Physics
OSAKA UNIVERSITY

スーパーBファクトリーの物理

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Introduction

簡単な歴史

1950's

1956: T.D. Lee, C.N. Yang (ノーベル賞1957)

弱い相互作用におけるパリティーの破れ

1957: C.S. Wu et al.

^{60}Co β崩壊実験

パリティーの破れの発見

1957: L. D. Landau

$K_S \to \pi\pi,\ K_L \to \pi\pi\pi \qquad \tau_{K_S} \ll \tau_{K_L}$

中性K中間子崩壊におけるCP保存

1960's

1961: S. L. Glashow (ノーベル賞1979)

1964: J. W. Cronin, V. L. Fitch, ... (ノーベル賞1980)

中性K中間子崩壊におけるCPの破れ

$$K_L \to \pi^+\pi^- \qquad \mathrm{BR} \simeq 2 \times 10^{-3}$$

1967: S. Weinberg (ノーベル賞1979)

1968: A. Salam (ノーベル賞1979)

1970's

1970: S.L.Glashow, J. Iliopoulos, L. Maiani

FCNCに基づくチャームクォークの予言

1971: G. 't Hooft (ノーベル賞1999)

ゲージ理論の繰り込み

1973: M. Kobayashi, T. Maskawa (ノーベル賞2008)

CPを破る6クォーク模型

1974: S. Ting, B. Richter (ノーベル賞1976)

J/Ψ (チャーム)の発見

1975: M. L. Perl (ノーベル賞1995)

タウの発見

1977: L. M. Lederman　ボトムの発見

1980's - present

1983: UA1, UA2 (C. Rubia, S. van der Meer,
W, Zの発見 ノーベル賞1984)

1987: ARGUS B^0–$\bar{B}^0$混合の発見

1989: CLEO $b \to u$ 遷移の発見

1994: CDF, D0 トップの発見

2002: Belle, BABAR
B中間子崩壊におけるCPの破れ

2012: ATLAS, CMS
ヒッグスボソンの発見 (P. Higgs, F. Englert,
標準模型の確立 ノーベル賞2013)

Plan of talk

1. Introduction (4)
2. (Super) B factory and LHCb (25)
3. Some observed anomalies (16)
4. Summary and outlook (1)

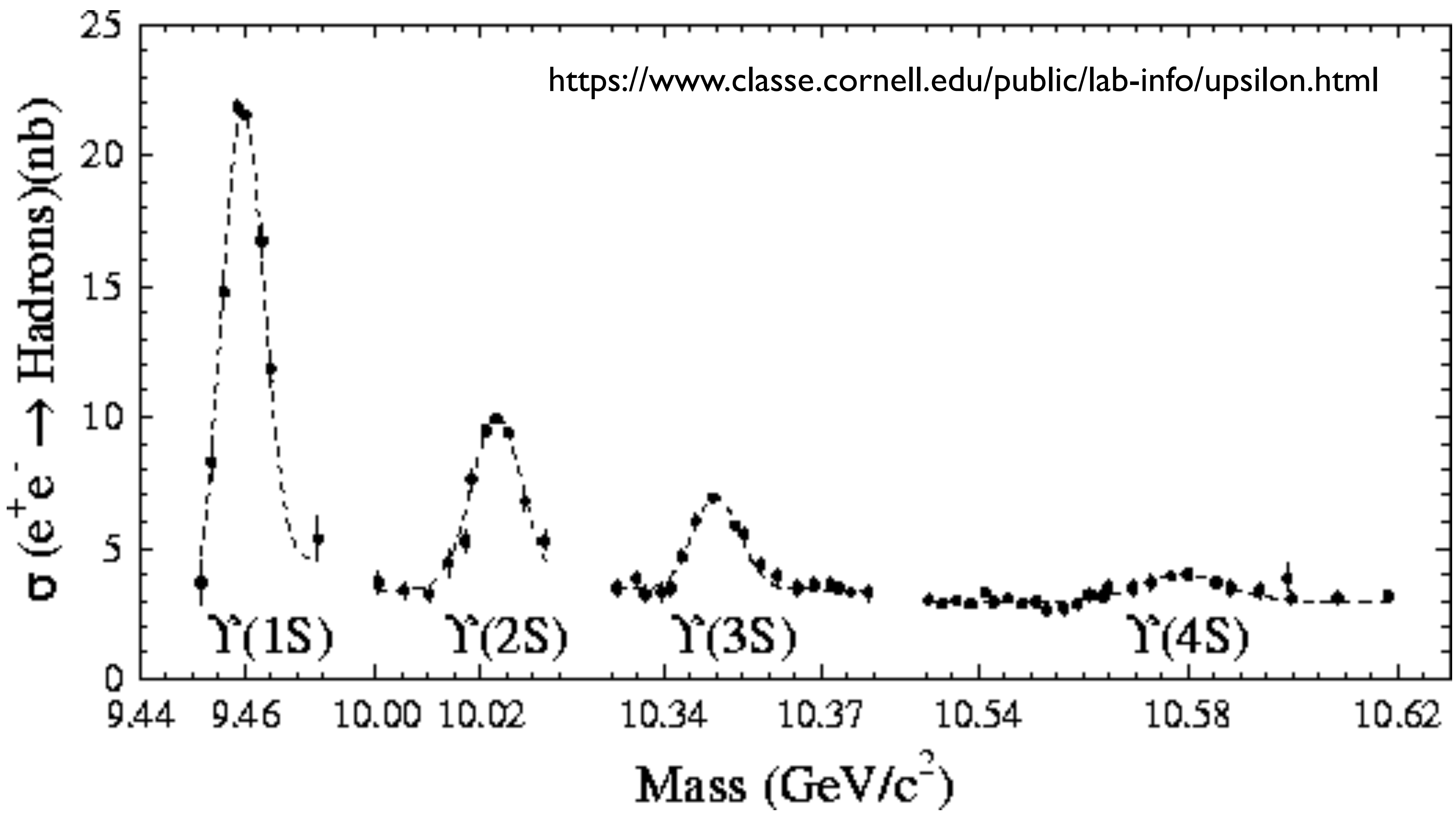
(Super) B factory

Symmetric B factory: ARGUS, CLEO

electron-positron colliders: $e^+e^- \to \Upsilon(4S) \to B\bar{B}$

$$\sqrt{s} \simeq m_{\Upsilon(4S)} = 10.5794(12)\ \mathrm{GeV}$$

$$m_{B^\pm} = 5.27931(15)\,,\ m_{B^0} = 5.27962(15)\ \mathrm{GeV}$$



Total cross section on Upsilon 4S

Table 18: Total production cross section from various physics processes from collisions at $\sqrt{s} = 10.58\,\mathrm{GeV}$. $W_{\ell\ell}$ is the minimum invariant secondary fermion pair mass.

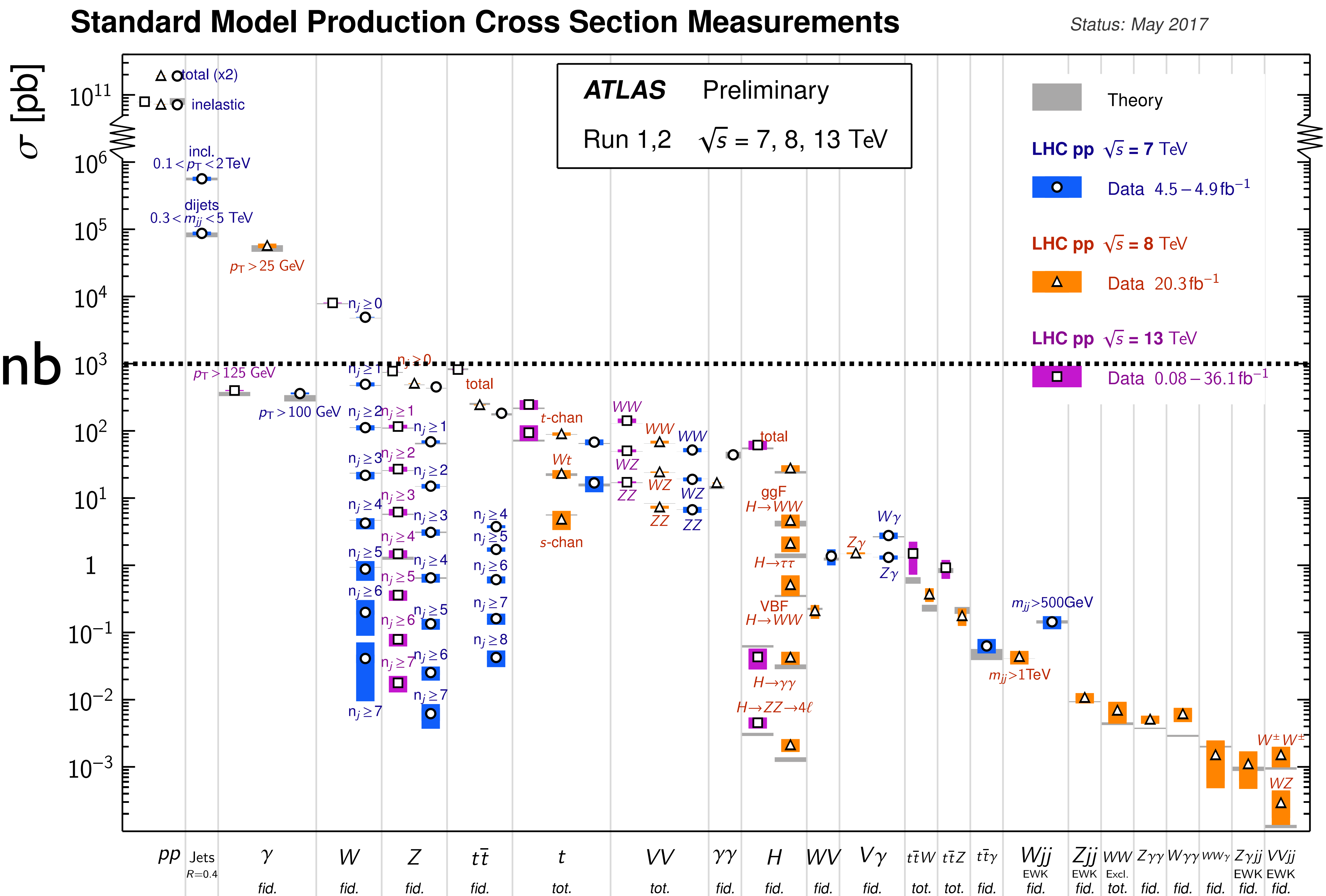
Physics process	Cross section [nb]	Selection Criteria	Reference
$\Upsilon(4S)$	1.110 ± 0.008	-	[2]
$u\bar{u}(\gamma)$	1.61	-	KKMC
$d\bar{d}(\gamma)$	0.40	-	KKMC
$s\bar{s}(\gamma)$	0.38	-	KKMC
$c\bar{c}(\gamma)$	1.30	-	KKMC
$e^+e^-(\gamma)$	300 ± 3 (MC stat.)	$10^\circ < \theta_e^* < 170^\circ$, $E_e^* > 0.15\,\mathrm{GeV}$	BABAYAGA.NLO
$e^+e^-(\gamma)$	74.4	$p_e > 0.5\,\mathrm{GeV}/c$ and e in ECL	-
$\gamma\gamma(\gamma)$	4.99 ± 0.05 (MC stat.)	$10^\circ < \theta_\gamma^* < 170^\circ$, $E_\gamma^* > 0.15\,\mathrm{GeV}$	BABAYAGA.NLO
$\gamma\gamma(\gamma)$	3.30	$E_\gamma > 0.5\,\mathrm{GeV}$ in ECL	-
$\mu^+\mu^-(\gamma)$	1.148	-	KKMC
$\mu^+\mu^-(\gamma)$	0.831	$p_\mu > 0.5\,\mathrm{GeV}/c$ in CDC	-
$\mu^+\mu^-\gamma(\gamma)$	0.242	$p_\mu > 0.5\,\mathrm{GeV}$ in CDC, $\geq 1\ \gamma\ (E_\gamma > 0.5\,\mathrm{GeV})$ in ECL	-
$\tau^+\tau^-(\gamma)$	0.919	-	KKMC
$\nu\bar{\nu}(\gamma)$	0.25×10^{-3}	-	KKMC
$e^+e^-e^+e^-$	39.7 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5\,\mathrm{GeV}/c^2$	AAFH
$e^+e^-\mu^+\mu^-$	18.9 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5\,\mathrm{GeV}/c^2$	AAFH

E. Kou et al., "The Belle II Physics book", 1808.10567.

cf. Cross sections at LHC

J. Kretzschmar, 1803.10800

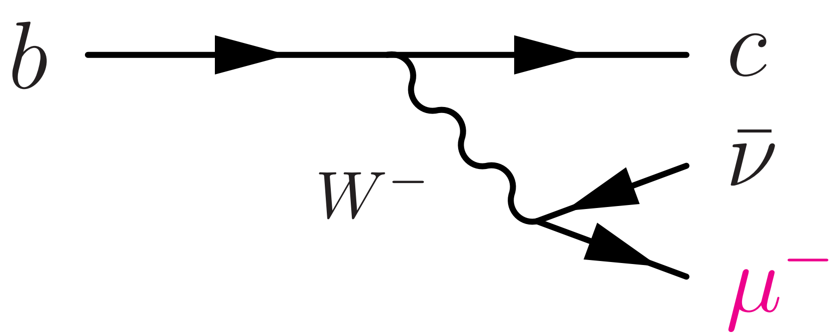
1 nb



B^0–$\bar{B}^0$ mixing discovery by ARGUS (1987)

$B^0(\bar{b}d),\ \bar{B}^0(b\bar{d})$

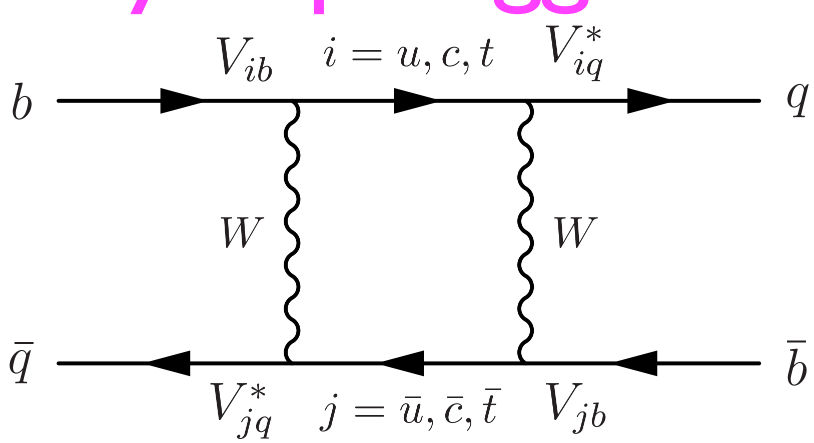
flavor tagging



$$b \to c\mu^-\bar{\nu}$$

$$\bar{b} \to \bar{c}\mu^+\nu$$

heavy top suggested



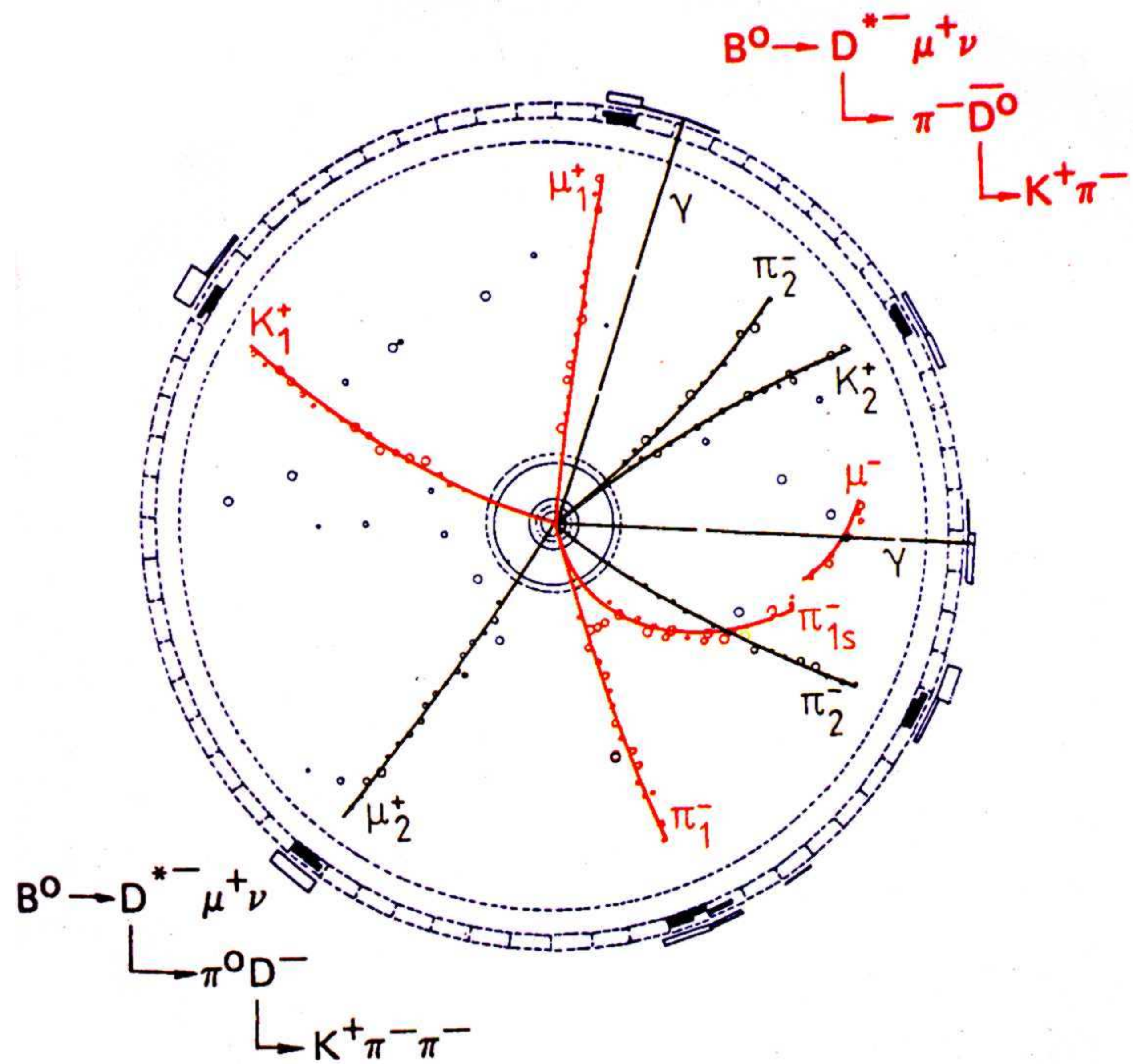


Figure 25: The golden event found by H. Schröder. It shows the reaction $\Upsilon(4S) \to B^0\overline{B^0} \to B^0B^0$, which is evidence for $B\overline{B}$ mixing.

https://argus-fest.desy.de/e301/e305/wsp_arg_new.pdf

b → u discovery by CLEO (1989)

lepton endpoint spectrum

in $b \to c\ell\nu\,,\, u\ell\nu$

$$E_\ell^{b\to c} \le \frac{m_B^2 - m_D^2 + m_\ell^2}{2m_B}$$

$$\simeq 2.3\ \mathrm{GeV}$$

KM CPV possible

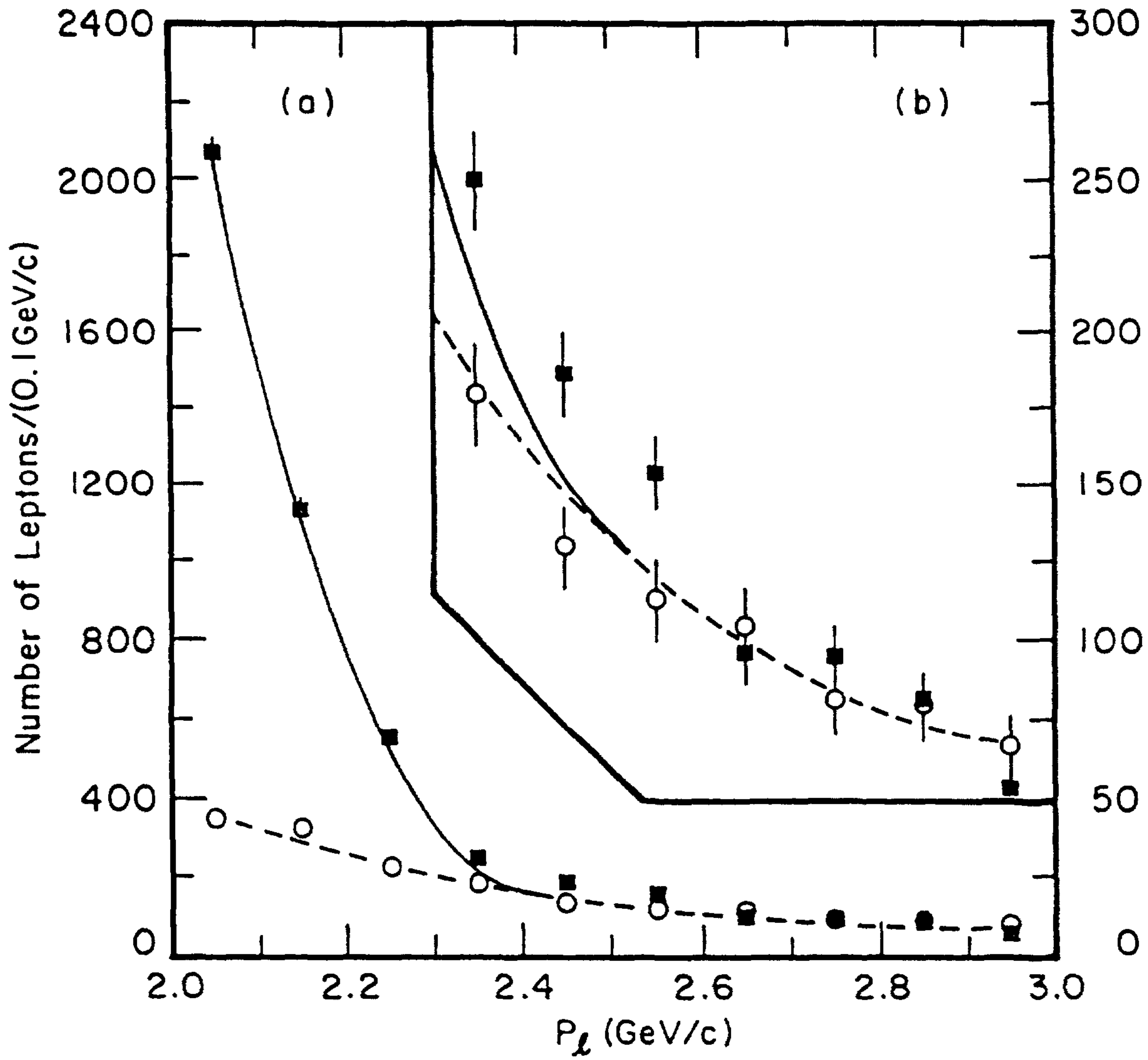


FIG. 1. Sum of the e and μ momentum spectra for ON data (filled squares), scaled OFF data (open circles), the fit to the OFF data (dashed line), and the fit to the OFF data plus the $b \to c l \nu$ yield (solid line). Note the different vertical scales in (a) and (b).

https://doi.org/10.1103/PhysRevLett.64.16

Asymmetric B factories: BaBar and Belle

EPJC74(2014)3026

Asymmetric electron-positron colliders

$e^+e^- \to \Upsilon(4S) \to B\bar{B}$ boosted B pairs

mixing-induced CP violation

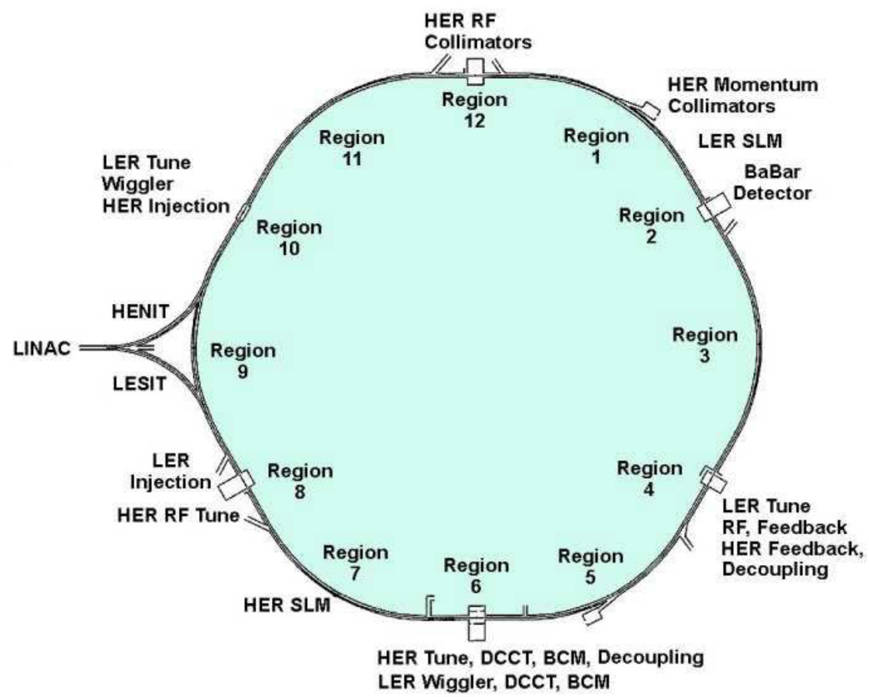
time-dependent CP asymmetry

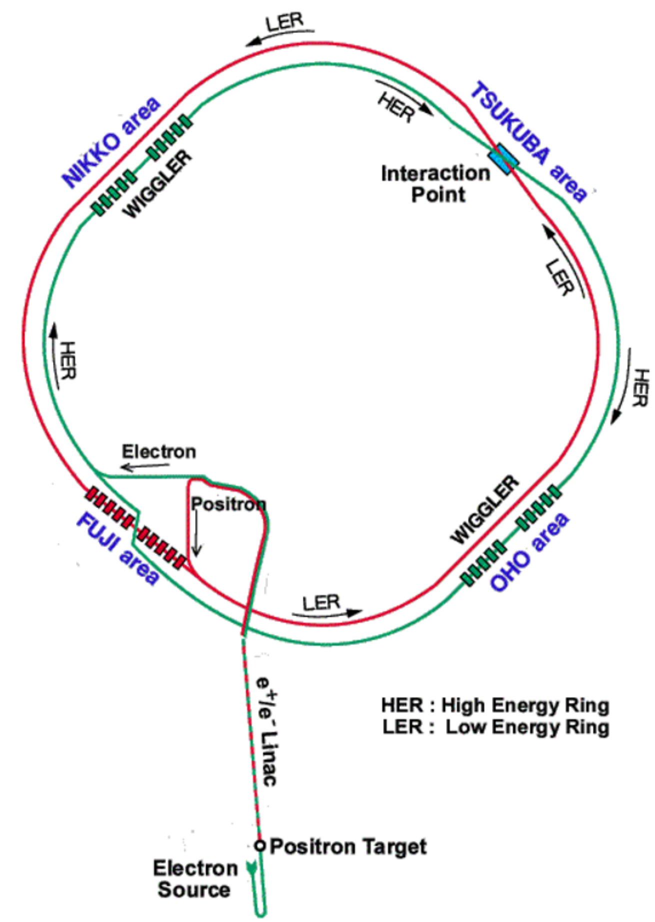
decay time $\longleftrightarrow$ decay position

$\tau \simeq 1.5$ ps $\qquad c\tau \simeq 460\ \mu$m

PEP-II

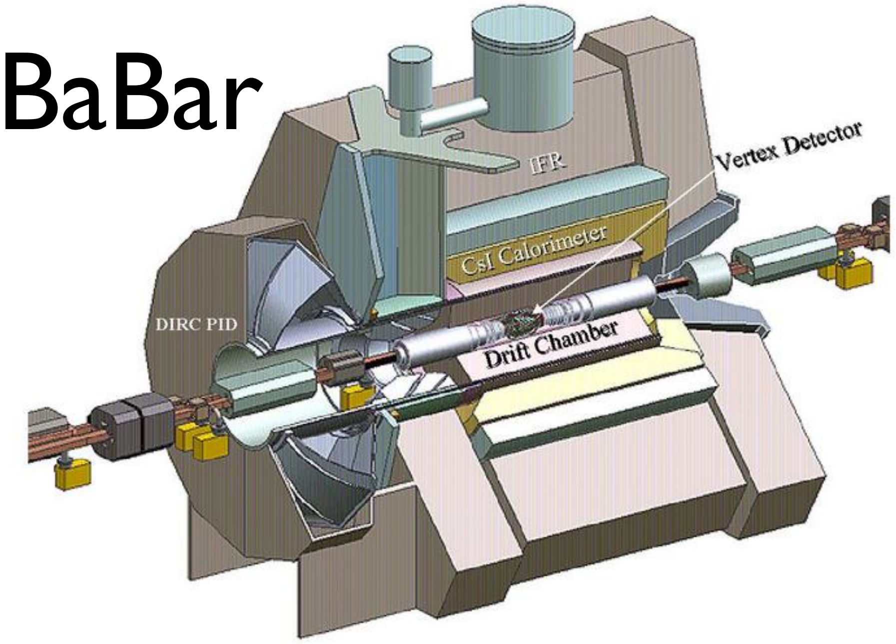
KEKB



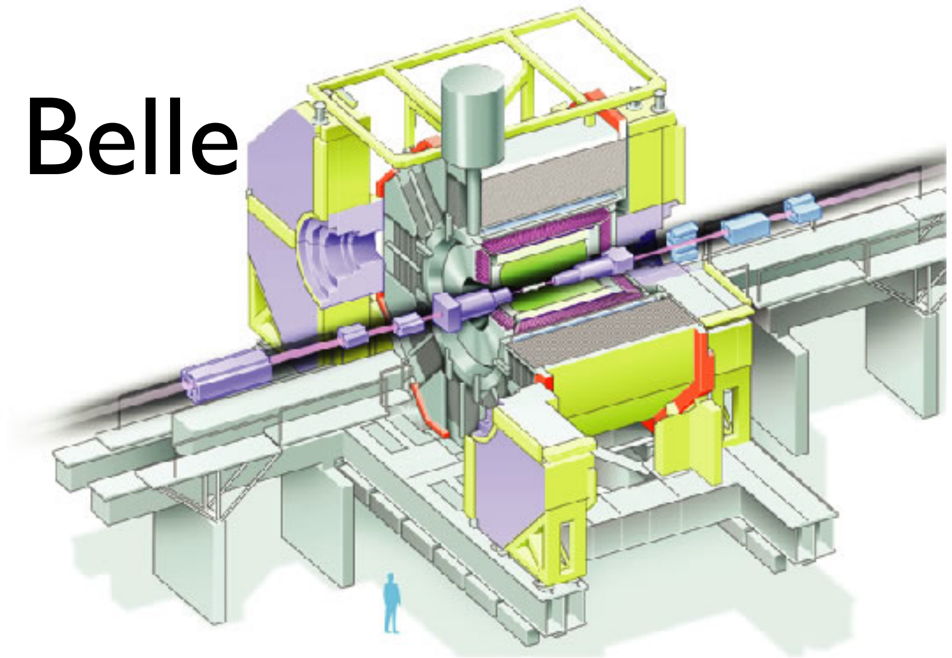


B Factory	e^- beam energy E_- (GeV)	e^+ beam energy E_+ (GeV)	Lorentz factor $\beta\gamma$	crossing angle φ (mrad)
PEP-II	9.0	3.1	0.56	0
KEKB	8.0	3.5	0.425	22

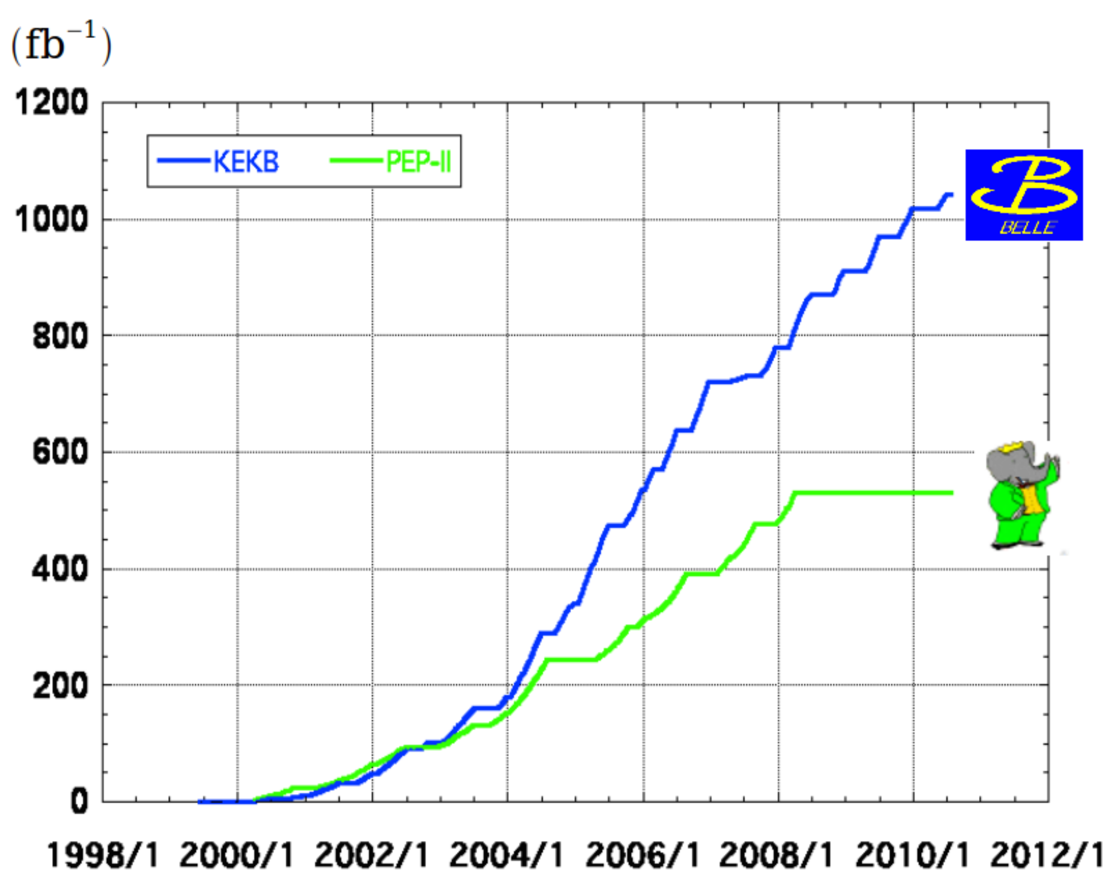
BaBar



Belle



Integrated luminosity of B factories



> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

~1 /ab

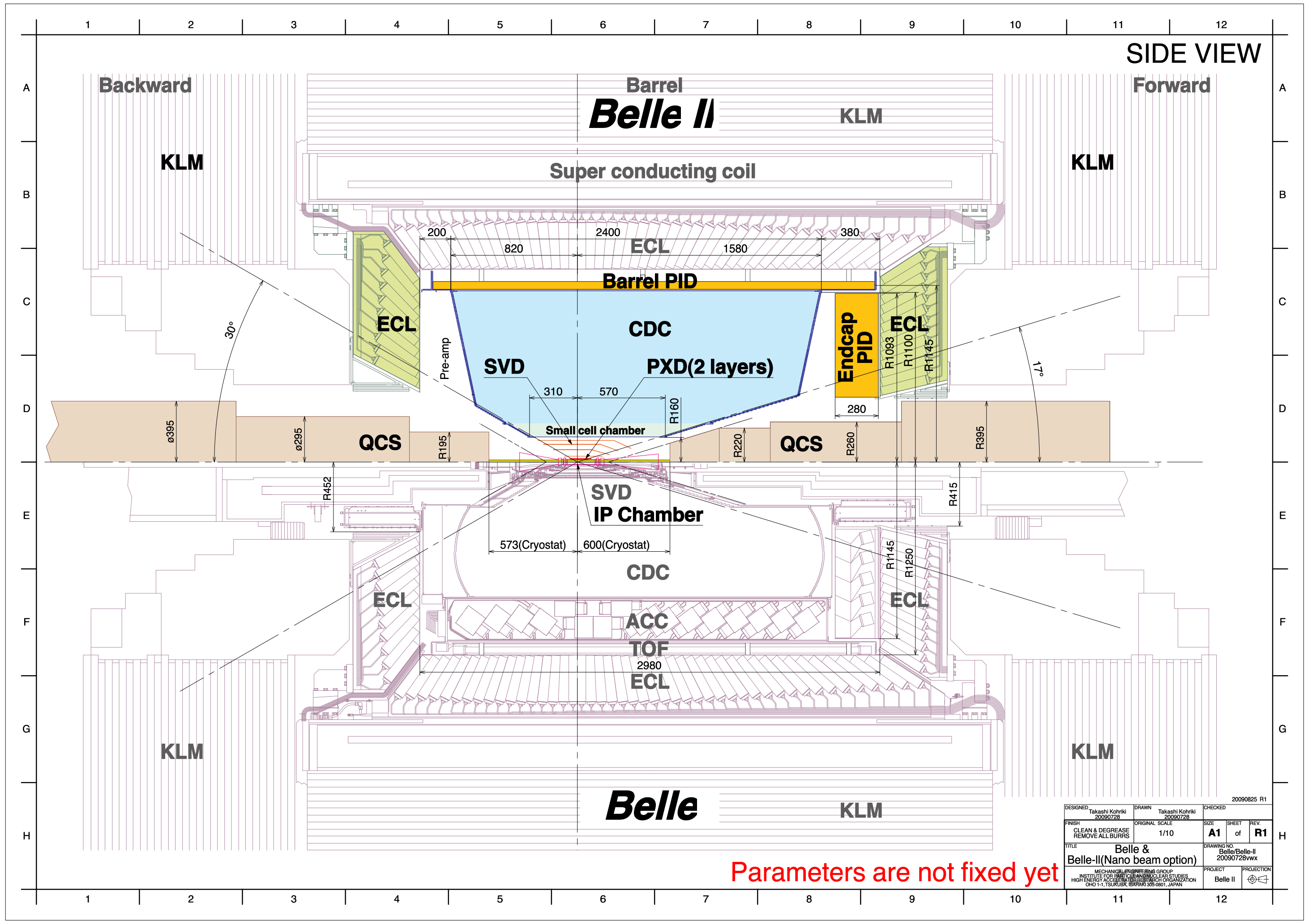
$O(10^9)\ B$

SuperKEKB/Belle II

	KEKB Achieved	SuperKEKB
Energy (GeV) (LER/HER)	3.5/8.0	4.0/7.0
ξ_y	0.129/0.090	0.090/0.088
β_y^* (mm)	5.9/5.9	0.27/0.41
I (A)	1.64/1.19	3.60/2.62
Luminosity ($10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	2.11	80

$\beta\gamma = 0.28$

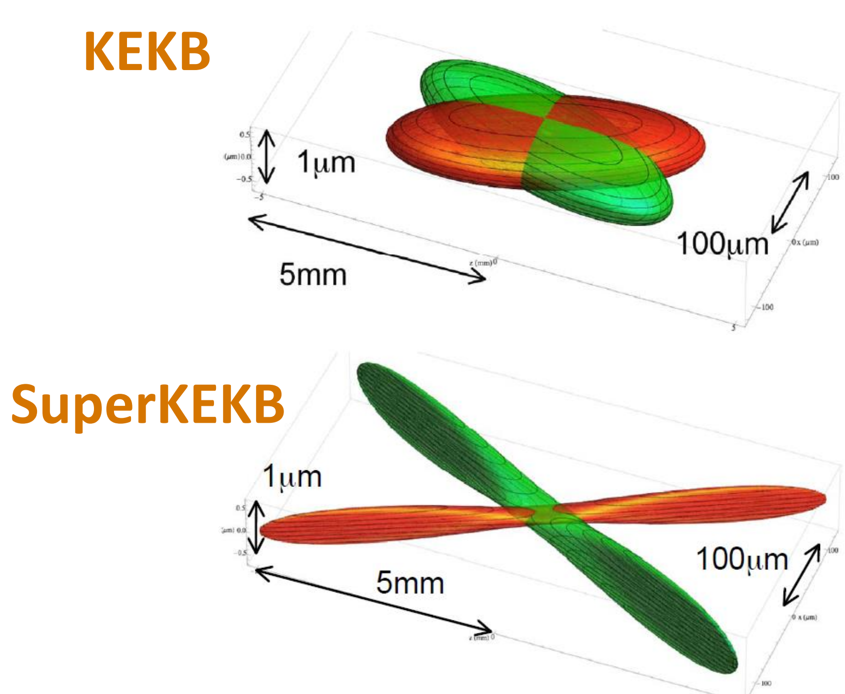
x40

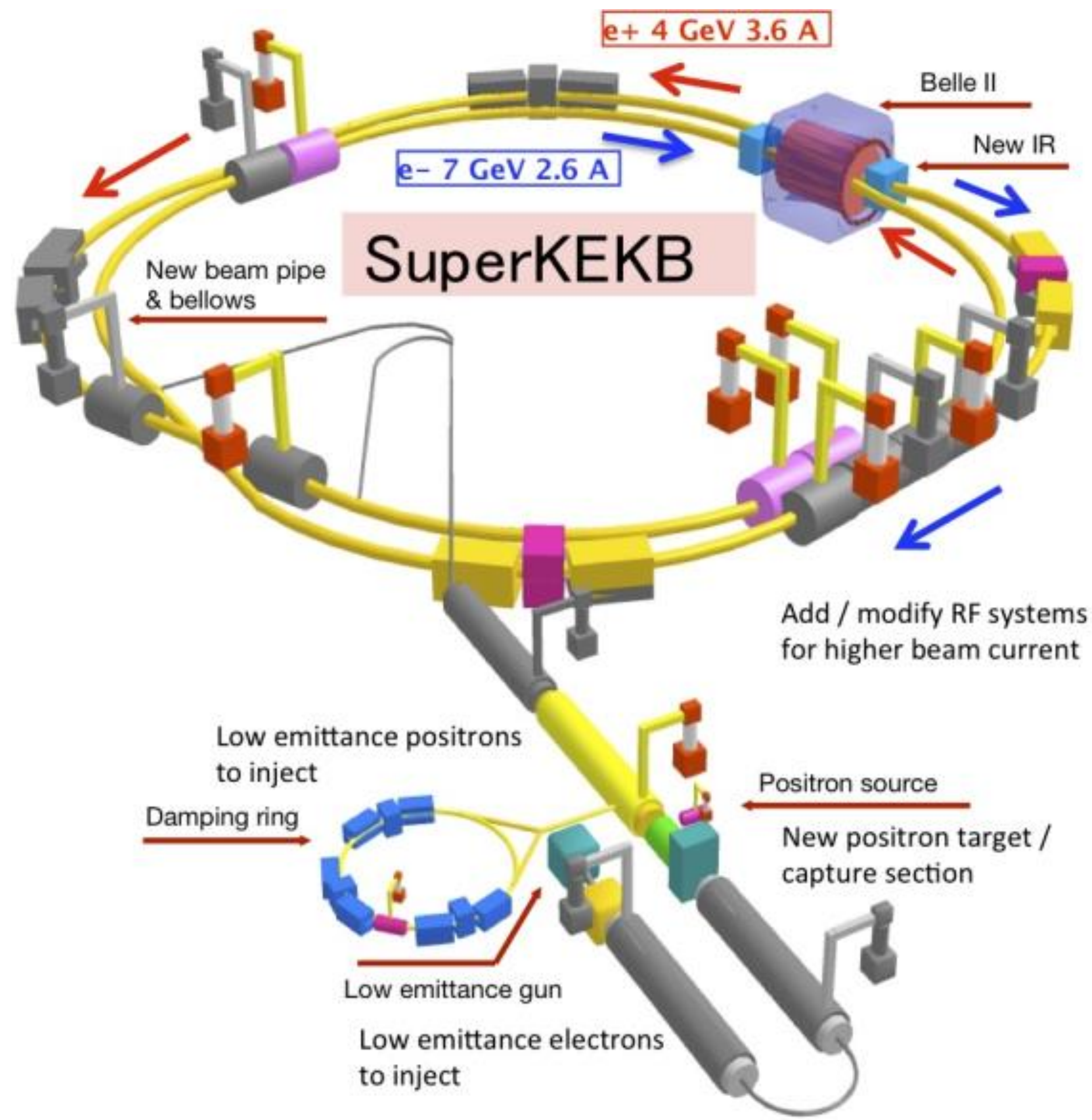


Accelerator Upgrade – SuperKEKB

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*

- **40x increase in luminosity**
- "Nano-beam" interaction point
- Increase in current





- **First turns achieved Feb 2016!**

See: Y. Onishi, ICHEP Highlights 08 Aug 12:10

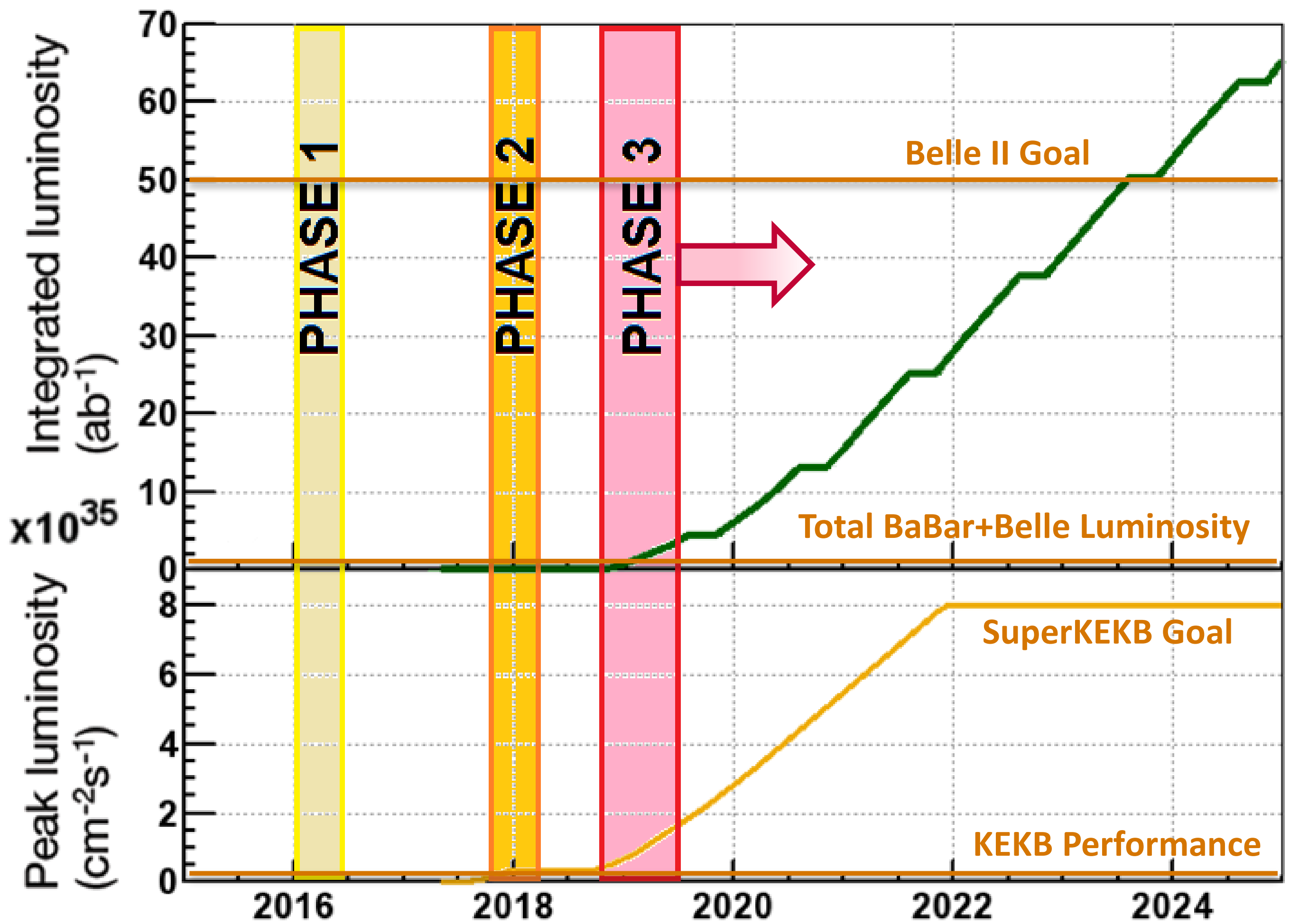
Current Status and Schedule

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

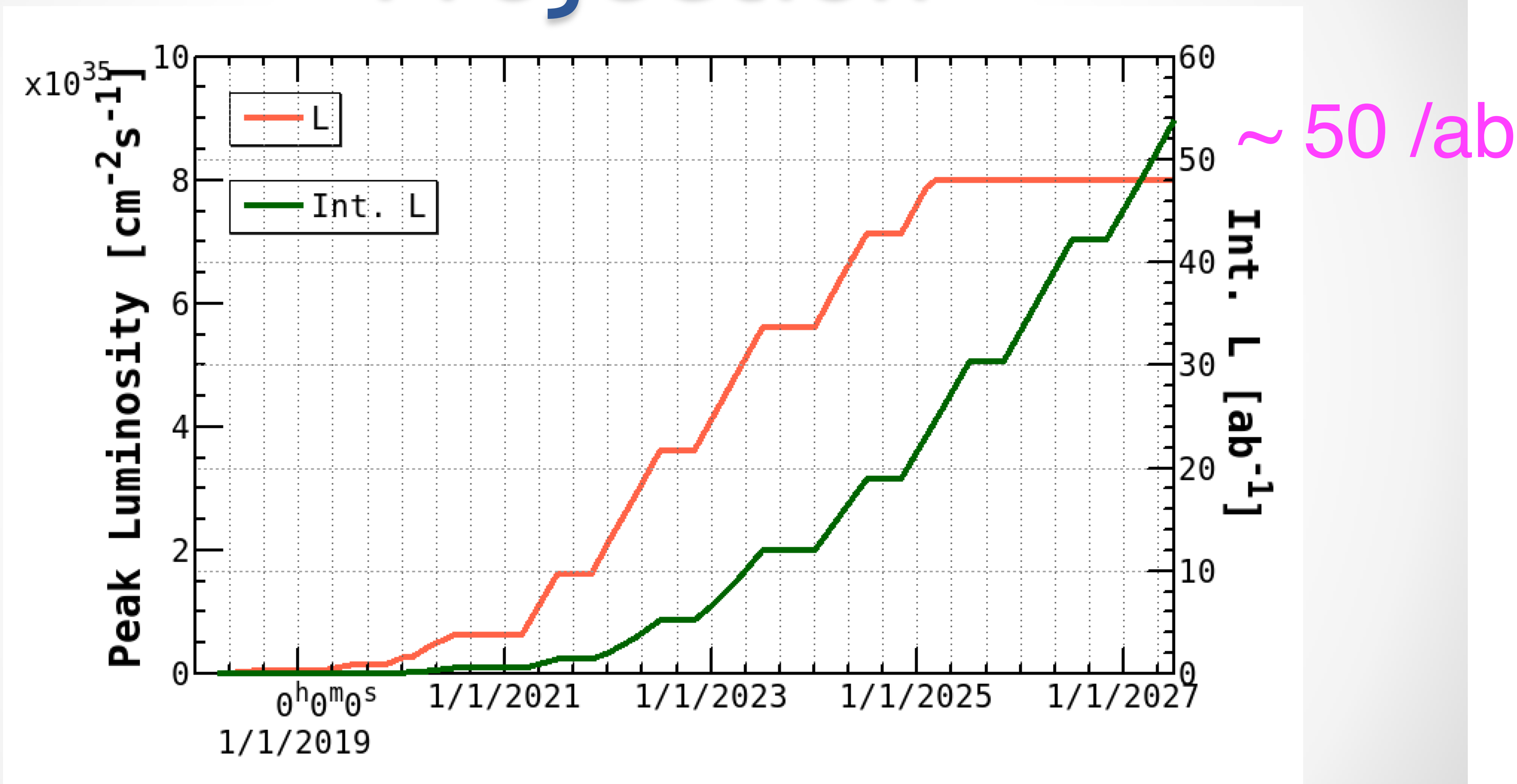
- Belle II Collaboration: ~700 members, ~100 institutions, 23 countries
- Phase 1 (complete)
  - Accelerator commissioning

See: P. Lewis, Detector 05 Aug 09:20

- Phase 2 (2017)
  - First collisions
  - Partial detector
  - Background study
  - Physics possible
- Phase 3 (“Run 1”)
  - Nominal Belle II start
- **Ultimate goal: 50 ab^{-1}**



SuperKEKB Luminosity Projection



Accumulate 50ab^{-1}, x50 of Belle/KEKB

6th KEKFF K. Hara Feb. 14, 2019 5

Early Phase3 Physics

- Luminosity will depend on machine and detector performance
- Plausible assumption of about 10fb-1 by summer 2019

Semileptonic
- $B \rightarrow \pi\, l\, \nu$ and $\rho\, l\, \nu$ untagged (CLEO saw a signal with 2.66 fb^{-1})

Time Dependent B and D measurements
- D lifetimes (2 fb^{-1})
- Doubly Cabibbo suppressed $D^0 \rightarrow K^+ \pi^-$, $D^0 \rightarrow K^+ \pi^- \pi^0$ (10 fb^{-1})
- B lifetimes (2-10 fb^{-1})
- Time dependent B-anti B mixing (10 fb^{-1})

Verification of full Belle II physics performance

Radiative/Electroweak Penguins
- $B \rightarrow K^* \gamma$ ($b \rightarrow s$) (2 fb^{-1}) rediscover penguins
- $B \rightarrow X_s \gamma$ ($b \rightarrow s$) (~10 fb^{-1} but *needs off-resonance data taking*)

Hadronic B decays (not time dependent)
- $B \rightarrow K \pi$ ($b \rightarrow u$) (10 fb^{-1})
- $B \rightarrow \Phi K$ ($b \rightarrow s$) (10 fb^{-1})
- $B \rightarrow J/\psi K$ (with more significance 2-10 fb^{-1})

++ Dark Sector Physics

6th KEKFF

K. Hara

Feb. 14, 2019 25

SuperKEKB Snapshot History

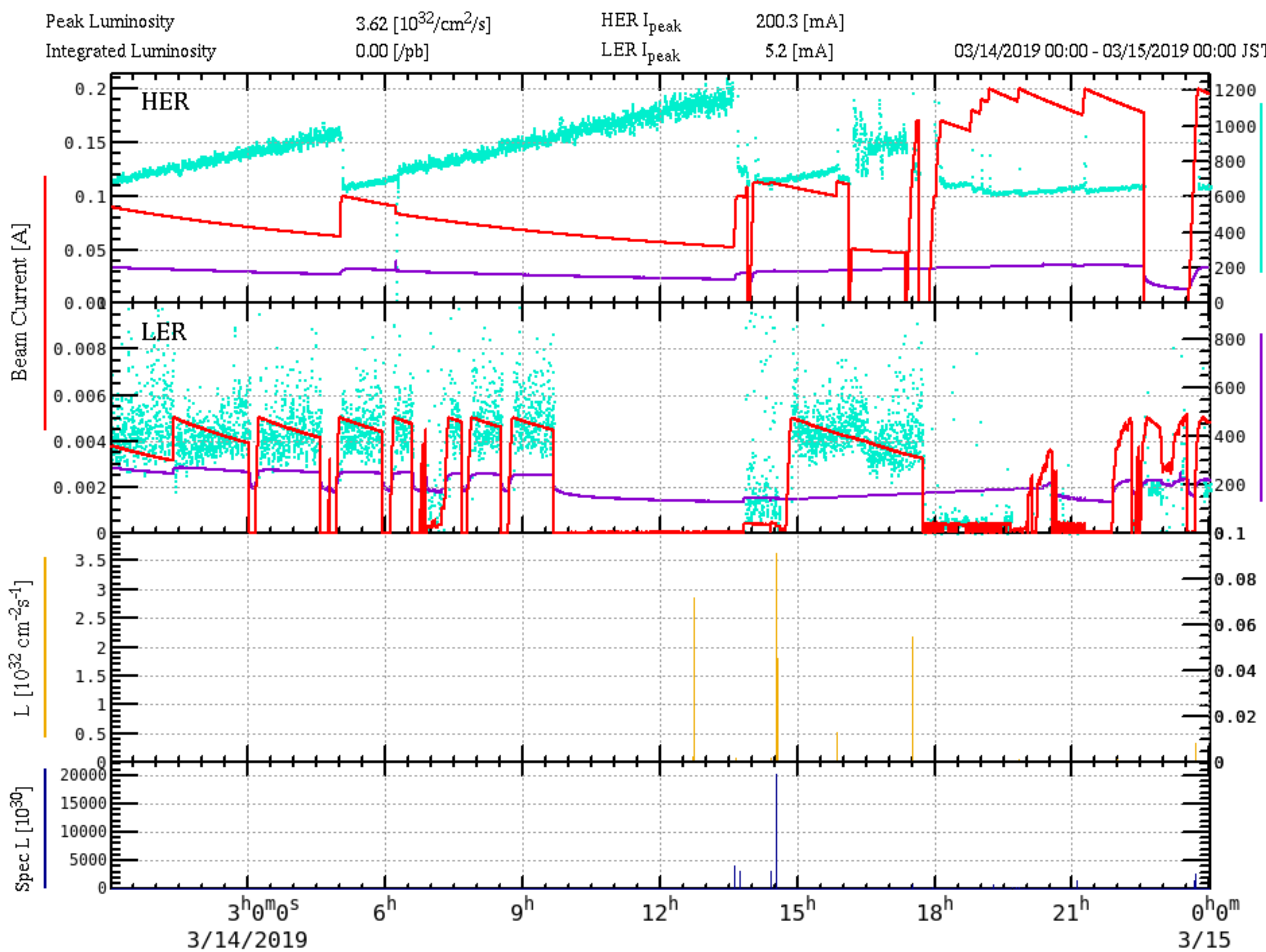
http://www-linac.kek.jp/skekb/snapshot/ring/dailysnap-2019/

e^-

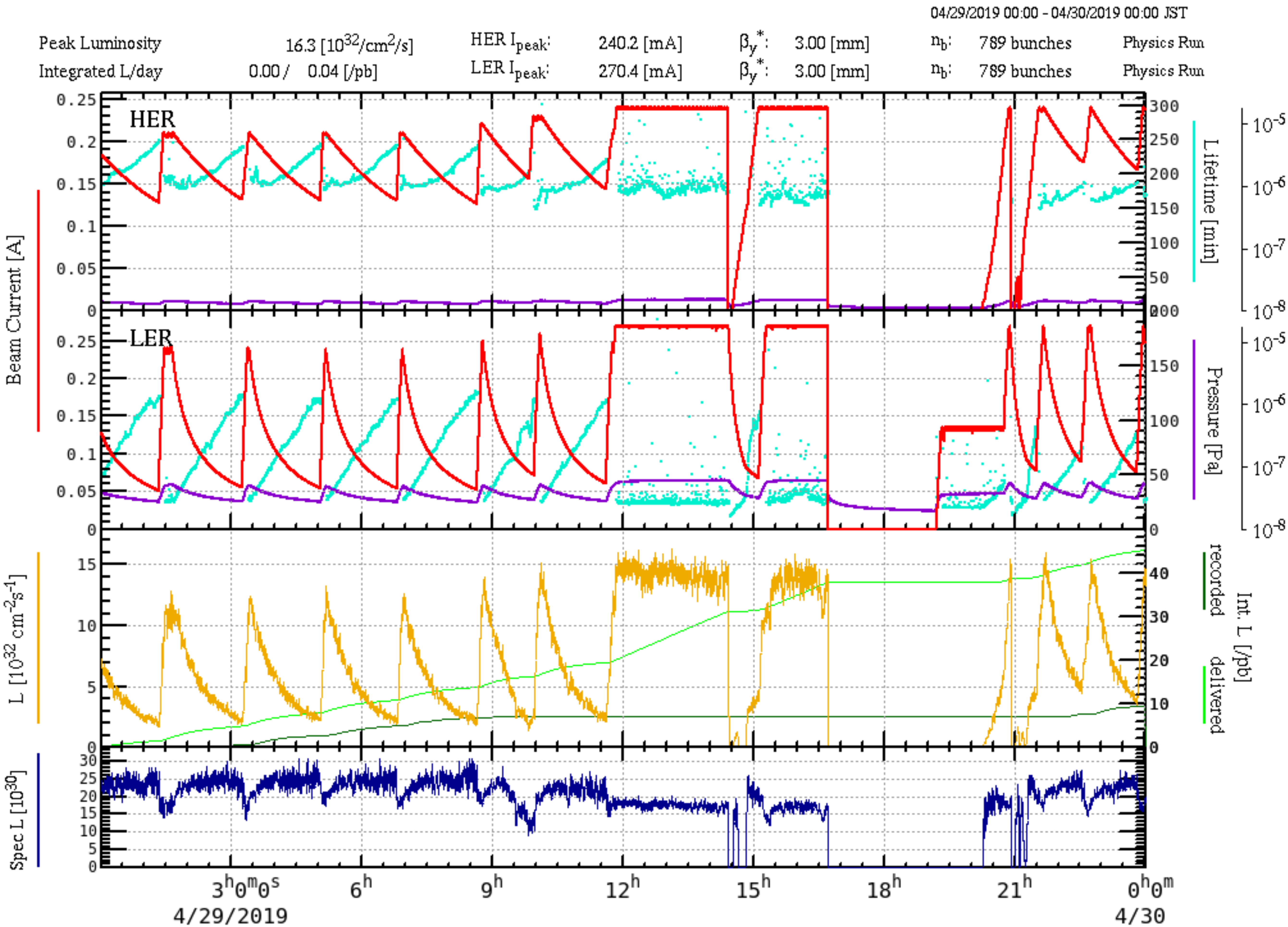
e^+

Luminosity

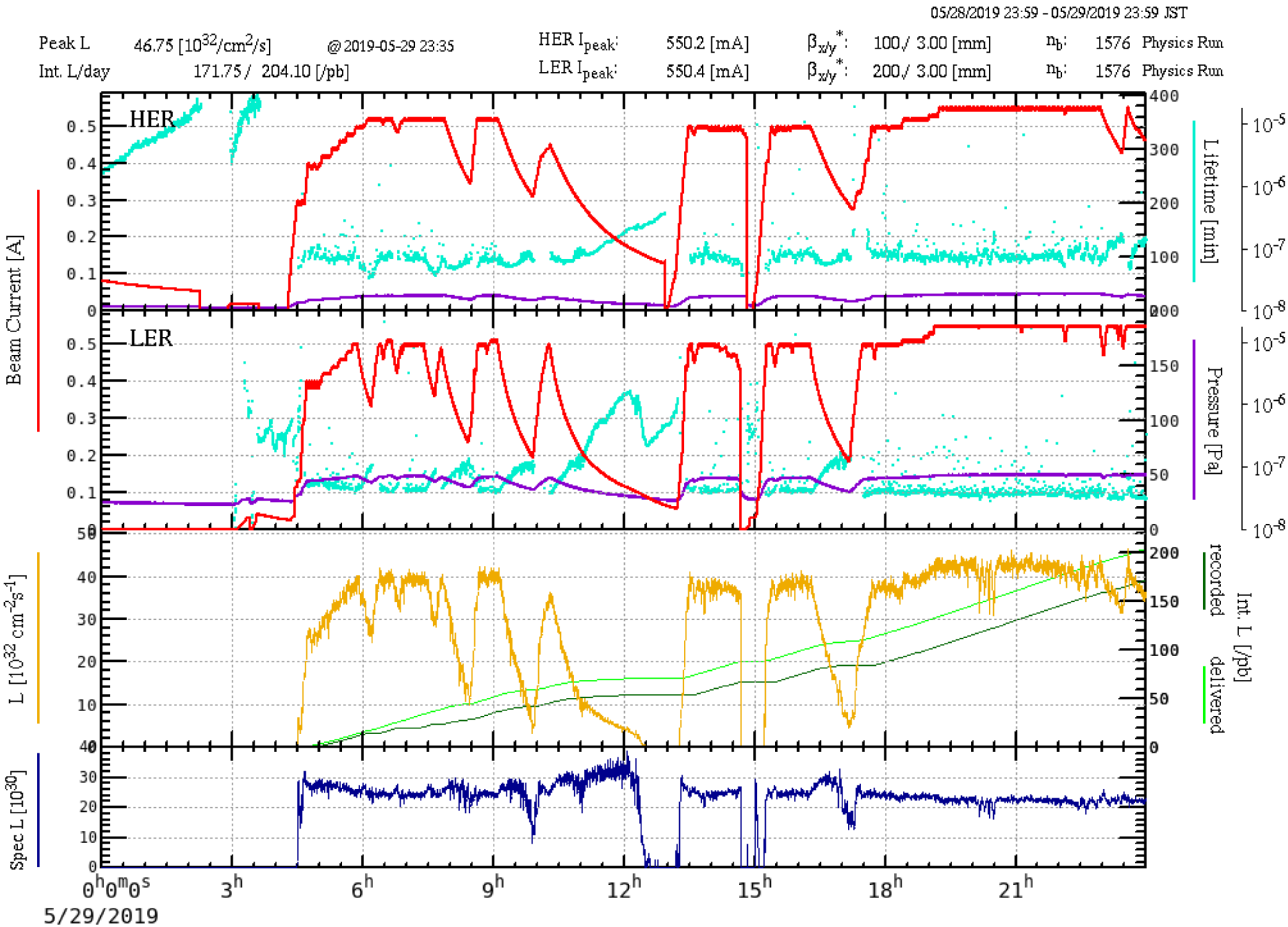
L / current



3/14/2019



04/29/2019 00:00 - 04/30/2019 00:00 JST
Peak Luminosity 16.3 [10^32/cm^2/s]
Integrated L/day 0.00 / 0.04 [/pb]
HER I_peak: 240.2 [mA]
LER I_peak: 270.4 [mA]
β_y*: 3.00 [mm]
β_y*: 3.00 [mm]
n_b: 789 bunches
n_b: 789 bunches
Physics Run
Physics Run
HER
LER
Beam Current [A]
Lifetime [min]
Pressure [Pa]
L [10^32 cm^-2 s^-1]
Int. L [/pb]
recorded
delivered
Spec L [10^30]
3h0m0s
6h
9h
12h
15h
18h
21h
0h0m
4/29/2019
4/30

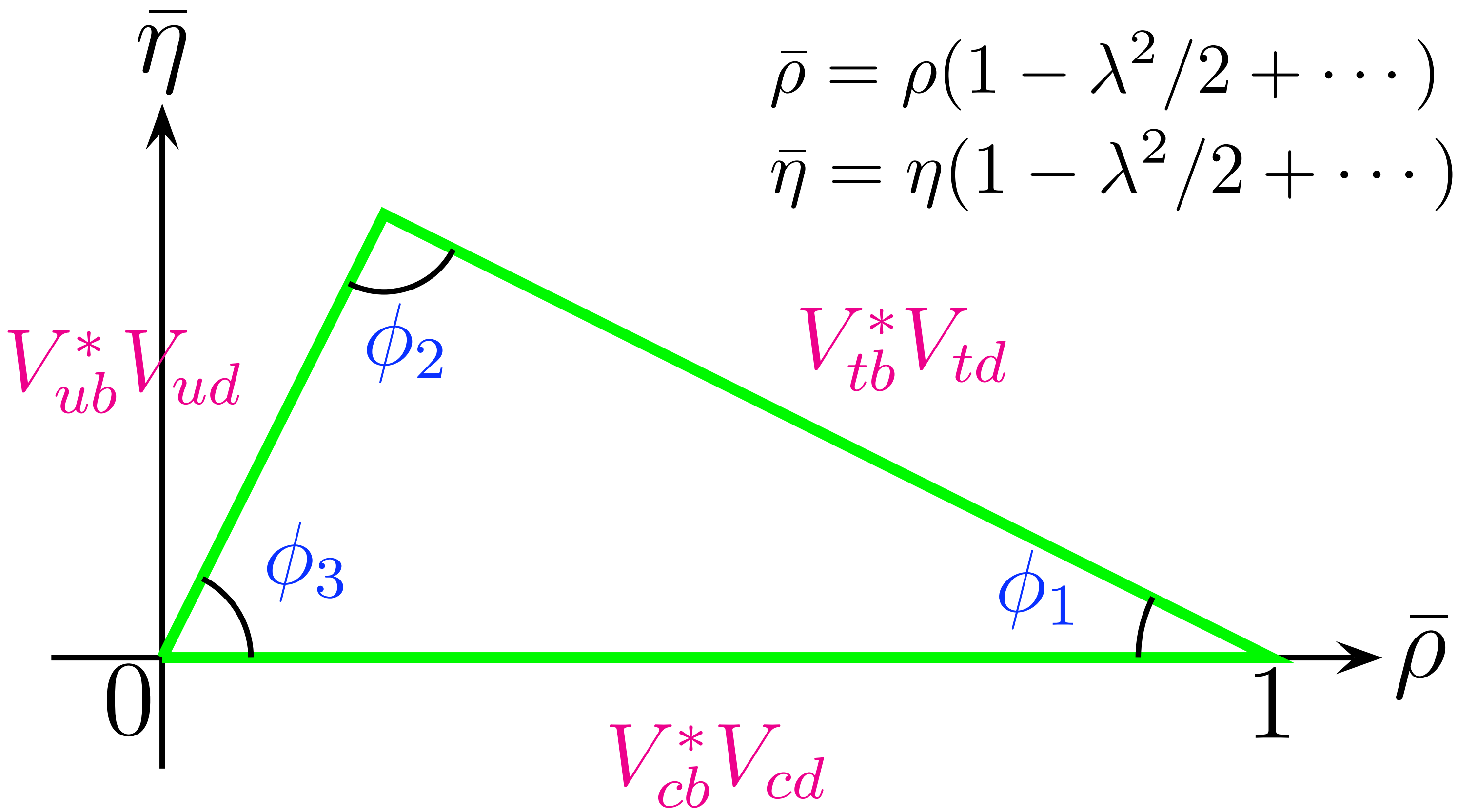

05/28/2019 23:59 - 05/29/2019 23:59 JST
Peak L 46.75 [10^32/cm^2/s] @2019-05-29 23:35
Int. L/day 171.75 / 204.10 [/pb]
HER I_peak: 550.2 [mA]
LER I_peak: 550.4 [mA]
β_x/y*: 100 / 3.00 [mm]
β_x/y*: 200 / 3.00 [mm]
n_b: 1576 Physics Run
n_b: 1576 Physics Run
HER
LER
Beam Current [A]
Lifetime [min]
Pressure [Pa]
L [10^32 cm^-2 s^-1]
recorded
delivered
Int. L [/pb]
Spec L [10^30]
0h0m0s
5/29/2019
3h
6h
9h
12h
15h
18h
21h

Unitarity triangle

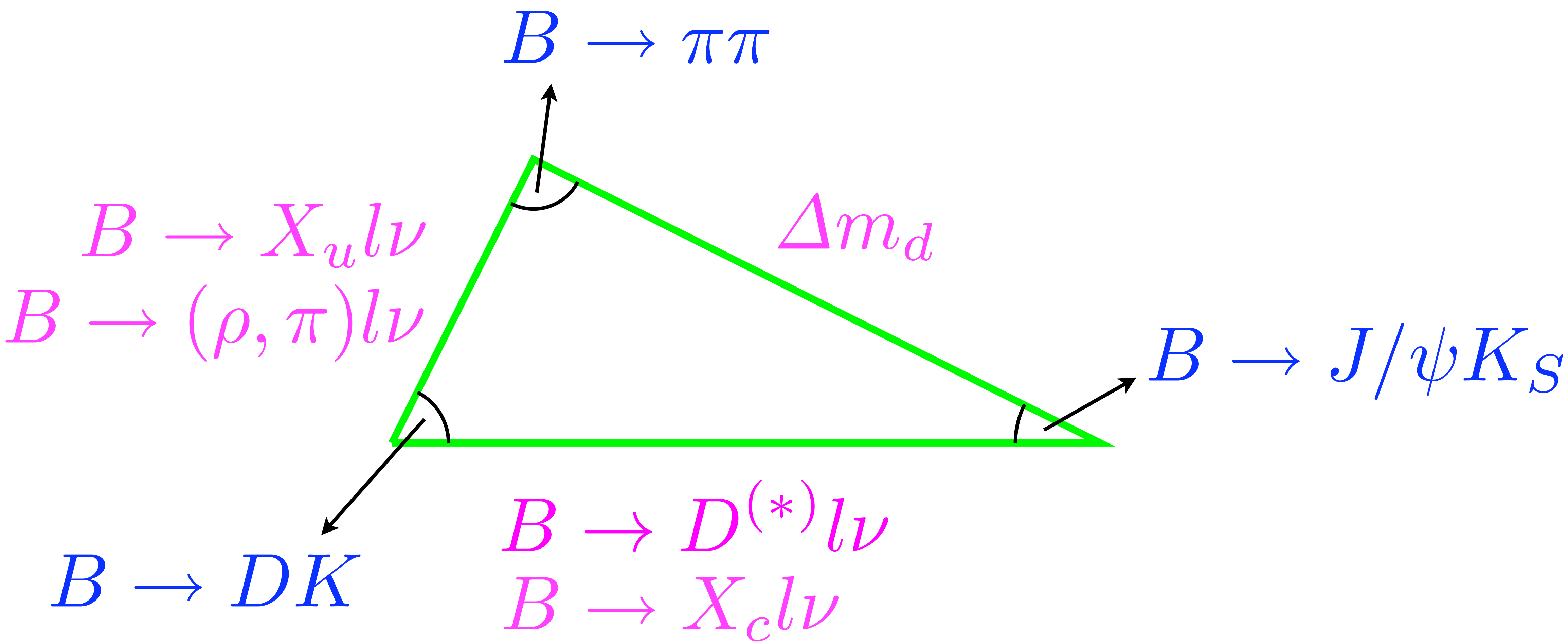
$$\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} W_\mu^+ \, \bar{u}_L \gamma^\mu V_{\mathrm{CKM}} d_L + \mathrm{h.\,c.}$$

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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



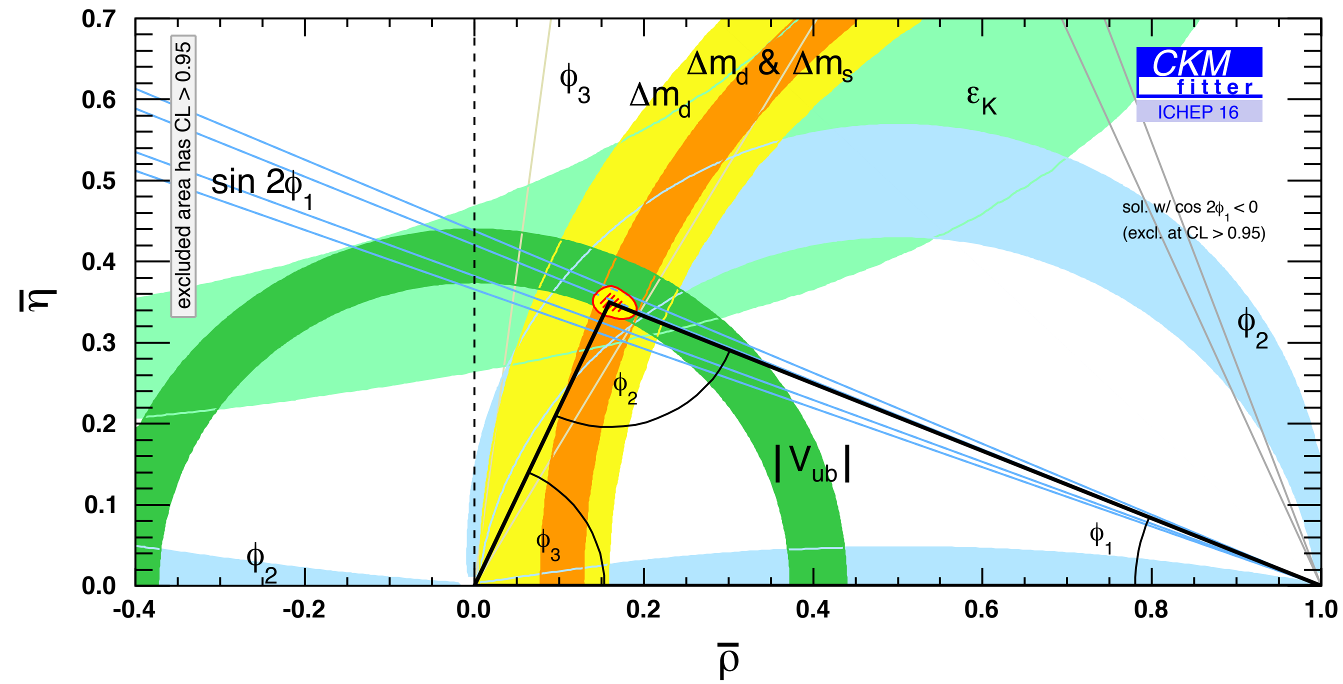
$$\bar{\rho} = \rho(1 - \lambda^2/2 + \cdots)$$
$$\bar{\eta} = \eta(1 - \lambda^2/2 + \cdots)$$



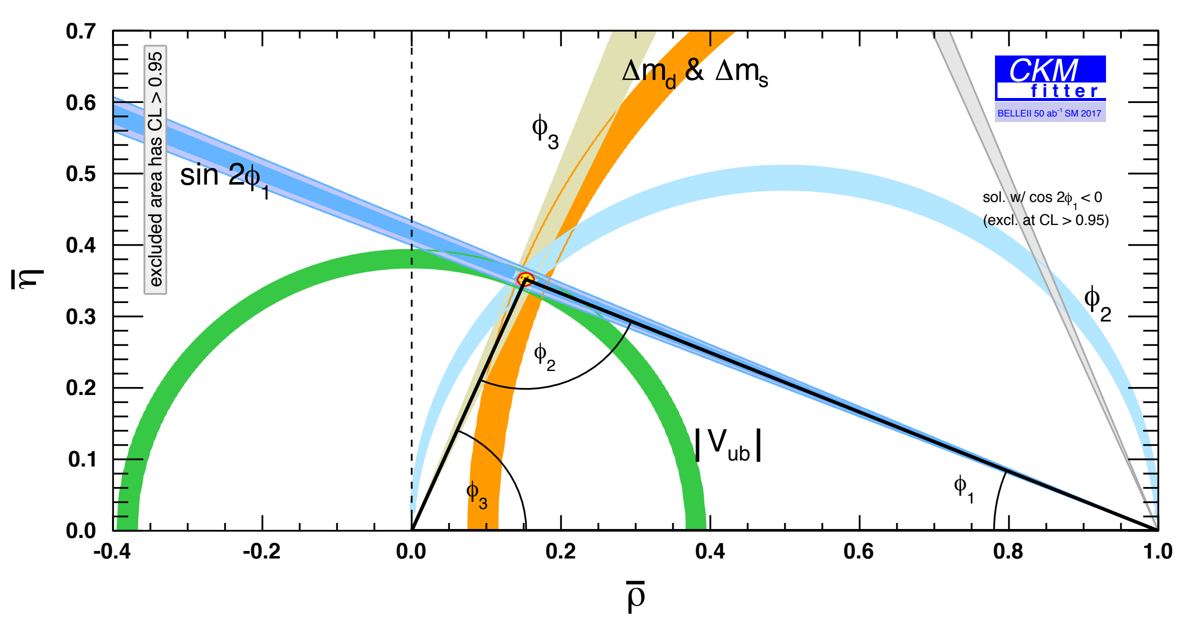
$B \to \pi\pi$
$B \to X_u l\nu$
$B \to (\rho, \pi) l\nu$
Δm_d
$B \to J/\psi K_S$
$B \to DK$
$B \to D^{(*)} l\nu$
$B \to X_c l\nu$

Belle II: UT global fit

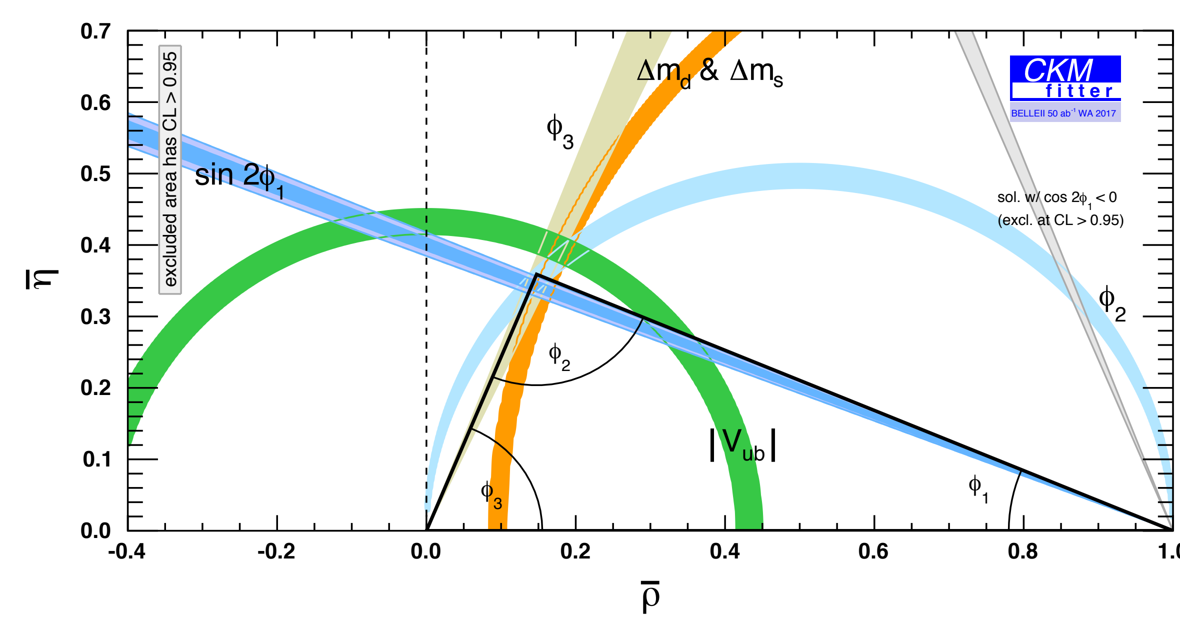
present



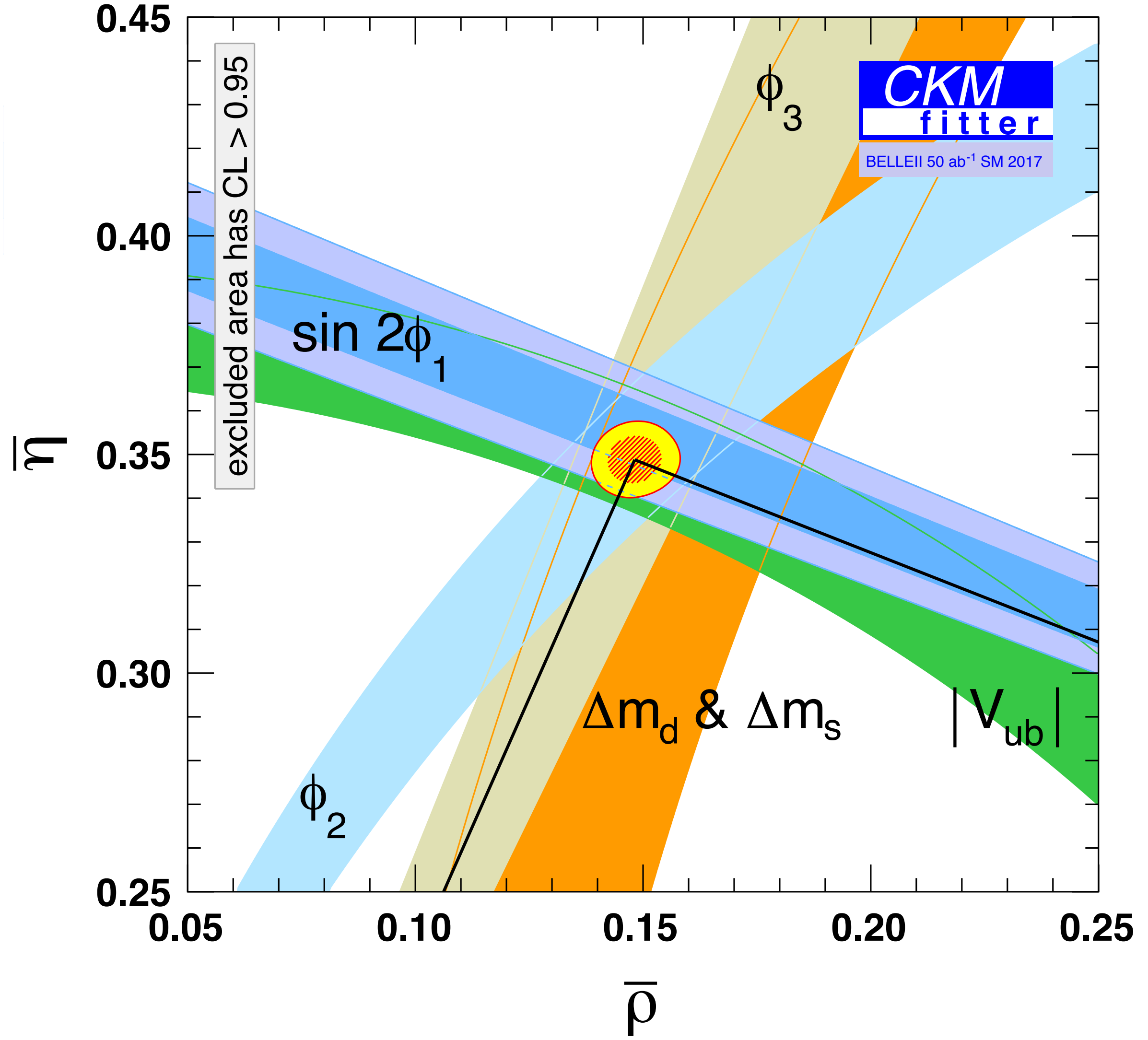
50/ab (2027)



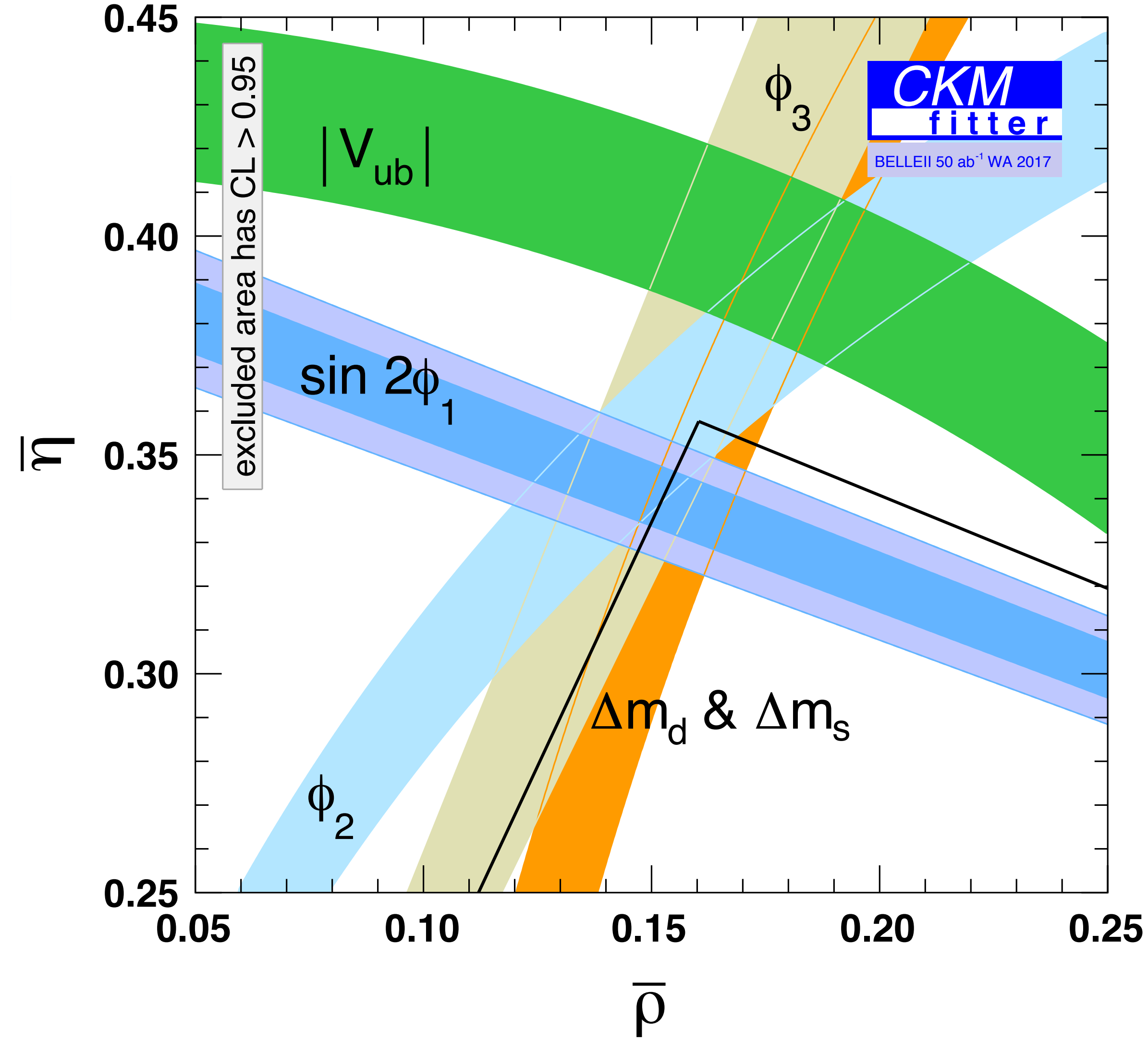
SM



present world av.



SM

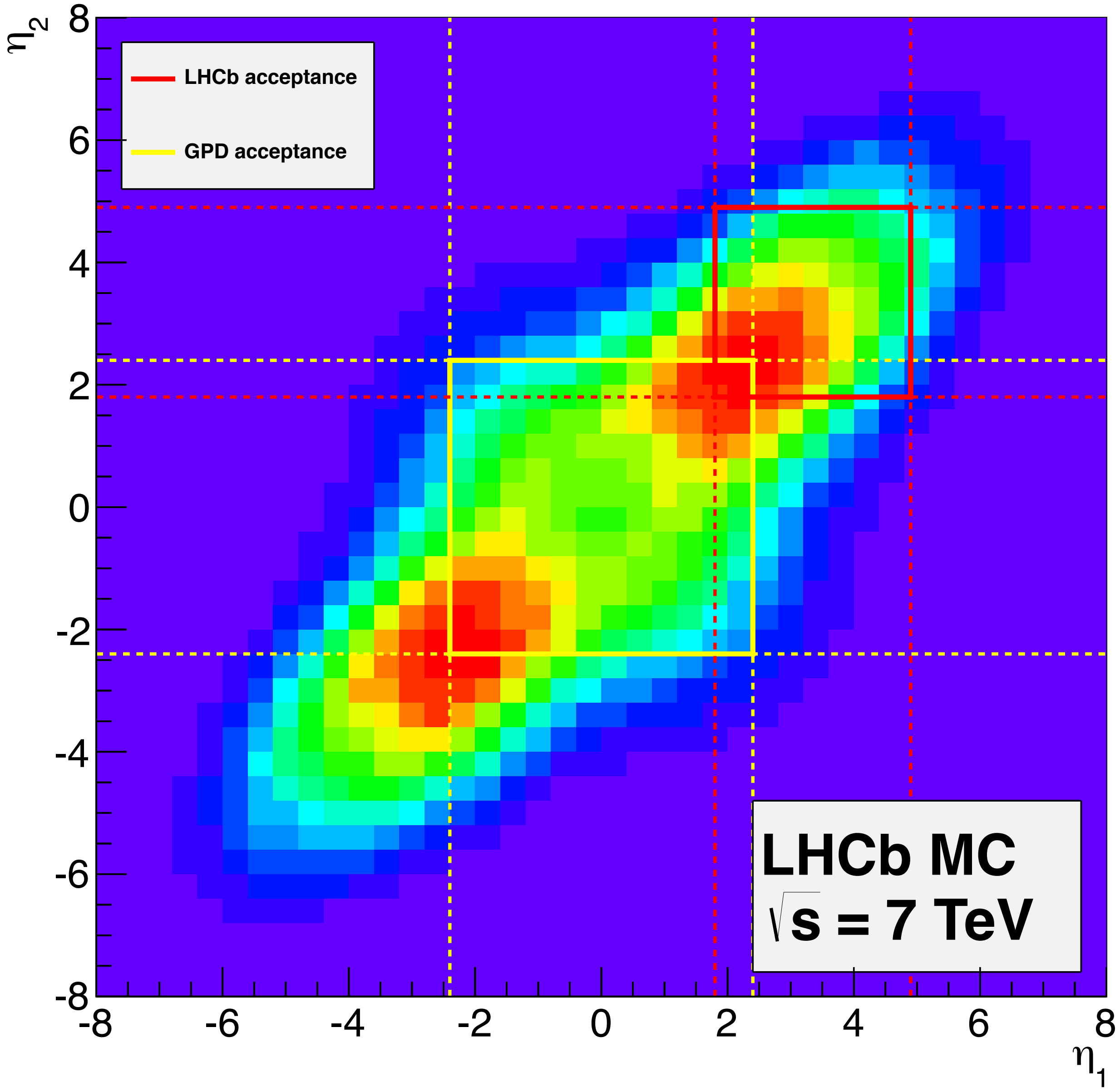


present world av.

LHCb

One of LHC experiments, dedicated to b physics

$pp \to b\bar{b}X$ peak in forward direction



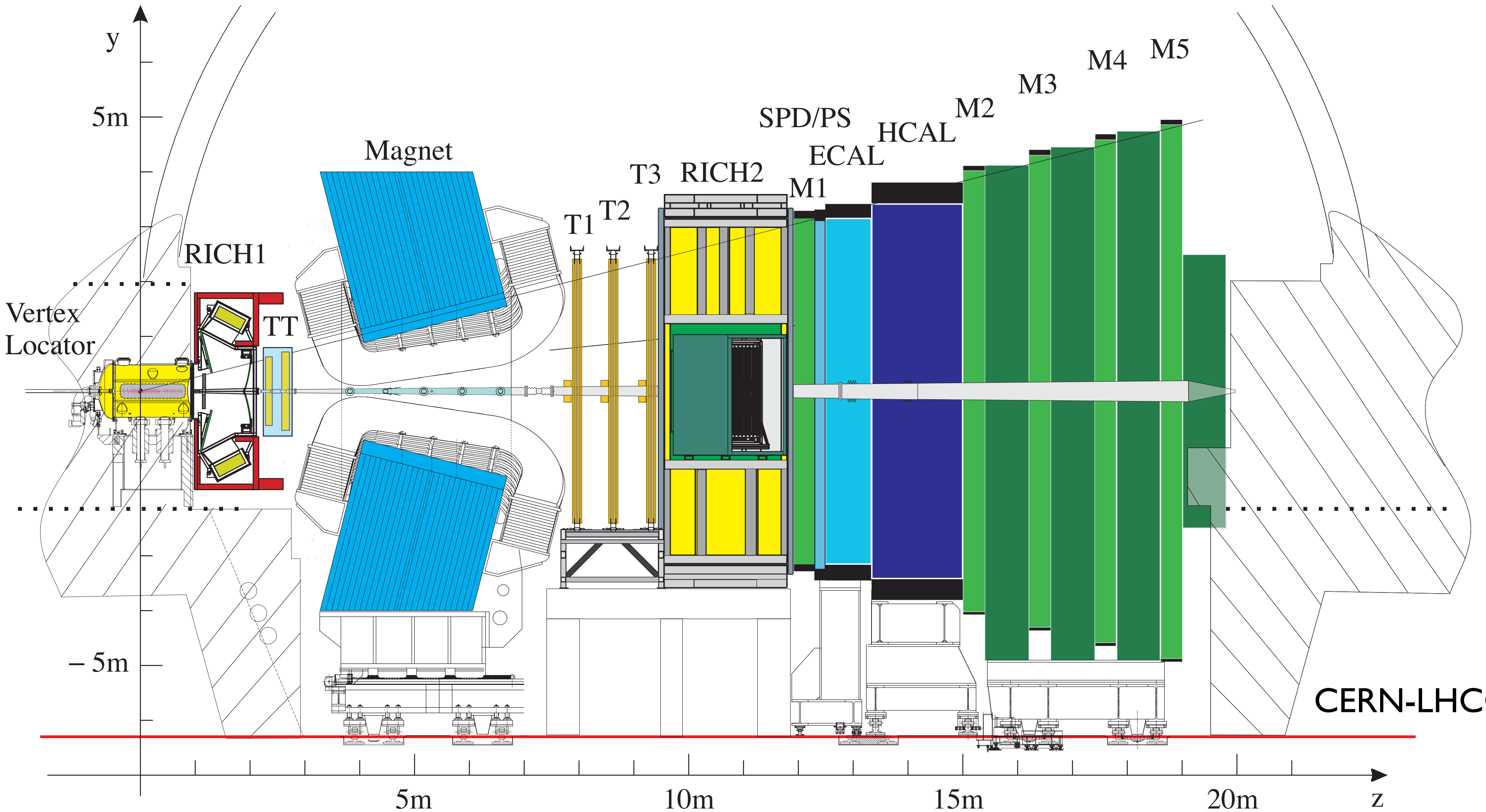
$$\eta := -\ln(\tan(\theta/2))$$

acceptance

$$2 < \eta < 5$$

$$(0.8^\circ < \theta < 16^\circ)$$

https://lhcb.web.cern.ch/lhcb/speakersbureau/html/bb_ProductionAngles.html



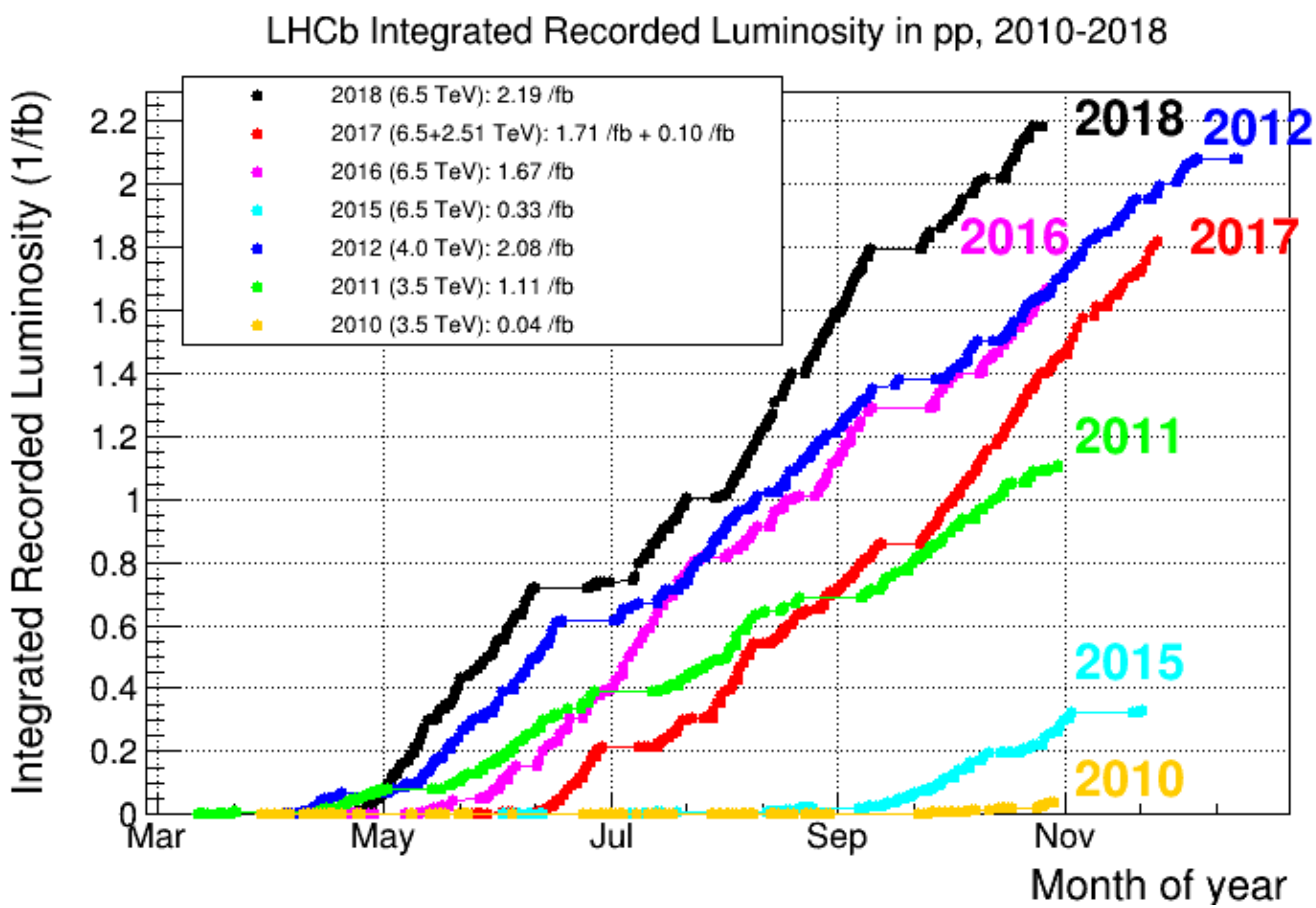
CERN-LHCC-2003-030

large boost, good vertex resolution

$B_s\,, \Lambda_b$

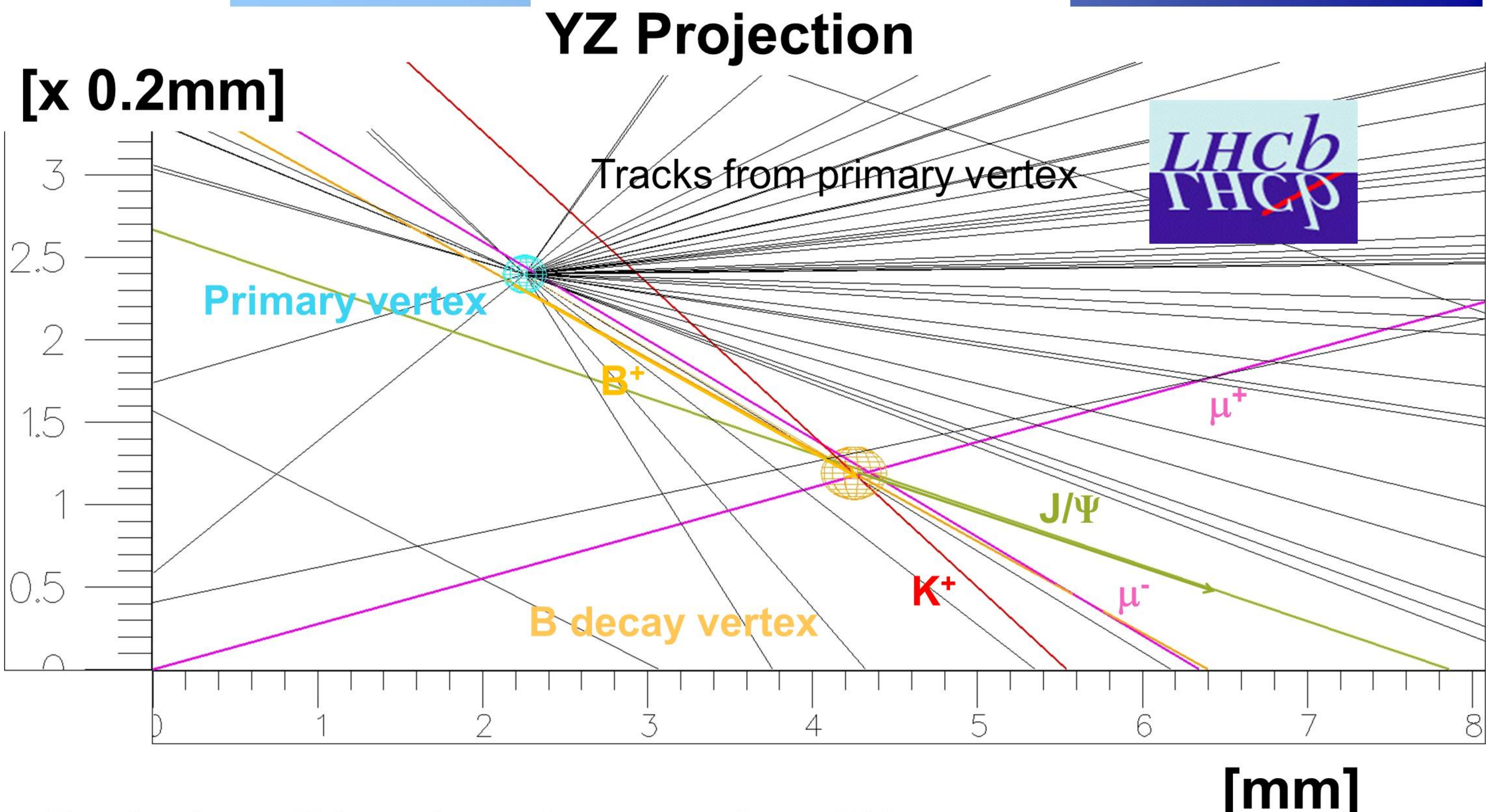
$$\sigma(pp \to b\bar{b}X,\ 2 < \eta < 5,\ \sqrt{s} = 7\ \mathrm{TeV}) = 72 \pm 0.3 \pm 6.8\ \mu\mathrm{b}$$

$$7 \times 10^{10}\ \mathrm{events/fb}^{-1}$$



http://lhcb-public.web.cern.ch/lhcb-public/Images2018/IntRecLumiR12.png

$B^+ \to J/\Psi\ K^+$

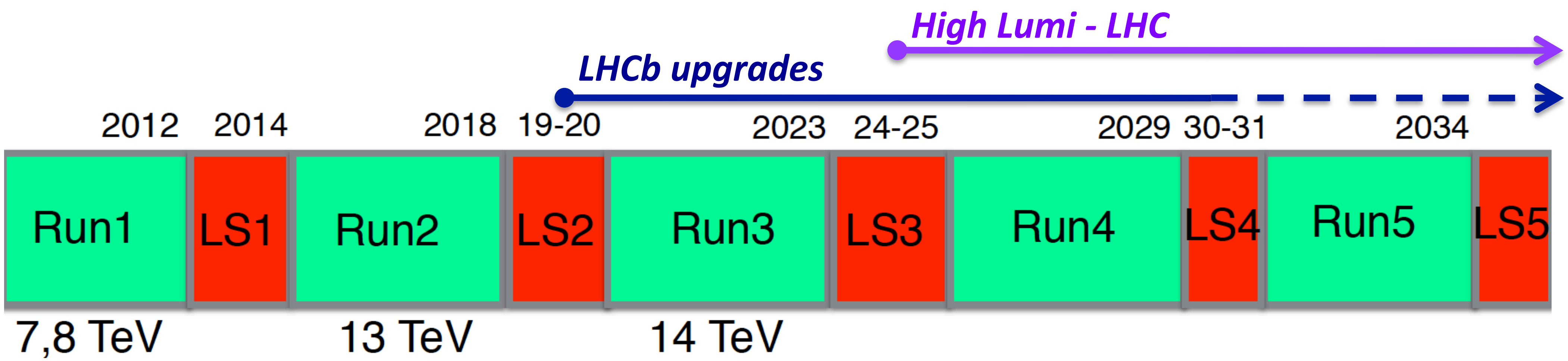


Tracks from PV are forced to come from PV

http://lhcb-public.web.cern.ch/lhcb-public/Welcome_270811.html

the next years @ LHCb

- upgrade installation started this January 2019 to be ready at the end of Long Shutdown 2 (LS2)
- restart data taking in 2021 at Run3
- higher instantaneous luminosity ➔ from 2×10^{32} $cm^{-2}s^{-1}$ to 2×10^{33} $cm^{-2}s^{-1}$



- more visible interactions per bunch crossing ➔ from 1 to about 5
- upgrade detector qualified to accumulate 50 fb^{-1} at the end of Run4, ***LHCb-TDR{13,14,15,66}***
- LS3: consolidation of the detector
- LS4: to take full advantage of the High Lumi-LHC, $\mathcal{L}$ up to 1-2 $\times10^{34}$ $cm^{-2}s^{-1}$, the collaboration is proposing a major upgrade of the detector with the intent to collect 300 fb^{-1} at the end of Run5, ***CERN/LHCC 2017-003, CERN/LHCC 2018-027***

Some observed anomalies

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

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

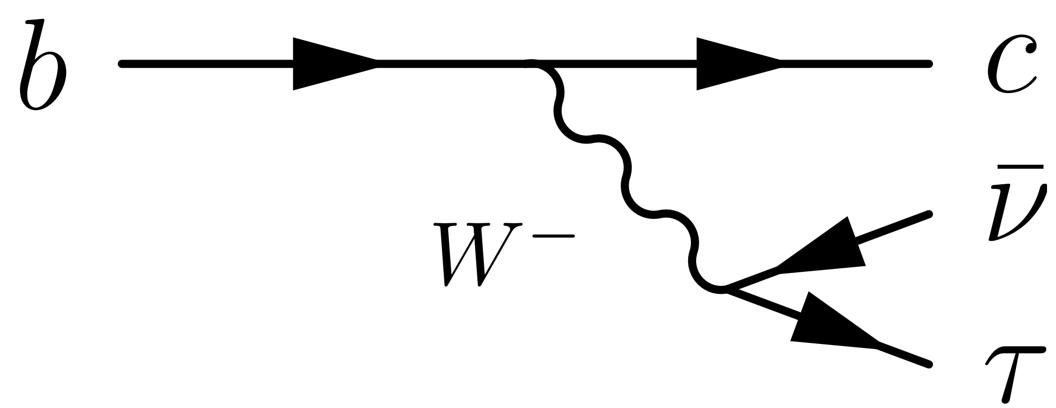
Br ~ 0.7+1.3 % in the SM

Not rare, but two or more missing neutrinos

Data available since 2007 (Belle, BABAR, LHCb)

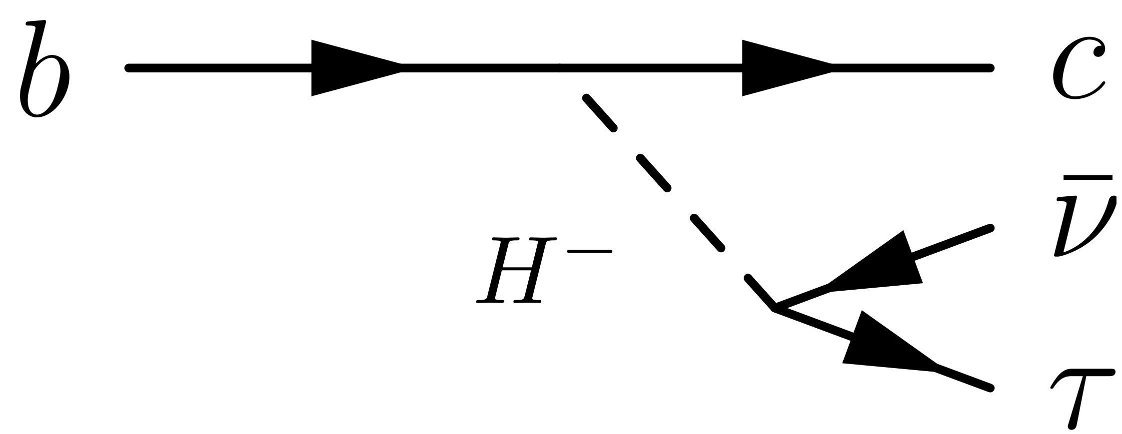
Archetypal theoretical motivation

B. Grzadkowski, W.S. Hou, PLB283, 427 (1992)



SM: gauge coupling

lepton universality



Type-II 2HDM (SUSY)

Yukawa coupling

$\propto m_b m_\tau \tan^2\beta$

Lepton Flavor (Non-)Universality

Ratio of branching fractions

$$R(D^{(*)}) := \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell\bar{\nu}_\ell)} \qquad \ell = e, \mu$$

Predictable in the SM: Source of LFNU = mass

Smaller theoretical errors in the SM (and beyond)

No Vcb in the ratio

MT, Z. Phys. C67, 321 (1995)

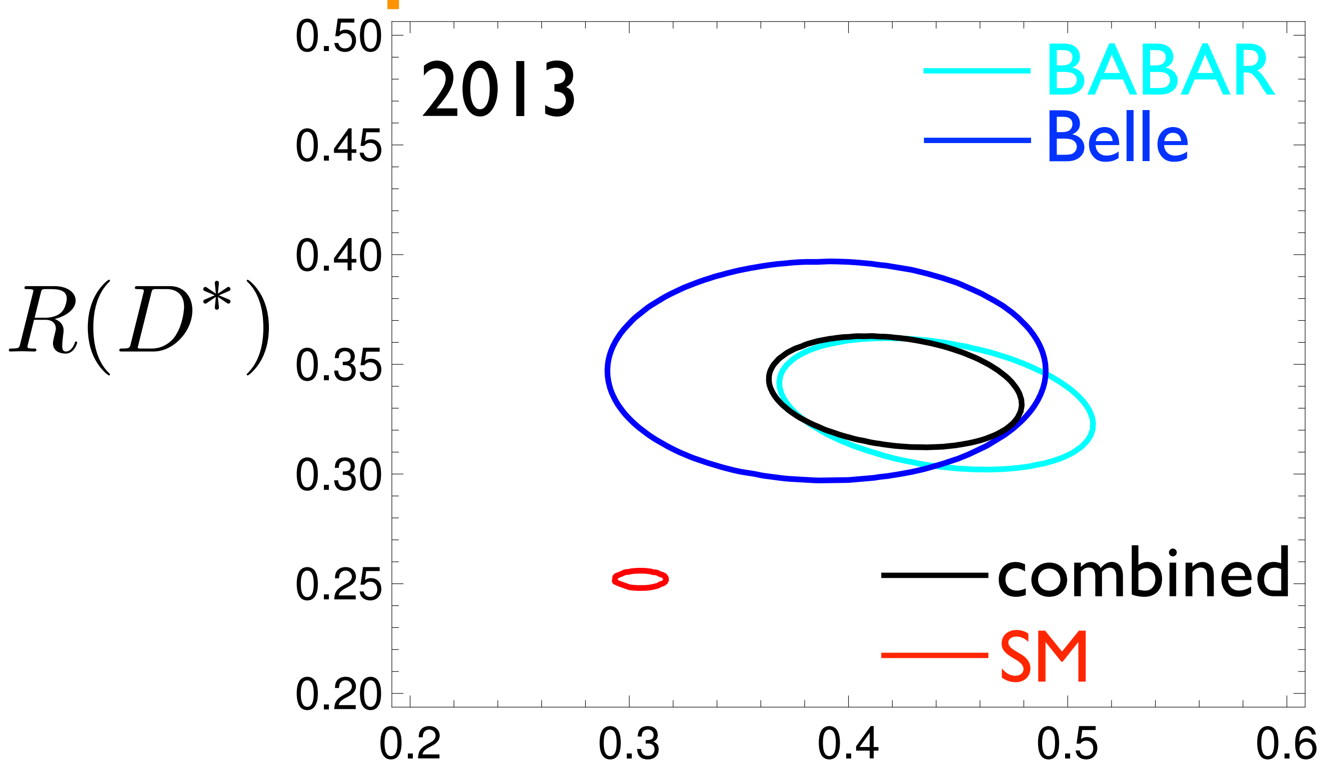
Form factor uncertainty tends to cancel.

Controlled by

$\bar{B} \to D^{(*)}\ell\bar{\nu}_\ell$ experimental data, lattice QCD,

Heavy Quark Effective Theory, QCD sum rule

Experiments and status of the SM

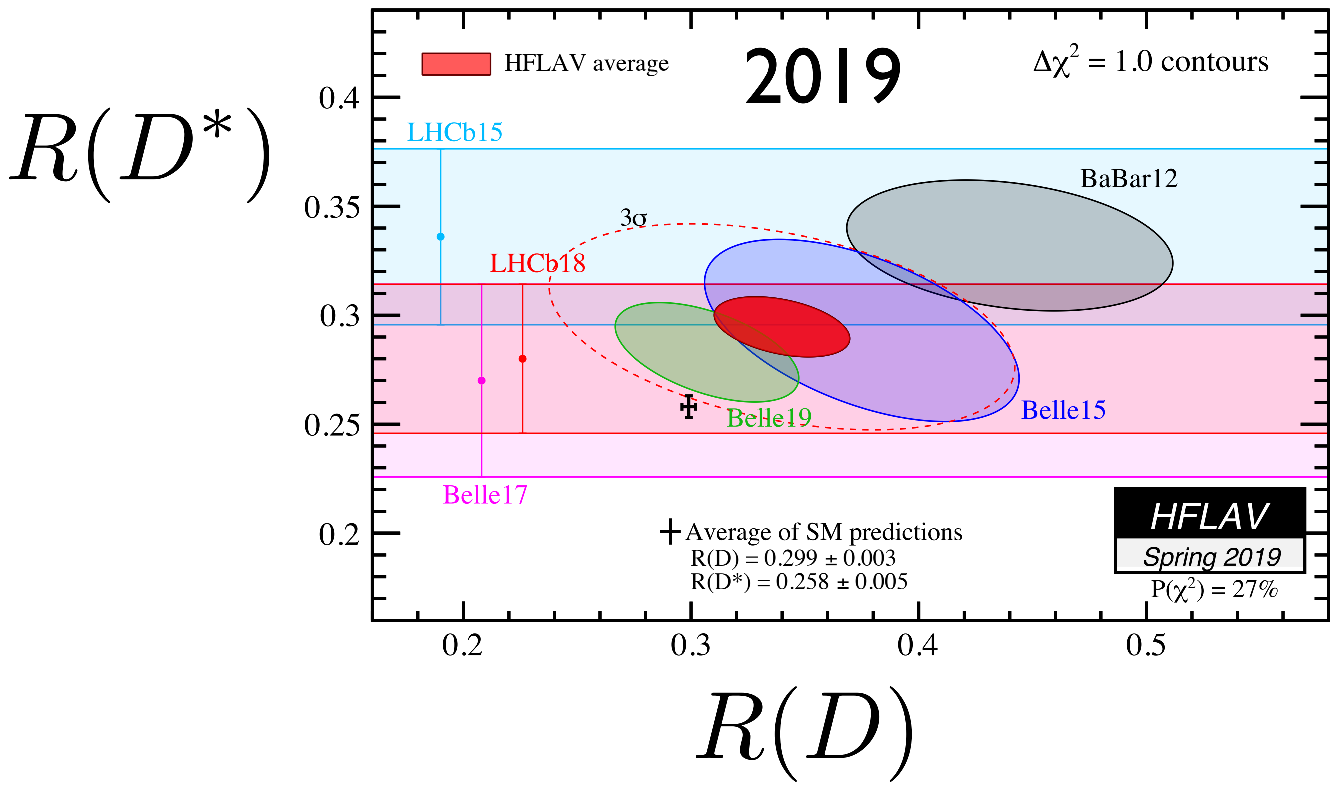


$$R(D^{(*)}) := \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell\bar{\nu}_\ell)}$$

$$R(D) = 0.421 \pm 0.058$$
$$R(D^*) = 0.337 \pm 0.025$$

~3.5 σ

Y. Sakaki, MT, A. Tayduganov, R. Watanabe, PRD88, 094012 (2013)



$$R(D) = 0.340 \pm 0.027 \pm 0.013$$
$$R(D^*) = 0.295 \pm 0.011 \pm 0.008$$

~3.1 σ HFLAV

Model-independent approach

MT, R.Watanabe, arXiv1212.1878, PRD87.034028(2013).

Effective Lagrangian for $b \to c\tau\bar{\nu}$

all possible 4f operators with LH neutrinos

$$-\mathcal{L}_{\rm eff} = 2\sqrt{2}G_F V_{cb} \sum_{l=e,\mu,\tau} \left[(\delta_{l\tau} + C^l_{V_1})\mathcal{O}^l_{V_1} + C^l_{V_2}\mathcal{O}^l_{V_2} + C^l_{S_1}\mathcal{O}^l_{S_1} + C^l_{S_2}\mathcal{O}^l_{S_2} + C^l_T\mathcal{O}^l_T\right]$$

SM

$$\mathcal{O}^l_{V_1} = \bar{c}_L\gamma^\mu b_L\,\bar{\tau}_L\gamma_\mu\nu_{Ll}\,,$$ SM-like, RPV, LQ, W'

$$\mathcal{O}^l_{V_2} = \bar{c}_R\gamma^\mu b_R\,\bar{\tau}_L\gamma_\mu\nu_{Ll}\,,$$ RH current

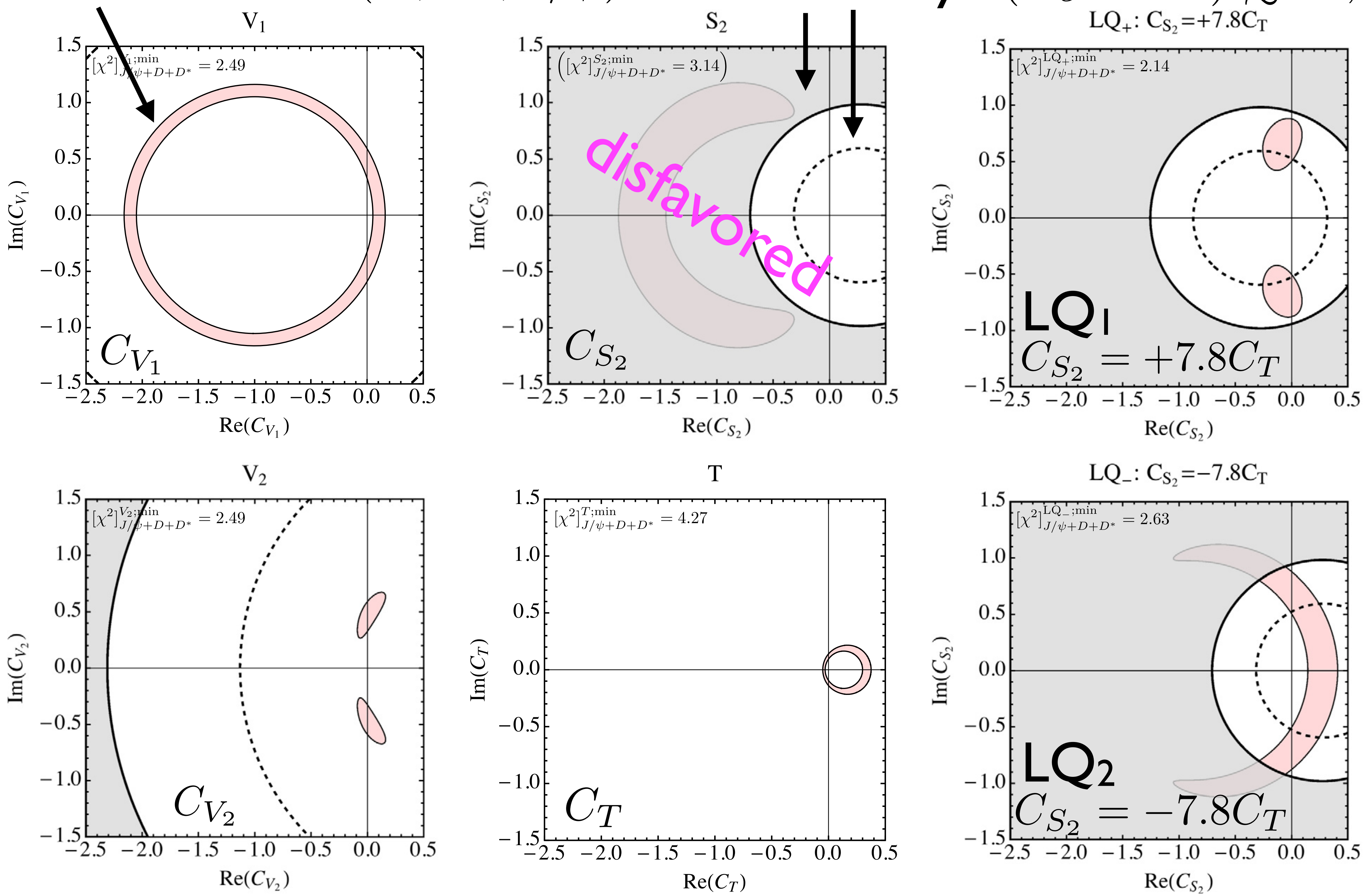
$$\mathcal{O}^l_{S_1} = \bar{c}_L b_R\,\bar{\tau}_R\nu_{Ll}\,,$$ charged Higgs II, RPV, LQ

$$\mathcal{O}^l_{S_2} = \bar{c}_R b_L\,\bar{\tau}_R\nu_{Ll}\,,$$ charged Higgs III, LQ

$$\mathcal{O}^l_T = \bar{c}_R\sigma^{\mu\nu} b_L\,\bar{\tau}_R\sigma_{\mu\nu}\nu_{Ll}$$ LQ

Allowed regions in complex Cx plane

Allowed at 95% CL$(D, D^*, J/\psi)$ **Excluded by** $\mathcal{B}(B_c \to \tau\bar{\nu}) \lesssim 30, 10\ \%$



R. Watanabe, PLB776 (2018) 5

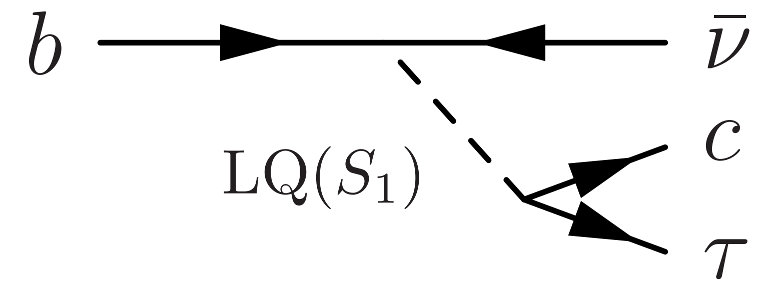
Leptoquark models

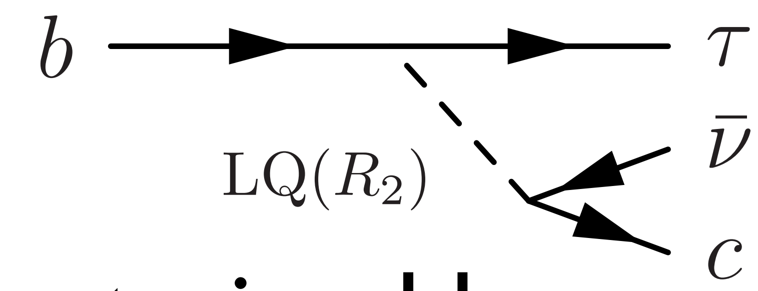
Y. Sakaki, MT, A. Tayduganov, R. Watanabe
arXiv:1309.0301; PRD88, 094012 (2013)

Six of ten types of LQ contribute.

Buchmüller, Rückl, Wyler
PLB191 (1987) 442

	S_1	S_3	V_2	R_2	U_1	U_3
spin	0	0	1	0	1	1
$F = 3B + L$	-2	-2	-2	0	0	0
$SU(3)_c$	3^*	3^*	3^*	3	3	3
$SU(2)_L$	1	3	2	2	1	3
$U(1)_{Y=Q-T_3}$	1/3	1/3	5/6	7/6	2/3	2/3





$$C^l_{V_1} = \frac{1}{2\sqrt{2}G_F V_{cb}} \sum_{k=1}^{3} V_{k3}\left[\frac{g^{kl}_{1L} g^{23*}_{1L}}{2M^2_{S_1^{1/3}}} - \frac{g^{kl}_{3L} g^{23*}_{3L}}{2M^2_{S_3^{1/3}}} + \frac{h^{2l}_{1L} h^{k3*}_{1L}}{M^2_{U_1^{2/3}}} - \frac{h^{2l}_{3L} h^{k3*}_{3L}}{M^2_{U_3^{2/3}}}\right],$$

constrained by $\bar{B} \to X_s \nu \bar{\nu}$

$$C^l_{V_2} = 0,$$

$$C^l_{S_1} = \frac{1}{2\sqrt{2}G_F V_{cb}} \sum_{k=1}^{3} V_{k3}\left[-\frac{2 g^{kl}_{2L} g^{23*}_{2R}}{M^2_{V_2^{1/3}}} - \frac{2 h^{2l}_{1L} h^{k3*}_{1R}}{M^2_{U_1^{2/3}}}\right],$$

disfavored

$$C^l_{S_2} = \frac{1}{2\sqrt{2}G_F V_{cb}} \sum_{k=1}^{3} V_{k3}\left[-\frac{g^{kl}_{1L} g^{23*}_{1R}}{2M^2_{S_1^{1/3}}} - \frac{h^{2l}_{2L} h^{k3*}_{2R}}{2M^2_{R_2^{2/3}}}\right],$$

$$C^l_{T} = \frac{1}{2\sqrt{2}G_F V_{cb}} \sum_{k=1}^{3} V_{k3}\left[\frac{g^{kl}_{1L} g^{23*}_{1R}}{8M^2_{S_1^{1/3}}} - \frac{h^{2l}_{2L} h^{k3*}_{2R}}{8M^2_{R_2^{2/3}}}\right],$$

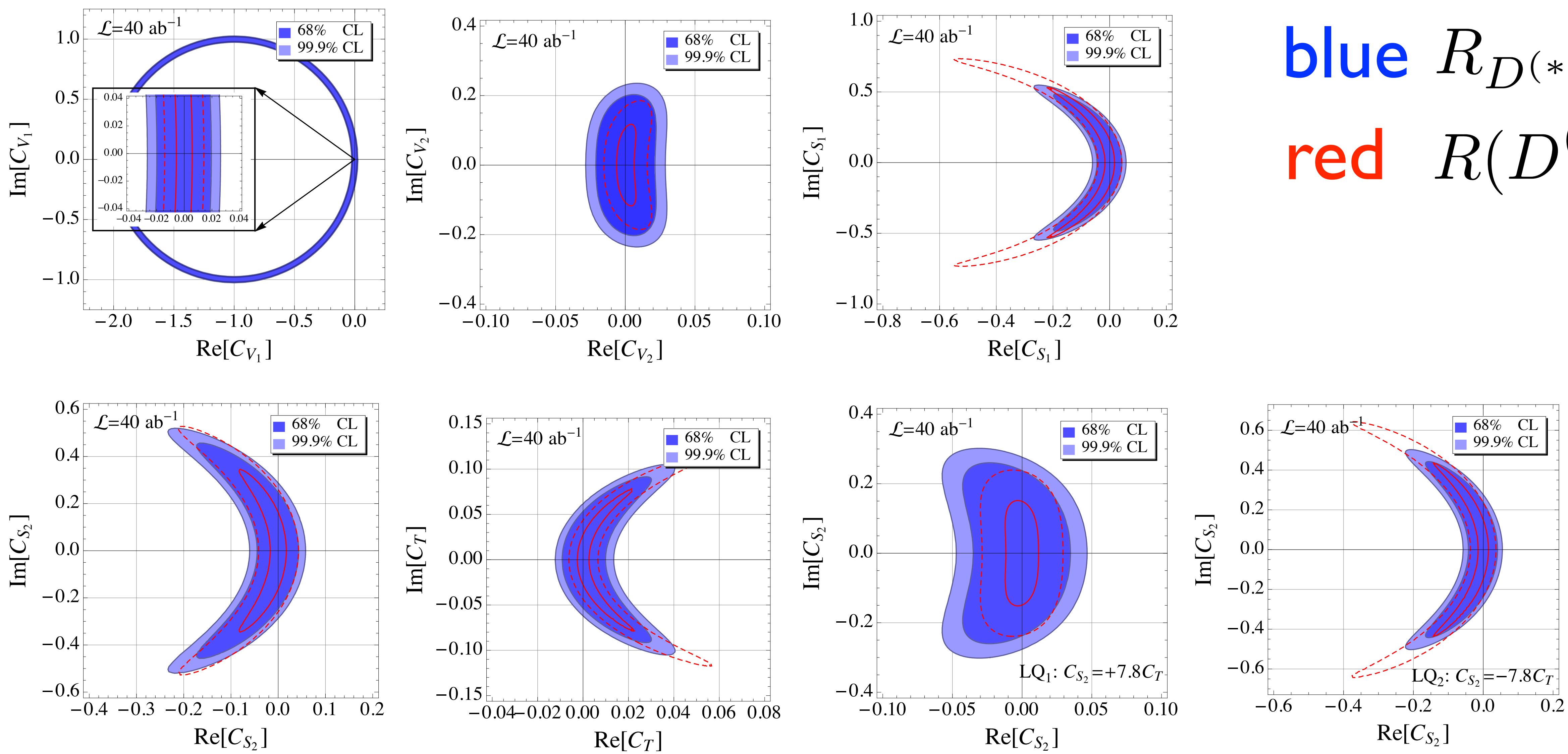
$$C_{S_2}(m_{\mathrm{LQ}}) = \pm 4 C_T(m_{\mathrm{LQ}})$$

RG

$$C_{S_2}(m_b) = \pm 7.8 C_T(m_b)$$

Belle II sensitivity at 40/ab

Assuming exp. = SM for $R(D),\ R(D^*)$



blue $R_{D^{(*)}}(q^2)$

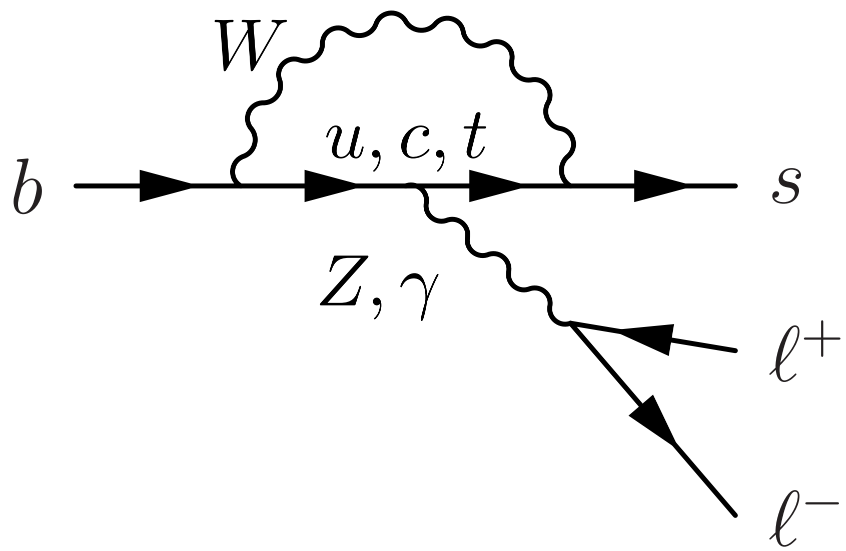
red $R(D^{(*)})$

$$M_{\rm NP} \equiv (2\sqrt{2} G_F V_{cb} C_X)^{-1/2}$$

$$\gtrsim \underset{V_{1,2}}{5(7)},\ \underset{S_{1,2}}{5(6)},\ \underset{T}{7(10)},\ \underset{\mathrm{LQ}_1}{5(7)},\ \underset{\mathrm{LQ}_2}{5(6)} \quad \text{TeV}$$

$$b \to s\ell^+\ell^-$$

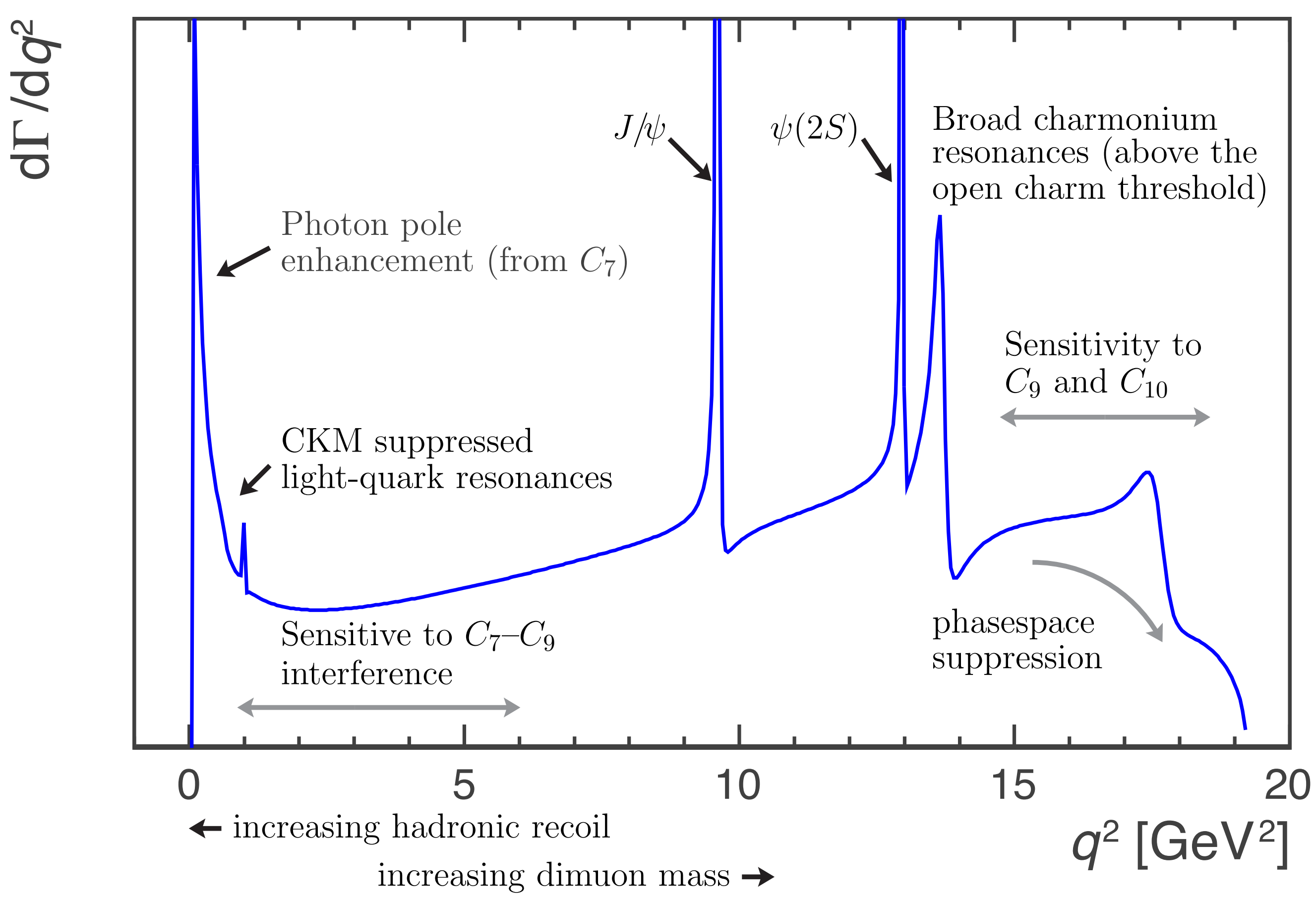
FCNC at one-loop in the SM



+ box diagram

top dominates

$b \to s\ell^+\ell^-$ spectrum



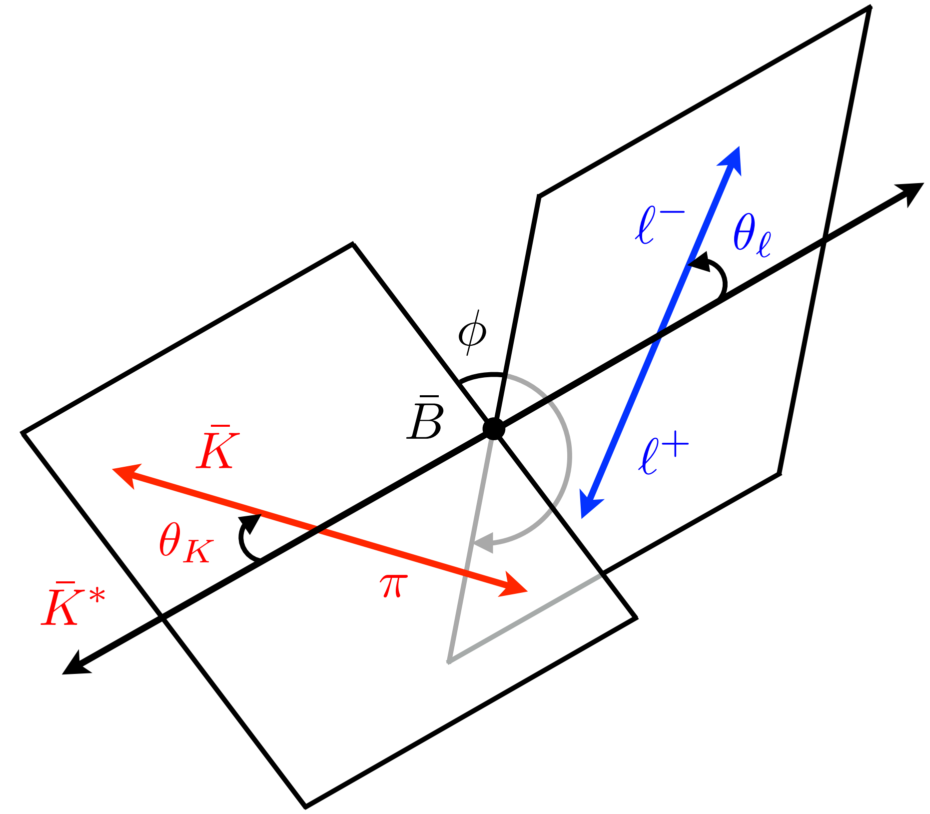
observed processes

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

$$B_s \to \phi\ell^+\ell^-$$

$$B_s \to \mu^+\mu^-$$

Angular distribution



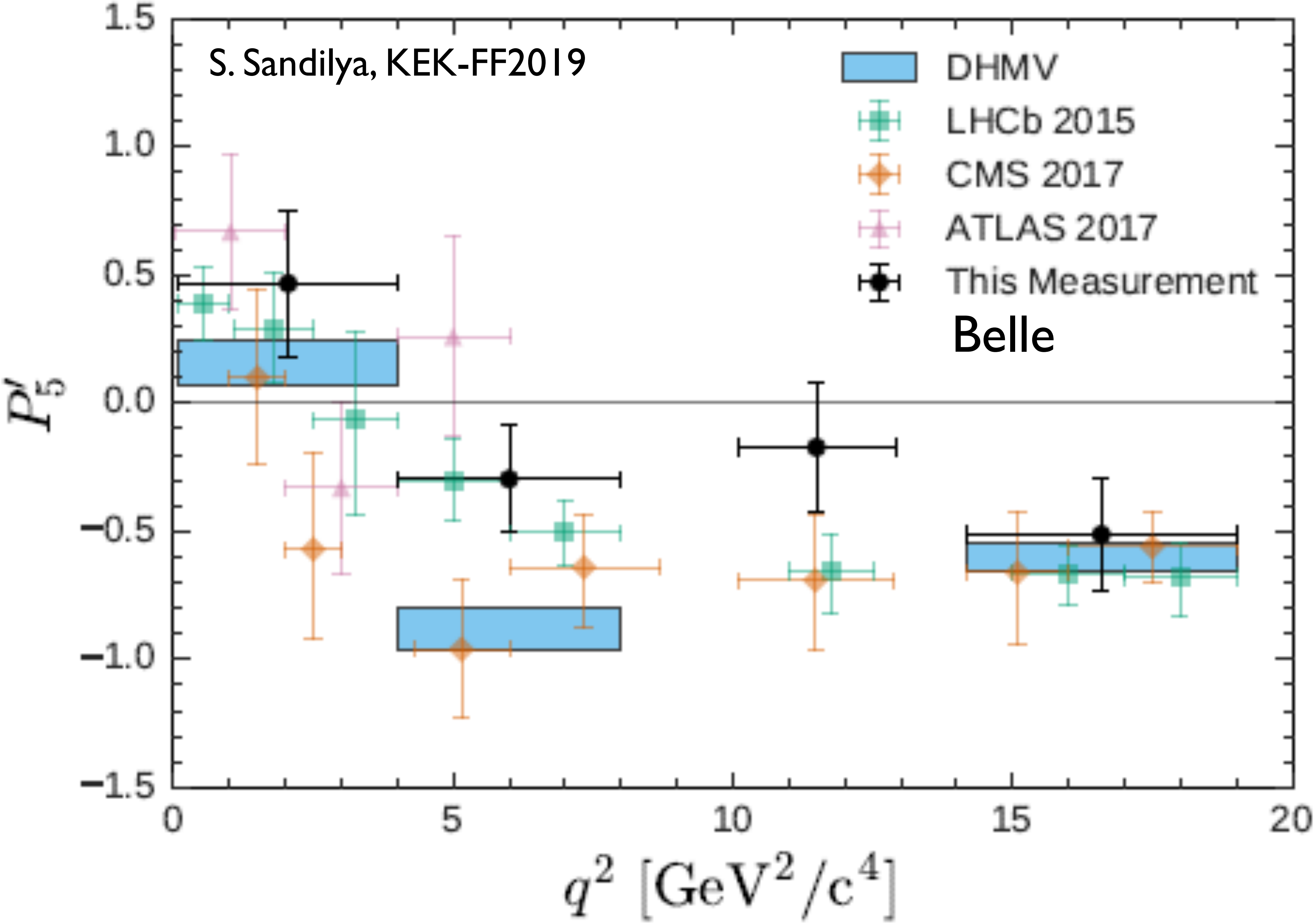
$$\bar{B} \to \bar{K}^*(\to \bar{K}\pi)\ell^+\ell^-$$

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi} I(q^2, \theta_\ell, \theta_K, \phi)$$

$$\begin{aligned} I(q^2, \theta_\ell, \theta_K, \phi) = {} & I_1^s \sin^2\theta_K + I_1^c \cos^2\theta_K + (I_2^s \sin^2\theta_K + I_2^c \cos^2\theta_K) \cos 2\theta_\ell \\ & + I_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + I_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi \\ & + I_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + (I_6^s \sin^2\theta_K + I_6^c \cos^2\theta_K) \cos\theta_\ell \\ & + I_7 \sin 2\theta_K \sin\theta_\ell \sin\phi + I_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi \\ & + I_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi\,. \end{aligned}$$

$$S_j = (I_j + \bar{I}_j) \Big/ \frac{d\Gamma}{dq^2} \qquad P_5' = \frac{S_5}{2\sqrt{-S_{2s}S_{2c}}}$$

E. Kou et al.,"The Belle II Physics book", 1808.10567.



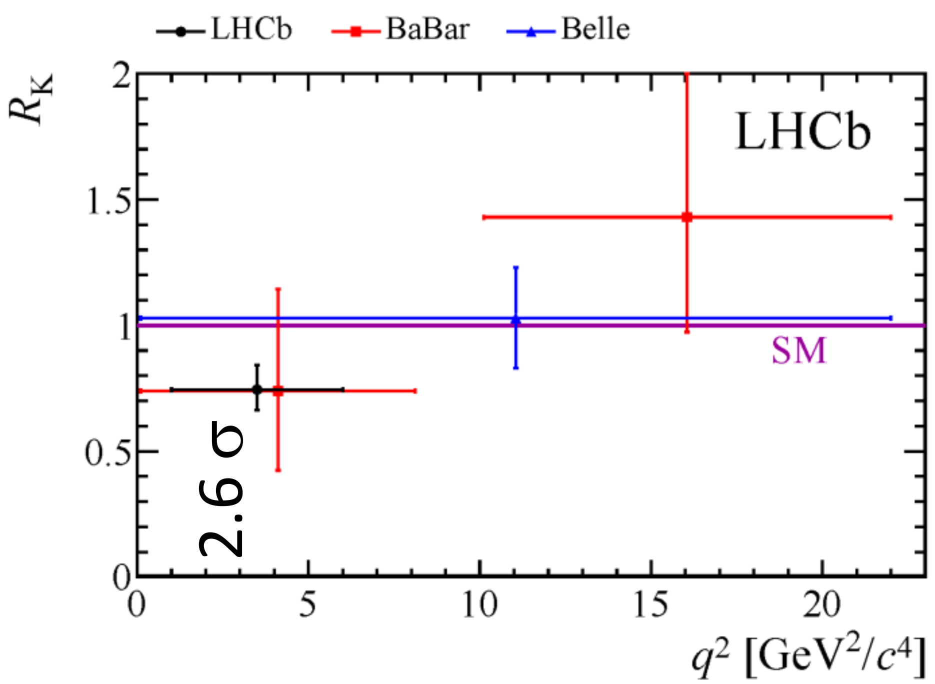
2.5σ tension

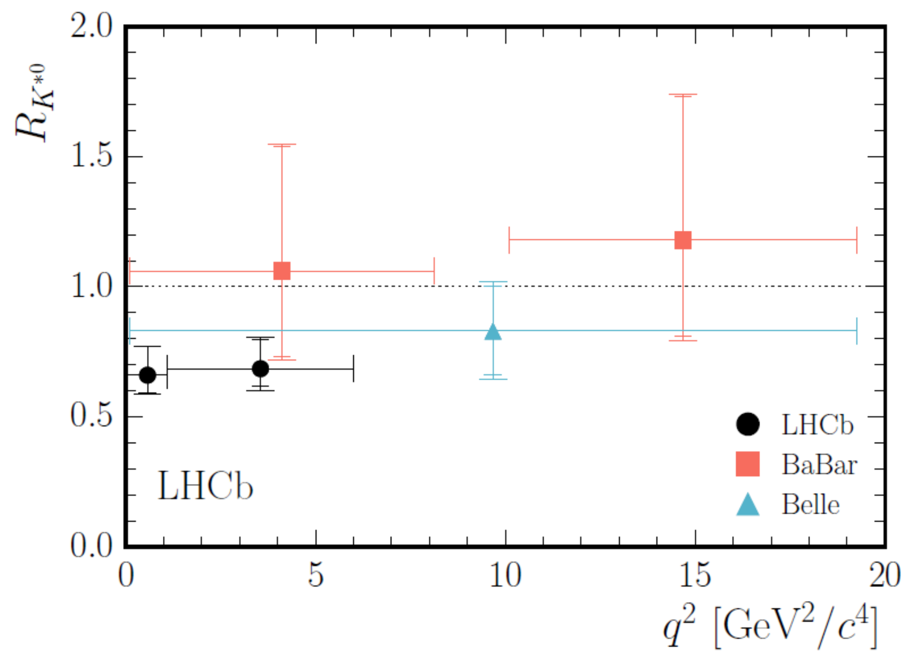
NP or QCD in charm loop?

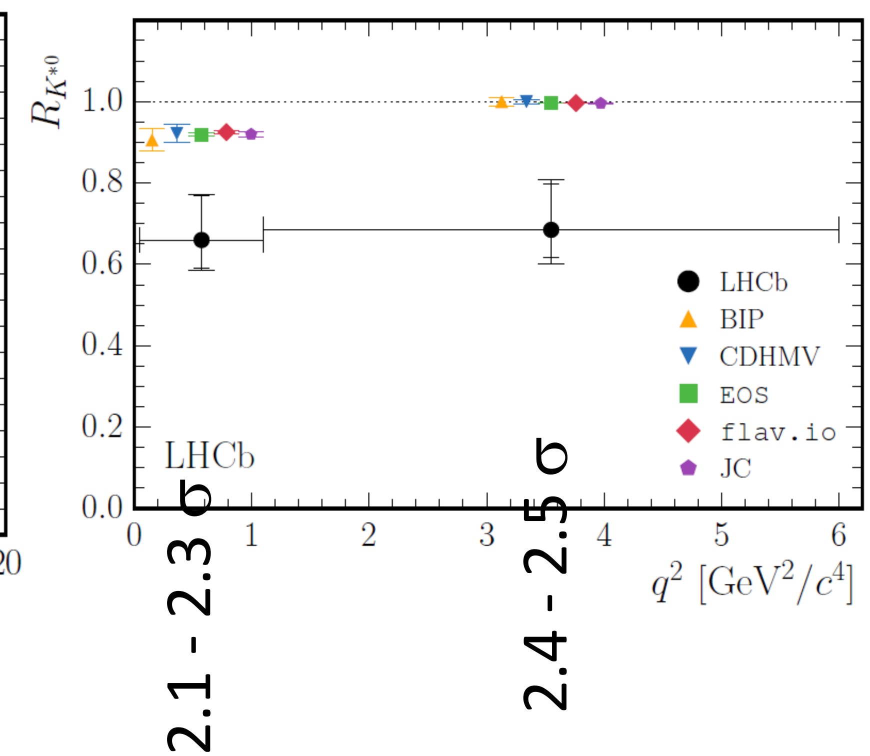
Lepton flavor universality (LFU)

$$R_{K^{(*)}} = \frac{\int dq^2 \frac{d\Gamma(B\to K^{(*)}\mu^+\mu^-)}{dq^2}}{\int dq^2 \frac{d\Gamma(B\to K^{(*)}e^+e^-)}{dq^2}}$$

in various q^2 ranges







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

LHCb, JHEP08(2017)055

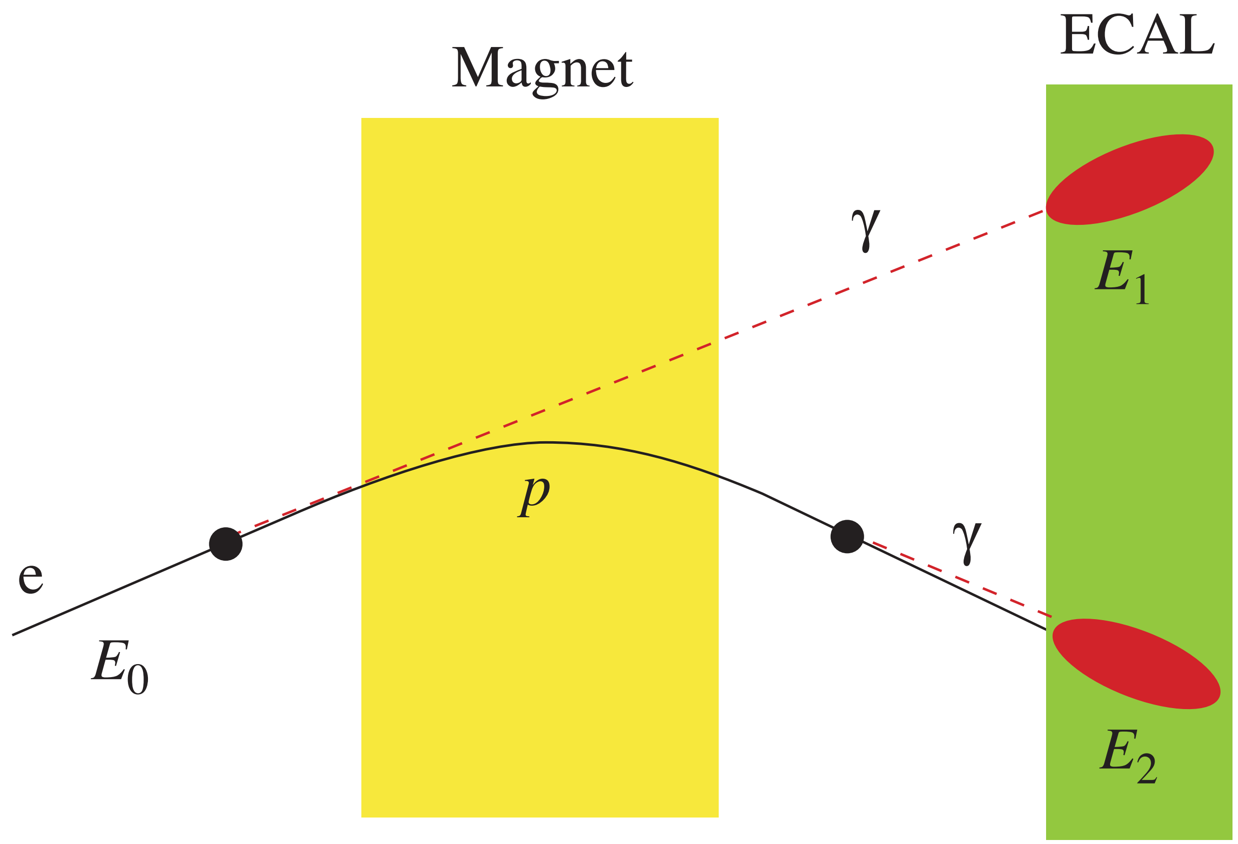
Belle, Phys. Rev. Lett. 103 (2009) 171801

BaBar, Phys. Rev. D 86 (2012) 032012

[BIP, EPJC 76 440] [CDHMV, JHEP04(2017)016]
[EOS, PRD 95 035029] [flav.io, EPJC 77 377] [JC, PRD93 014028]

S. Sandilya, KEK-FF2019

electron reconstruction in LHCb



tested with J/ψ, $q^2 = m^2_{J/\psi} \sim 10\ \mathrm{GeV}^2$

anomalies observed in lower q^2 bins

the lowest q^2 bin of R_{K^*} dominated by $B \to K^* \gamma$

Effective hamiltonian

$$\mathcal{H}_{\rm eff} = -2\sqrt{2} G_F V_{tb} V_{ts}^* \sum_i C_i O_i$$

$$O_7 = \frac{e}{16\pi^2} m_b \, \bar{s} \sigma_{\mu\nu} P_R b \, F^{\mu\nu} \qquad O_{7'} = O_7(R \to L)$$

$$O_{9\ell} = \frac{\alpha}{4\pi} \bar{s} \gamma_\mu P_L b \, \bar{\ell} \gamma^\mu \ell \qquad O_{9'\ell} = O_{9\ell}(L \to R)$$

$$O_{10\ell} = \frac{\alpha}{4\pi} \bar{s} \gamma_\mu P_L b \, \bar{\ell} \gamma^\mu \gamma_5 \ell \qquad O_{10'\ell} = O_{10\ell}(P_L \to P_R)$$

SM+NP　　　　NP only

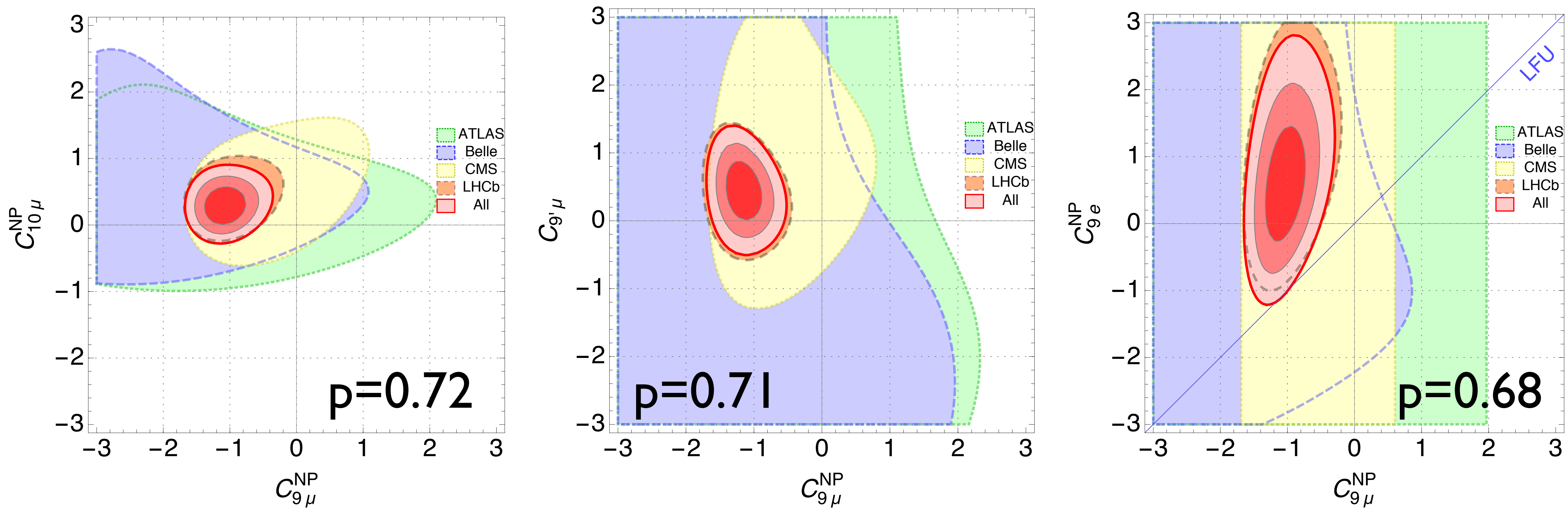
SM prediction

$$C^{\rm SM}_{7,9\ell,10\ell} = -0.29, 4.07, 4.31 \text{ at } \mu = 4.8 \text{ GeV}$$

Global fit

Capdevila et al. JHEP01(2018)093.

175 observables p value of SM = 0.11



$C_{9\mu}^{\rm NP} \sim -1.1$ favored

possible NP: Z’, leptoquark, …

Summary and outlook

- SuperKEKB/ Belle II in physics run

  Integrated luminosity 50/ab by ~2027

  $5.5 \times 10^{10}\ B\bar{B}$ pairs

- LHCb run 3,4: 2021~

  50/fb by ~2029 $3.5 \times 10^{12}\ b\bar{b}$ events

- Precision test of CKM unitarity
- Hadronic uncertainties: role of lattice QCD
- Anomalies in $b \to c\tau\bar{\nu}\,,\ b \to s\ell^+\ell^-$
- Related modes to be studied

  $b \to s\tau^+\tau^-,\ b \to s\nu\bar{\nu}$