Flavour physics: a brief tour

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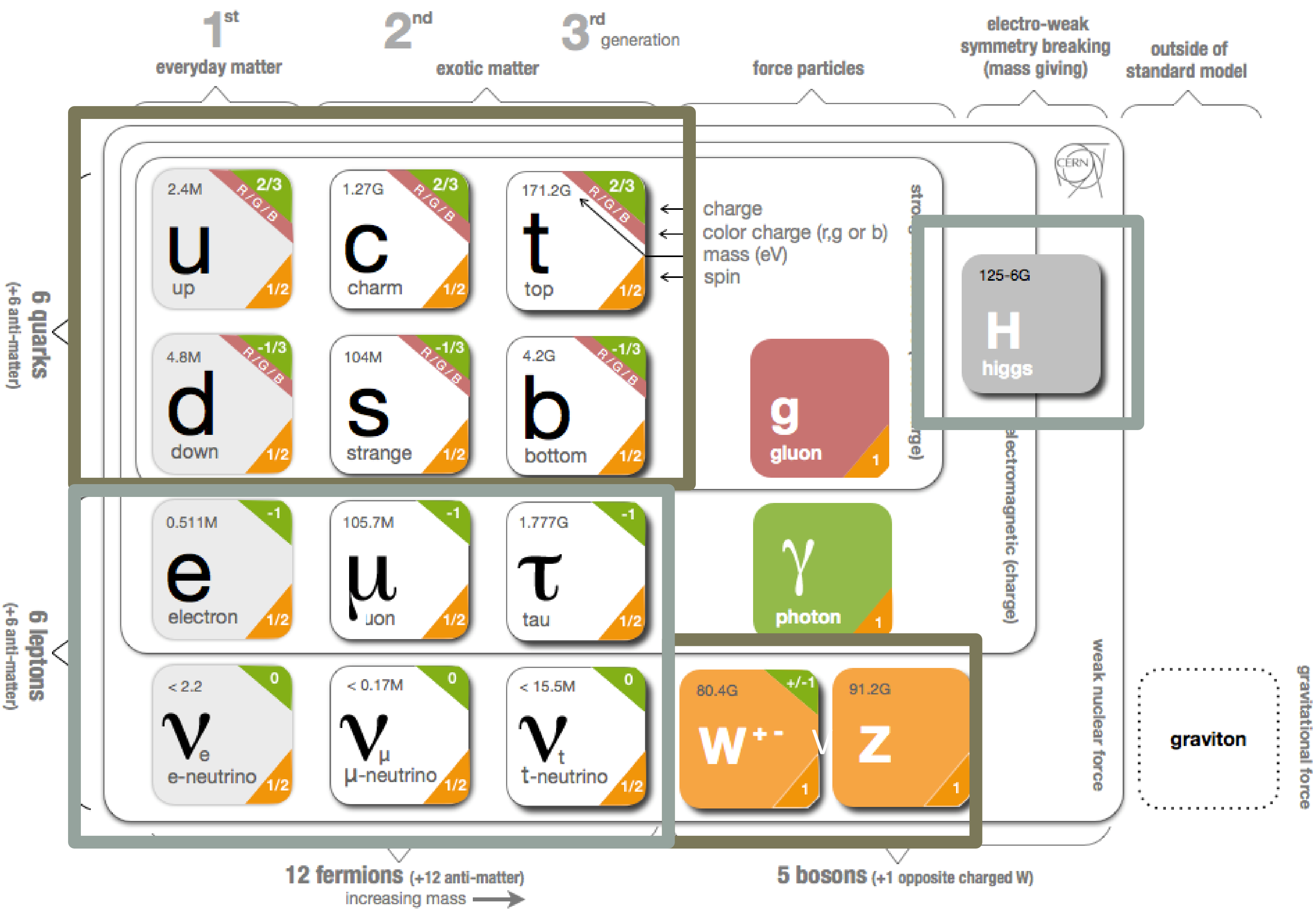
14th July 2021

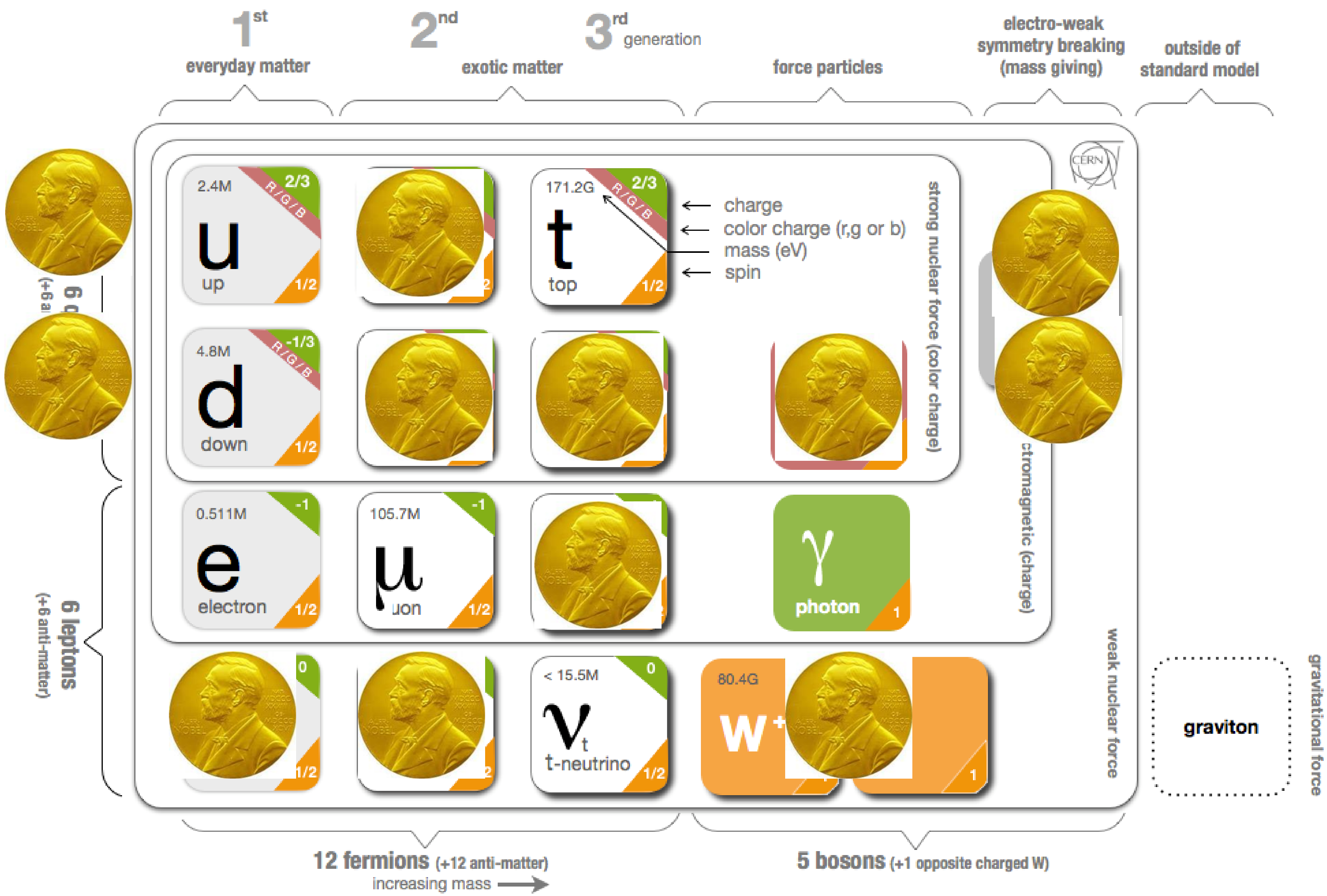
Overview

- Particle physics and frontiers
- Some flavour history
  - Flavour as a predictor
  - Belle and CP violation
  - Belle II and complementarity with LHCb
- Current hot topic
  - Anomalies
- Future

The standard model flavour



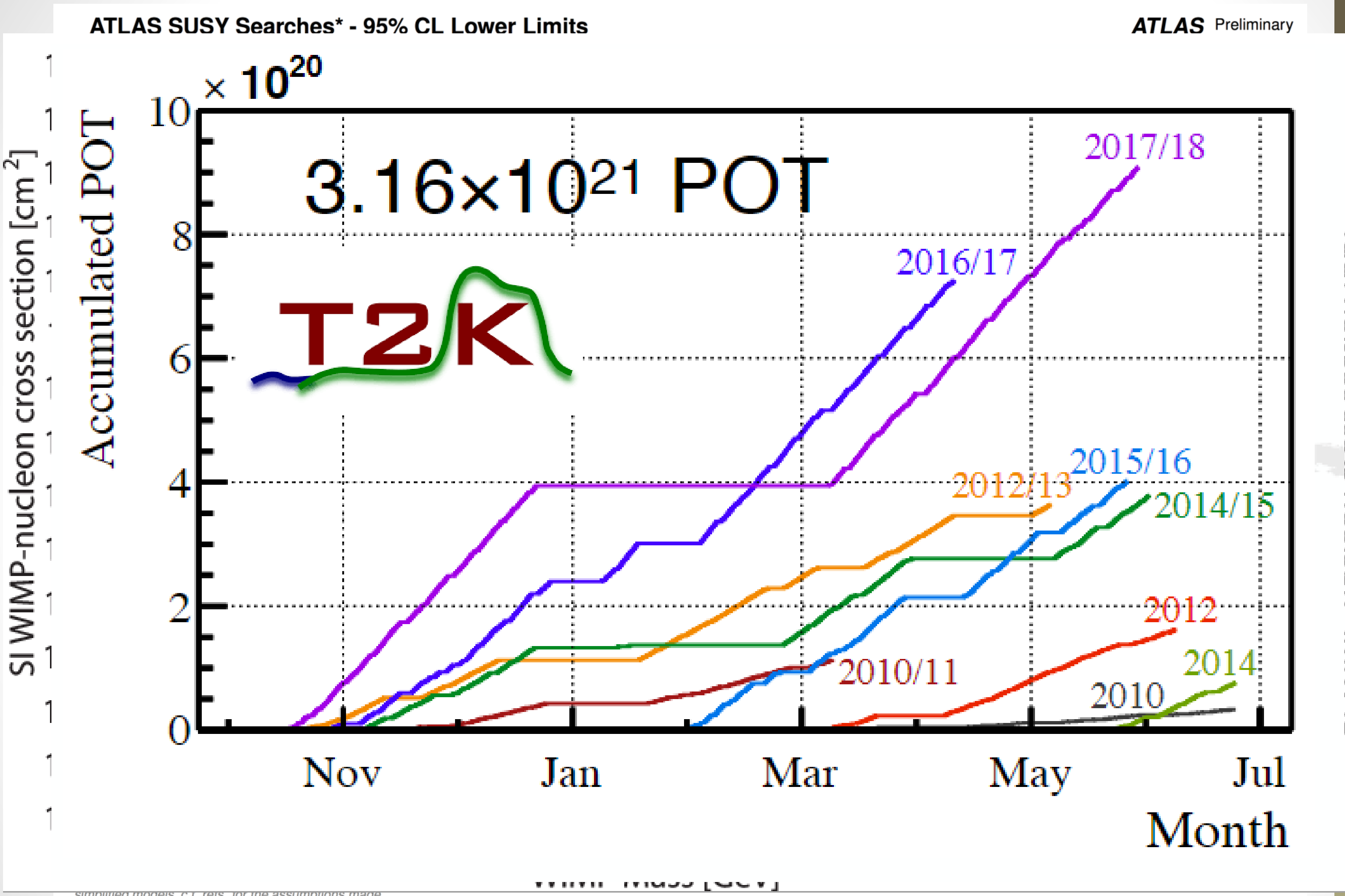
The standard model



Problems

- **Empirical**
  - Neutrinos are massive
  - Dark matter
  - Dark energy!!!!
  - Matter rather than antimatter
  - Gravity

- **Aesthetic**
  - Why three of everything?
  - Why eighteen parameters?
    - Many with a distinct hierarchy?
  - Why do we need to know them to 18 decimal places?
  - Unification


ATLAS SUSY Searches* - 95% CL Lower Limits
ATLAS Preliminary
SI WIMP-nucleon cross section [cm²]
× 10²⁰
Accumulated POT
3.16×10²¹ POT
T2K
2017/18
2016/17
2015/16
2012/13
2014/15
2012
2014
2010/11
2010
0
2
4
6
8
10
Nov
Jan
Mar
May
Jul
Month
simplified models, c.f. refs. for the assumptions made.

Problems: addressed by flavour

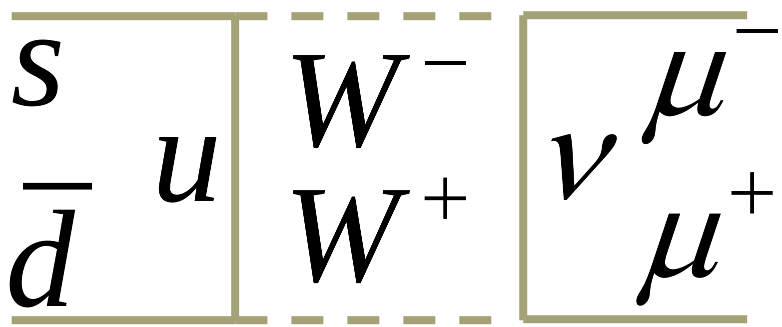
- **Empirical**
  - Neutrinos are massive
  - Dark matter
  - Dark energy!!!!
  - Matter rather than antimatter
  - Gravity
- **Aesthetic**
  - Why three of everything?
  - Why eighteen parameters?
    - Many with a distinct hierarchy?
  - Why do we need to know them to 18 decimal places?
  - Unification

Flavour physics – history of discovery

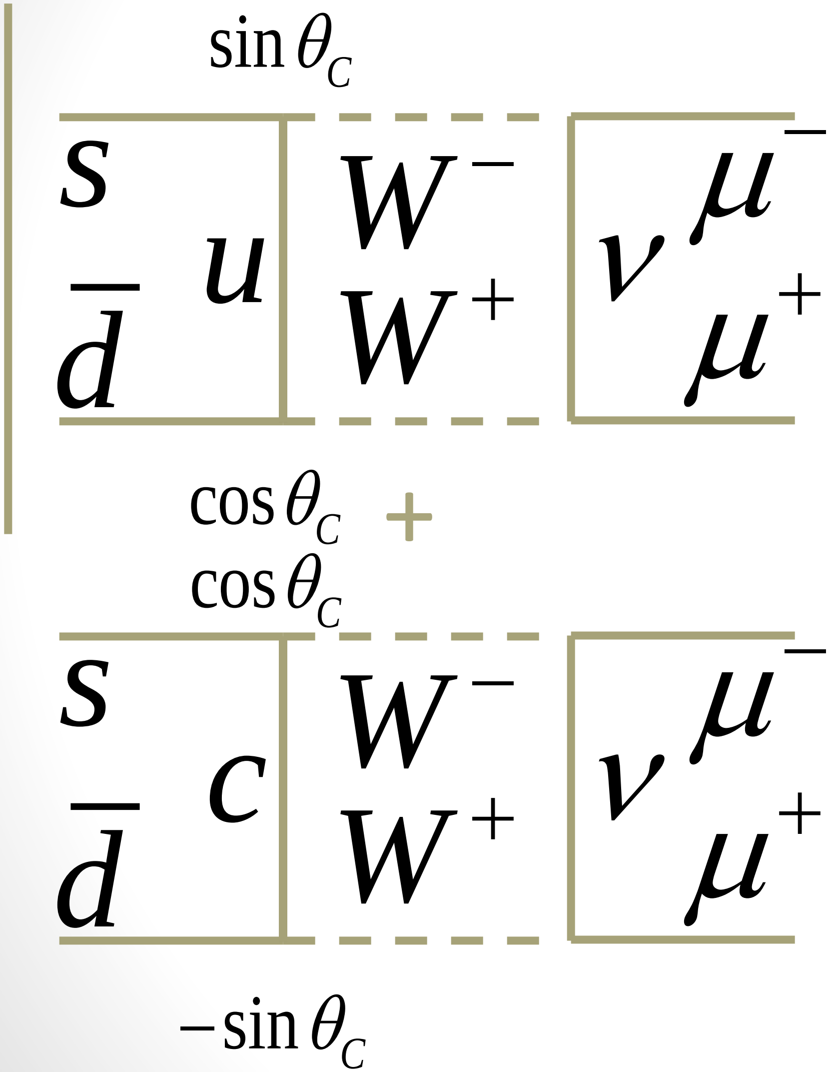
- Particle zoo of mesons and baryons discovered in 1950s and early 1960s lead to the quark model
  - up (u)
  - down (d)
  - strange (s)
- An allowed but rare decay such as

$$K_L^0(s\bar{d}) \rightarrow \mu^+\mu^-$$

- **Predicted but not seen!**



Flavour physics – history of discovery



Glashow

Iliopoulos

Maiani

Phys. Rev. D 2, 1285 (1970)

2 $\propto$ Rate ~ 0

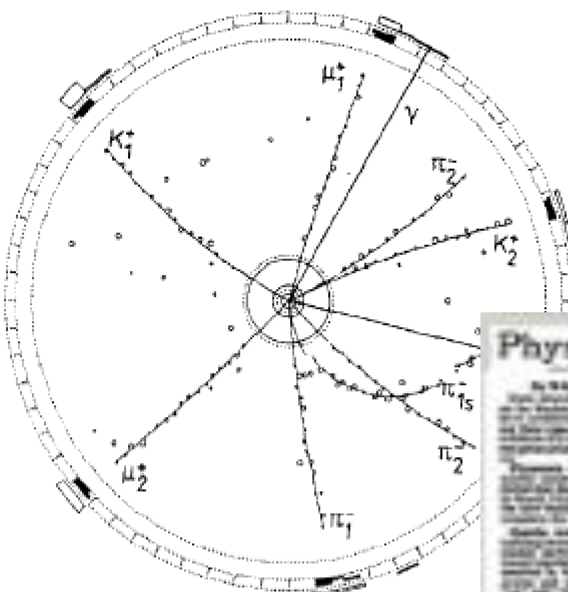
$m_c \sim 3\ m_K$

Such rare virtual processes tell you about higher energy particles

ARGUS: B mixing ⇒ heavy top

OBSERVATION OF B^0–$\bar{B}^0$ MIXING

ARGUS Collaboration

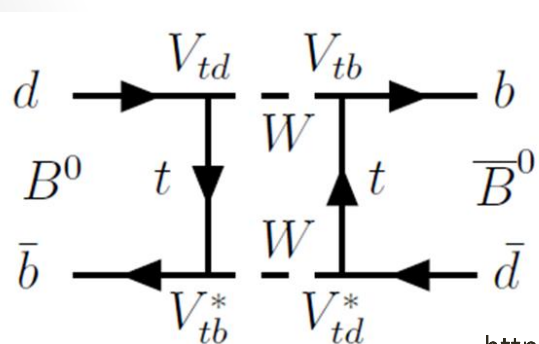


reconstructed event consisting of

$$B_1^0 \to D_1^{*-} \mu_1^+ \nu_1$$
$$\downarrow$$
$$D_1^{*-} \to \pi_1^- \bar{D}^0$$
$$\downarrow$$
$$\bar{D}^0 \to K_1^+ \pi_1^- ,$$

and


Physicists May Have Tracked Last Quark to Lair



m_t> 50 Gev

https://www.nytimes.com/1984/06/25/us/physicists-may-have-tracked-last-quark-to-lair.html

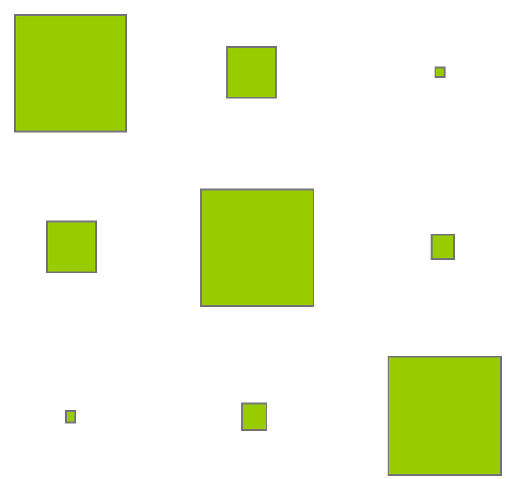
CKM matrix

$$\begin{pmatrix} u & c & t \end{pmatrix} \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} u & c \end{pmatrix} \begin{bmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{bmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

- Two by two mixing matrix proposed by Cabibbo
  - Kobayashi-Maskawa proposed third generation to explain observed CP violation by Cronin and Fitch
- 3 × 3 unitary complex matrix
  - 4 parameters
  - 3 mixing angle and 1 phase
- Intergenerational coupling disfavoured

Relative magnitude of elements



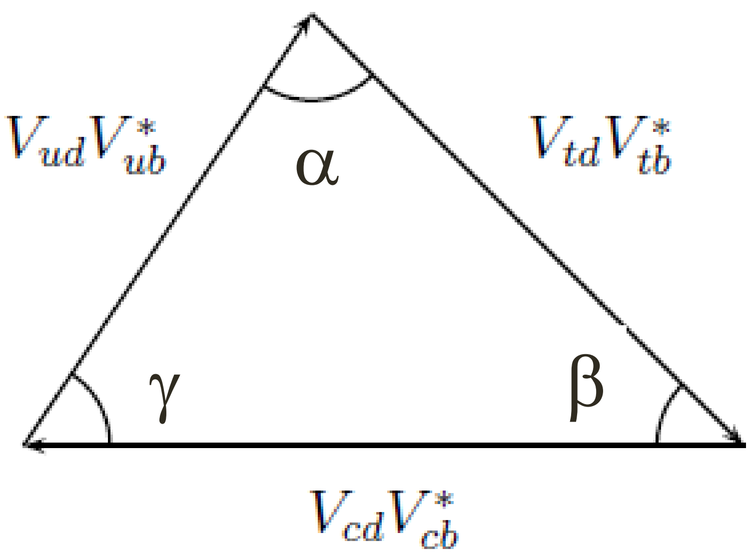
Responsible for CP violation

Visualising CP violation: the unitarity triangle

1) $$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3\left[1-(\rho-i\eta)\right] & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

2) Exploit unitarity (1st and 3rd col.) $$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

3)

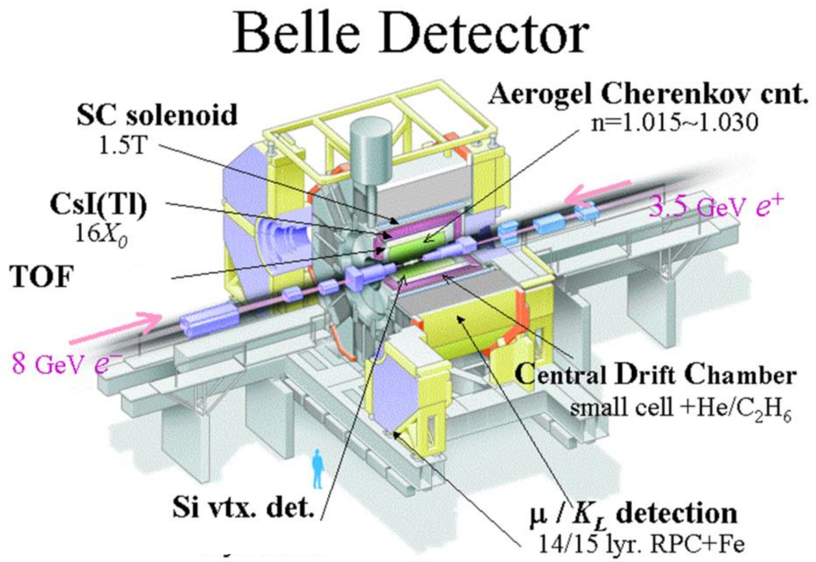


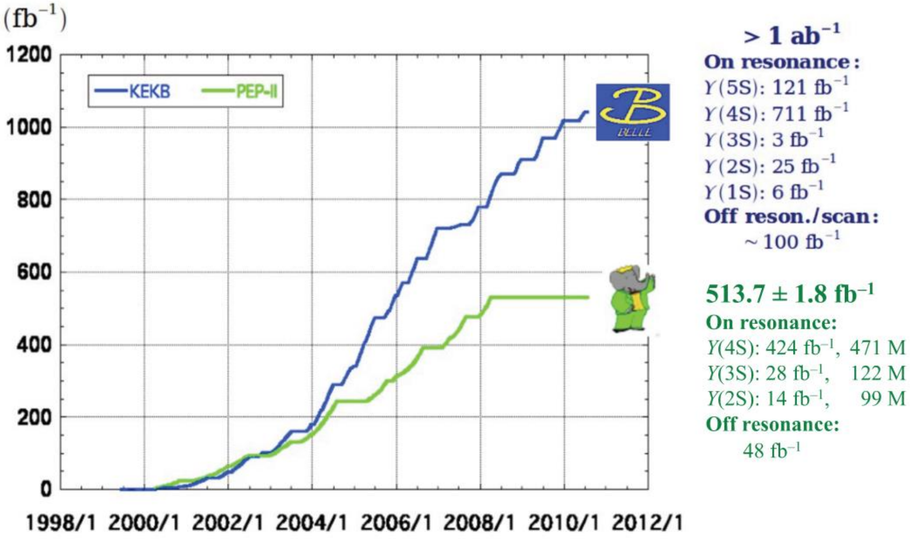
$$\phi_1 = \beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\simeq \arg\left(\frac{1}{1-\rho-i\eta}\right)$$

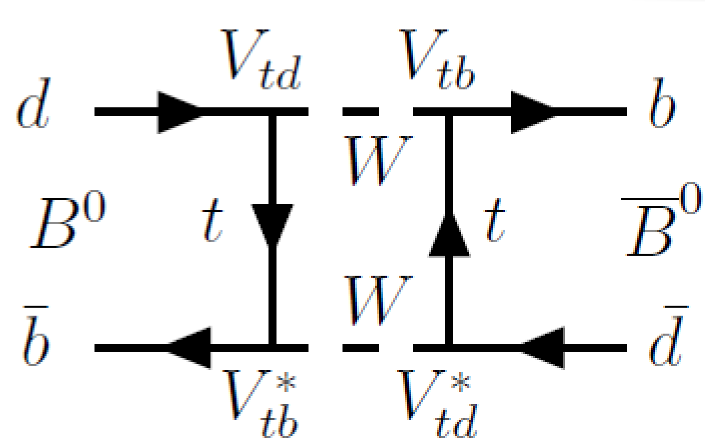
Belle

- Operation from 1999 to 2010
- $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ for CKM measurements
- Asymmetric energy to allow time-dependent measurements
- Coherent production of $B^0\overline{B^0}$
- Low multiplicity
- Detectors with good tracking, PID and calorimetry
  - plus hermeticity for full event reconstruction/tagging



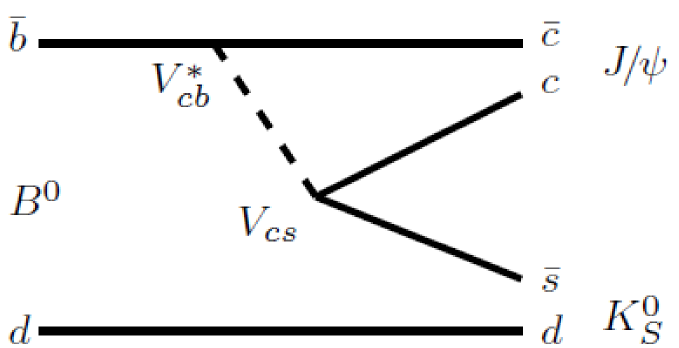


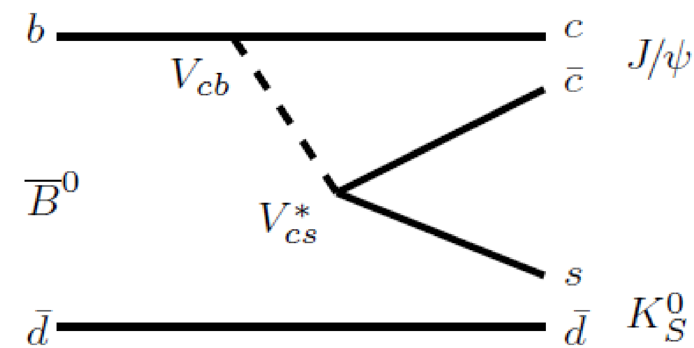
The Golden Mode



$B^0 \to J/\psi K_S^0$ sensitive to

$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$





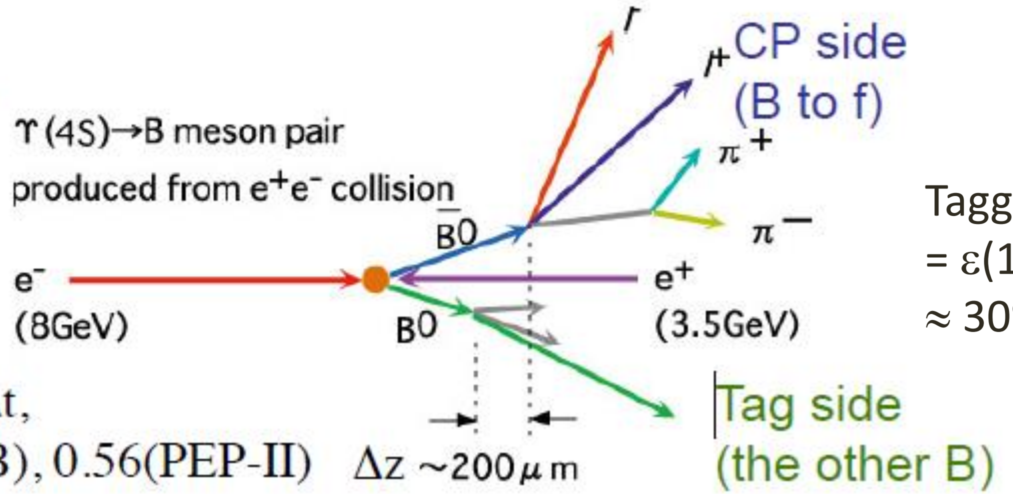
CP violation in the 'interference of mixing and decay amplitudes'

$$A_{CP}(\Delta t) = \frac{\Gamma\left[\bar{B}^0(\Delta t) \to f\right] - \Gamma\left[B^0(\Delta t) \to f\right]}{\Gamma\left[\bar{B}^0(\Delta t) \to f\right] + \Gamma\left[B^0(\Delta t) \to f\right]} = S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t)$$

In SM $S_f = \sin 2\beta$ and $C_f = 0$ when no CPV in f

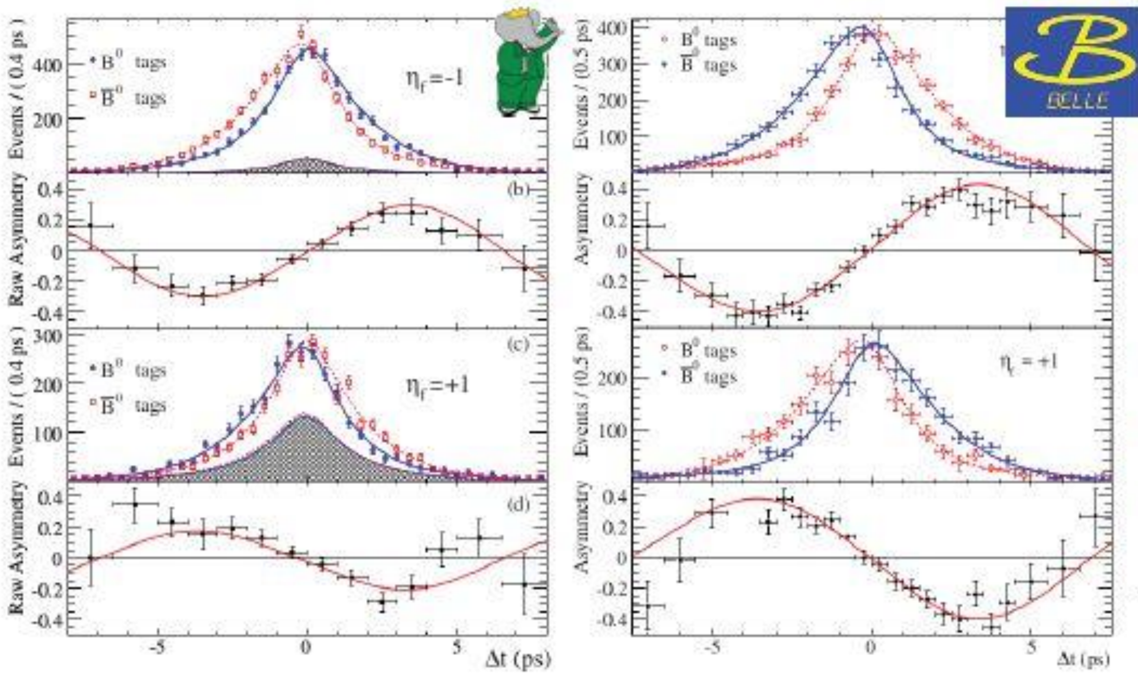
Time-dependent CPV violation

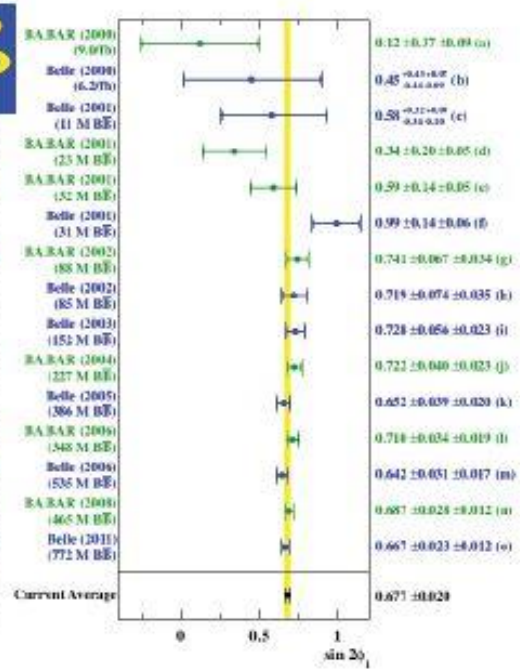
In order to see CPV by interference between decay and mixing.



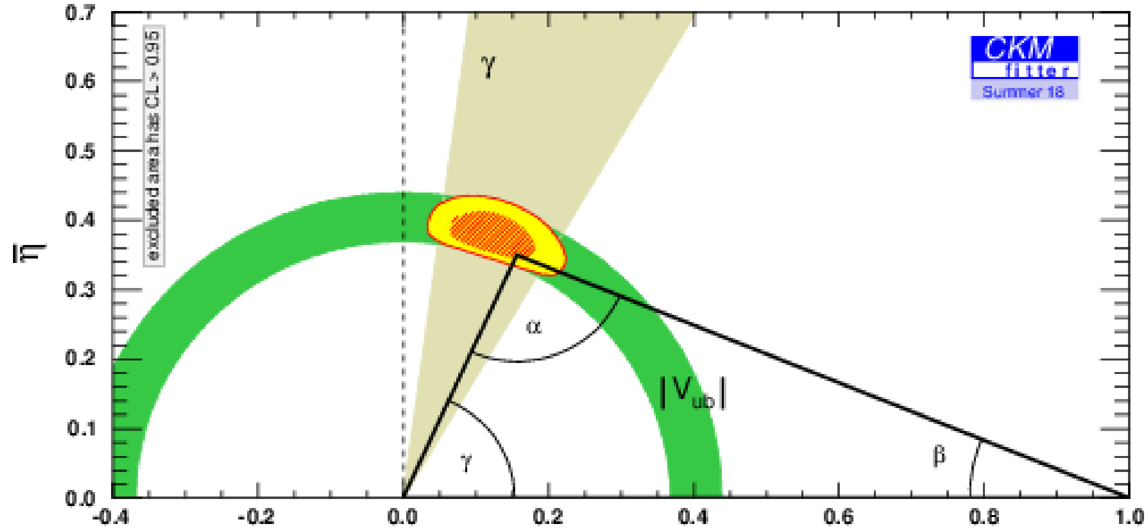
Tagging power $= \varepsilon(1-2\omega)^2 \approx 30\%$

$\Delta z=\beta\gamma c\Delta t$,
$\beta\gamma=0.425$(KEKB), 0.56(PEP-II)

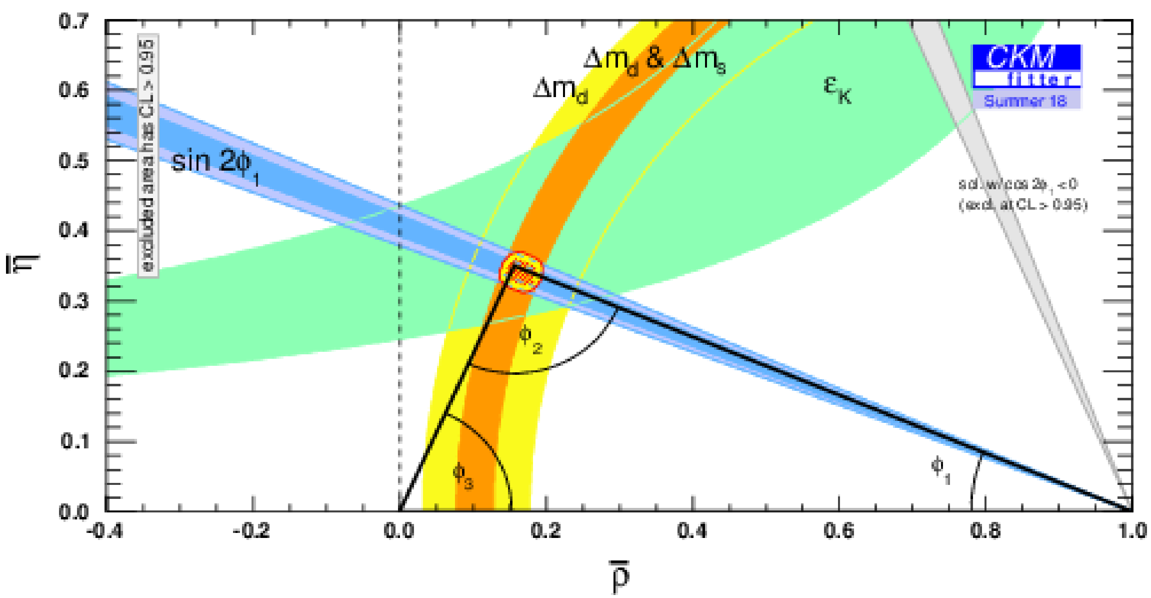




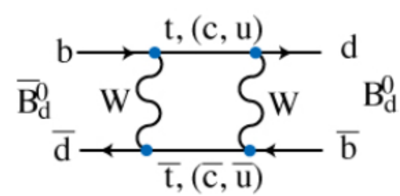
Over constraint



Tree level only



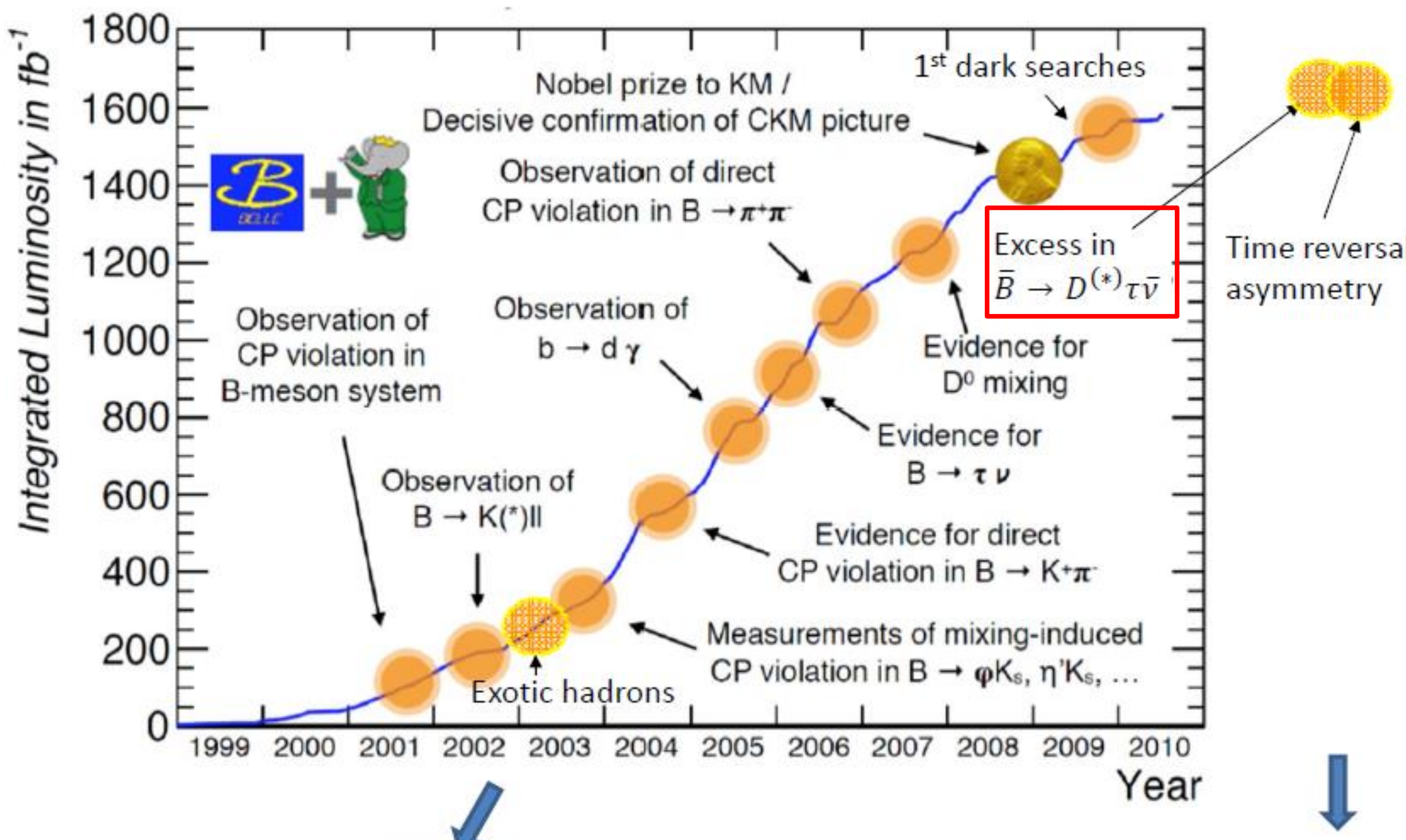
Loop-level only



NP at O(>TeV)?

Belle achievements

From Abi Soffer: HEPMAD

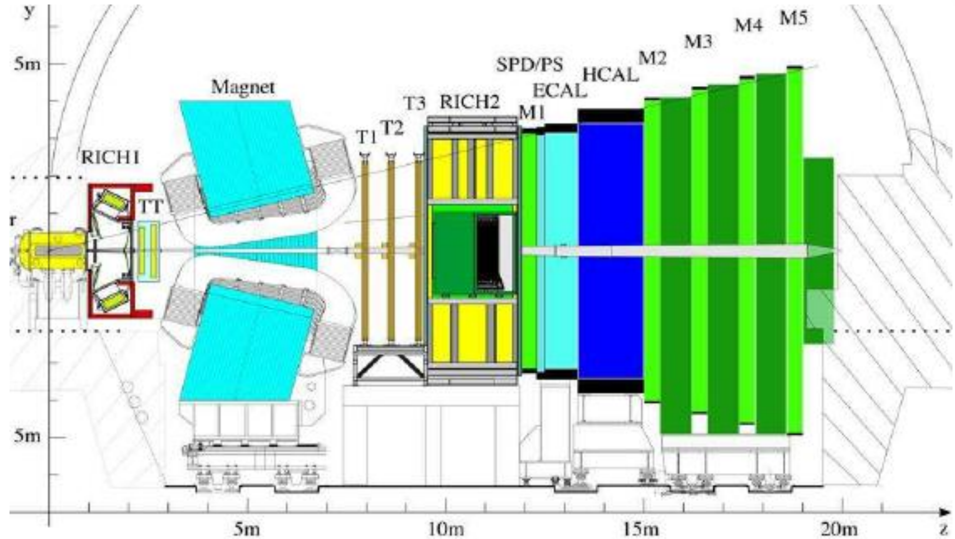


>100 unique CPV results

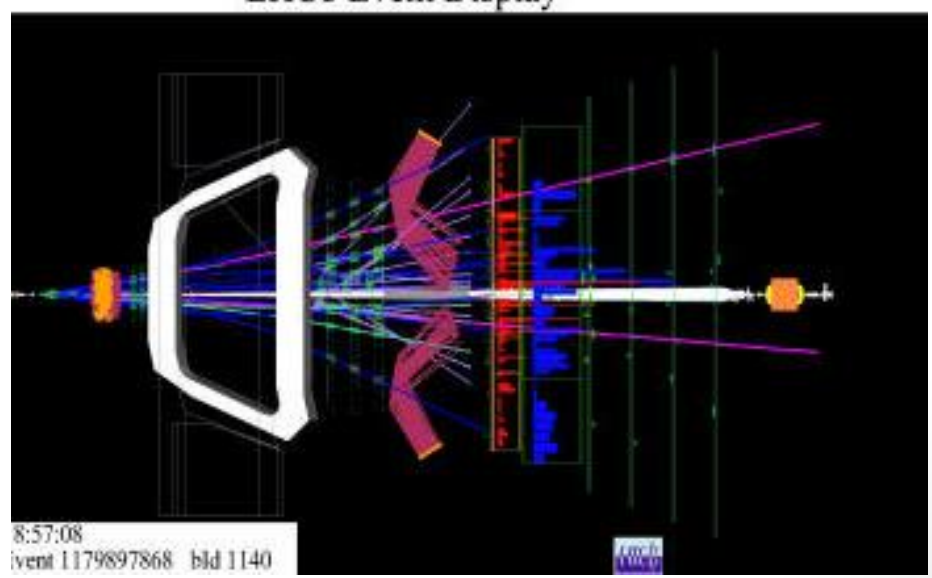
~350 papers published after shutdown, 21 in 2018

Belle II's rival LHCb in a slide

- 13 TeV pp collisions
  - trillion bb/2 fb^{-1}
  - 6 fb^{-1} @ 13 TeV
  - + 3 fb^{-1} @ 7/8 TeV
- Forward geometry gets both b quarks in acceptance and boosted – exploit b lifetime to separate background
- RICHes for π/K separation
- Full trigger bandwidth for B physics



LHCb Event Display

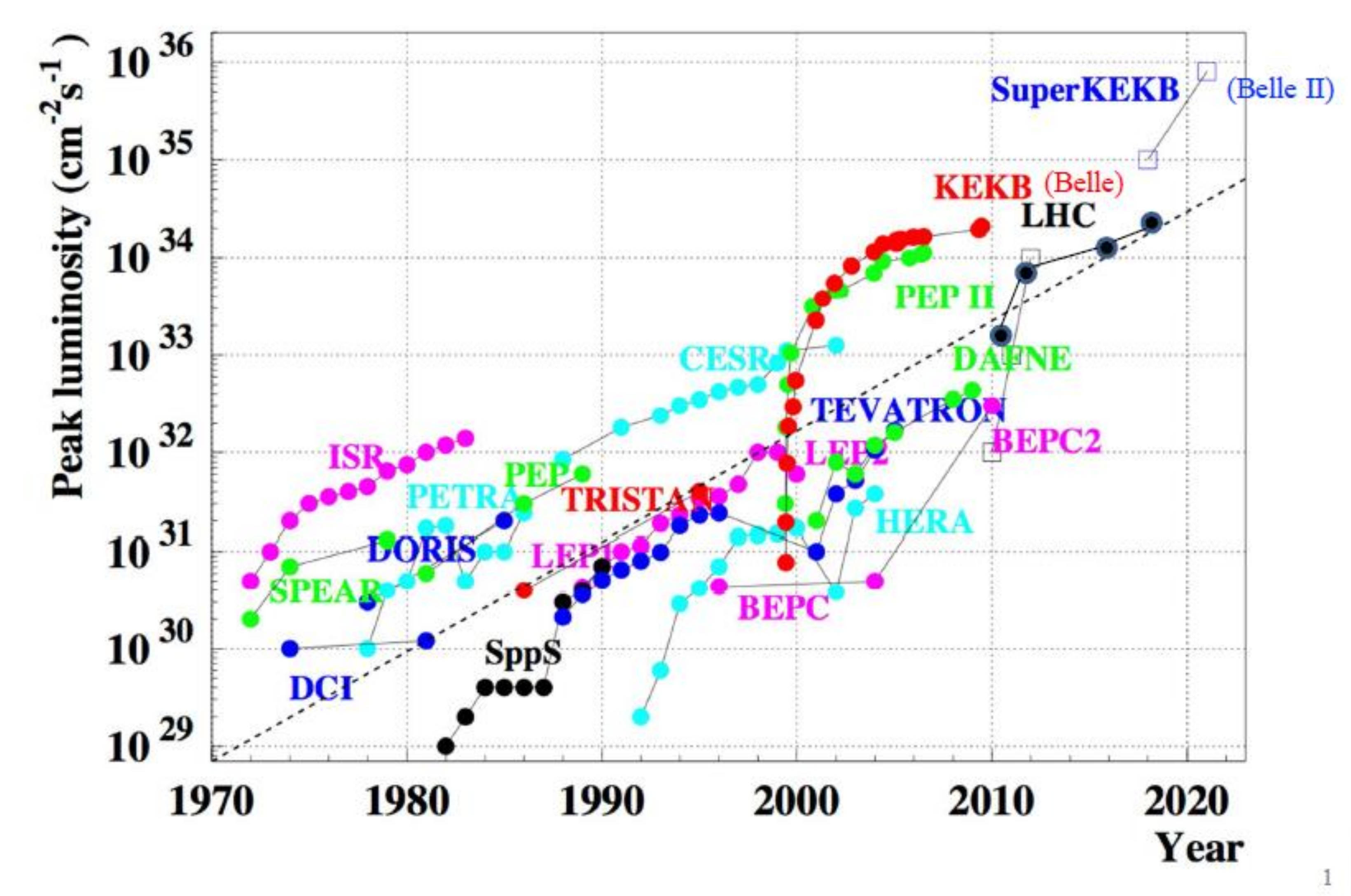


Belle II: can never have too much of a good thing (× 50 Belle)

- But isn't LHCb doing this already?

Property	LHCb	Belle II
$\sigma_{b\bar{b}}$ (nb)	~150,000	~1
$\int L\,dt$ (fb^{-1})	~25	~50,000
Background level	Very high	Low
Typical efficiency	Low	High
π^0, K_S reconstruction	Inefficient	Efficient
Initial state	Not well known	Well known
Decay-time resolution	Excellent	Very good
Collision spot size	Large	Tiny
Heavy bottom hadrons	B_s, B_c, b-baryons	Partly B_s
τ physics capability	Limited	Excellent
B-flavor tagging efficiency	3.5 - 6%	36%

"Moore's" Law of Luminosity



The path to higher luminosity

$$\xi \propto \sqrt{\frac{\beta^*}{\varepsilon}}$$

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

Lorentz factor

Beam current

Beam-beam parameter

Lumi. reduction factor (crossing angle)&
Tune shift reduction factor (hour glass effect)
0.8 ~ 1
(short bunch)

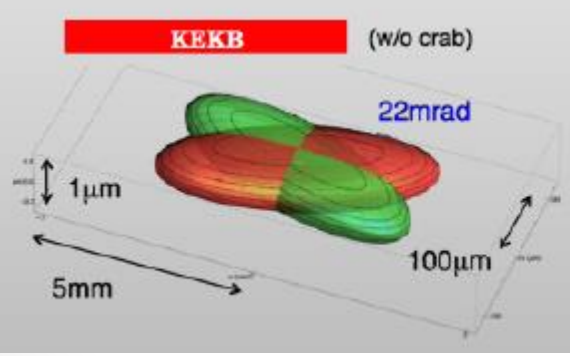
Classical electron radius

Beam size ratio@IP
1 ~ 2 % (flat beam)

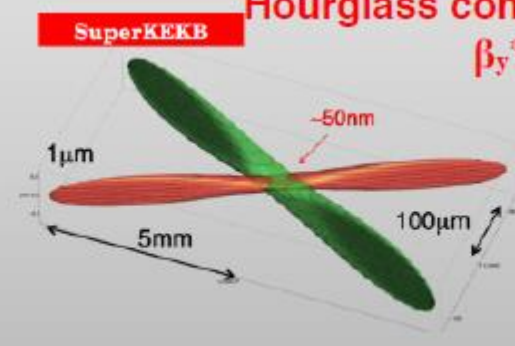
Vertical beta function@IP

(1) Smaller β_y^* (20 x)

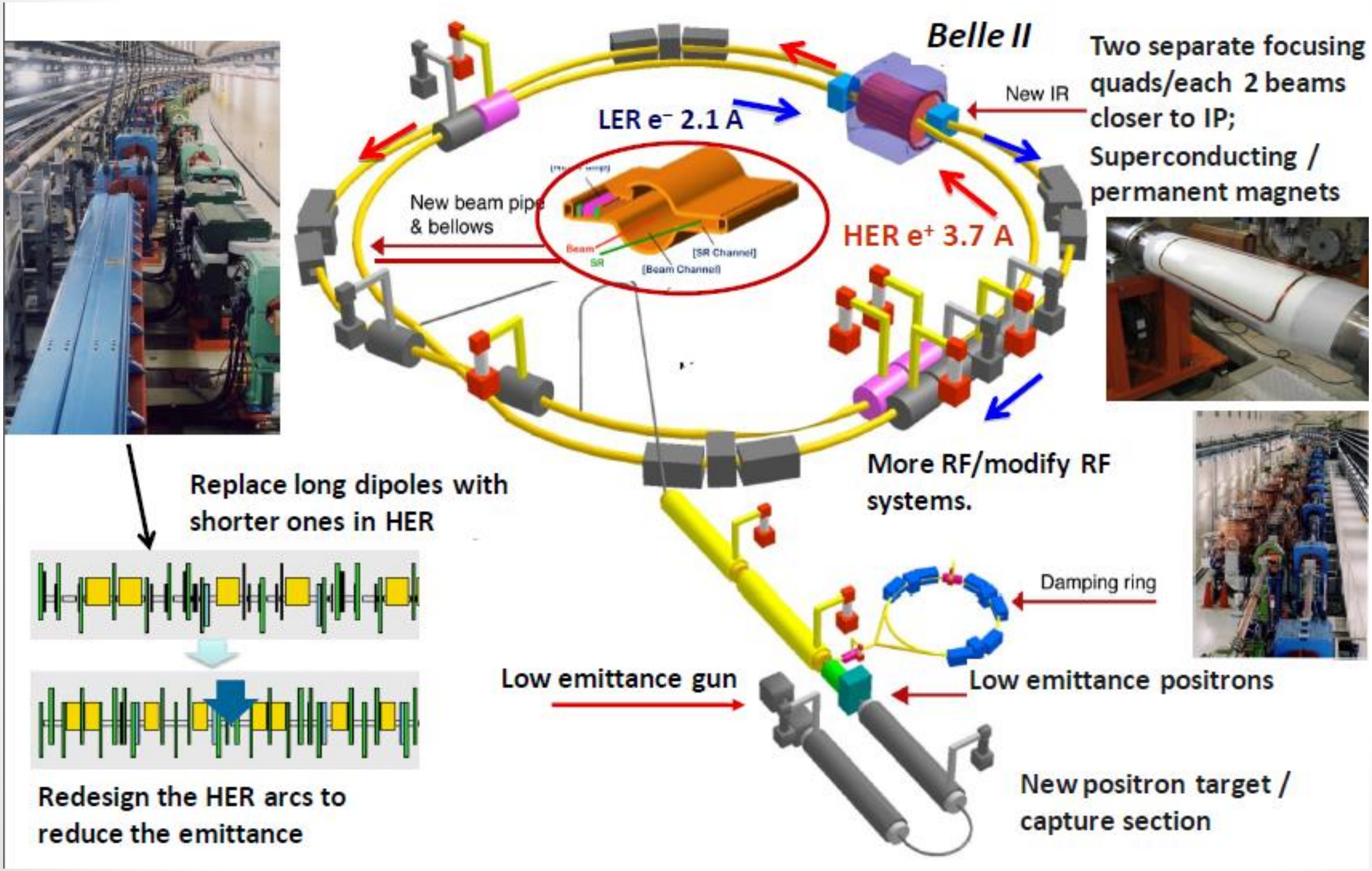
(2) Increase beam currents (~2-3x)



Hourglass condition:
$\beta_y^* >\sim L = \sigma_x/\phi$

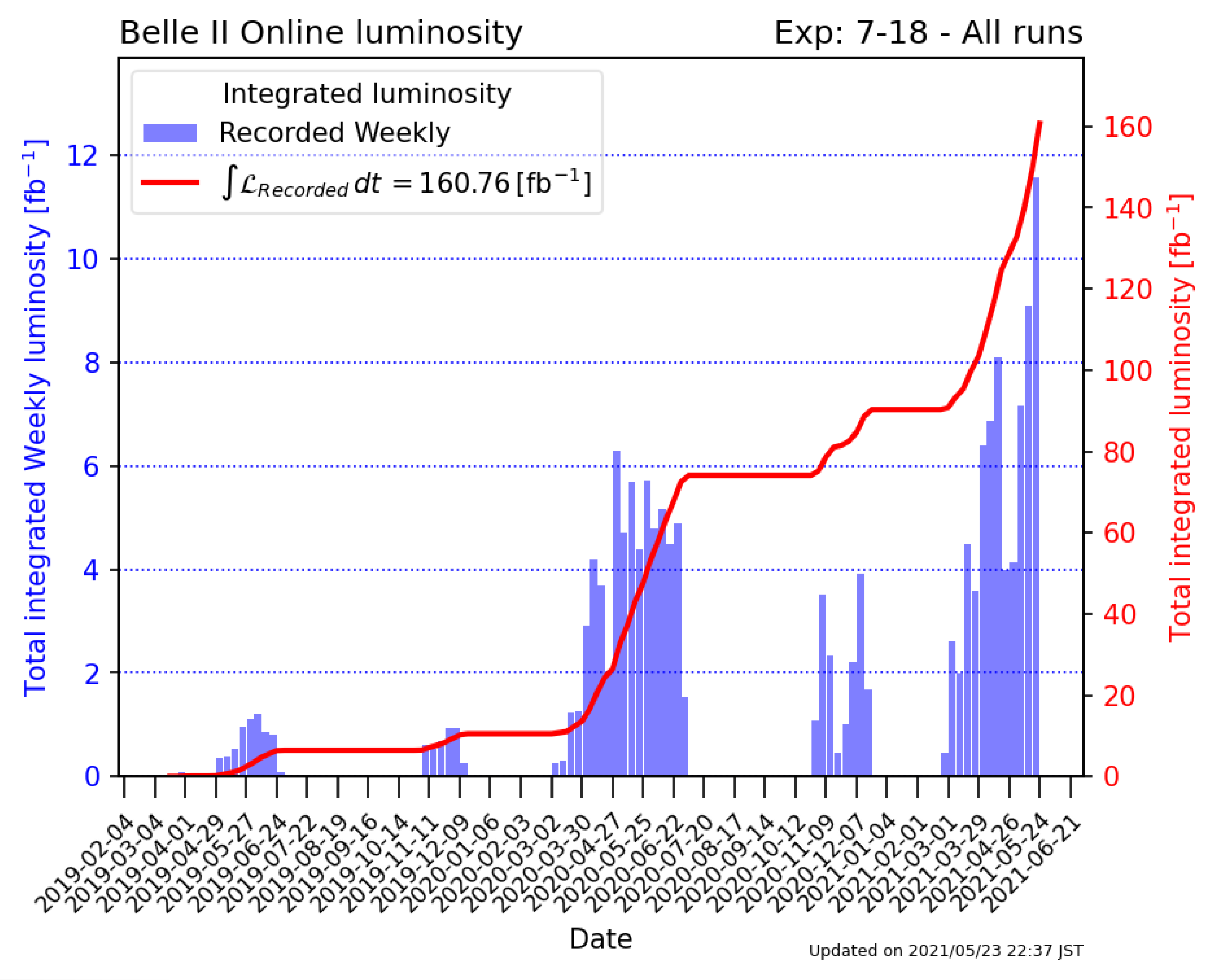


SUPERKEKB

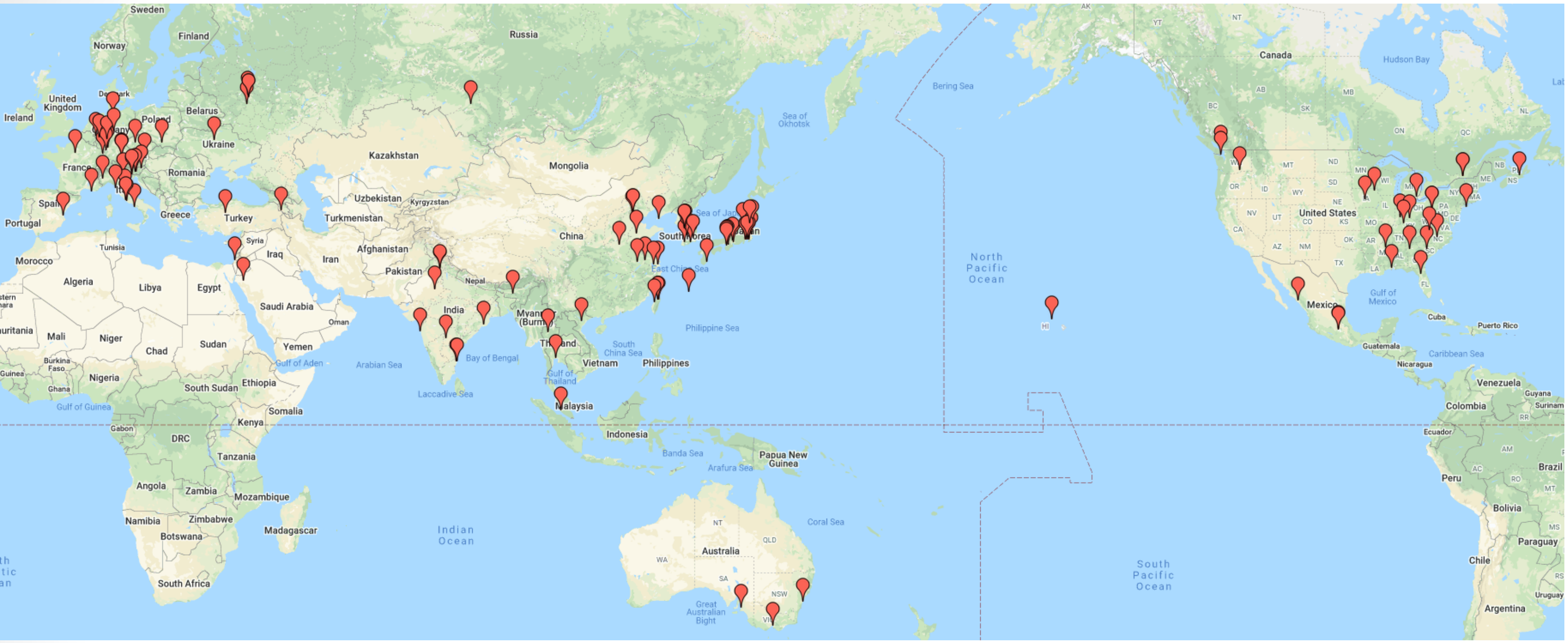


Belle II
Two separate focusing quads/each 2 beams closer to IP;
Superconducting / permanent magnets
New IR
LER e⁻ 2.1 A
HER e⁺ 3.7 A
New beam pipe & bellows
Beam
SR
[SR Channel]
[Beam Channel]
Replace long dipoles with shorter ones in HER
Redesign the HER arcs to reduce the emittance
More RF/modify RF systems.
Damping ring
Low emittance gun
Low emittance positrons
New positron target / capture section

Integrated luminosity

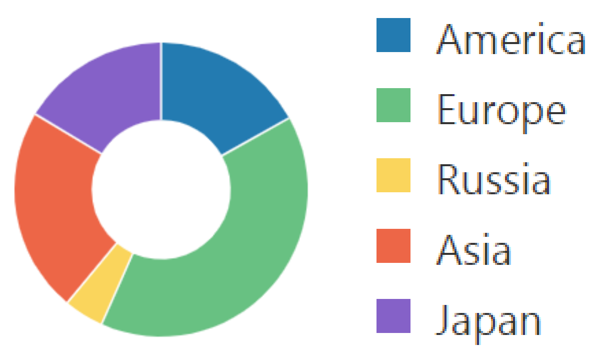


Belle II Collaboration

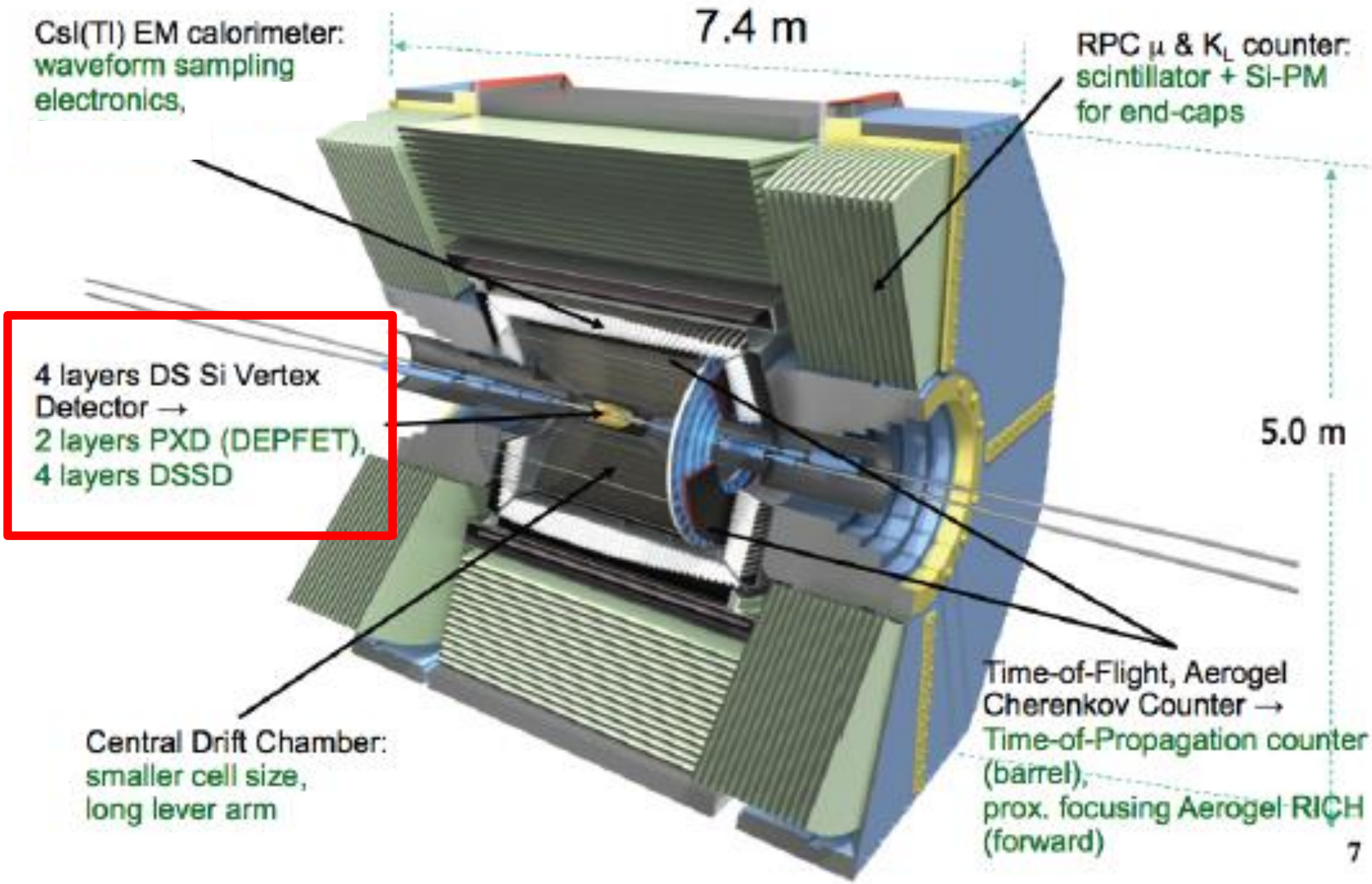


1024 physicists from 26 countries

India: 48 at IITX (X=M, H, G, BBS), MNIT, IISER Mohali, TIFR, PU, PAU, IMSc



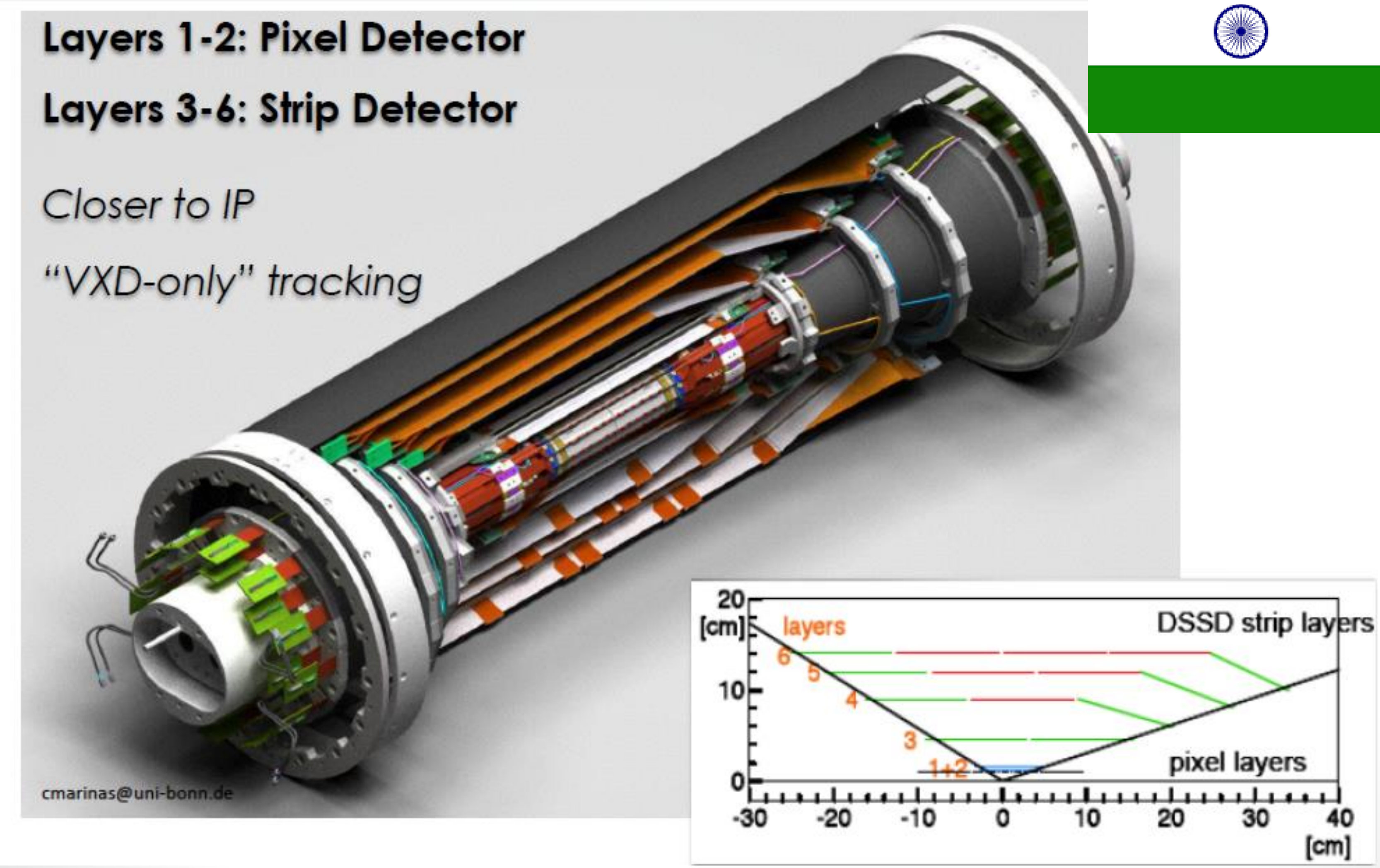
Belle II



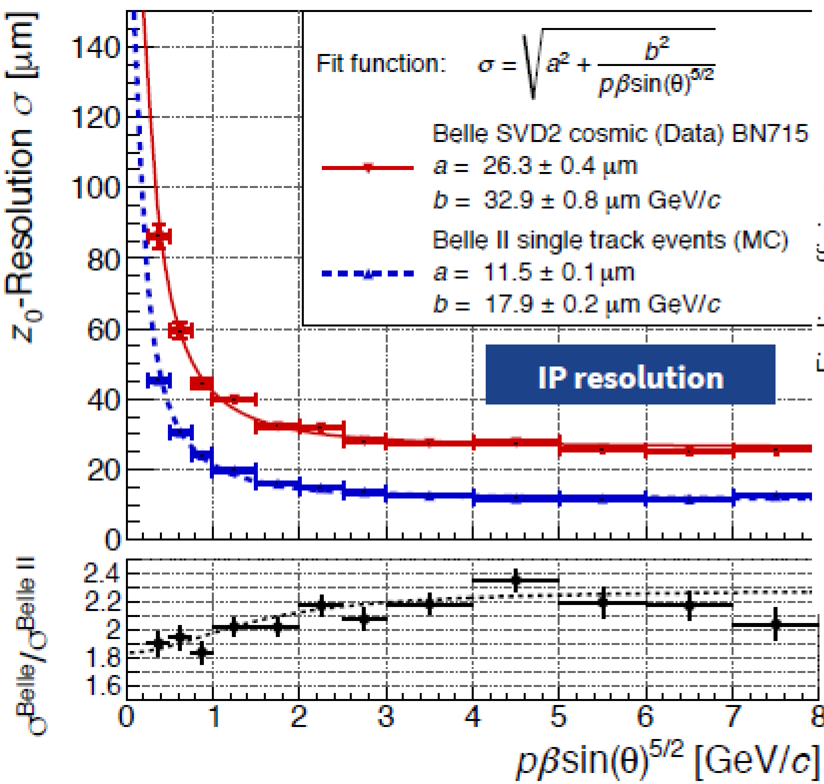
CsI(Tl) EM calorimeter:
waveform sampling electronics,
7.4 m
RPC μ & K_L counter:
scintillator + Si-PM for end-caps
4 layers DS Si Vertex Detector →
2 layers PXD (DEPFET),
4 layers DSSD
5.0 m
Central Drift Chamber:
smaller cell size,
long lever arm
Time-of-Flight, Aerogel Cherenkov Counter →
Time-of-Propagation counter (barrel),
prox. focusing Aerogel RICH (forward)
7

Belle II – Silicon Vertex Dectector

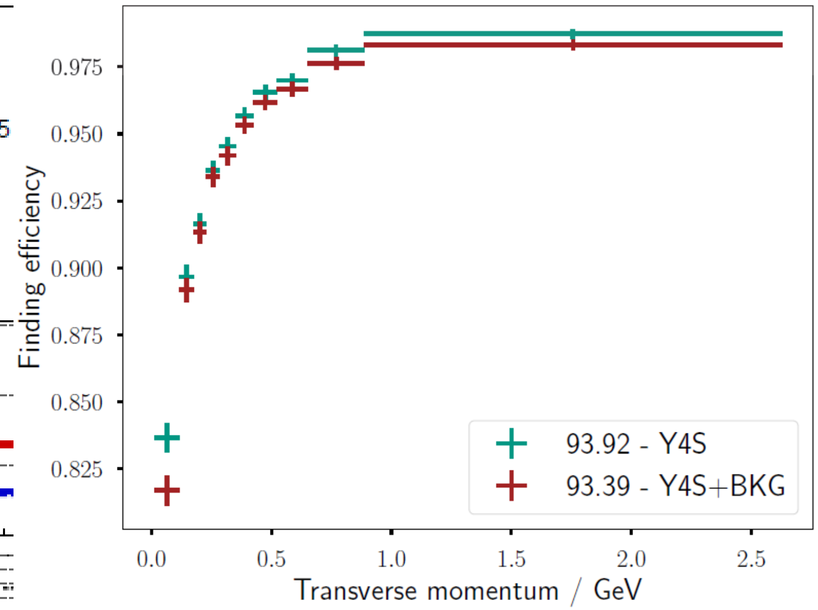
Only one layer of pixels for Phase III



SVD performance



Belle a factor two worse than Belle II

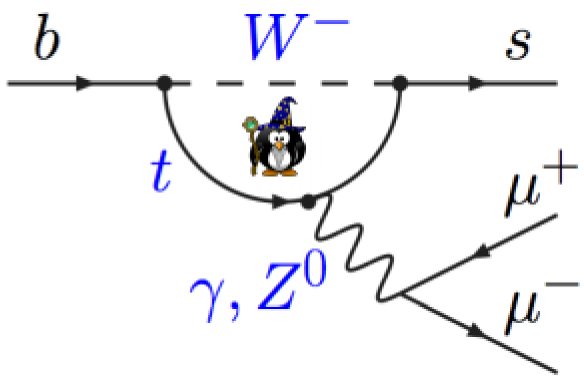


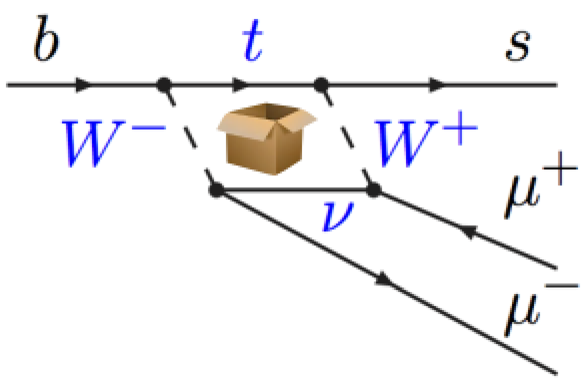
Stand alone SVD track finding efficiency good for K_S finding (30% over Belle) and slow π from D*

HOT TOPIC: ANOMALIES

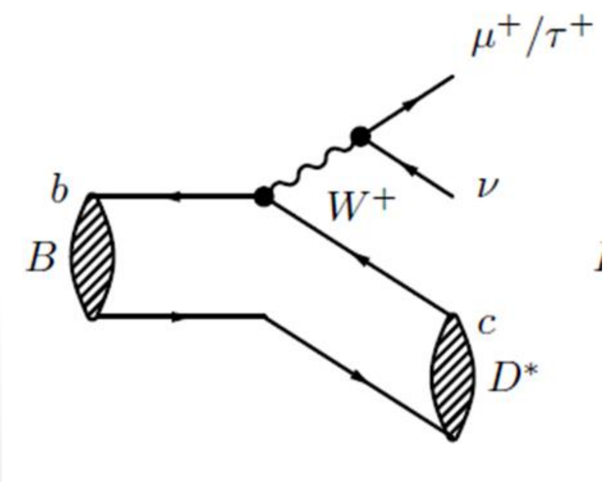
Overview of modes with anomalies

- Flavour changing neutral current b→sll at loop level only



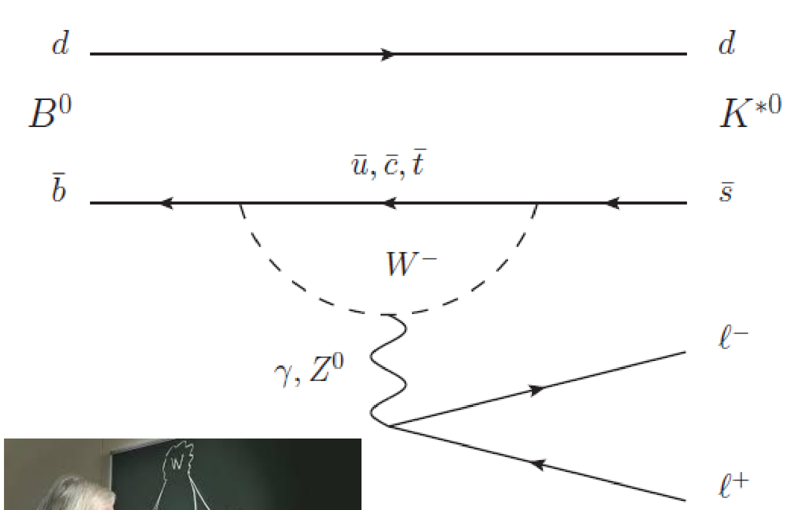


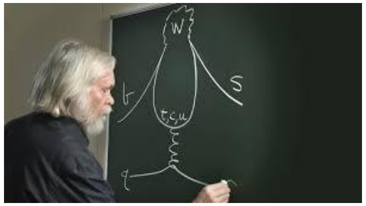
- Tree level b→cτν semileptonic



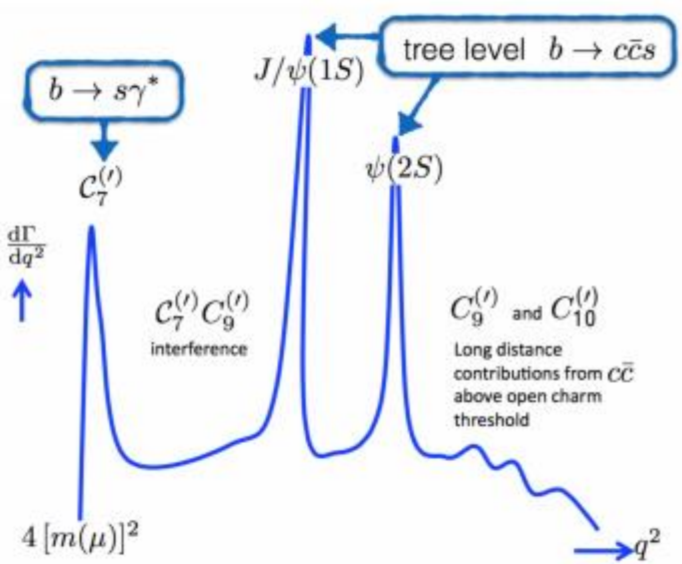
	Pro	Con
b→sll	New physics reach O(10 TeV)	One experiment
b→cτν	Three experiments	New physics near the EW scale

$B \to K^{*}(892) l^{+} l^{-}$



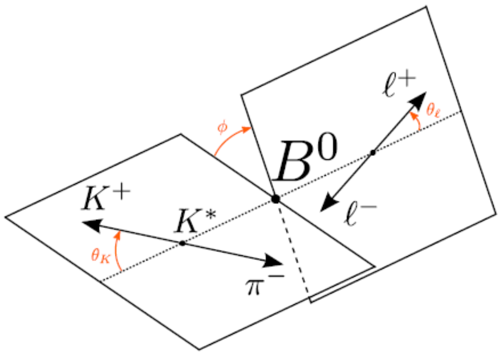


- This is a rare flavour changing neutral current process
- The four-body final state allows differential distributions to be probed
  - Large new physics contributions possible as they appear via interference c.f. forward-backward asymmetries in e^+e^-
- Also variation with the invariant mass of the l^+l^- system - q^2



$B \to K^*(892) l^+ l^-$ nomenclature

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_L \, d\cos\theta_K \, d\phi \, dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K$$
$$+ \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_L$$
$$- F_L\cos^2\theta_K\cos 2\theta_L + S_3\sin^2\theta_K\sin^2\theta_L\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_L\cos\phi + S_5\sin 2\theta_K\sin\theta_L\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_L + S_7\sin 2\theta_K\sin\theta_L\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_L\sin\phi + S_9\sin^2\theta_K\sin^2\theta_L\sin 2\phi\Big]$$

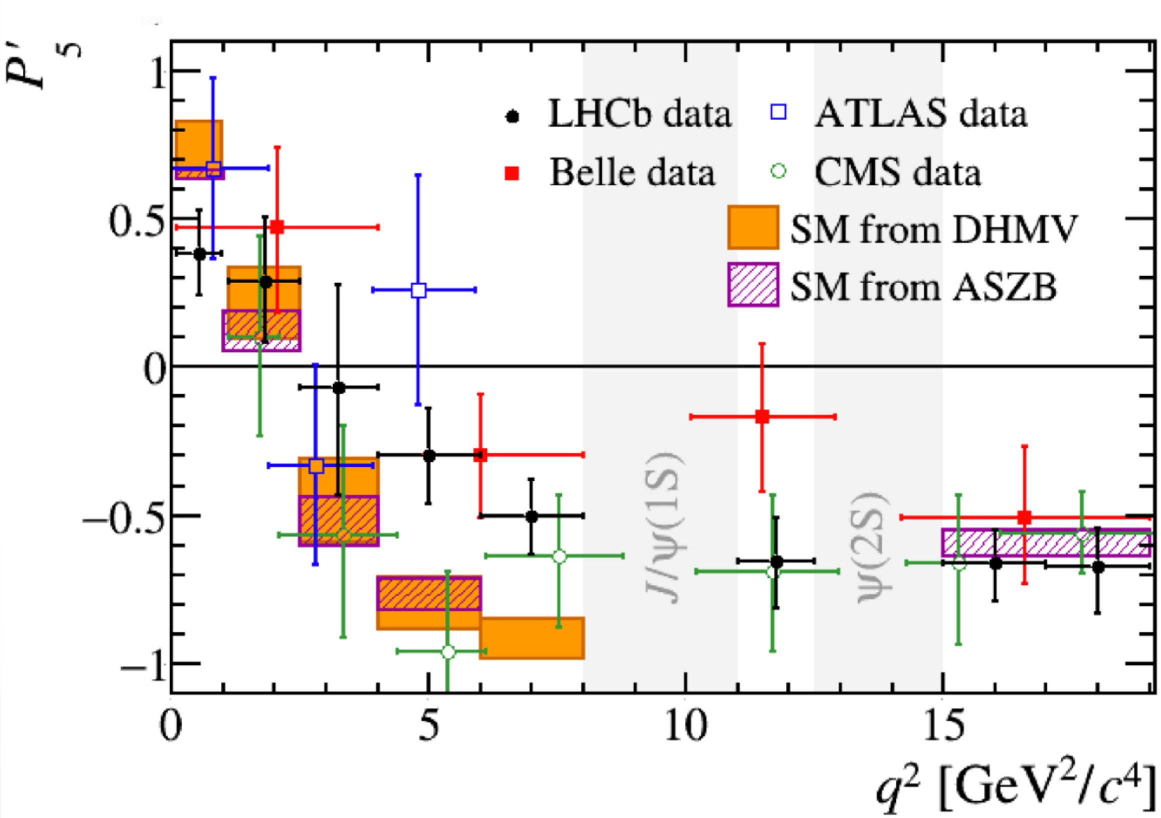


- Goal is to measure this 4D differential distribution and extract the coefficients from data to compare to the SM predictions
- Much work on defining observables with minimal theoretical uncertainties
- Let us focus on S_5 which get normalized as $P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$ to minimize form factor uncertainties

Theory: S. Descotes-Genon et al., JHEP 12 (2014) 125

P_5' anomaly: the first $b \to s l^+ l^-$

- Constructed in such a way that the form factor dependence is minimized



Note this is just for $B \to K^* \mu\mu$ - time to talk about LHCb

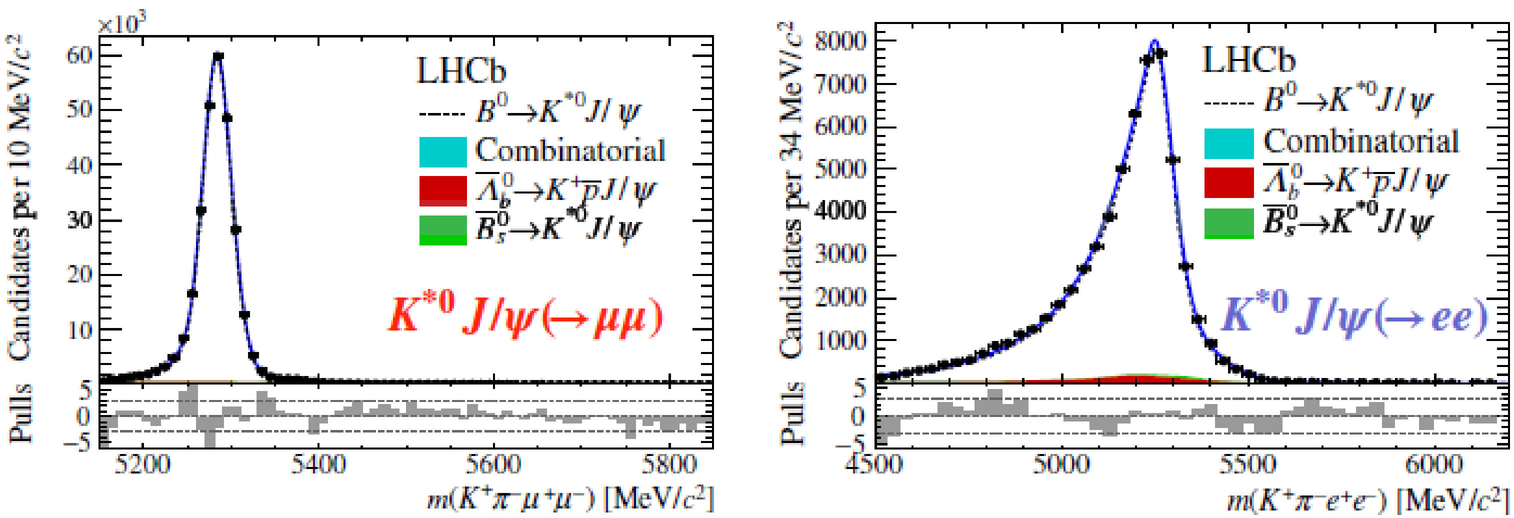
> 3 σ disagreement with Standard Model

Tests of Lepton Universality Violation (LUV)

$$R_H = \frac{\int \frac{d\Gamma(B\to H\mu^+\mu^-)}{dq^2}\, dq^2}{\int \frac{d\Gamma(B\to He^+e^-)}{dq^2}\, dq^2}, \qquad \text{H=K or K*}$$

- Standard Model prediction ~1 to a few %
  - limited theoretical uncertainties
- $B \to K^{(*)} J/\psi(l^+l^-)$ bountiful control channel

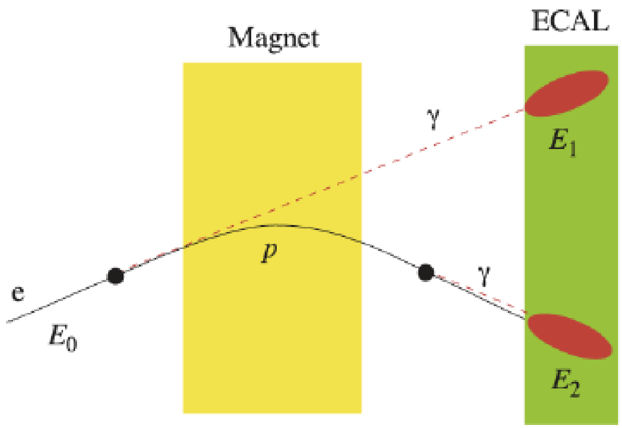
arXiv:2103.11769



The experimental challenge

JHEP 08, 055 (2017) arXiv 2103.11769 Fresh!

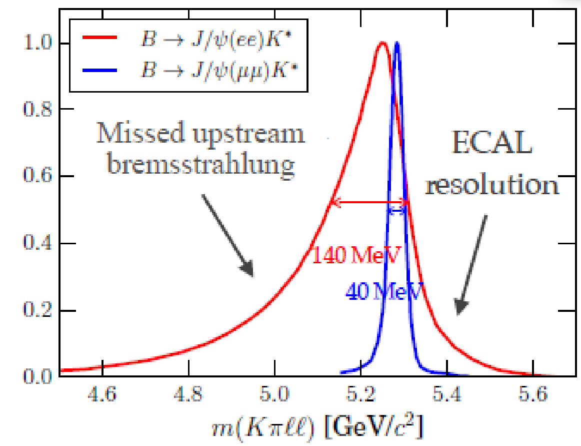
- Measurements of $\mathcal{R}_{K^{*0}}$ (3 fb^{-1}) and $\mathcal{R}_{K^+}$ (9 fb^{-1})
- At LHCb, **electrons** are **major challenge**



Algorithm to recover **upstream bremsstrahlung** when $E_\gamma > 75$ MeV

Downstream bremsstrahlung follows the track: easy to find

Unofficial from M. Borsato



Electrons have **worse mass resolution** and are **more difficult to trigger on**

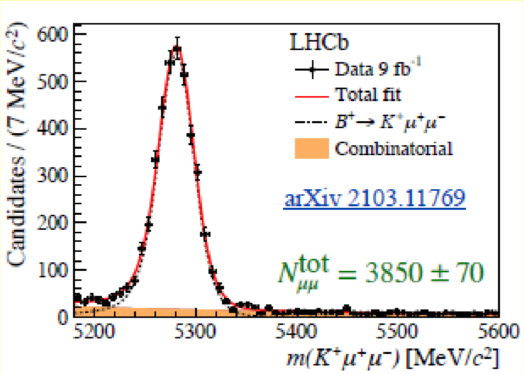
- Use **double ratio** with $B \to K^{(*)} J/\psi(\to \ell\ell)$

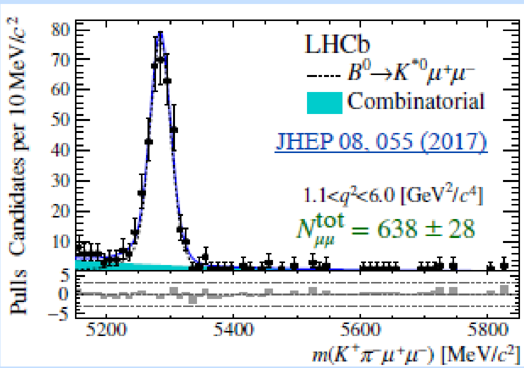
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+\mu^-))} \bigg/ \frac{\mathcal{B}(B^+ \to K^+ e^+ e^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+e^-))} = \frac{N^{\text{rare}}_{\mu^+\mu^-}}{N^{J/\psi}_{\mu^+\mu^-}} \frac{\varepsilon^{J/\psi}_{\mu^+\mu^-}}{\varepsilon^{\text{rare}}_{\mu^+\mu^-}} \times \frac{N^{J/\psi}_{e^+e^-}}{N^{\text{rare}}_{e^+e^-}} \frac{\varepsilon^{\text{rare}}_{e^+e^-}}{\varepsilon^{J/\psi}_{e^+e^-}}$$

Slide from M.F. Sevilla APS Meeting

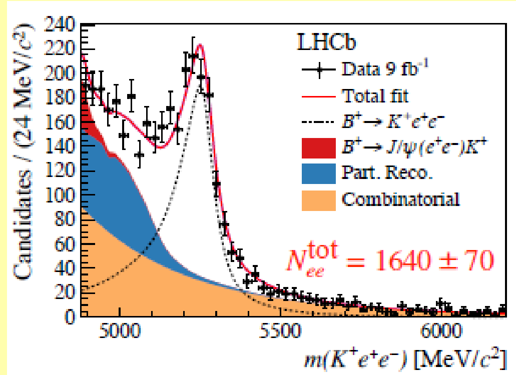
The results: muons low

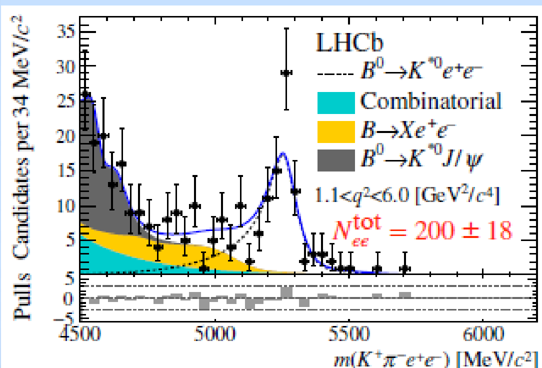
$B \to K^{(*)}\mu^+\mu^-$





$B \to K^{(*)}e^+e^-$





$\mathcal{R}_{K+}$ with 100% of Run 1+2

Fresh!

$$\mathcal{R}_{K^+}^{[1.1,6]} = 0.846^{+0.042+0.013}_{-0.039-0.012}$$

3.1σ from SM

$\mathcal{R}_{K^{*0}}$ with 25% of Run 1+2

$$\mathcal{R}_{K^{*0}}^{[0.045,1.1]} = 0.66^{+0.11}_{-0.07} \pm 0.03$$

2.1σ from SM

$$\mathcal{R}_{K^{*0}}^{[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

2.4σ from SM

Slide from M.F. Sevilla APS Meeting

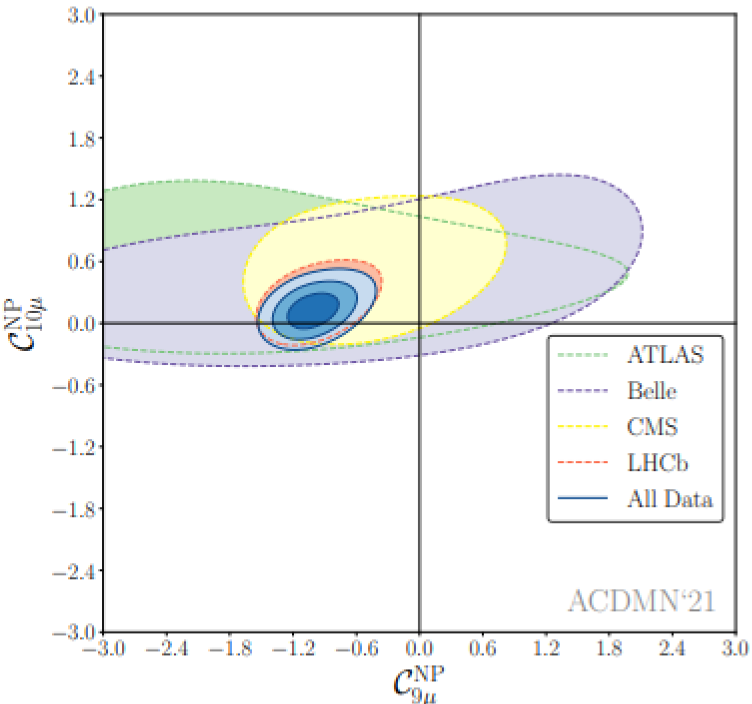
Global fit to b→sμ$^+$μ$^-$ data

- Perform global model independent fit to include all observables (≈250)
  - Belle, BaBar, ATLAS and CMS
  - Related observables e.g $B_s \to \mu^+\mu^-$
- Several new physics hypothes give a good fit to data significantly preferred over the SM hypothesis

$$O_9 = \bar{s}\gamma^\mu P_L b \bar{\ell}\gamma_\mu \ell$$

$$O_{10} = \bar{s}\gamma^\mu P_L b \bar{\ell}\gamma_\mu \gamma^5 \ell$$

arXiv:2105.09693 [hep-ph]

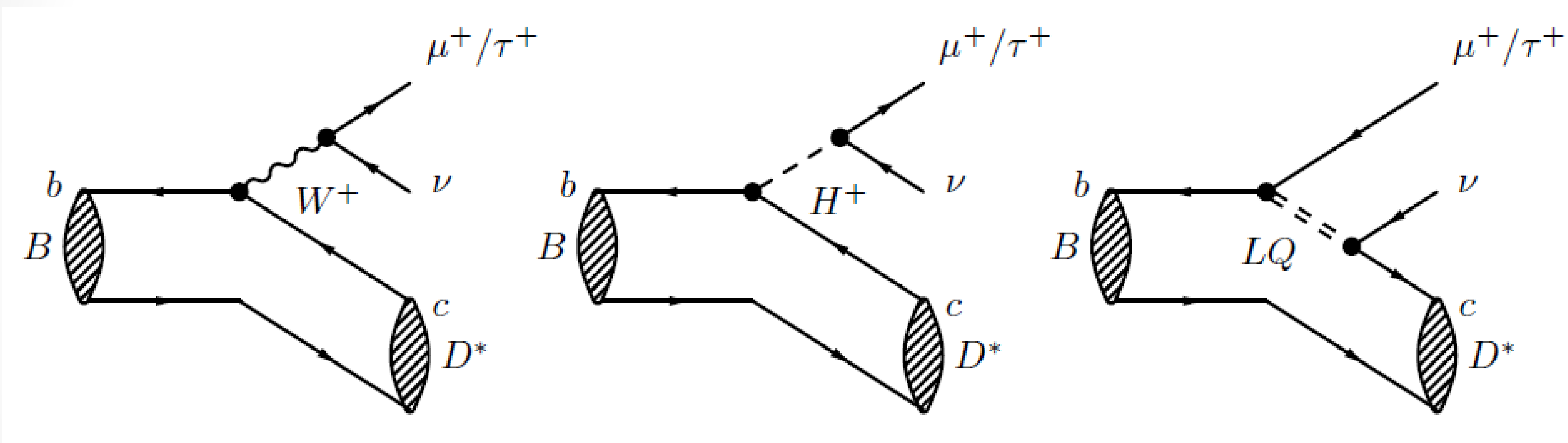


This fit assumption and others 6-7 sigma from SM

Just the LFUV observables 3-5 sigma

Semi-tauonic decays

- Tree level in the SM but allows lepton universality tests

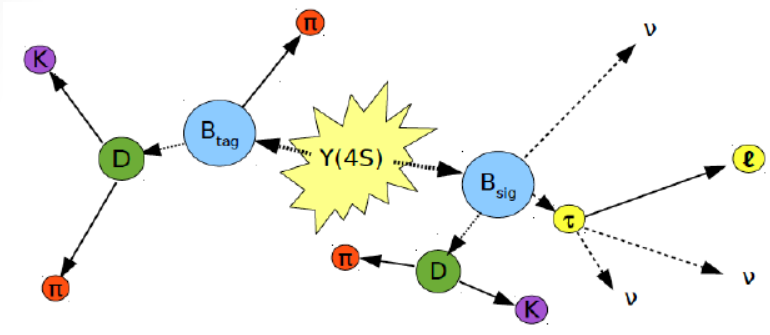


- Measure ratios to reduce theoretical and experimental uncertainties

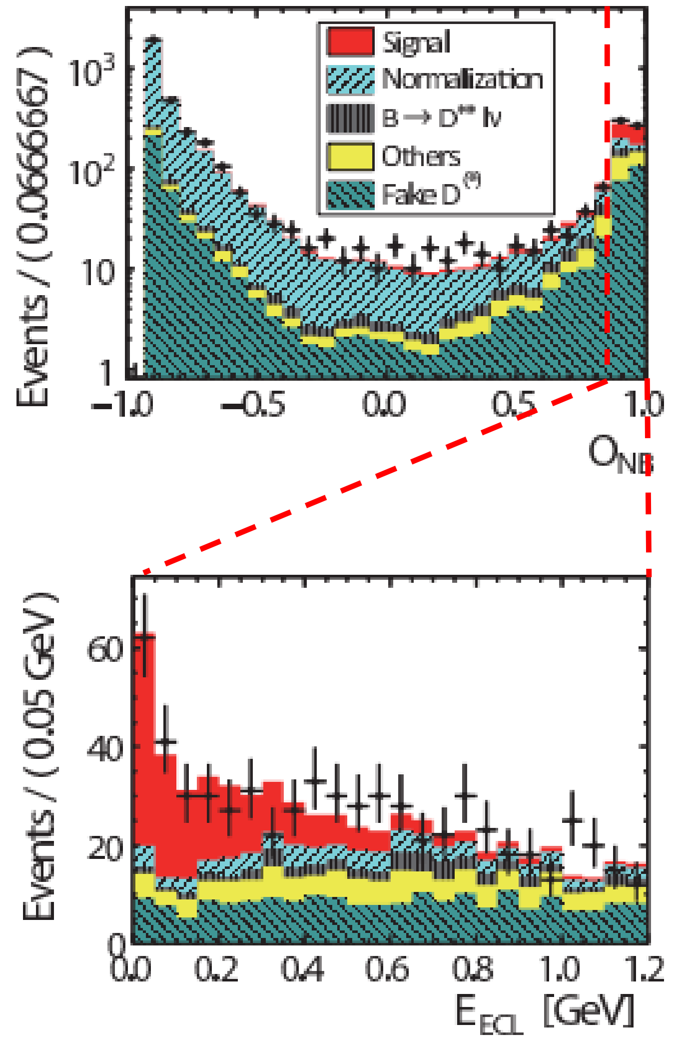
$$R(D) = \frac{\Gamma(\overline{B} \to D\tau\nu)}{\Gamma(\overline{B} \to D\ell\nu)} \qquad R(D^*) = \frac{\Gamma(\overline{B} \to D^*\tau\nu)}{\Gamma(\overline{B} \to D^*\ell\nu)}$$

- BaBar reported an anomalous result PRL 109, 101802 (2012) much activity since

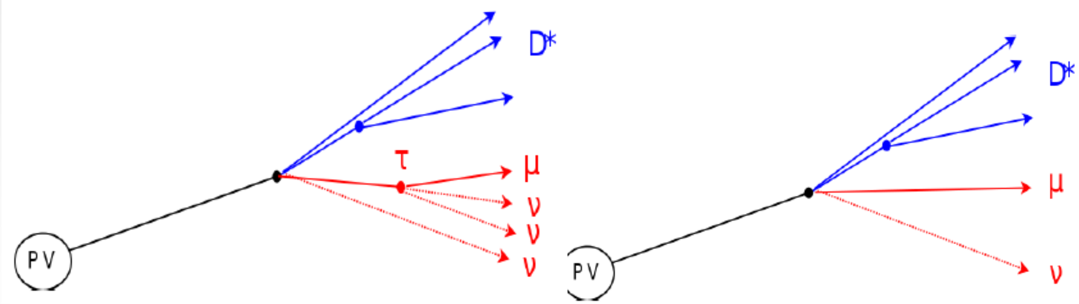
Belle results

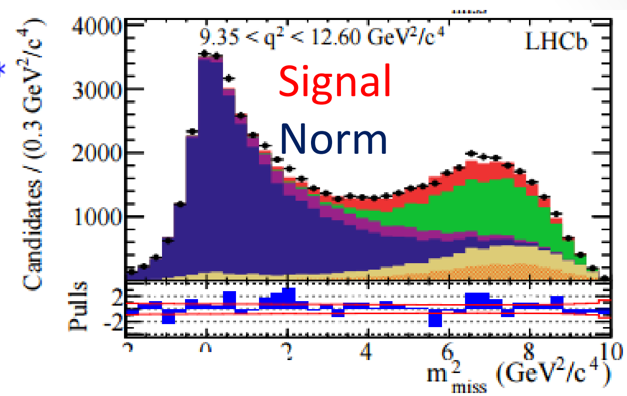


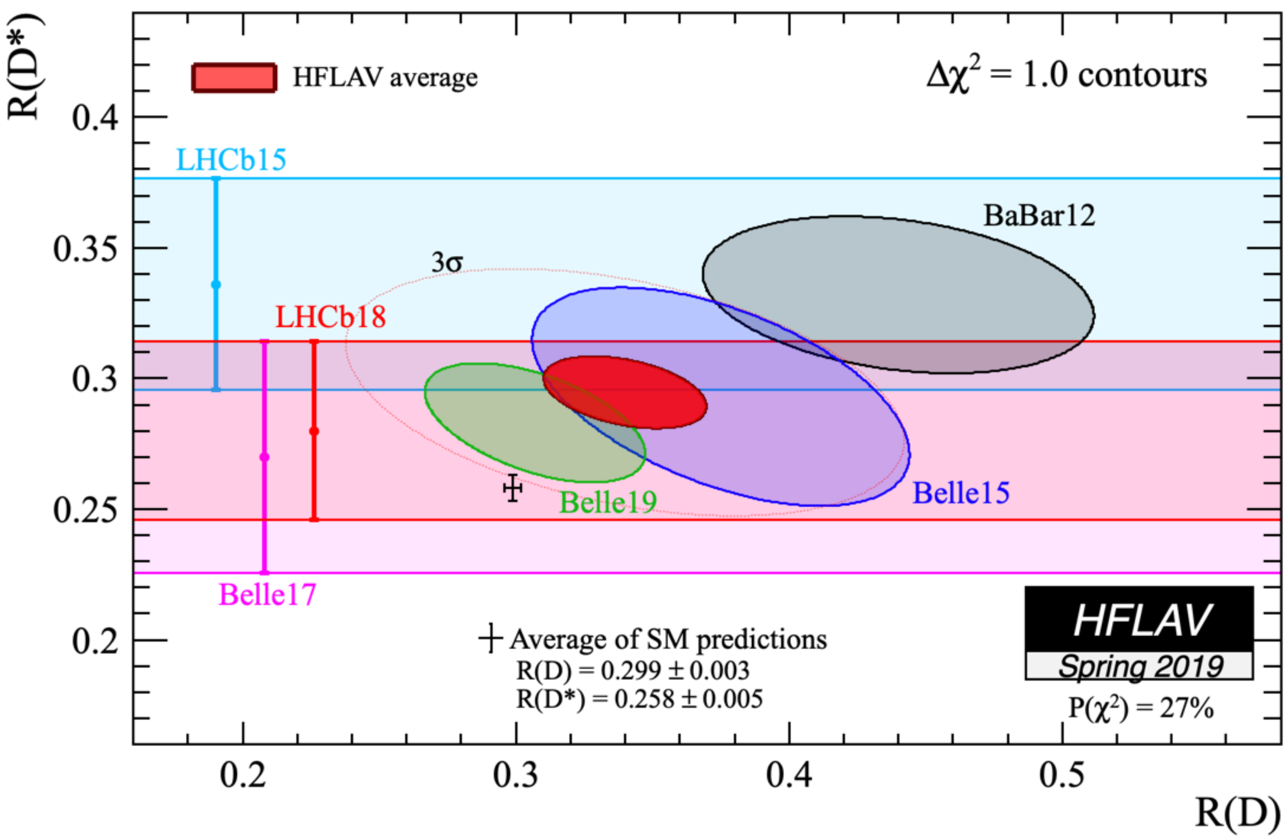
- Tag signal by fully reconstructing or identifying a semileptonic (SL) decay of the other B
- Then use residual energy in ECL, missing mass, multivariates and/or lepton momentum to separate signal
- Example: Phys. Rev. D 94, 072007 (2016) – SL tag



- LHCb also in the game using their vertexing prowess







Average 3.1σ from SM

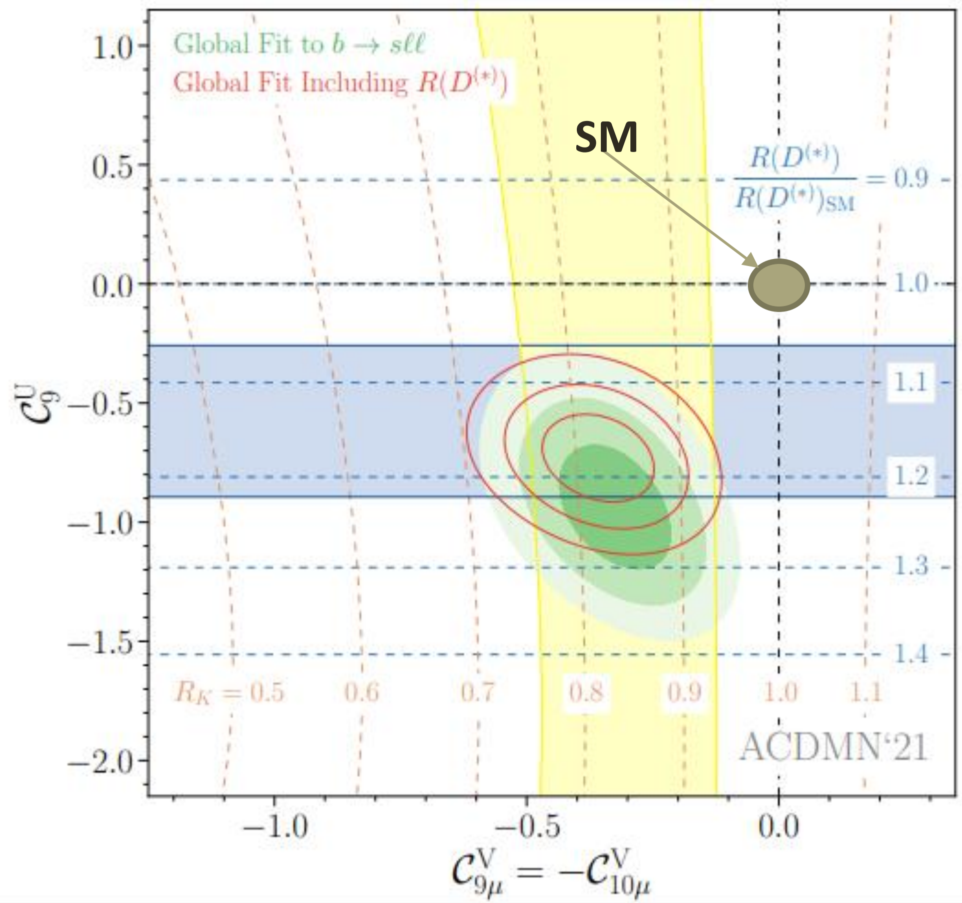
Global interpretation I

Some combinations of new physics Wilson coefficients allow the two sets of anomalies to be simultaneously fit

Here some new physics is lepton flavour universal (U) and some violating (V)

But what is the underlying physics interpretation?

arXiv:2105.09693 [hep-ph]

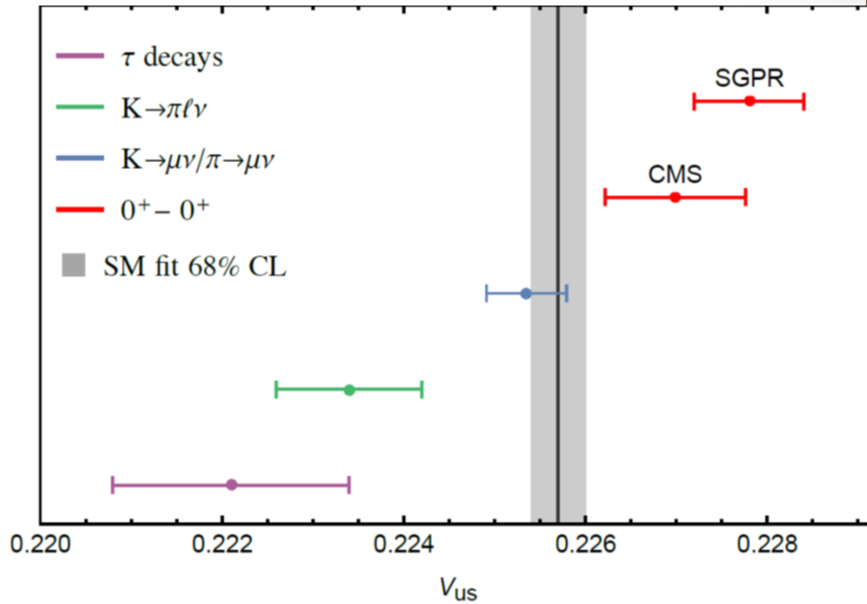


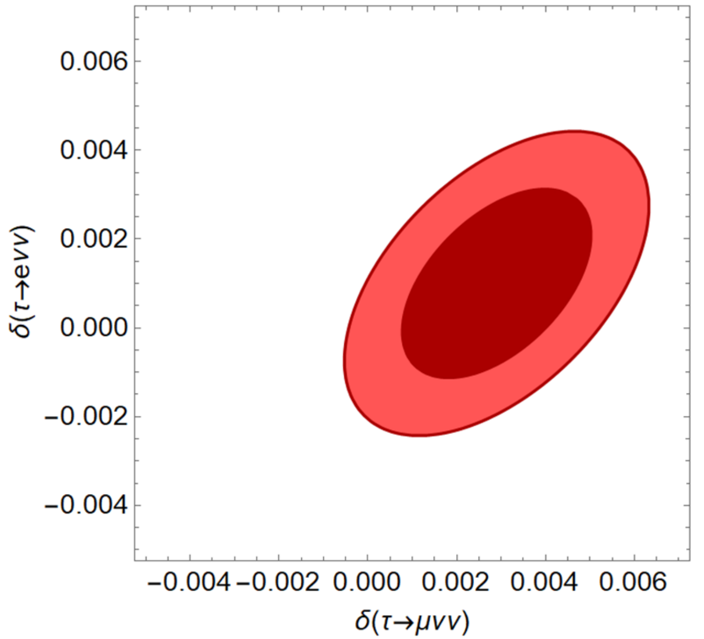
Other anomalies

- Cabibbo angle anomaly
  - WA violates unitarity at 3σ

$$\left|V_{ud}^2\right|+\left|V_{us}^2\right|+\left|V_{ub}^2\right|$$
$$=0.9985\pm0.0005\,(\text{PDG})$$

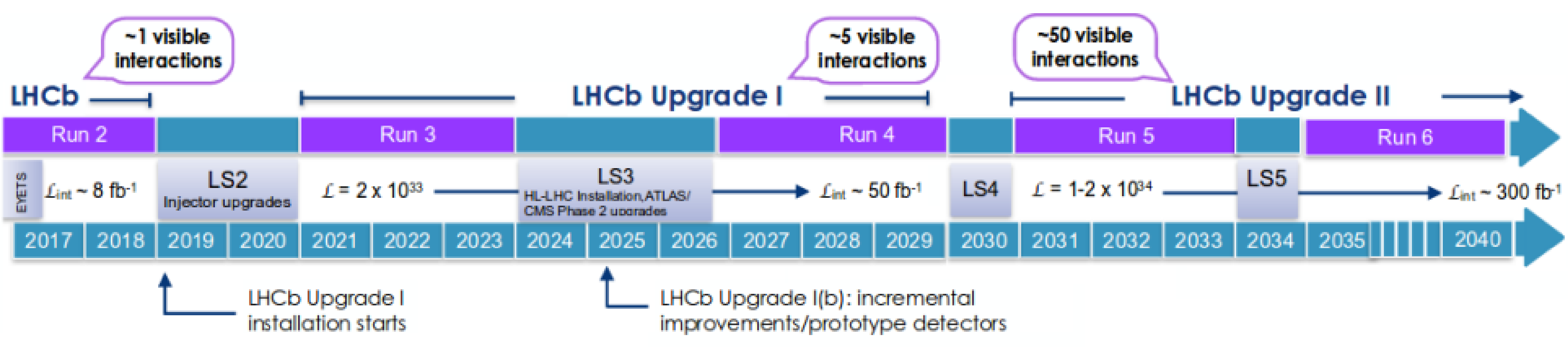
- $\tau\to\mu\nu\nu$
  - Average of measurements around 2σ
- $pp\to ee + X$
  - Excess at high invariant mass (> 1.8 TeV) around 2σ
- Can all be linked to LFUV
- but 2σ should happen in 1 in 20 measurements



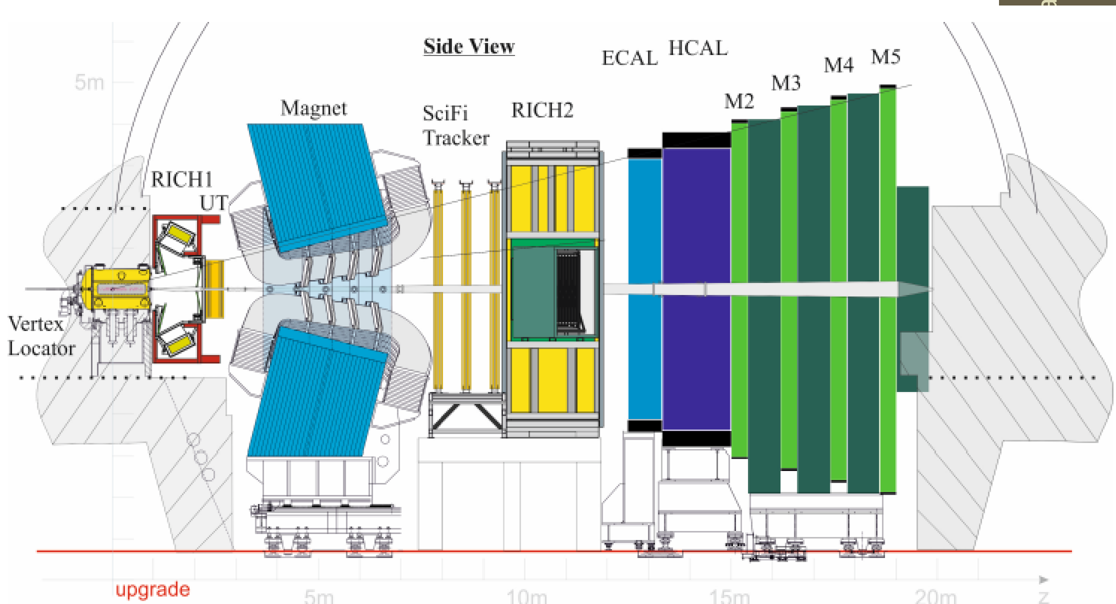


FLAVOUR FUTURE

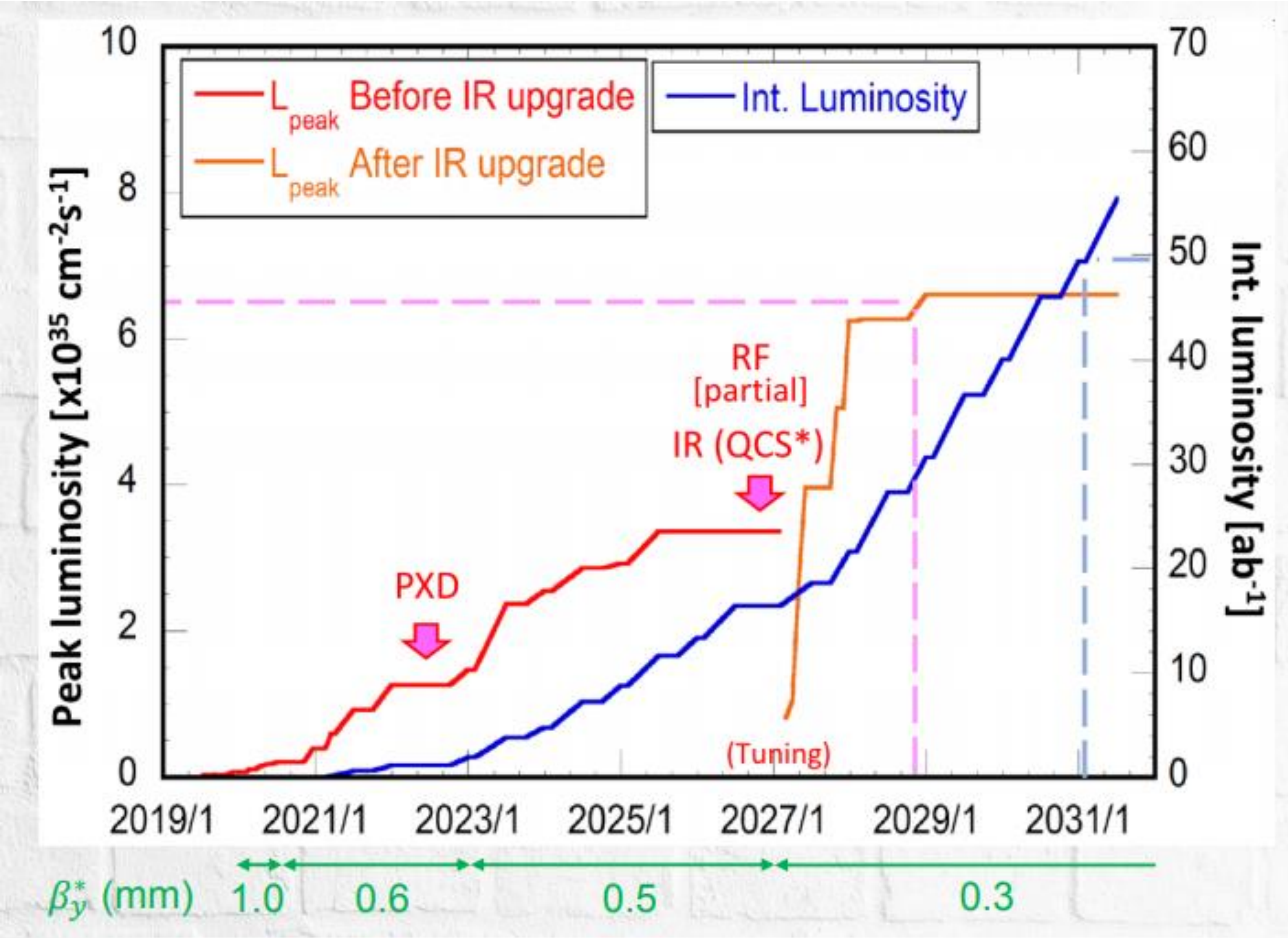
LHCb upgrade



- New silicon vertex, tracker and SciFi tracker
- 40 MHz readout – factor 2-4 more in the trigger efficiency for hadrons (not so important for anomalies)
- LHCb will continue to have a big impact
- CMS and ATLAS also focusing more on B-physics in the future

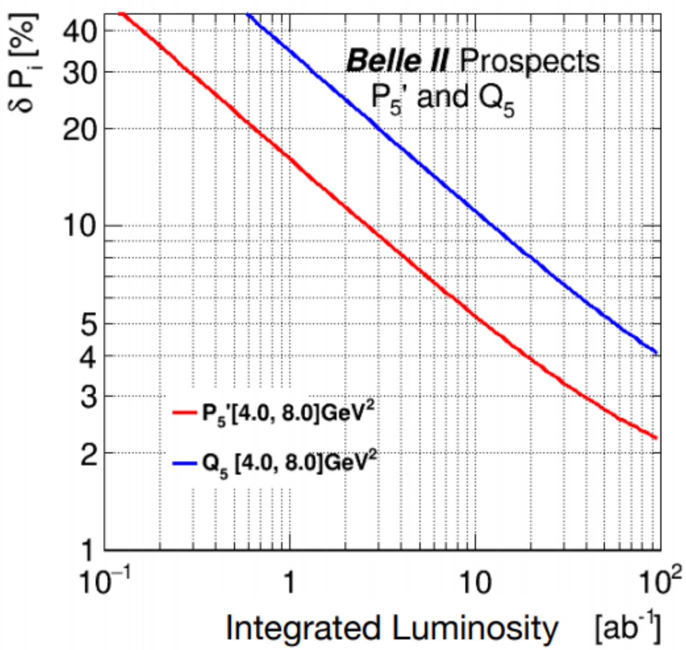


Belle II data taking plan

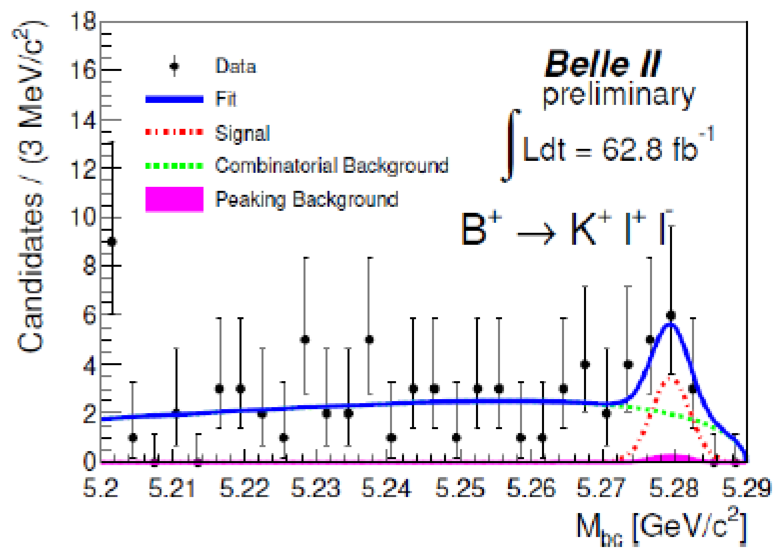


Belle II projections

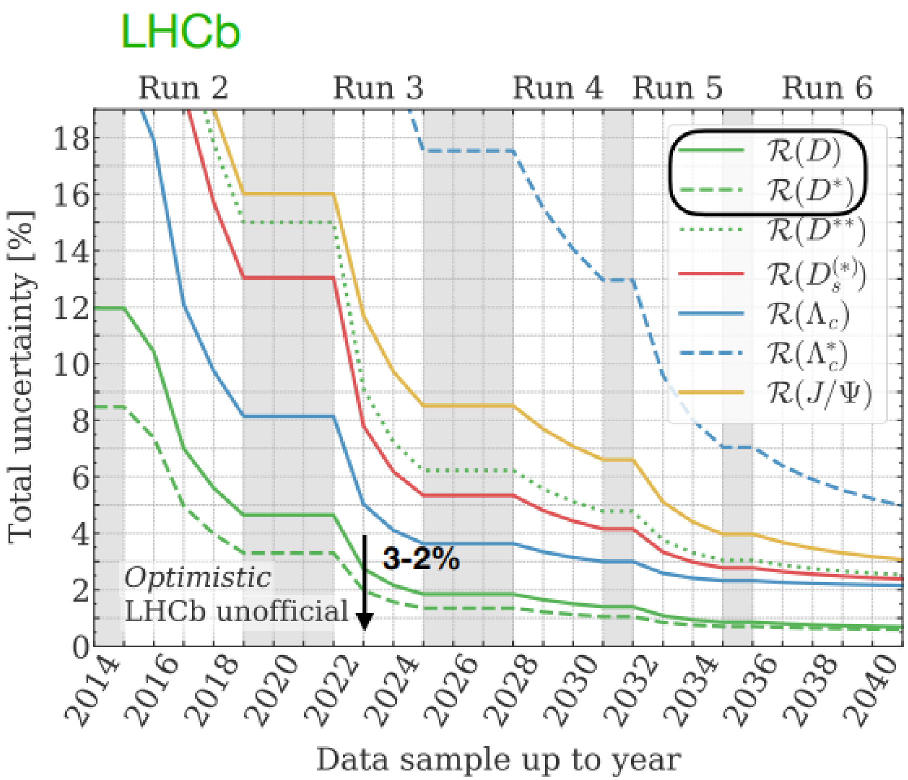
Observables	Belle $0.71\,\mathrm{ab}^{-1}$	~2024 Belle II $5\,\mathrm{ab}^{-1}$	~2031 Belle II $50\,\mathrm{ab}^{-1}$
R_K ([1.0, 6.0] GeV^2)	28%	11%	3.6%
R_K (> 14.4 GeV^2)	30%	12%	3.6%
R_{K^*} ([1.0, 6.0] GeV^2)	26%	10%	3.2%
R_{K^*} (> 14.4 GeV^2)	24%	9.2%	2.8%
R_{X_s} ([1.0, 6.0] GeV^2)	32%	12%	4.0%
R_{X_s} (> 14.4 GeV^2)	28%	11%	3.4%

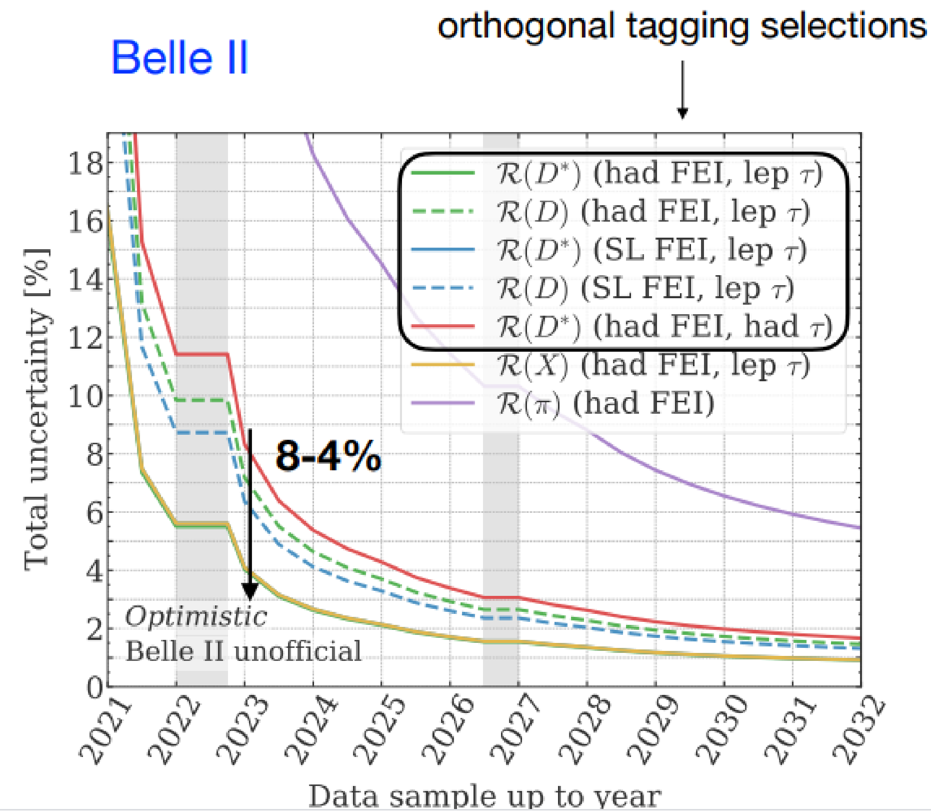


Where we are now



b→cτν





- A few inverse ab^{-1} Belle II will have something interesting to say

Conclusion

- Particle physics is tackling its problems on three complementary frontiers
  1. Energy
  2. Cosmic
  3. Intensity
- Flavour physics has played a significant role in the development of the Standard Model
- **Belle II** and **LHCb** are project that will continue flavour physics at the intensity frontier until the end of the decade