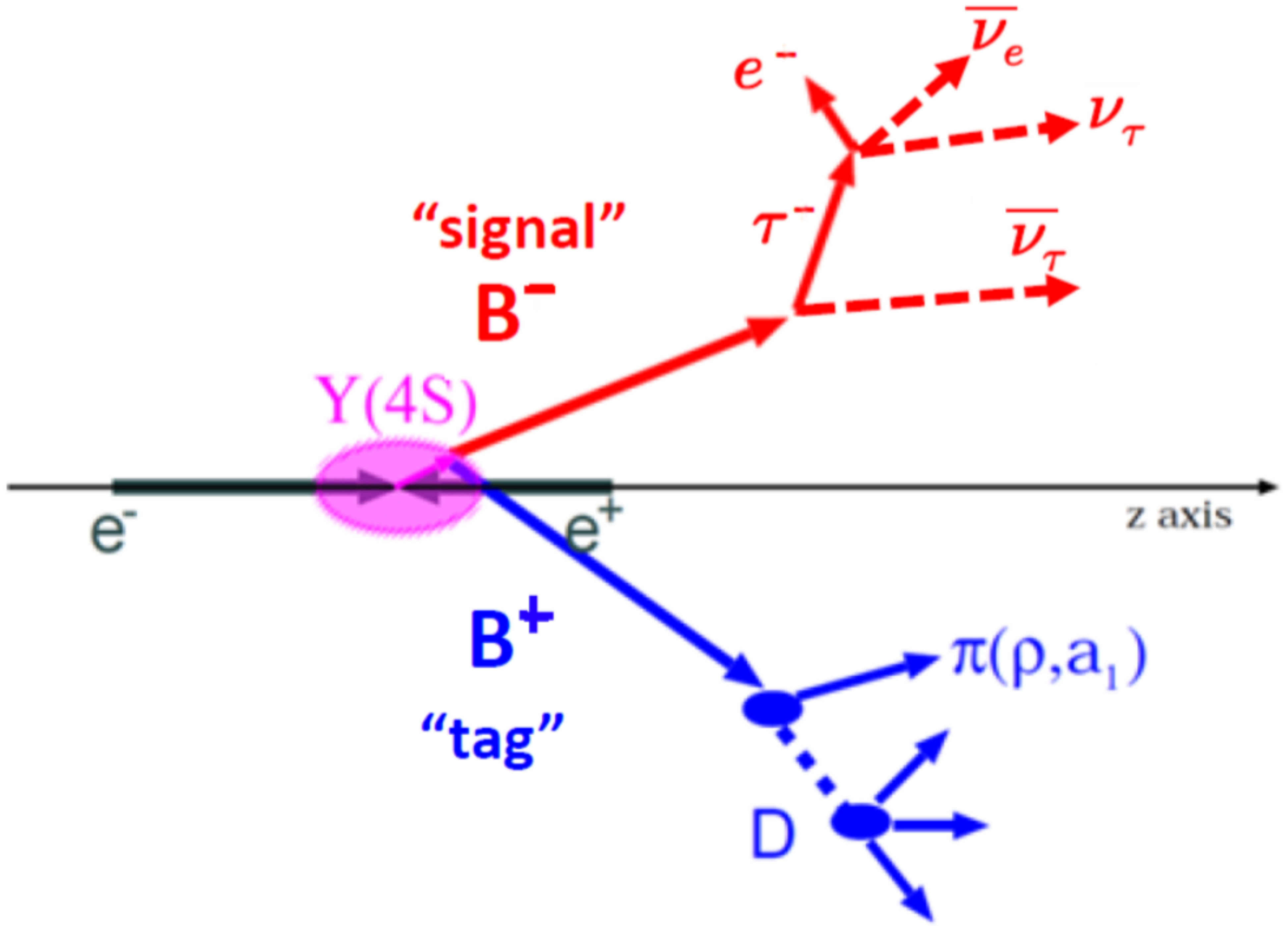
Flavour Physics at Belle II *- Unitarity Triangle*



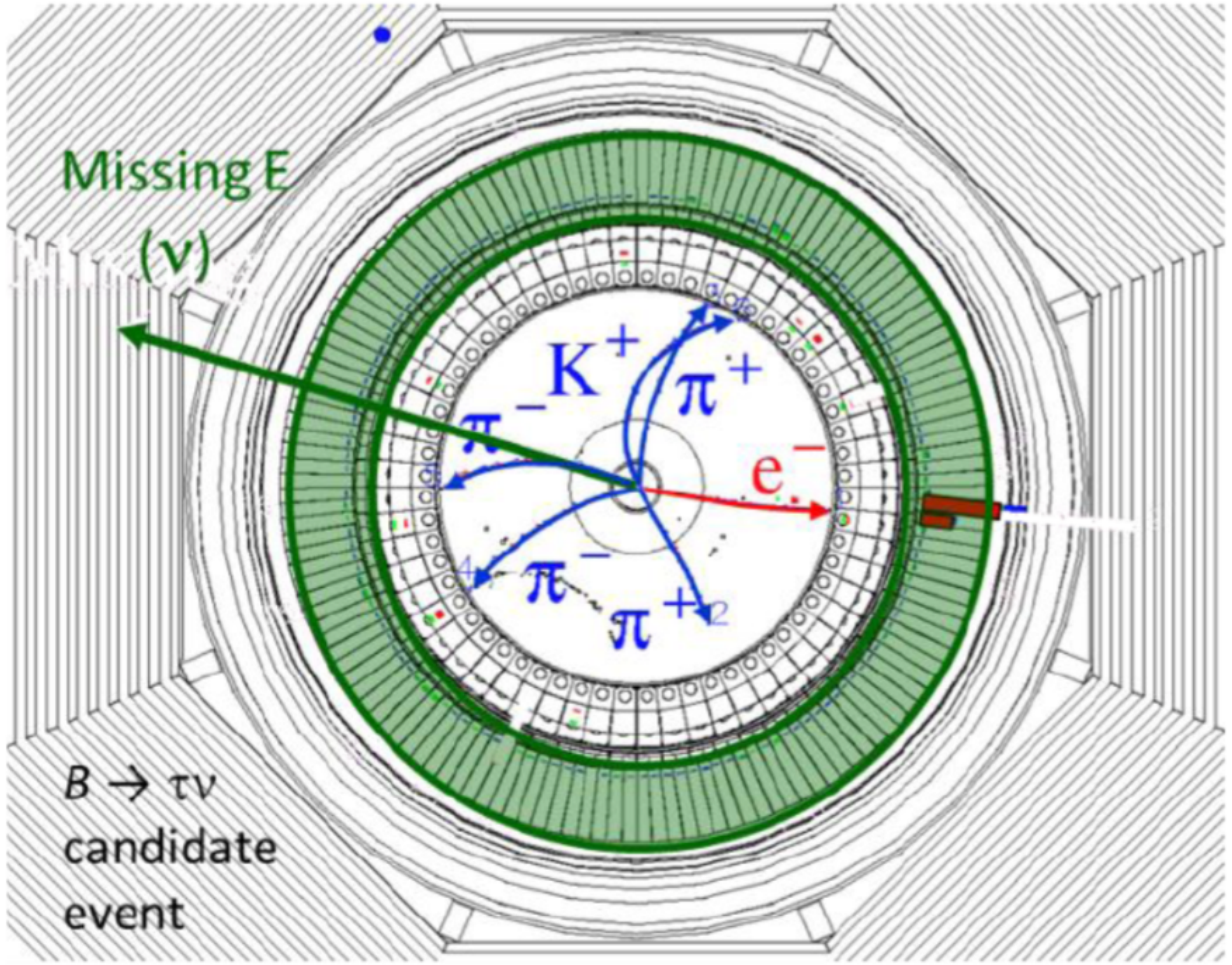
Flavour Physics at Belle II *- Unitarity Triangle*



Missing Energy Modes



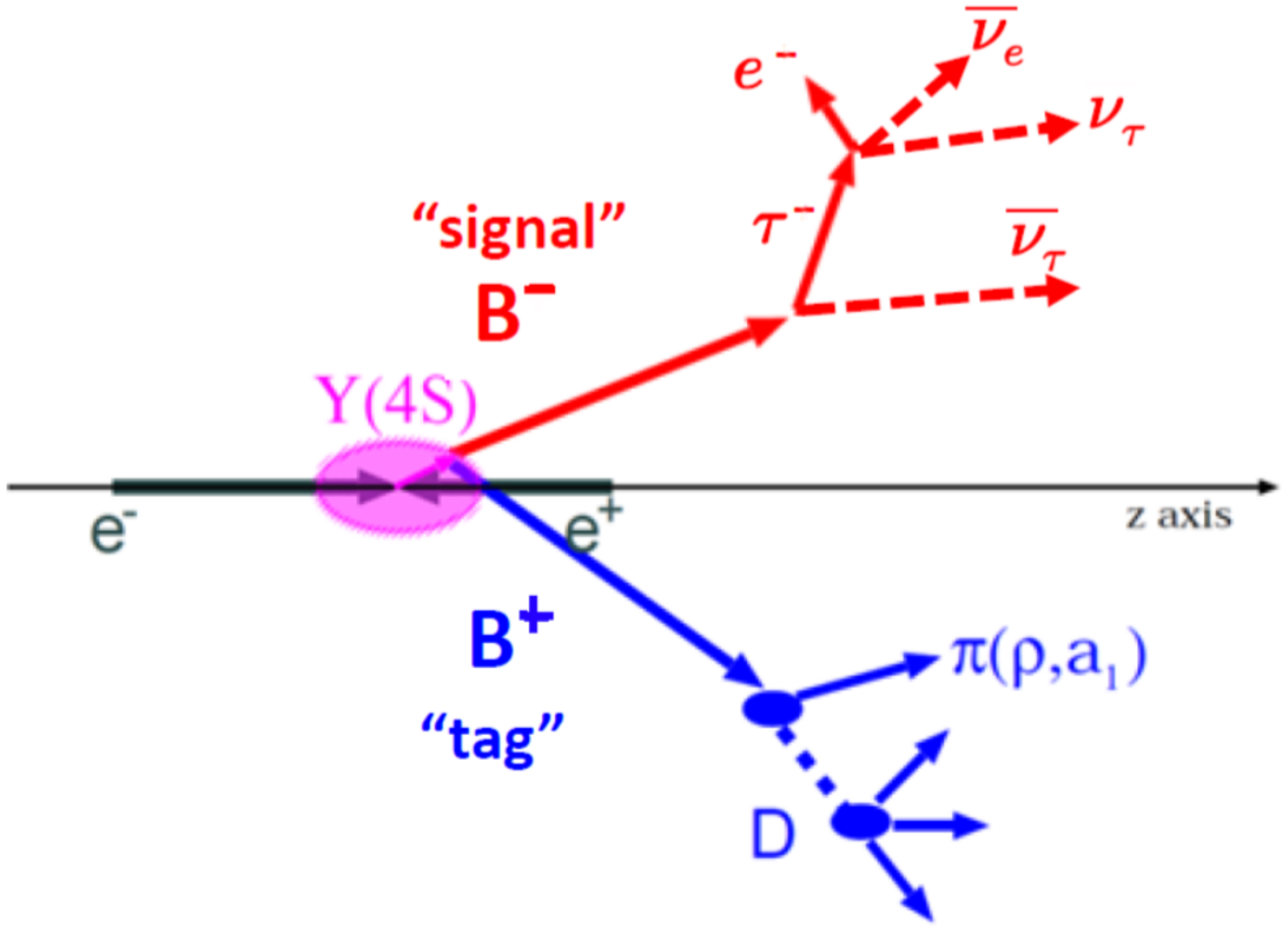
Example Belle $B \to \tau\nu$ candidate



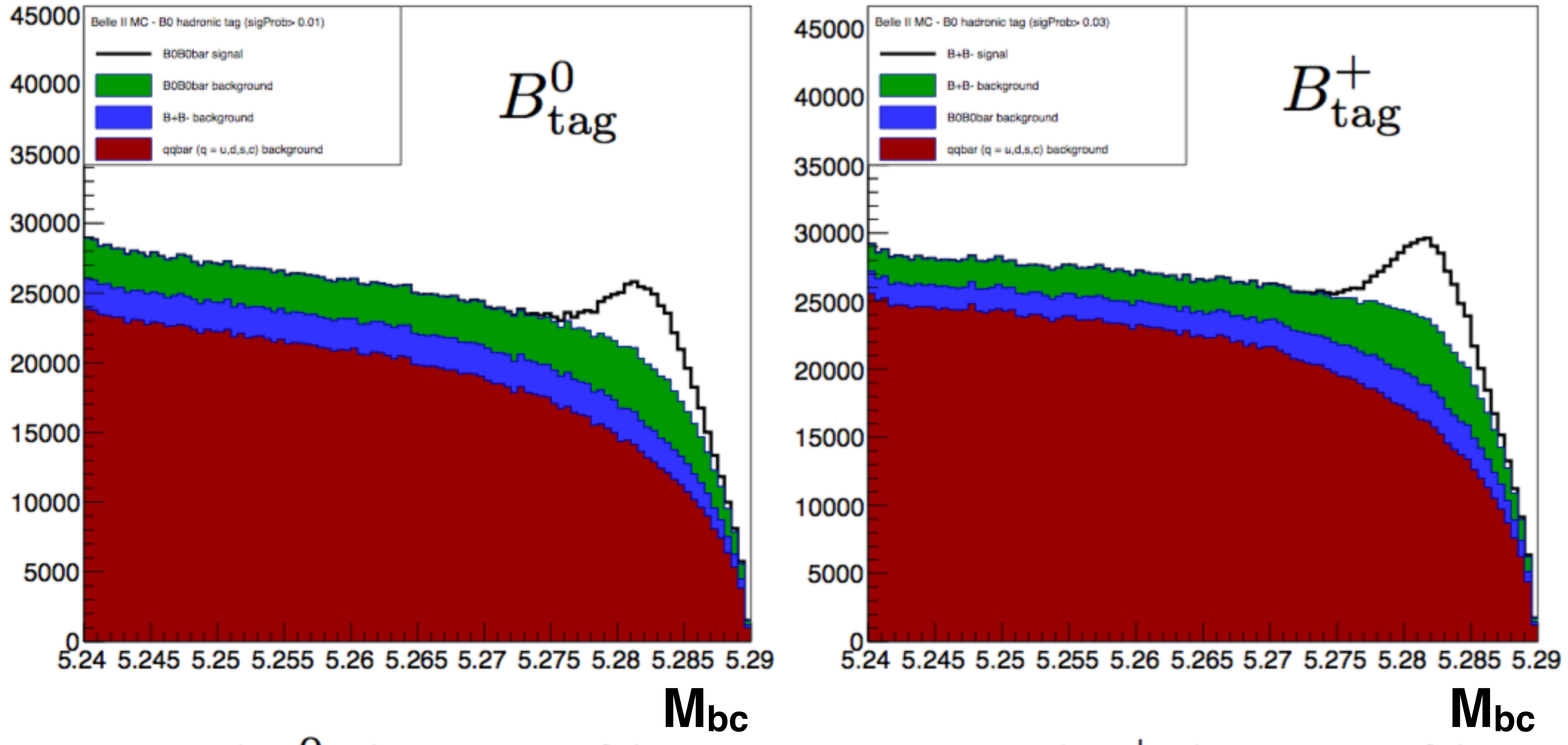
Hermeticity of the detector and cleanliness of the events allow us to reconstruct the full event:

- one B in known hadronic or semileptonic decay mode
- all remaining tracks/neutrals belong to signal B (there should be no additional calorimeter activity)

Missing Energy Modes



Hadronic B_{tag} reconstruction



Belle II: $\varepsilon(B^0_{\rm tag}) = 0.33\%$, $\varepsilon(B^+_{\rm tag}) = 0.36\%$

Belle: $\varepsilon(B^0_{\rm tag}) = 0.19\%$, $\varepsilon(B^+_{\rm tag}) = 0.28\%$

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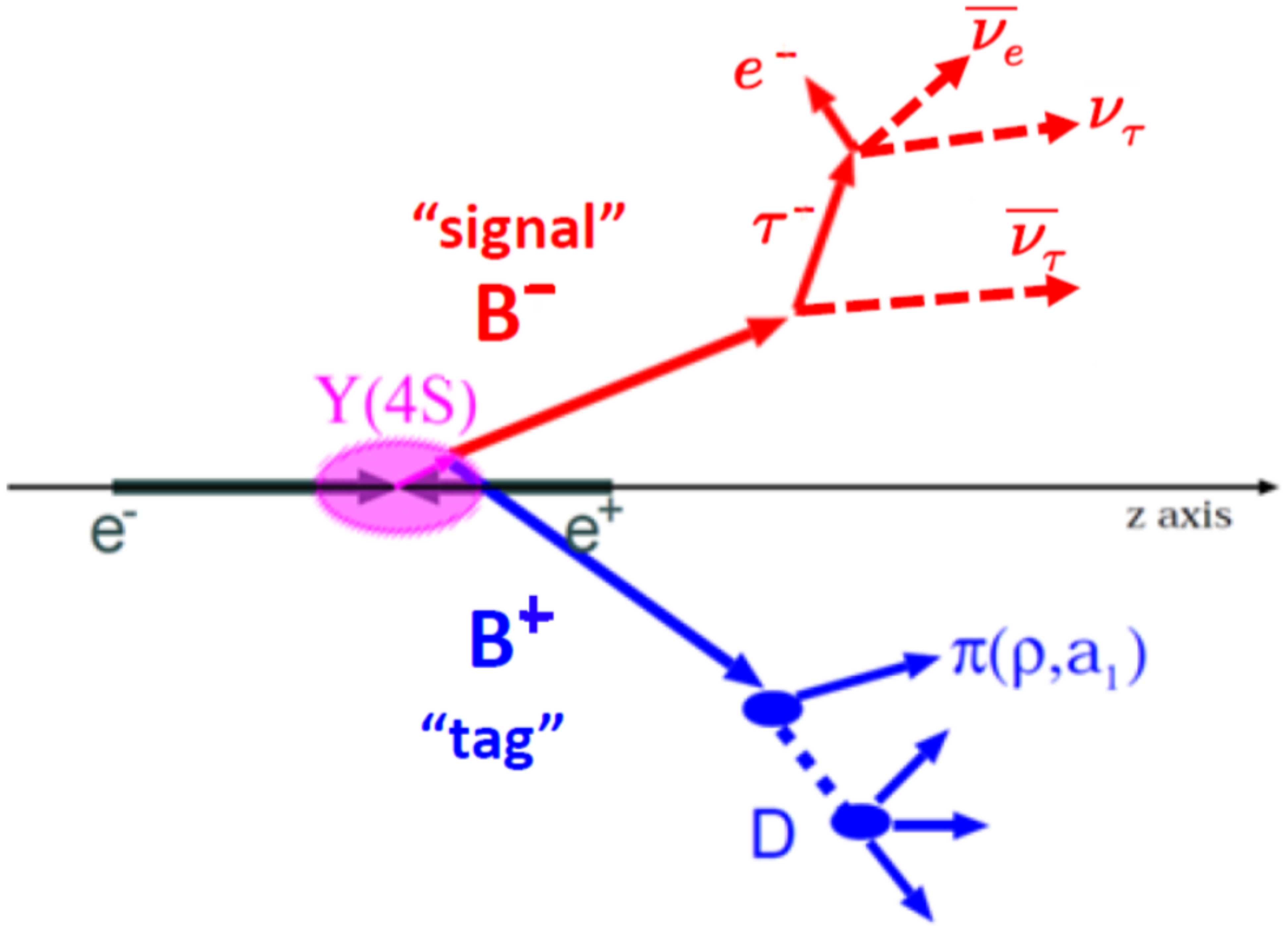
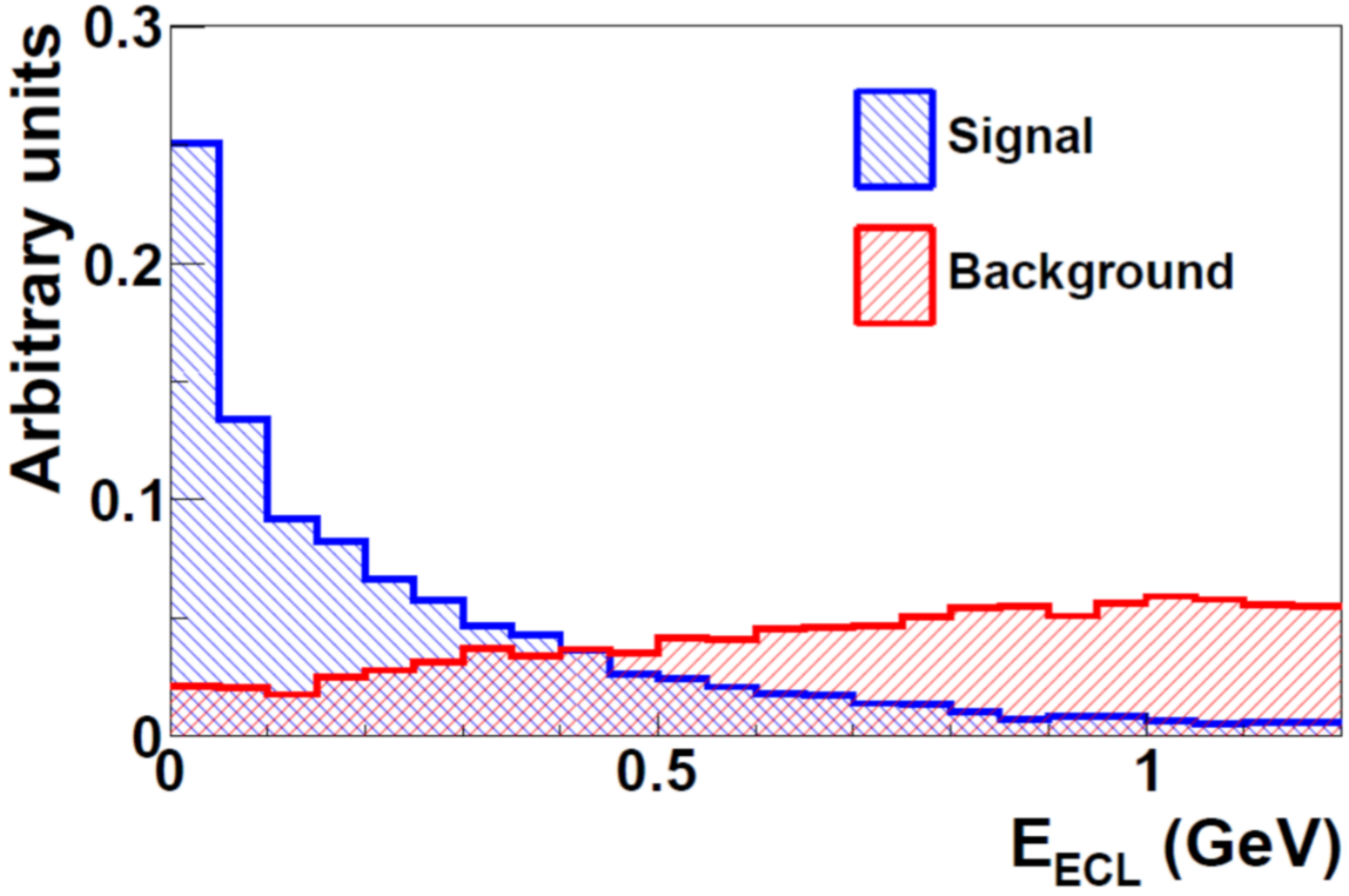
$$\varepsilon(B_{\rm tag}) = \sum_i \mathcal{B}(B \to i)\varepsilon_i$$

Missing Energy Modes





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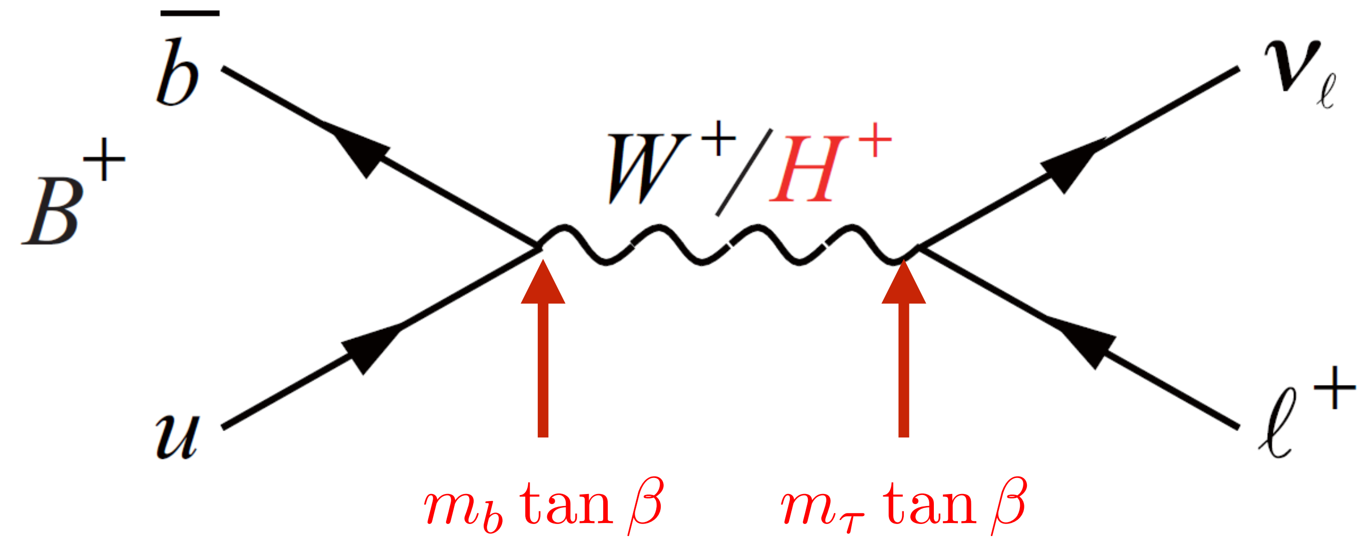
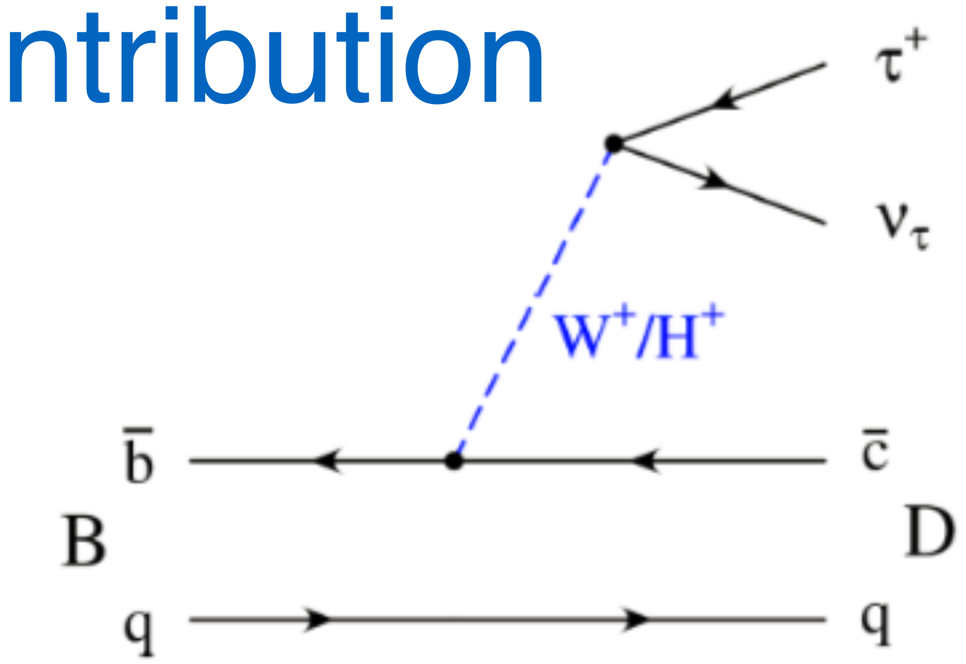
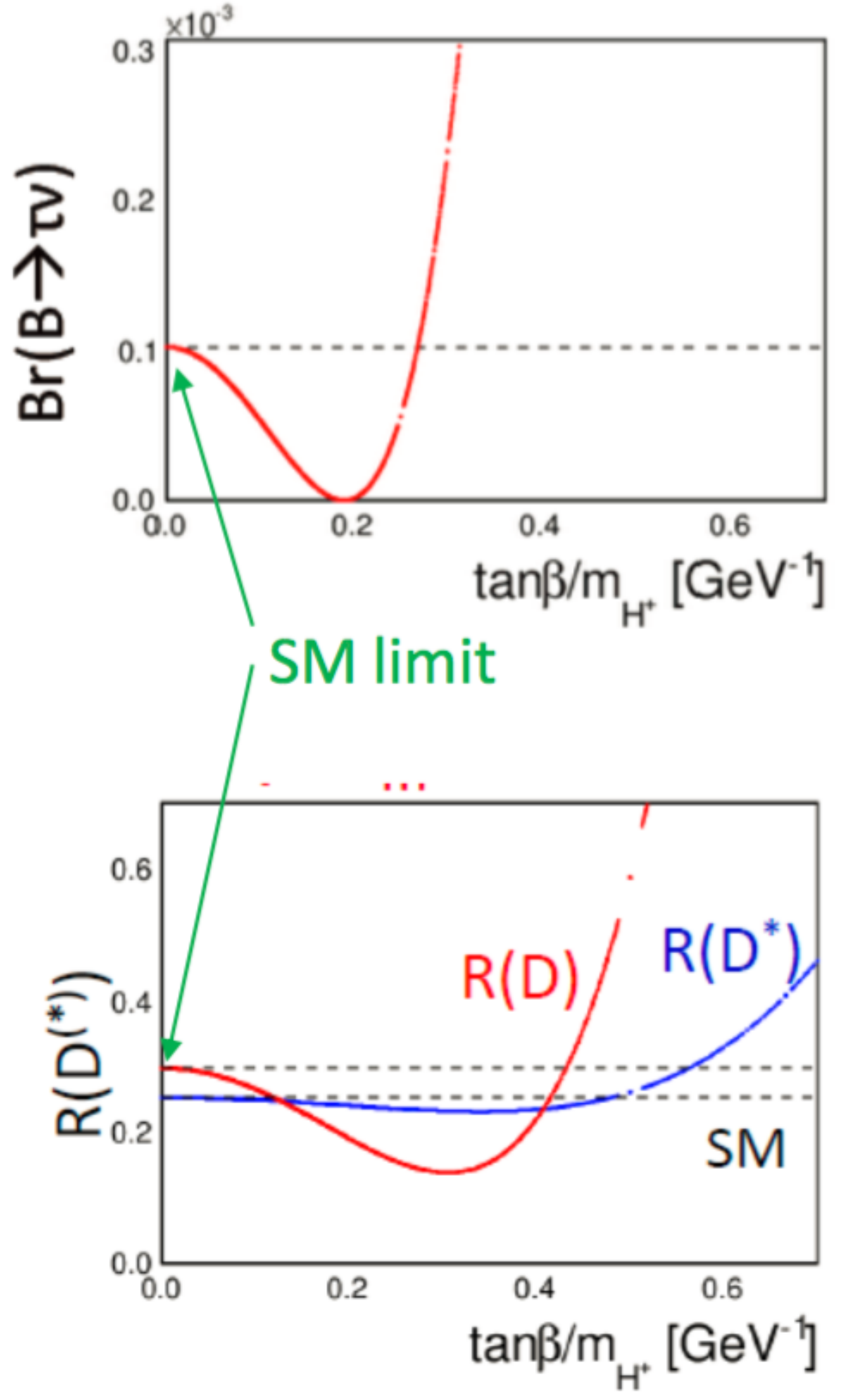
Missing Energy Modes - $B \to \tau\nu$ and $B \to D^{(*)}\tau\nu$

Sensitive to charged Higgs contribution





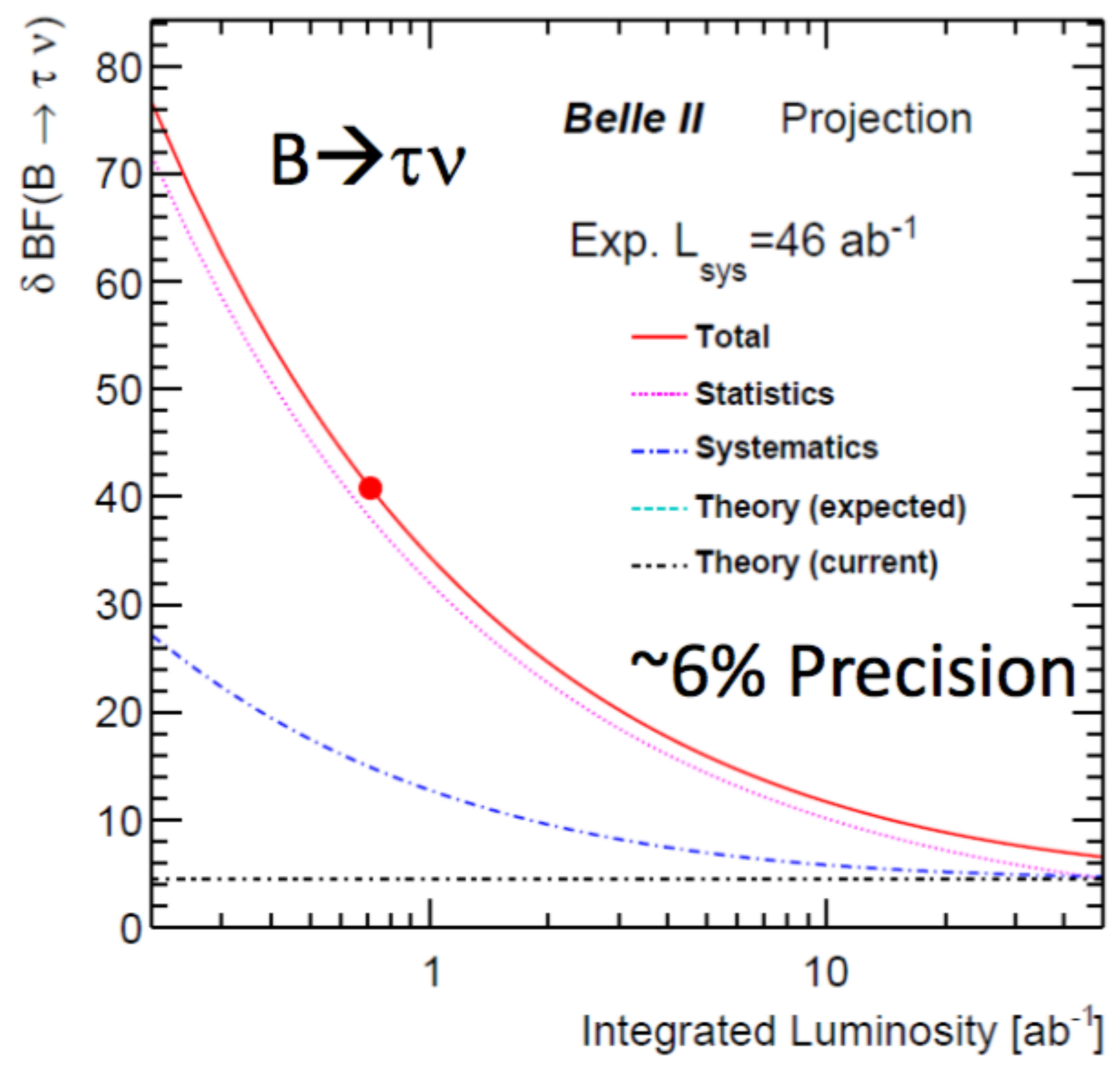


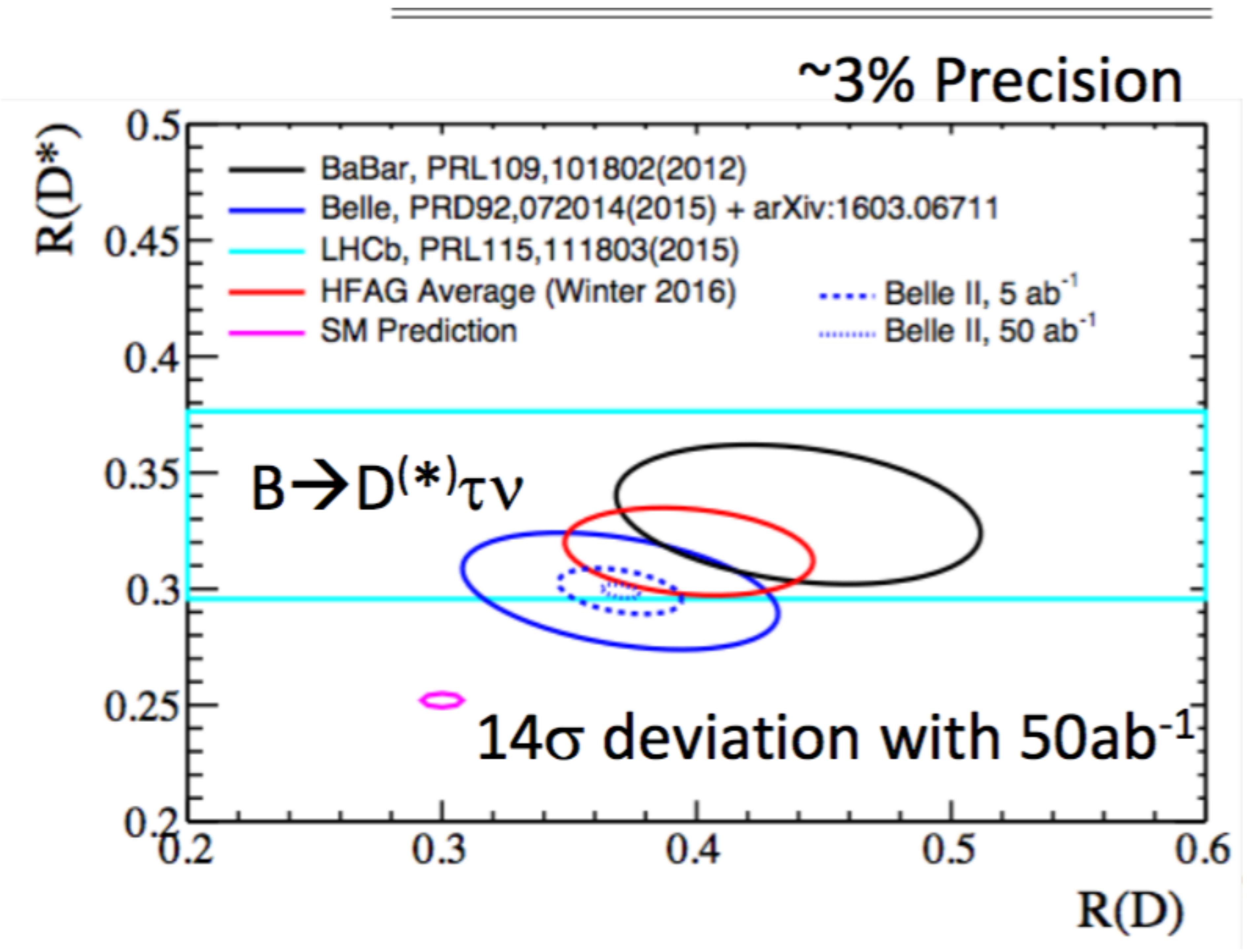
$$\mathcal{B}(B \to \tau\nu) = \underbrace{\overbrace{\frac{G_F^2}{8\pi}\tau_B f_B^2 |V_{ub}|^2 m_B^3 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \left(\frac{m_\tau}{m_B}\right)^2}^{SM}}_{\equiv \mathcal{B}^{SM}} \times \underbrace{\overbrace{\left(1 - m_B^2 \frac{\tan^2\beta}{m_{H\pm}^2}\right)^2}^{2HDM(TypeII)}}_{\equiv r_H}$$

$$R(D) = \frac{\mathcal{B}(\bar{B} \to D\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D\ell^-\bar{\nu}_\ell)}$$

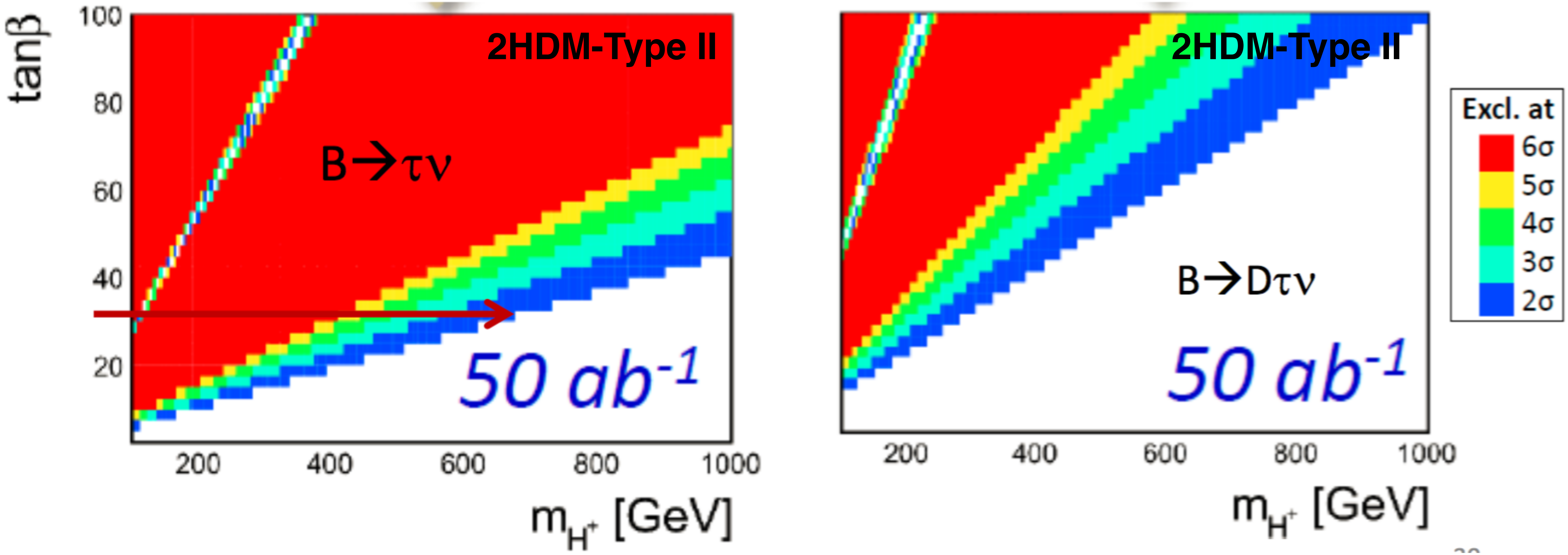
$$R(D^*) = \frac{\mathcal{B}(\bar{B} \to D^*\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^*\ell^-\bar{\nu}_\ell)}$$

Missing Energy Modes - $B \to \tau\nu$ and $B \to D^{(*)}\tau\nu$





Missing Energy Modes - $B \to \tau\nu$ and $B \to D^{(*)}\tau\nu$



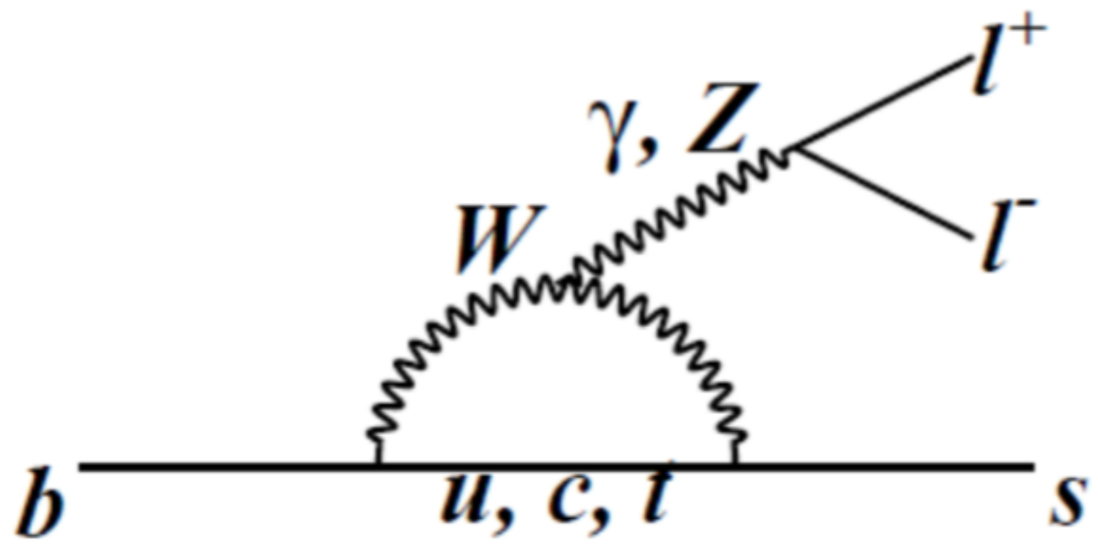
Potential to exclude Higgs with M_H up to 700 GeV at tanβ~40.
tanβ independent exclusion from $b \to s\gamma$ will be obtained as well:
M_H > 600 GeV (assuming 4% th. error)

Semileptonic modes - $b \to see$ / $b \to s\mu\mu$

- Within SM these decays proceed via one loop diagram

$$\mathcal{R}_K = \frac{\mathcal{B}(B \to K\mu\mu)}{\mathcal{B}(B \to Kee)} \approx 1$$

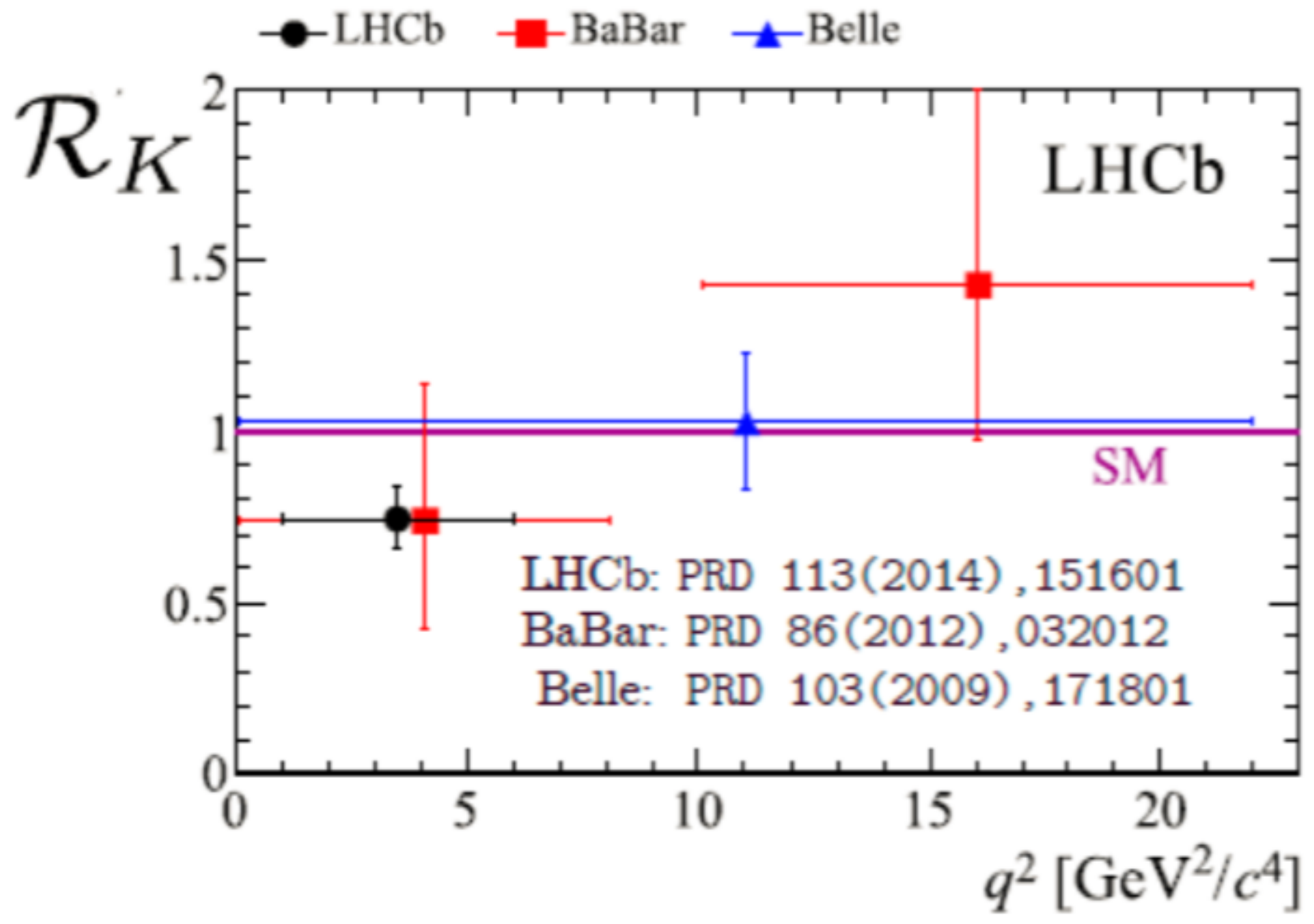
SM LFU [JHEP0712:040,2007]



- LHCb reported 2.6σ deviation from SM expectation

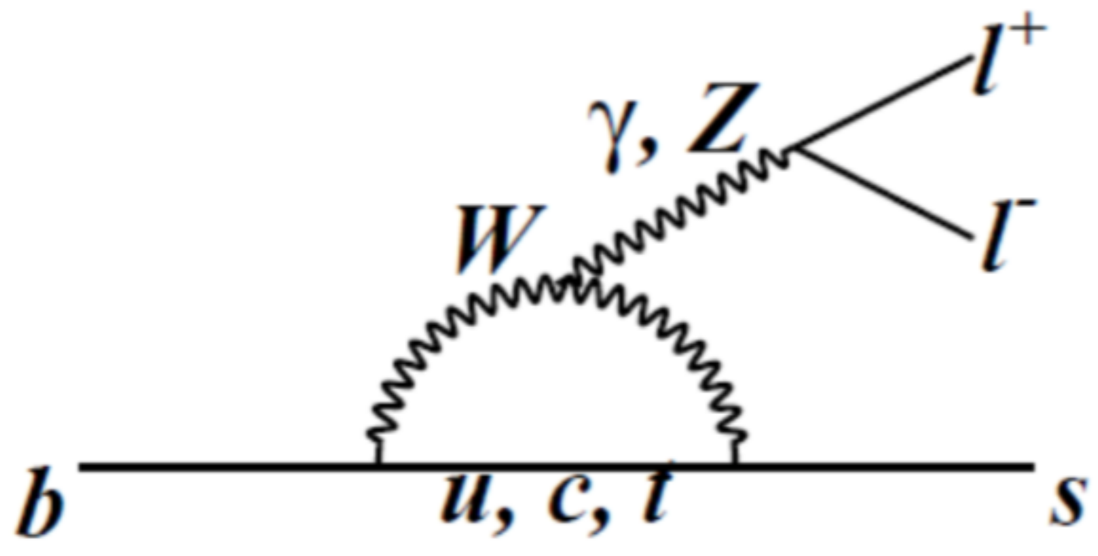
$$\mathcal{R}_K = 0.745^{+0.090}_{-0.074} \pm 0.036$$

  - electron mode difficult at LHCb (at high q^2)



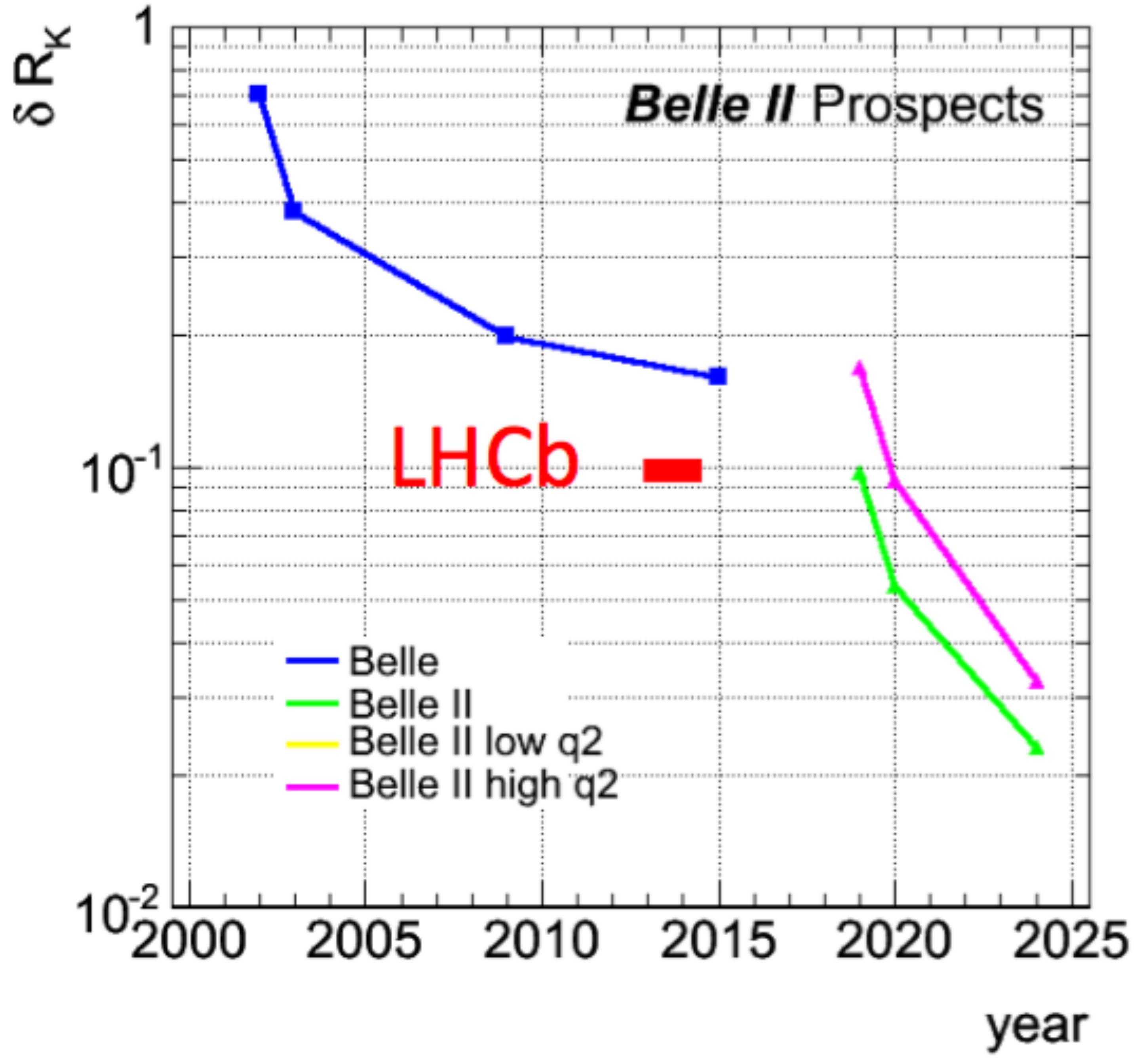
Phys. Rev. Lett. 113, 151601 (2014)

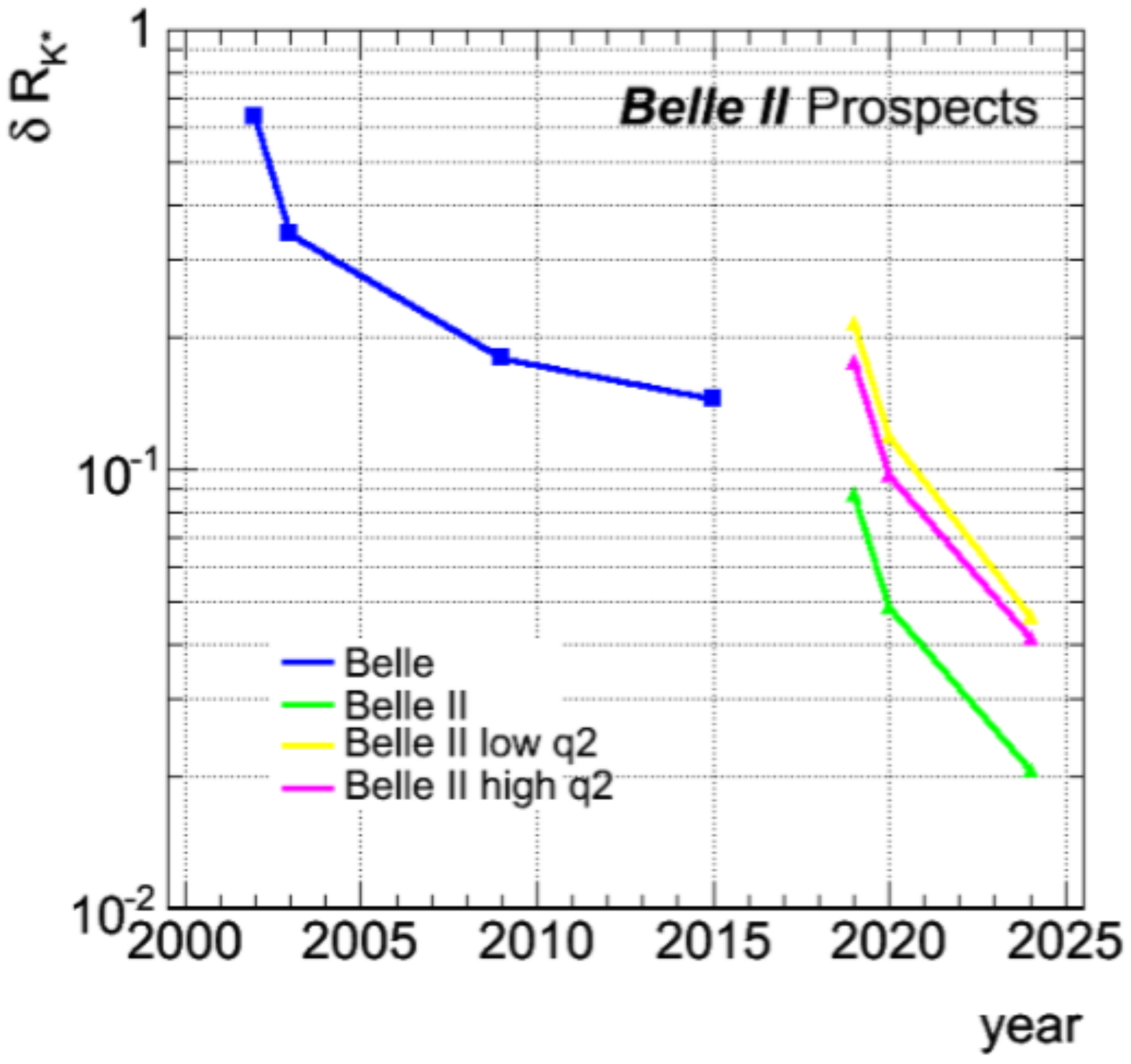
Semileptonic modes - $b \to see$ / $b \to s\mu\mu$

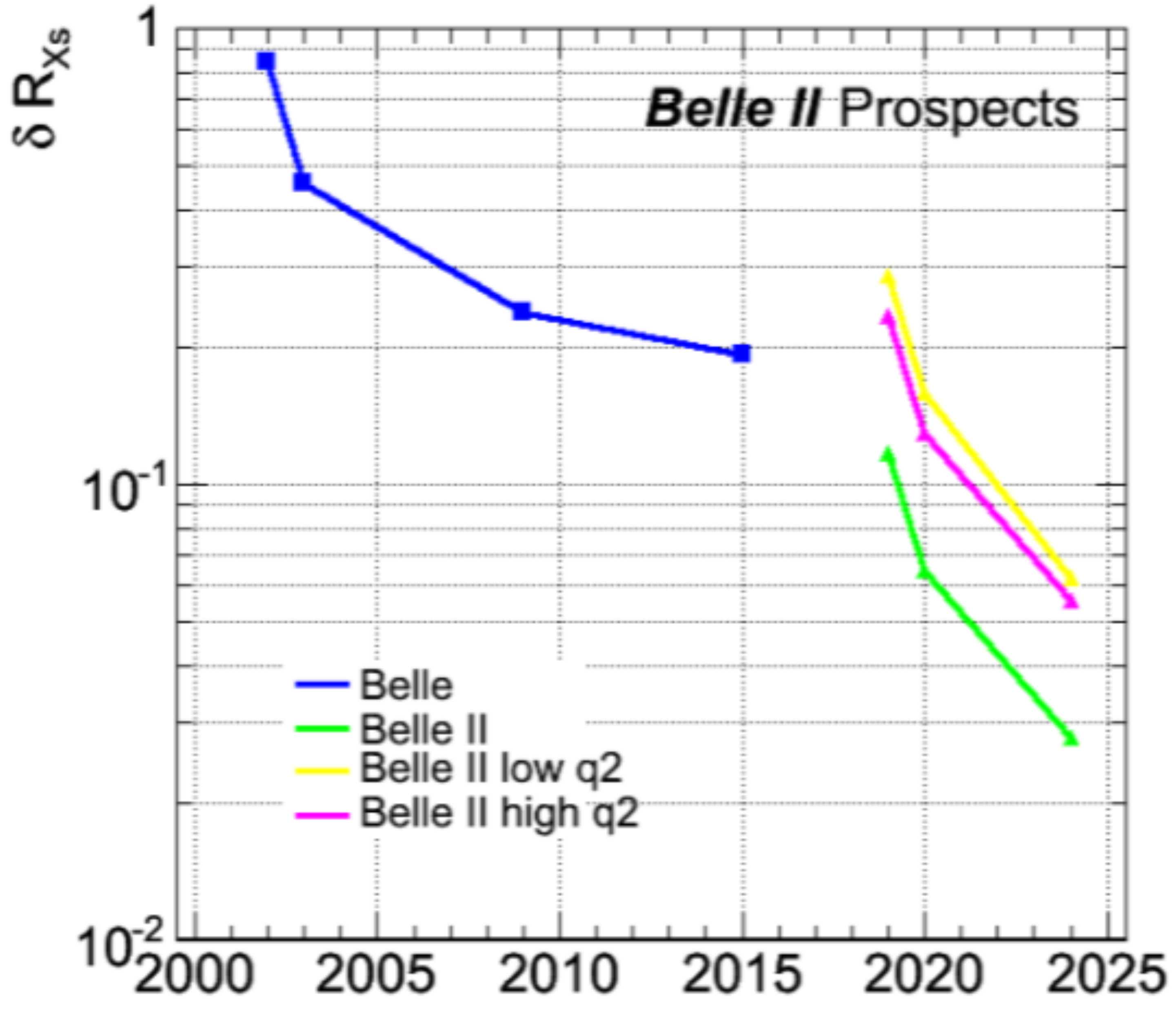


Belle II:

- electron and muons have the same efficiency
- both low and high q^2 regions possible



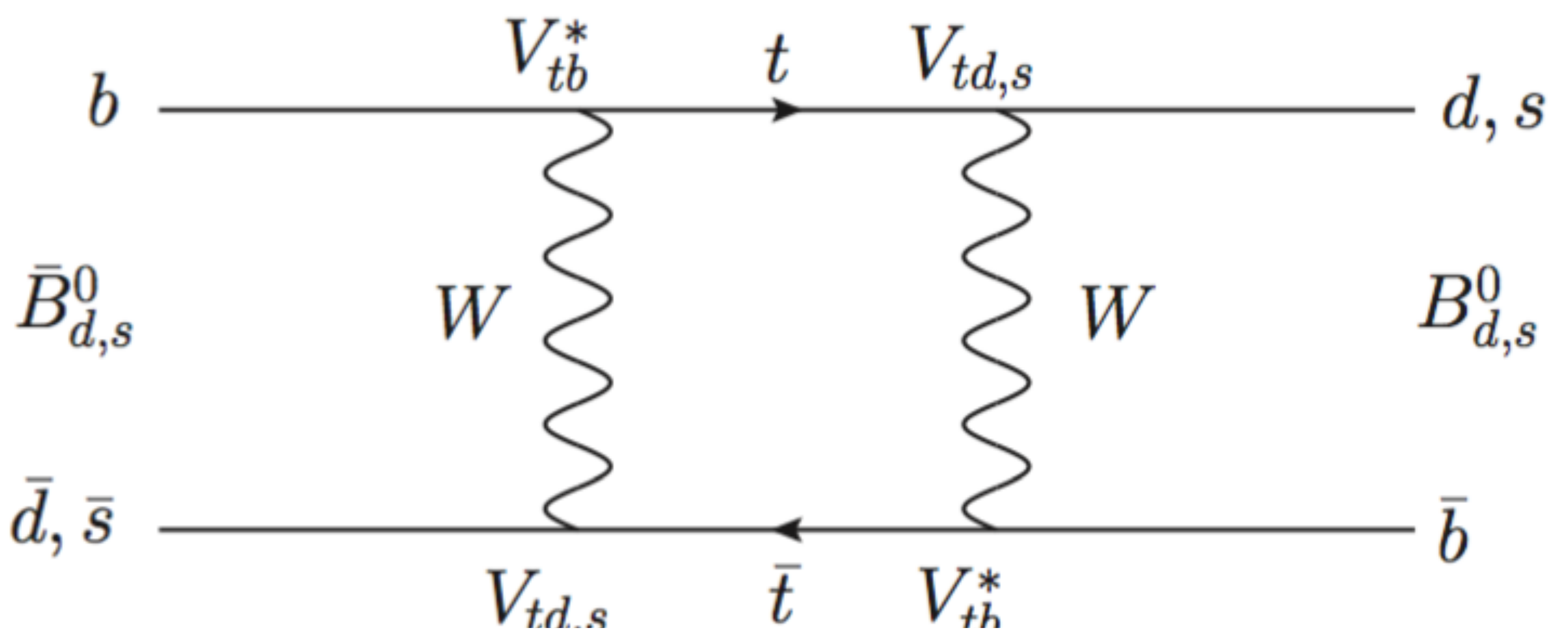




Time dependent measurements - Mixing

- Mediated by one loop processes in the SM
  - dominant contribution from top quark
  - new particles (beyond SM) can enter the loop and modify the mixing amplitude

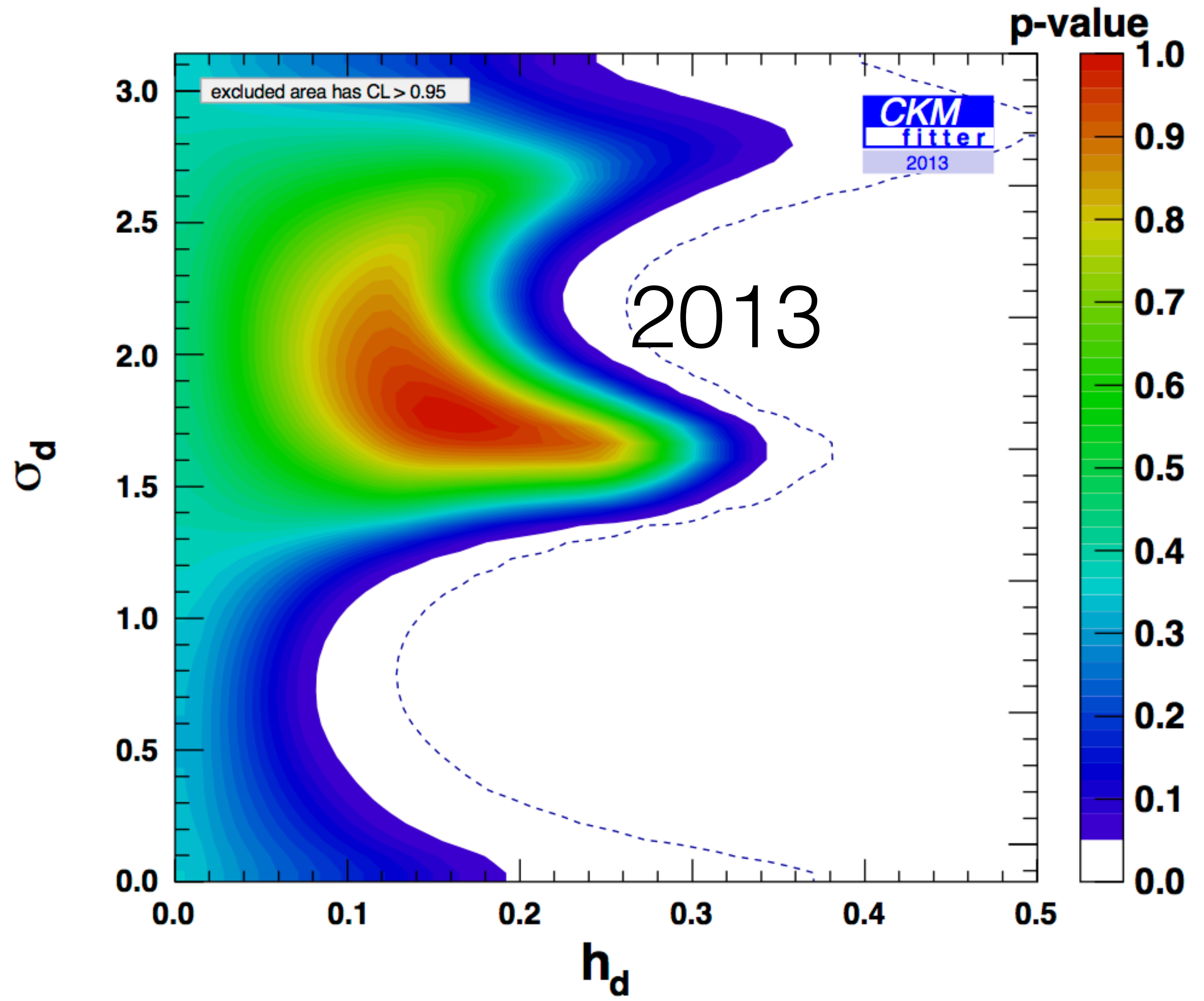
[NB: global fit needs to be performed to disentangle SM from NP]



$$M_{12}^{d,s} = (M_{12}^{d,s})_{\rm SM} \times \left(1 + h_{d,s}\, e^{2i\sigma_{d,s}}\right)$$

$$h \simeq 1.5\,\frac{|C_{ij}|^2}{|\lambda^t_{ij}|^2}\,\frac{(4\pi)^2}{G_F\Lambda^2} \simeq \frac{|C_{ij}|^2}{|\lambda^t_{ij}|^2}\left(\frac{4.5\,\rm TeV}{\Lambda}\right)^2$$

$$\sigma = \arg\left(C_{ij}\,\lambda^{t*}_{ij}\right),$$



CKM fitter PRD 89, 033016 (2014)

Time dependent measurements - *Mixing*

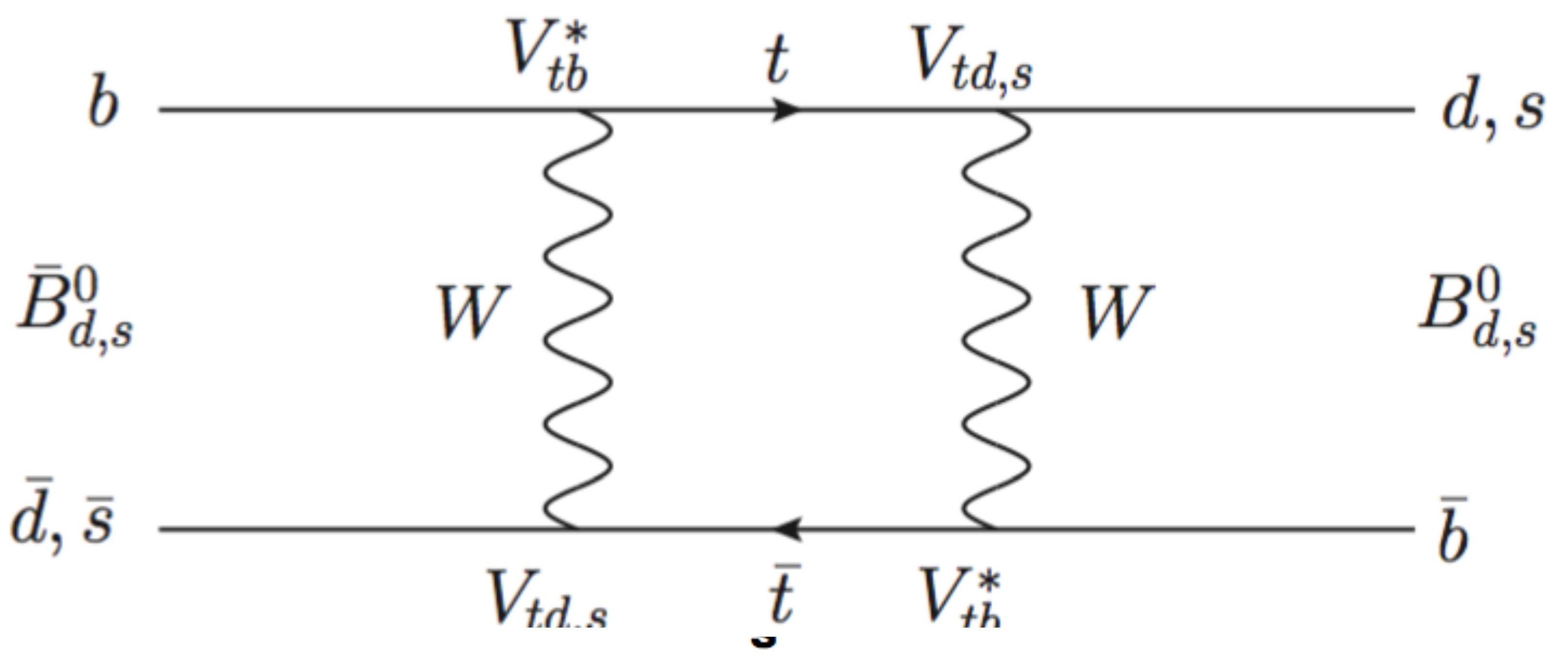
- Mediated by one loop processes in the SM
  - dominant contribution from top quark
  - new particles (beyond SM) can enter the loop and modify the mixing amplitude

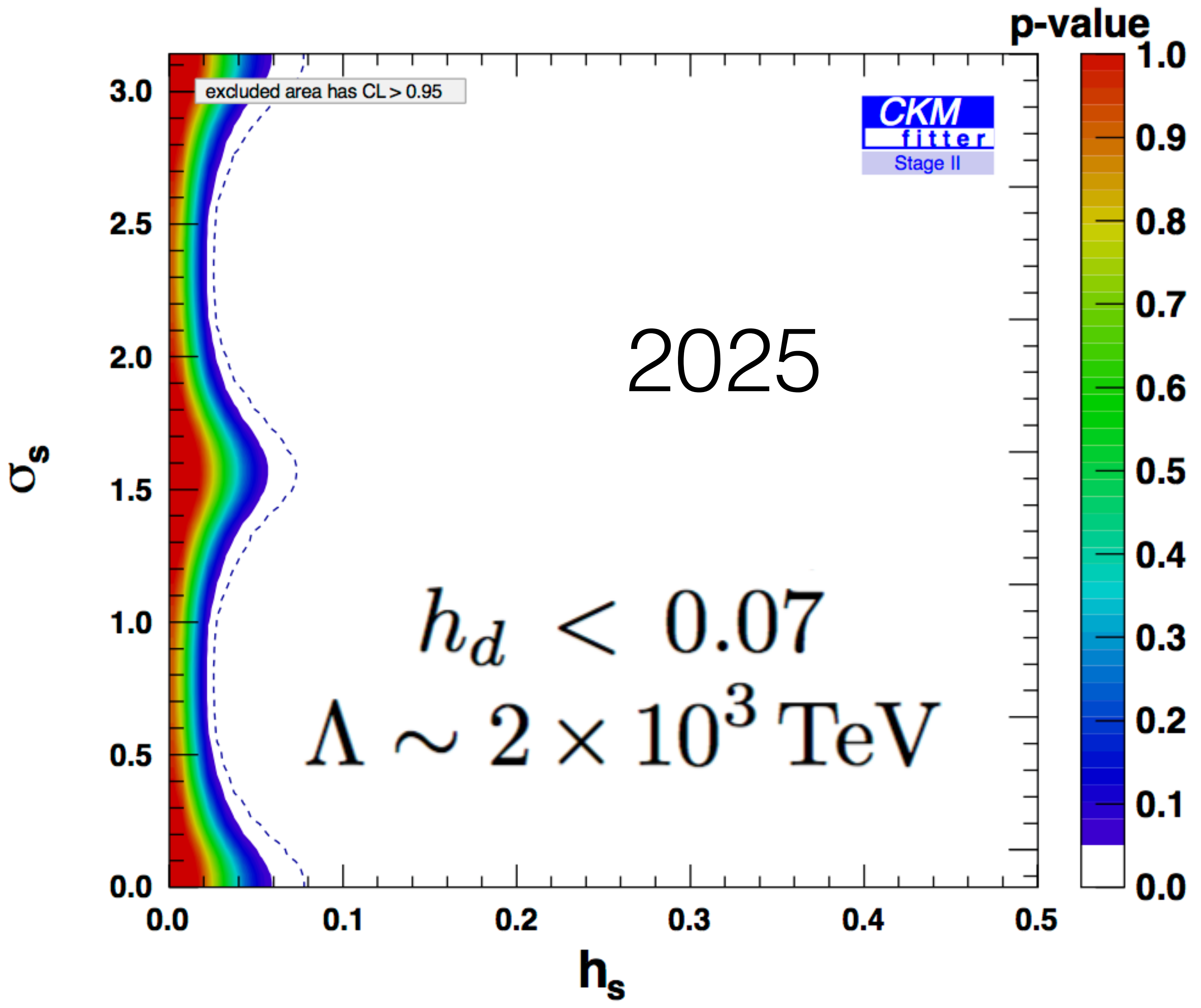
[NB: global fit needs to be performed to disentangle SM from NP]

$$M_{12}^{d,s} = (M_{12}^{d,s})_{\rm SM} \times \left(1 + h_{d,s}\, e^{2i\sigma_{d,s}}\right)$$

$$h \simeq 1.5 \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2} \frac{(4\pi)^2}{G_F \Lambda^2} \simeq \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2} \left(\frac{4.5\,\mathrm{TeV}}{\Lambda}\right)^2$$

$$\sigma = \arg\left(C_{ij}\, \lambda_{ij}^{t*}\right),$$





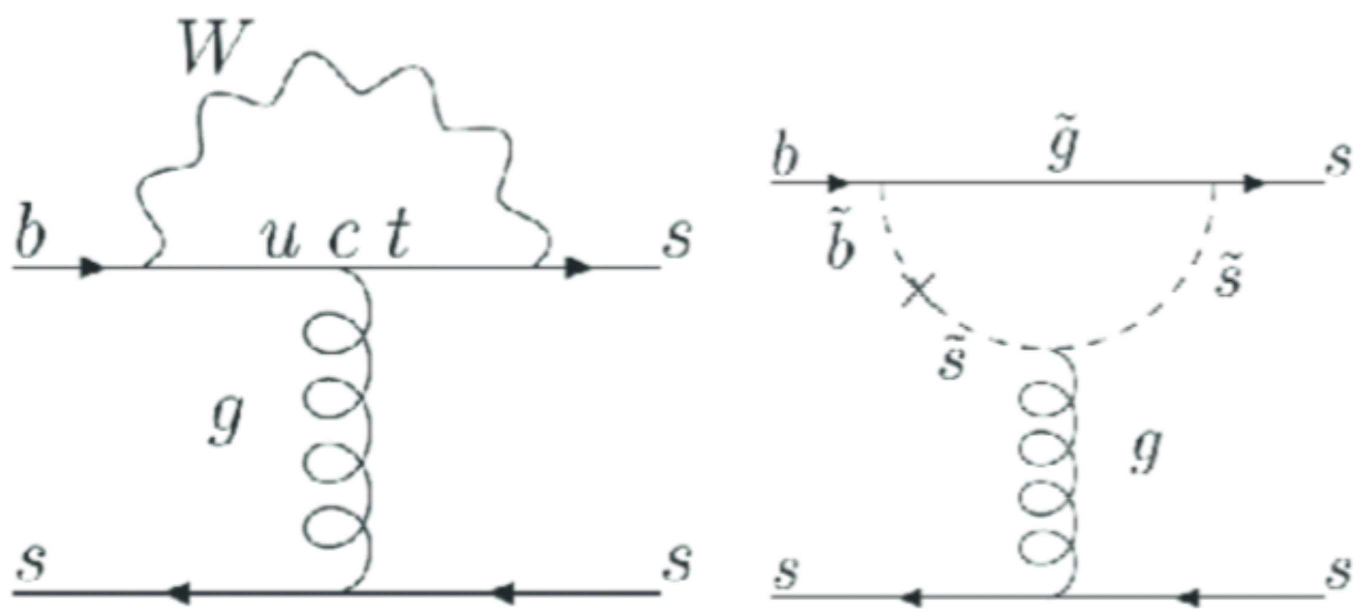
CKM fitter PRD 89, 033016 (2014)

Time dependent measurements *- CPV in $b \to s q\bar{q}$*

- Within the SM

$$\sin 2\phi_1^{\rm eff}|_{b\to sq\bar{q}} \sim \sin 2\phi_1|_{B\to J/\psi K_s}$$

  - unless particles beyond SM entering the loop introduce new CP violating phases

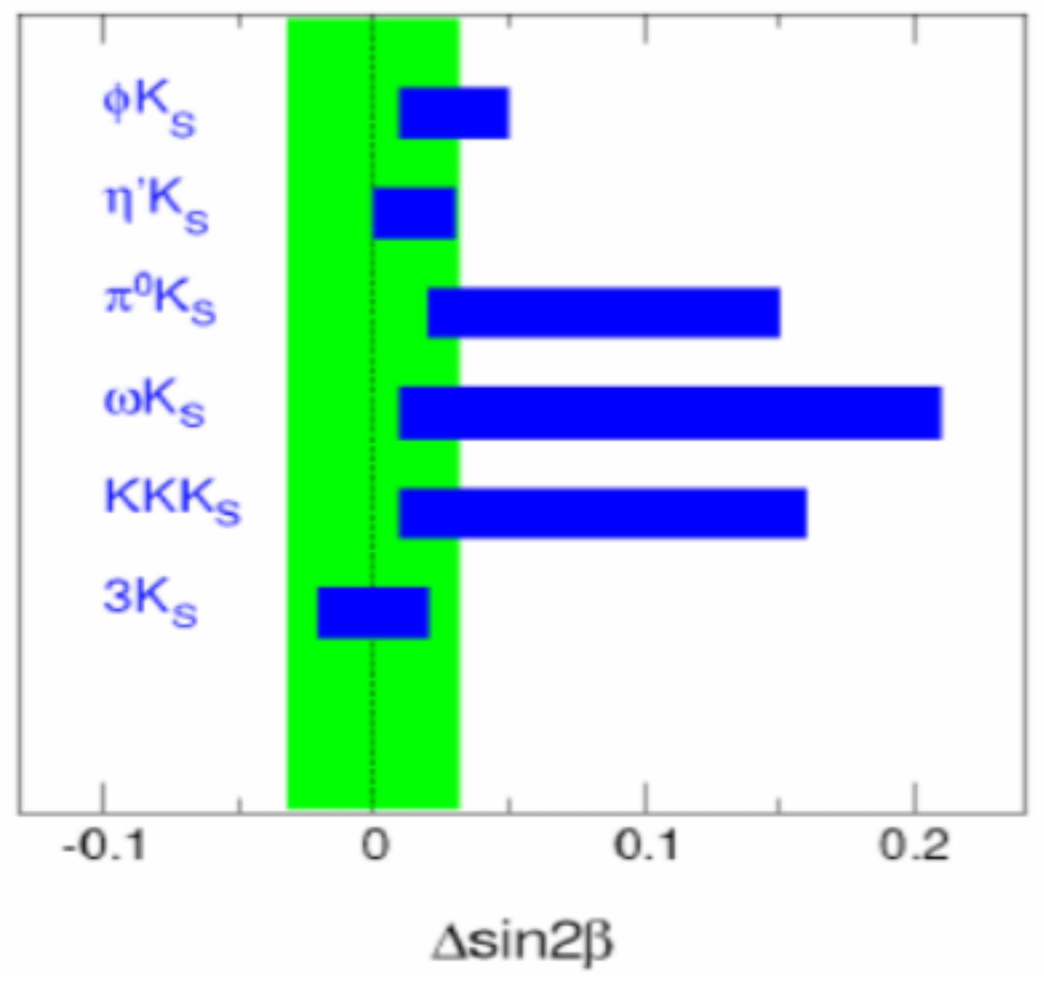


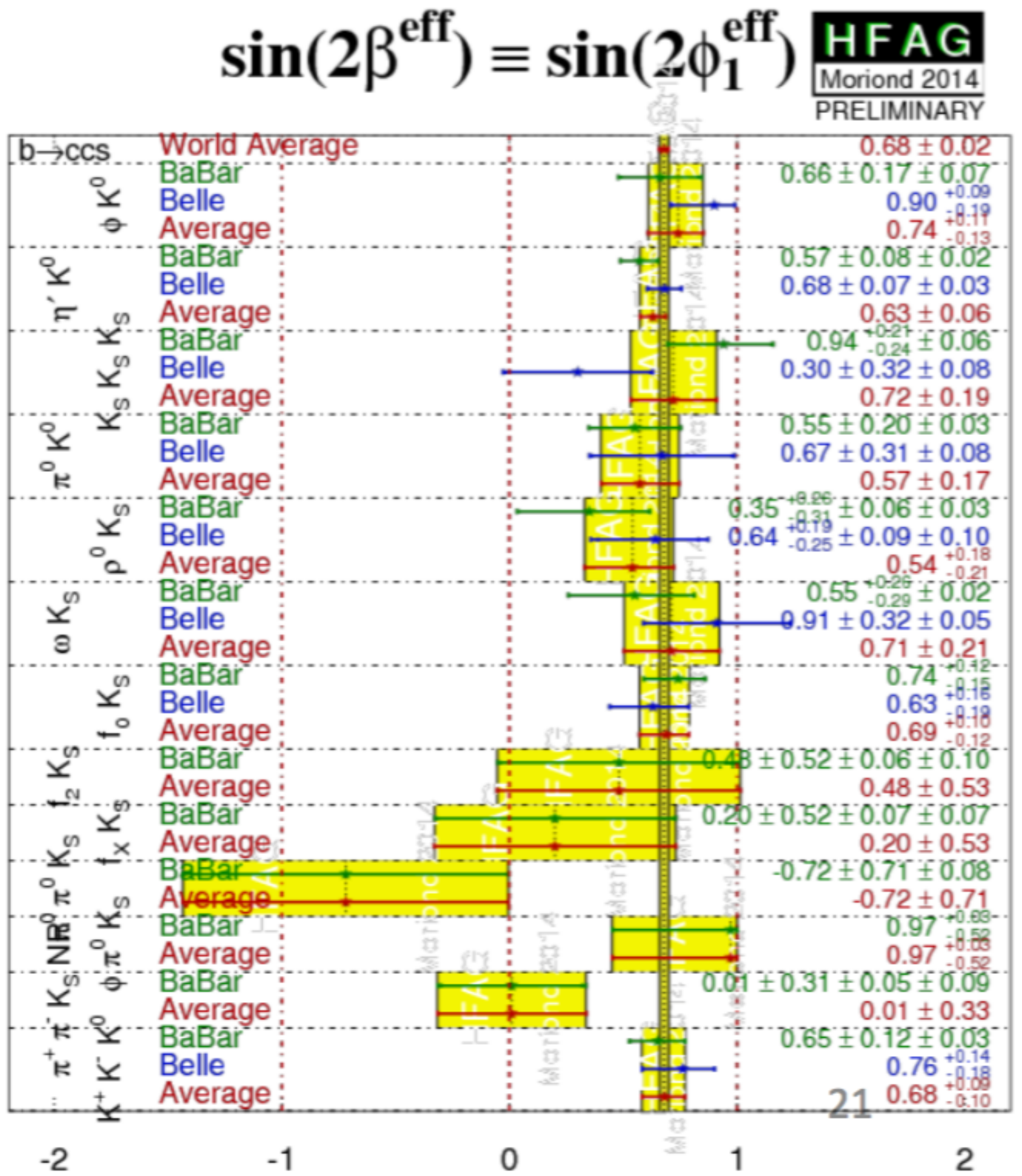
Decay modes

- $B \to \phi K_s$
- $B \to \eta' K_s$
- $B \to K_sK_sK_s$
- ~2% theoretical error

some of recent QCDF estimates

$\sin 2\beta^f_{\rm eff} - \sin 2\beta$





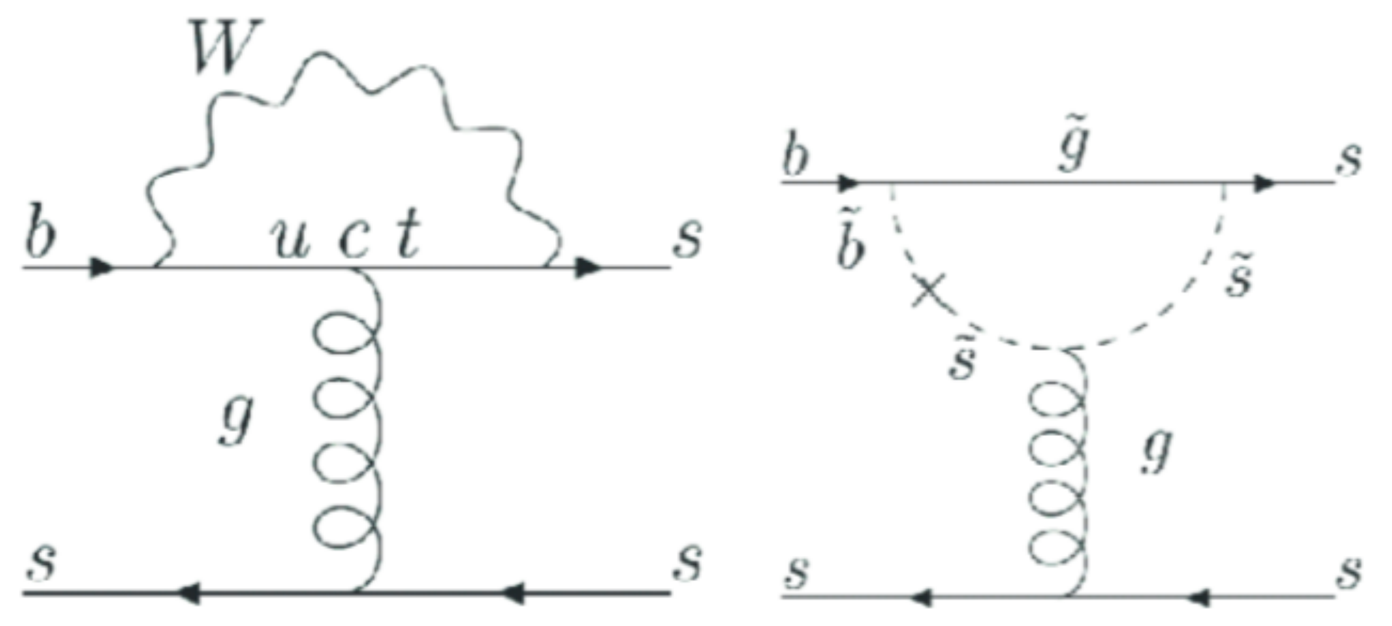
Current measurements consistent with $B \to J/\psi K_s$

Time dependent measurements - CPV in $b \to sq\bar{q}$

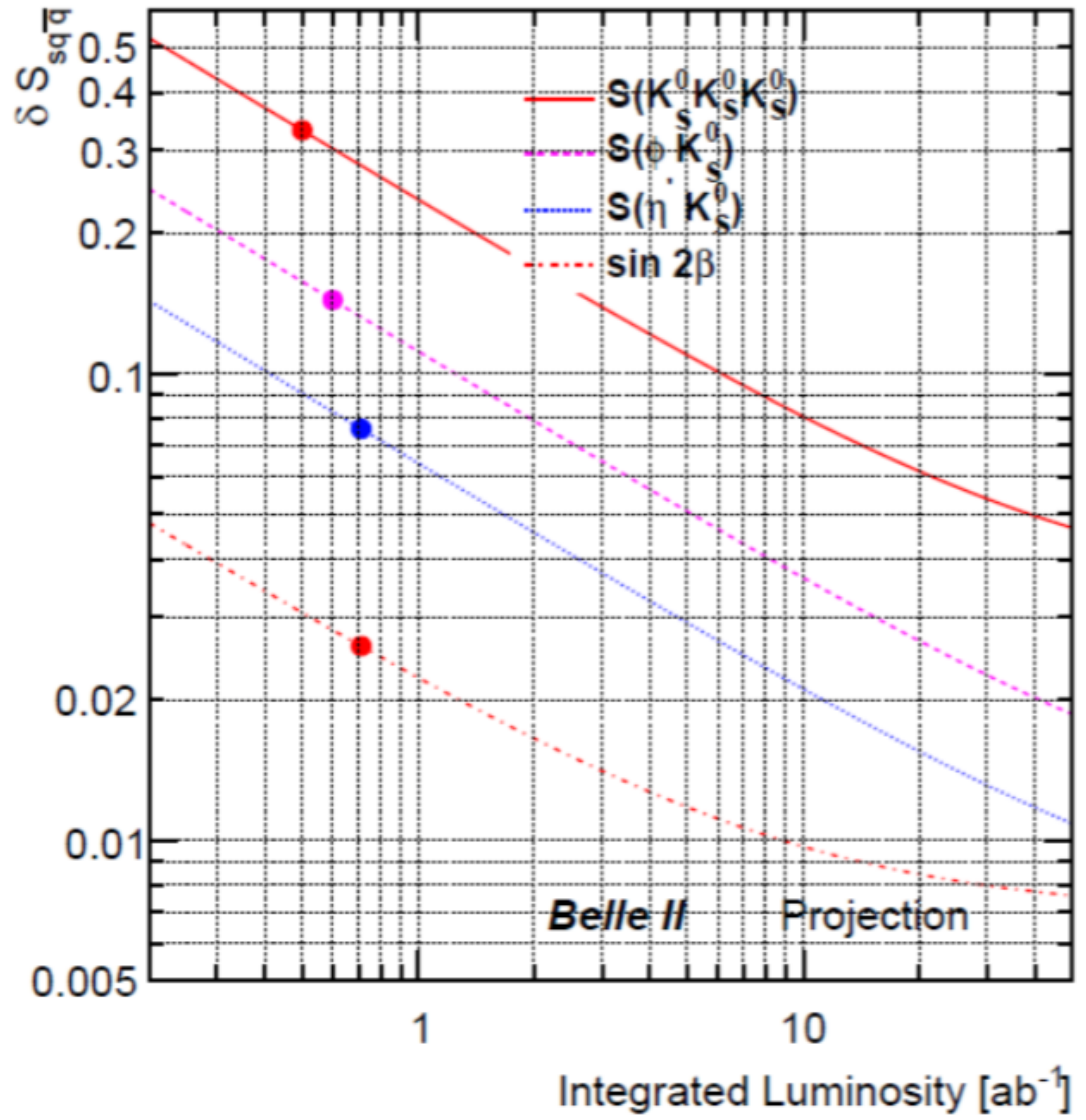
- Within the SM

$$\sin 2\phi_1^{\mathrm{eff}}|_{b\to sq\bar{q}} \sim \sin 2\phi_1|_{B\to J/\psi K_s}$$

  - unless particles beyond SM entering the loop introduce new CP violating phases



Mode	5 ab^{-1}		50 ab^{-1}	
	$\sigma(\mathcal{S})$	$\sigma(\mathcal{A})$	$\sigma(\mathcal{S})$	$\sigma(\mathcal{A})$
$\eta' K^0$	0.028	0.020	0.011	0.009
ϕK^0_S	0.053	0.070	0.018	0.023
$K_S K_S K_S$	0.101	0.064	0.033	0.021



Expected error commensurates the theoretical one.

Conclusions

- Belle II is the super flavor factory experiment at SuperKEKB
- Rich program to search for NP with flavor observables.
- SuperKEKB commissioning is on-going.
- First physics results will come out in 2017 (phase2)
- Full detector running starts in 2018 (phase3)