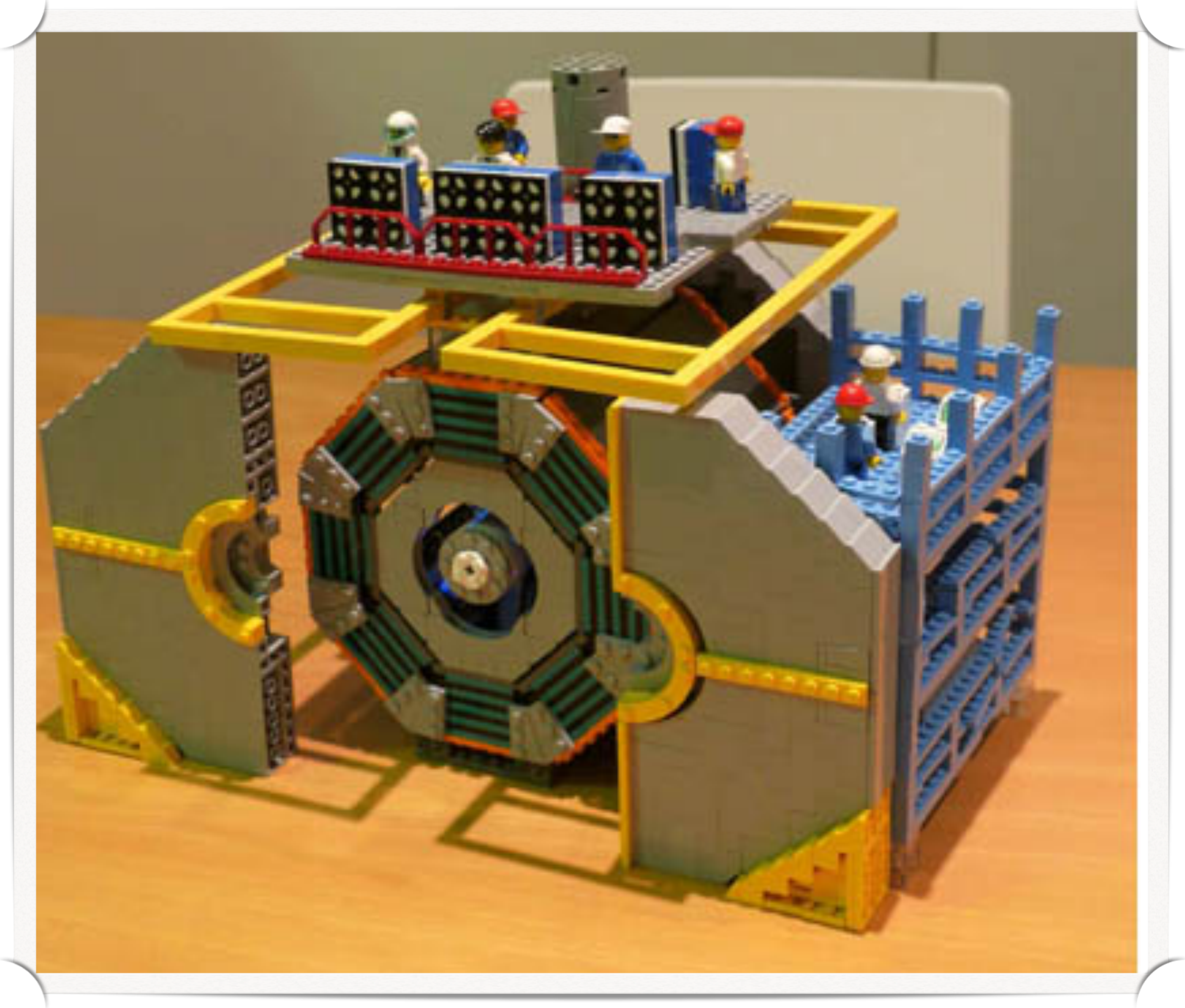
59th Winter Meeting on Nuclear Physics

Recent Results from *Belle II*



Giulia Casarosa

IN SUPREMÆ DIGNITATIS 1343

INFN Istituto Nazionale di Fisica Nucleare

on behalf of the *Belle II* Collaboration

Belle II

Bormio, January 25th, 2023

Outline

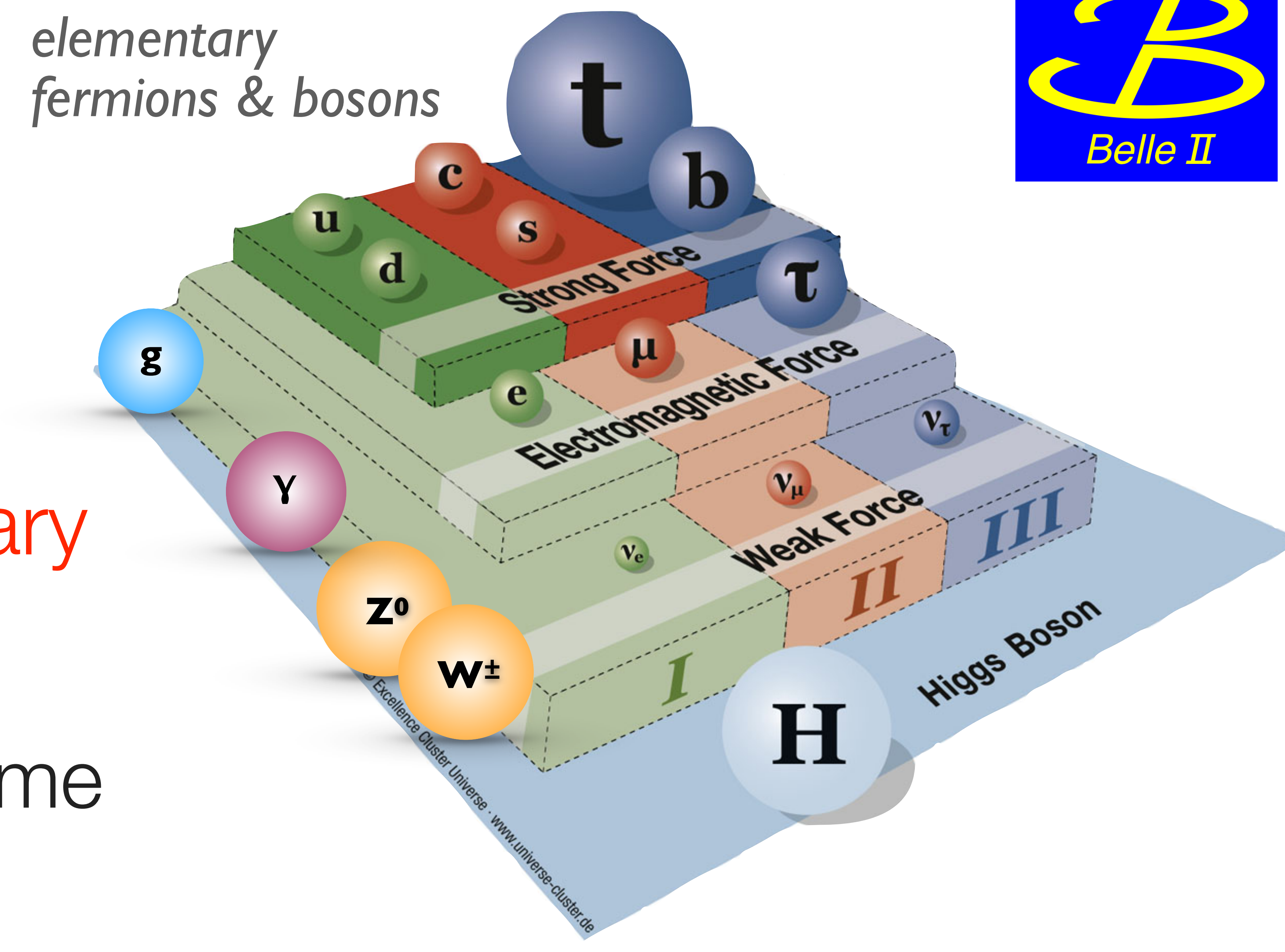
- *Introduction*
- *Belle II at the High-Luminosity B-Factory SuperKEKB*
- *Overview of the Physics Program & Some Recent Highlights*
    - *B, charm, τ & Dark Sector*
- *Conclusions*

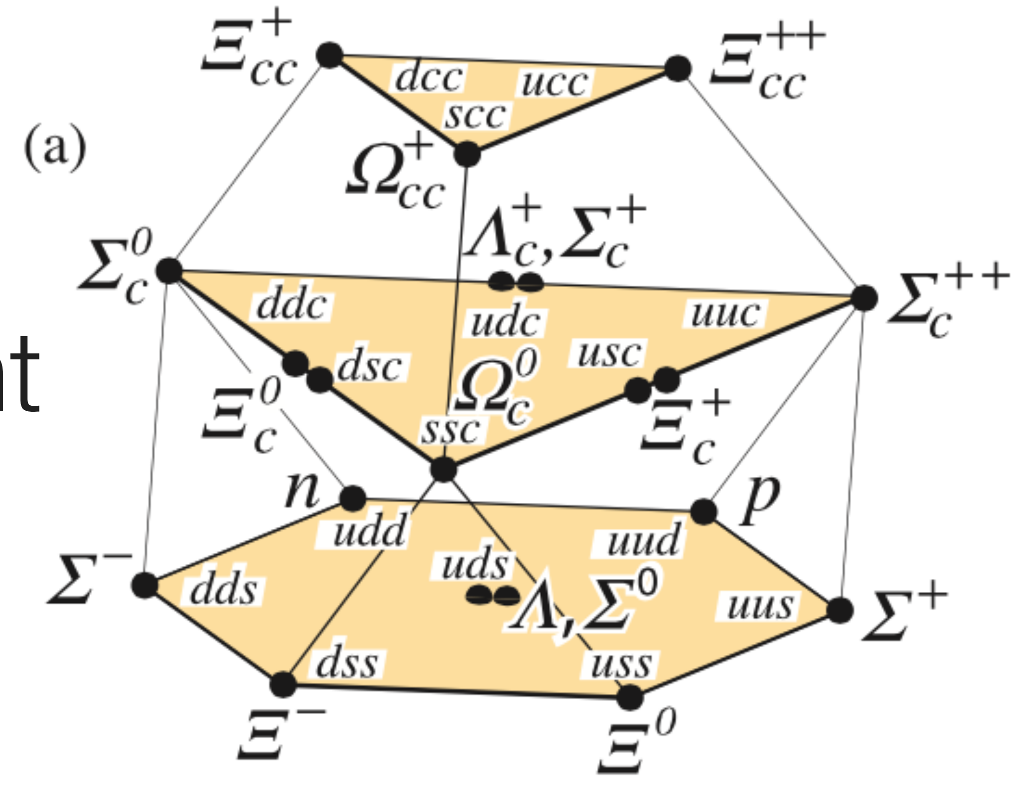
The Standard Model …

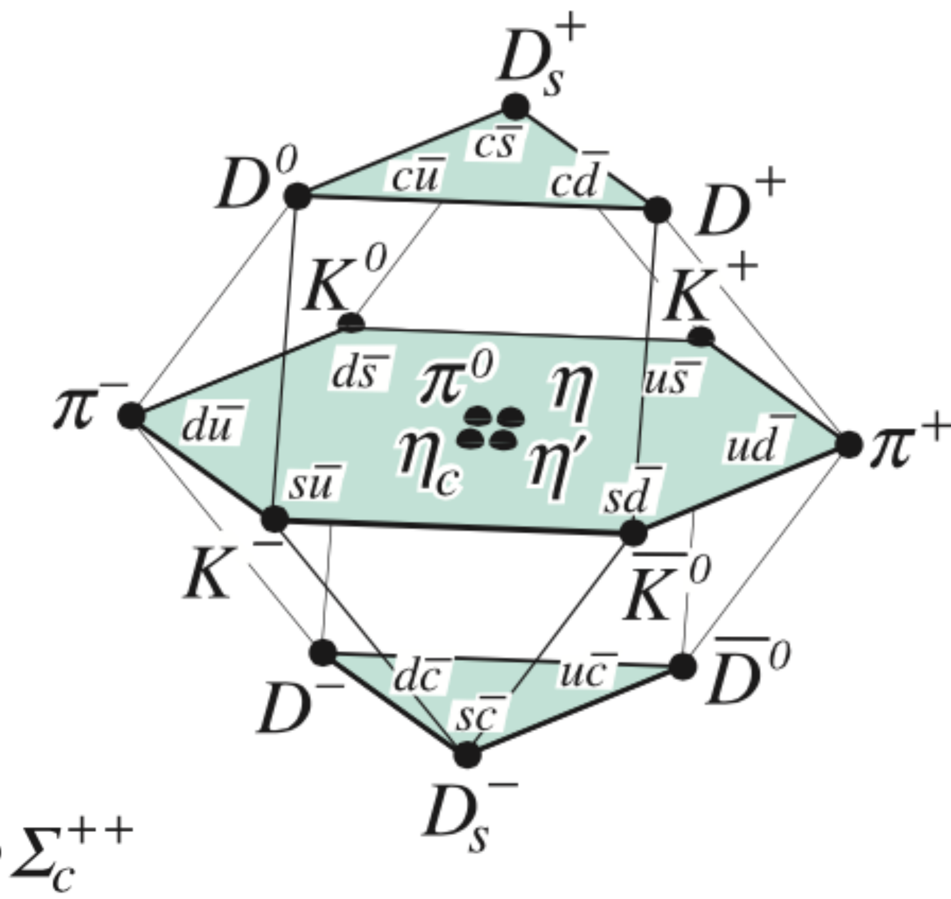
➡ the SM is the most successful theory that describes elementary particles and interactions

- 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

elementary fermions & bosons







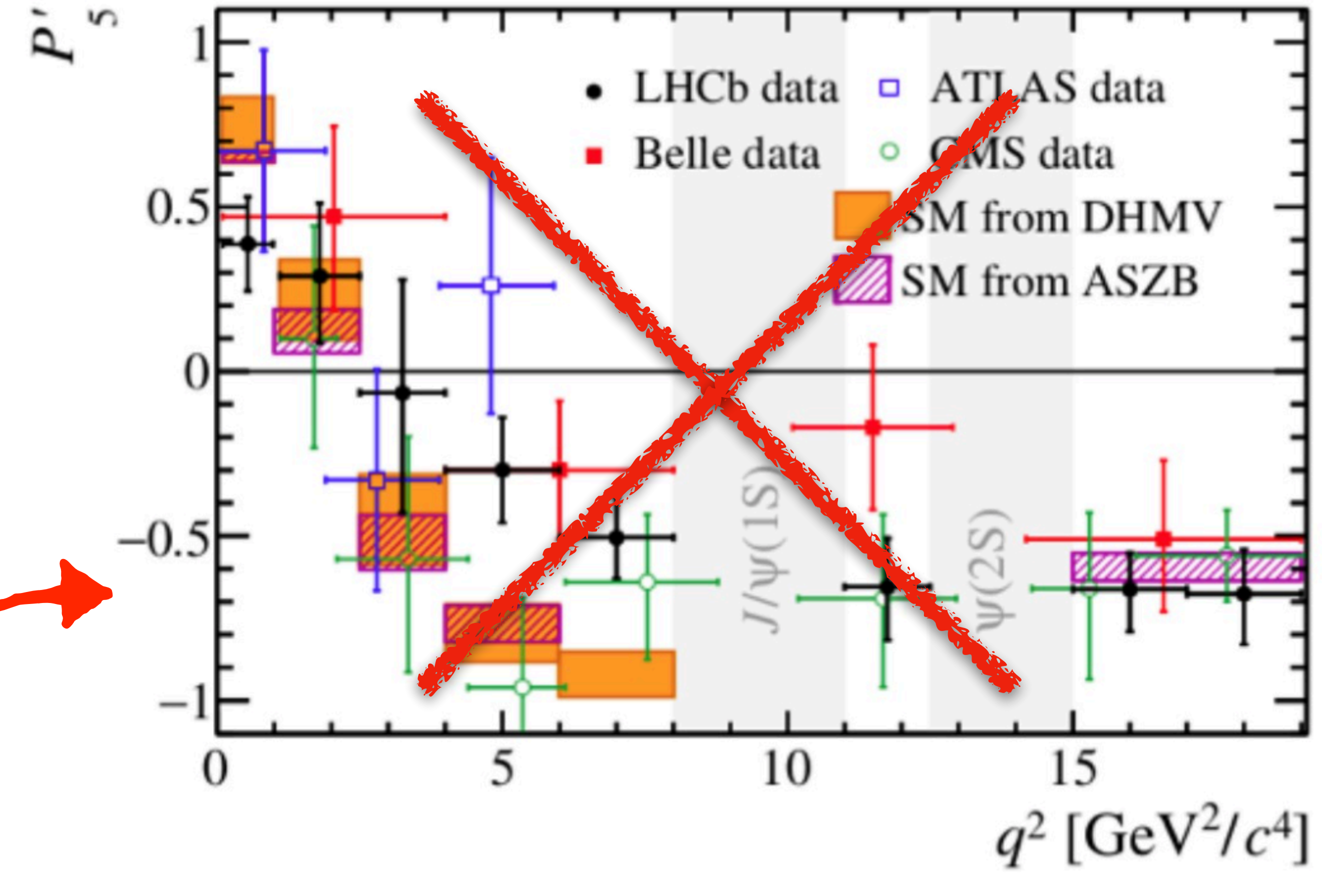
SU(4) multiplets of pseudoscalar mesons and baryons

… 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, …

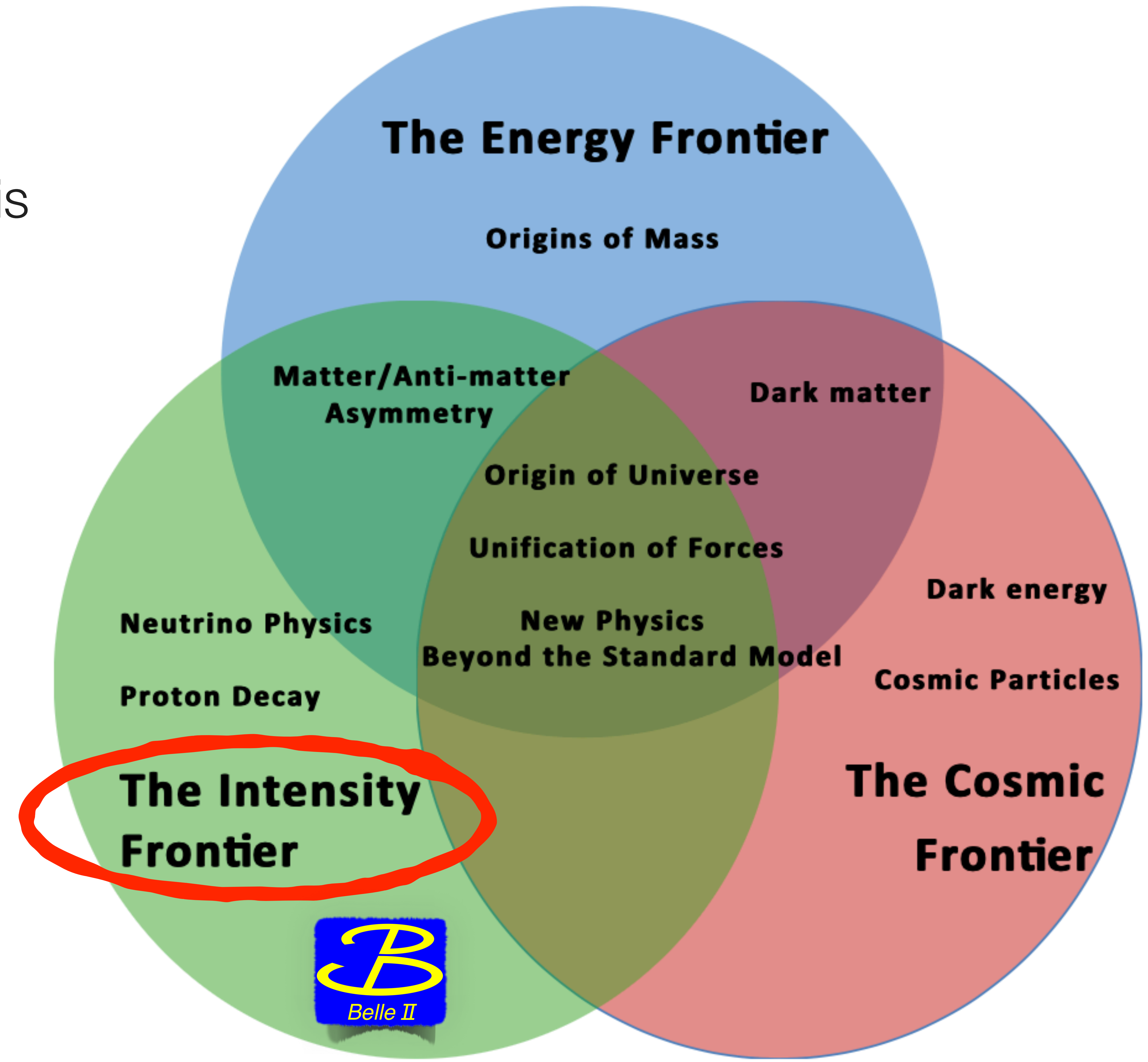
- ➡ and tensions between measurements and SM predictions that need progress in either theory or experiment (or both) to be interpreted
  - $(g\text{-}2)_\mu$
  - tensions come & go…
  - … anomalies in angular observables in $b \to s\ell\ell$?



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

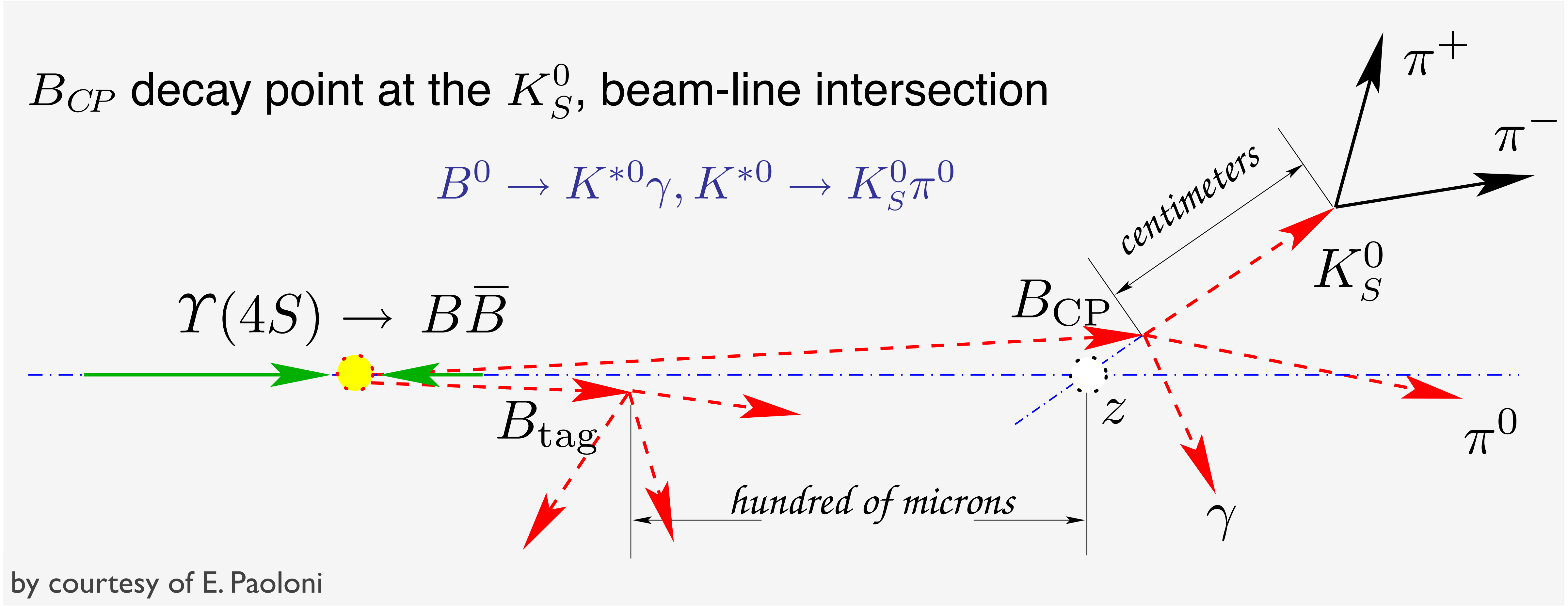


Physics Frontiers

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

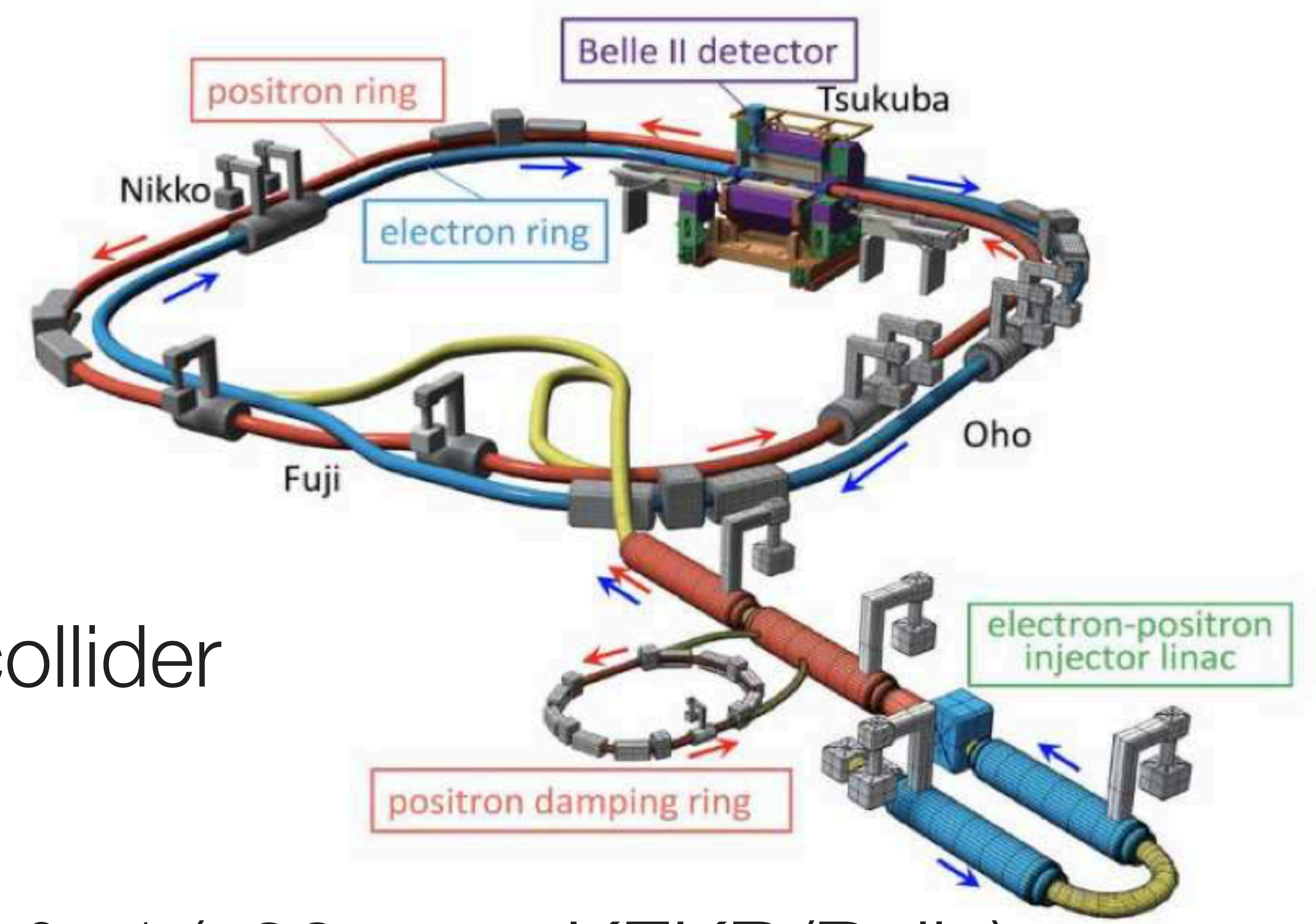
- ➡ Belle & *BABAR*, have collected together 1.5/ab
  - 1.7×10^9 $B\bar{B}$, 2×10^9 $c\bar{c}$, 1.4×10^9 $\tau^+\tau^-$ events
  - the majority of existing measurements are (still) limited by the statistical uncertainty

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

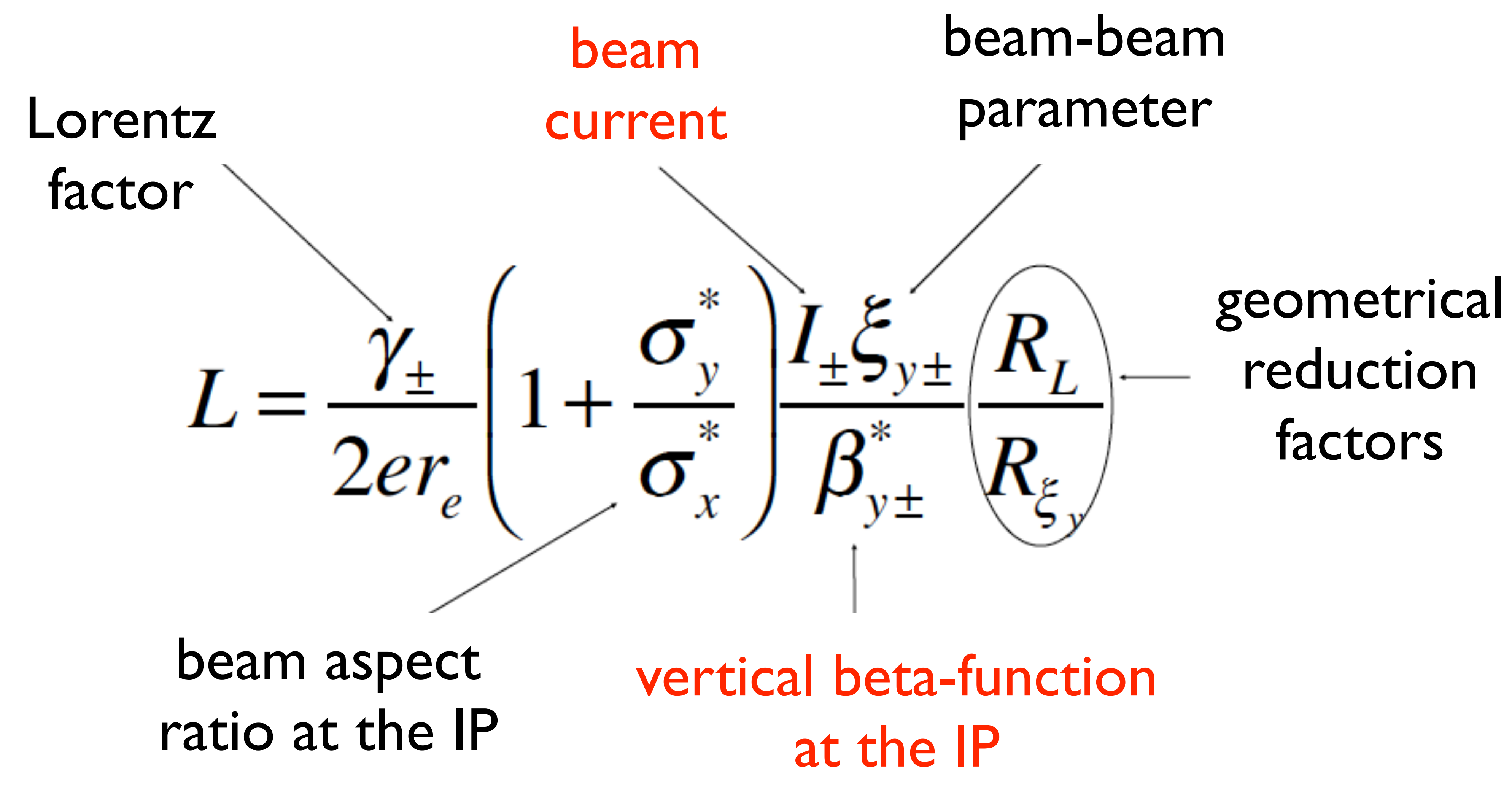
* *Belle II* goal is 50/ab = x30 (Belle + *BABAR* datasets)

SuperKEKB

High-Luminosity B-Factory



- ➡ SuperKEKB is a 2nd generation **asymmetric** e^+e^- collider at the Y(4S) mass energy
- ➡ Target instantaneous luminosity is $\mathscr{L}$ = 6×10^{35} $cm^{-2}s^{-1}$ (x30 w.r.t. KEKB/Belle)
  - max instantaneous luminosity $\mathscr{L}$ = 4.7×10^{34} $cm^{-2}s^{-1}$ (world record)
- ➡ Achievable in the *nano-beam scheme**
  - increase beam currents
  - squeeze beams at the interaction point
  - reduced beam energy asymmetry



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

* proposed by P. Raimondi for SuperB

SuperKEKB

High-Luminosity B-Factory

- ➡ SuperKEKB is a 2nd generation **asymmetric** e^+e^- collider at the Y(4S) mass energy
- ➡ Target instantaneous luminosity is $\mathscr{L} = 6\text{x}10^{35}\ \text{cm}^{-2}\text{s}^{-1}$ (x30 w.r.t. KEKB/Belle)
  - max instantaneous luminosity $\mathscr{L} = 4.7\text{x}10^{34}\ \text{cm}^{-2}\text{s}^{-1}$ (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**

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

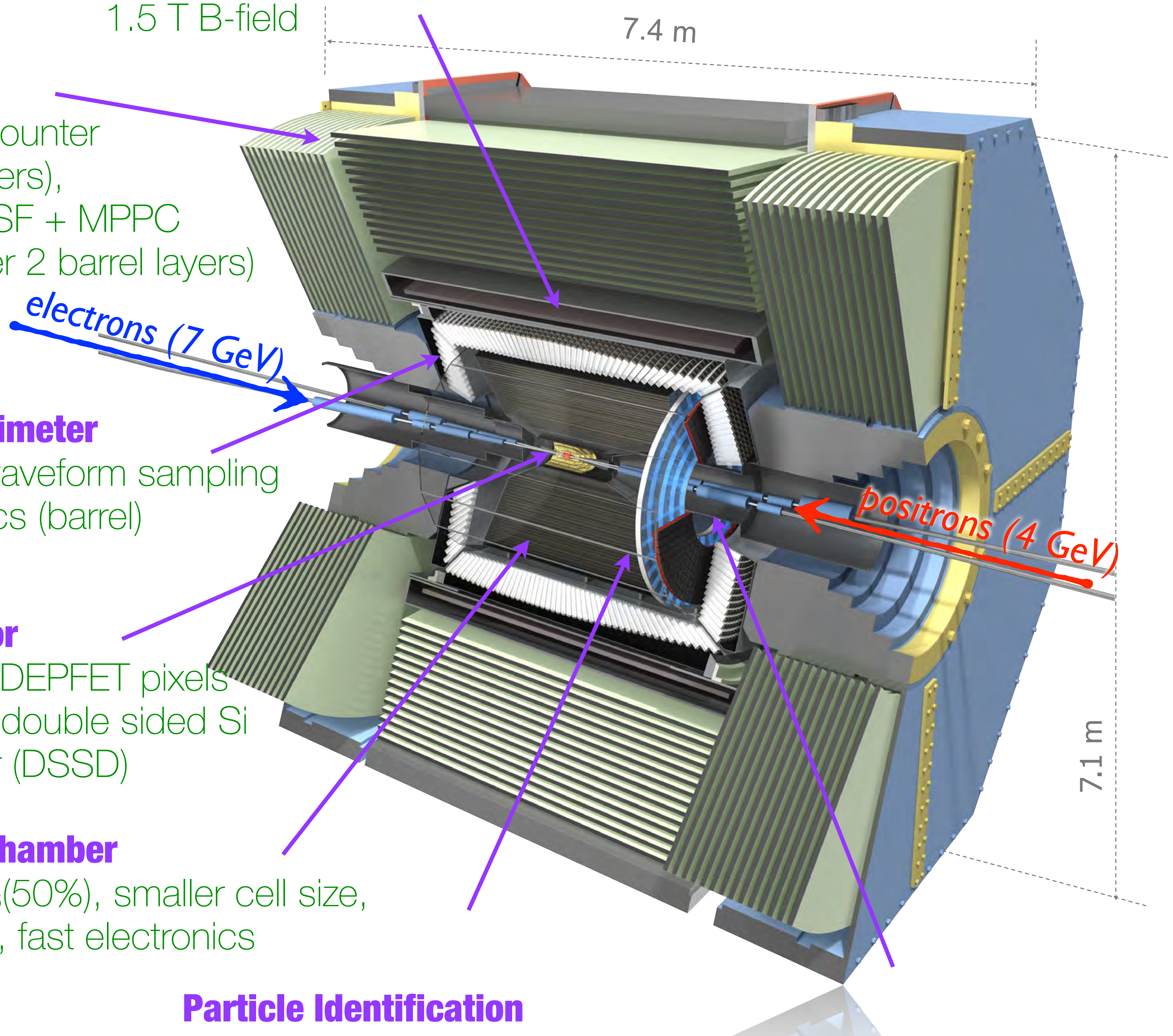
Lorentz factor; beam current; beam-beam parameter; geometrical reduction factors; beam aspect ratio at the IP; vertical beta-function at the IP

* proposed by P. Raimondi for SuperB

Belle II

experiment @ SuperKEKB High-Luminosity B-Factory

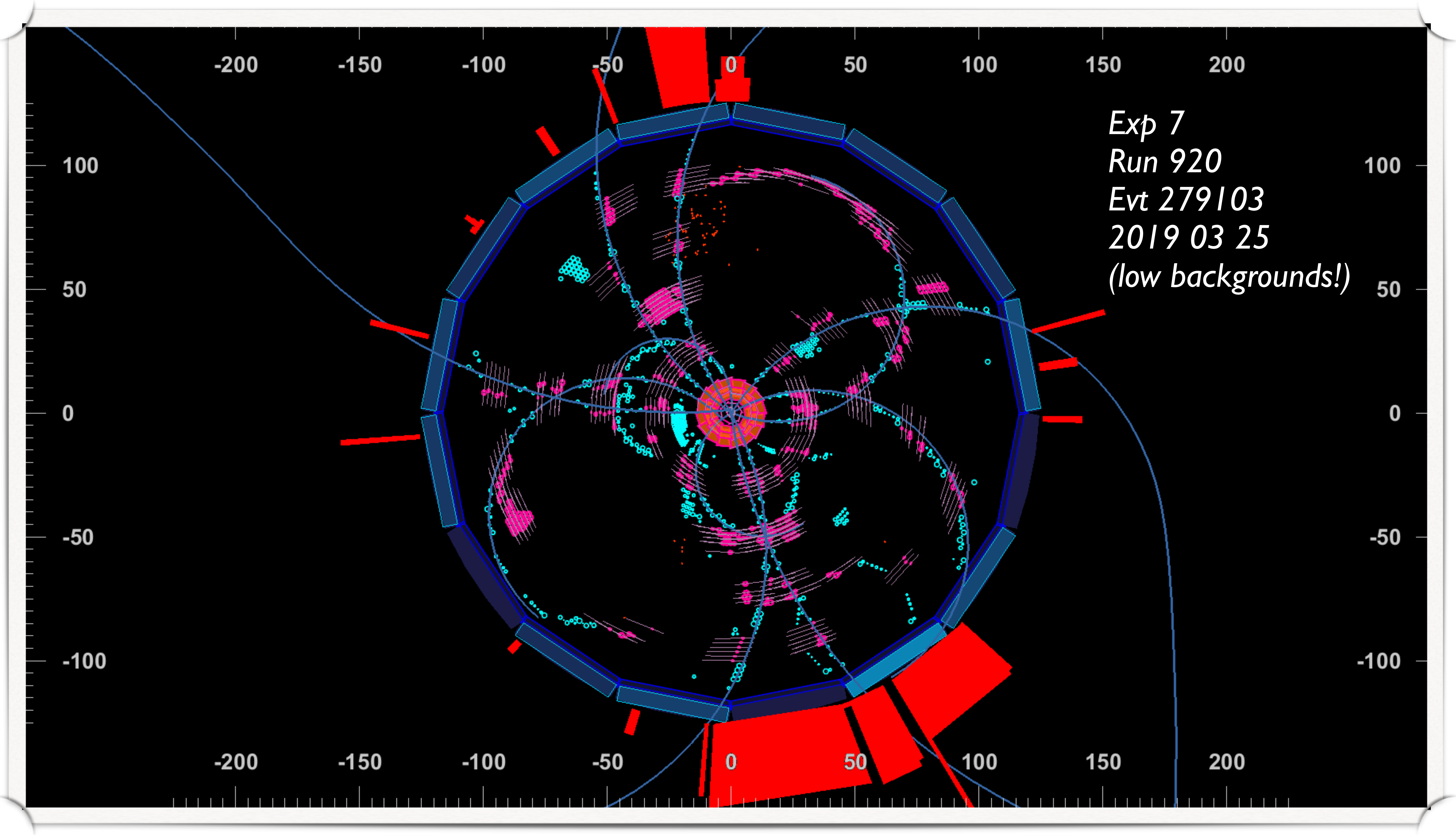
- ➡ *multi-purpose detector* designed to reconstruct *all** particles from the e^+e^- collision
- ➡ excellent vertexing
- ➡ high-efficiency detection of neutrals (γ, π^0, η, η', …)
- ➡ high trigger efficiency, including for low-multiplicity events
- ➡ reconstruction performance *at least as good as*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



Belle II TDR

* particles that interact with the detector

A Candidate Hadronic Event



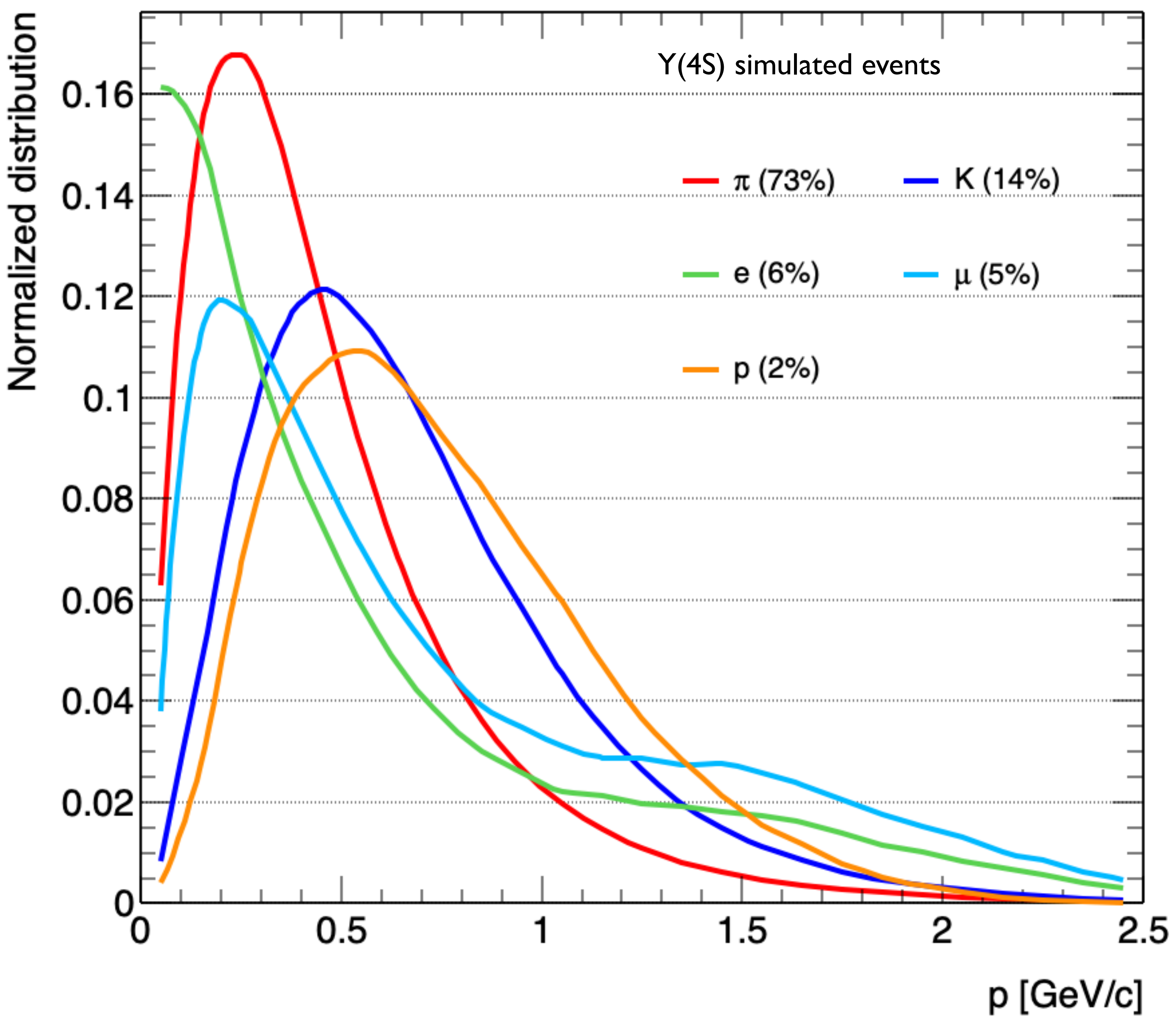
NOTE: the DAQ is not synchronous to the bunch crossing (150÷250 MHz)

→ detectors integrate many collisions (+ beam background)

→ reconstruction is not as easy as it may look!

A Typical Υ(4S) Event

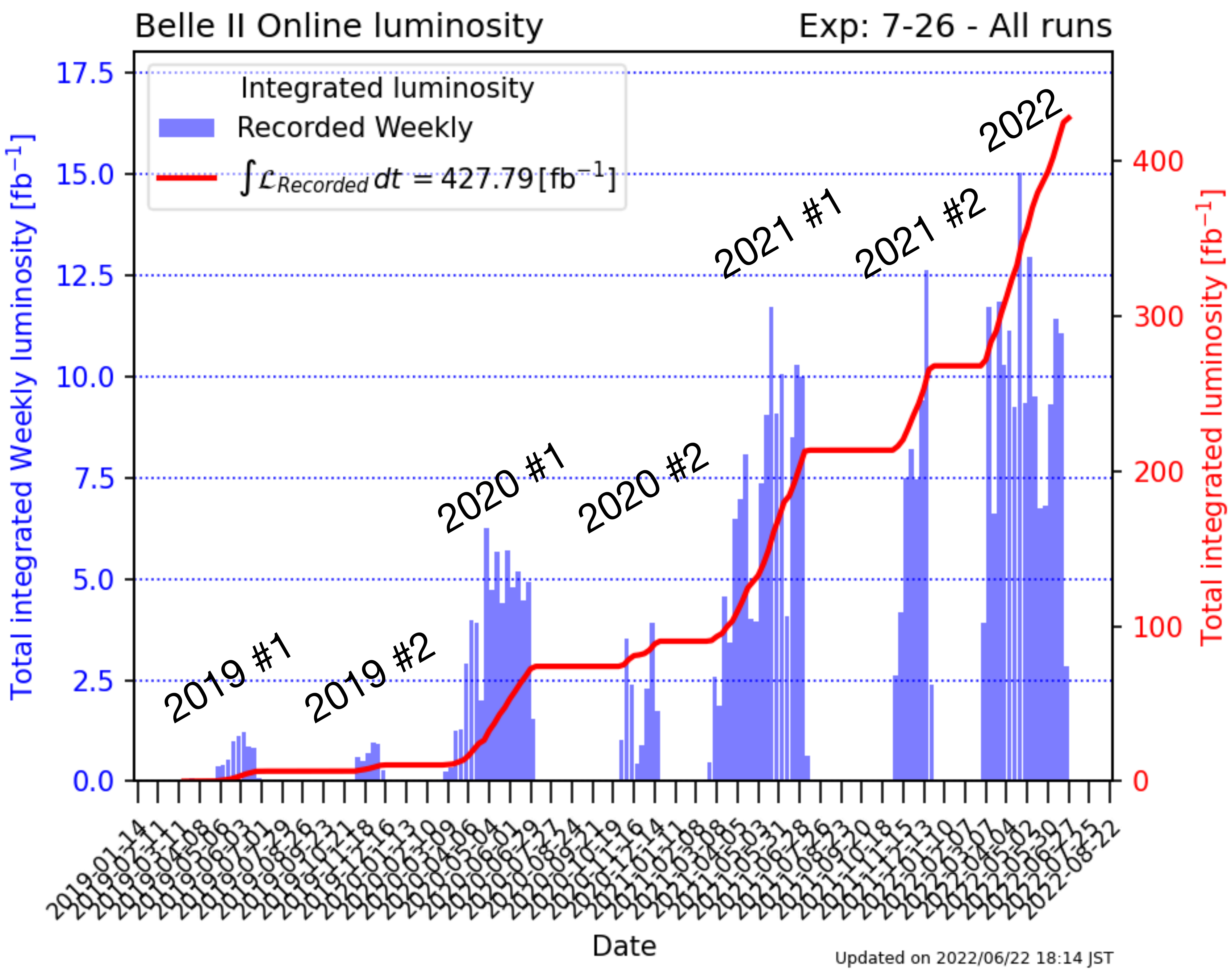
- average multiplicities:
  - 11 charged tracks
  - 5 neutral pions
  - 1 neutral kaon
- soft charged tracks momentum spectrum



Current Dataset …

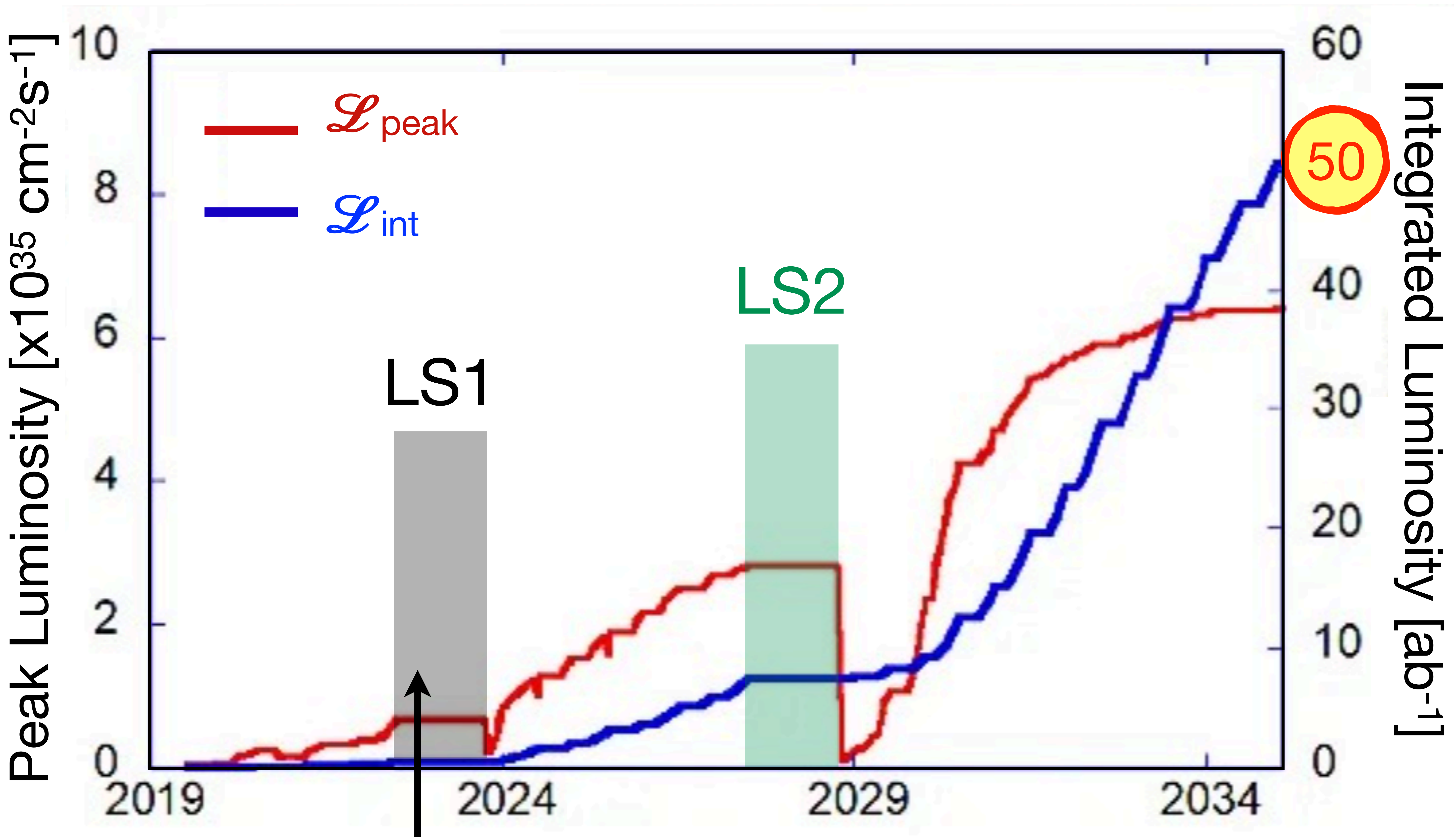
- ➡ First data recorded in 2019
  - 2 data-taking period per year
- ➡ Collected data
  - 362/fb at Υ(4S)*
  - 42/fb off-resonance, 60 MeV below Υ(4S)
  - 19/fb energy scan between 10.6 to 10.8 GeV for exotic hadron studies

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
- $\mathscr{L}_{peak}$ = 4.7x10^{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

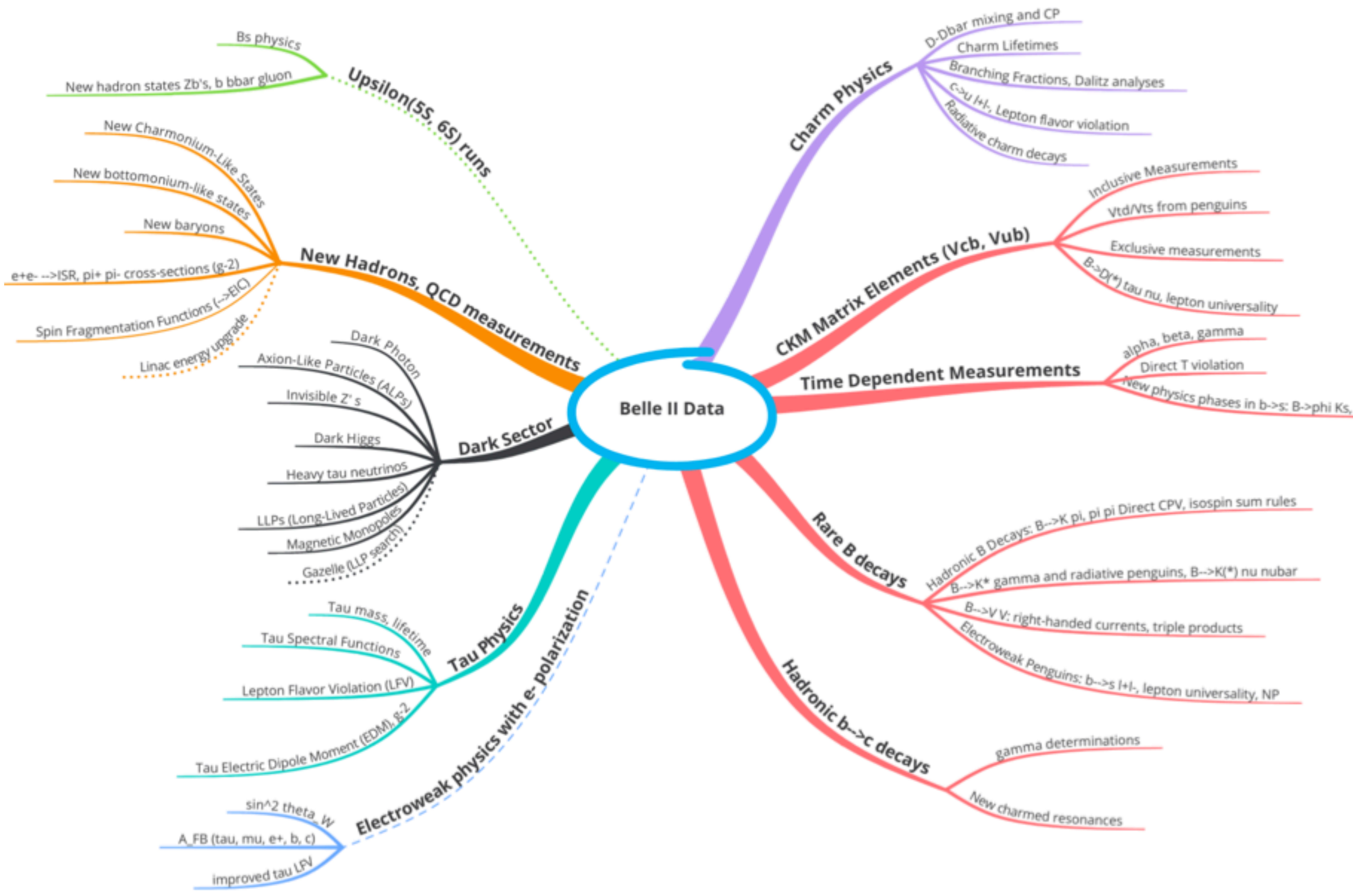
a snapshot

➡ *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:

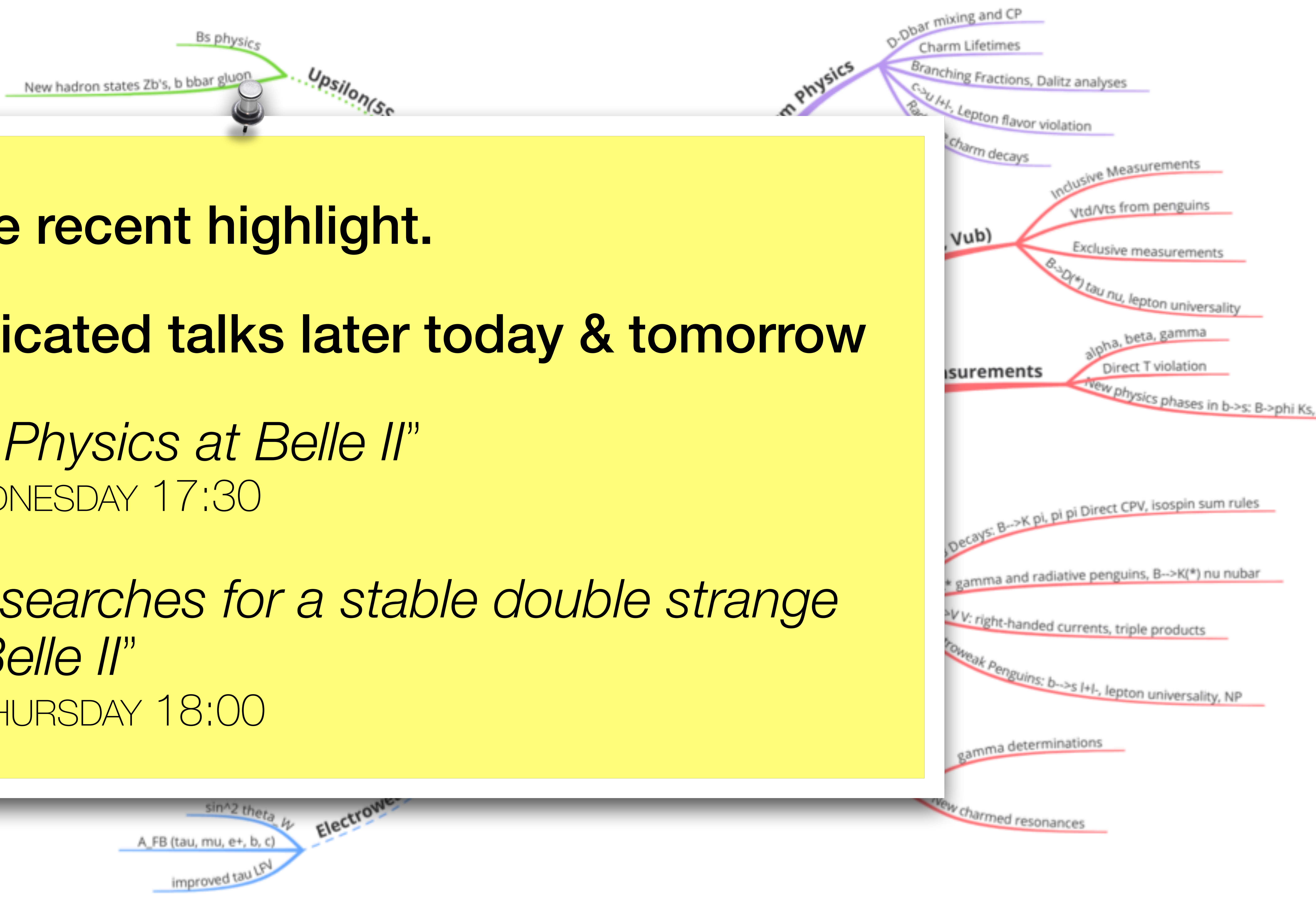
- (many sort of) searches
- time-dependent
- missing energy and missing mass
- on the Dalitz Plot (multi-body)



The Physics Program

a snapshot

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



I will show some recent highlight.

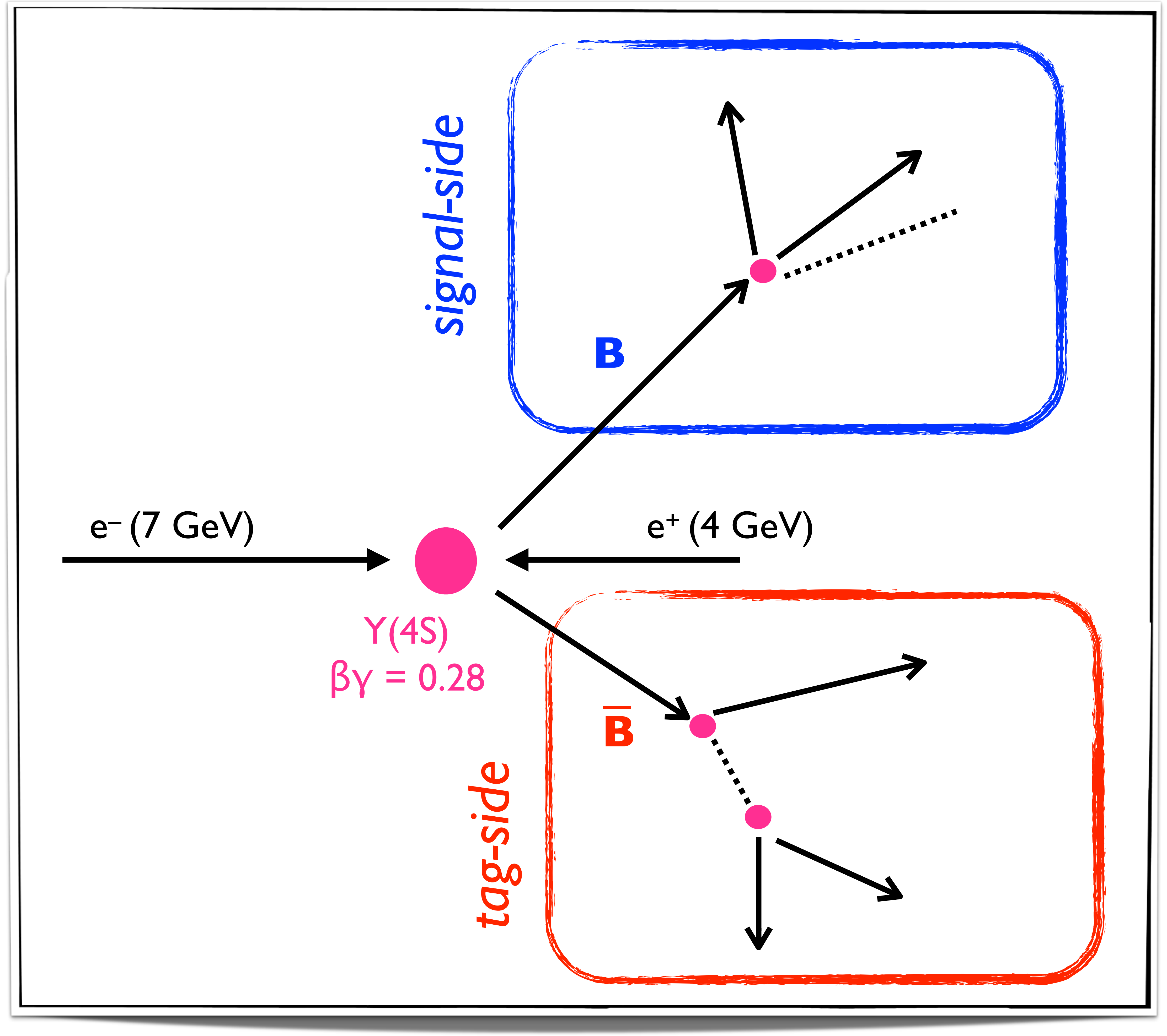
There are 2 dedicated talks later today & tomorrow

- "*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. $B^+ \rightarrow \tau^+\nu$
- hadronic tag: $\varepsilon = \mathcal{O}(0.5\%)$, less background
- semileptonic tag: $\varepsilon = \mathcal{O}(2\%)$, more background

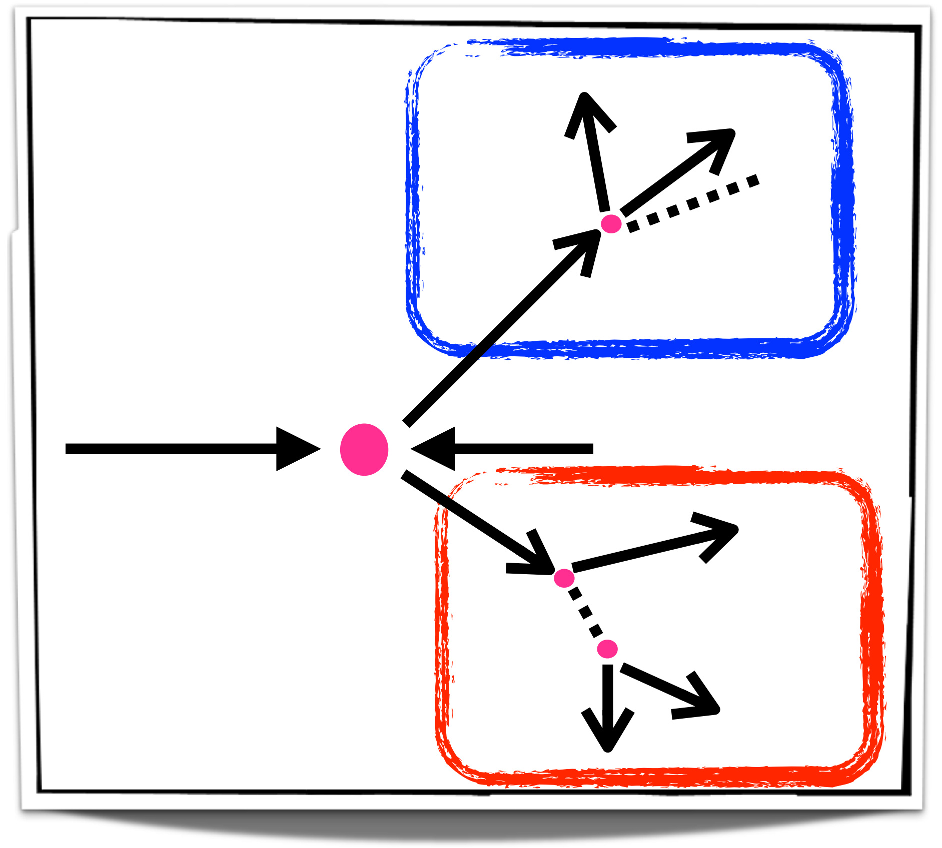
➡ tag-side *Inclusive Reconstruction (+ FT)*:

- 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

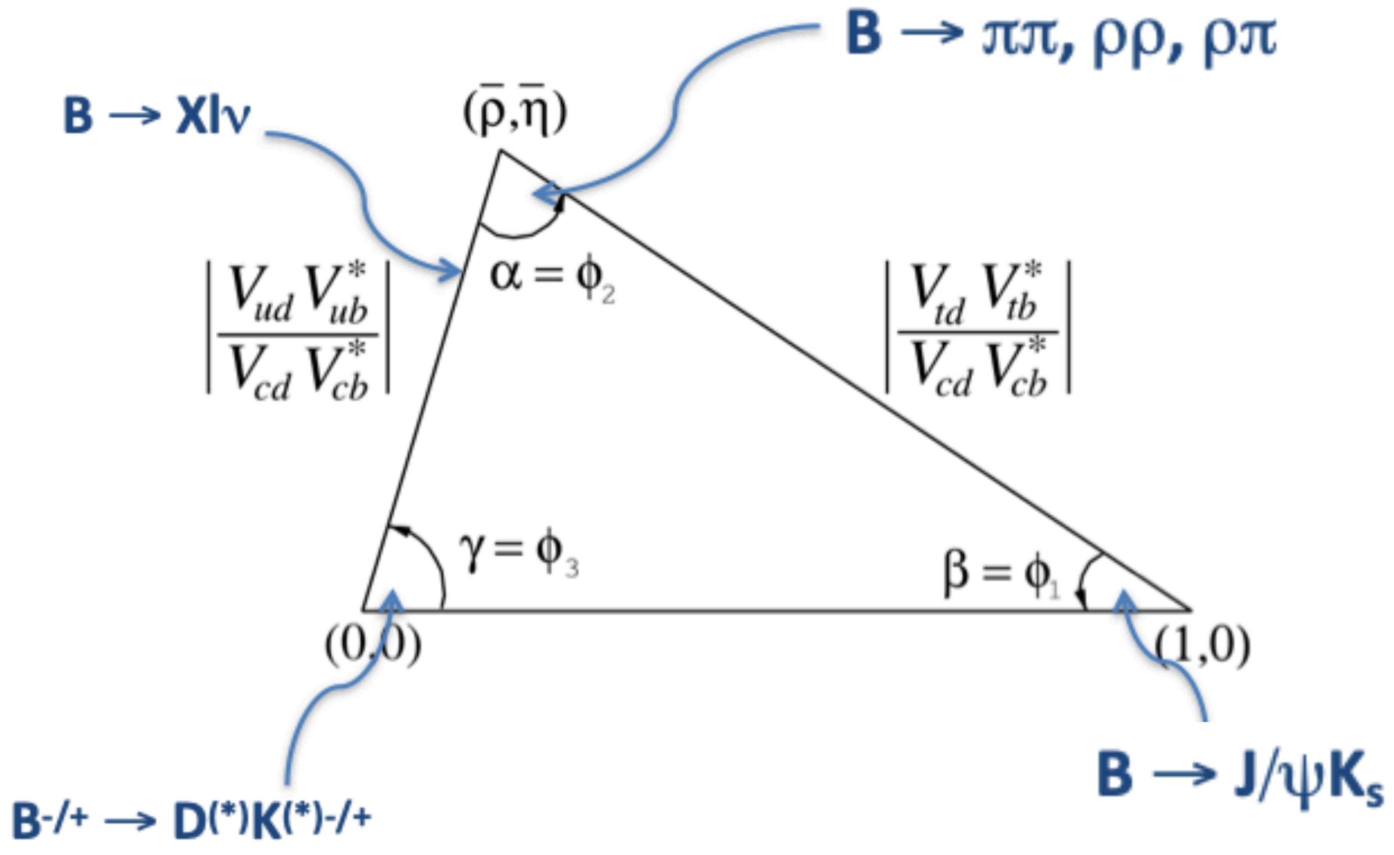
a very rich program



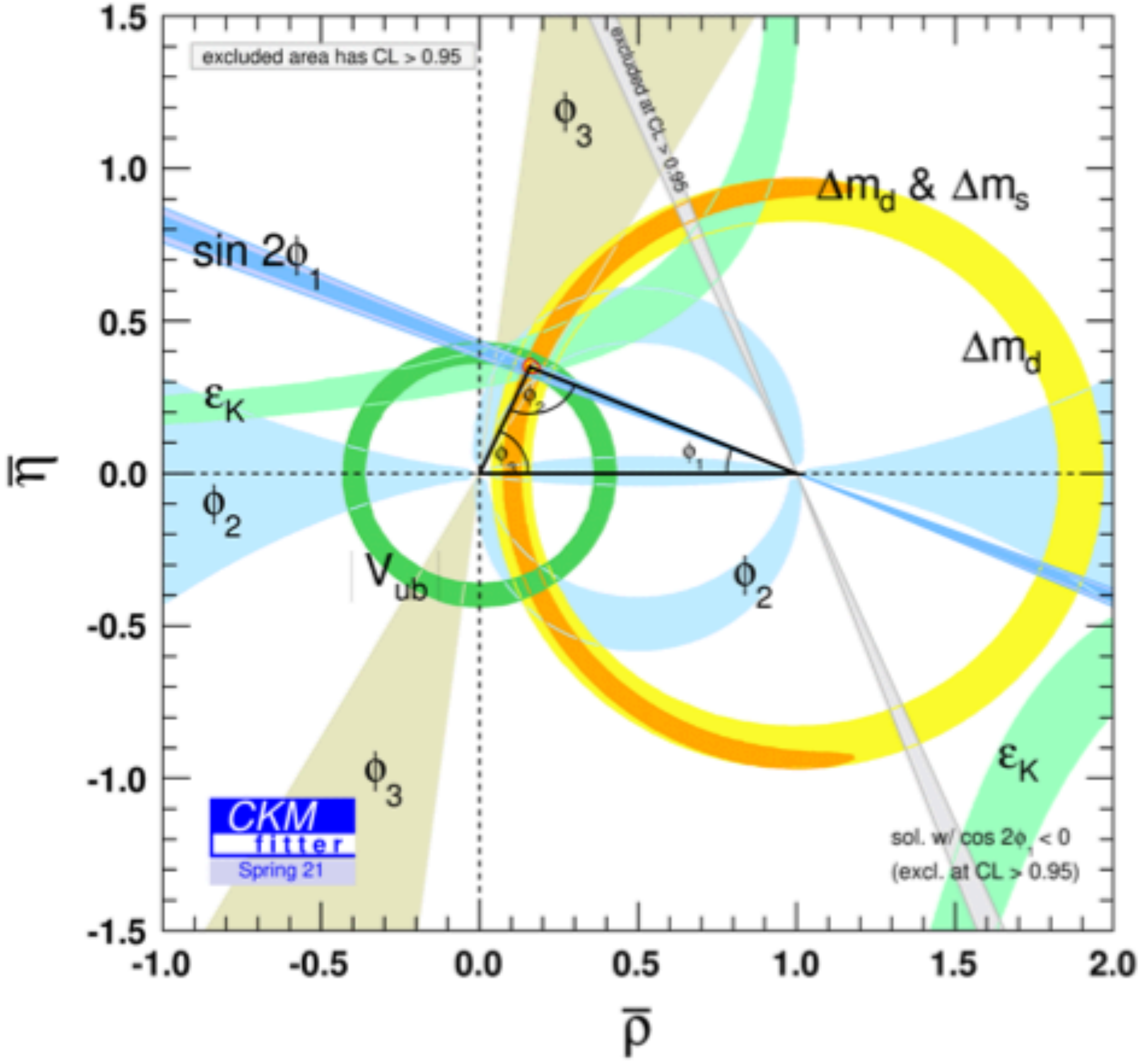
- ➡ B mixing & searches for new sources of CPV
- ➡ non-SM probes from radiative & (semi)-leptonic decays
- ➡ tests of LFU, e.g. $R(X_{e/\mu})$,
- ➡ measurements of CKM Unitary Triangle sides & angles

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

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



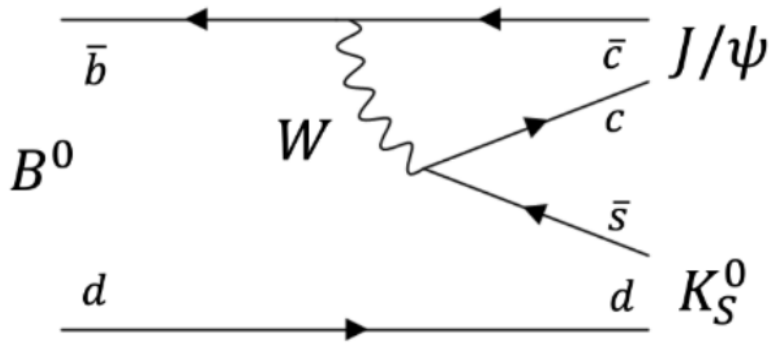
overconstraining the UT is a very powerful test of the SM



sin 2 β/φ1

the B⁰ mixing phase

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



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

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

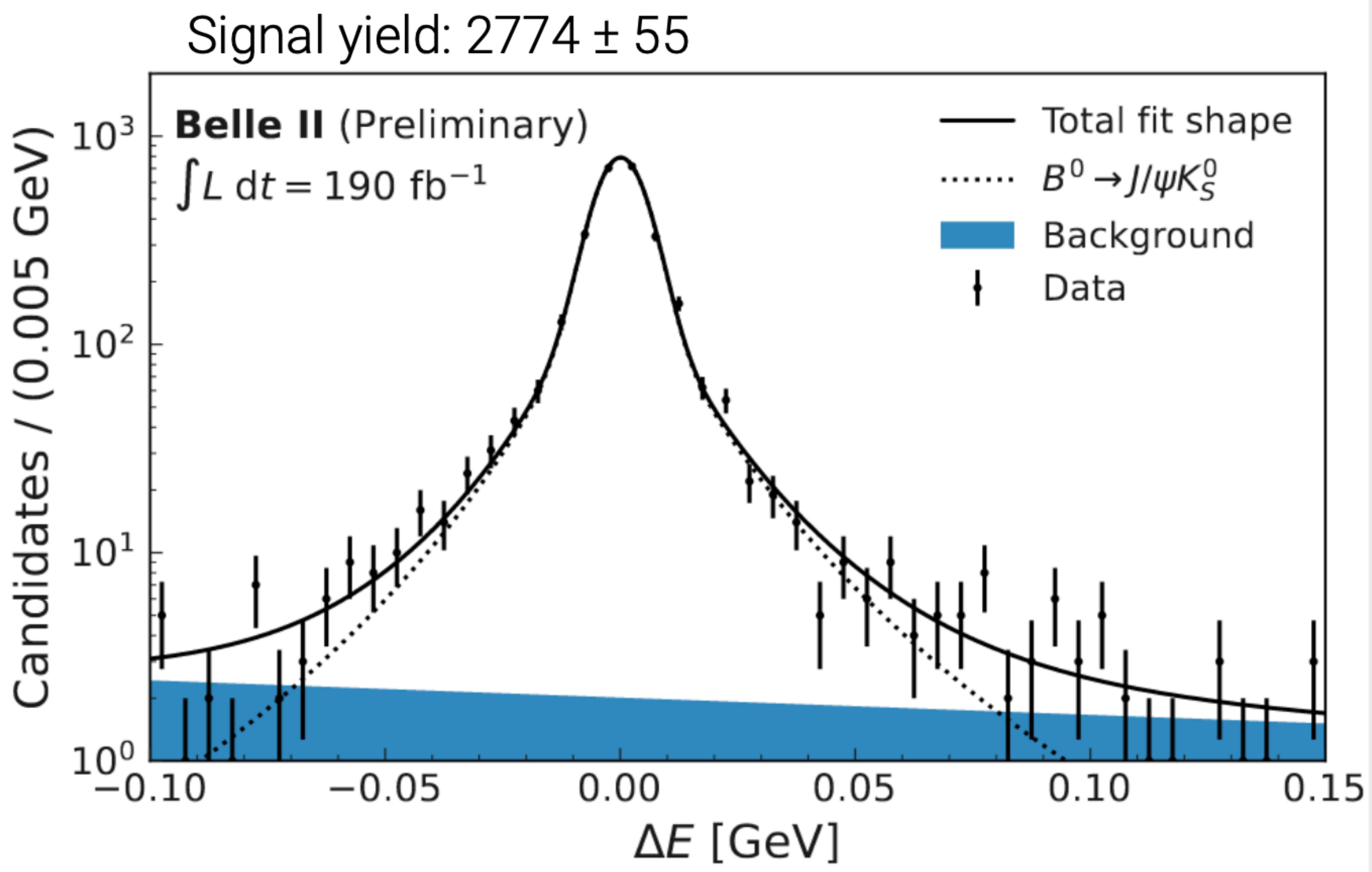
A_{CP}: direct CP asymmetry; S_{CP}: mixing-induced CP asymmetry

- ➡ SM measurement, but important analysis to refine all our tools for future measurement sensitive to NP (e.g. B⁰ → 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:

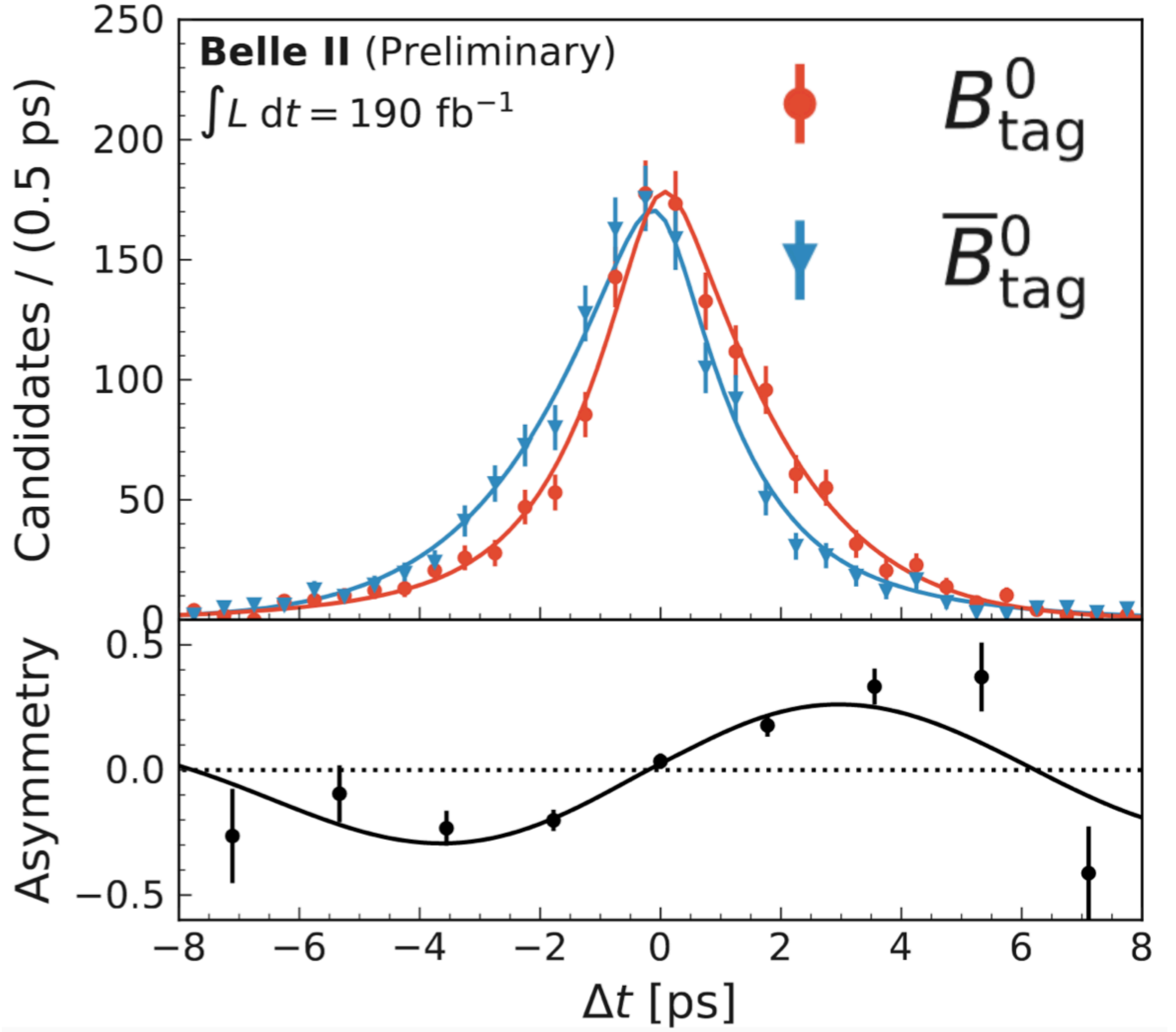
$$\varepsilon_{\text{eff}} = \epsilon\,(1-2\omega)^2 = (30.0 \pm 1.2 \pm 0.4)\,\%$$

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

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



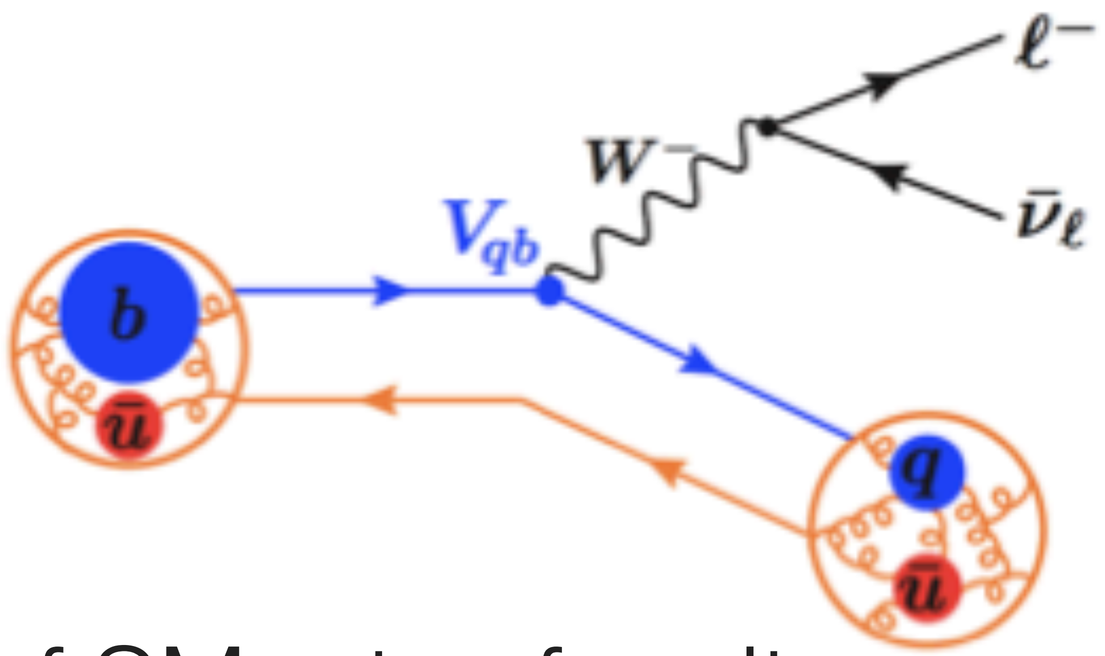
WA (K_S mode only)
S_{CP} = 0.695±0.019
A_{CP} = 0.000±0.020



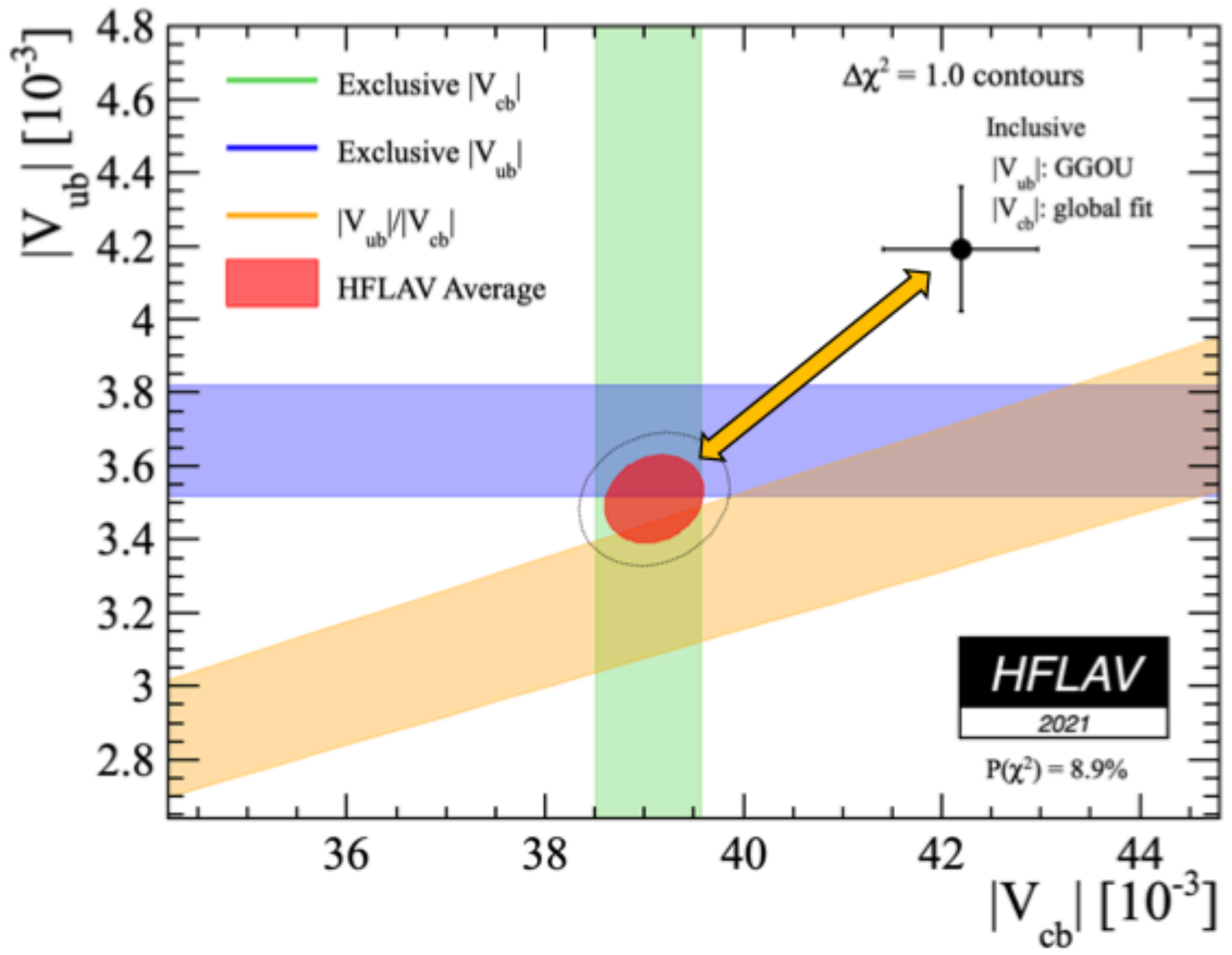
S_{CP} = 0.720 ± 0.062 (stat.) ± 0.016 (syst.)
A_{CP} = 0.094 ± 0.044 (stat.) $^{+0.042}_{-0.017}$ (syst.)

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**$_{\mathbf{ub}}$: $B \to h\ell\bar{\nu}_\ell$ with $h = \pi, \rho, \omega$
    - **V**$_{\mathbf{cb}}$: $B_{(s)} \to D^{(*)}_{(s)}\ell\bar{\nu}_\ell$
  - (signal) inclusive $B \to X_{u,c}\ell\bar{\nu}_\ell$

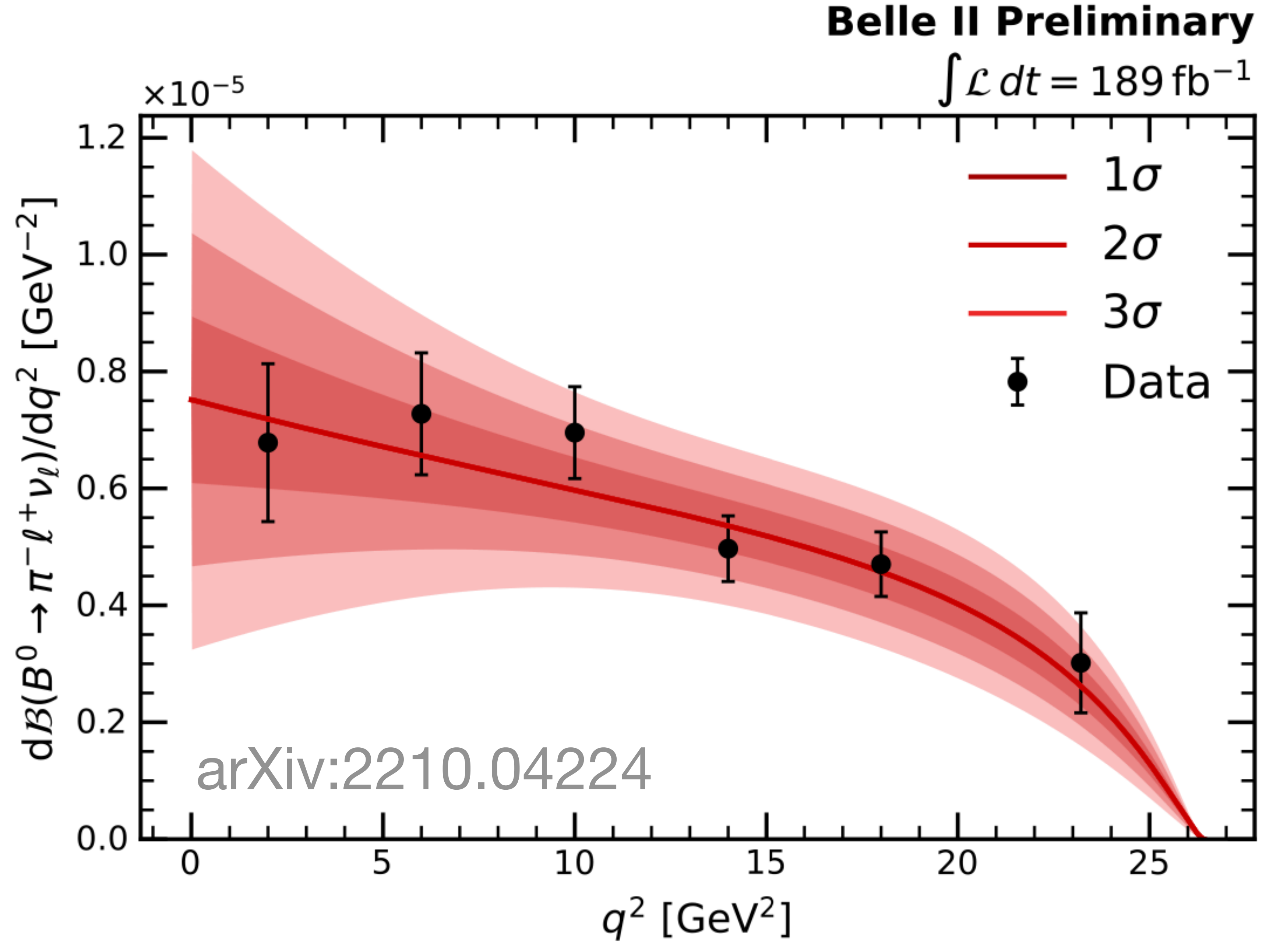


rest-of-event informations used to compute q^2

$|V_{ub}|$ 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)

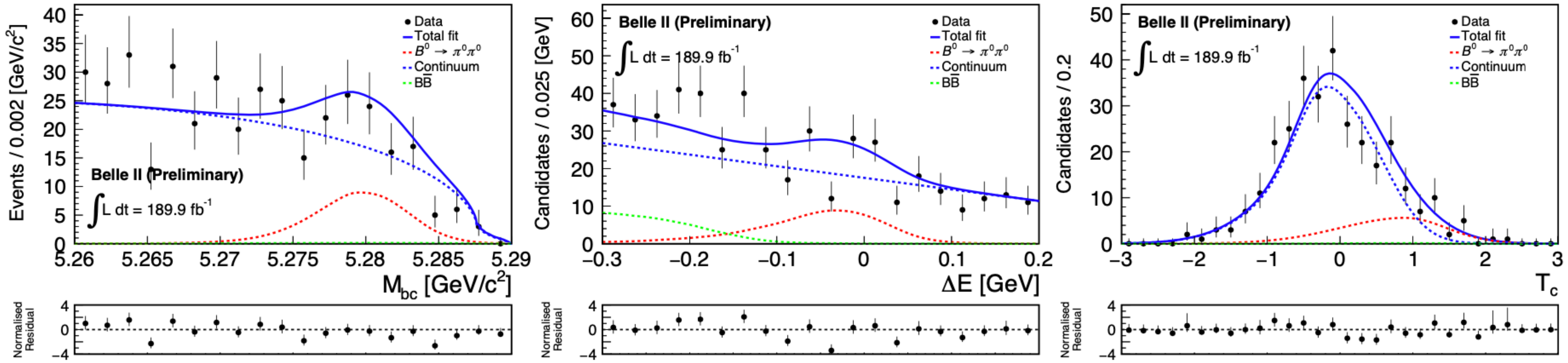
important channel for the measurement of the CKM angle α/ϕ_2

➡ 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, $\varepsilon_{tag} = (30.0\pm1.2\pm0.4)\%$



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

$\Delta E = E_B^* - E_{beam}^*$

continuum suppression output (another B-tool)

➡ Results:

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

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

WA: $A_{CP} = 0.33\pm0.22$, BR = $(1.59\pm0.26)10^{-6}$

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

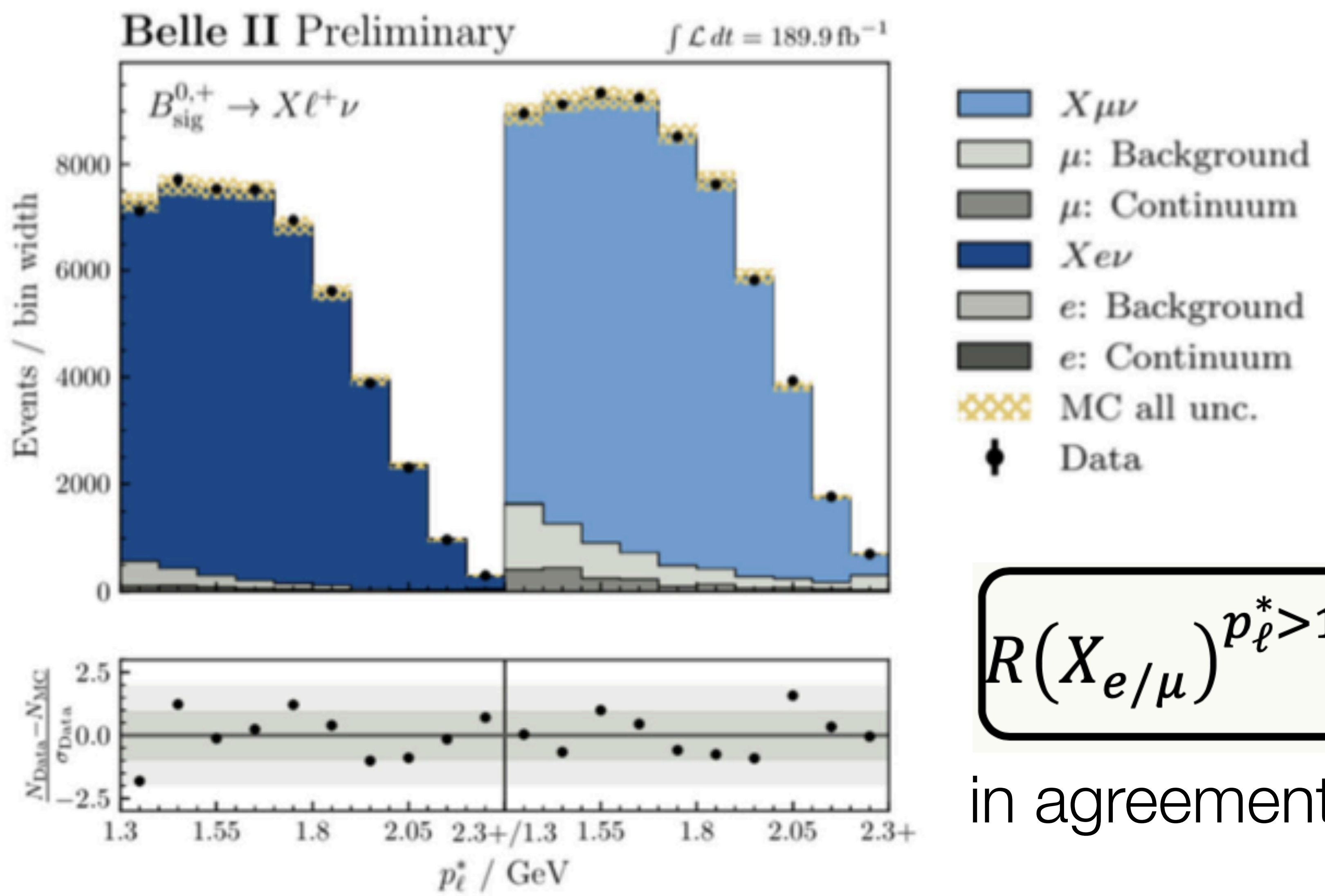
$$A_{CP} = 0.14 \pm 0.36 \pm 0.10$$

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

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

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



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

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

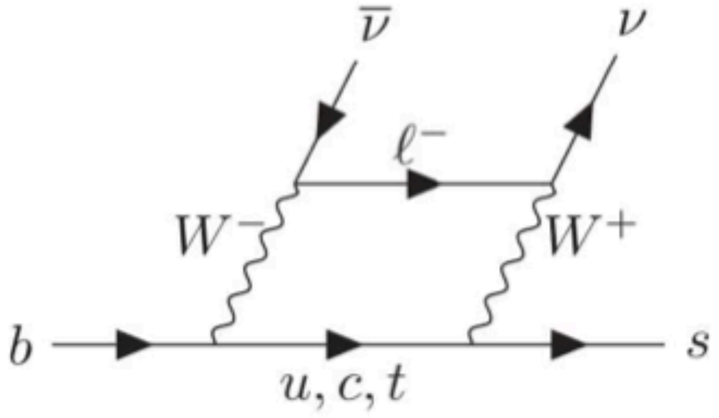
$$R(X_{e/\mu})^{p_\ell^* > 1.3\text{GeV}} = \mathbf{1.033 \pm 0.010^{stat} \pm 0.020^{syst}}$$

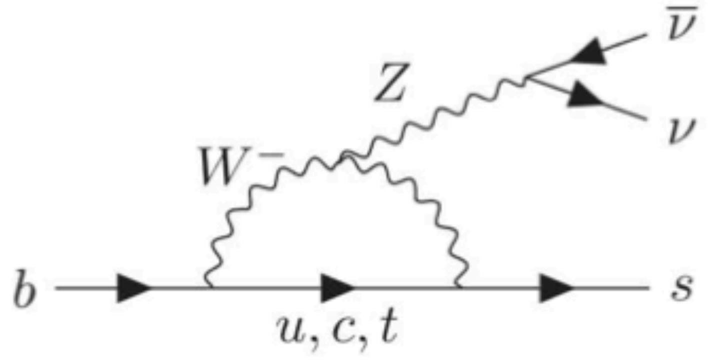
in agreement with SM: 1.006±0.001 (K.Vos, M. Rahimi) in progress

- 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 $R(X_{\tau/\ell})$

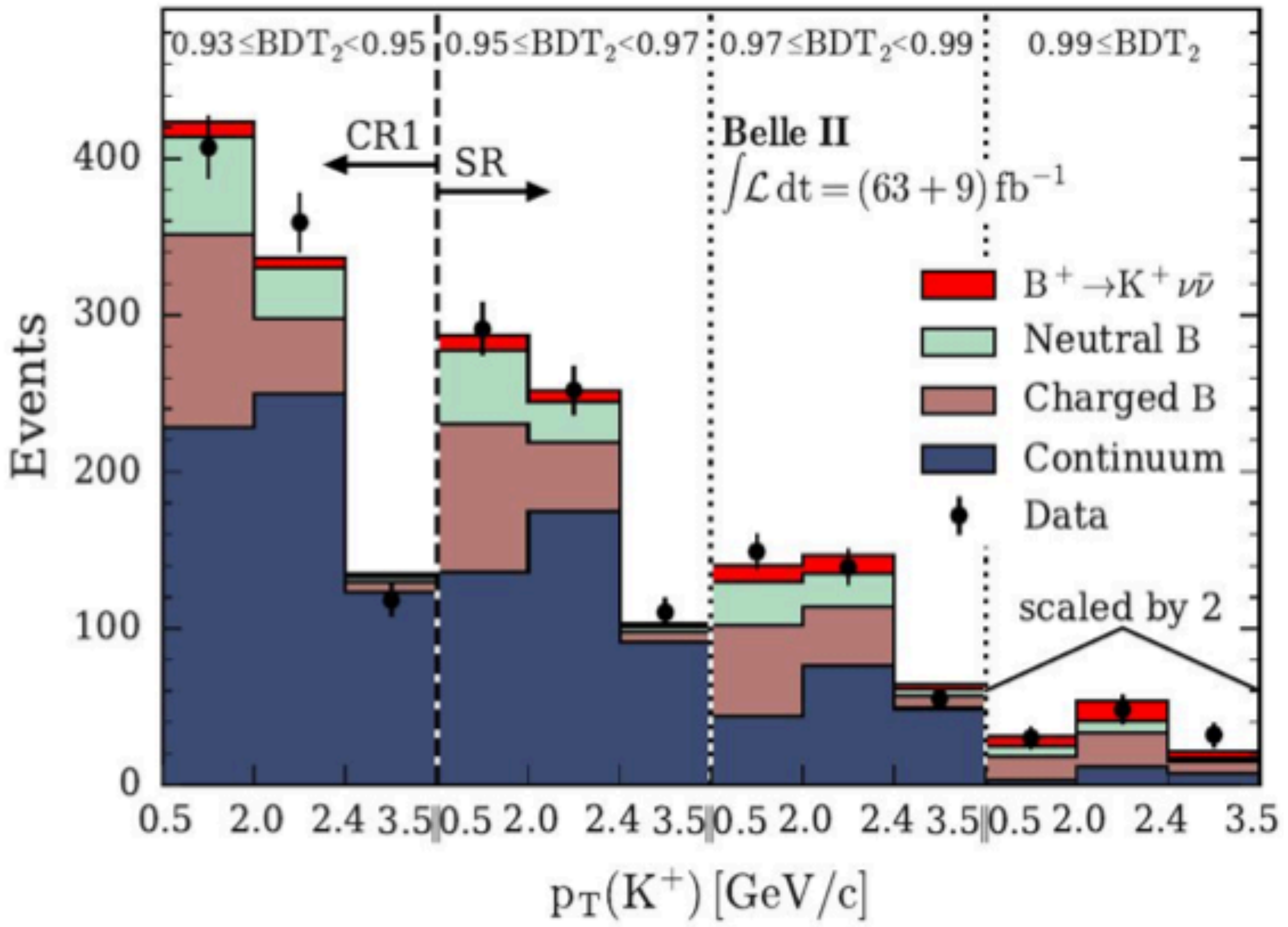
arXiv/2301.08266

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

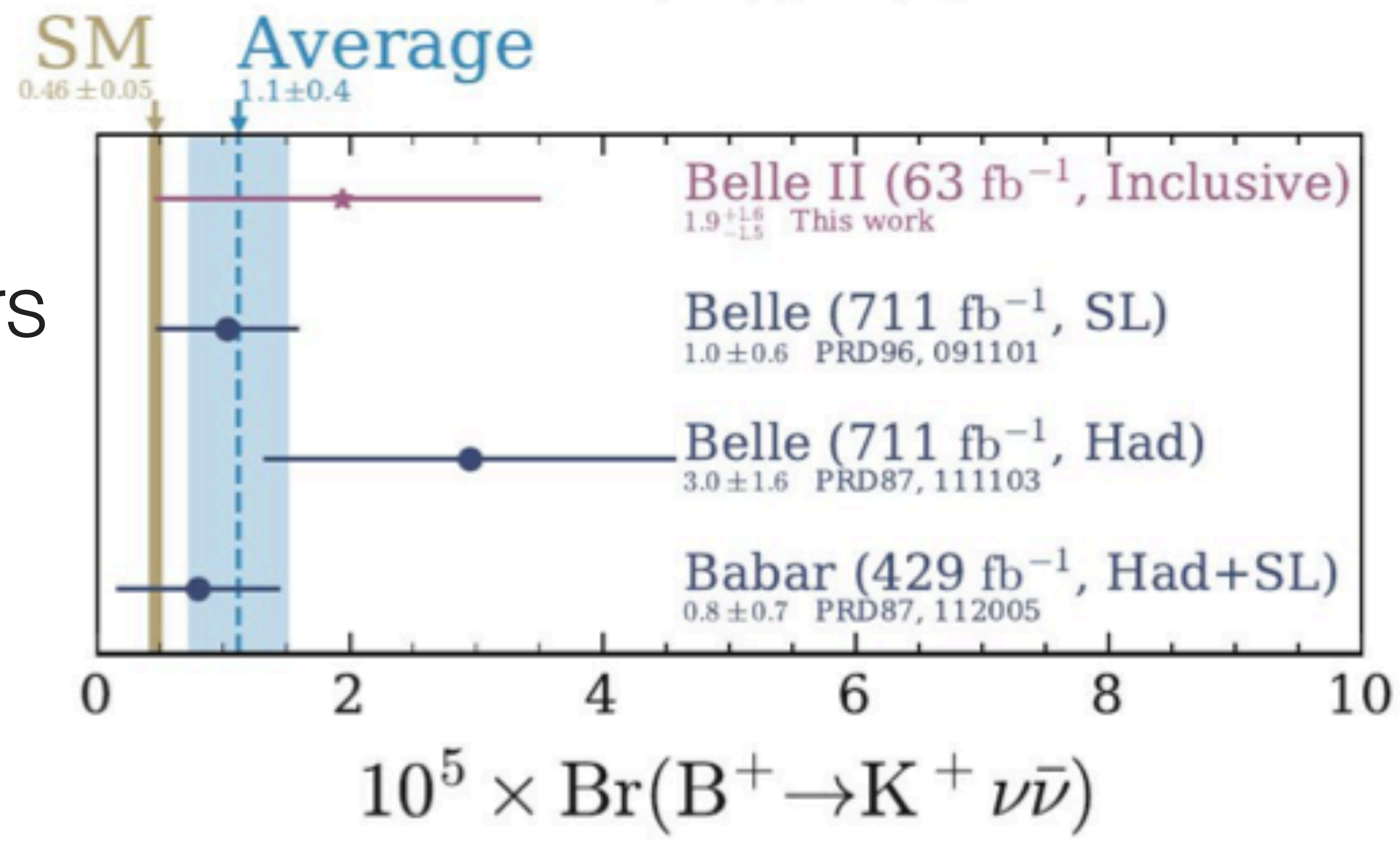




interesting flavour changing neutral current process



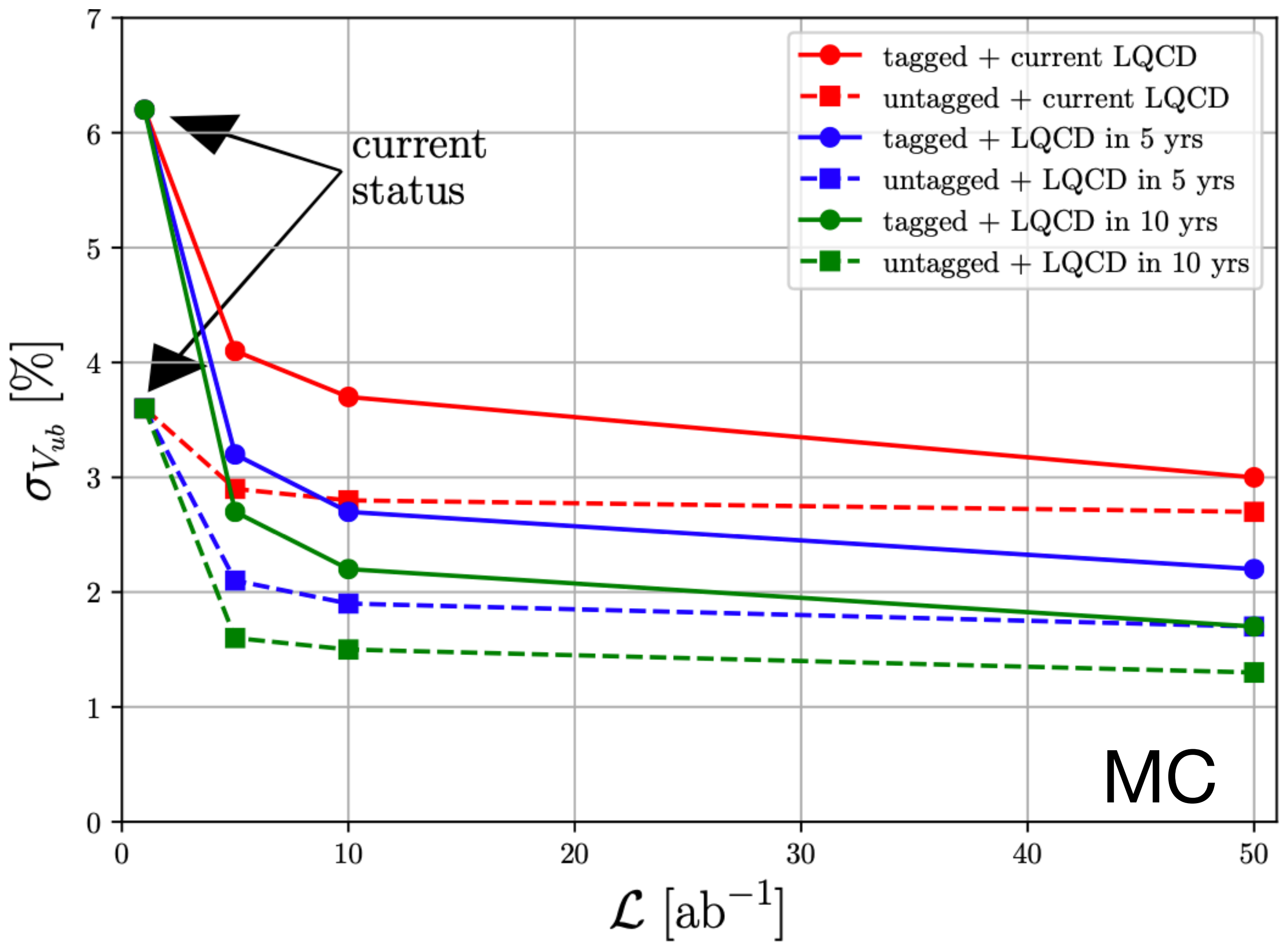
- ➡ FCNC potentially sensitive to non-SM contributions via new particles contributing both in the box and in the penguin diagrams
  - only one Wilson coefficient in SM (C_L^{SM}) , while C_L and C_R probe NP
- ➡ Previous measurements at Belle & *BABAR* were based on *exclusive* reconstruction of the 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

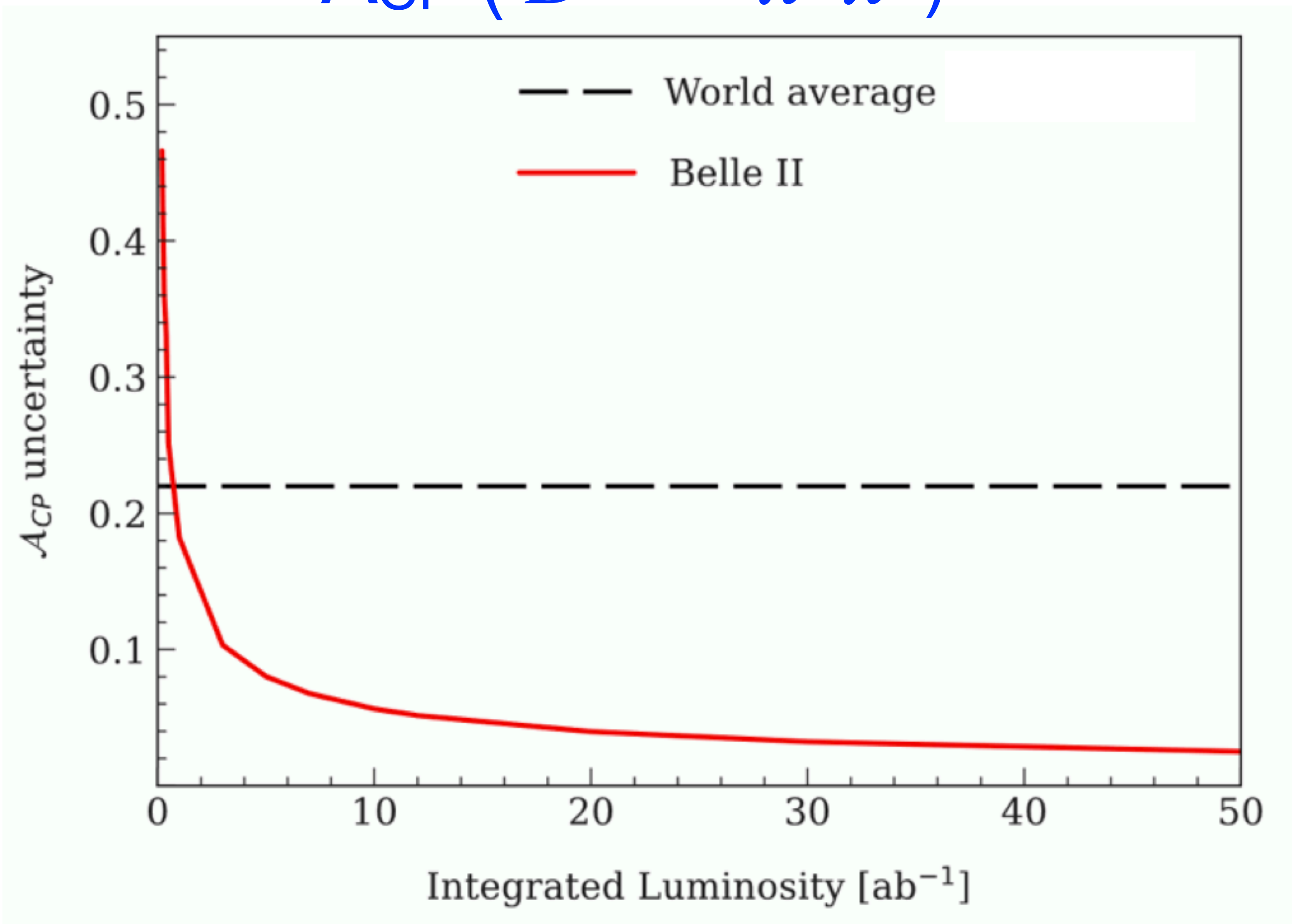
Snowmass White Paper

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



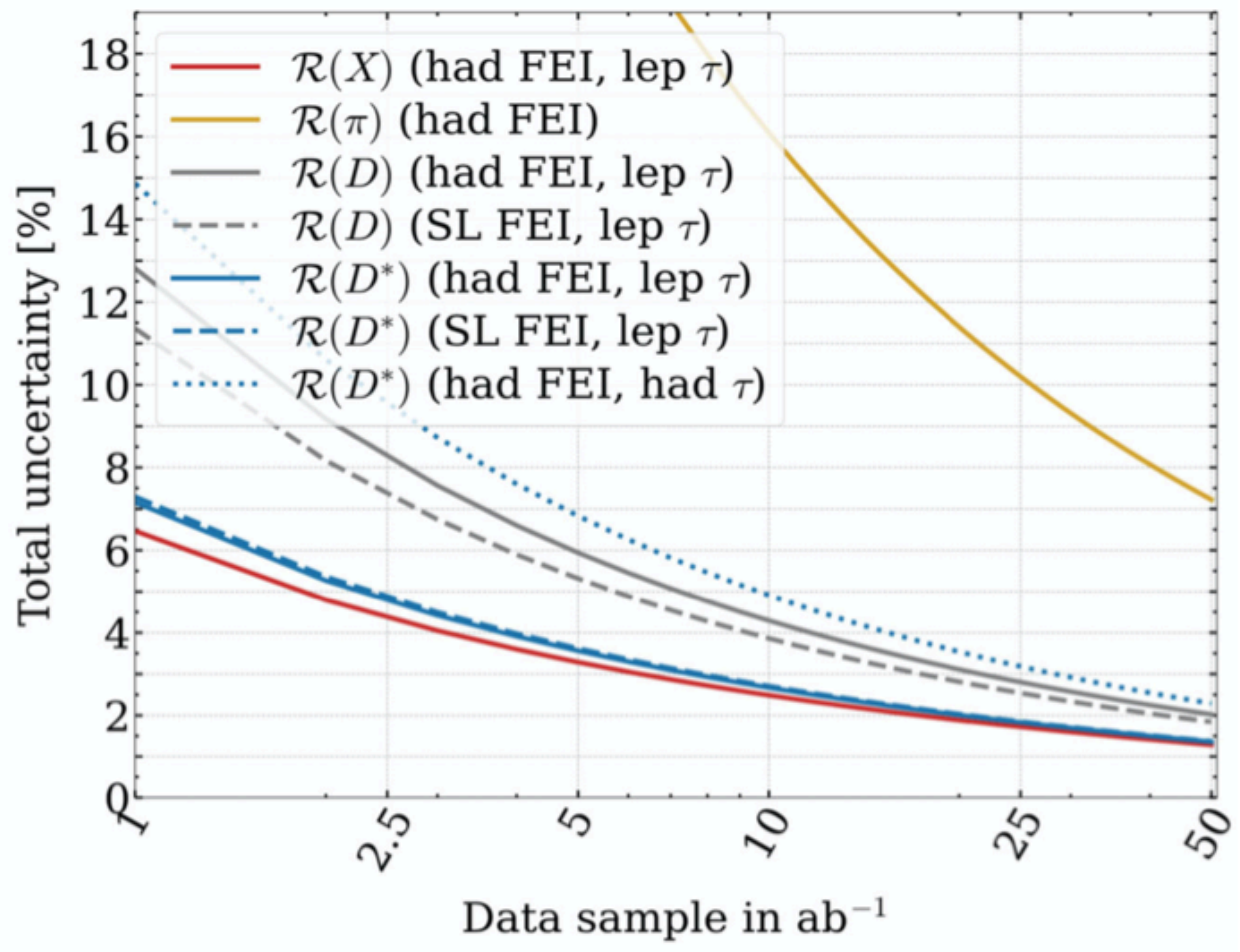
- factional uncertainties below 3% are expected
- will double the global precision exclusive $|V_{ub}|$, also in absence of improvements in theoretical inputs
- with advances in LQCD we can do even better

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



- 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

semitauonic R



- 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

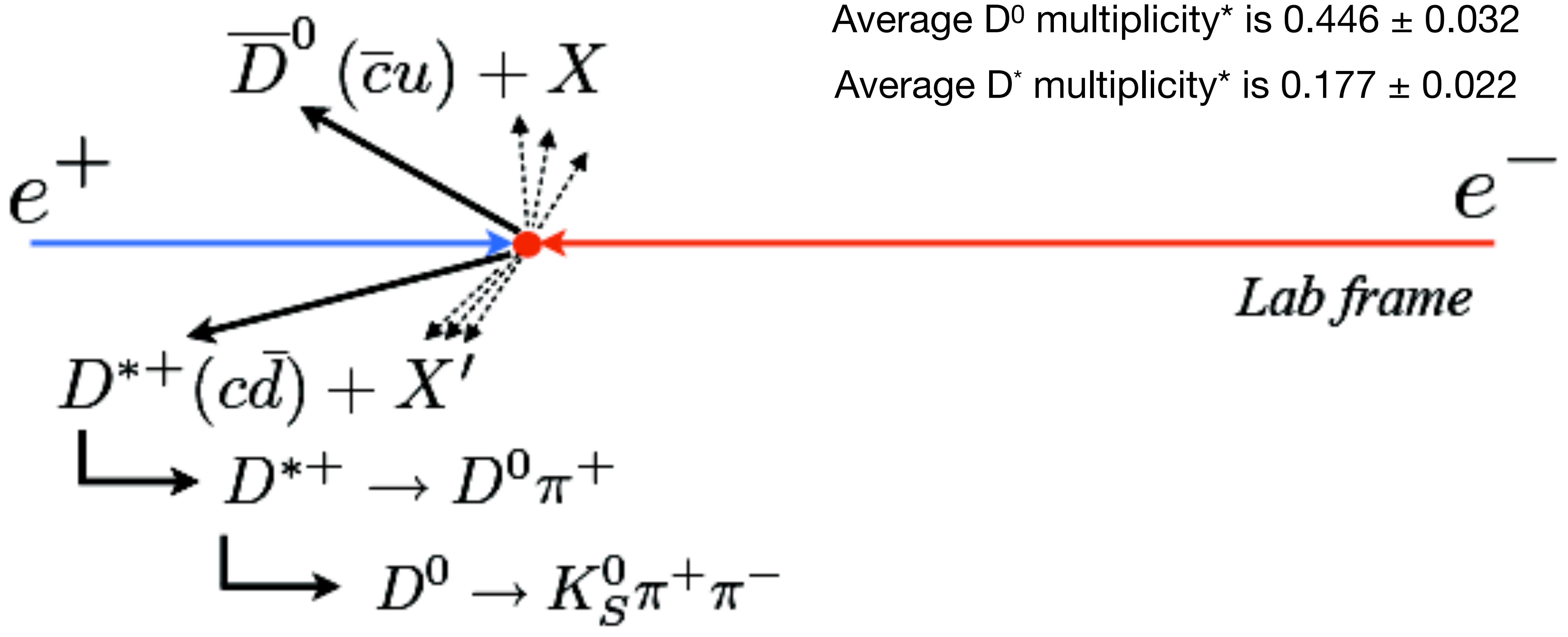
A Charm Event is Different

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

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

mixing & CPV

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

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

➡ 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)

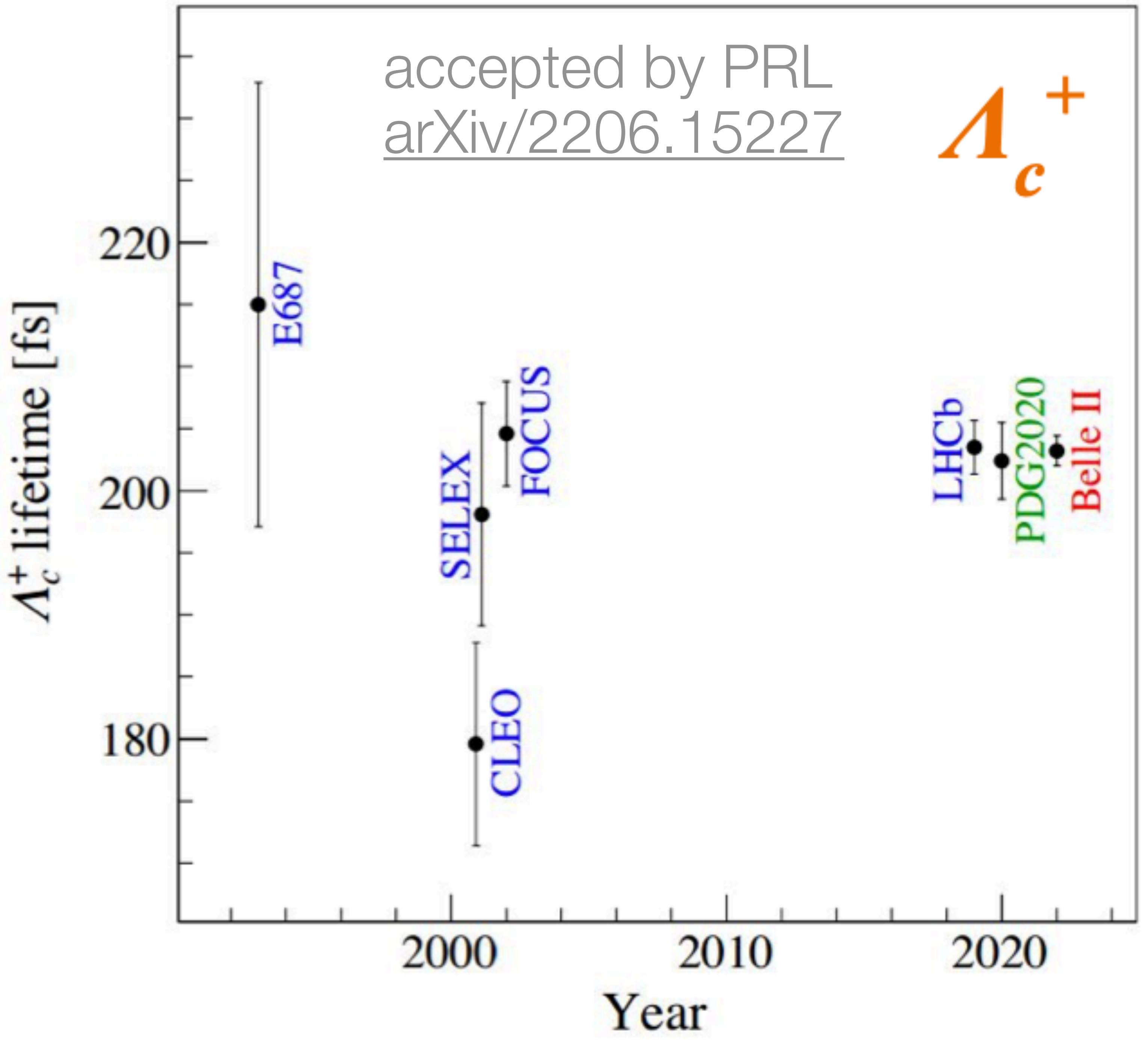
- ➡ interest in improving the precision on these SM measurements

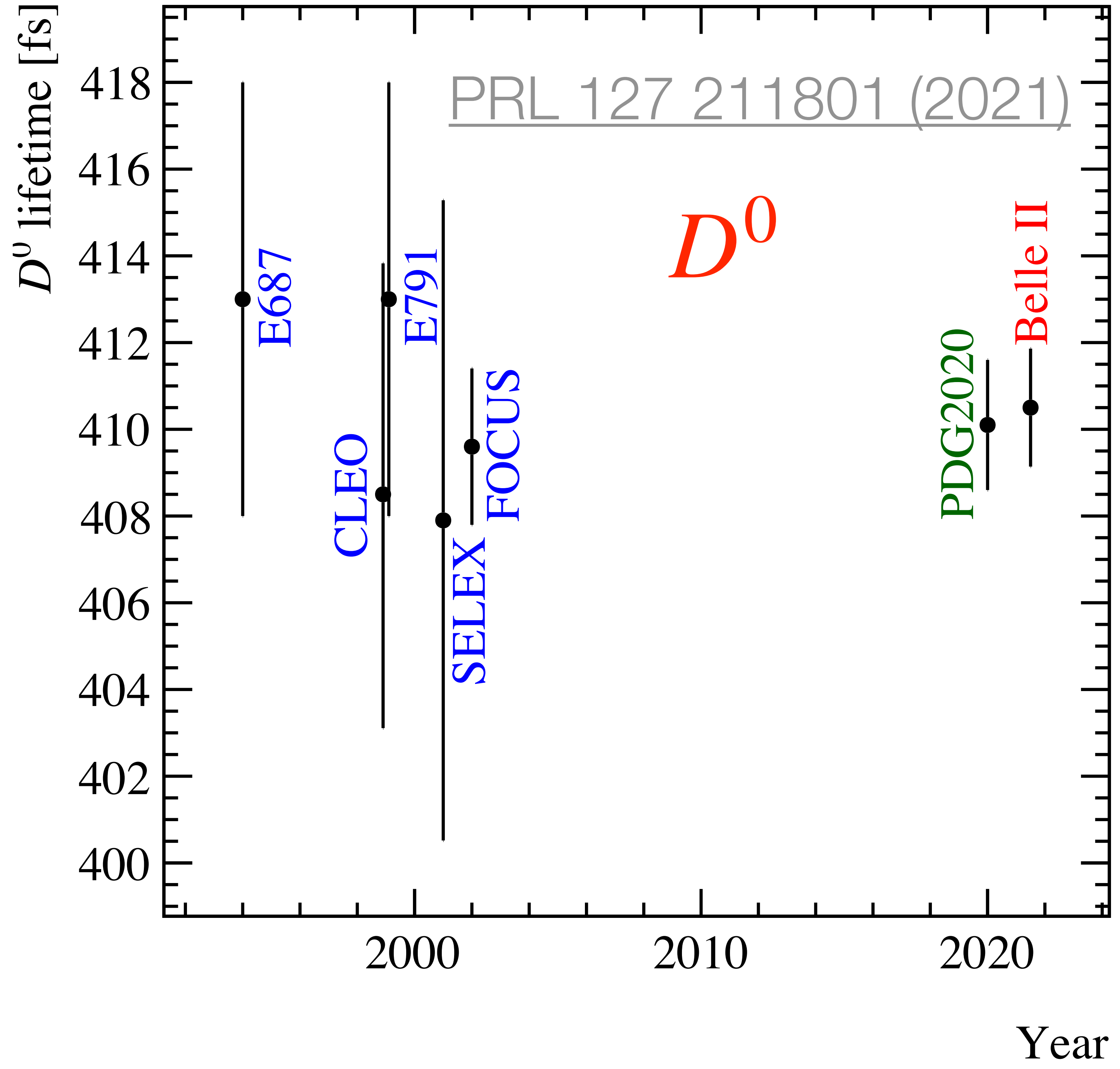
PRL, 121, 092003 (2018)

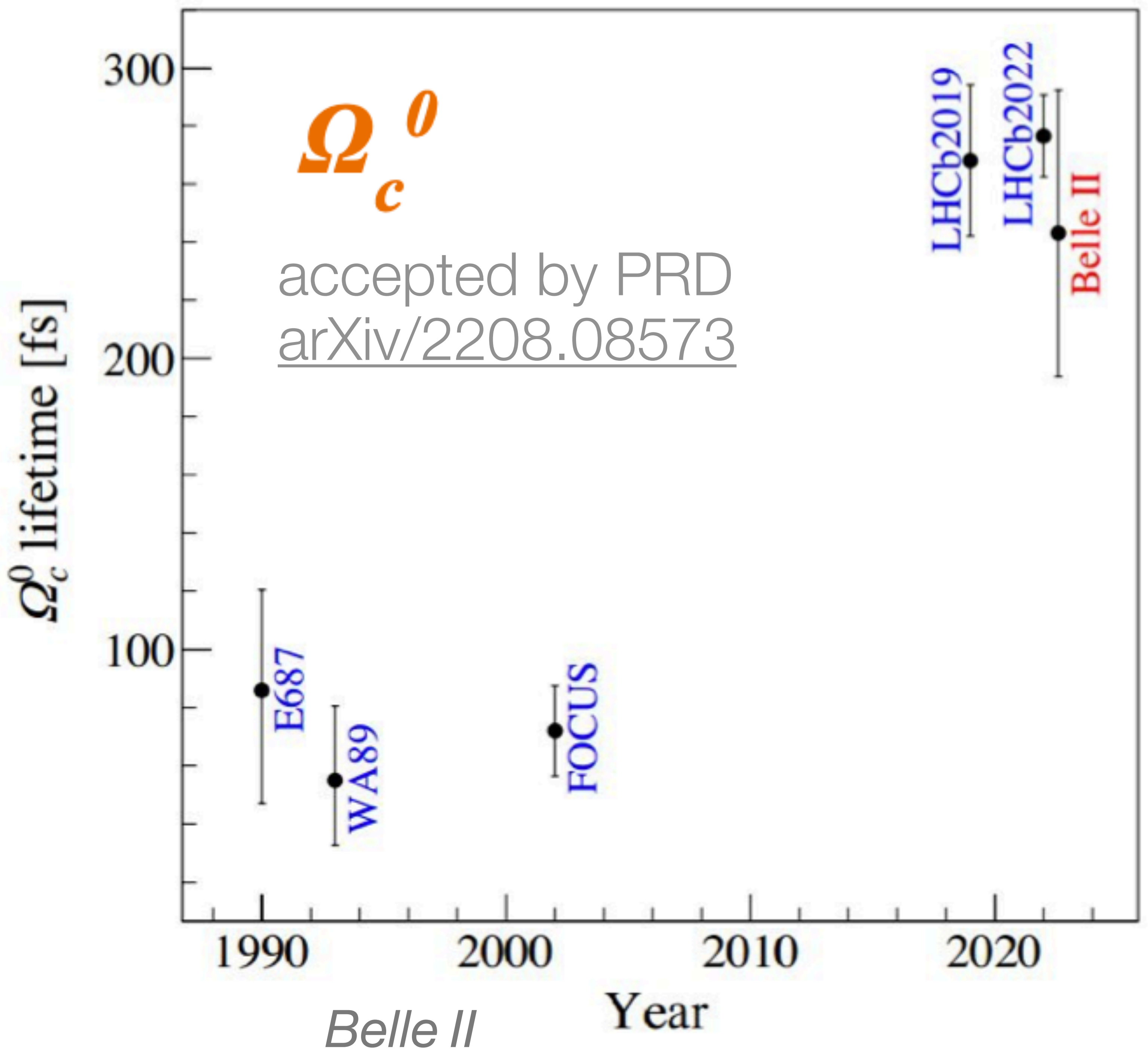
* $\Omega_c \to pKK\pi$ from semileptonic B decays

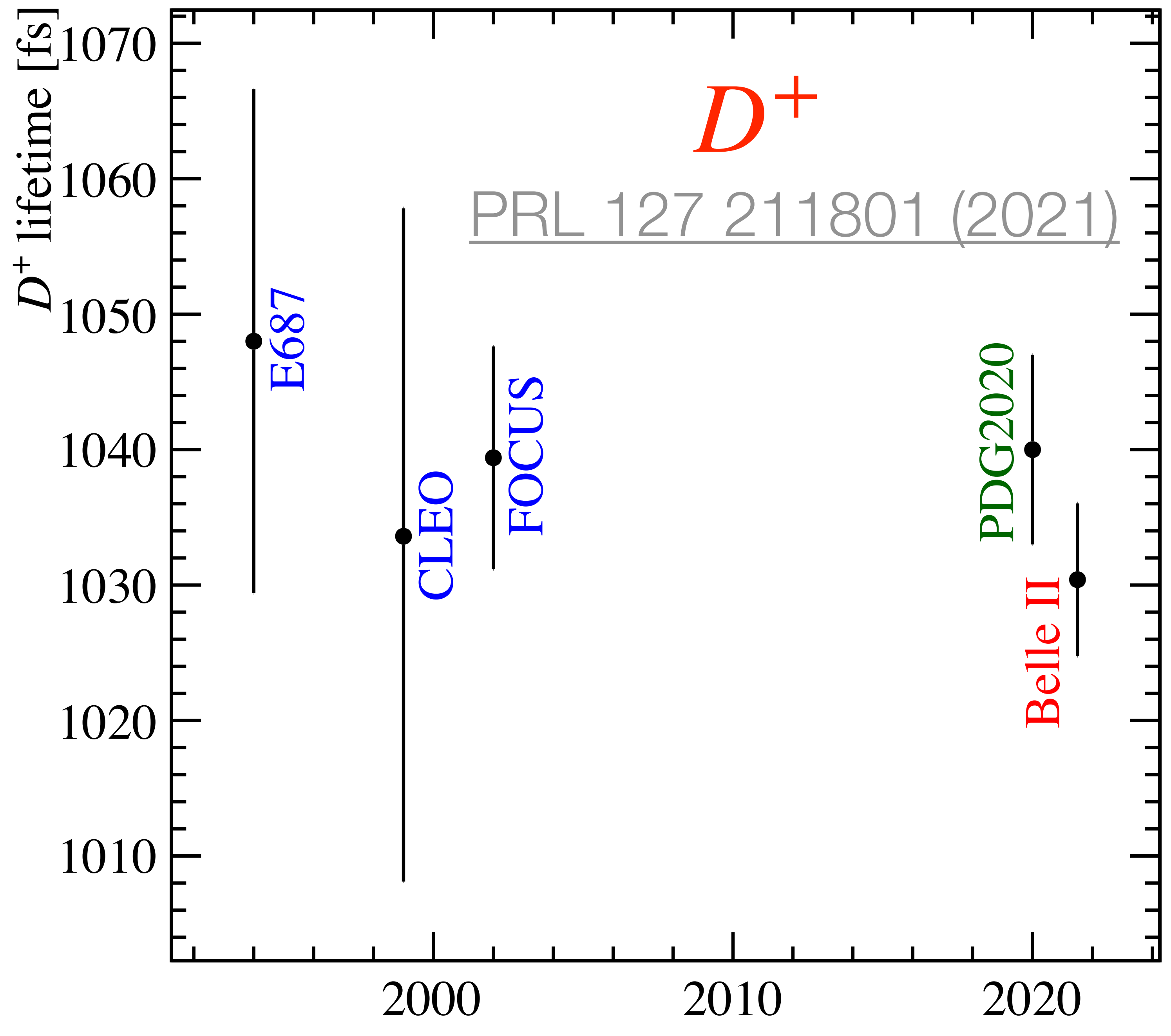
Results

- ➡ 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
$D^0 \to K_S^0\pi^0$	966	$-0.21 \pm 0.16 \pm 0.07$	± 0.02
$D^0 \to K_S^0K_S^0$	921	$-0.02 \pm 1.53 \pm 0.02 \pm 0.17$	± 0.23
$D^0 \to K_S^0\eta$	791	$+0.54 \pm 0.51 \pm 0.16$	± 0.07
$D^0 \to K_S^0\eta'$	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
$D^+ \to K_S^0\pi^+$	977	$-0.36 \pm 0.09 \pm 0.07$	± 0.02
$D^+ \to K_S^0K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	± 0.04
$D_s^+ \to K_S^0\pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	± 0.29
$D_s^+ \to K_S^0K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.05

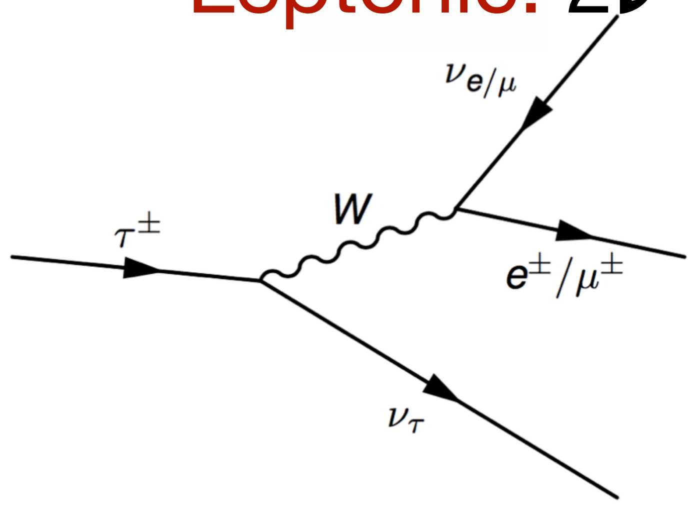
$D_s^+ \to K^+\pi^0$

note: this is not a complete list

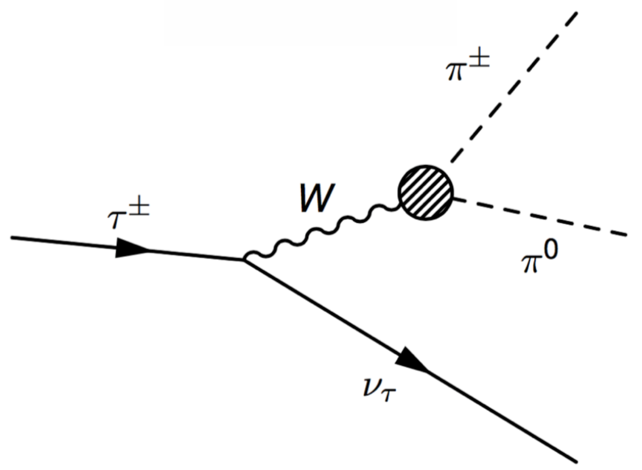
τ physics

τ Physics
at Belle II

Leptonic: 2ν



Hadronic: 1ν



➡ rich program of high-precision measurements:

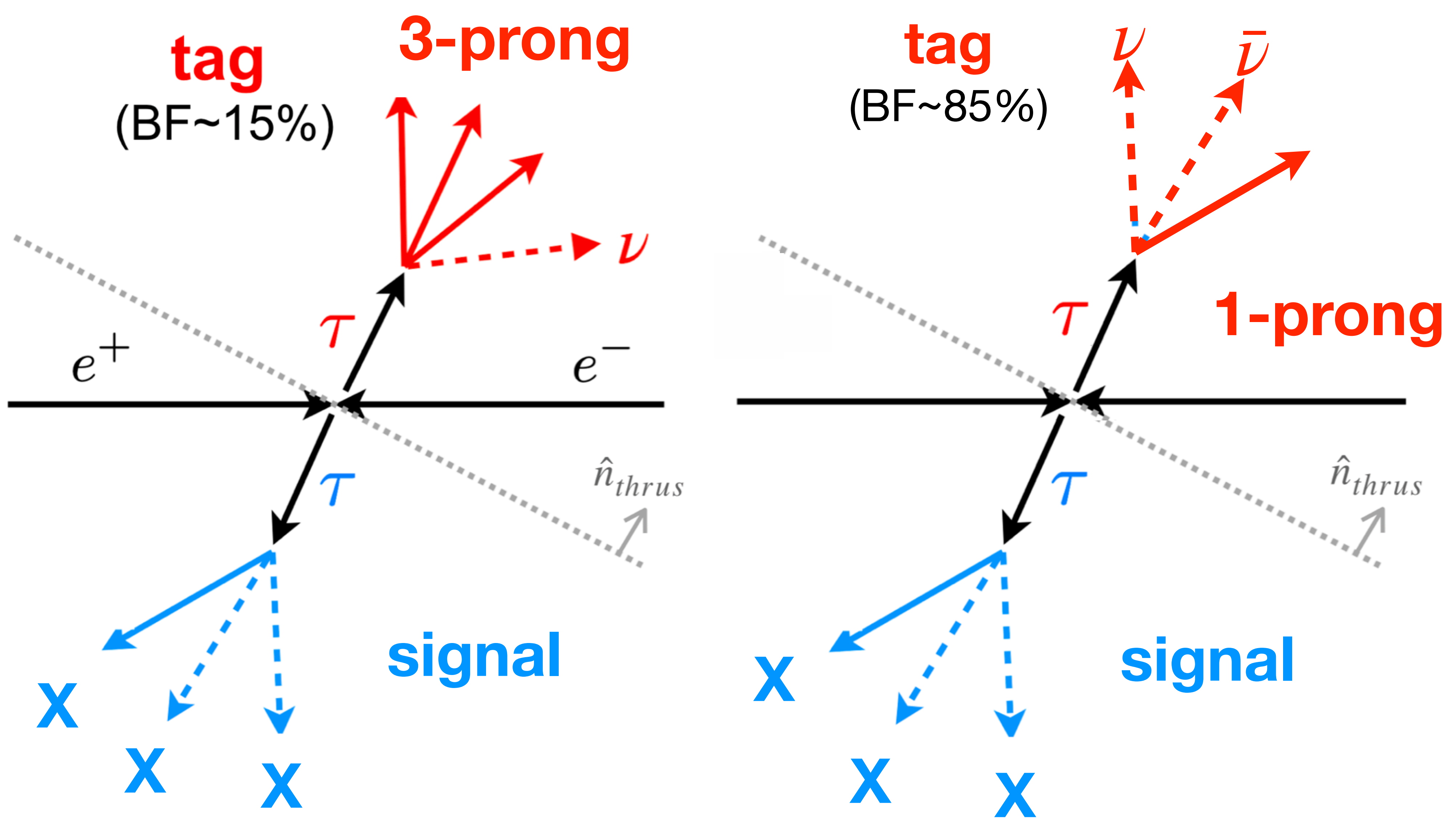
- lifetime & mass (SM)
- V_{us}, CP asymmetries e.g. $\tau \to K_S\pi\nu$
- LFV searches & LFU tests

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

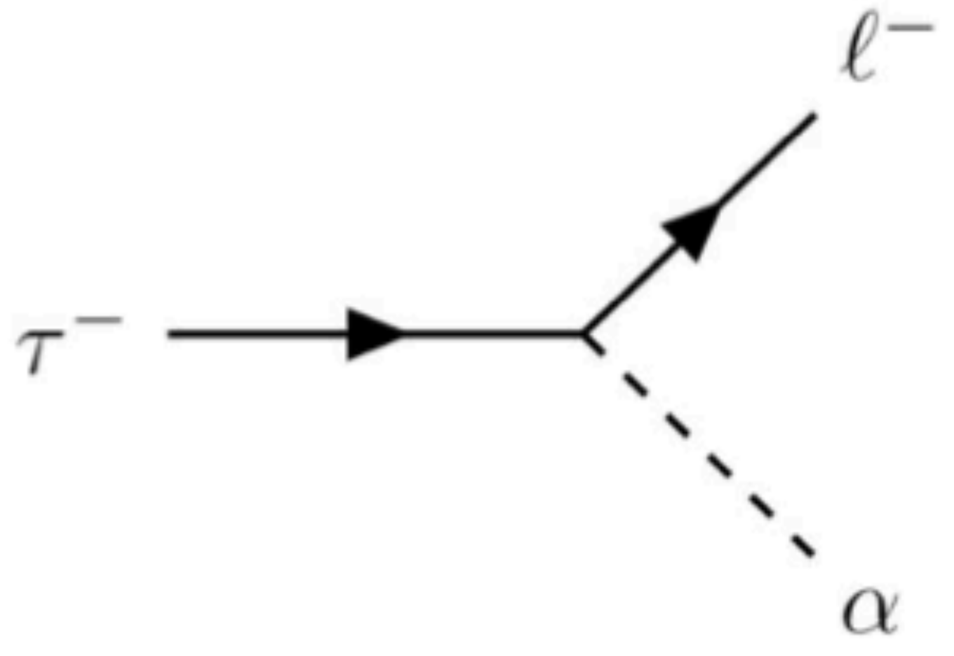
- well defined initial state energy & clean environment
- high hermiticity of the detector & precise knowledge of acceptance and efficiency
- dedicated low-multiplicity triggers lines

➡ 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



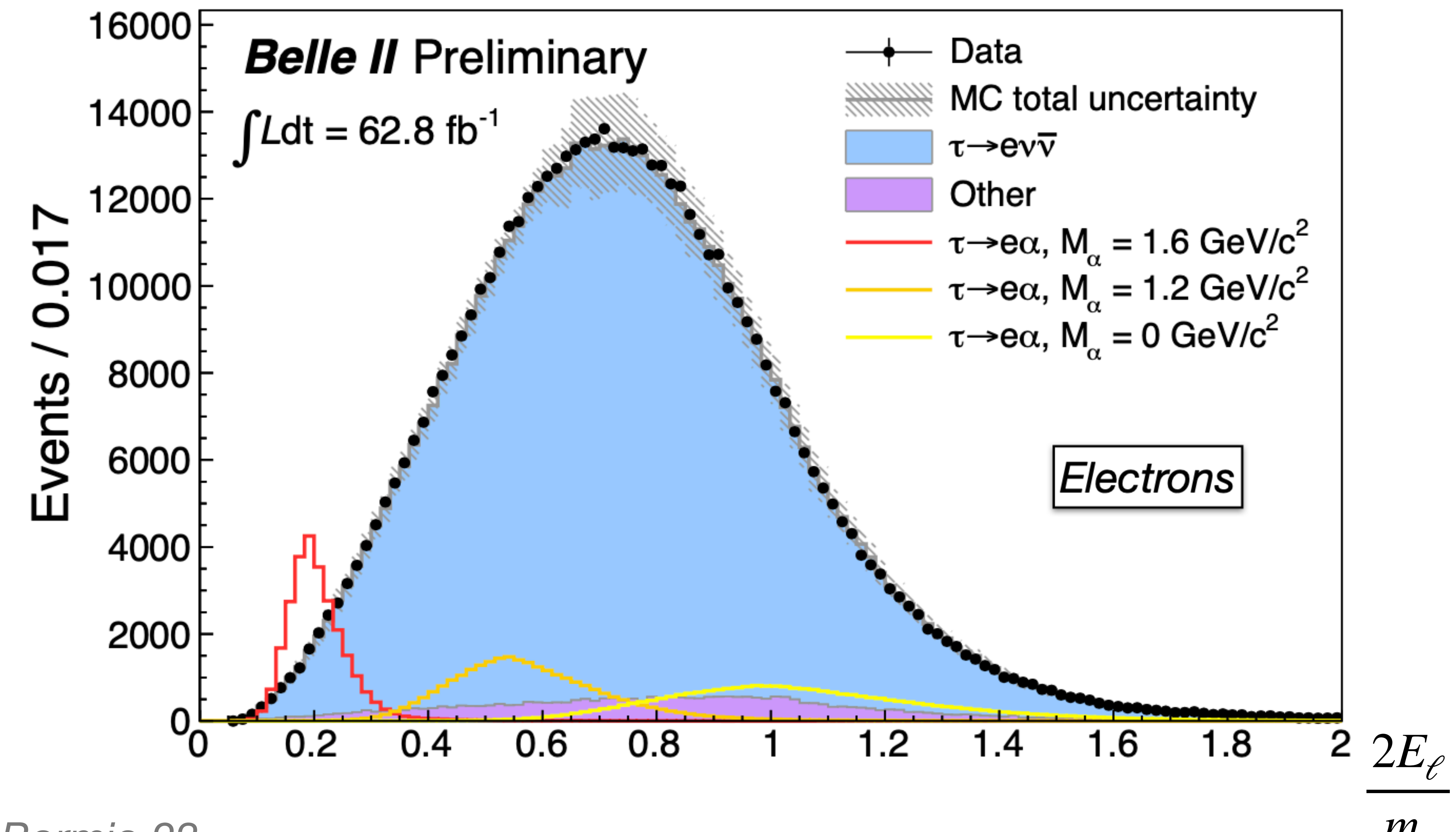
$\tau \to \ell\, \alpha$ (invisible)

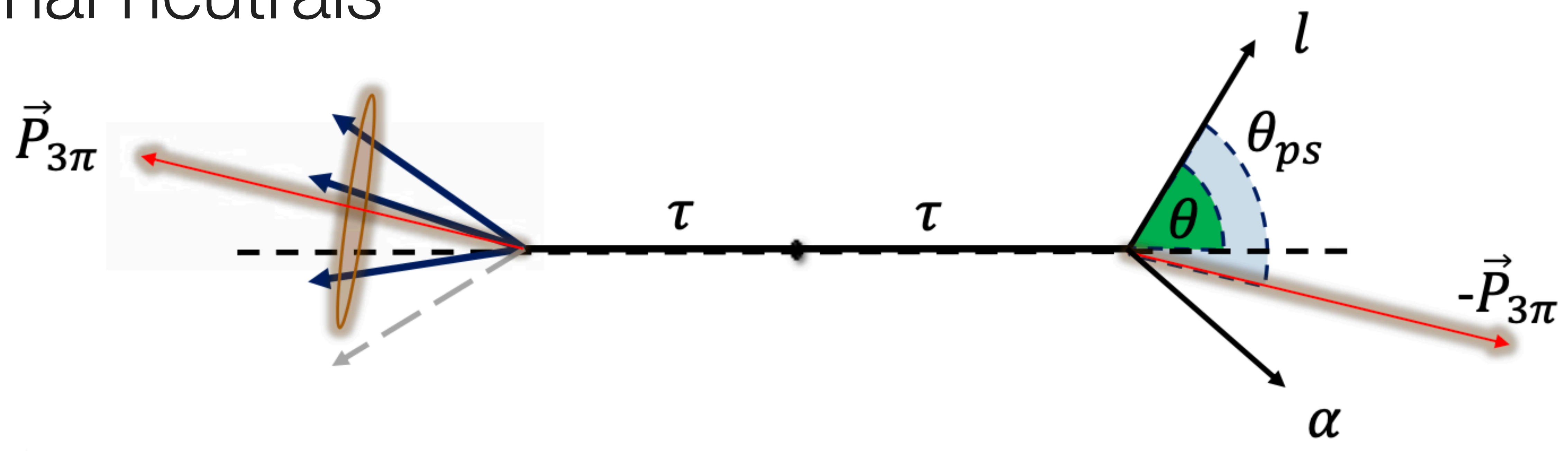


➡ Neutrino-less LFV decays are sensitive probes of New Physics

- 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)

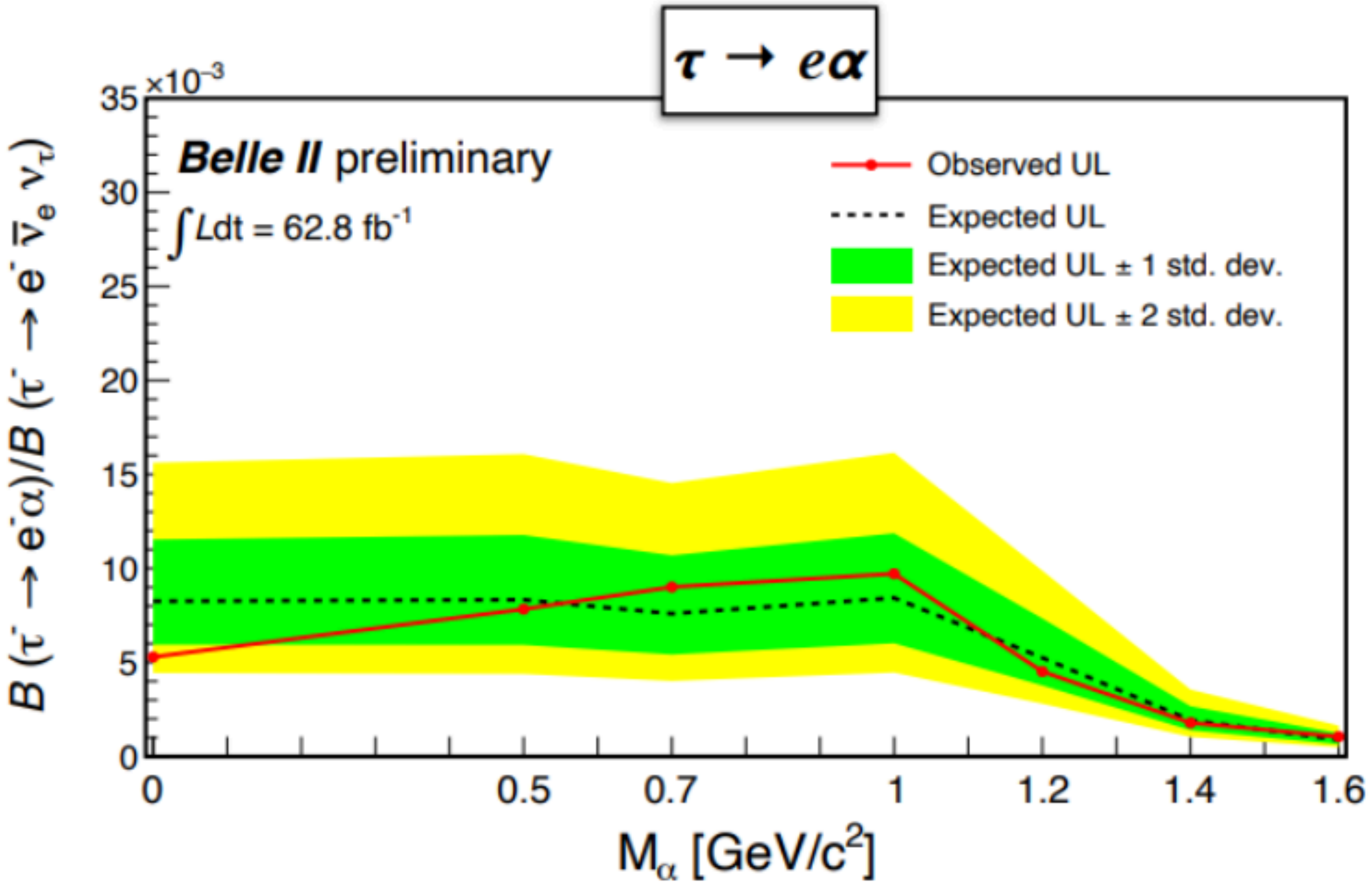
results

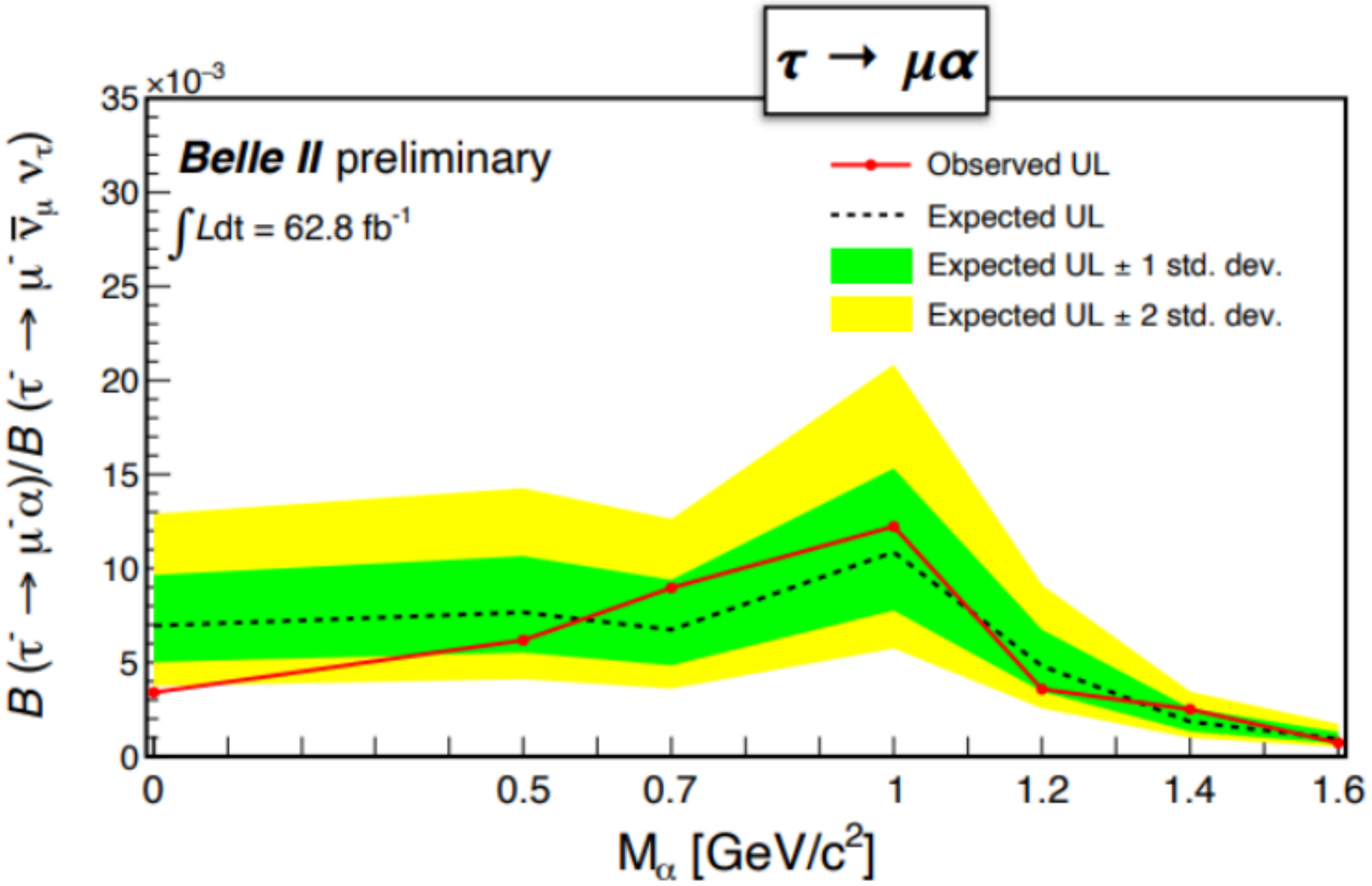
submitted to PRL
arXiv/2212.03634

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

- previous measurement by ARGUS with 0.5/fb

Z. Phys. C 68 (1995) 25



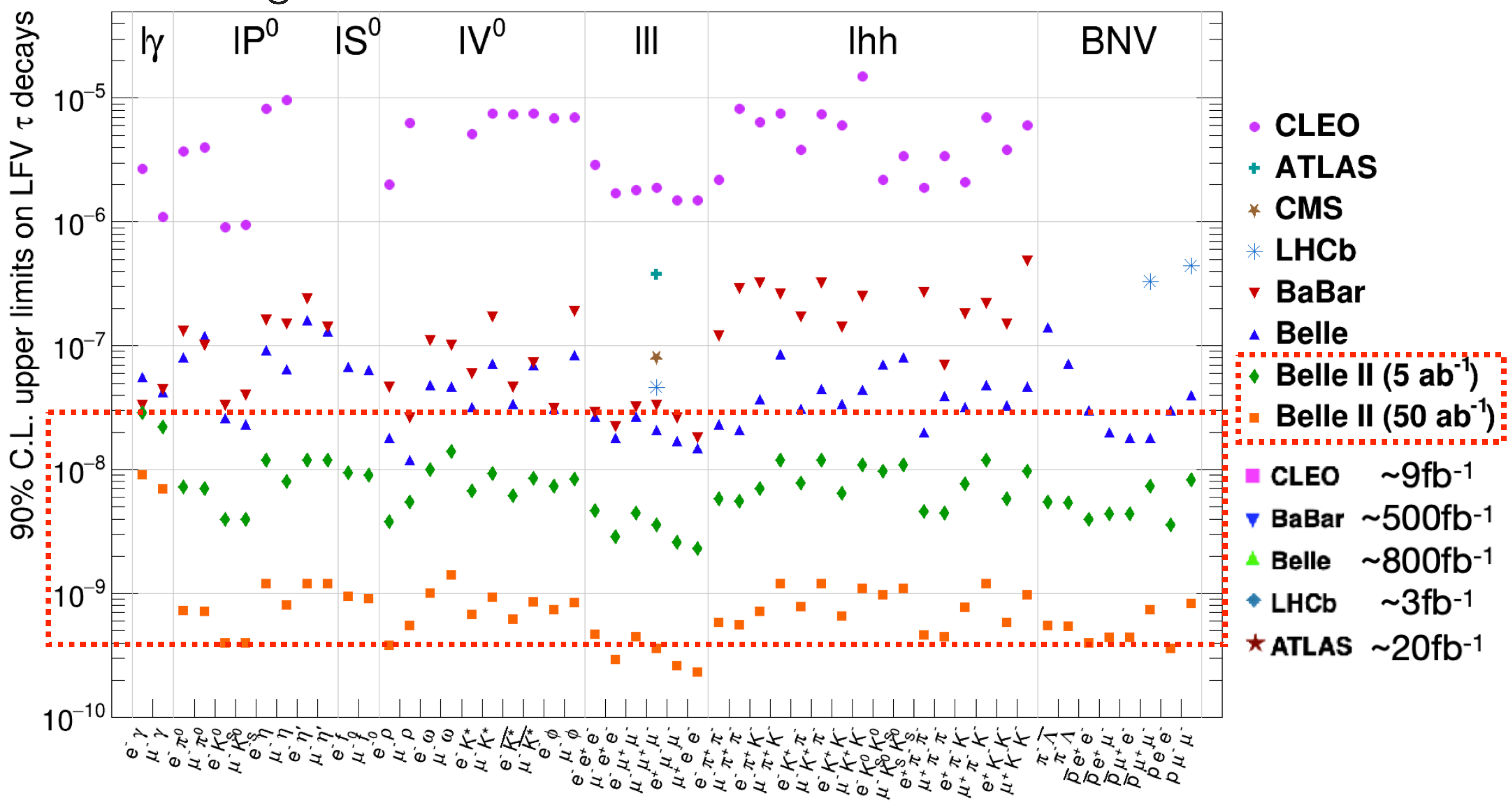


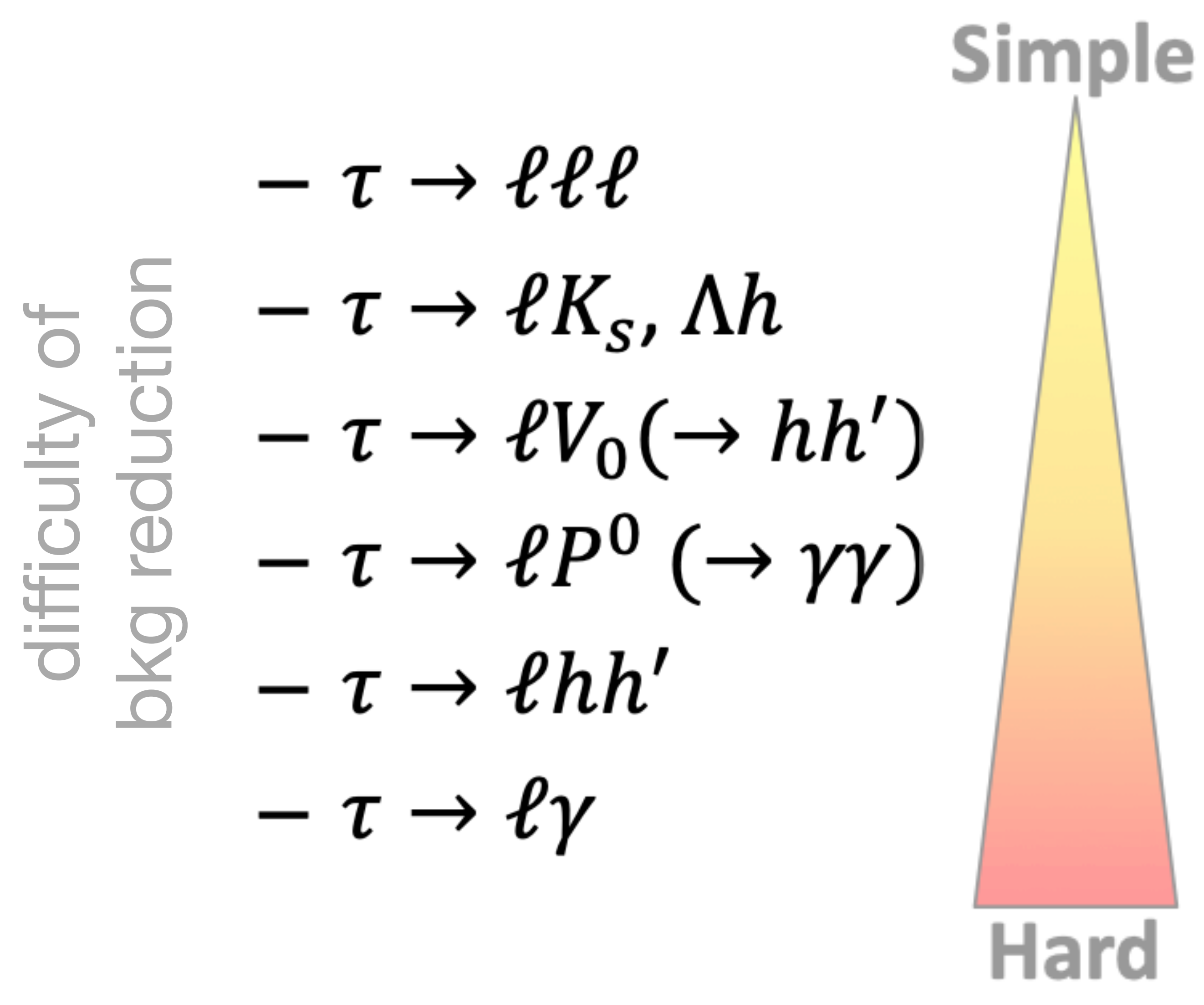
➡ most stringent limits in these channels to date

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





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).

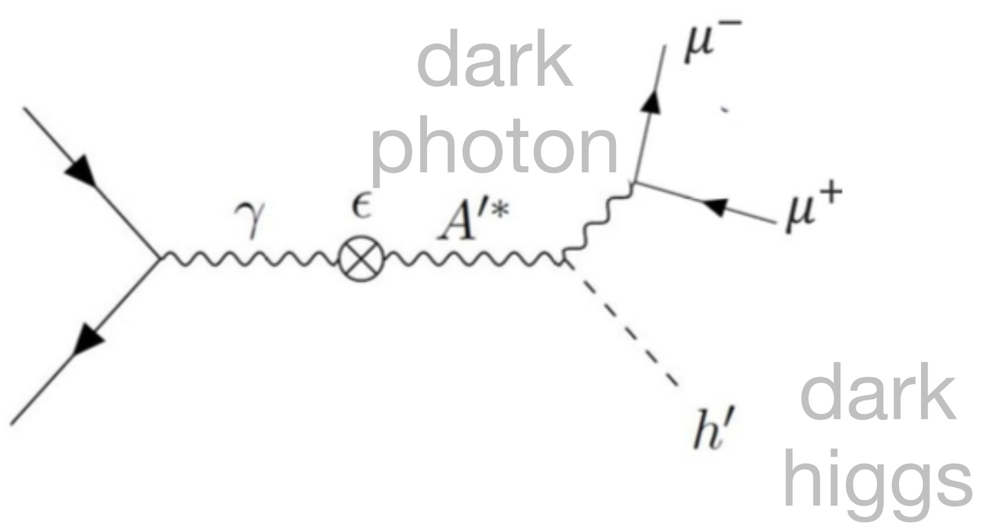
dark sector physics

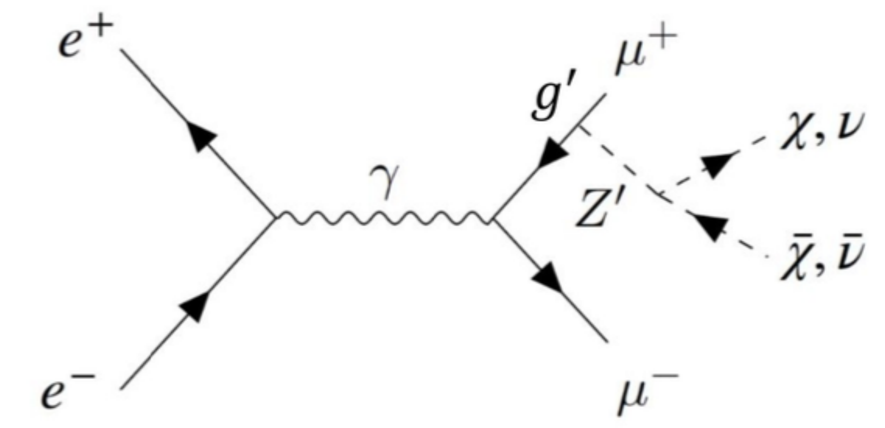
Dark Sector

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

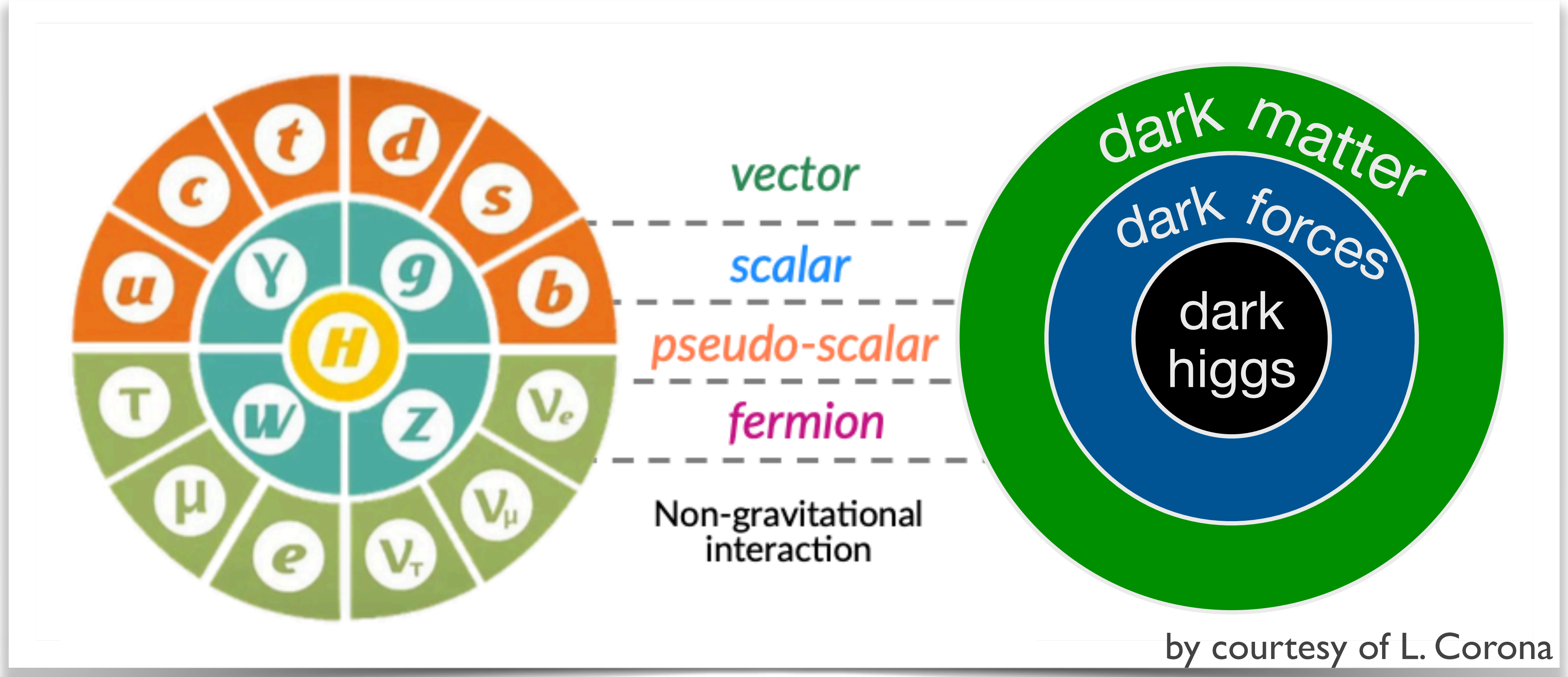


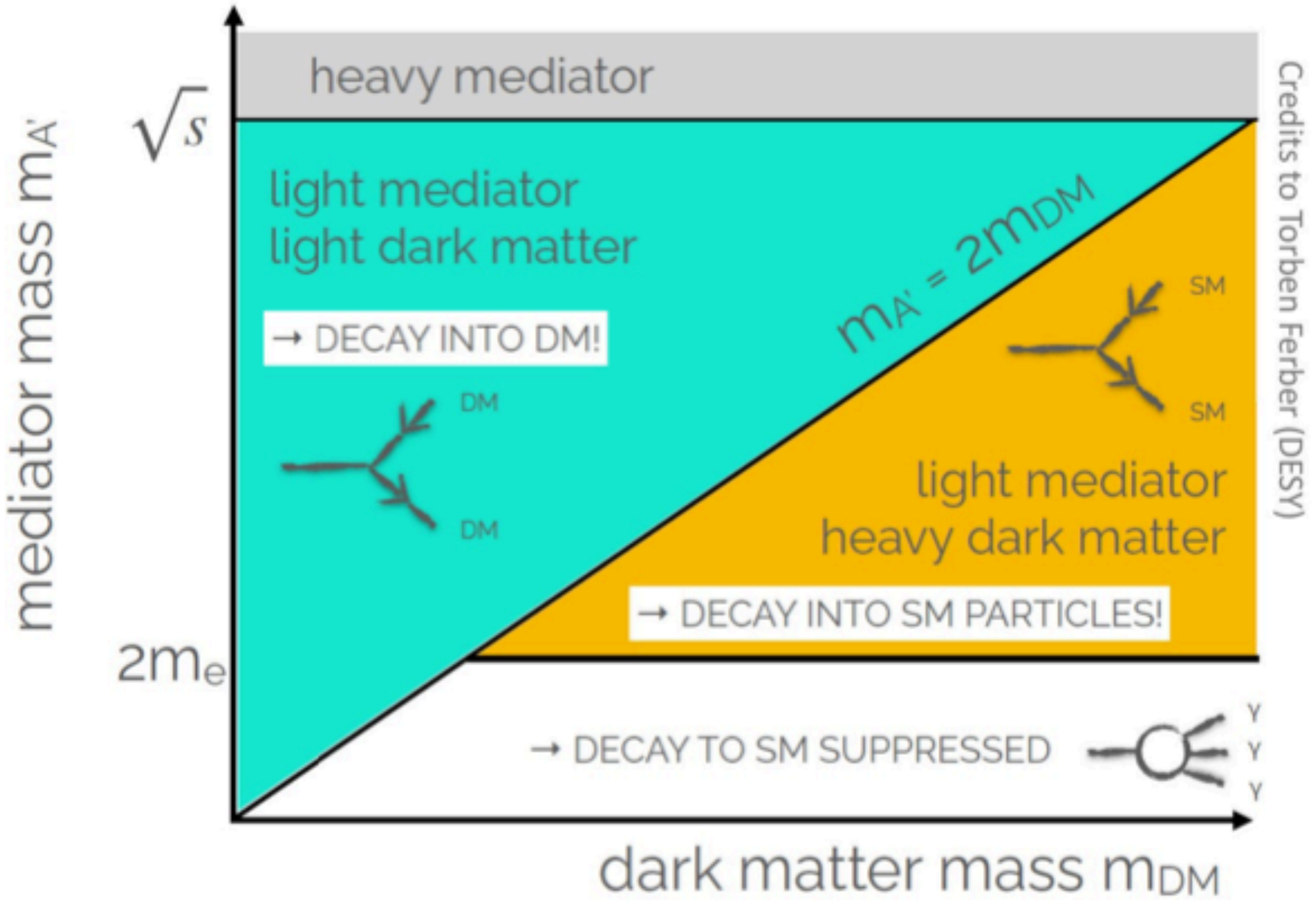


$e^+e^- \to \mu^+\mu^- Z'(\to \text{invisible})$

➡ The main challenge at *Belle II* is to suppress the large SM background, saving the signal

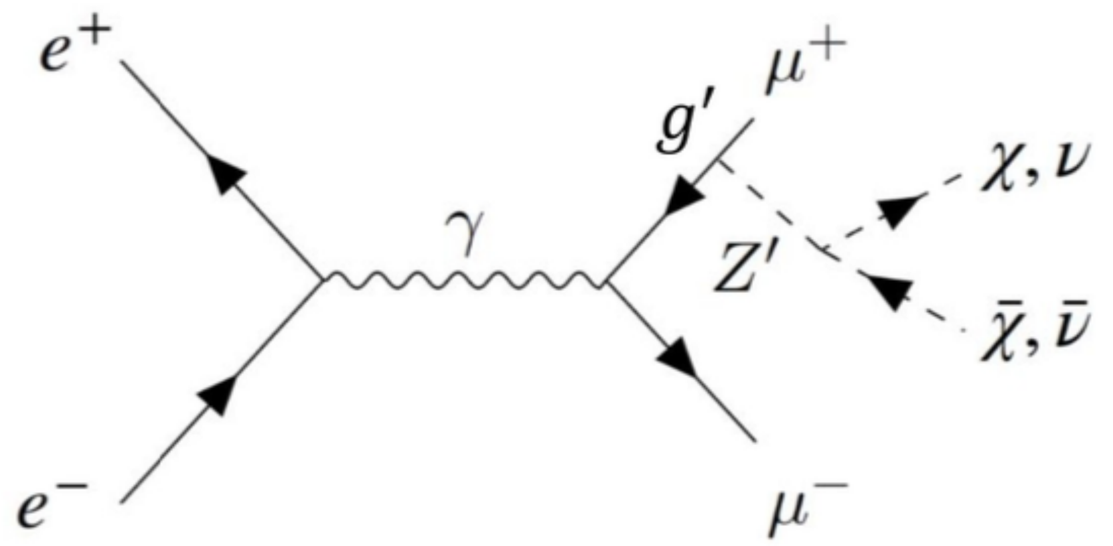
- dedicated low-multiplicity triggers
- precise knowledge of acceptance and efficiency





submitted to PRL
arXiv/2212.03066

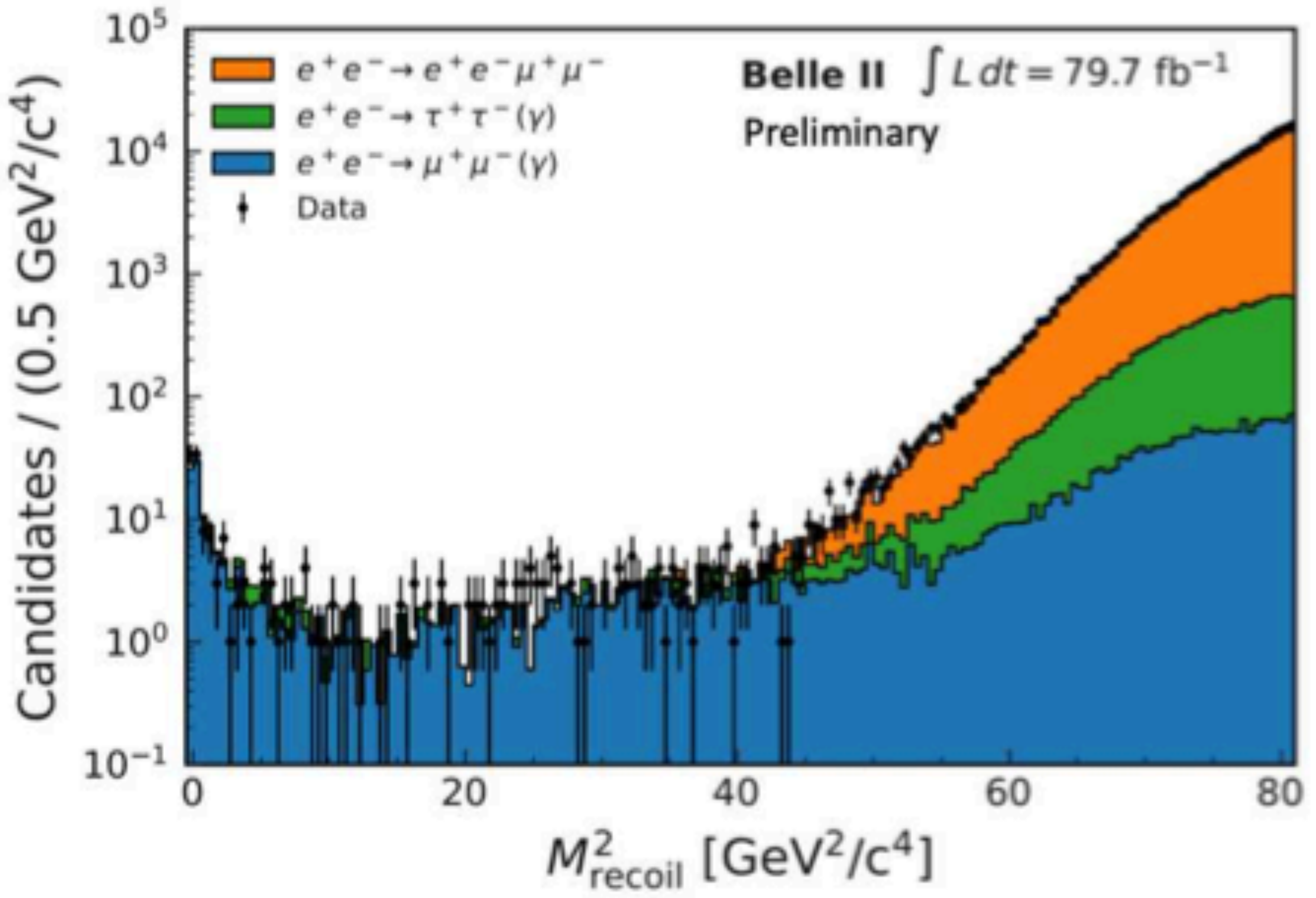
Z’ → Invisibile



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

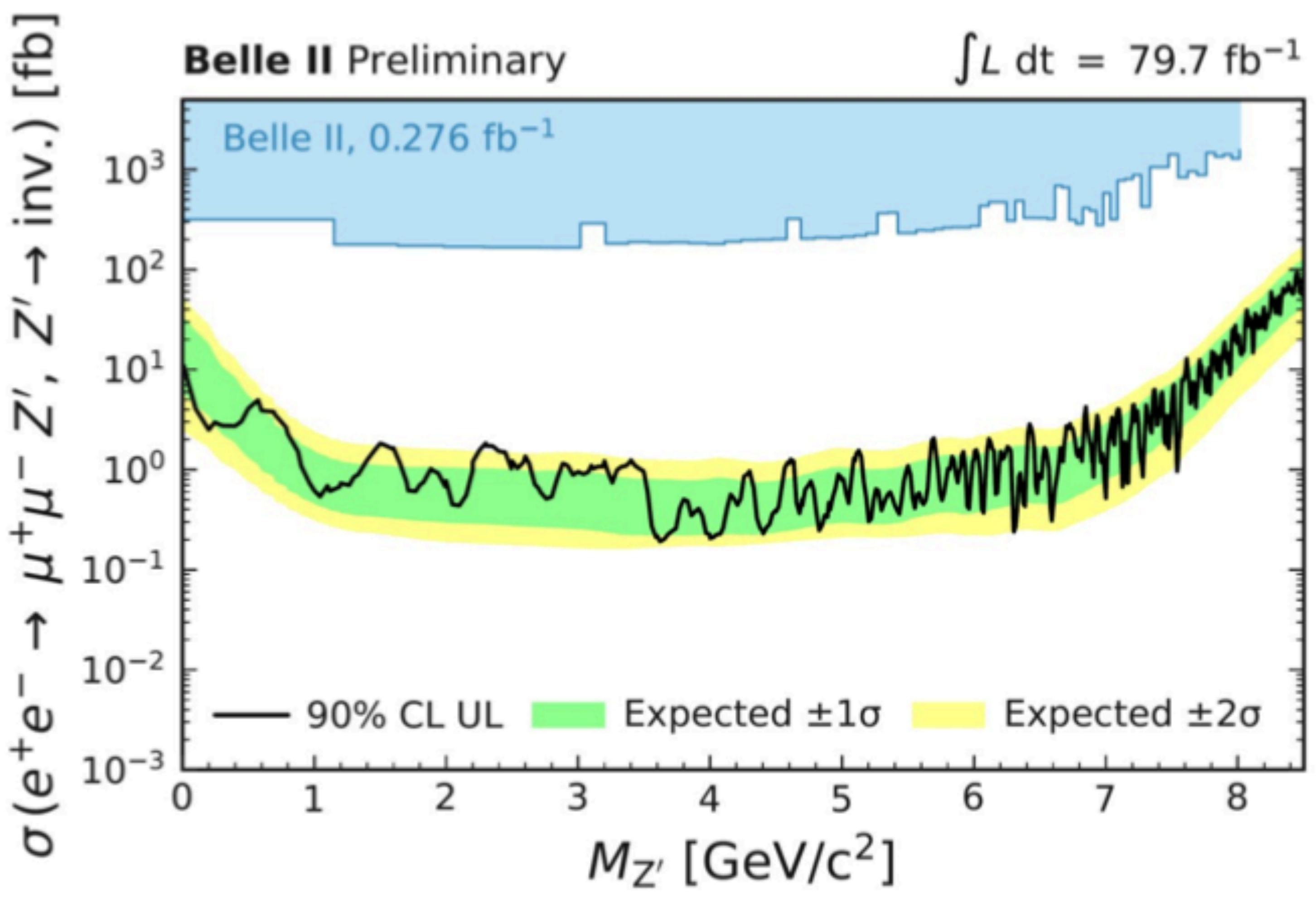
➡ we search for $e^+e^- \rightarrow \mu^+\mu^-$ + missing energy

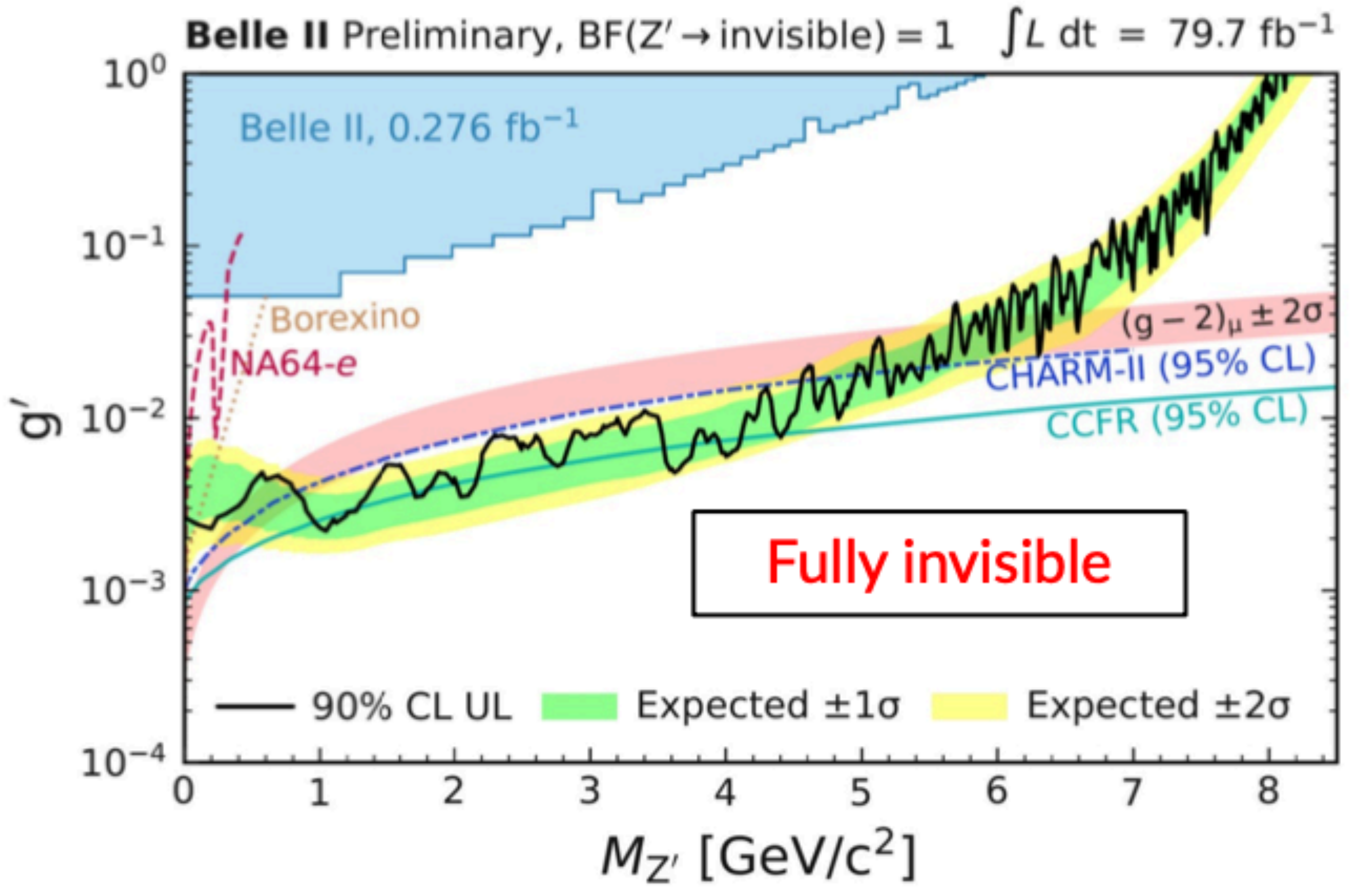
- Z’ searched in the recoil mass of the di-muon system
- high-suppression of SM backgrounds



➡ no excess was found

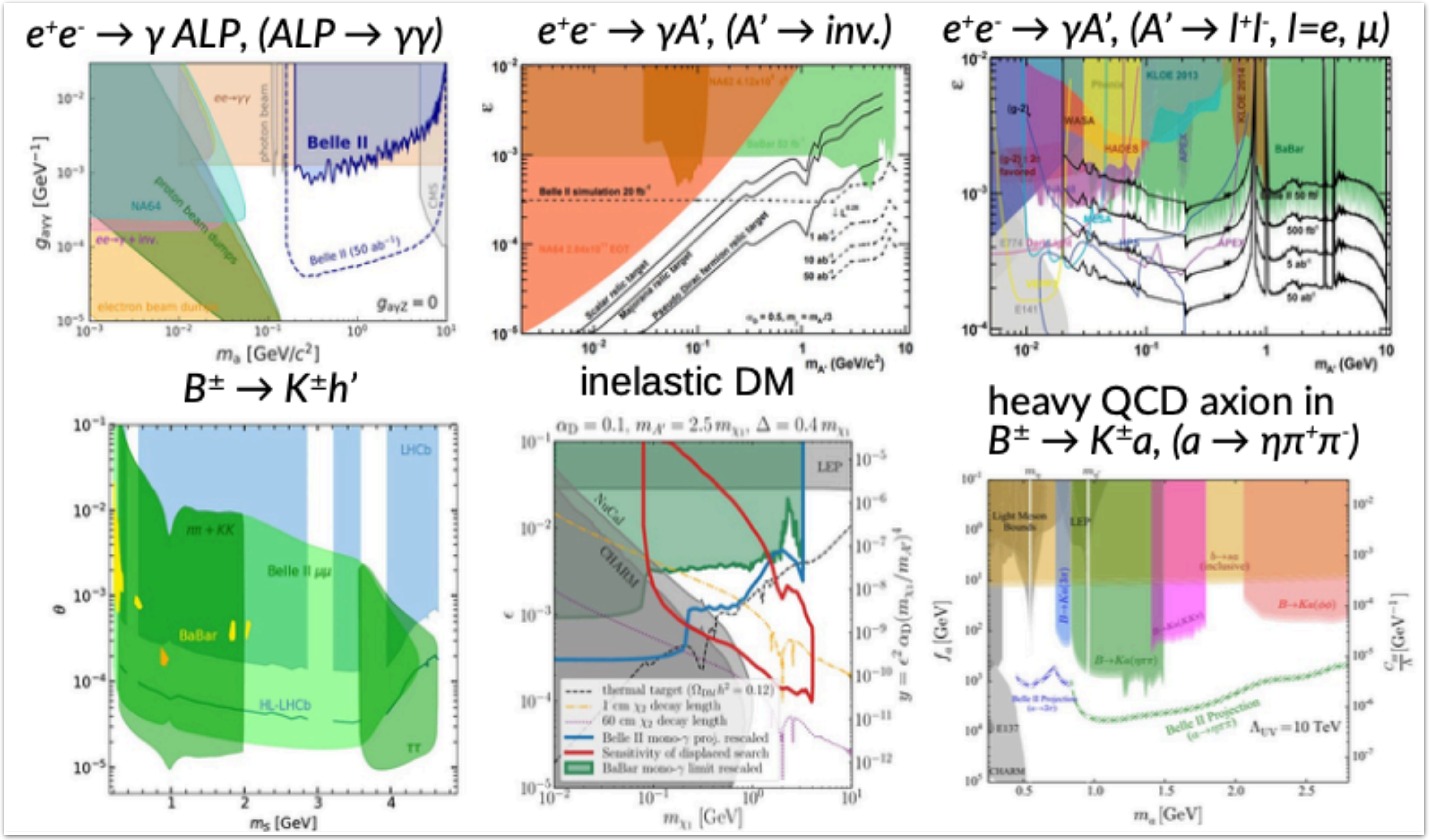
- set 90% CL limits
- fully invisible means BR(Z’ → invisible) = 1
- most stringent limits to date





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.