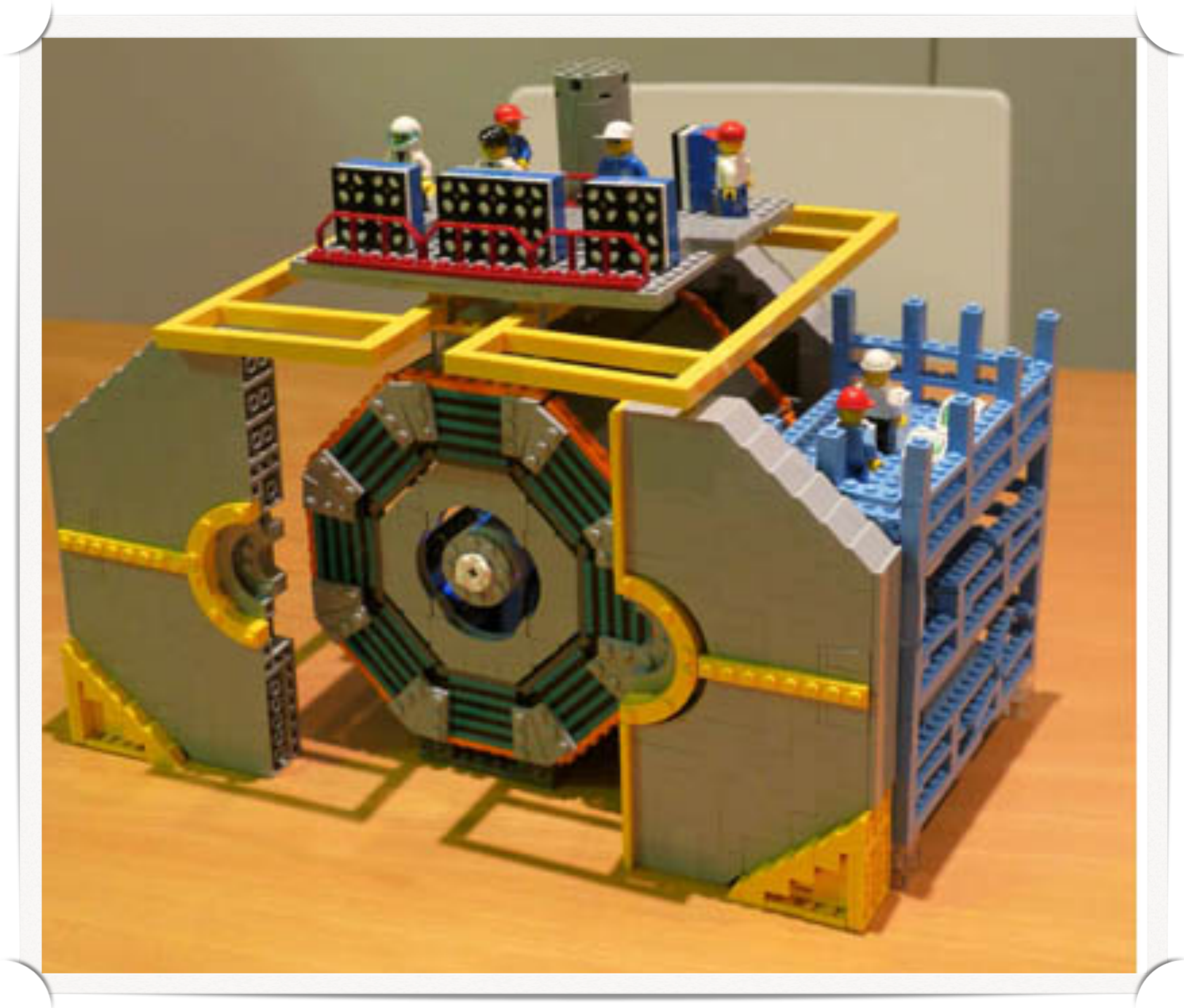
59th Winter Meeting on Nuclear Physics

Recent Results from *Belle II*



Giulia Casarosa

on behalf of the *Belle II* Collaboration

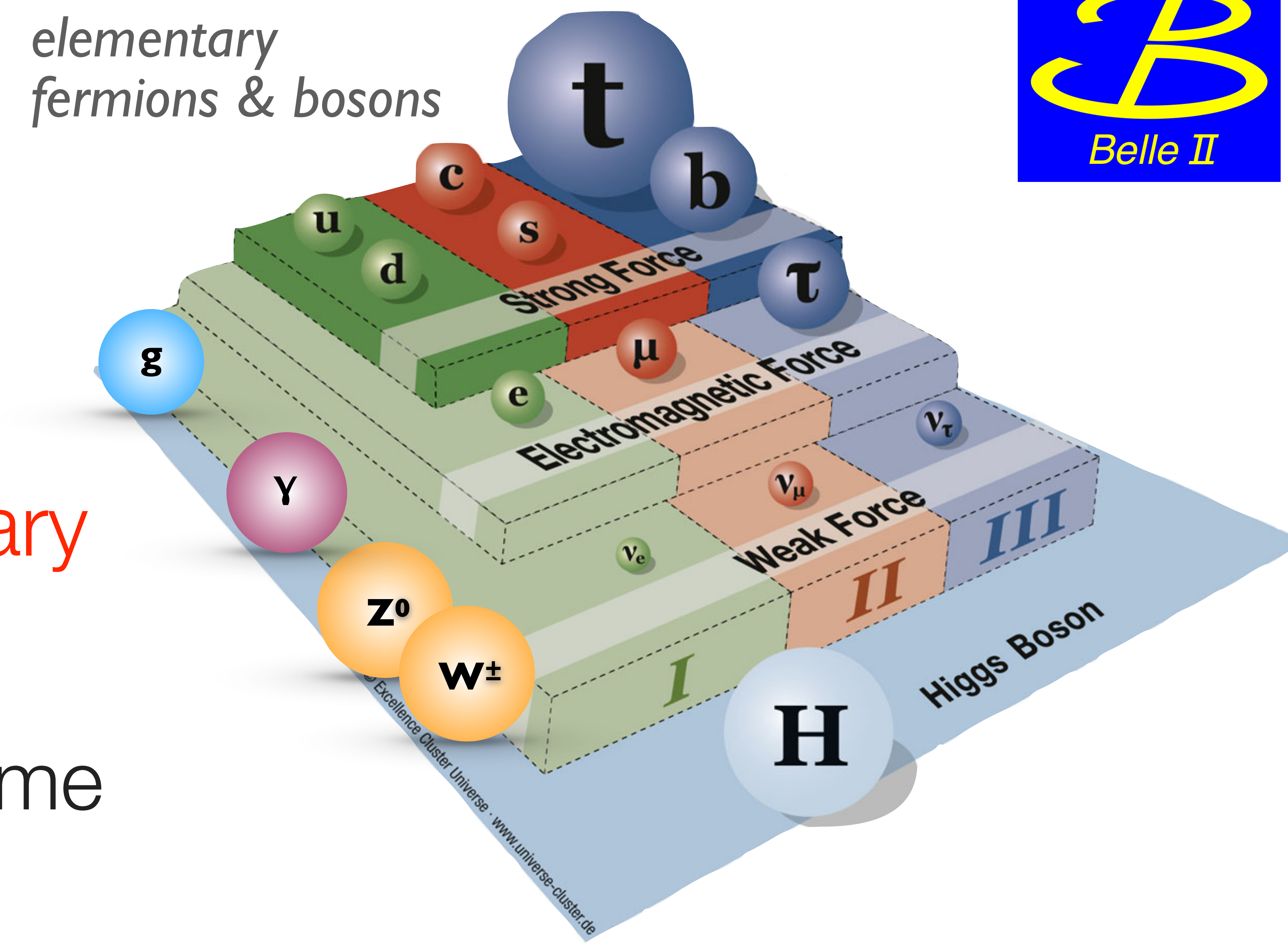
Bormio, January 25th, 2023

Outline

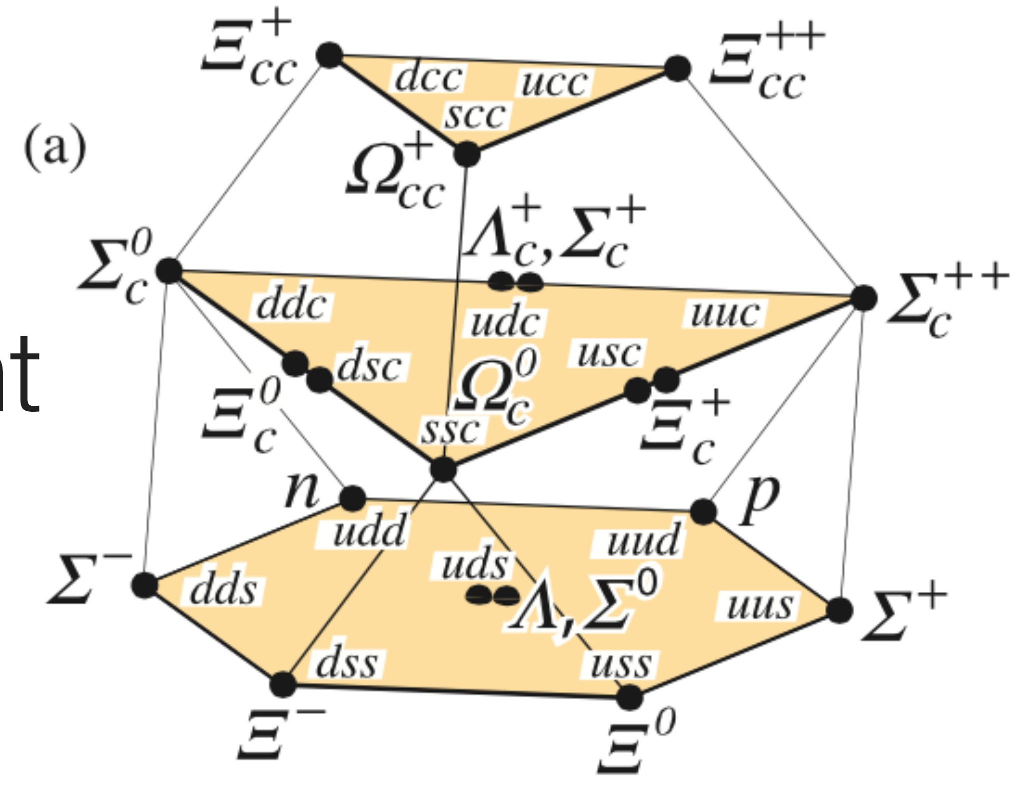
- *Introduction*
- *Belle II at the High-Luminosity B-Factory SuperKEKB*
- *Overview of the Physics Program & Some Recent Highlights*
    - *B, charm, τ & Dark Sector*
- *Conclusions*

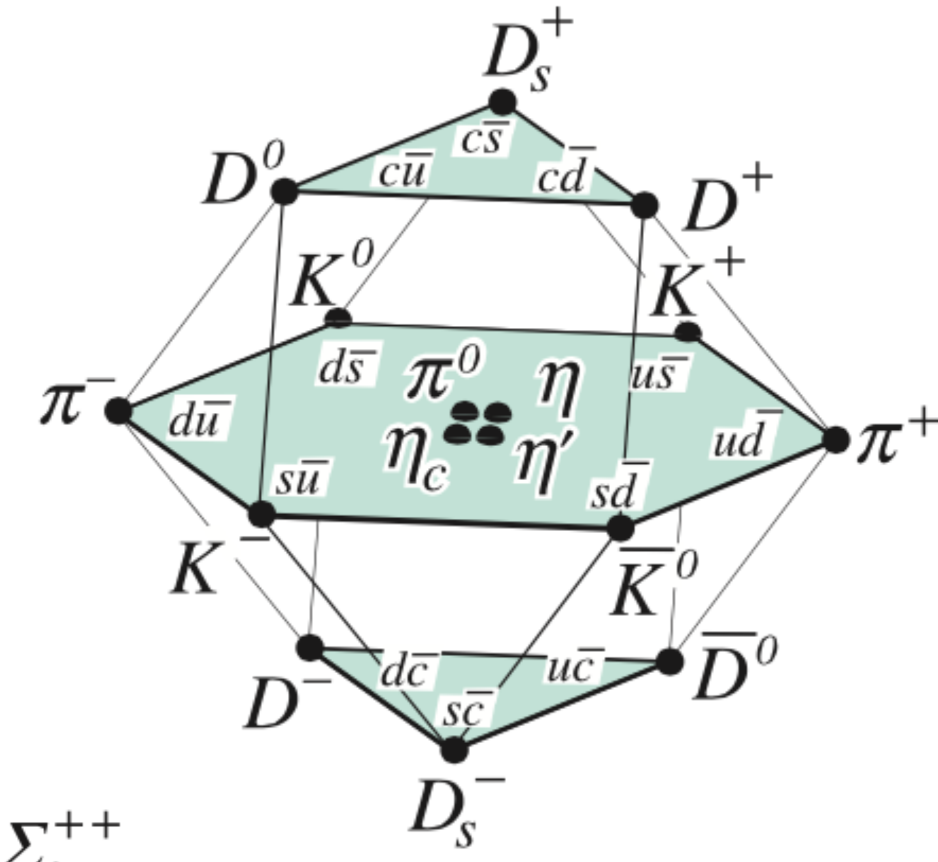
The Standard Model …

elementary fermions & bosons



- ➡ the SM is the most successful theory that describes elementary particles and interactions
  - the elementary fermions and bosons have been observed (some indirectly) and their properties have been measured
  - the quark model predicts the vast majority of observed bound states, mesons and baryons
  - interactions between mesons, baryons and leptons are predicted with a precision of $\mathcal{O}(1\%)$
  - hundreds of observables (branching ratios, CP violation parameters, asymmetries, …) are measured to be consistent with the theory predictions – within the theoretical and the experimental uncertainty





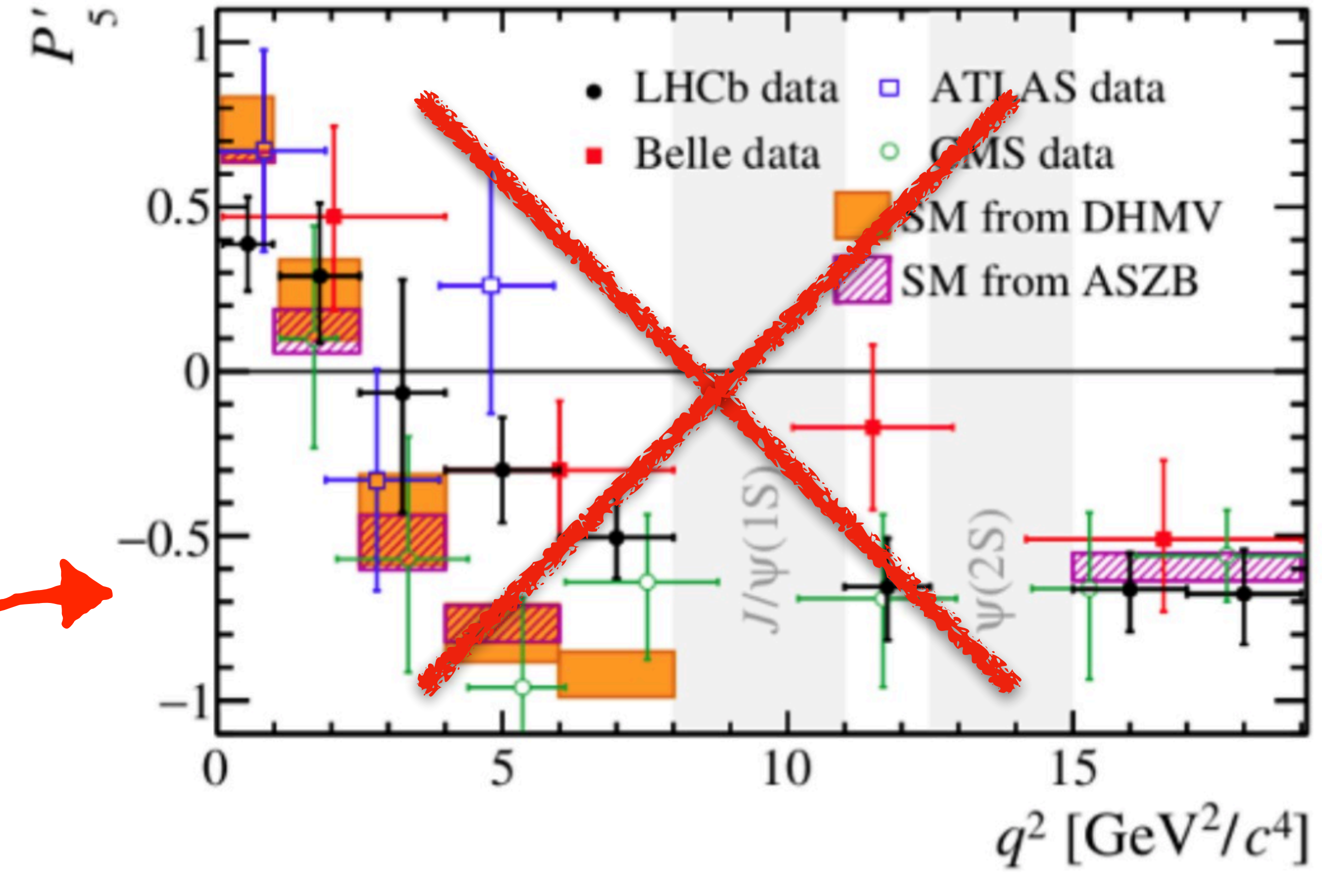
SU(4) multiplets of pseudoscalar mesons and baryons

… and its open questions

physics *beyond* the SM
(New Physics) is likely to exist

- but still we have (big) open questions coming from *observations* unexplained by the SM
  - no explanation of the size of the observed matter-antimatter asymmetry
    [effect $\mathcal{O}$(100%)]
  - no dark matter candidate nor dark energy explanation
    [95% of the universe is unknown]
  - no explanation of masses hierarchy, …

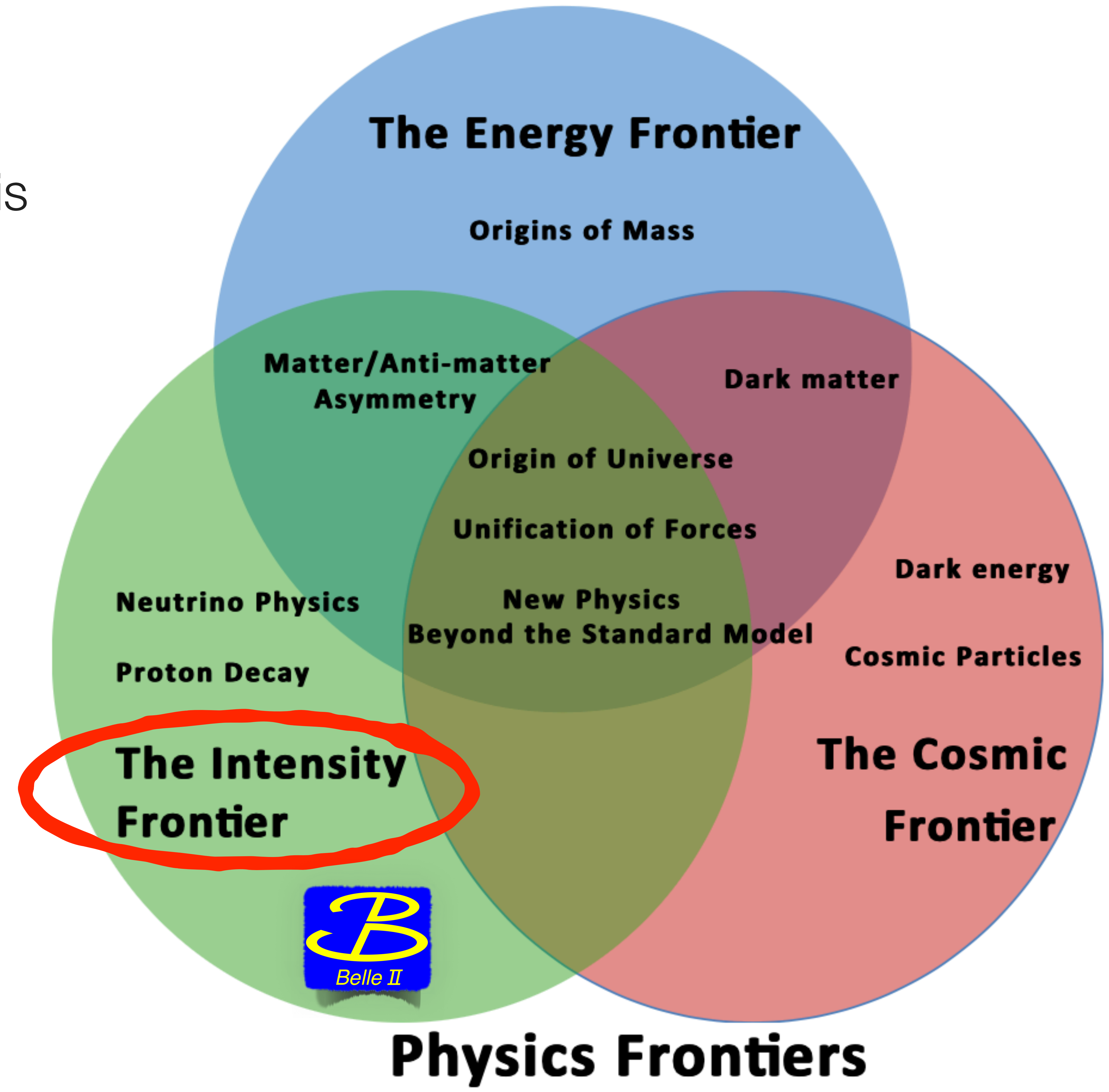
- and tensions between measurements and SM predictions that need progress in either theory or experiment (or both) to be interpreted
  - (g-2)$_\mu$
  - tensions come & go…
  - … anomalies in angular observables in $b \to s\ell\ell$?



not confirmed :(

Hunting for New Physics

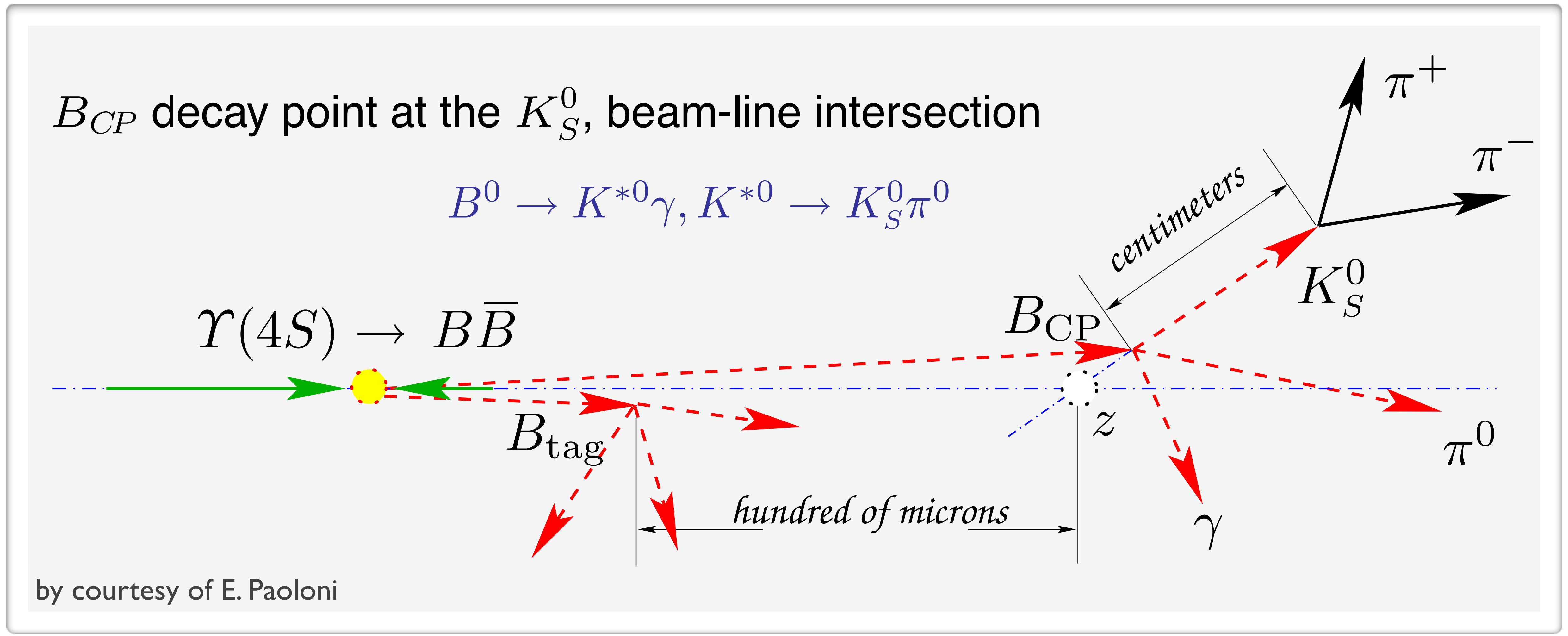
- ➡ *Belle II* belongs to the Intensity Frontier, New Physics is searched in:
  - very high-precision measurements to detect (tiny) deviations from SM predictions produced by *virtual* New Physics particles
  - SM-forbidden processes enabled by the presence of virtual NP particles in box / loops / …
- ➡ probes NP mass scale higher than the one accessed at the Energy Frontier, e.g. $\mathcal{O}$(10 TeV) in $b \to s\ell\ell$
- ➡ what is needed at the intensity frontier?
  - a *larger* dataset to minimise statistical uncertainty
  - keep systematics under control



B-Factories

KEKB & PEPII, now SuperKEKB

Belle	*BABAR*	*Belle II*
06/1999 – 06/2010	10/1999 – 04/2008	03/2019 –



➡ significantly contributed to the SM success

➡ main process: $e^+e^- \to_{(boosted)} \Upsilon(4S) \to B\bar{B}$

- B mesons are produced in an entangled state: use the B_{tag} to add informations on the flavour/CP-state of other B decaying in the signal channel

➡ not only $B\bar{B}$ events are produced → rich charm, τ, quarkonium, and low-multiplicity physics program!

$\sigma(e^+e^- \to b\bar{b}) = 1.1$ nb
$\sigma(e^+e^- \to c\bar{c}) = 1.3$ nb
$\sigma(e^+e^- \to \tau^+\tau^-) = 0.9$ nb
$\sigma(e^+e^- \to uds) = 2.1$ nb

➡ Belle & *BABAR*, have collected together 1.5/ab

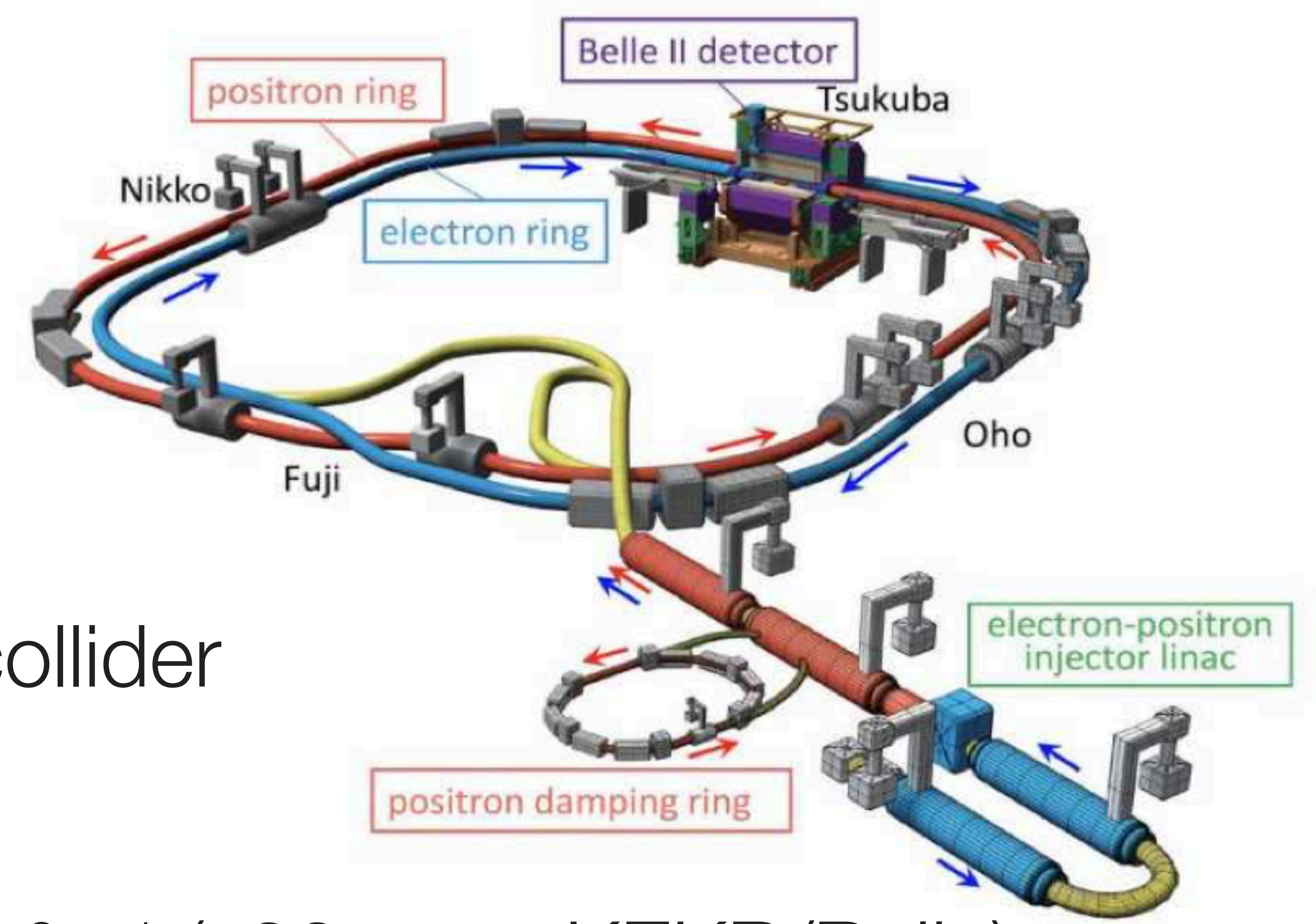
- 1.7×10^9 $B\bar{B}$, 2×10^9 $c\bar{c}$, 1.4×10^9 $\tau^+\tau^-$ events
- the majority of existing measurements are (still) limited by the statistical uncertainty

Belle II is a 2nd generation experiment that'll collect a much larger* dataset to significantly increase the precision!

* *Belle II* goal is 50/ab = x30 (Belle + *BABAR* datasets)

SuperKEKB

High-Luminosity B-Factory



- SuperKEKB is a 2nd generation **asymmetric** e^+e^- collider at the Υ(4S) mass energy
- Target instantaneous luminosity is $\mathscr{L}$ = 6x10^35 cm^−2s^−1 (x30 w.r.t. KEKB/Belle)
  - max instantaneous luminosity $\mathscr{L}$ = 4.7x10^34 cm^−2s^−1 (world record)
- Achievable in the *nano-beam scheme**
  - increase beam currents
  - squeeze beams at the interaction point
  - reduced beam energy asymmetry

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

Lorentz factor

beam current

beam-beam parameter

geometrical reduction factors

beam aspect ratio at the IP

vertical beta-function at the IP

* proposed by P. Raimondi for SuperB

SuperKEKB

High-Luminosity B-Factory

- ➡ SuperKEKB is a 2nd generation **asymmetric** e^+e^- collider at the $\Upsilon(4S)$ mass energy
- ➡ Target instantaneous luminosity is $\mathscr{L} = 6\times10^{35}\ \mathrm{cm^{-2}s^{-1}}$ (x30 w.r.t. KEKB/Belle)
  - max instantaneous luminosity $\mathscr{L} = 4.7\times10^{34}\ \mathrm{cm^{-2}s^{-1}}$ (WR)
- ➡ Achievable in the *nano-beam scheme**
  - increase beam currents
  - squeeze beams at the interaction point
  - reduced beam energy asymmetry

single beam backgrounds

- higher background rates ($\mathcal{O}$(10-100))
  - detector occupancy, radiation damage, fake hits, pile-up noise in the calorimeter
- higher event rate
  - higher trigger rate, DAQ, computing
- **x30 produced signal events**

- machine instabilities
- **greatly improved constraint for decay chain vertex fitting**

- reduced vertex separation, Δt resolution
- **increased detector hermeticity**

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

Lorentz factor

beam current

beam-beam parameter

geometrical reduction factors

beam aspect ratio at the IP

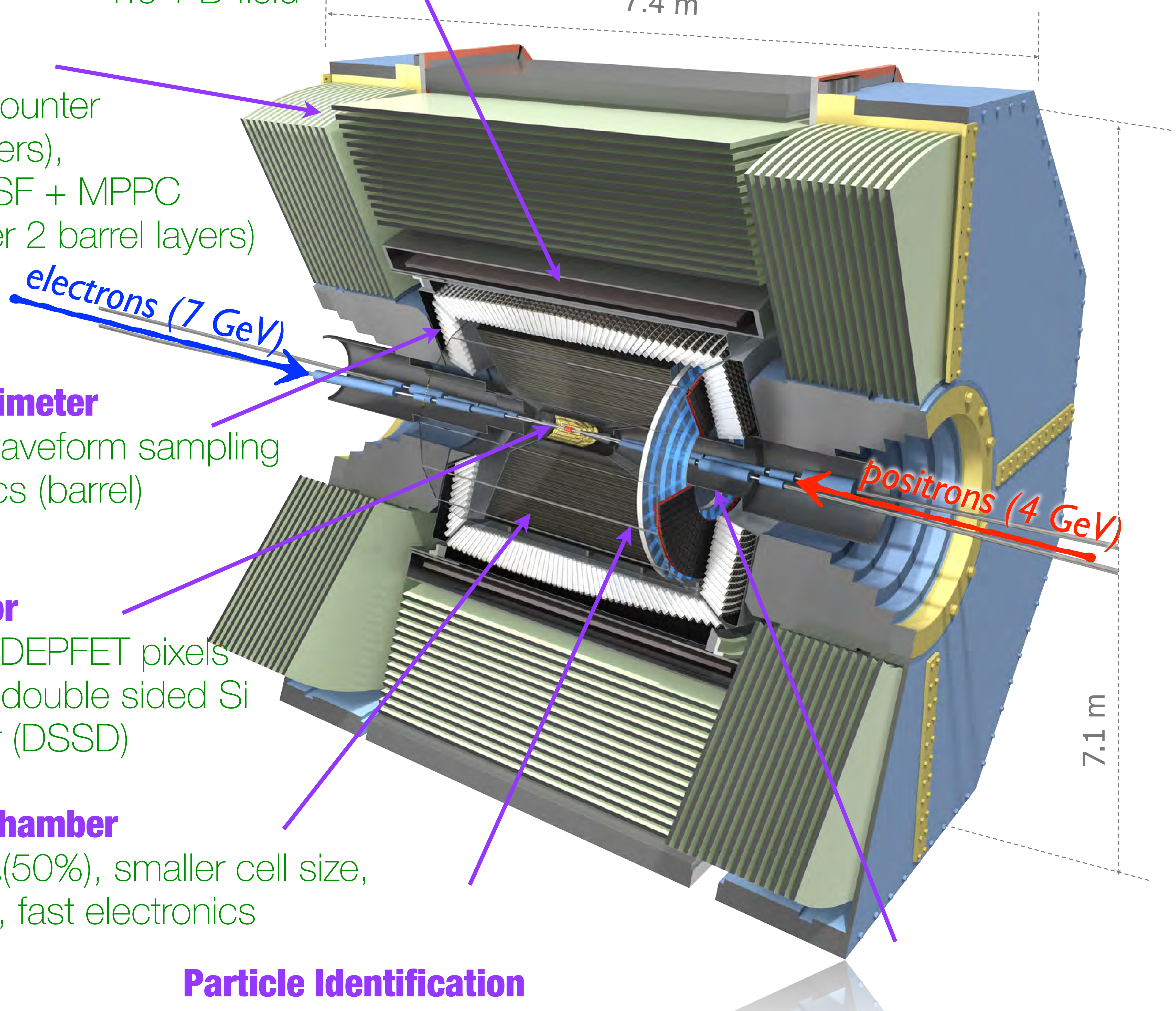
vertical beta-function at the IP

* proposed by P. Raimondi for SuperB

Belle II

experiment @ SuperKEKB High-Luminosity B-Factory

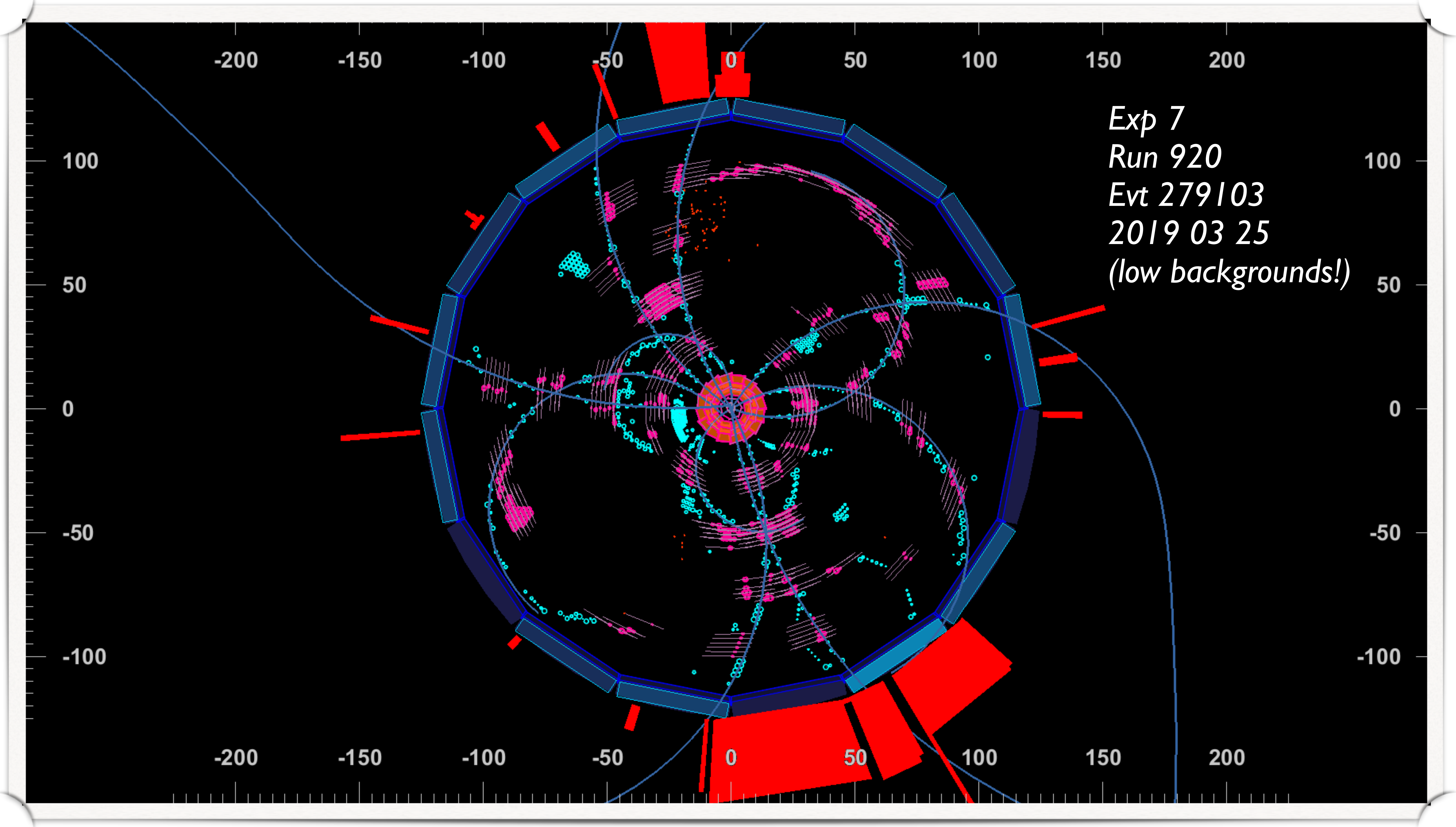
- ➡ *multi-purpose detector* designed to reconstruct *all** particles from the e^+e^- collision
- ➡ excellent vertexing
- ➡ high-efficiency detection of neutrals (γ, π^0, η, η', …)
- ➡ high trigger efficiency, including for low-multiplicity events
- ➡ reconstruction performance *at least as good as* Belle & *BABAR*



Belle II TDR

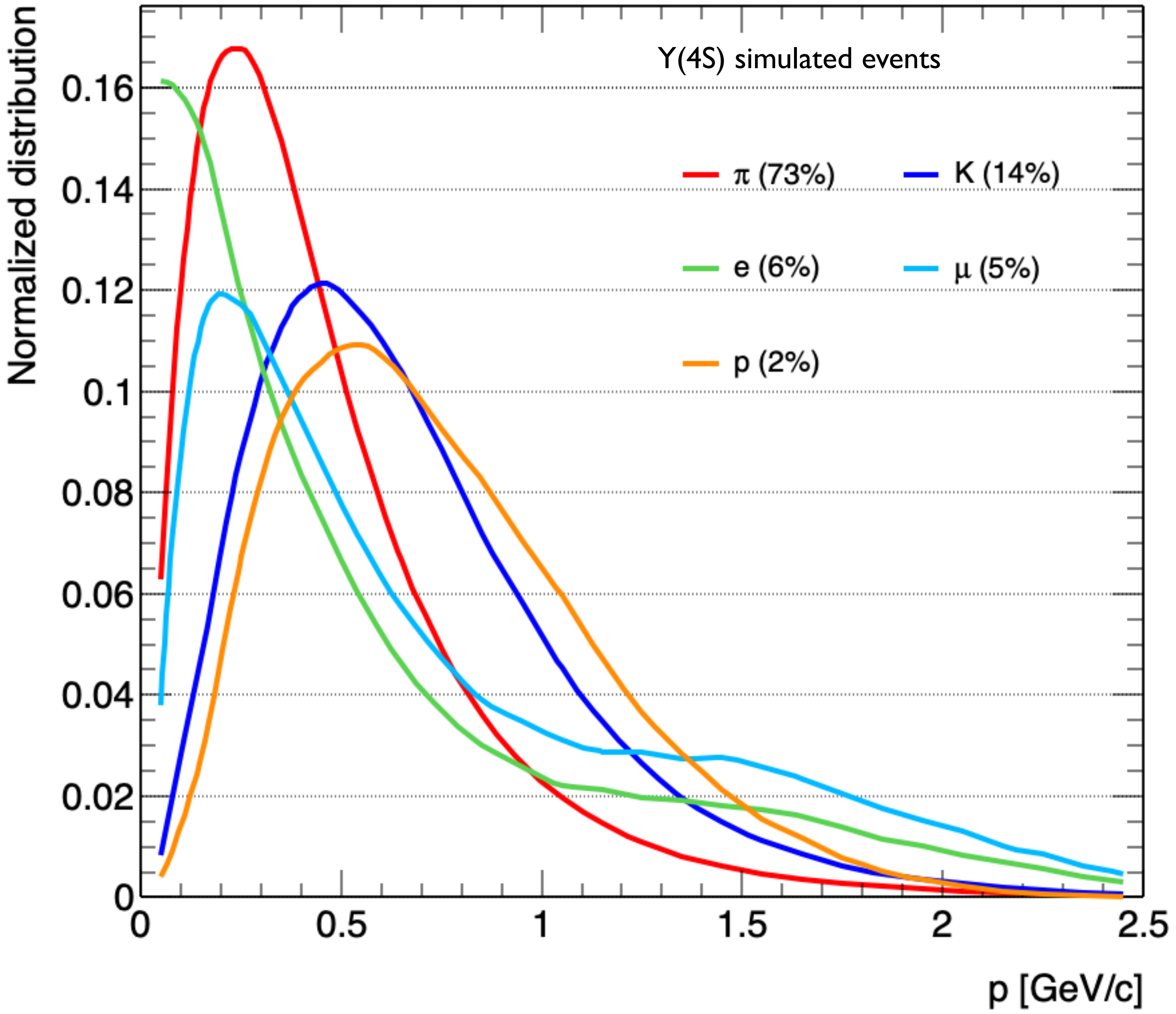
* particles that interact with the detector

A Candidate Hadronic Event



A Typical Υ(4S) Event

- average multiplicities:
  - 11 charged tracks
  - 5 neutral pions
  - 1 neutral kaon
- soft charged tracks momentum spectrum



NOTE: the DAQ is not synchronous to the bunch crossing (150÷250 MHz)

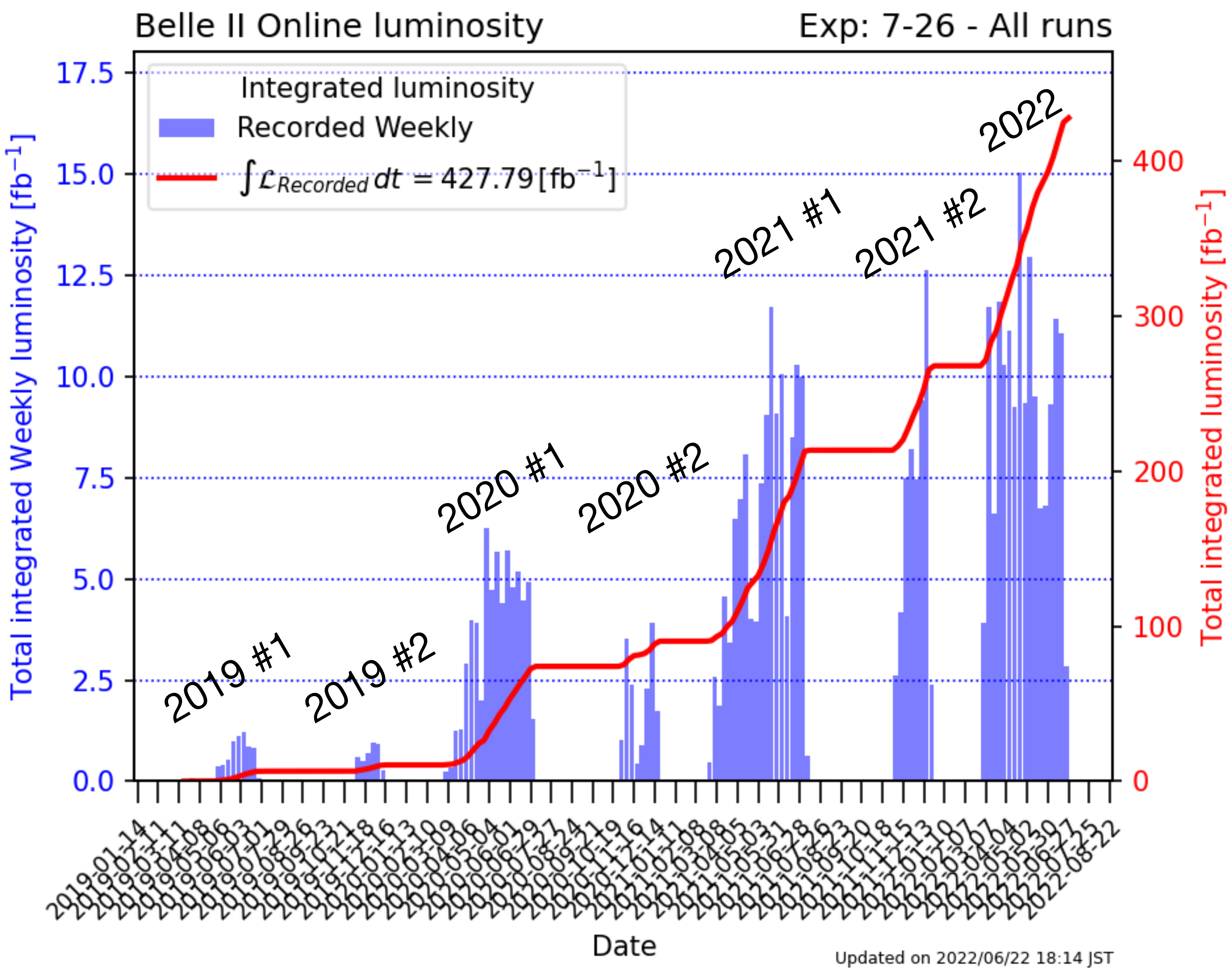
→ detectors integrate many collisions (+ beam background)

→ reconstruction is not as easy as it may look!

Current Dataset ...

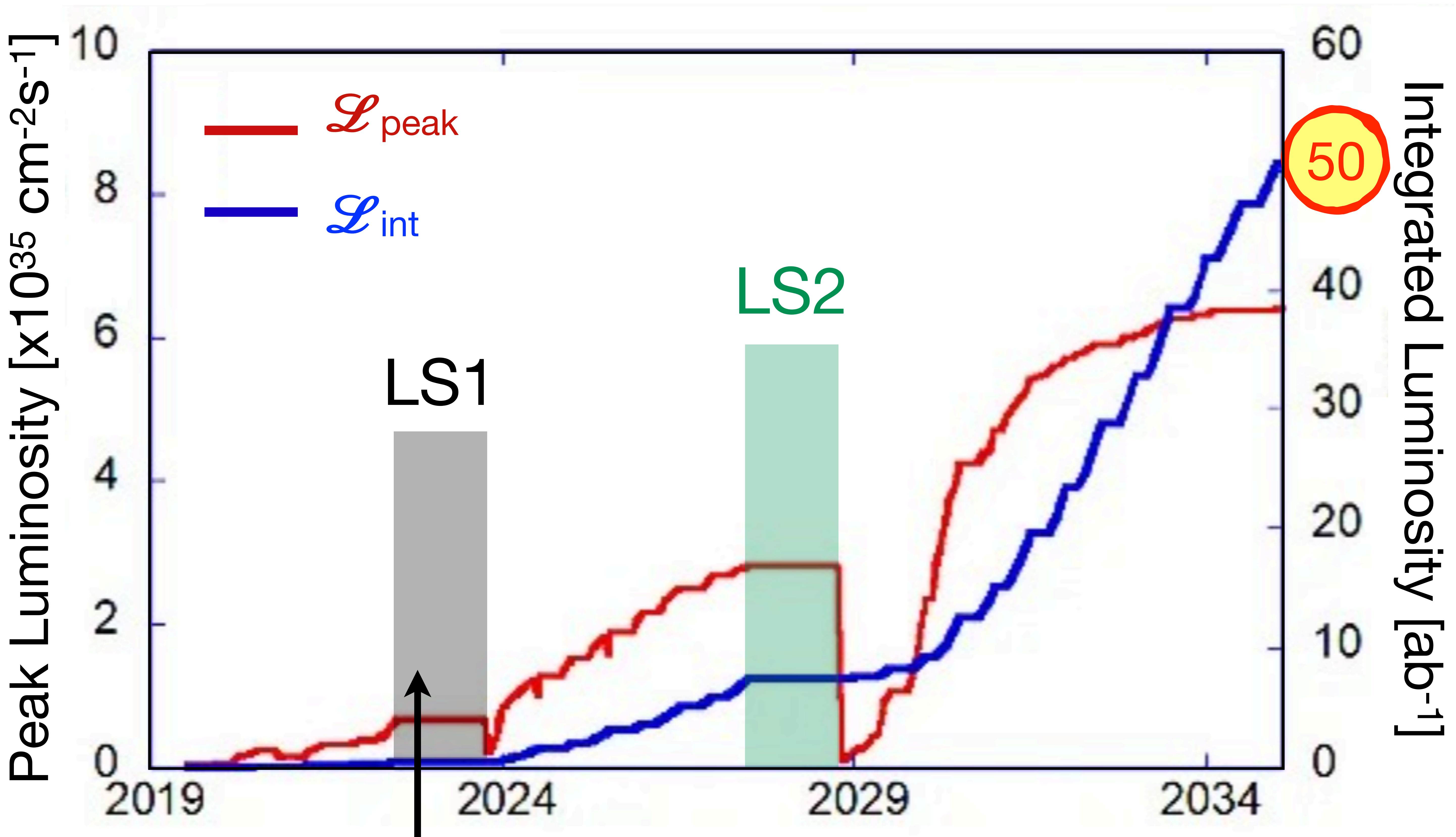
- ➡ First data recorded in 2019
  - 2 data-taking period per year
- ➡ Collected data
  - 362/fb at Υ(4S)*
  - 42/fb off-resonance, 60 MeV below Υ(4S)
  - 19/fb energy scan between 10.6 to 10.8 GeV for exotic hadron studies

L (fb^{-1})	Belle	BABAR	total
Υ(5S)	121	-	121
Υ(4S)	711	433	1144
Υ(3S)	3	30	33
Υ(2S)	25	14	39
Υ(1S)	6	-	6
off-res	100	54	154



* results shown today using only ~1/2 of the dataset: 0.27 of the Belle & 0.44 of the BABAR Υ(4S) datasets

… and road to 50/ab



we are here:

- $\mathscr{L}_{int}$ = 424/fb
- $\mathscr{L}_{peak}$ = 4.7×10^{34} $cm^{-2}s^{-1}$

➡ Long Shutdown 1 (LS1)

- now
- end 2022 - 2023
- maintenance/upgrade of machine & sub-detectors

➡ Long Shutdown 2 (LS2)

- to be confirmed
- 2026 - 2027
- upgrade of the SuperKEKB Interaction Region

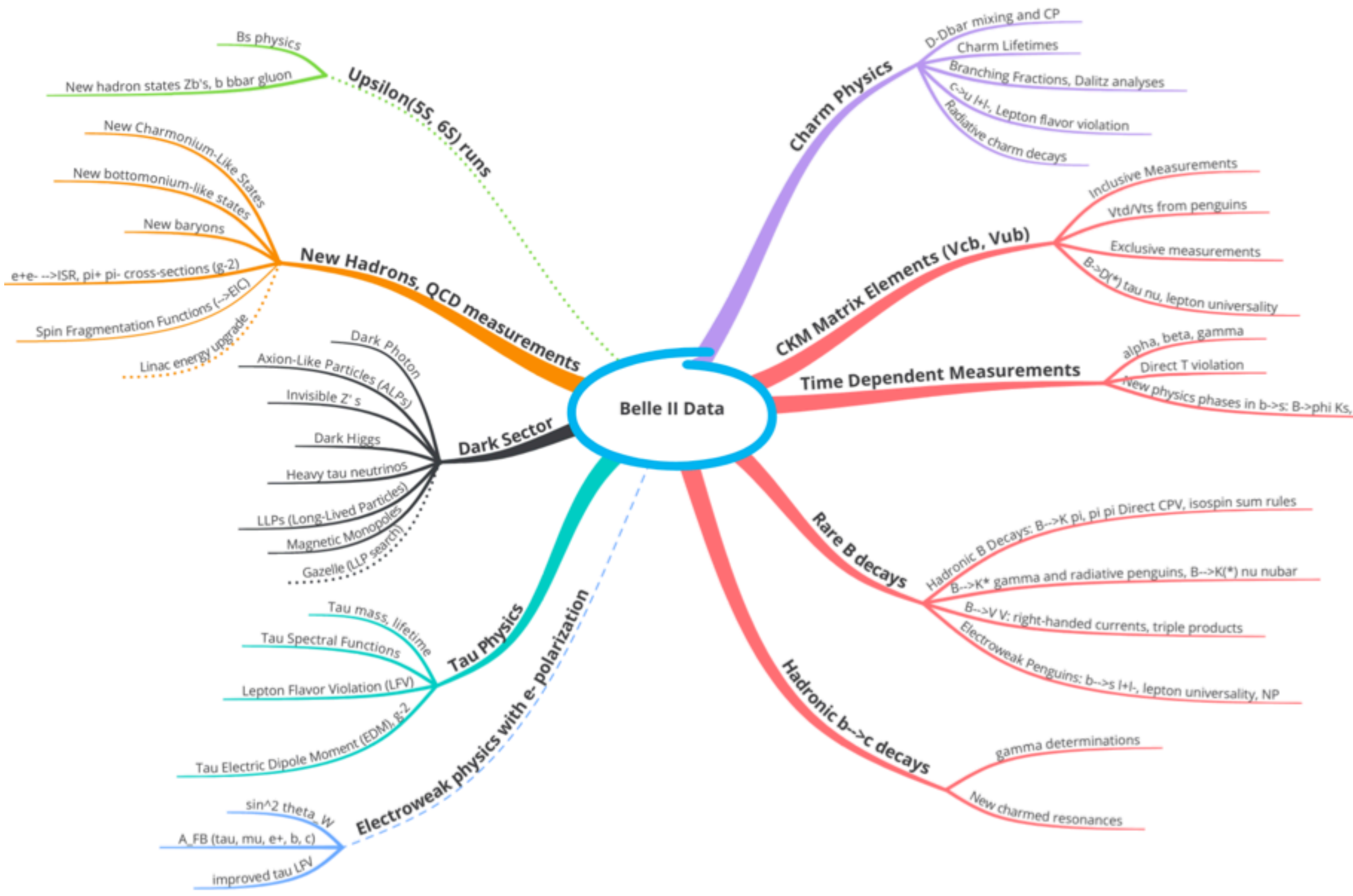
Overview Of the Physics Program

and its rich menu

The Physics Program

a snapshot

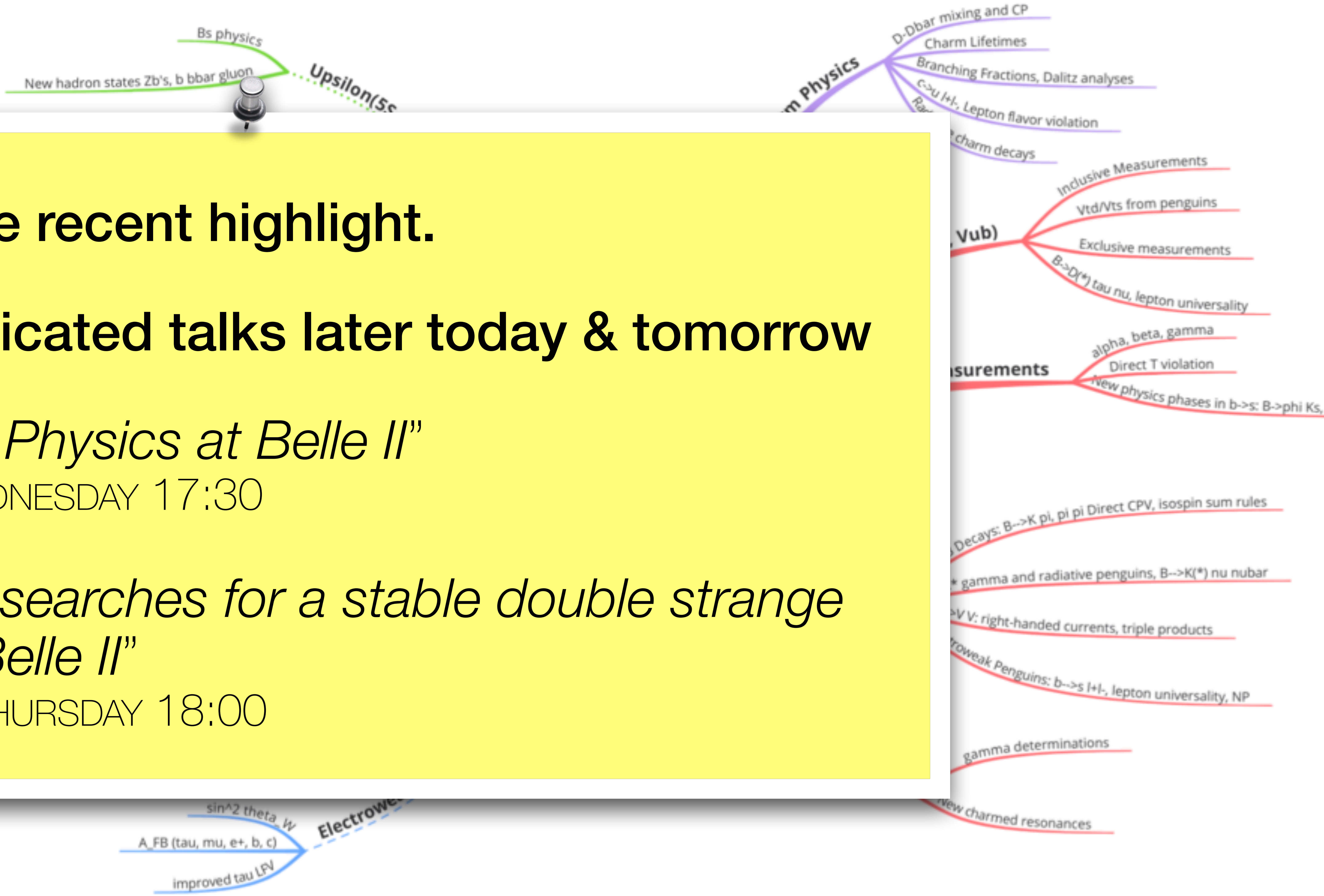
- *Belle II* is (going to) contribute in many sectors
  - Standard Model Physics, CPV
  - Dark Sector (ALPs, Z', Dark Higgs)
  - LFU, LFV, EDM, …
- … with many types of analyses:
  - (many sort of) searches
  - time-dependent
  - missing energy and missing mass
  - on the Dalitz Plot (multi-body)



The Physics Program

a snapshot

- Belle II is (goi… many sectors
  - Standard M…
  - Dark Sector…
  - LFU, LFV, E…
- … with many…
  - (many sort…
  - time-depen…
  - missing ene…
  - on the Dalitz Plot (multi-body)



I will show some recent highlight.

There are 2 dedicated talks later today & tomorrow

- "*Bottomonium Physics at Belle II*"
  A. Boschetti, Wednesday 17:30
- "*Prospects for searches for a stable double strange hexaquark at Belle II*"
  Dr. B. Scavino, Thursday 18:00

Belle II Physics Book, PTEP 2019 123C01 Snowmass White Paper

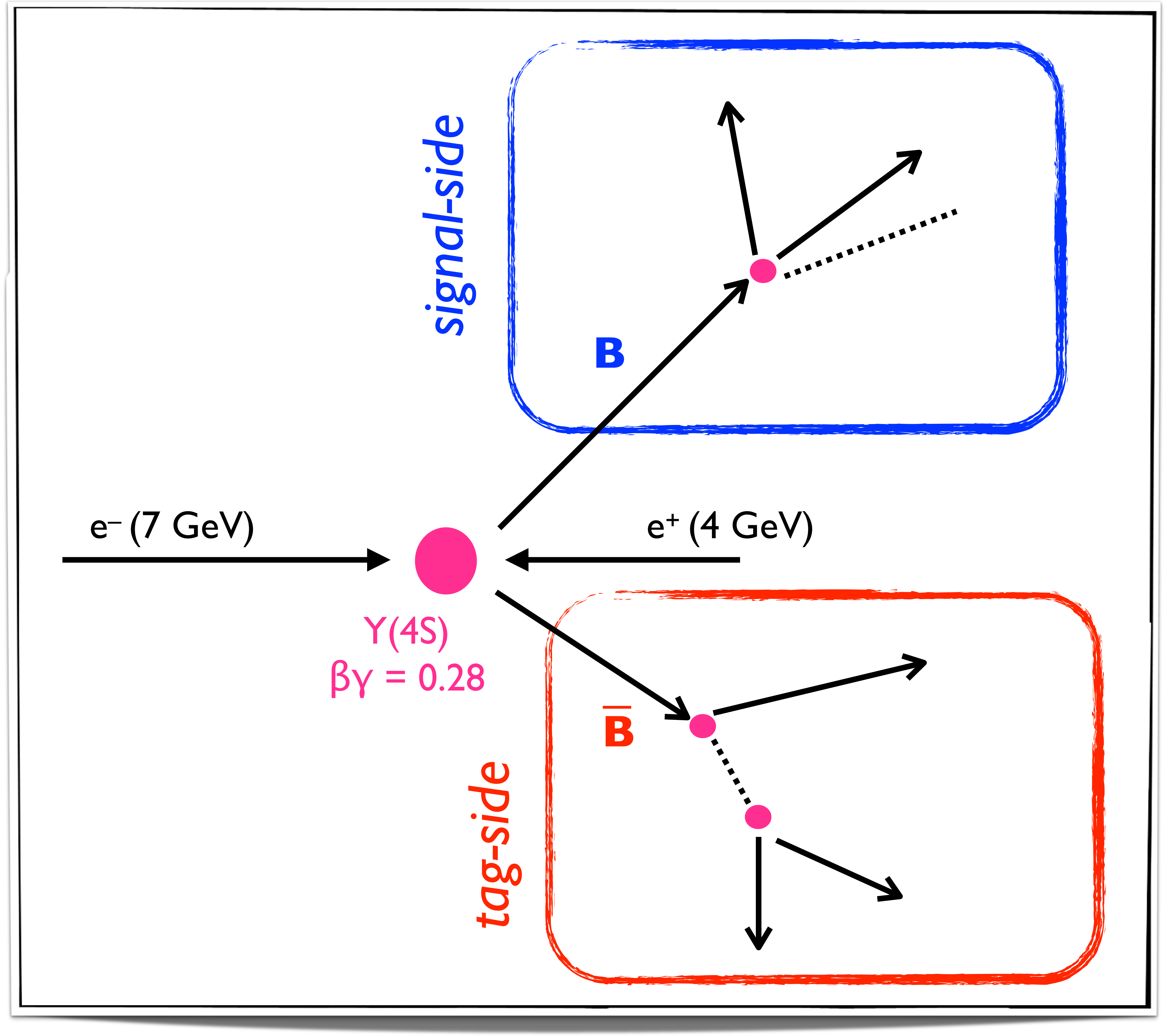
B physics

A $B\bar{B}$ Event

machine-learning based tools for B-physics

Full Event Interpretation (FEI) [Comput Softw Big Sci **3**, 6 (2019)]

Flavour Tagger (FT) [Eur. Phys. J. C 82, 2083 (2022)]



➡ tag-side *Exclusive Reconstruction (FEI)*:

- for weak signature signals, e.g. $B^+ \to \tau^+\nu$
- hadronic tag: $\varepsilon = \mathcal{O}(0.5\%)$, less background
- semileptonic tag: $\varepsilon = \mathcal{O}(2\%)$, more background

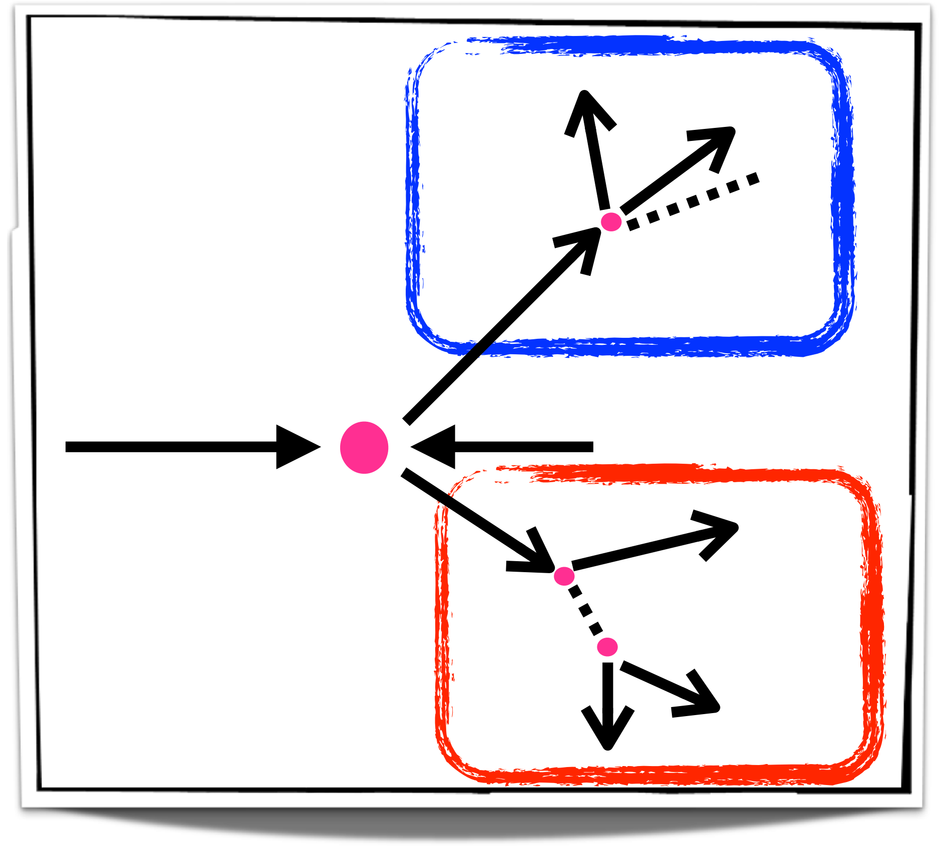
➡ tag-side *Inclusive Reconstruction (+ FT)*:

- for stronger signature signals
- ignore details, measure inclusive observables
- higher efficiency but more background

✓ effective offline B meson beam
✓ high-efficiency flavour/CP tagging
✓ high performances in channels with missing energy

$B\bar{B}$ Physics

a very rich program



➡ B mixing & searches for new sources of CPV

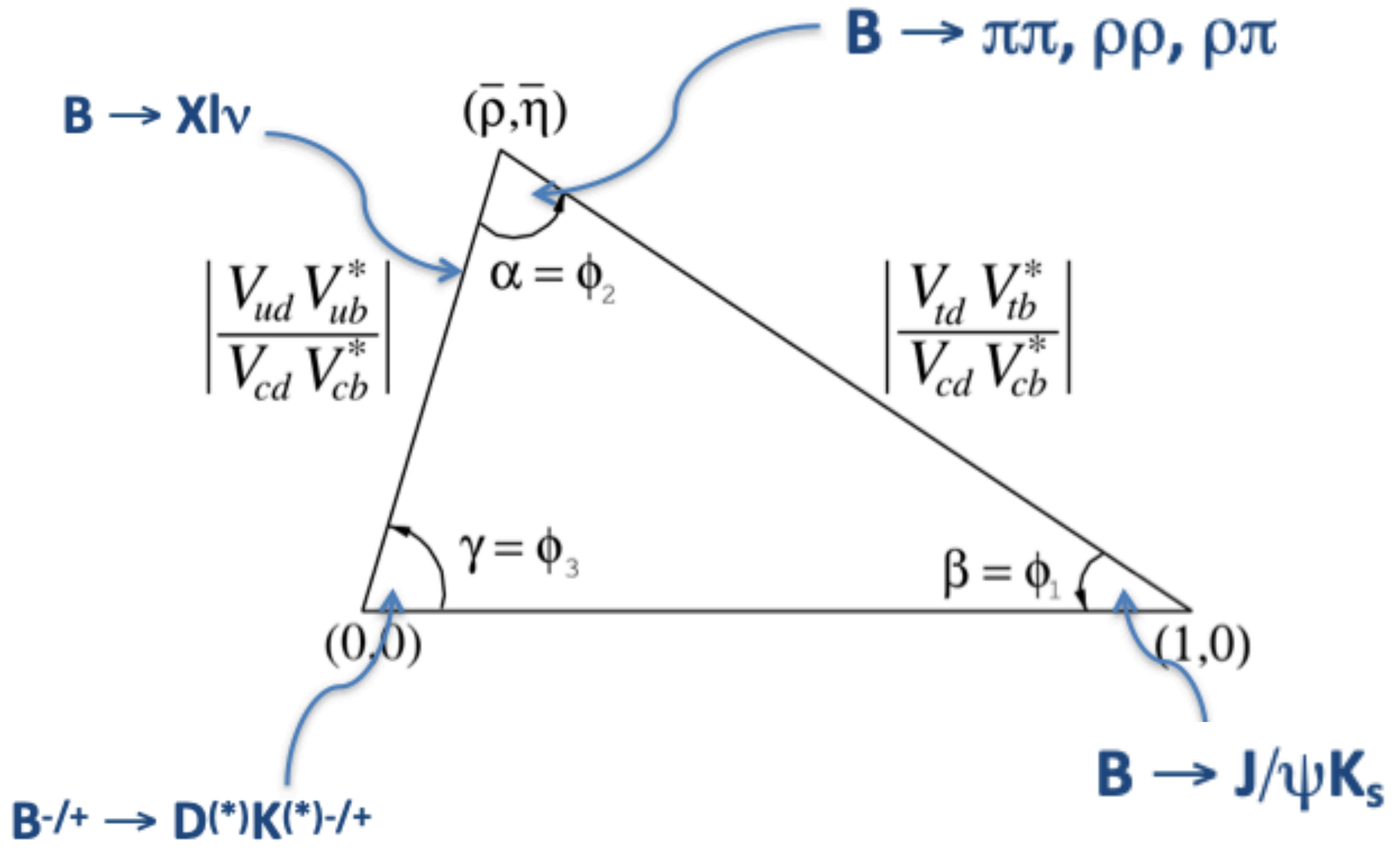
➡ non-SM probes from radiative & (semi)-leptonic decays

➡ tests of LFU, e.g. $R(X_{e/\mu})$,

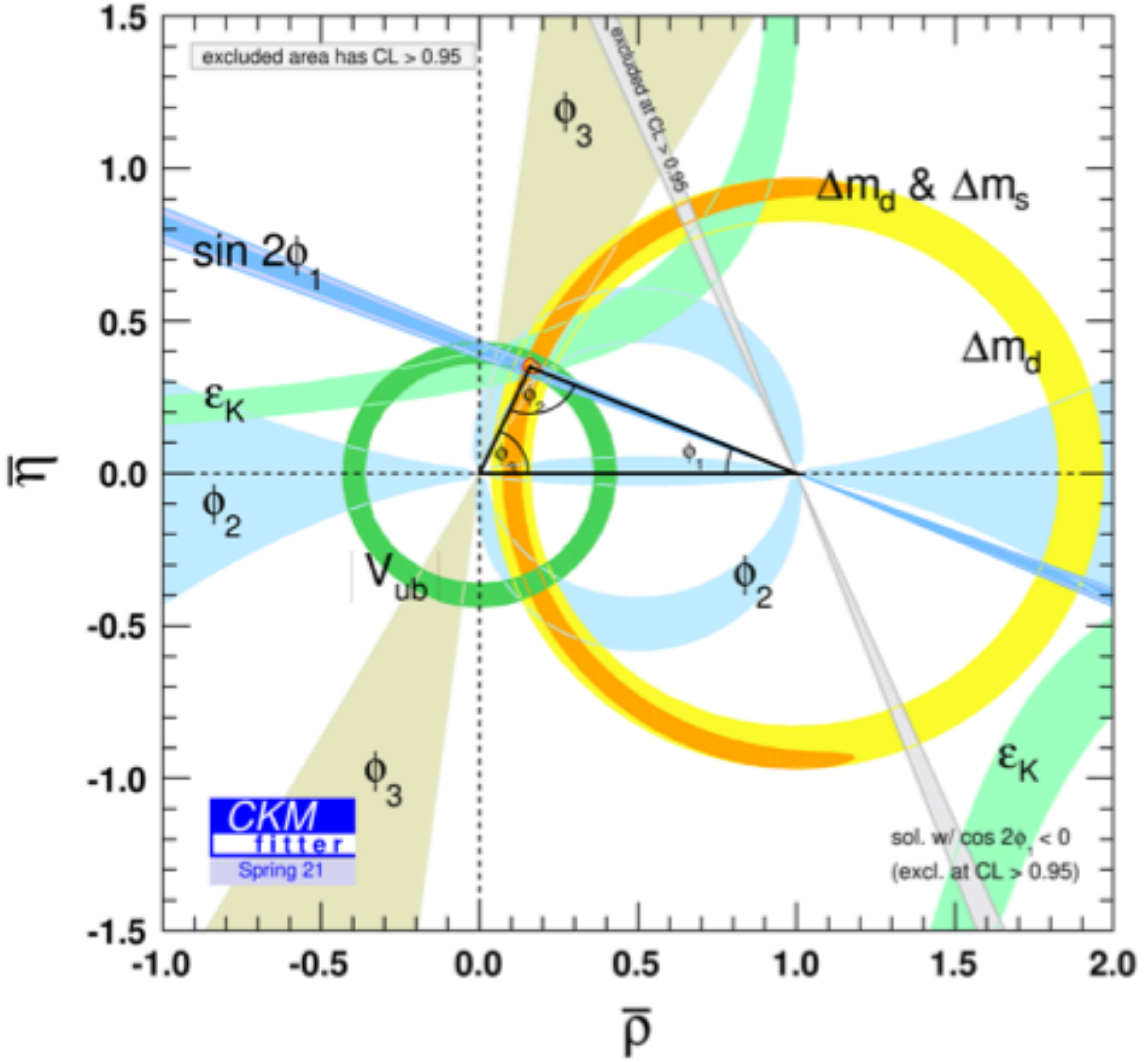
➡ measurements of CKM Unitary Triangle sides & angles

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

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



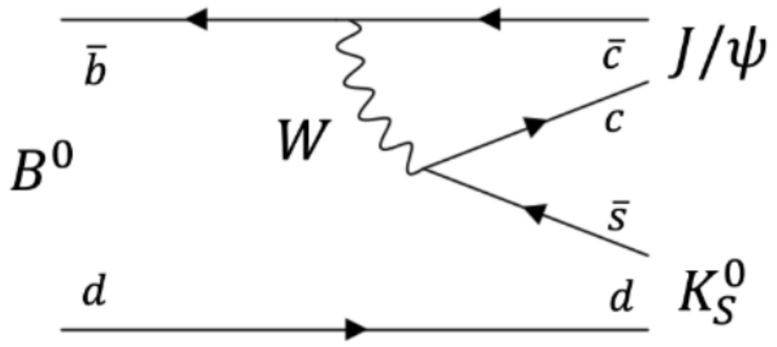
overconstraining the UT is a very powerful test of the SM



sin 2 β/ϕ1

the B^0 mixing phase

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



$\Delta t \simeq \Delta z / \beta\gamma c$

$$\mathcal{A}^{raw}(\Delta t) = \frac{N(\bar{B}^0 \to f_{CP}) - N(B^0 \to f_{CP})}{N(\bar{B}^0 \to f_{CP}) + N(B^0 \to f_{CP})}(\Delta t) = A_{CP}\cos(\Delta m_d \Delta t) + S_{CP}\sin(\Delta m_d \Delta t)$$

direct CP asymmetry (A_{CP}); mixing-induced CP asymmetry (S_{CP})

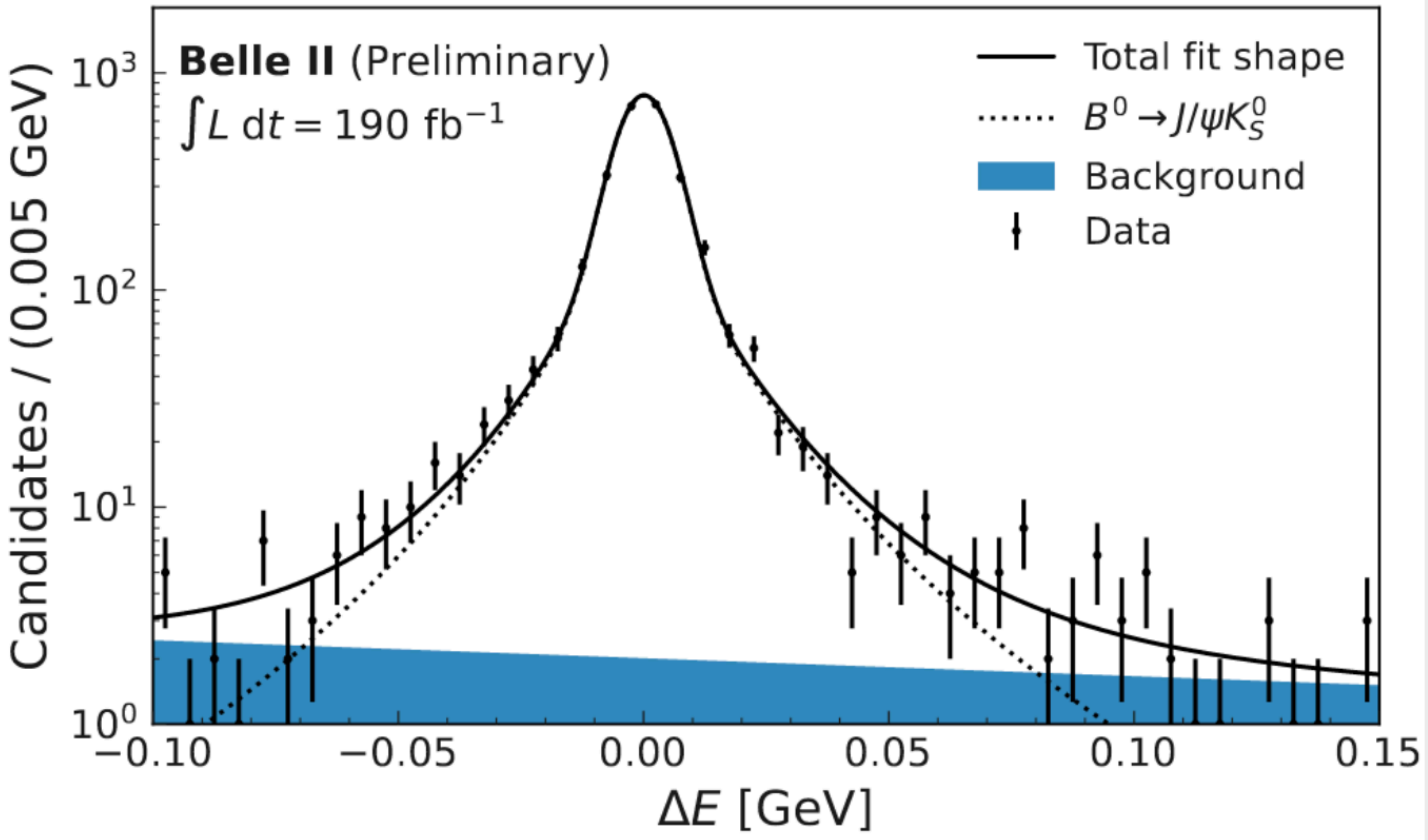
- ➡ SM measurement, but important analysis to refine all our tools for future measurement sensitive to NP (e.g. $B^0 \to K_S K_S K_S$): we are ready!
  - 1st generation B-factories golden channel for SM mixing
- ➡ Δt resolution function & flavour tagger parameters from other analyses
  - flavour tagger effective efficiency:

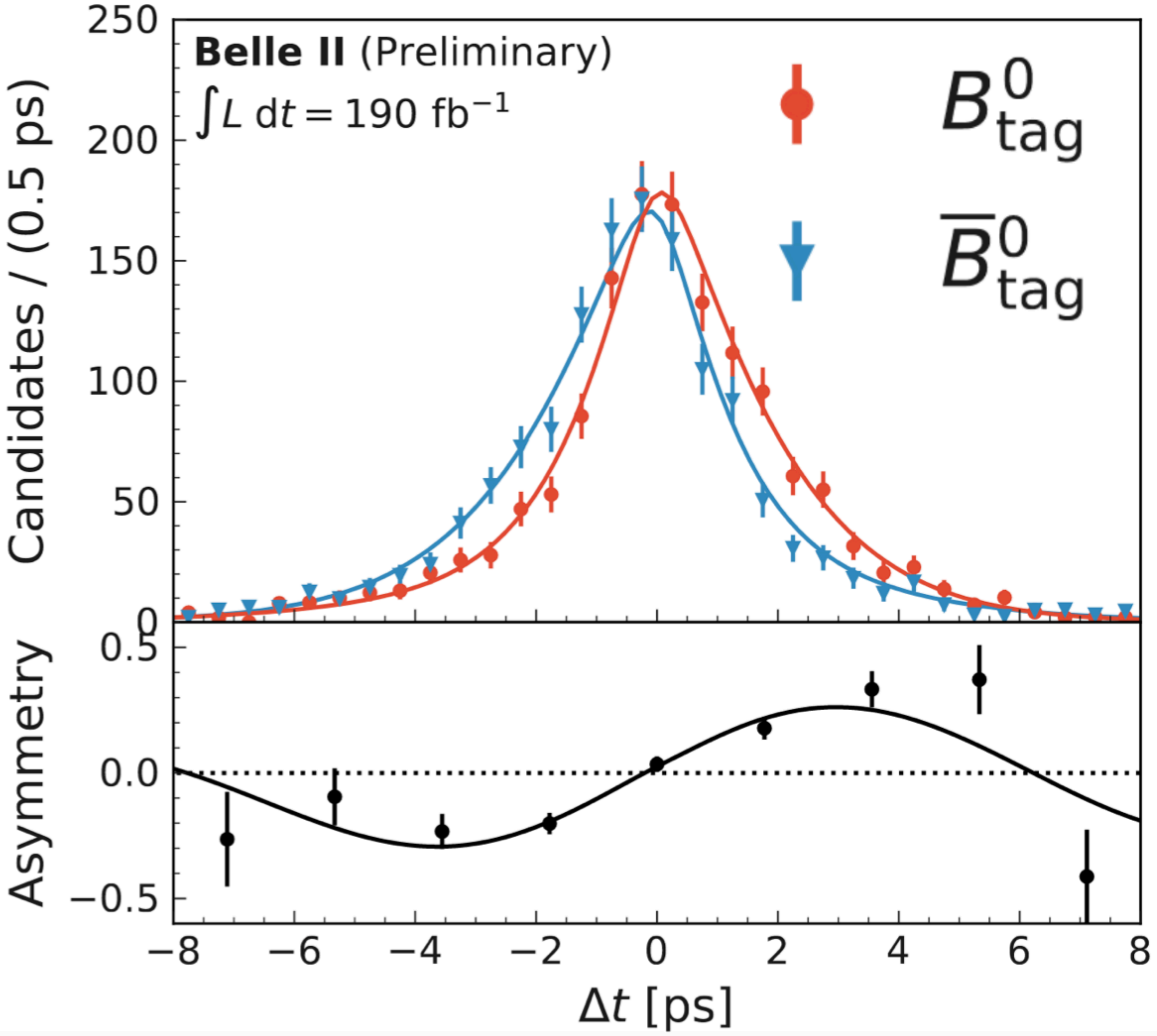
$$\varepsilon_{\rm eff} = \epsilon\,(1-2\omega)^2 = (30.0 \pm 1.2 \pm 0.4)\,\%$$

$$\epsilon = N_{tag}/N$$

$$\omega = \text{dilution factor}$$

Signal yield: 2774 ± 55



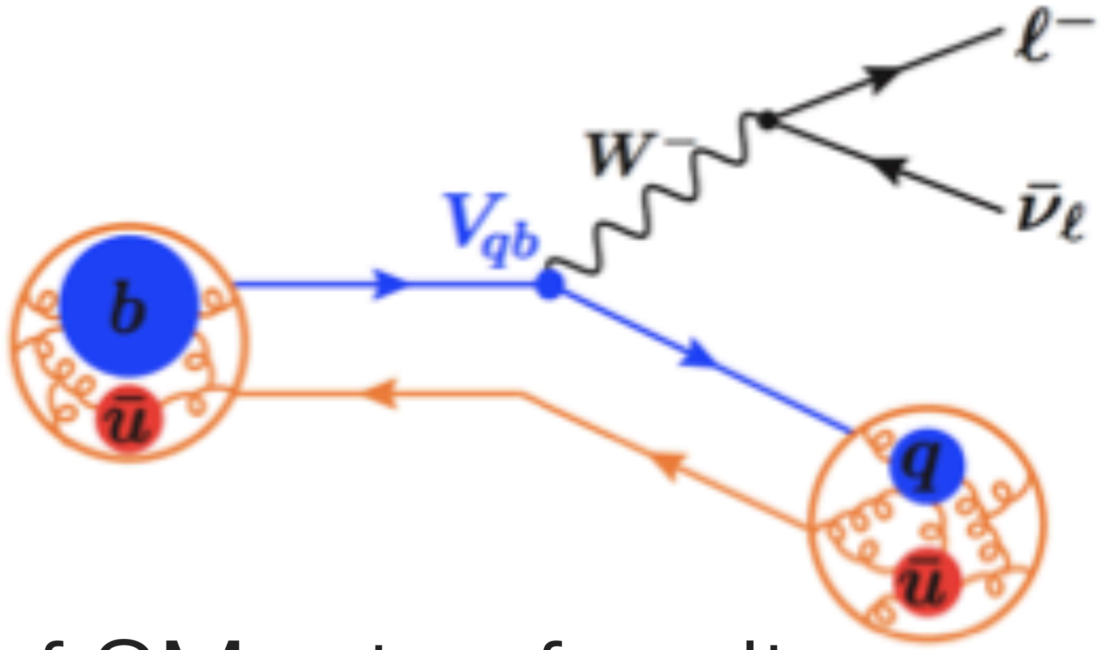


WA (K_S mode only)
S_{CP} = 0.695±0.019
A_{CP} = 0.000±0.020

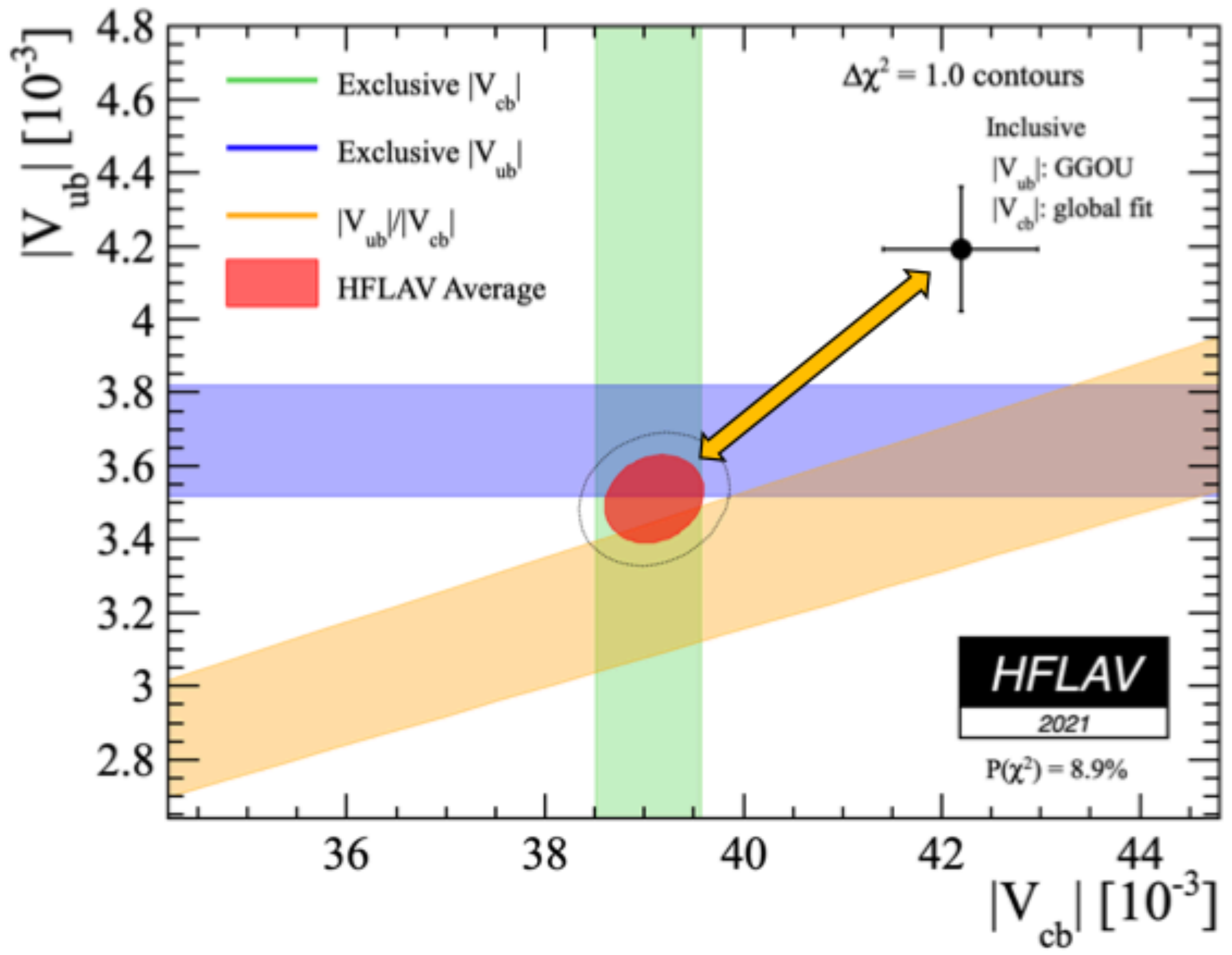
S_{CP} = 0.720 ± 0.062 (stat.) ± 0.016 (syst.)
A_{CP} = 0.094 ± 0.044 (stat.) $^{+0.042}_{-0.017}$ (syst.)

CKM Elements $|V_{ub}|$ & $|V_{cb}|$

SM tests



- ➡ main limiting factors to the UT constraining power
- ➡ are important inputs in predictions of SM rates for ultra rare decays, e.g. B → μν, K → πνν (that may have NP contributions)
- ➡ extracted from semileptonic decays:
  - (signal) exclusive
    - **V**
  - (signal) inclusive $B \to X_{u,c}\ell\bar{\nu}_\ell$

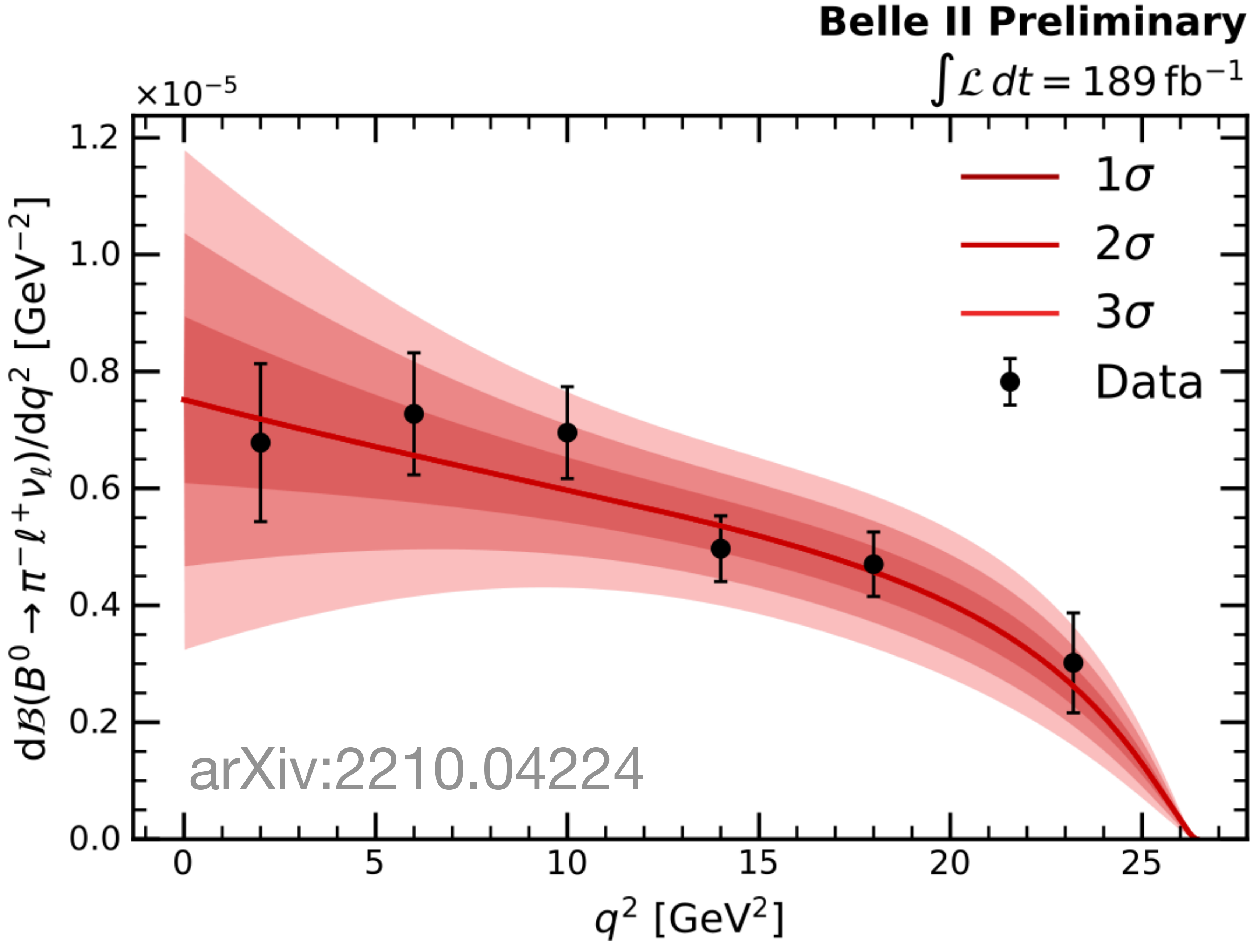


rest-of-event informations used to compute q^2

$|V_{ub}|$ from untagged $B^0 \to \pi^-\ell^+\nu_\ell$

Differential rate in terms of $q^2 = (p_\ell + p_\nu)^2$

$$\frac{d\Gamma(B^0 \to \pi^-\ell^+\nu)}{dq^2} = \frac{G_F^2}{24\pi^3}|V_{ub}|^2|p_\pi|^3|f_+(q^2)|^2$$



$$|V_{ub}| = (3.54 \pm 0.12 \pm 0.15 \pm 0.16) \cdot 10^{-3}$$

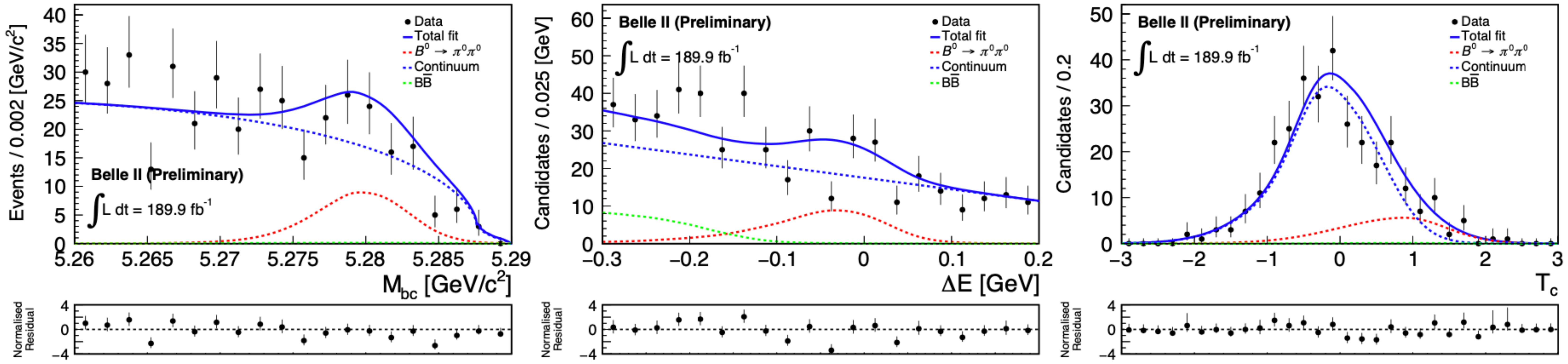
consistent with the exclusive determination

$B^0 \to \pi^0 \pi^0$ Branching Ratio & A_{CP}

(to be submitted to PRD)

important channel for the measurement of the CKM angle α/ϕ_2

- ➡ The most experimentally difficult ππ mode
  - shows that we can do all-neutrals final states
- ➡ signal yields extracted with a 3D fit to M_{bc}, ΔE and the continuum-suppression BDT output
  - use $B \to D^0(K^+\pi^-\pi^0)\,\pi^0$ as control channel
  - B flavour extract with flavour tagger, $\varepsilon_{tag} = (30.0 \pm 1.2 \pm 0.4)\%$



$$M_{bc} = \sqrt{s/4 - (p^*c)^2}$$

$$\Delta E = E^*_B - E^*_{beam}$$

continuum suppression output (another B-tool)

➡ Results:

$$A_{CP} = 0.14 \pm 0.46 \pm 0.07$$

$$\mathscr{B} = (1.27 \pm 0.25 \pm 0.17) \cdot 10^{-6}$$

WA: $A_{CP} = 0.33 \pm 0.22$, BR = $(1.59 \pm 0.26)10^{-6}$

➡ close to Belle precision with only ~1/4 of the dataset!

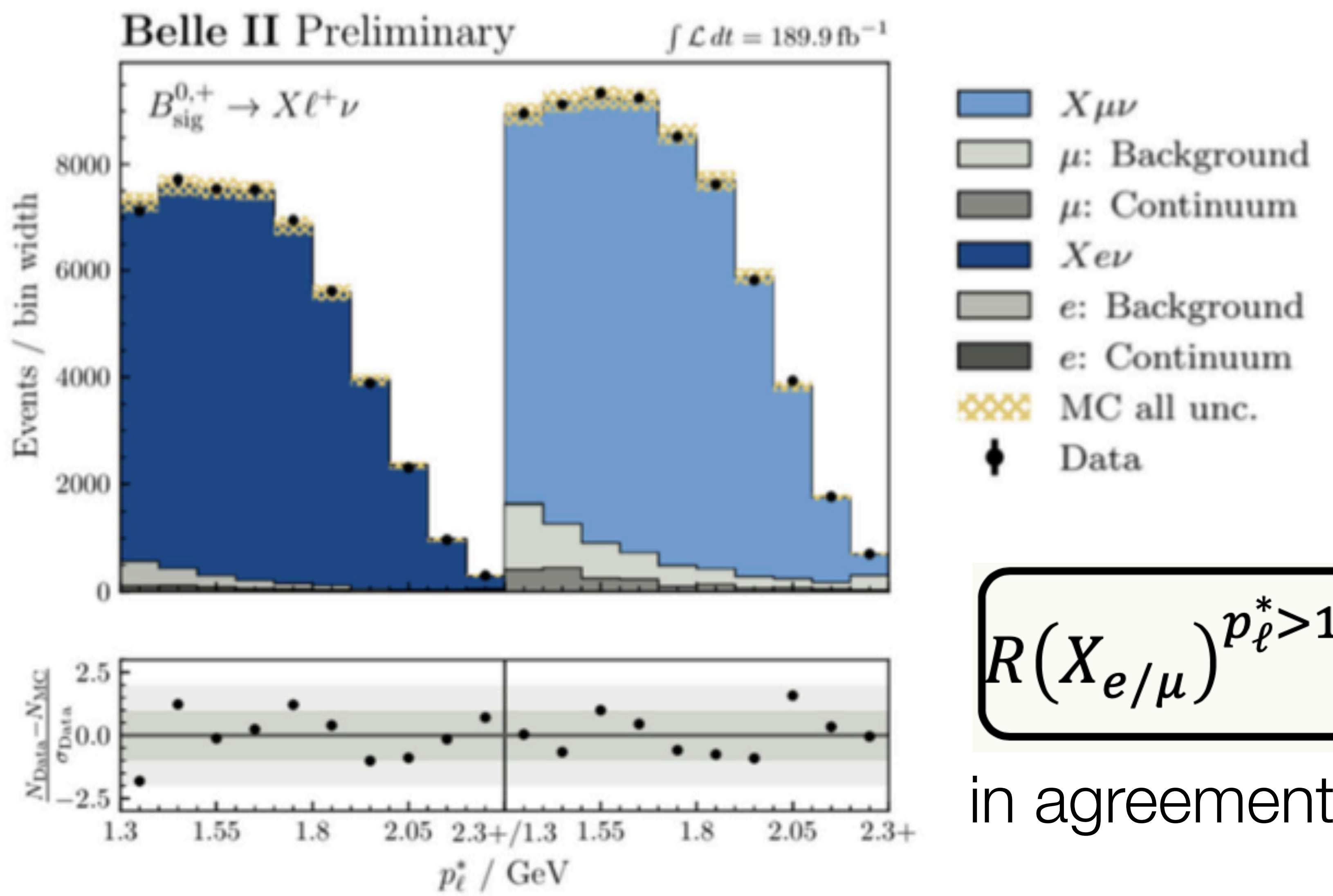
$$A_{CP} = 0.14 \pm 0.36 \pm 0.10$$

$$\mathscr{B} = (1.31 \pm 0.19 \pm 0.19) \cdot 10^{-6}$$

Test LFU in B decays with $R(X_{e/\mu}) = \frac{\mathcal{B}(B^{0,-} \to X e^- \nu_e)}{\mathcal{B}(B^{0,-} \to X \mu^- \nu_\mu)}$

using the Full Event Interpretation (FEI)

- ➡ First ever *inclusive* measurement of $R(X_{e/\mu})$, with hadronic tagging of the B_{tag} & $p^*_\ell > 1.3$ GeV/c
  - precise knowledge of the B_{tag} kinematics allows to inclusively reconstruct B_{sig}
- ➡ signal yields are extracted with a template fit to the center-of-mass lepton momentum
  - continuum background constrained with off-res data
  - rest is contained from bkg-enriched regions in data



$$R(X_{e/\mu}) = \frac{N_{Xe\nu} \cdot \epsilon_{X\mu\nu}}{N_{X\mu\nu} \cdot \epsilon_{Xe\nu}} \quad \text{with}$$

$$\epsilon_{X\ell\nu} = \frac{N^{\ell}_{sel} \cdot (\epsilon^{data}_{B_{tag}} / \epsilon^{MC}_{B_{tag}})}{2 \cdot N_{BB} \cdot BR(B \to X\ell\nu)}$$

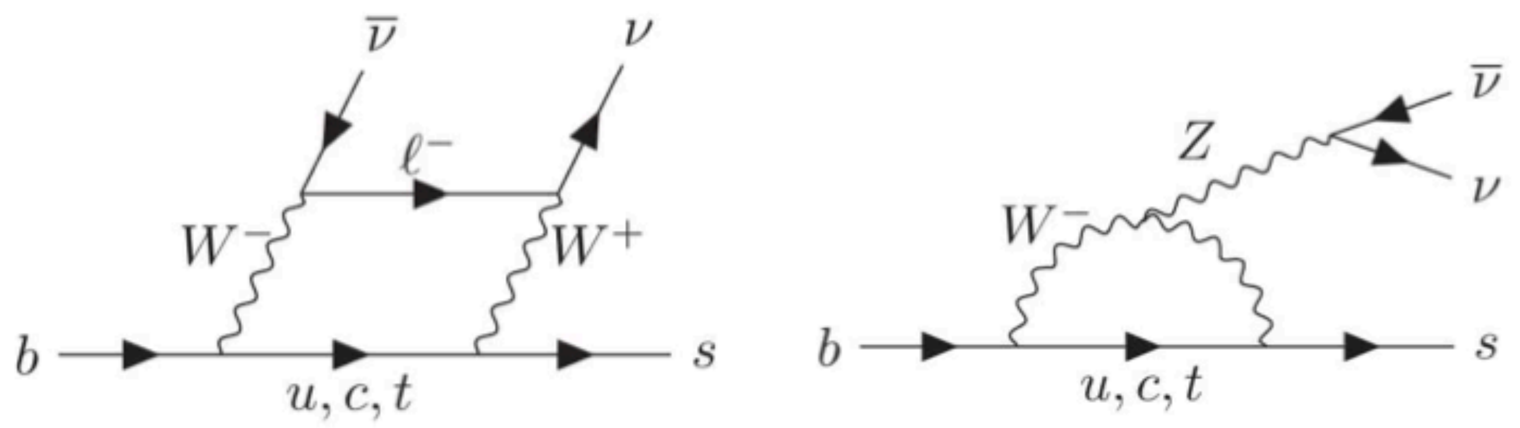
$$R(X_{e/\mu})^{p^*_\ell > 1.3\text{GeV}} = \mathbf{1.033 \pm 0.010^{stat} \pm 0.020^{syst}}$$

in agreement with SM: 1.006±0.001 (K.Vos, M. Rahimi) in progress

- ➡ Most precise BF-based LFU test with semileptonic B decays
  - main systematic due to lept-ID
  - can be extended to lower p_ℓ
- ➡ This measurement enables the measurement of $R(X_{\tau/\ell})$

arXiv/2301.08266

$B^+ \to K^+ \nu\bar{\nu}$

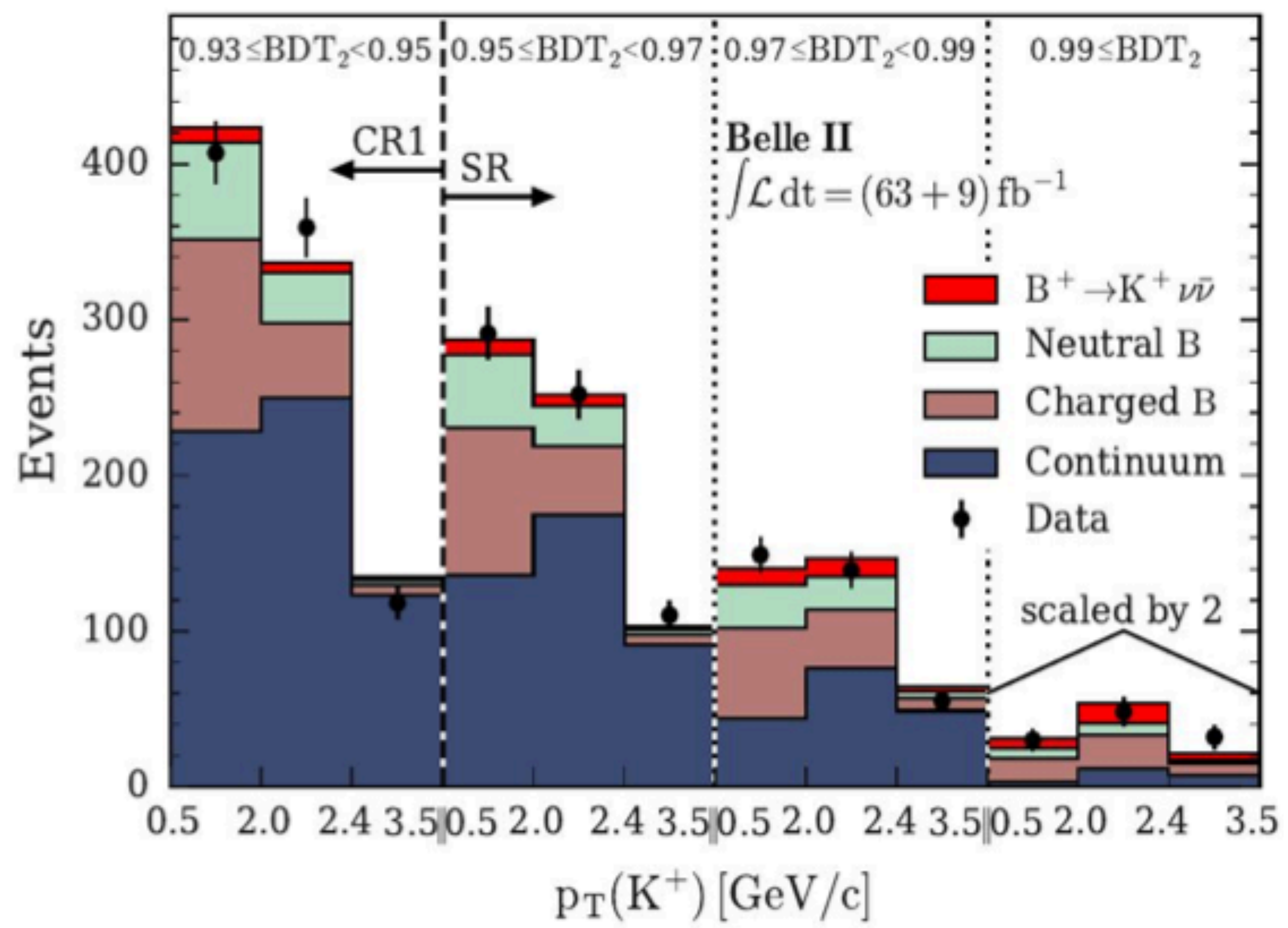


[PRL 127, 181802 (2021)](PRL 127, 181802 (2021))

interesting flavour changing neutral current process

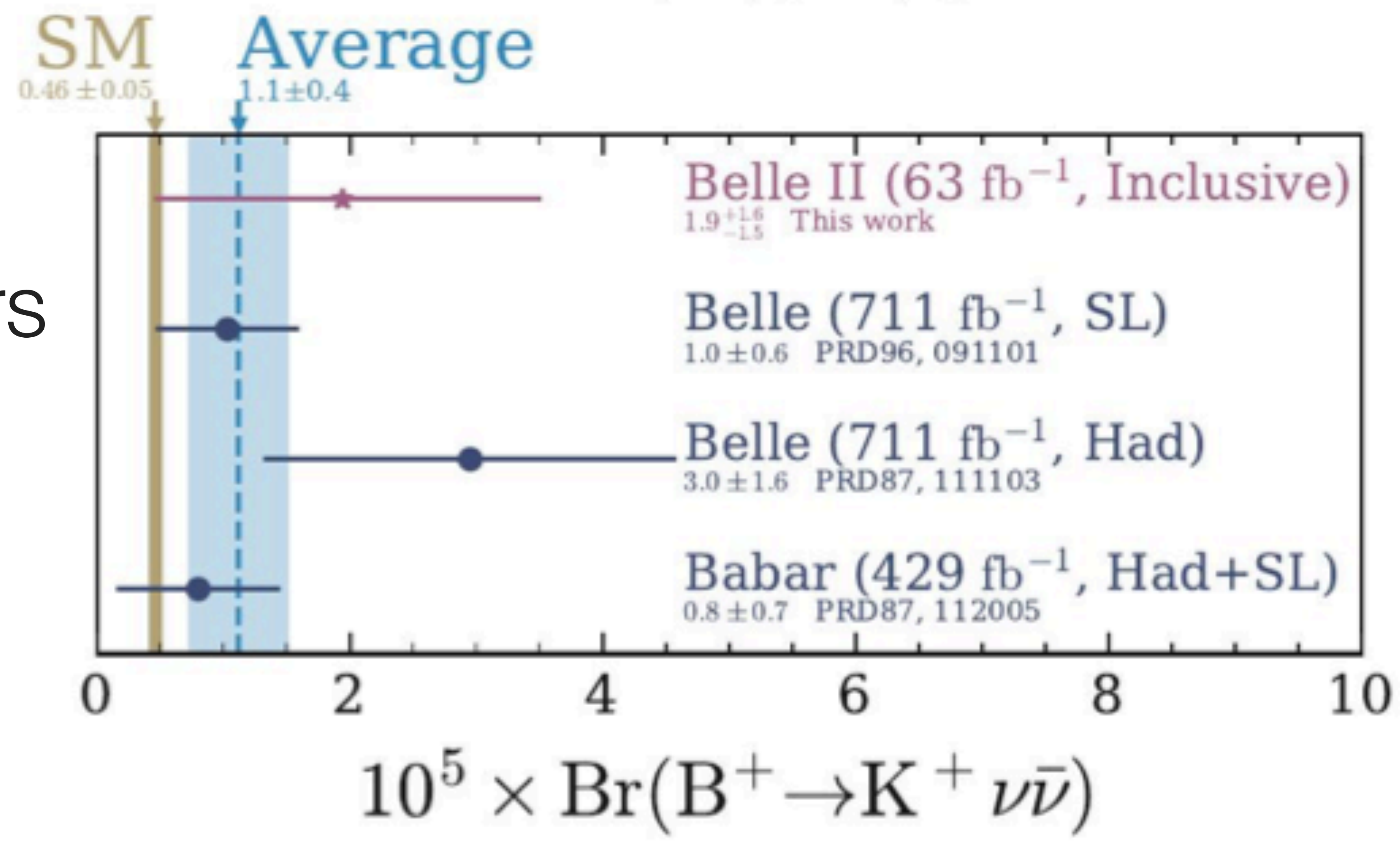
➡ FCNC potentially sensitive to non-SM contributions via new particles contributing both in the box and in the penguin diagrams

- only one Wilson coefficient in SM (C_L^{SM}) , while C_L and C_R probe NP



➡ Previous measurements at Belle & *BABAR* were based on *exclusive* reconstruction of the second B meson → new approach at *Belle II* with the *inclusive* reconstruction

- much higher reconstruction efficiency with respect to the exclusive reconstruction
- … but higher backgrounds → suppressed with BDT classifiers that identify the distinctive characteristics of the signal



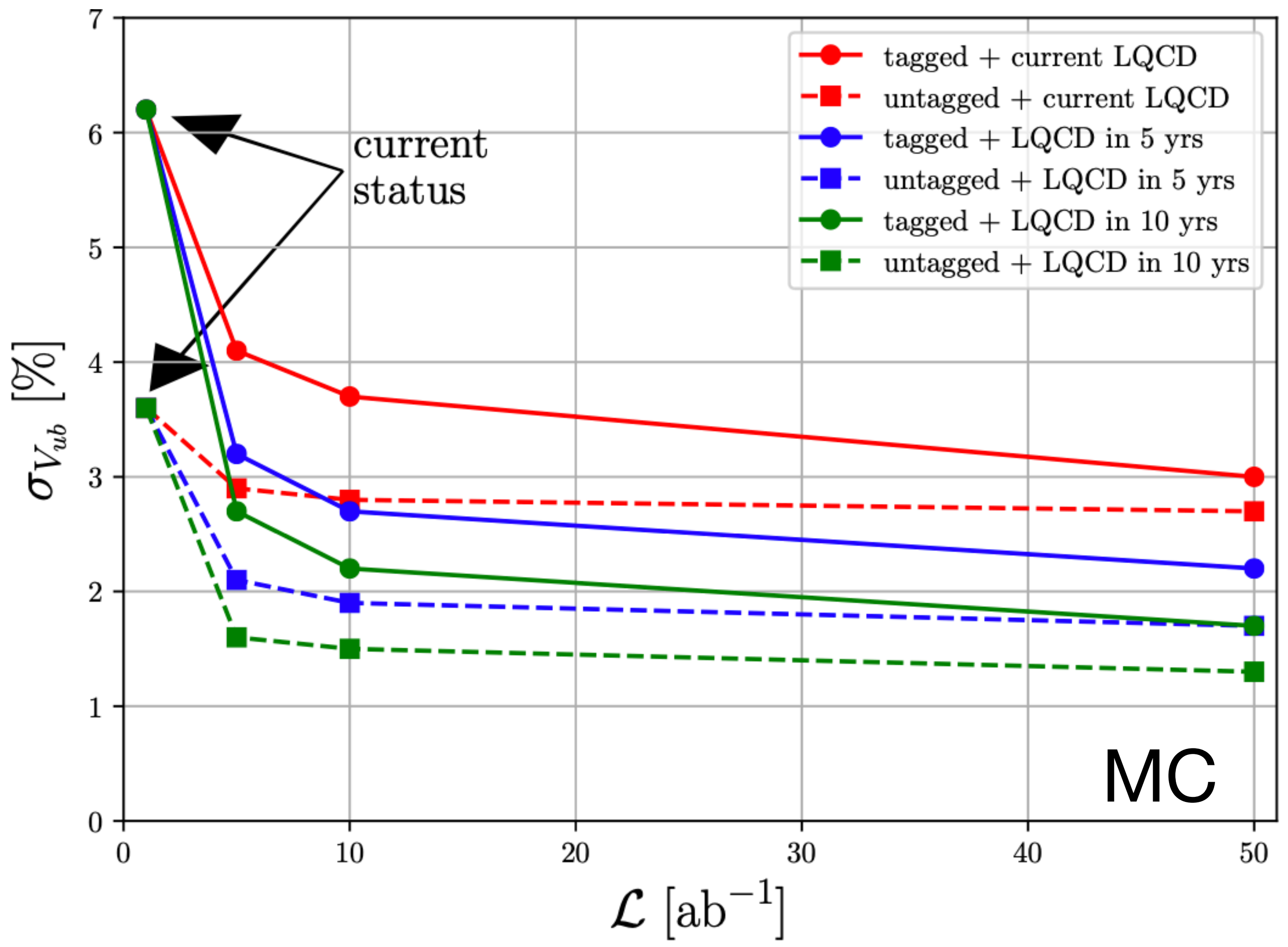
➡ Competitive performance already with a small data sample!

- *Belle II* is more than "redoing" Belle & *BABAR* measurements

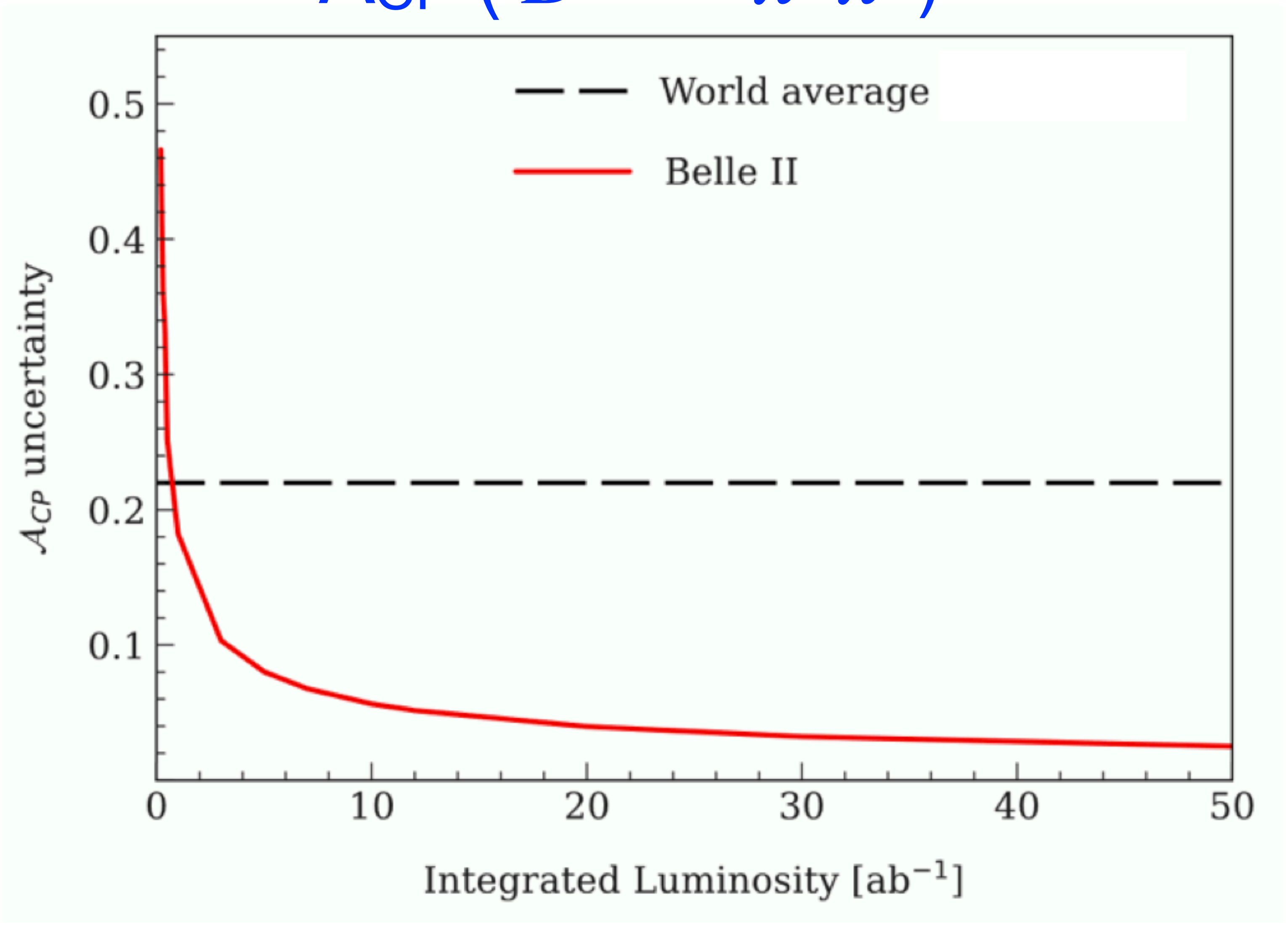
(Some) Prospects for B physics

Snowmass White Paper

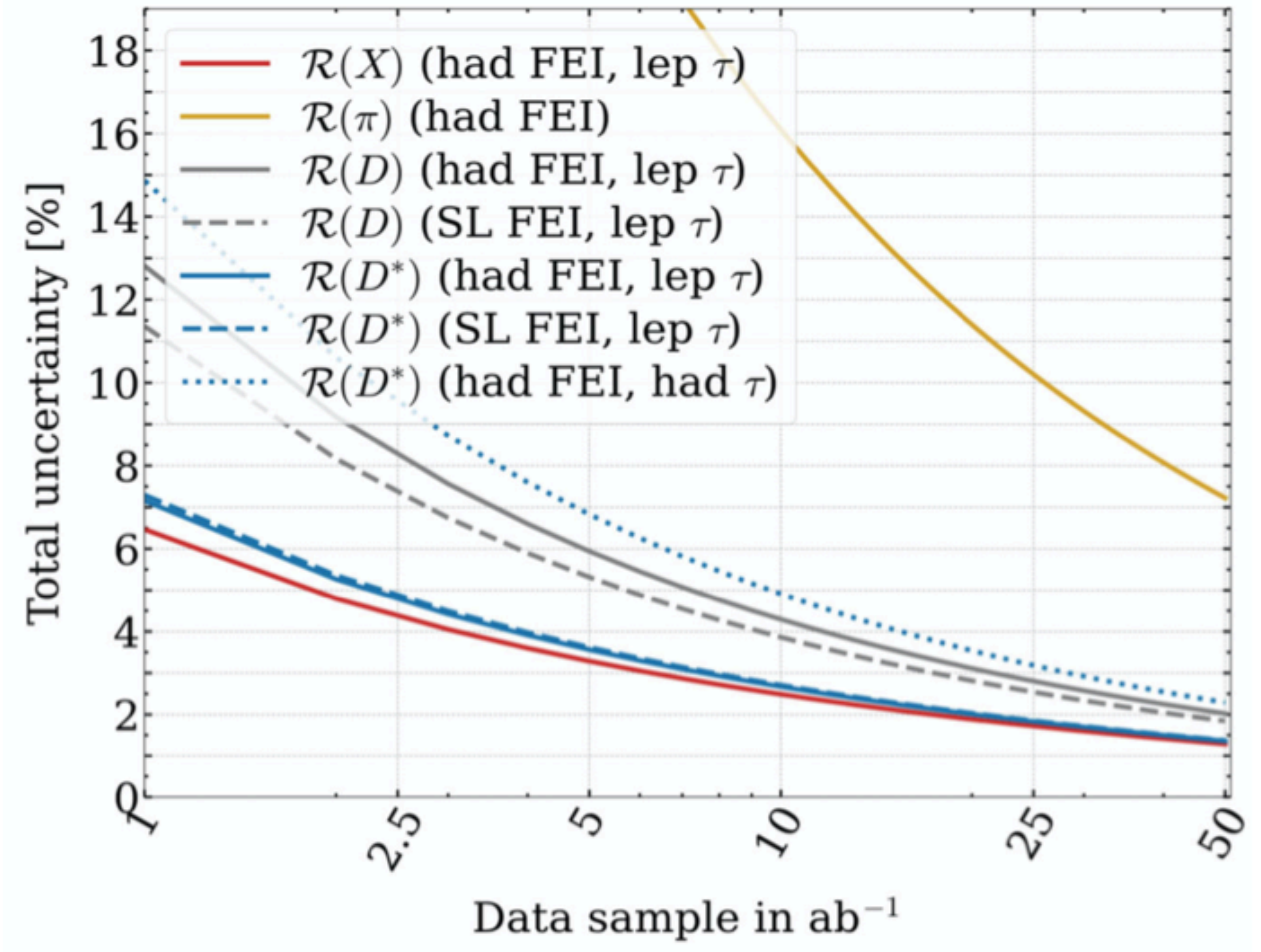
V_{ub} with $\bar{B}^0 \to \pi^+ \ell^- \bar{\nu}_\ell$



A_{CP} ($B^0 \to \pi^0 \pi^0$)



semitauonic R



- ➡ factional uncertainties below 3% are expected
- ➡ will double the global precision exclusive $|V_{ub}|$, also in absence of improvements in theoretical inputs
- ➡ with advances in LQCD we can do even better

- ➡ fundamental channel for the α/ϕ_2 determination, unique to *Belle II*
- ➡ can improve by one order of magnitude, as the main systematic (π^0 reconstruction efficiency) scales with statistics

- ➡ uncertainties on $R(D^{(*)})$ should be under 10% with few ab^{-1}
- ➡ inclusive R(X) measurements unique for Belle II will be performance with high accuracy
- ➡ possible additional observables: D^* and τ polarization

charm physics

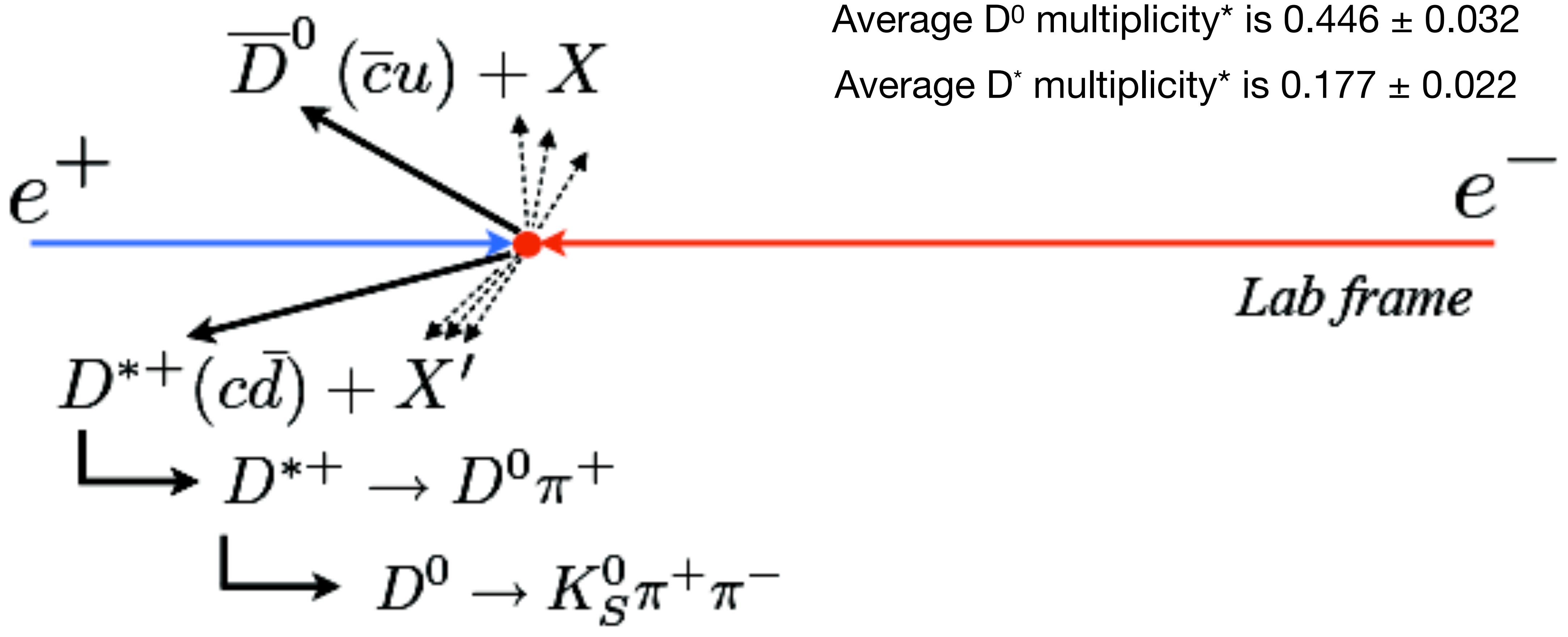
A Charm Event is Different

$e^+e^- \to c\bar{c} \to D_{\text{tag}} X_{\text{frag}} D_{\text{sig}}$

a brief picture

Average D⁰ multiplicity* is 0.446 ± 0.032

Average D* multiplicity* is 0.177 ± 0.022



➡ e^+e^- ➞ two charm hadrons + *fragmentation*

- no entanglement between the two charm hadrons, inaccessible strong phase between the two charm hadrons

➡ reconstruct the signal channel:

- D^0 flavour tagging: $D^{*+} \to D^0\pi^+$ decays, or exploiting the rest-of-the-event informations

(new for *Belle II*, coming soon!)

mixing & CPV

high-precision SM (e.g. lifetimes), searches of new states, D ➞ Vγ , …

➡ Full Charm Event Reconstruction, *similar* to B-physics exclusive reconstruction

- inclusive charm mesons & baryons samples to study (semi-)leptonic decays (missing energy), or to invisible, …

search of rare/forbidden decays, form factors & CKM elements

* per e^+e^- annihilation at $\sqrt{s}$ = 10 GeV

Charm Lifetimes

status & motivation

➡ Lifetimes measurements test non-perturbative QCD and provide guidance to describe strong interactions

- HQE used to determine heavy-quark hadron lifetimes as expansion in $1/m_q$ but the charm mass is not so heavy → the spectator quark contribution can't be neglected

➡ HQE predicted hierarchy of hadron lifetimes (<2018), disproved by LHCb Ω_c lifetime measurement*:

LHCb 2018

$$\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$$

➡ *Belle II* confirmed the new picture

- Λ_c & Ω_c lifetime measurement (200/fb)
- D^0 & D^+ lifetime measurement (72/fb)

(world best)

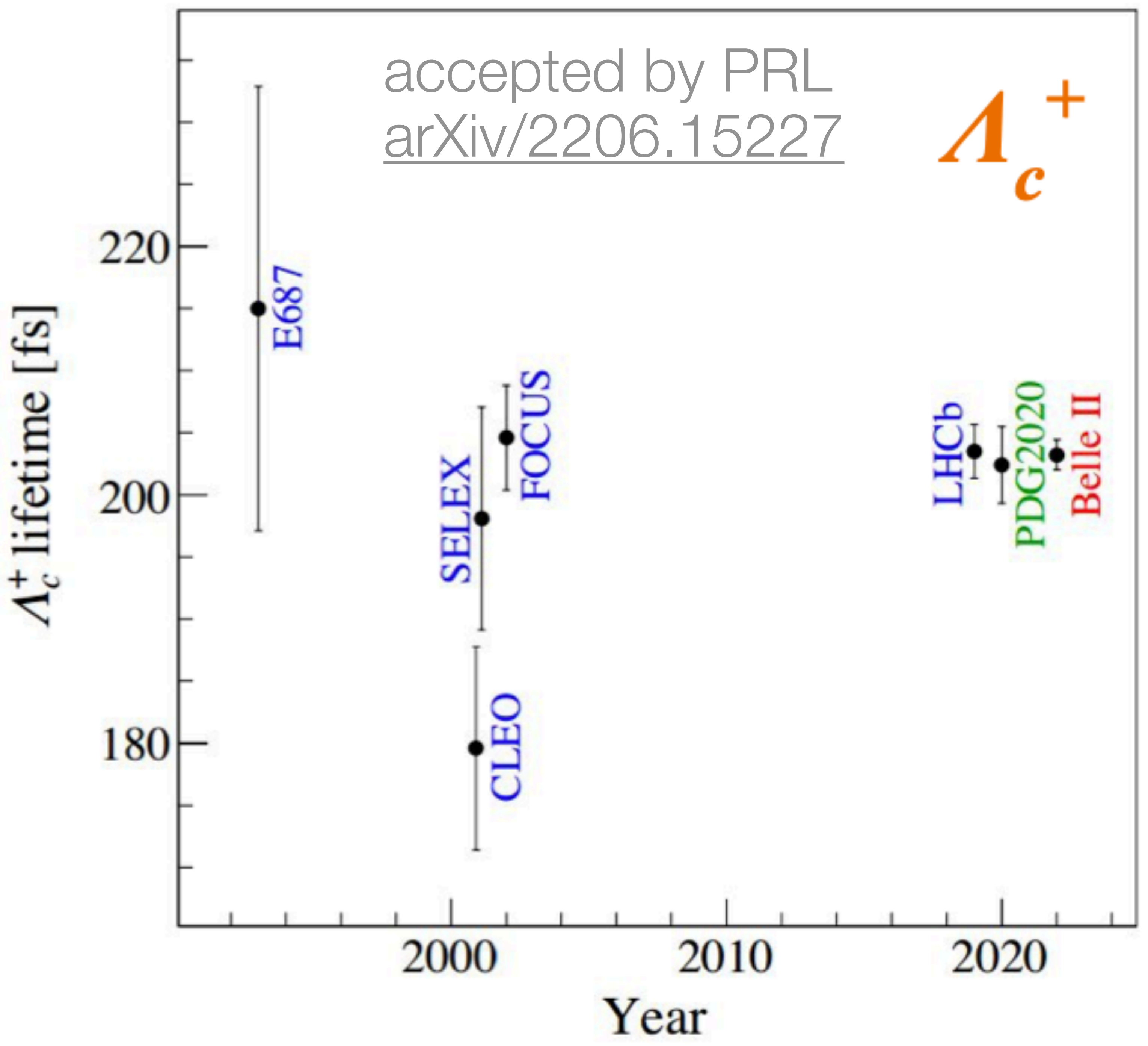
➡ interest in improving the precision on these SM measurements

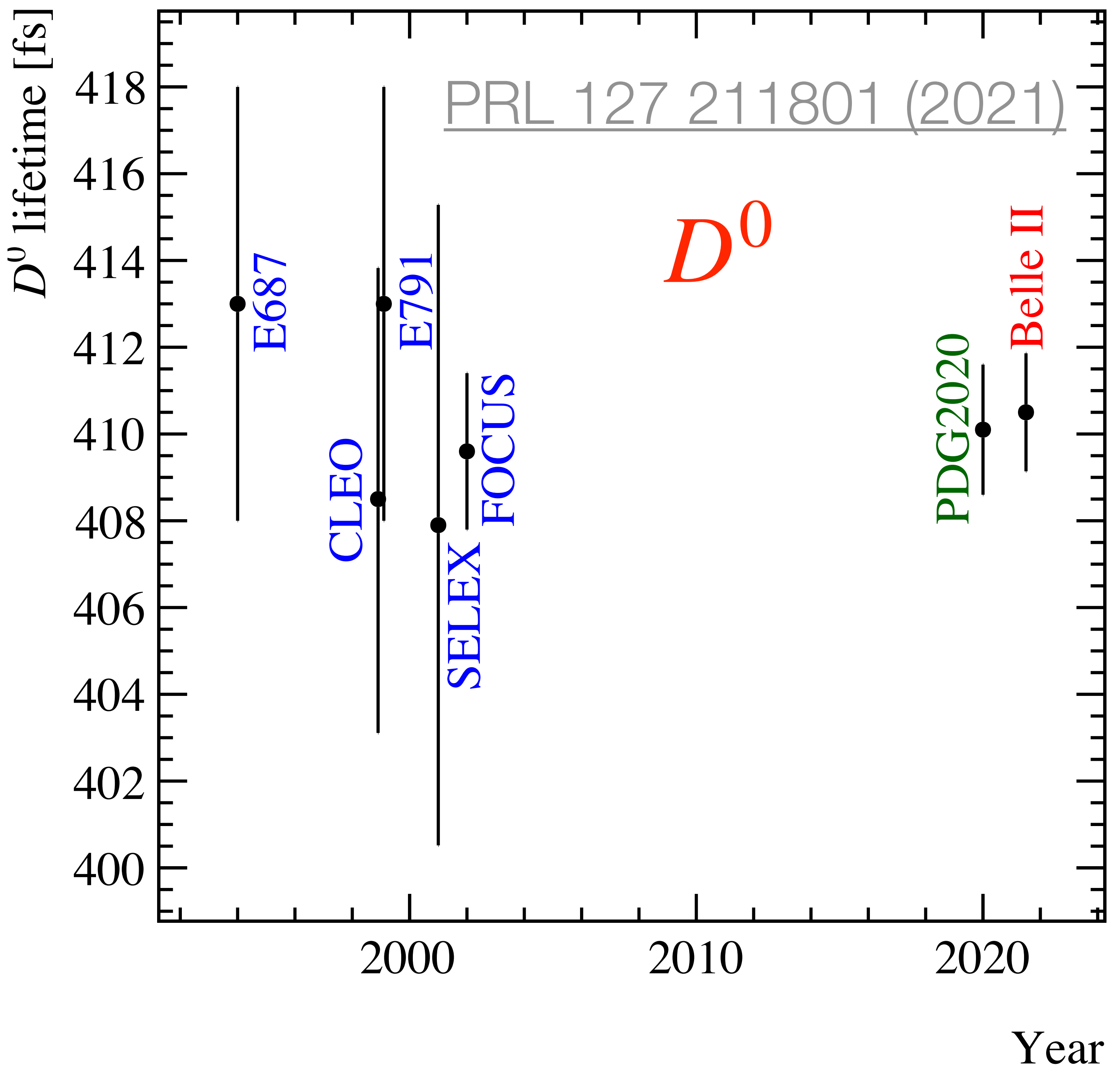
PRL, 121, 092003 (2018)

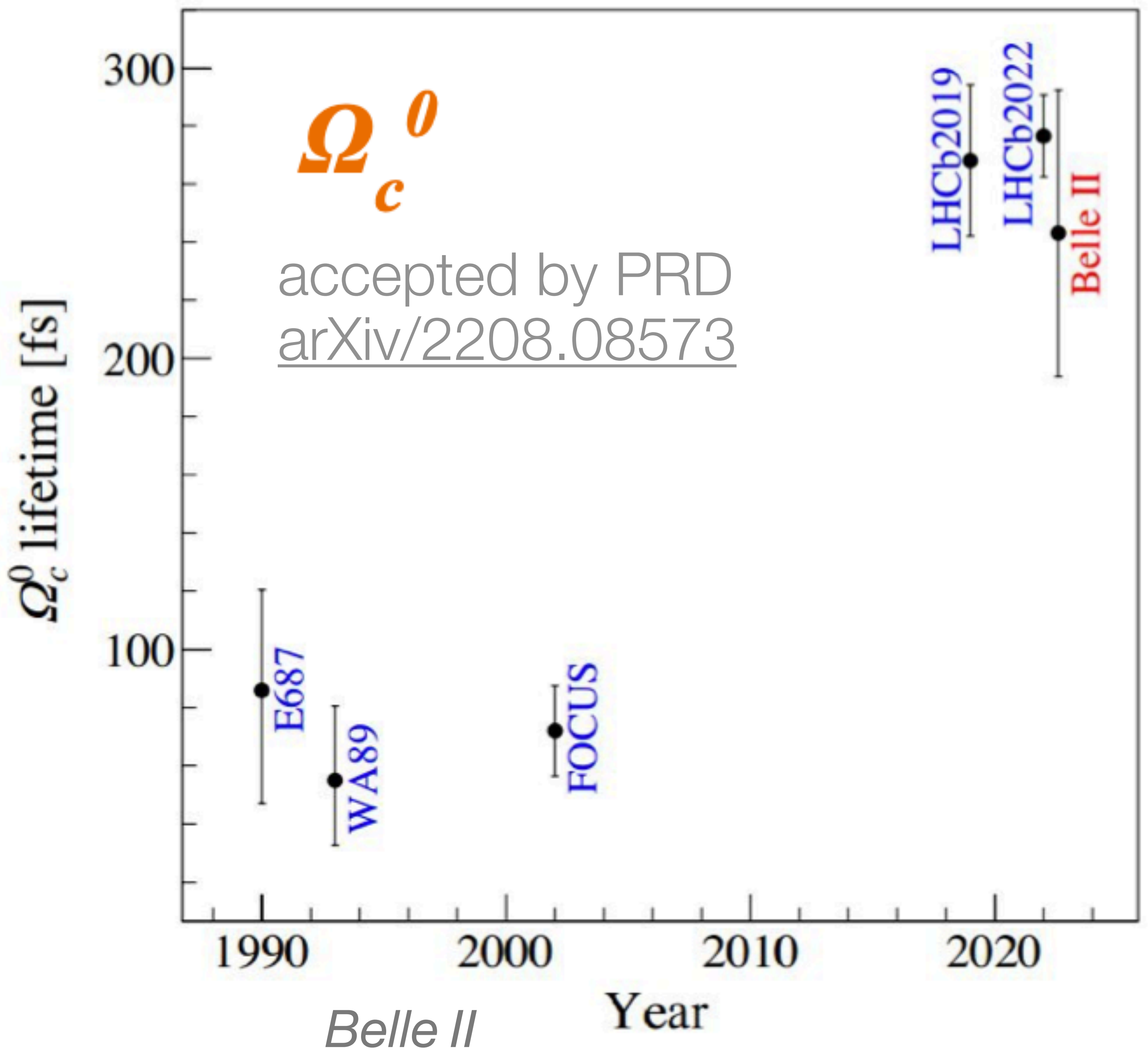
* $\Omega_c \to pKK\pi$ from semileptonic B decays

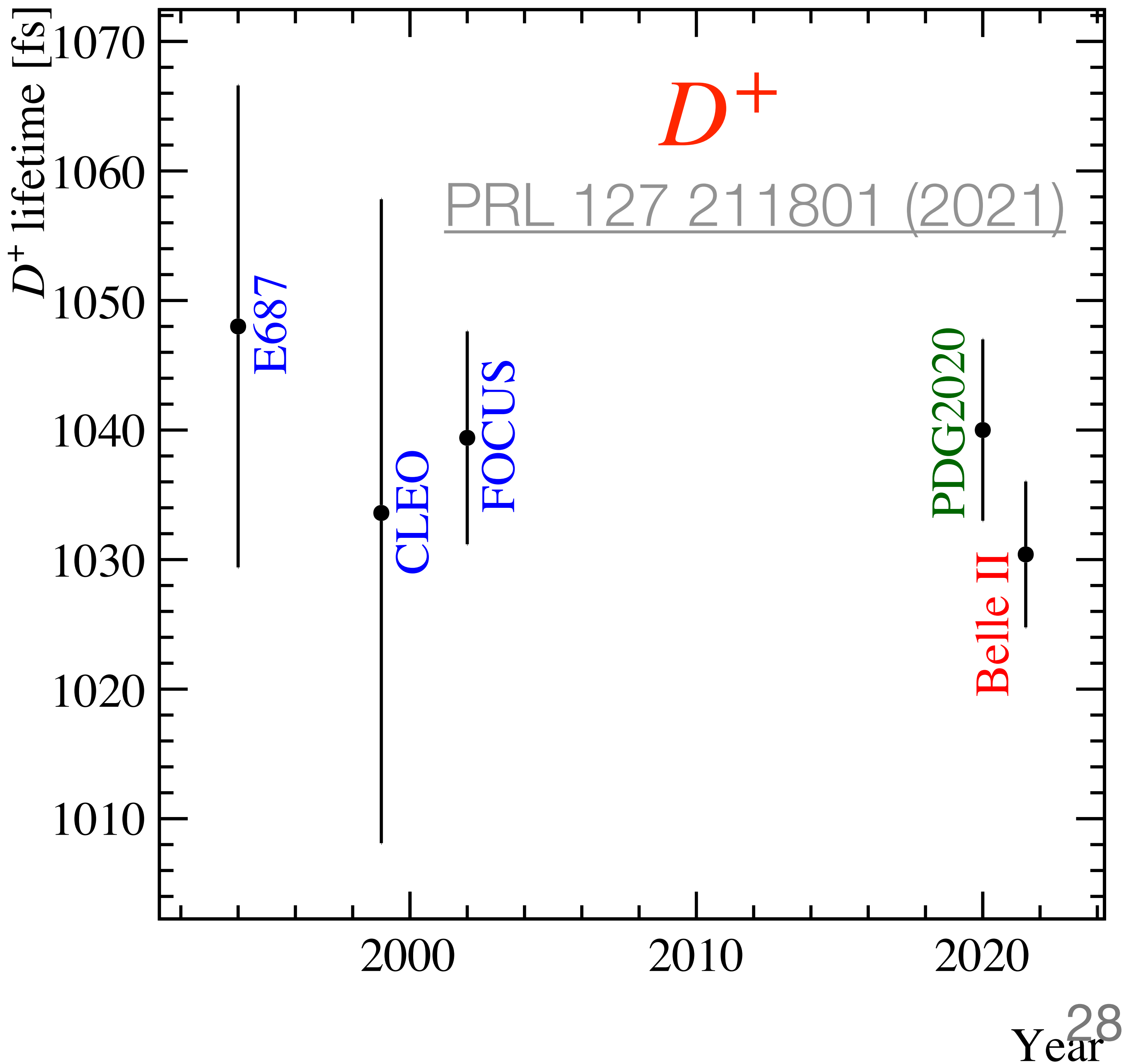
Results

- ➡ World's most precise measurements of the Λ_c (~200/fb), D^0 and D^+ lifetimes (72/fb)
- ➡ Lifetimes consistent with world averages (D^0, D^+, Λ_c) and with LHCb value (Ω_c).
- ➡ First lifetime measurements done at experiments at B-Factories
  - *Belle II* can do more than what Belle & *BABAR* have done
- ➡ Few per-mill accuracy establishes the excellent performance of our detector!









Prospects on Charm CPV

based on extrapolations from Belle analysis

$$A_{CP} = \frac{N(D) - N(\bar{D})}{N(D) + N(\bar{D})}$$

- Charm is unique to search for CPV in the up-type quark sector
  - D^0 is the only mixing system made of up-type quarks
- Measurement of A_{CP} in several channels are needed to overcome difficulties in the computation of SM predictions
  - e.g. use sum rules, estimating $SU(3)_F$ symmetry breaking effects (need A_{CP} and BR of $SU(3)_F$—connected channels)
- *Belle II* contribution will be important especially on neutrals in the final state
  - first measurements will be out soon!

Mode	$\mathcal{L}$ (fb^{-1})	A_{CP} (%)	Belle II 50 ab^{-1}
$D^0 \to K^+K^-$	976	$-0.32 \pm 0.21 \pm 0.09$	± 0.03
$D^0 \to \pi^+\pi^-$	976	$+0.55 \pm 0.36 \pm 0.09$	± 0.05
$D^0 \to \pi^0\pi^0$	966	$-0.03 \pm 0.64 \pm 0.10$	± 0.09
$D^0 \to K^0_S\pi^0$	966	$-0.21 \pm 0.16 \pm 0.07$	± 0.02
$D^0 \to K^0_S K^0_S$	921	$-0.02 \pm 1.53 \pm 0.02 \pm 0.17$	± 0.23
$D^0 \to K^0_S\eta$	791	$+0.54 \pm 0.51 \pm 0.16$	± 0.07
$D^0 \to K^0_S\eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	± 0.09
$D^0 \to \pi^+\pi^-\pi^0$	532	$+0.43 \pm 1.30$	± 0.13
$D^0 \to K^+\pi^-\pi^0$	281	-0.60 ± 5.30	± 0.40
$D^0 \to K^+\pi^-\pi^+\pi^-$	281	-1.80 ± 4.40	± 0.33
$D^+ \to \phi\pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	± 0.04
$D^+ \to \pi^+\pi^0$	921	$+2.31 \pm 1.24 \pm 0.23$	± 0.17
$D^+ \to \eta\pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	± 0.14
$D^+ \to \eta'\pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	± 0.14
$D^+ \to K^0_S\pi^+$	977	$-0.36 \pm 0.09 \pm 0.07$	± 0.02
$D^+ \to K^0_S K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	± 0.04
$D^+_s \to K^0_S\pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	± 0.29
$D^+_s \to K^0_S K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.05

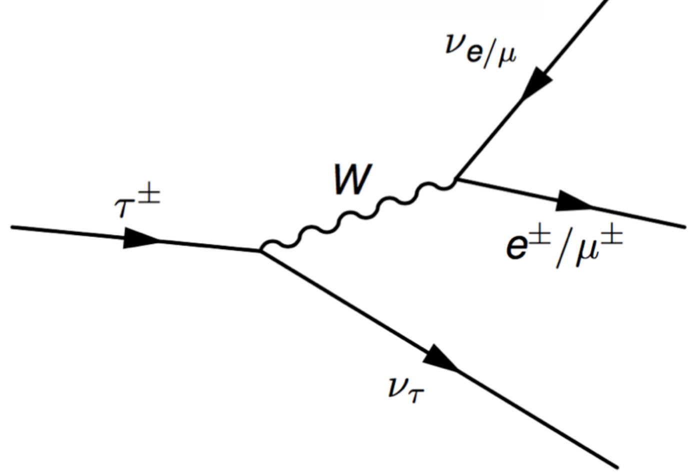
$D^+_s \to K^+\pi^0$

note: this is not a complete list

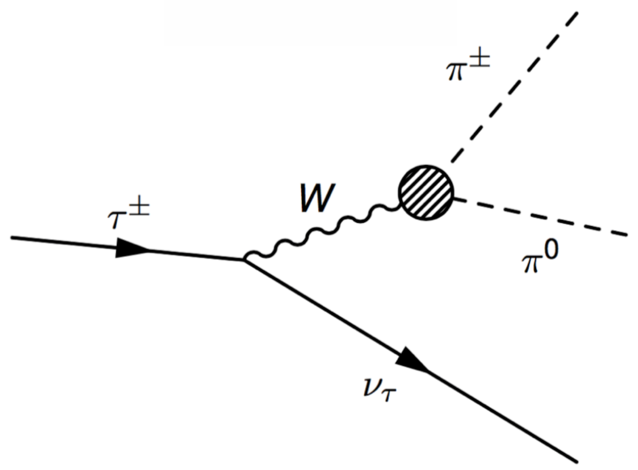
τ physics

τ Physics
at Belle II

Leptonic: 2ν



Hadronic: 1ν



➡ rich program of high-precision measurements:

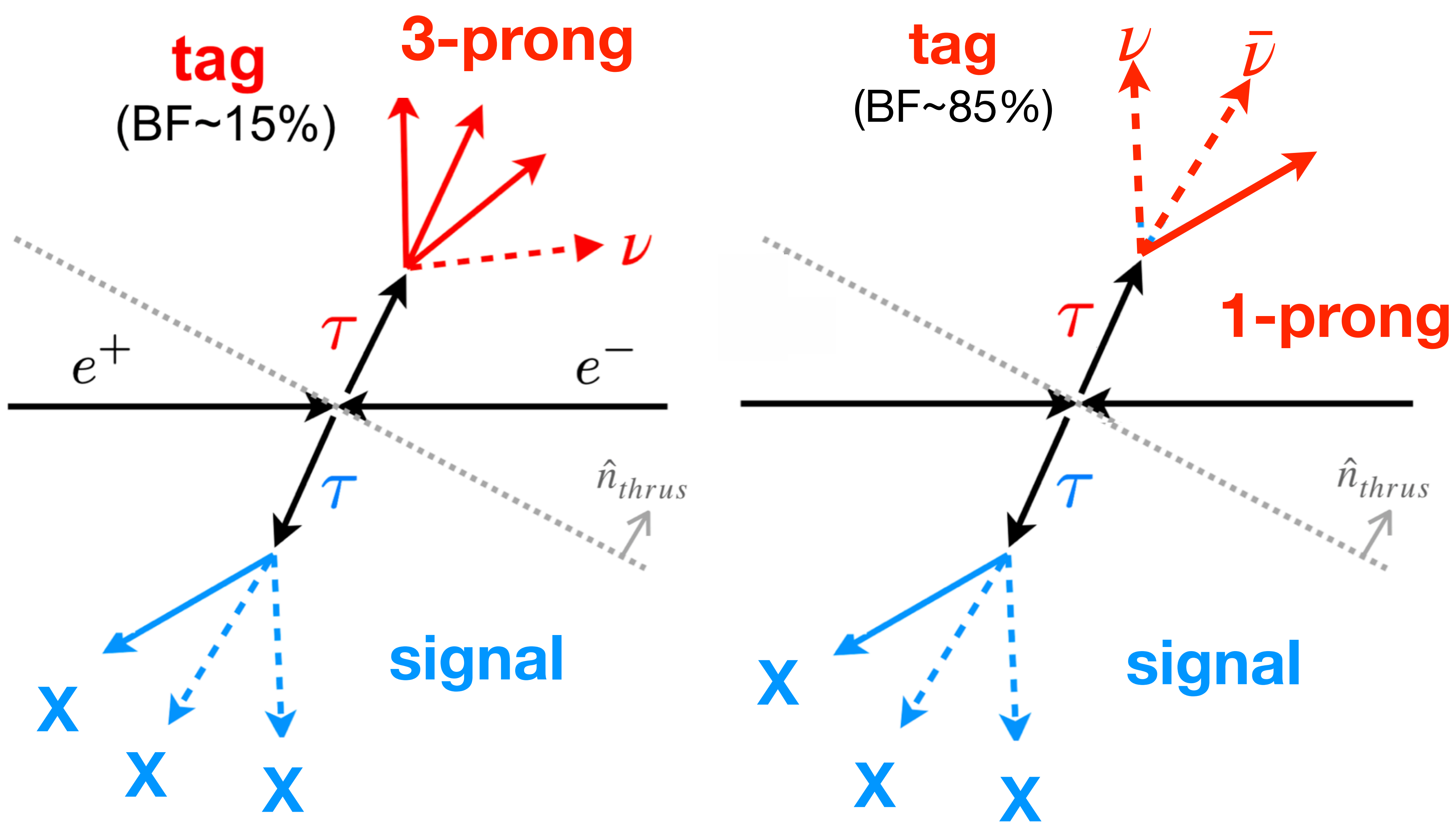
- lifetime & mass (SM)
- V_{us}, CP asymmetries e.g. $\tau \to K_S\pi\nu$
- LFV searches & LFU tests

➡ main advantages of studying τ (and dark matter) physics at *Belle II*

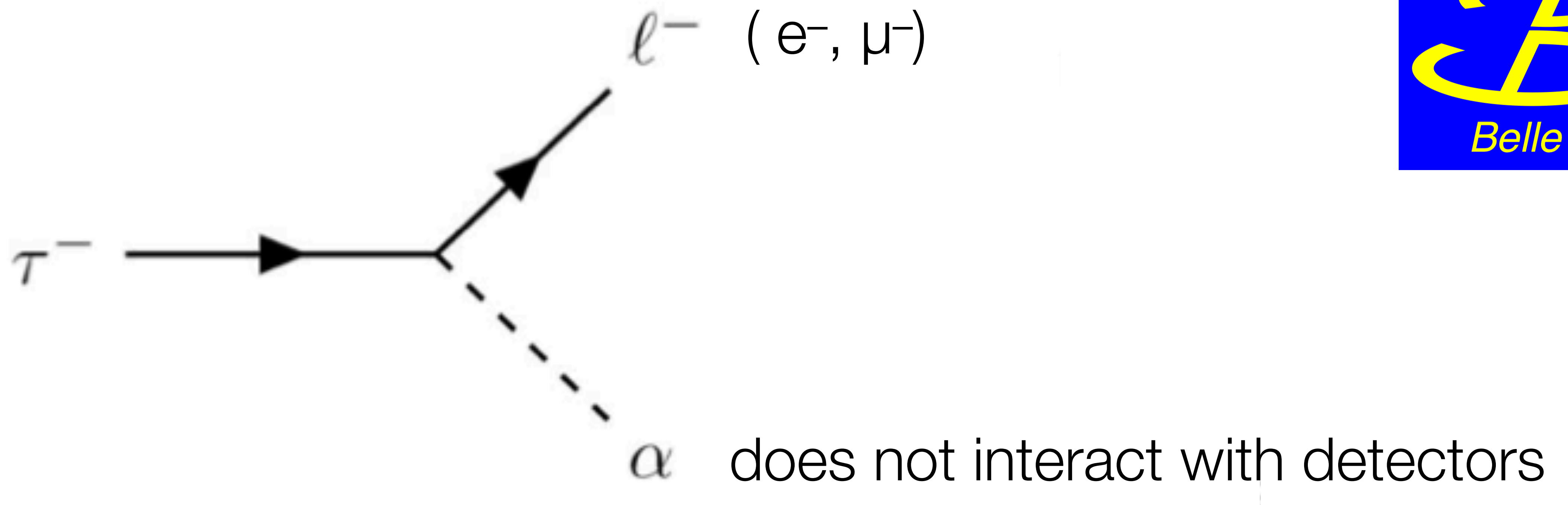
- well defined initial state energy & clean environment
- high hermiticity of the detector & precise knowledge of acceptance and efficiency
- dedicated low-multiplicity triggers lines

➡ τ events are classified by the of number of tracks in the final state:

- 1-prong: 50% from hadronic decays, 35% of leptonic decays
- 3-prong: 15%, from hadronic decays



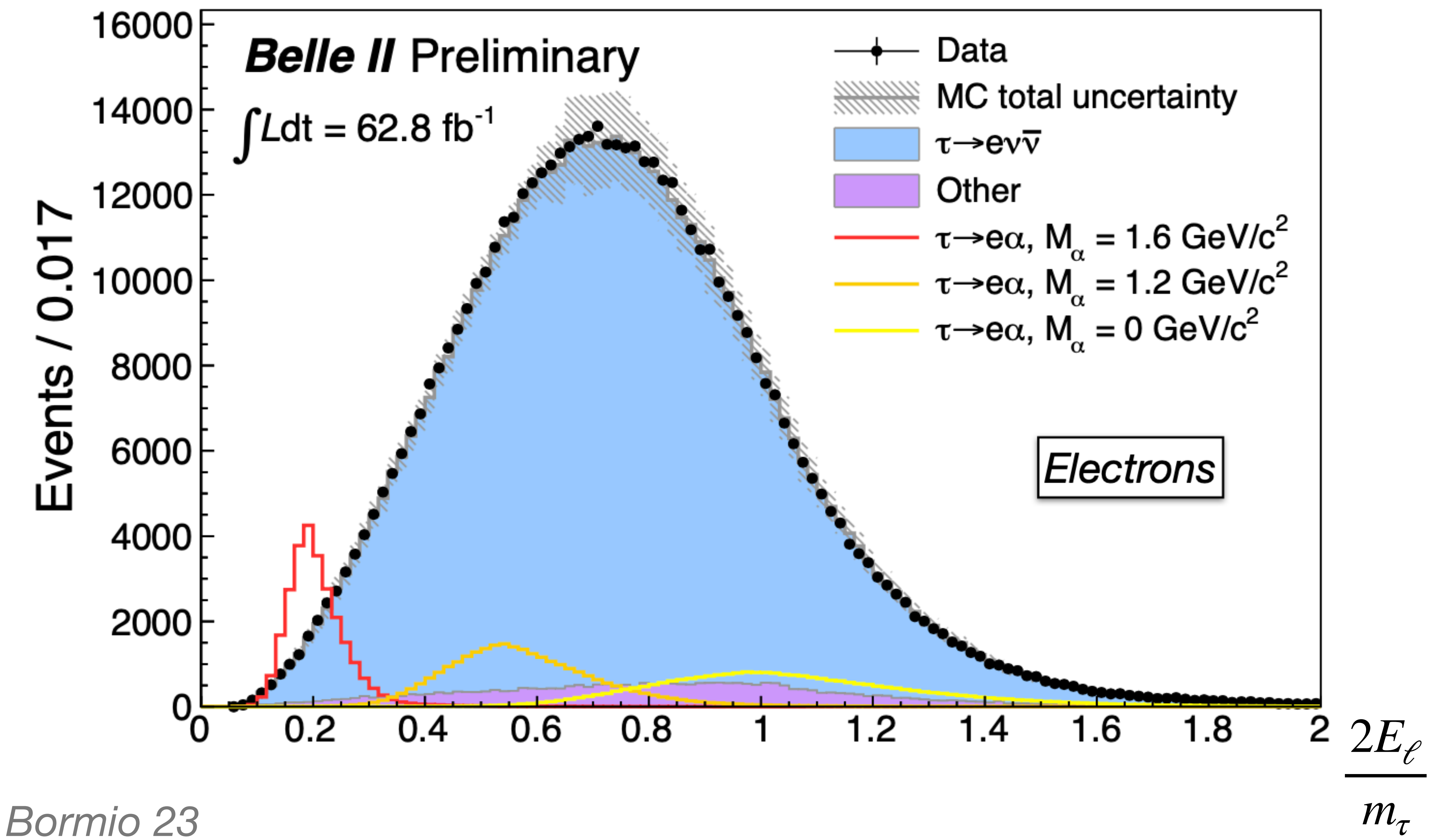
$\tau \to \ell\, \alpha$ (invisible)

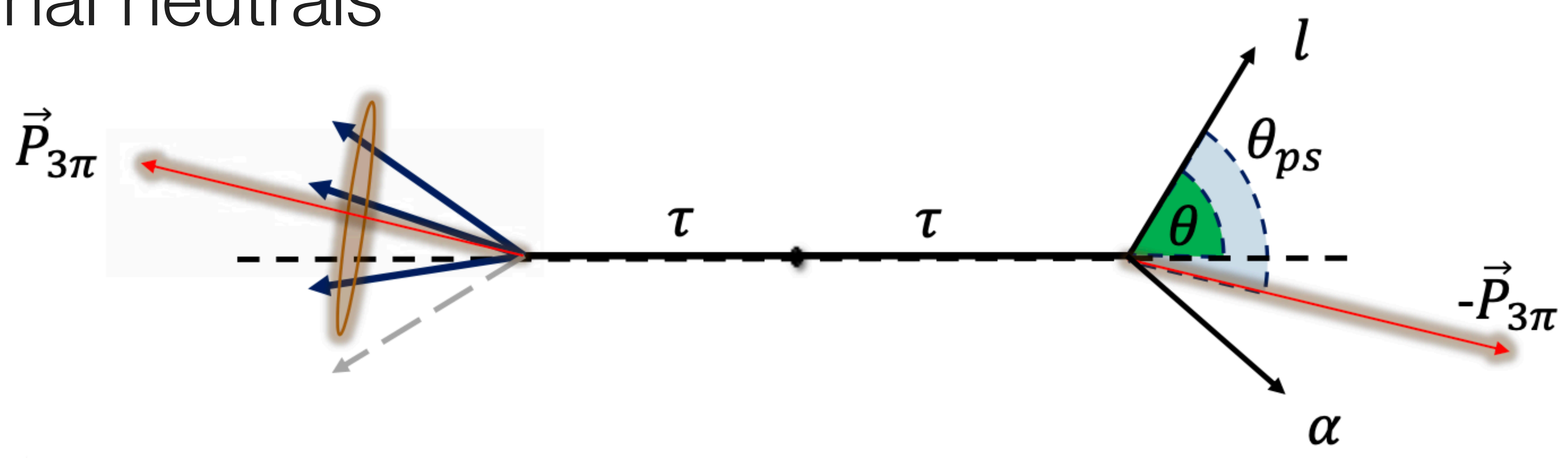


➡ Neutrino-less LFV decays are sensitive probes of New Physics

- e.g. long-lived ALPs or LFV Z'

➡ require 1x3 prong event topology, veto additional neutrals





➡ SM background $\tau \to \ell\nu\nu$ but lepton is mono-energetic in the τ rest frame

- τ rest frame *approximated* using the 3 tracks in the tag side

➡ look for a bump in the lepton energy spectrum

$\tau \to \ell\ \alpha$ (invisible)

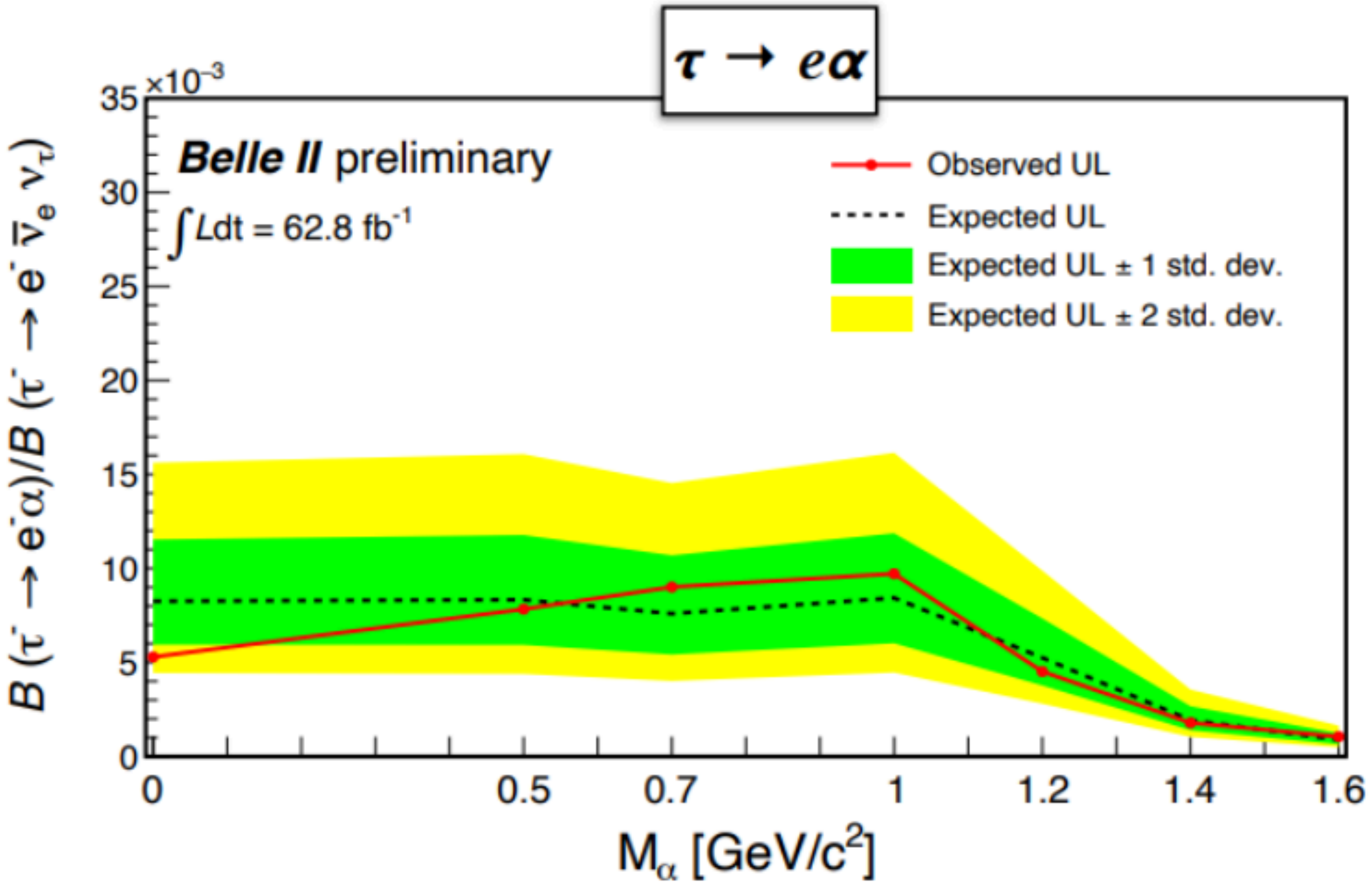
results

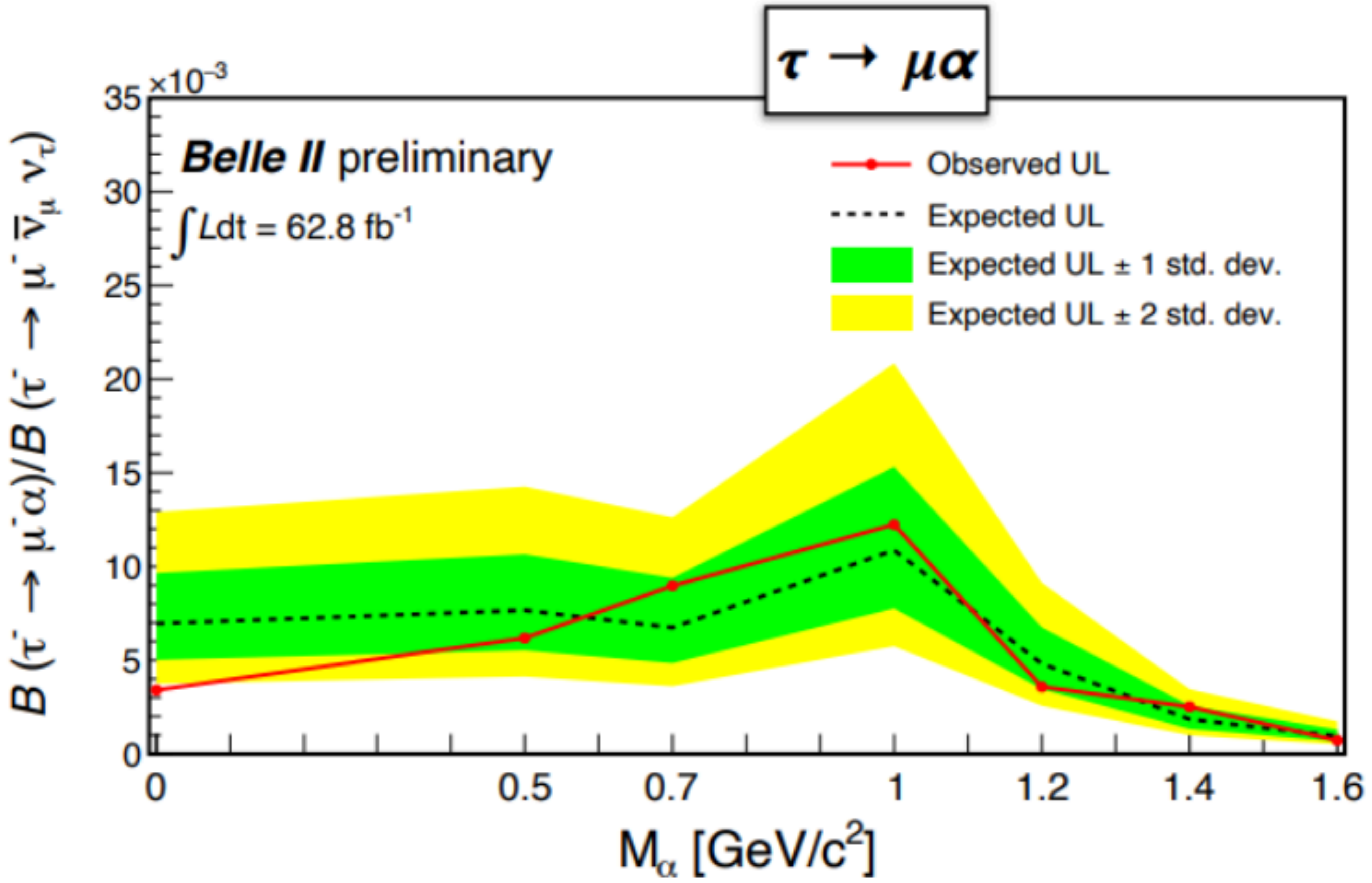
submitted to PRL
arXiv/2212.03634

➡ no significant excess observed → set 95% CL upper limits on $\dfrac{\mathscr{B}(\tau^- \to \ell^-\alpha)}{\mathscr{B}(\tau^- \to \ell^-\nu\bar{\nu})}$

- previous measurement by ARGUS with 0.5/fb

Z. Phys. C 68 (1995) 25



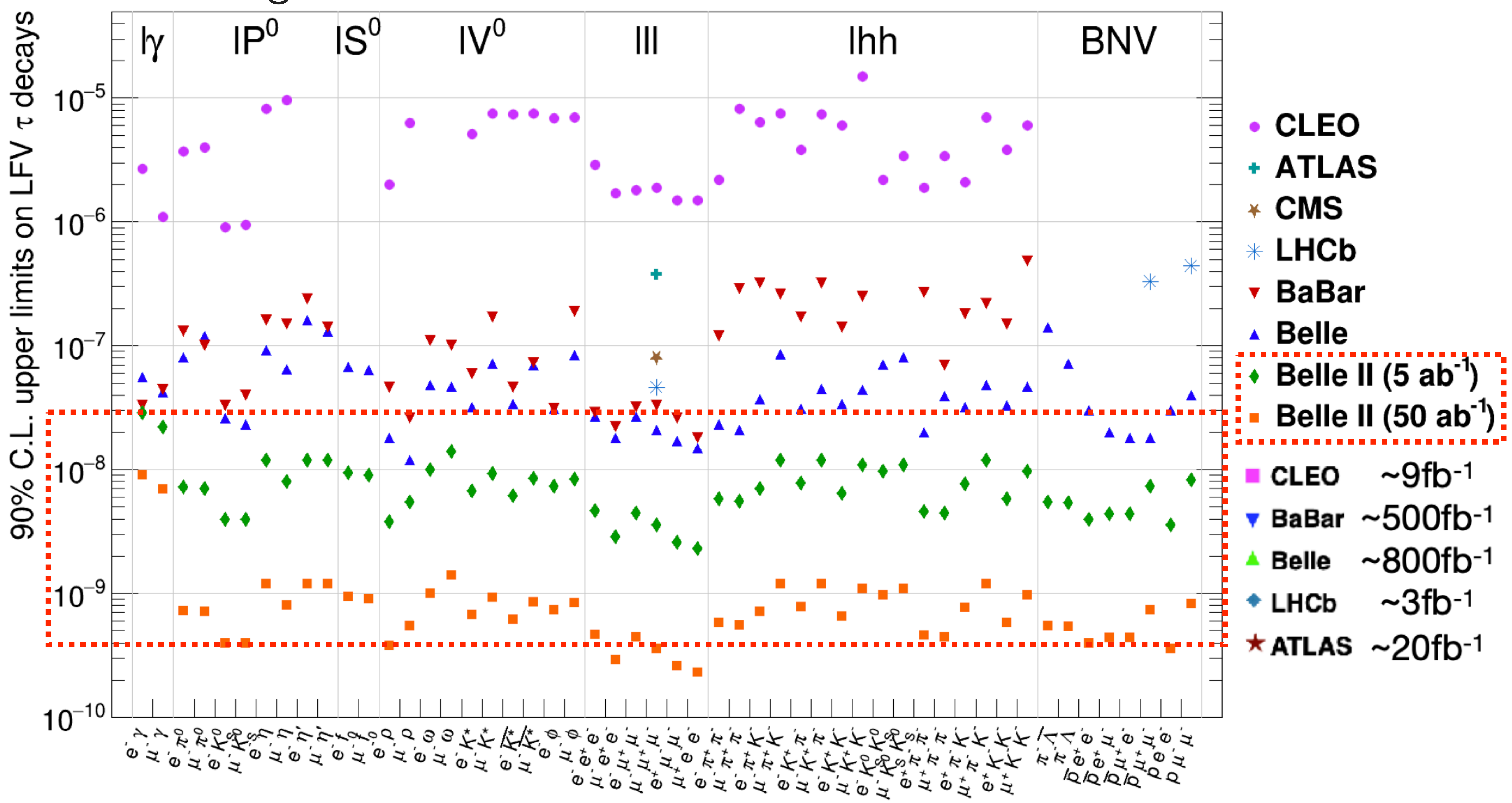


➡ most stringent limits in these channels to date

Program for LFV searches in τ decays

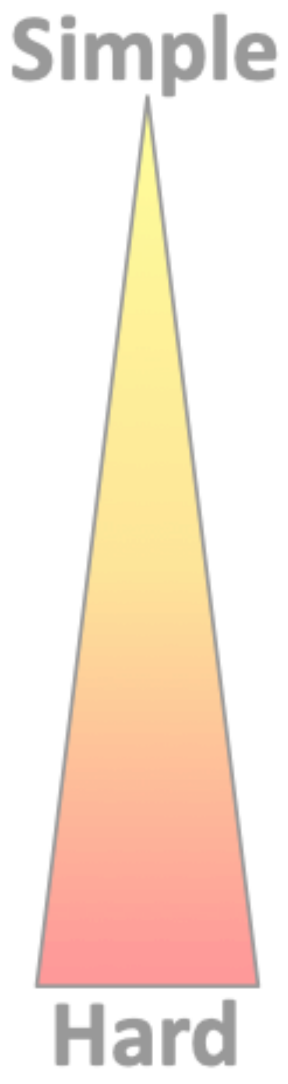
- ➡ Charged LFV is allowed in various extensions of the SM but it was never observed
  - many channels accessible (only) at *Belle II*

existing limits + *Belle II* reach



difficulty of bkg reduction

- $\tau \to \ell\ell\ell$
- $\tau \to \ell K_s, \Lambda h$
- $\tau \to \ell V_0(\to hh')$
- $\tau \to \ell P^0\ (\to \gamma\gamma)$
- $\tau \to \ell hh'$
- $\tau \to \ell\gamma$



Physics models	$B(\tau \to \mu\gamma)$	$B(\tau \to \mu\mu\mu)$
SM + ν mixing	$10^{-49} \sim 10^{-52}$	$10^{-53} \sim 10^{-56}$ [1]
SM+heavy Majorana ν_R	10^{-9}	10^{-10}
Non-universal Z'	10^{-9}	10^{-8}
SUSY SO(10)	10^{-8}	10^{-10}
mSUGRA + seesaw	10^{-7}	10^{-9}
SUSY Higgs	10^{-10}	10^{-7}

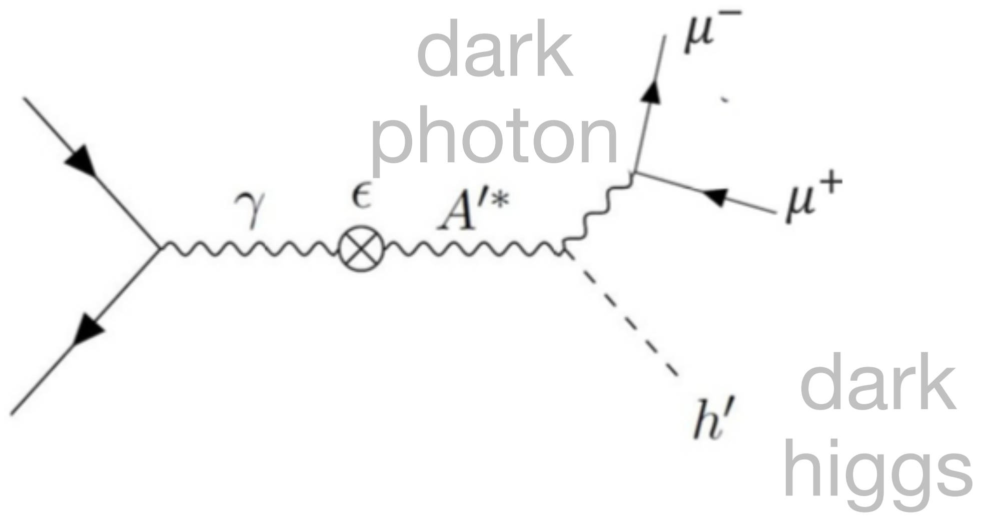
Ref: M. Blanke, et al., Charged Lepton Flavour Violation and (g – 2)μ in the Littlest Higgs Model with T-Parity: a clear Distinction from Supersymmetry, JHEP 0705, 013 (2007).

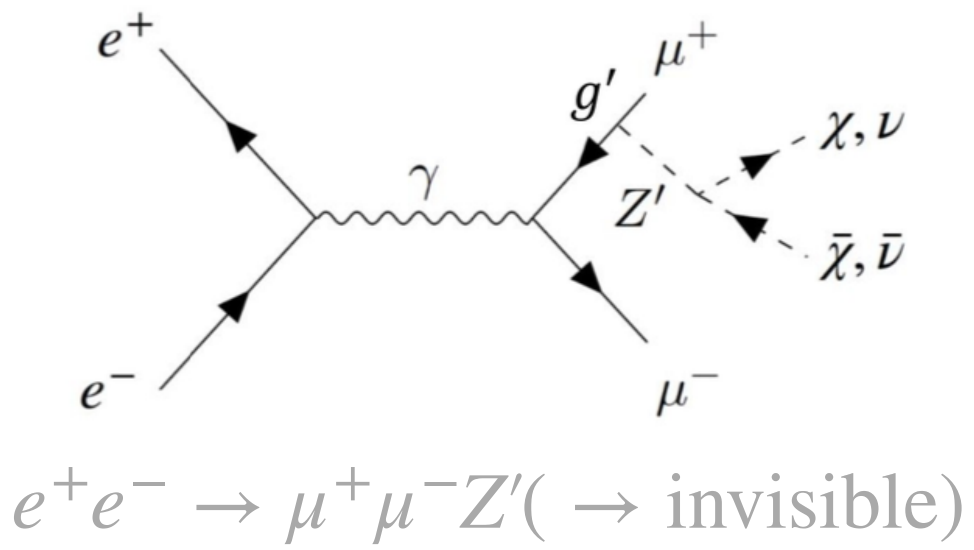
dark sector physics

Dark Sector

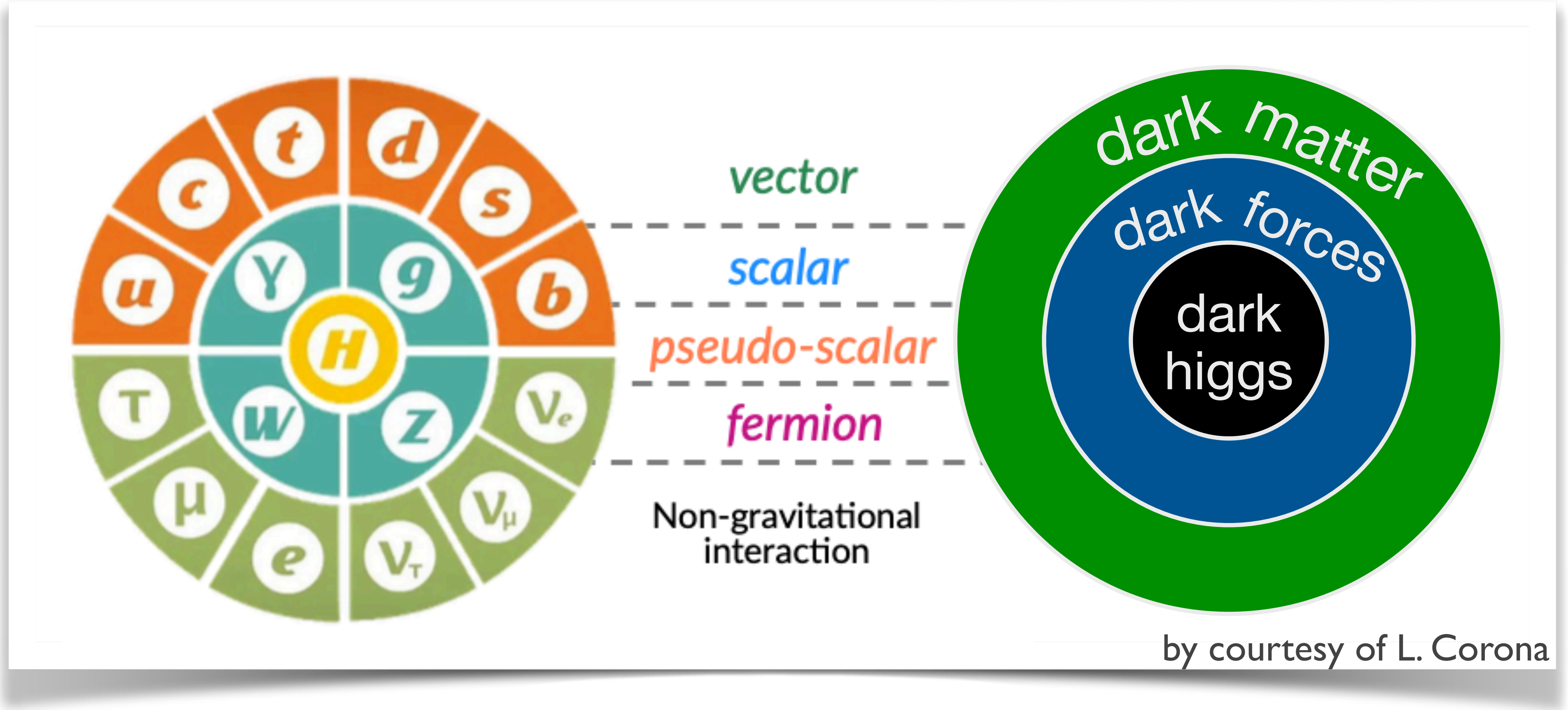
search for (light) Dark Bosons & Dark Matter

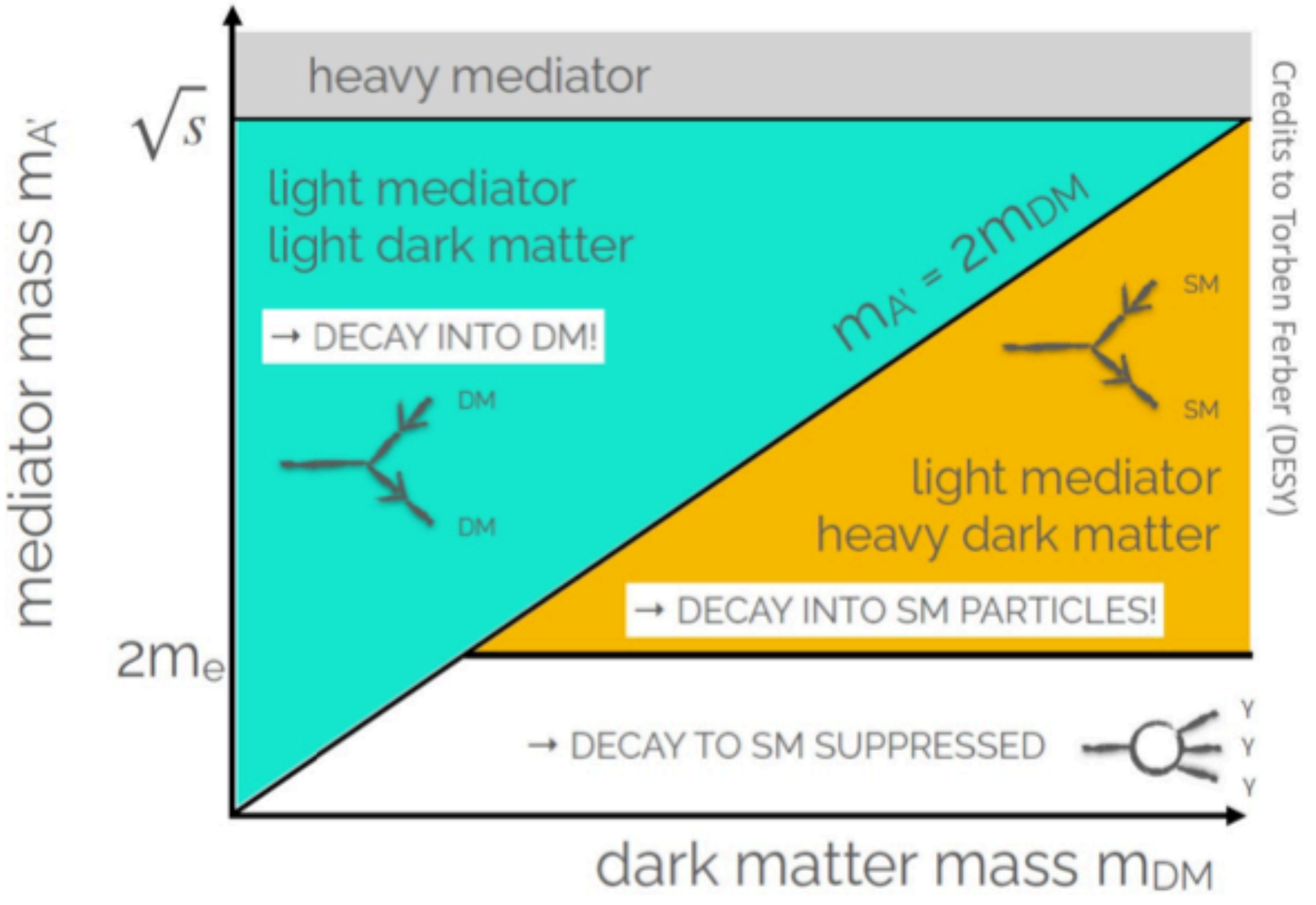
- ➡ light DM with masses $\mathcal{O}$(MeV-GeV) can be searched at *Belle II*
  - interest for models with low-mass dark matter candidates growing after null searches @ LHC & direct searches
  - theoretical models predict light mediators that couples DM to SM particles





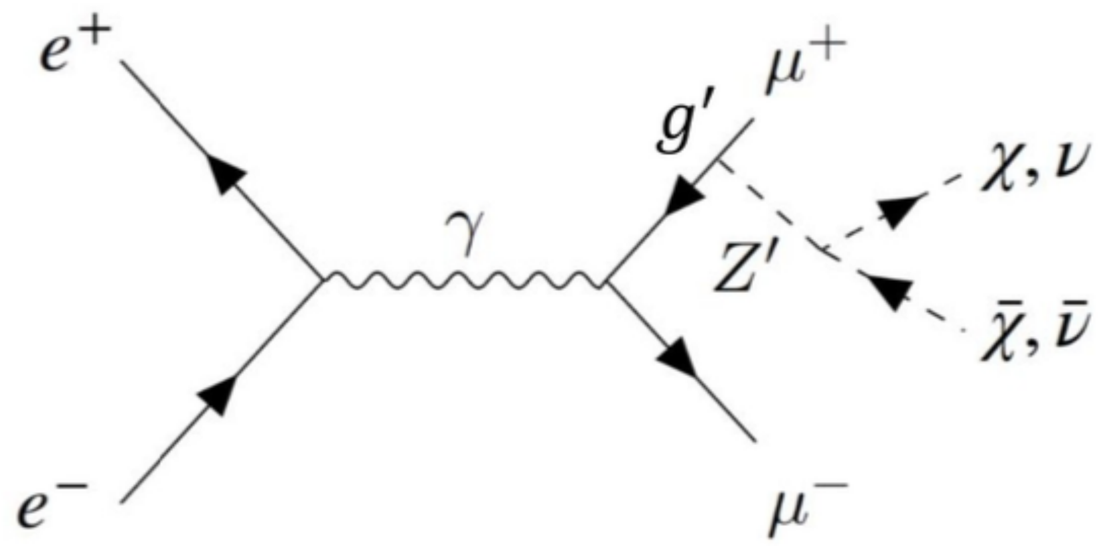
- ➡ The main challenge at *Belle II* is to suppress the large SM background, saving the signal
  - dedicated low-multiplicity triggers
  - precise knowledge of acceptance and efficiency





submitted to PRL
arXiv/2212.03066

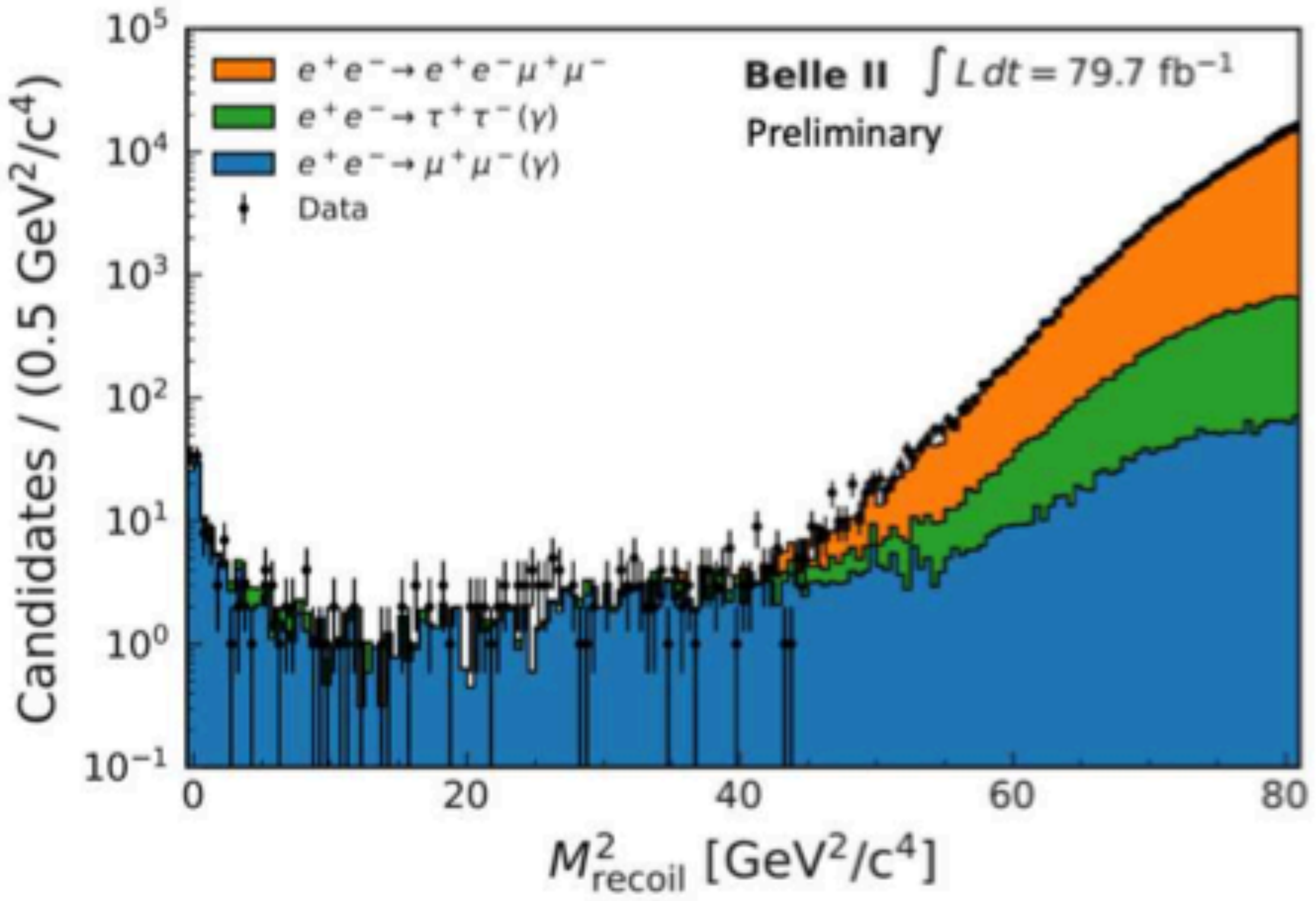
Z’ → Invisibile



➡ L_μ-L_τ gauge boson Z’ could explain $(g\text{-}2)_\mu$ and other flavour anomalies

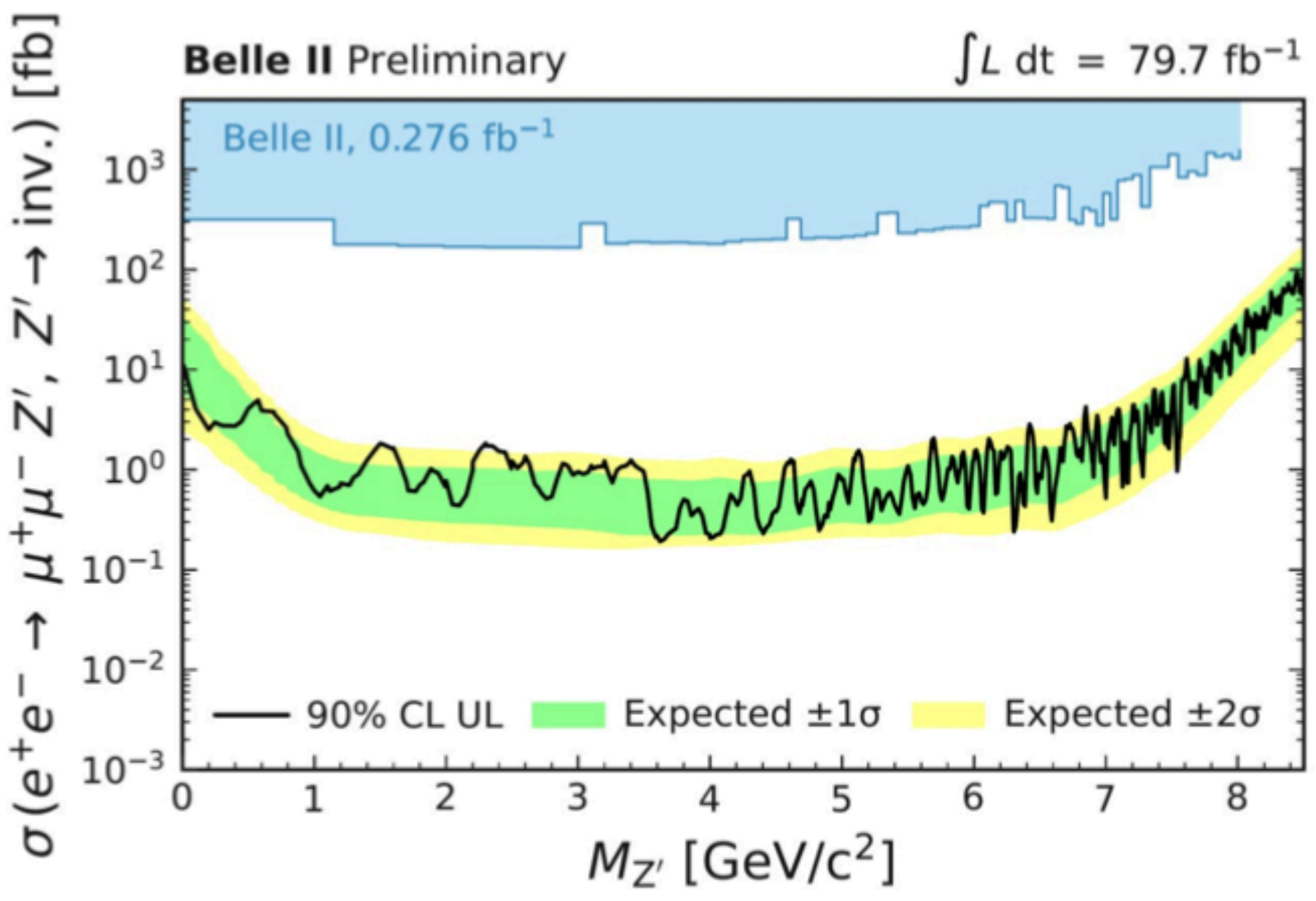
➡ we search for $e^+e^- \to \mu^+\mu^-$ + missing energy

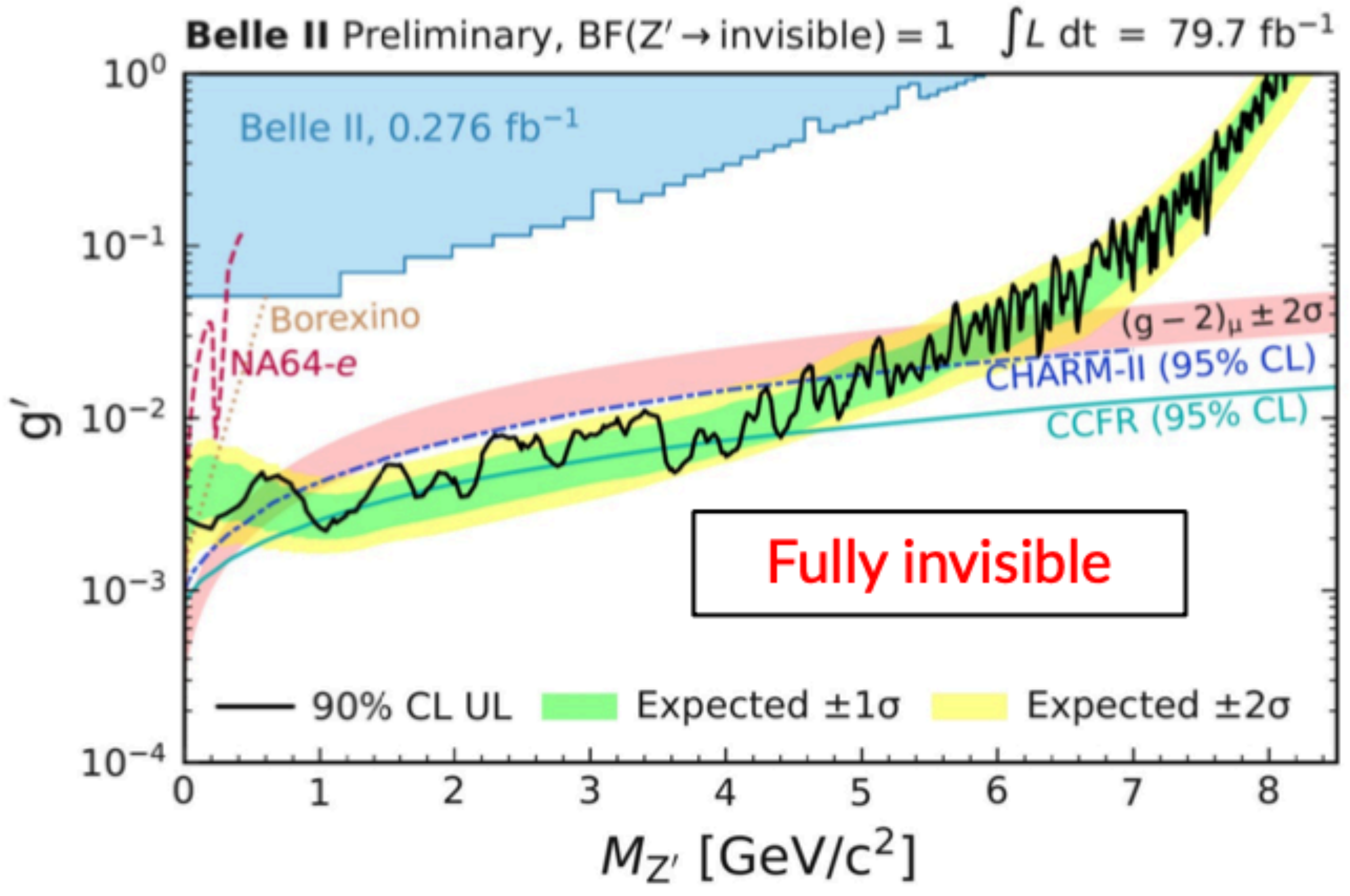
- Z’ searched in the recoil mass of the di-muon system
- high-suppression of SM backgrounds



➡ no excess was found

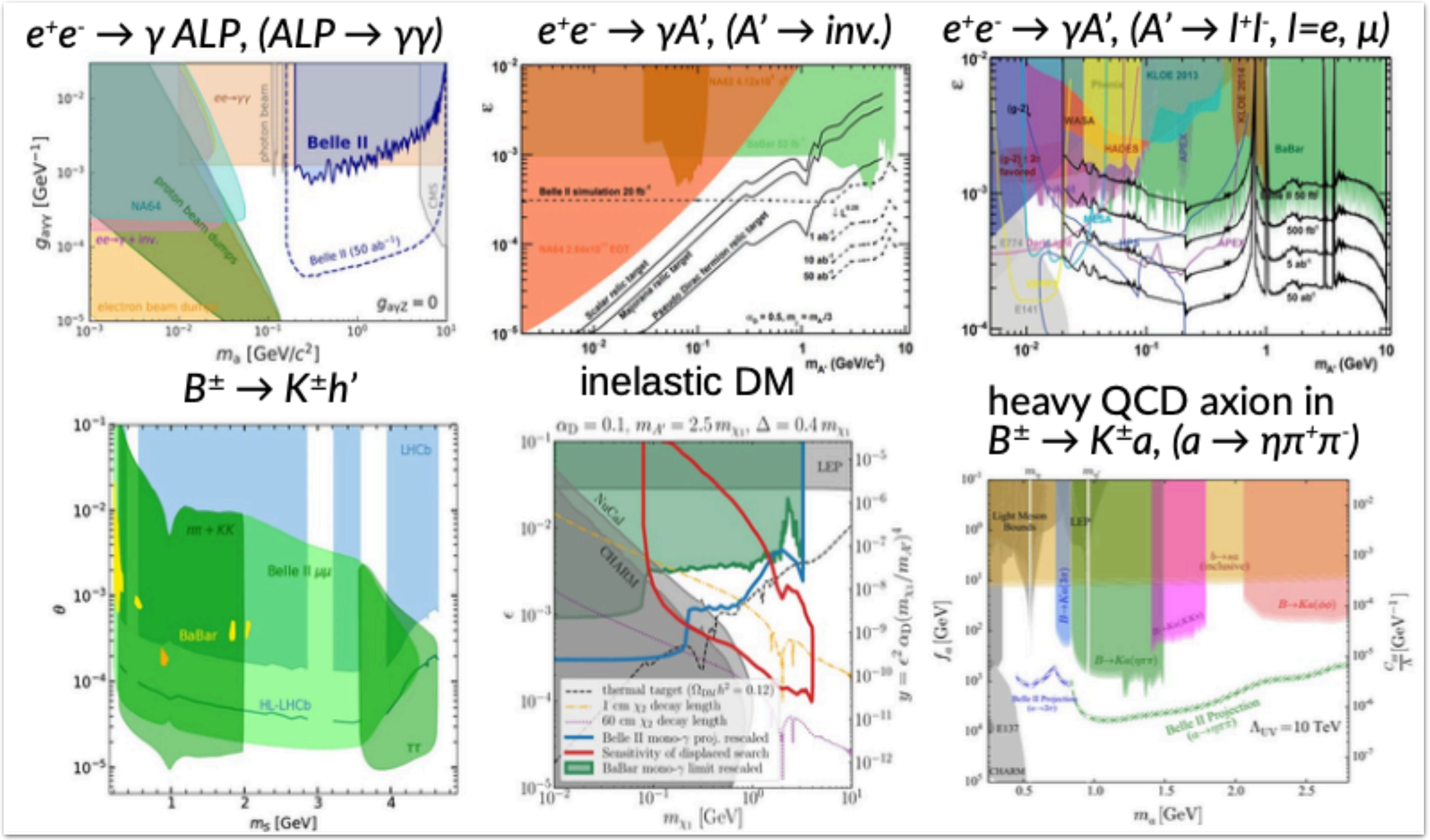
- set 90% CL limits
- fully invisible means BR(Z’ → invisible) = 1
- most stringent limits to date





Dark Matter Prospects

- several world leading results:
  - Z' → invisible (PRL 124 141801, 2020) now superseded by 2022 result
  - ALP → γγ   PRL 125 161806 (2020)
  - Z', ALP, S → ττ (to be submitted to PRL)
  - dark higgs → invisible accepted by PRL arXiv/2207.00509
- and many other searches ongoing

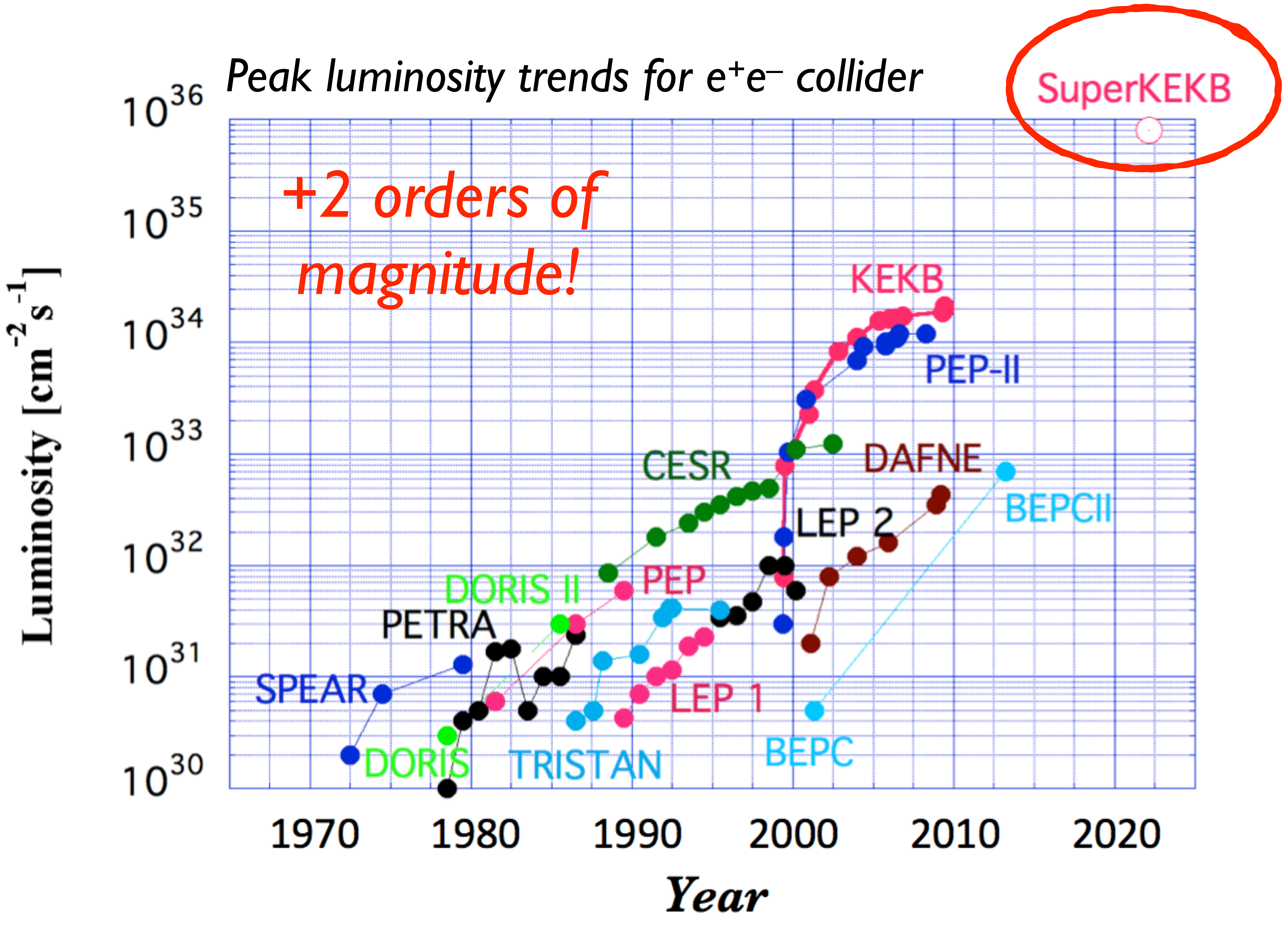


Conclusions

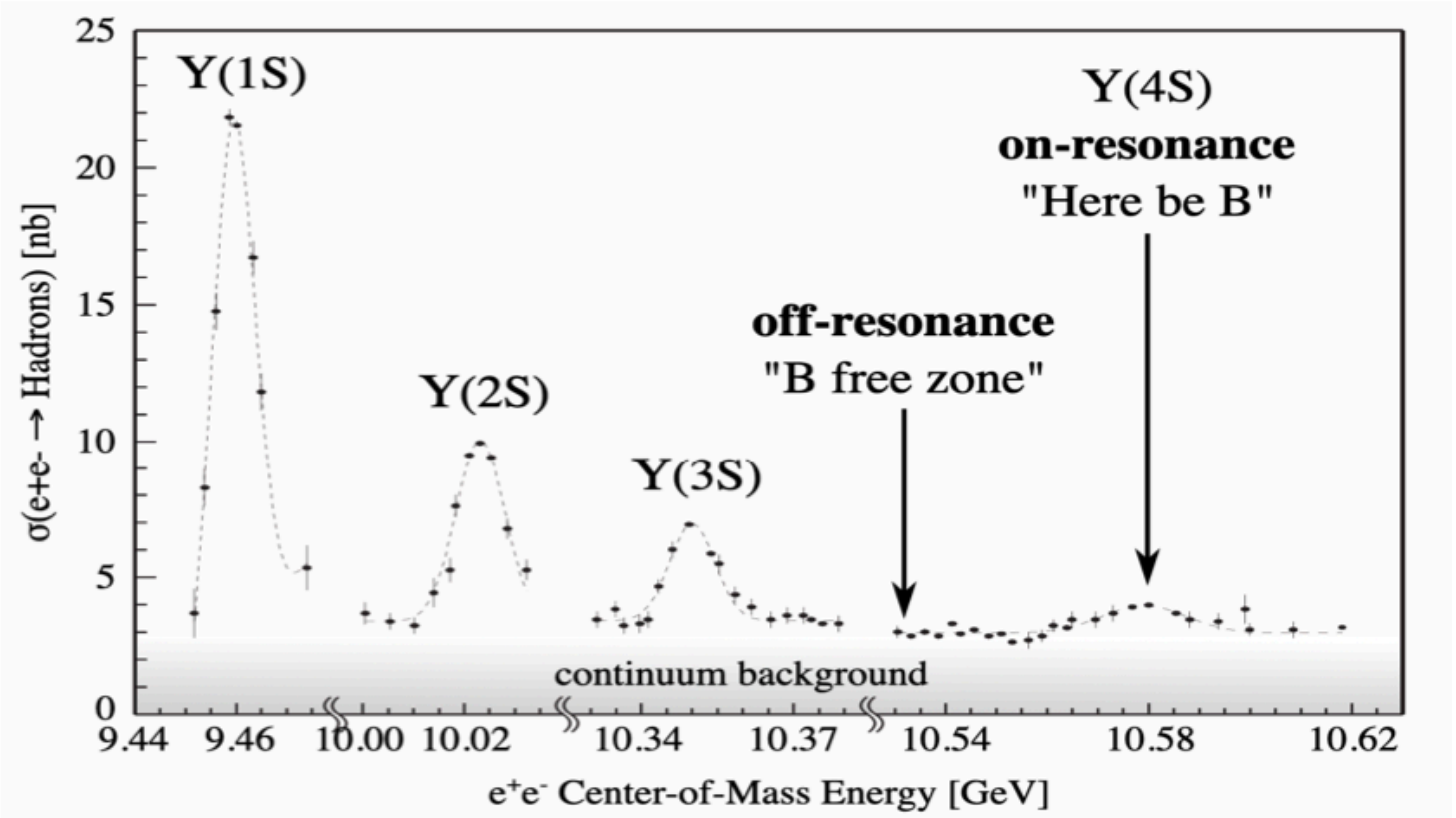
- ➡ *Belle II* physics program is very broad, I discussed just a small fraction of it!
  - B, charm, τ, dark matter (…) physics
- ➡ First results confirm the very good detector performance & status of our tools: we are ready for the NP search!
- ➡ Innovative analysis & reconstruction techniques (wrt 1st generation B-Factories) will push our precision *beyond* the increase of luminosity
- ➡ Even with a data sample smaller than that of *BABAR* and Belle we produced world leading measurements
  - charm lifetimes, $R(X_{e/\mu})$, upper limits on Z' → invisible & $\tau \to \ell\, \alpha$, …

Thank you for your attention.

backup slides



Peak luminosity trends for e⁺e⁻ collider
SuperKEKB
+2 orders of magnitude!
KEKB
PEP-II
CESR
DAFNE
LEP 2
BEPCII
DORIS II
PEP
PETRA
SPEAR
LEP 1
DORIS
TRISTAN
BEPC
Luminosity [cm⁻² s⁻¹]
Year



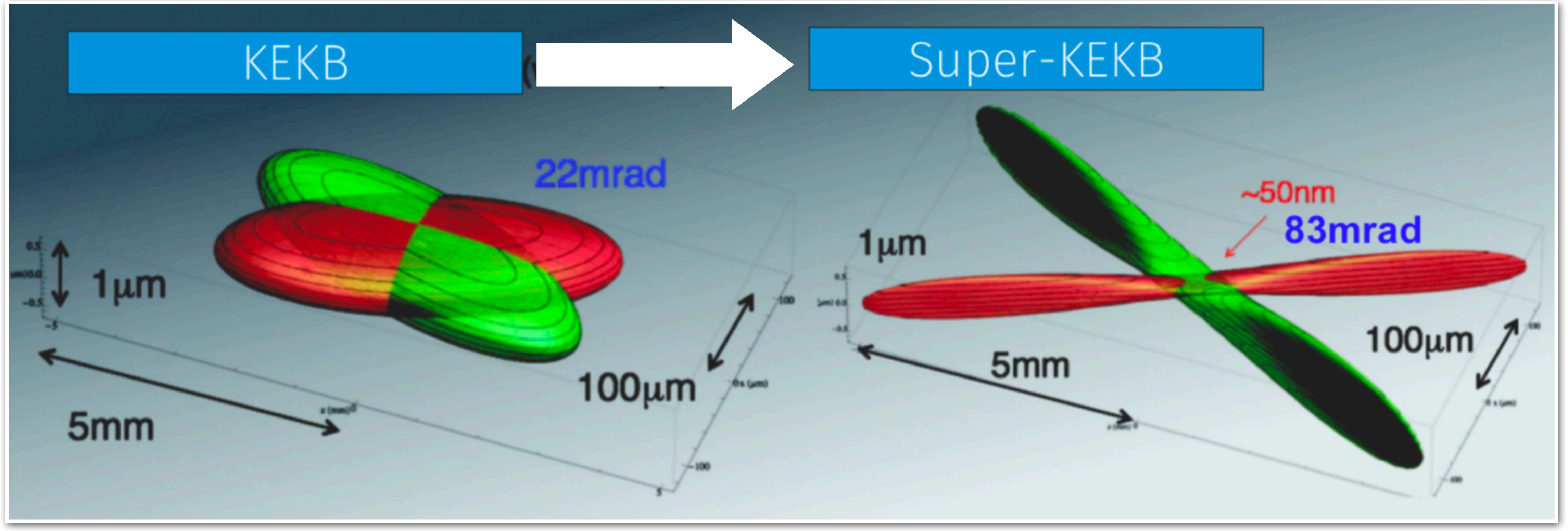
Υ(1S)
Υ(2S)
Υ(3S)
Υ(4S)
on-resonance
"Here be B"
off-resonance
"B free zone"
continuum background
σ(e+e- → Hadrons) [nb]
e⁺e⁻ Center-of-Mass Energy [GeV]

Highlight from SuperKEKB

size of the e^+e^- interaction region

➡ SuperKEKB implements the "**nano-beam**" scheme (P. Raimondi), needed to reach the target instantaneous luminosity of 6×10^{35} cm^{-2}s^{-1}

- squeeze beams at the interaction point with a set of final focus superconductive magnets
- typical e^+e^- interaction region sizes (x/y): 10/0.2 μm at *Belle II* vs 100/1 μm at Belle!



➡ Extremely small size of the e^+e^- interaction region allows to apply a **powerful *constraint* on the D/B/τ production vertex position**

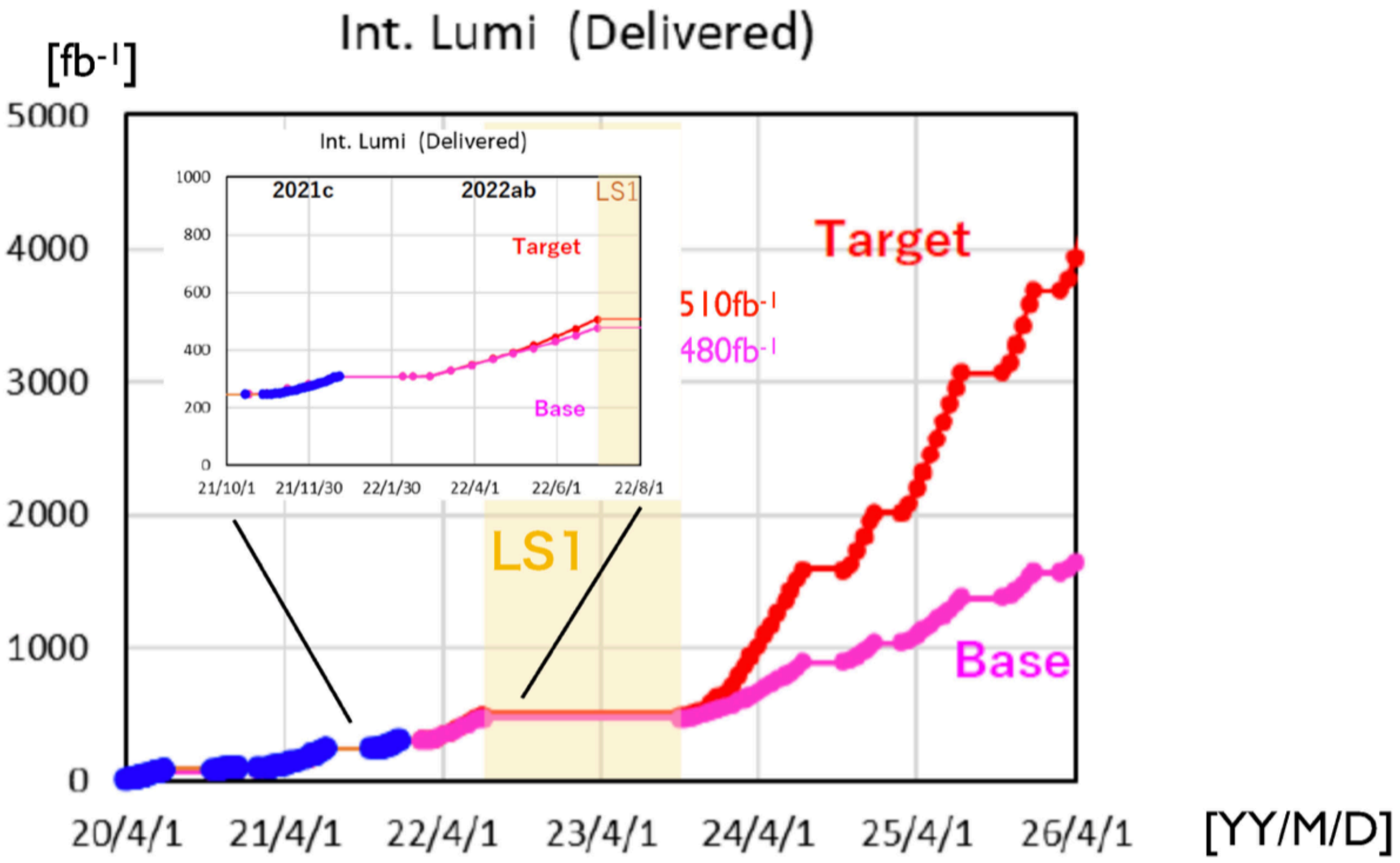
- periodic track-based calibrations of the position and size of the $e^+ e^-$ interaction region using di-muon samples

➡ Will further squeeze the vertical size to increase the luminosity, down to ~ 60 nm

Projection of integrated luminosity delivered by SuperKEKB to Belle II

Target scenario: extrapolation from 2021 run including expected improvements.

Base scenario: conservative extrapolation of SuperKEKB parameters from 2021 run

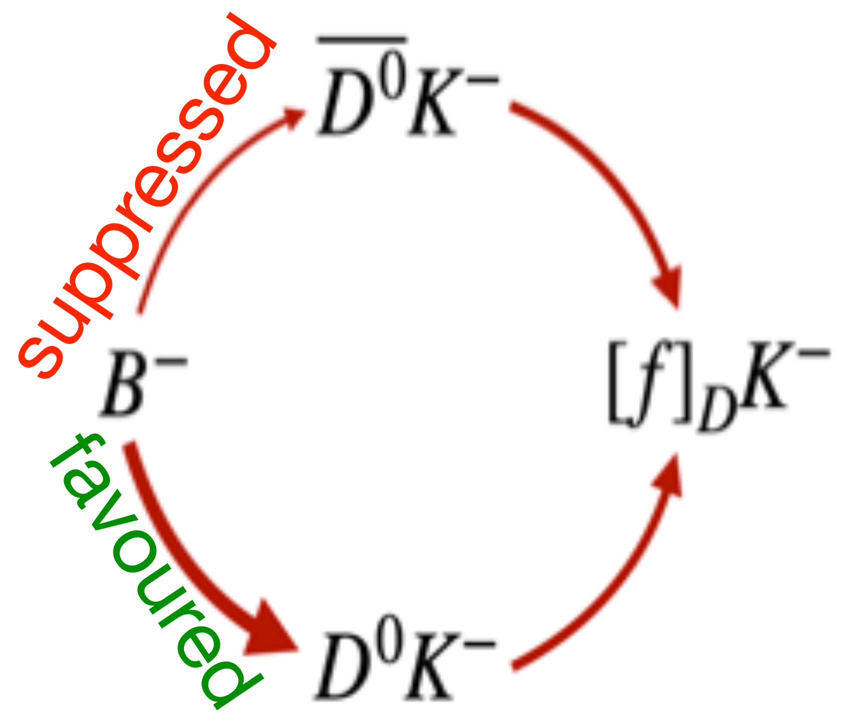


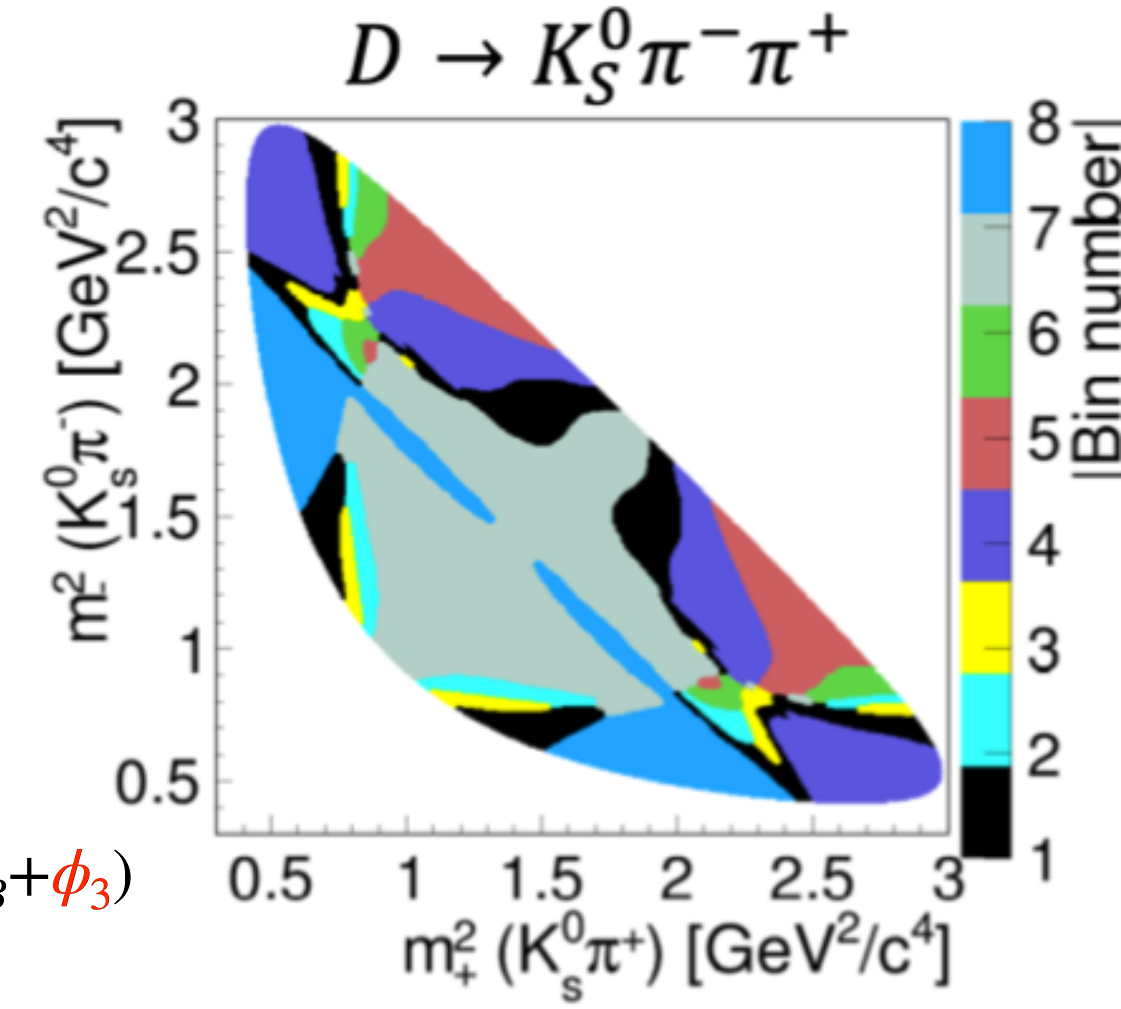
- We start long shutdown 1 (LS1) from summer 2022 for 15 months to replace VXD. There will be other maintenance/improvement works of machine and detector.
- We resume physics running from Fall 2023.
- A SuperKEKB International Taskforce (aiming to conclude in summer 2022) is discussing additional improvements.
- An LS2 for machine improvements could happen on the time frame of 2026-2027

BPGGSZ method (binned model-independent) Phys.Rev.D68, 054018

CKM Angle γ/ϕ3

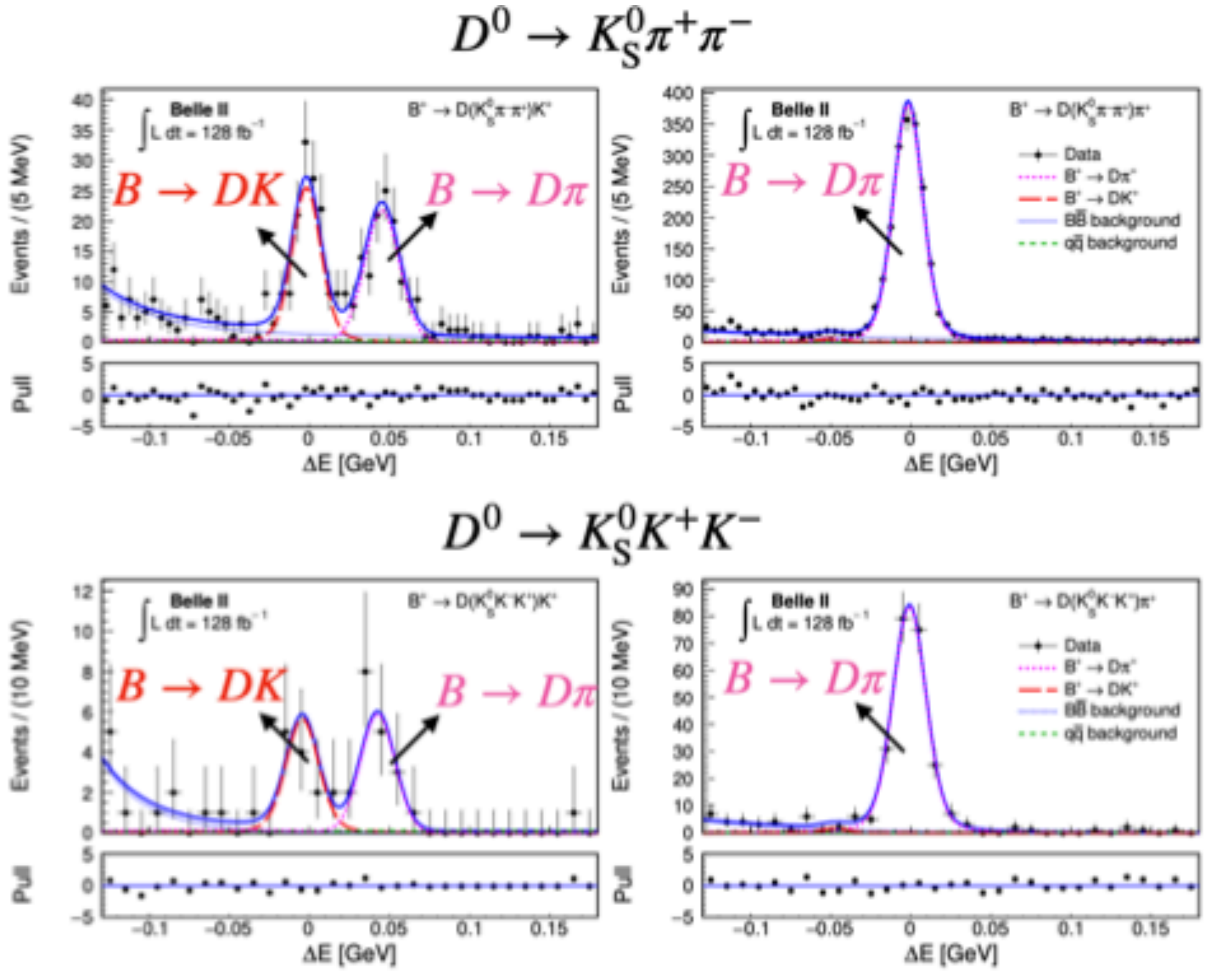
Belle + Belle II combined analysis

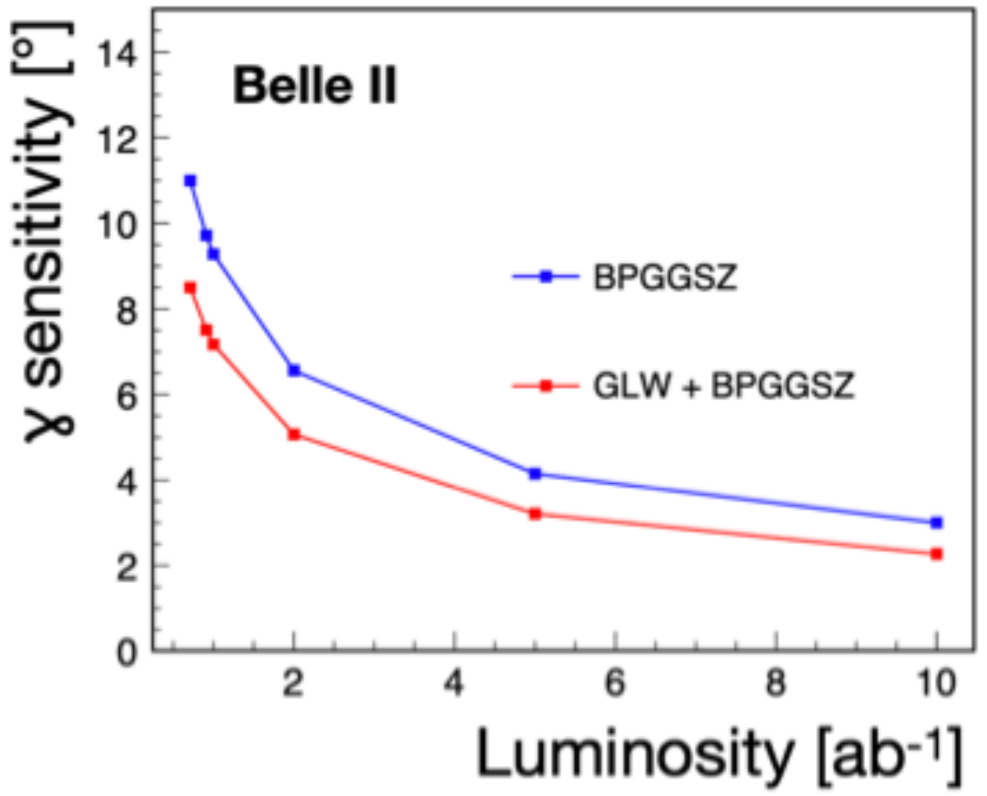




$$\frac{A(B^- \to \bar{D}^0K^-)}{A(B^- \to D^0K^-)} = r_B e^{i(\delta_B+\phi_3)}$$

- ➡ interference between the favoured and the suppressed B decay allows direct access to γ/ϕ3
  - D⁰ → Kshh (h= π,K) final state accessible by D and $\overline{D}$
  - r_B, δ_b, γ are extracted by simultaneously fitting the number of candidates in Dalitz Plot bin
- ➡ Best results from B-Factories, but still not competitive with LHCb → need 10x more data!





$$\delta_B[^\circ] = 124.8 \pm 12.9 \text{ (stat)} \pm 0.5 \text{ (syst)} \pm 1.7 \text{ (ext)}$$

$$r_B^{DK} = 0.129 \pm 0.024 \text{ (stat)} \pm 0.001 \text{ (syst)} \pm 0.002 \text{ (ext)}$$

$$\gamma[^\circ] = 78.4 \pm 11.4 \text{ (stat)} \pm 0.5 \text{ (syst)} \pm 1.0 \text{ (ext)}$$

JHEP 02, 063 (2022), arXiv:2110.12125

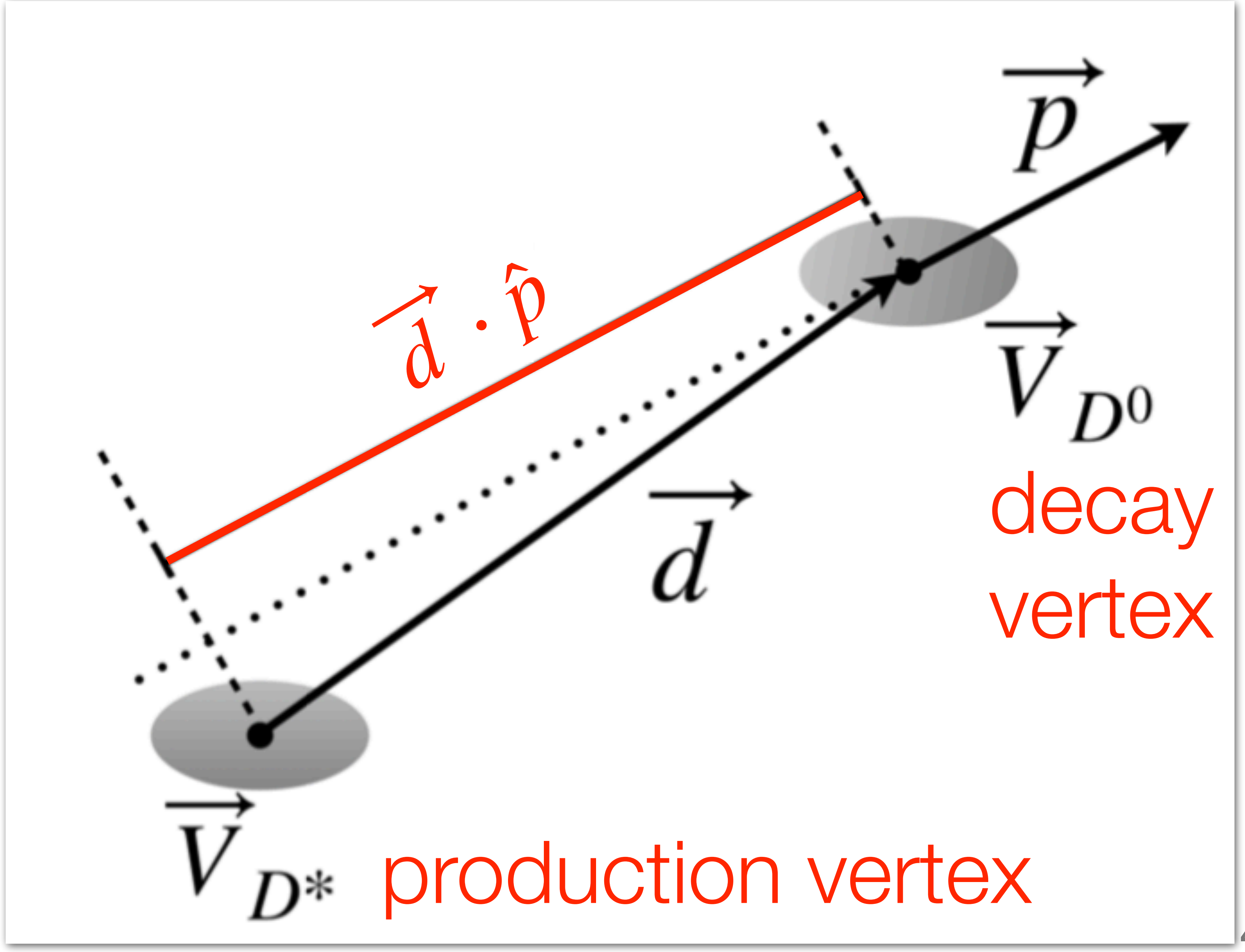
Belle II charm lifetimes

use $e^+e^- \to c\bar{c}$ events

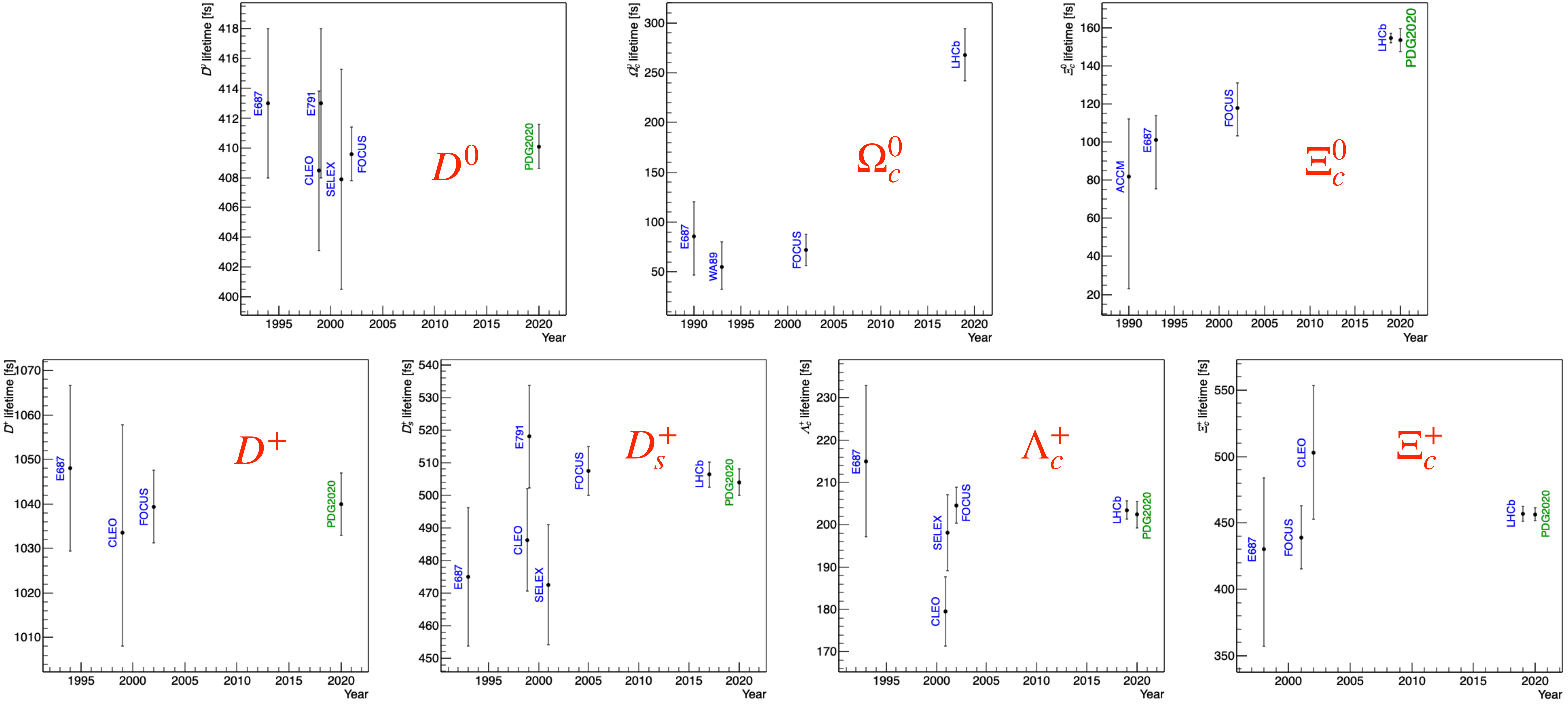
- ➡ Select high-purity signal candidates, D^*-tagged $D^0 \to K\pi$ (>99%), $D^+ \to K\pi\pi$ (92%), $\Lambda_c^+ \to pK\pi$ (92.5%), Ω_c (70%)
  - (3) $\Omega_c^0 \to \Omega^-\pi^+$
  - (2) $\Omega^- \to \Lambda^0 K^-$
  - (1) $\Lambda^0 \to p\pi^-$
  - avoid selection criteria that bias the D proper time, remove signal from B decays
- ➡ Compute the D proper time t and its uncertainty σ_t from the reconstructed D production and decay vertices and its momentum $\vec{p}$:

$$t = \frac{m_D}{p}\left(\vec{d}\cdot\hat{p}\right)$$

  - production vertex lies inside the e^+e^- interaction region
  - decay vertex is displaced on average by ~200/500 μm D^0/D^+
- ➡ Extract the lifetime with a fit to the (t, σ_t) distribution
  - signal & bkg PDFs extracted from data, no input from MC



Charm Lifetimes Experimental Picture



Improved Proper Time Resolution

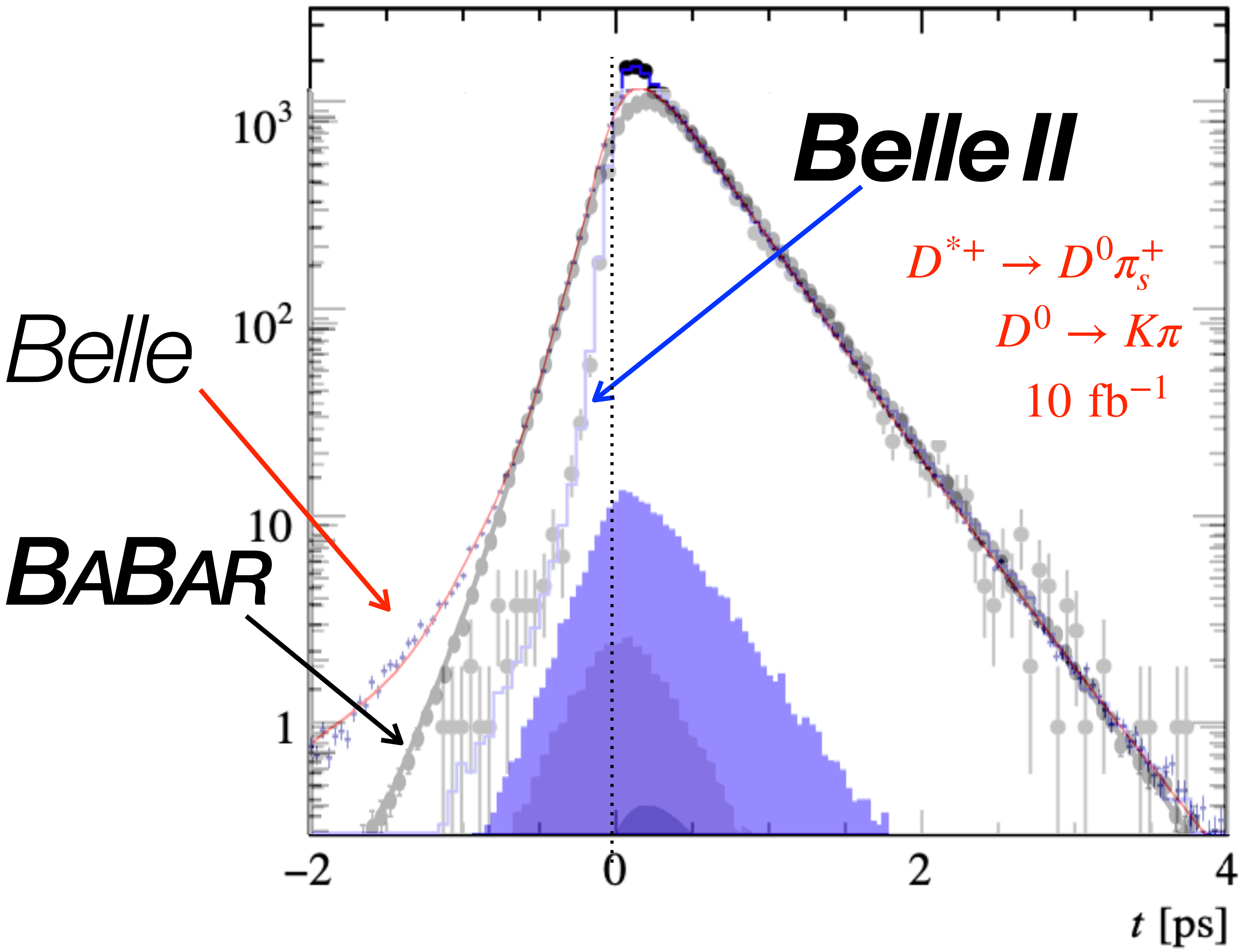
impact on time-dependent measurements

➡ Proper time resolution at *Belle II* is a factor 2 better than *Belle* & BABAR

- *Belle II* will improve the precision on observables extracted in time-dependent measurements, beyond the increase of luminosity, thanks to the improved resolution
- there are ongoing studies to quantify the impact on the charm time-dependent measurements (including Dalitz analyses)

Belle II Physics Book

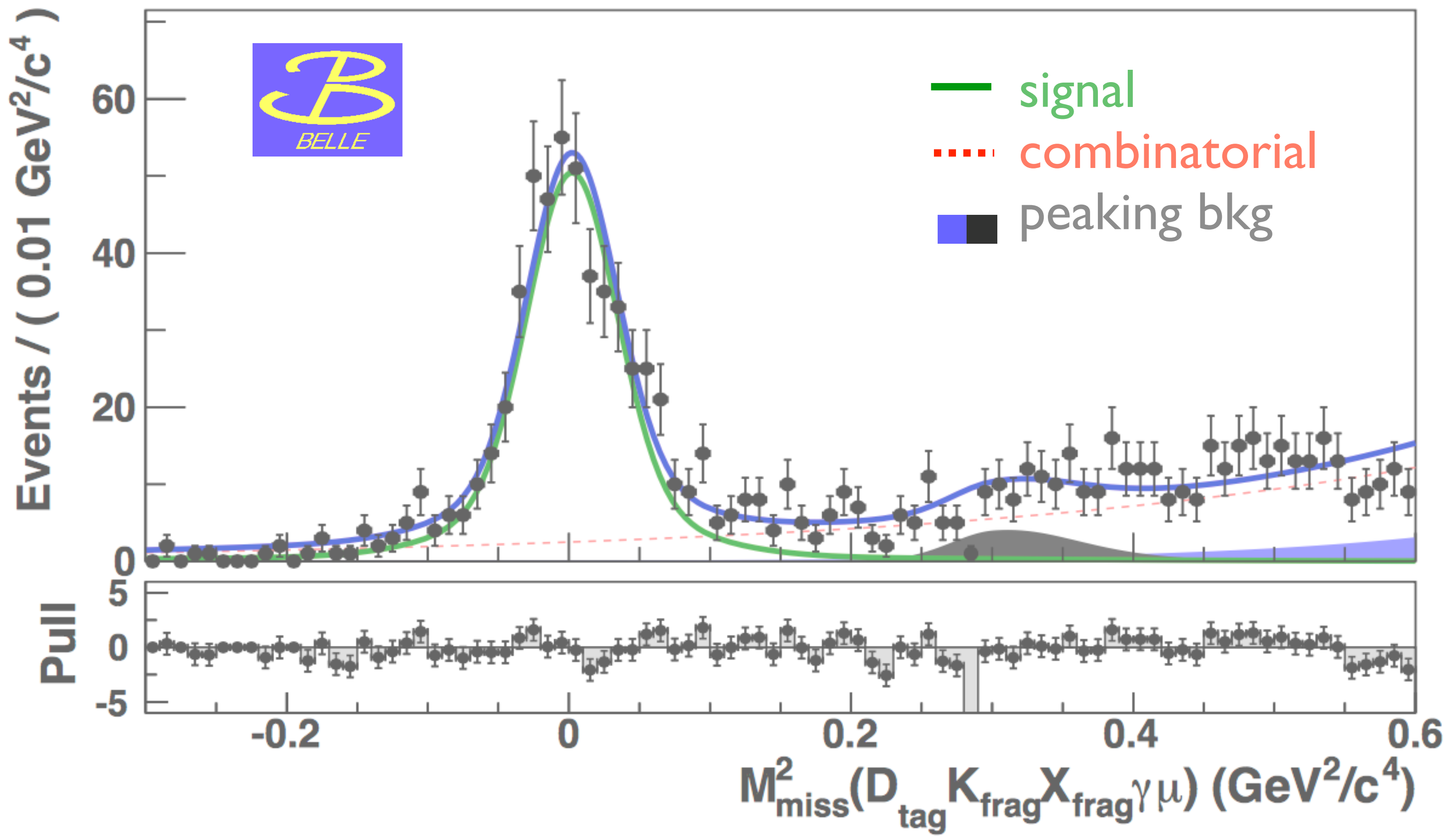
- resolution improvement visible at $t < 0$:



Full Charm Event Reconstruction

- (semi-) leptonic decays
- decays to invisible
- inclusive Λ_c sample

JHEP09(2013)139



➡ **recoil method** successfully exploited for D_s decays:

light mesons (K, π, …)

$$e^+e^- \to c\bar{c} \to D_{\rm tag} X_{\rm frag} D_{\rm sig}$$

reconstructed in several channels (D^0, D^*, D_s, …)

signal channel

➡ use energy and momentum conservation to search for the desired final state:

- *example*: $e^+e^- \to D_{\rm tag} X_{\rm frag} K D_s^{*+}$
  $D_s^{*+} \to D_s^+ \gamma \quad \boldsymbol{D_s^+ \to \mu^+ \nu}$
- "miss" quantities computed for the system:
  $$D_{\rm tag} + X_{\rm frag} + K + \gamma + \mu^+$$
- compute the missing mass squared

$$M^2_{\rm miss}(\nu) = (E_{\rm miss} - |\vec{p}_{\rm miss}|)(E_{\rm miss} + |\vec{p}_{\rm miss}|)$$