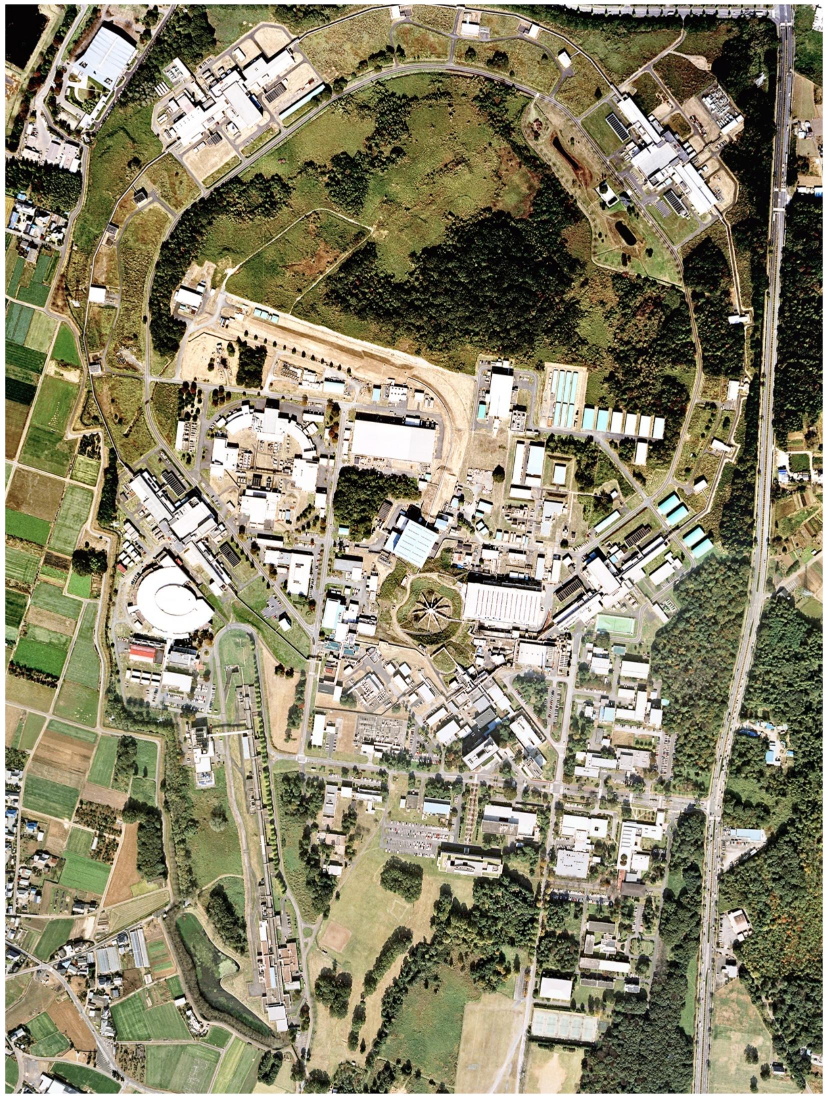
Belle II @ SuperKEKB



Livio Lanceri - INFN, Trieste - on behalf of the Belle II Collaboration
August 12, 2019 - SLAC Summer Institute 2019

A tale of two B factories

Eur. Phys. J. C74 (2014) 3026

BaBar @ PEP-II (SLAC)

Belle @ KEKB (KEK)

energy-asymmetric electron-positron colliders
mostly E_{CM} = 10.580 GeV: Y(4S)

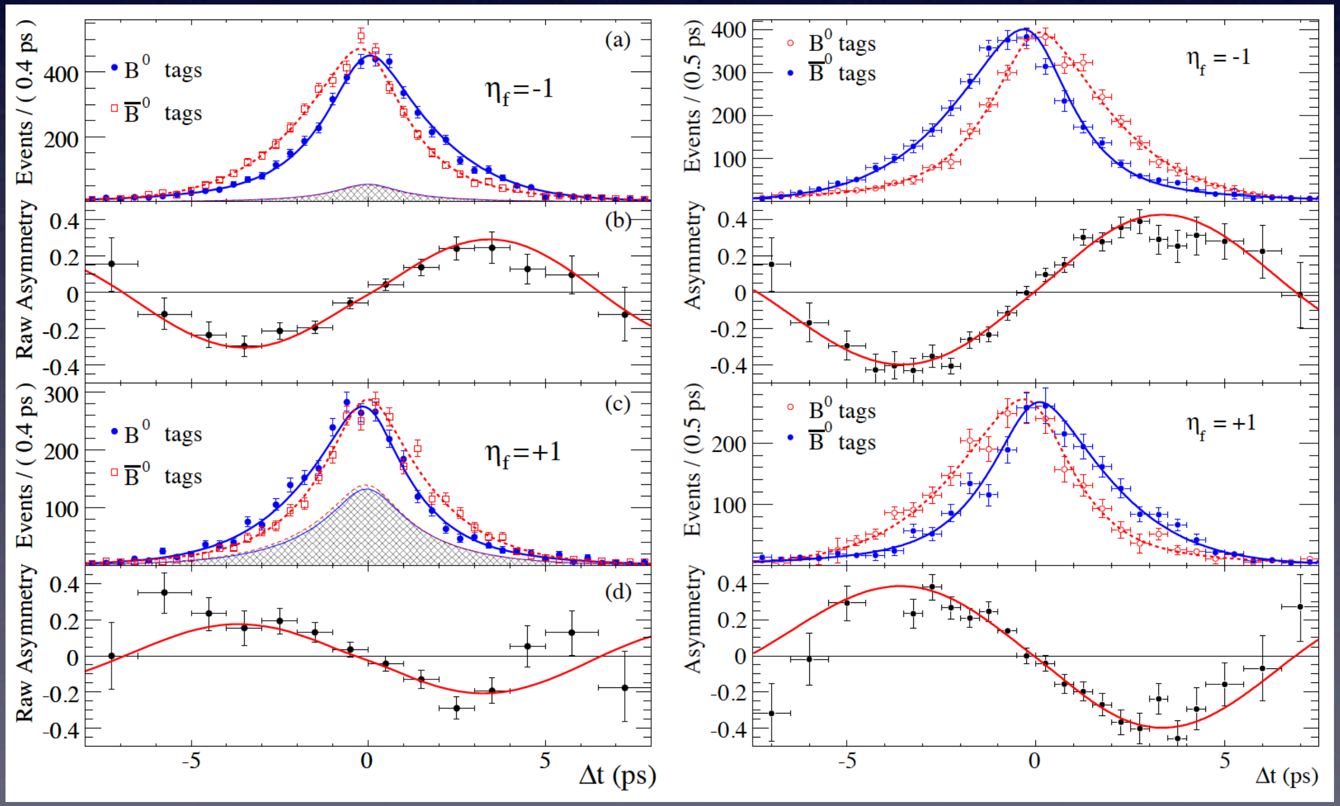
1999 - 2008
> 560 fb^{-1}
470M $B\bar{B}$ pairs @ Y(4S)

1999 - 2010
>1000 fb^{-1}
770M $B\bar{B}$ pairs @ Y(4S)

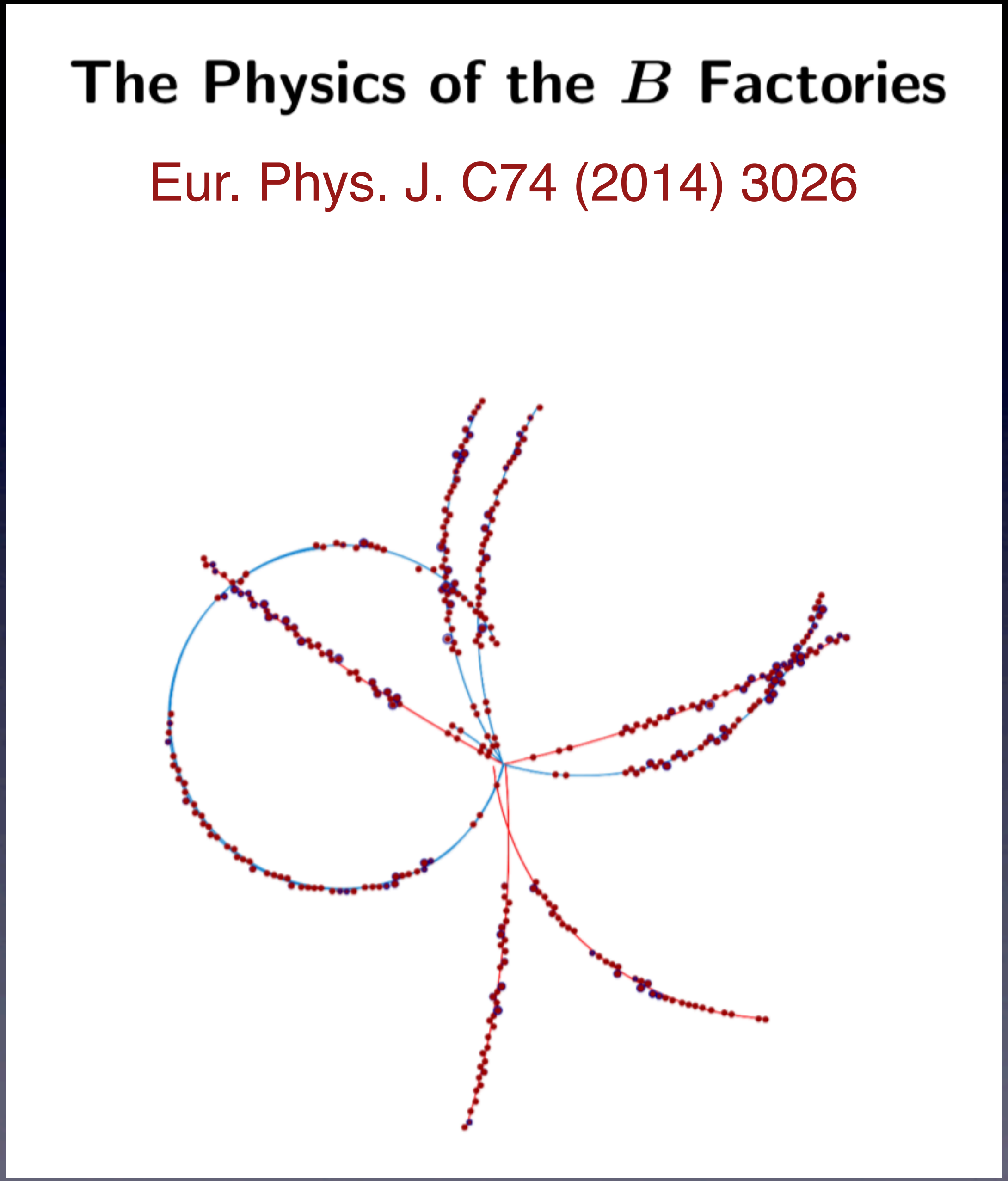
A tale of two B factories

since 2000:
KM mechanism of CPV validated
+ a lot of Flavour Physics

BaBar Belle



CP violation in $b \longrightarrow c\bar{c}s$ decays



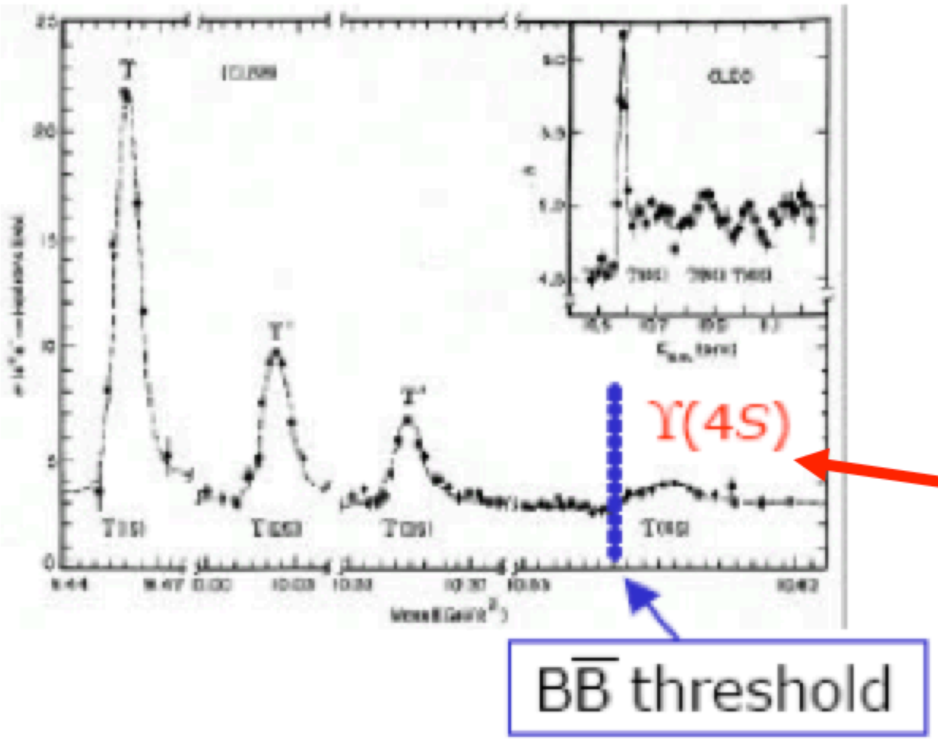
The Physics of the *B* Factories

Eur. Phys. J. C74 (2014) 3026

a must-have book,
joint enterprise

The B factory approach

- CM energy = 10.580 GeV



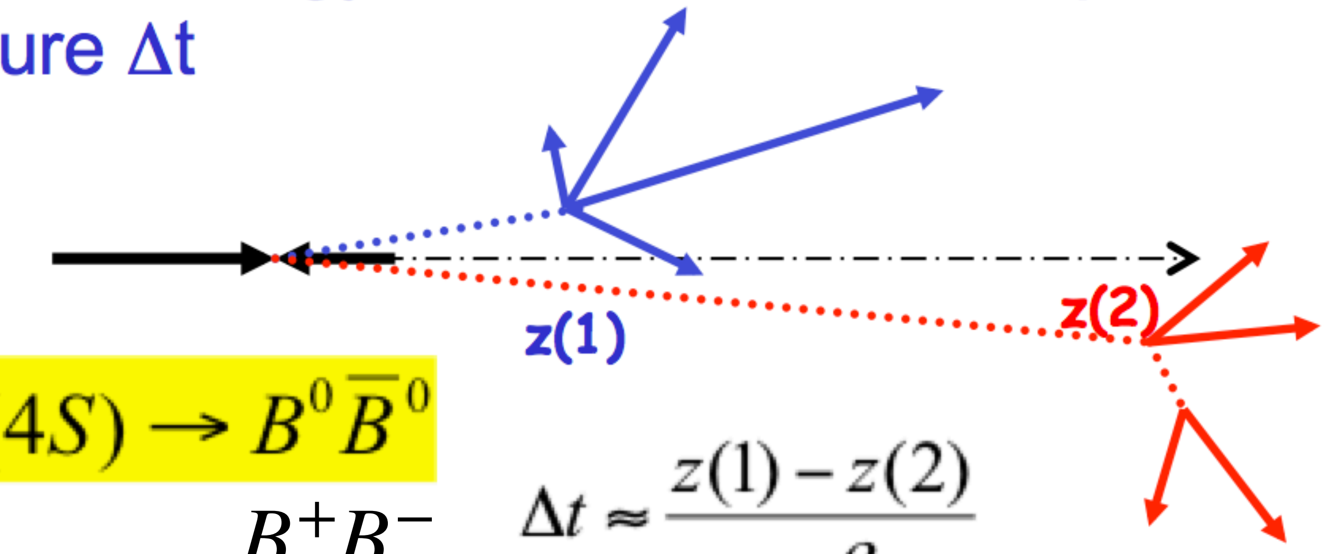
Favorable
Signal / Background:

$$\frac{\sigma_{b\bar{b}}}{\sigma_{had}} \cong 0.28$$

Effective cross sections:

$e^+e^- \rightarrow$	σ (nb)
bb	1.05
cc	1.30
ss	0.35
uu	1.39
dd	0.35
$\tau^+\tau^-$	0.94
$\mu^+\mu^-$	1.16
e^+e^-	≈ 40

- Asymmetric energy beams: boost the B pair to measure Δt



$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\overline{B}^0$$

$$B^+B^-$$

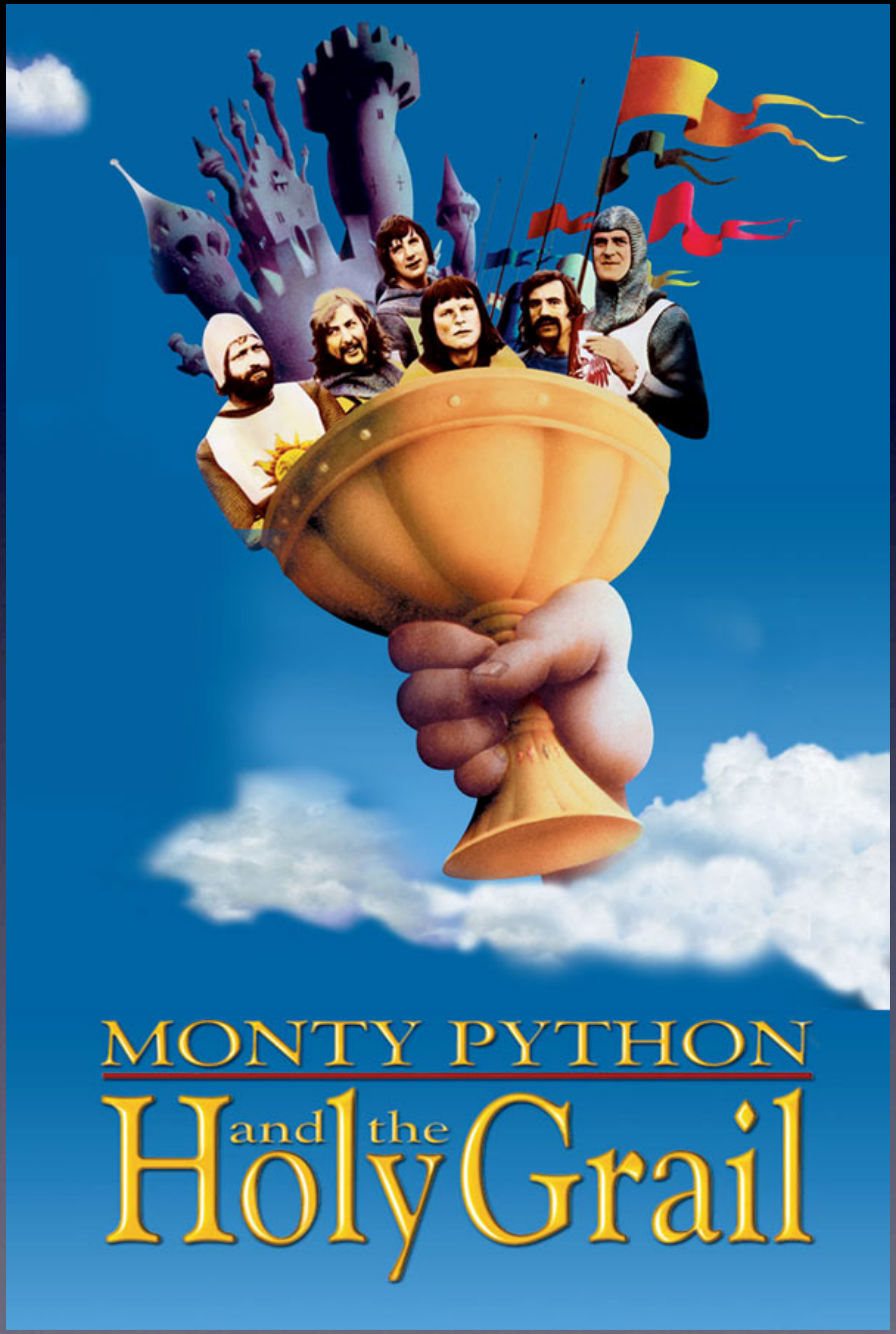
$$\Delta t \approx \frac{z(1) - z(2)}{c\gamma\beta}$$

Boost:

SuperKEKB
E_{HER} = 7.0 GeV
E_{LER} = 4.0 GeV

$$\gamma\beta \simeq 0.28$$

Quest for the new Holy Grail



Physics Beyond the Standard Model
at the intensity frontier

New CP violating phases in the quark sector?

Is Lepton Flavour universality conserved?

Is there a Left-Right symmetry in nature?

FCNC beyond the SM?

Sources of Lepton Flavour violation?

Dark sector of particle physics?

…

and, still within SM: QCD, spectroscopy:

Nature of strong force in hadrons?

…

Challenges for a new B factory

Belle II @ SuperKEKB

Hunting for small BSM effects in many observed events:

$$N_{obs} = L \cdot \sigma \cdot \epsilon$$

HF cross-sections: no game !?

$$\sigma_{bb,\ LHC} \simeq \text{mb}$$

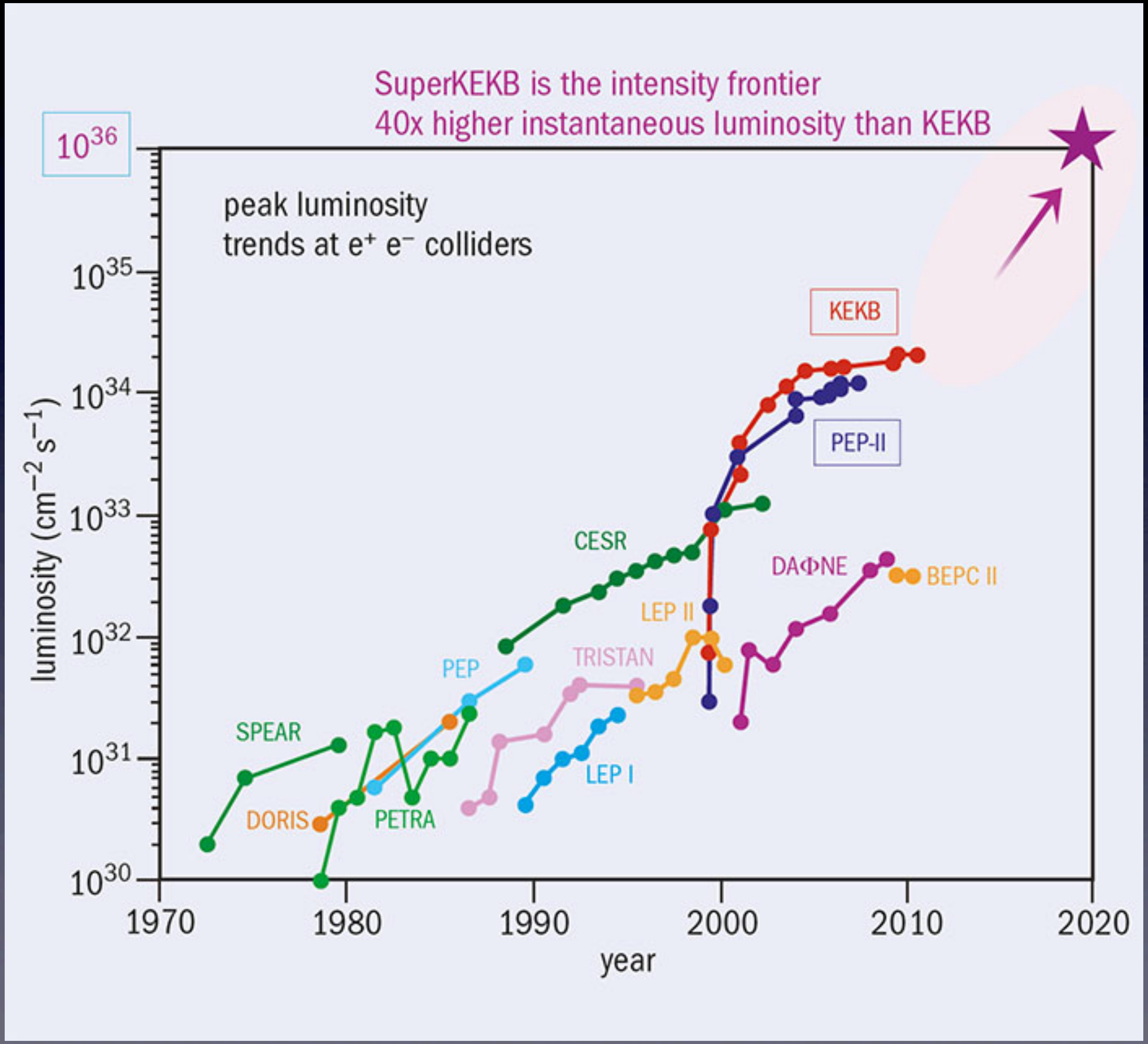
$$\sigma_{bb,\ Y(4S)} \simeq \text{nb}$$

Need strong compensations:

accelerator luminosity L

detector/analysis efficiencies ϵ

Luminosity at e^+e^- colliders



KEKB peak-L record:

$$L = 2.1 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$$

SuperKEKB aim:

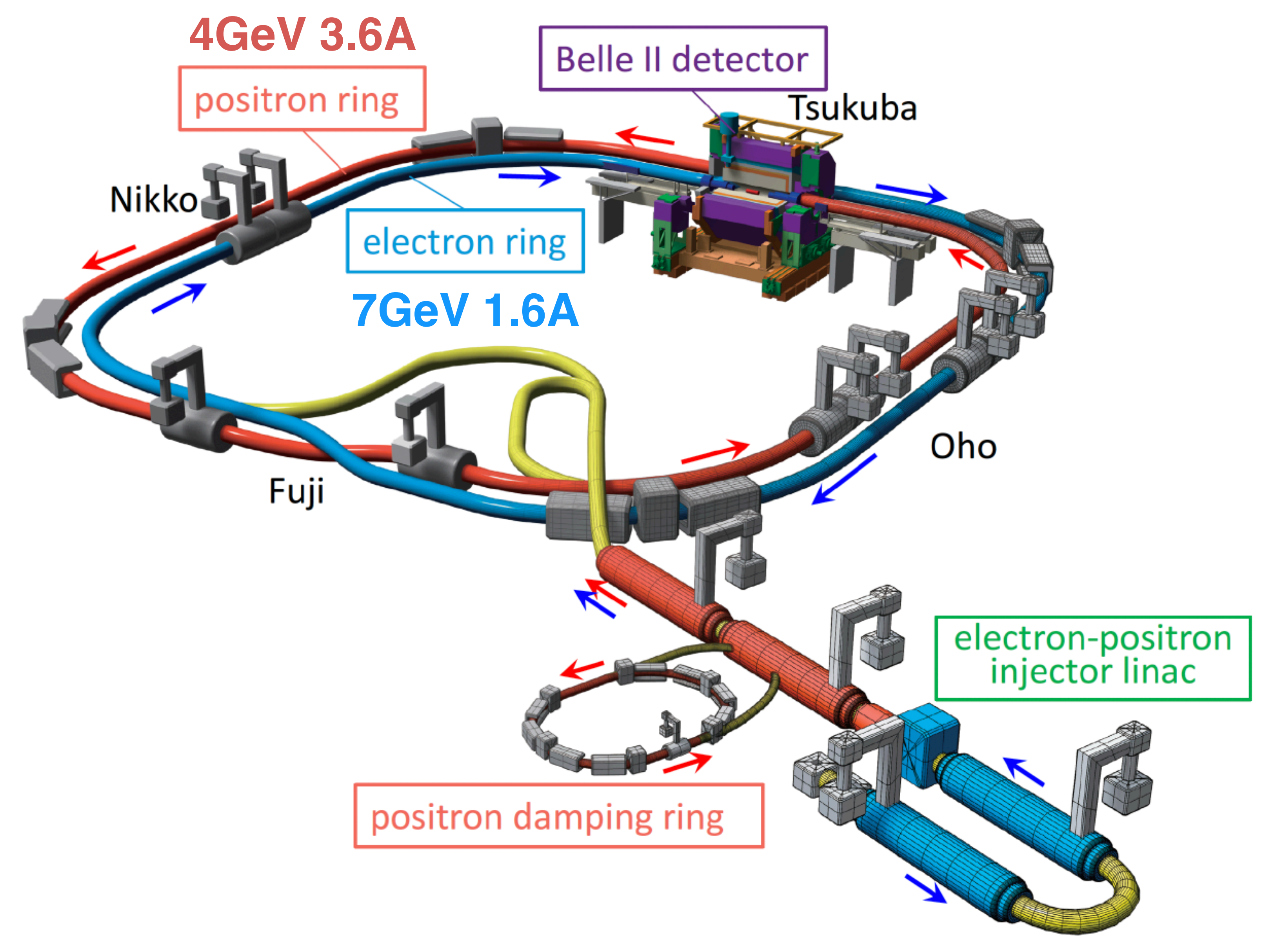
$$L = 8 \times 10^{35}\ \text{cm}^{-2}\text{s}^{-1}$$

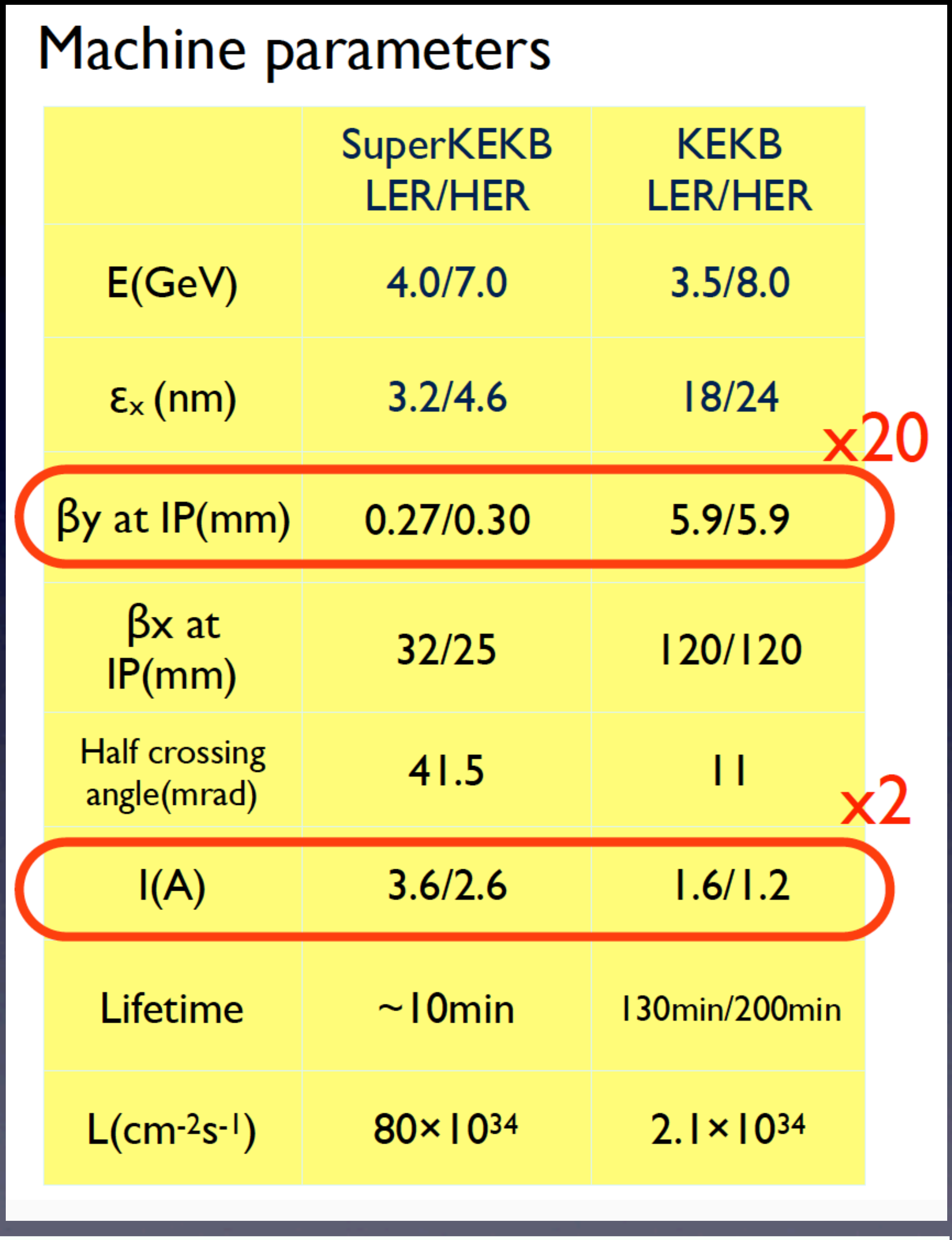
A factor 40 !!

Ingredients?

Present progress?

SuperKEKB vs KEKB




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
βy at IP(mm)	0.27/0.30	5.9/5.9
βx 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($\mathrm{cm^{-2}s^{-1}}$)	80×10^{34}	2.1×10^{34}

lower emittance: new lattice, e^- e^+ sources, e^+ damping ring, LER bending magnets, beam pipe; new SC final focussing (β_y^*)

x 20 smaller beams (ϵ, β_y^*)

x 2 larger currents

=> luminosity x 40

nano-beam & final focus

luminosity: beam currents

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

β_y function at the IP

"hourglass" requirement:

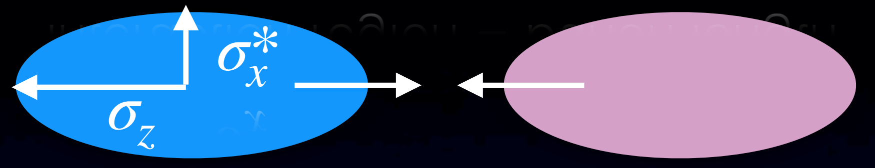
KEKB: $\beta_y^* \geq \sigma_z \simeq 6$ mm

SuperKEKB: $\beta_y^* \geq d = \dfrac{\sigma_x^*}{\phi} \simeq 300\ \mu$m

β_y^* squeezed by a factor 20 !

KEKB head-on (crab crossing)

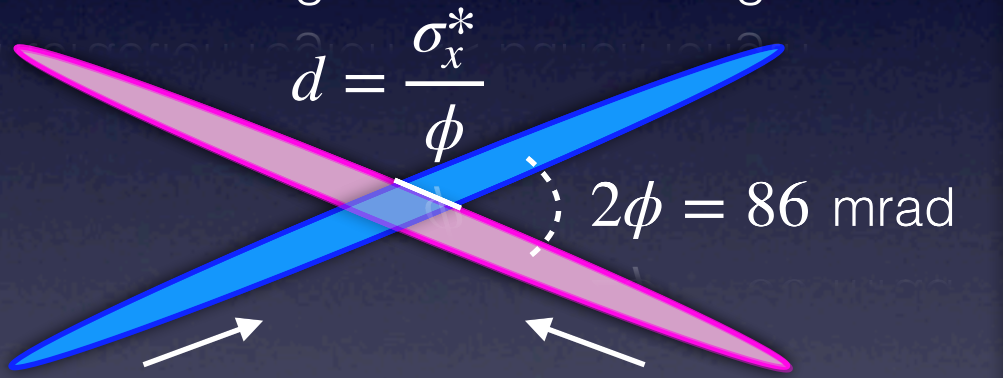
interaction region = bunch length



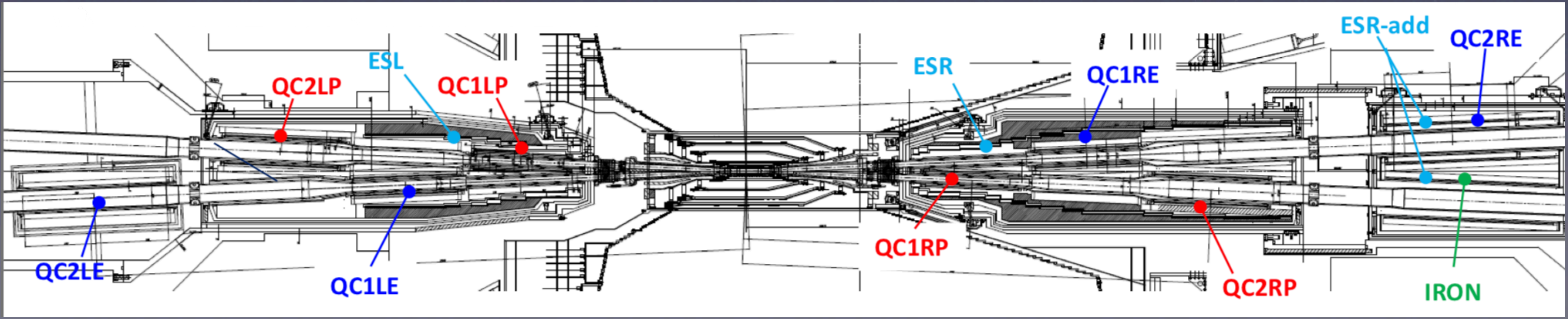
$\sigma_z \simeq 6-7$ mm, $\sigma_x^* \simeq 100-150\ \mu$m

SuperKEKB nano-beam

interaction region << bunch length

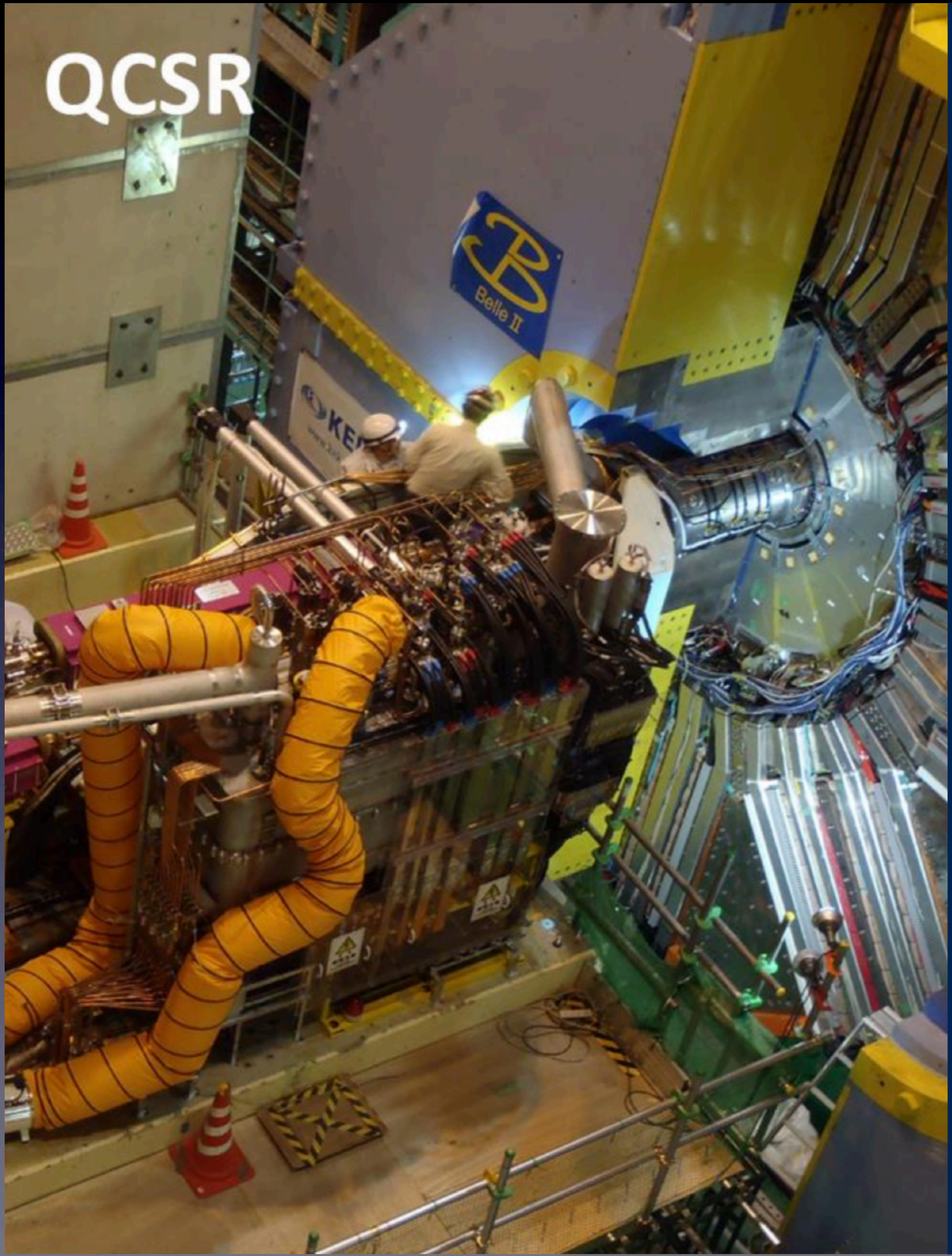


$\sigma_z \simeq 5-6$ mm, $\sigma_x^* \simeq 10-12\ \mu$m



QCS system: SC quadrupoles & solenoids

Insertion of QCS magnets

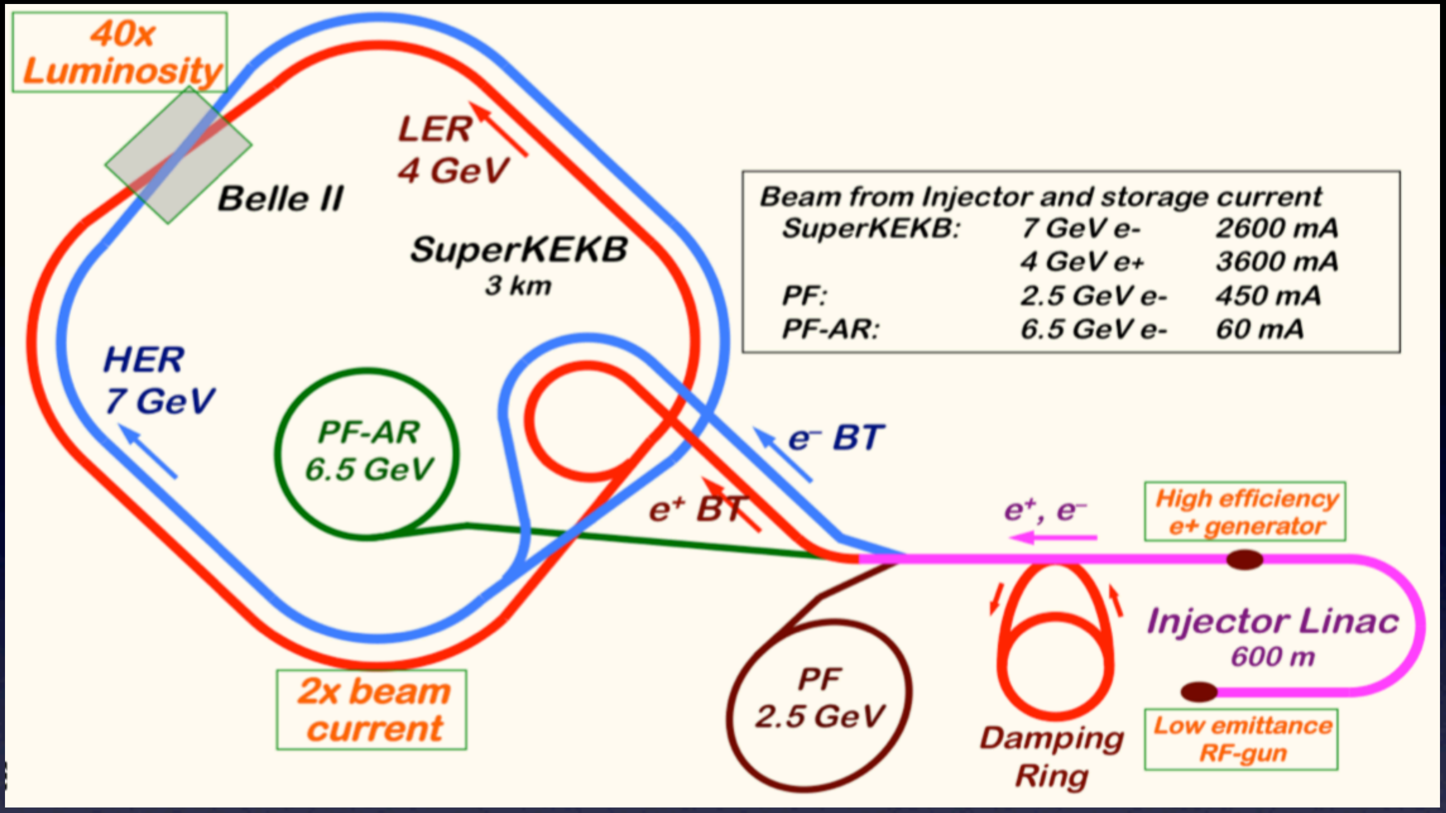


Continuous injection

The Japanese are very efficient in injecting large crowds at rush hours into fast, frequent and precisely timed trains


Alamy Stock Photo

Continuous injection

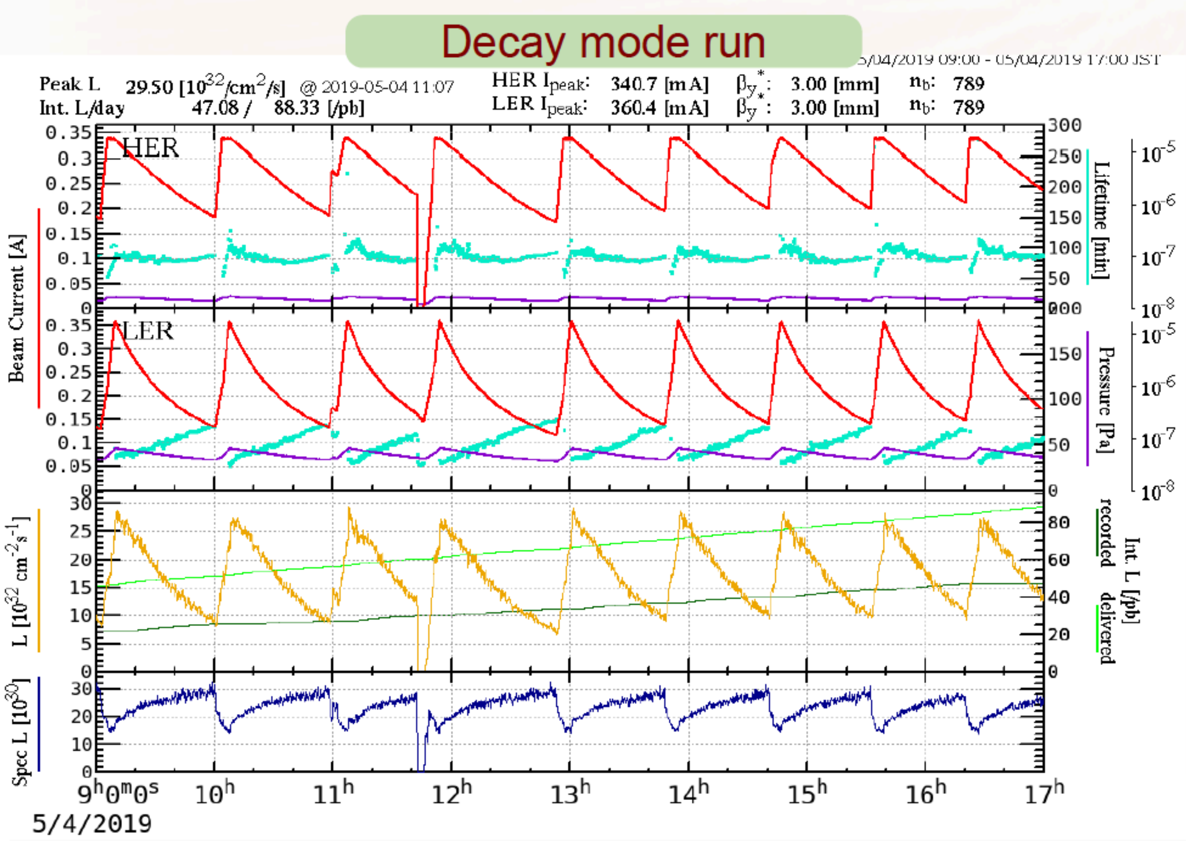


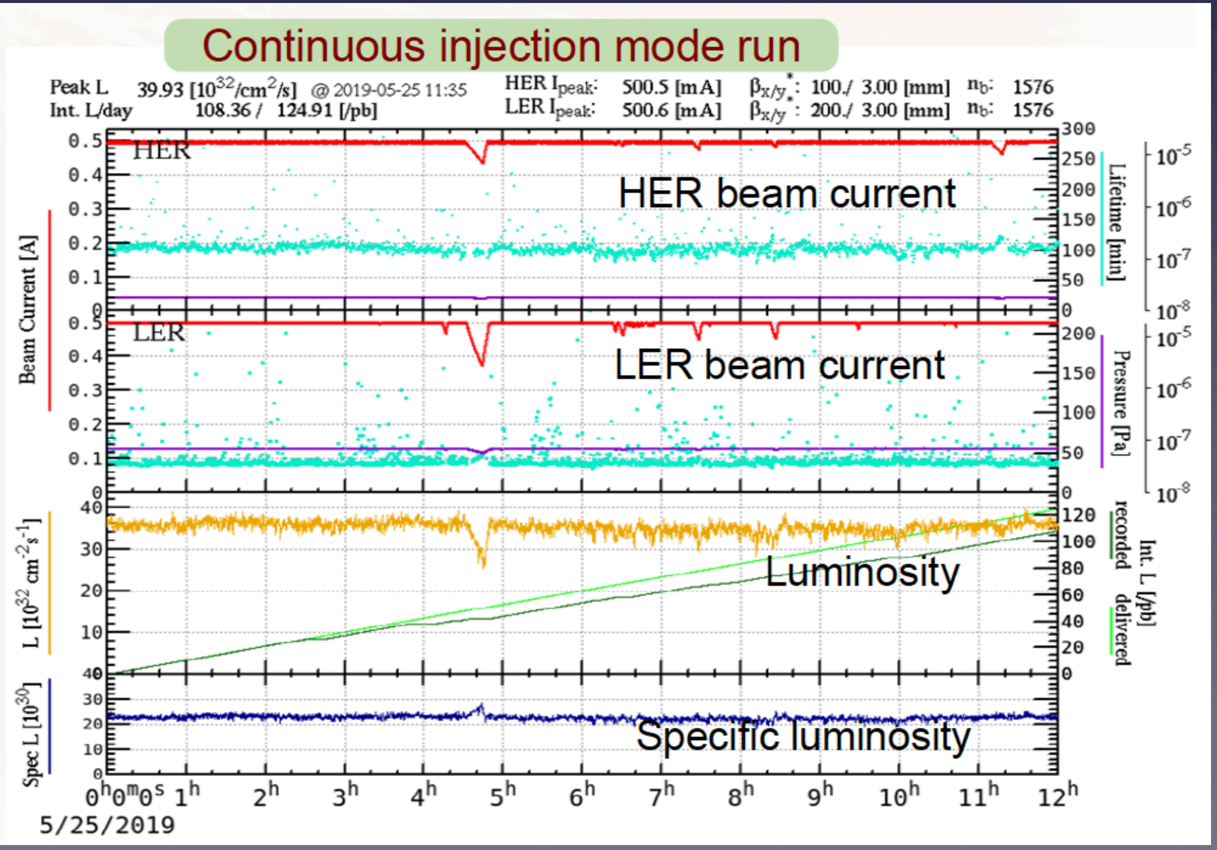
Beam from Injector and storage current

SuperKEKB:	7 GeV e-	2600 mA
	4 GeV e+	3600 mA
PF:	2.5 GeV e-	450 mA
PF-AR:	6.5 GeV e-	60 mA

The Injector pushes particles into 4 rings simultaneously at 50 Hz, topping off the 1576 HER and LER bunches

=> HER, LER currents: constant at < 1 % level





SuperKEKB, past and present

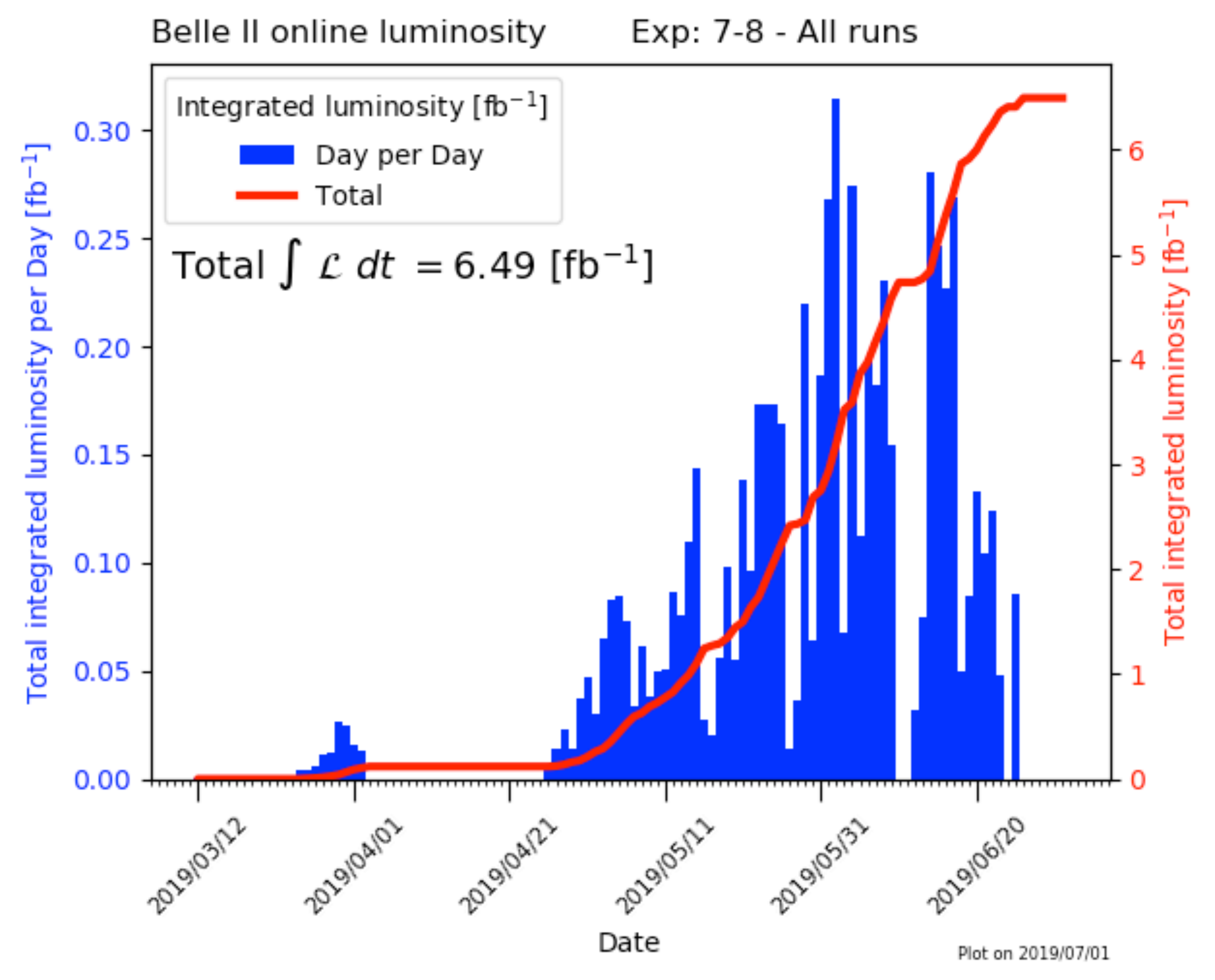
Phase 1 (2016)
single beam commissioning

Phase 2 (2018)
pilot run (500 pb^{-1}) with collisions,
Belle II: without vertex detector

Phase 3 (2019 ⟶ …)
physics run (6.5 fb^{-1}), squeezing β_y^*
Belle II: complete detector

parameter	achieved	design
$I_{HER,max}$ [A]	0.940	3.6
$I_{LER,max}$ [A]	0.880	2.6
β_y^* [mm]	2	0.3
#bunches	1576	2364
L_{peak} [cm^{-2} s^{-1}]	6.1 x 10^{33}	8 x 10^{35}
L_{max} (det.off)	12 x 10^{33}	

Phase 3 (March-June 2019)
daily integrated luminosity



progressively squeezing β_y^*
fighting beam blow-up, QCS quenches, backgrounds in Belle II

beam backgrounds

e^+e^- colliders are “clean”, but…
at high luminosity, beam-induced backgrounds become a challenge

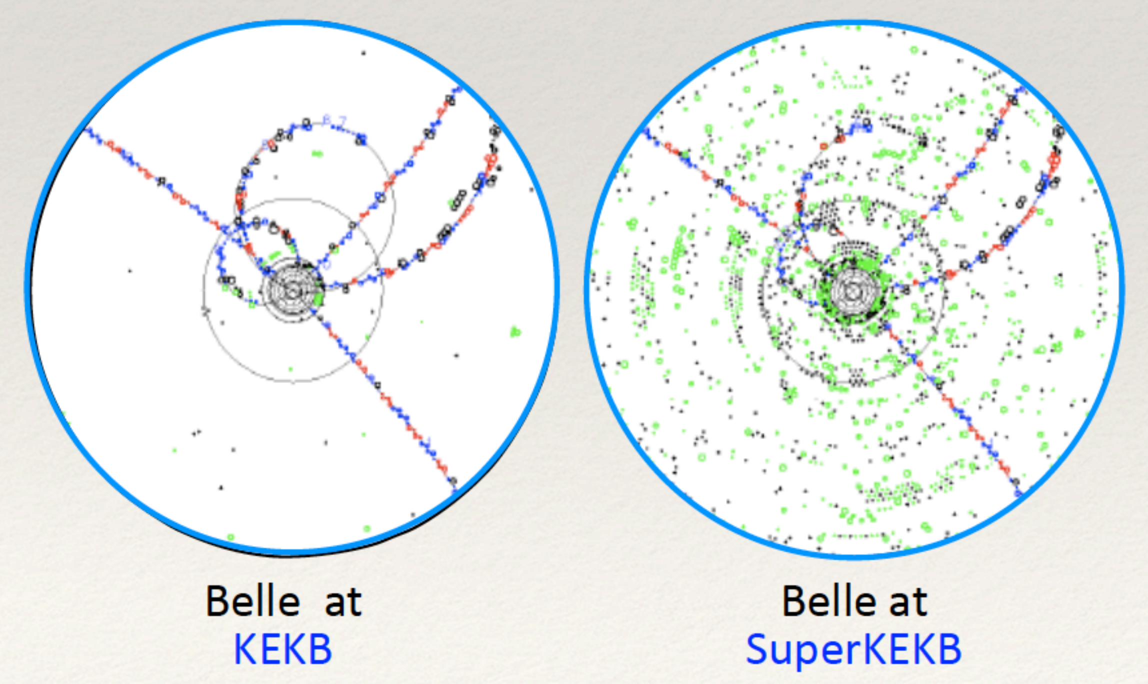
at the highest luminosities,
QED backgrounds will dominate:

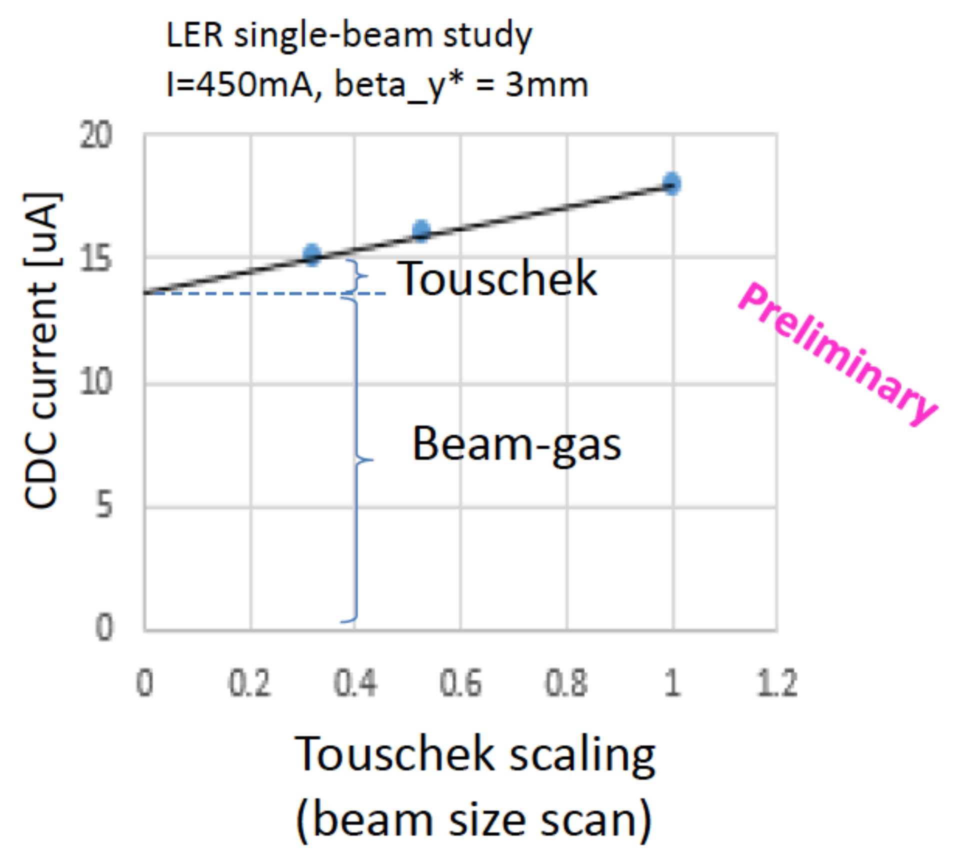
$$e^+e^- \rightarrow e^+e^-\gamma$$
$$e^+e^- \rightarrow e^+e^-e^+e^-$$

at present, single beam backgrounds are predominant, higher in LER:

- beam-gas (residual gas in beam pipe)
- Touschek (intra-bunch scattering)
- injection-induced
- “dust events”, occasional large losses

CDC HV trips with large bkgd
beam abort protection against radiation spikes
simulations & collimator studies



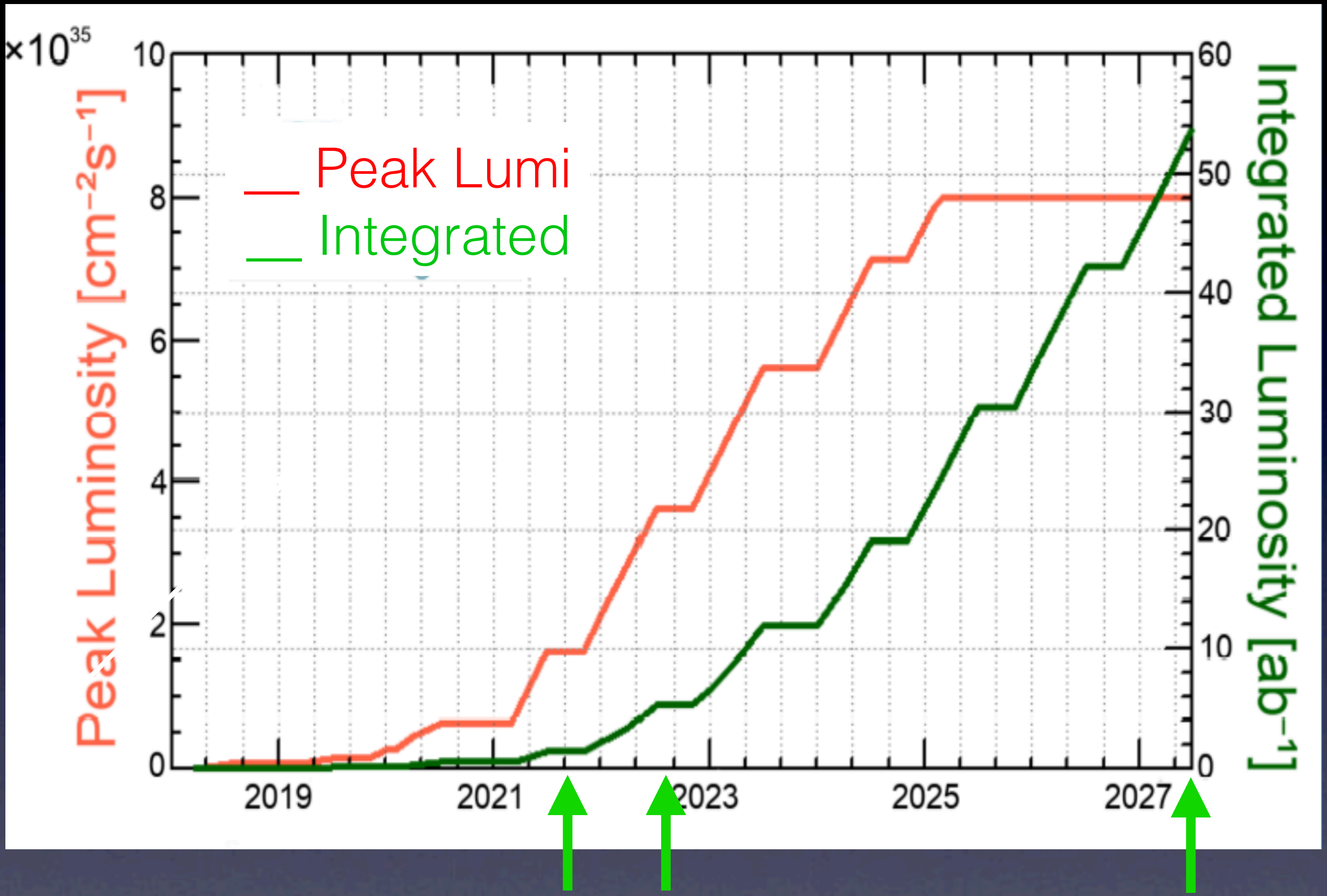


Luminosity plans

aggressive plan for monthly increase in peak luminosity: MD alternating with physics

continue with β_y^* squeeze (11 months), then increase beam currents

design peak lumi in 2025…!



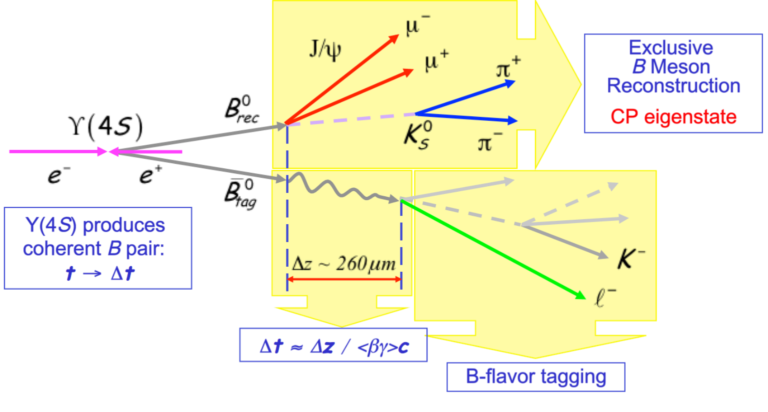
Integrated luminosity approximate targets:

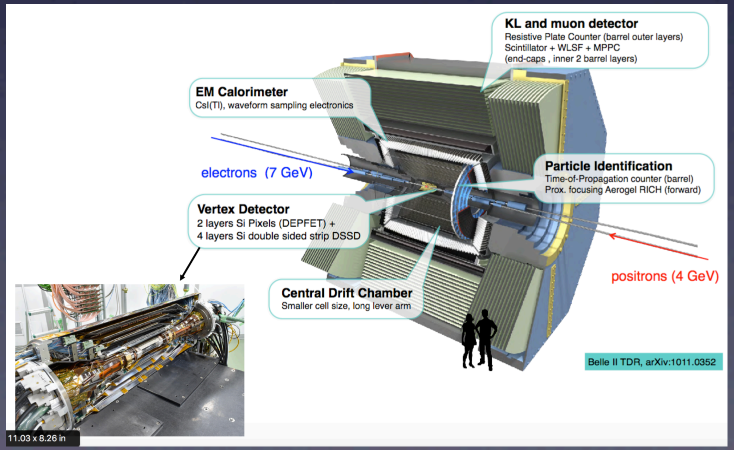
1 ab^{-1} (= Belle data sample) in 2021
5 ab^{-1} in 2022
50 ab^{-1} in 2027

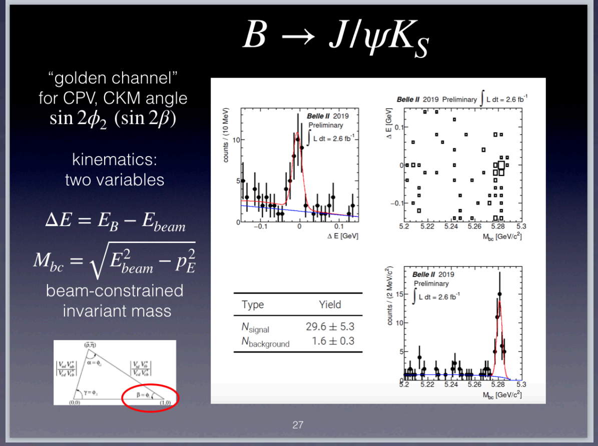
rough rule of thumb:
1ab^{-1}(Belle II) $\simeq$ 1fb^{-1}(LHCb)

Belle II assets

Observables & analysis methods







$B \to J/\psi K_S$

"golden channel"
for CPV, CKM angle
$\sin 2\phi_2$ $(\sin 2\beta)$

kinematics:
two variables

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

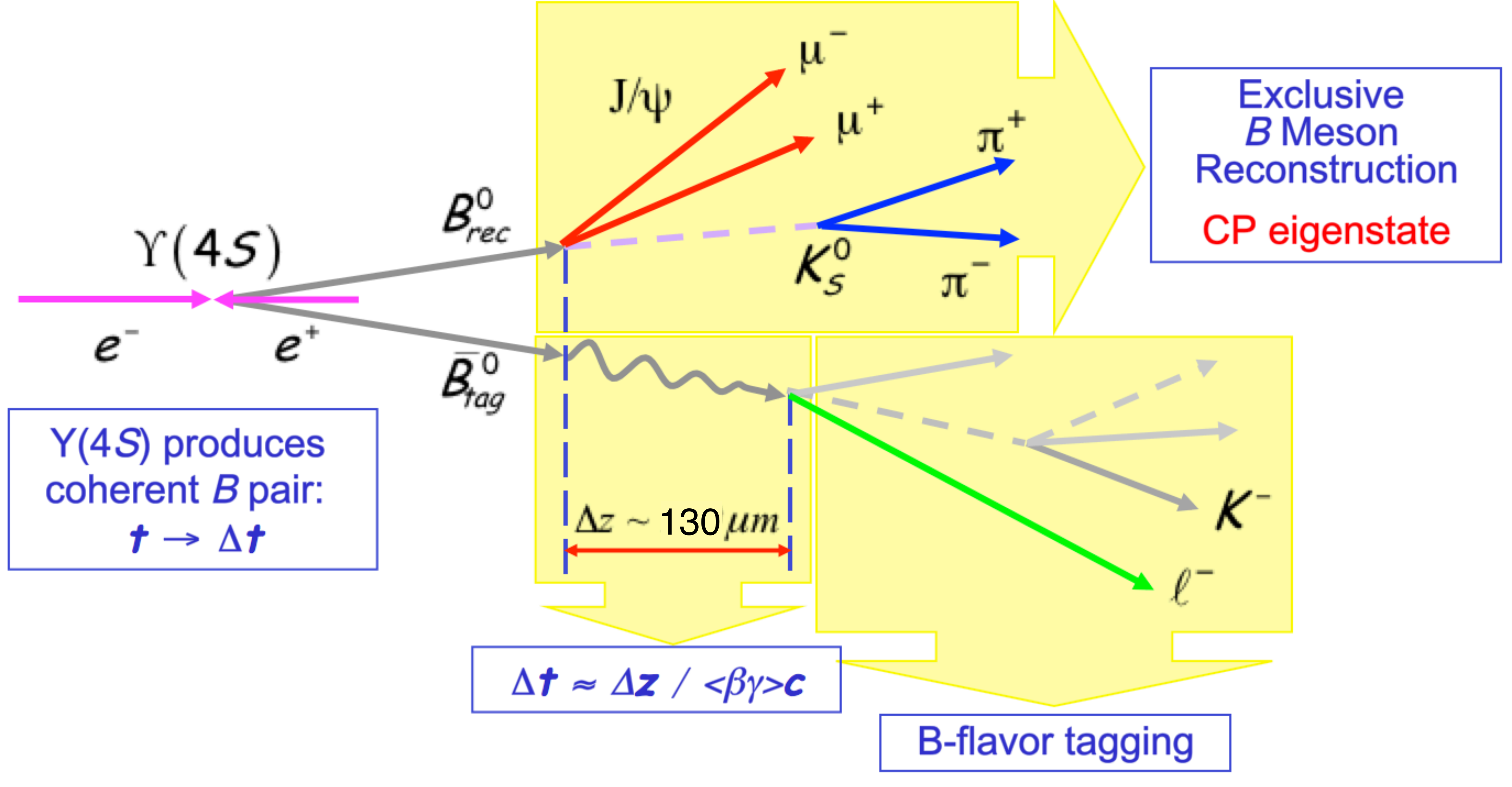
$$M_{bc} = \sqrt{E^2_{beam} - p^2_E}$$

beam-constrained
invariant mass

Type	Yield
N_{signal}	29.6 ± 5.3
$N_{background}$	1.6 ± 0.3

Belle II detector performance & first results from Phase 3

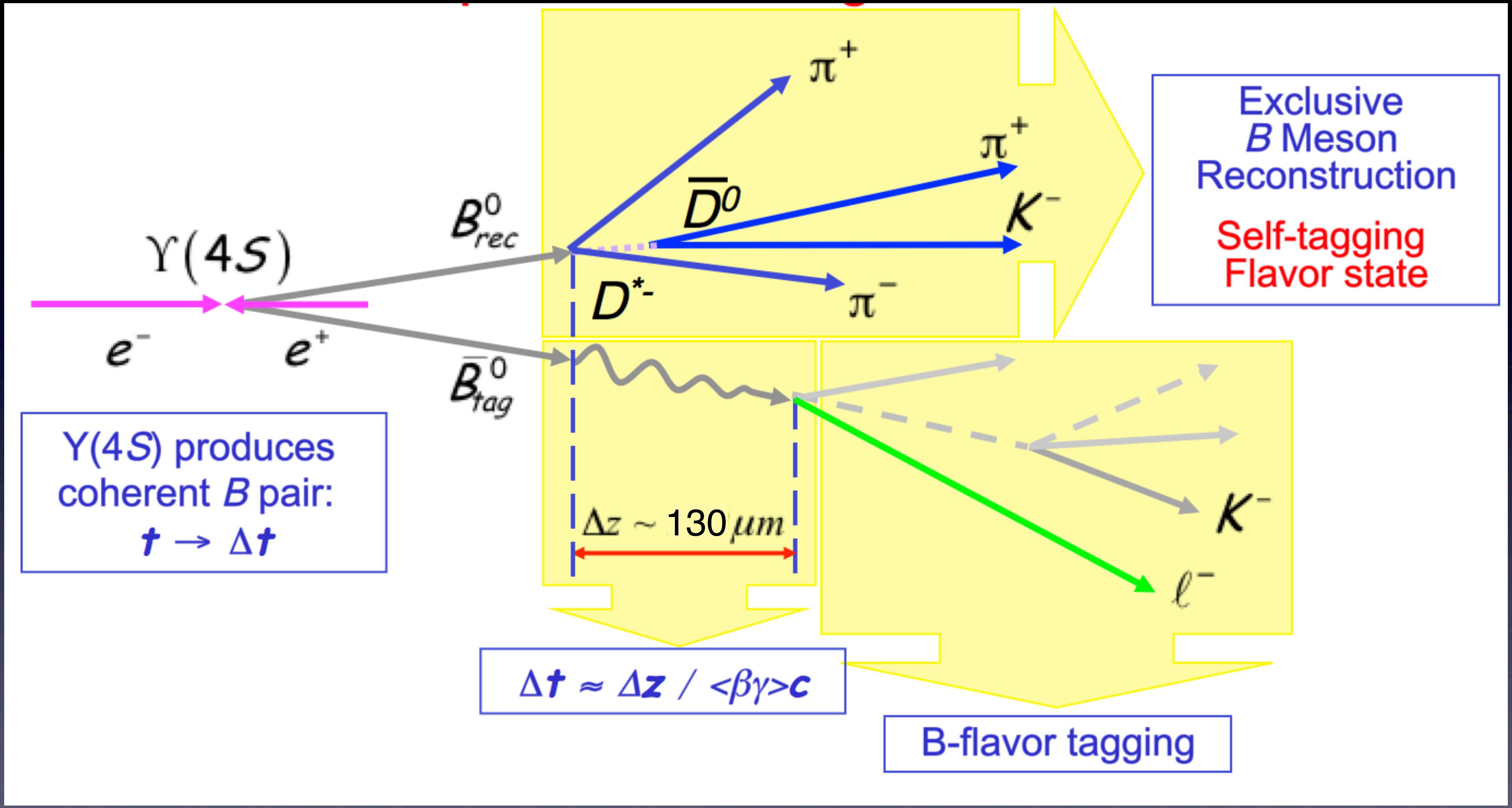
Time-dependent CP asymmetry



Y(4S) decays into a coherent, entangled, anti-symmetric $B\bar{B}$ state

B-flavor tagging efficiency and Δt resolution function are obtained from data (measurement of mixing, with exclusively reconstructed self-tagging B states)

Time-dependent mixing

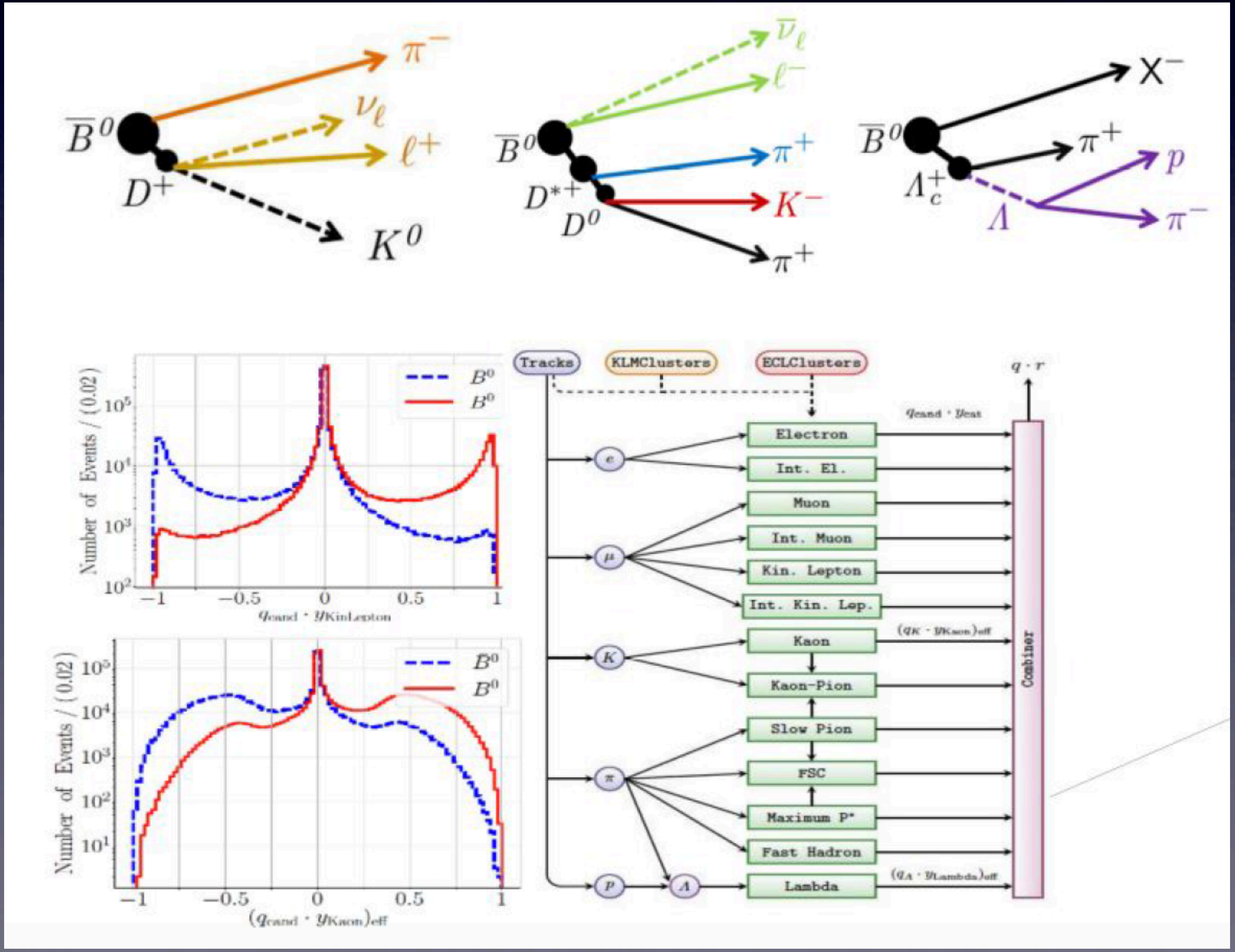


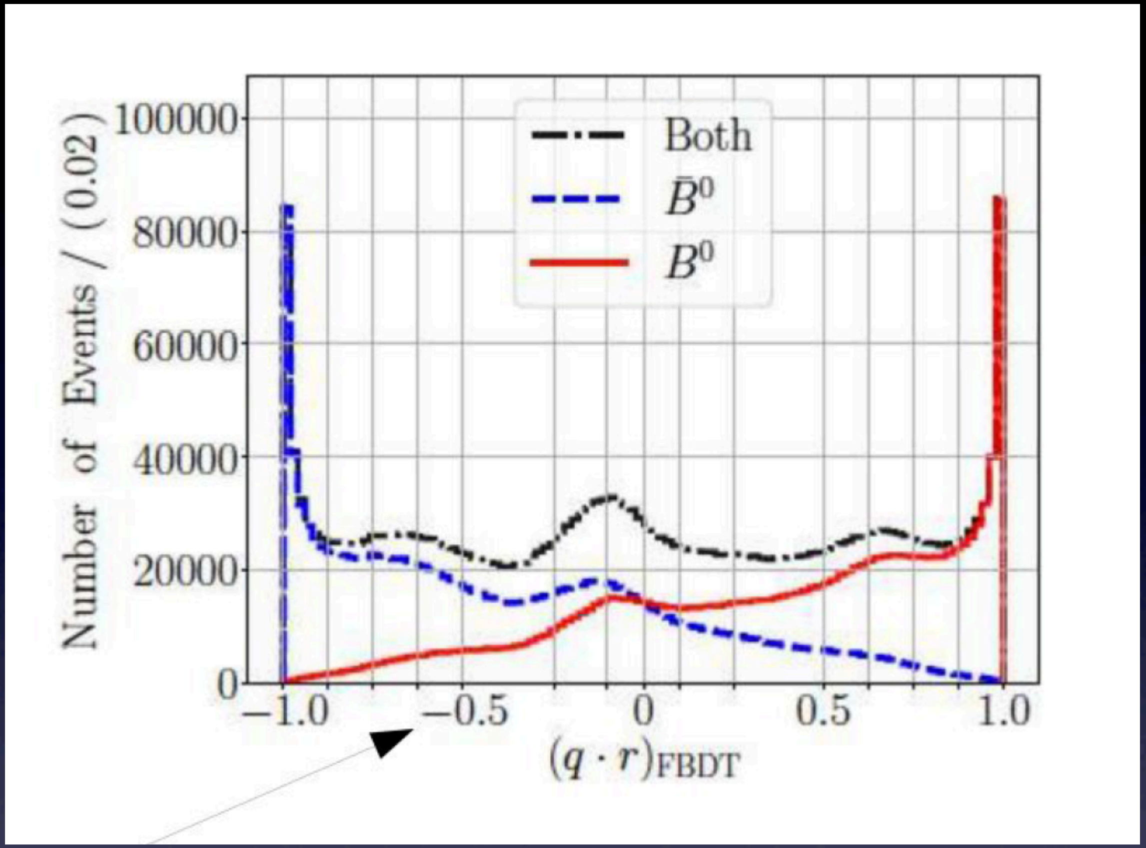
Y(4S) decays into a coherent, entangled, anti-symmetric BB state

B-flavor tagging efficiency and Δt resolution function are obtained from data (measurement of mixing, with exclusively reconstructed self-tagging B states)

inclusive B-flavour tagging

Multi-variate analysis tagger
many sub-taggers with many variables
exploiting correlations with B flavour





Expected total effective efficiency

$$\sum_i \epsilon_i (1-2w_i)^2 \simeq 37\,\%$$

(compare with Belle, BaBar 30, 33%)
dilution factor due to mis-tag w:

$$A_{CP}^{obs} = (1-2w)A_{CP}$$

“Back-of-the-envelope” sensitivity

Sensitivity for CP asymmetries

Observed asymmetry is diluted: $A_{obs} = DA_{CP}$

Uncertainty on $A_{CP} = A_{obs}/D$:

$$\boxed{\delta A_{CP} \simeq \frac{1}{D\sqrt{N_{obs}}} = \frac{1}{D\sqrt{\epsilon \cdot BR \cdot N_{prod}}}}$$

Figures of merit

Number of produced events $N_{prod} = \int Ldt \times \sigma_{bb} \times 2f_0$

Efficiency $\epsilon = \epsilon_{det} \cdot \epsilon_{CP} \cdot \epsilon_{tag}$

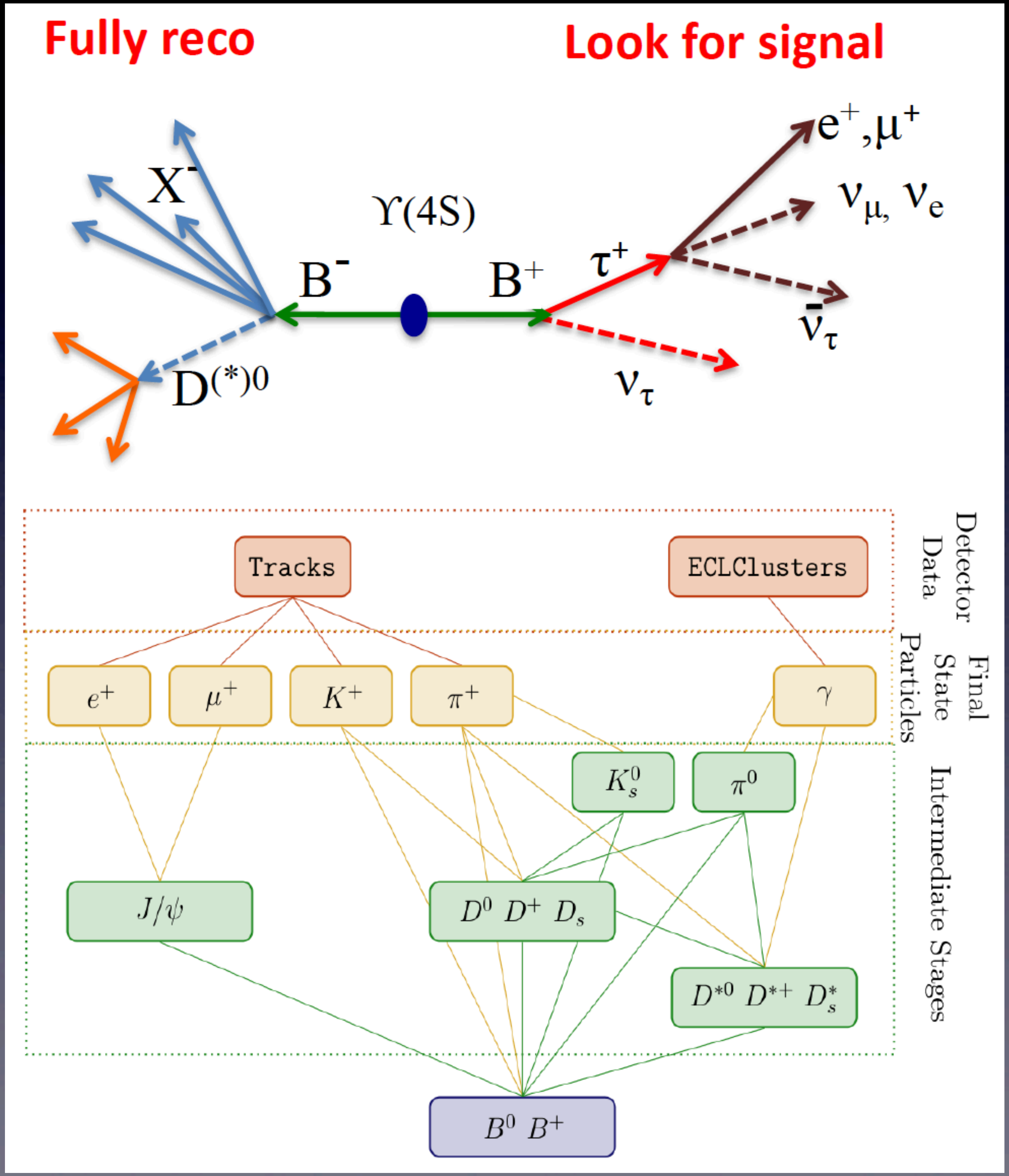
Dilution factors $D = d_{mix} \cdot d_{mistag} \cdot d_{bkgd}$

B factory is strong here!

$\uparrow$ $d_{mix} \simeq 0.47$ for integrated asymm.

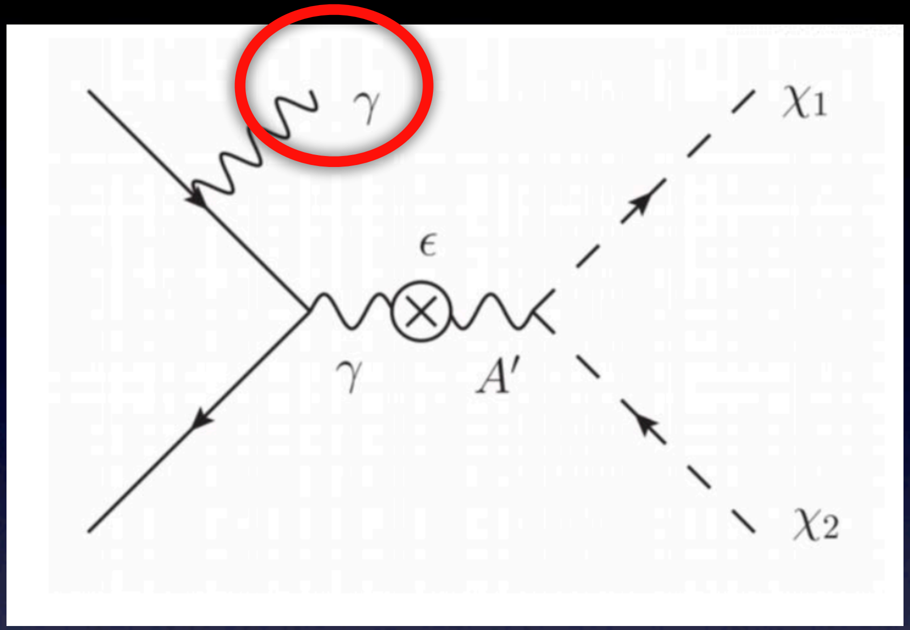
Full event reconstruction

- for signals with weak signature:
  - decays with missing momentum (many neutrinos in the final state)
  - inclusive analyses
- background rejection improved fully reconstructing the “tag” B
- tag with semileptonic decays
  - PRO: higher efficiency $\epsilon_{tag} \simeq 1.5\,\%$
    CON: more background,
    B momentum unmeasured
- tag with hadronic decays
  - PRO: cleaner events, B momentum OK
    CON: smaller efficiency $\epsilon_{tag} \simeq 0.3\,\%$
- New algorithm developed by Belle II:”Full Event Interpretation”:
  Comput.Softw. Big Sci. 3 (2019) no.1, 6



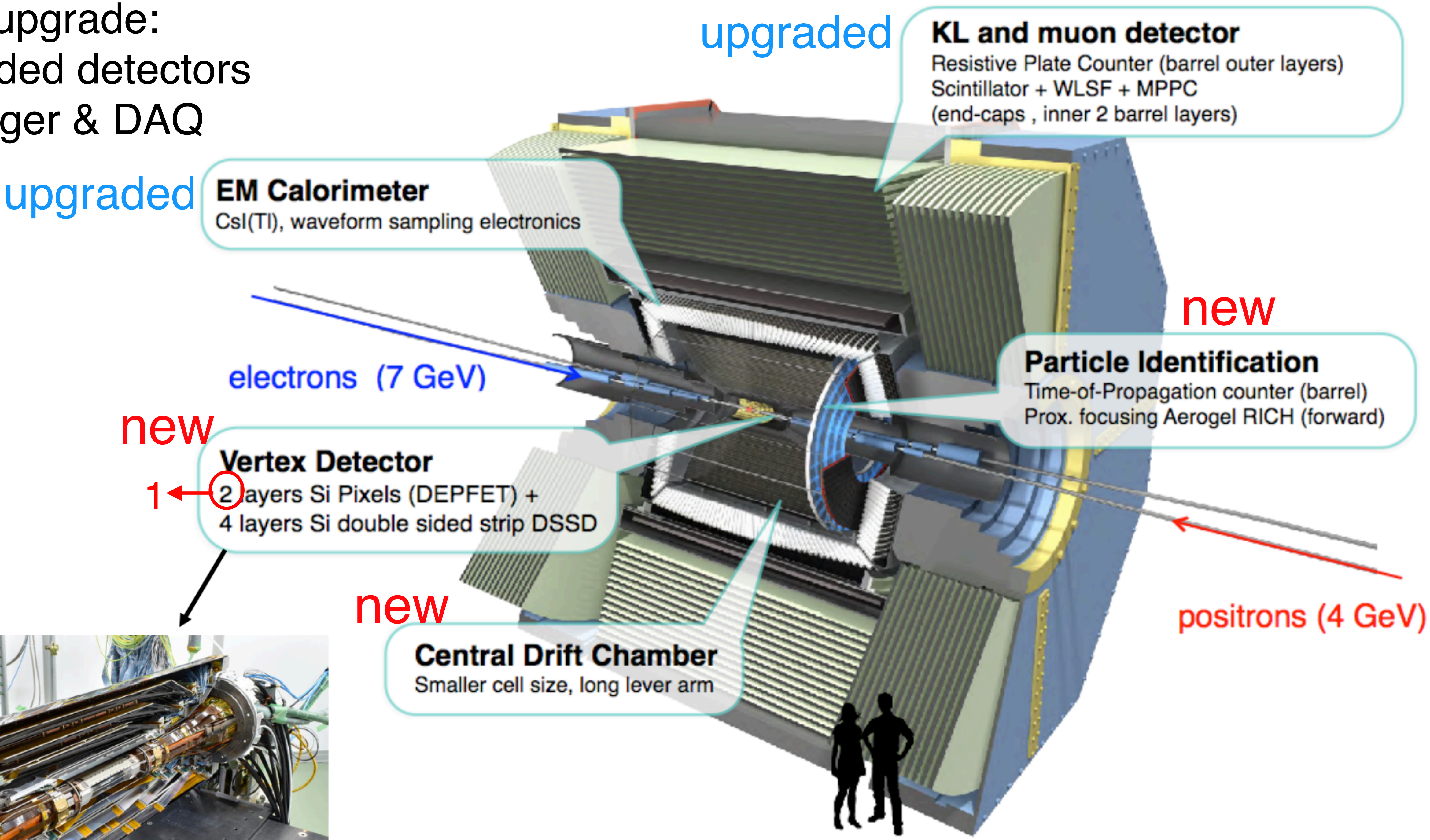
single-photon trigger

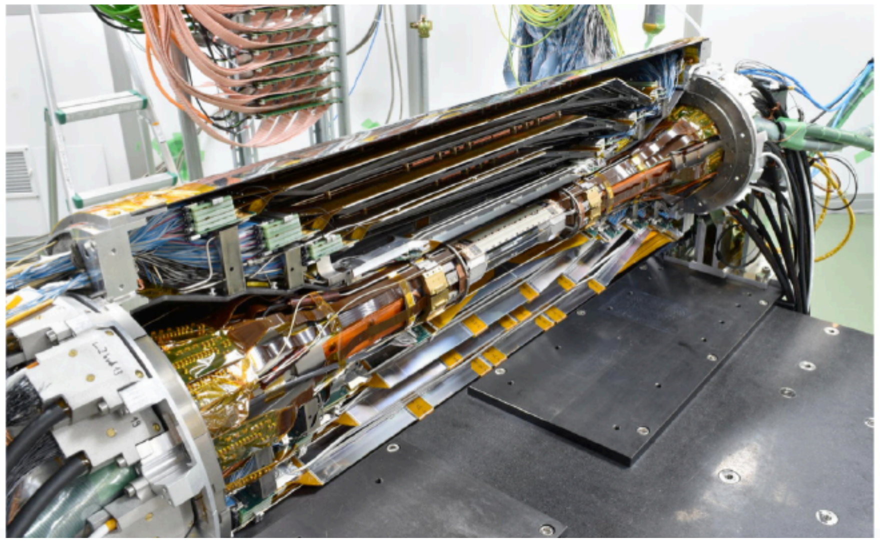
- only possible at a B factory!
- special **single-photon trigger**
- not available in Belle,
  only 10% of BaBar data set
- allows searches for exotics
  such as:
  - dark photons A'
    $e^+e^- \to \gamma A'$, $A' \to$ invisible



The Belle II detector

Extensive upgrade:
new/upgraded detectors
30 kHz trigger & DAQ

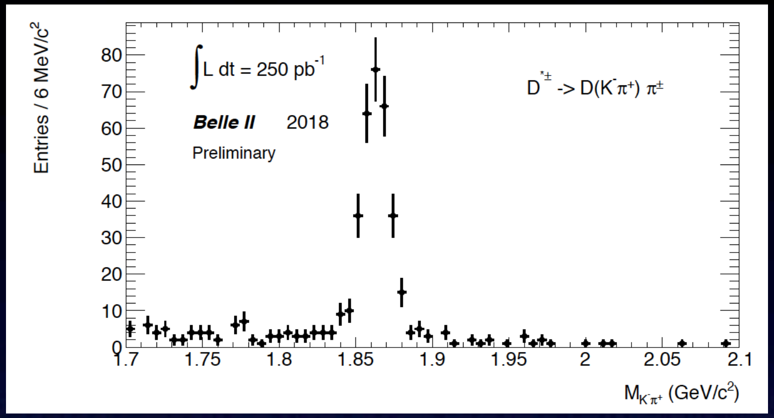




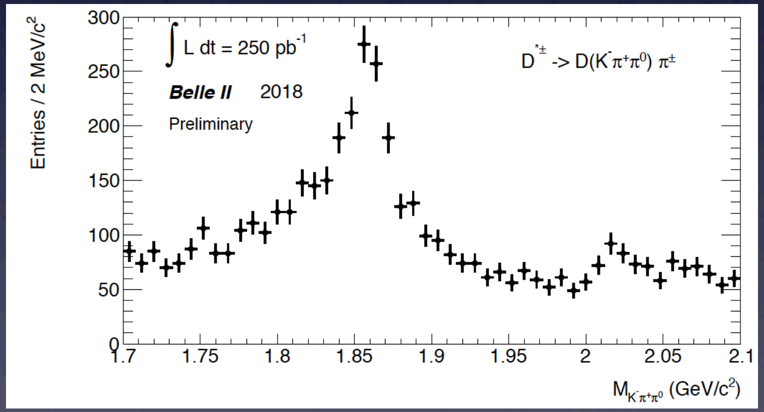
Performance in Phase 3 studied on a 2.6 fb^{-1} data set, see next slides

examples of particle reconstruction

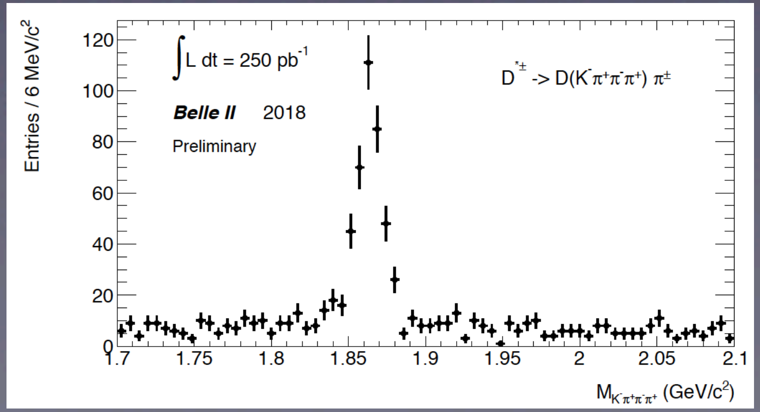
$D^{*\pm} \rightarrow D(K^-\pi^+)\pi^\pm$



$D^{*\pm} \rightarrow D(K^-\pi^+\pi^0)\pi^\pm$

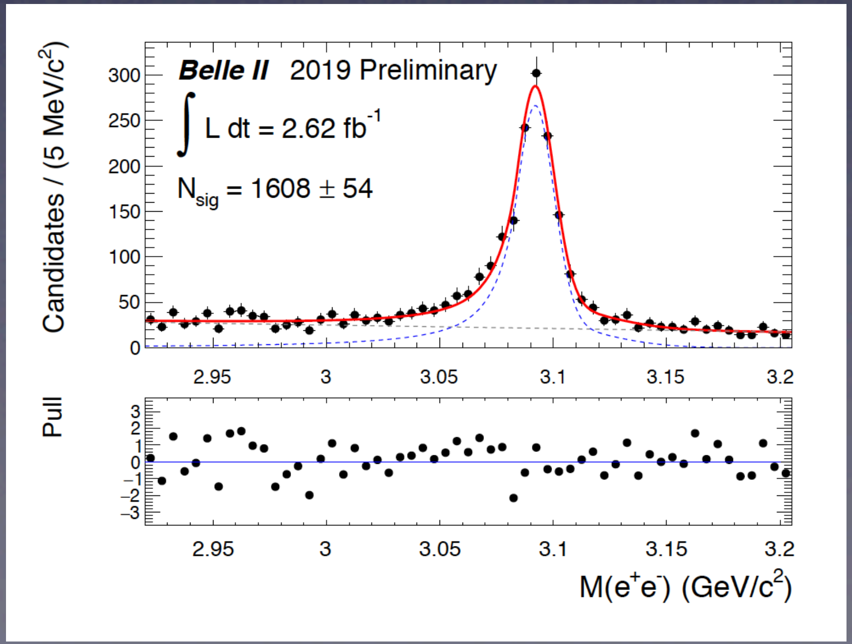


$D^{*\pm} \rightarrow D(K^-\pi^+\pi^-\pi^+)\pi^\pm$

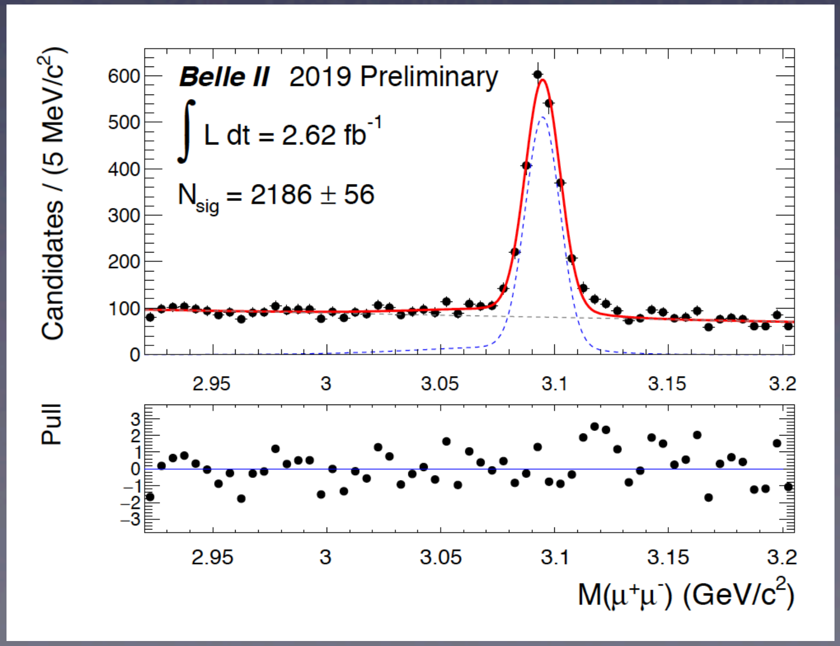


- charmed mesons (already shown, Phase 2)
  - ready for charm physics!
- charmonium: J/ψ
  - electrons and muons on almost equal footing

$J/\psi \rightarrow e^+e^-$

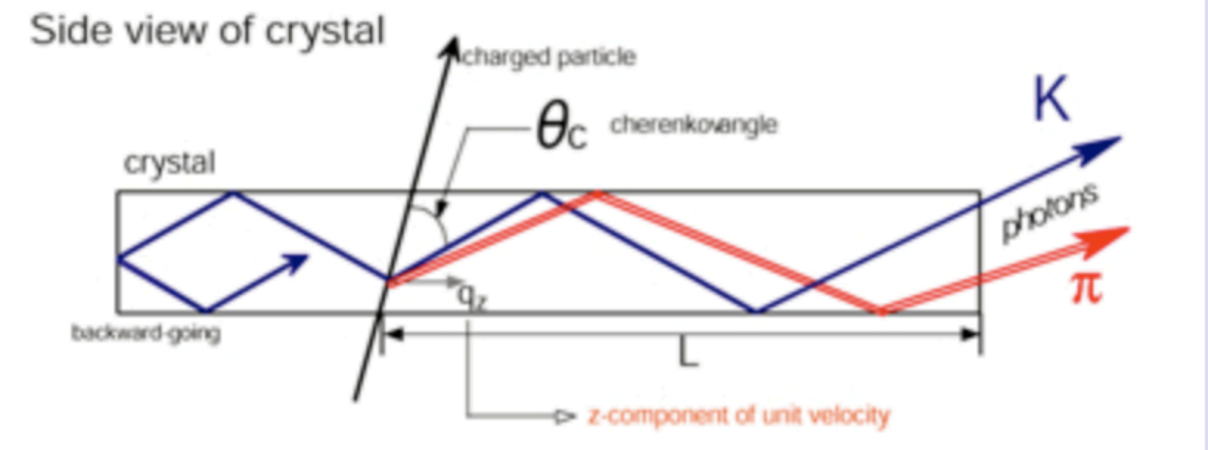


$J/\psi \rightarrow \mu^+\mu^-$

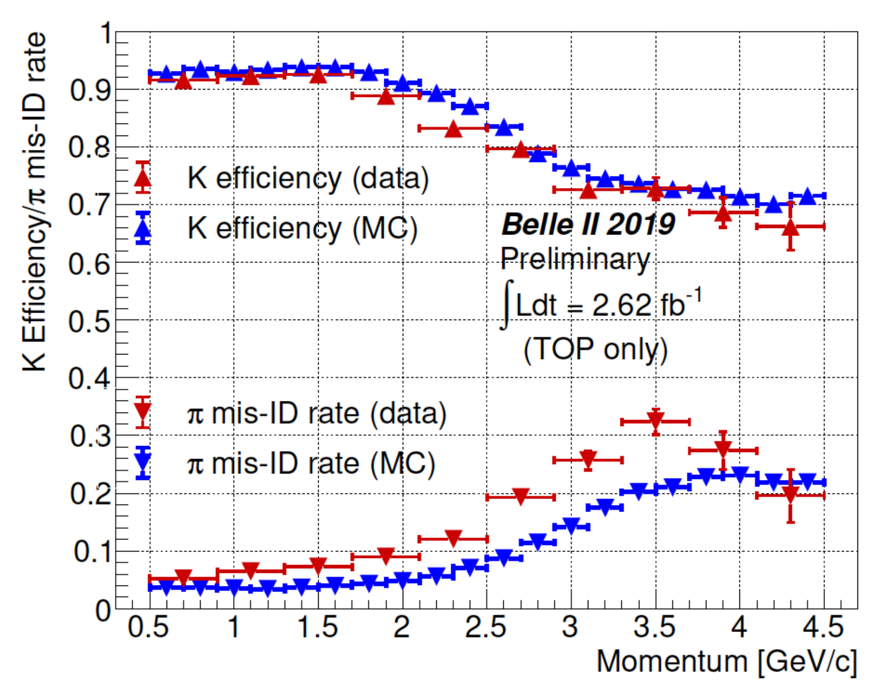


PID performance

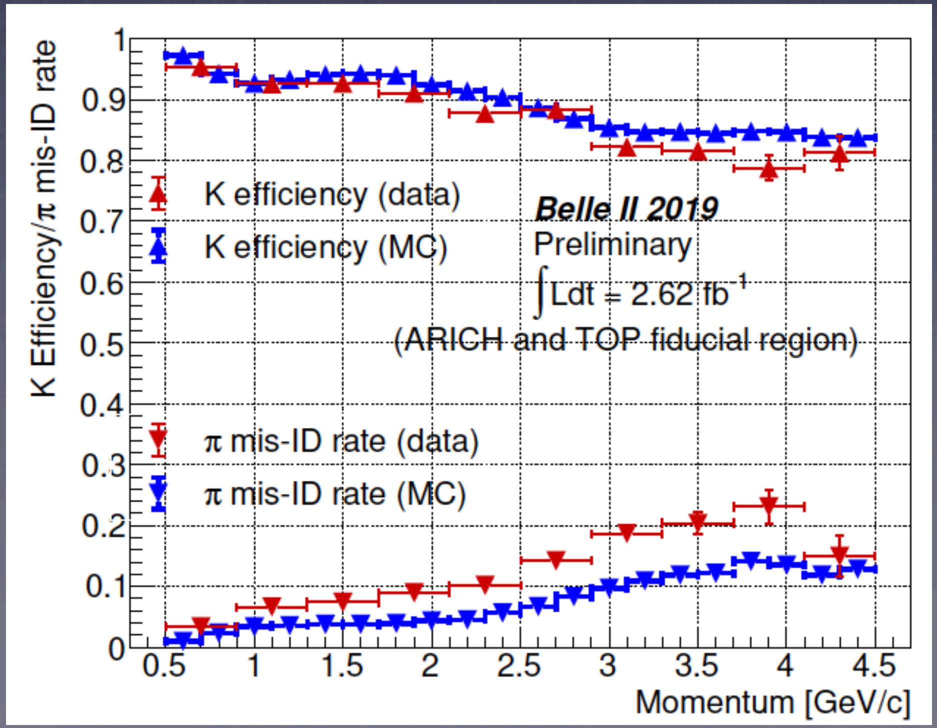
- Particle IDentification ($\pi, K, e, \mu, \ldots$) is crucial:
  - particle reconstruction
  - B-flavour tagging
- Contributions from sub-detectors: here an example of K efficiency&mis-ID, from TOP only and combined with CDC, ARICH
  - measured on a control sample: $D^{*+} \to D^0[K^-\pi^+]\pi^+$
  - compared with MC expectations



K ID from TOP only



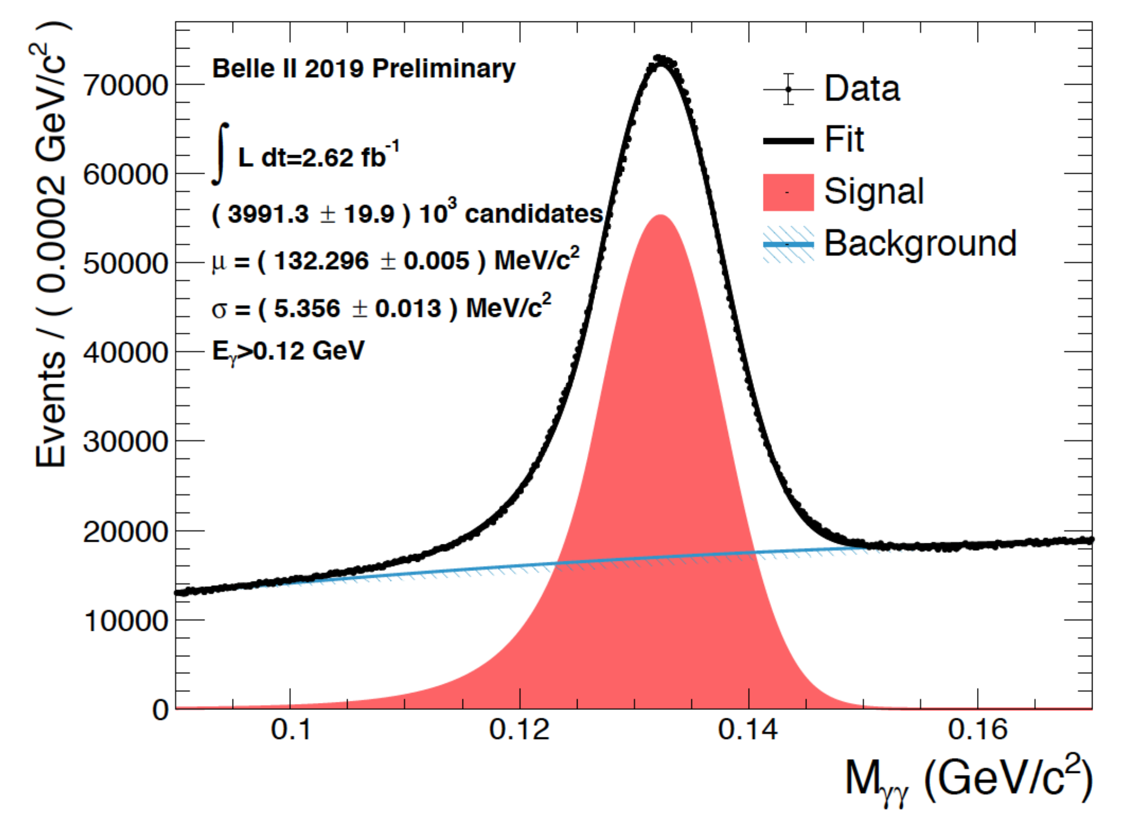
K ID from CDC, TOP, ARICH



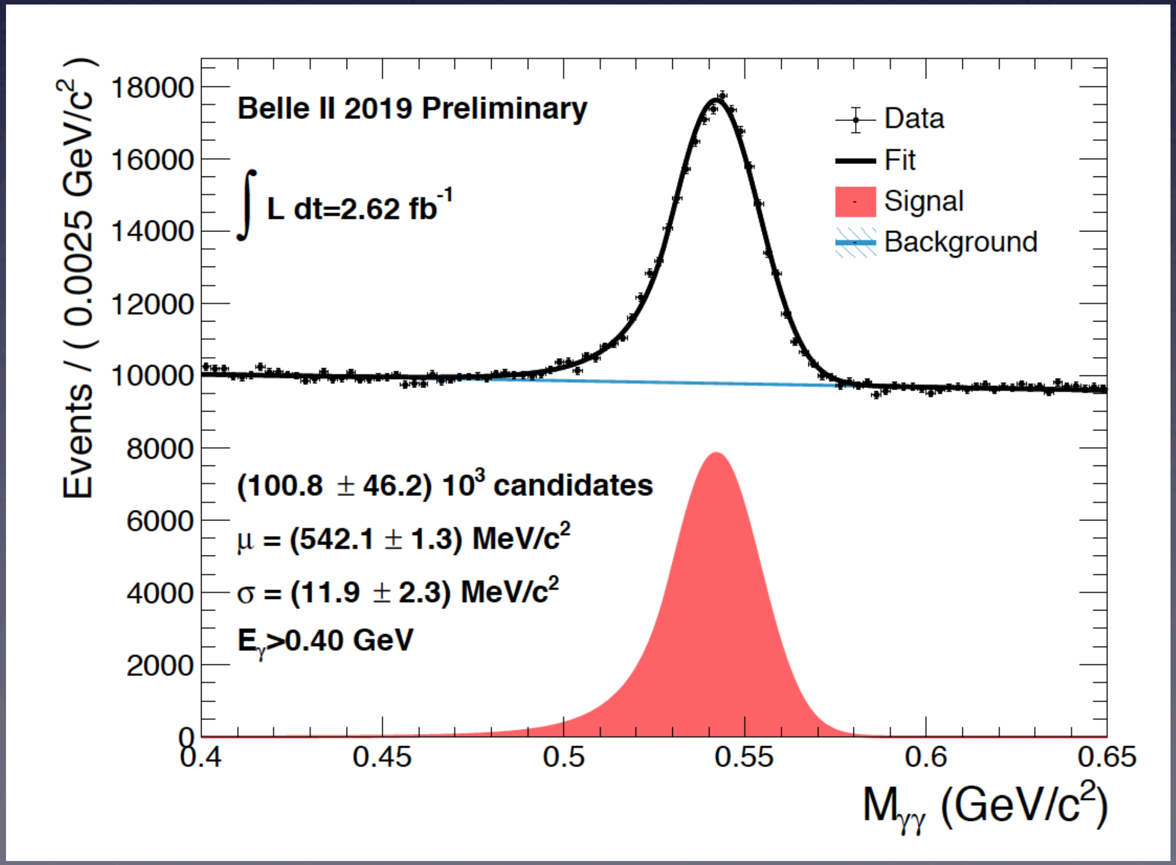
photons

- Electromagnetic calorimeter: clustering works well
- good resolution in inclusive π^0, η reconstruction from photon pairs

$\pi^0 \to \gamma\gamma$



$\eta \to \gamma\gamma$



$B \to J/\psi K_S$

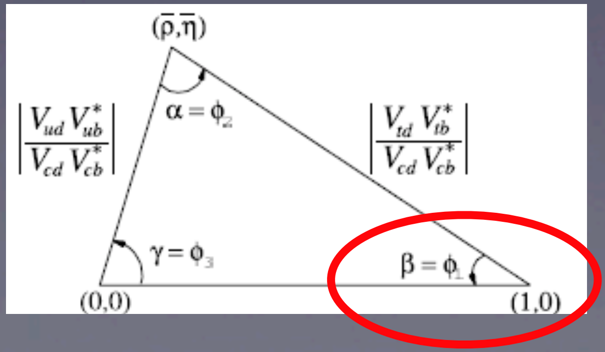
"golden channel"
for CPV, CKM angle
$\sin 2\phi_2\ (\sin 2\beta)$

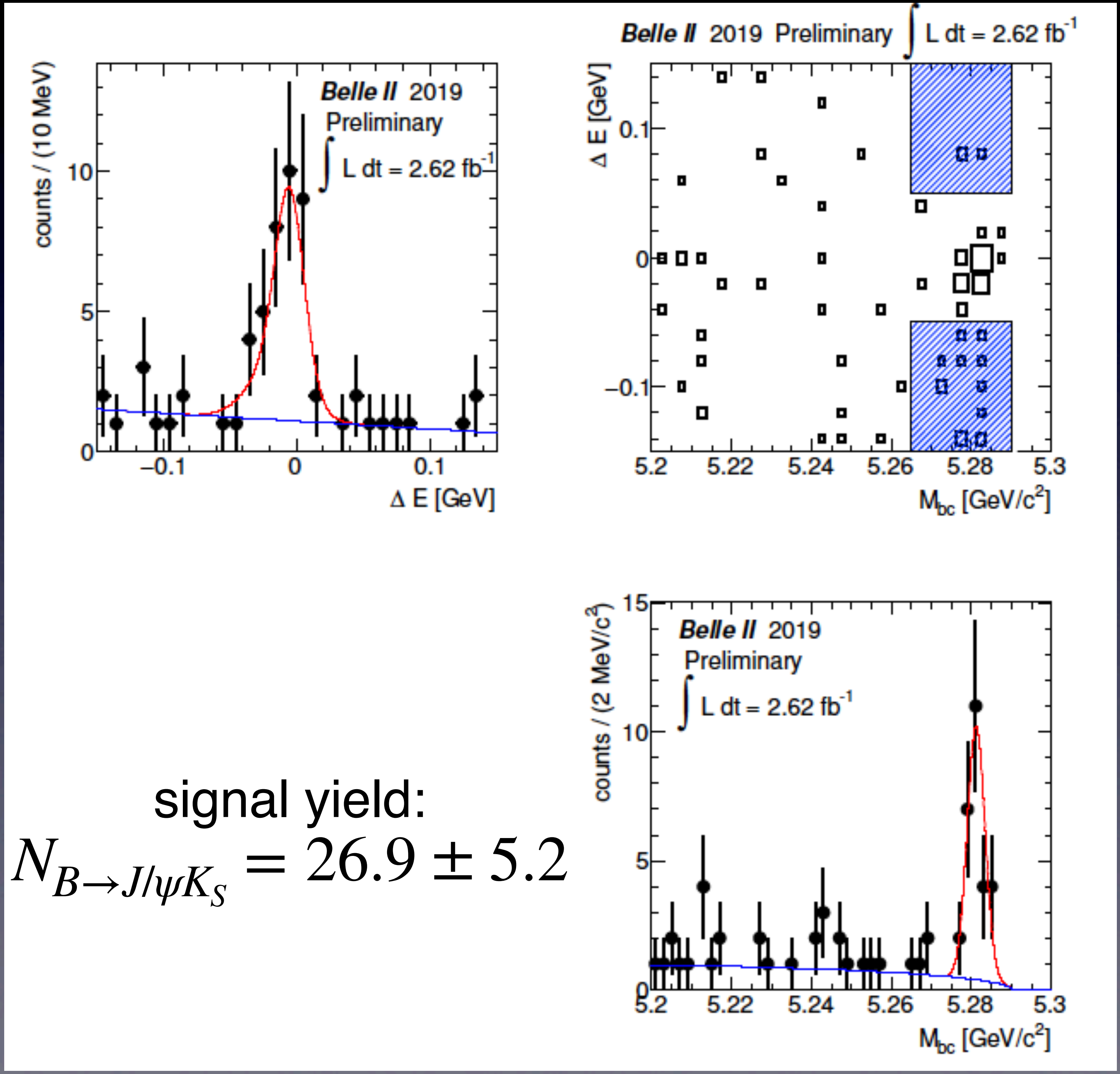
kinematics:
two variables

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

$$M_{bc} = \sqrt{E_{beam}^2 - p_E^2}$$

beam-constrained
invariant mass





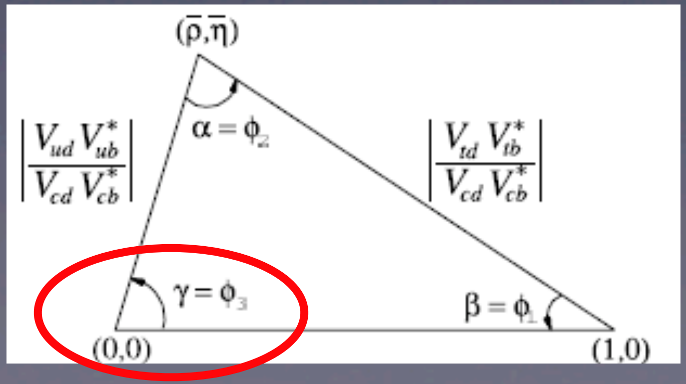
signal yield:

$$N_{B\to J/\psi K_S} = 26.9 \pm 5.2$$

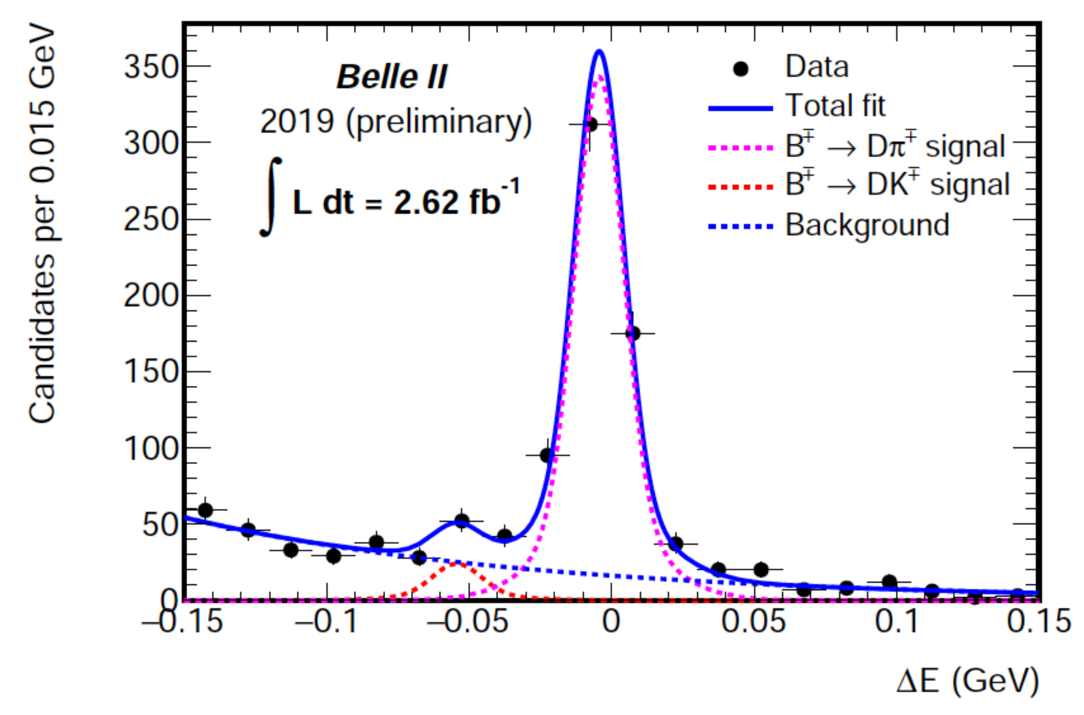
$B^{\pm} \to DK^{\pm}$

- an example: observation of one of the decay modes that will be essential for the measurement of the CKM unitarity angle $\phi_3 = \gamma$

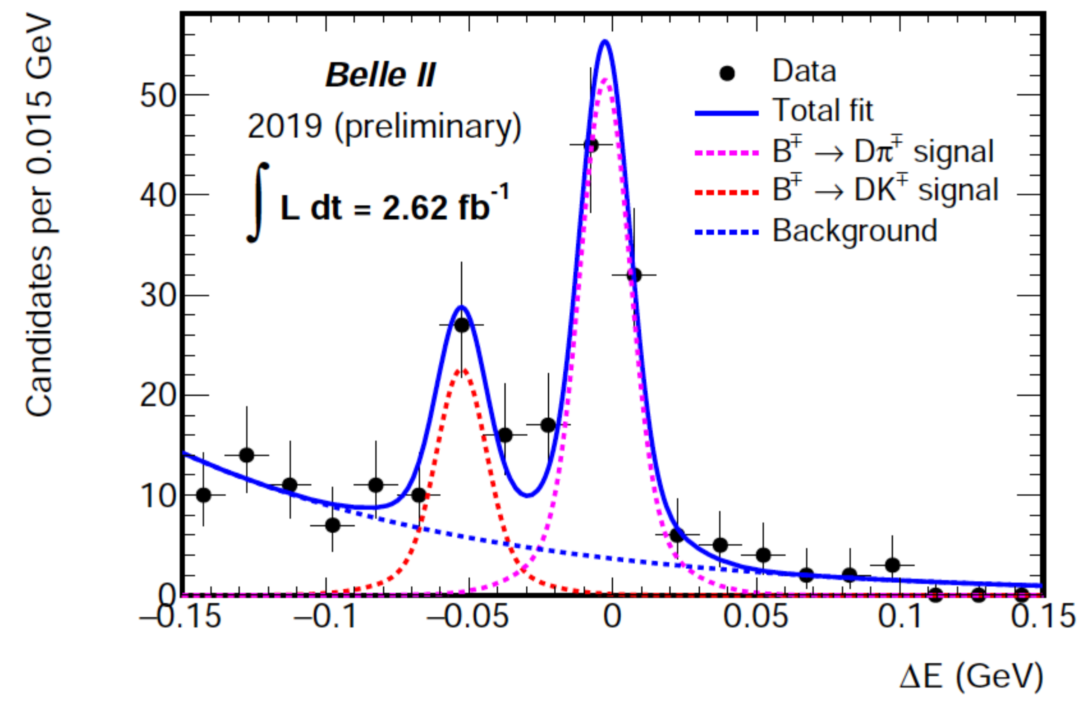
- it demonstrates the relevance of PID at high momenta to improve the signal/bkgd ratio



no PID



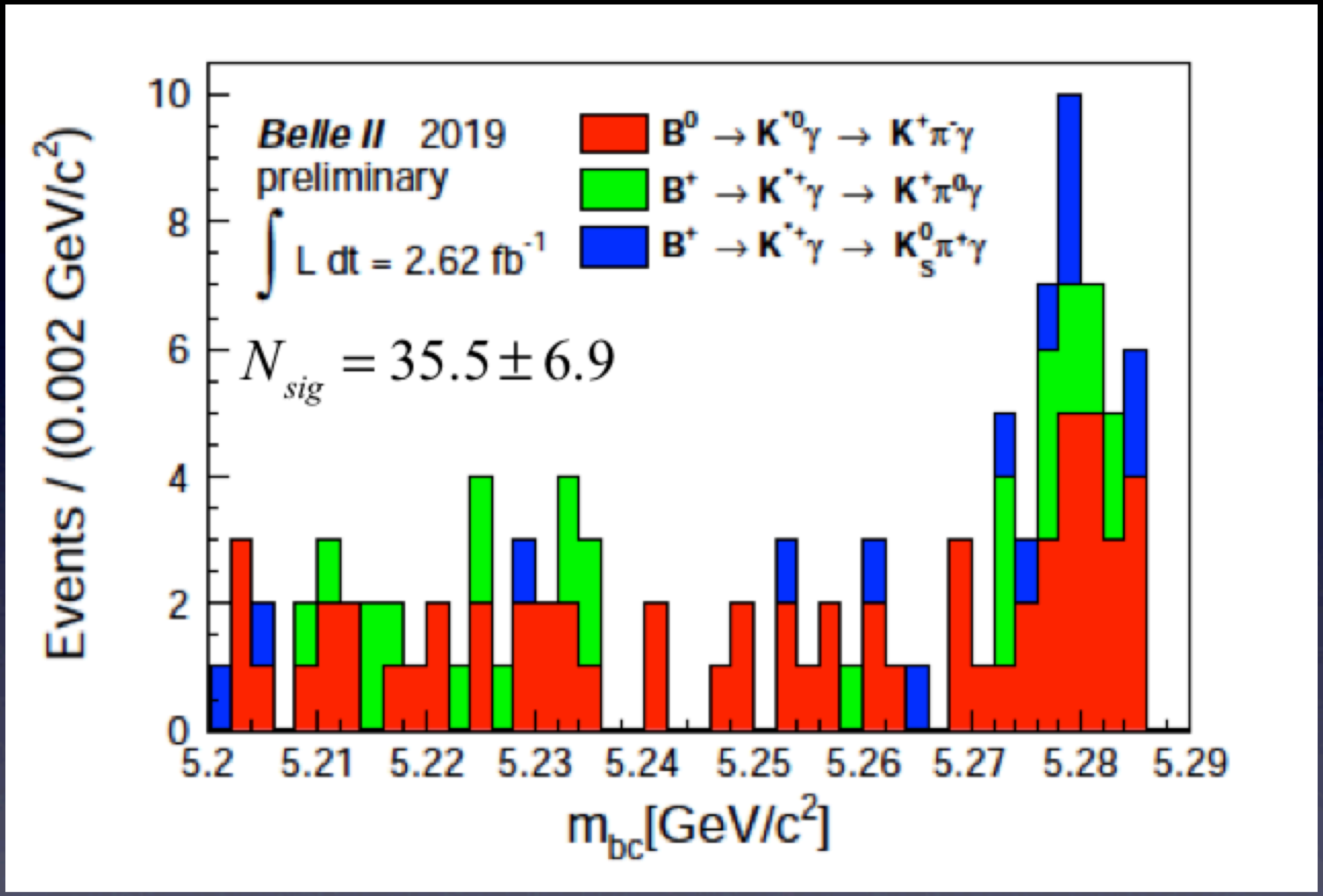
with high-momentum PID

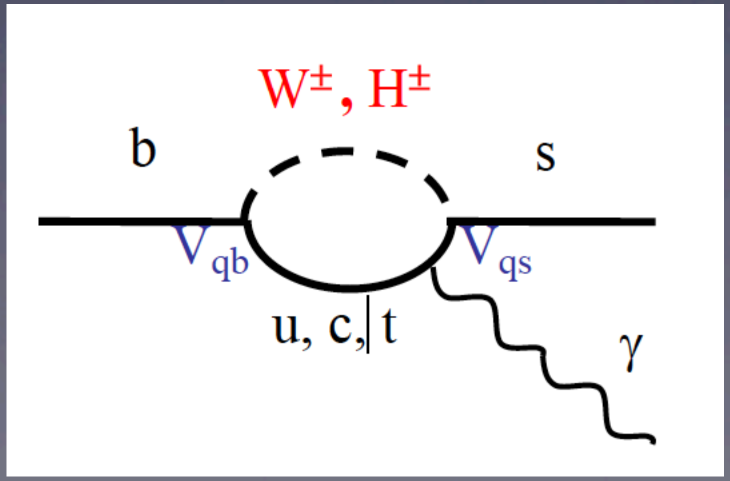


$B \to K^*\gamma$

- Searching for BSM contributions to the loops in $b \to s\gamma$ radiative penguins will be an important part of the physics program

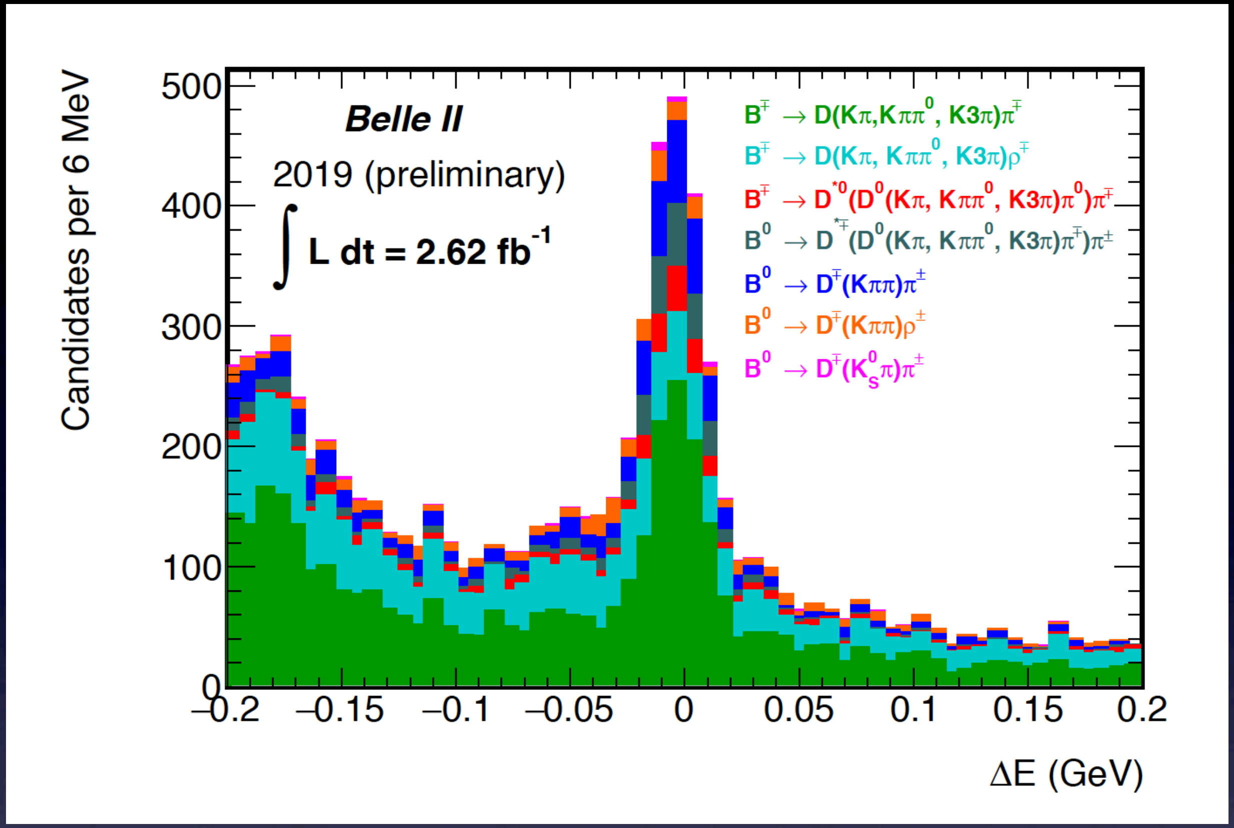
- re-discovery of $B \to K^*\gamma$ in the 2.6 fb^{-1} data sample

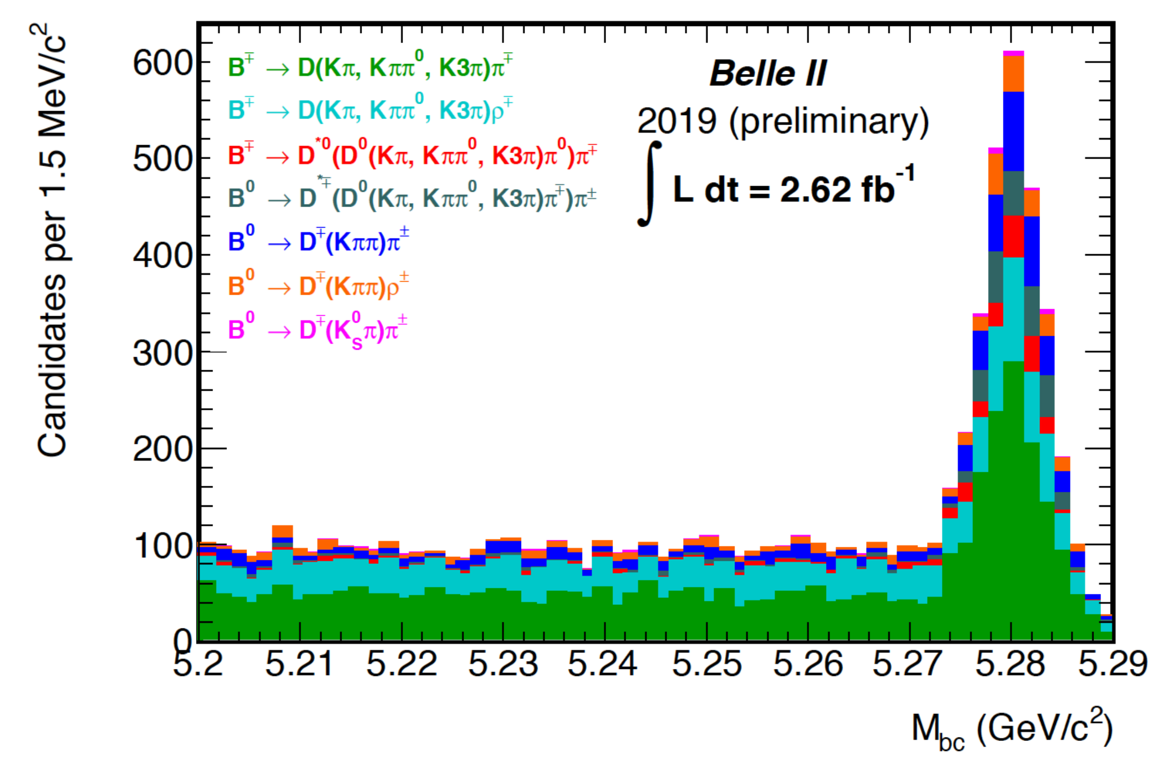




Hadronic B decays

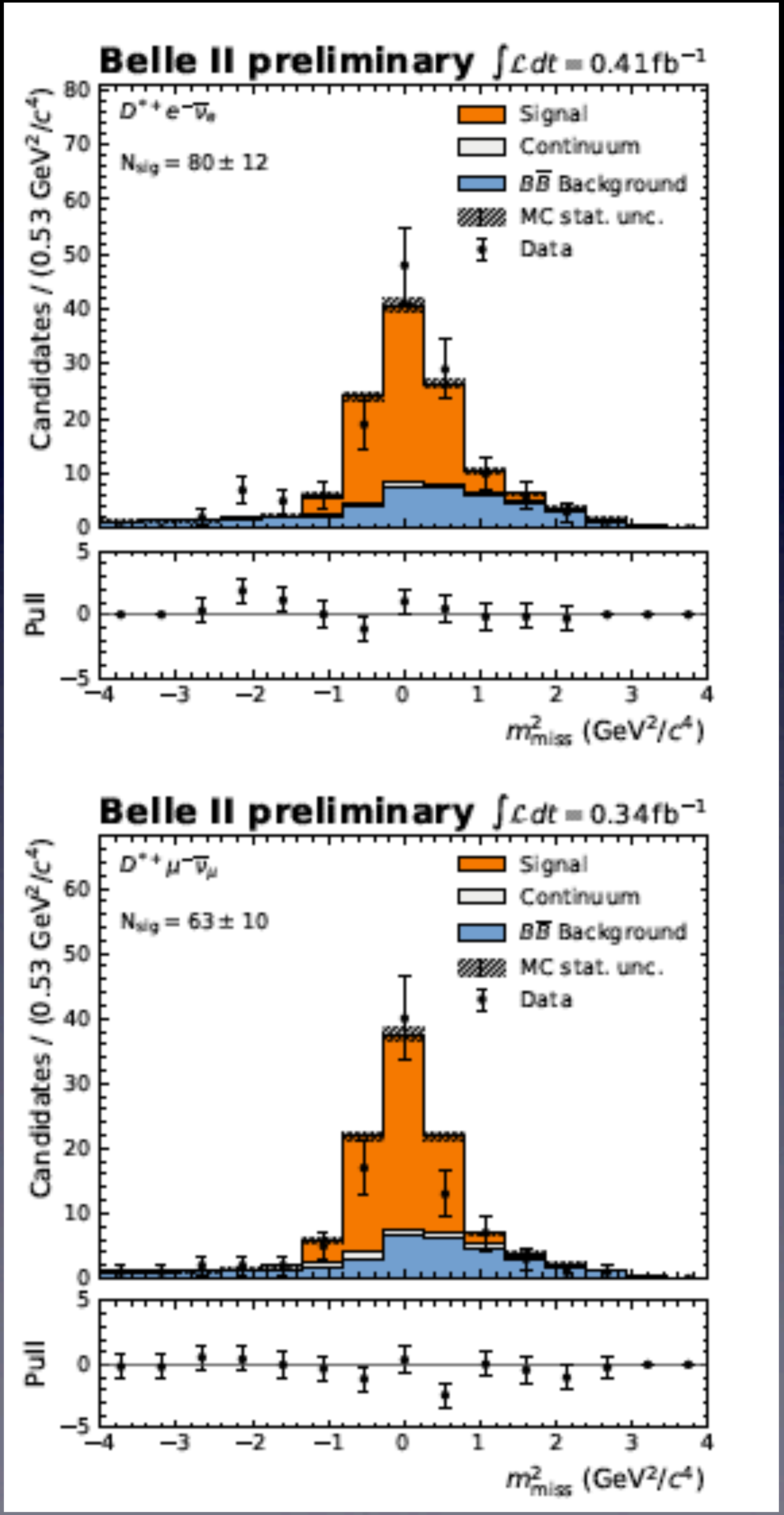
- Very important for the “full event reconstruction”
- A collection of B decays to hadrons “re-discovered” in Phase 3 data (2.6 fb^{-1})
- $B^{+/0} \to D^{(*)}h$
- distributions of candidates in the $(M_{bc}, \Delta E)$ variables



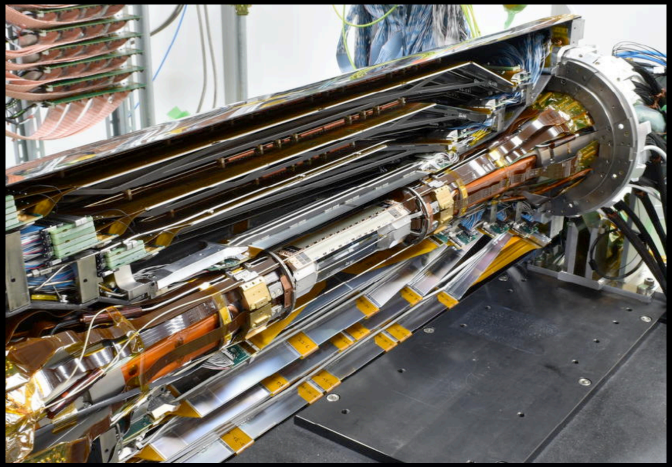


Semileptonic B decays

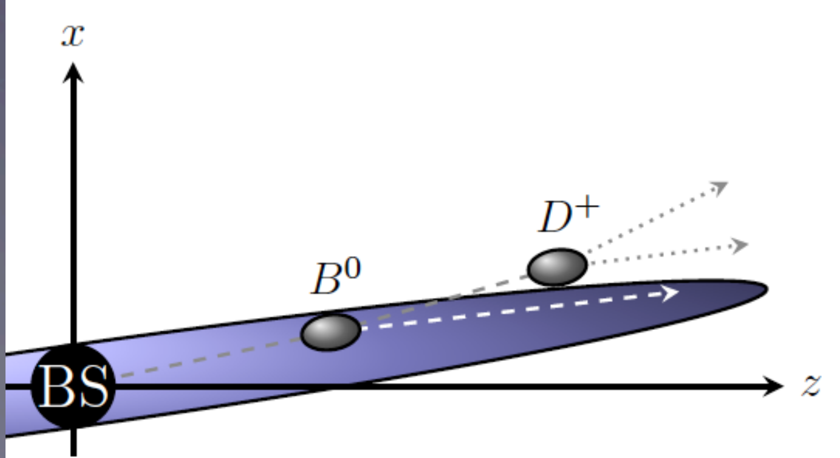
- Signals for $B \to D^{*+}\ell^-\bar{\nu}, \;\; D^{*+} \to D^0\pi^+$
- recoil mass technique: M^2_{miss}
- analysis performed on small sub-samples of the available data:
  - 0.41 fb-1 for ℓ = electrons
  - 0.34 fb-1 for ℓ = muons
- clear signals for both electrons and muons



time measurements

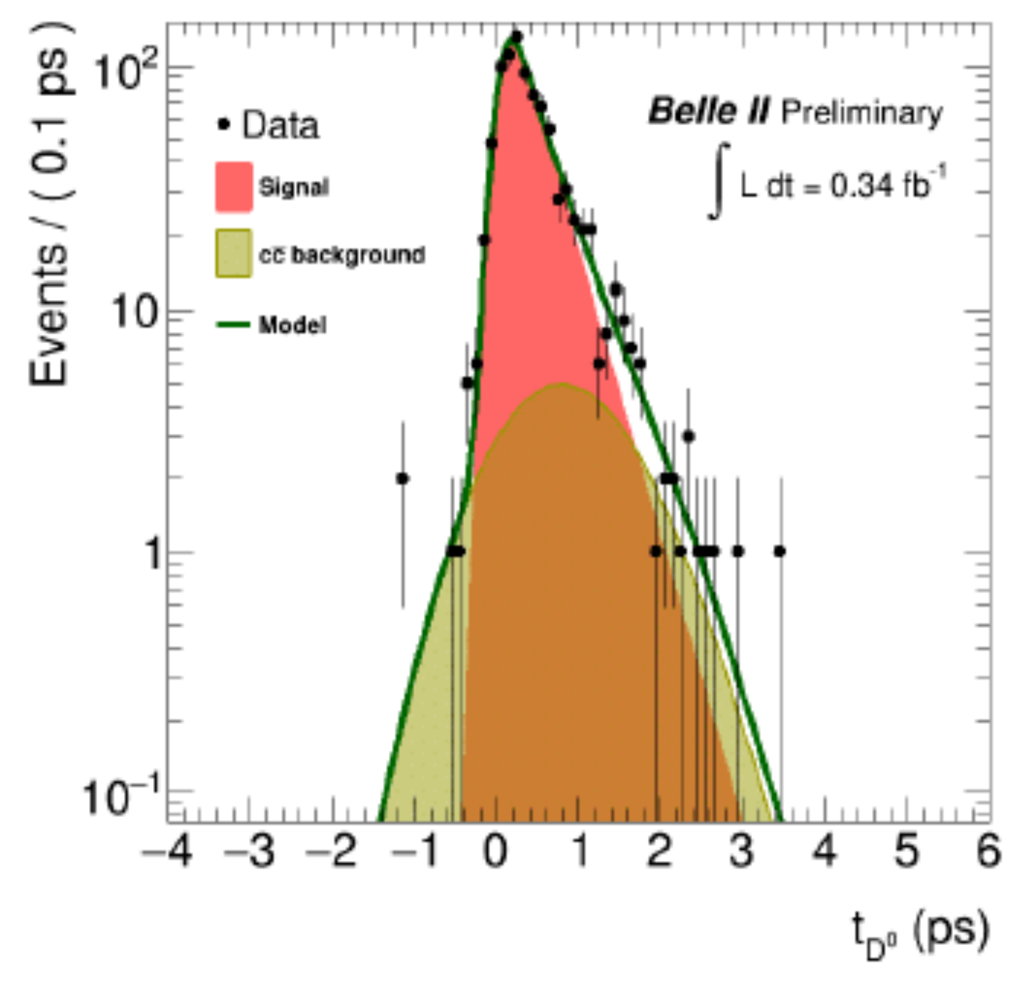


- VXD: 4 double-sided Si-strip layers + 1 pixel layer at 14mm from the beam
- impact parameter resolution $\simeq 14\mu$m, 2x better than Belle
- $\Delta t = \gamma\beta c\Delta z$ resolution is dominated by tag side
- traditional beam-spot constrained z measurement will be biased at smaller beam spots: study required



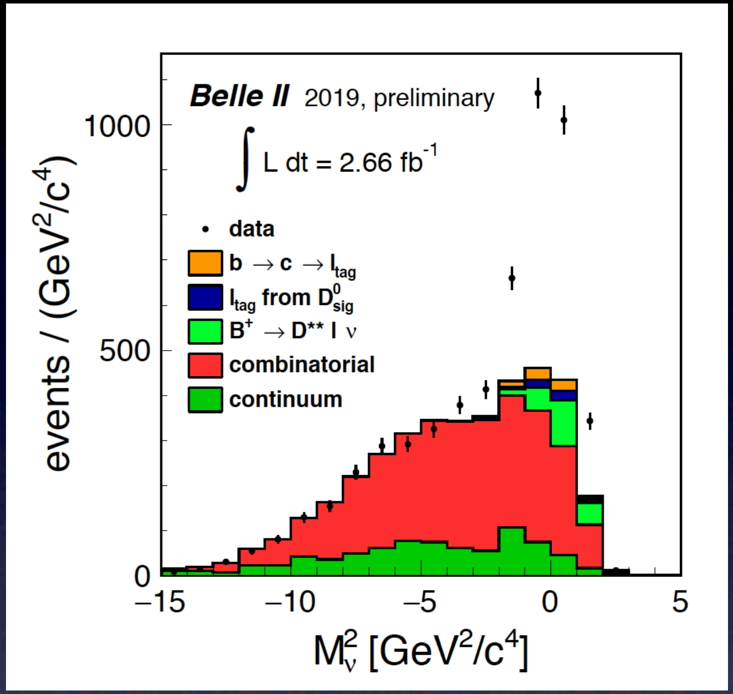
demo exercise: D^0 lifetime on a small data set (0.34 fb^{-1})

$$\tau_{D^0} = (370 \pm 40)\ \text{fs}$$

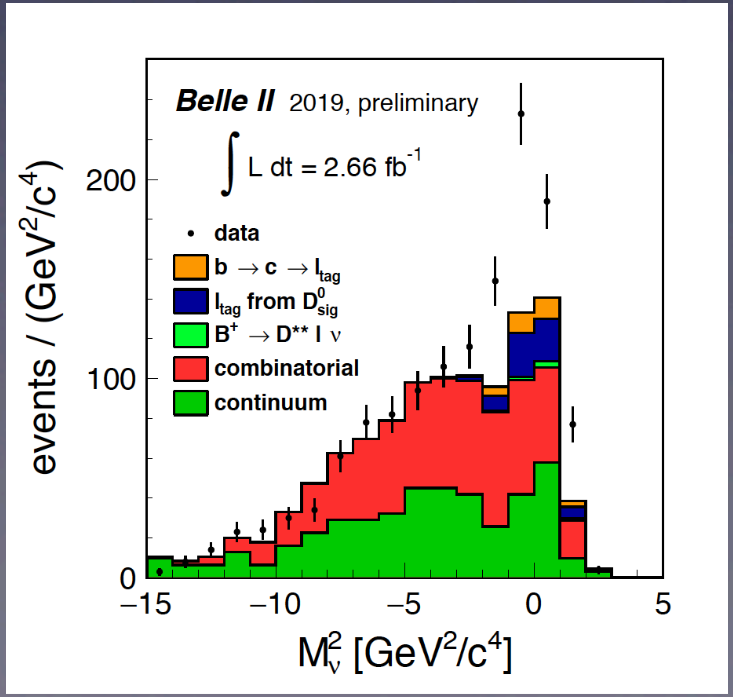


time-dependent B mixing

unmixed (U)
opposite-flavour tag



mixed (M)
same-flavour tag



integrated: $\chi_d = \dfrac{N_M}{N_U + N_M} = (17.3 \pm 3.6)\,\%$

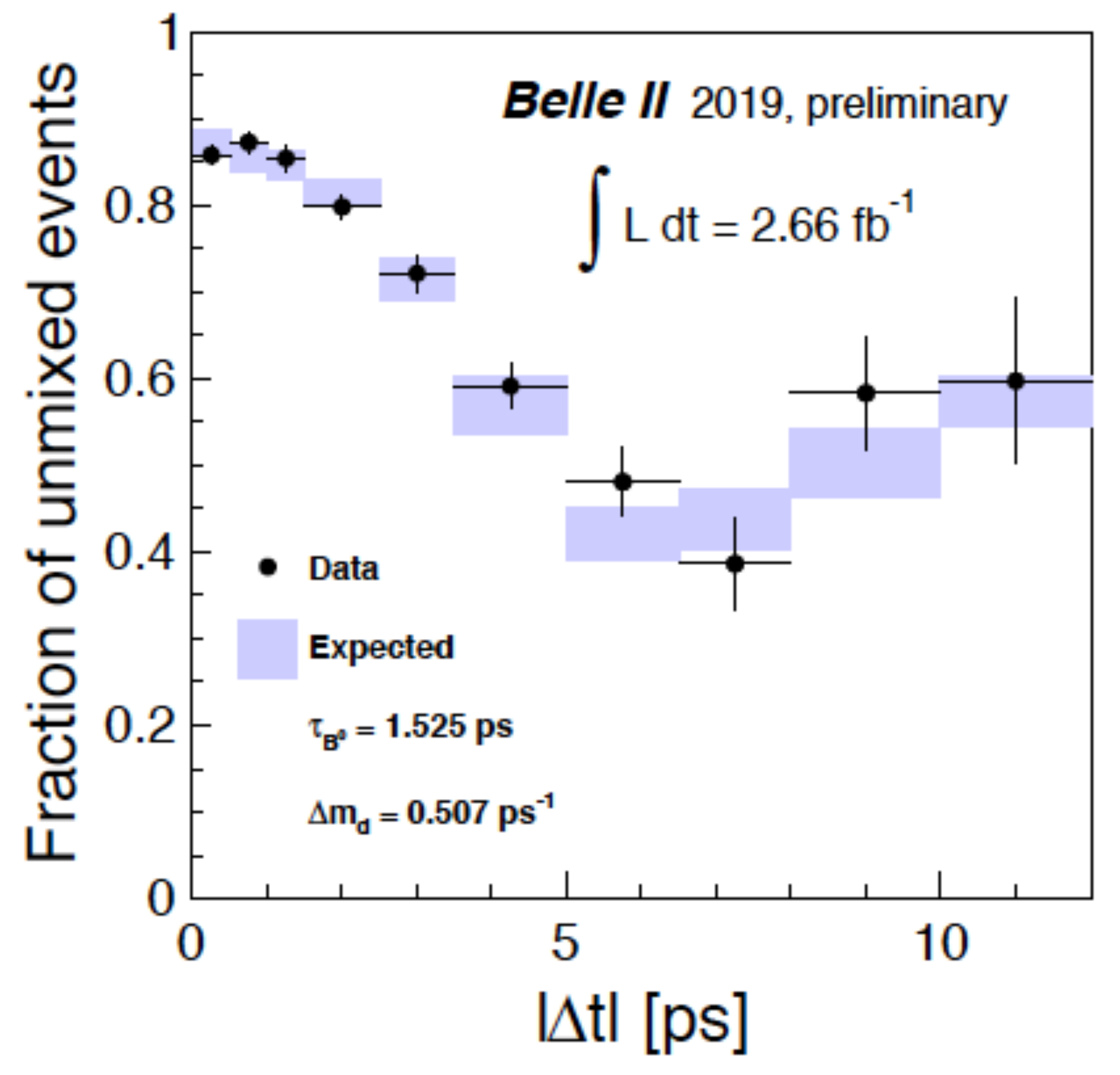
WA $18.6\,\%$

time-dependent:

$$A(|\Delta t|) = \frac{N_U(|\Delta t|)}{N_U(|\Delta t|) + N_M(|\Delta t|)}$$

self-tagging
signal:
$B \to D^* \ell \nu$

+other-side
tag:
opposite flavour
or
same flavour



dark sector: Z’ → invisible

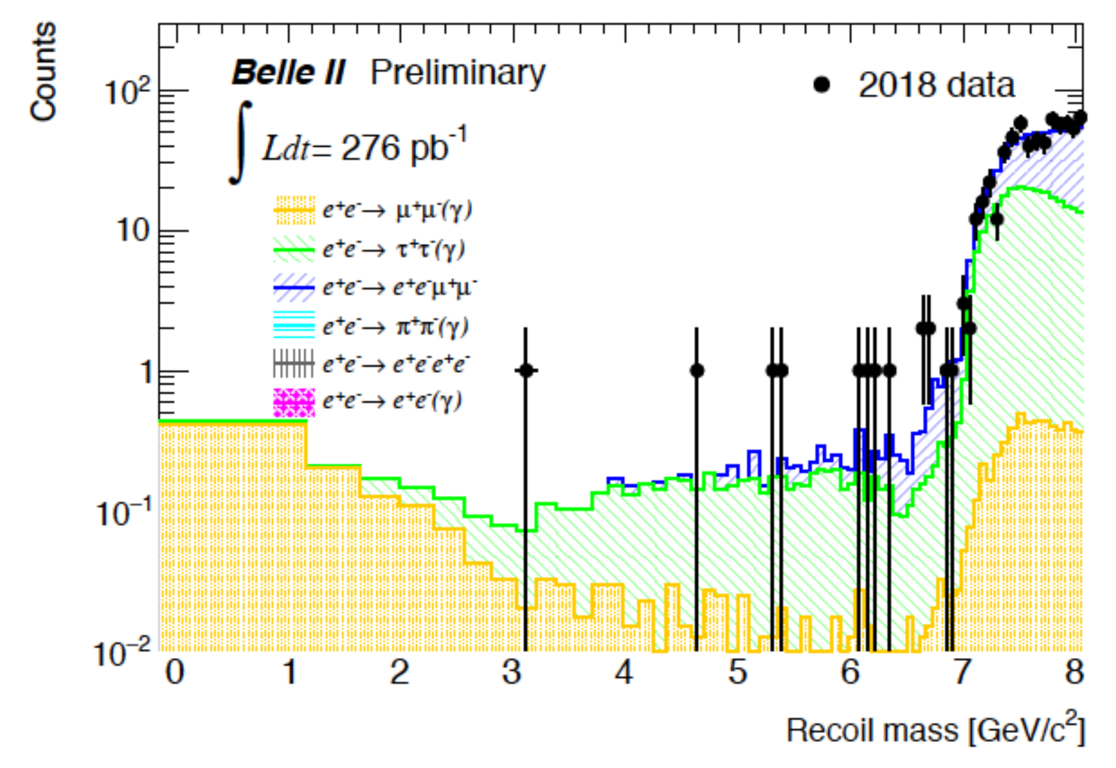
- search for $e^+e^- \to \mu^+\mu^- Z'$
  $Z' \to$ invisible

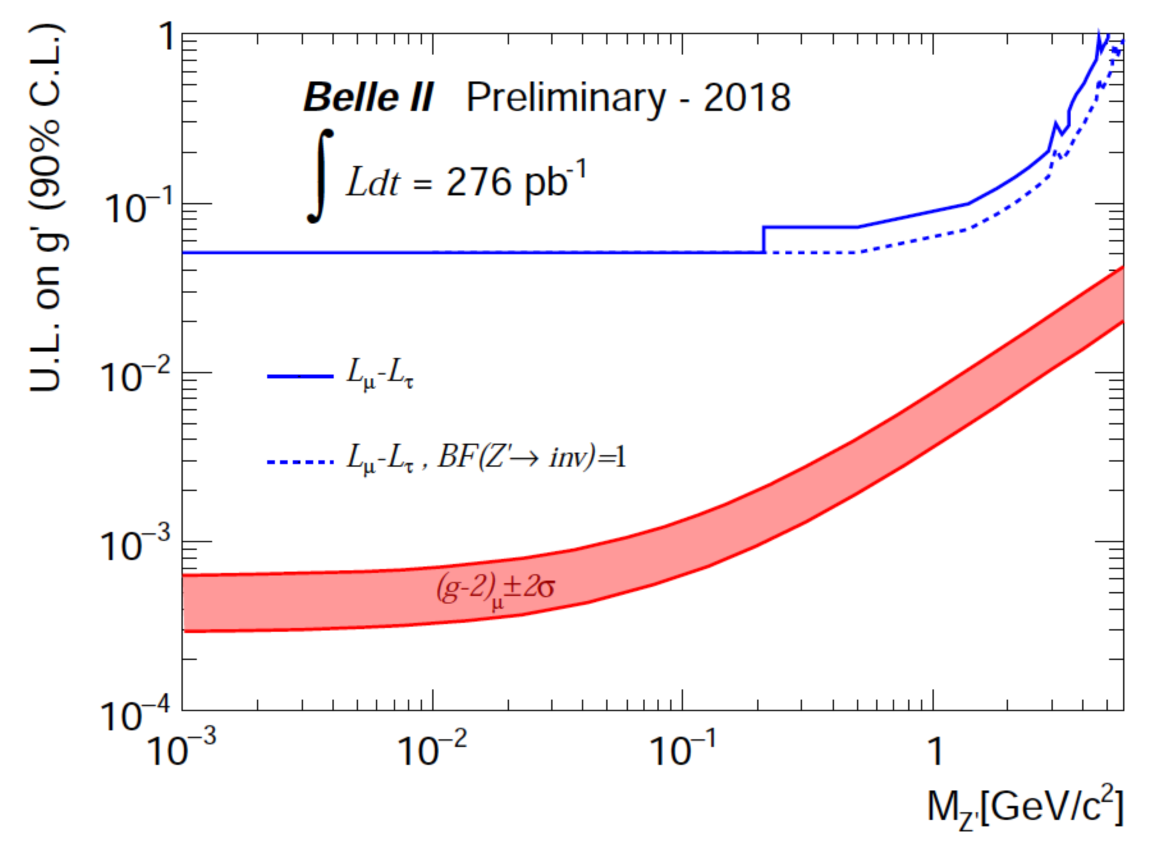
- Z’ poorly constrained at low mass, could explain the $(g-2)_\mu$ anomaly

- recoil mass distribution compatible with backgrounds

- first physics from Belle II…
  the upper limit will improve with more data

- similar analysis completed for
  $e^+e^- \to \mu^\pm e^\mp Z'_{LFV}$
  $Z'_{LFV} \to$ invisible



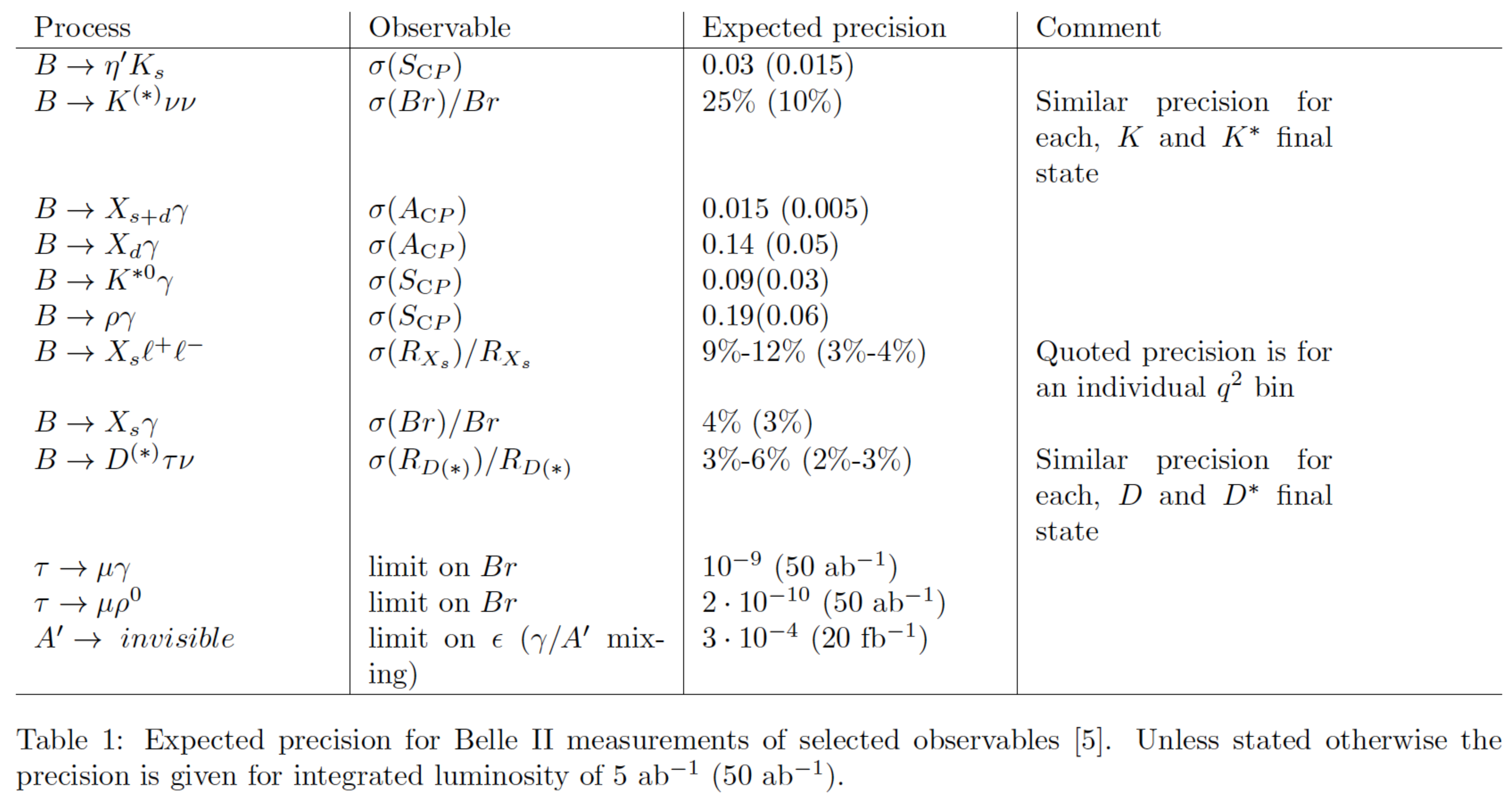


Physics prospects

- Physics potential of Belle II: discussed in a series of “B2TIP” workshops (experiment + theory)
  - The Belle II Physics Book: https://arxiv.org/abs/1808.10567
  - an executive summary: input to the European Particle Physics Strategy update (October 2018)
- general idea: complementary to LHCb, in particular for final states with photons, neutrinos, missing energy

- Physics program of Belle II:
  - CP Violation & CKM
  - Lepton universality
  - Lepton flavour violation
  - Dark sector
  - Hadron spectroscopy

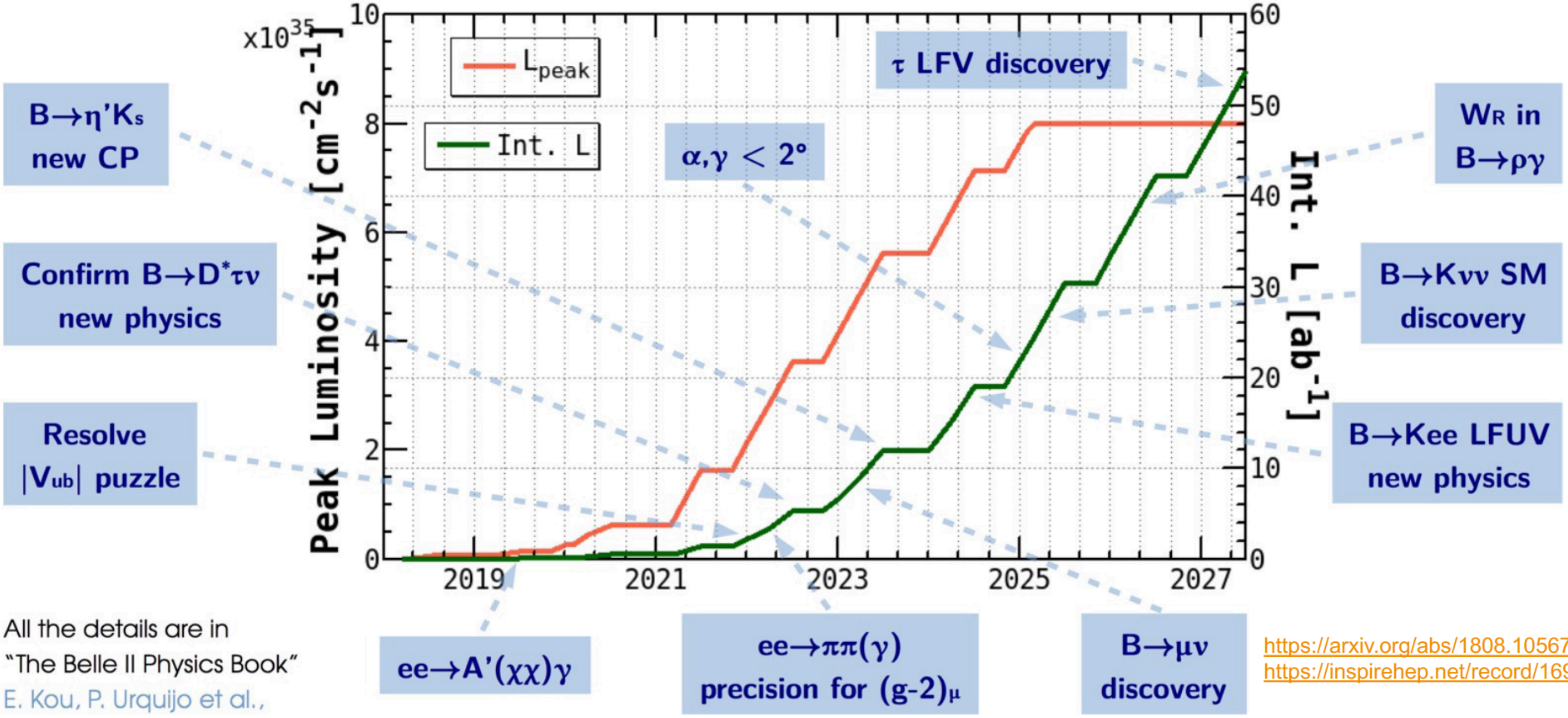
Selected observables



Process	Observable	Expected precision	Comment
$B \to \eta' K_s$	$\sigma(S_{CP})$	0.03 (0.015)	
$B \to K^{(*)}\nu\nu$	$\sigma(Br)/Br$	25% (10%)	Similar precision for each, K and K^* final state
$B \to X_{s+d}\gamma$	$\sigma(A_{CP})$	0.015 (0.005)	
$B \to X_d\gamma$	$\sigma(A_{CP})$	0.14 (0.05)	
$B \to K^{*0}\gamma$	$\sigma(S_{CP})$	0.09(0.03)	
$B \to \rho\gamma$	$\sigma(S_{CP})$	0.19(0.06)	
$B \to X_s\ell^+\ell^-$	$\sigma(R_{X_s})/R_{X_s}$	9%-12% (3%-4%)	Quoted precision is for an individual q^2 bin
$B \to X_s\gamma$	$\sigma(Br)/Br$	4% (3%)	
$B \to D^{(*)}\tau\nu$	$\sigma(R_{D(*)})/R_{D(*)}$	3%-6% (2%-3%)	Similar precision for each, D and D^* final state
$\tau \to \mu\gamma$	limit on Br	10^{-9} (50 ab^{-1})	
$\tau \to \mu\rho^0$	limit on Br	$2 \cdot 10^{-10}$ (50 ab^{-1})	
$A' \to$ *invisible*	limit on ϵ (γ/A' mixing)	$3 \cdot 10^{-4}$ (20 fb^{-1})	

Table 1: Expected precision for Belle II measurements of selected observables [5]. Unless stated otherwise the precision is given for integrated luminosity of 5 ab^{-1} (50 ab^{-1}).

an optimistic roadmap



$B \to \eta' K_s$ new CP

Confirm $B \to D^* \tau \nu$ new physics

Resolve $|V_{ub}|$ puzzle

$ee \to A'(\chi\chi)\gamma$

$ee \to \pi\pi(\gamma)$ precision for $(g\text{-}2)_\mu$

$B \to \mu\nu$ discovery

τ LFV discovery

$\alpha, \gamma < 2°$

W_R in $B \to \rho\gamma$

$B \to K\nu\nu$ SM discovery

$B \to Kee$ LFUV new physics

All the details are in
"The Belle II Physics Book"
E. Kou, P. Urquijo et al.,

https://arxiv.org/abs/1808.10567
https://inspirehep.net/record/1692393/

Summary

- B factories have unique features, that make them ideal tools to investigate flavour physics.

- Luminosity and beam backgrounds are the main challenges for a successful participation in the quest for BSM physics.

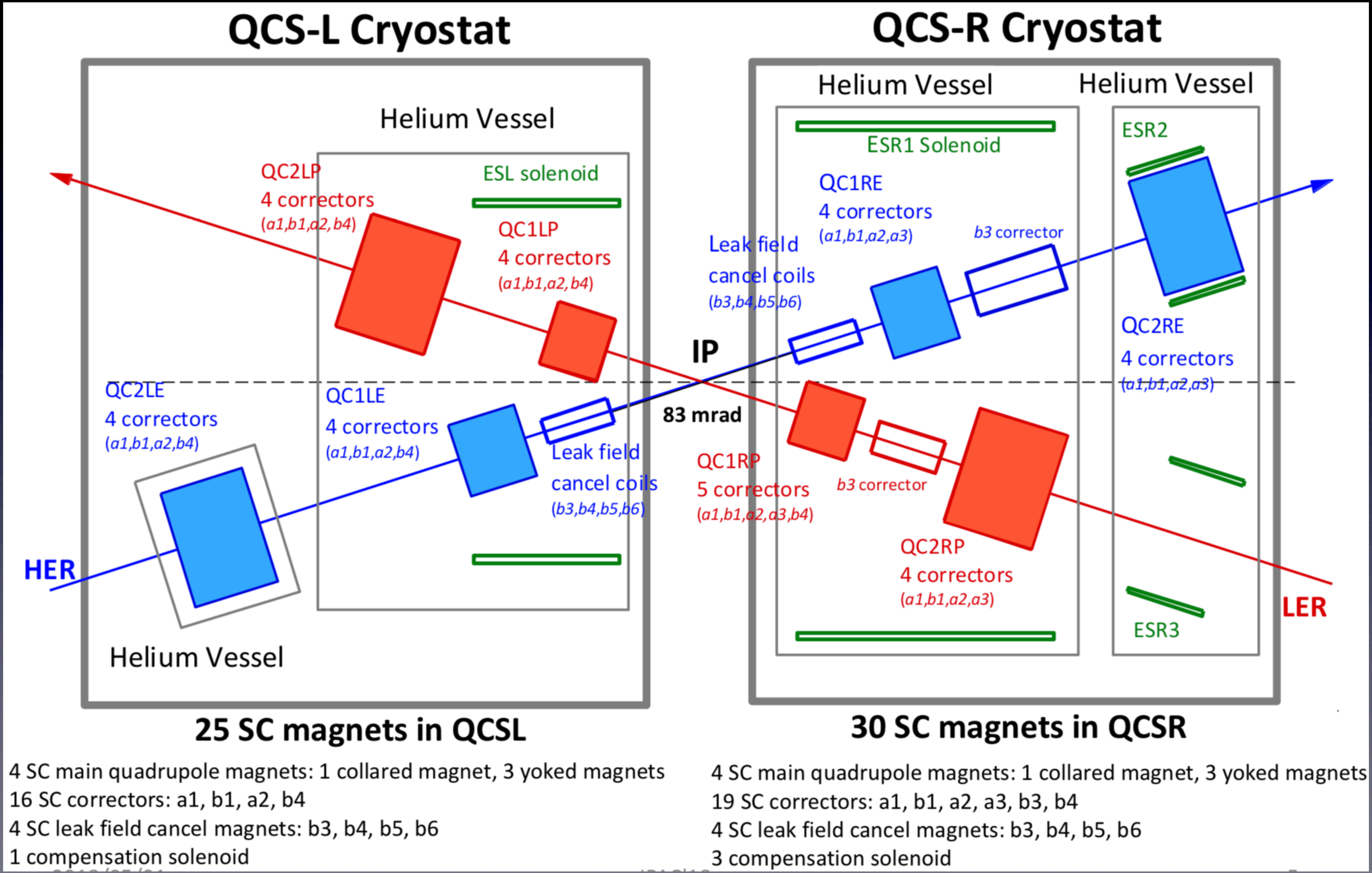
- SuperKEKB is progressing with an aggressive plan to step up from the KEKB peak luminosity by a factor 40.

- Belle II has been taking the first physics data with the complete detector, with very good performance. Our analysis tools are getting ready to deal with physics.

- The road ahead will certainly be bumpy and not easy, with strong competition from LHCb, but the journey will be exciting and rewarding: we may even glimpse at BSM physics, if it really is there!

back-up slides

IR magnets



25 SC magnets in QCSL

4 SC main quadrupole magnets: 1 collared magnet, 3 yoked magnets
16 SC correctors: a1, b1, a2, b4
4 SC leak field cancel magnets: b3, b4, b5, b6
1 compensation solenoid

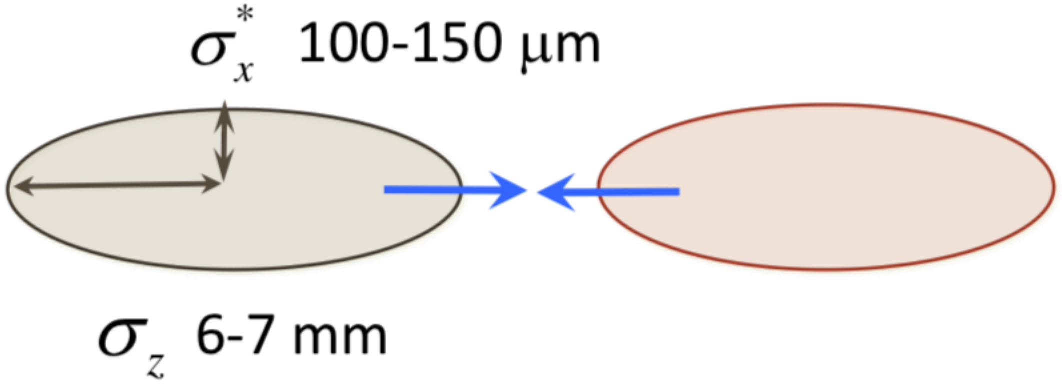
30 SC magnets in QCSR

4 SC main quadrupole magnets: 1 collared magnet, 3 yoked magnets
19 SC correctors: a1, b1, a2, a3, b3, b4
4 SC leak field cancel magnets: b3, b4, b5, b6
3 compensation solenoid

Collision Scheme

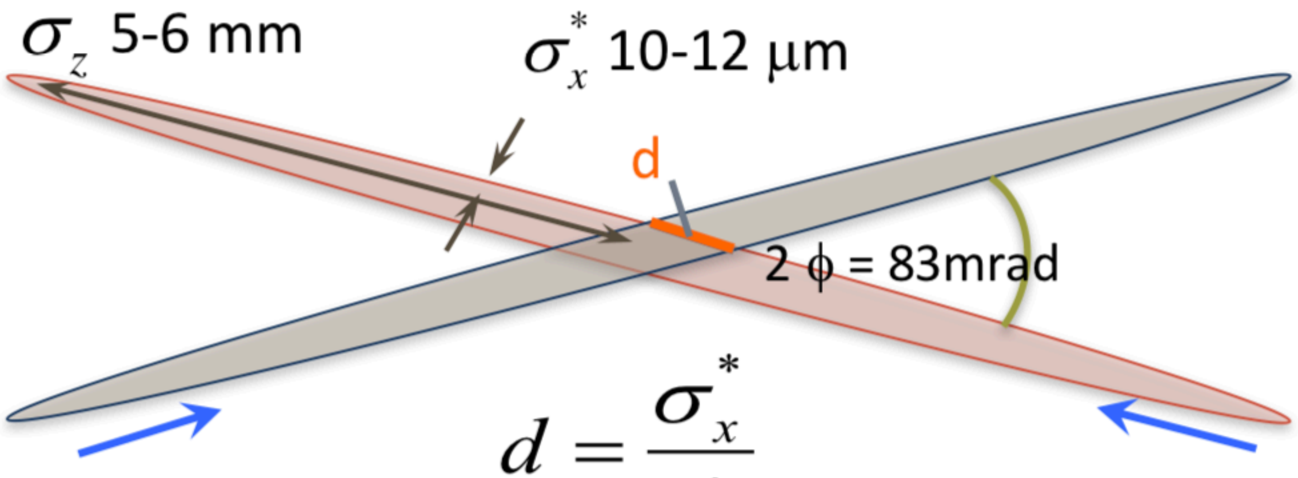
P. Raimondi

KEKB head-on (crab crossing)



interaction region = bunch length

Nano-Beam Scheme SuperKEKB



$$d = \frac{\sigma_x^*}{\phi}$$

$\phi_{pwinski} \sim 20$

Half crossing angle: ϕ

interaction region << bunch length

Hourglass requirement

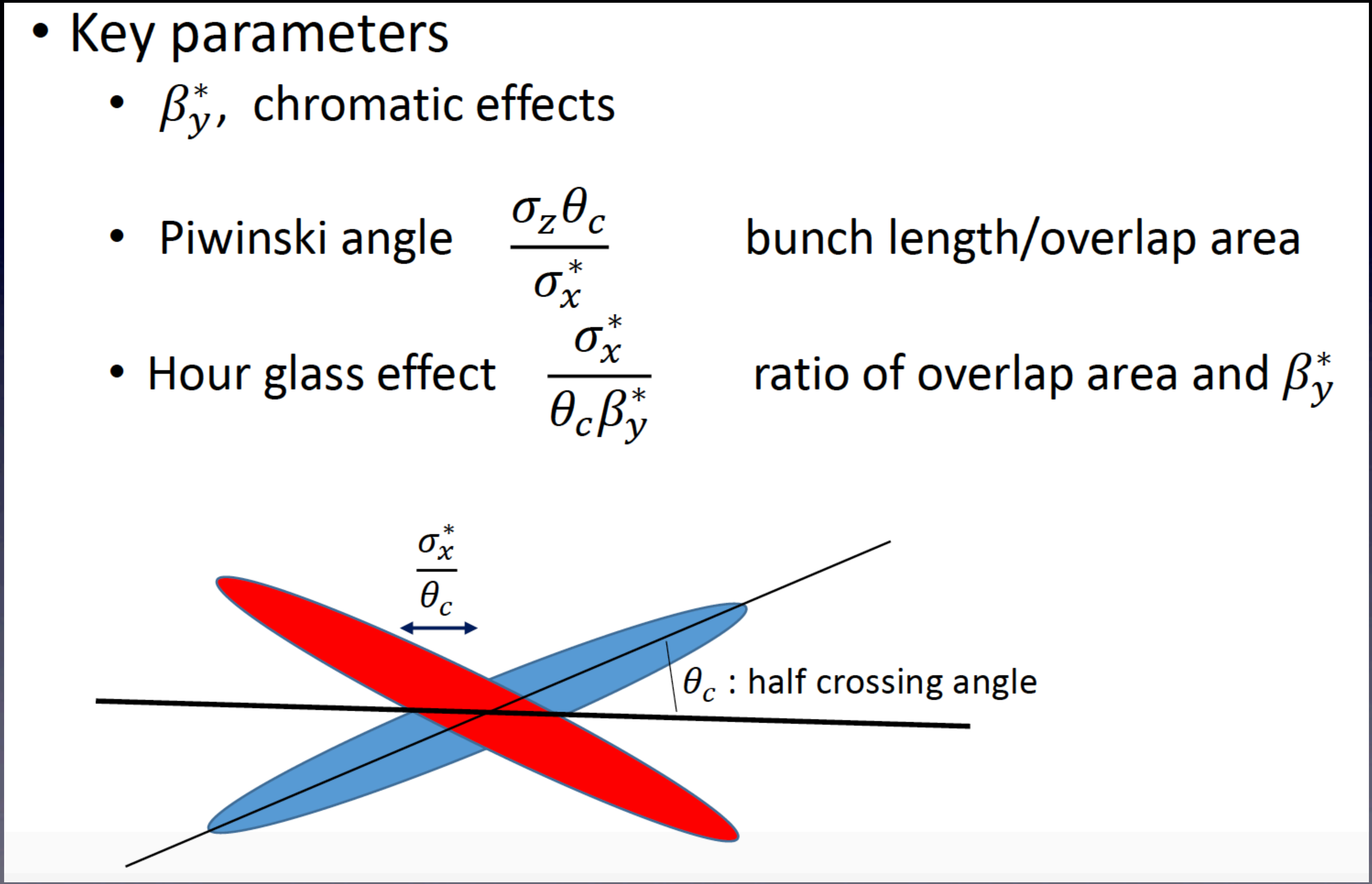
$$\beta_y^* \geq \sigma_z \sim 6 \text{ mm}$$

$$\beta_y^* \geq \frac{\sigma_x^*}{\phi} \sim 300 \text{ µm}$$

Vertical beta function at IP can be squeezed to ~300µm.
Need small horizontal beam size at IP.
→ low emittance, small horizontal beta function at IP.

No crab waist scheme has been assumed at SuperKEKB

Some definitions

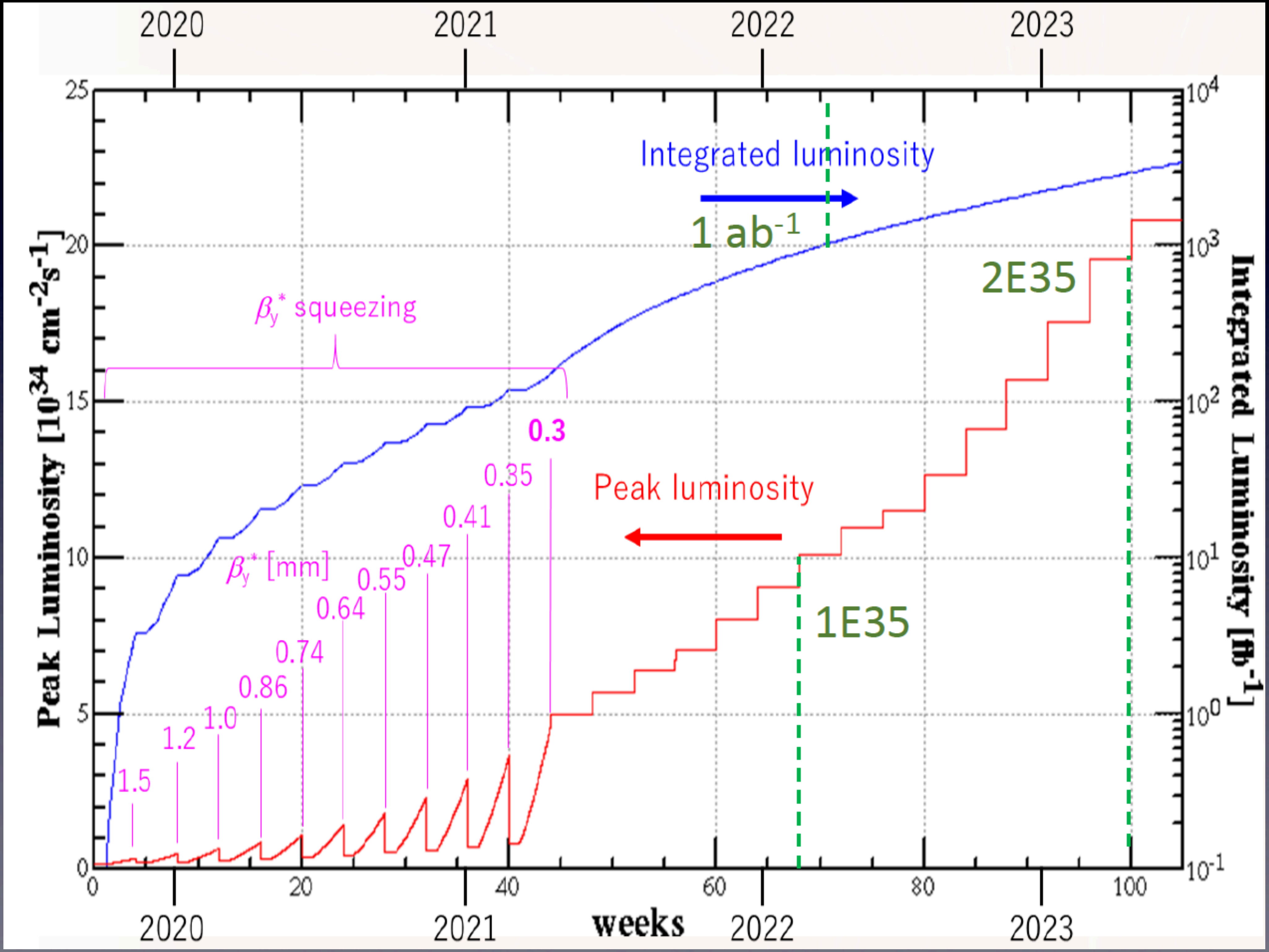


- Key parameters
  - β_y^*, chromatic effects
  - Piwinski angle $\frac{\sigma_z \theta_c}{\sigma_x^*}$ bunch length/overlap area
  - Hour glass effect $\frac{\sigma_x^*}{\theta_c \beta_y^*}$ ratio of overlap area and β_y^*

$\frac{\sigma_x^*}{\theta_c}$

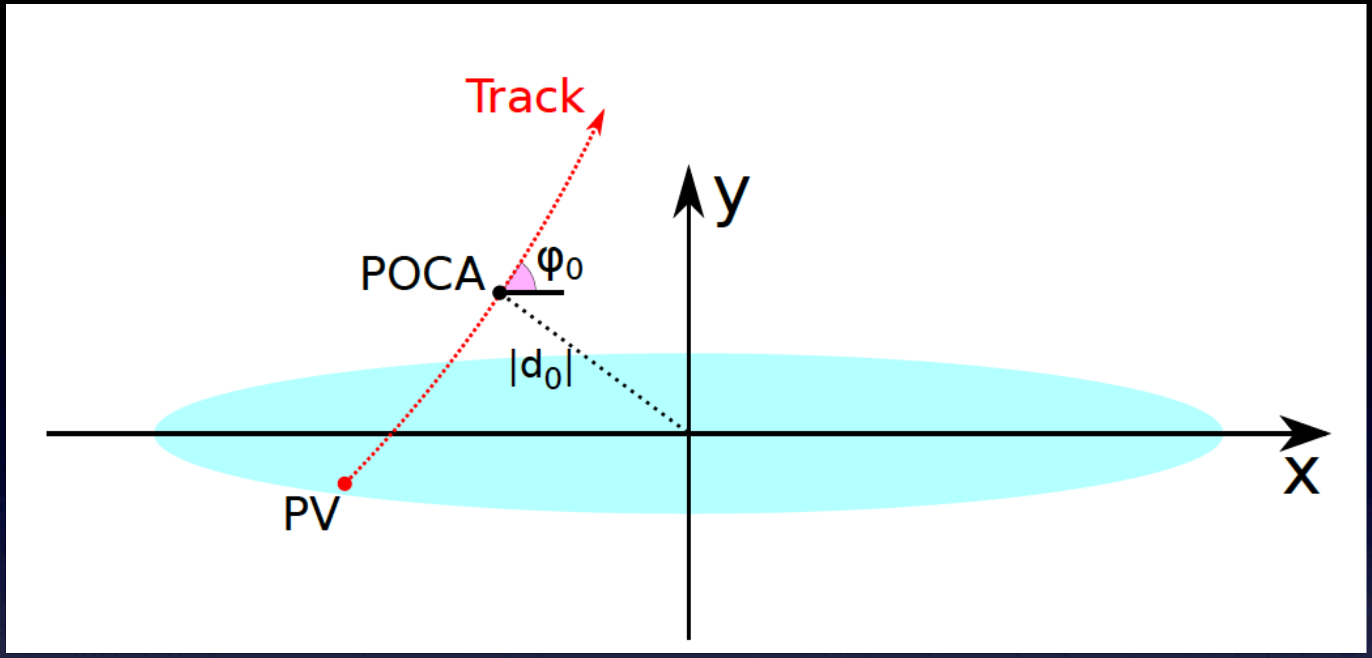
θ_c : half crossing angle

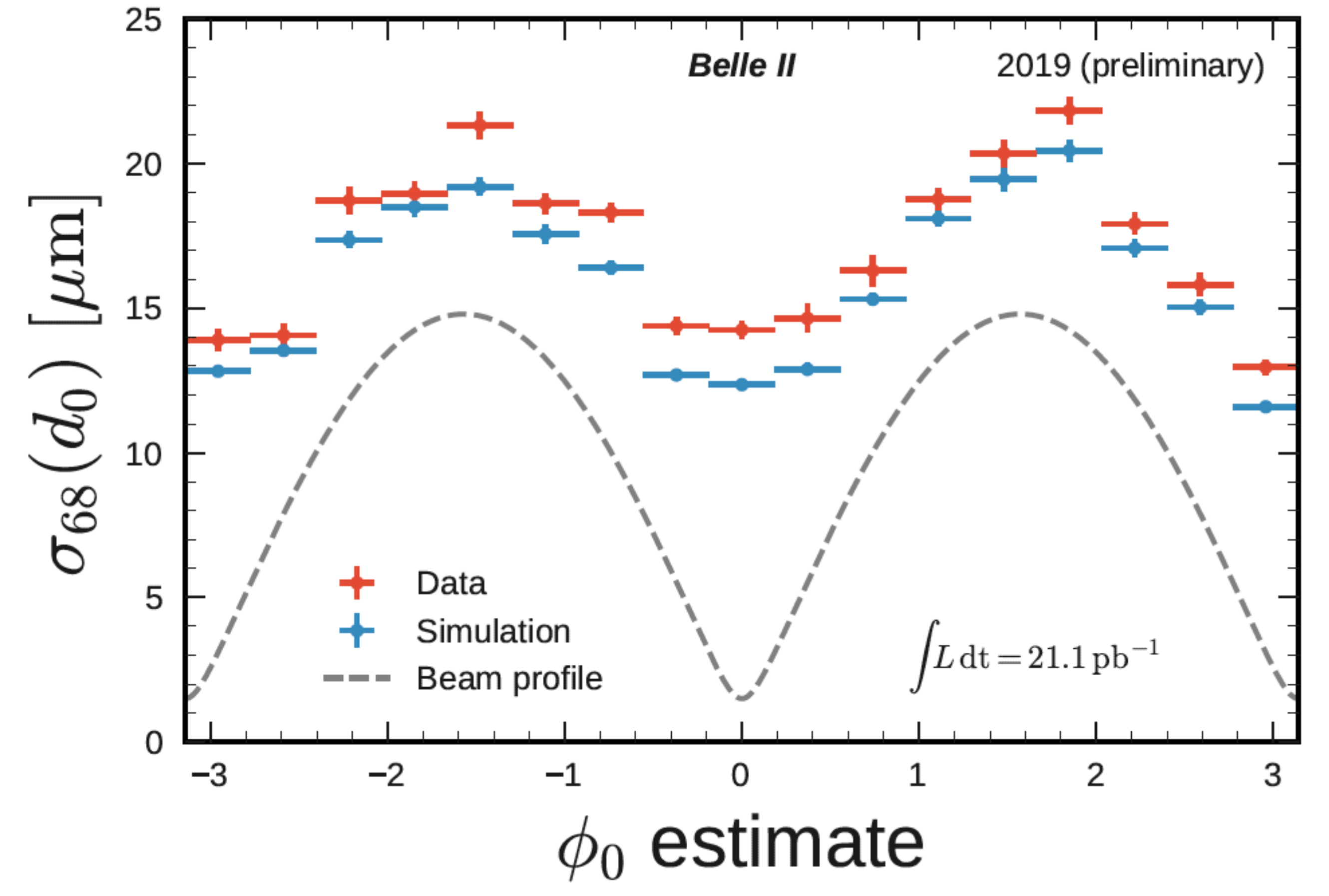
Luminosity projections



tracking performance: as expected

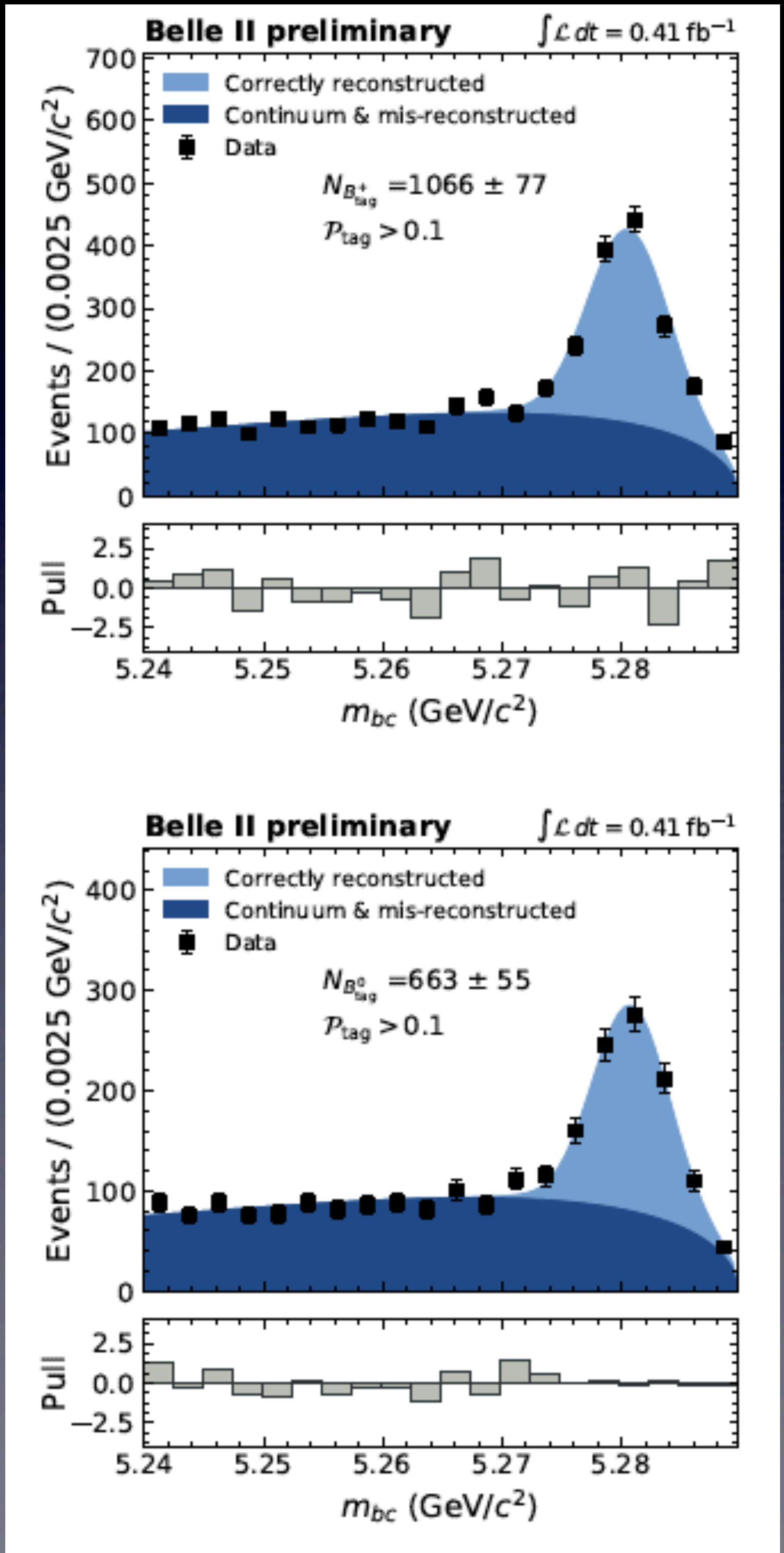
- impact parameter d_0 distribution for 2-track events
- alignment and calibration are working well
- VXD resolution in impact parameter $\delta d_0 \simeq 14\ \mu\text{m}$





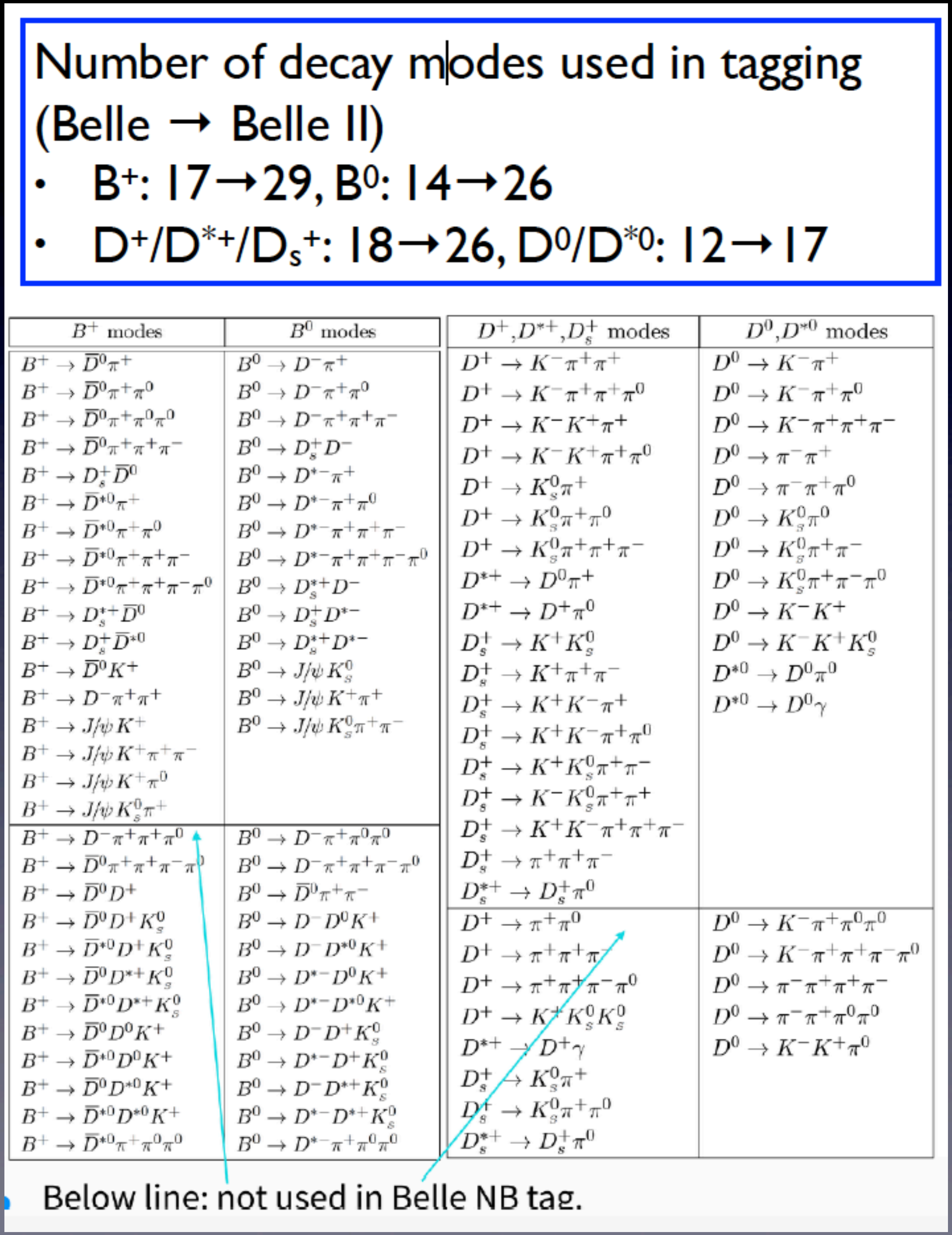
Full Event Interpretation

- A new implementation of the “full event reconstruction” concept at a B-factory
- the “tag side” B is exclusively reconstructed in many hadronic and semileptonic final states
- FEI = Full Event Interpretation: using a machine learning technique (BDT = Boosted Decision Trees) and a large number of decay modes
- Comput.Softw. Big Sci. 3 (2019) no.1, 6
- Example shown here: on a data sub-sample of 0.41 fb^{-1}



Full Event Interpretation

- More decay modes included in full reconstruction of tag side
- Fast Boosted Decision Tree (BDT) method



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

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

$B^+ \to D^-\pi^+\pi^+\pi^0$	$B^0 \to D^-\pi^+\pi^0\pi^0$
$B^+ \to \overline{D}^0\pi^+\pi^+\pi^-\pi^0$	$B^0 \to D^-\pi^+\pi^+\pi^-\pi^0$
$B^+ \to \overline{D}^0D^+$	$B^0 \to \overline{D}^0\pi^+\pi^-$
$B^+ \to \overline{D}^0D^+K_s^0$	$B^0 \to D^-D^0K^+$
$B^+ \to \overline{D}^{*0}D^+K_s^0$	$B^0 \to D^-D^{*0}K^+$
$B^+ \to \overline{D}^0D^{*+}K_s^0$	$B^0 \to D^{*-}D^0K^+$
$B^+ \to \overline{D}^{*0}D^{*+}K_s^0$	$B^0 \to D^{*-}D^{*0}K^+$
$B^+ \to \overline{D}^0D^0K^+$	$B^0 \to D^-D^+K_s^0$
$B^+ \to \overline{D}^{*0}D^0K^+$	$B^0 \to D^{*-}D^+K_s^0$
$B^+ \to \overline{D}^0D^{*0}K^+$	$B^0 \to D^-D^{*+}K_s^0$
$B^+ \to \overline{D}^{*0}D^{*0}K^+$	$B^0 \to D^{*-}D^{*+}K_s^0$
$B^+ \to \overline{D}^{*0}\pi^+\pi^0\pi^0$	$B^0 \to D^{*-}\pi^+\pi^0\pi^0$

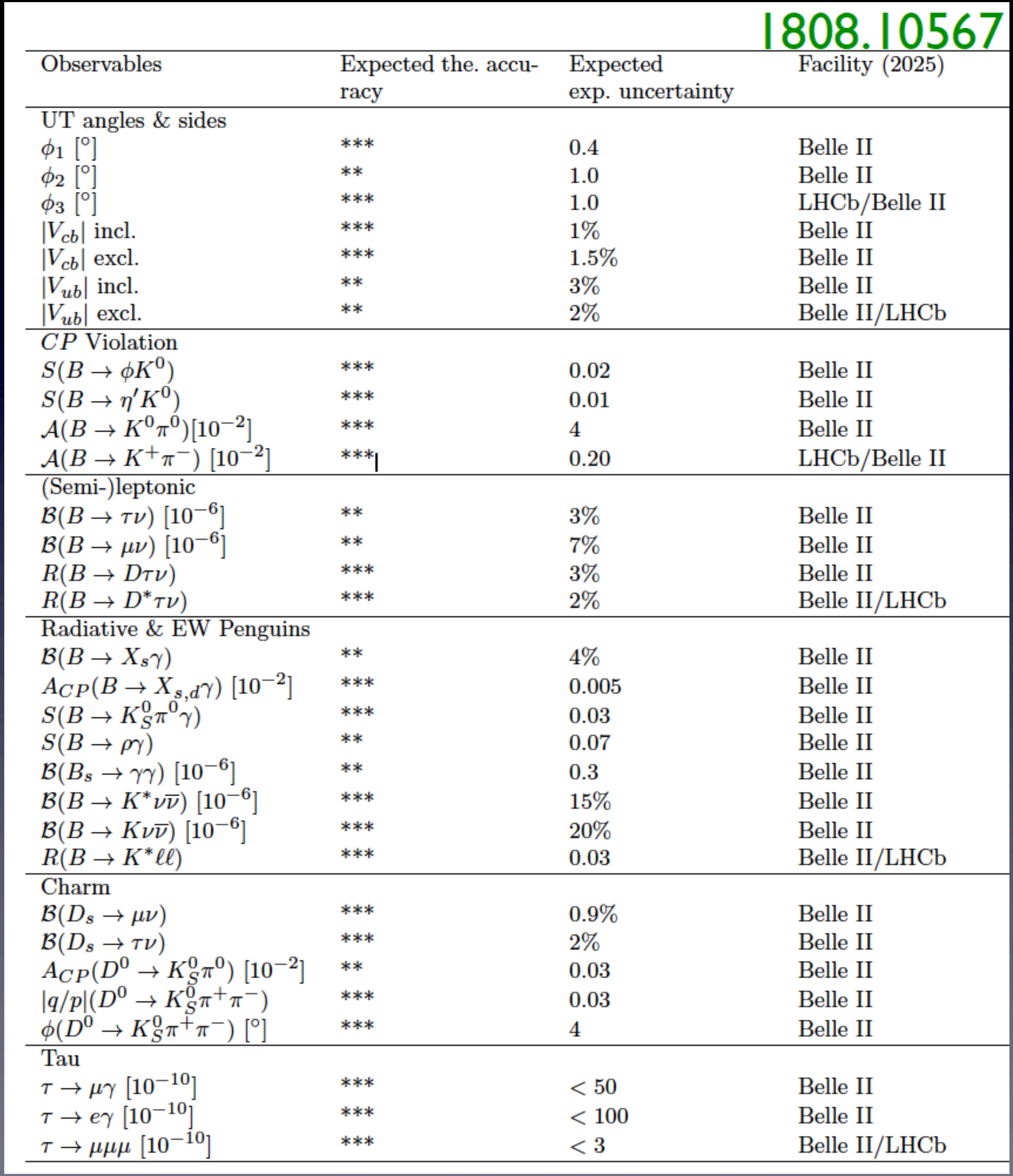
D^+,D^{*+},D_s^+ modes	D^0,D^{*0} modes
$D^+ \to K^-\pi^+\pi^+$	$D^0 \to K^-\pi^+$
$D^+ \to K^-\pi^+\pi^+\pi^0$	$D^0 \to K^-\pi^+\pi^0$
$D^+ \to K^-K^+\pi^+$	$D^0 \to K^-\pi^+\pi^+\pi^-$
$D^+ \to K^-K^+\pi^+\pi^0$	$D^0 \to \pi^-\pi^+$
$D^+ \to K_s^0\pi^+$	$D^0 \to \pi^-\pi^+\pi^0$
$D^+ \to K_s^0\pi^+\pi^0$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

$D^+ \to \pi^+\pi^0$	$D^0 \to K^-\pi^+\pi^0\pi^0$
$D^+ \to \pi^+\pi^+\pi^-$	$D^0 \to K^-\pi^+\pi^+\pi^-\pi^0$
$D^+ \to \pi^+\pi^+\pi^-\pi^0$	$D^0 \to \pi^-\pi^+\pi^+\pi^-$
$D^+ \to K^+K_s^0K_s^0$	$D^0 \to \pi^-\pi^+\pi^0\pi^0$
$D^{*+} \to D^+\gamma$	$D^0 \to K^-K^+\pi^0$
$D_s^+ \to K_s^0\pi^+$	
$D_s^+ \to K_s^0\pi^+\pi^0$	
$D_s^{*+} \to D_s^+\pi^0$	

- Below line: not used in Belle NB tag.

Belle II physics program

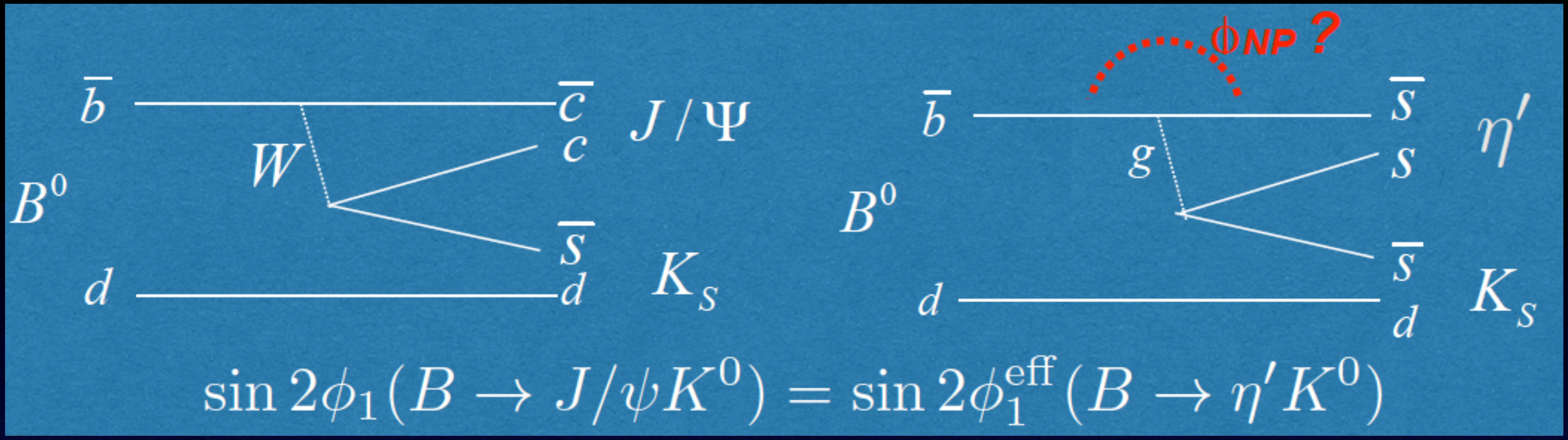
- Precision CKM
- CPV in b → s penguin decays
- Tauonic decays
- FCNC
- Charm decays
- LFV tau decays
- Hadron spectroscopy
- Dark sector



1808.10567

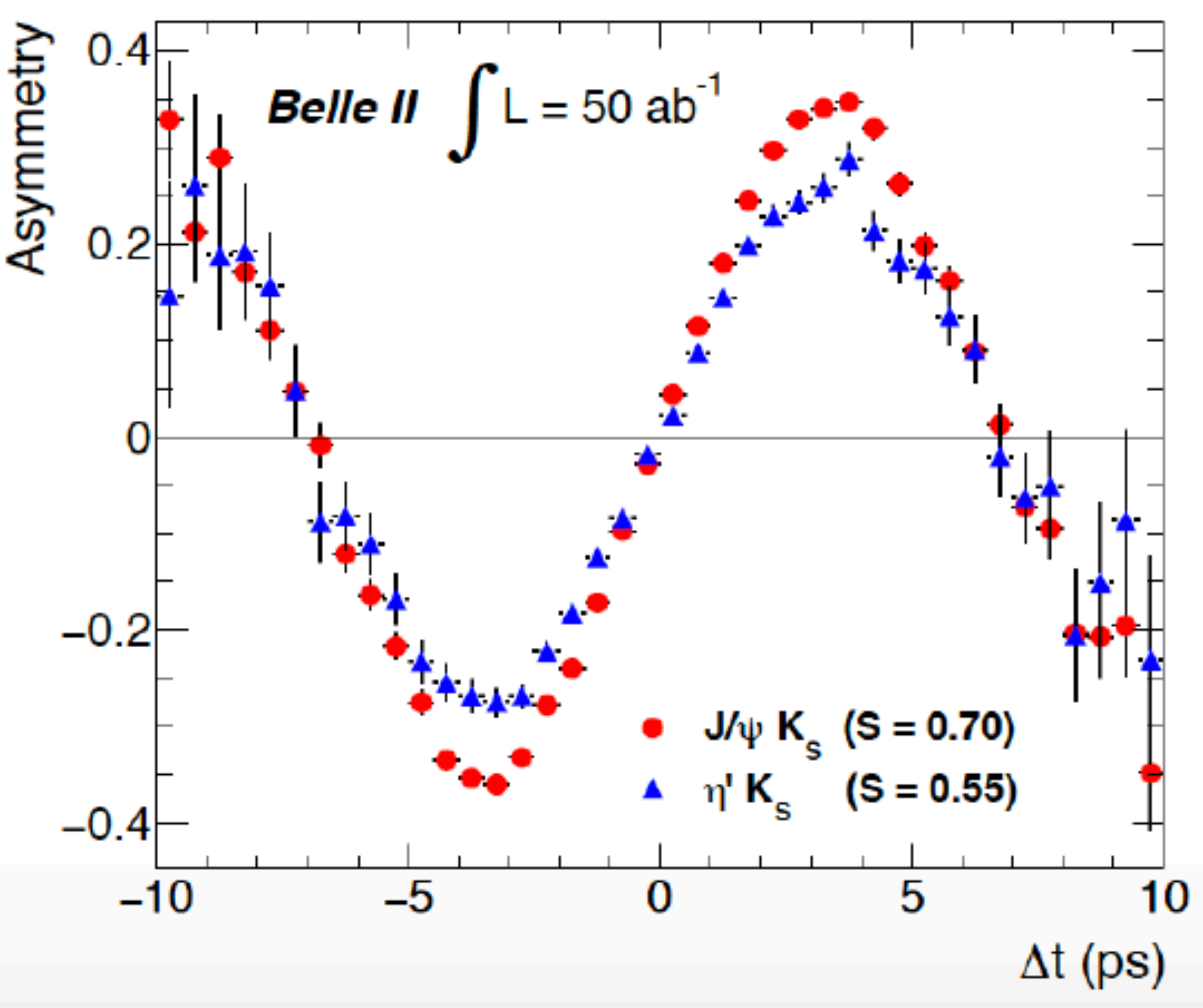
Observables	Expected the. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	LHCb/Belle II
$\|V_{cb}\|$ incl.	***	1%	Belle II
$\|V_{cb}\|$ excl.	***	1.5%	Belle II
$\|V_{ub}\|$ incl.	**	3%	Belle II
$\|V_{ub}\|$ excl.	**	2%	Belle II/LHCb
CP Violation			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb
Radiative & EW Penguins			
$\mathcal{B}(B \to X_s\gamma)$	**	4%	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***	0.005	Belle II
$S(B \to K_S^0\pi^0\gamma)$	***	0.03	Belle II
$S(B \to \rho\gamma)$	**	0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**	0.3	Belle II
$\mathcal{B}(B \to K^*\nu\overline{\nu})$ $[10^{-6}]$	***	15%	Belle II
$\mathcal{B}(B \to K\nu\overline{\nu})$ $[10^{-6}]$	***	20%	Belle II
$R(B \to K^*\ell\ell)$	***	0.03	Belle II/LHCb
Charm			
$\mathcal{B}(D_s \to \mu\nu)$	***	0.9%	Belle II
$\mathcal{B}(D_s \to \tau\nu)$	***	2%	Belle II
$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	**	0.03	Belle II
$\|q/p\|(D^0 \to K_S^0\pi^+\pi^-)$	***	0.03	Belle II
$\phi(D^0 \to K_S^0\pi^+\pi^-)$ [°]	***	4	Belle II
Tau			
$\tau \to \mu\gamma$ $[10^{-10}]$	***	< 50	Belle II
$\tau \to e\gamma$ $[10^{-10}]$	***	< 100	Belle II
$\tau \to \mu\mu\mu$ $[10^{-10}]$	***	< 3	Belle II/LHCb

$B \to \eta' K_S$ projection

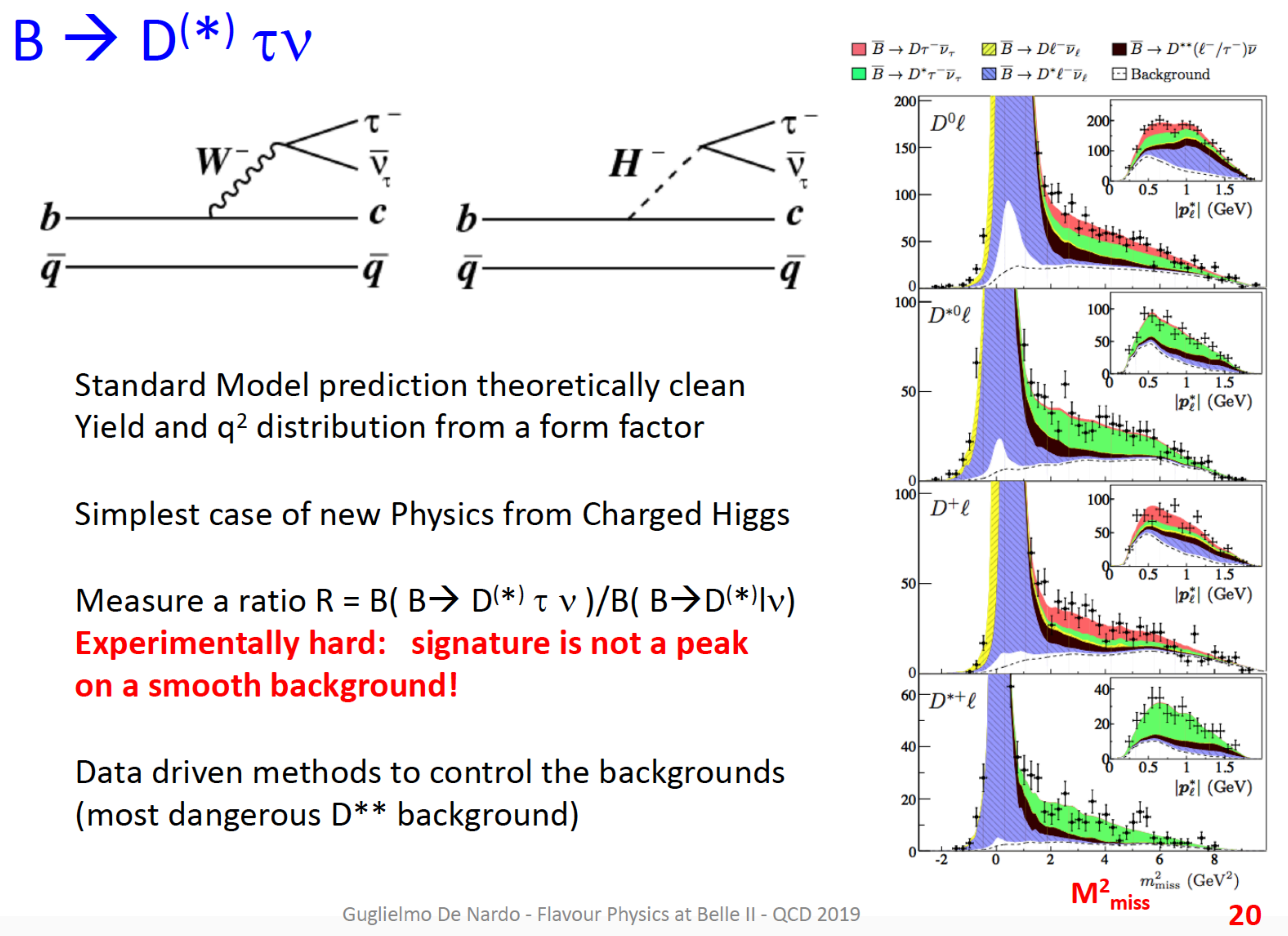


$$\sin 2\phi_1(B \to J/\psi K^0) = \sin 2\phi_1^{\mathrm{eff}}(B \to \eta' K^0)$$

- BSM physics in penguin loops
- Measurement of $\sin 2\phi_1^{eff}(B \to \eta' K_S)$
- projection to 50 ab^{-1} Belle II data set



tests of LFU in semileptonic decays



B → $D^{(*)}\tau\nu$

Standard Model prediction theoretically clean
Yield and q^2 distribution from a form factor

Simplest case of new Physics from Charged Higgs

Measure a ratio R = B(B→ $D^{(*)}$ τ ν)/B(B→$D^{(*)}$lν)
Experimentally hard: signature is not a peak on a smooth background!

Data driven methods to control the backgrounds
(most dangerous D** background)

$M^2_{\rm miss}$

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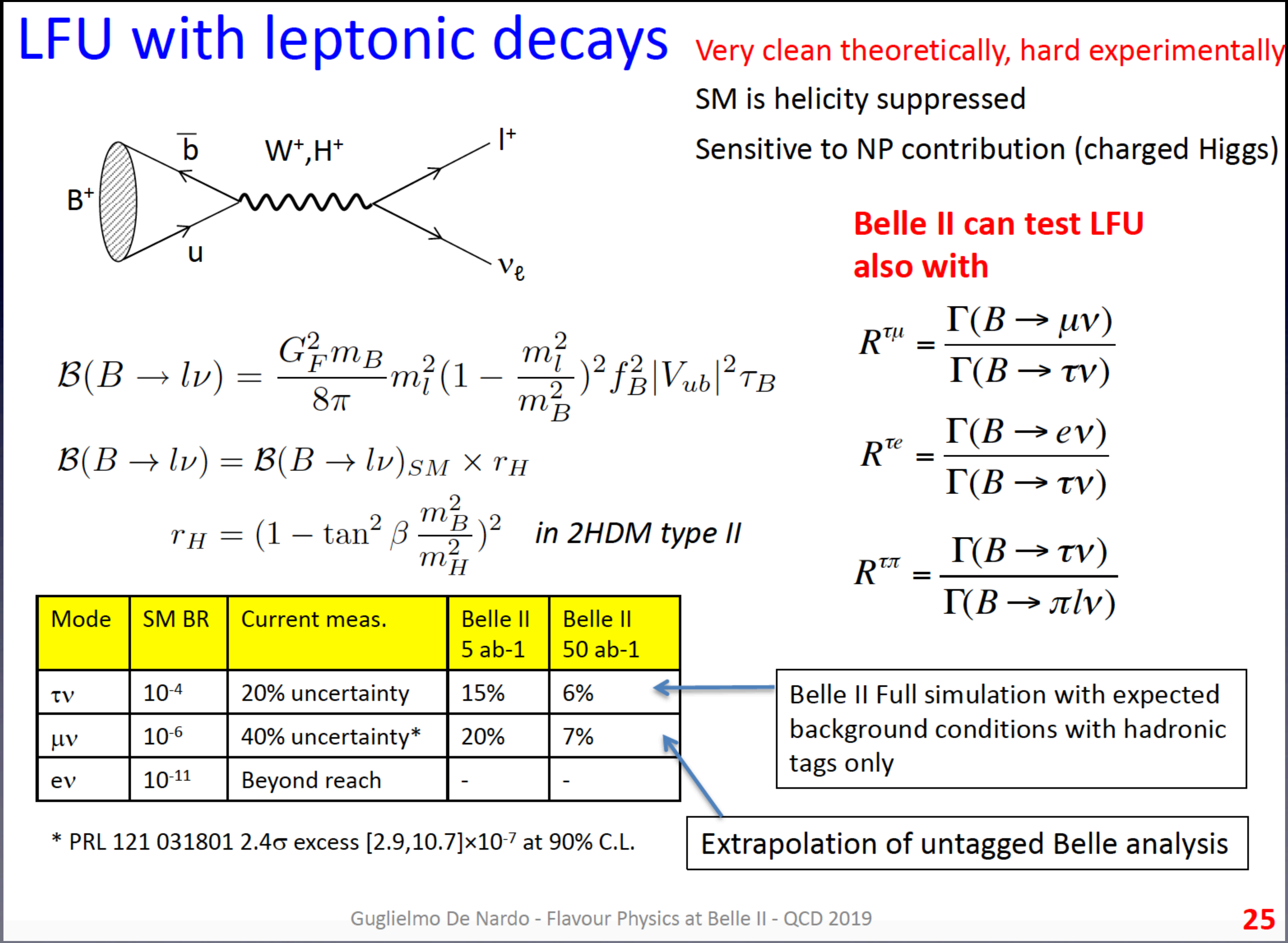
test of LFU in leptonic decays



LFU with leptonic decays

Very clean theoretically, hard experimentally

SM is helicity suppressed

Sensitive to NP contribution (charged Higgs)

$$\mathcal{B}(B\to l\nu)=\frac{G_F^2 m_B}{8\pi}m_l^2(1-\frac{m_l^2}{m_B^2})^2 f_B^2|V_{ub}|^2\tau_B$$

$$\mathcal{B}(B\to l\nu)=\mathcal{B}(B\to l\nu)_{SM}\times r_H$$

$$r_H=(1-\tan^2\beta\,\frac{m_B^2}{m_H^2})^2$$ *in 2HDM type II*

Belle II can test LFU also with

$$R^{\tau\mu}=\frac{\Gamma(B\to\mu\nu)}{\Gamma(B\to\tau\nu)}$$

$$R^{\tau e}=\frac{\Gamma(B\to e\nu)}{\Gamma(B\to\tau\nu)}$$

$$R^{\tau\pi}=\frac{\Gamma(B\to\tau\nu)}{\Gamma(B\to\pi l\nu)}$$

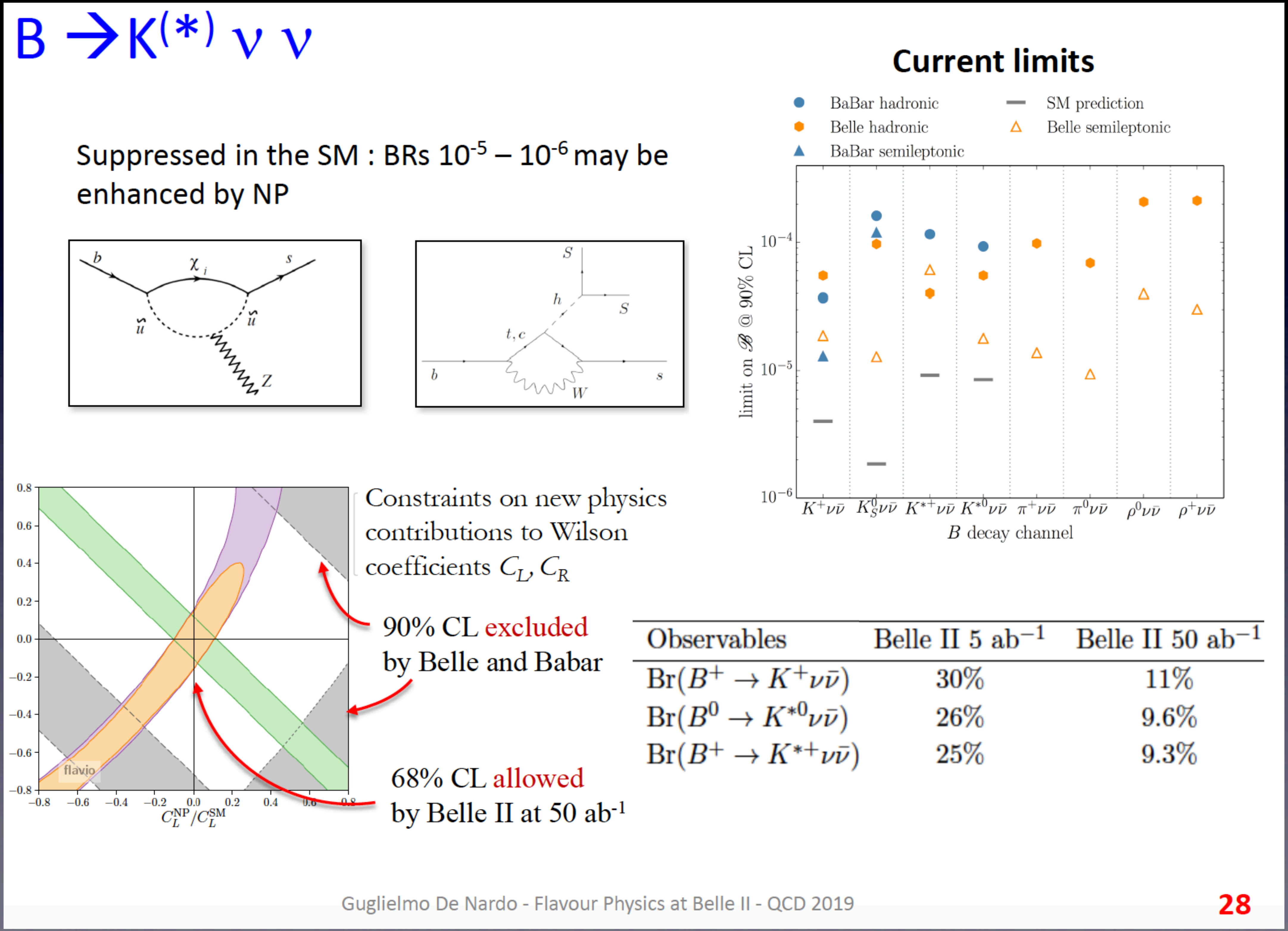
Mode	SM BR	Current meas.	Belle II 5 ab-1	Belle II 50 ab-1
$\tau\nu$	10^{-4}	20% uncertainty	15%	6%
$\mu\nu$	10^{-6}	40% uncertainty*	20%	7%
$e\nu$	10^{-11}	Beyond reach	-	-

Belle II Full simulation with expected background conditions with hadronic tags only

Extrapolation of untagged Belle analysis

* PRL 121 031801 2.4σ excess [2.9,10.7]×10^{-7} at 90% C.L.

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



$B \to K^{(*)} \nu \nu$

Suppressed in the SM : BRs 10^{-5} – 10^{-6} may be enhanced by NP

Constraints on new physics contributions to Wilson coefficients C_L, C_R

90% CL excluded by Belle and Babar

68% CL allowed by Belle II at 50 ab^{-1}

Observables	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B^+ \to K^+\nu\bar{\nu})$	30%	11%
$\mathrm{Br}(B^0 \to K^{*0}\nu\bar{\nu})$	26%	9.6%
$\mathrm{Br}(B^+ \to K^{*+}\nu\bar{\nu})$	25%	9.3%

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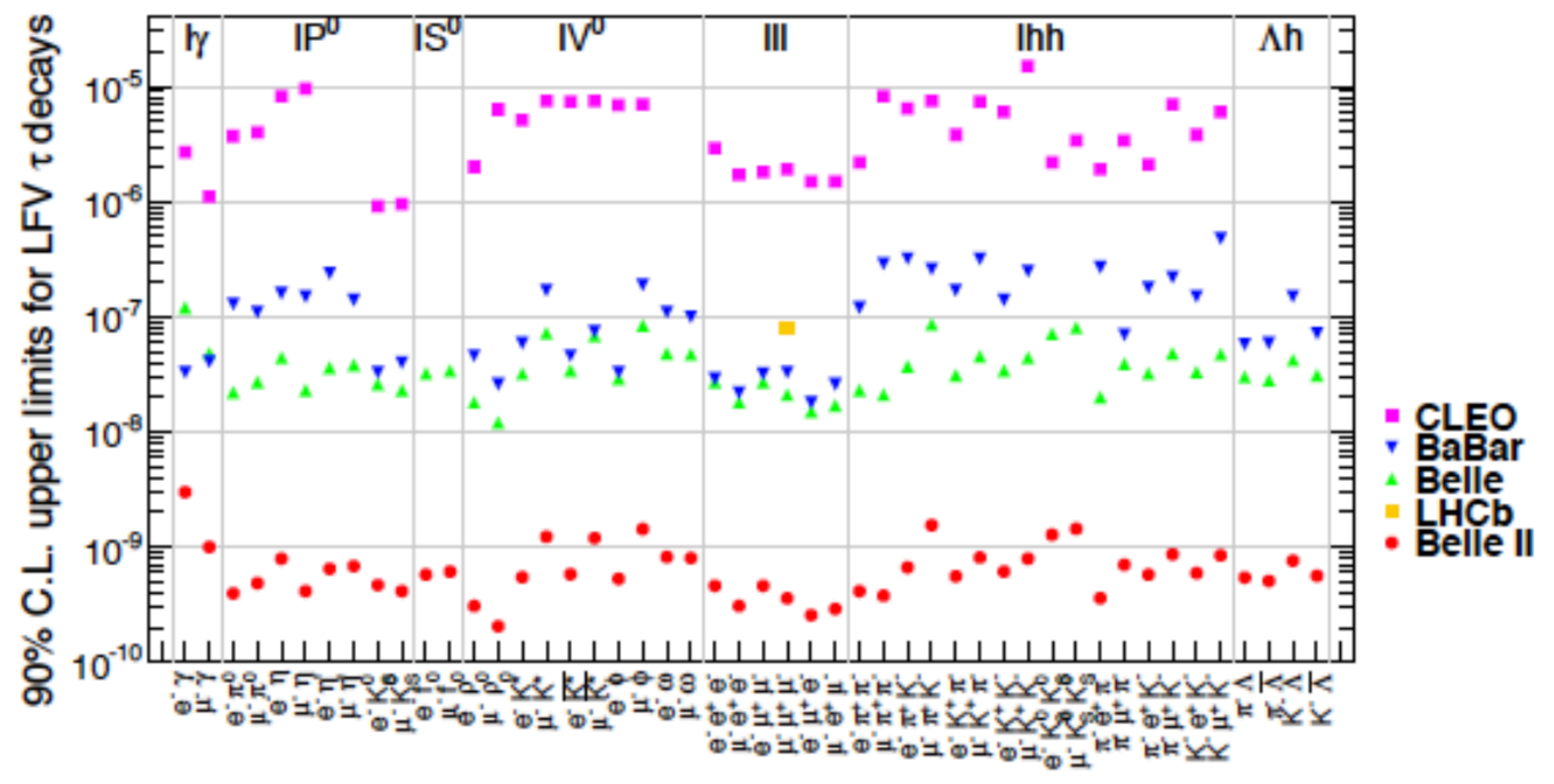
Tau LFV decays: projections



- expect an improvement by more than an order of magnitude in tau LFV decay limits by Belle II