# Flavour physics: a brief tour

Jim Libby (IIT Madras)


# Flavour physics: a brief ~~tour~~ taste

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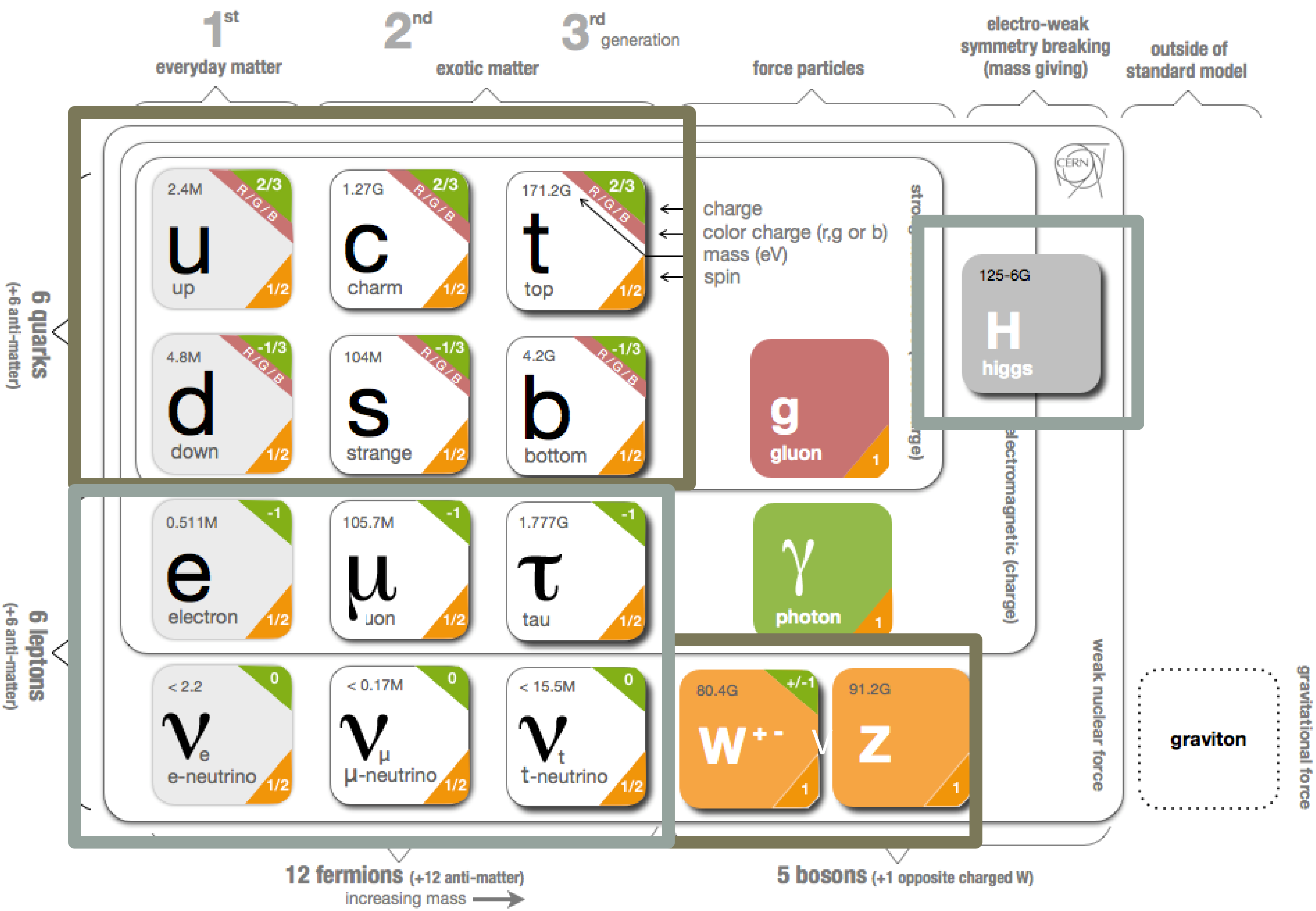
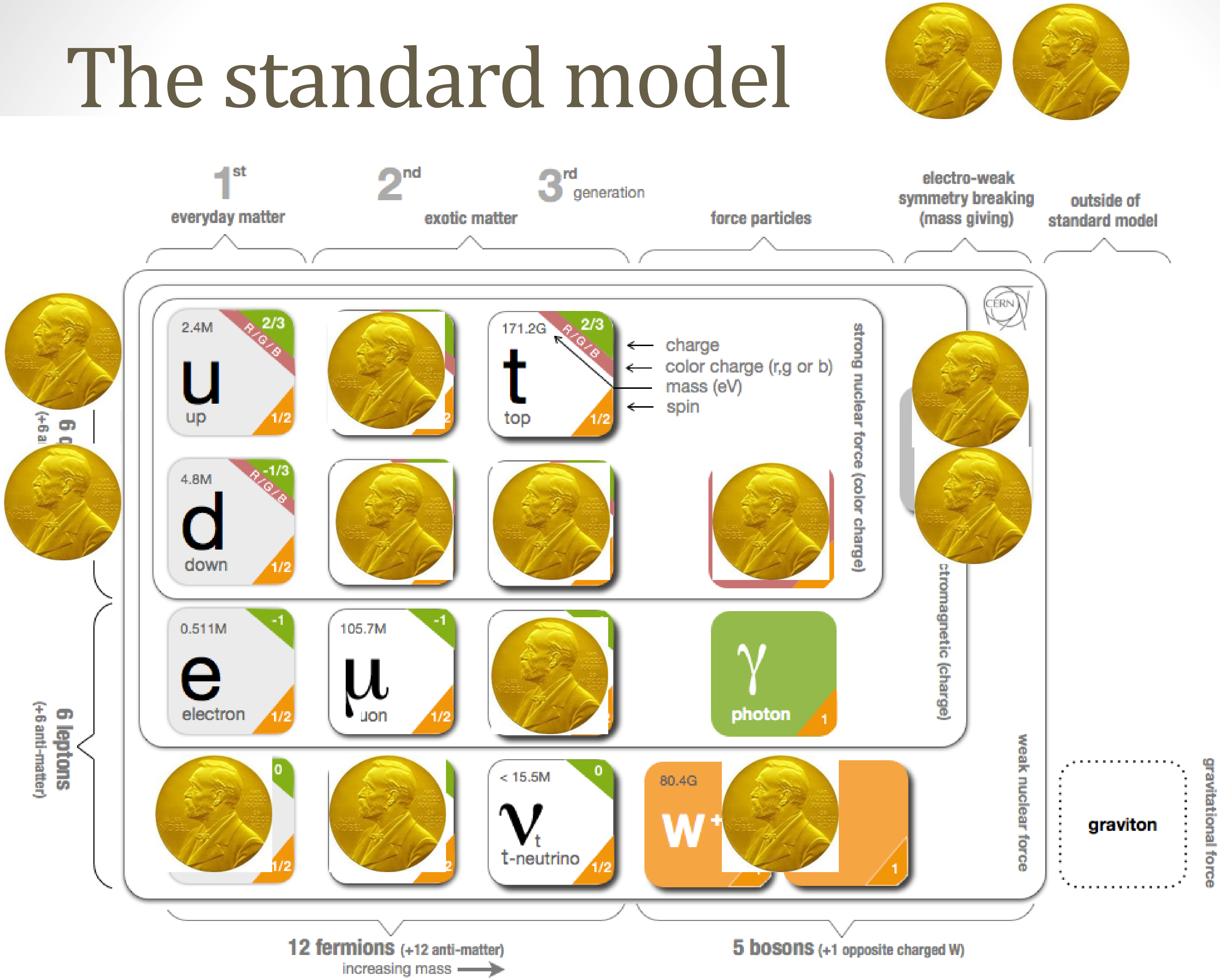
# Overview

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

# The standard model flavour



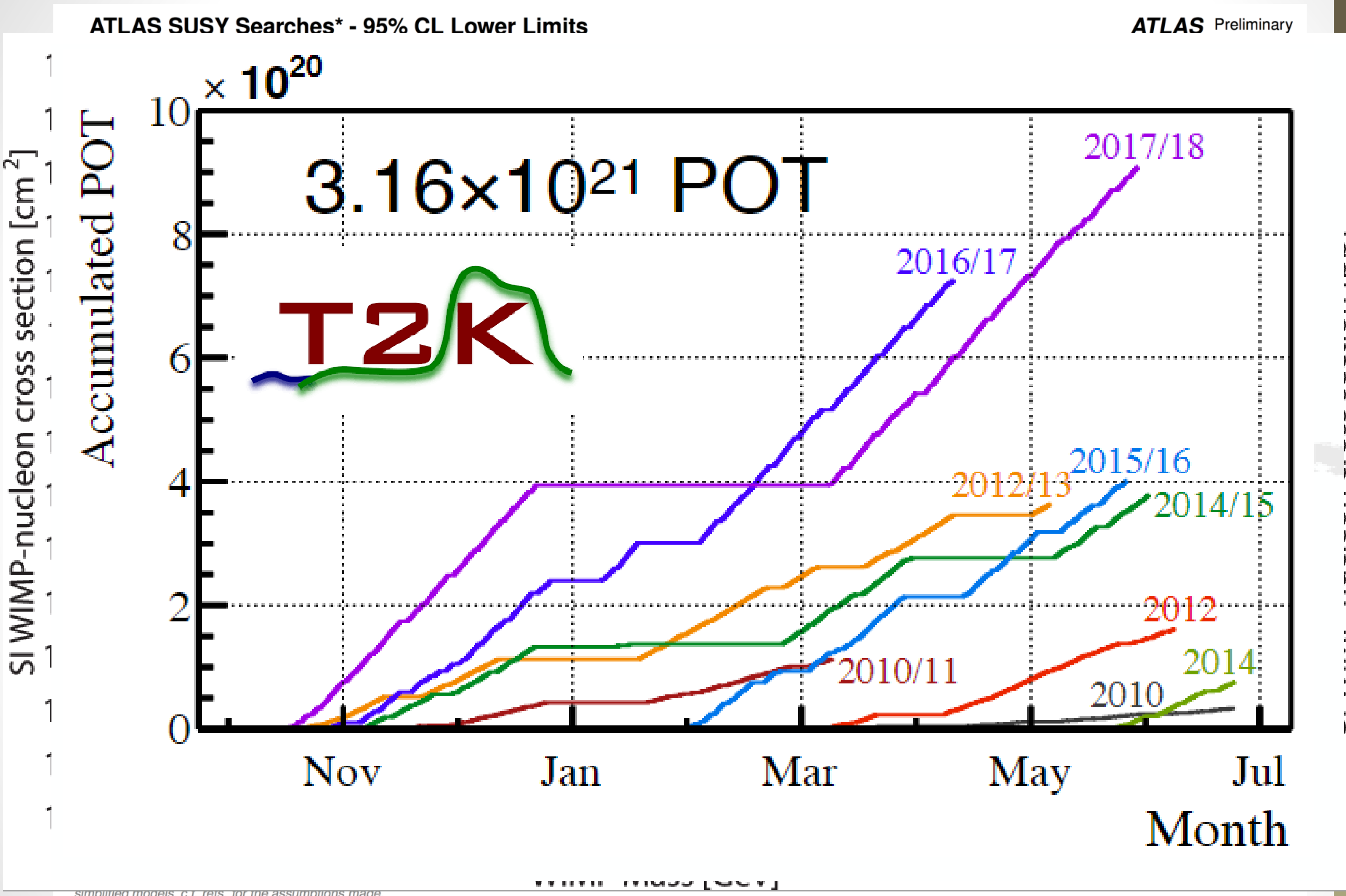
# The standard model



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

# Problems: addressed by flavour

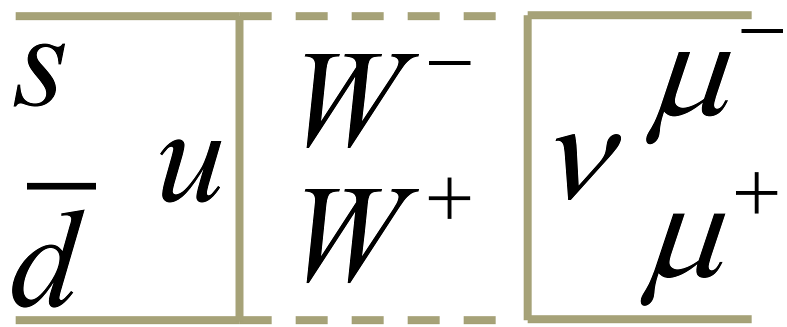
- **Empirical**
  - Neutrinos are massive
  - Dark matter
  - Dark energy!!!!
  - Matter rather than antimatter
  - Gravity
- **Aesthetic**
  - Why three of everything?
  - Why eighteen parameters?
    - Many with a distinct hierarchy?
  - Why do we need to know them to 18 decimal places?
  - Unification

# Flavour physics – history of discovery

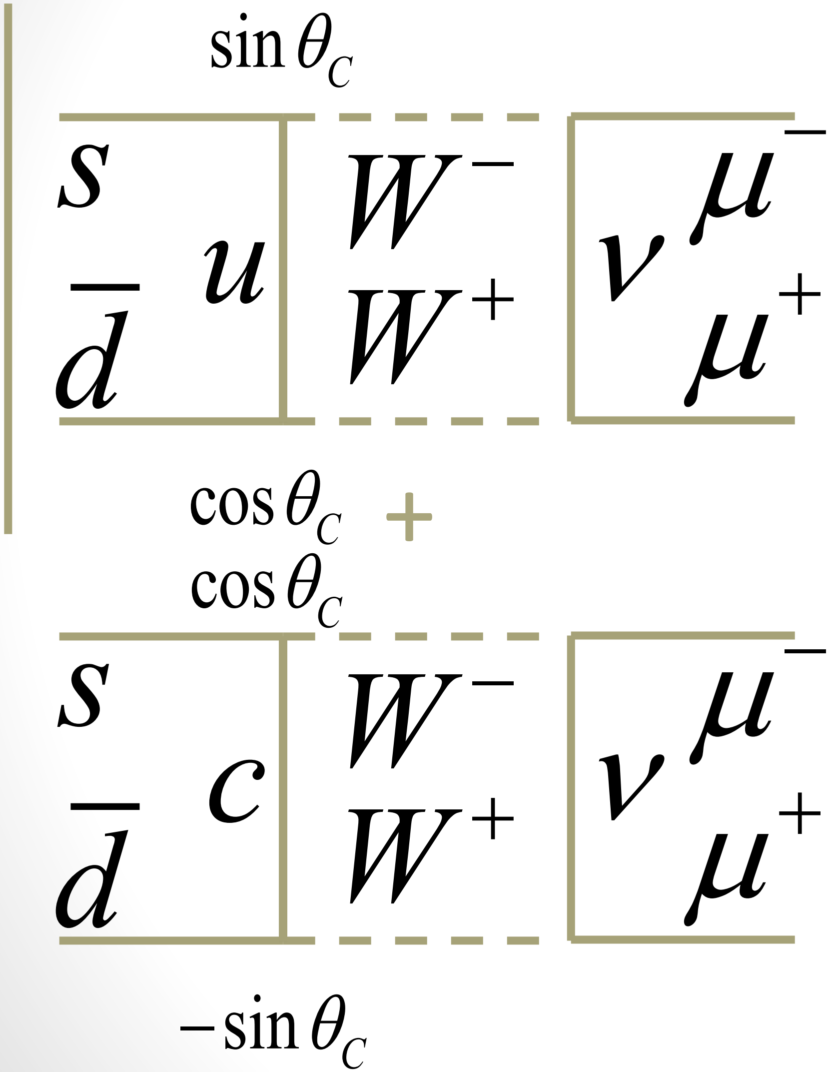
- Particle zoo of mesons and baryons discovered in 1950s and early 1960s lead to the quark model
  - up (u)
  - down (d)
  - strange (s)
- An allowed but rare decay such as

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

- **Predicted but not seen!**



# Flavour physics – history of discovery




**G**lashow

**I**liopoulos

**M**aiani

Phys. Rev. D 2, 1285 (1970)

$2 \propto$ Rate ~ 0

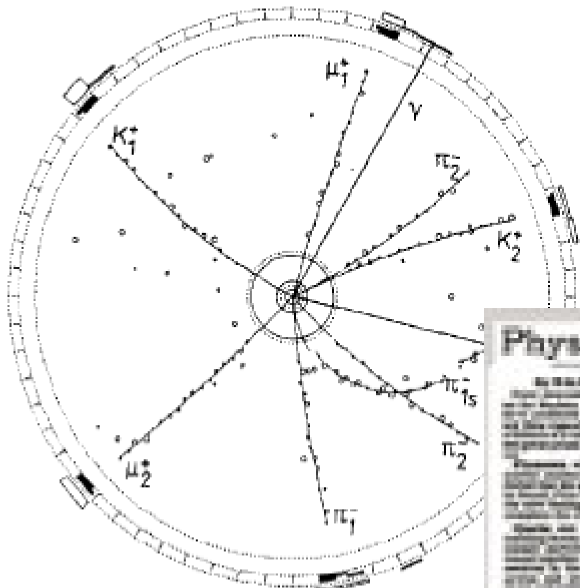
$m_c \sim 3\ m_K$

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

$B_1^0 \to D_1^{*-} \mu_1^+ \nu_1$

$\downarrow$

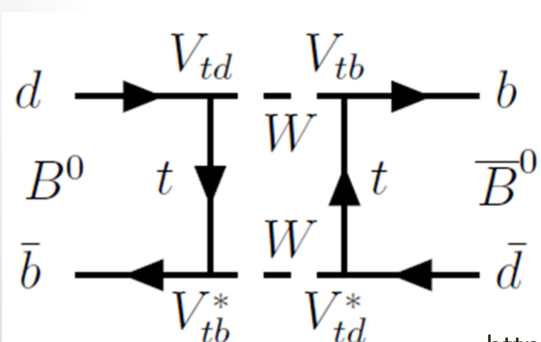
$D_1^{*-} \to \pi_1^- \bar{D}^0$

$\downarrow$

$\bar{D}^0 \to K_1^+ \pi_1^-$ ,

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

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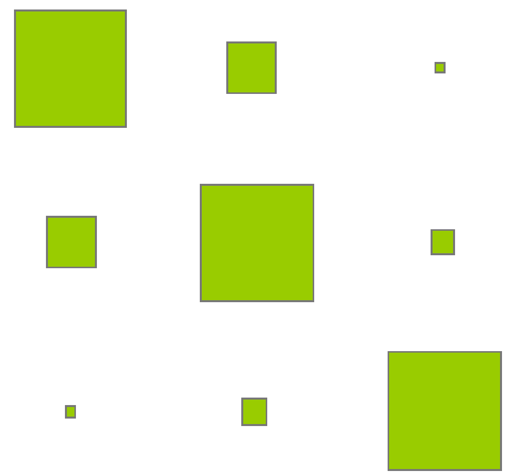
# CKM matrix

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

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

- 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**

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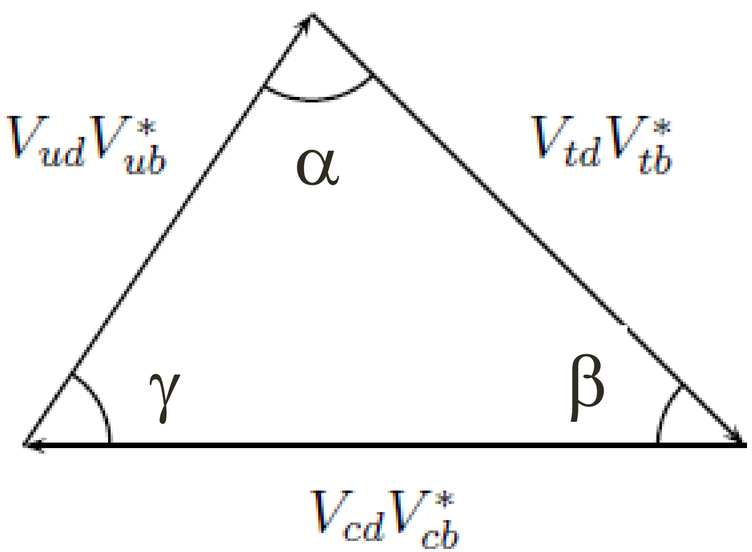
# Visualising CP violation: the unitarity triangle

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

2) Exploit unitarity (1st and 3rd col.)

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

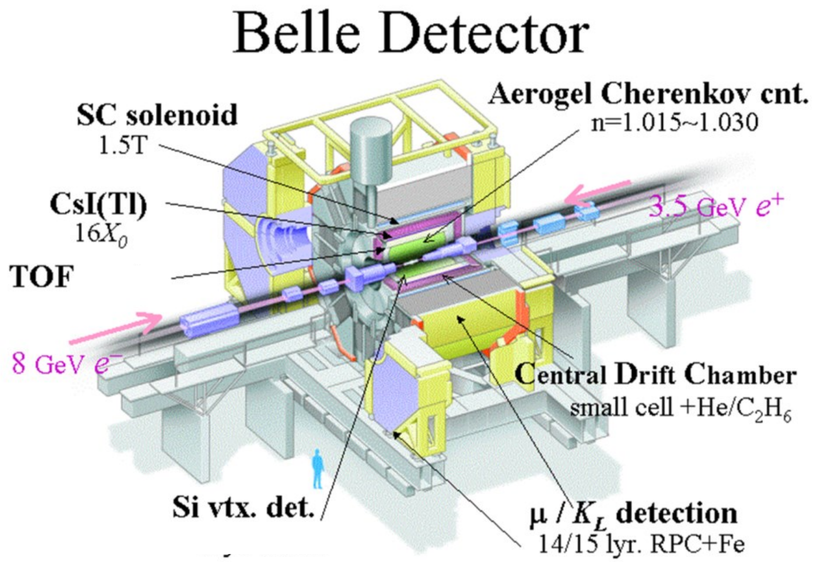
3)

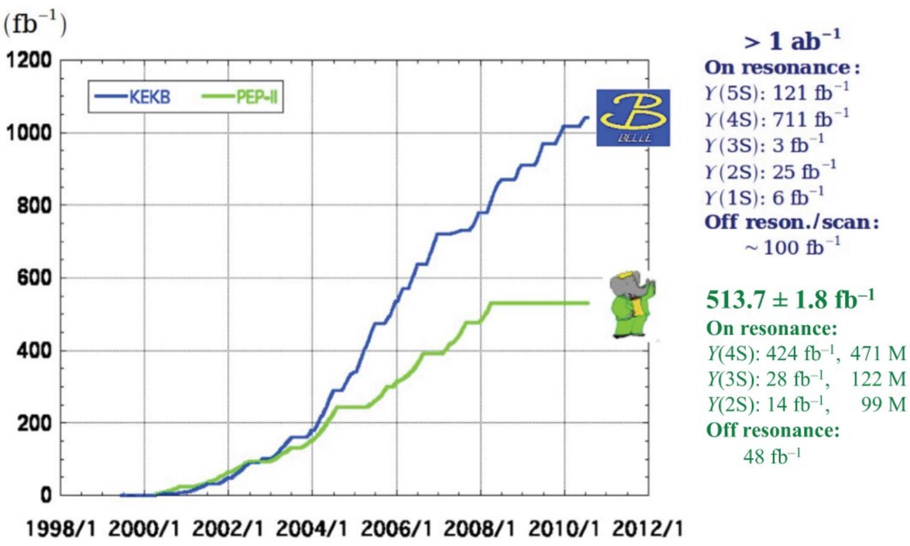



$$\phi_1 = \beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \simeq \arg\left(\frac{1}{1-\rho-i\eta}\right)$$

# Belle

- Operation from 1999 to 2010
- $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ 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

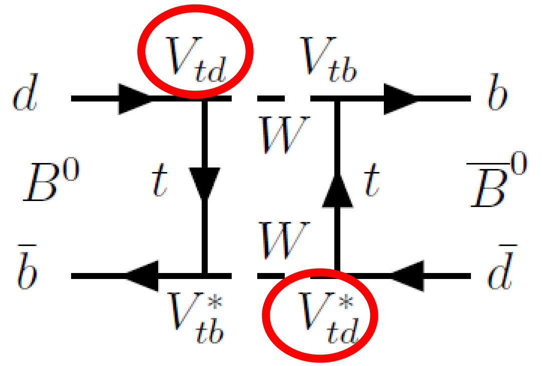


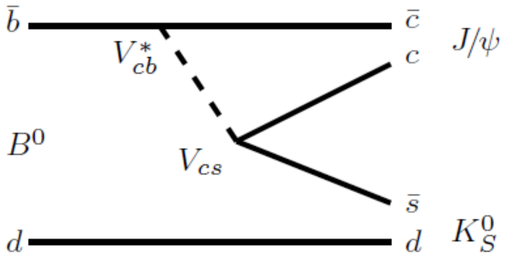



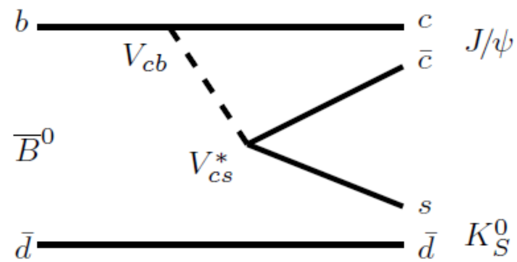
# The Golden Mode

$B^0 \to J/\psi K_S^0$ 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’ – decay time dependent

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

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

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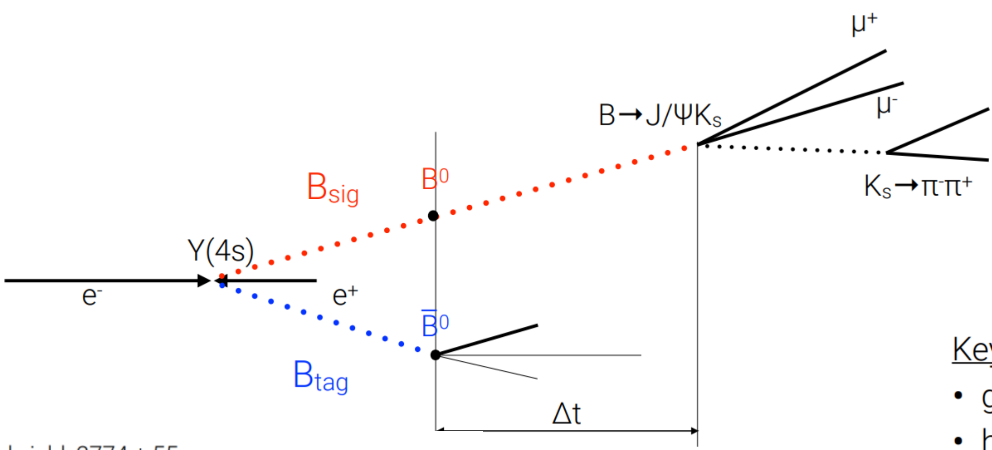
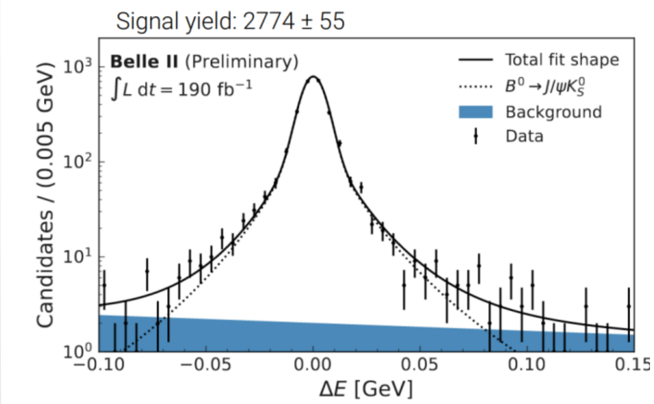
Chiara La Licata ICHEP
Conference note in preparation

# Time-dependent CPV violation

7-GeV electrons on 4-GeV positrons produce Υ(4S) that decays promptly in a quantum-coherent $B\bar{B}$ pair




$B_{sig}$ => fully reconstructed in a final state $f_{CP}$ common to $B^0$ and $\bar{B}^0$
$B_{tag}$ ⇒ only flavor information + vertex position




Key aspects:

- good vertex resolution
- high tagging efficiency

$\varepsilon_{eff}$(Belle II) = (30.0 ± 1.2 ± 0.4)%

$\Delta E = E_B - E_{\text{beam}}$ (in c.m. frame)

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# $\sin 2\phi_1$ results

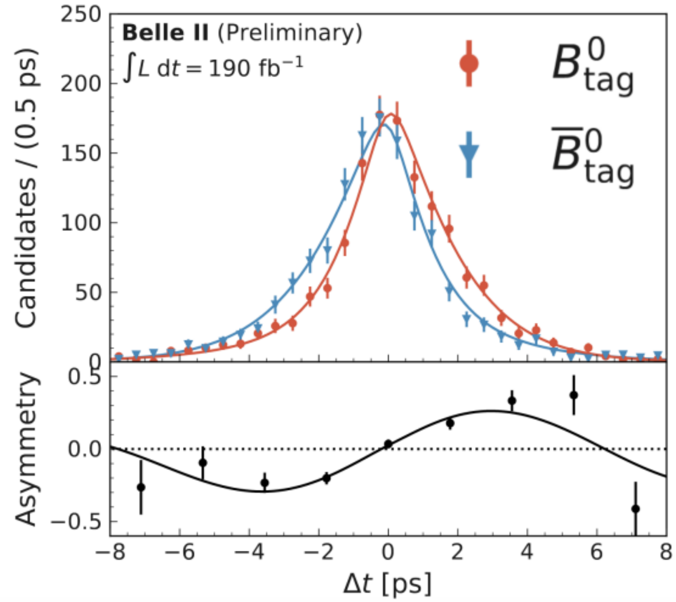
Apply analysis to $B^0 \to J/\psi\, K_s^0$ sample

| Source | $\sigma(S_{CP})$ | $\sigma(A_{CP})$ |
|---|---|---|
| Statistical | 0.0622 | 0.0439 |
| $B^0 \to D^{(*)-}\pi^+$ sample size | 0.0111 | 0.0093 |
| Analysis bias | 0.0080 | 0.0020 |
| Signal charge asymmetry | 0.0027 | 0.0126 |
| $w_6^+ = 0$ limit | 0.0014 | 0.0001 |
| Resolution function parametrization | 0.0039 | 0.0008 |
| $\tau_{B^0}$, $\Delta m_d$ | 0.0007 | 0.0002 |
| Alignment | 0.0020 | 0.0042 |
| Beam spot | 0.0024 | 0.0020 |
| Momentum scale | 0.0005 | 0.0013 |
| $\sigma_{\Delta t}$ binning | 0.0050 | 0.0051 |
| Multiple candidates | 0.0005 | 0.0008 |
| Tag-side interference | 0.0020 | $^{+0.0380}_{-0.000}$ |
| Total systematic | 0.0159 | $^{+0.0418}_{-0.0173}$ |

Milestone: tools are ready for an impactful $\sin 2\phi_1$ measurement

NEW

Signal yield: 2774 ± 55

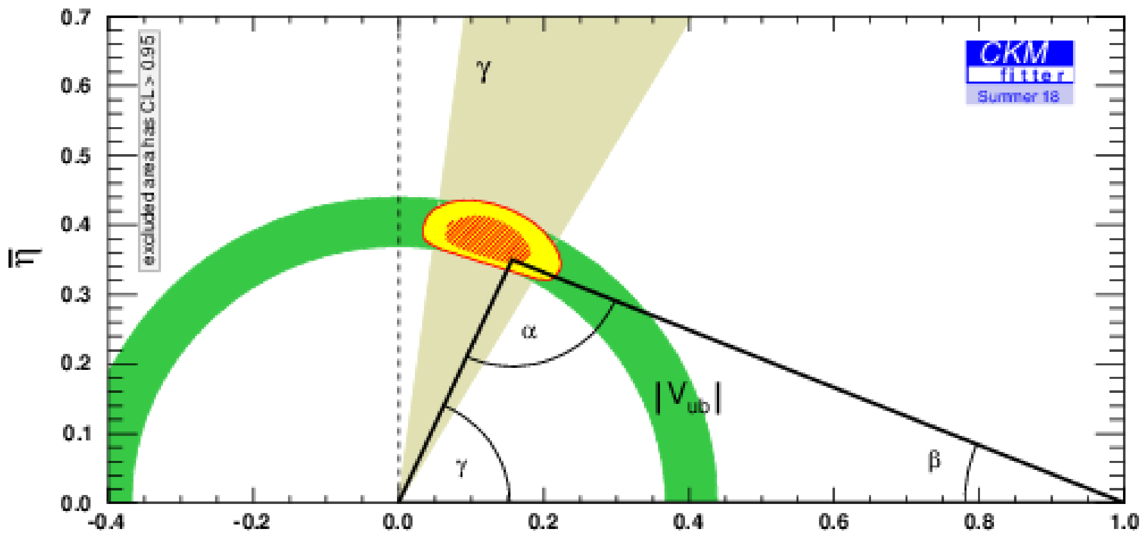



$S_{CP} = 0.720 \pm 0.062\ \text{(stat.)} \pm 0.016\ \text{(syst.)}$

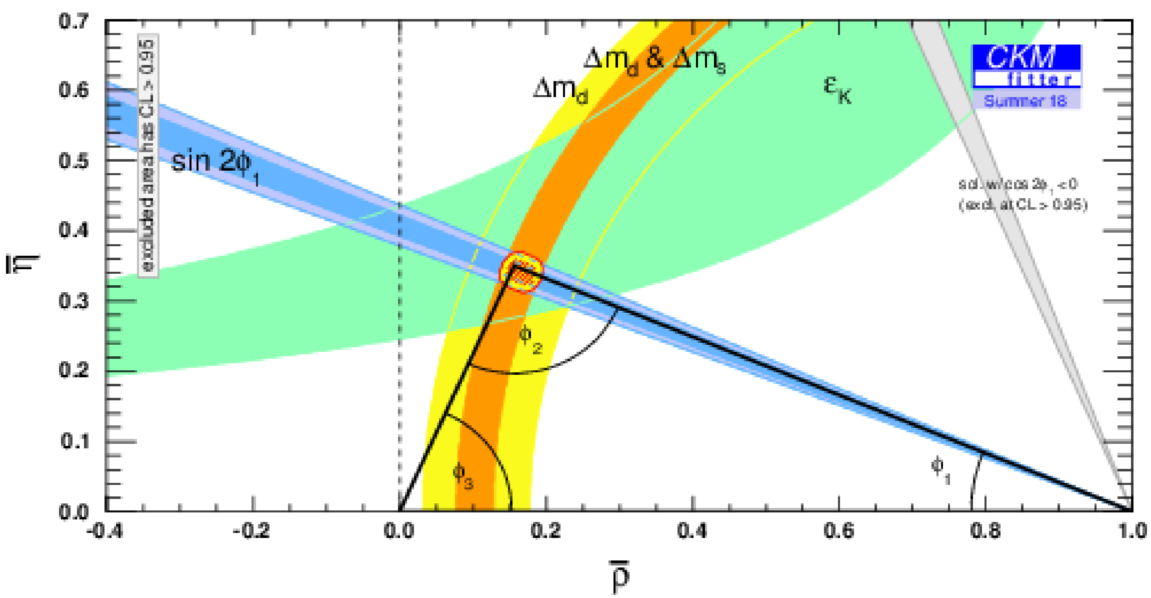
$A_{CP} = 0.094 \pm 0.044\ \text{(stat.)}\ ^{+0.042}_{-0.017}\ \text{(syst.)}$

What next? Gluonic penguin modes $B^0 \to \phi K_S^0$ and $B^0 \to \eta' K_S^0$ - BSM physics can shift $S_{CP}$ and $A_{CP}$

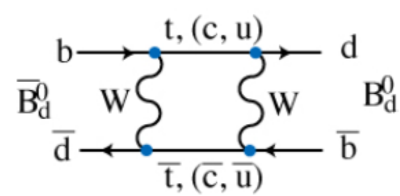
# Over constraint




Tree level only

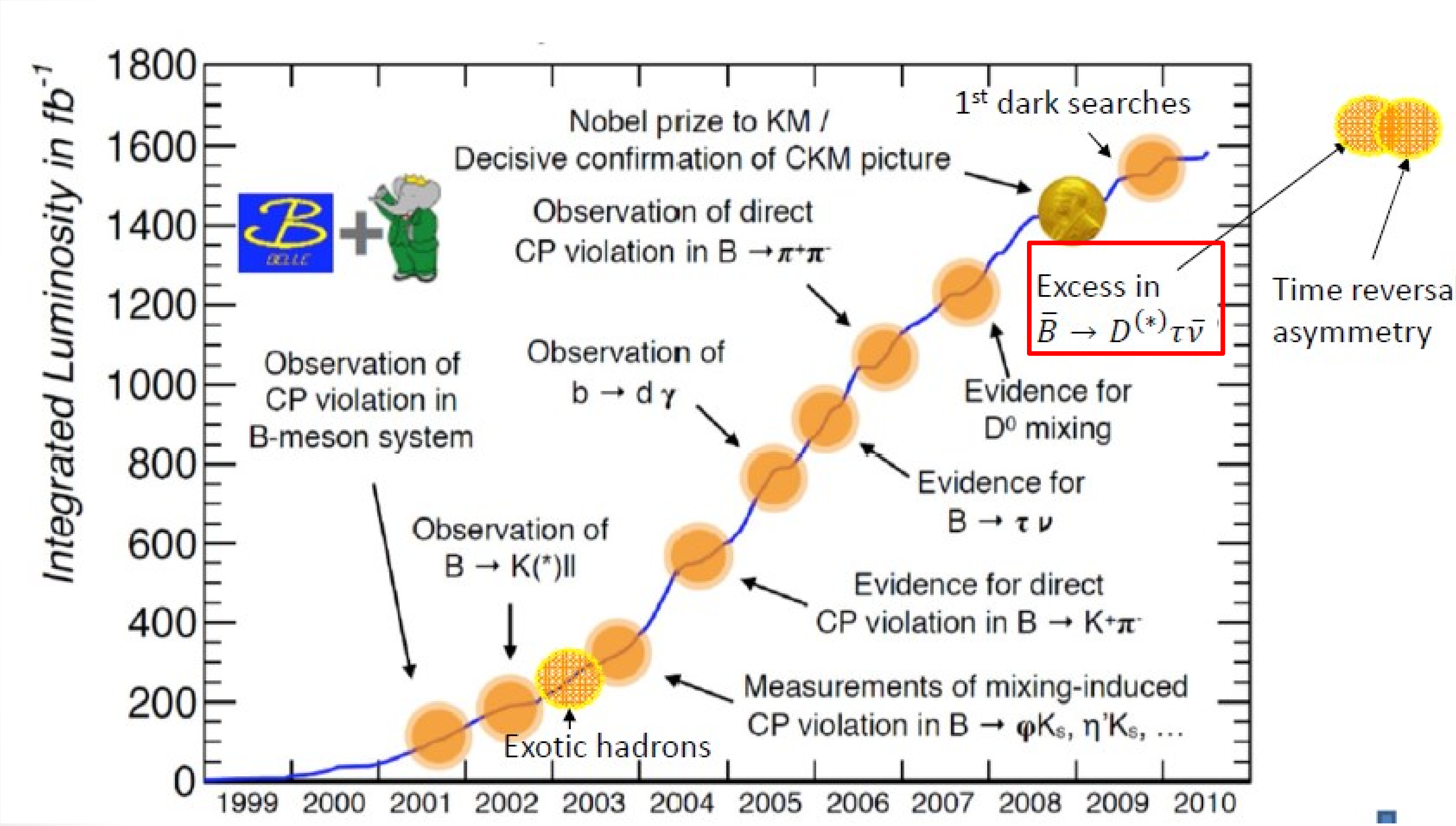



Loop-level only



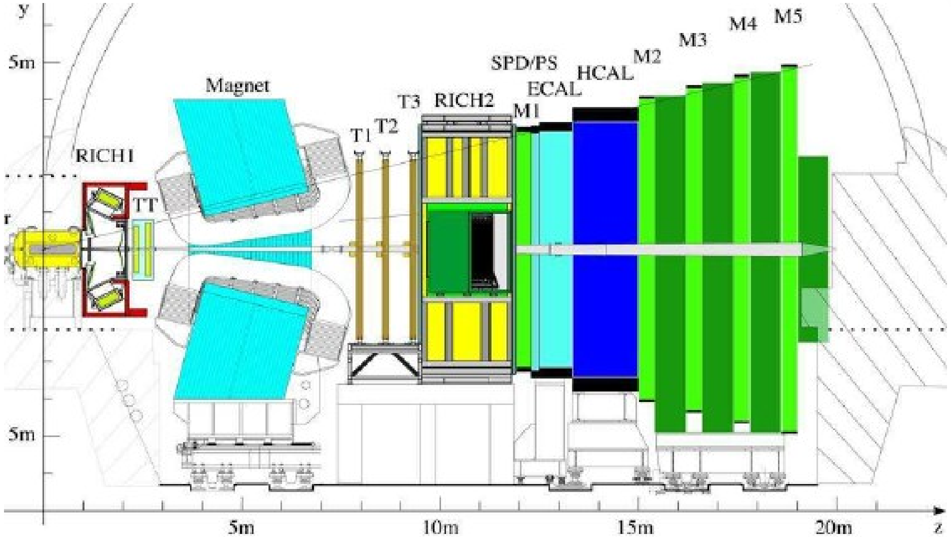

NP at O(>TeV)?

# Belle and Babar achievements

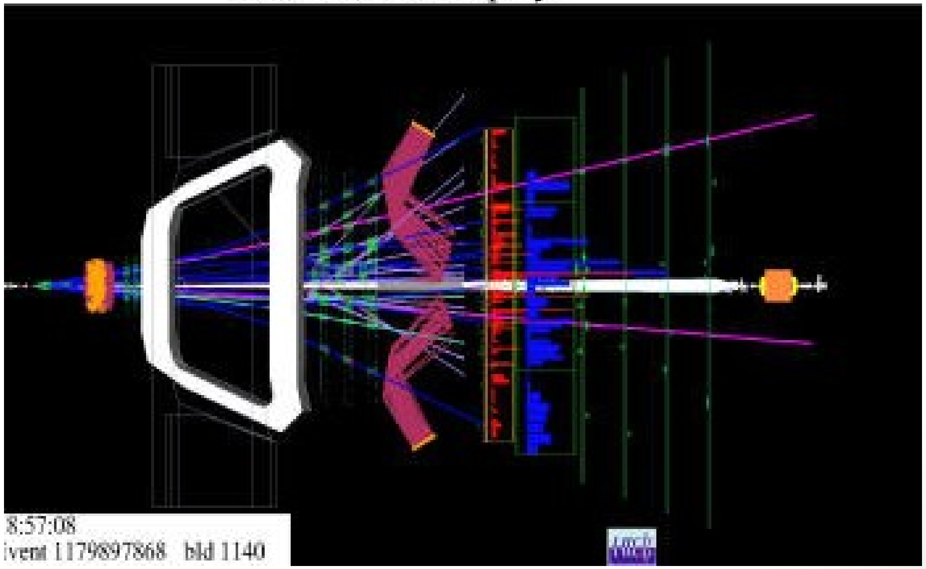


# Belle II's rival LHCb in a slide

- 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 $\pi$/K separation
- Full trigger bandwidth for B physics




LHCb Event Display

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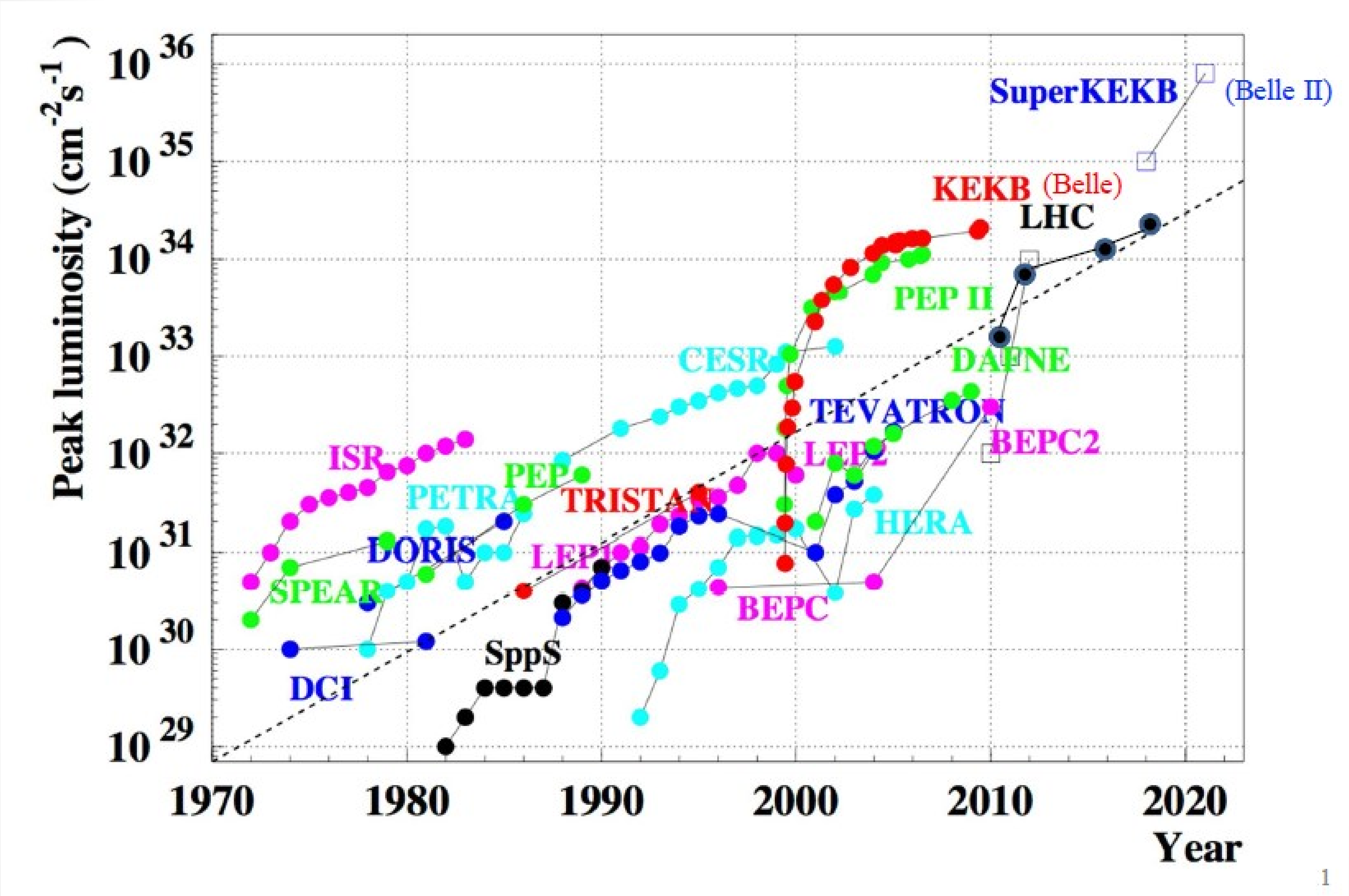
# Belle II: can never have too much of a good thing (× 50 Belle)

- 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 |
| $\pi^0, K_S$ 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 $B_s$ |
| $\tau$ physics capability | Limited | Excellent |
| B-flavor tagging efficiency | 3.5 - 6% | 36% |

# “Moore’s” Law of Luminosity



# The path to higher luminosity

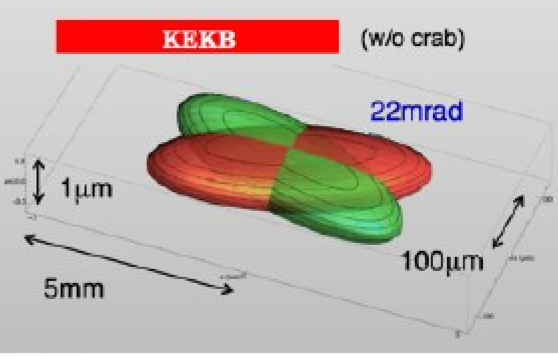
$$\xi \propto \sqrt{\frac{\beta^*}{\varepsilon}}$$

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

- Lorentz factor
- Beam current
- Beam-beam parameter
- Classical electron radius
- Beam size ratio@IP 1 ~ 2 % (flat beam)
- Vertical beta function@IP
- Lumi. reduction factor (crossing angle)& Tune shift reduction factor (hour glass effect) 0.8 ~ 1 (short bunch)

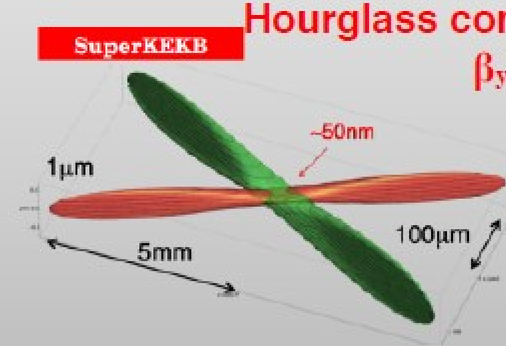
**(1) Smaller $\beta_y^*$ (20 x)**

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



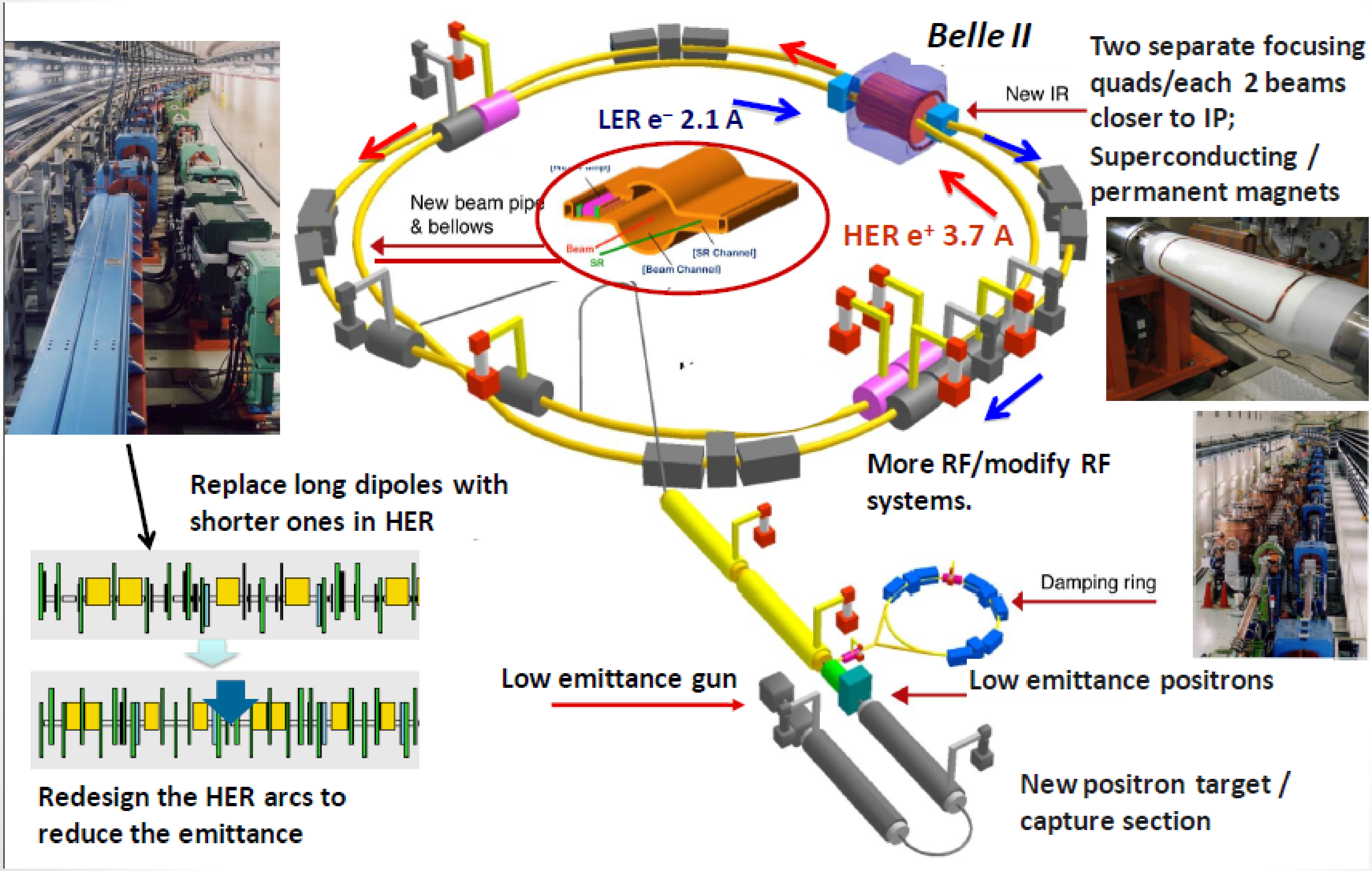

**Hourglass condition:**

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



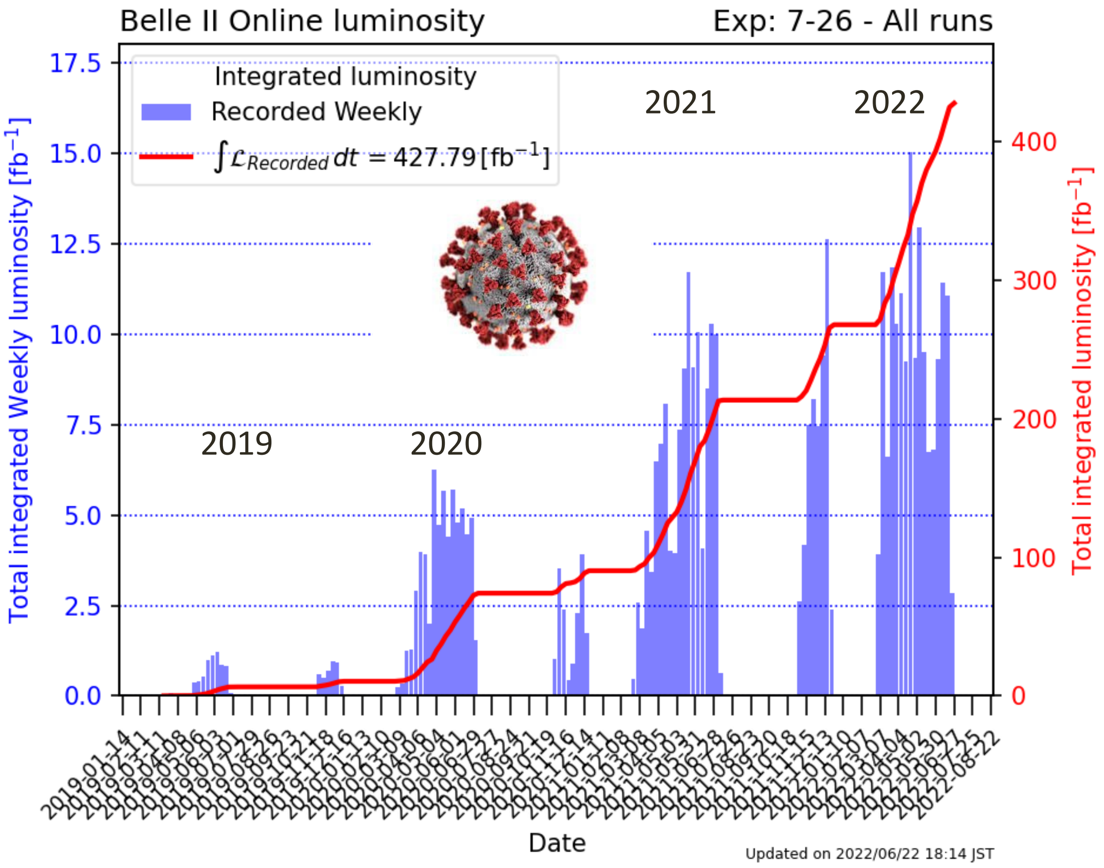

83 mrad

# SUPERKEKB

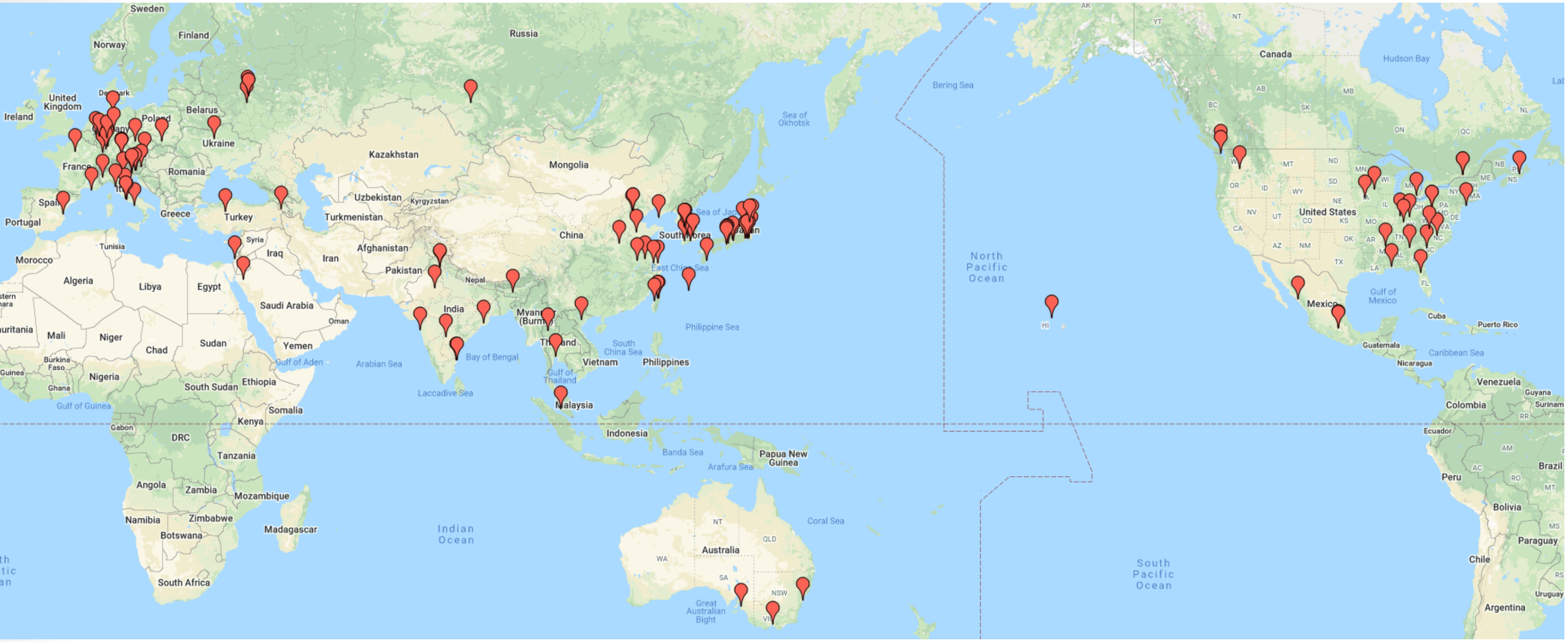


Belle II
Two separate focusing quads/each 2 beams closer to IP;
Superconducting / permanent magnets
New IR
LER e⁻ 2.1 A
HER e⁺ 3.7 A
New beam pipe & bellows
Beam
SR
[SR Channel]
[Beam Channel]
More RF/modify RF systems.
Replace long dipoles with shorter ones in HER
Redesign the HER arcs to reduce the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

# Integrated luminosity so far

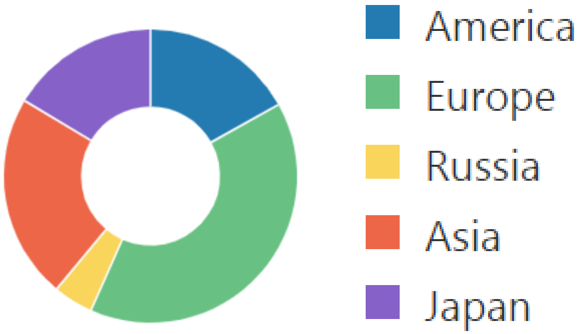


# Belle II Collaboration

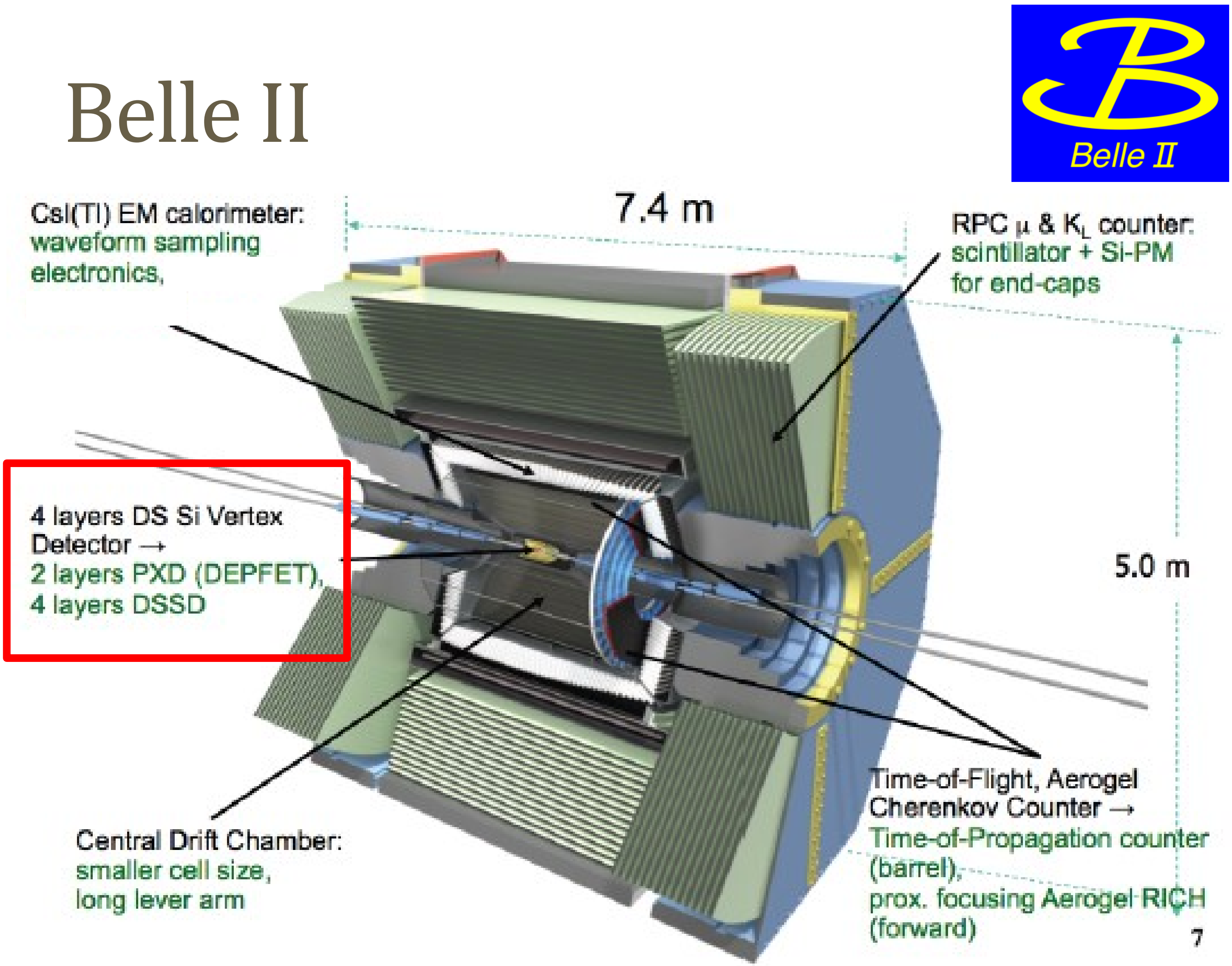



1024 physicists from 26 countries

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



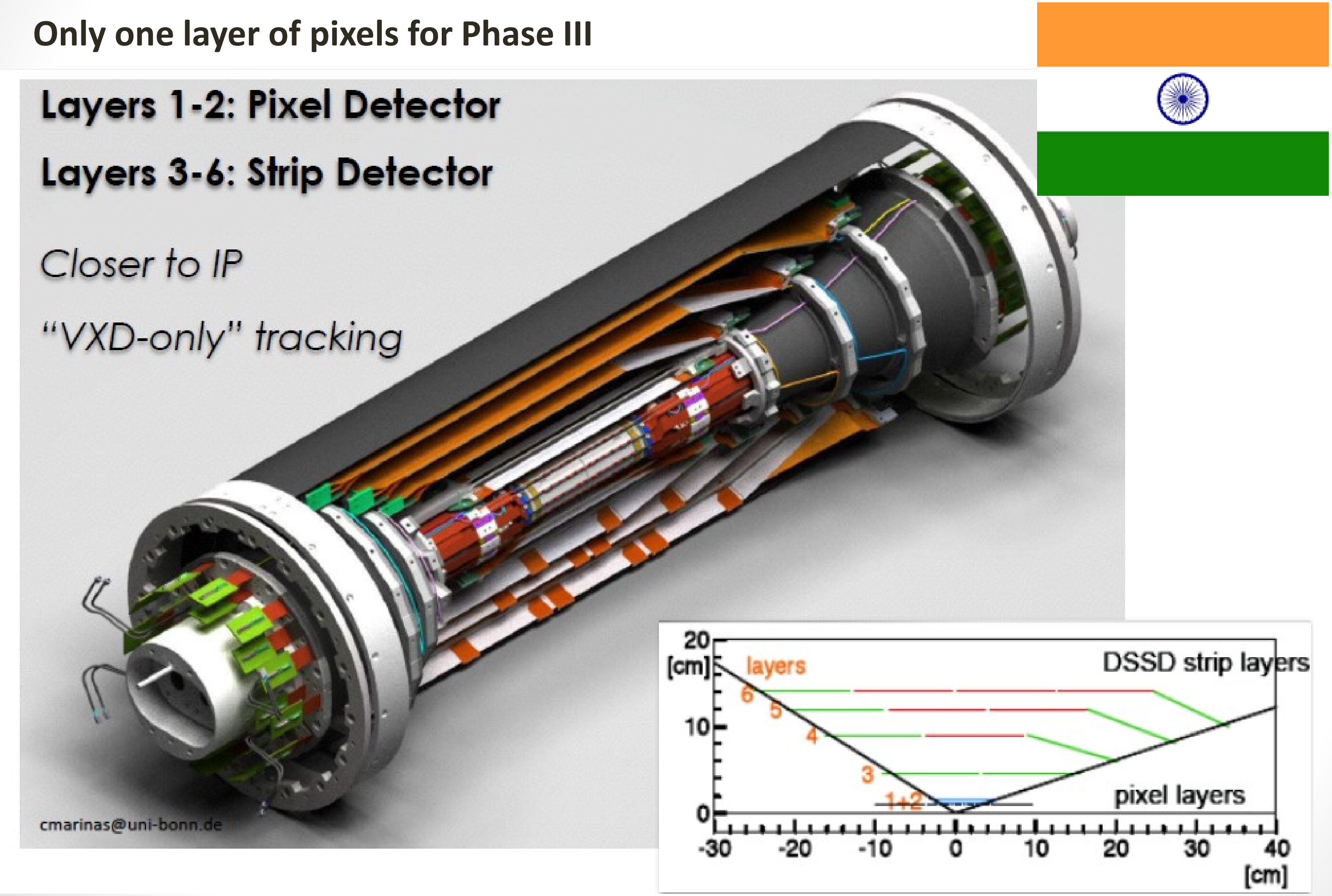
# Belle II



Belle II
7.4 m
CsI(Tl) EM calorimeter:
waveform sampling
electronics,
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
Time-of-Flight, Aerogel
Cherenkov Counter →
Time-of-Propagation counter
(barrel),
prox. focusing Aerogel RICH
(forward)
Central Drift Chamber:
smaller cell size,
long lever arm
7

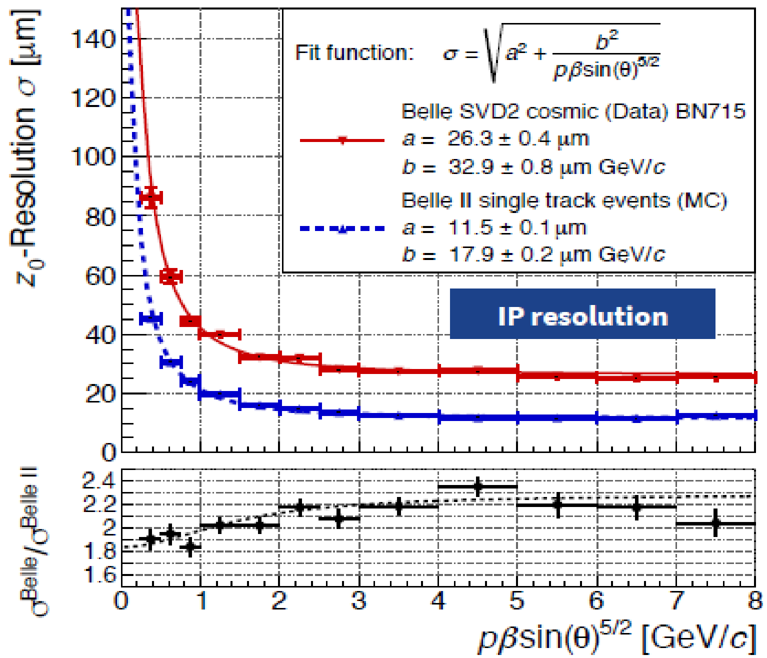
# Belle II – Silicon Vertex Dectector

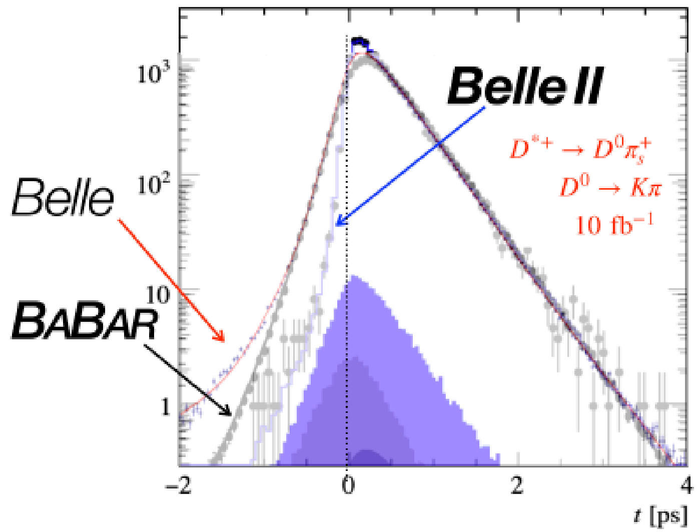
**Only one layer of pixels for Phase III**



# SVD performance

PRL **127**, 211801 (2021)




Belle II decay time resolution nearly twice as better as Belle's

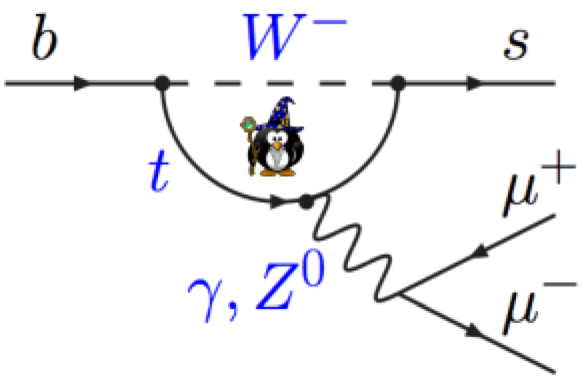
| | Belle II | World Average Value |
|---|---|---|
| $\tau(D^0)$ = | (410.5 ± 1.1 ± 0.8) fs | (410.1 ± 1.5) fs |
| $\tau(D^+)$ = | (1030.4 ± 4.7 ± 3.1) fs | (1040 ± 7) fs |

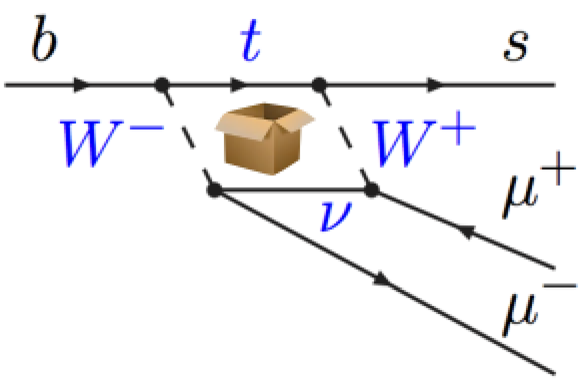
**Belle a factor two worse than Belle II**

# HOT TOPIC: ANOMALIES

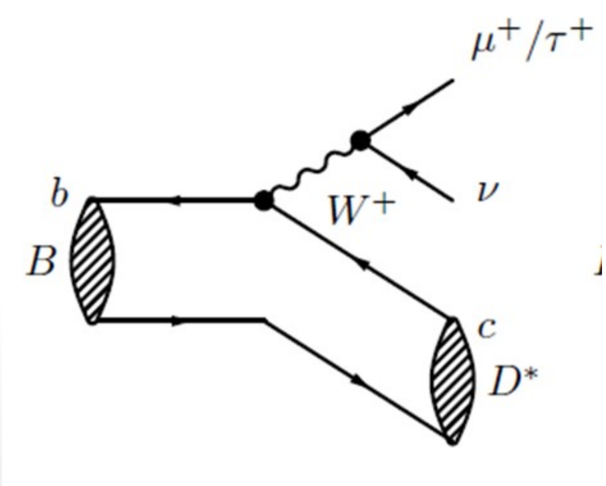
# Overview of modes with anomalies

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



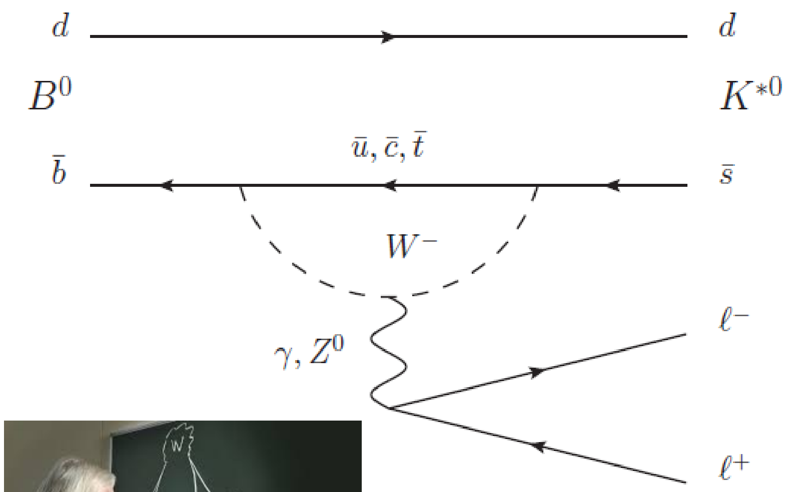

- Tree level b→cτν semileptonic

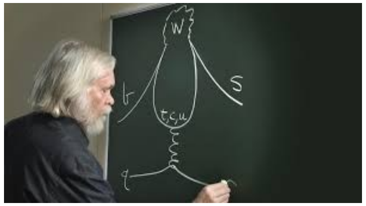


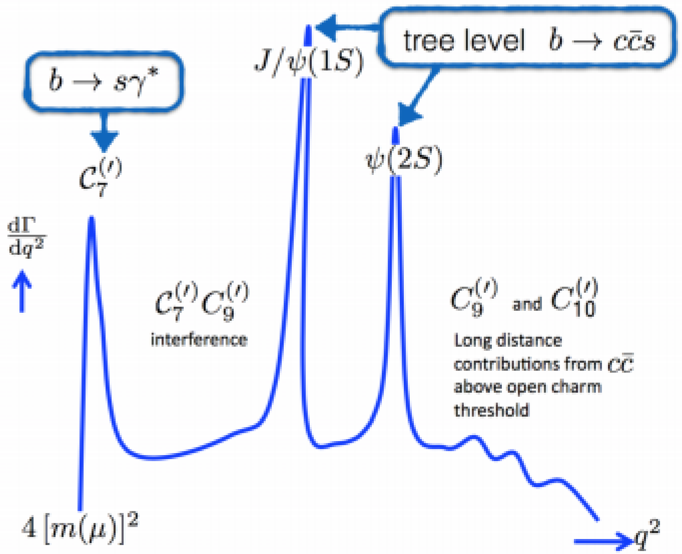

| | Pro | Con |
|---|---|---|
| b→sll | New physics reach O(10 TeV) | One experiment |
| b→cτν | Three experiments | New physics near the EW scale |

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

- 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 - $q^2$



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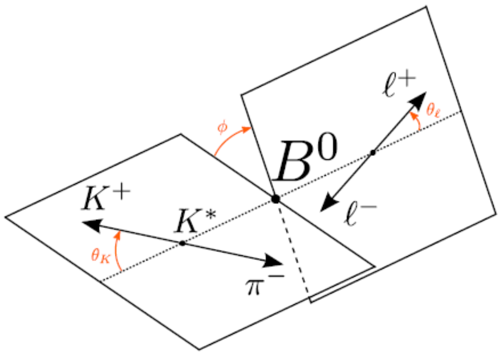
# $B \to K^*(892) l^+ l^-$ nomenclature

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



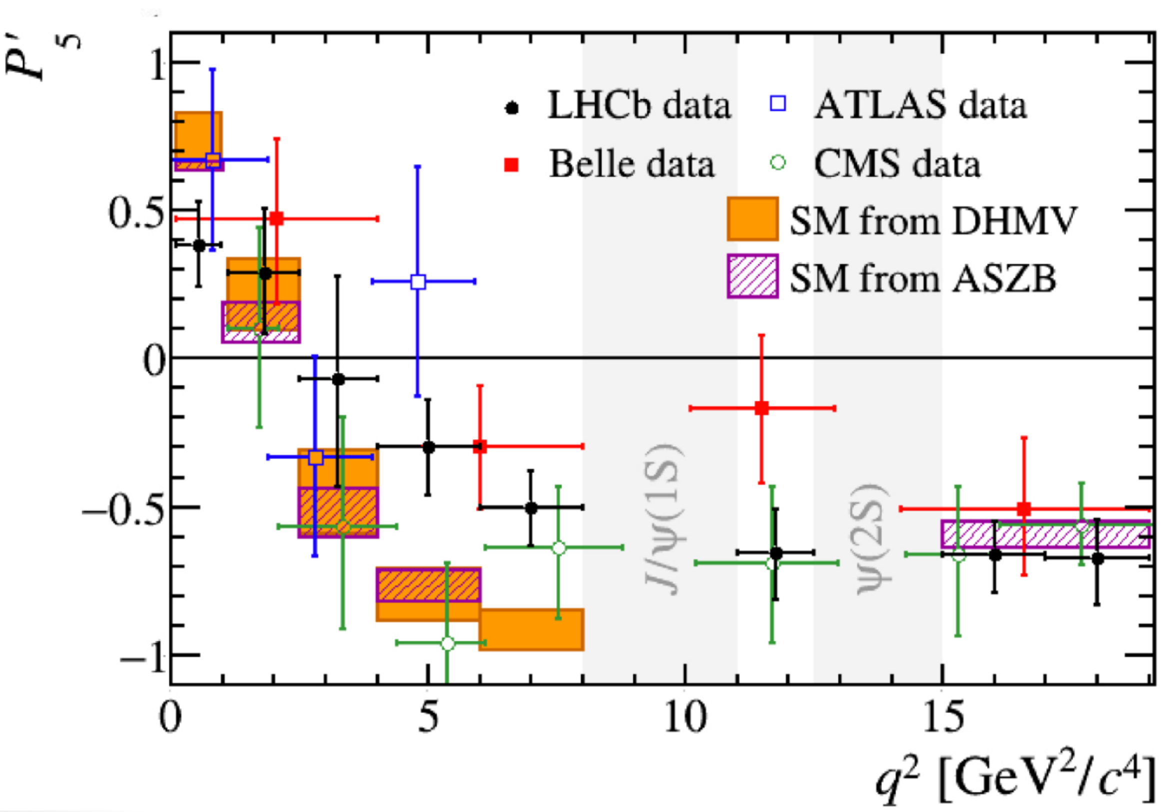

- Goal is to measure this 4D differential distribution and extract the coefficients from data to compare to the SM predictions
- Much work on defining observables with minimal theoretical uncertainties
- Let us focus on $S_5$ which get normalized as $P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$ to minimize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

ICFA school

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

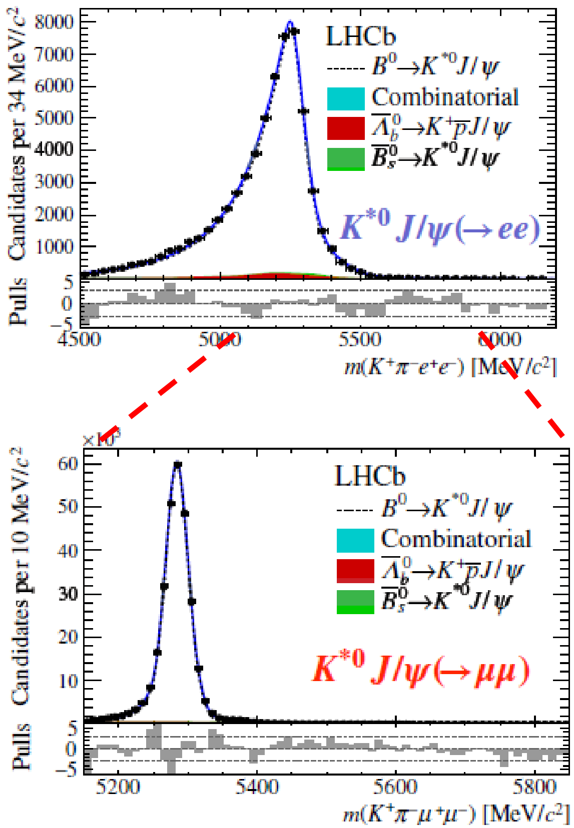
**> 3 σ disagreement with Standard Model**

# Tests of Lepton Universality Violation (LUV)

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

H=K or K*

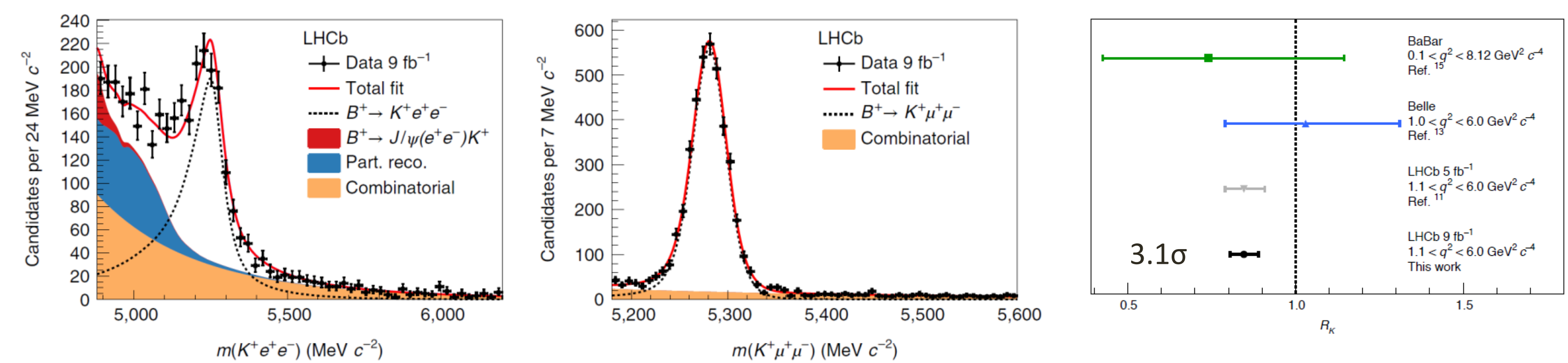
JHEP **08** (2017) 055



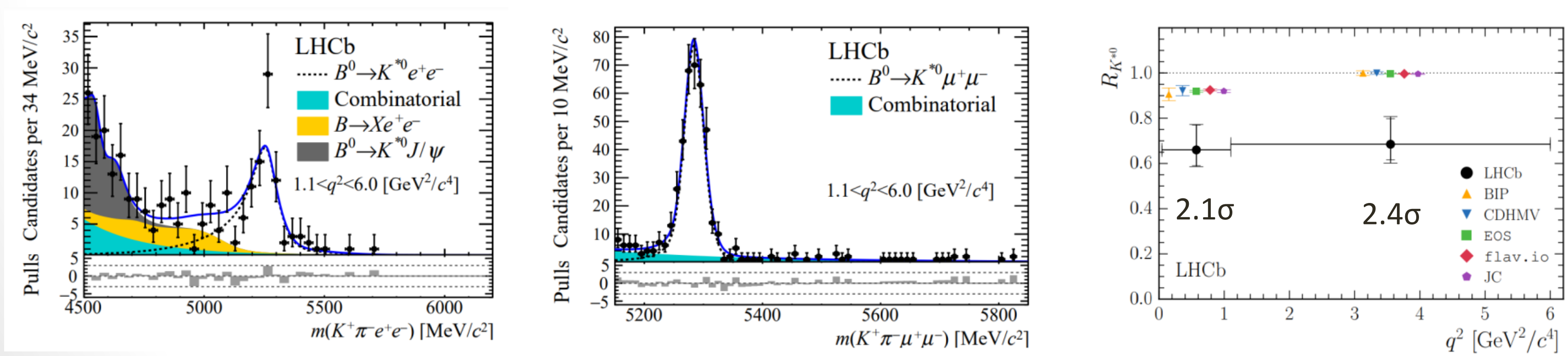

- Standard Model prediction ~1 to a few %
  - limited theoretical uncertainties
- $B\to K^{(*)}J/\psi(l^+l^-)$ bountiful control channel

# The results: muons low

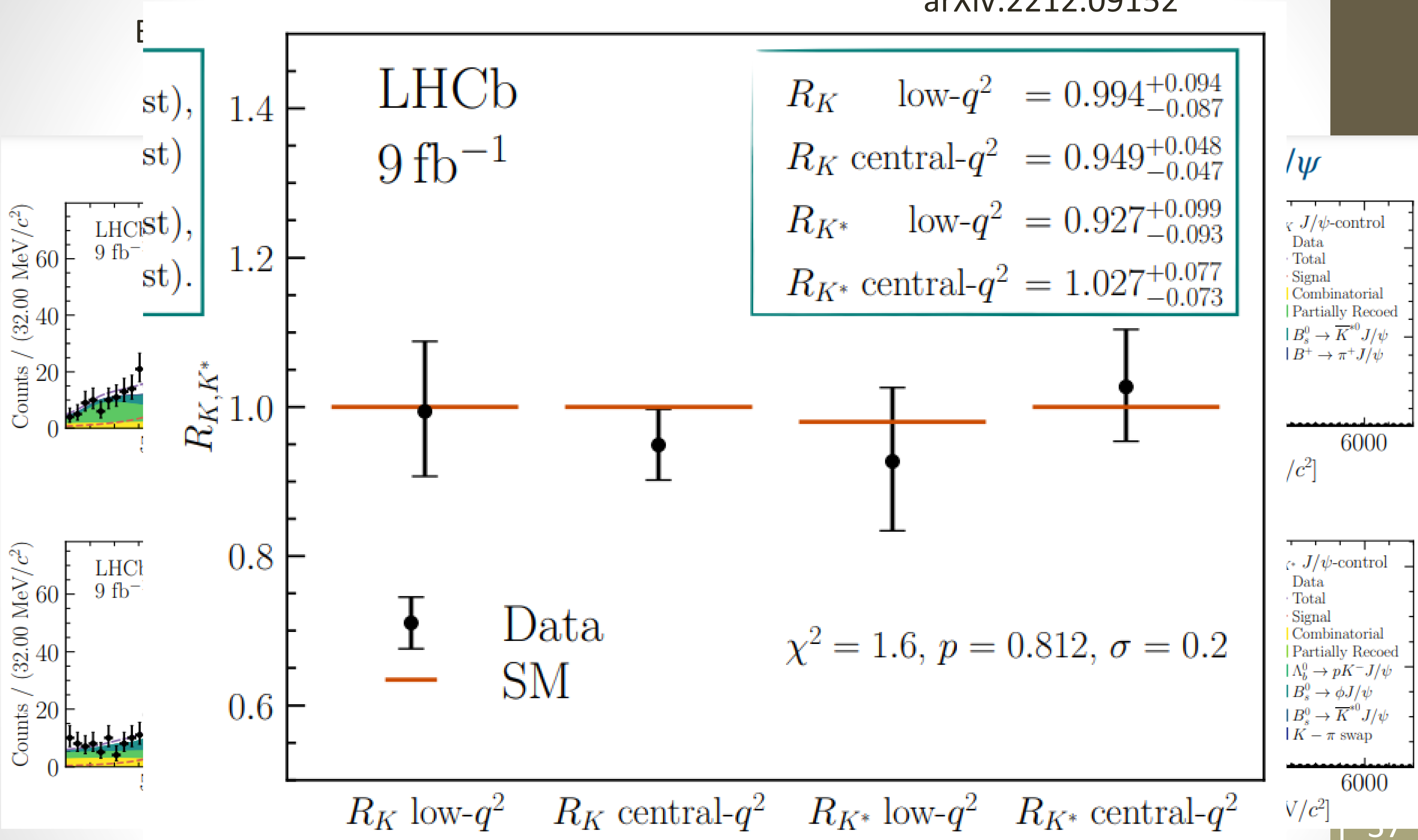
**$B \to K^* l^+ l^-$ PRL Nature Physics 18 (2022) 277 – Run 1 + 2**




**$B \to K^* l^+ l^-$ JHEP 08 (2017) 055 – Run 1 (25% data)**



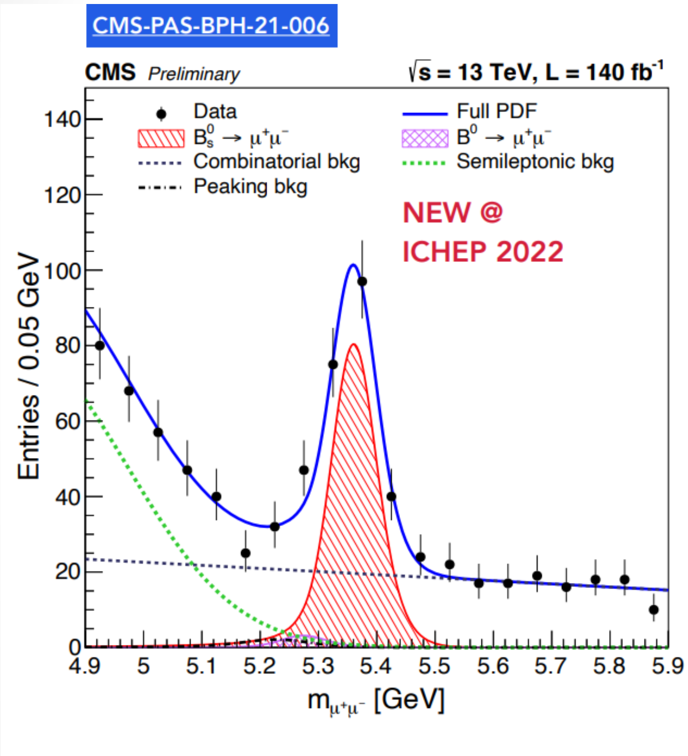
arXiv:2212.09153
arXiv:2212.09152

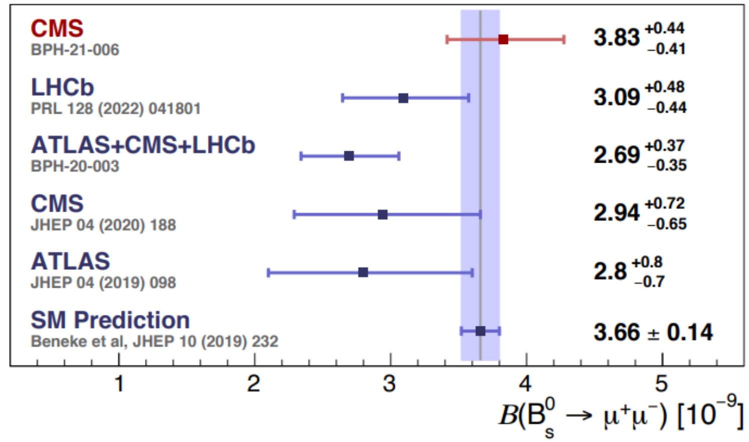


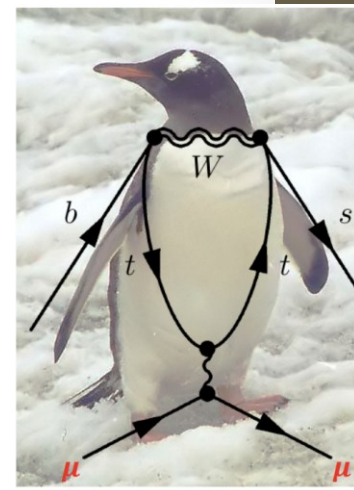

Nothing to see here …… except the importance of understanding particle ID

That does not mean these modes uninteresting

# Anomaly related: $B_{(s)}\to\mu^+\mu^-$



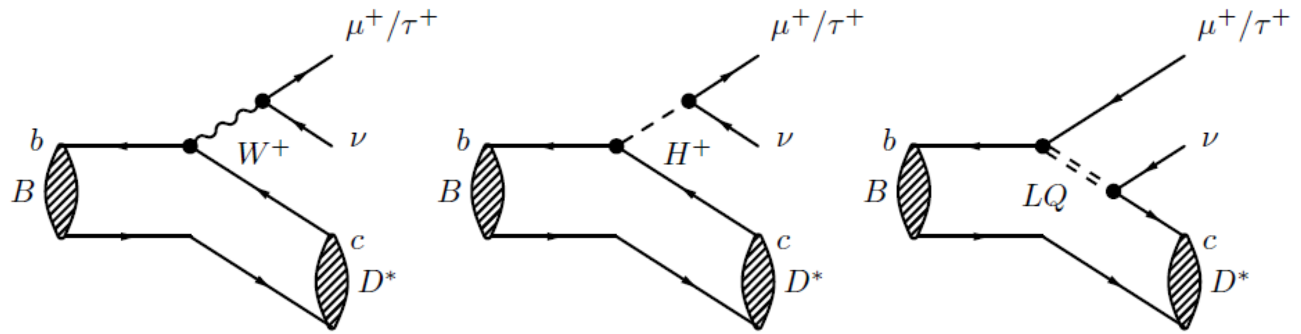




- Highly suppressed in the SM
- Therefore, readily enhanced by non-SM contributions
- Clean experimental signature
- Theoretically clean: decay constant vs form factors

# Semi-tauonic decays

- Tree level in the SM but allows lepton universality tests

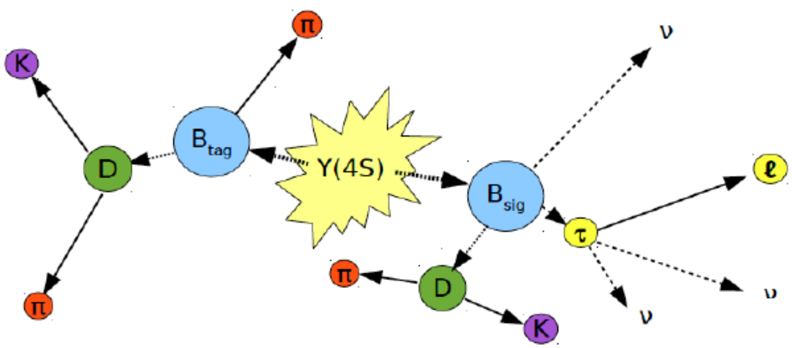



- Measure ratios to reduce theoretical and experimental uncertai

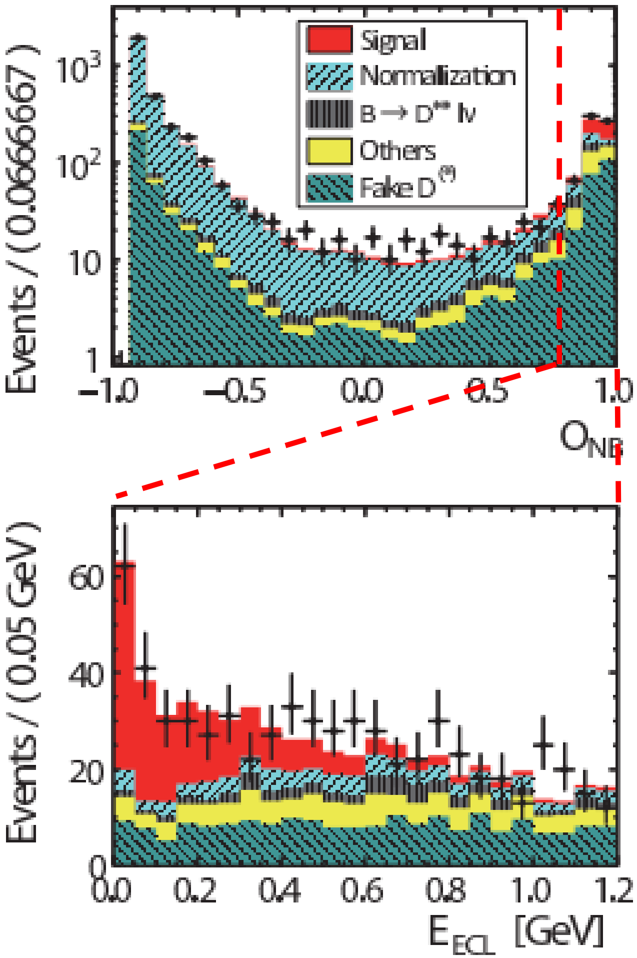
$$R(D) = \frac{\Gamma(\overline{B} \to D\tau\nu)}{\Gamma(\overline{B} \to D\ell\nu)} \qquad R(D^*) = \frac{\Gamma(\overline{B} \to D^*\tau\nu)}{\Gamma(\overline{B} \to D^*\ell\nu)}$$

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

# Belle results

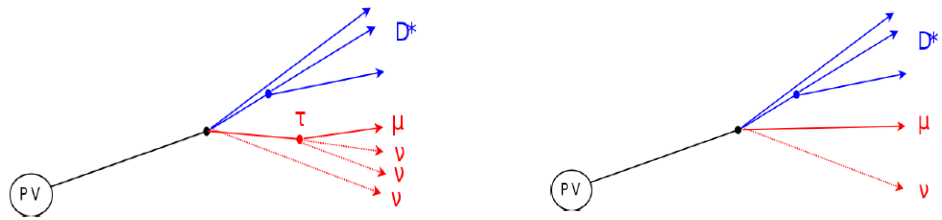



- Tag signal by fully reconstructing or identifying a semileptonic (SL) decay of the other B
- Then use residual energy in ECL, missing mass, multivariates and/or lepton momentum to separate signal
- Example: Phys. Rev. D **94**, 072007 (2016)
  - Semileptonic tag

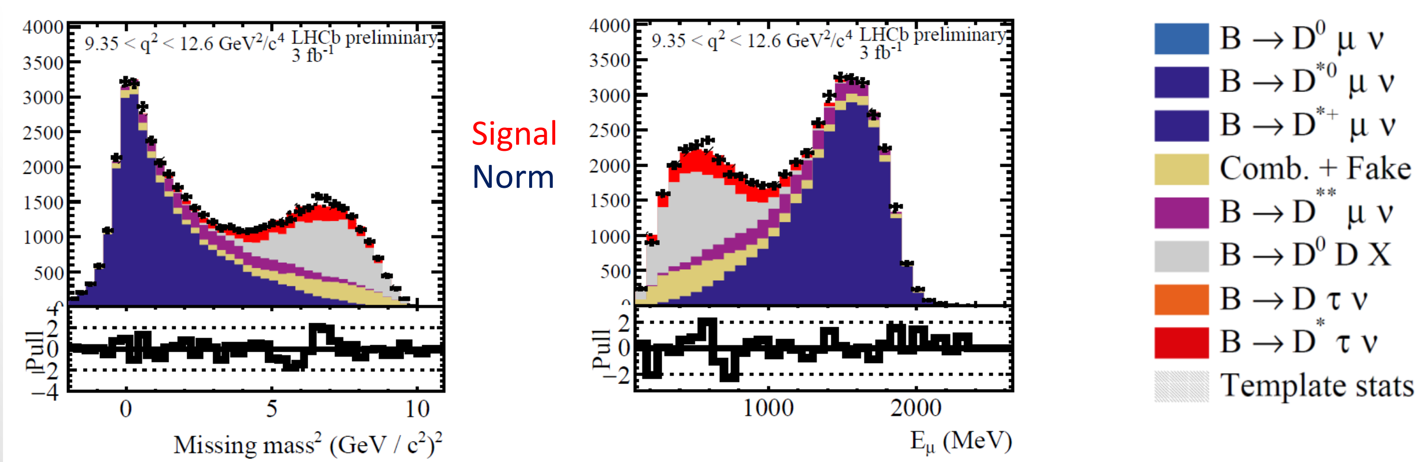


LHCb-PAPER-2022-039 in preparation

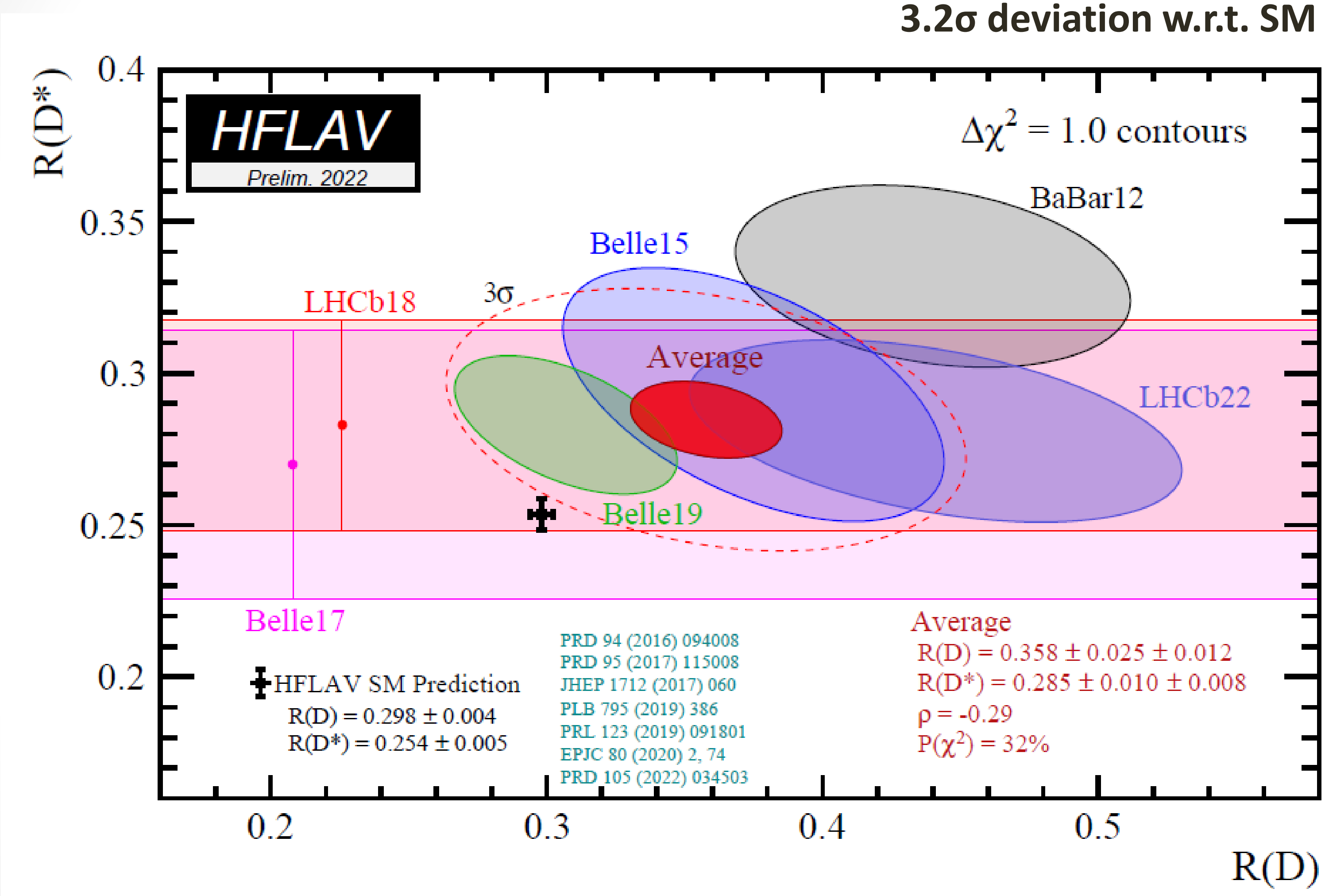
- LHCb also in the game using their vertexing prowess – Run 1 data only 3 fl




- Use B flight for transverse momentum and approximate full longitudinal boost to measured component → 20% B momentum resolution
- Template fit in bins of $q^2$, $E_\mu$ and missing-mass square in B's frame
  - **New: simultaneously fit to D and D* signal + control samples**



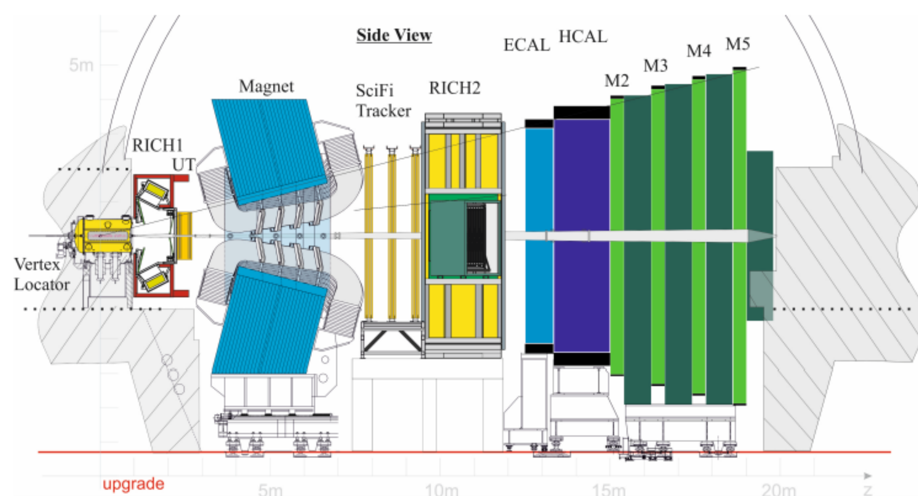
**3.2σ deviation w.r.t. SM**



# FLAVOUR FUTURE

# LHCb status


- 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

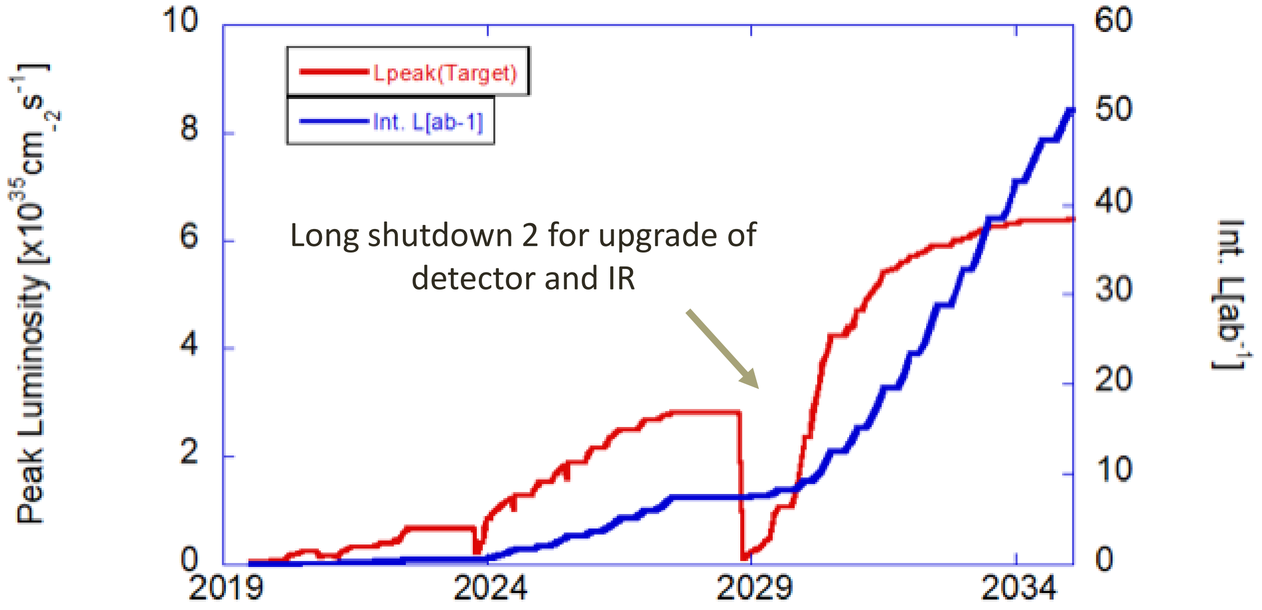
**High backgrounds from the beams have made stable running at high luminosity difficult**

**We have not accumulated data at the rate anticipated**

**Long shutdown ongoing: accelerator and detector improvements**

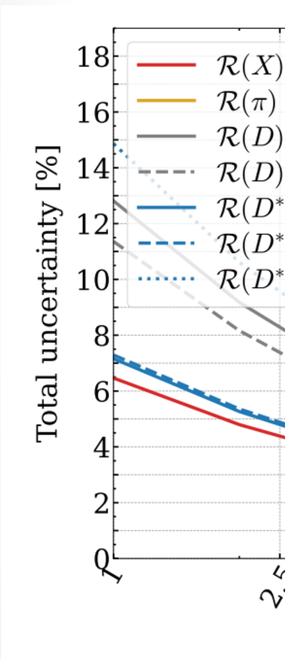
**Path to 2 x $10^{35}$ $cm^{-2}s^{-1}$**

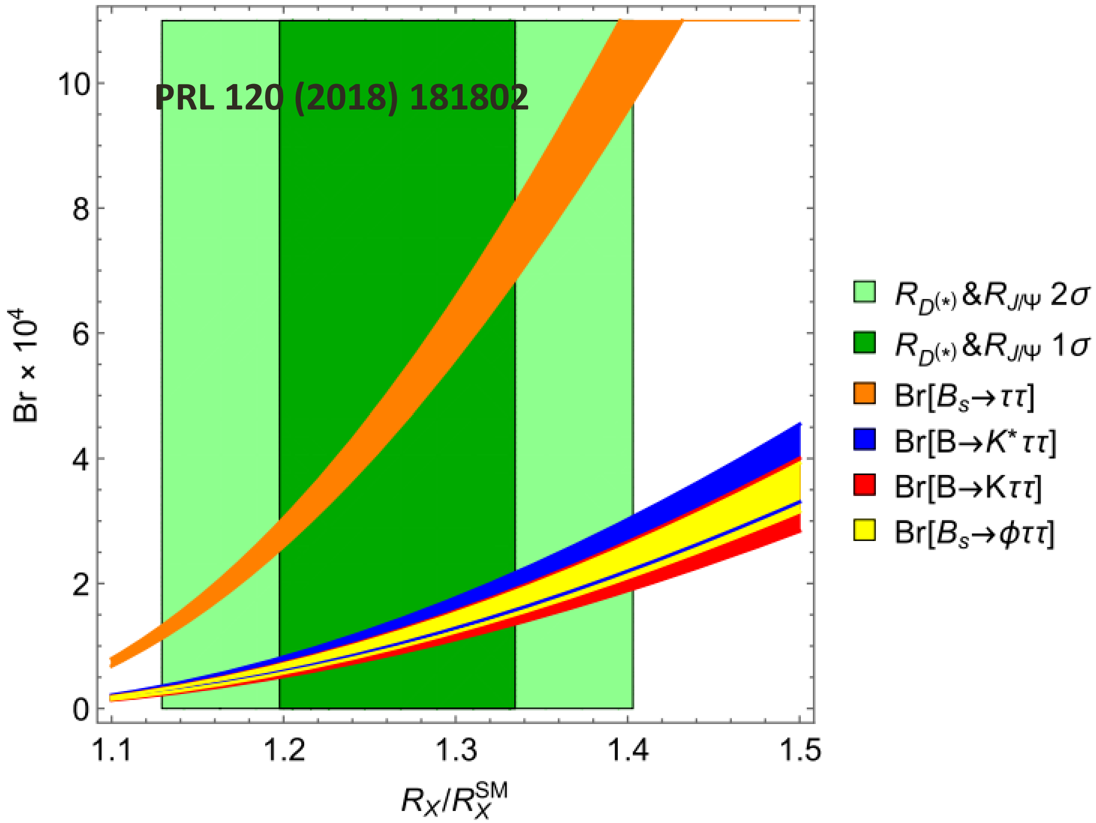
**but thereafter more work required**

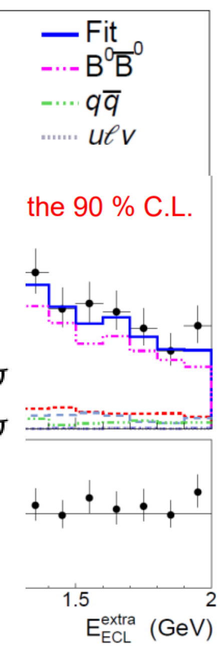


# Some Belle II prospects

arXiv:2110.03871




| | |
|---|---|
| ) (had tag) | |
| improved” scenario | |
| | $< 1.2 \times 10^{-3}$ |
| | $< 6.8 \times 10^{-4}$ |
| | $< 6.5 \times 10^{-4}$ |
| 50 $< 1.0 \times 10^{-}$ | $< 5.3 \times 10^{-4}$ |

https://arxiv.org/pdf/2207.06307.pdf - Belle II Snowmass
Nitty gritty and up to date predictions of what we can achieve

# 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