Belle II: Interplay with LHC

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NAGOYA UNIVERSITY

Belle II

Super KEKB

Talk Outline

Interplay bet. Belle II and LHCb
Interplay bet. B (flavor) and high P_T programs

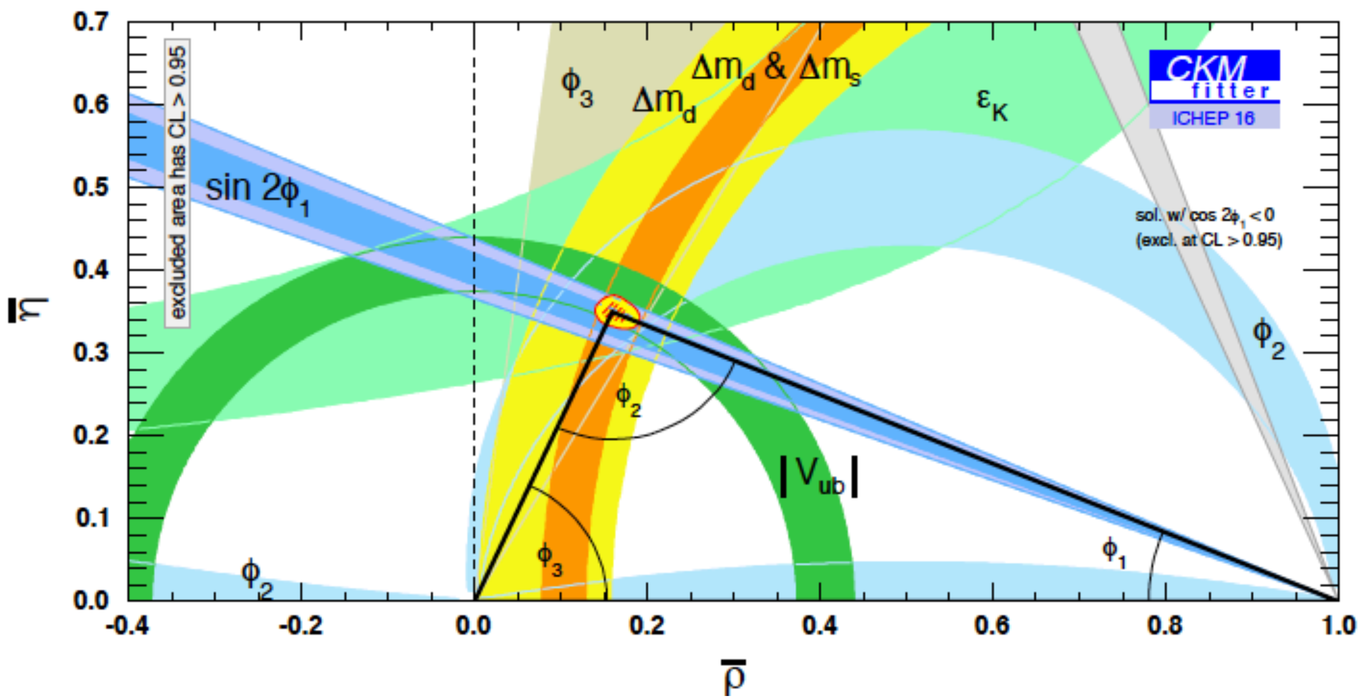
- Introduction
- Advantage of Belle II and interplay with LHC(b)
  - CKM
  - $B \to D^{(*)} \tau \nu$, $\tau \nu$, $l \nu$
  - $B \to X_s l l$, $B \to K^{(*)} \tau \tau$
  - Lepton flavor violation
- Status and prospect of SuperKEKB/Belle II
- Summary

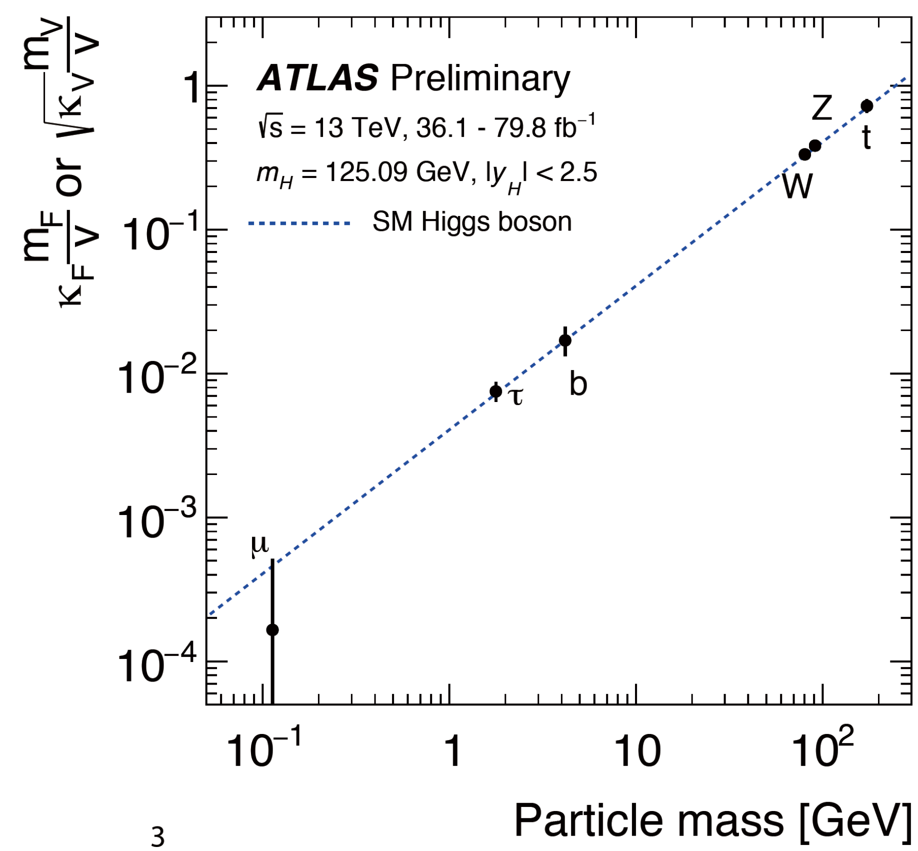
"The Belle II Physics Book" 1808.10567

Apology: I cannot cover all topics.

Perfect SM

- CP violation explained by the mechanism proposed by Kobayashi and Maskawa.
- Higgs has been discovered and its couplings to fermions are being measured.



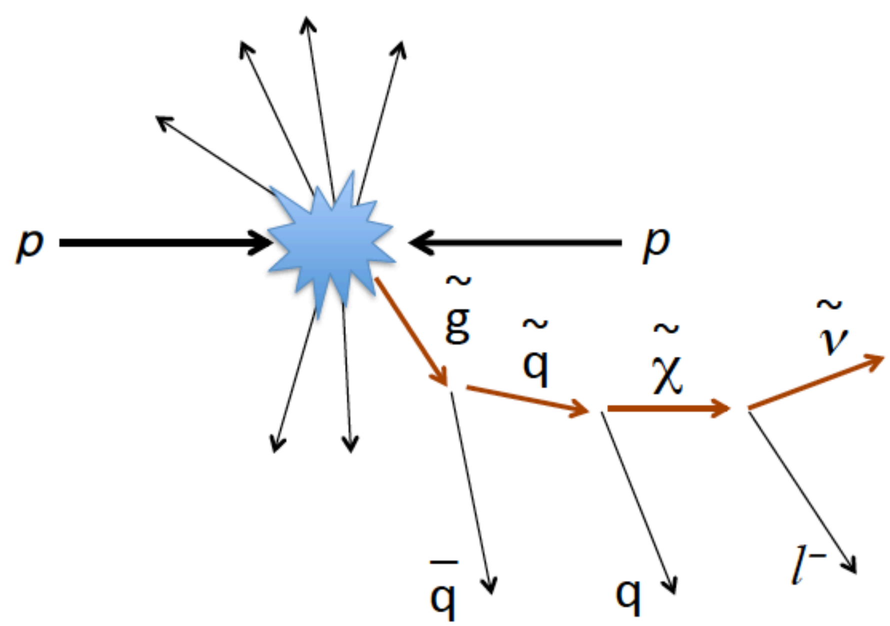


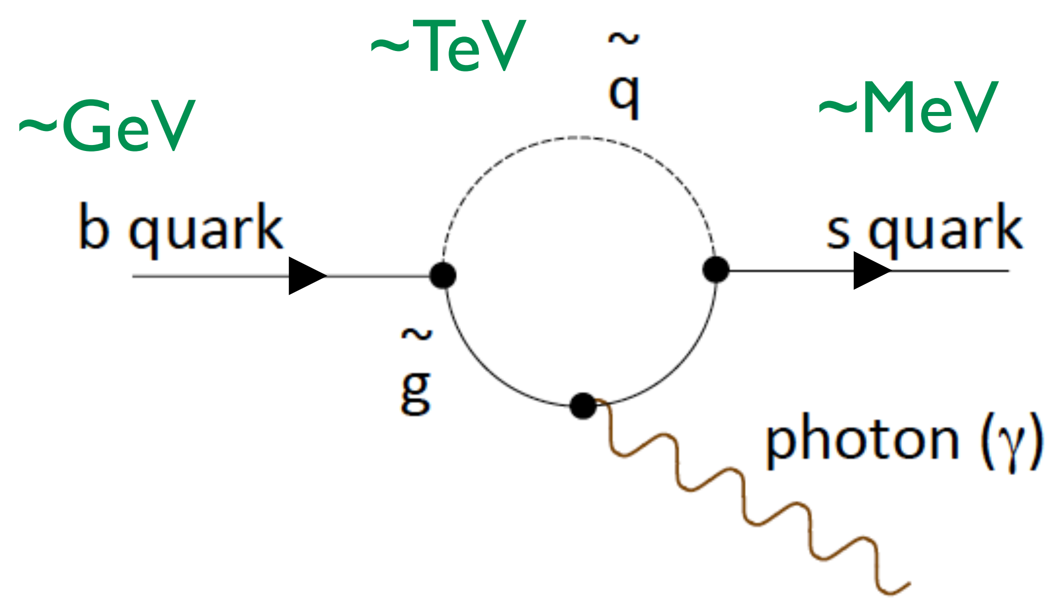
Problems in the SM: naturalness, dark matter, matter-antimatter asymmetry in the Universe, …

→ New Physics beyond the SM

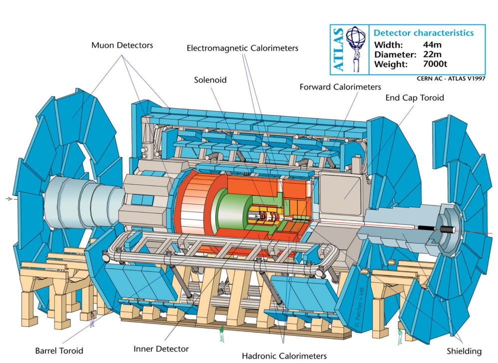
Role of Flavor Physics

- Search for New Physics through processes sensitive to presence of virtual heavy particles.
- Complementary to direct search at LHC high P_T programs.
- Becoming more and more important, since no NP signal at LHC at this moment.

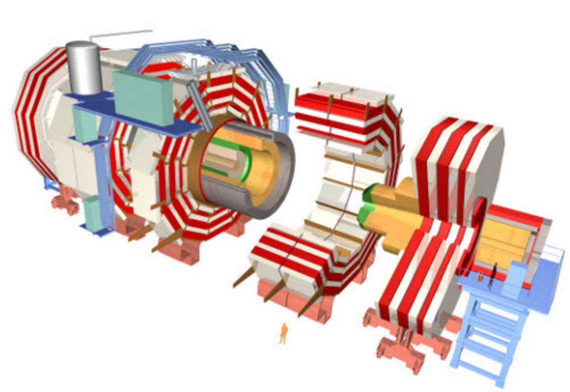




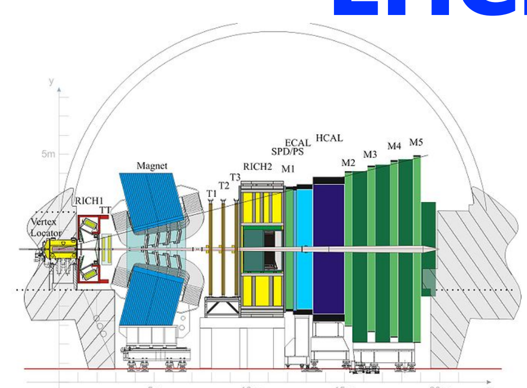
ATLAS



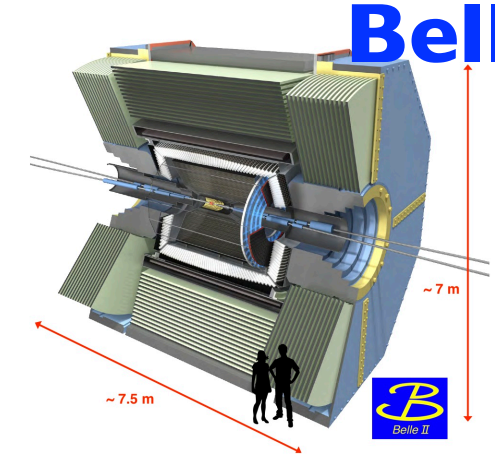
CMS



LHCb

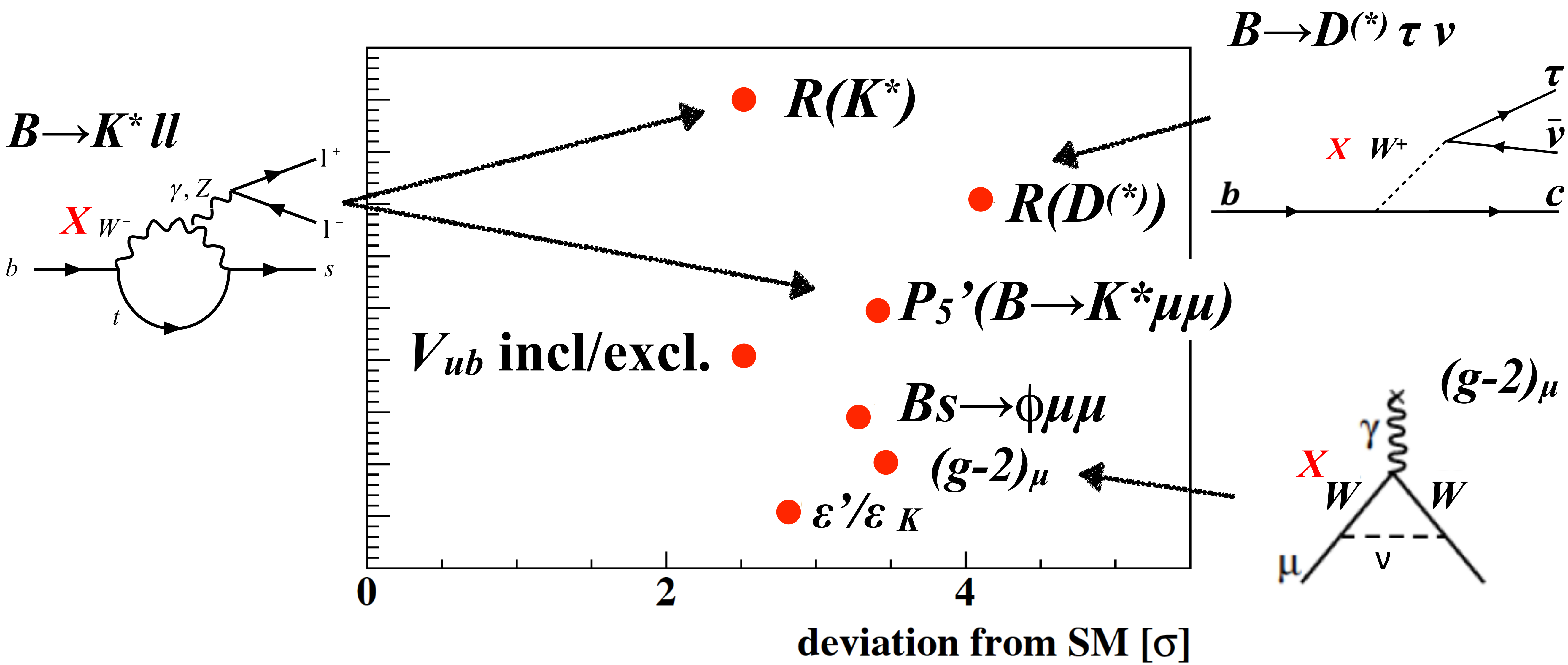


Belle II



Hints of New Physics !

Observed deviation from SM



Is Lepton Non-universality the clue to NP ?

SuperKEKB/Belle II

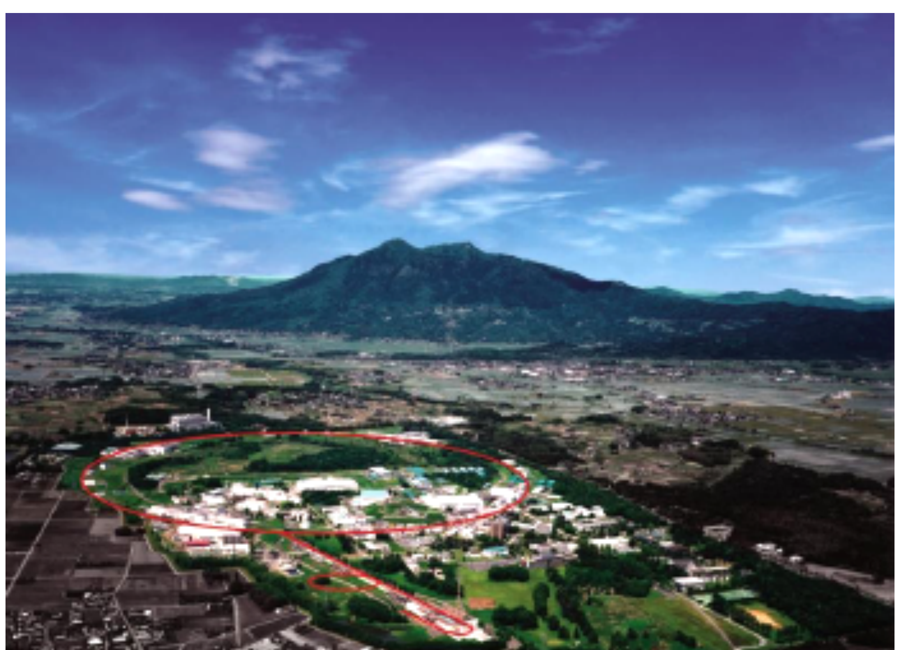
New intensity frontier facility at KEK

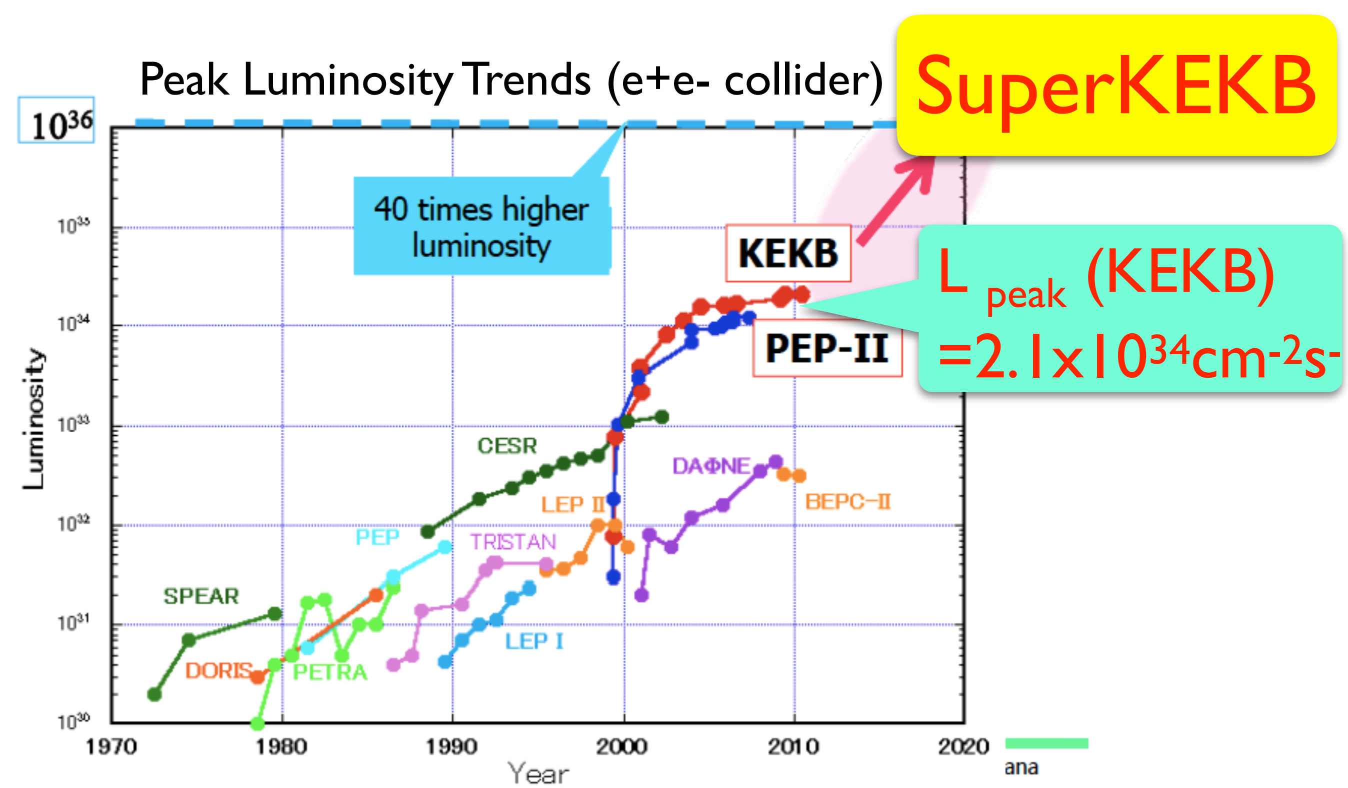
- Target luminosity ; $L_{peak} = 8 \times 10^{35} cm^{-2}s^{-1}$

  $\Rightarrow \sim 10^{10}$ $B\overline{B}$, $\tau^+\tau^-$ and charms per year !

  $L_{int} > 50\ ab^{-1}$

- Rich physics program
  - Search for New Physics through processes sensitive to virtual heavy particles.
  - New QCD phenomena (XYZ, new states including heavy flavors) + more





The first particle collider after the LHC !

SuperKEKB Accelerator

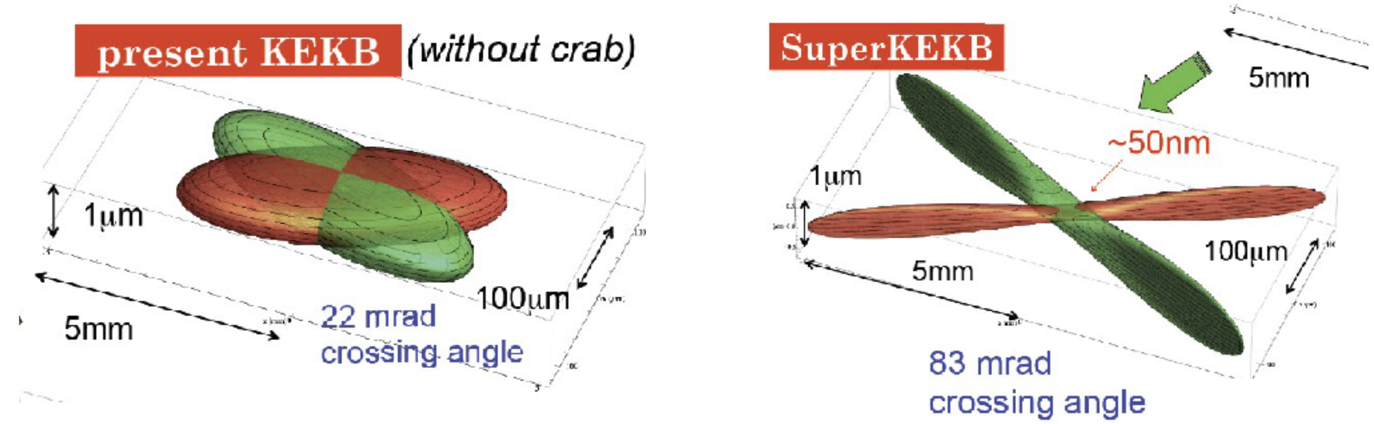
- Low emittance ("nano-beam") scheme employed (originally proposed by P. Raimondi)

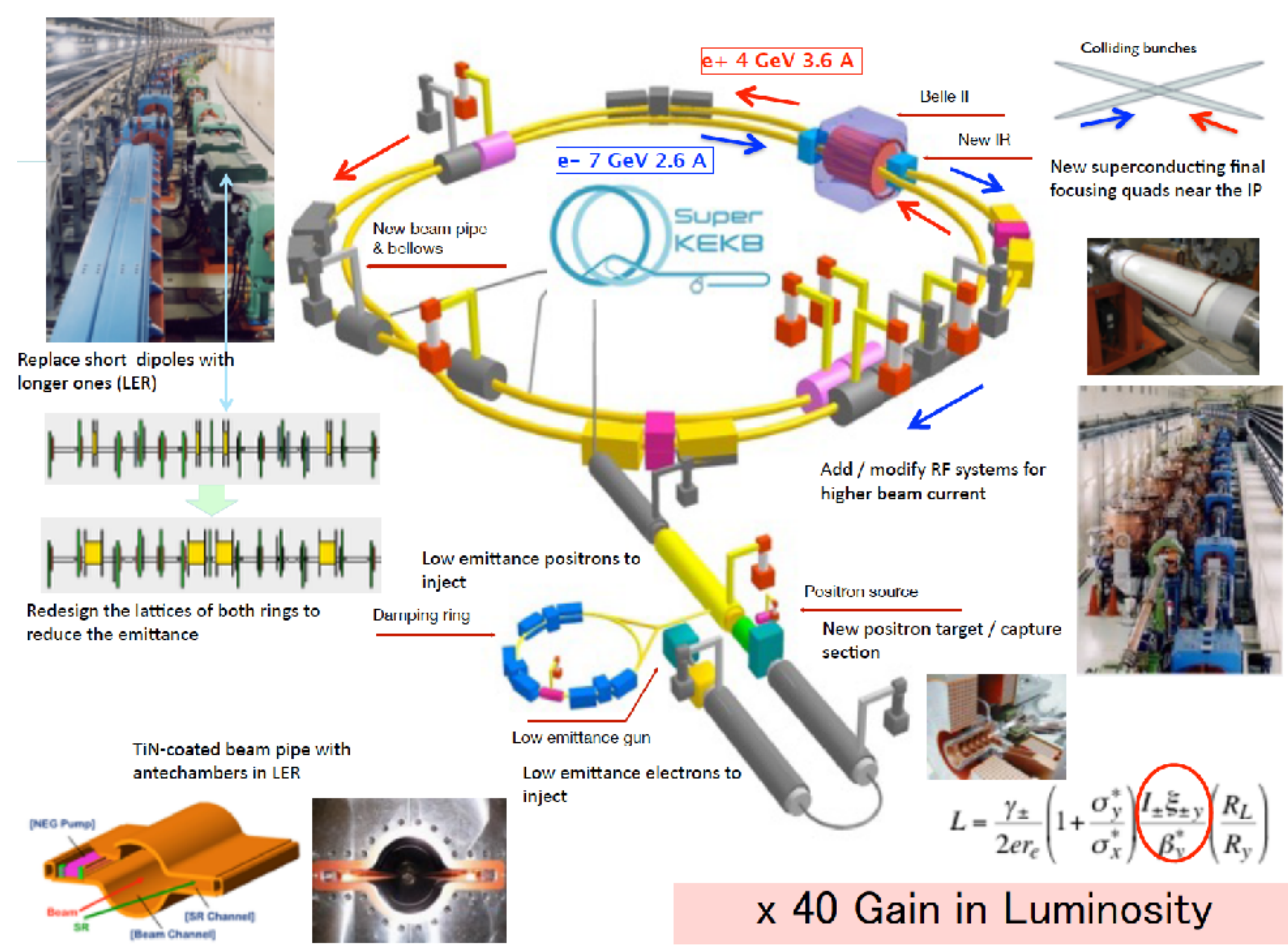
Machine parameters

	SuperKEKB LER/HER	KEKB LER/HER
E(GeV)	4.0/7.0	3.5/8.0
ε_x (nm)	3.2/4.6	18/24
β_y at IP(mm)	0.27/0.30	5.9/5.9
β_x at IP(mm)	32/25	120/120
Half crossing angle(mrad)	41.5	11
I(A)	3.6/2.6	1.6/1.2
Lifetime	~10min	130min/200min
L(cm^{-2}s^{-1})	80×10^{34}	2.1×10^{34}

x20

x2





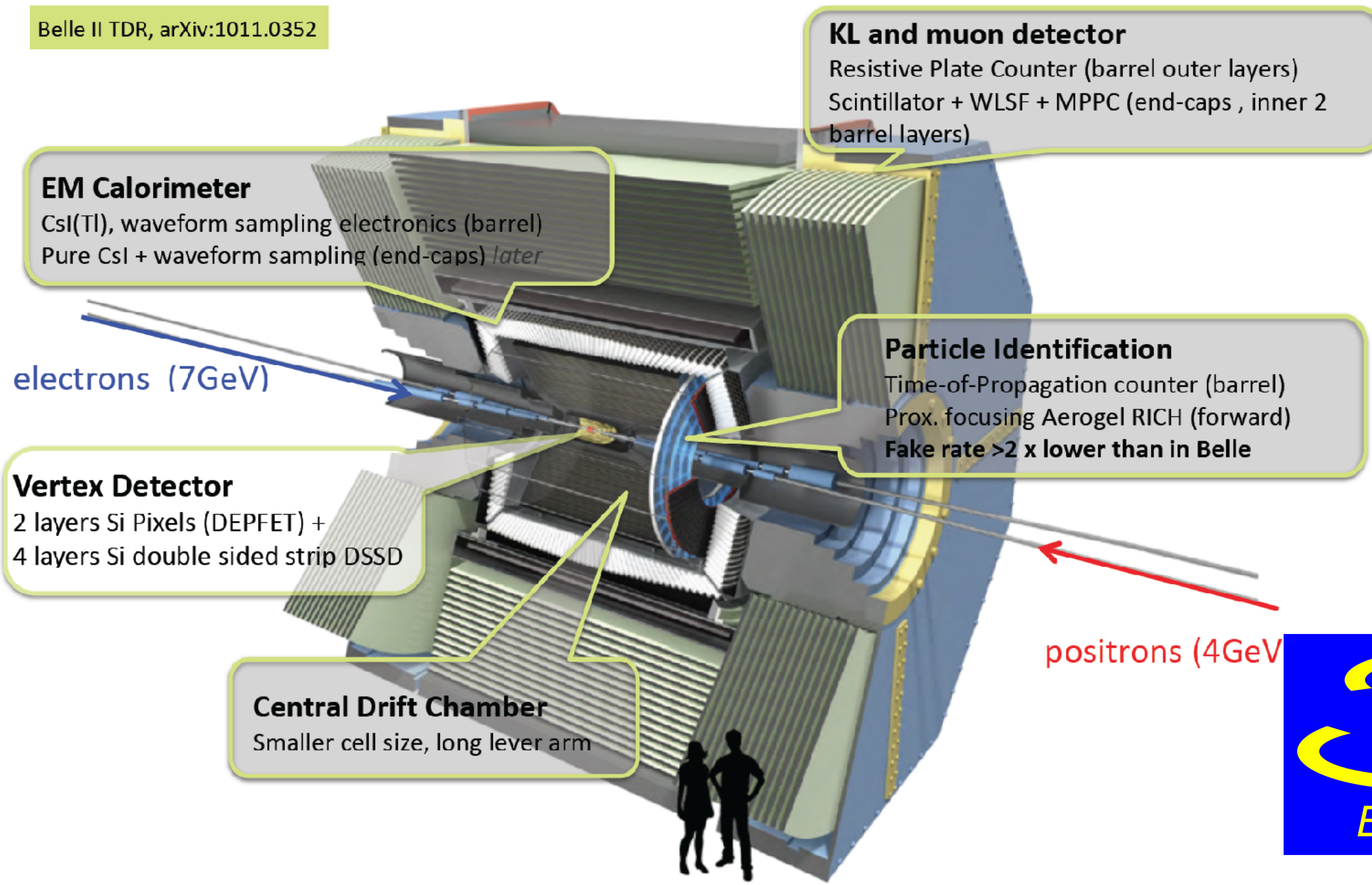
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

x 40 Gain in Luminosity

Belle II Detector

- Deal with higher background (10-20×), radiation damage, higher occupancy, higher event rates (L1 trigg. 0.5→30 kHz)
- Improved performance and hermeticity

Belle II TDR, arXiv:1011.0352



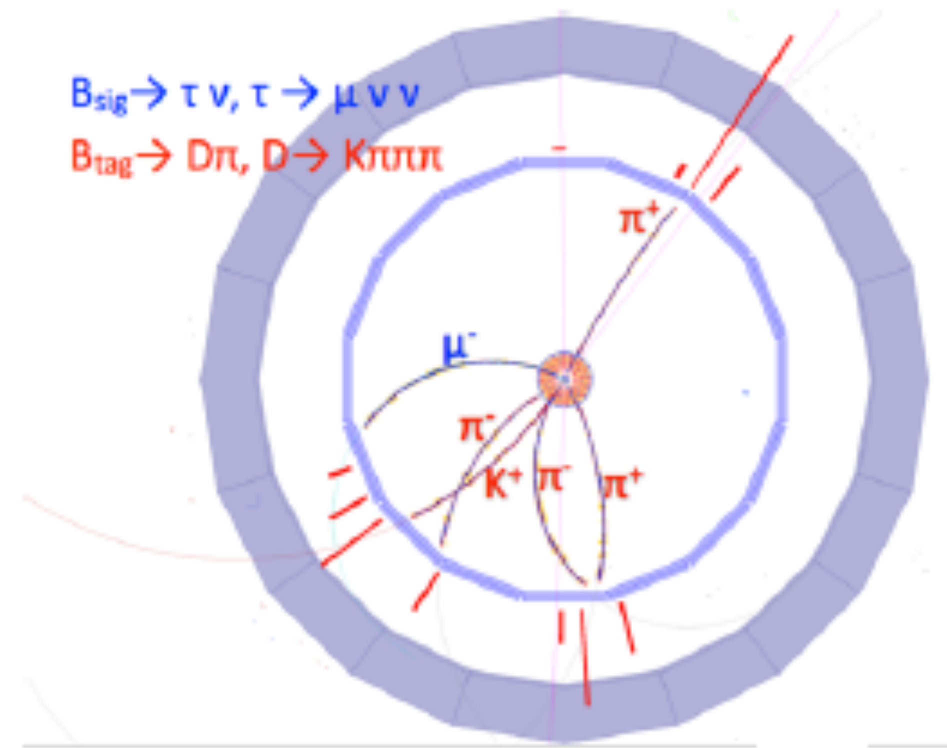
The Belle II Collaboration

- Belle II now has grown to ~800 researchers from 25 countries
  - ~270 graduate students
- Large international collaboration hosted by KEK, Japan

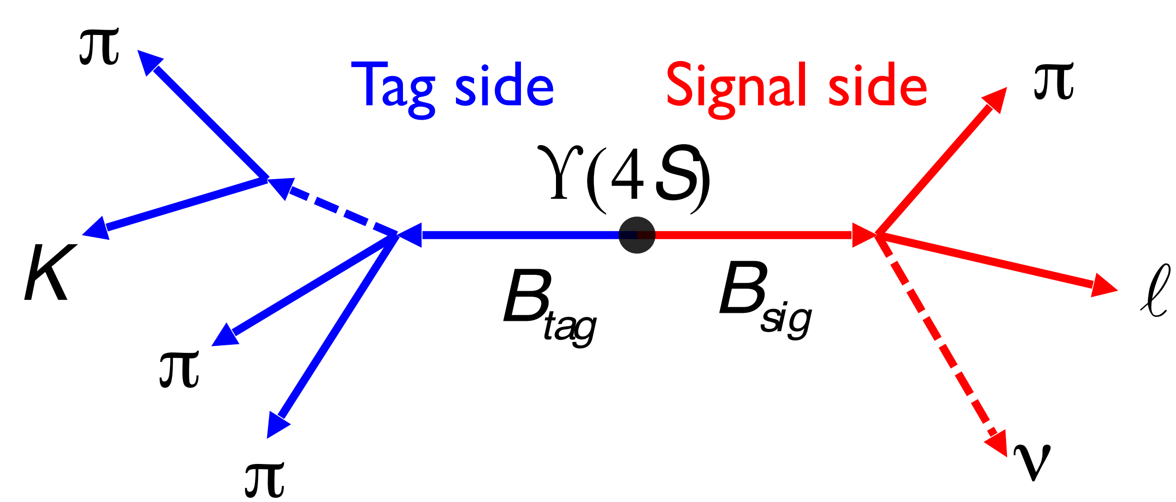
Advantage of e^+e^- Flavor Factory

- Clean environment
  - Efficient detection of neutrals (γ, π^0, η, …)
- Quantum correlated $B^0\overline{B}^0$ pairs
  - High effective flavor tagging efficiency :

  ~34%(Belle II) ⟷ ~3% (LHCb)
- Large sample of τ leptons
  - Search for LFV τ decays at $O(10^{-9})$



- Full reconstruction tagging possible
  - A powerful tool to measure;
    - b→u semileptonic decays (CKM)
    - decays with large missing energy



- Systematics different from LHCb
  - Two experiments are required to establish NP

$B \to \pi l \nu$

$B \to \tau\nu, D\tau\nu$

$B \to K\nu\nu$

Advantage of e^+e^- Flavor Factory

- Cl
  -
- Q
  -
- La
  -
- Fu
  -
- Sy
  -

pp collision
large production rate

e^+e^- collision
low background

Powerful !

Clean !

TOYOTA FCV
NOW ON MARKET !

π

ℓ

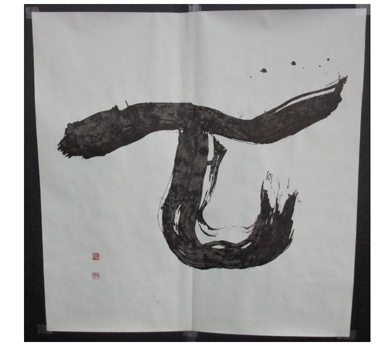
ν

τ l ν

, D τ ν

K ν ν

The role of τ lepton



τ lepton

- The heaviest charged lepton
- High sensitivity to New Physics

	electron	muon	tau
	e	μ	τ
Gen.	I	II	III
Mass [MeV]	0.511	106	1780
Life	∞	2.20μs	0.291ps

Unique probe to search for New Physics

$e^+e^- \rightarrow \tau^+\tau^- \rightarrow$ decays

- LFV (Lepton Flavor Violation)
- EDM, CPV, g-2
- LNV (Lepton Number Violation)
- BNV (Baryon Number Violation)
- Precision test of SM

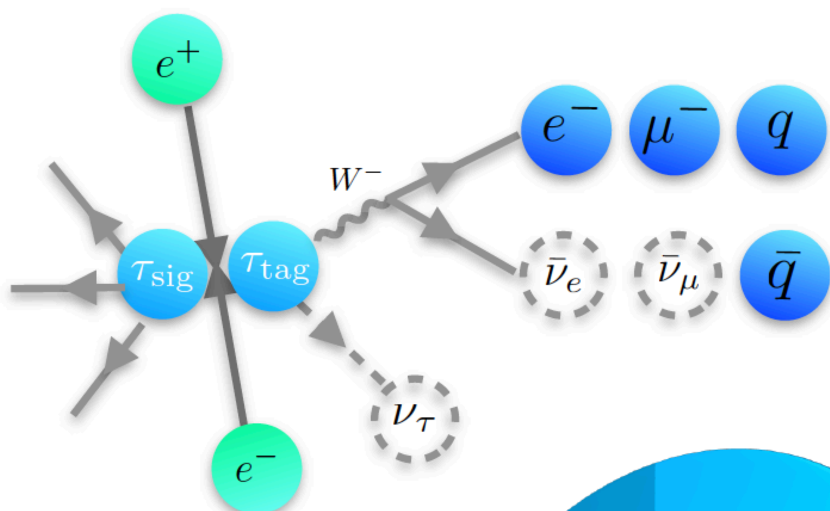
decays w/ τ in the final state

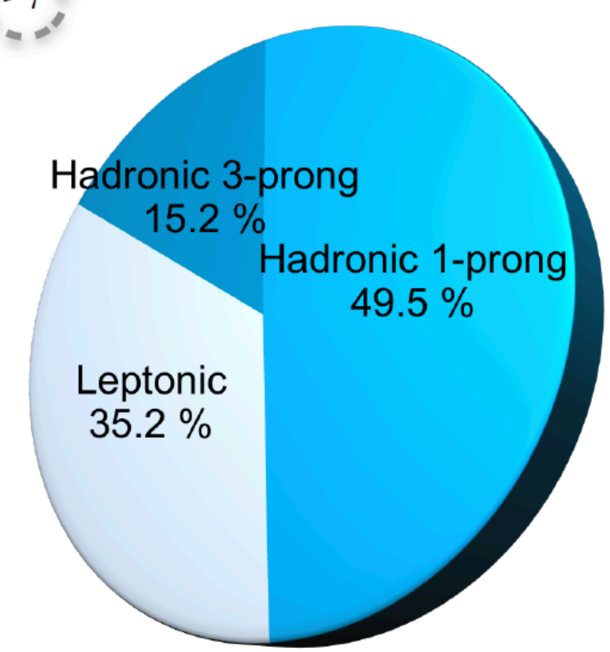
- charm
- bottom
- top
- Higgs

Belle II has advantage for these measurements !

Missing energy decays

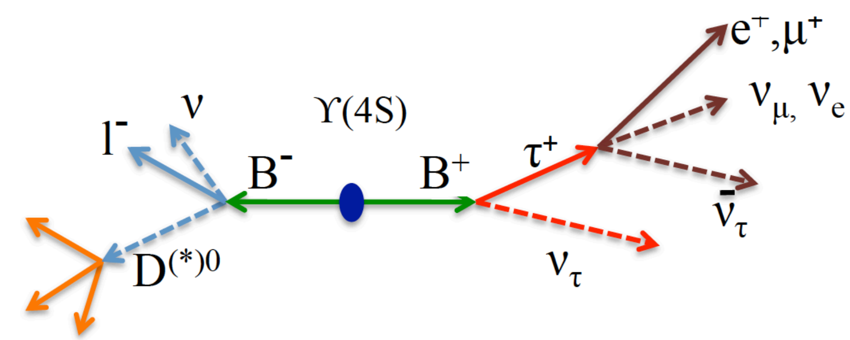
- e+e- annihilation data is ideal to decays with large missing energy.
- B tagging analysis enables also precise inclusive measurements; b→u l ν, b→s γ, b→s l l



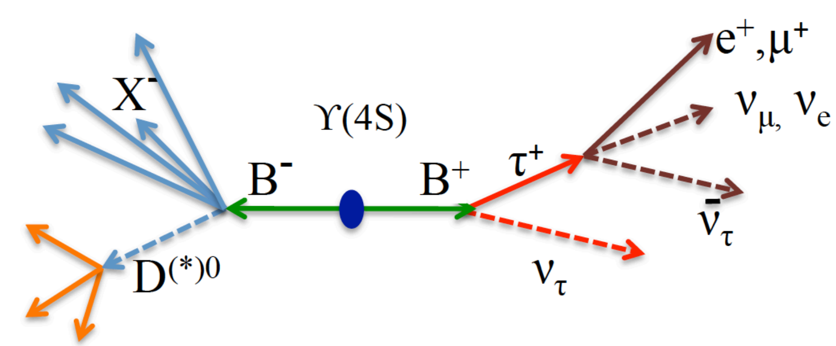


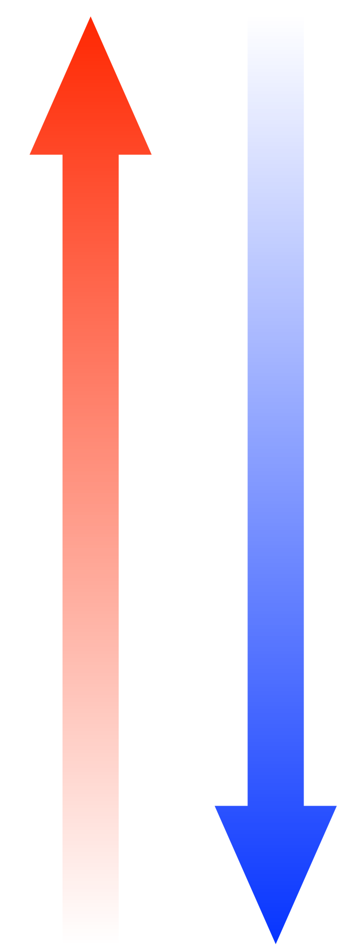
efficiency

B tag w/ semileptonic decays



B tag w/ hadronic decays





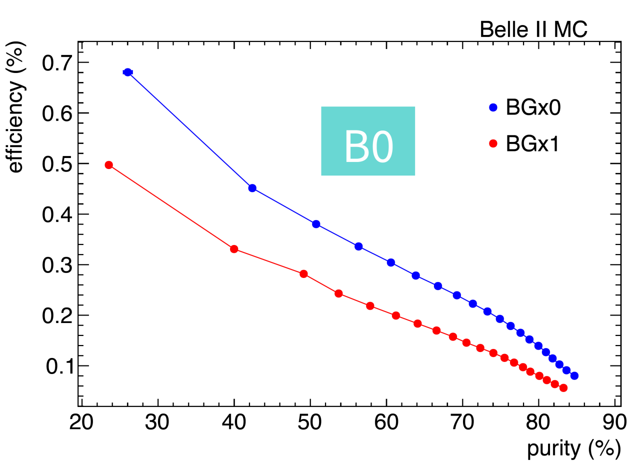
purity

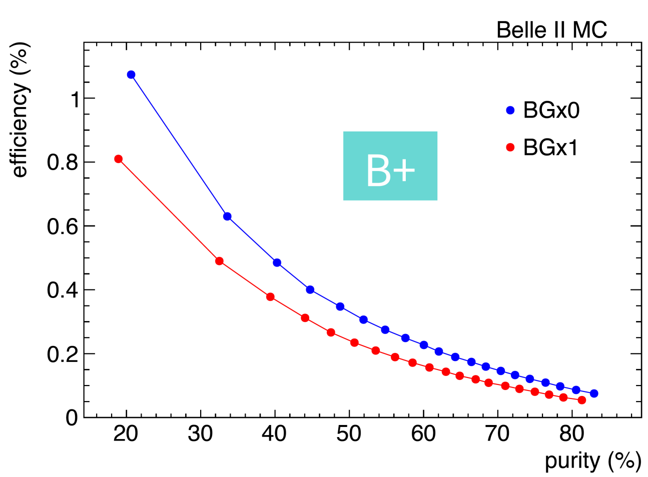
Belle II Full Event Reconstruction

- Belle II has developed a new "Full Event Interpretation" tool based on fast BDT.

Number of decay modes used in tagging (Belle → Belle II)
- B^+: 17→29, B^0: 14→26
- $D^+/D^{*+}/D_s^+$: 18→26, D^0/D^{*0}: 12→17

Tag algorithm date	MVA	Efficiency	Purity
Belle v1 (2004)	Cut-based (Vcb)	-	-
Belle v3 (2007)	Cut-based	0.1	0.25
Belle NB (2011)	**Neurobayes**	**0.2**	**0.25**
Belle II FEI (2017)	Fast BoostedDecisionTree	0.5	0.25





- + NEW FEI method based on semileptonic tag Fast BDT tag in B → D(*) l ν + B → D(*)π l ν.

B^+ modes	B^0 modes
$B^+ \to \bar{D}^0\pi^+$	$B^0 \to D^-\pi^+$
$B^+ \to \bar{D}^0\pi^+\pi^0$	$B^0 \to D^-\pi^+\pi^0$
$B^+ \to \bar{D}^0\pi^+\pi^0\pi^0$	$B^0 \to D^-\pi^+\pi^+\pi^-$
$B^+ \to \bar{D}^0\pi^+\pi^+\pi^-$	$B^0 \to D_s^+D^-$
$B^+ \to D_s^+\bar{D}^0$	$B^0 \to D^{*-}\pi^+$
$B^+ \to \bar{D}^{*0}\pi^+$	$B^0 \to D^{*-}\pi^+\pi^0$
$B^+ \to \bar{D}^{*0}\pi^+\pi^0$	$B^0 \to D^{*-}\pi^+\pi^+\pi^-$
$B^+ \to \bar{D}^{*0}\pi^+\pi^+\pi^-$	$B^0 \to D^{*-}\pi^+\pi^+\pi^-\pi^0$
$B^+ \to \bar{D}^{*0}\pi^+\pi^+\pi^-\pi^0$	$B^0 \to D_s^{*+}D^-$
$B^+ \to D_s^{*+}\bar{D}^0$	$B^0 \to D_s^+D^{*-}$
$B^+ \to D_s^+\bar{D}^{*0}$	$B^0 \to D_s^{*+}D^{*-}$
$B^+ \to \bar{D}^0K^+$	$B^0 \to J/\psi K_S^0$
$B^+ \to D^-\pi^+\pi^+$	$B^0 \to J/\psi K^+\pi^+$
$B^+ \to J/\psi K^+$	$B^0 \to J/\psi K_S^0\pi^+\pi^-$
$B^+ \to J/\psi K^+\pi^+\pi^-$	
$B^+ \to J/\psi K^+\pi^0$	
$B^+ \to J/\psi K_S^0\pi^+$	
$B^+ \to D^-\pi^+\pi^+\pi^0$	$B^0 \to D^-\pi^+\pi^0\pi^0$
$B^+ \to \bar{D}^0\pi^+\pi^+\pi^-\pi^0$	$B^0 \to D^-\pi^+\pi^+\pi^-\pi^0$
$B^+ \to \bar{D}^0D^+$	$B^0 \to \bar{D}^0\pi^+\pi^-$
$B^+ \to \bar{D}^0D^+K_S^0$	$B^0 \to D^-D^0K^+$
$B^+ \to \bar{D}^{*0}D^+K_S^0$	$B^0 \to D^-D^{*0}K^+$
$B^+ \to \bar{D}^0D^{*+}K_S^0$	$B^0 \to D^{*-}D^0K^+$
$B^+ \to \bar{D}^{*0}D^{*+}K_S^0$	$B^0 \to D^{*-}D^{*0}K^+$
$B^+ \to \bar{D}^0D^0K^+$	$B^0 \to D^-D^+K_S^0$
$B^+ \to \bar{D}^{*0}D^0K^+$	$B^0 \to D^{*-}D^+K_S^0$
$B^+ \to \bar{D}^0D^{*0}K^+$	$B^0 \to D^-D^{*+}K_S^0$
$B^+ \to \bar{D}^{*0}D^{*0}K^+$	$B^0 \to D^{*-}D^{*+}K_S^0$
$B^+ \to \bar{D}^{*0}\pi^+\pi^0\pi^0$	$B^0 \to D^{*-}\pi^+\pi^0\pi^0$

D^+,D^{*+},D_s^+ modes	D^0,D^{*0} modes
$D^+ \to K^-\pi^+\pi^+$	$D^0 \to K^-\pi^+$
$D^+ \to K^-\pi^+\pi^+\pi^0$	$D^0 \to K^-\pi^+\pi^0$
$D^+ \to K^-K^+\pi^+$	$D^0 \to K^-\pi^+\pi^+\pi^-$
$D^+ \to K^-K^+\pi^+\pi^0$	$D^0 \to \pi^-\pi^+$
$D^+ \to K_S^0\pi^+$	$D^0 \to \pi^-\pi^+\pi^0$
$D^+ \to K_S^0\pi^+\pi^0$	$D^0 \to K_S^0\pi^0$
$D^+ \to K_S^0\pi^+\pi^+\pi^-$	$D^0 \to K_S^0\pi^+\pi^-$
$D^{*+} \to D^0\pi^+$	$D^0 \to K_S^0\pi^+\pi^-\pi^0$
$D^{*+} \to D^+\pi^0$	$D^0 \to K^-K^+$
$D_s^+ \to K^+K_S^0$	$D^0 \to K^-K^+K_S^0$
$D_s^+ \to K^+\pi^+\pi^-$	$D^{*0} \to D^0\pi^0$
$D_s^+ \to K^+K^-\pi^+$	$D^{*0} \to D^0\gamma$
$D_s^+ \to K^+K^-\pi^+\pi^0$	
$D_s^+ \to K^+K_S^0\pi^+\pi^-$	
$D_s^+ \to K^-K_S^0\pi^+\pi^+$	
$D_s^+ \to K^+K^-\pi^+\pi^+\pi^-$	
$D_s^+ \to \pi^+\pi^+\pi^-$	
$D_s^{*+} \to D_s^+\pi^0$	
$D^+ \to \pi^+\pi^0$	$D^0 \to K^-\pi^+\pi^0\pi^0$
$D^+ \to \pi^+\pi^+\pi^-$	$D^0 \to K^-\pi^+\pi^+\pi^-\pi^0$
$D^+ \to \pi^+\pi^+\pi^-\pi^0$	$D^0 \to \pi^-\pi^+\pi^+\pi^-$
$D^+ \to K^+K_S^0K_S^0$	$D^0 \to \pi^-\pi^+\pi^0\pi^0$
$D^{*+} \to D^+\gamma$	$D^0 \to K^-K^+\pi^0$
$D_s^+ \to K_S^0\pi^+$	
$D_s^+ \to K_S^0\pi^+\pi^0$	
$D_s^{*+} \to D_s^+\pi^0$	

- Below line: not used in Belle NB tag.

Prospect for CKM

- Details have been discussed by other speakers.
  - See talks by J. Charles, A. Passeri, M.A. Vesterinen, A. Poluektov, M. Jung
- For $|V_{xb}|$, Belle II is able to perform both inclusive and exclusive measurements with B tagging, including
  - detailed studies of exclusive decays to understand the difference, which is presently seen.
  - precise branching fractions for normalization modes used at LHCb
- Interplay with theoretical studies is important.

1808.10567

Belle II prospect for $|V_{xb}|$

% uncertainties	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory Lattice projections	Total
$\lvert V_{ub}\rvert$ exclusive (had. tagged)					
711 fb^{-1}	3.0	(2.3, 1.0)	3.8	7.0	8.0
5 ab^{-1}	1.1	(0.9, 1.0)	1.8	1.7	3.2
50 ab^{-1}	0.4	(0.3, 1.0)	1.2	0.9	1.7
$\lvert V_{ub}\rvert$ exclusive (untagged)					
605 fb^{-1}	1.4	(2.1, 0.8)	2.7	7.0	7.5
5 ab^{-1}	1.0	(0.8, 0.8)	1.2	1.7	2.1
50 ab^{-1}	0.3	(0.3, 0.8)	0.9	0.9	1.3
$\lvert V_{ub}\rvert$ inclusive					
605 fb^{-1} (old B tag)	4.5	(3.7, 1.6)	6.0	2.5–4.5	6.5–7.5
5 ab^{-1}	1.1	(1.3, 1.6)	2.3	2.5–4.5	3.4–5.1
50 ab^{-1}	0.4	(0.4, 1.6)	1.7	2.5–4.5	3.0–4.8

CKM fit w/ Belle II + LHCb

Input	Current WA	SM value Belle II	SM value Belle II+LHCb
A	$0.8227^{+0.0066}_{-0.0136}$	$^{+0.0025}_{-0.0027}$	$^{+0.0024}_{-0.0028}$
λ	$0.22543^{+0.00042}_{-0.00031}$	$^{0.00036}_{-0.00030}$	$^{0.00035}_{-0.00030}$
$\bar{\rho}$	$0.1504^{+0.0121}_{-0.0062}$	$^{+0.0054}_{-0.0044}$	$^{+0.0042}_{-0.0040}$
$\bar{\eta}$	$0.3540^{+0.00069}_{-0.0076}$	$^{+0.0037}_{-0.00040}$	$^{+0.0036}_{-0.00037}$

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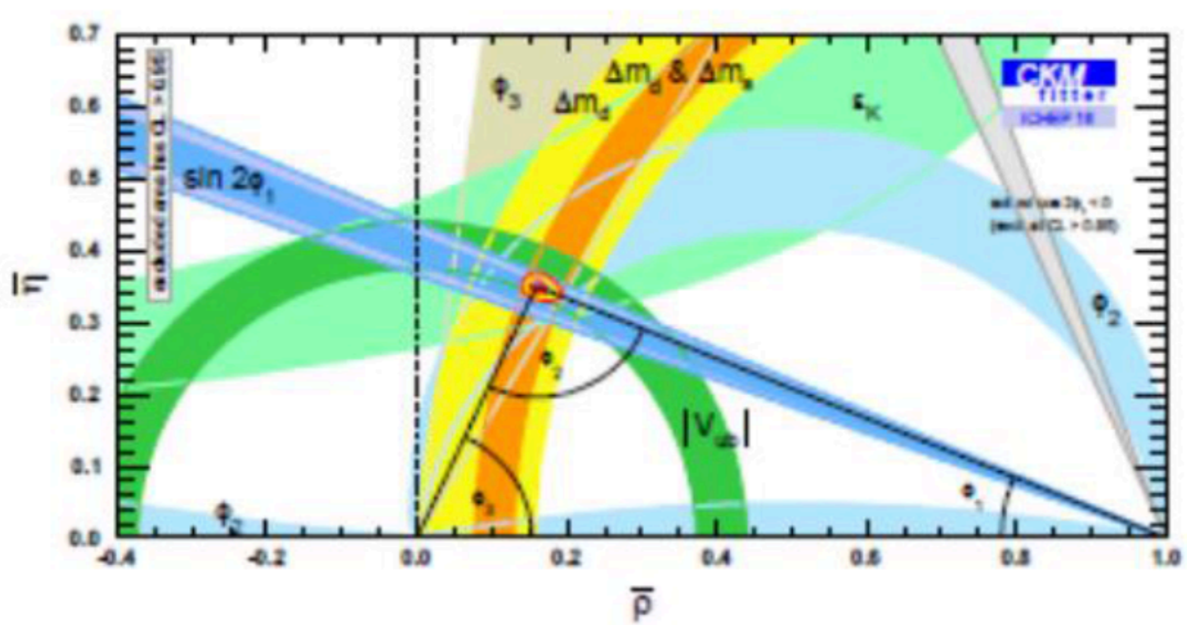
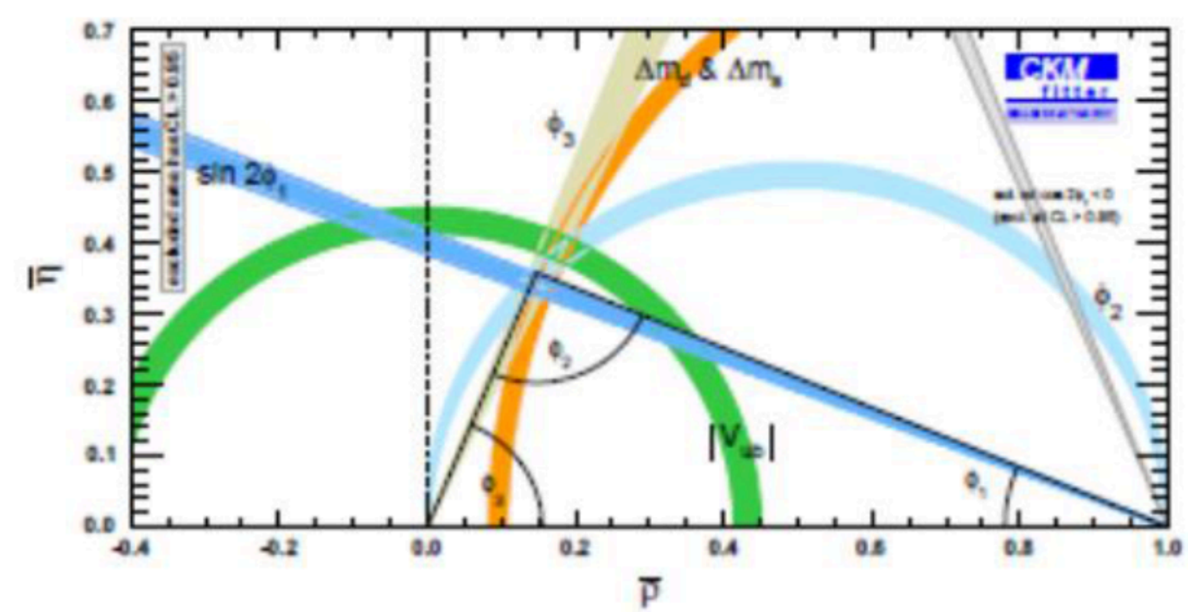
Current world average



Belle II projection @ 50ab^{-1}



CKM fit w/ Belle II + LHCb

Input	Current WA	SM value Belle II	SM value Belle II+LHCb
A	$0.8227^{+0.0066}_{-0.0136}$	$^{+0.0025}_{-0.0027}$	$^{+0.0024}_{-0.0028}$
λ	$0.22543^{+0.00042}_{-0.00031}$	$^{0.00036}_{-0.00030}$	$^{0.00035}_{-0.00030}$
$\bar{\rho}$	$0.1504^{+0.0121}_{-0.0062}$	$^{+0.0054}_{-0.0044}$	$^{+0.0042}_{-0.0040}$
$\bar{\eta}$	$0.3540^{+0.00069}_{-0.0076}$	$^{+0.0037}_{-0.00040}$	$^{+0.0036}_{-0.00037}$

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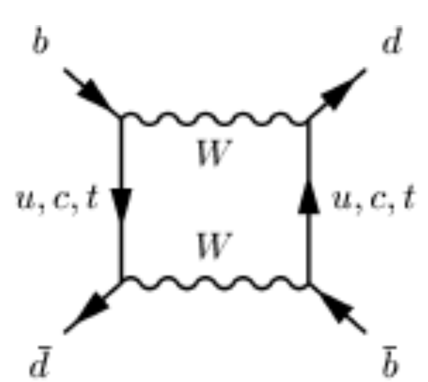
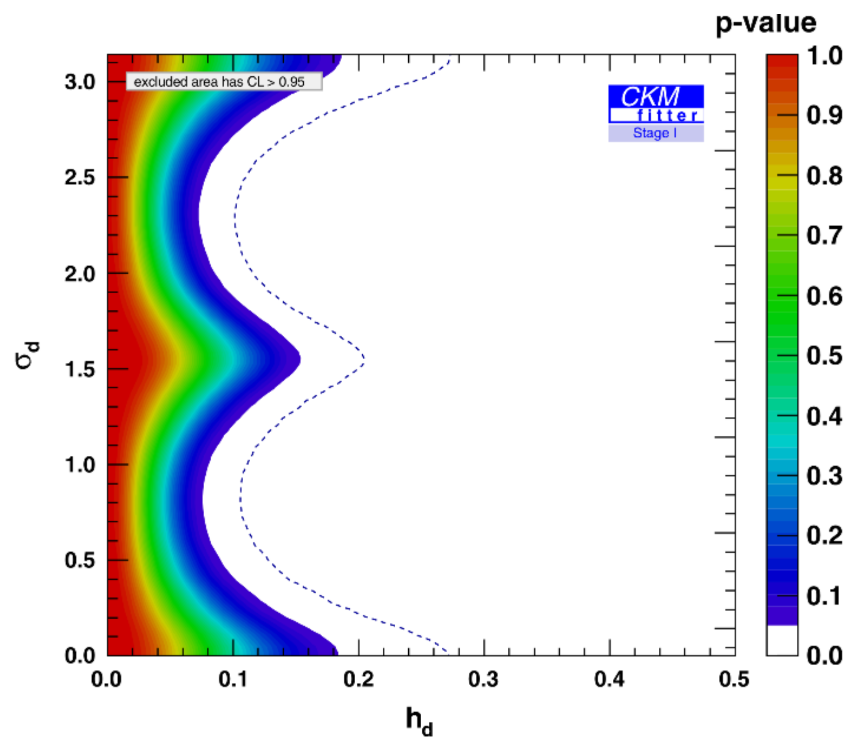
$$M_{12}^{d,s} = (M_{12}^{d,s})_{\rm SM} \times (1 + h_{d,s} e^{2i\sigma_{d,s}})$$

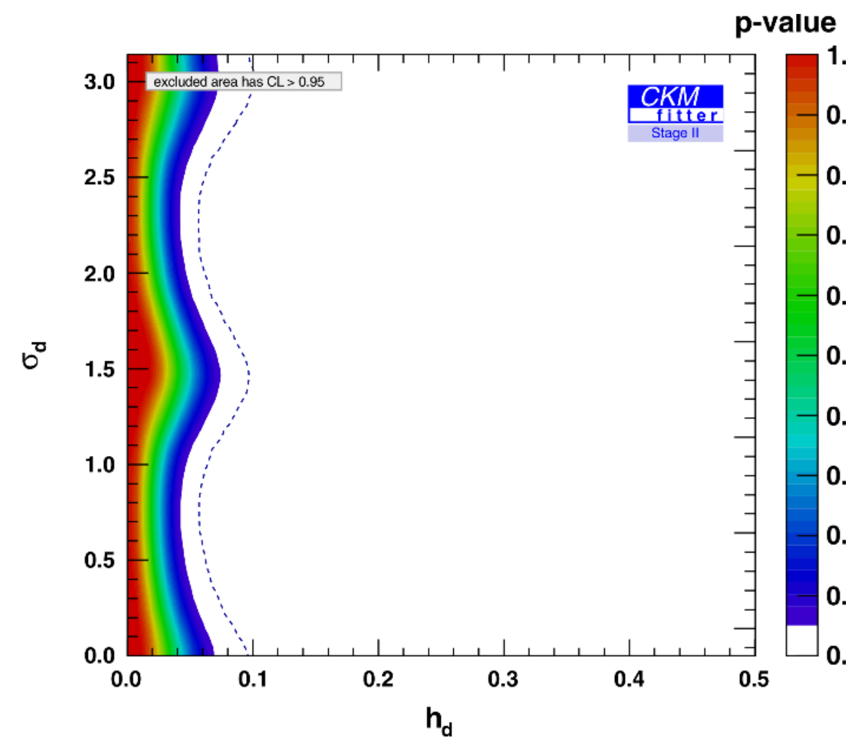
Relative amplitude phase



Belle II 5ab^{-1} + LHCb 7fb^{-1}

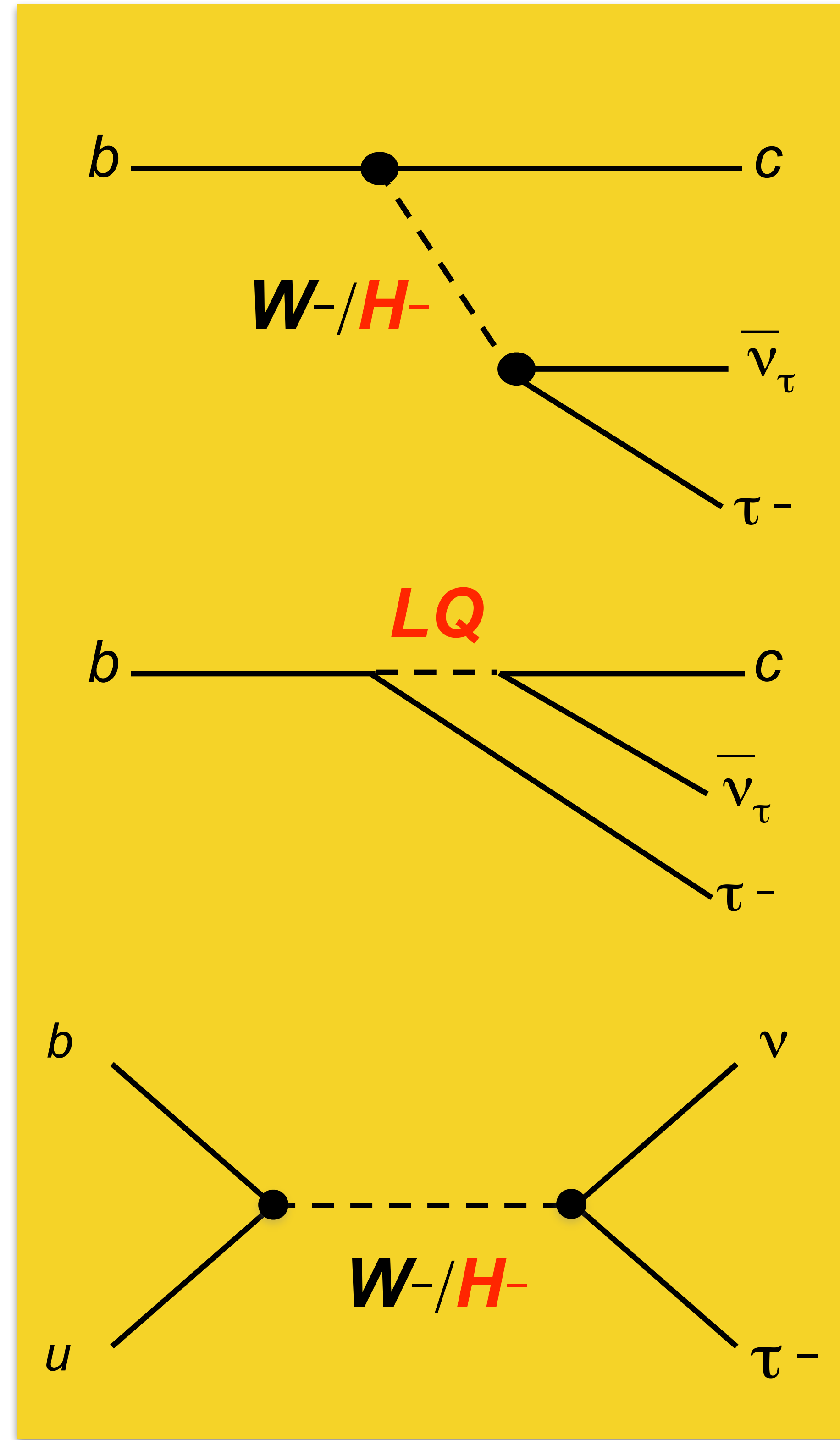


Belle II 50ab^{-1} + LHCb 50fb^{-1}



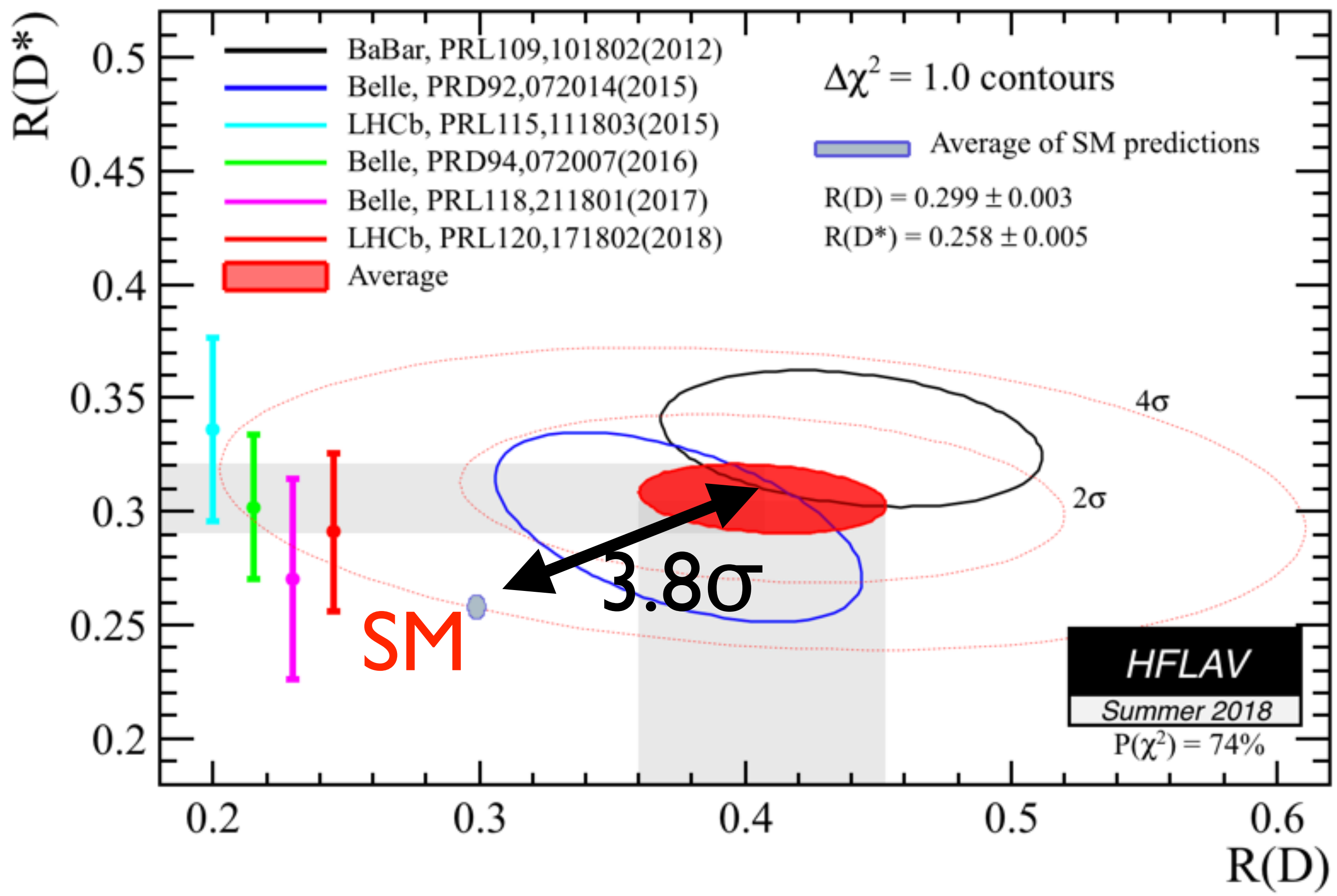
$B \to D^{(*)}\tau\nu$, $B \to \tau\nu$

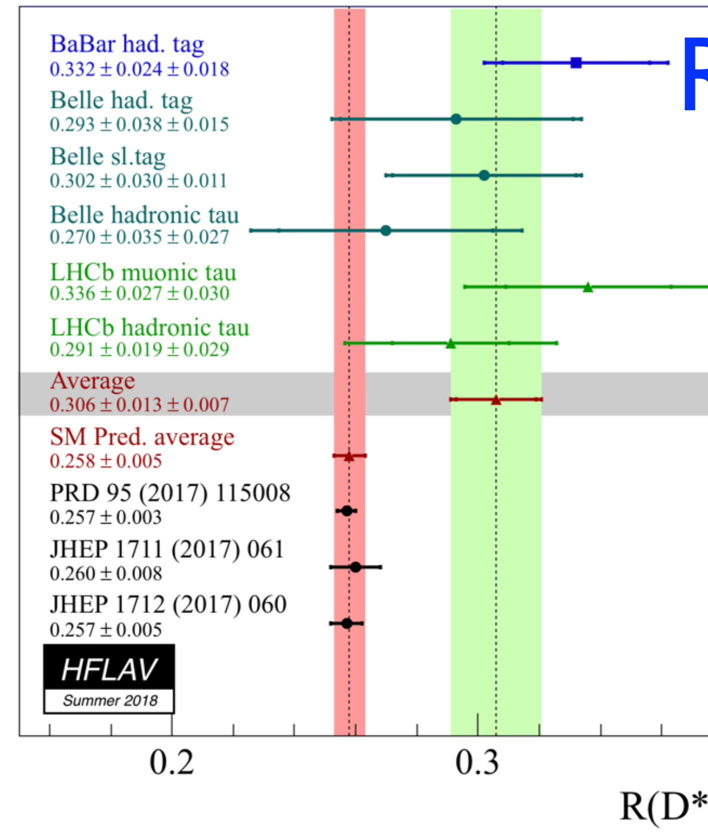
- New Physics may appear in tree level.
- 3rd generation quark (b) and lepton (τ) involved.
  - large masses → sensitivity to NP
  - Charged Higgs, Leptoquark, …
- $B \to D^{(*)} \tau \nu$ and $B \to \tau \nu$ are complementary
- Quantities of interest
  - Lepton Flavor Universality :
    - R(D), R(D*)
  - Polarization: P_τ, P_{D^*}
  - q^2 distribution etc.



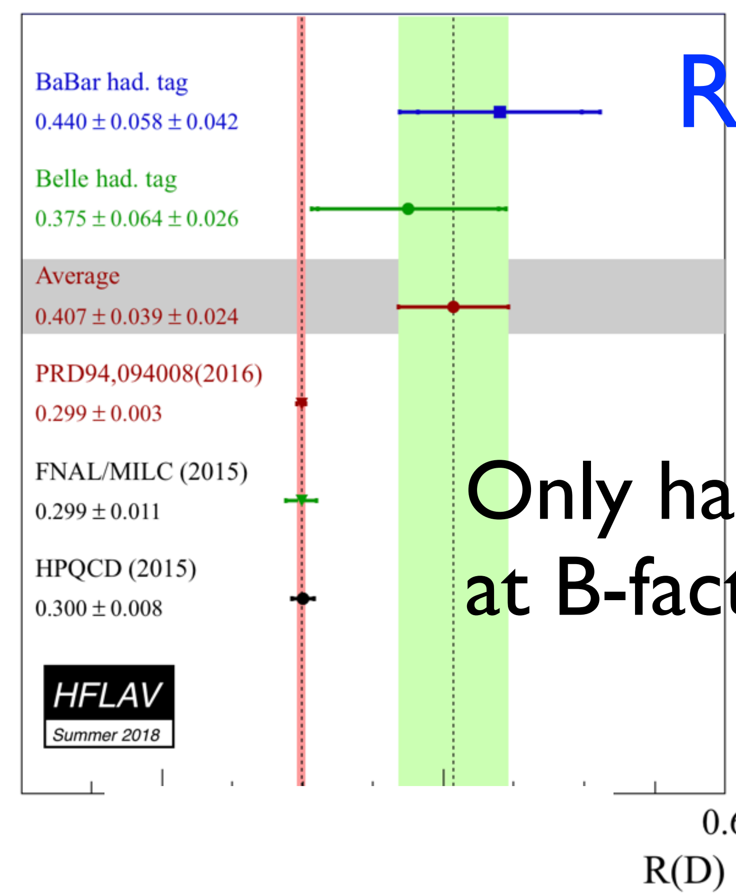
R(D), R(D*)

Summer 2018 update





R(D*)

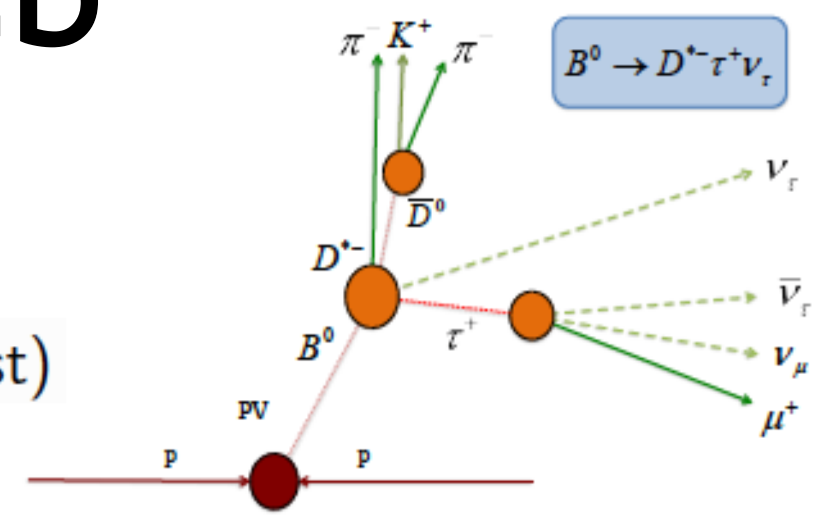


R(D)

Only had. tag. at B-factories

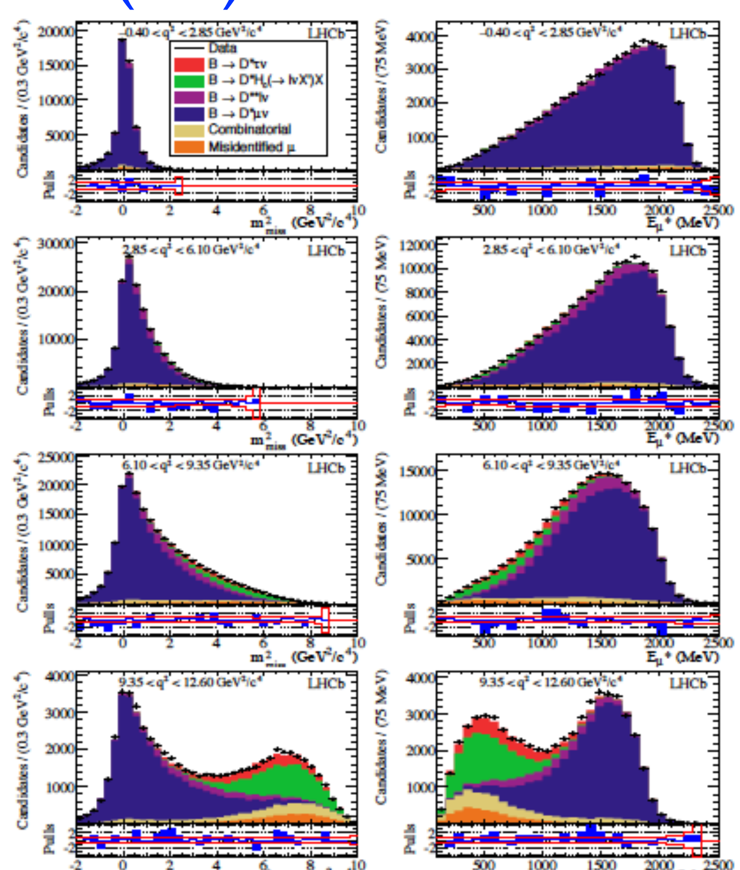
Deviation from SM slightly decreased from 4.1 →3.8σ, mainly due to change in theoretical SM prediction.

R(D*) at LHCb



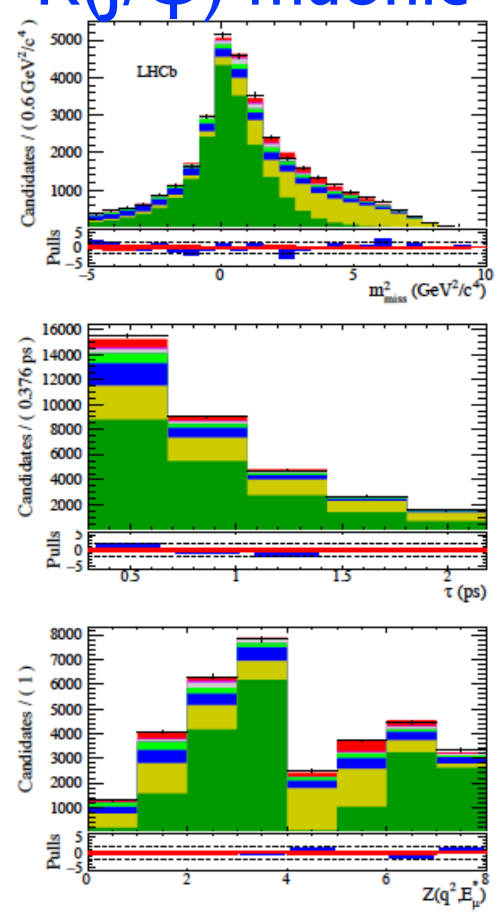
- Exploit the τ vertex isolation.
- R(D*) muonic $R(D^*) = 0.336 \pm 0.027\,(\text{stat}) \pm 0.030\,(\text{syst})$
- R(J/ψ) muonic $R(J/\psi) = 0.71 \pm 0.17\,(\text{stat}) \pm 0.18\,(\text{syst})$
- R(D*) hadronic $R(D^*) = 0.291 \pm 0.019\,(\text{stat}) \pm 0.026\,(\text{syst}) \pm 0.013\,(\text{ext}).$

R(D*) muonic



[PRL 115, 112001 (2015)]

R(J/ψ) muonic



[PRL 120, 121801 (2018)]

R(D*) hadronic systematics

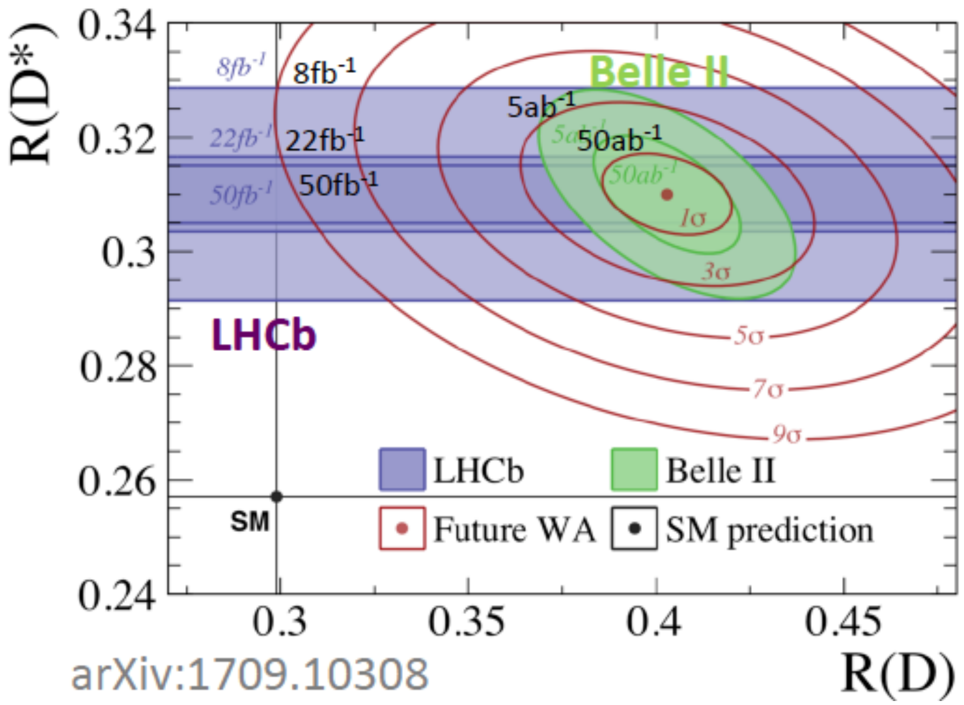
Source	$\frac{\delta R(D^*)}{R(D^*)}$ [%]
Simulated sample size	4.7
Empty bins in templates	1.3
Signal decay model	1.8
$D^{**}\tau\nu_\tau$ and $D_s^{**}\tau\nu_\tau$ feed-down	2.7
$D_s^+ \to 3\pi^\pm X$ decay model	2.5
$B \to D^* D_s^+ X$, $D^* D^+ X$, $D^* D^0 X$ backgrounds	3.9
Combinatorial background	0.7
$B \to D^{*-} 3\pi^\pm X$ background	2.8
Efficiency ratio	3.9
Normalisation channel efficiency (modelling of $B^0 \to D^{*-} 3\pi^\pm$)	2.0
Total systematic uncertainty	9.1

[PRL 120, 171802 (2018), PRD 97, 072013 (2018)]

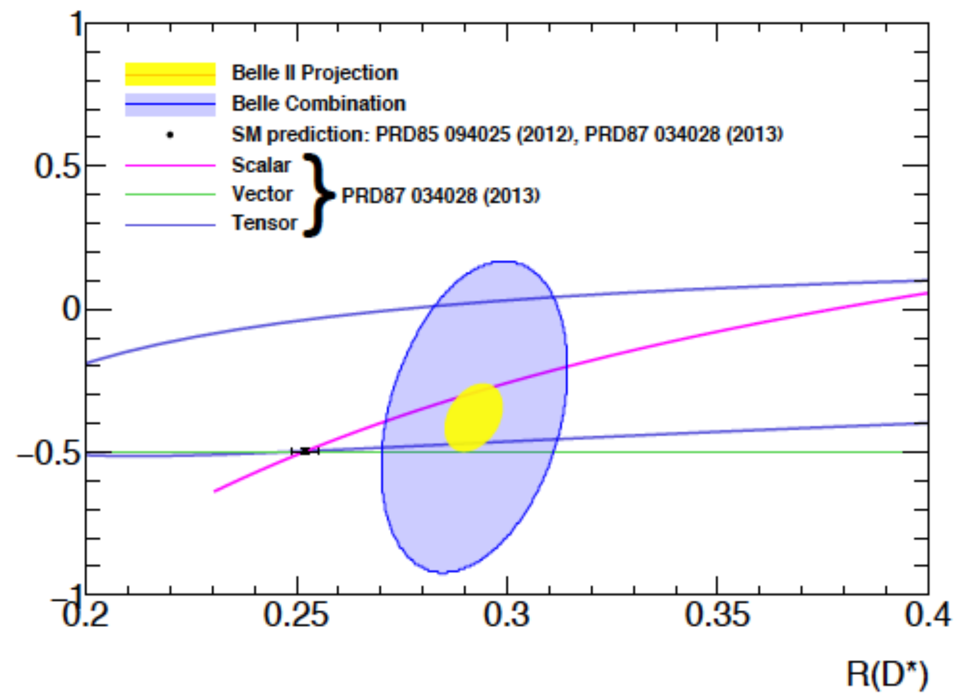
Belle II may help !

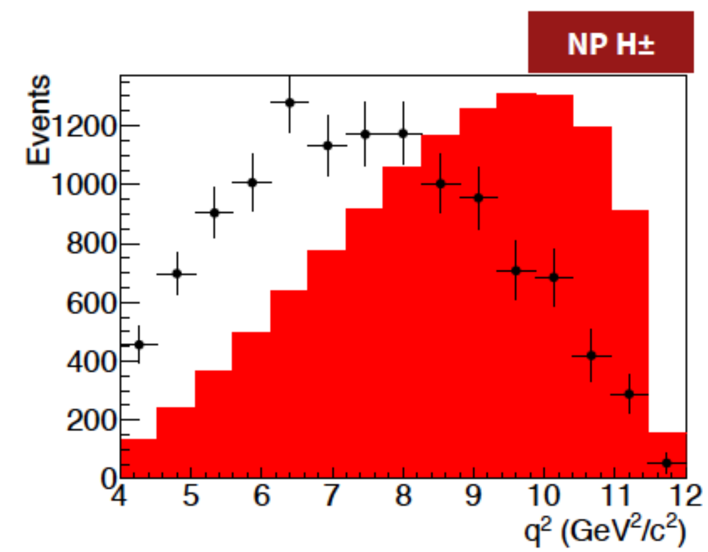
Belle II Projections

- Lepton universality violation may be established even with $5ab^{-1}$ (2020).
- High statistics data will provide more detailed information, such as τ polarization, q^2 distribution, to discriminate type of NP.



arXiv:1709.10308





50 ab-1 projection of the subtracted q^2 spectrum in $B \to D^* \tau \nu$ (HT)

	ΔR(D) [%]			ΔR(D*) [%]		
	Stat	Sys	Total	Stat	Sys	Total
Belle 0.7 ab^{-1}	14	6	16	6	3	7
Belle II 5 ab^{-1}	5	3	6	2	2	3
Belle II 50 ab^{-1}	2	3	3	1	2	2

Will soon hit the systematic limit !

- More observables (distributions) !
  - P(τ), P(D*)
  - $d\Gamma/dq^2$, $d\Gamma/dp_{D(*)}$, $d\Gamma/dp_e$, …
- More modes !
  - $B \to \pi \tau \nu$,
  - $B_S \to D_S \tau \nu$ (at 5S runs) , …

Pinning down leading systematic errors

- Measurement of R(D*) will be systematic dominated rather soon (at ~5ab^{-1} at Belle II)
- Leading systematic errors:
  - Uncertainty in D** composition
  - Uncertainty in modeling of B→D** l ν kinematics
  - Uncertainty in hadronic B decays as well (for measurements with τ hadronic decays)

Belle II will provide much more information

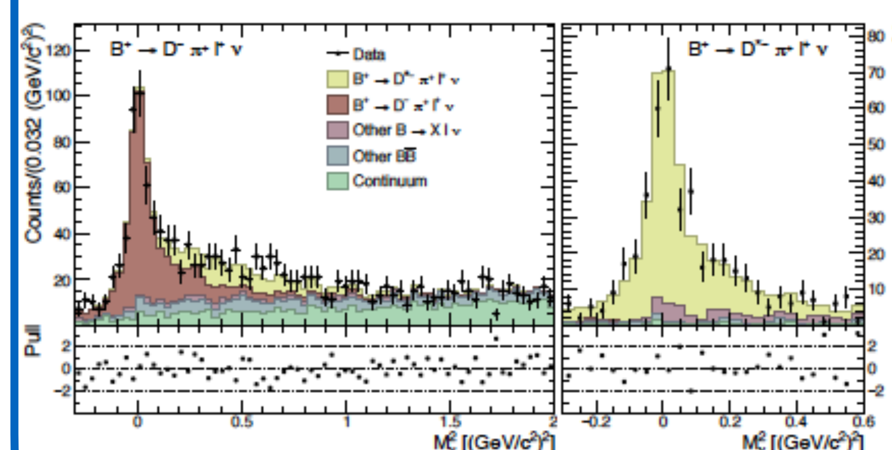
- Differential distribution of narrow and broad components
- More complete study of D** decay width m^2_{miss} studies and hadronic modes

Belle, arXiv: 1803.06444

New hadronic tag analysis

- $B^+ \to D^{(*)}\pi^+ l\nu$ (1.4k signal)
- $B^0 \to D^{(*)}\pi^+ l\nu$ (1.1k signal)

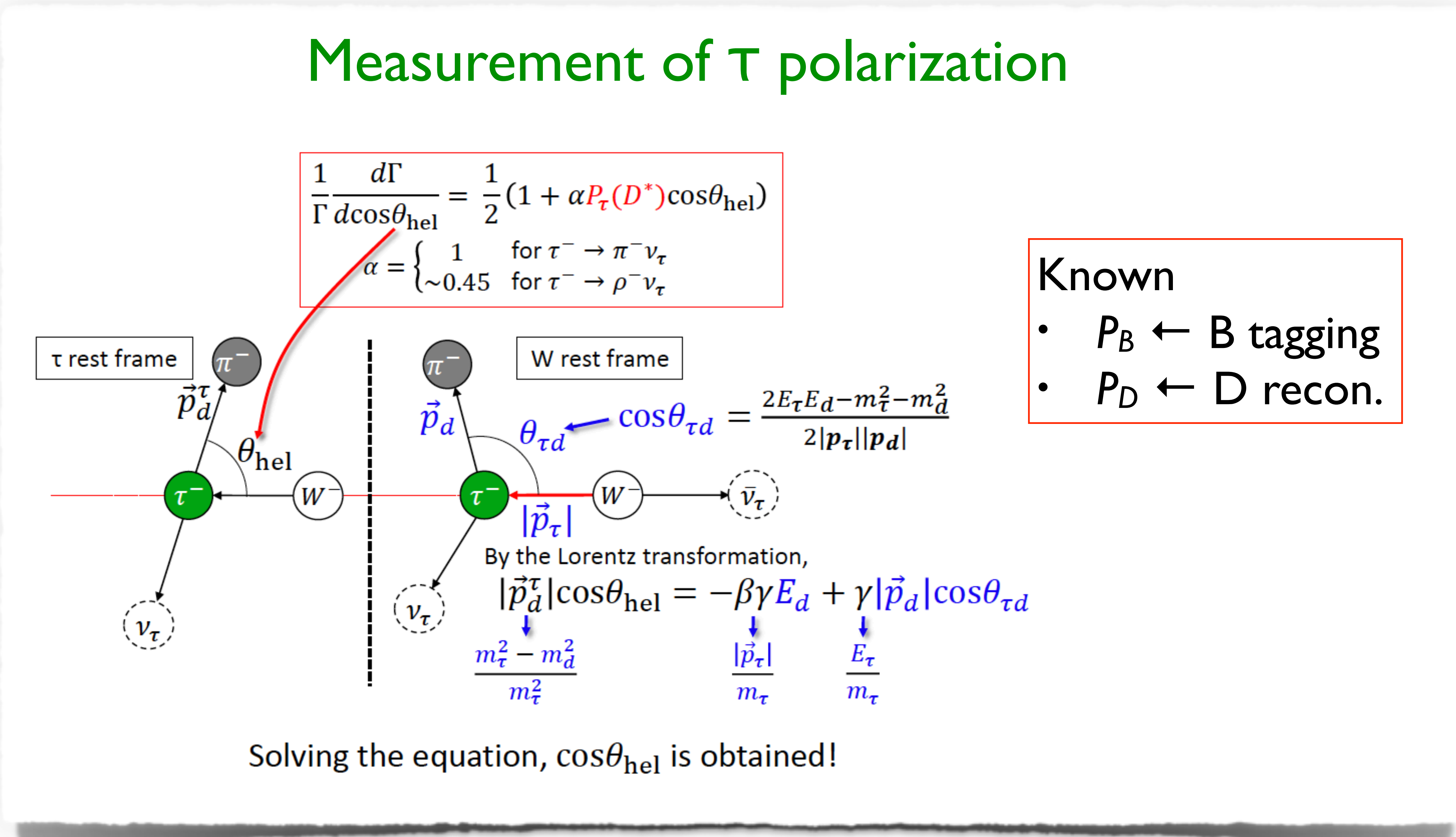
- $\mathcal{B}(B^+ \to D^-\pi^+\ell^+\nu)$ $= [4.55 \pm 0.27\ (\text{stat.}) \pm 0.39\ (\text{syst.})] \times 10^{-3}$,
- $\mathcal{B}(B^0 \to \bar{D}^0\pi^-\ell^+\nu)$ $= [4.05 \pm 0.36\ (\text{stat.}) \pm 0.41\ (\text{syst.})] \times 10^{-3}$,
- $\mathcal{B}(B^+ \to D^{*-}\pi^+\ell^+\nu)$ $= [6.03 \pm 0.43\ (\text{stat.}) \pm 0.38\ (\text{syst.})] \times 10^{-3}$,
- $\mathcal{B}(B^0 \to \bar{D}^{*0}\pi^-\ell^+\nu)$ $= [6.46 \pm 0.53\ (\text{stat.}) \pm 0.52\ (\text{syst.})] \times 10^{-3}$.



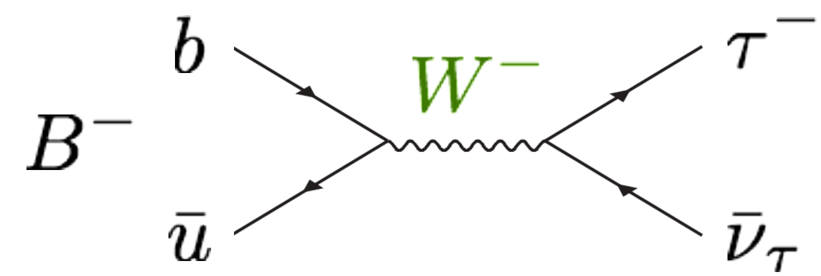
O(10) more tags expected !

Measurement of τ polarization

- Belle II will be able to measure distributions; such as τ polarization, q^2 distribution, to discriminate type of NP.



B → τ ν, l ν



- Belle II will be able to measure B→τ ν precisely, and also measure B→μ ν for the first time.
- They will provide useful information to digest NP models (if the present anomalies are confirmed).
- SM branching fraction $$\mathcal{B}(B^- \to \ell^- \bar{\nu}) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$
- Parameters
  - B decay constant (FLAG 2016) : $f_B = (186 \pm 4)\,\mathrm{MeV}$
  - CKM element (HFLAV 2016?) : $|V_{ub}| = (3.55 \pm 0.12) \times 10^{-3}$
    - From exclusive measurements

$$\begin{cases} B_\tau = (7.7 \pm 0.6) \times 10^{-5} \\ B_\mu = (3.5 \pm 0.3) \times 10^{-7} \\ B_e = (8.1 \pm 0.6) \times 10^{-12} \end{cases}$$

Possible correction by NP

$$Br = Br_{SM} \times r_H \qquad r_H = |1 - g_S|^2$$

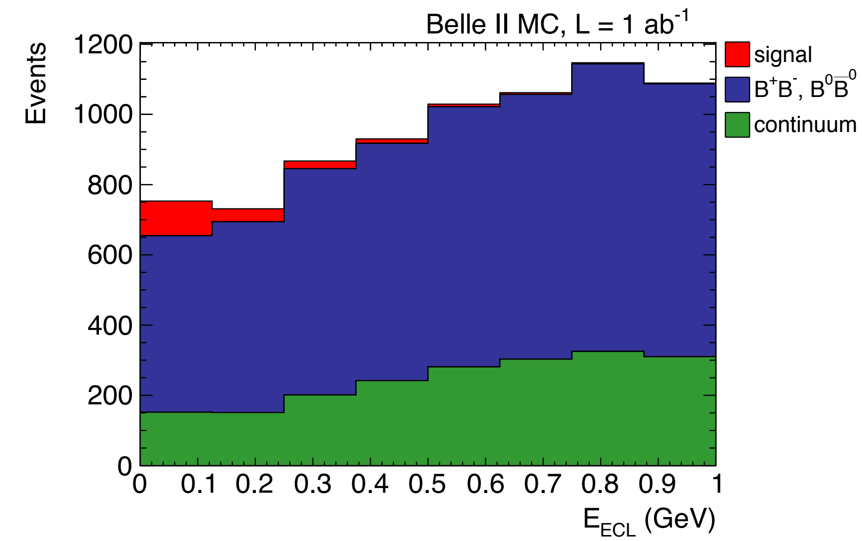
Type II 2HDM, W. S. Hou, PRD 48, 2342 (1993), $r_H = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$

B → τ ν, l ν at Belle II

1808.10567

B→τν

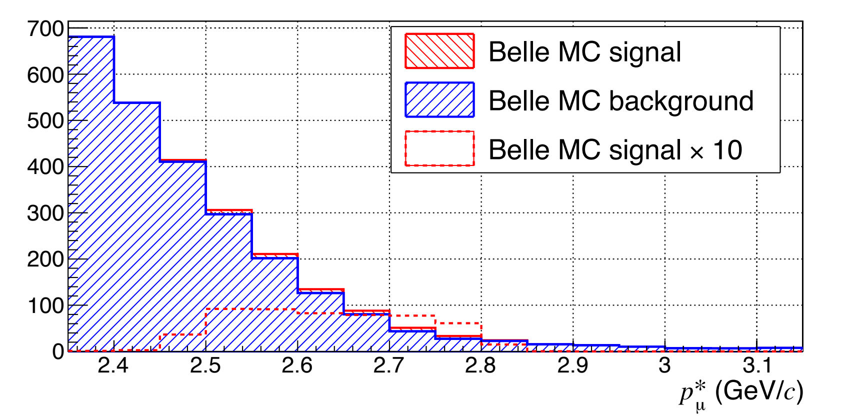
- Exploits high efficiency of the hadronic tag method through the Full Event Interpretation (FEI).
- Selection of photon candidates is important to cope with machine background in Belle II (x20 w.r.t. Belle)
  - Cluster energy, timing, shape (E9/E25)
- Multivariate continuum suppression



E_{ECL}		$< 1\,\mathrm{GeV}$	$< 0.25\,\mathrm{GeV}$
without background	Background yield [events]	12835	2062
	Signal yield [events]	332	238
	Signal efficiency (‰)	3.8	2.7
with background	Background yield [events]	7420	1348
	Signal yield [events]	188	136
	Signal efficiency (‰)	2.2	1.6

B→μν

- Tagged searches are possible, but efficiency is too low
- Extrapolation from Belle to Belle II
  - Branching fraction error : 7%(stat.) at 50ab^{-1}
  - 5σ observation at 6 ab^{-1}



Experiment	Upper limit @ 90% C.L.	Comment
Belle [225]	2.7×10^{-6}	Fully reconstructed hadronic tag, 711 fb^{-1}
Belle [226]	1.1×10^{-6}	Untagged analysis, 711 fb^{-1}
BaBar [222]	1.0×10^{-6}	Untagged analysis, 468×10^6 $B\overline{B}$ pairs

Constraint on NP

- Effect by New physics

$$\mathcal{B}(B^- \to \ell^- \bar{\nu}_\ell)_{\rm NP} = \mathcal{B}(B^- \to \ell^- \bar{\nu}_\ell)_{\rm SM} \times \left|1 + r^\ell_{\rm NP}\right|^2$$

- Present constraints

$$\left|1 + r^\tau_{\rm NP}\right| = 1.17 \pm 0.12\,, \quad \left|1 + r^\mu_{\rm NP}\right| < 1.7 \;(90\% \;{\rm CL})\,, \quad \left|1 + r^e_{\rm NP}\right| < 348 \;(90\% \;{\rm CL})\,.$$

- Two ratios to reduce theoretical uncertainties:

$$R_{\rm ps} = \frac{\tau_{B^0}}{\tau_{B^-}} \frac{\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to \pi^+ \ell^- \bar{\nu}_\ell)}, \qquad R_{\rm pl} = \frac{\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau)}{\mathcal{B}(B^- \to \mu^- \bar{\nu}_\mu)}.$$

$|V_{ub}|$ $\quad f_B$

$$R^{\rm NP}_{\rm ps} = (0.539 \pm 0.043)\left|1 + r^\tau_{\rm NP}\right|^2,$$

Error from B→π form factor (f+)

$$R^{\rm NP}_{\rm pl} = \frac{m_\tau^2}{m_\mu^2}\frac{(1 - m_\tau^2/m_B^2)^2}{(1 - m_\mu^2/m_B^2)^2}\left|1 + r^\tau_{\rm NP}\right|^2 \simeq 222.37\left|1 + r^\tau_{\rm NP}\right|^2.$$

- Current constraint from $R^{\rm exp}_{\rm ps}$ = 0.73 ± 0.14

$$\left|1 + r^\tau_{\rm NP}\right| = 1.16 \pm 0.11$$

Belle II projection

$$R^{5\,{\rm ab}^{-1}}_{\rm ps} = 0.54 \pm 0.11\,, \quad R^{50\,{\rm ab}^{-1}}_{\rm ps} = 0.54 \pm 0.04\,,$$

$$R^{5\,{\rm ab}^{-1}}_{\rm pl} = 222 \pm 76\,, \quad R^{50\,{\rm ab}^{-1}}_{\rm pl} = 222 \pm 26\,.$$

95%C.L. limit on $r^\tau_{\rm NP}$

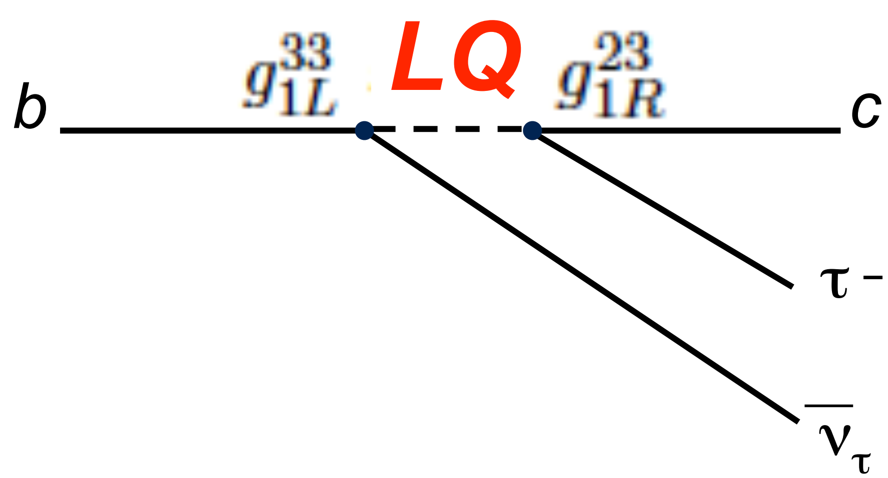
Luminosity	$R_{\rm ps}$	$R_{\rm pl}$
$5\,{\rm ab}^{-1}$	$[-0.22, 0.20]$	$[-0.42, 0.29]$
$50\,{\rm ab}^{-1}$	$[-0.11, 0.12]$	$[-0.12, 0.11]$

Testing B anomalies at ATLAS/ CMS (e.g. LQ model)

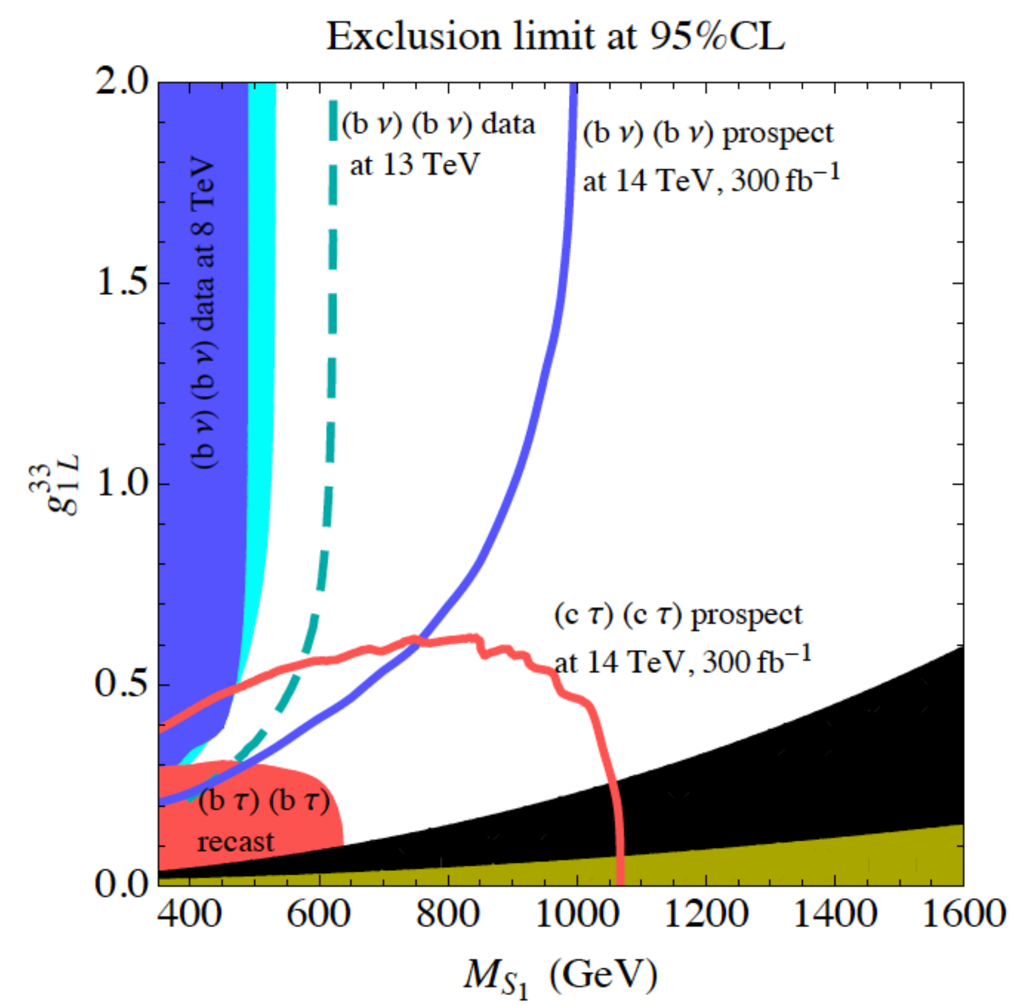
1808.10567

- The Leptoquark (LQ) model is a favored model, which can explain observed anomalies consistently: P5', R_K(*), R(D(*))
  - Coupling to 3rd gen. > to 2nd gen. >> to 1st gen.

e.g. : scalar leptoquark



$$2\sqrt{2}G_F V_{cb} C_{\mathrm{LQ}_2} = -\frac{g_{1L}^{33}\, g_{1R}^{23*}}{M_{S_1}^2}$$

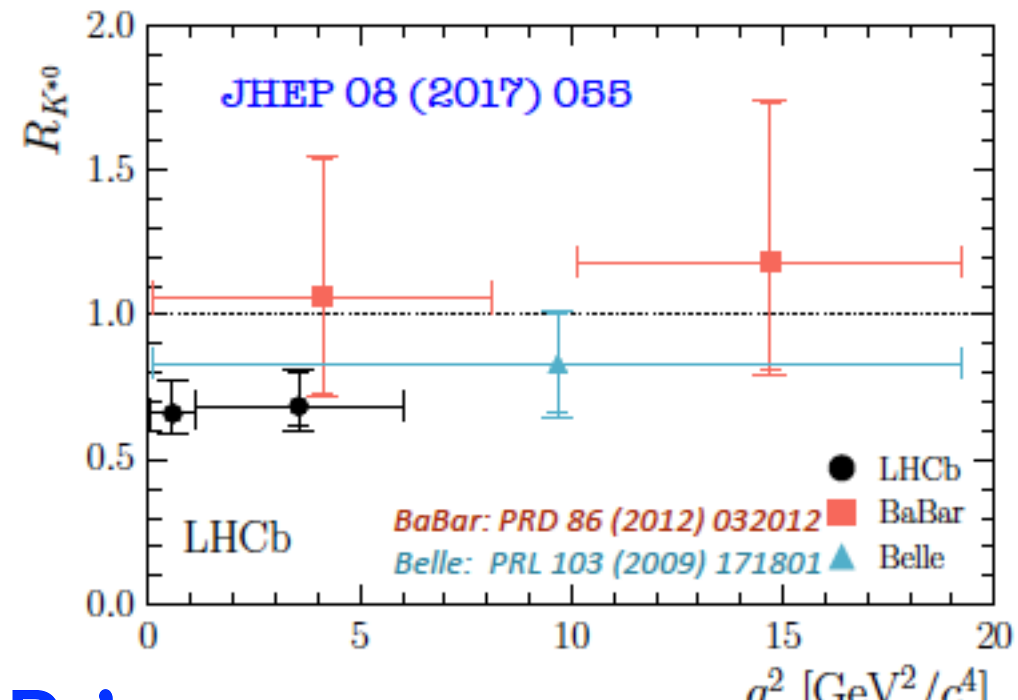


Once B anomalies are confirmed, it would be interesting to see results of ATLAS/CMS w/ 300fb^{-1}

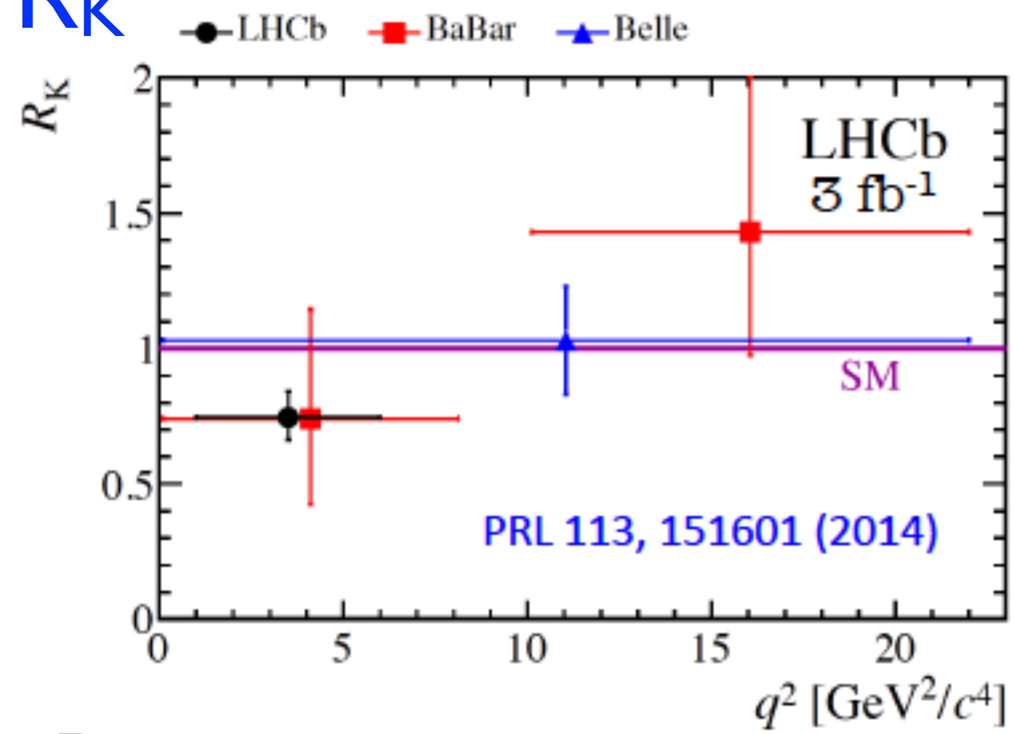
$b \to s\, l\, l$ decays

Talks by Francesco Polci

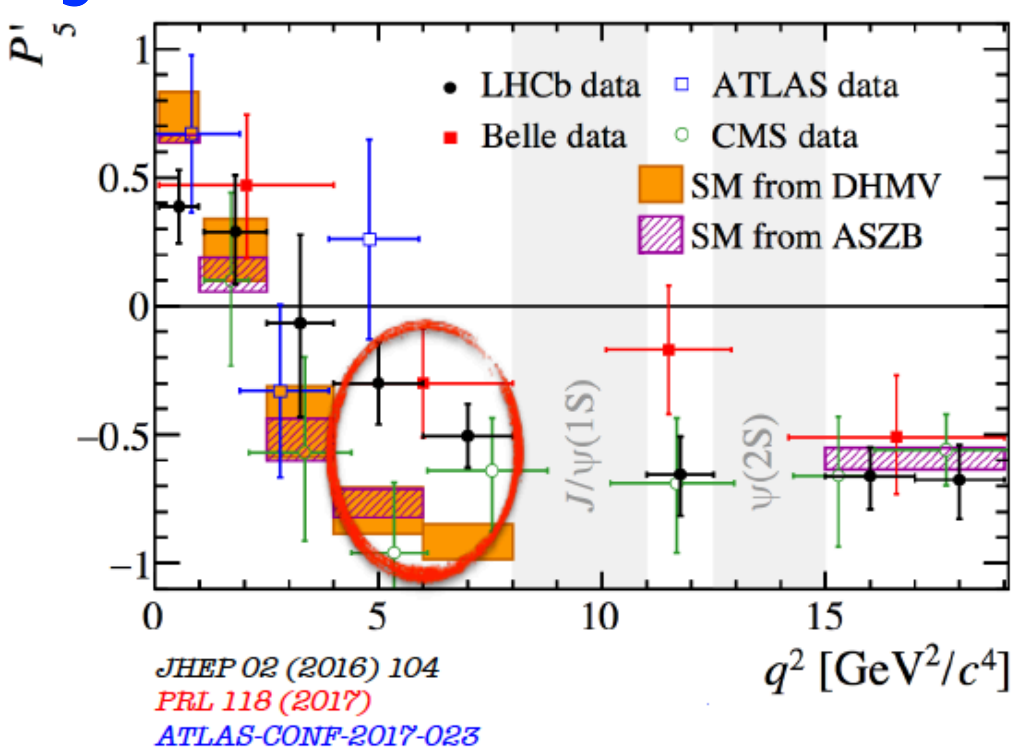
$R_{K^{*0}}$



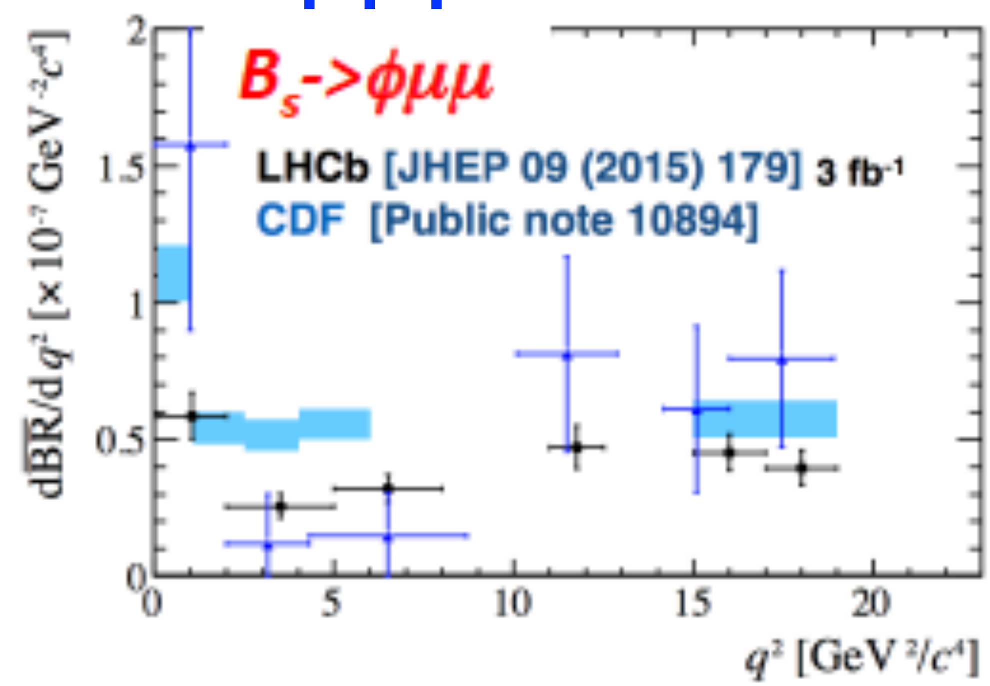
R_K



P_5'



$B_s \to \varphi\mu\mu$



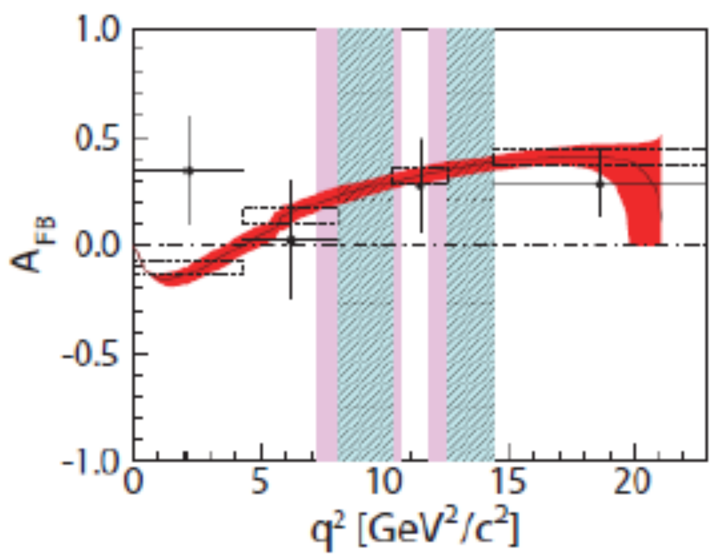
$b \to s\, l\, l$ inclusive

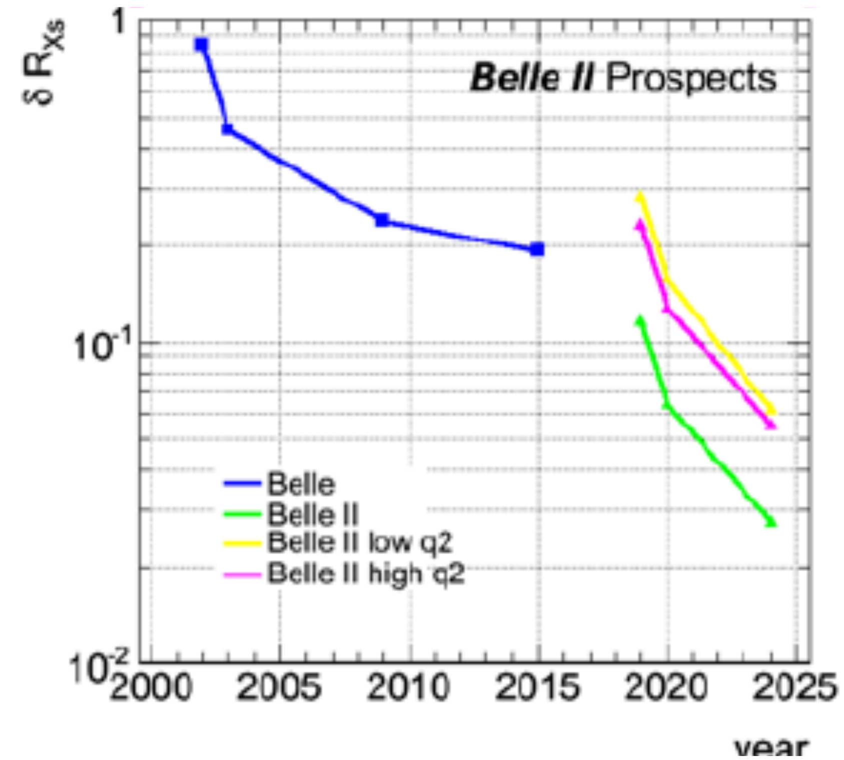
Belle II can provide data from inclusive measurements

- sum of exclusive, as done by Belle

[Belle, arXiv:1402.7134]
10 modes, $M(X_s) < 2.0$ GeV
50% of total inclusive rate
(goal here was A_{FB}, flavor of B needed)

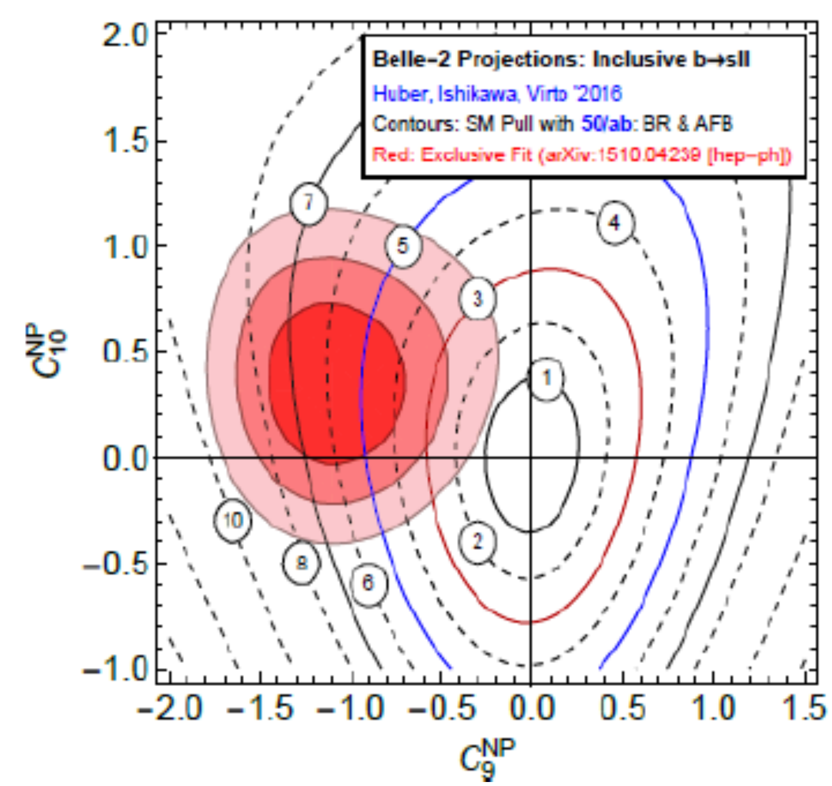
B^0 decays		B^- decays	
	(K_S^0)	K^-	
$K^-\pi^+$	$(K_S^0\pi^0)$	$K^-\pi^0$	$K_S^0\pi^-$
$K^-\pi^+\pi^0$	$(K_S^0\pi^-\pi^+)$	$K^-\pi^+\pi^-$	$K_S^0\pi^-\pi^0$
$K^-\pi^+\pi^-\pi^+$	$(K_S^0\pi^-\pi^+\pi^0)$	$K^-\pi^+\pi^-\pi^0$	$K_S^0\pi^-\pi^+\pi^-$
$(K^-\pi^+\pi^-\pi^+\pi^0)$	$(K_S^0\pi^-\pi^+\pi^-\pi^+)$	$(K^-\pi^+\pi^-\pi^+\pi^-)$	$(K_S^0\pi^-\pi^+\pi^-\pi^0)$





1808.10567

Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B \to X_s\ell^+\ell^-)$ ([1.0, 3.5] GeV^2)	29%	13%	6.6%
$\mathrm{Br}(B \to X_s\ell^+\ell^-)$ ([3.5, 6.0] GeV^2)	24%	11%	6.4%
$\mathrm{Br}(B \to X_s\ell^+\ell^-)$ (> 14.4 GeV^2)	23%	10%	4.7%
$A_{CP}(B \to X_s\ell^+\ell^-)$ ([1.0, 3.5] GeV^2)	26%	9.7 %	3.1 %
$A_{CP}(B \to X_s\ell^+\ell^-)$ ([3.5, 6.0] GeV^2)	21%	7.9 %	2.6 %
$A_{CP}(B \to X_s\ell^+\ell^-)$ (> 14.4 GeV^2)	21%	8.1 %	2.6 %
$A_{FB}(B \to X_s\ell^+\ell^-)$ ([1.0, 3.5] GeV^2)	26%	9.7%	3.1%
$A_{FB}(B \to X_s\ell^+\ell^-)$ ([3.5, 6.0] GeV^2)	21%	7.9%	2.6%
$A_{FB}(B \to X_s\ell^+\ell^-)$ (> 14.4 GeV^2)	19%	7.3%	2.4%
$\Delta_{CP}(A_{FB})$ ([1.0, 3.5] GeV^2)	52%	19%	6.1%
$\Delta_{CP}(A_{FB})$ ([3.5, 6.0] GeV^2)	42%	16%	5.2%
$\Delta_{CP}(A_{FB})$ (> 14.4 GeV^2)	38%	15%	4.8%



$b \to s\,\tau\,\tau, s\,\tau\,l$

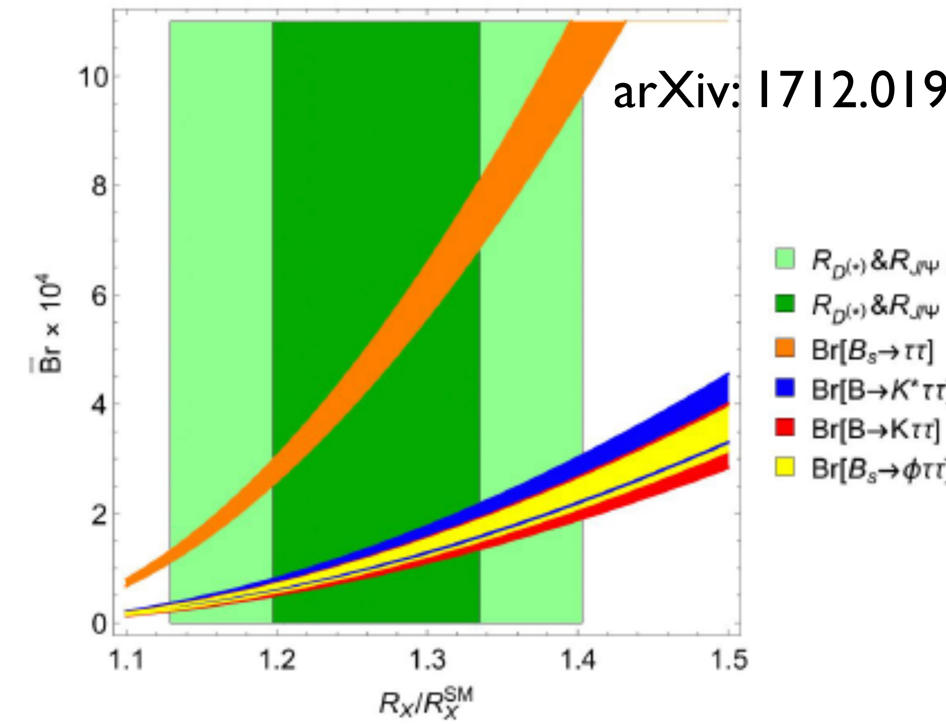
Tauonic channels become more interesting, as $R(D^{(*)})$ get more precise !

$B \to K^{(*)}\,\tau\,\tau$

$$B(B^+ \to K^+ \tau^+ \tau^-)_{SM} = (1.22 \pm 0.10)\,10^{-7}$$
$$B(B^0 \to K^0 \tau^+ \tau^-)_{SM} = (1.13 \pm 0.09)\,10^{-7}$$
$$B(B^+ \to K^{*+} \tau^+ \tau^-)_{SM} = (0.99 \pm 0.12)\,10^{-7}$$
$$B(B^0 \to K^{*0} \tau^+ \tau^-)_{SM} = (0.91 \pm 0.11)\,10^{-7}$$

1808.10567

Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$Br(B^+ \to K^+\tau^+\tau^-) \cdot 10^5$	< 32	< 6.5	< 2.0
$Br(B^0 \to \tau^+\tau^-) \cdot 10^5$	< 140	< 30	< 9.6
$Br(B_s^0 \to \tau^+\tau^-) \cdot 10^4$	< 70	< 8.1	–

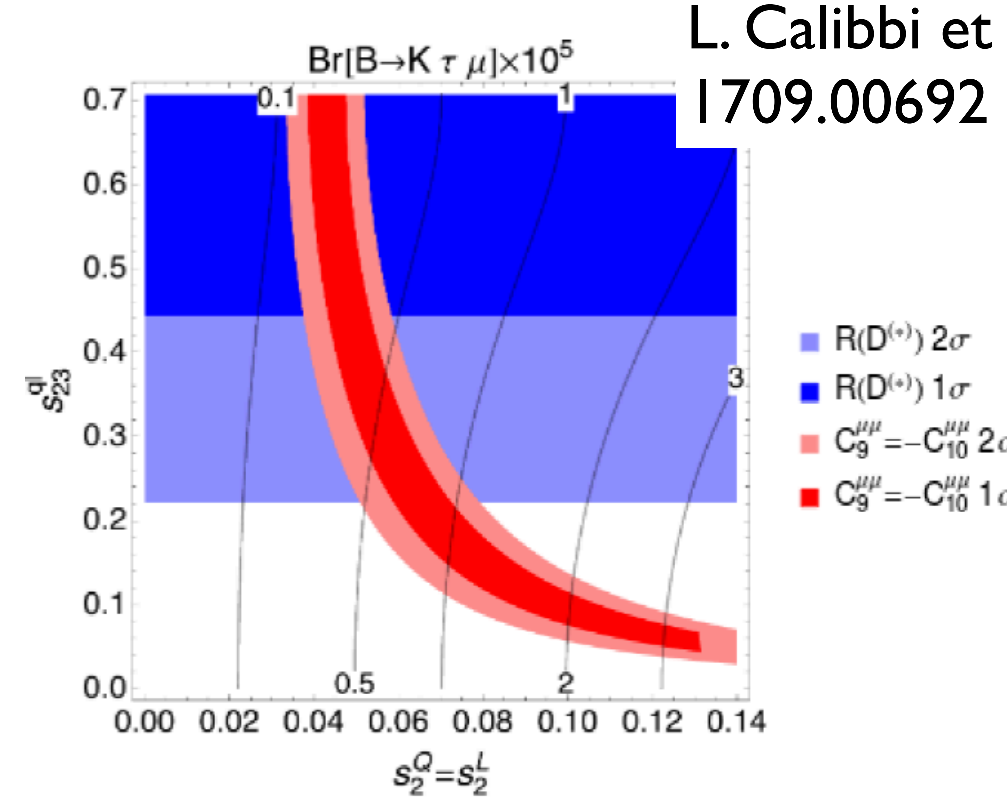


arXiv: 1712.01919

$B \to K^{(*)}\,\tau\,\mu$

1808.10567

Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$Br(B^+ \to K^+\tau^\pm e^\mp) \cdot 10^6$	–	–	< 2.1
$Br(B^+ \to K^+\tau^\pm \mu^\mp) \cdot 10^6$	–	–	< 3.3
$Br(B^0 \to \tau^\pm e^\mp) \cdot 10^5$	–	–	< 1.6
$Br(B^0 \to \tau^\pm \mu^\mp) \cdot 10^5$	–	–	< 1.3



L. Calibbi et al., 1709.00692

Wilson coefficients with Belle II and LHCb

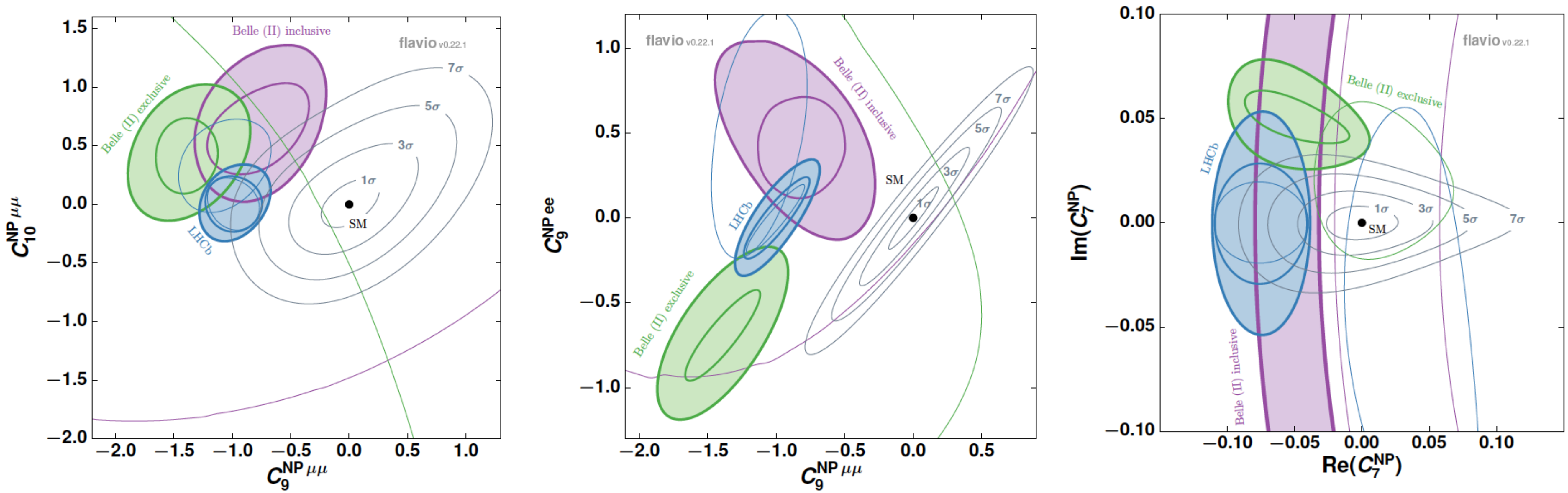
J. Albrecht et al., 1709.10308

- Wilson coefficient scan under given NP scenarios.

	$(C_9^{\mathrm{NP}\mu\mu}, C_{10}^{\mathrm{NP}\mu\mu})$	$(C_9'^{\mu\mu}, C_{10}'^{\mu\mu})$	$(C_9^{\mathrm{NP}\mu\mu}, C_9^{\mathrm{NP}ee})$	$(\mathcal{R}e\,(C_7'^{\mathrm{NP}}), \mathcal{I}m\,(C_7'^{\mathrm{NP}}))$	$(\mathcal{R}e\,(C_7^{\mathrm{NP}}), \mathcal{I}m\,(C_7^{\mathrm{NP}}))$
LHCb	$(-1.0, 0.0)$	$(-0.2, -0.2)$	$(-1.0, 0.0)$	$(0.00, 0.04)$	$(-0.075, 0.000)$
Belle II exclusive	$(-1.4, 0.4)$	$(0.4, 0.2)$	$(-1.4, -0.7)$	$(0.08, 0.00)$	$(-0.050, 0.050)$
Belle II inclusive	$(-0.8, 0.6)$	$(0.8, 0.2)$	$(-0.8, 0.4)$	$(0.02, -0.06)$	$(-0.050, -0.075)$

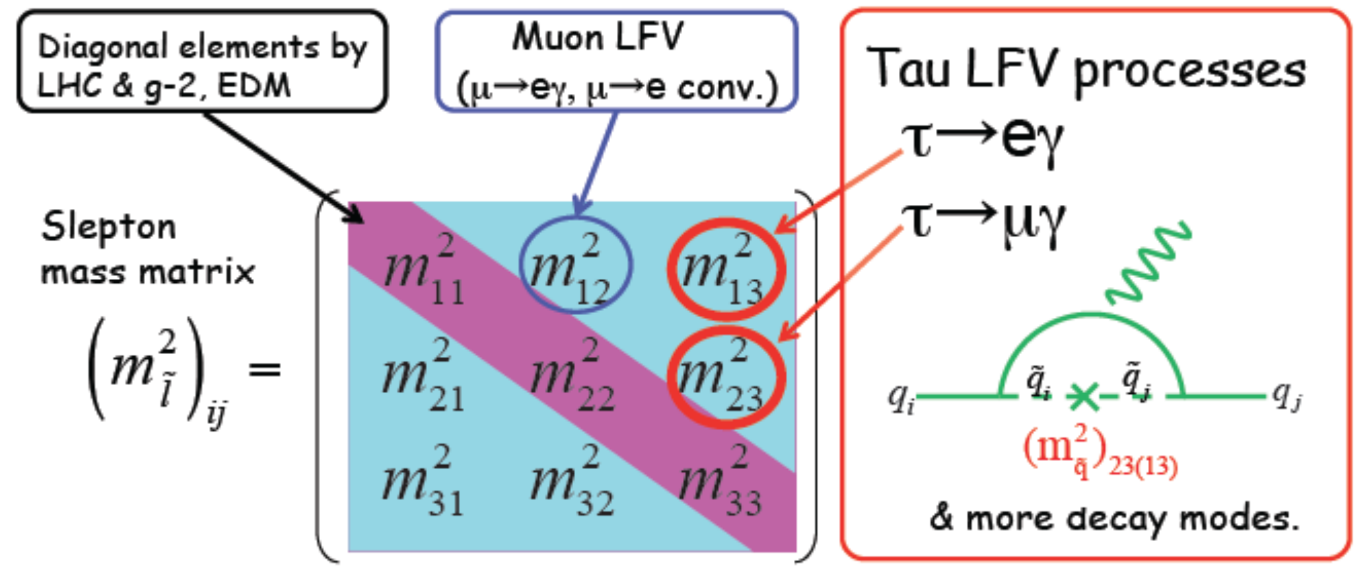
- With projected uncertainties at milestones

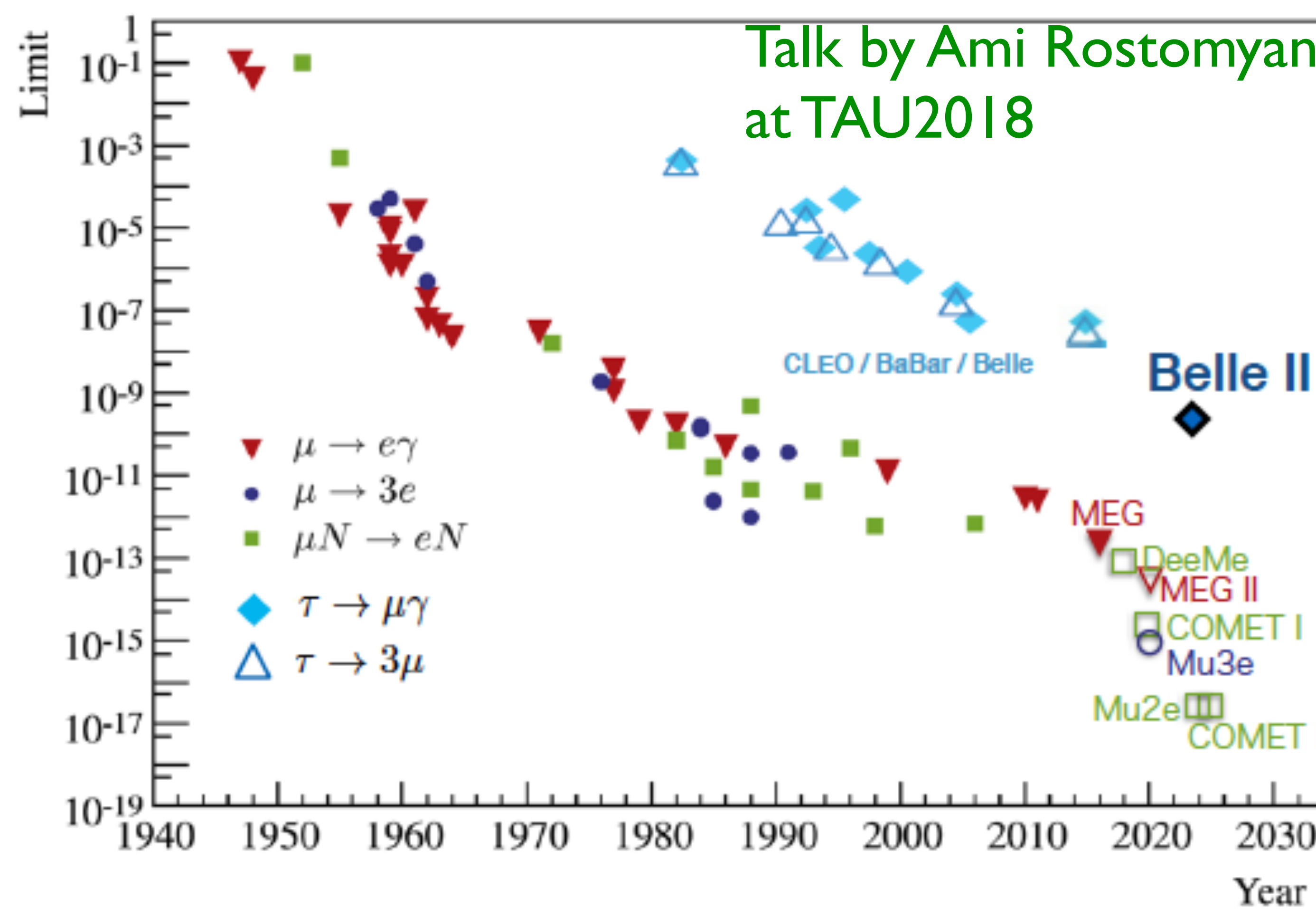
	Belle II(ab^{-1})	LHCb(fb^{-1})
I	5	8
II	50	22
III		50



LFV τ Decays

- Lepton flavor violated in the neutrino sector.
- Some NP models predicts LFV to be observed in 'near' future experiments.
- Complementary to LHC
- τ LFV complementary to muon programs
  - μ→eγ, eee
  - μ→e conversion



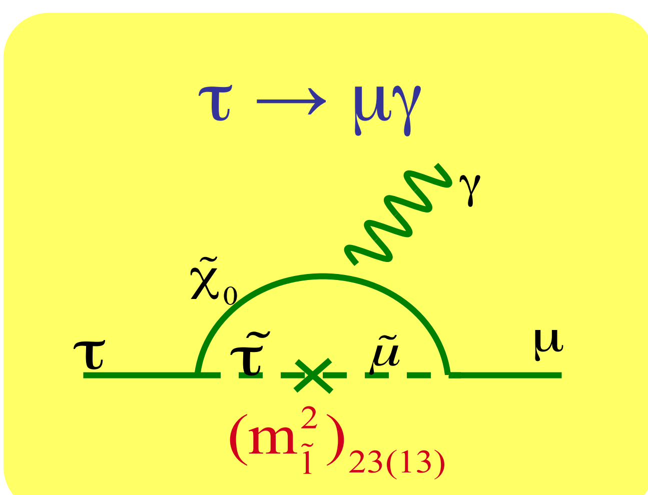


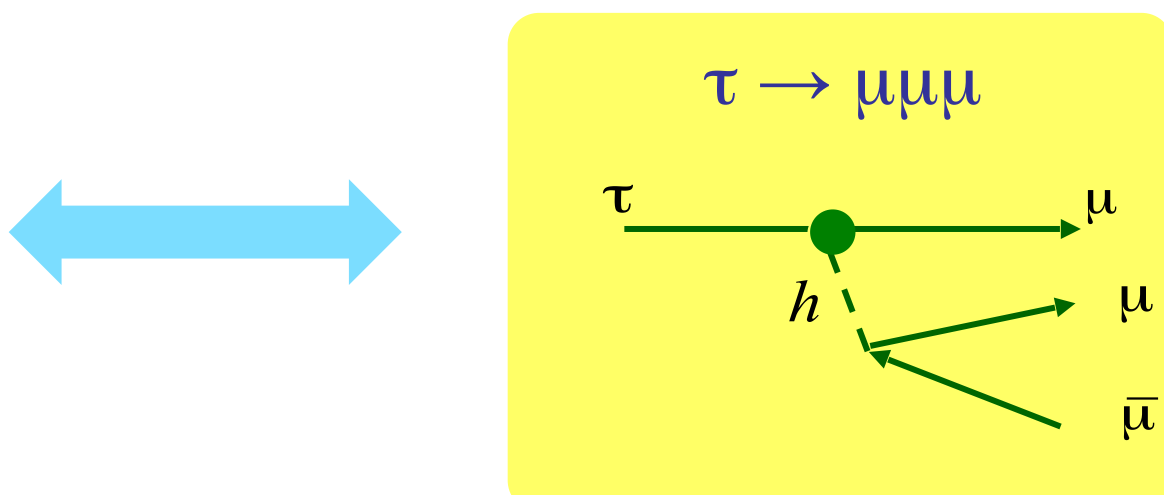
Comparison between NP models

- Ratios of tau LFV decay BF allow to discriminate between new physics models.

	SUSY+GUT (SUSY+Seesaw)	Higgs mediated	Little Higgs	non-universal Z' boson
$\frac{\mathcal{B}(\tau \to \mu\mu\mu)}{\mathcal{B}(\tau \to \mu\gamma)}$	$\sim 2\times10^{-3}$	0.06 - 0.1	0.4 - 2.3	~16
$\frac{\mathcal{B}(\tau \to \mu ee)}{\mathcal{B}(\tau \to \mu\gamma)}$	$\sim 1\times10^{-2}$	$\sim 1\times10^{-2}$	0.3 - 1.6	~16
$\mathcal{B}(\tau \to \mu\gamma)_{\rm max}$	$< 10^{-7}$	$< 10^{-10}$	$< 10^{-10}$	$< 10^{-9}$

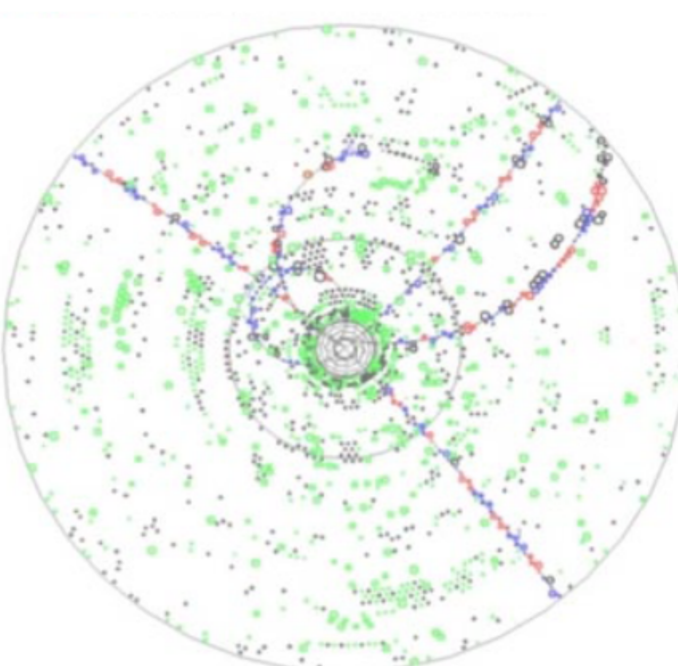
Favorite modes

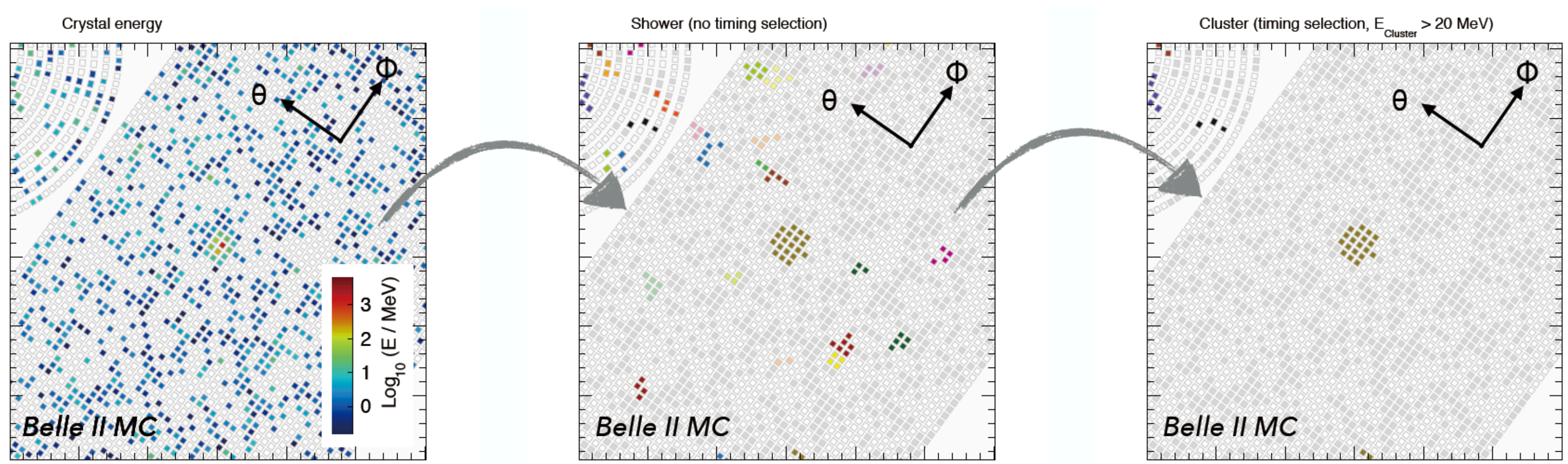




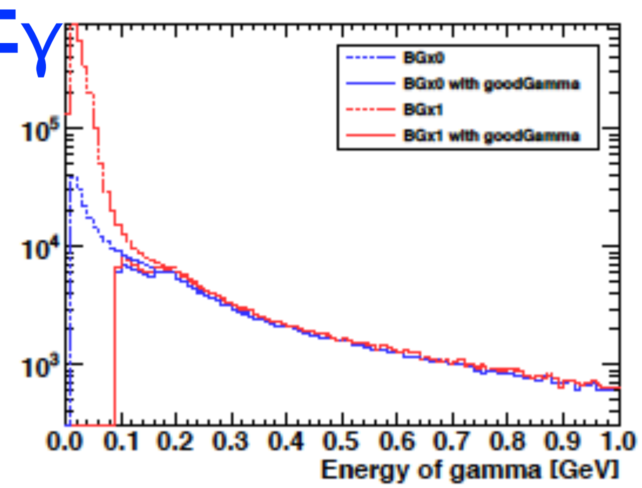
Tau analysis at Belle II

- 40 times higher luminosity gives higher machine induced backgrounds, which complicate tau analyses.
  - Touschek, beam gas, SR, radiative Bhabha, …
- Mitigation of backgrounds have been studied based on MC.
  - Cluster energy, timing, + charged track selection (Pt, dz)

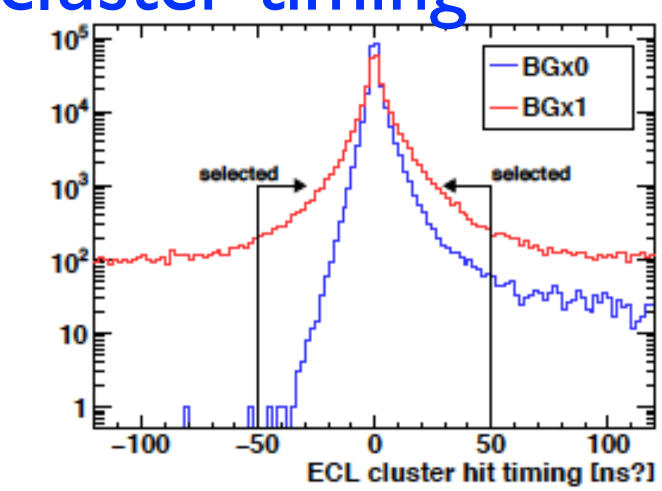




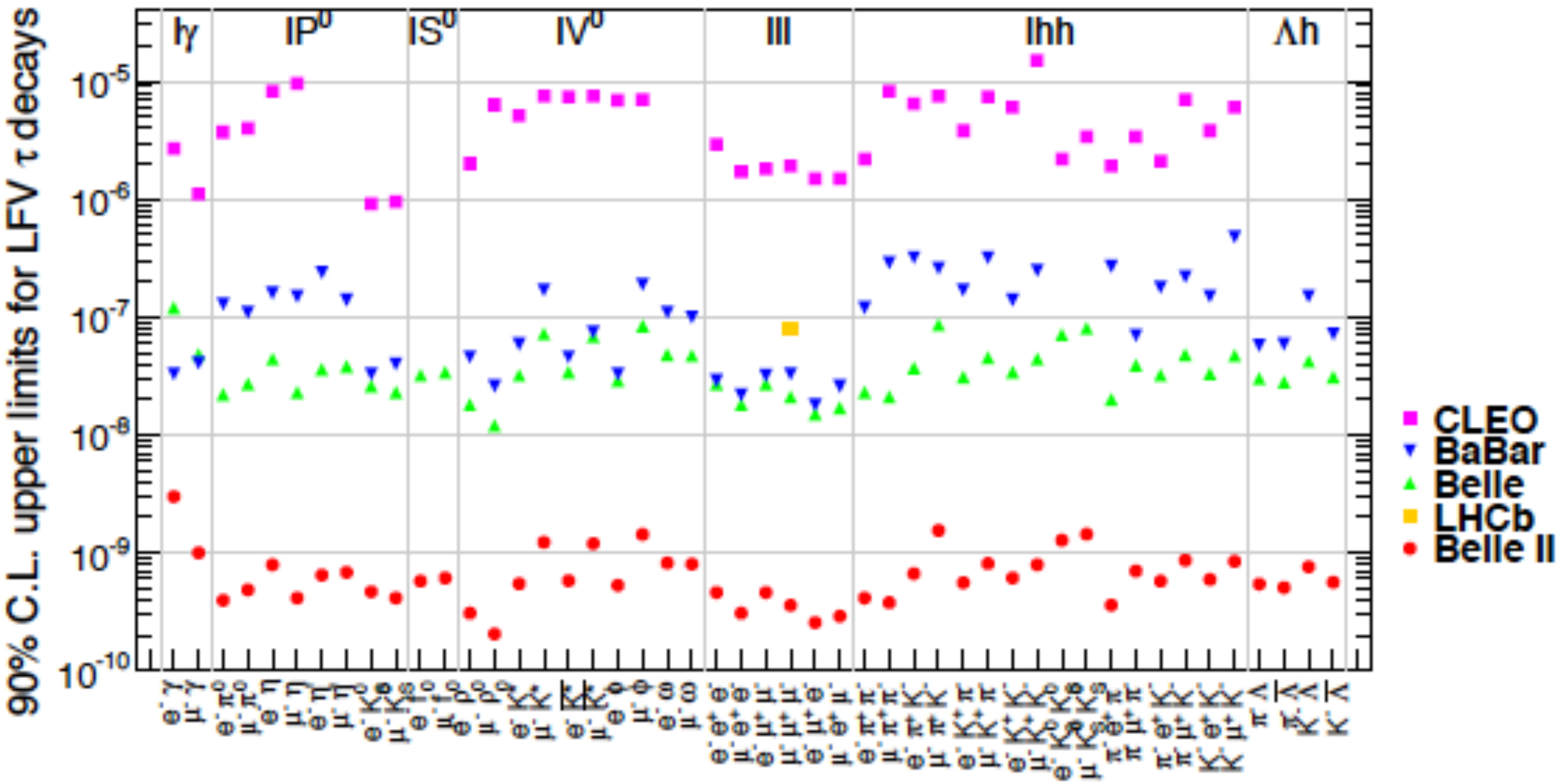
E_γ



cluster timing



Tau LFV prospect at Belle II



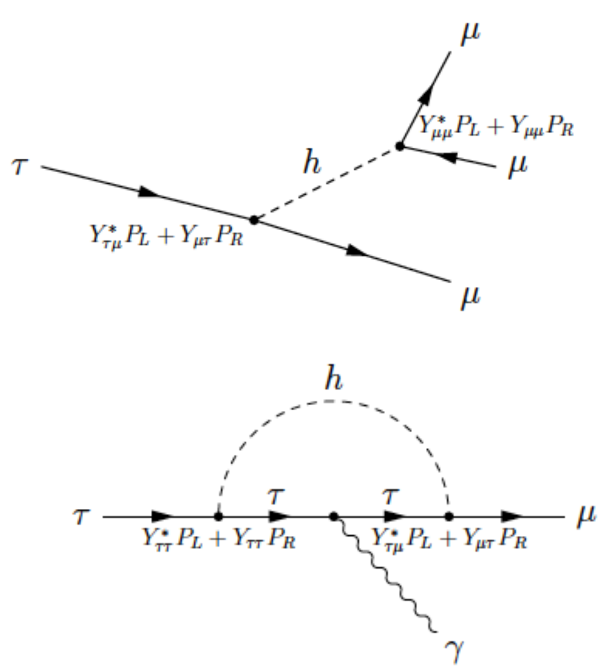
- Belle II will push down the current bounds further by more than an order of magnitude.
- Need to check the actual background situation with real beams.
- It is also important to increase sensitivity by improved analysis technique.

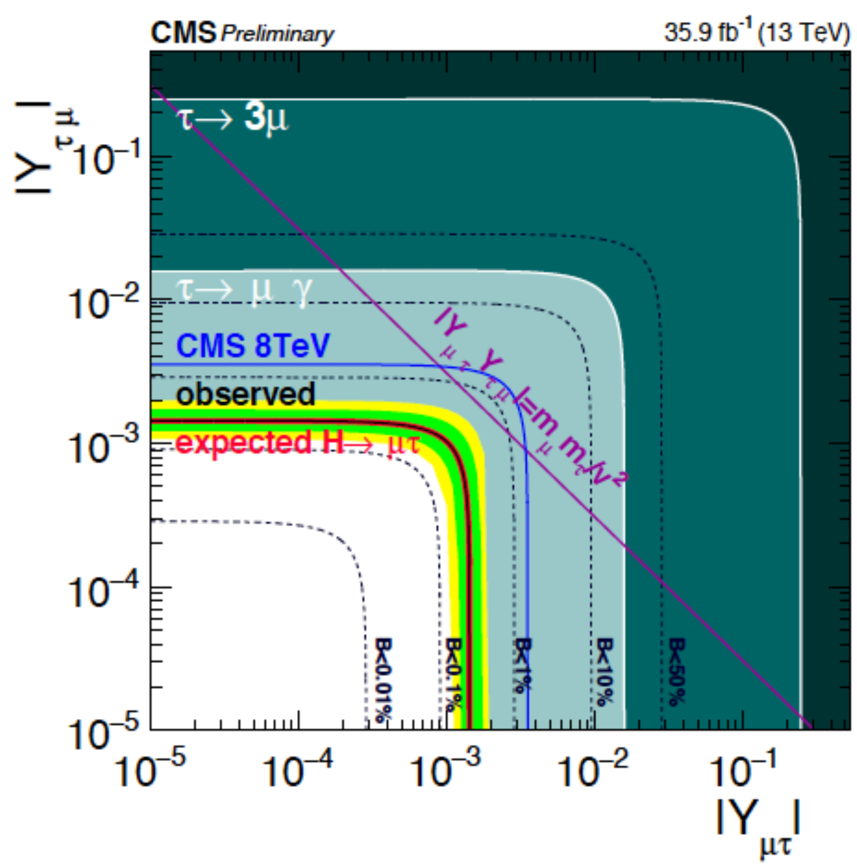
Tau LFV and Higgs LFV decays

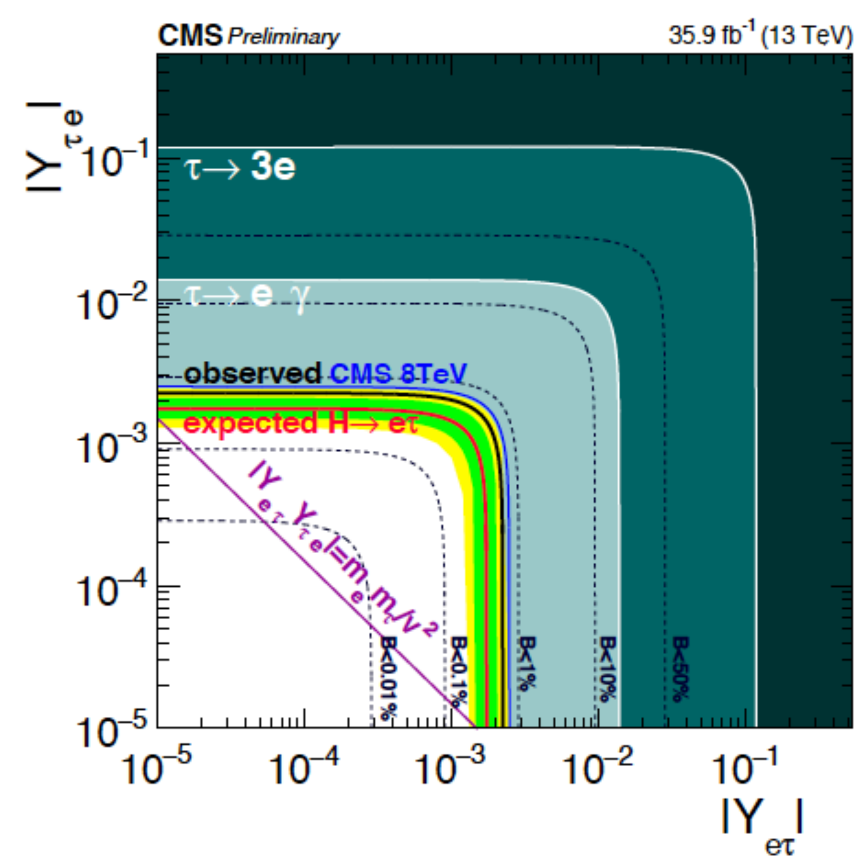
- CMS, 35.9 fb^{-1}, 13 TeV — CMS PAS HIG-17-001
- tau reconstructed by both septic and hadronic decays.
- The observed (expected) limit (95%C.L.):
  - Br(H→μτ)< 0.25 (0.25) %
  - Br(H→eτ)< 0.61 (0.37) %

$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 1.43 \times 10^{-3}$$

$$\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 2.26 \times 10^{-3}$$





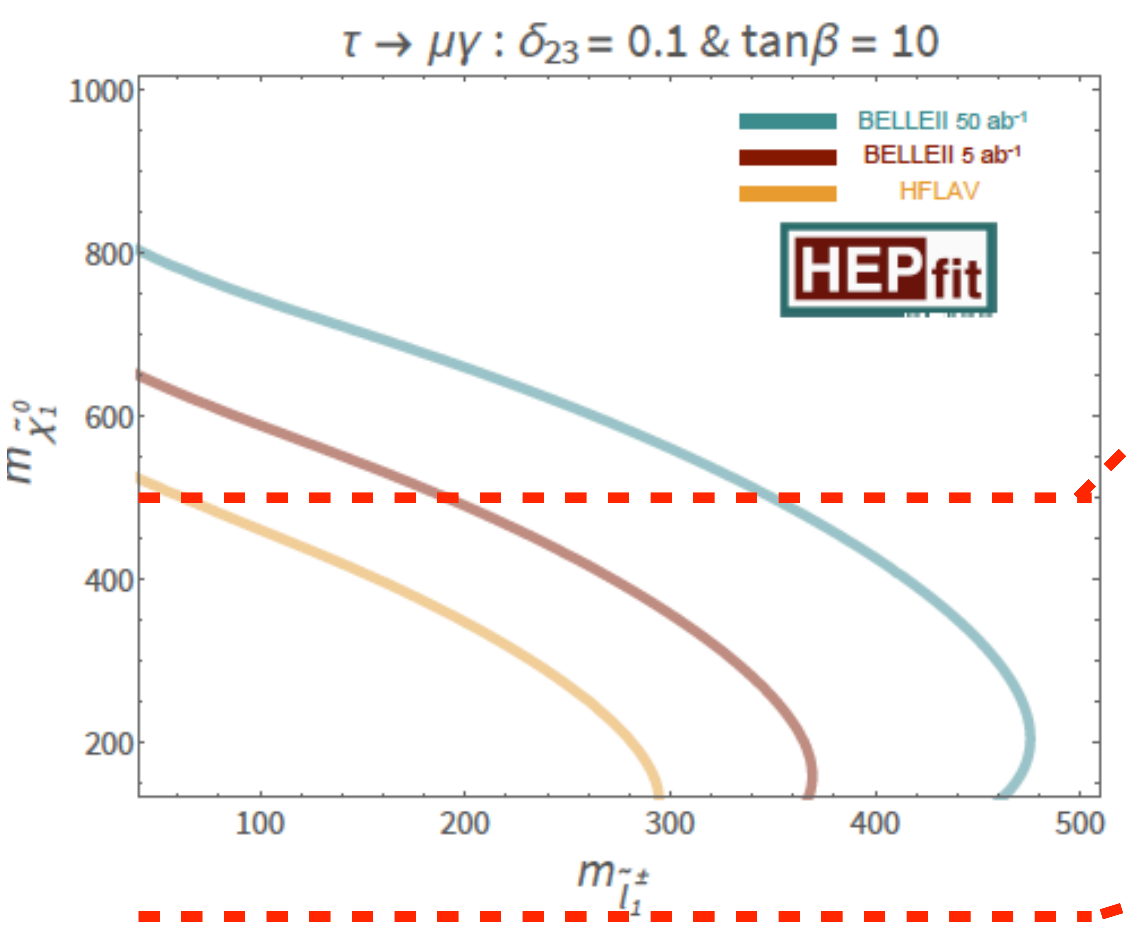


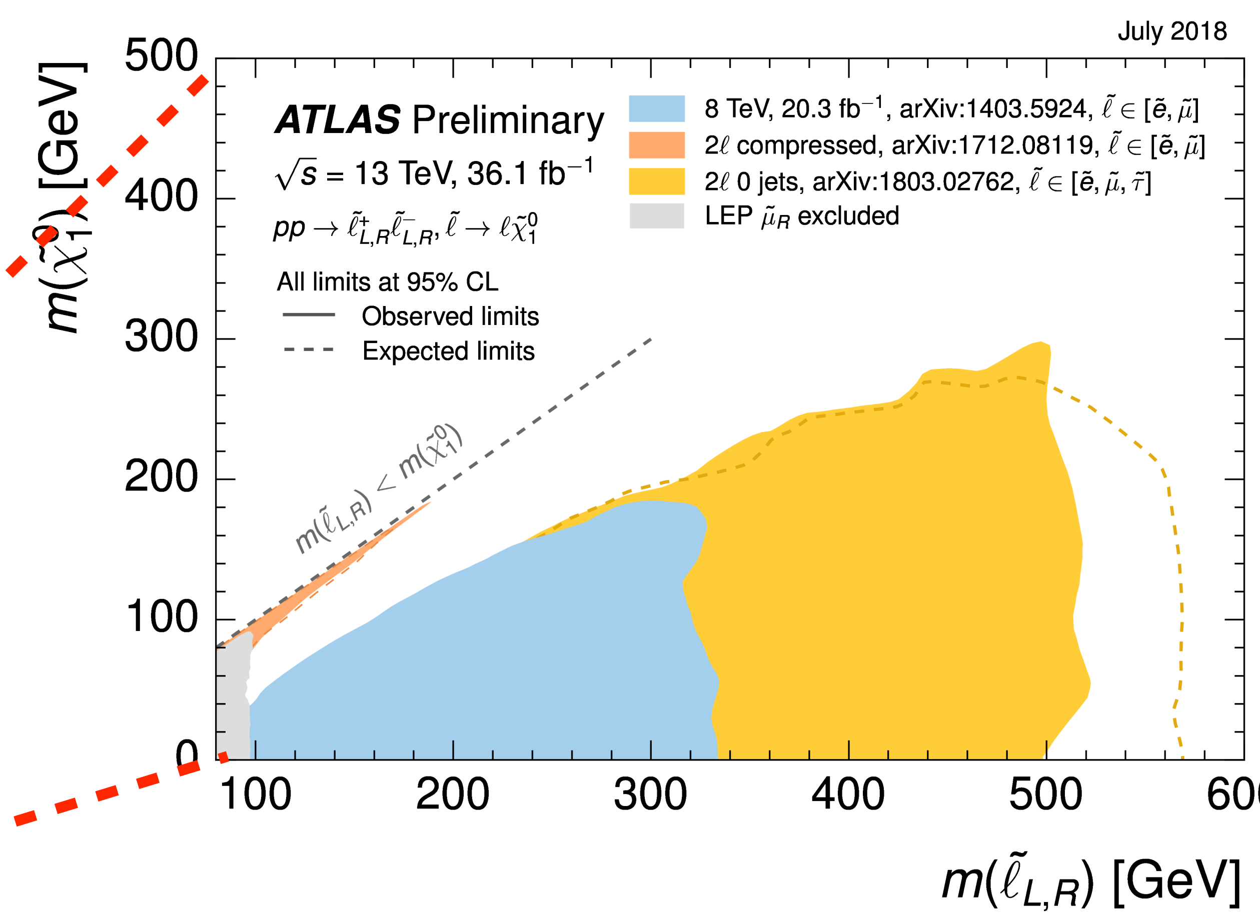
Comparison of improved limits by Belle II with LHC will be interesting.

Tau LFV and SUSY direct search at ATLAS/CMS

- Constraints on neutralino and slept mass from $\tau \to \mu\gamma$ based on MSSM.

1808.10567





SuperKEKB/Belle II Plan

Phase 1 (w/o QCS/Belle II)

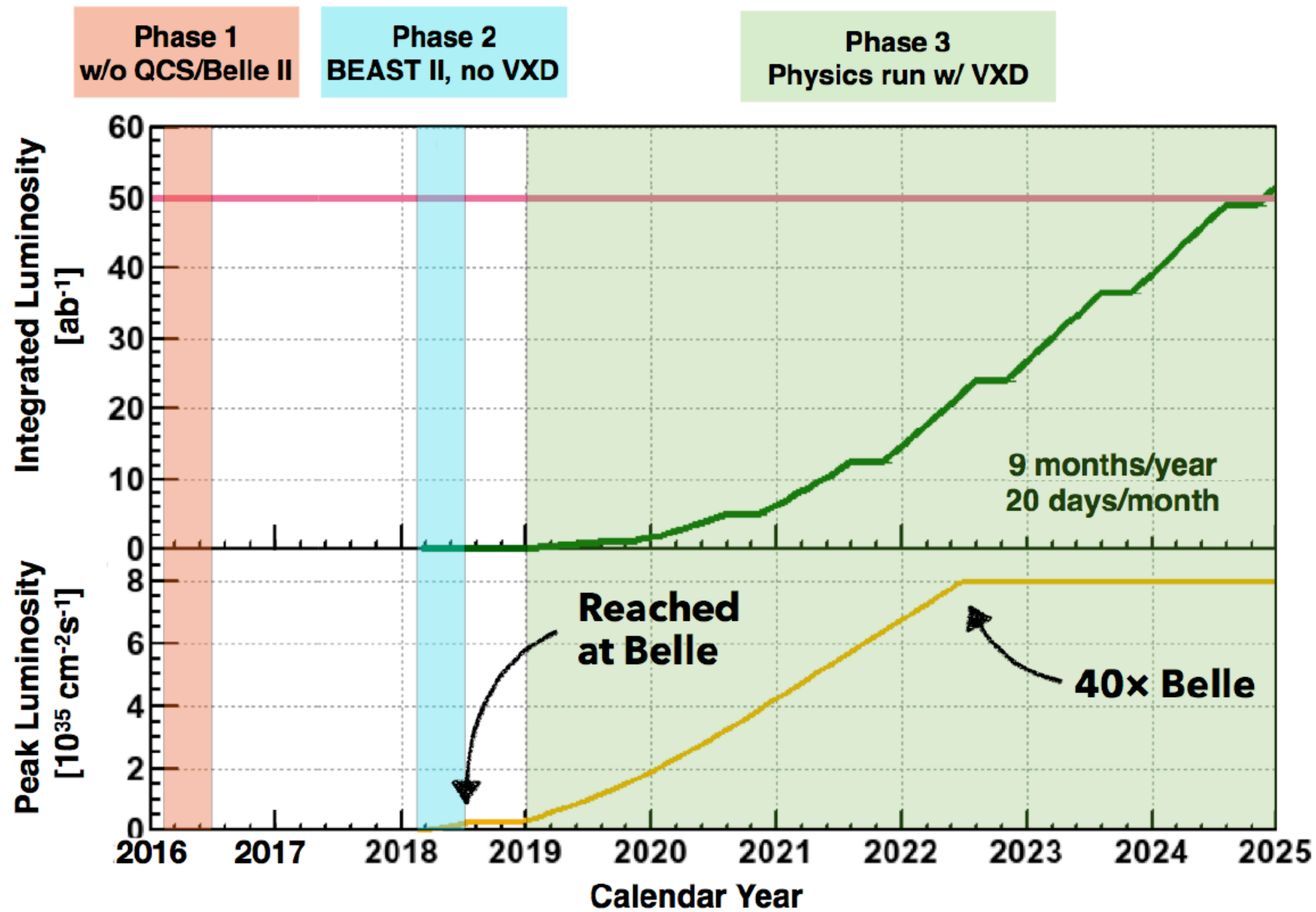
- Accelerator basic tuning with single beams

Phase 2 (w/ QCS/Belle II but w/o VXD)

- Verification of nano-beam scheme
- Understand beam background

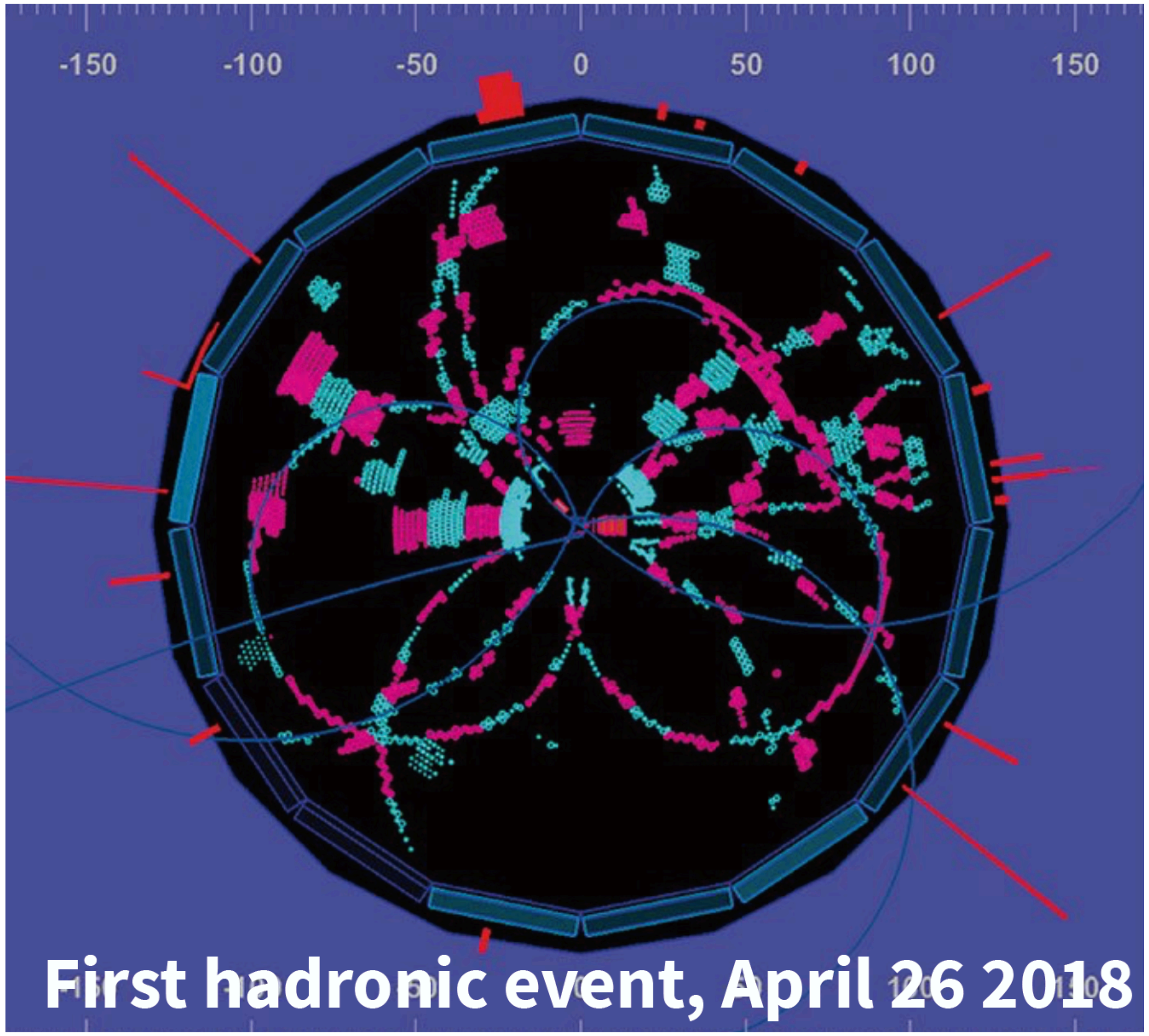
Phase 3 (w/ full detector)

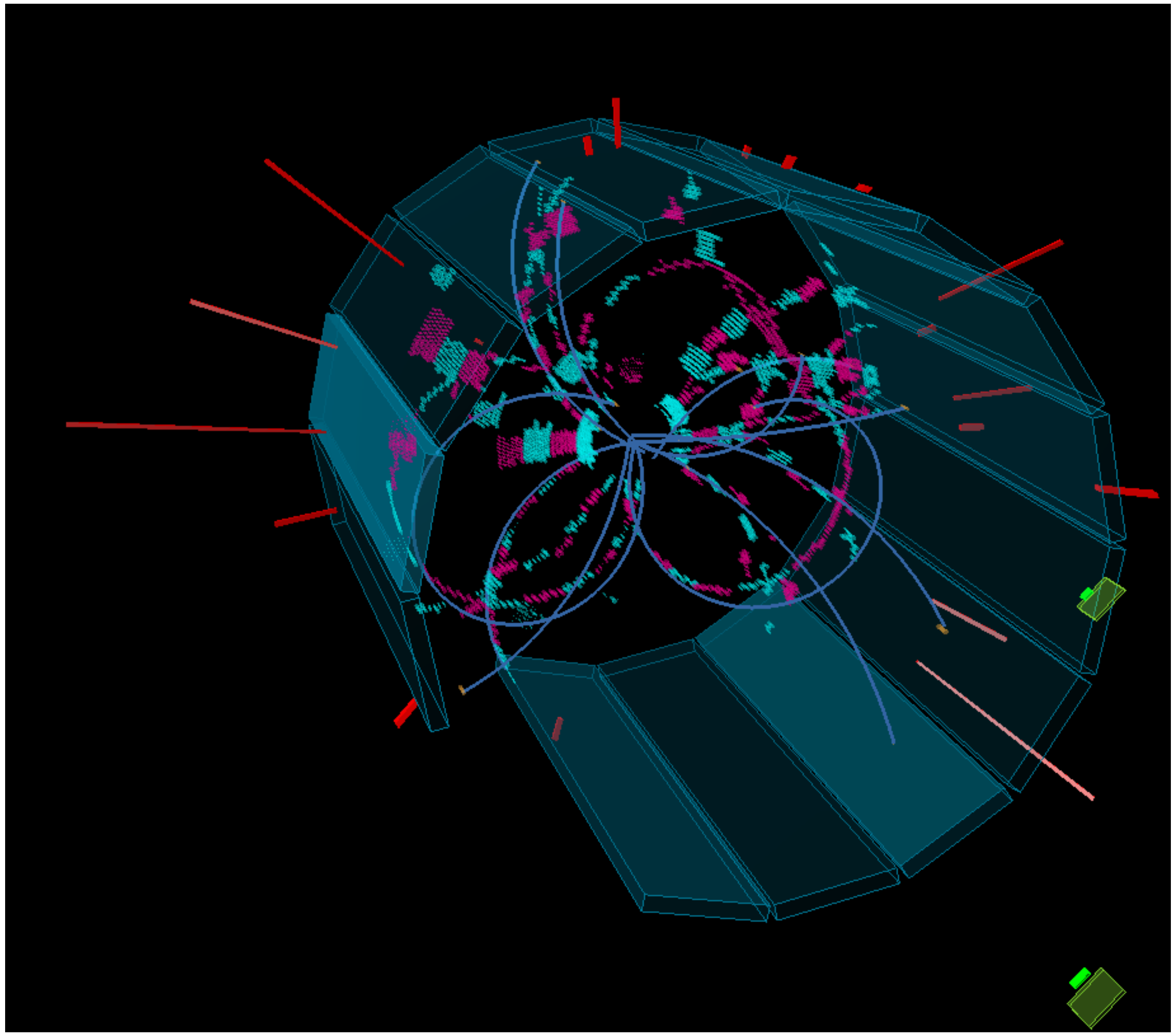
- $1 ab^{-1}$ after 1 year
- $5 ab^{-1}$ by ~2020
- $50 ab^{-1}$ by ~2025



First Collision !

0:38, April 26, 2018



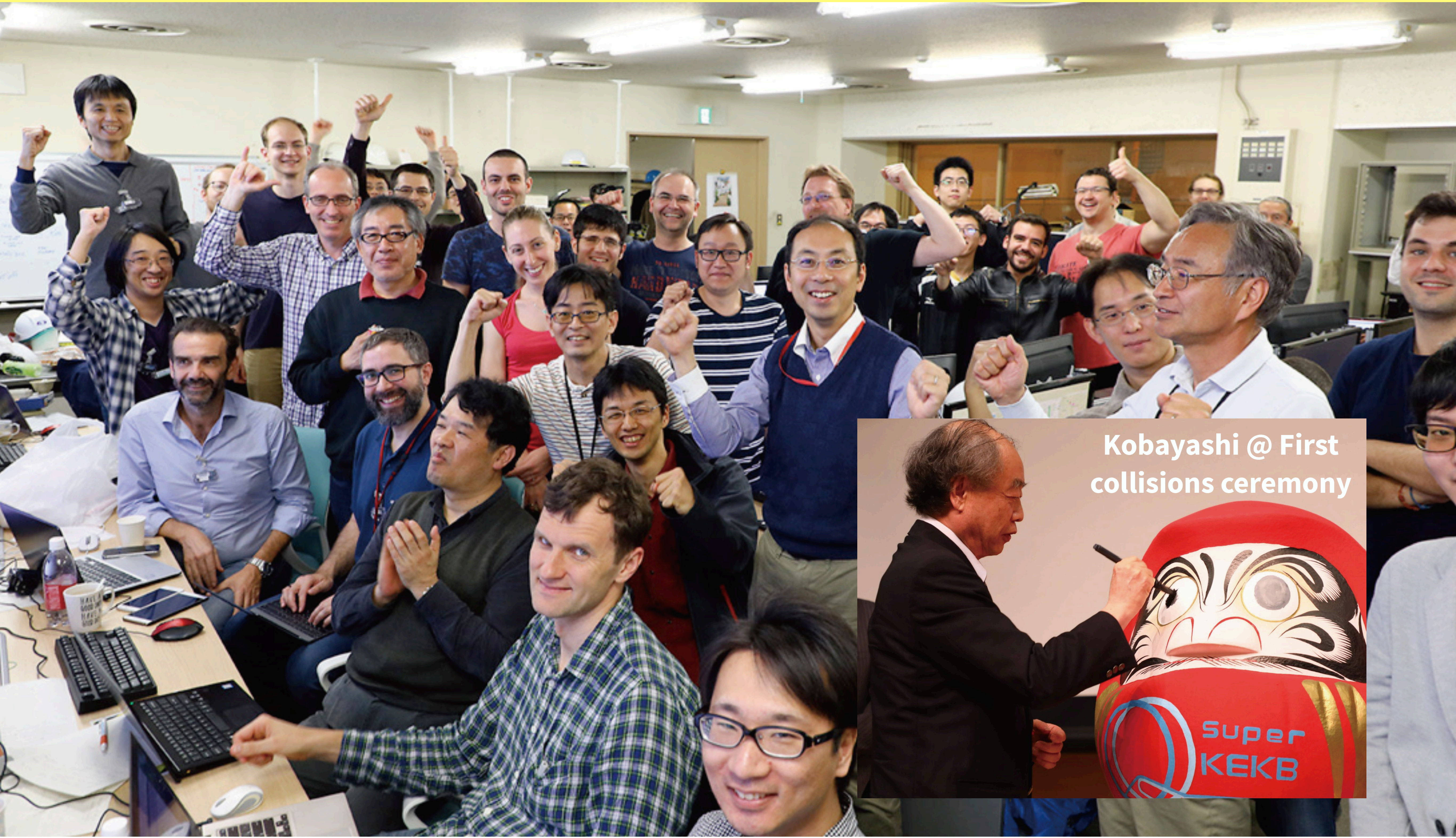


First Collision !

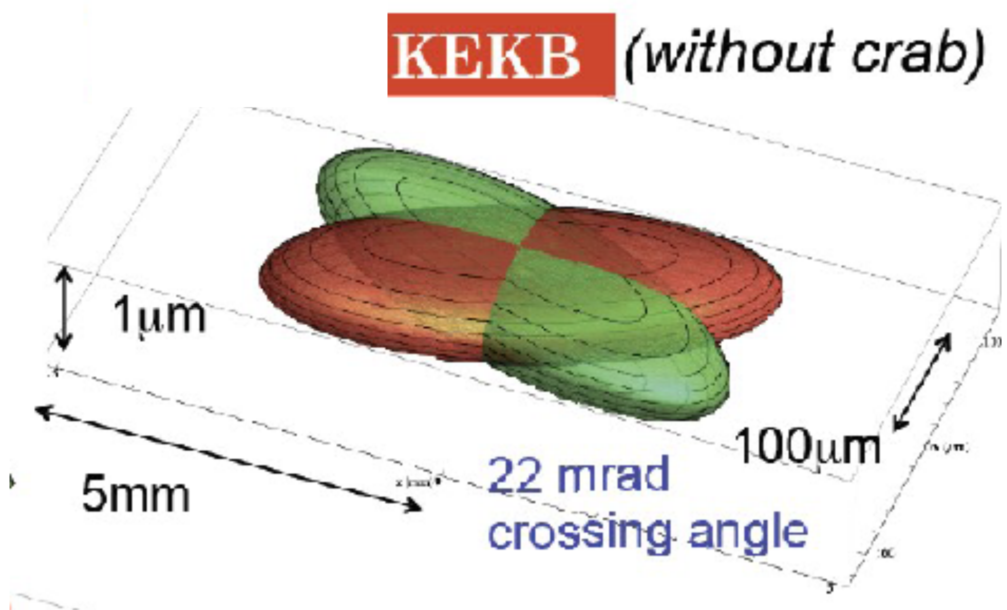
0:38, April 26, 2018

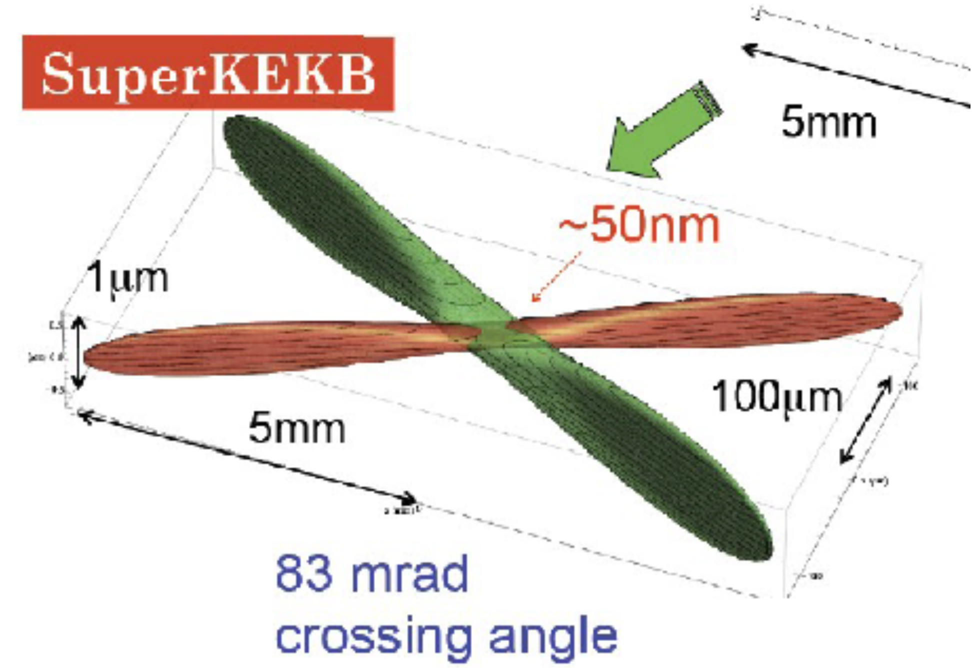
First Collision !

0:38, April 26, 2018

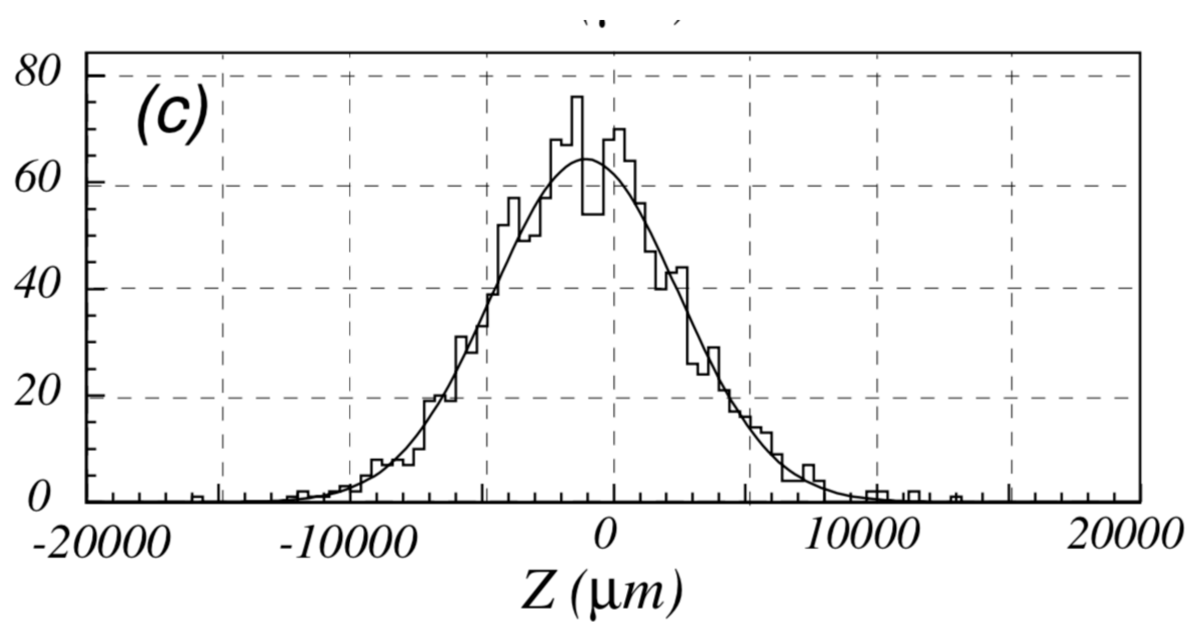


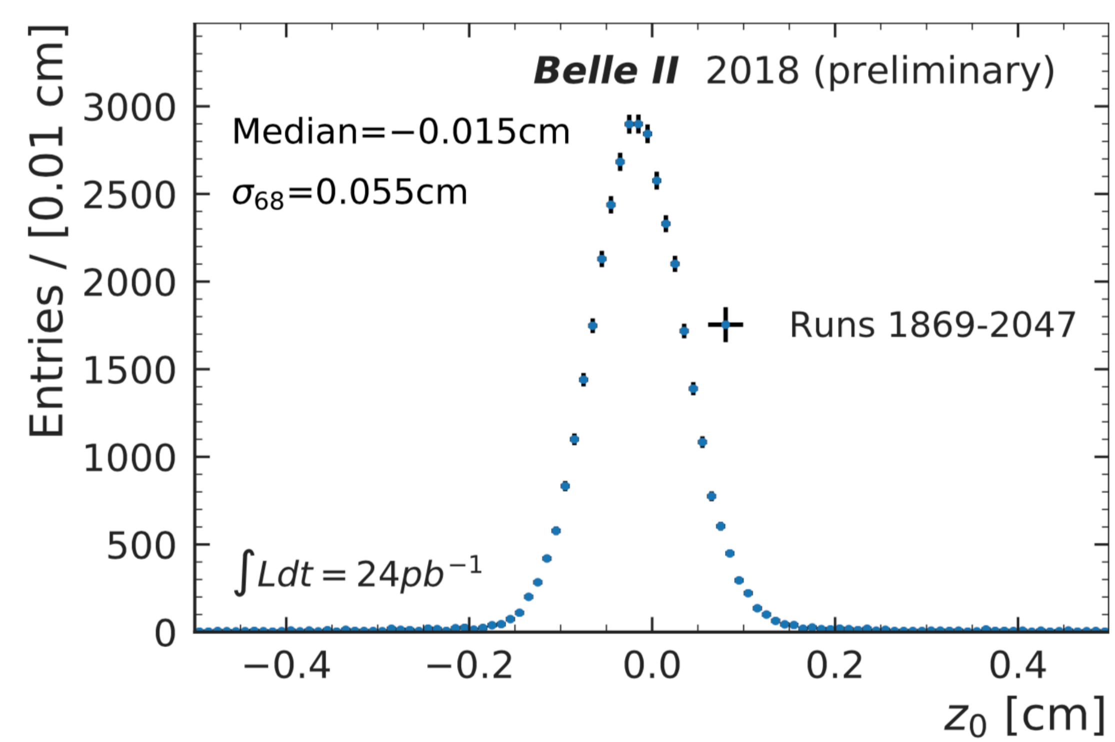
Collision with Nano-Beam





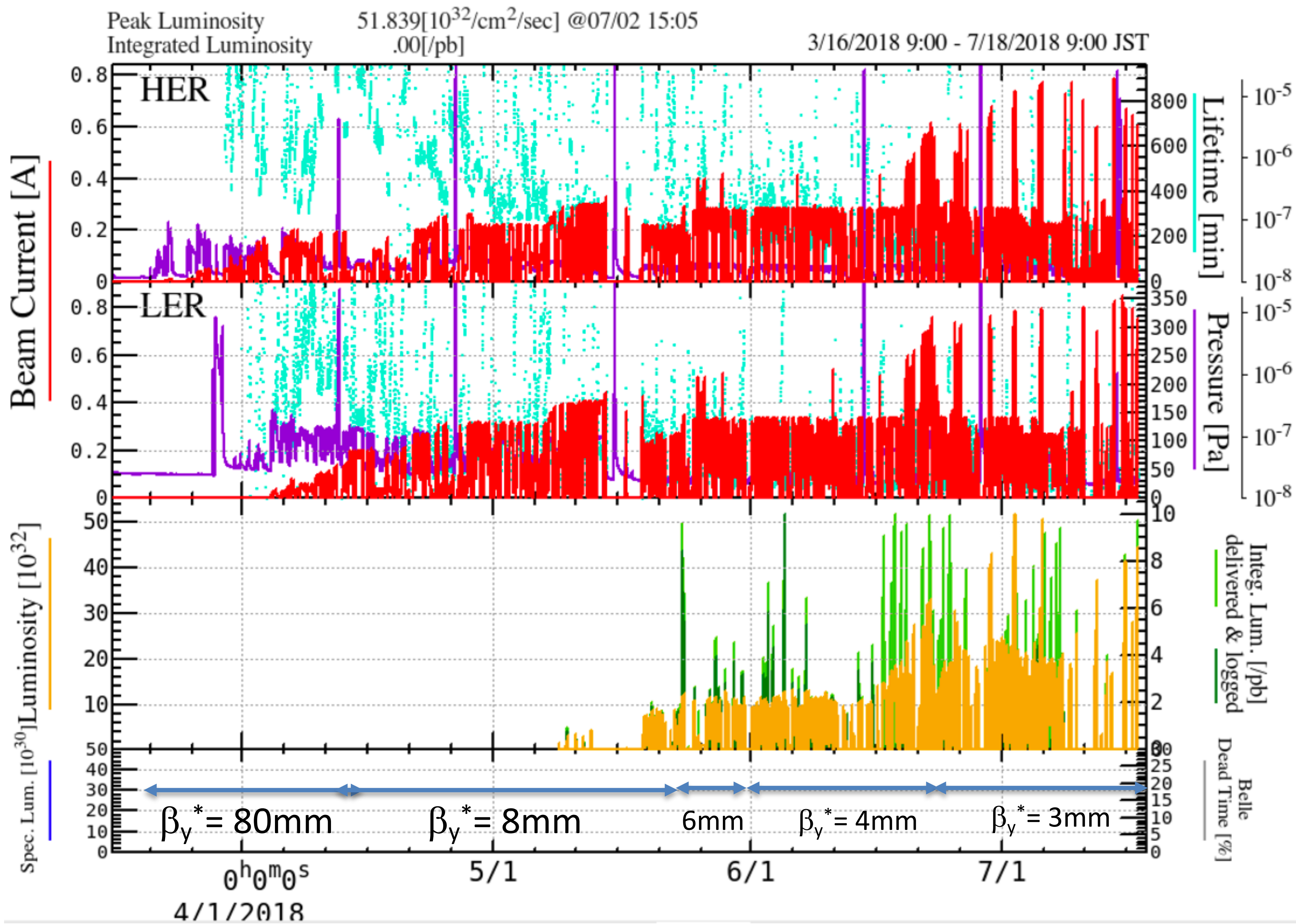
Belle case 1999 data





Phase 2 vertex data verify collision spot much shorter than the bunch length.

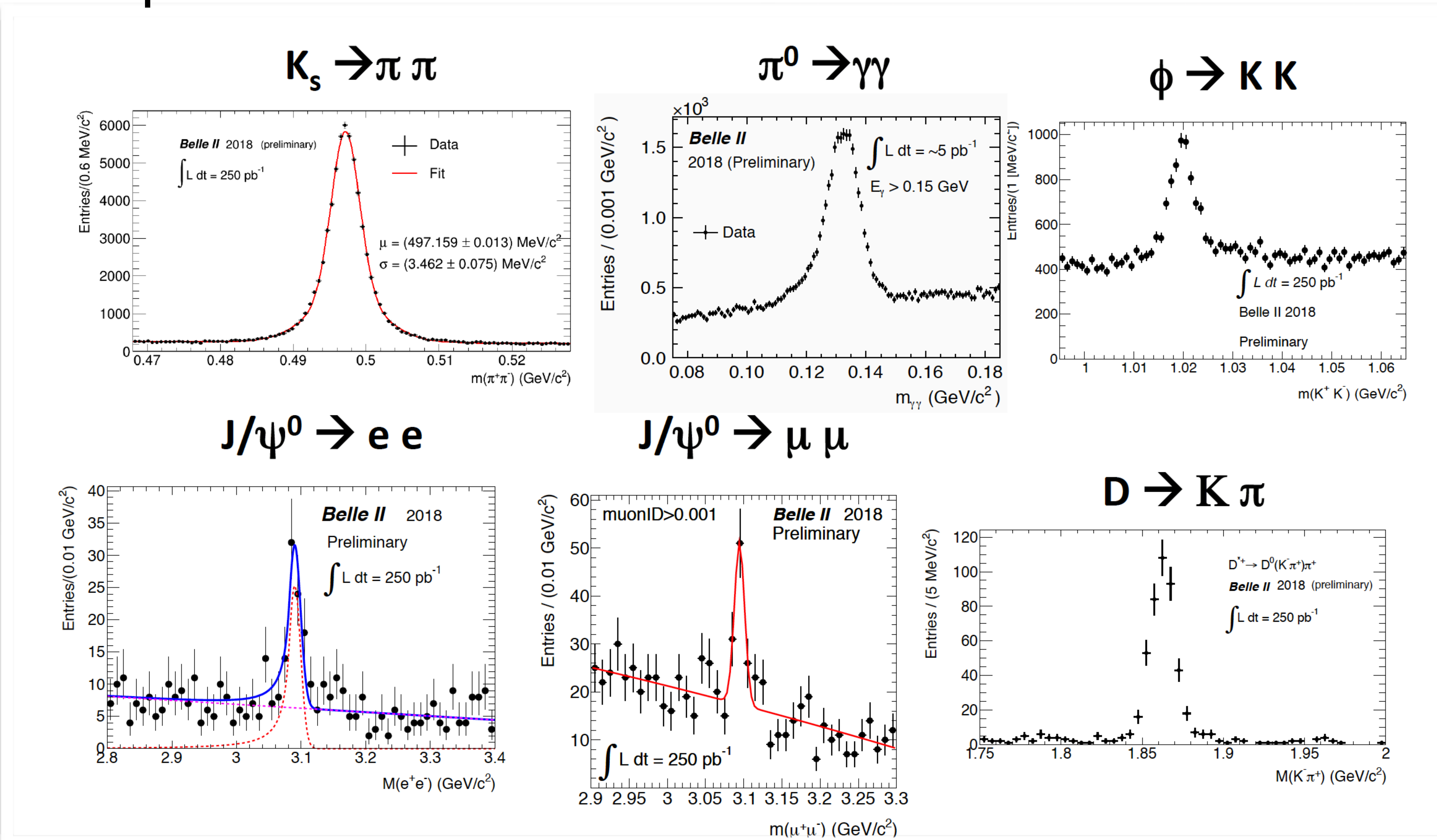
Luminosity during Phase 2



5.55 x 10^{33}/cm^2/s (βy*3mm, LER: 800mA, HER: 780mA, 1576 bunches/beam July 5th)
2.29 x 10^{33}/cm^2/s (βy*3mm, LER: 270mA, HER: 225mA, 394 bunches/beam July 3rd)

Belle II performance in Phase 2

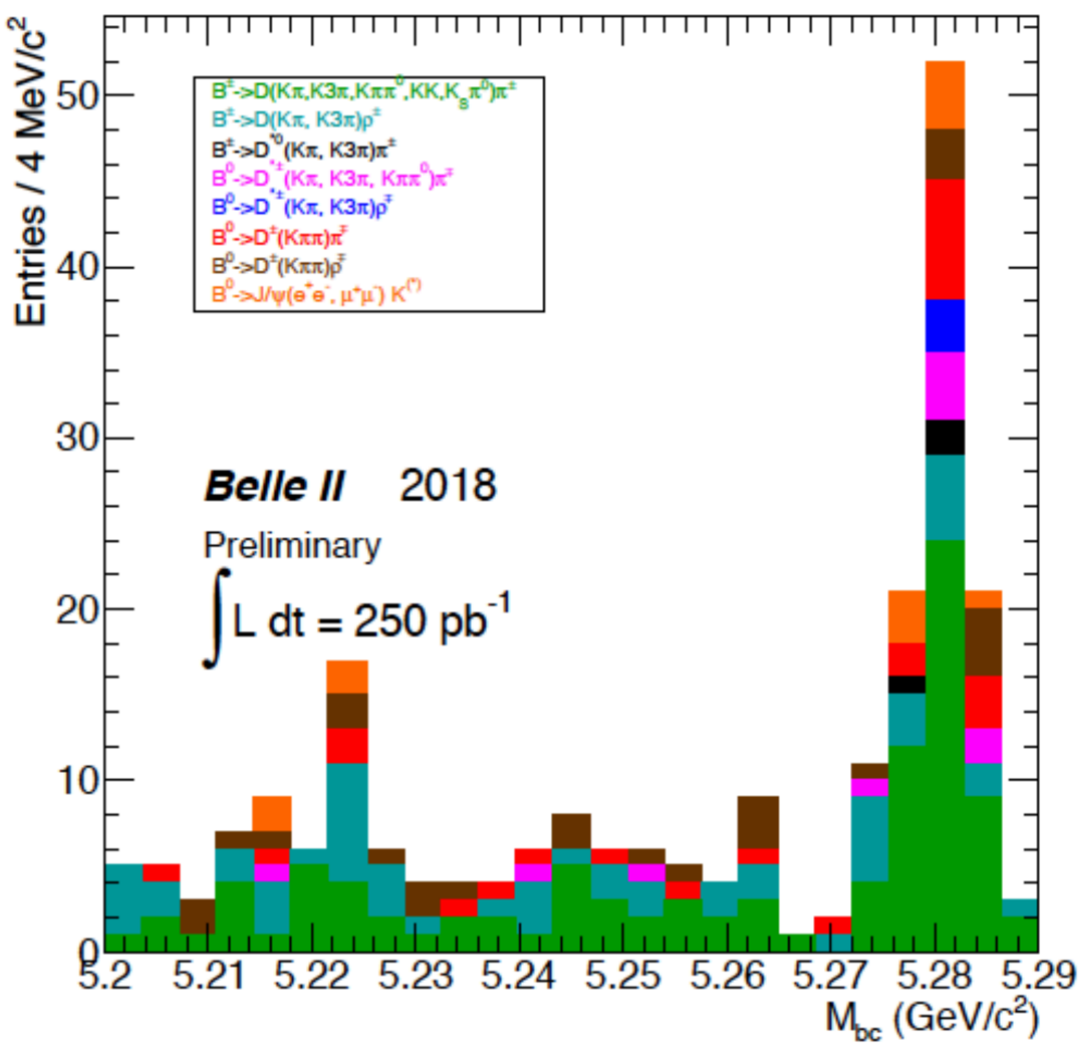
- Clear mass peak observed by combining charged tracks and photons



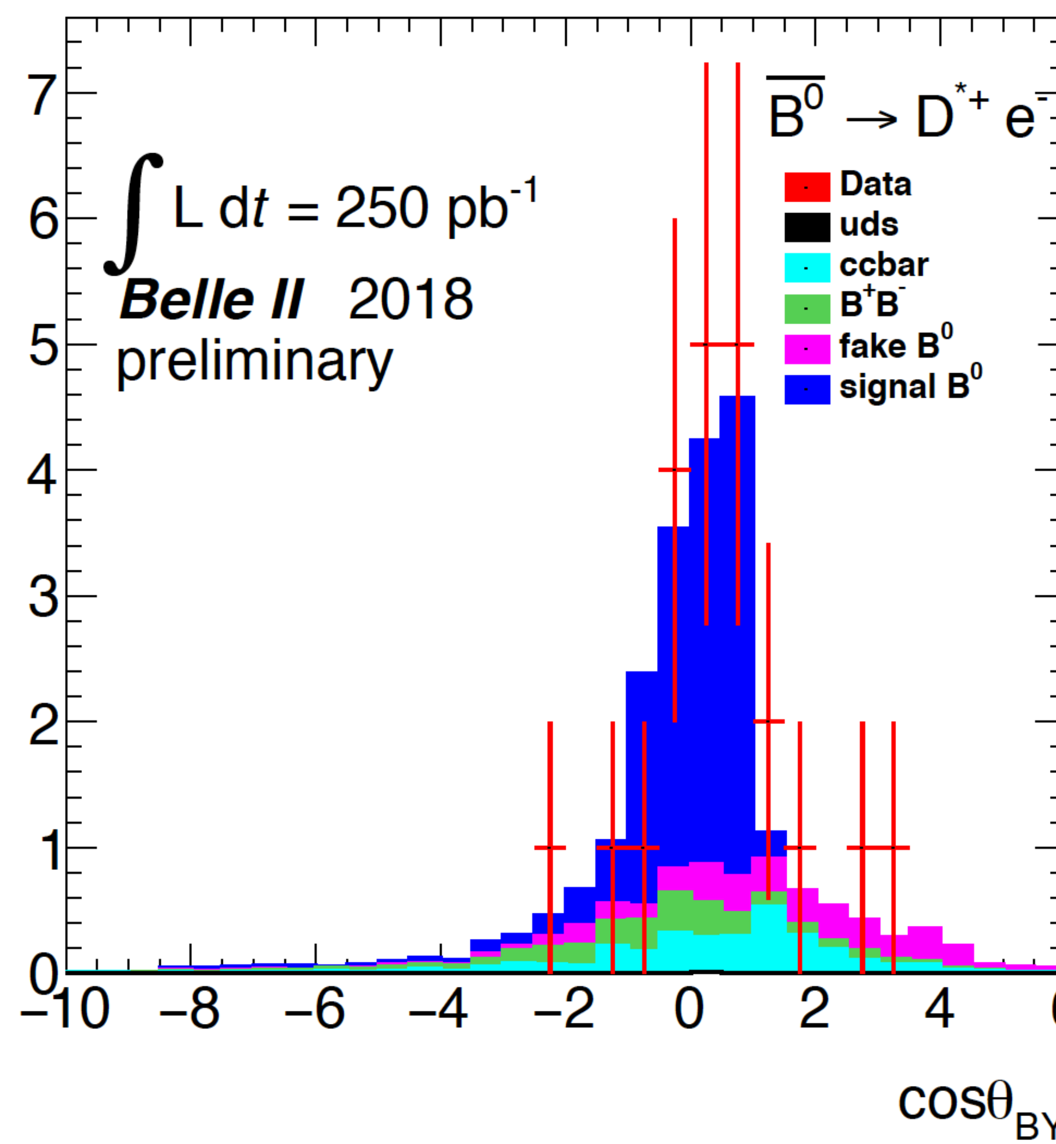
B reconstruction in Phase 2

- B meson signals have been seen in Phase 2 data.

Hadronic B decay modes



Semileptonic B decay modes

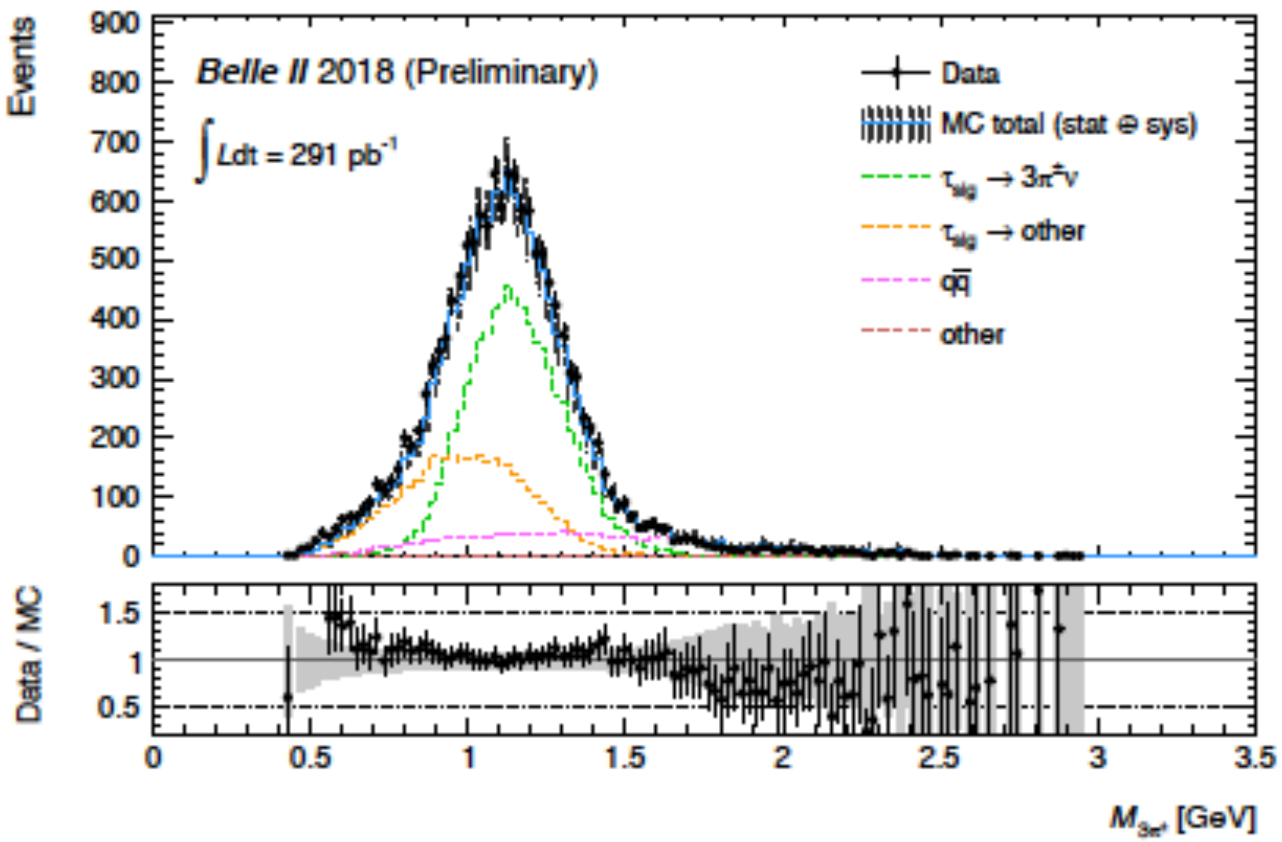


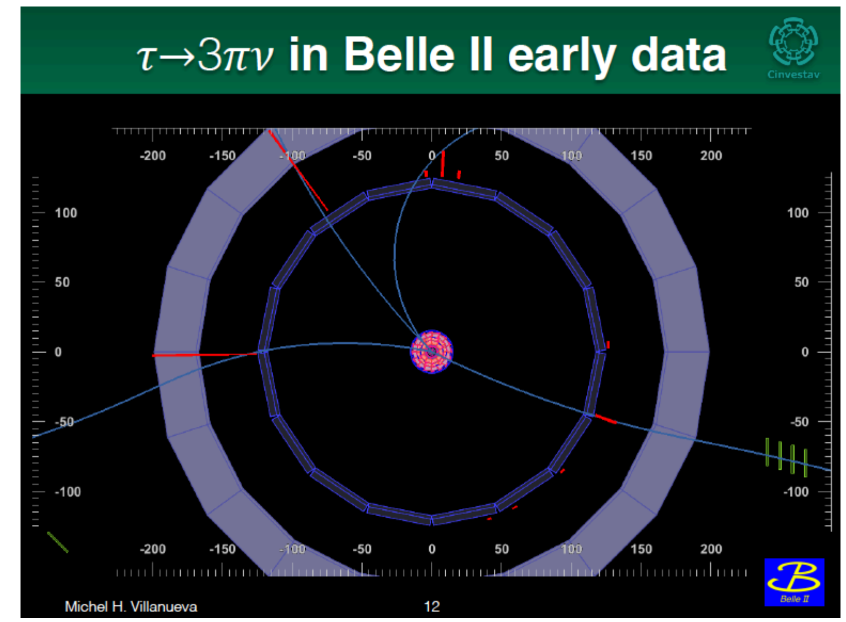
τ→3πν in Belle II early data

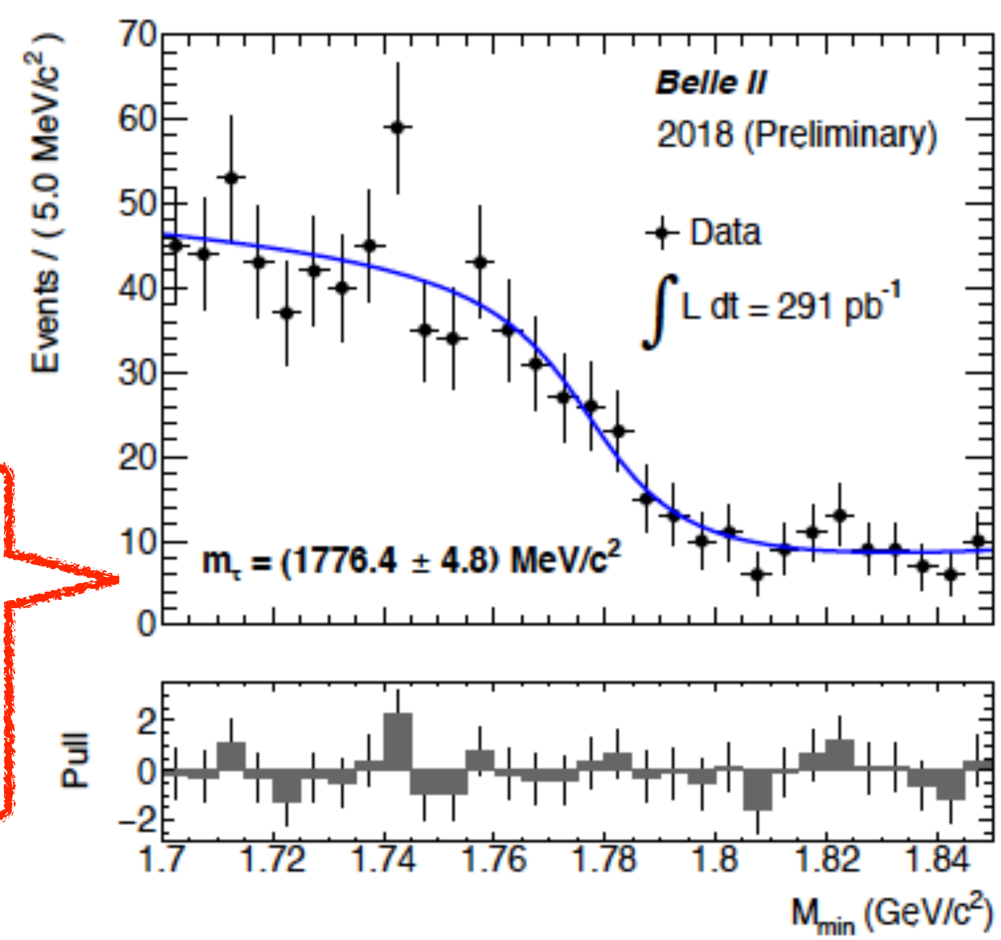
Talk by Michel H. Villanueva at TAU2018

- 291pb^{-1} in Phase 2 run.

$M_{3\pi}$ distribution







Preliminary τ mass measurement

m_τ = (1776.4 ± 4.8 (stat)) MeV/c^2

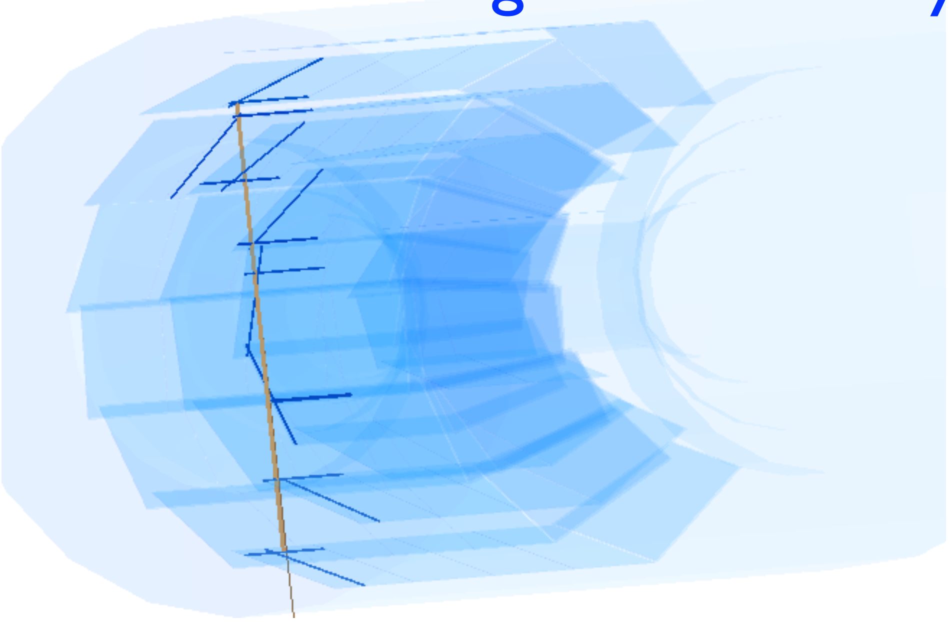
consistent with previous results

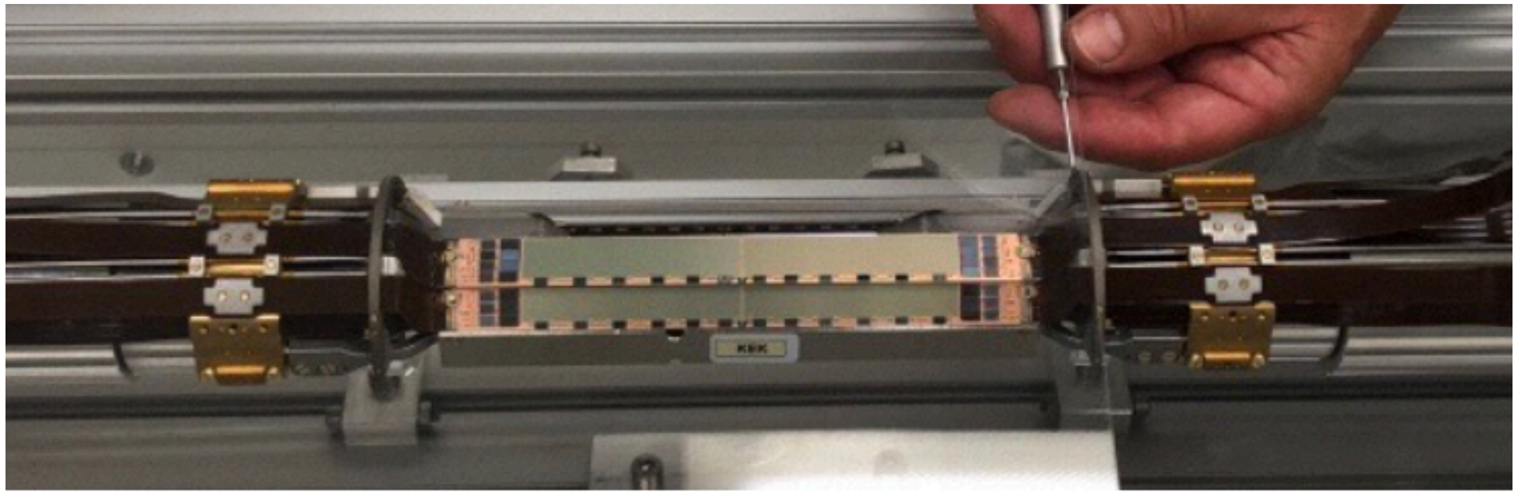
Prospect toward Phase 3

- SVD has been constructed, and being commissioned with cosmic rays.
- PXD ladders have been delivered to KEK.
- VXD mounting on beam pipe in progress.
- VXD installation in Belle II expected in November.
- Phase 3 will start near the end of JFY2018.

Completion of 2nd SVD half shell

SVD commissioning w/ cosmic ray

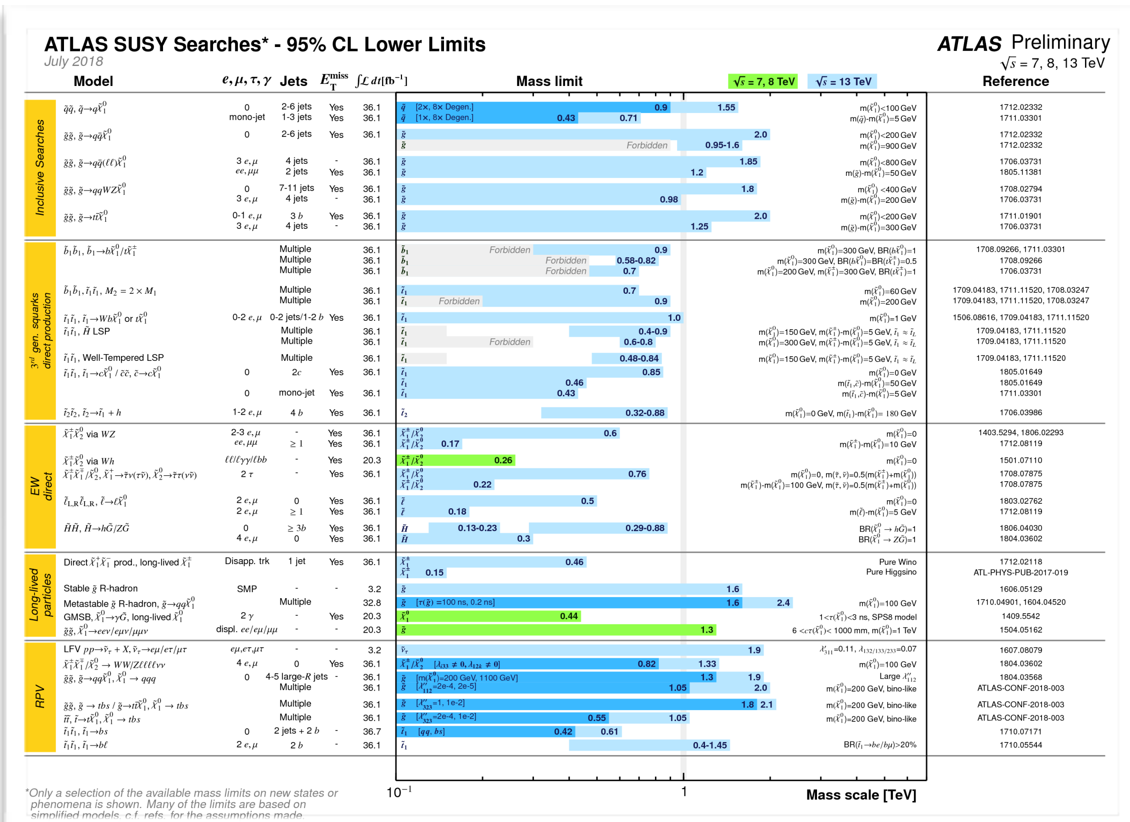


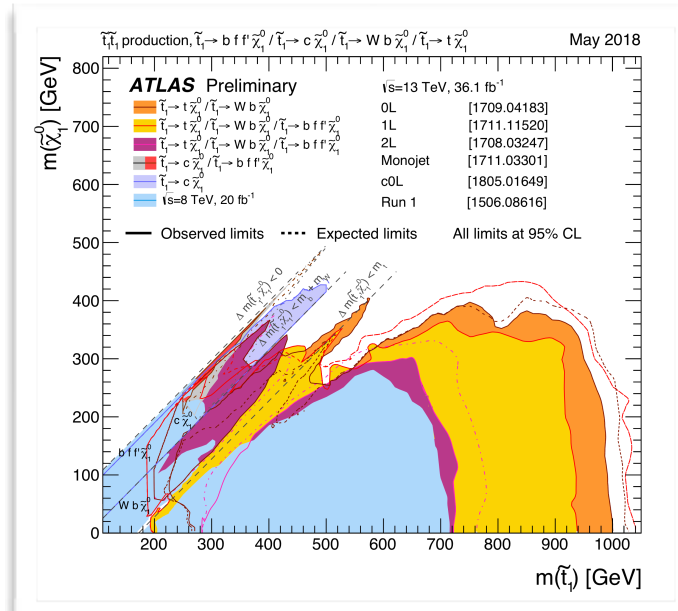


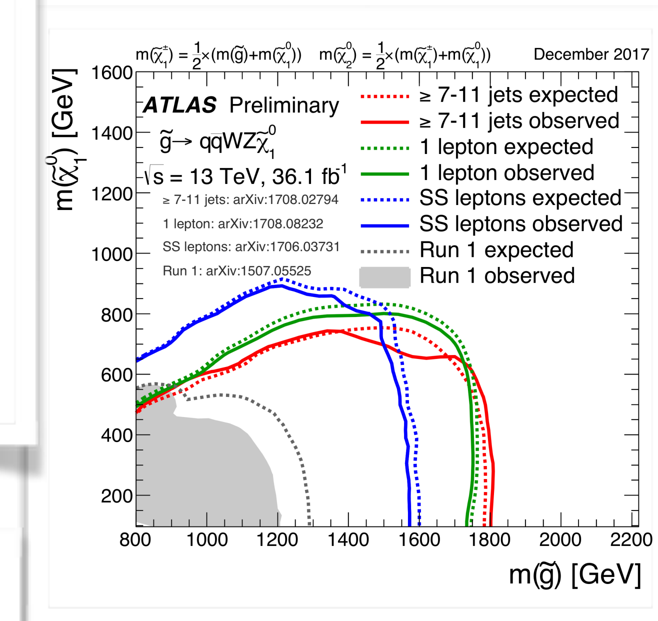
PXD 2nd half shell

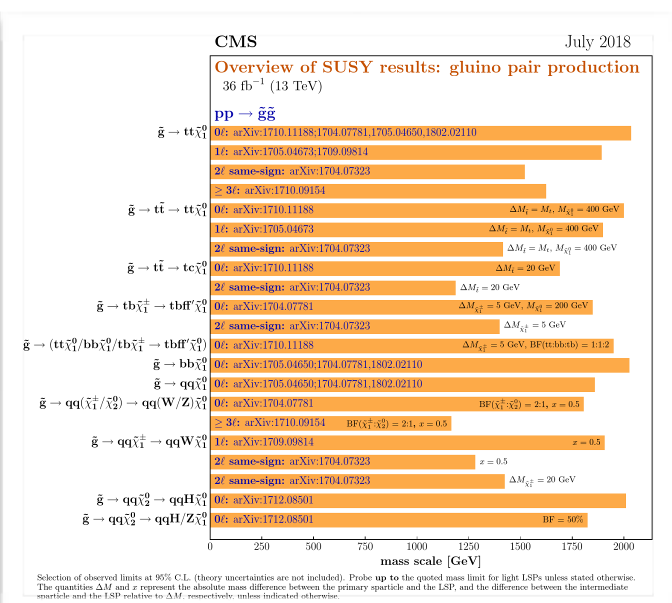
No NP at LHC so far

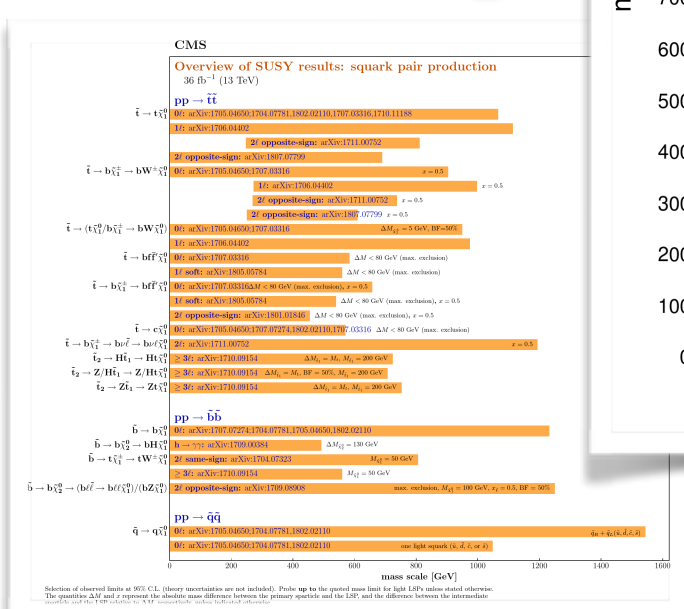
The mass region ~1TeV almost excluded ?

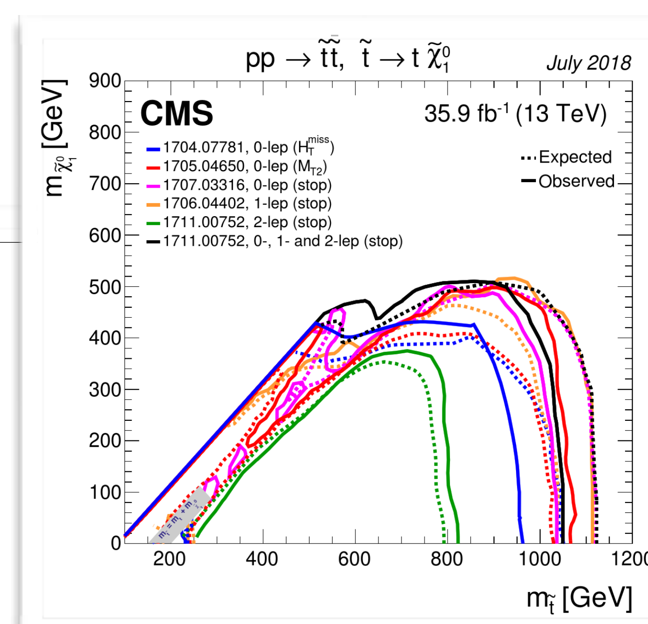


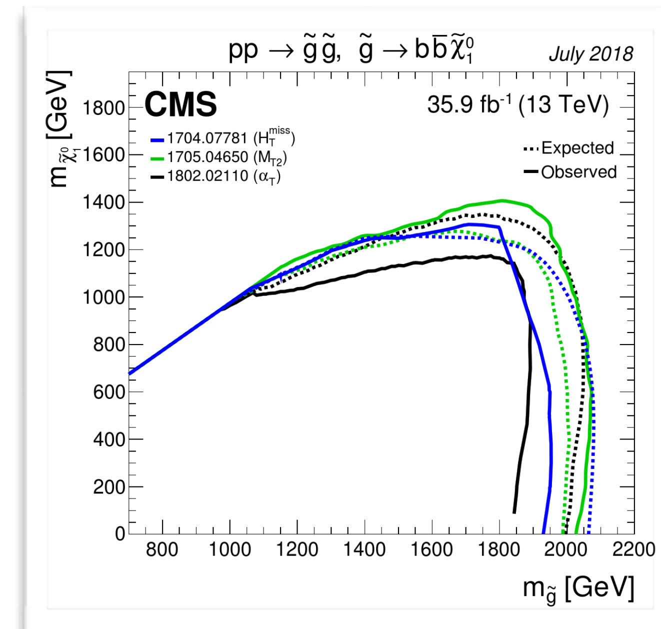




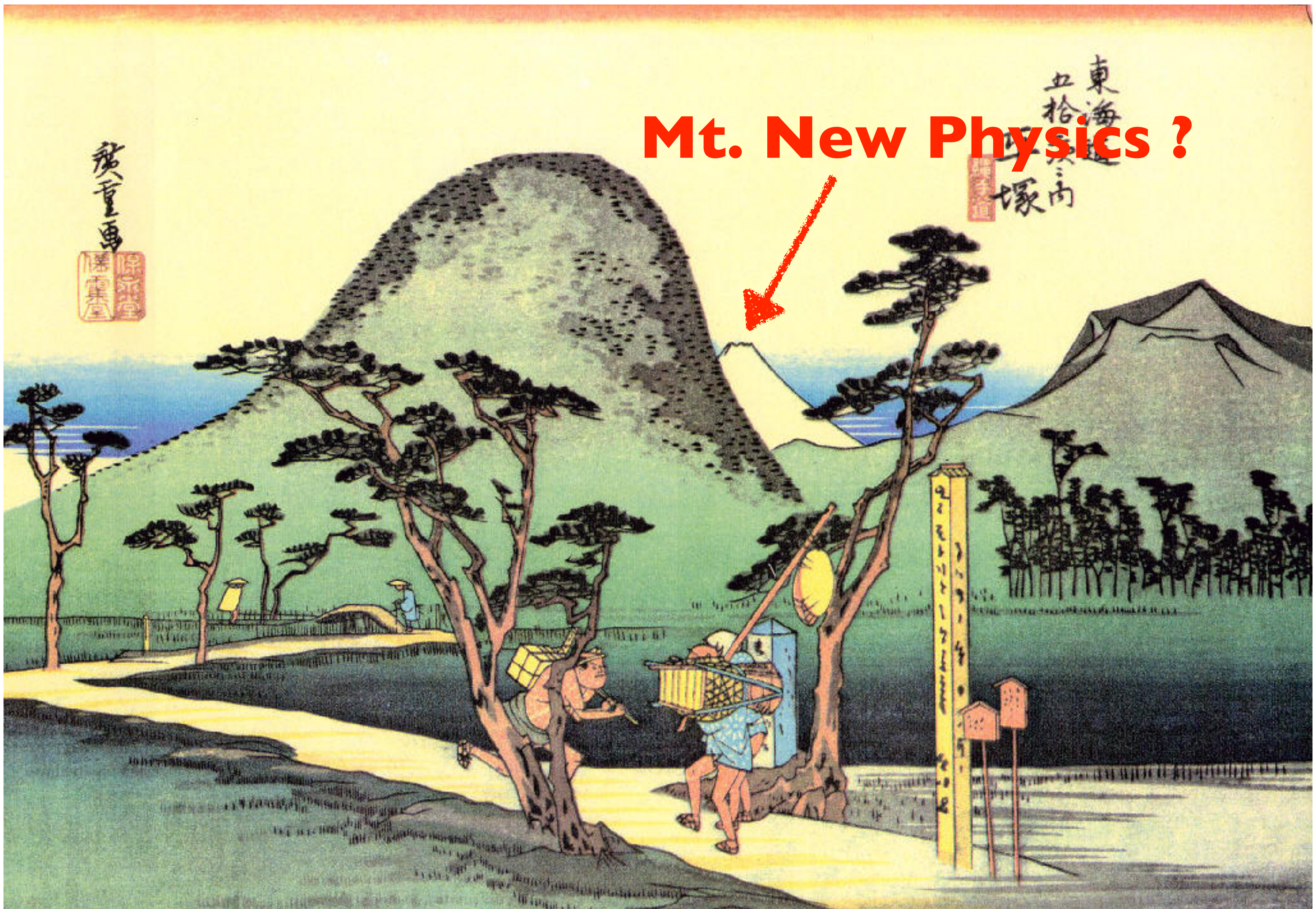








We know this old road…



by Hiroshige Utagawa (1797-1858)

Learning from history

- Suppressed $K^0 \to \mu\mu$ (GIM) → Charm quark !
- CPV in $K_L^0 \to \pi\pi$(KM) → 3rd generation !!
- $B\text{-}\overline{B}$ oscillation → Top is heavy !!!

OBSERVATION OF B^0–$\bar{B}^0$ MIXING

ARGUS Collaboration

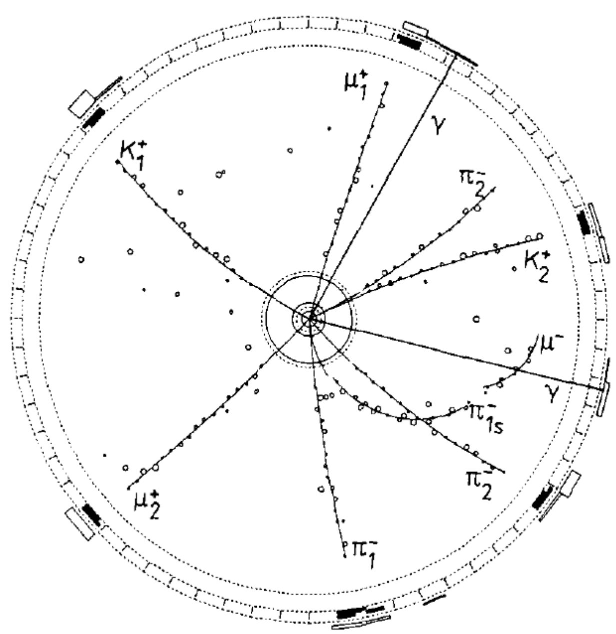


Fig. 2. Completely reconstructed event consisting of the decay $\Upsilon(4S) \to B^0 B^0$.

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

and

$$B_2^0 \to D_2^{*-} \mu_2^+ \nu_2$$
$$\downarrow$$
$$D_2^{*-} \to \pi^0 D^-$$
$$\downarrow$$
$$D^- \to K_2^+ \pi_2^- \pi_2^- .$$

Table 3
Limits on parameters consistent with the observed mixing rate.

Parameters	Comments
$r > 0.09$ (90%CL)	this experiment
$x > 0.44$	this experiment
$B^{1/2} f_B \approx f_\pi < 160$ MeV	B meson ($\approx$ pion) decay constant
$m_b < 5$ GeV/c^2	b-quark mass
$\tau < 1.4 \times 10^{-12}$s	B meson lifetime
$\|V_{td}\| < 0.018$	Kobayashi–Maskawa matrix element
$\eta_{QCD} < 0.86$	QCD correction factor [a)]
$m_t > 50$ GeV/c^2	t quark mass

Mt > 50 GeV/c^2

Physicists were rather optimistic before ARGUS observed this !

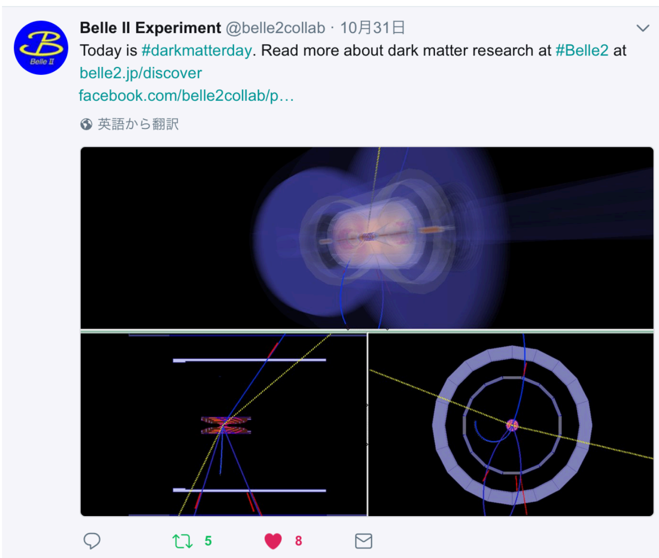
Summary to find NP

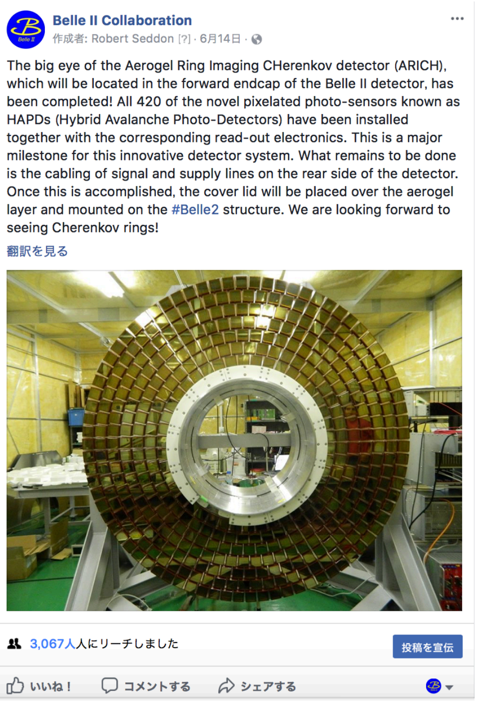
- The role of flavor physics is important.
- Belle II is ramping up !, and data will be on market soon !! As Belle II accumulate data, interplays are important with
  - LHCb
    - friendly competition
    - supplement information: precise branching fractions for normalization modes, detailed studies of physical background such as $D^{**} l \nu$ for $R(D^{(*)})$
  - ATLAS / CMS
    - it would be interesting to test collider data with given NP models, which can explain anomalies in flavor data.
  - Theorists
    - to reduce theoretical uncertainties
    - to interpret data and feedback.

Stay Tuned !

Belle II

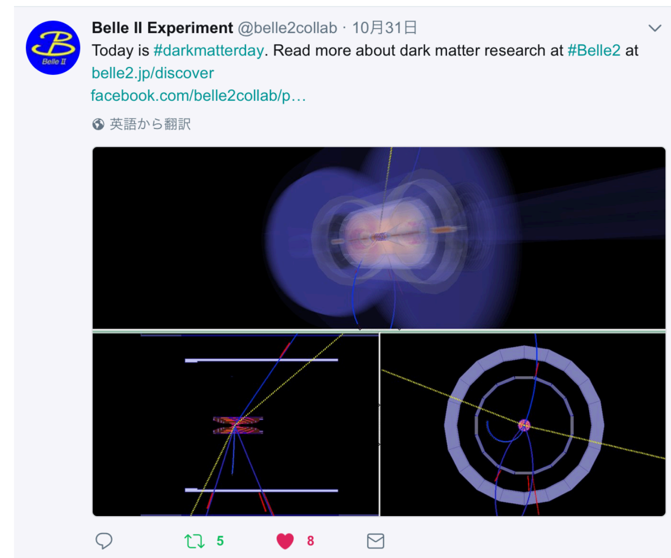
Belle II Outreach

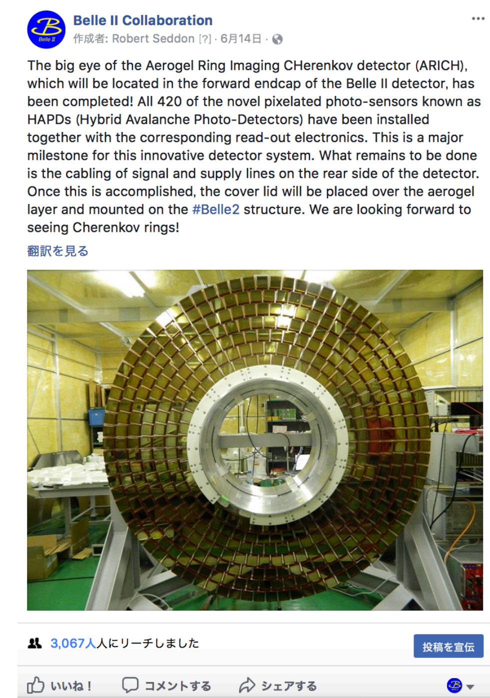




Also public HP: belle2.jp

Belle II Outreach





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Thank you !

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