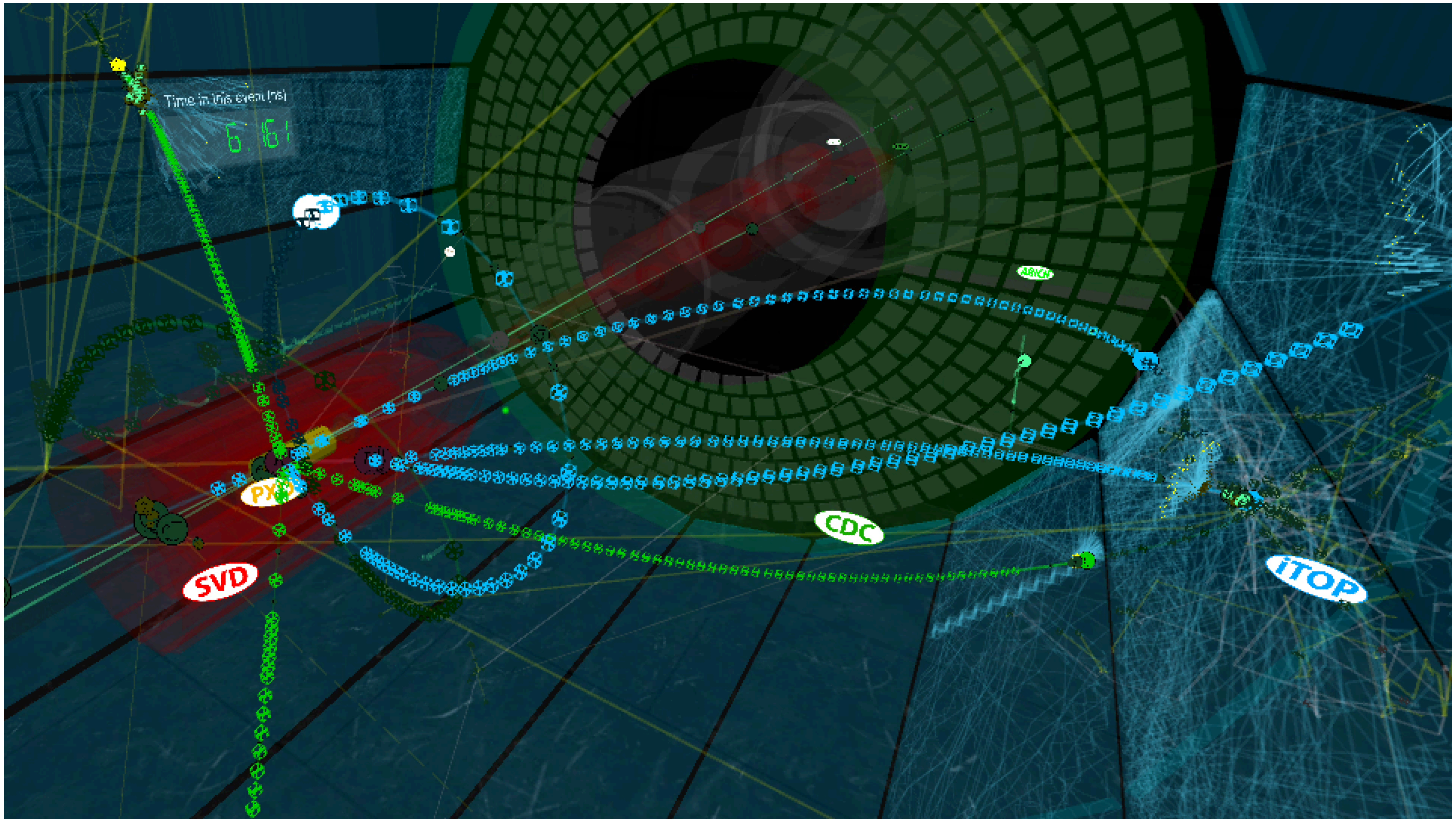
The Belle II Physics Program

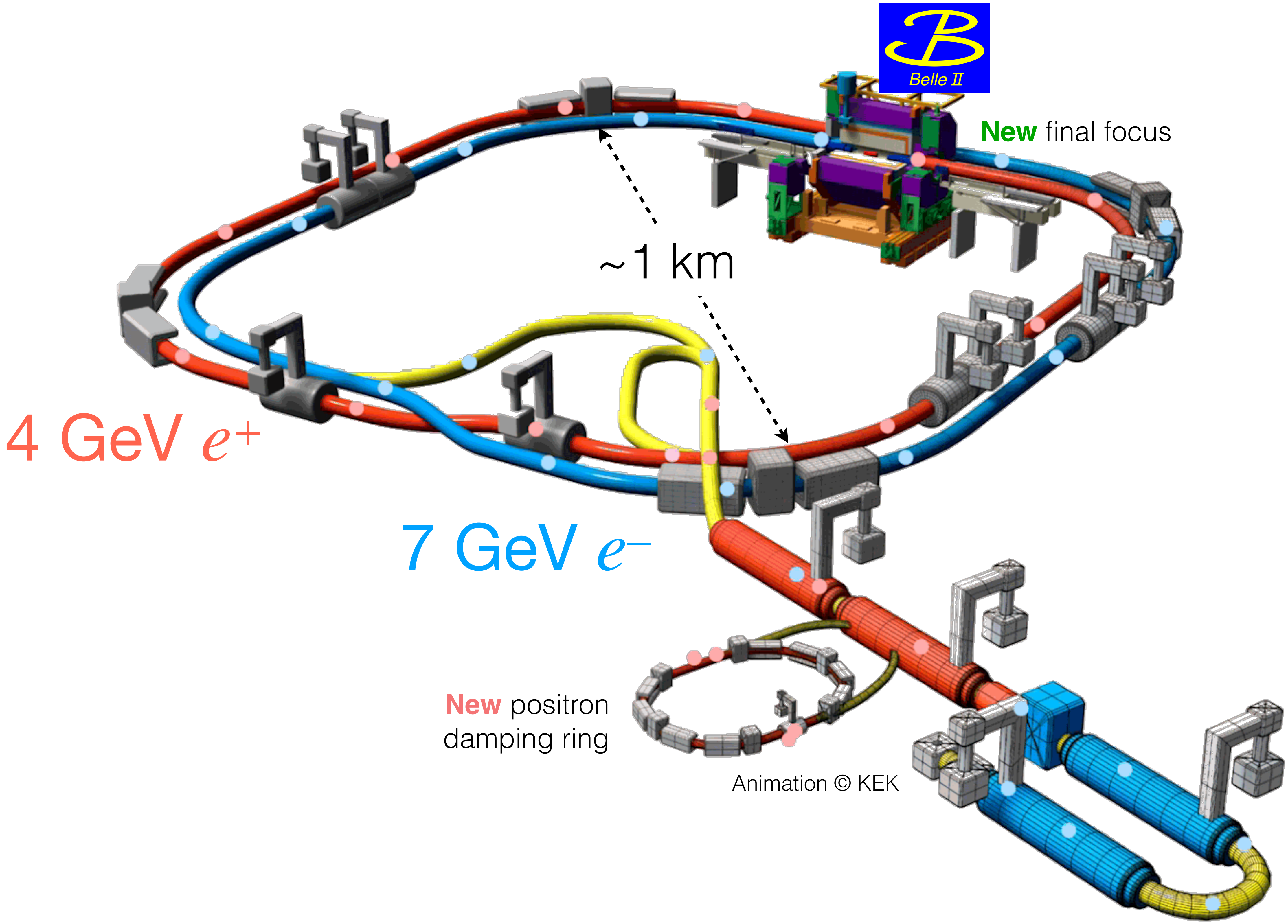
Leo Piilonen, Virginia Tech

Belle II Summer School BNL July 2019



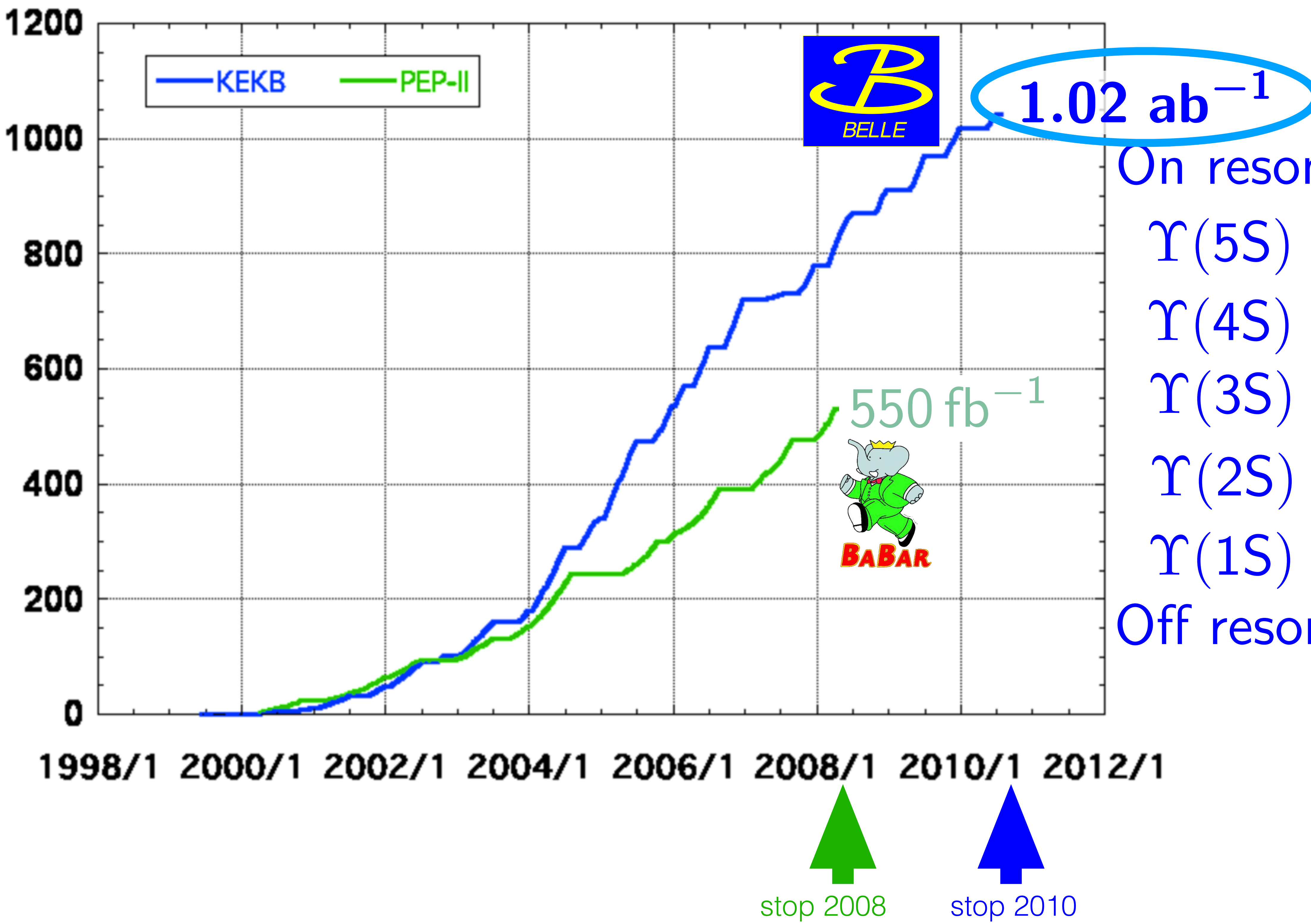
This work supported by U.S. DEPARTMENT OF ENERGY | Office of Science

SuperKEKB and Belle II: 2nd generation B Factory



$$c\bar{c},\ u\bar{u},\ d\bar{d},\ \ell^+\ell^- \leftarrow e^+e^- \rightarrow \Upsilon(\mathrm{nS}) \rightarrow B^{(*)}\bar{B}^{(*)}$$

Integrated luminosity at the first-generation B factories



On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

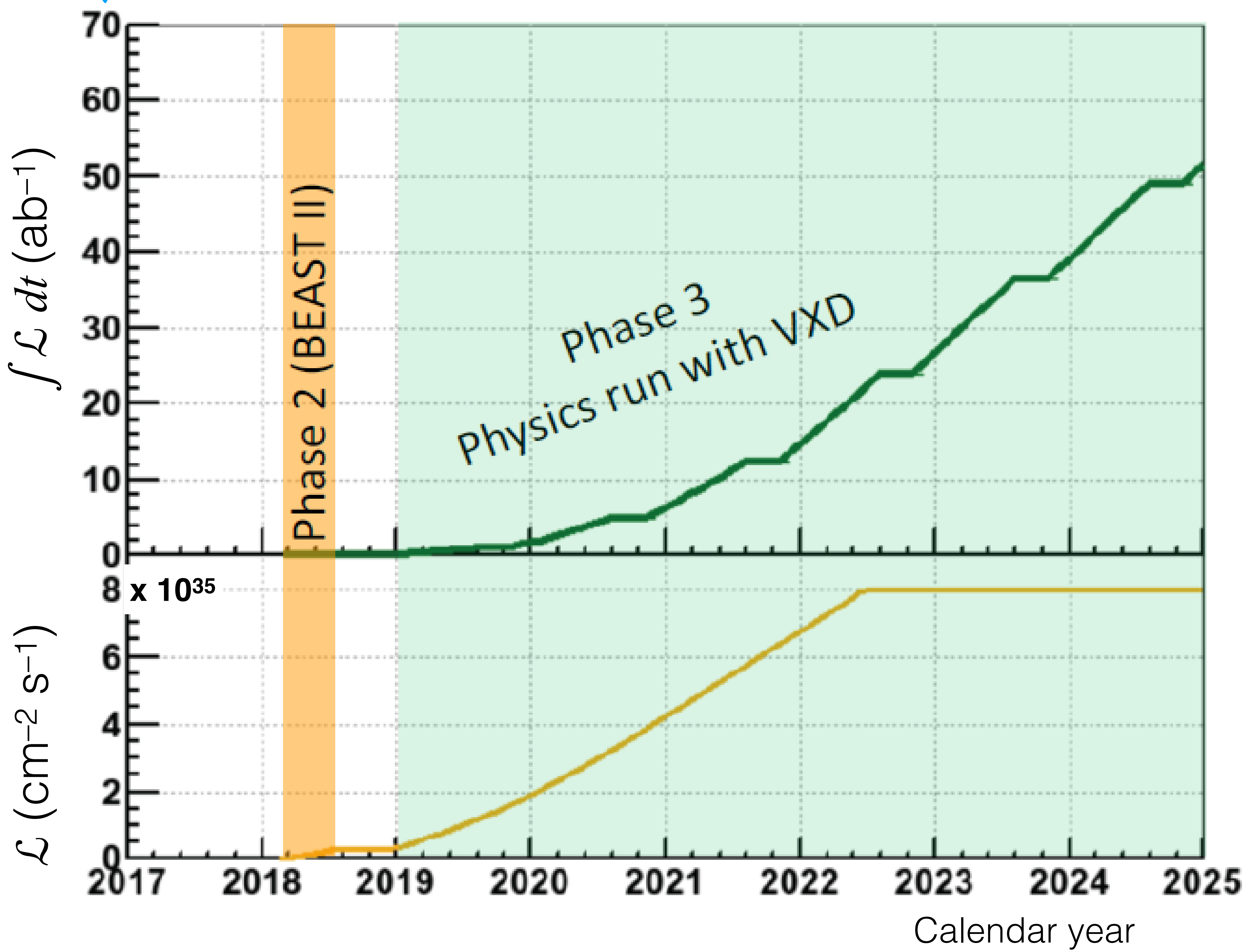
$\Upsilon(1S)$: 6 fb^{-1}

Off resonance/scan:

155 fb^{-1}

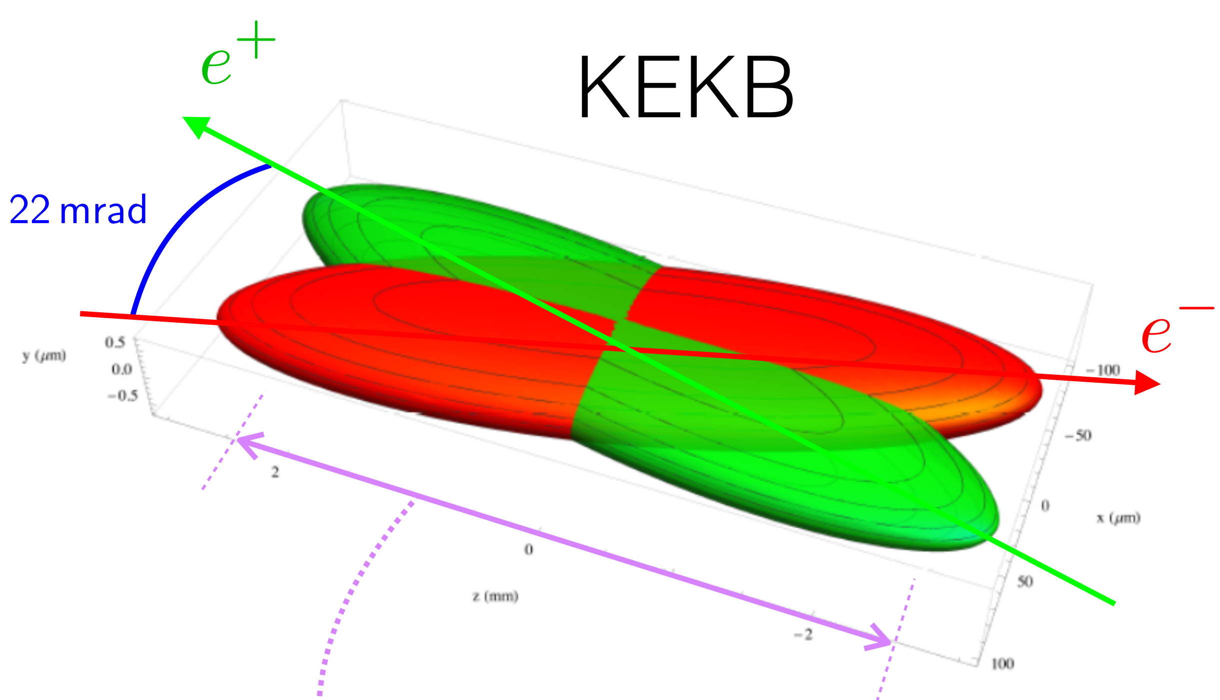
SuperKEKB luminosity profile vs time

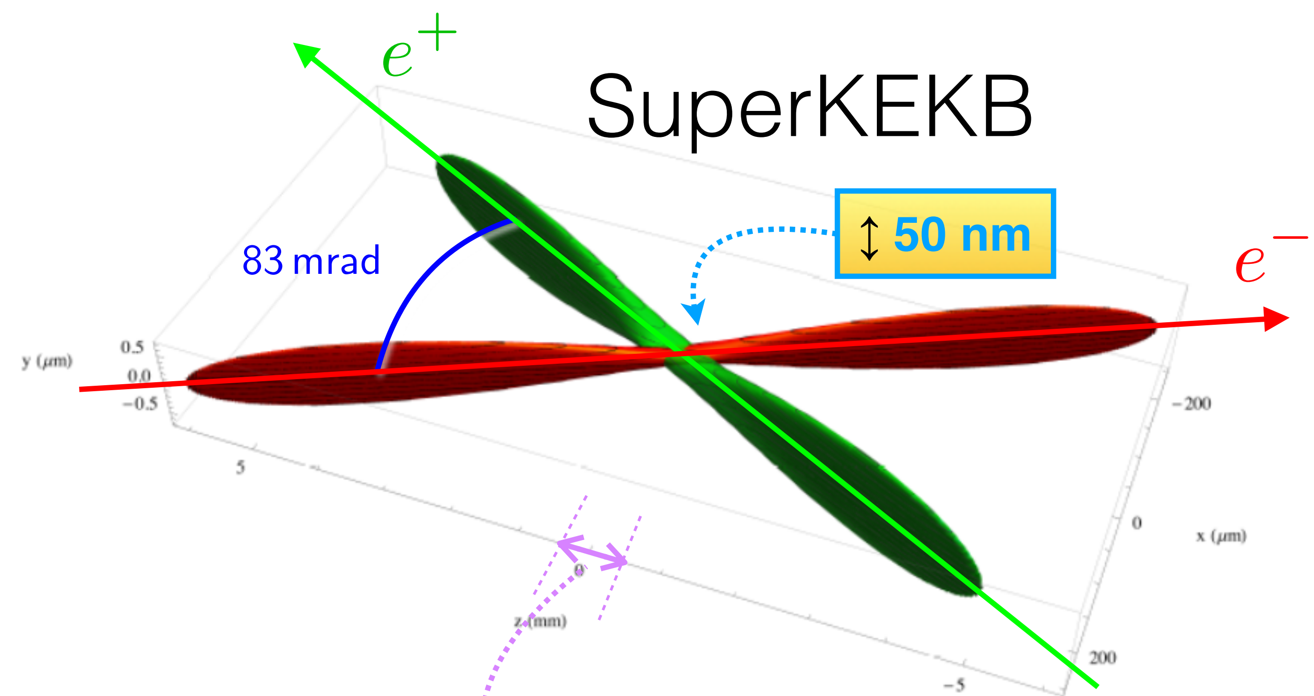
multiples of Belle's integrated luminosity



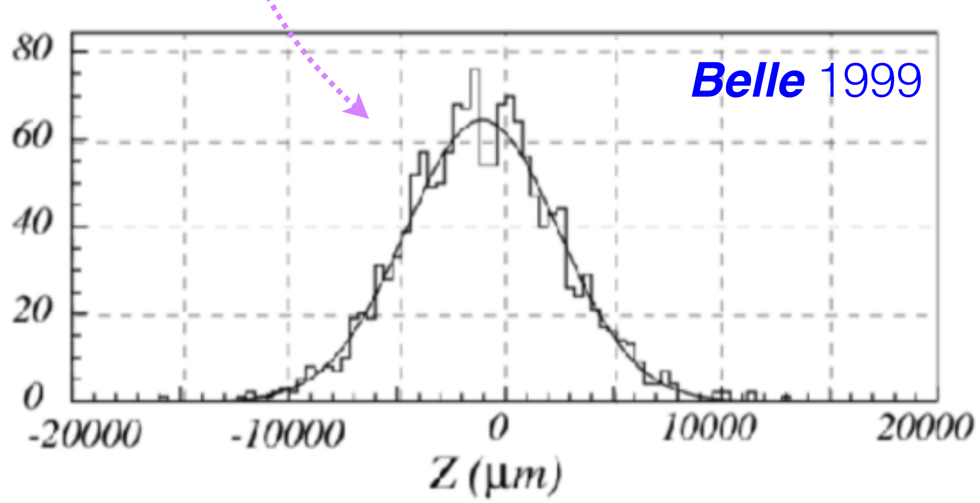
Instantaneous luminosity is 40 times that of KEKB

- ✓ Beam currents ≈doubled → x2
- ✓ Much smaller β_y^* → x20

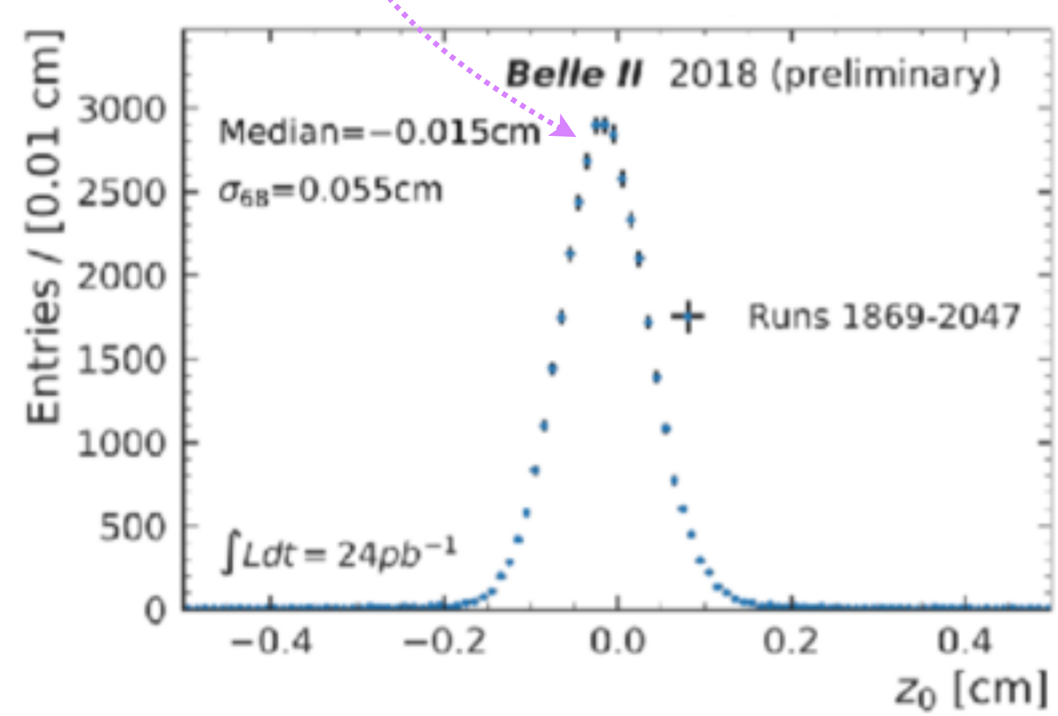




Nano-beam scheme invented by
Pantaleo Raimondi for Italian SuperB Factory

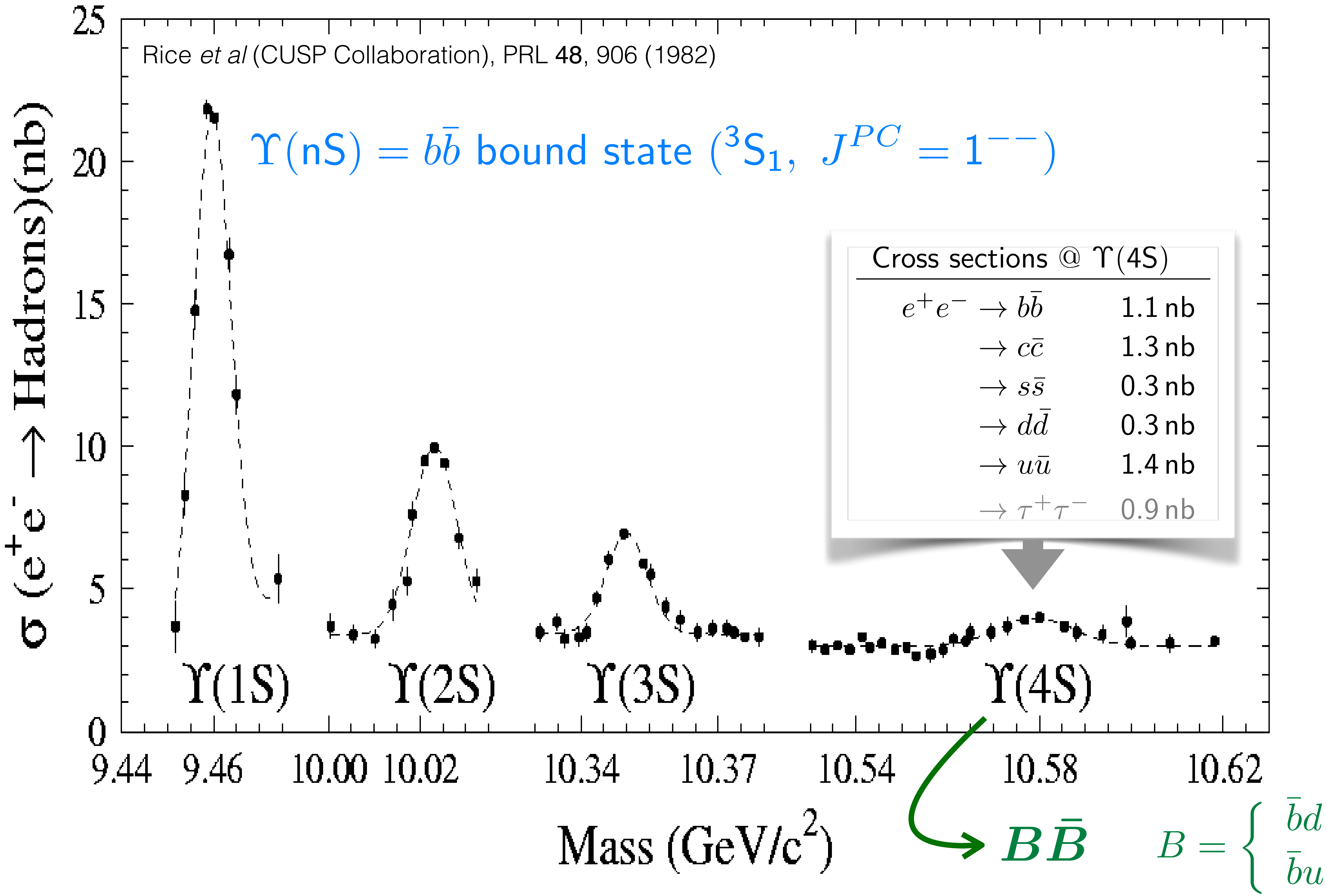


$\sigma = 4.5\,\text{mm}$

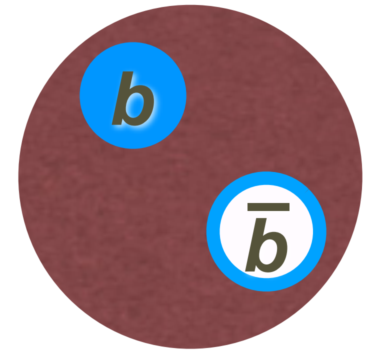


$\sigma = 0.55\,\text{mm}$

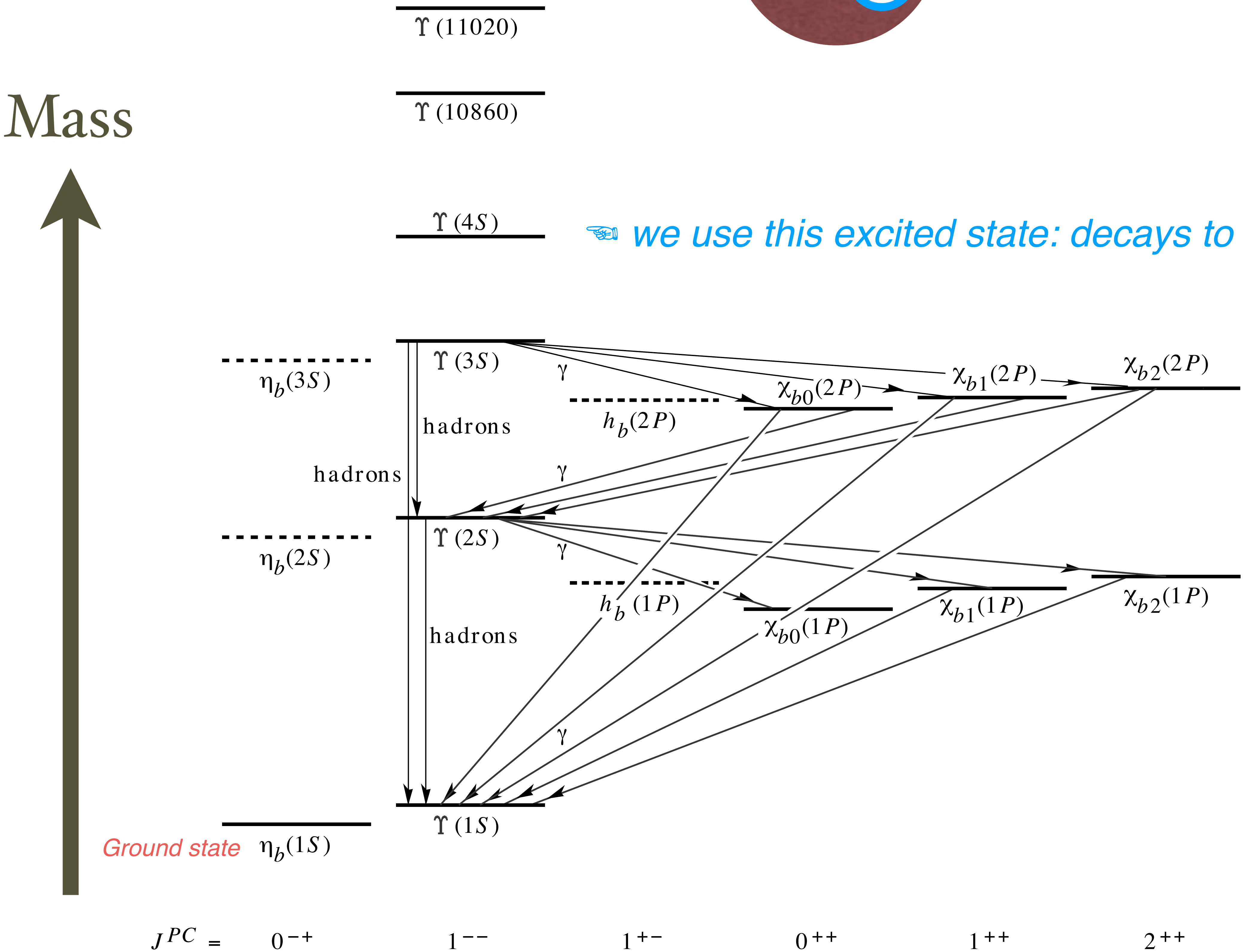
SuperKEKB operates at/near the $\Upsilon(nS)$ resonances



Bottomonium

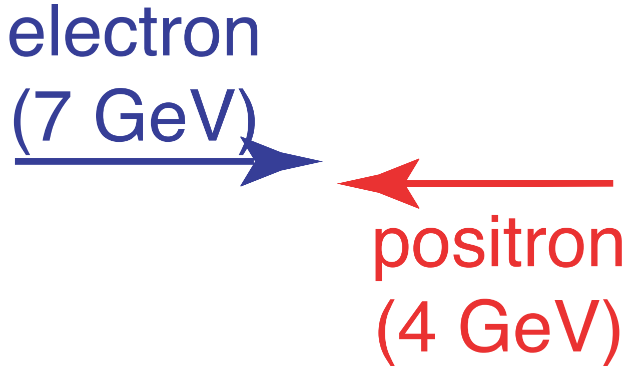


... a bound state of a
b quark and an anti-*b* quark
with a mass of ~10 protons

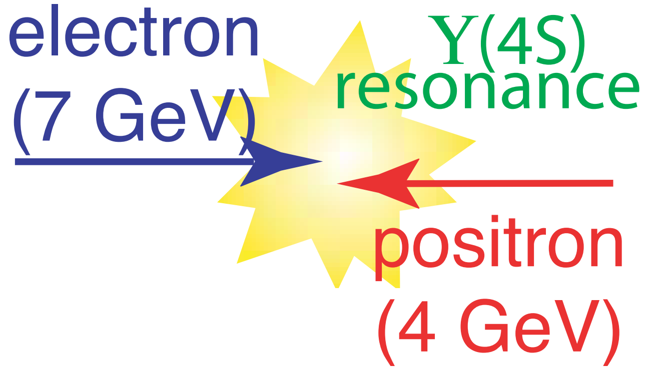


☞ *we use this excited state: decays to $B\bar{B}$ meson pair*

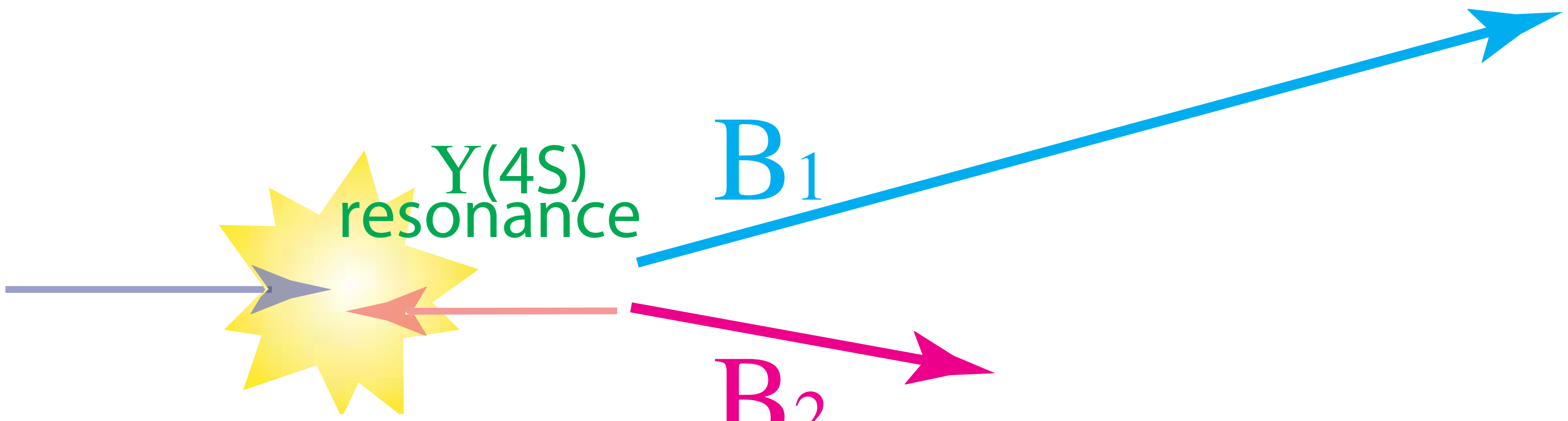
A canonical $B\overline{B}$ Event



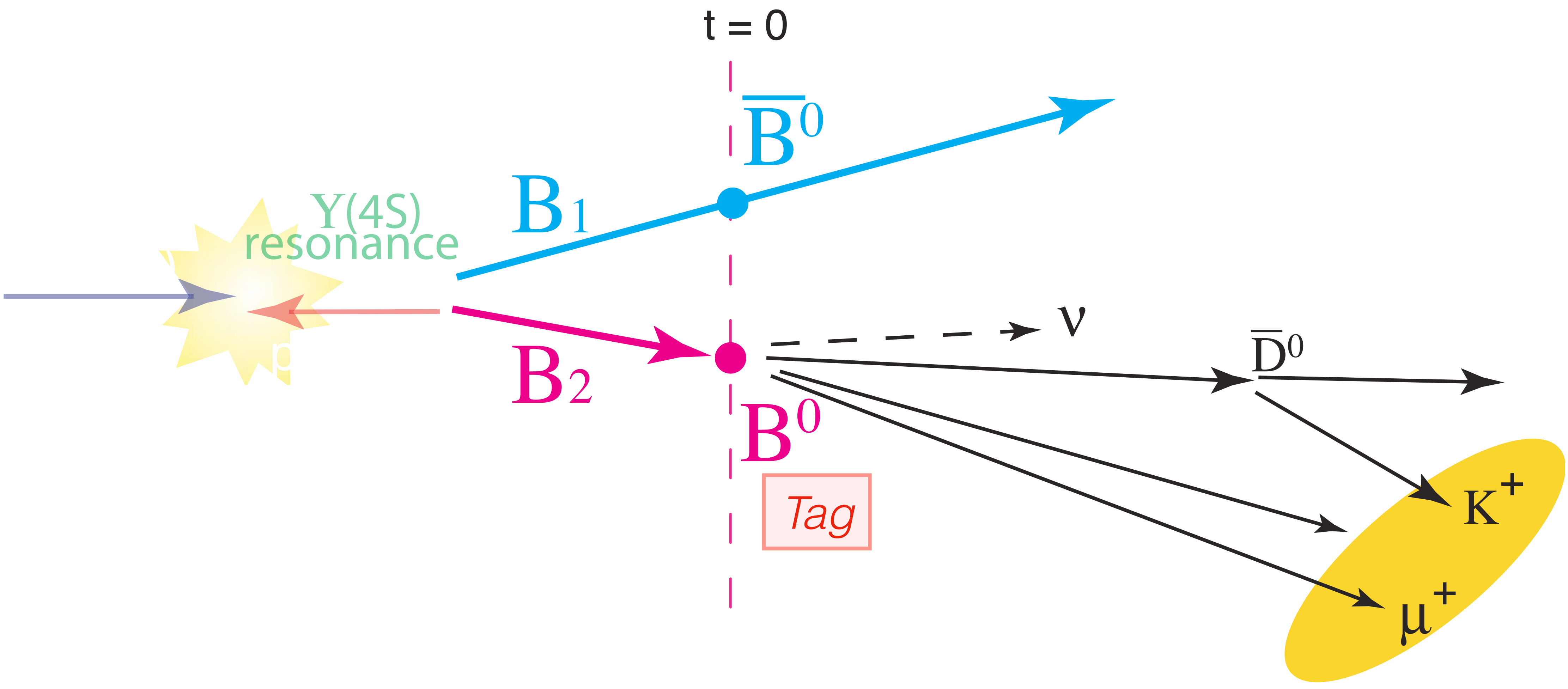
A canonical $B\overline{B}$ Event



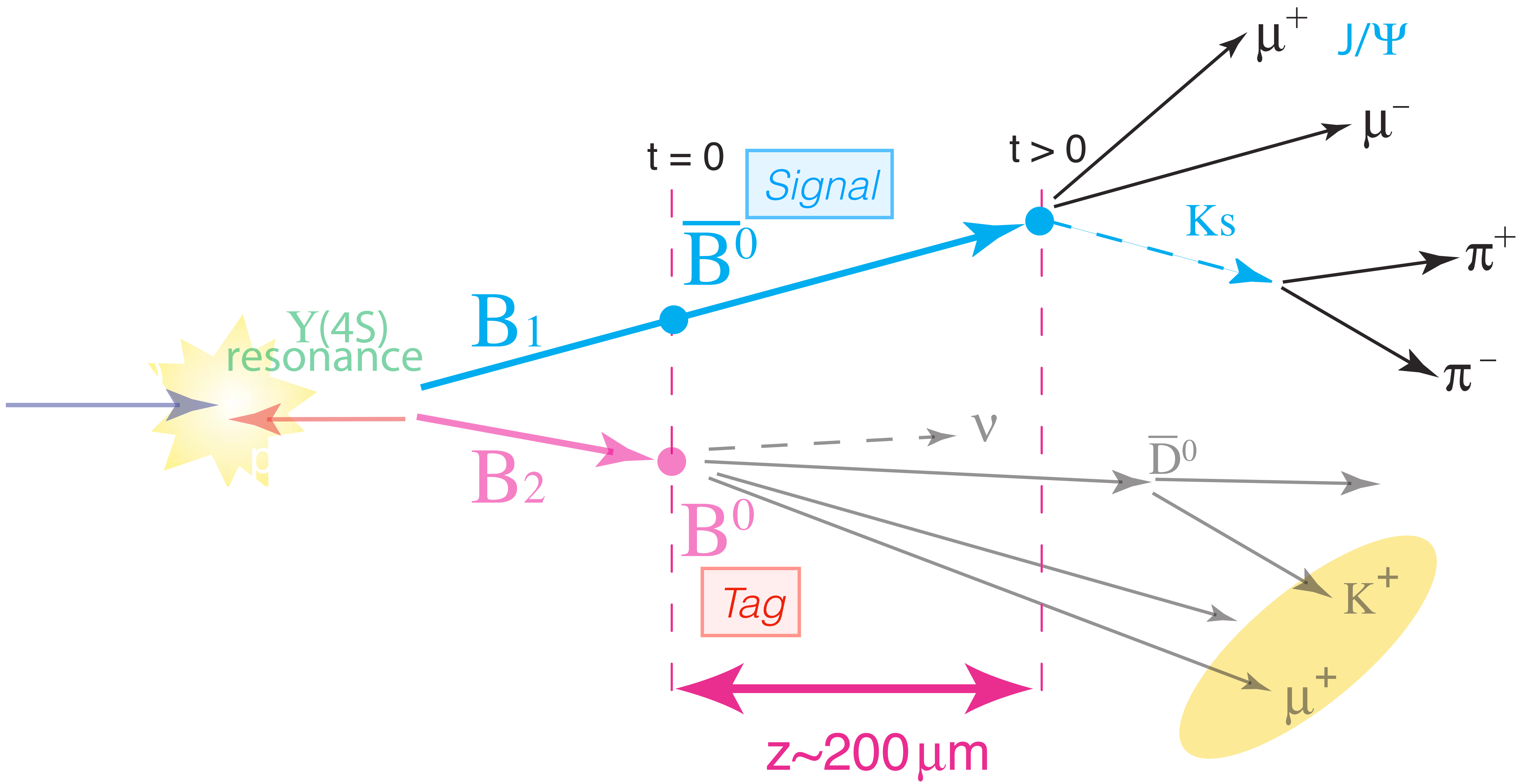
A canonical $B\overline{B}$ Event



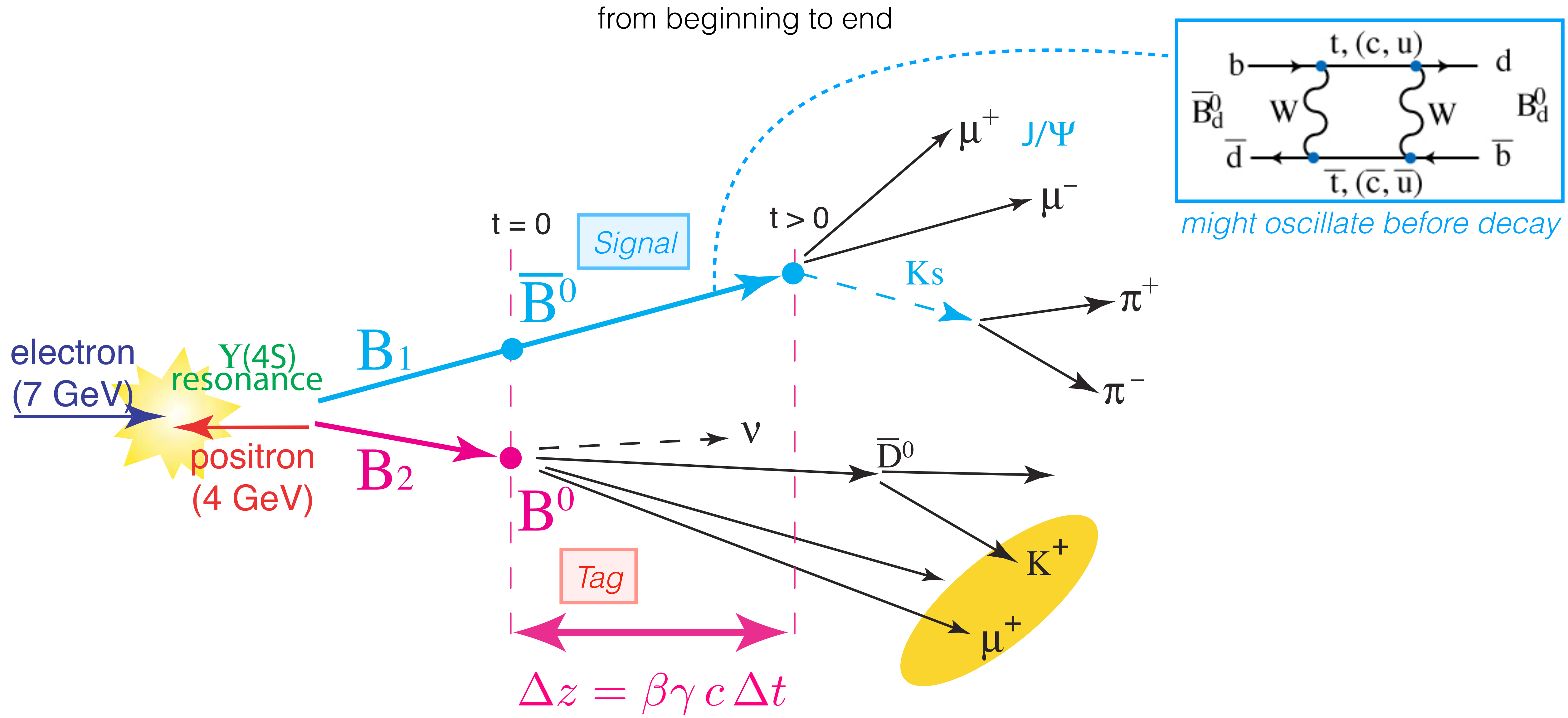
A canonical $B\bar{B}$ Event



A canonical $B\bar{B}$ Event



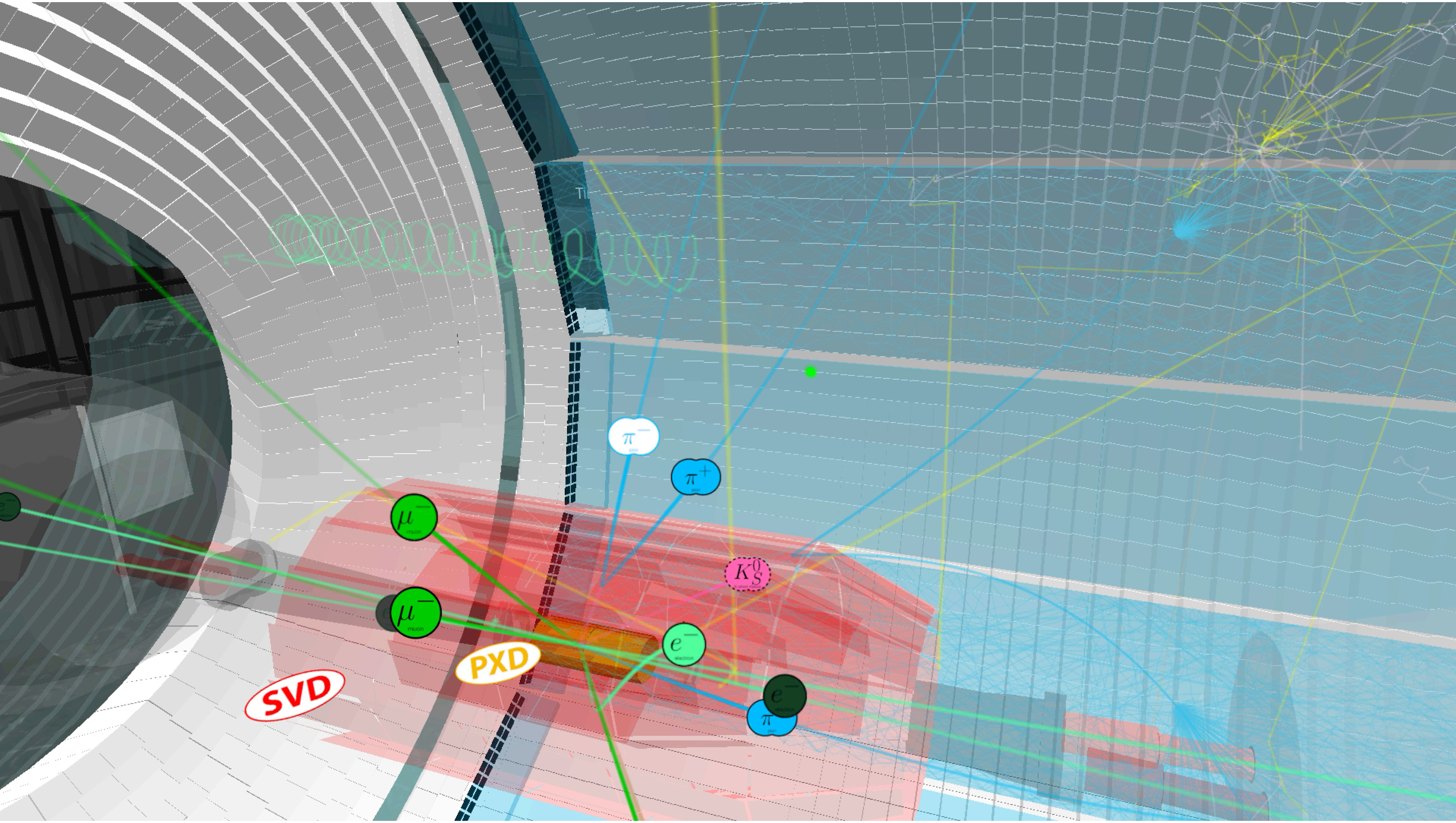
A canonical $B\bar{B}$ Event: “Golden Mode”



Measured asymmetry:

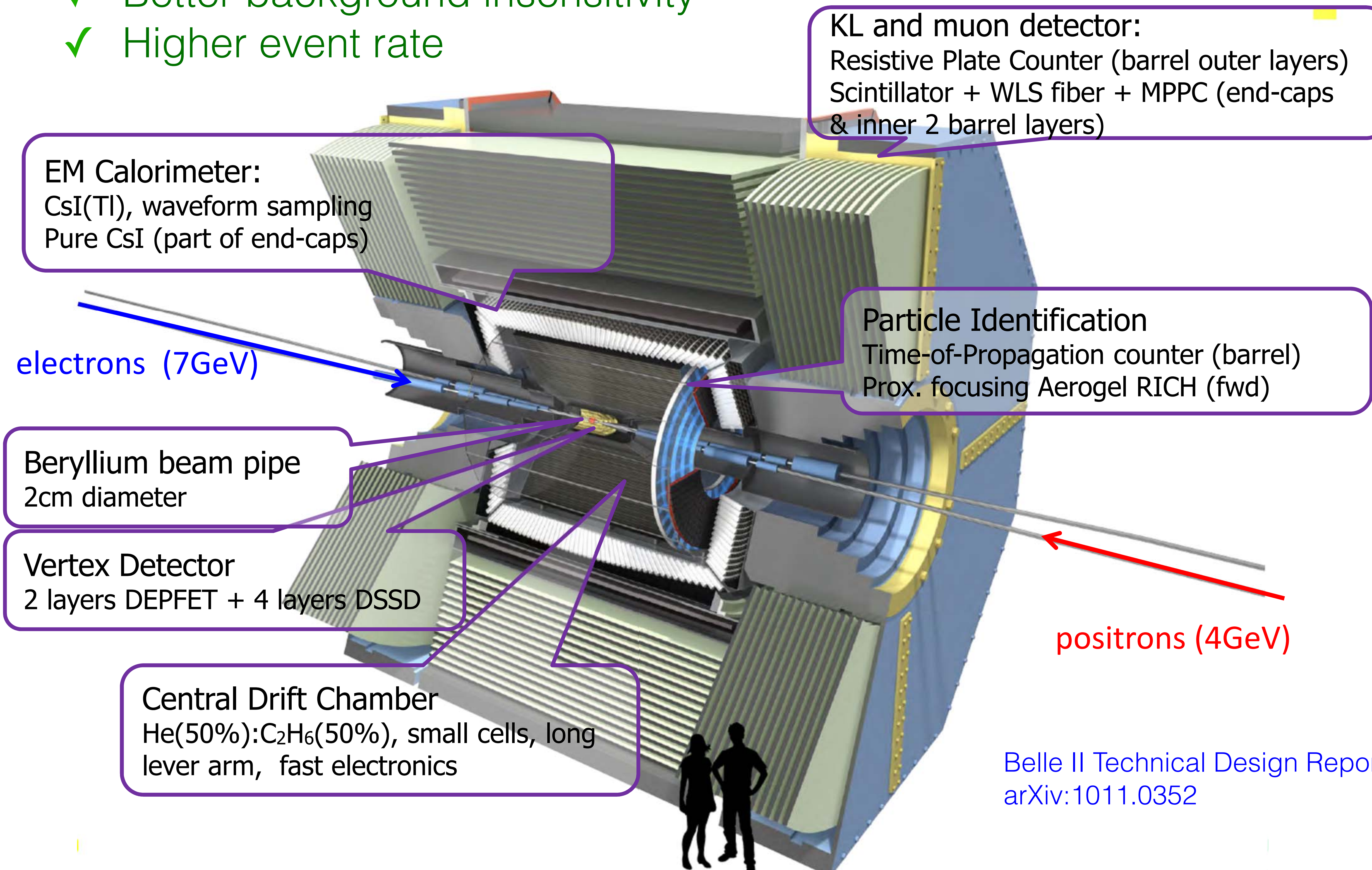
$$A_{CP}(\Delta t) = \frac{\Gamma[\bar{B}^0(\Delta t) \to f] - \Gamma[B^0(\Delta t) \to f)}{\Gamma[\bar{B}^0(\Delta t) \to f] + \Gamma[B^0(\Delta t) \to f)} = \mathcal{S}_f \sin(\Delta m_d\, \Delta t) + \mathcal{A}_f \cos(\Delta m_d\, \Delta t)$$

A canonical $B\overline{B}$ Event



Belle II is a significant upgrade of Belle

- ✓ Improved vertexing and tracking
- ✓ Improved particle identification
- ✓ Better background insensitivity
- ✓ Higher event rate



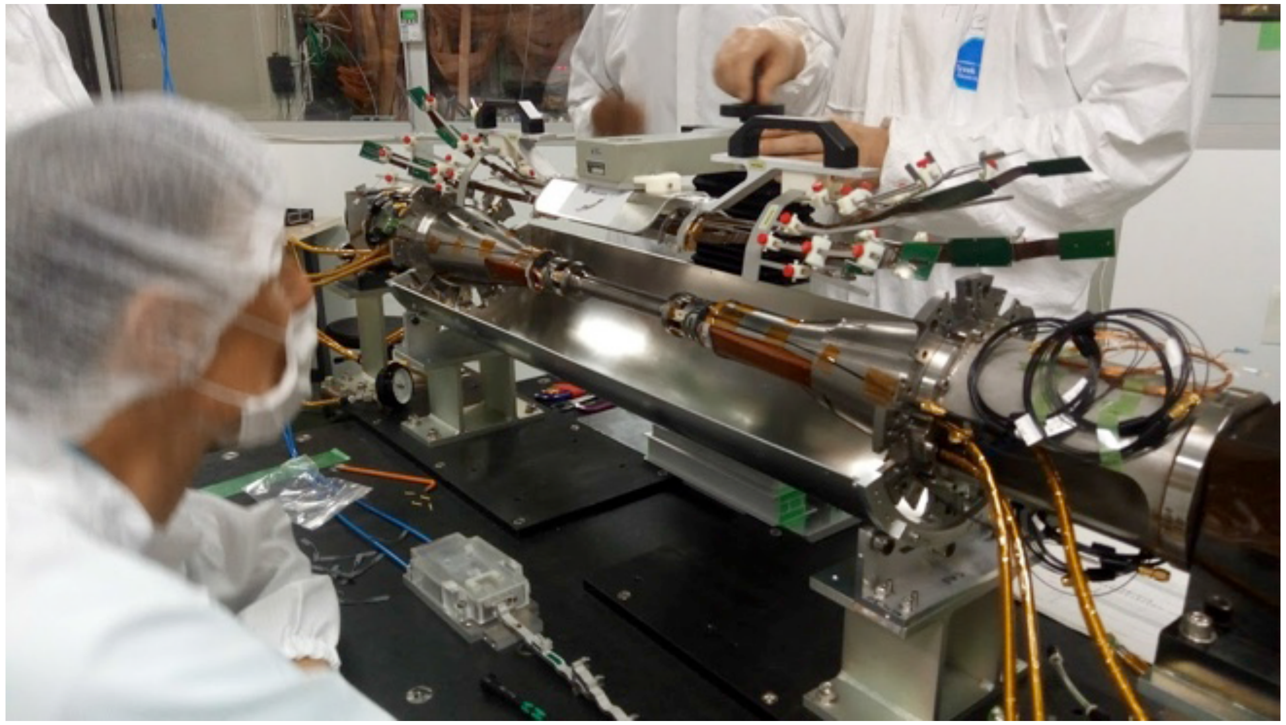
Belle II Technical Design Report
arXiv:1011.0352

Vertex Detector

Component	r (mm)
Beam pipe	10
Pixels – layer 1	14
Pixels – layer 2	22
Strips – layer 3	39
Strips – layer 4	80
Strips – layer 5	104
Strips – layer 6	135

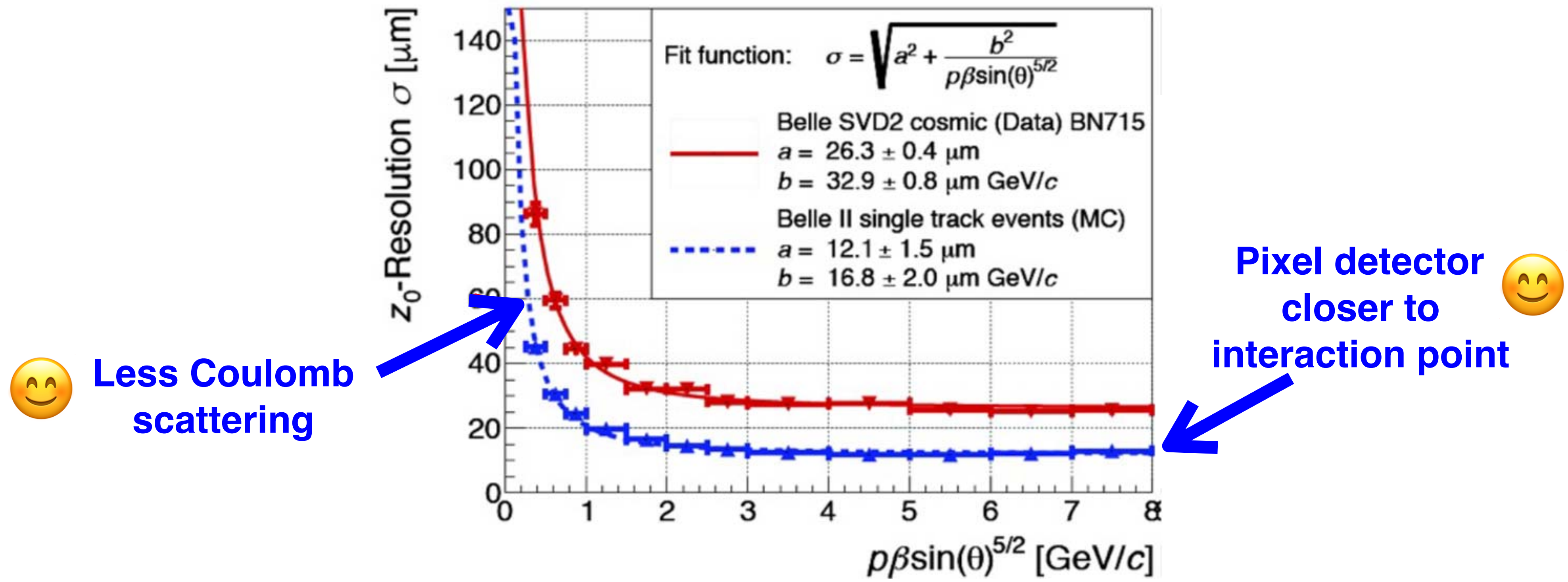
beryllium beam pipe at interaction point

assembled SVD



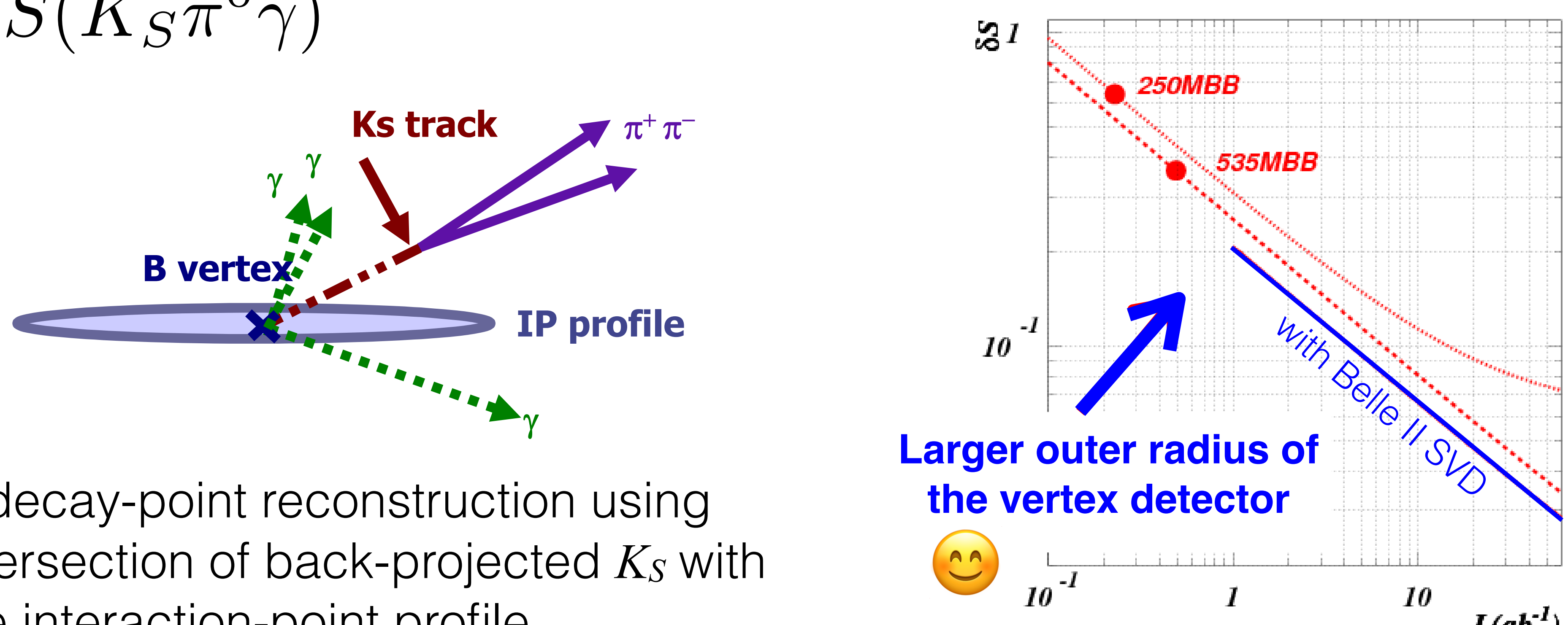
assembled PXD

Vertexing performance improves significantly vs Belle



Improved vertexing is vital for a key time-dependent CP-violation measurement

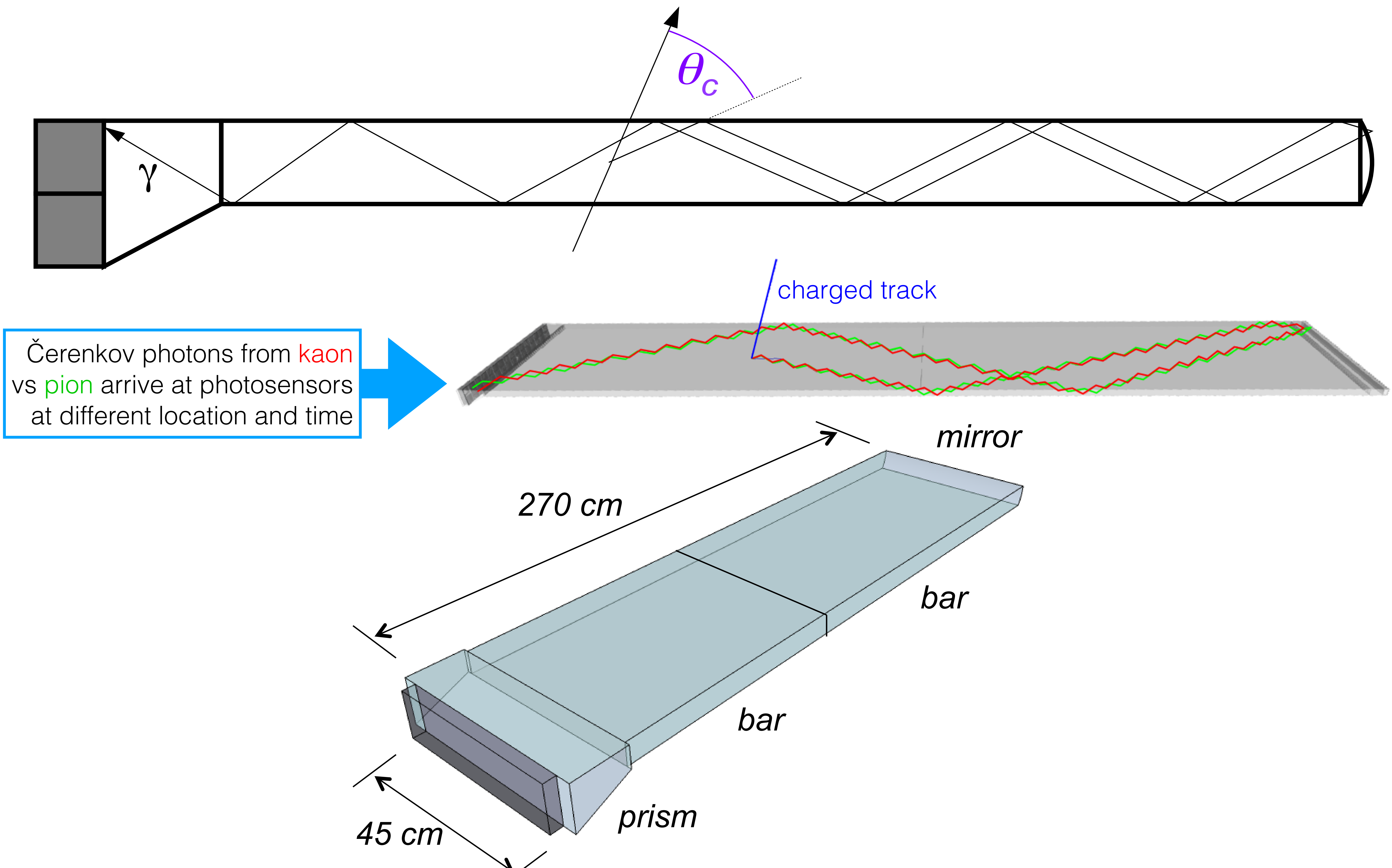
$\delta S(K_S\pi^0\gamma)$



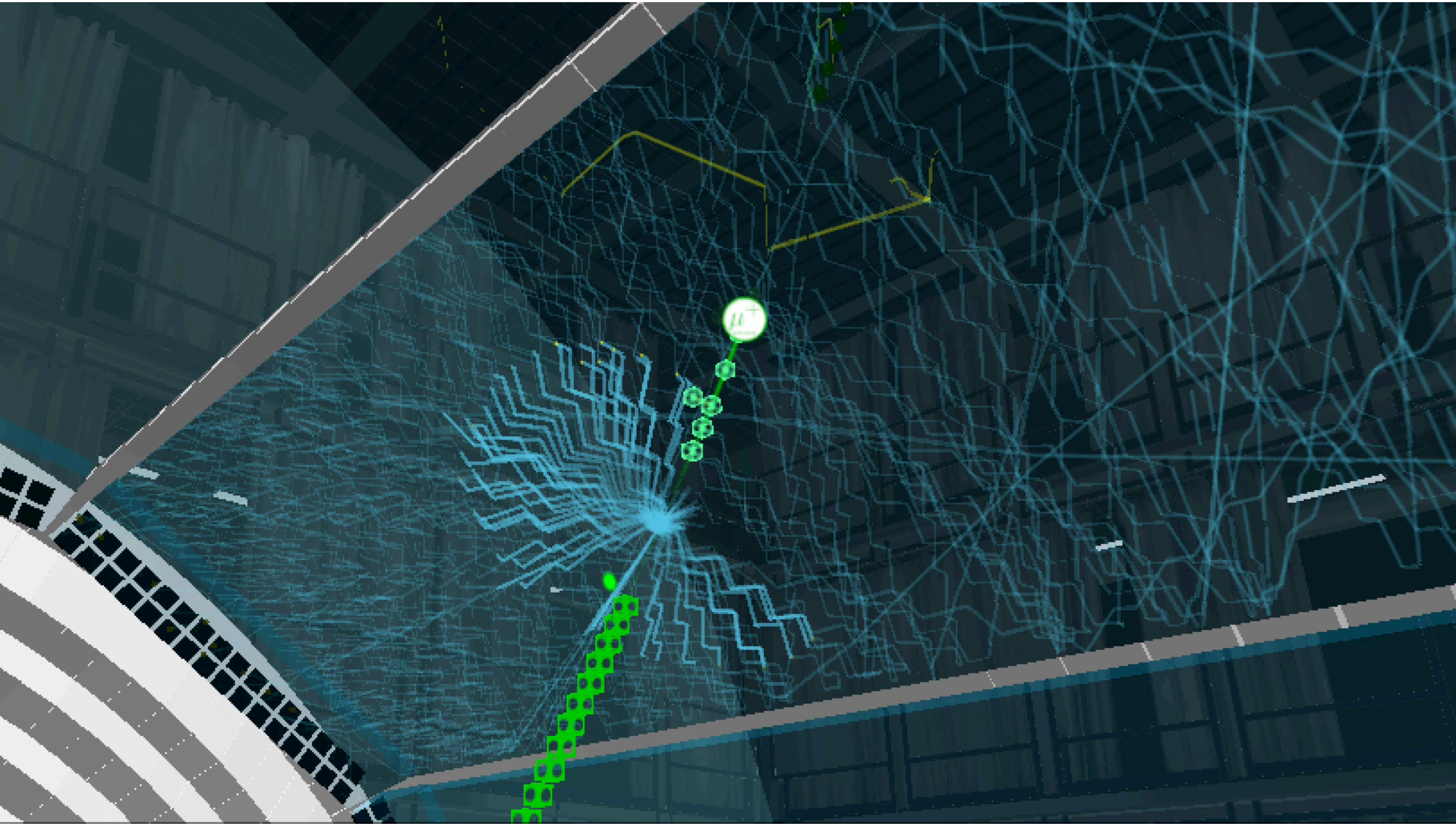
B decay-point reconstruction using intersection of back-projected K_S with the interaction-point profile

Particle ID: measure the Čerenkov cone

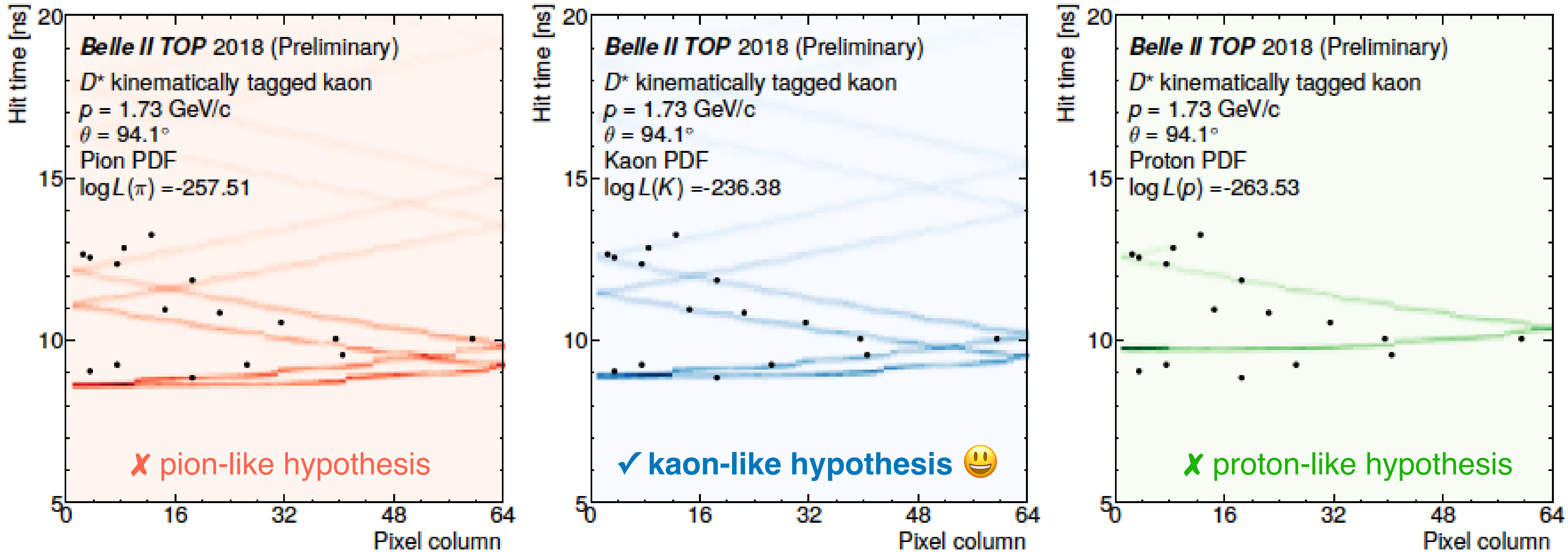
Barrel PID uses imaging time-of-propagation counter (16 quartz staves)

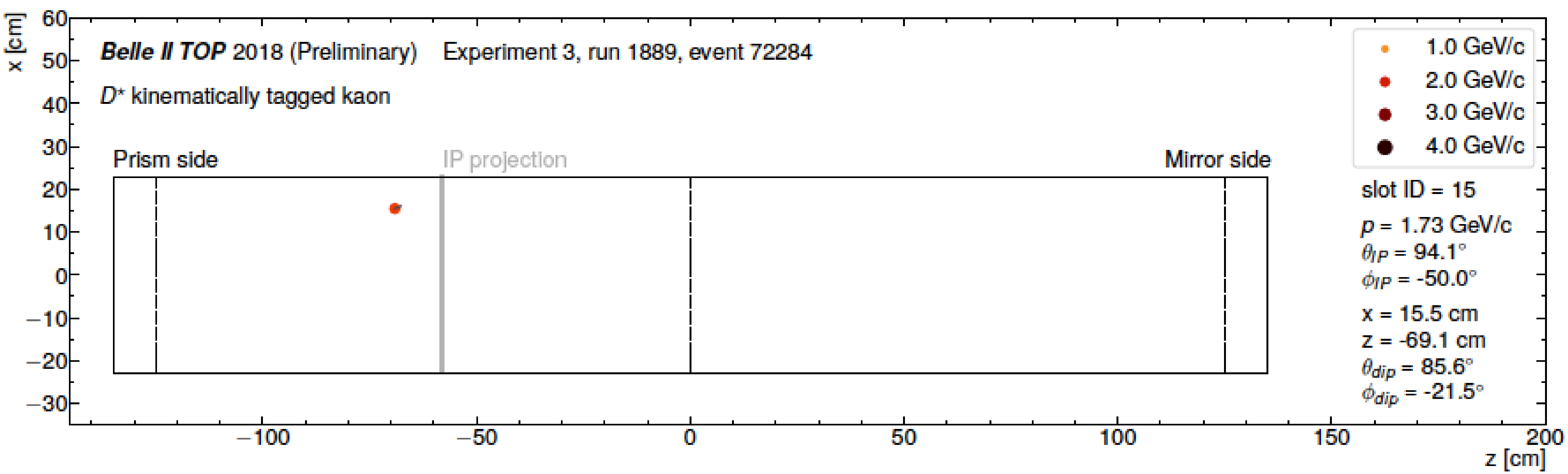


Čerenkov light in the TOP (barrel particle ID)



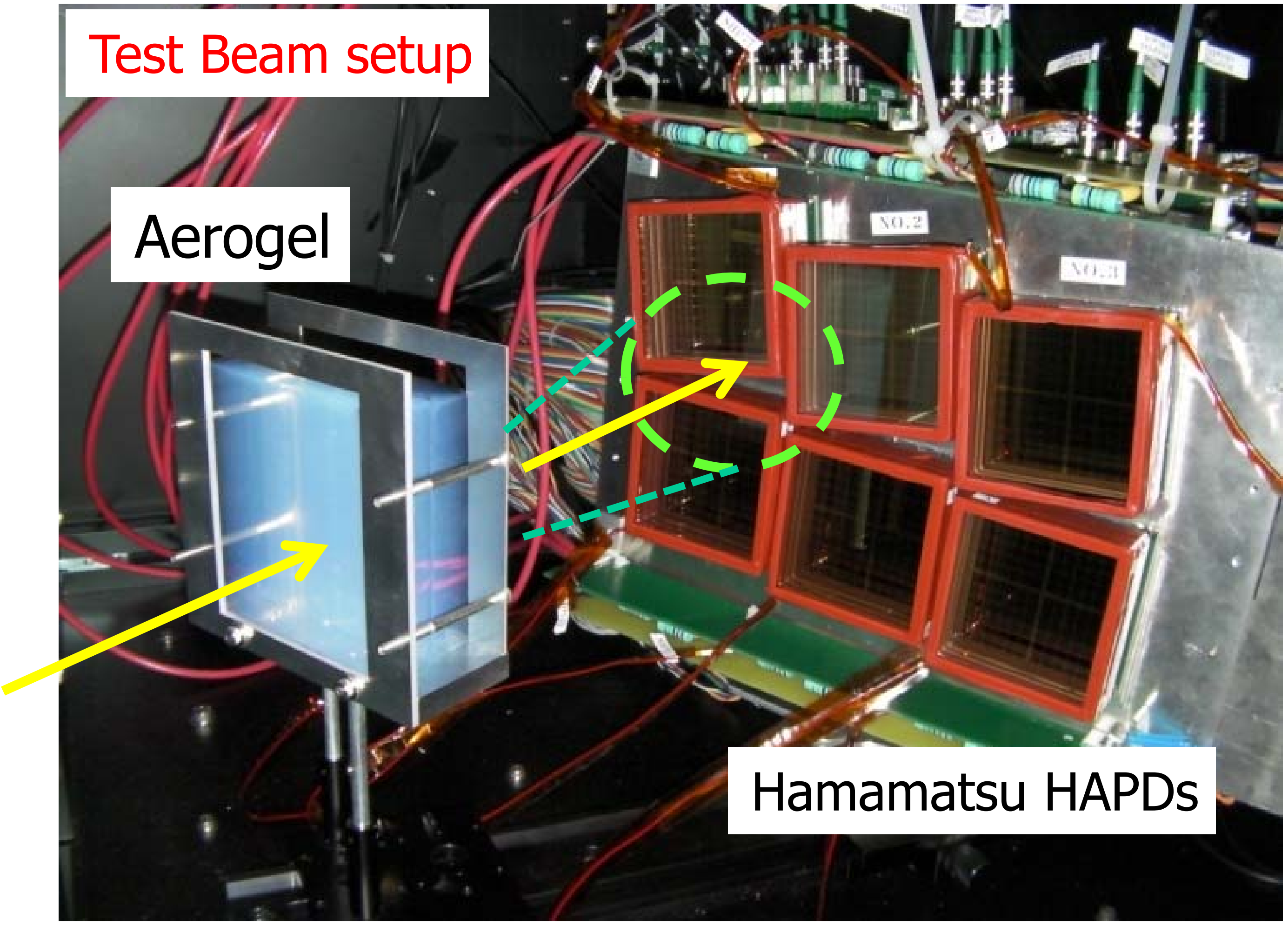
Measure the Čerenkov cone in barrel PID (TOP)

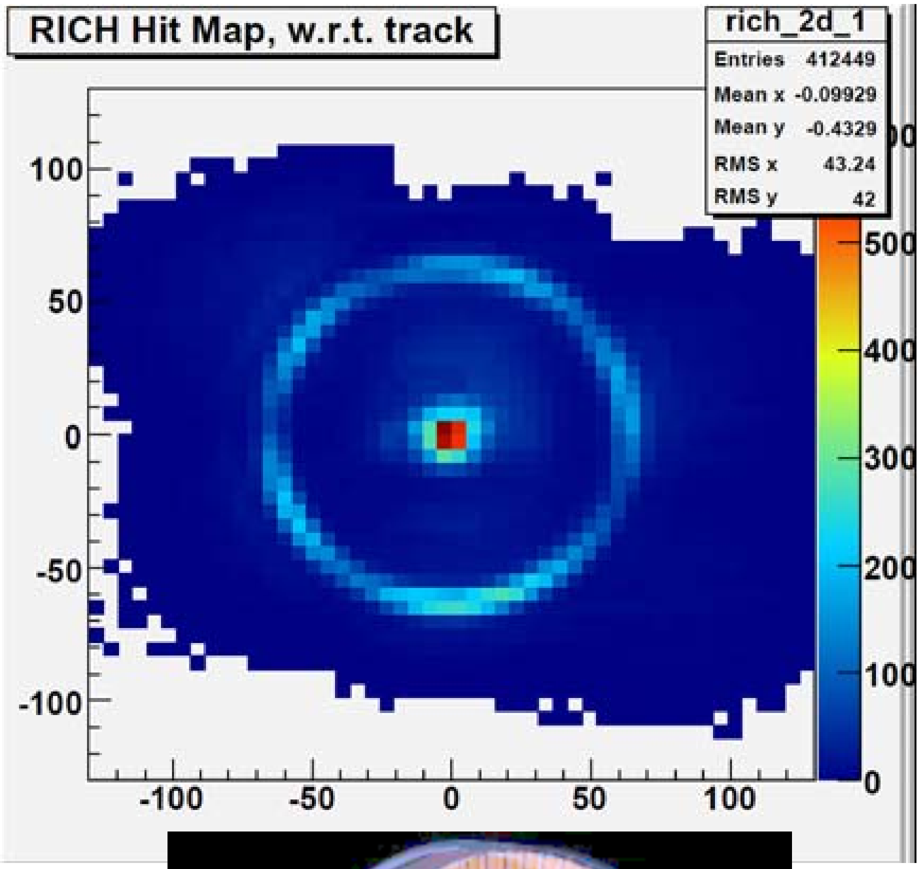




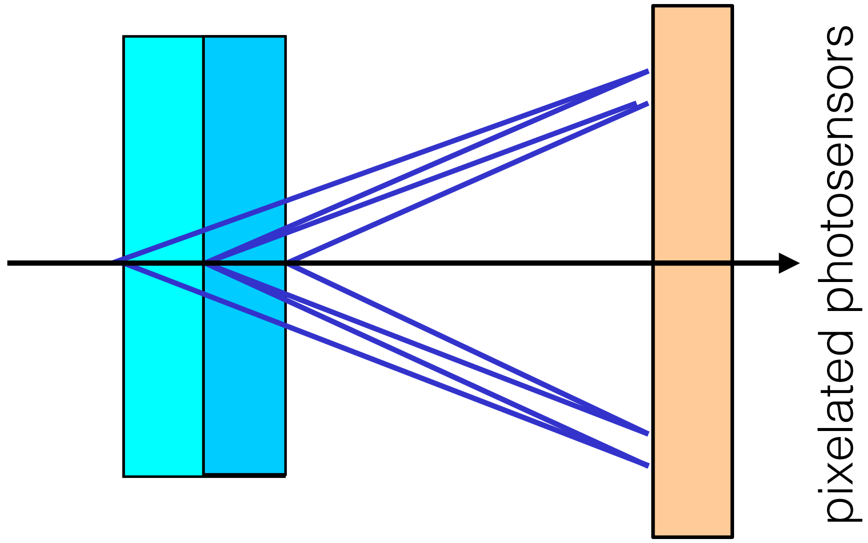
Particle ID: measure the Čerenkov cone

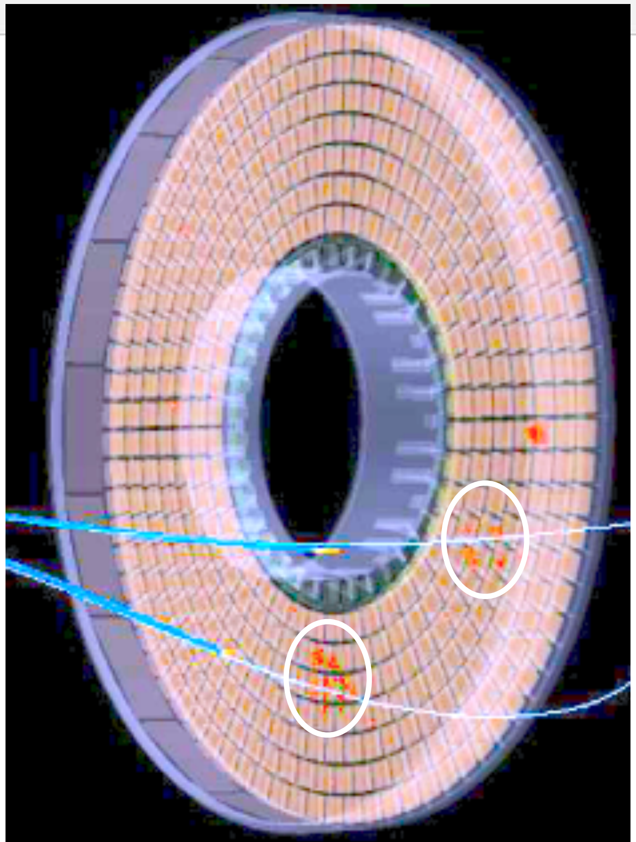
Forward-endcap PID uses aerogel RICH with two-layer radiator (“focusing”)



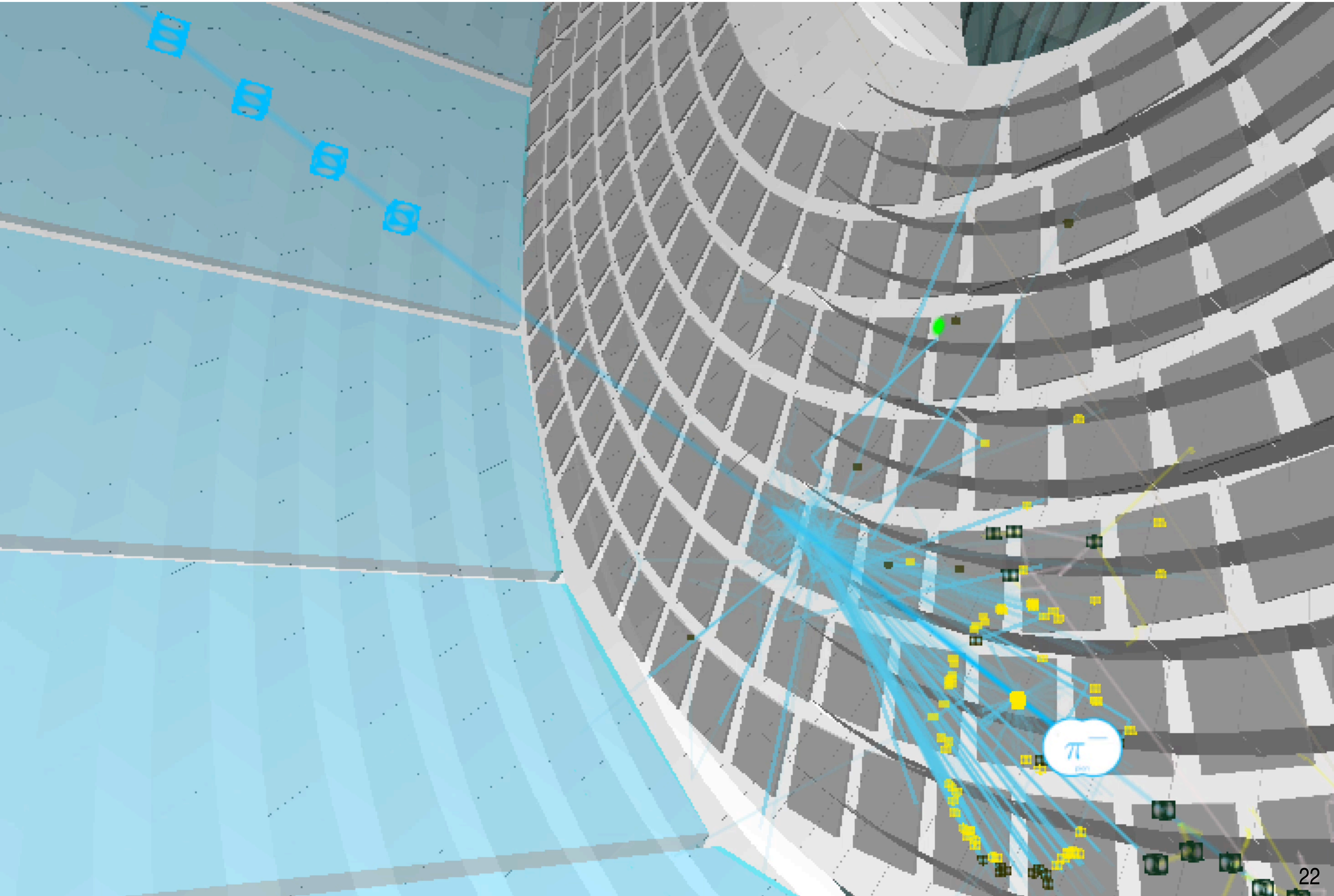


Graded-n aerogel radiator focuses light onto photosensors





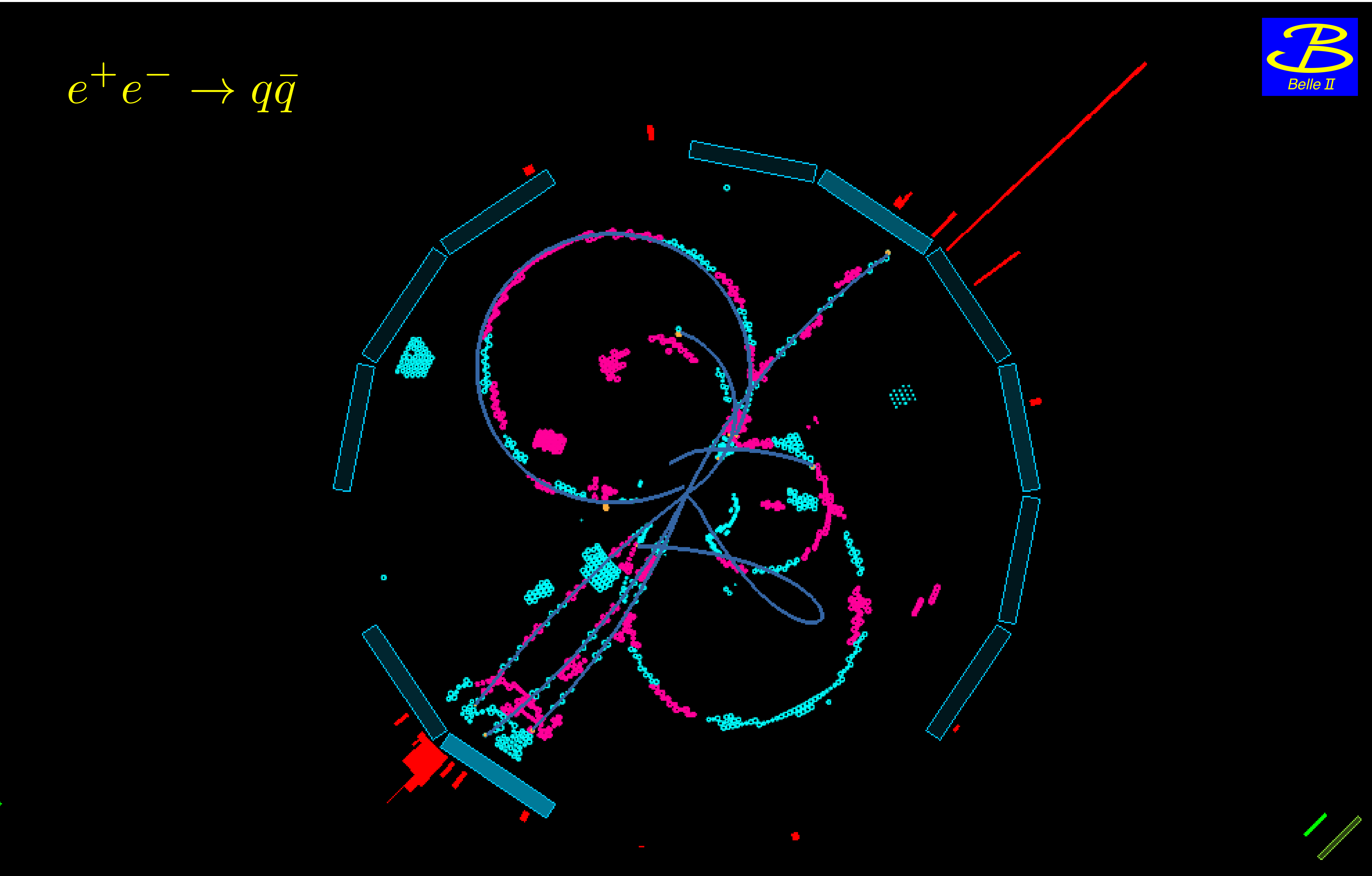
Čerenkov light in the ARICH (forward particle ID)



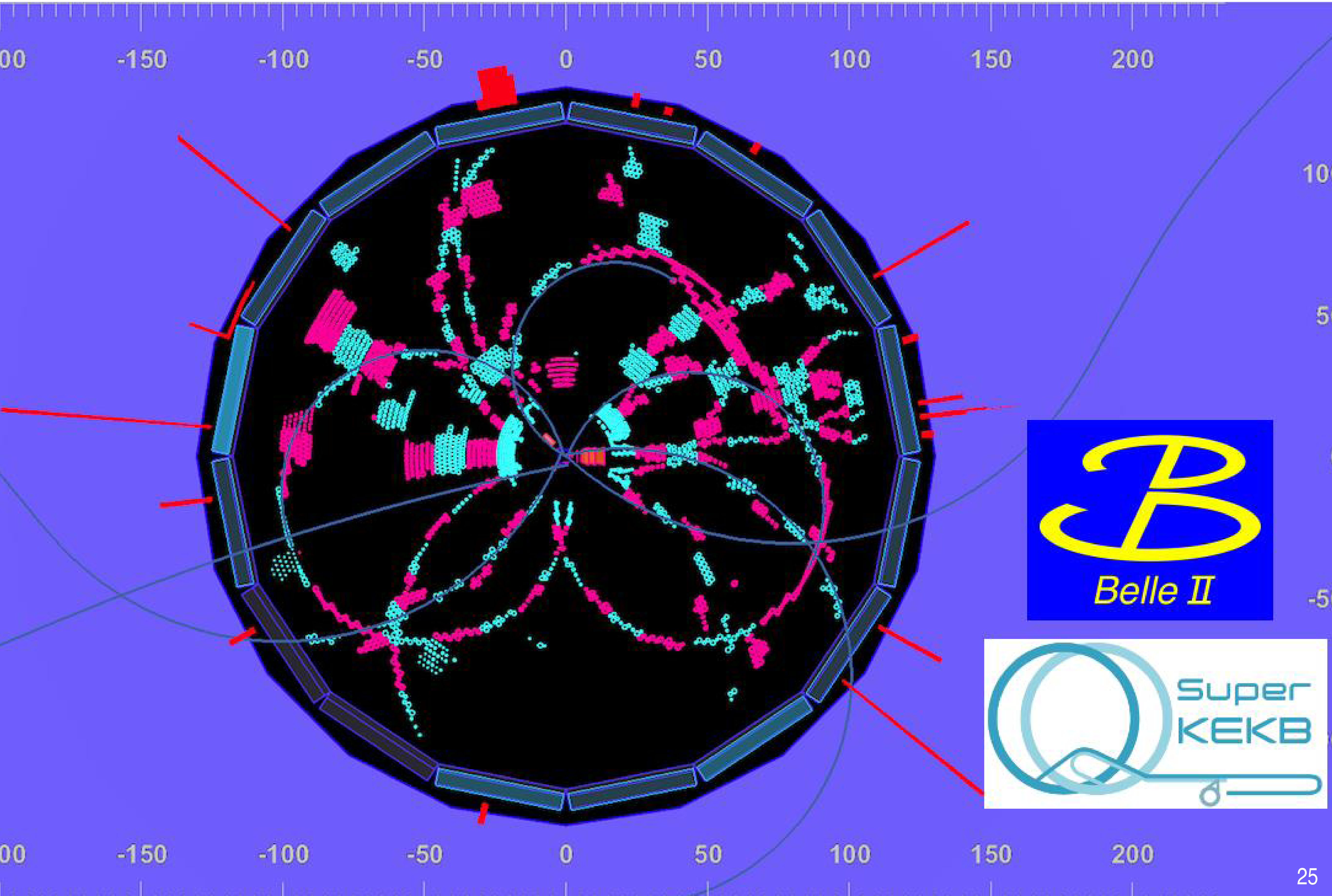
April 26, 2018: SuperKEKB/Belle II joins DORIS/ARGUS, CESR/CLEO, PEP-II/BaBar, and KEKB/Belle

rejoicing first collisions in the Belle II control room

First hadronic event in April 2018 (Phase 2 day 1)

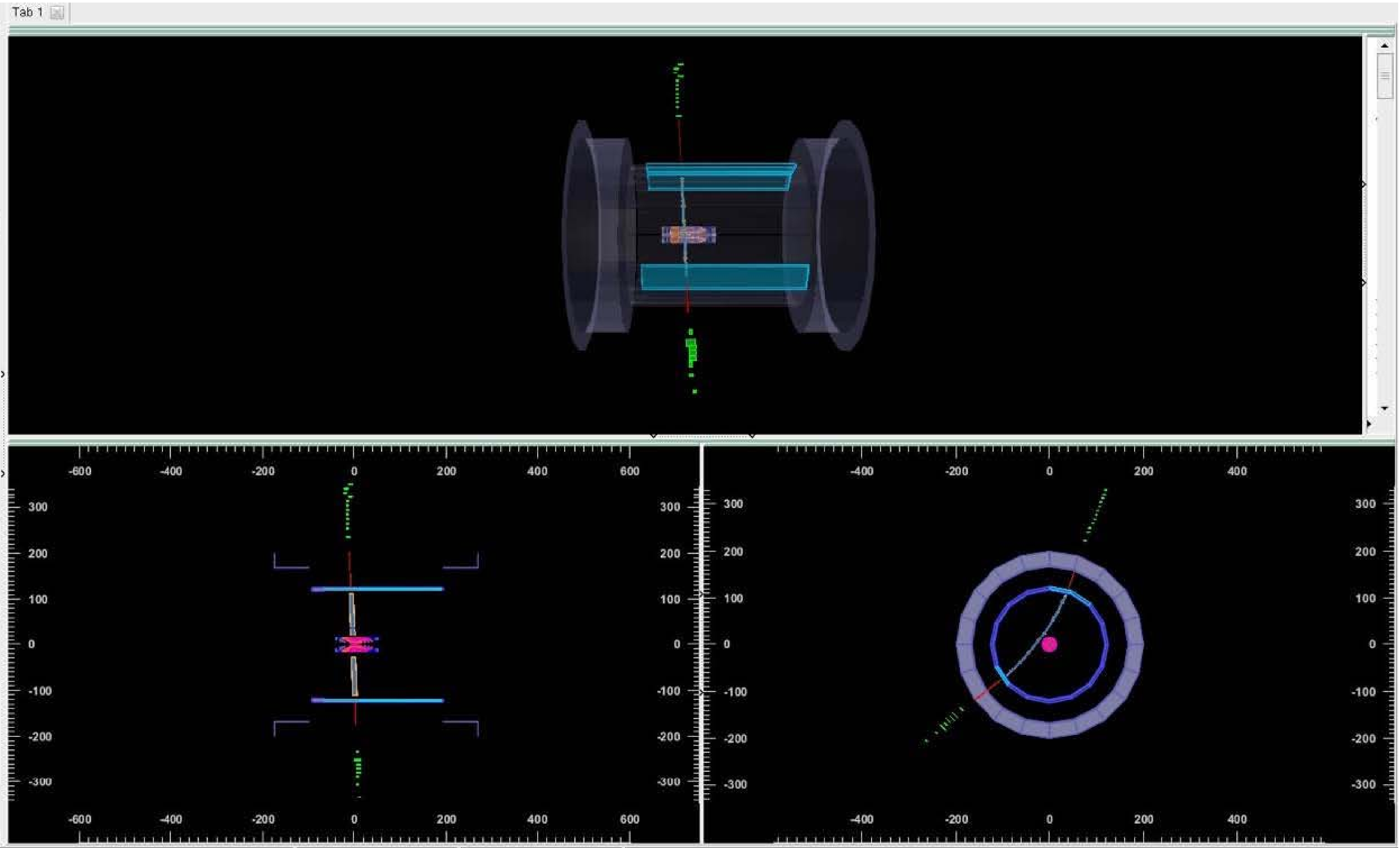


First $B\bar{B}$ event in April 2018 (Phase 2 day 1)



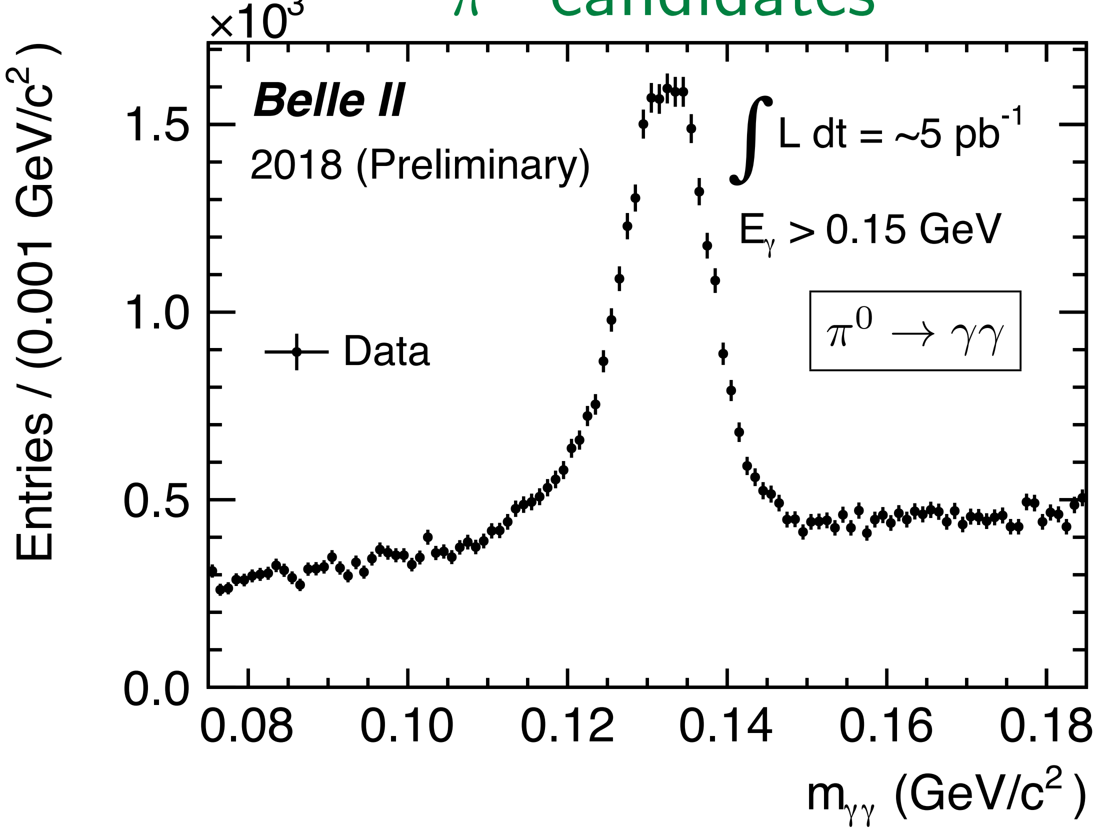
Event activates CDC, TOP, ECL, KLM

tracking chamber | particle identifier | calorimeter | K_L – muon identifier

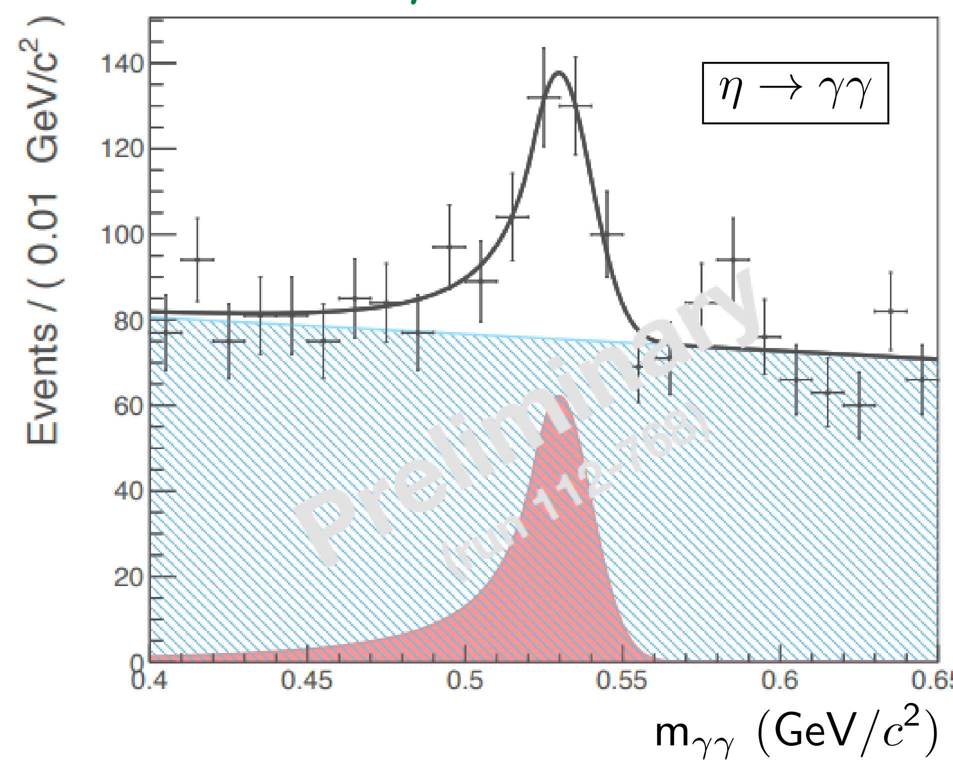


First results from Phase 2: neutrals

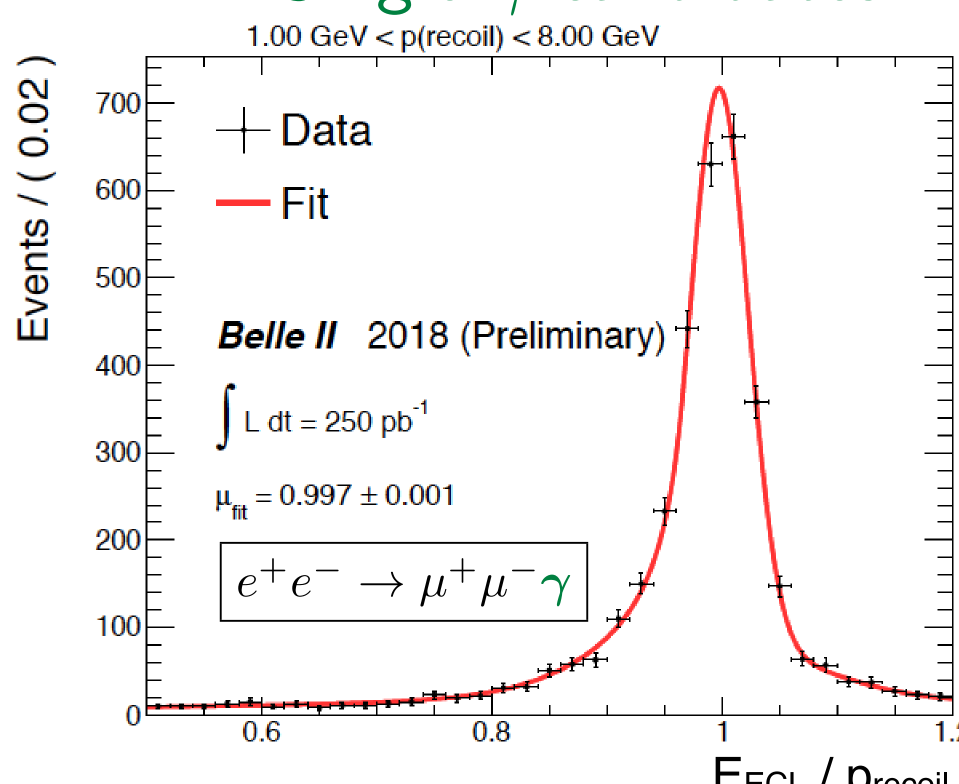
π^0 candidates



η candidates

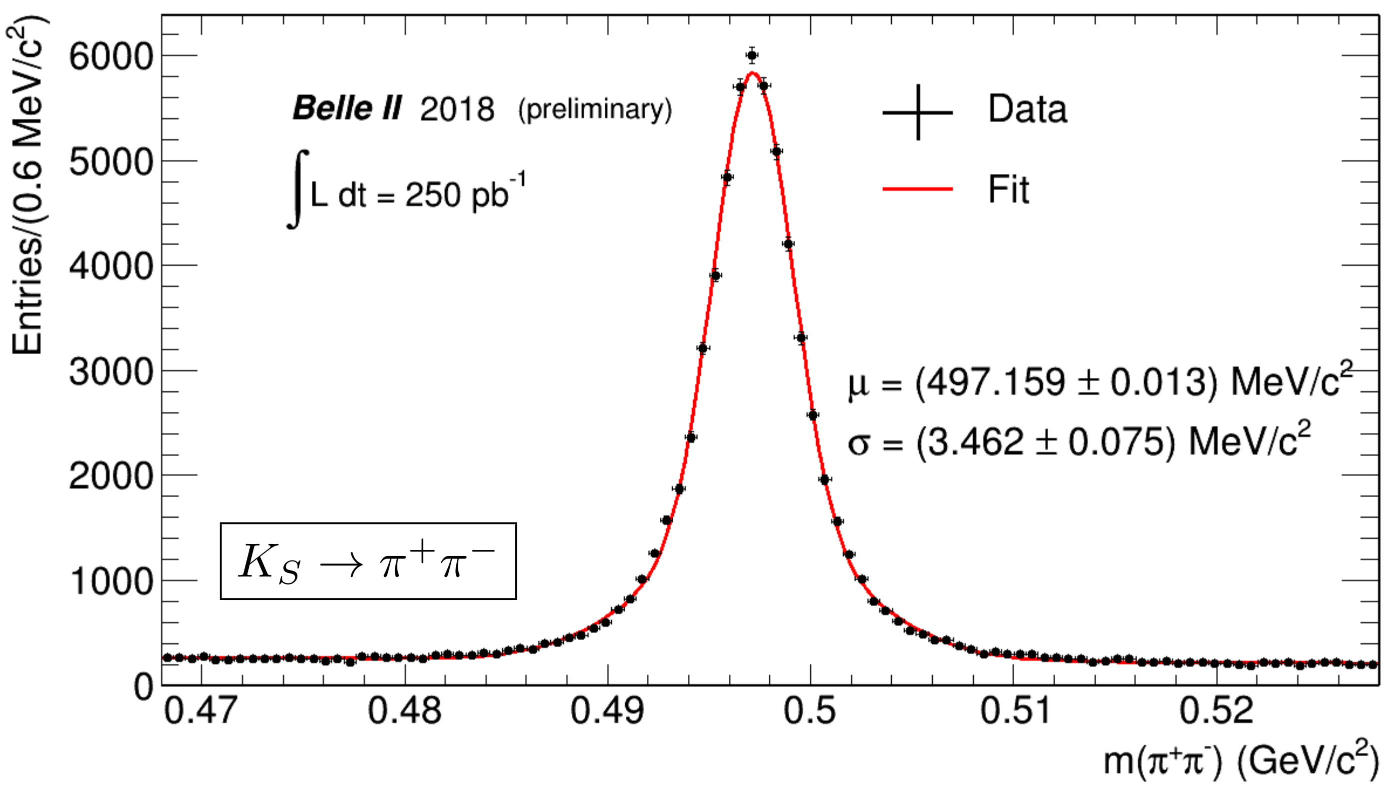


Single-γ candidates

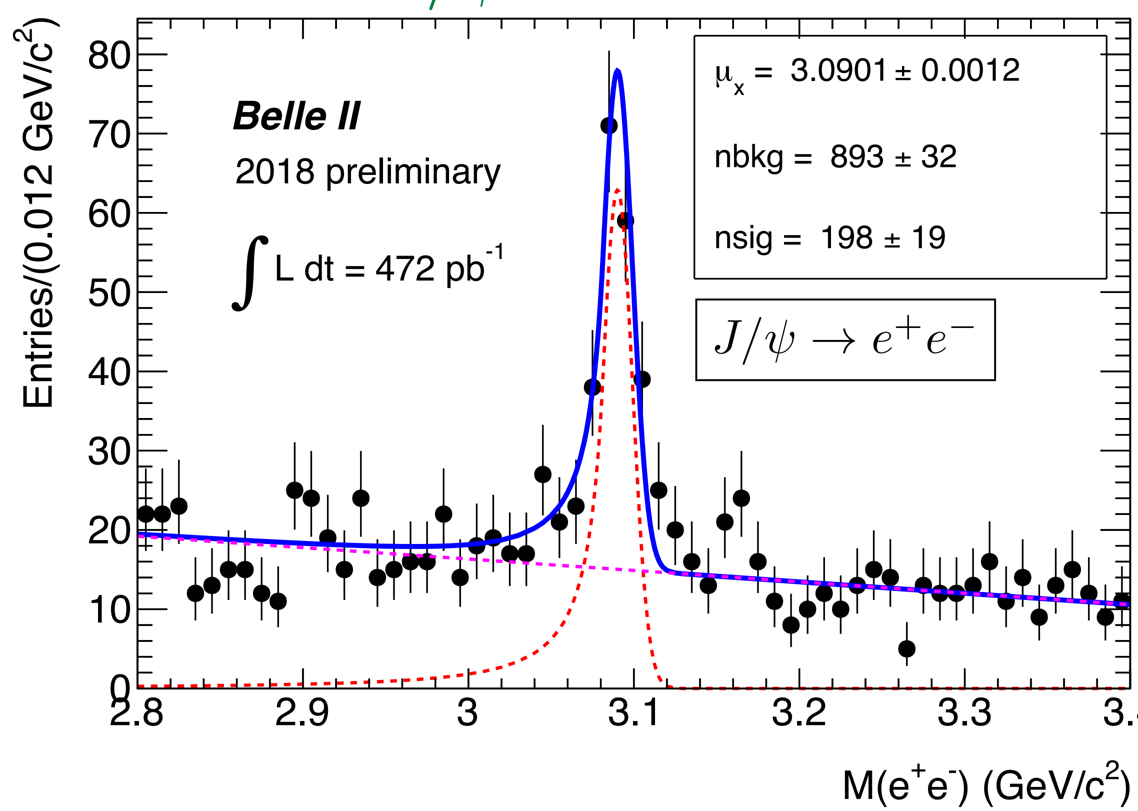


First results from Phase 2: charged-track combos

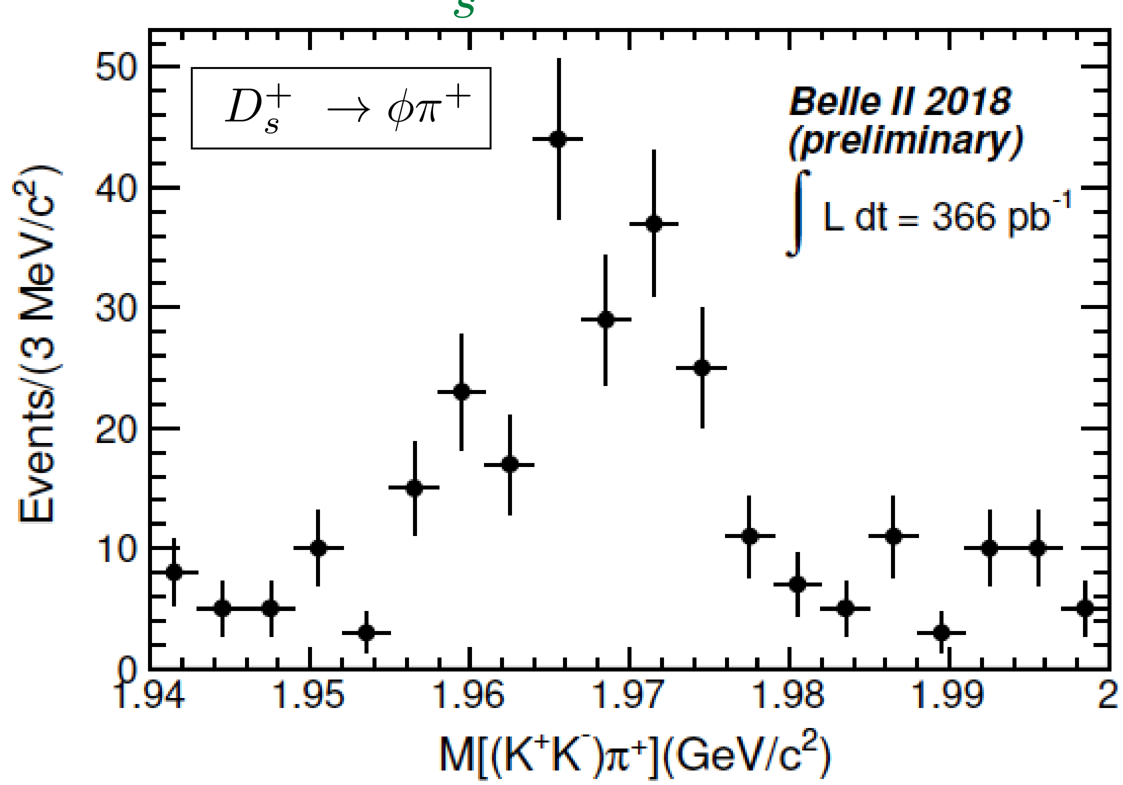
K_S candidates



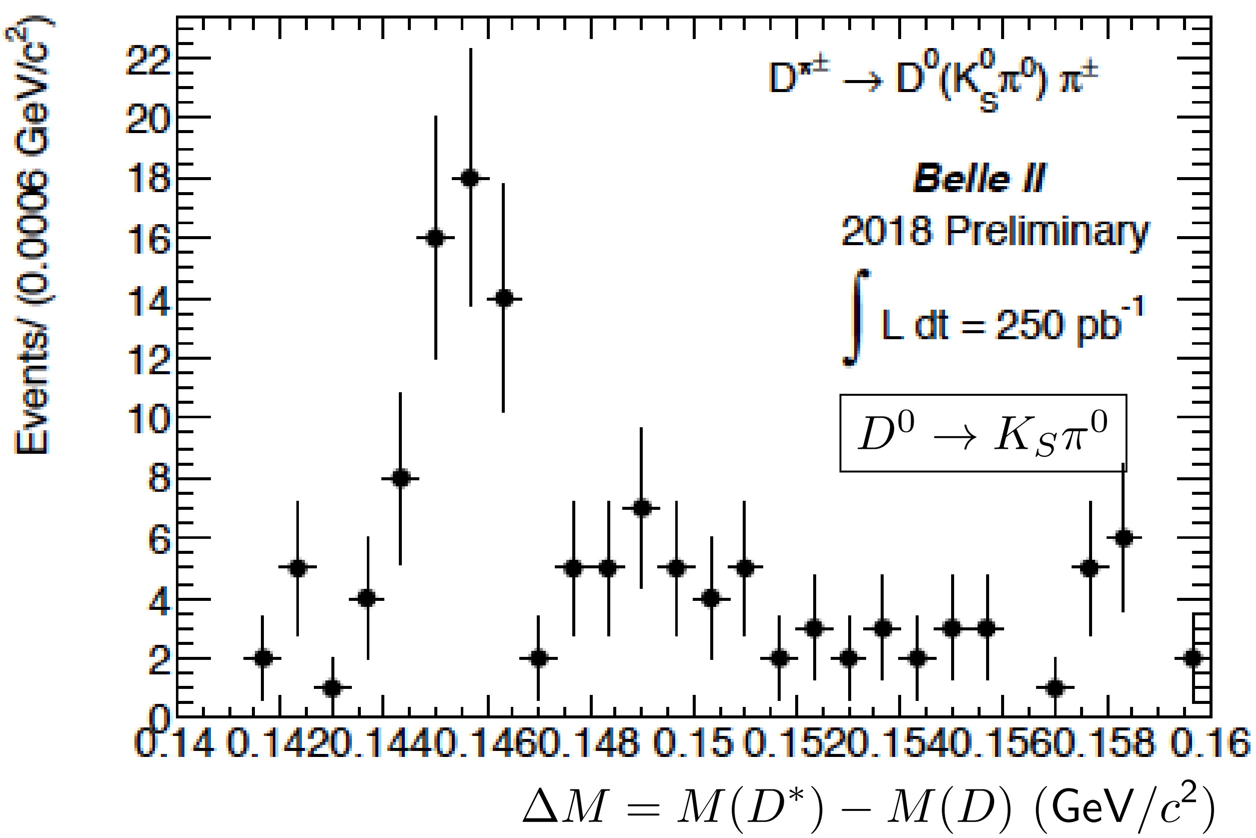
J/ψ candidates

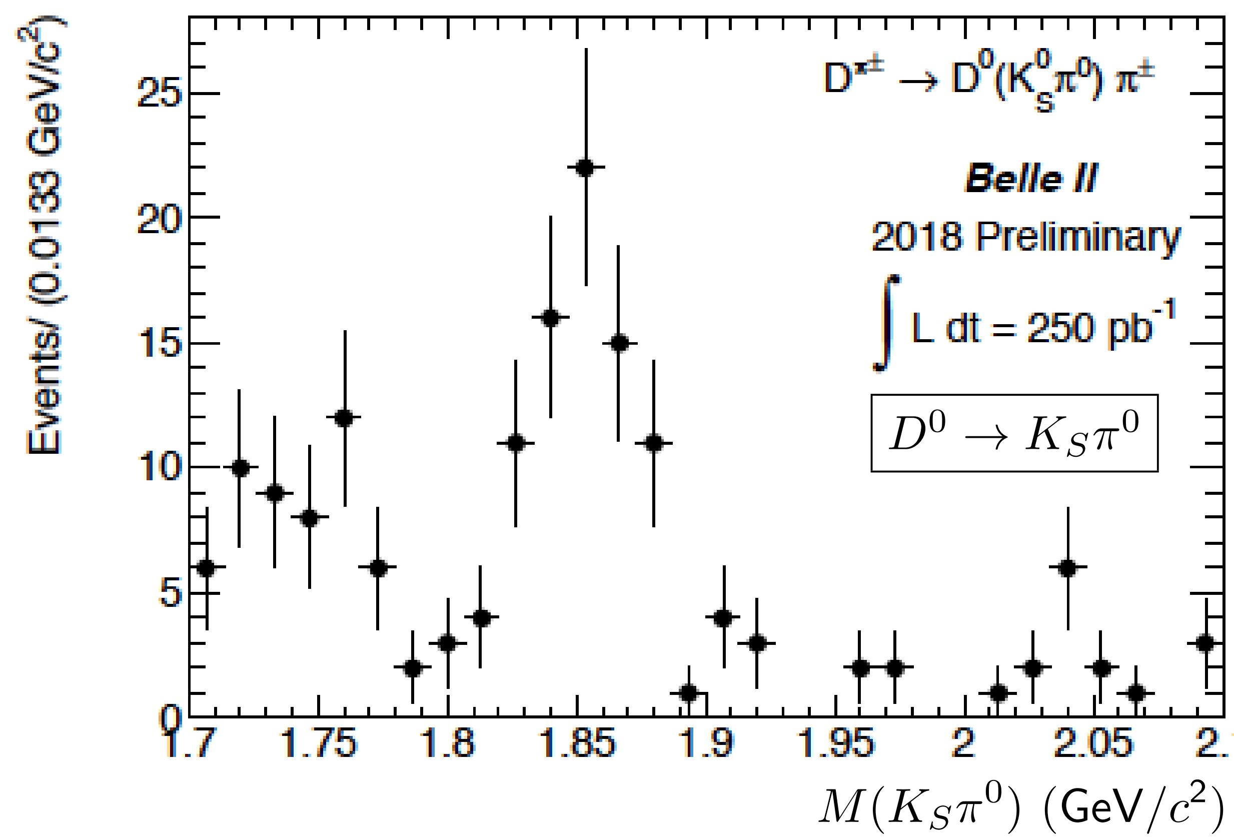


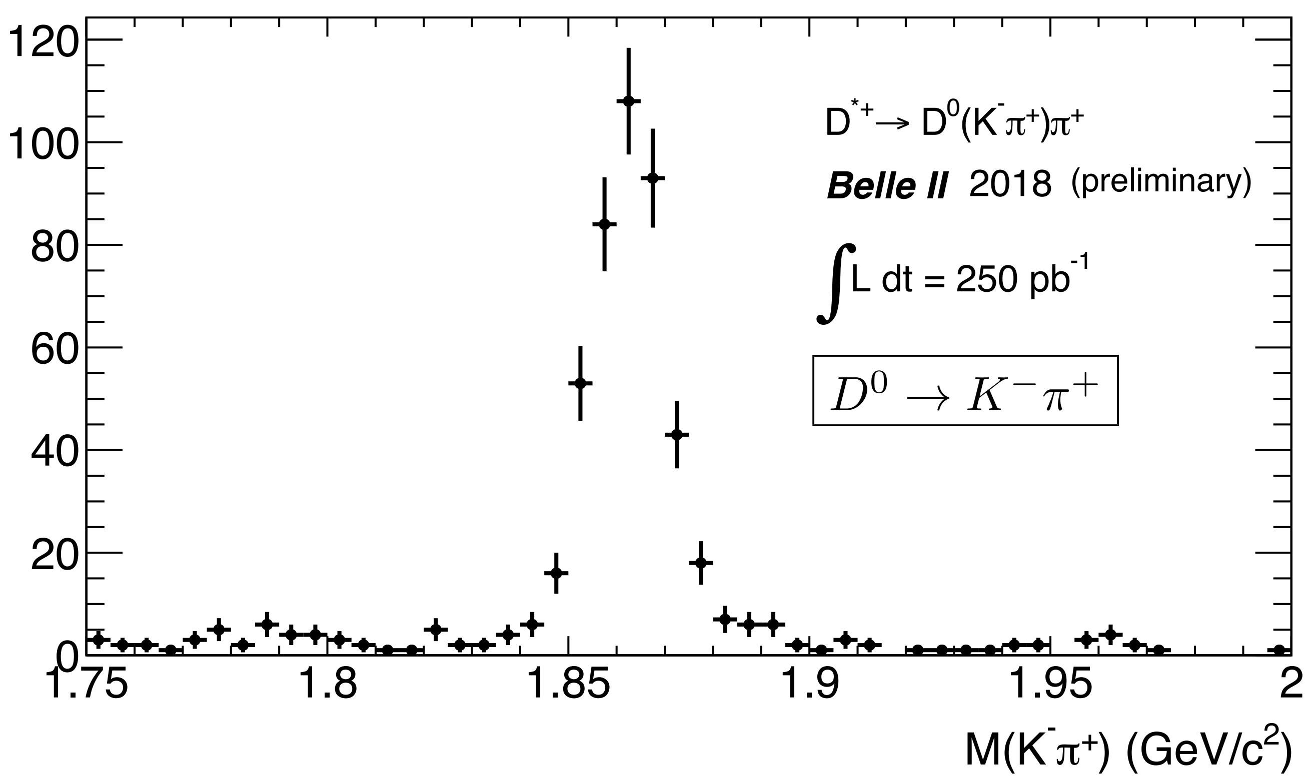
D_s^+ candidates

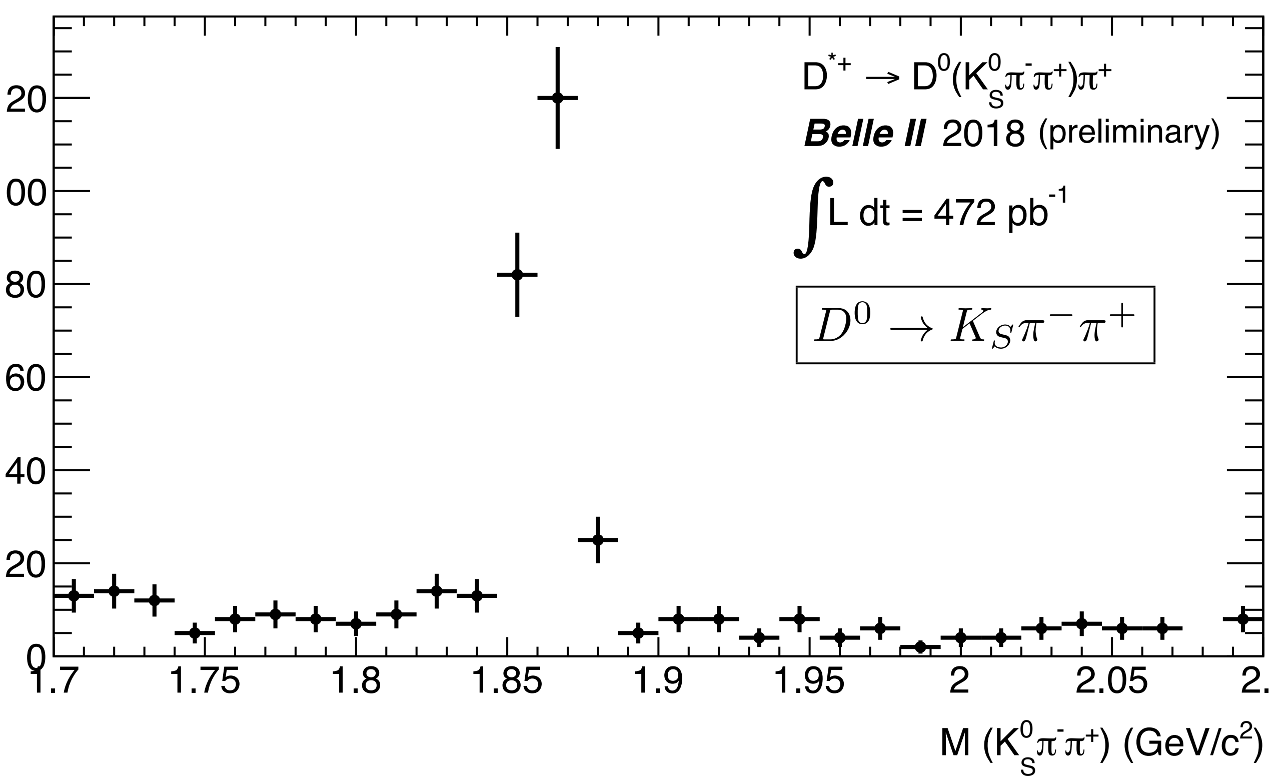


First results from Phase 2: D^0 candidates

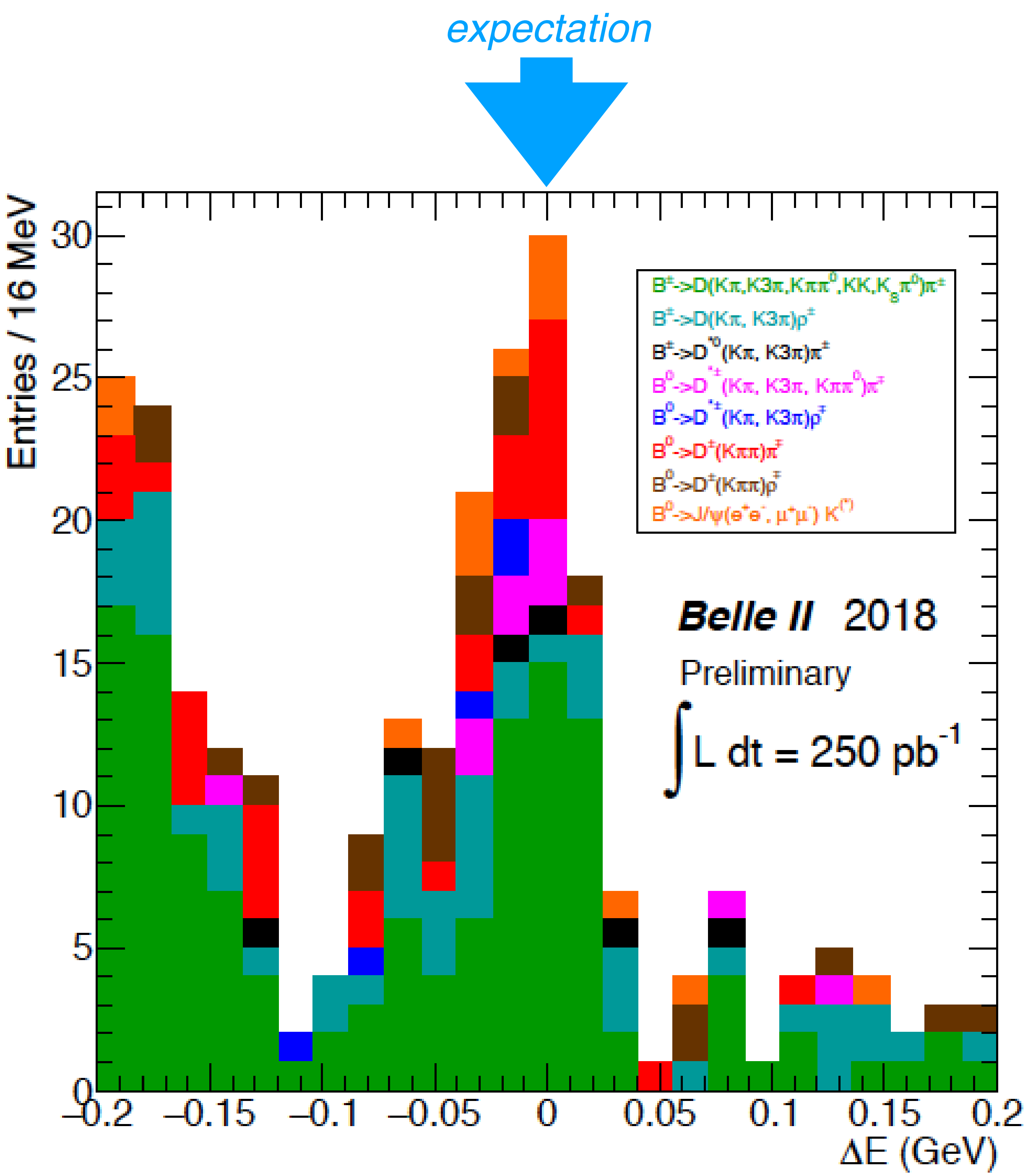


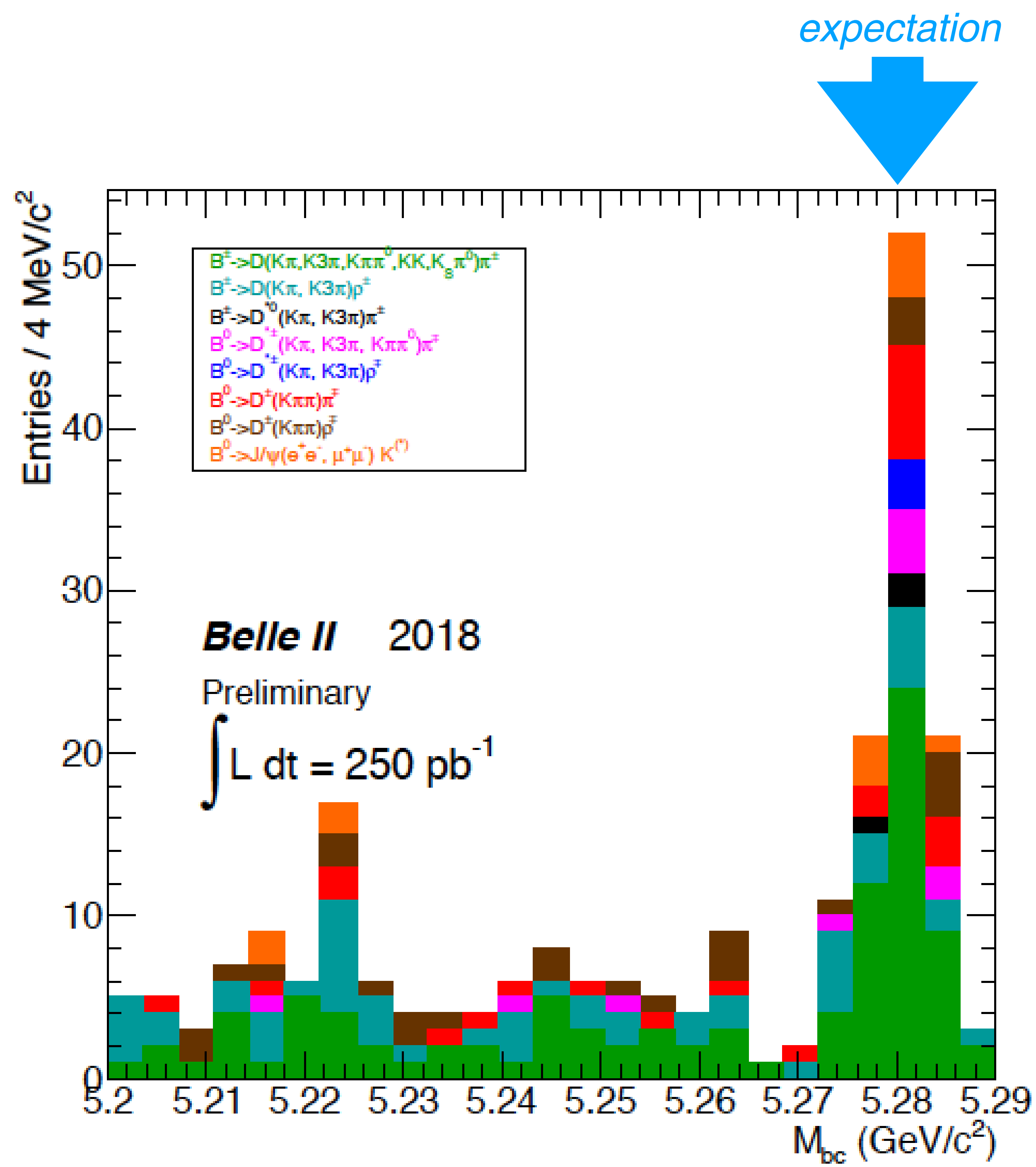






First results from Phase 2: B mesons





Belle II physics program is broad and deep

Belle II Theory Interface Platform (B2TIP)
Workshop series, 2015-2018:

WG1
Semileptonic & Leptonic B decays

WG2
Radiative & Electroweak Penguins

WG3
α/φ_2 β/φ_1

WG4
γ/φ_3

WG5
Charmless Hadronic B Decay

WG6
Charm

WG7
Quarkonium(-like)

WG8
Tau, low multiplicity

WG9
New Physics

The Belle II Physics Book
Emi Kou and Phill Urquijo, editors

689 pages
arXiv: 1808.10567
submitted to PTEP

… a fruitful collaboration among theorists and experimentalists

Belle II, like other particle-physics experiments, is looking for evidence of **New Physics**

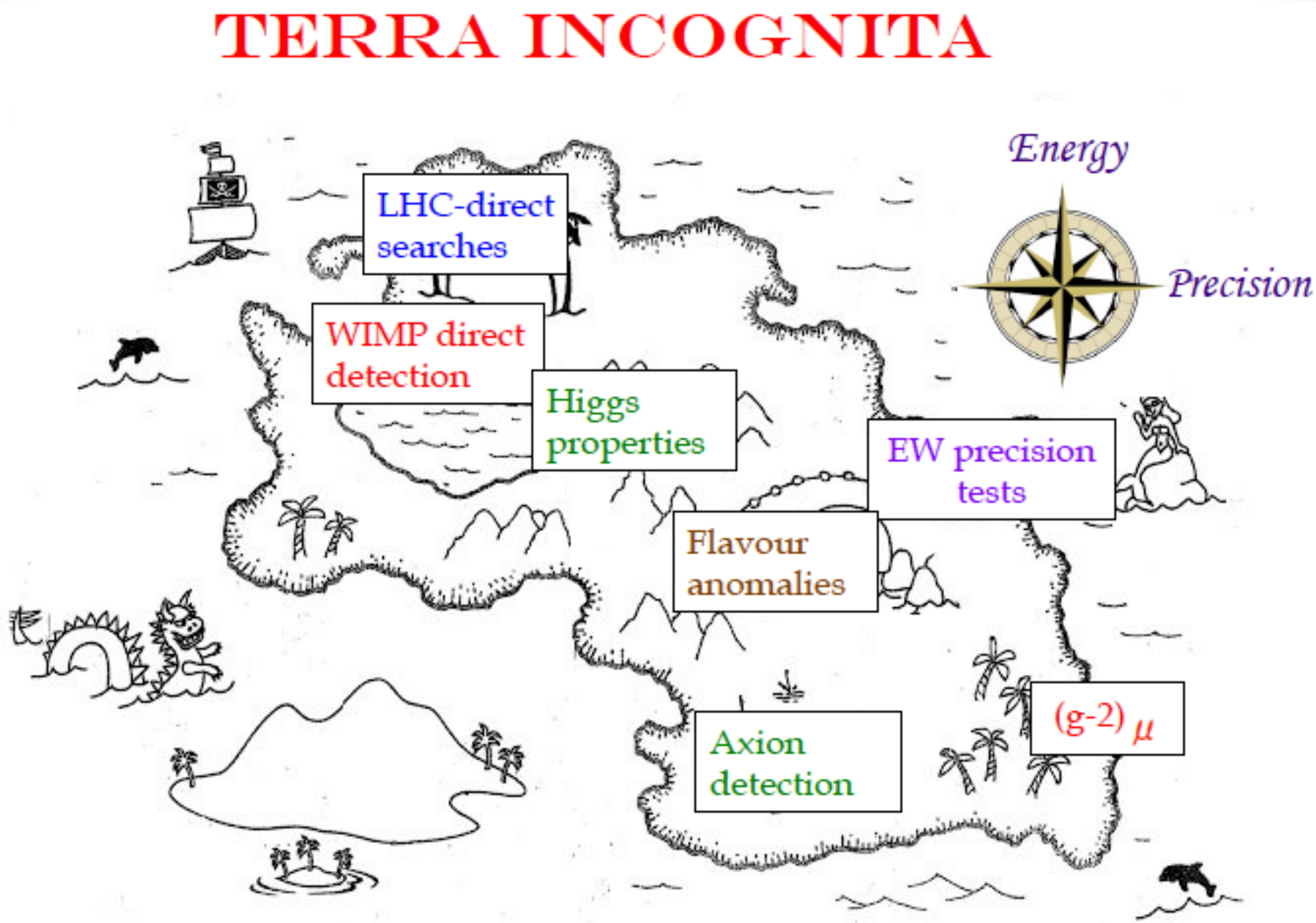


Image credit: A. Casas (Moriond 2017)

The New York Times June 19, 2017

CERN hosts thousands of scientists, representing 22 member countries, all working to understand how the universe was created. CMS is one of seven detectors on site. Leslye Davis/The New York Times

Yearning for New Physics at CERN, in a Post-Higgs Way

Physicists monitoring the Large Hadron Collider are seeking clues to a theory that will answer deeper questions about the cosmos. But the silence from the frontier has been ominous.

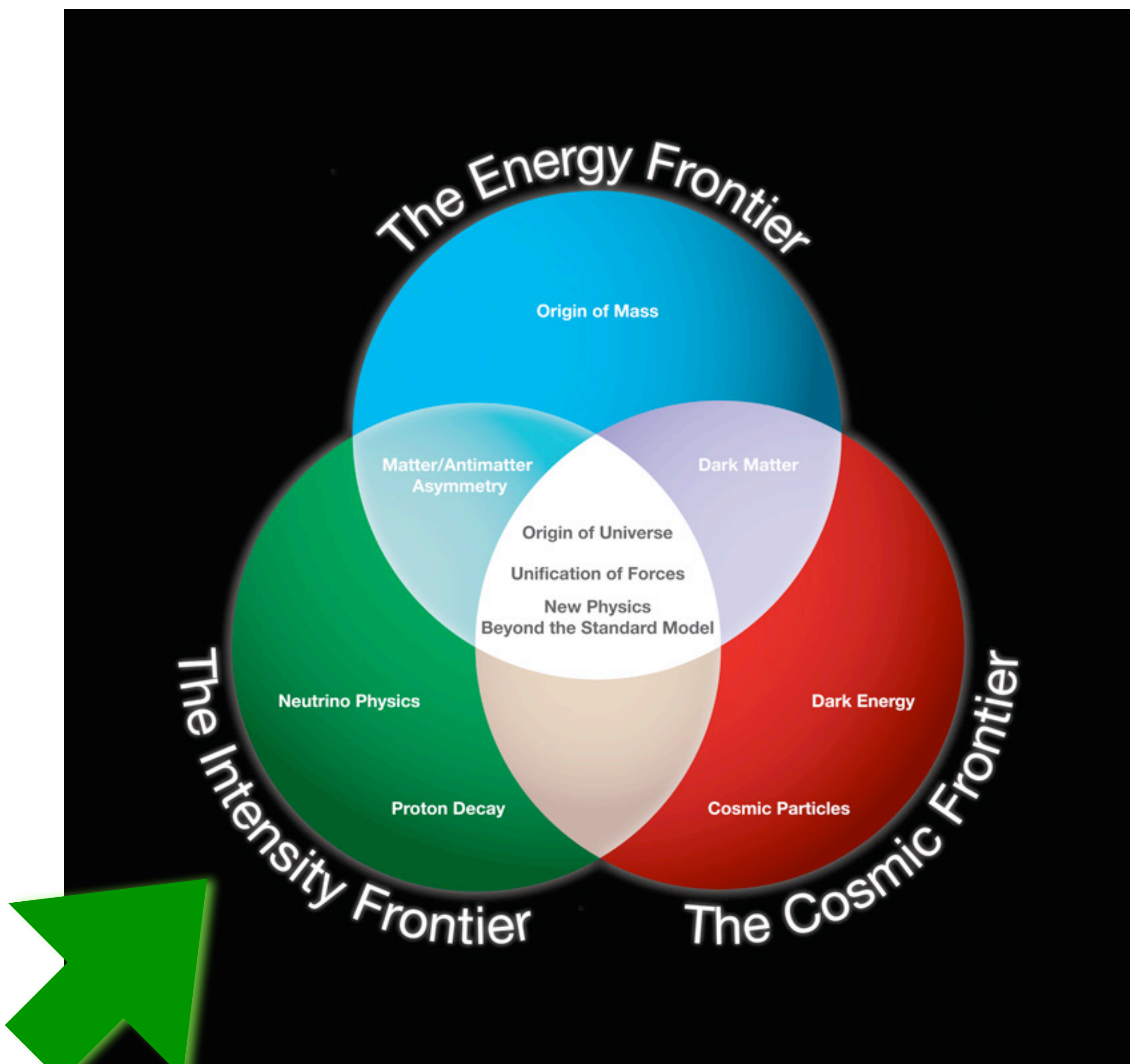
By DENNIS OVERBYE JUNE 19, 2017

But since then, the silence from the energy frontier has been ominous. "The feeling in the field is at best one of confusion and at worst depression," Adam Falkowski, a particle physicist at the Laboratoire de Physique Théorique d'Orsay in France, wrote recently in an article for the science journal *Inference*. *"These are difficult times for the theorists,"* Gian Giudice, the head of CERN's theory department, said. *"Our hopes seem to have been shattered. We have not found what we wanted."*

from Tom Browder's 2017 B2SS presentation

Stay calm. Don't panic !!

The intensity frontier will save you – *again!* – as it has done in the past. ($K_L \to \mu\mu$, B mixing, $A_{FB}(e^+e^- \to \mu^+\mu^-)$, electroweak corrections, …



from Tom Browder's 2017 B2SS presentation

Belle II is looking for evidence of New Physics

SuperKEKB/Belle II is the *Intensity Frontier facility* for beauty mesons, charm mesons and τ leptons.

Unique new physics capabilities and unique detector capabilities ("single B meson beam," neutrals, neutrinos), clean environment with good systematics, which are **critical for New Physics searches**: *charged Higgs, new weak couplings and phases, lepton flavor violation, …*

Photo credit: Ron Lipton, Fermilab

2014 US P5 report: This provides unique sensitivity to physics at energy scales far higher than can be accessed directly at colliders.

from Tom Browder's 2017 B2SS presentation

Belle II Physics: confluence.desy.de/display/BI/Physics+WebHome

Physics Coordinator: **@ Phillip Urquijo** ➠ Alessandro Gaz (on August 31)

Analysis Groups

Semileptonic & Missing Energy Decay	@ Florian Bernlochner , @ Racha Cheaib
Radiative & Electroweak Penguin	@ Saurabh Sandilya , @ Simon Wehle
Time Dependent CP Violation	@ Alessandro Gaz , @ Yusa Yosuke
Hadronic B to Charmless	@ Pablo Goldenzweig , @ Diego Tonelli
Hadronic B to Charm	@ James Frederick Libby , @ Trabelsi Karim

Bottomonium	@ Bryan Fulsom , @ Umberto Tamponi
Charmonium	@ Chengping Shen , @ Elisabetta Prencipe
Charm	@ Vishal Bhardwaj , @ Giulia Casarosa
Low Multiplicity & Dark Sector	@ Torben Ferber , @ Enrico Graziani
τ	@ Kenji Inami , @ Armine Rostomyan

Belle II Physics Analysis Groups and their mandates:

confluence.desy.de/display/BI/Physics+Working+Groups

Semileptonic and Missing Energy Decay WG	• Inclusive and Exclusive Semileptonic b→c, b→u transitions: $\vert V_{ub}\vert$, $\vert V_{cb}\vert$, New physics. • Semileptonic b→c and b→u transitions with τ leptons • Charged leptonic decays, B+ → e/ μ/ τ ν • Neutral leptonic decays, B0 → τ τ , B(s)0 → τ τ, • EWP with neutrinos, B→ K(*) ν νbar, B→ ν ν bar

Radiative and Electroweak Penguin WG	• Inclusive radiative decays: b→ s γ via inclusive, partial and full reconstruction tagging methods.
	• Inclusive radiative decays: b→ s γ and b→ d γ via sum of exclusive methods.
	• Exclusive radiative decays (polarisation and asymmetries):
	  ◦ b→ s: B→ K1 γ , K* γ
	  ◦ b→ d: B→ ρ γ , ω γ
	• Bd,Bs→ γ γ
	• Exclusive dilepton decays with a focus on electron modes at low q^2 : B→ K(*) e+ e-
	• Inclusive dilepton decays via sum of exclusive, and fully inclusive methods: B→ Xs l+ l-
	• LFV B→ll', K(*)ll'

Belle II Physics Analysis Groups and their mandates:

confluence.desy.de/display/BI/Physics+Working+Groups

Time Dependent CP Violation WG	• Φ2: B→ ρ ρ , ρ π , a1 π • Φ1: New phases in b→ s anti-q q transitions, B→ Φ Ks • Φ1 gluonic penguins: B→ η 'Ks, KsKsKs • Φ 1 EWP: TCPV in Radiative decays, e.g. B→ Ks π0 γ , ρ γ (overlap with above) • CPT violation
Hadronic B to Charmless Decay WG	• Two-body $B_{(s)}$ → h h(') decays • Full angular analyses and triple product asymmetries in $B_{(s)}$ → VV decays • Three-body decays with Dalitz methods • Baryonic B decays • Direct CP Violation • Tests of QCD factorisation; flavour symmetry breaking
Hadronic B to Charm Decay WG	• Direct CP Violation • Φ3 from time integrated methods, e.g. Dalitz • Φ3 from time dependent methods

Belle II Physics Analysis Groups and their mandates:

confluence.desy.de/display/BI/Physics+Working+Groups

Bottomonium WG	• Bottomonia Υ(nS), n=1,2,3,4,5,6 • b-Hadron production at 5S • Searches for dark matter and light Higgs in Υ transitions • Energy scan studies of bottomonia

Charmonium WG	• Charmonia, exotic, charmonium-like
	    • below the open-charm threshold
	    • above the open-charm threshold
	    • ISR
	• Charm Spectroscopy

Charm WG	• D0 mixing • TCPV in Charm • Direct CPV in Charm • Rare/Forbidden charm decays and NP: $D\to\gamma\gamma$, $D\to e\,e$ • Leptonic and Semileptonic charm decays • Charm production • Light meson production

Belle II Physics Analysis Groups and their mandates:

confluence.desy.de/display/BI/Physics+Working+Groups

Low Multiplicity and Dark Sectors WG	• Dark sector searches in low multiplicity events
	  • Dark Photons
	  • ALPs
	  • iDM/SIMPs
	  • Magnetic Monopoles
	  • LLPs
	• Precision low multiplicity measurements
	• Fragmentation

Tau WG	• Lepton flavour violating τ decays
	  • Radiative τ → l γ
	  • Leptonic τ→ l l l
	  • Lepton plus pseudo-scalar, τ → l P0
	  • Lepton plus vector, τ → l V0
	  • Lepton plus 2-hadrons, τ → l h h'
	  • Lepton plus 3-hadrons, τ → l h
	• T properties and SM decays
	• τ Lepton universality
	• τ CP Violation

New Physics in B Decays

B Physics Analysis Groups

Semileptonic & Missing Energy Decay	@ Florian Bernlochner , @ Racha Cheaib
Radiative & Electroweak Penguin	@ Saurabh Sandilya , @ Simon Wehle
Time Dependent CP Violation	@ Alessandro Gaz , @ Yusa Yosuke
Hadronic B to Charmless	@ Pablo Goldenzweig , @ Diego Tonelli
Hadronic B to Charm	@ James Frederick Libby , @ Trabelsi Karim

New Physics strategy: look for deviations from Standard-Model expectations in precision measurements

Measuring the CKM-matrix unitarity-triangle angles

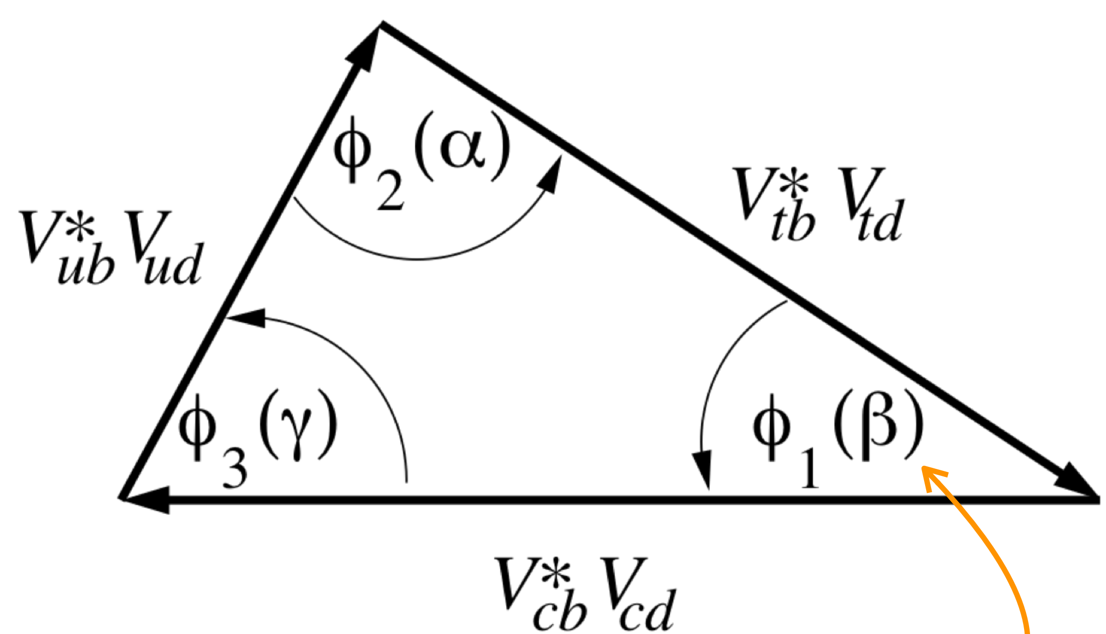
Unitarity:

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

Belle/BaBar
** = recent update*

LHCb
** = 3 fb^{-1} result*

* $B \to \pi^+\pi^- / \pi^+\pi^0 / \pi^0\pi^0$
** $B \to \rho^+\rho^- / \rho^+\rho^0 / \rho^0\rho^0$
$B^0 \to \rho\,\pi$
$B^0 \to a_1(\rho\pi)^+\,\pi^-$



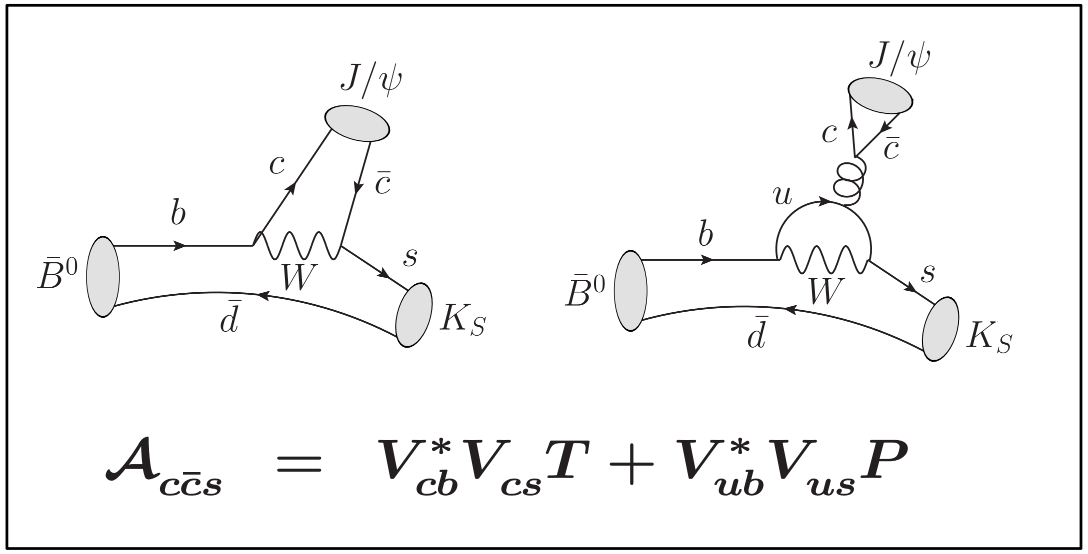
$B^- \to D^{(*)}{}_{CP}\, K^{(*)-}$
** $B^0 \to D_{CP}\, K^{*0}$
$B^- \to D^{(*)}(K^+\pi^-)\, K^{(*)-}$
$B^- \to D^{(*)0}\,\pi^-$
* $B^- \to D^{(*)}(K_S\,\pi^+\pi^-)\, K^{(*)-}$
$B^- \to D(\pi^0\pi^+\pi^-)\, K^-$
* $B^- \to D(K_S\, K^+\pi)\, K^-$

* $B^0 \to J/\psi\, K_S$
$B^0 \to J/\psi\, K_L$
$B^0 \to \psi'\, K_S$
$B^0 \to \chi_c\, K_S$
$B^0 \to \eta_c\, K_S$
$B^0 \to D^{(*)}{}_{CP}\, h^0$
* $B^0 \to (\phi/\eta'/\pi^0/f^0)K^0$
* $B^0 \to (K_S K_S/\rho^0/\omega)K_S$

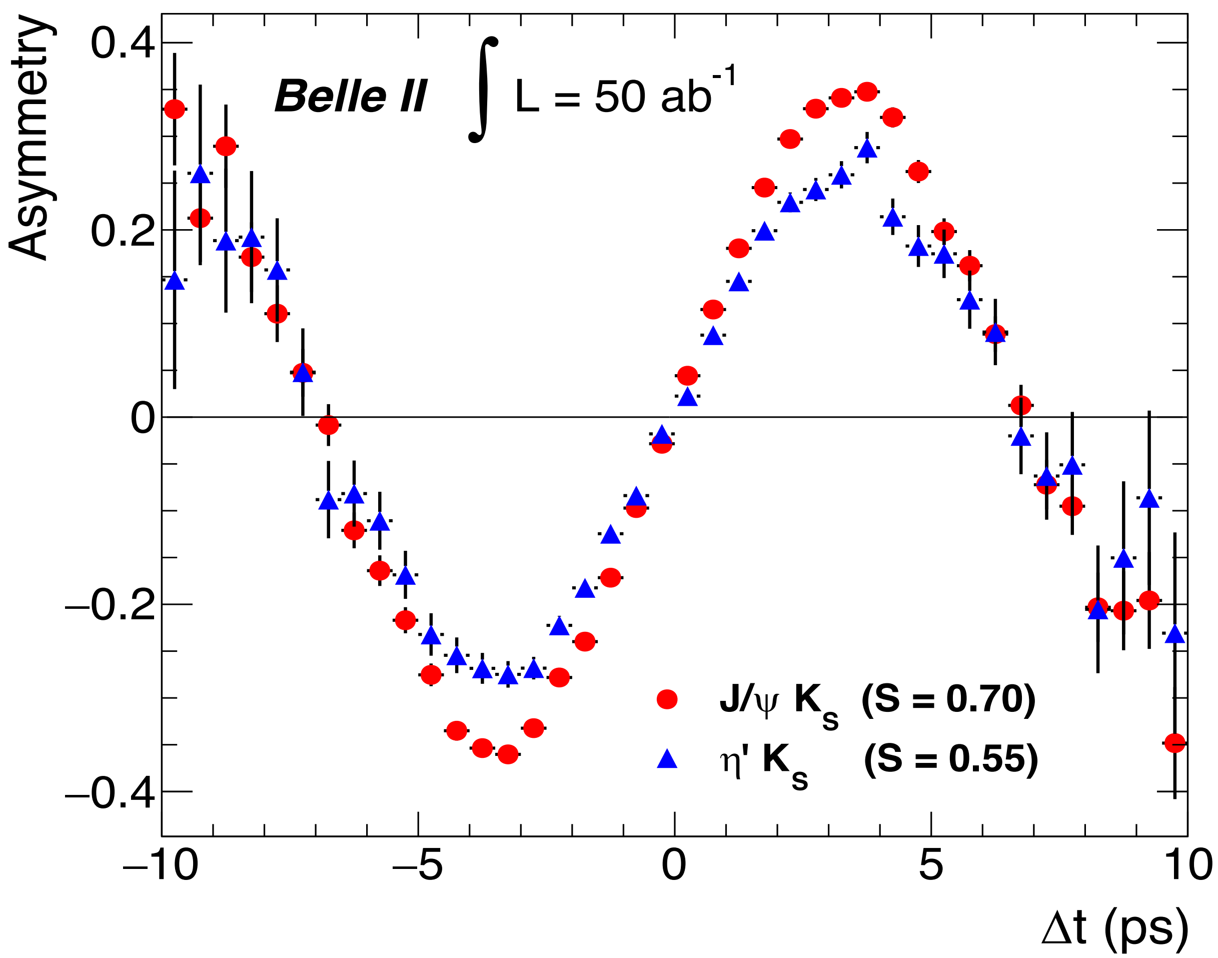
$$\mathcal{S}_f = \pm\sin(2\phi_1) = \pm\sin(2\beta)$$

Measuring the CKM-matrix angle ϕ_1 $[\beta]$

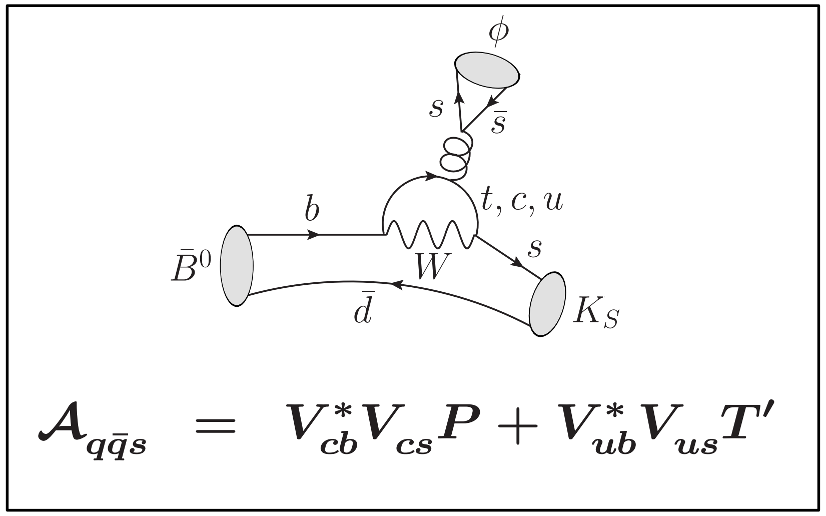
$B^0 \to J/\psi K_S$ (the "Golden" mode):



expected 50 ab^{-1} uncertainty: $\delta\phi_1$ = 0.4^o
(cf: current theory error is 1-2^o)



$B^0 \to \phi K_S, \eta' K_S, \omega K_S, \pi^0 K_S$ ("penguin" modes):



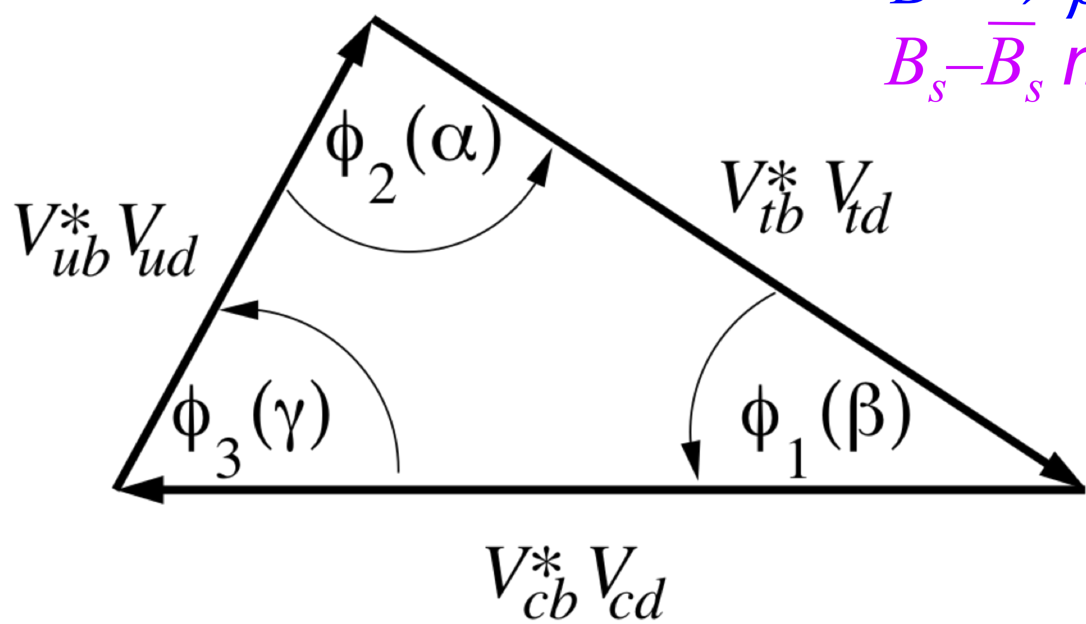
$$A_{CP} \;=\; A\cos(\Delta M \Delta t) + S\sin(\Delta M \Delta t)$$

	WA (2017)		5 ab^{-1}		50 ab^{-1}	
Channel	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$
$J/\psi K^0$	0.022	0.021	0.012	0.011	0.0052	0.0090
ϕK^0	0.12	0.14	0.048	0.035	0.020	0.011
$\eta' K^0$	0.06	0.04	0.032	0.020	0.015	0.008
ωK_S^0	0.21	0.14	0.08	0.06	0.024	0.020
$K_S^0 \pi^0 \gamma$	0.20	0.12	0.10	0.07	0.031	0.021
$K_S^0 \pi^0$	0.17	0.10	0.09	0.06	0.028	0.018

Measuring the CKM-matrix unitarity-triangle sides

$B^0 \to \rho^0 \gamma$
B_s–$\overline{B}_s$ *mixing*

$B^0 \to \pi \ell^+ \nu$
$B^0 \to X_u \ell \nu$
$B^+ \to \tau^+ \nu$
$\Lambda_b \to p \ell^+ \nu$



Belle
LHCb

$B^0 \to D^{(*)} \ell \nu$
$B^0 \to X_c \ell \nu$ *(ℓ energy, hadron mass moments)*
$B^0 \to X_s \gamma$ *(γ energy moments)*

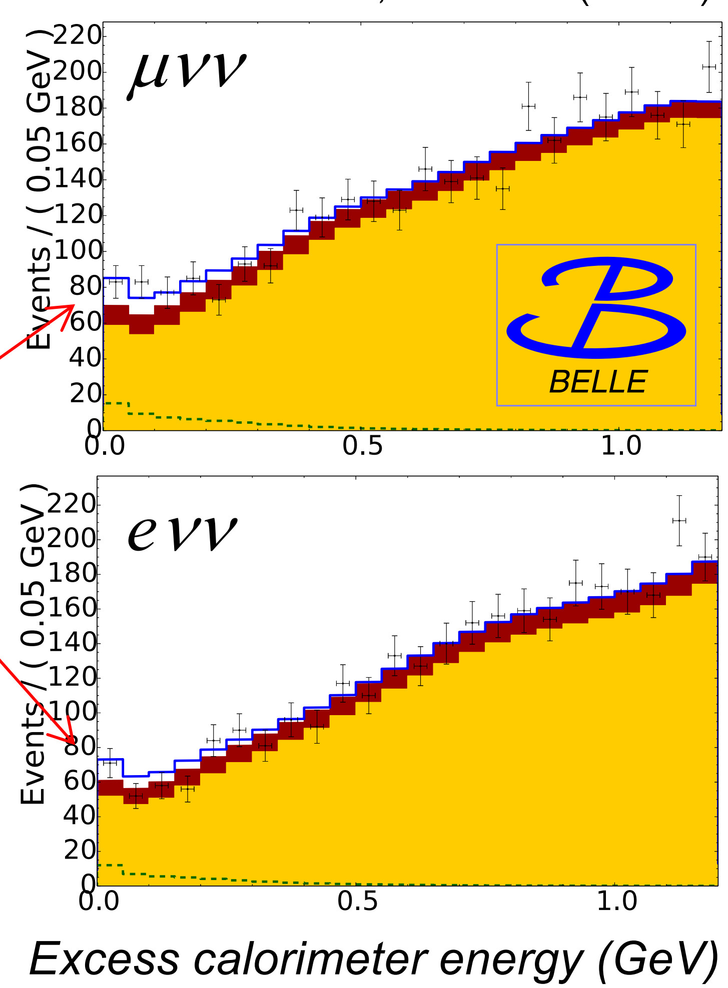
Measuring $|V_{ub}|$ via $B^+ \to \tau^+ \nu_\tau$

a missing-energy mode

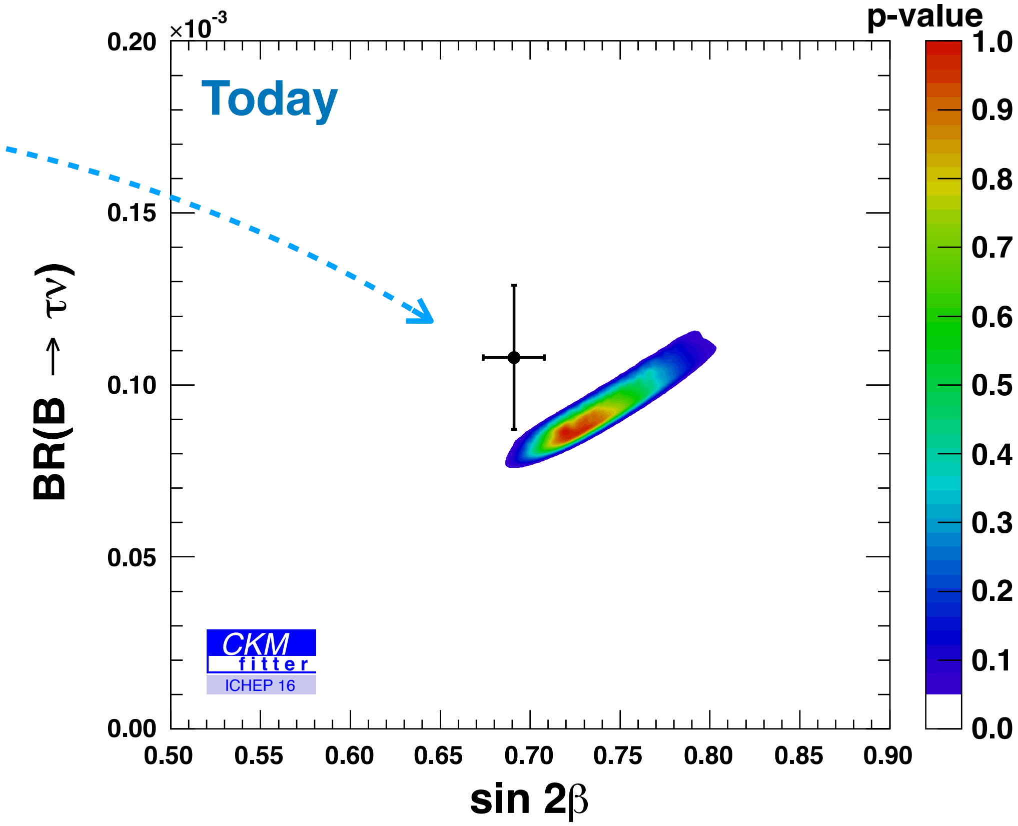
There is some **tension** at the CKM triangle apex from this measurement vs sin2ϕ_1

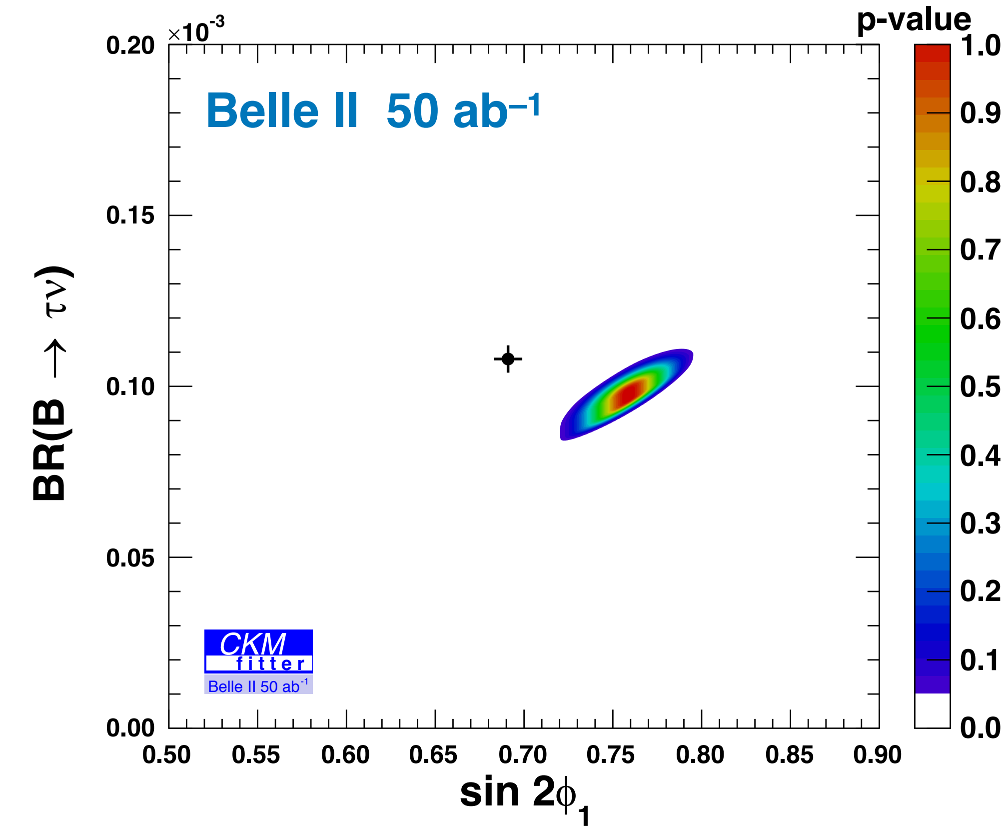
Leveraging fully-reconstructed tag B, there should be **zero excess energy** in the calorimeter.

PRD **92**, 051102 (2015)

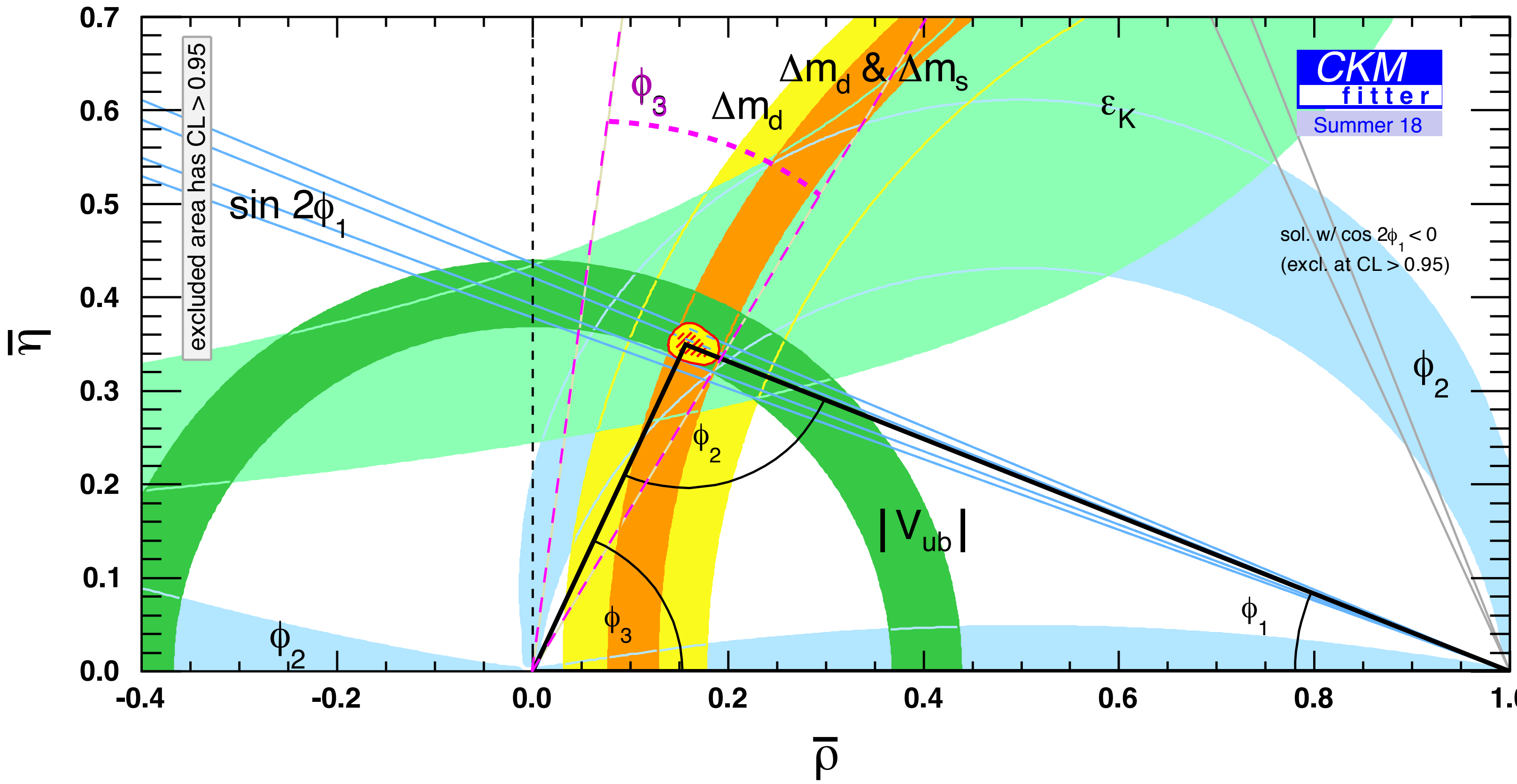


222 ± 50
(all channels)
3.8σ





Precise measurements of CKM unitarity triangle



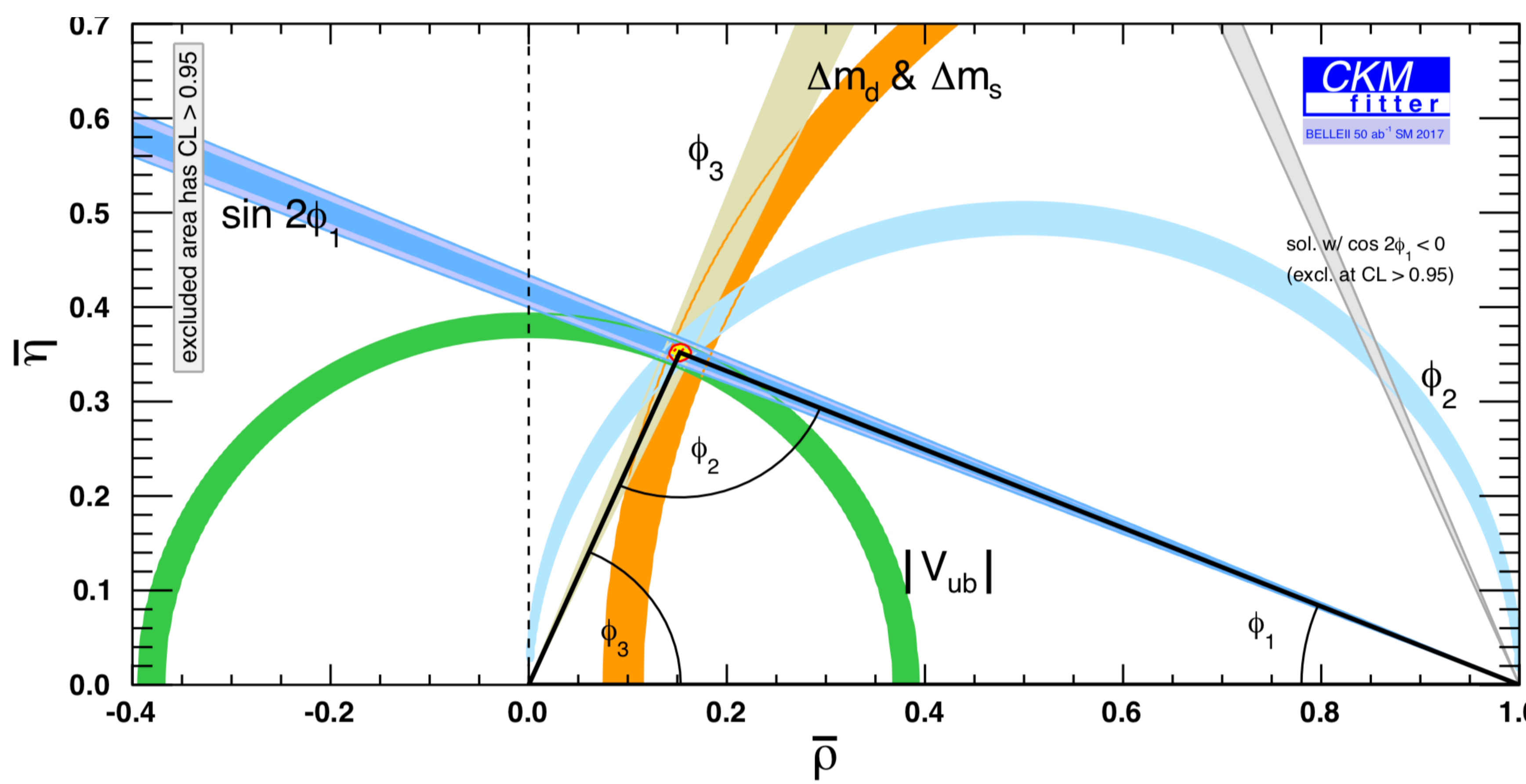
Unitarity triangle from CKM matrix elements (cols 1 & 3):

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

Now

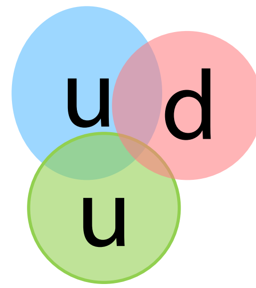
ϕ_1	$\leftrightarrow$	β
ϕ_2	$\leftrightarrow$	α
ϕ_3	$\leftrightarrow$	γ

with 50 ab^{-1}

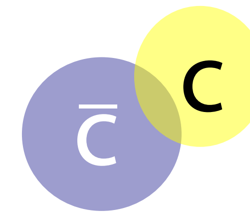


Selected New Physics Topics

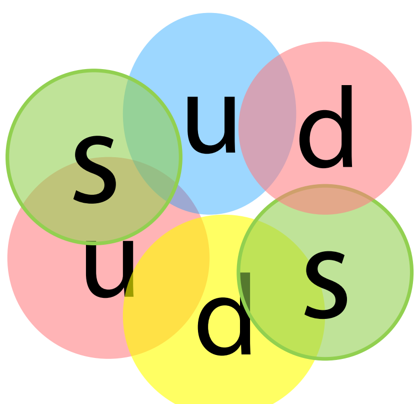
QCD allows many color singlets: baryons, mesons, **exotics**.



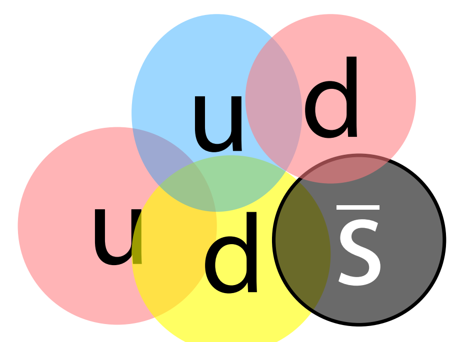
baryon



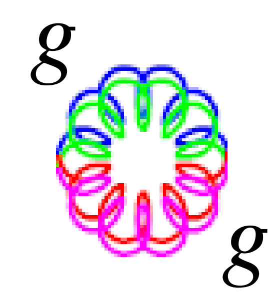
meson



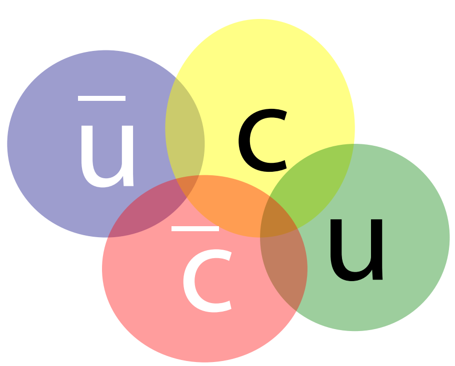
dibaryon



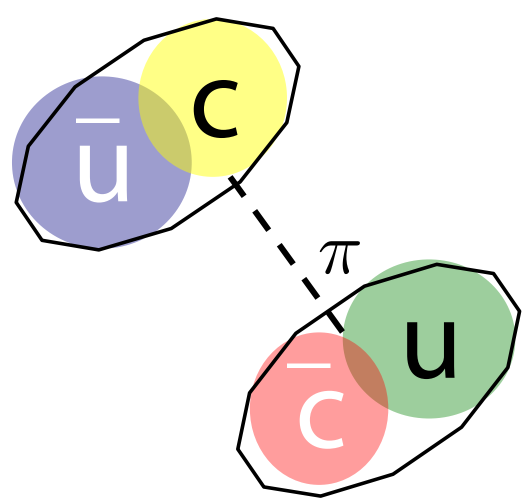
pentaquark



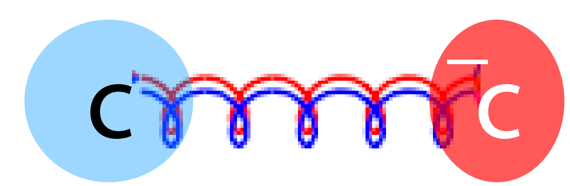
glueball



diquark + di-antiquark



dimeson molecule



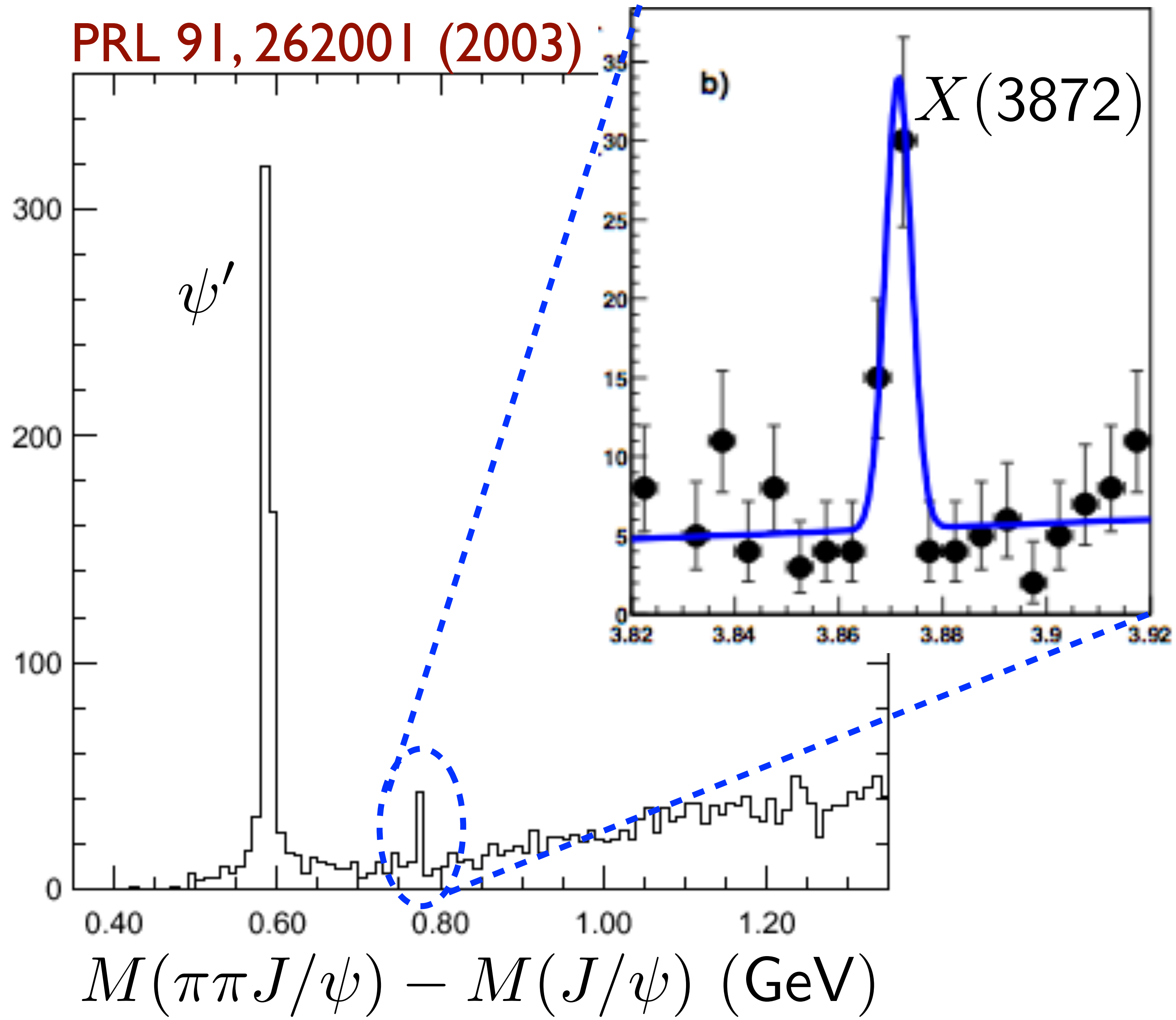
$q\,\bar{q}\,g$ hybrid

Charmonium-like exotica ...

2003: the X(3872) is found in $B \to K\,(J/\psi\pi^+\pi^-)$ by Belle; confirmed by CDF, DØ, BaBar, LHCb, CMS

Steve Olsen snags a big one!

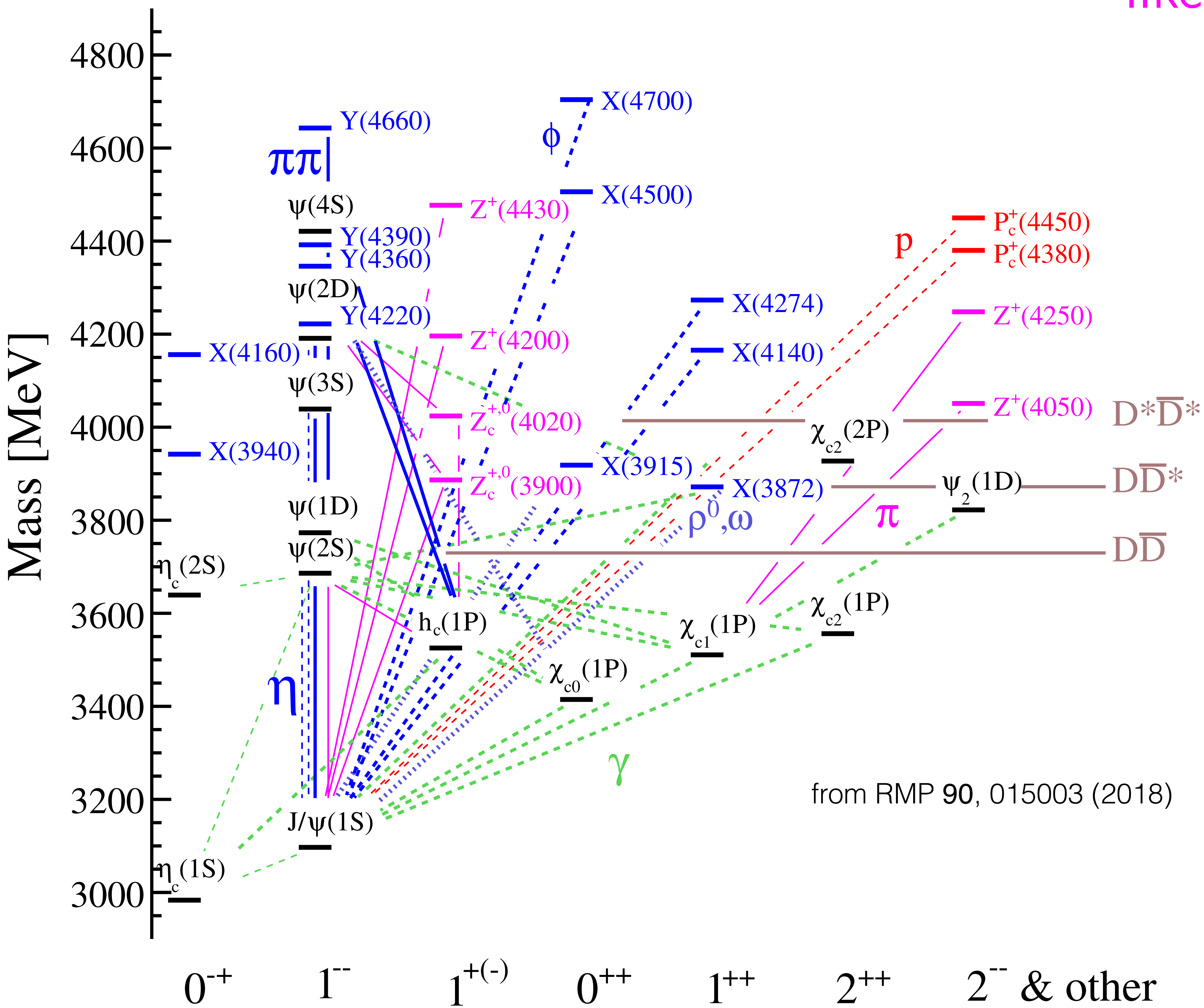
PRL 91, 262001 (2003)



This is Belle's most famous paper: 1640 citations.

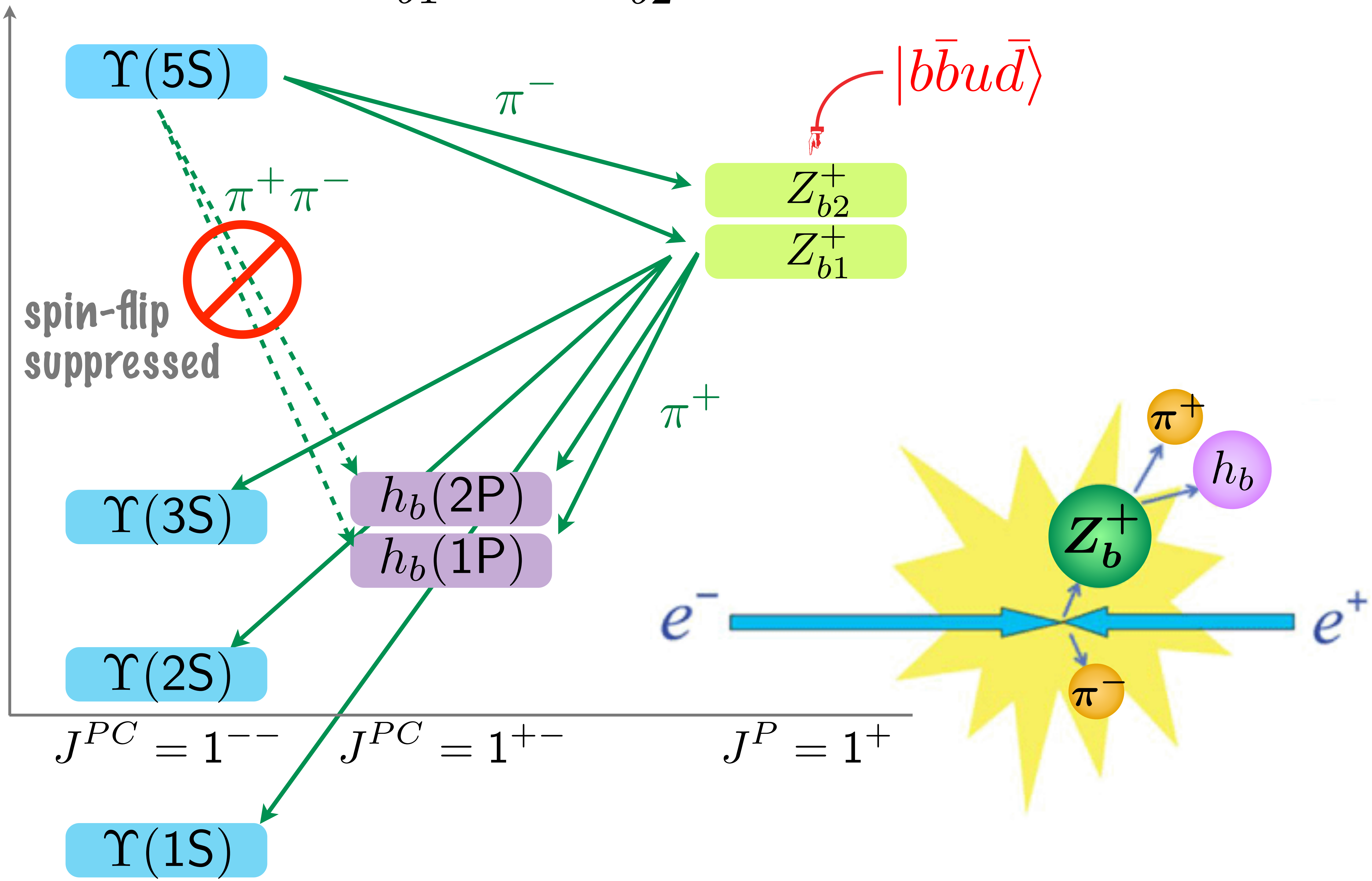
Charmonium(-bearing) states including exotica

like $|c\bar{c}u\bar{d}\rangle$



from RMP **90**, 015003 (2018)

$\Upsilon(5S) \to h_b(nP)\pi^+\pi^-$ and $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ proceed via Z_{b1}^+ and Z_{b2}^+



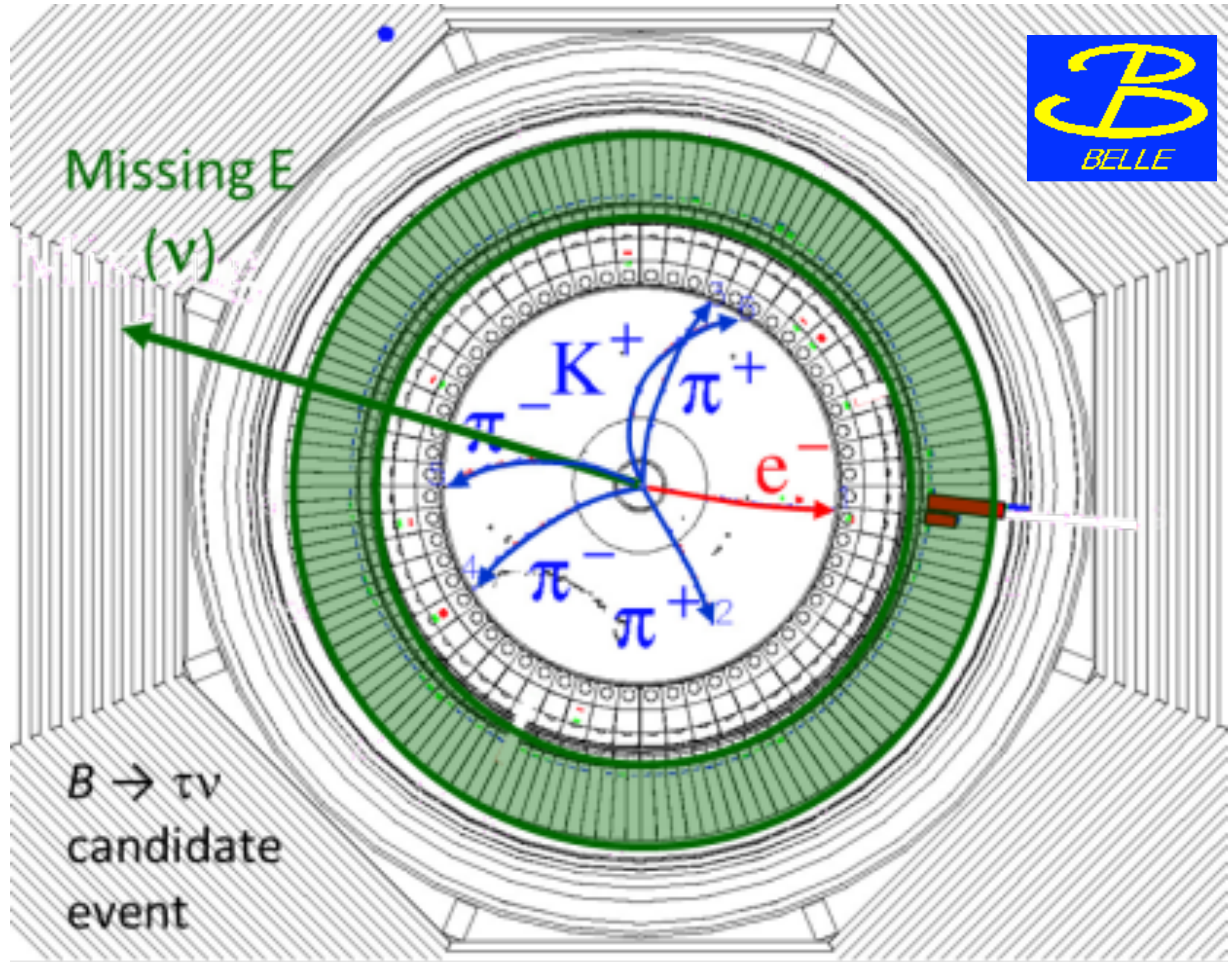
Belle II prospects for **New Physics**

in (semi-)leptonic B decays

	Process	Observable	Theory	Sys. limit (Discovery) [ab^{-1}]	vs LHCb	vs Belle	Anomaly	NP
●	$B \to \pi \ell \nu_l$	$\lvert V_{ub} \rvert$	⋆⋆⋆	10-20	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆
●	$B \to X_u \ell \nu_\ell$	$\lvert V_{ub} \rvert$	⋆⋆	2-10	⋆⋆⋆	⋆⋆	⋆⋆⋆	⋆
●	$B \to \tau \nu$	$Br.$	⋆⋆⋆	>50 (2)	⋆⋆⋆	⋆⋆⋆	⋆	⋆⋆⋆
●	$B \to \mu \nu$	$Br.$	⋆⋆⋆	>50 (5)	⋆⋆⋆	⋆⋆⋆	⋆	⋆⋆⋆
●	$B \to D^{(*)} \ell \nu_\ell$	$\lvert V_{cb} \rvert$	⋆⋆⋆	1-10	⋆⋆⋆	⋆⋆	⋆⋆	⋆
●	$B \to X_c \ell \nu_\ell$	$\lvert V_{cb} \rvert$	⋆⋆⋆	1-5	⋆⋆⋆	⋆⋆	⋆⋆	⋆⋆
●	$B \to D^{(*)} \tau \nu_\tau$	$R(D^{(*)})$	⋆⋆⋆	5-10	⋆⋆	⋆⋆⋆	⋆⋆⋆	⋆⋆⋆
●	$B \to D^{(*)} \tau \nu_\tau$	P_τ	⋆⋆⋆	15-20	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆⋆⋆
●	$B \to D^{**} \ell \nu_\ell$	$Br.$	⋆	-	⋆⋆	⋆⋆⋆	⋆⋆	-

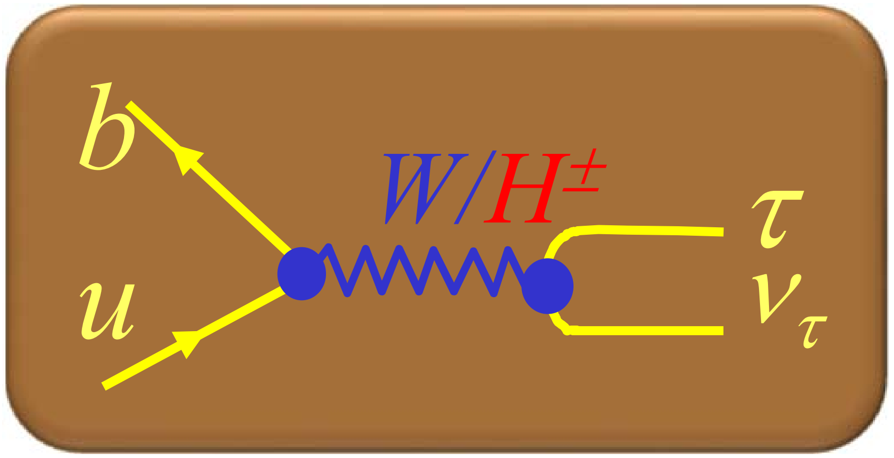
Example of a $B^+ \to \tau^+\nu$ decay *in Belle data*

$$B^+ \to D^0\pi^+ \; (\to K\pi^-\pi^+\pi^-)$$
$$B^- \to \tau(\to e\nu\bar{\nu})\nu$$



Clean e+e− environment and kinematic constraints *(known initial 4-momentum, hadronic tag decay)* make this possible

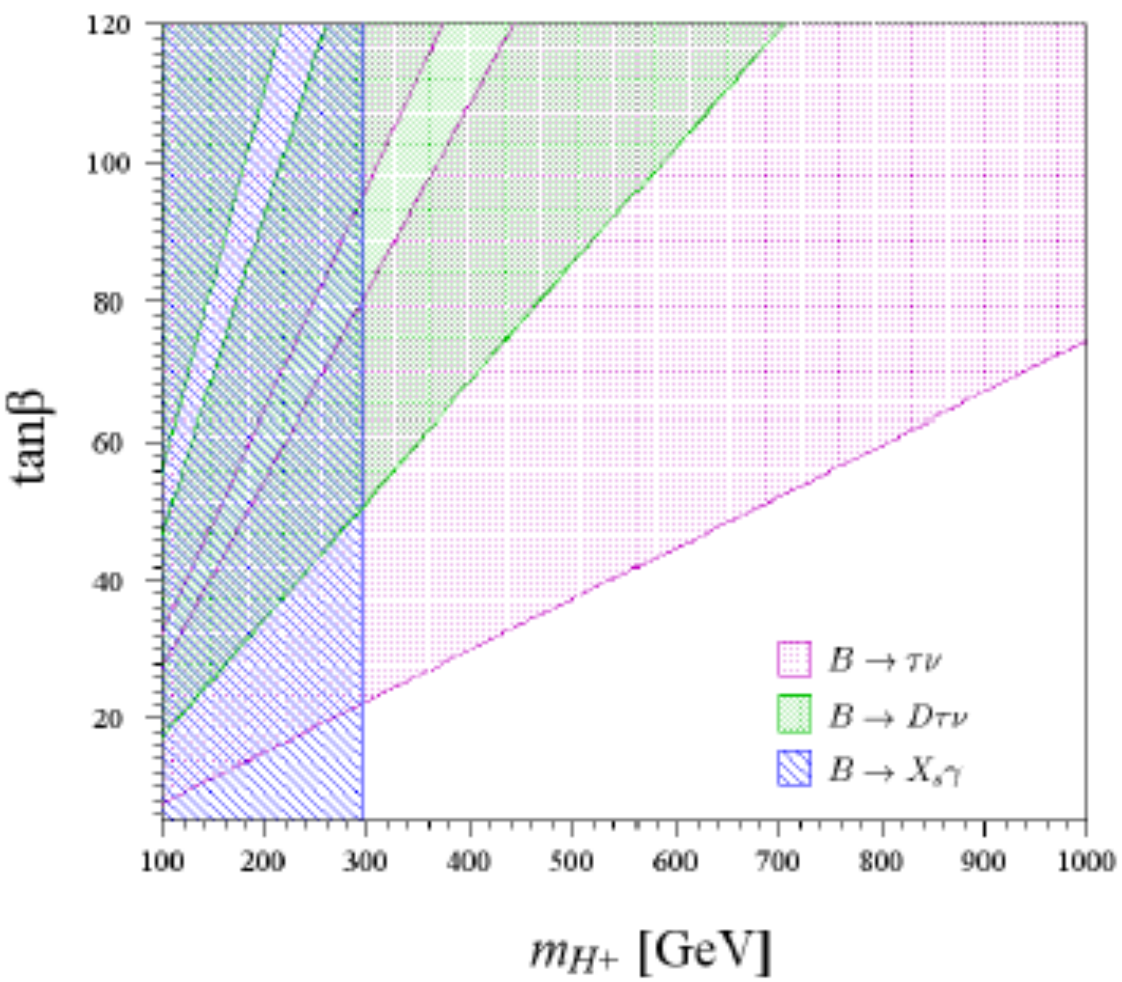
Search for NP (e.g., charged Higgs) in $B^+ \to \tau^+ \nu_\tau$

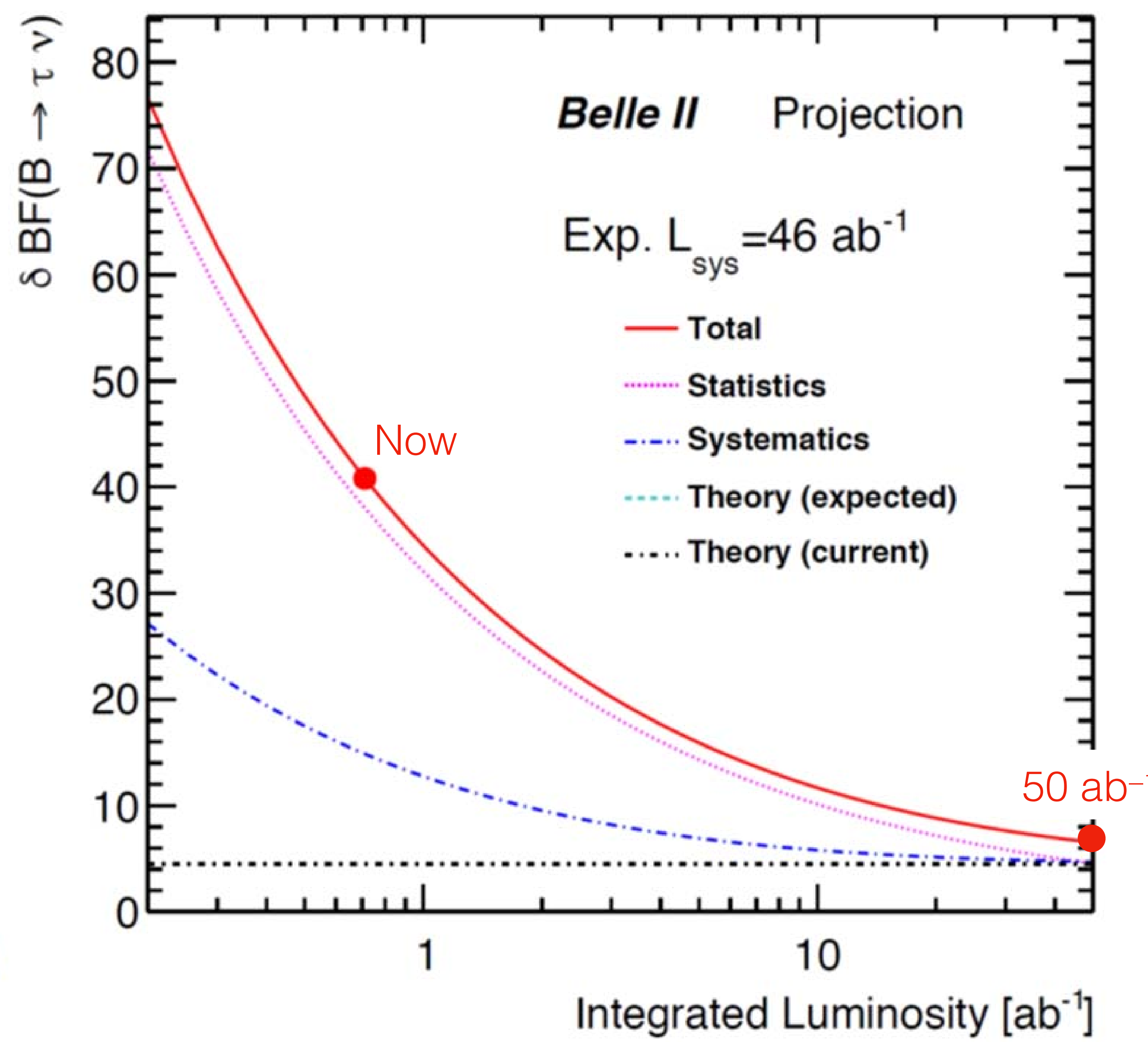


For example, in MSSM 2HDM Type II,

$$r = \frac{\mathcal{B}_{\text{meas}}(B \to \tau\nu)}{\mathcal{B}_{\text{SM}}(B \to \tau\nu)} = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$

B Factory exclusion plot (white=allowed)



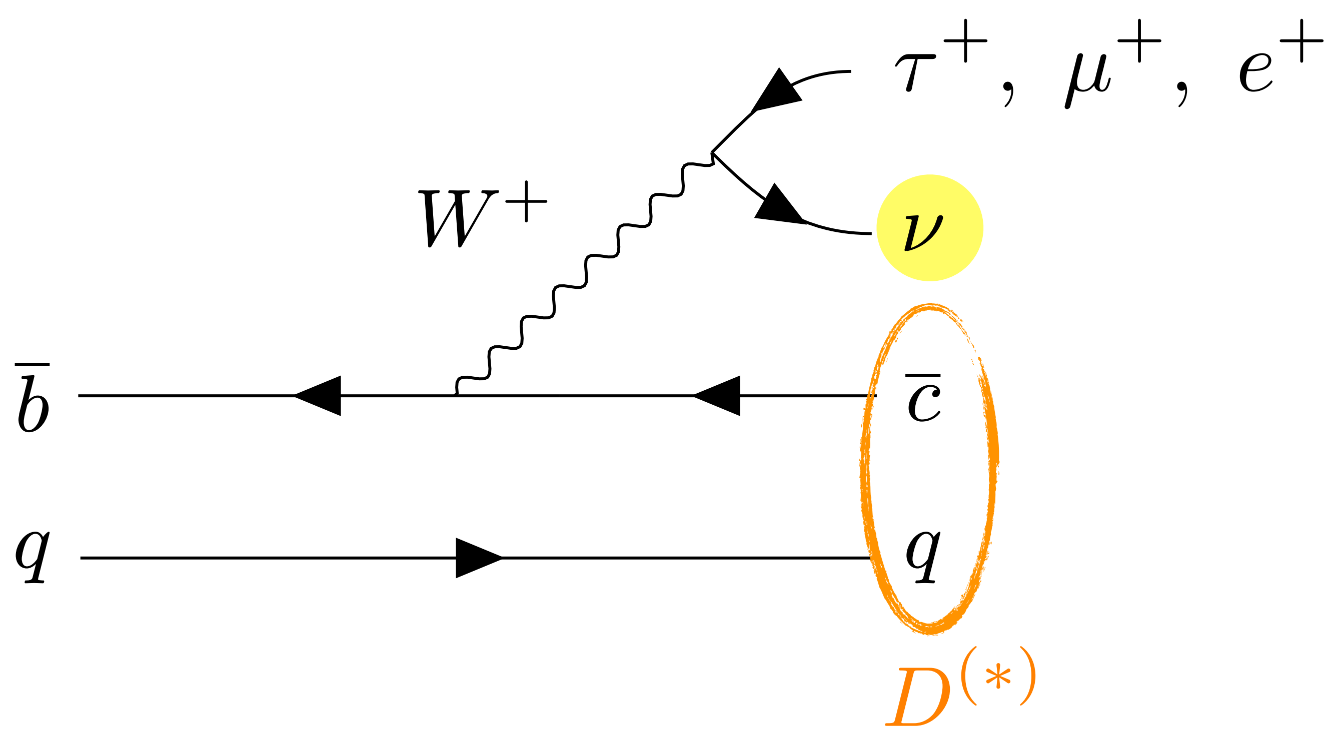


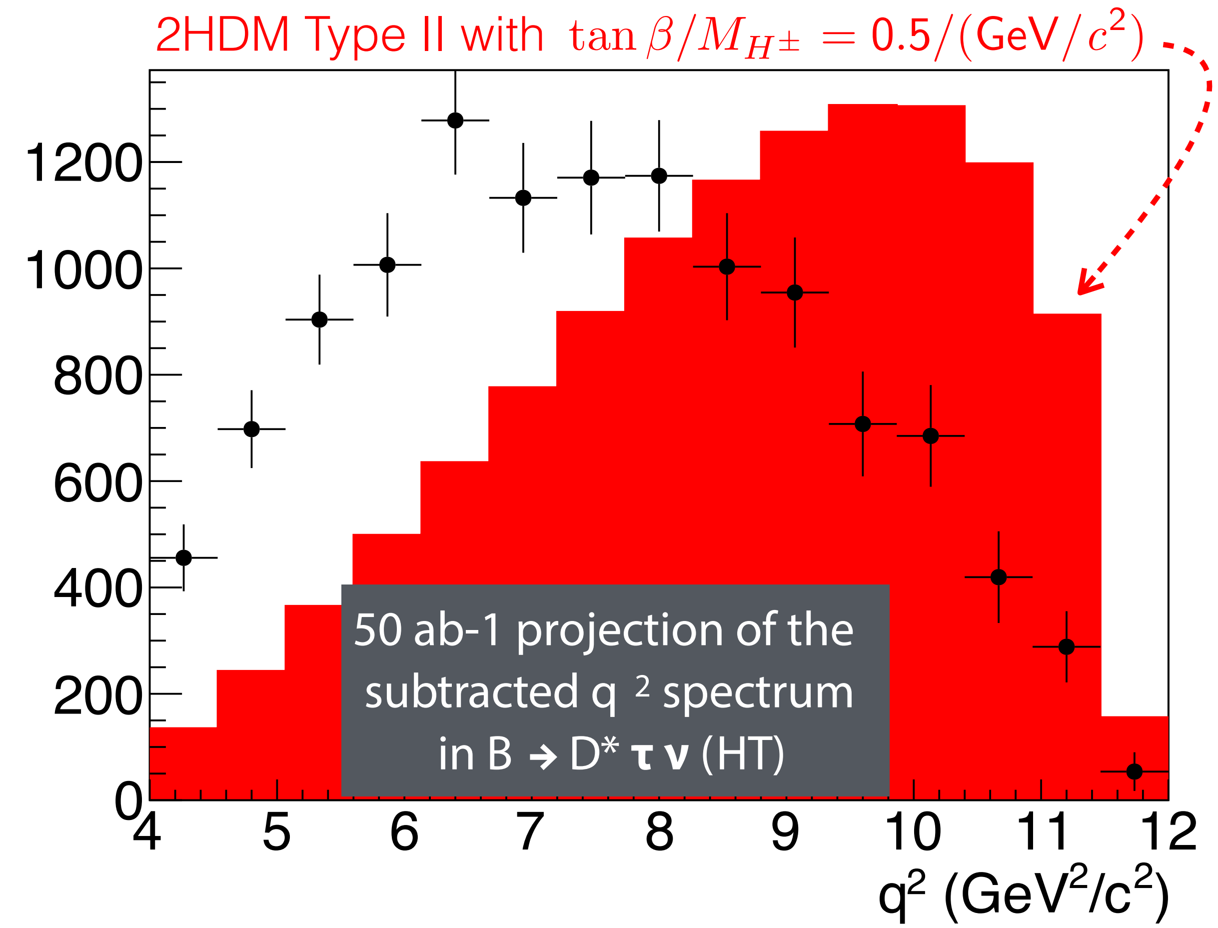
Is there new physics in $B \to D^{(*)}\ell\nu$?

missing-energy mode: multiple neutrinos in final state

Tagged analysis:

- ★ full or partial reconstruction
- ★ measure q^2 distribution, angular distribution, τ polarization, …

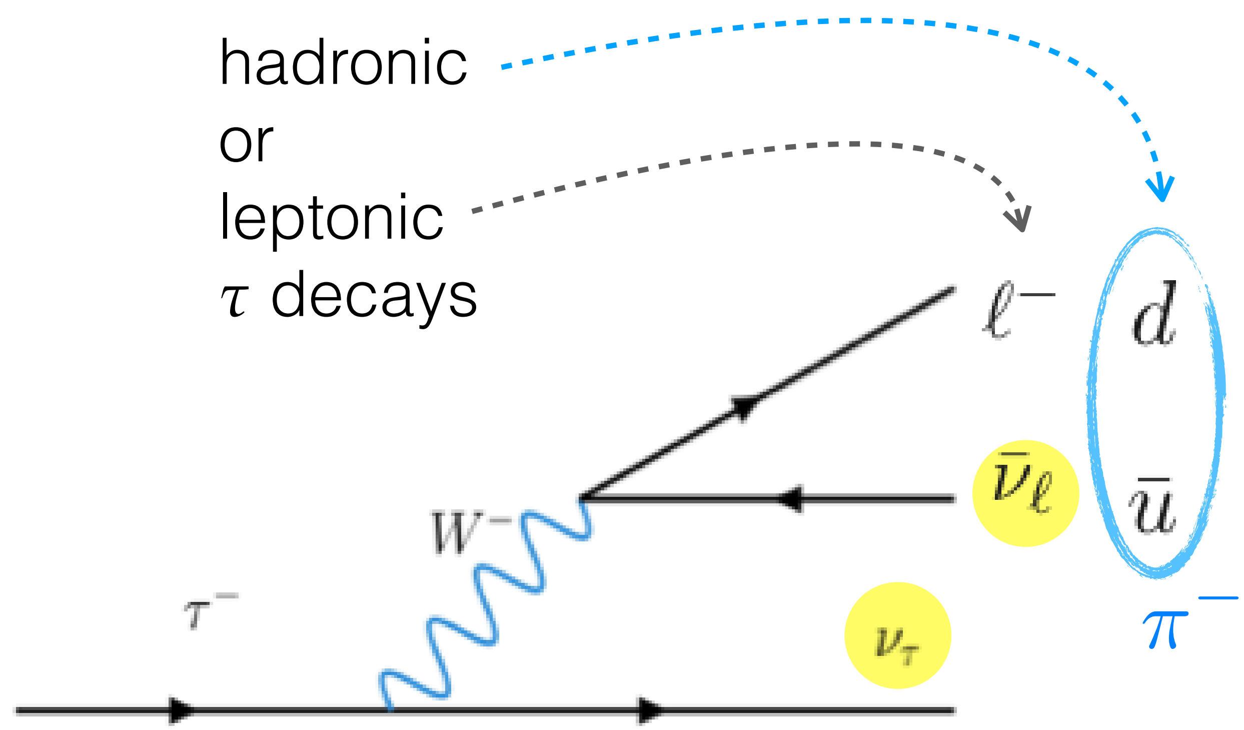




Standard Model:

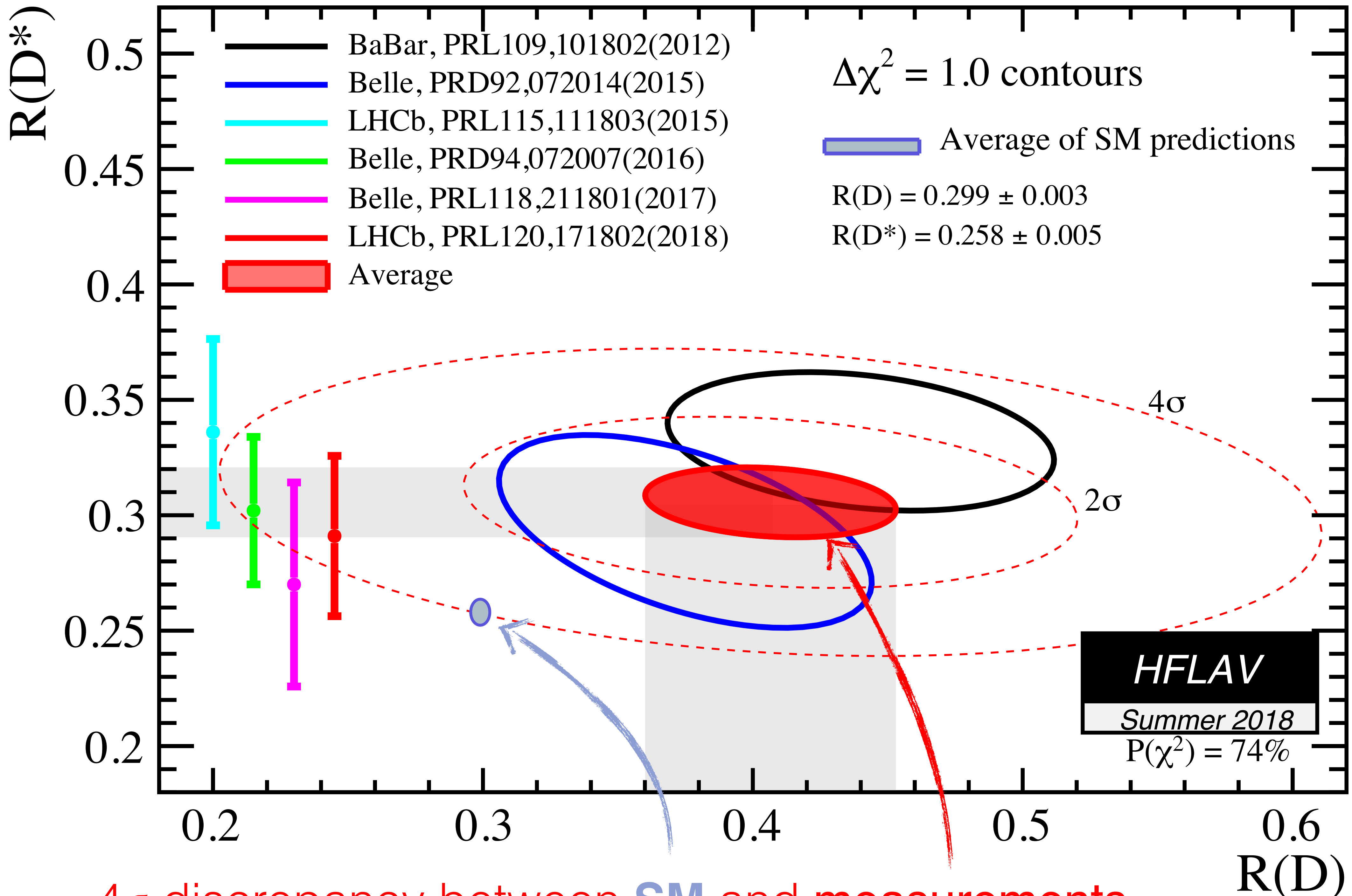
- ✓ lepton universality
- ✓ hadronic uncertainties ≈cancel (manageable)

hadronic or leptonic τ decays



Is there new physics in $B \to D^{(*)}\ell\nu$?

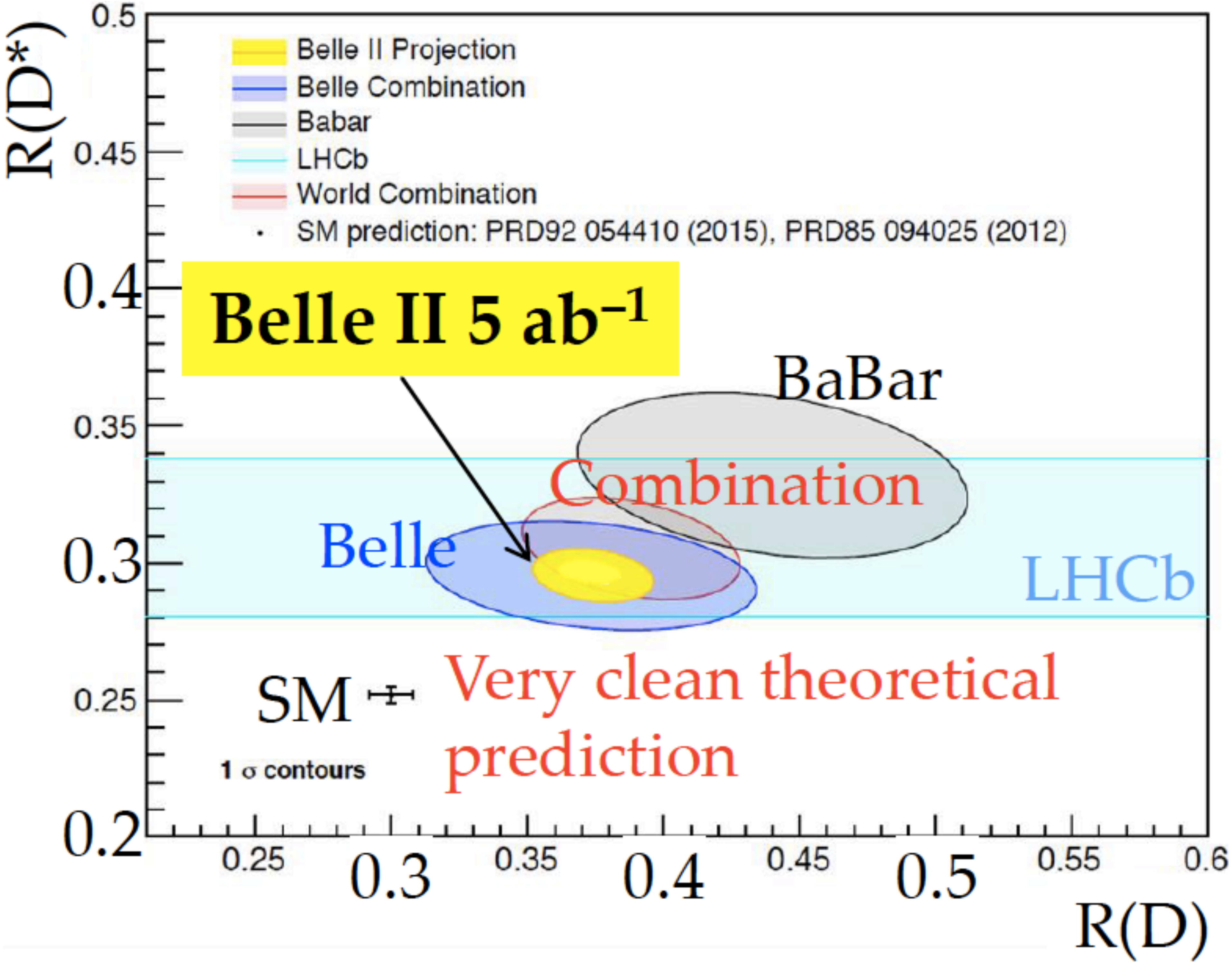
$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}\left(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau\right)}{\mathcal{B}\left(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell\right)}$$



4σ discrepancy between **SM** and **measurements**

Is there new physics in $B \to D^{(*)}\ell\nu$?

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

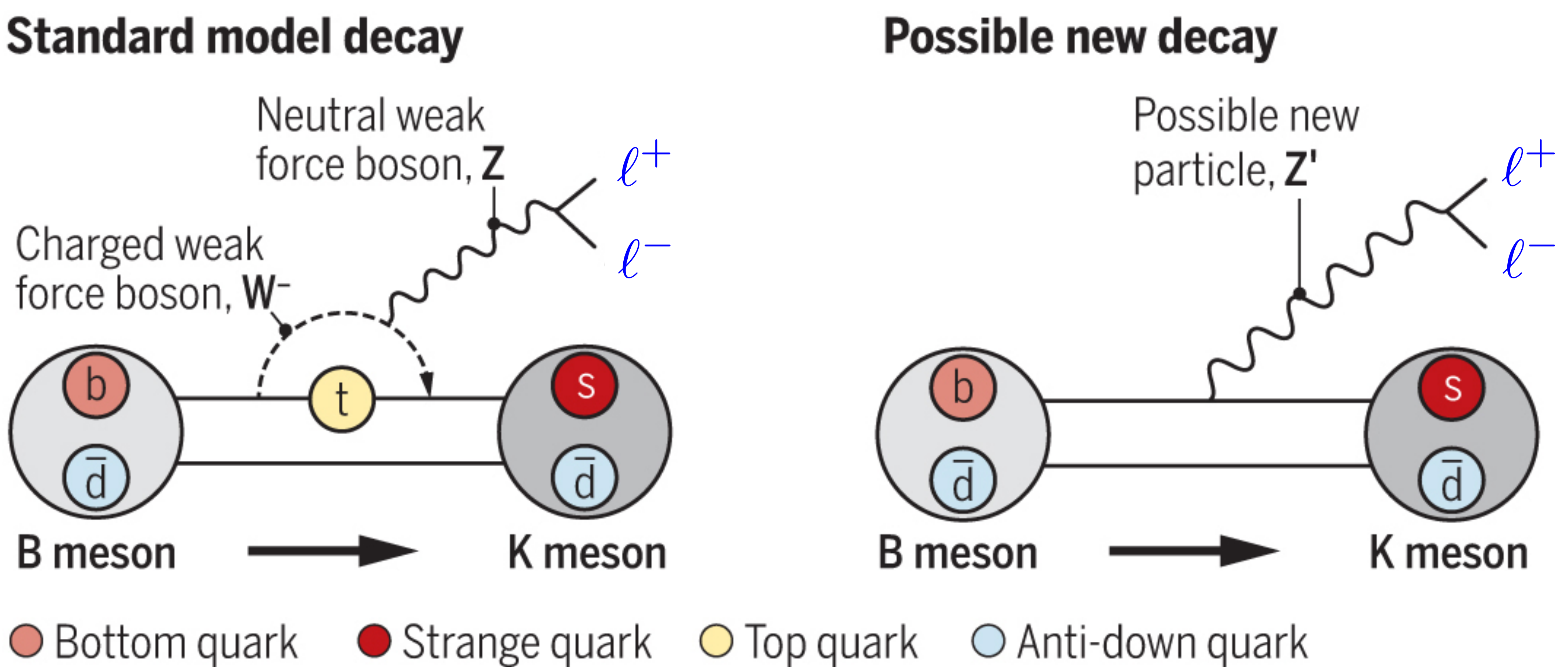


Belle II **New-Physics** potential in $b \to s$ transitions

Observables	Experimental Sensitivity	Multi-Higgs Models (§17.2)	generic SUSY	MFV (§17.3)	Z' models (§17.6.1)	gauged flavour (§17.6.2)	3-3-1 (§17.6.3)	left-right (§17.6.4)	leptoquarks (§18.2.1)	compositeness (§17.7)	dark sector (§16.1)	Sum
$B \to K^{(*)}\ell\ell$ angular	⋆⋆	×	×	⋆⋆	⋆⋆	×	⋆⋆	×	⋆⋆⋆	⋆⋆	×	13
$R(K^*)$, $R(K)$	⋆⋆	×	×	×	⋆⋆	×	⋆⋆	×	⋆⋆⋆	⋆⋆	×	11
$\mathcal{B}(B \to X_s\ell\ell)$	⋆⋆⋆	×	×	⋆⋆⋆	⋆⋆	×	⋆⋆	×	⋆⋆⋆	⋆⋆	×	15
$R(X_s)$	⋆⋆⋆	×	×	×	⋆⋆	×	⋆⋆	×	⋆⋆⋆	⋆⋆	×	12
$\mathcal{B}(B \to K^{(*)}\tau\tau)$	⋆⋆⋆	⋆⋆⋆	×	⋆	⋆	×	⋆	×	⋆⋆⋆	⋆	×	13
$\mathcal{B}(B \to X_s\tau\tau)$	□	⋆⋆⋆	×	⋆	⋆	×	⋆	×	⋆⋆⋆	⋆	×	10
$\mathcal{B}(B \to K^{(*)}\nu\nu)$	⋆⋆⋆	×	×	⋆	⋆	×	⋆	×	⋆⋆⋆	⋆	×	10
$\mathcal{B}(B \to X_s\nu\nu)$	□	×	×	⋆	⋆	×	⋆	×	⋆⋆⋆	⋆	×	7

⋆⋆⋆ Belle II
⋆⋆ Belle II + LHCb
⋆ LHCb
× unlikely
□ not studied

New-physics sensitivity in $b \to s\ell^+\ell^-$

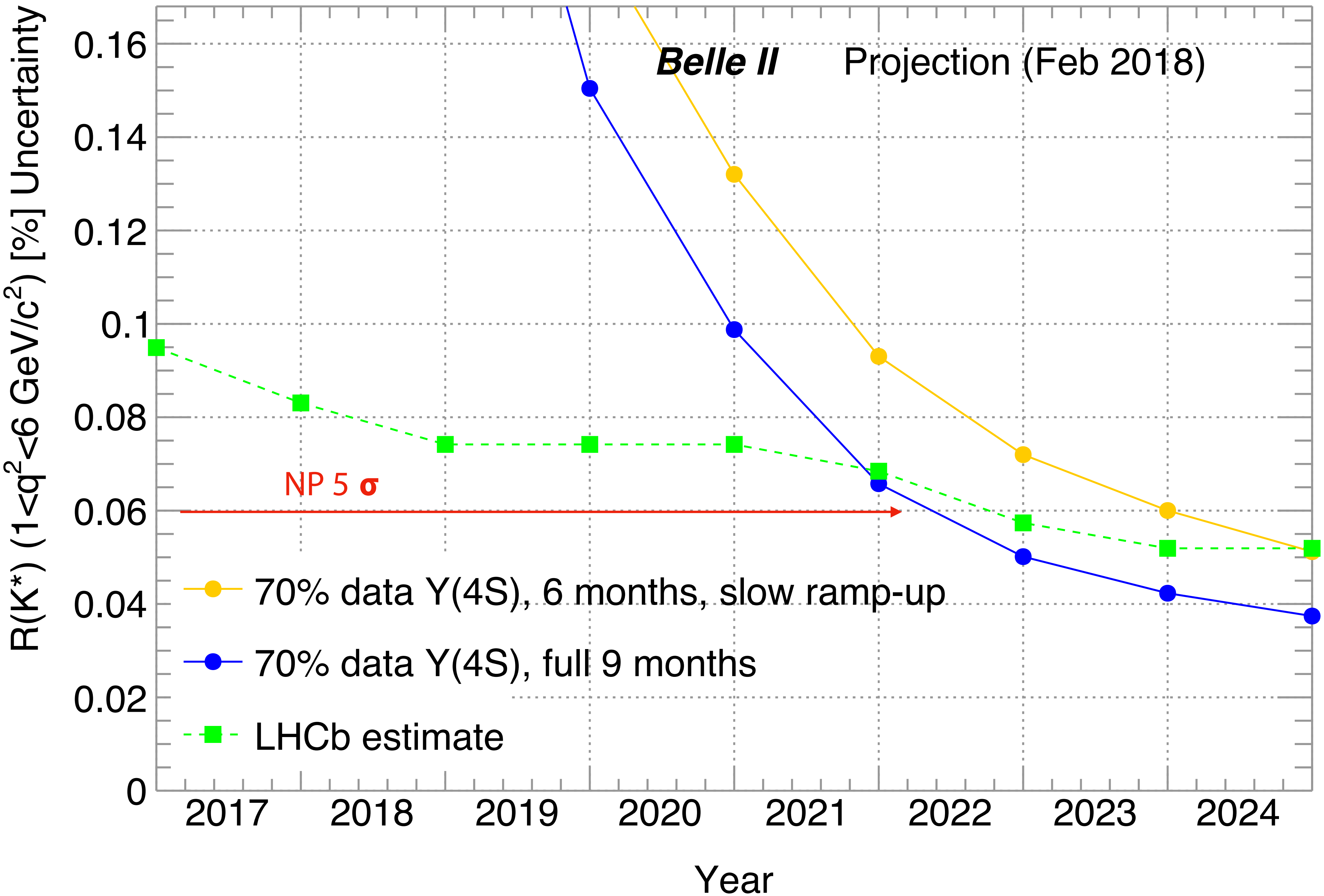


Lepton-universality test: $\ell \in \{e,\ \mu\}$

Belle II has strong capabilities for electrons **and** muons.

New-physics sensitivity in $b \to s\ell^+\ell^-$

$$\mathcal{R}(K^{(*)}) = \frac{\mathcal{B}\left(B \to K^{(*)}\mu\mu\right)}{\mathcal{B}\left(B \to K^{(*)}ee\right)}$$

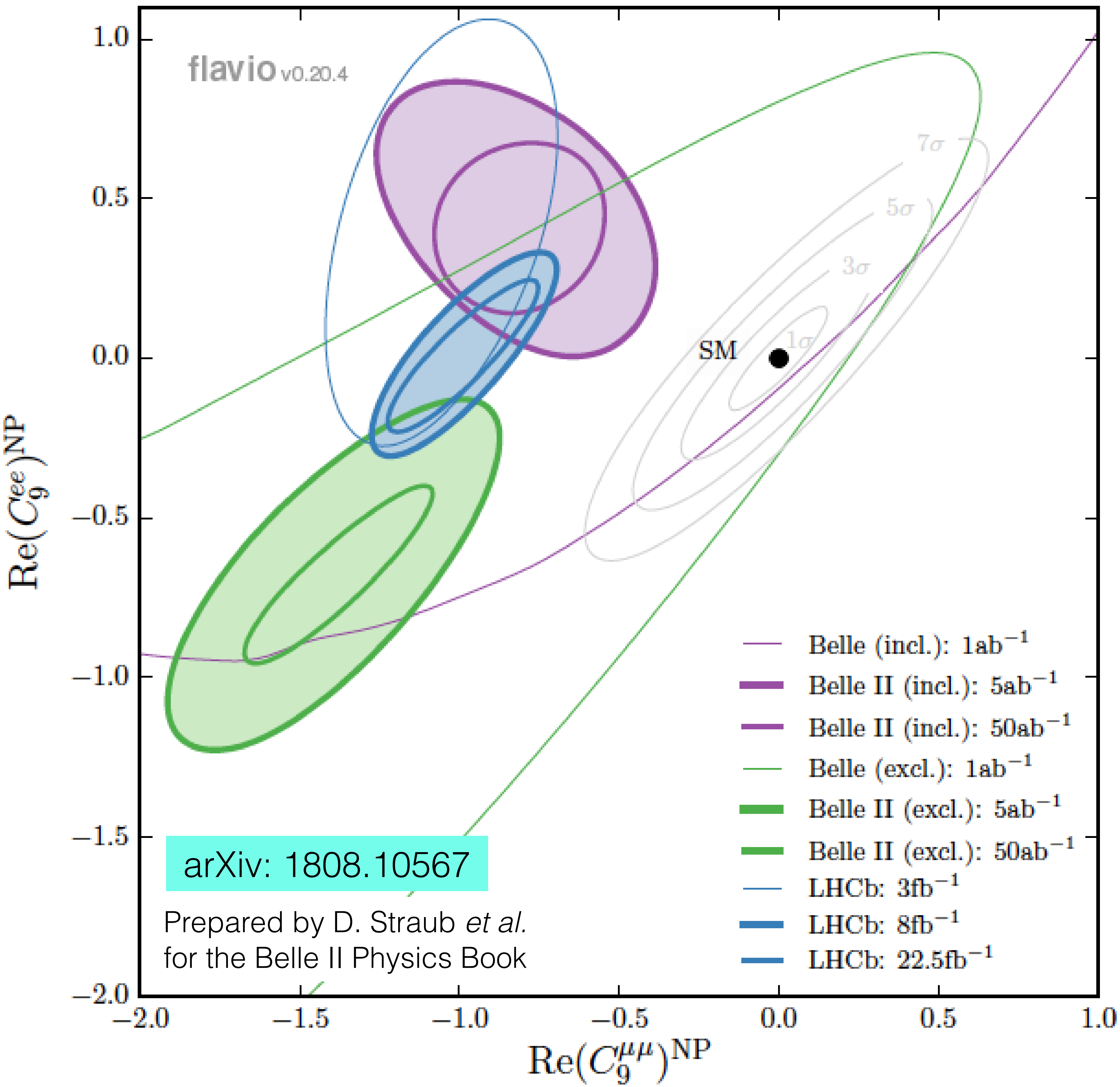


The effective Hamiltonian leading contribution for the $b \to s$ transition is

$$H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i \, \mathcal{O}_i$$

- ✓ G_F is the Fermi constant
- ✓ V_{ij} are quark mixing matrix (CKM) elements
- ✓ C_i are the Wilson coefficients and $\mathcal{O}_i$ the corresponding effective operators
  - ◉ $i = 1, 2$ tree
  - ◉ $i = 3\text{–}6, 8$ gluon penguin
  - ◉ $i = 7$ photon penguin
  - ◉ $i = 9, 10$ electroweak penguin
  - ◉ $i = S, P$ scalar or pseudoscalar penguin
- ✓ $B \to X_s\gamma$ is sensitive to C_7
- ✓ $B \to X_s\ell^+\ell^-$ and $K^{(*)}\ell^+\ell^-$ are sensitive to C_7, C_9, C_{10}

New-physics sensitivity in $b \to s\ell^+\ell^-$



Lepton-universality test

Belle II

$\ell \in \{e,\ \mu\}$

Belle II has strong capabilities for electrons and muons.

} inclusive modes

} exclusive modes

How to establish New Physics in $b \to s\ell^+\ell^-$?

> "Observe and measure the rate for $b \to s\nu\bar{\nu}$ and thereby isolate the Z penguin (C_9)."
>
> – *Buras et al.*

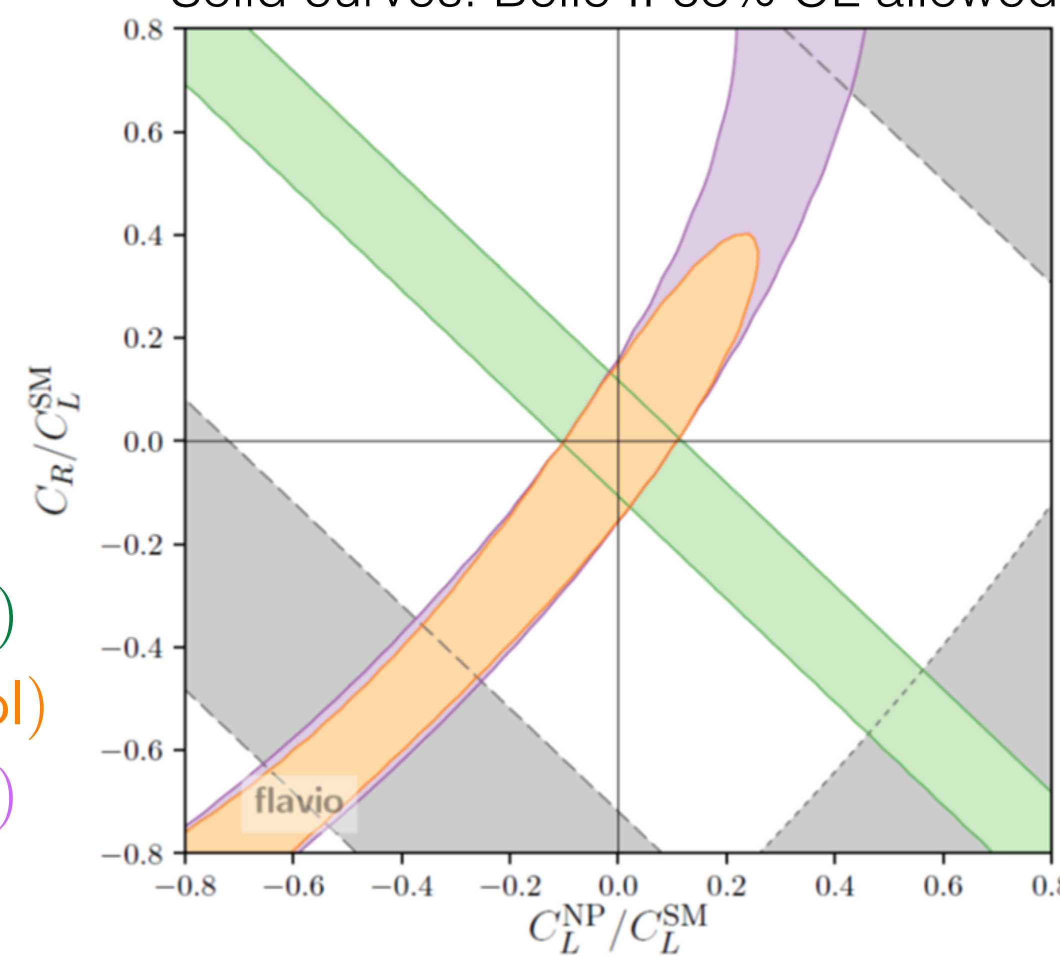


TABLE I: Projections for the statistical uncertainties on the $B \to K^{(*)}\nu\bar{\nu}$ branching fractions.

Mode	$\mathcal{B}$ [10^{-6}]	Efficiency Belle [10^{-4}]	$N_{\mathrm{Backg.}}$ 711 fb^{-1} Belle	$N_{\mathrm{Sig-exp.}}$ 711 fb^{-1} Belle	$N_{\mathrm{Backg.}}$ 50 ab^{-1} Belle II	$N_{\mathrm{Sig-exp.}}$ 50 ab^{-1} Belle II	Statistical error 50 ab^{-1}	Total Error
$B^+ \to K^+\nu\bar{\nu}$	3.98	5.68	21	3.5	2960	245	23%	24%
$B^0 \to K^0_S\nu\bar{\nu}$	1.85	0.84	4	0.24	560	22	110%	110%
$B^+ \to K^{*+}\nu\bar{\nu}$	9.91	1.47	7	2.2	985	158	21%	22%
$B^0 \to K^{*0}\nu\bar{\nu}$	9.19	1.44	5	2.0	704	143	20%	22%
$B \to K^*\nu\bar{\nu}$ combined							15%	17%

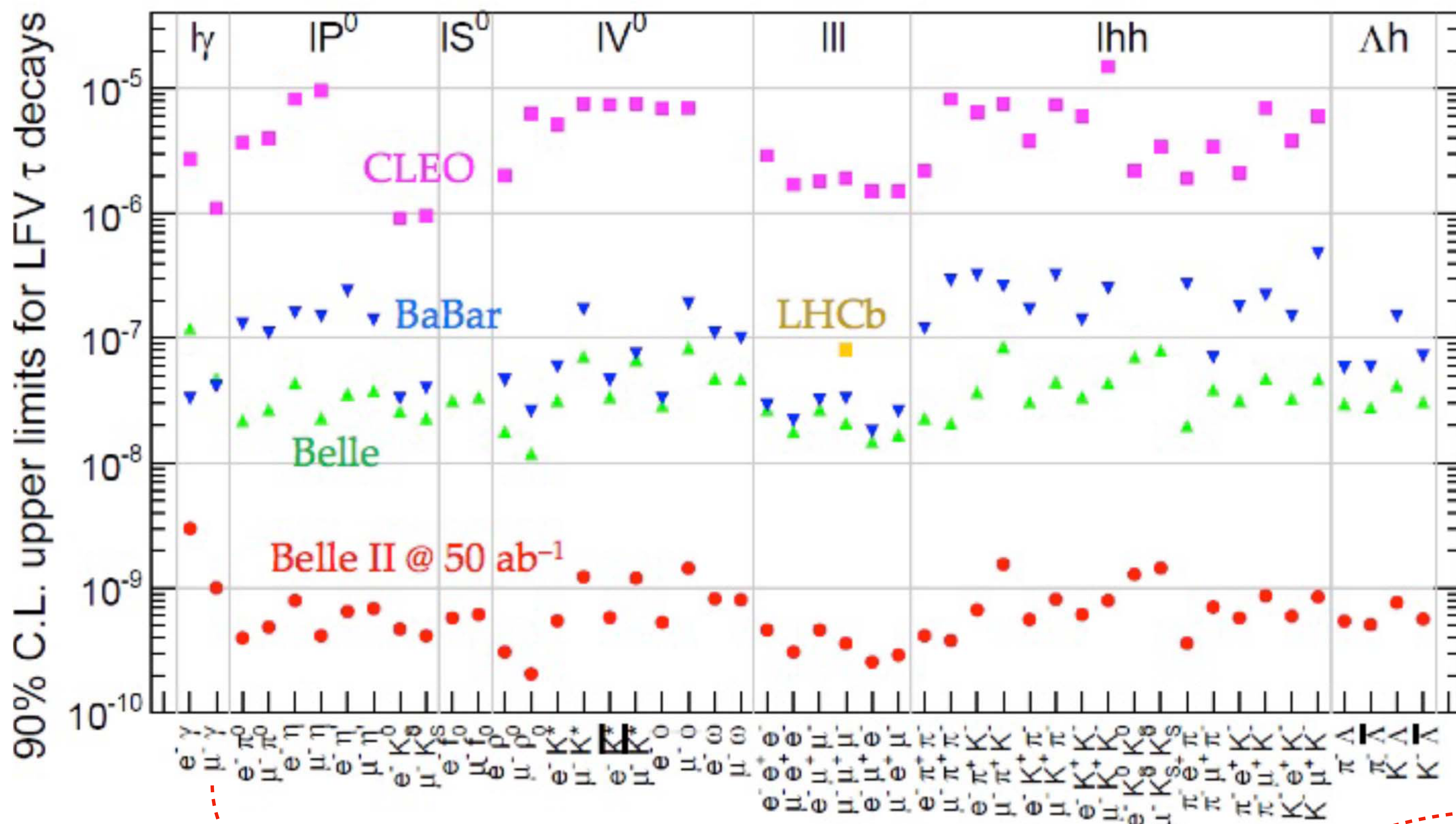
Belle II New-Physics potential in τ decays

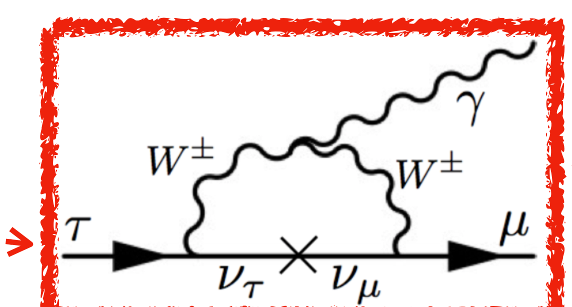
Observables	Experimental Sensitivity	Multi-Higgs Models (§17.2)	generic SUSY	MFV (§17.3)	Z' models (§17.6.1)	gauged flavour (§17.6.2)	3-3-1 (§17.6.3)	left-right (§17.6.4)	leptoquarks (§18.2.1)	compositeness (§17.7)	dark sector (§16.1)
τ tree decays:											
$\mathcal{B}(\tau \to K\nu)/\mathcal{B}(\tau \to \pi\nu)$	$\star\star\star$	$\star\star$	$\times$	$\times$	$\times$	$\times$	$\times$	$\star$	$\star\star\star$	$\square$	$\star\star$
$\mathcal{B}(\tau \to K^*\nu)/\mathcal{B}(\tau \to \rho\nu)$	$\star\star\star$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\star$	$\star\star\star$	$\square$	$\star\star$
$\tau \to \mu$ decays:											
$\tau \to \mu\gamma$	$\star\star\star$	$\star$	$\star\star\star$	$\star$	$\star$	$\star$	$\star$	$\times$	$\star$	$\star\star\star$	$\square$
$\tau \to \mu\pi^0$	$\star\star\star$	$\star$	$\star\star$	$\times$	$\star\star\star$	$\times$	$\star\star\star$	$\times$	$\star\star\star$	$\square$	$\square$
$\tau \to \mu K_S$	$\star\star\star$	$\star$	$\star$	$\times$	$\star$	$\times$	$\star$	$\times$	$\star\star\star$	$\square$	$\square$
$\tau \to \mu\rho^0$	$\star\star\star$	$\times$	$\star\star$	$\times$	$\star\star\star$	$\times$	$\star\star\star$	$\times$	$\star\star\star$	$\square$	$\square$
$\tau \to \mu K^{0*}$	$\star\star\star$	$\times$	$\star$	$\times$	$\star$	$\times$	$\star$	$\times$	$\star\star\star$	$\square$	$\square$
$\tau^- \to \mu^-\ell^-\ell^+$	$\star\star$	$\star\star$	$\star$	$\times$	$\star\star\star$	$\star\star\star$	$\star\star\star$	$\times$	$\star$	$\star\star\star$	$\square$
$\tau^- \to \mu^-\mu^-e^+$	$\star\star$	$\star$	$\times$	$\times$	$\star$	$\star\star\star$	$\star$	$\times$	$\times$	$\star\star\star$	$\square$

$\star\star\star$ Belle II
$\star\star$ Belle II + LHCb
$\star$ LHCb

$\times$ unlikely
$\square$ not studied

Belle II will improve sensitivity for **many** LFV τ decays

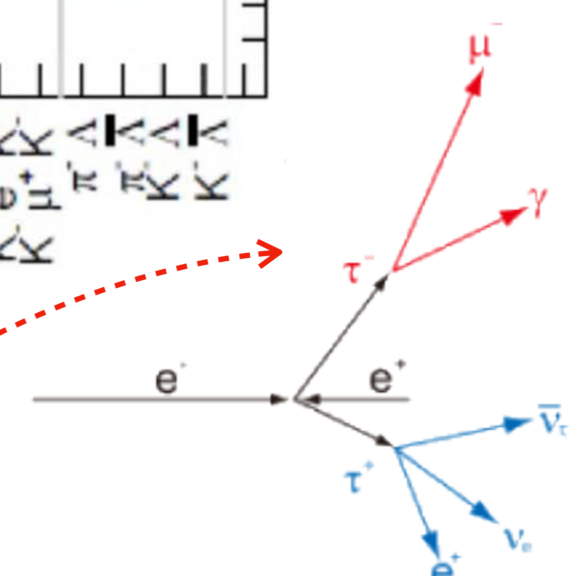




Standard Model ⇒ negligible!

Signal

$\tau \to \mu\gamma$



Tag

$\tau \to e\nu\bar{\nu}$

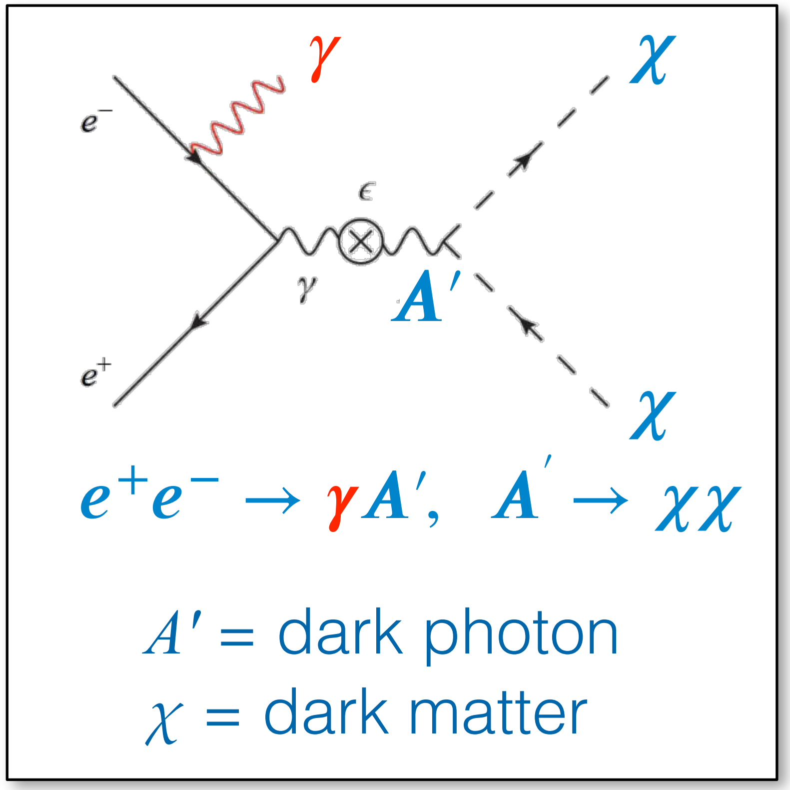
Belle II New-Physics potential in the dark sector

Observables Dark boson A', fermion χ	Experimental Sensitivity	Multi-Higgs Models (§17.2)	generic SUSY	MFV (§17.3)	Z' models (§17.6.1)	gauged flavour (§17.6.2)	3-3-1 (§17.6.3)	left-right (§17.6.4)	leptoquarks (§18.2.1)	compositeness (§17.7)	dark sector (§16.1)	Sum
$e^+e^- \to A' \to$ invisible	$\star\star\star$	$\times$	$\times$	$\square$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\star\star\star$	6
$e^+e^- \to A' \to \ell\ell$	$\star\star\star$	$\star$	$\times$	$\square$	$\star$	$\times$	$\star$	$\times$	$\times$	$\times$	$\star\star\star$	9
$e^+e^- \to A'\gamma$	$\star\star\star$	$\star$	$\times$	$\square$	$\star$	$\times$	$\star$	$\times$	$\times$	$\times$	$\star\star\star$	9
$B \to$ invisible	$\star\star\star$	$\times$	$\times$	$\square$	$\star$	$\times$	$\star$	$\times$	$\star\star\star$	$\times$	$\star\star\star$	11
$B \to KA'$	$\star\star\star$	$\times$	$\times$	$\square$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\star\star\star$	6
$B \to \pi A'$	$\star\star\star$	$\times$	$\times$	$\square$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\star\star\star$	6
$B^+ \to \mu^+\chi$	$\star\star\star$	$\times$	$\times$	$\square$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\star\star\star$	6
$B^+ \to \mu^+\nu A'$	$\star\star\star$	$\times$	$\times$	$\square$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\star\star\star$	6
$\Upsilon(3S) \to \gamma A'$	$\star\star\star$	$\times$	$\times$	$\square$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\star\star\star$	6

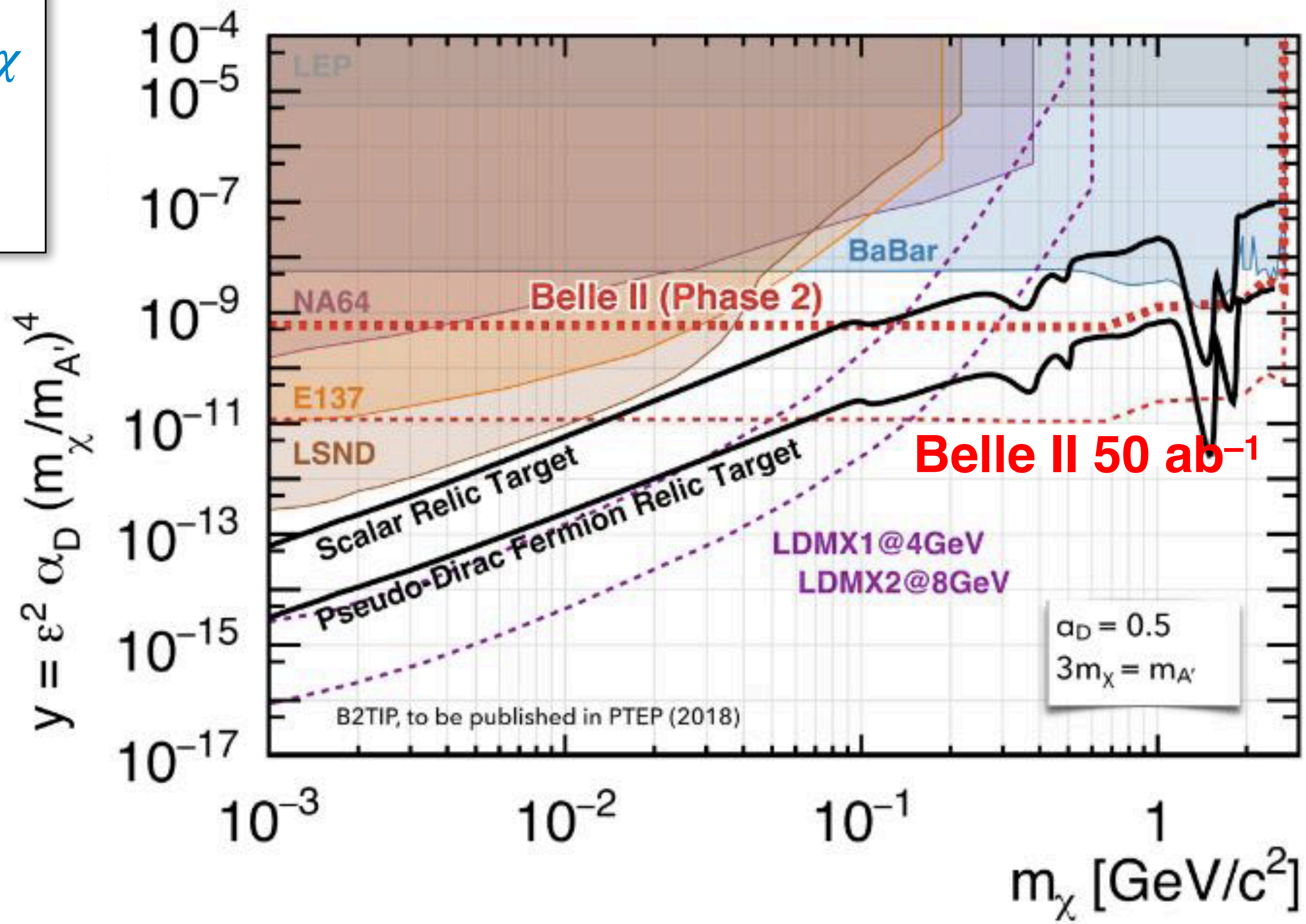
$\star\star\star$ Belle II
$\star\star$ Belle II + LHCb
$\star$ LHCb

$\times$ unlikely
$\square$ not studied

Dark-photon search requires single-photon trigger

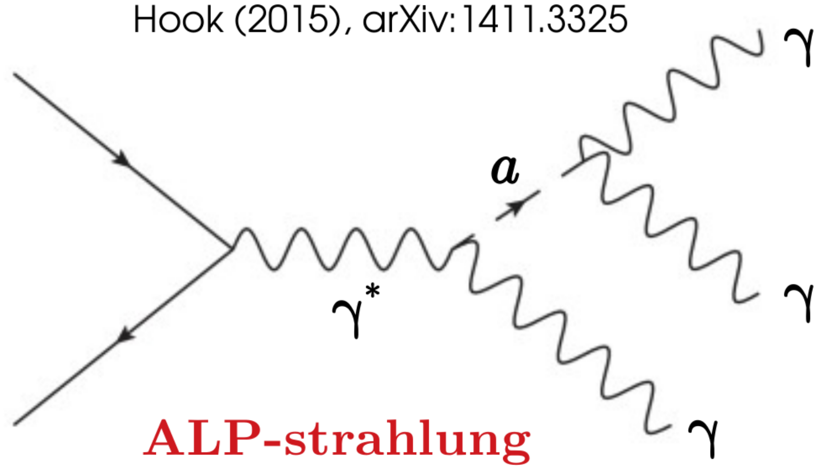


since the event contains exactly one photon … and nothing else



Axion-like pseudoscalars coupling to bosons

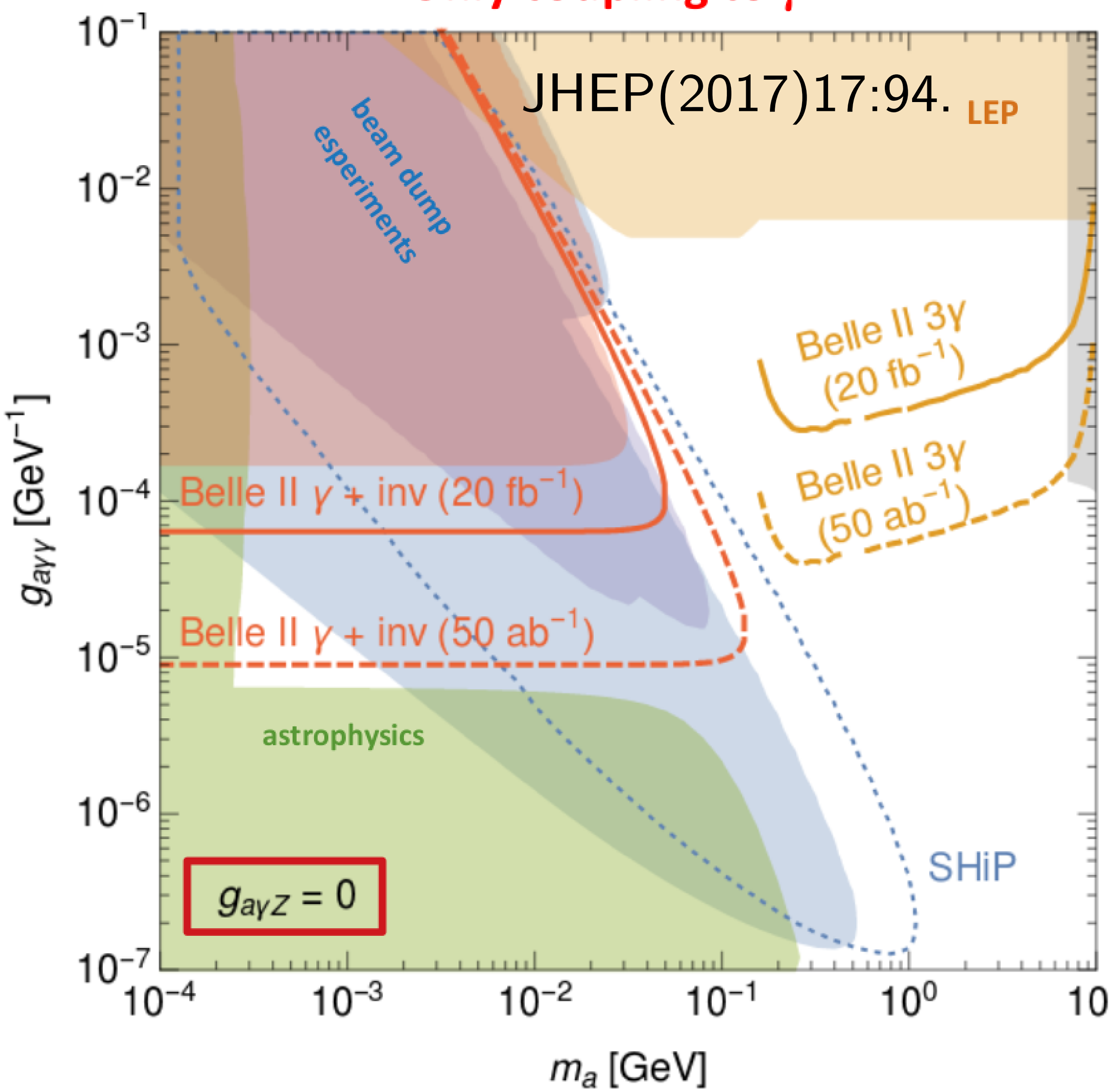
Hook (2015), arXiv:1411.3325



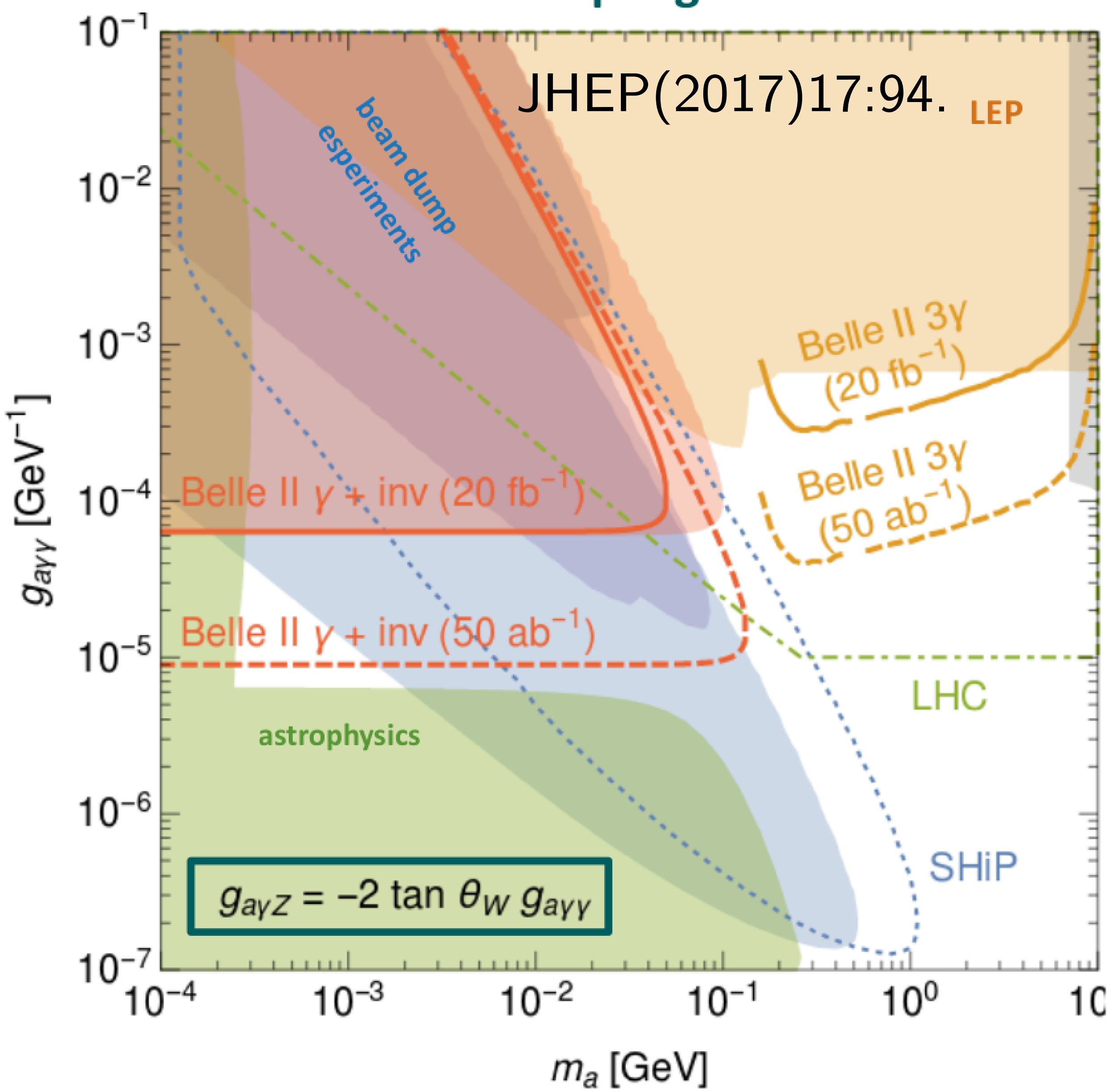
3-photon signature in ALP-strahlung

(1-photon signature if $a \rightarrow \chi\chi$)

Only coupling to γ

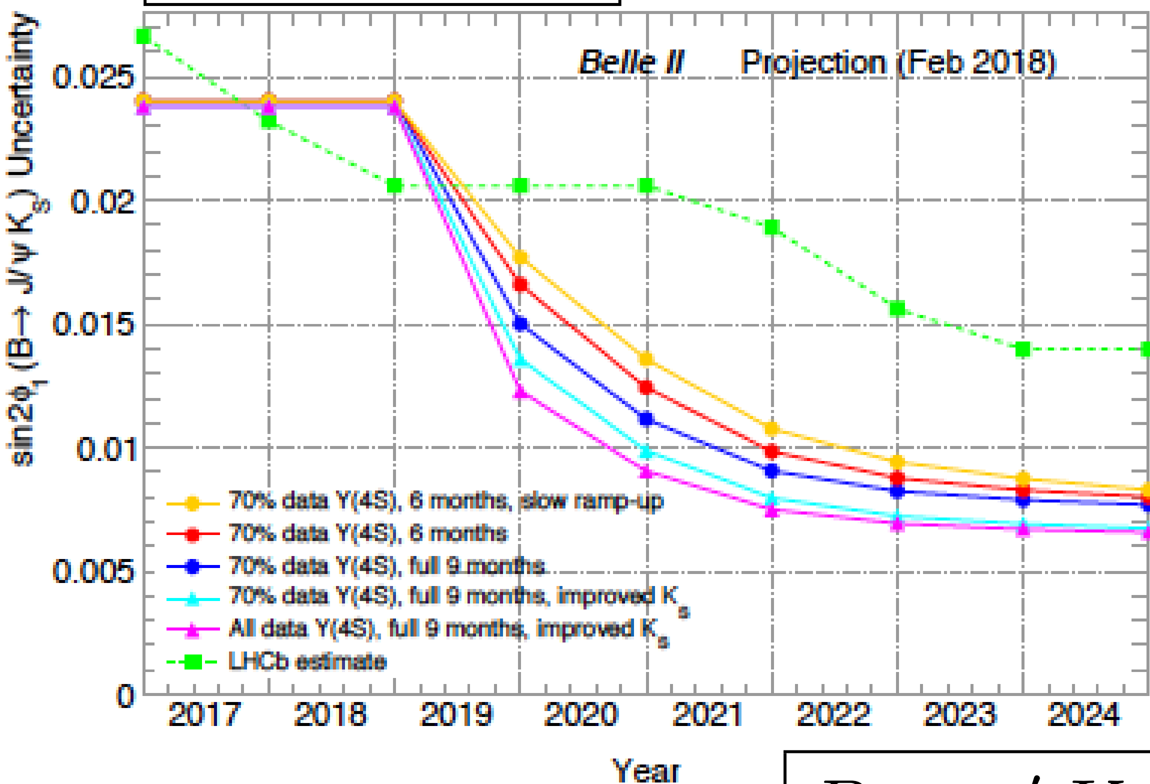


With coupling to Z

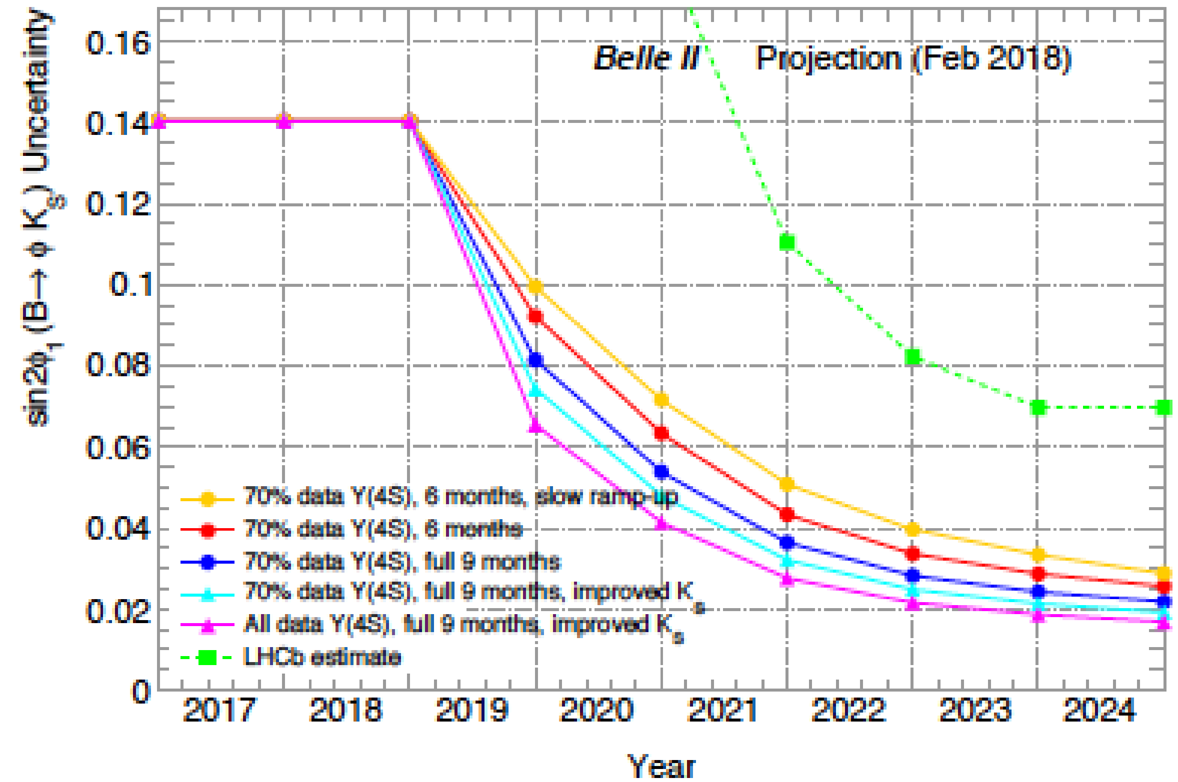


Belle II time-dependent CP sensitivity projections

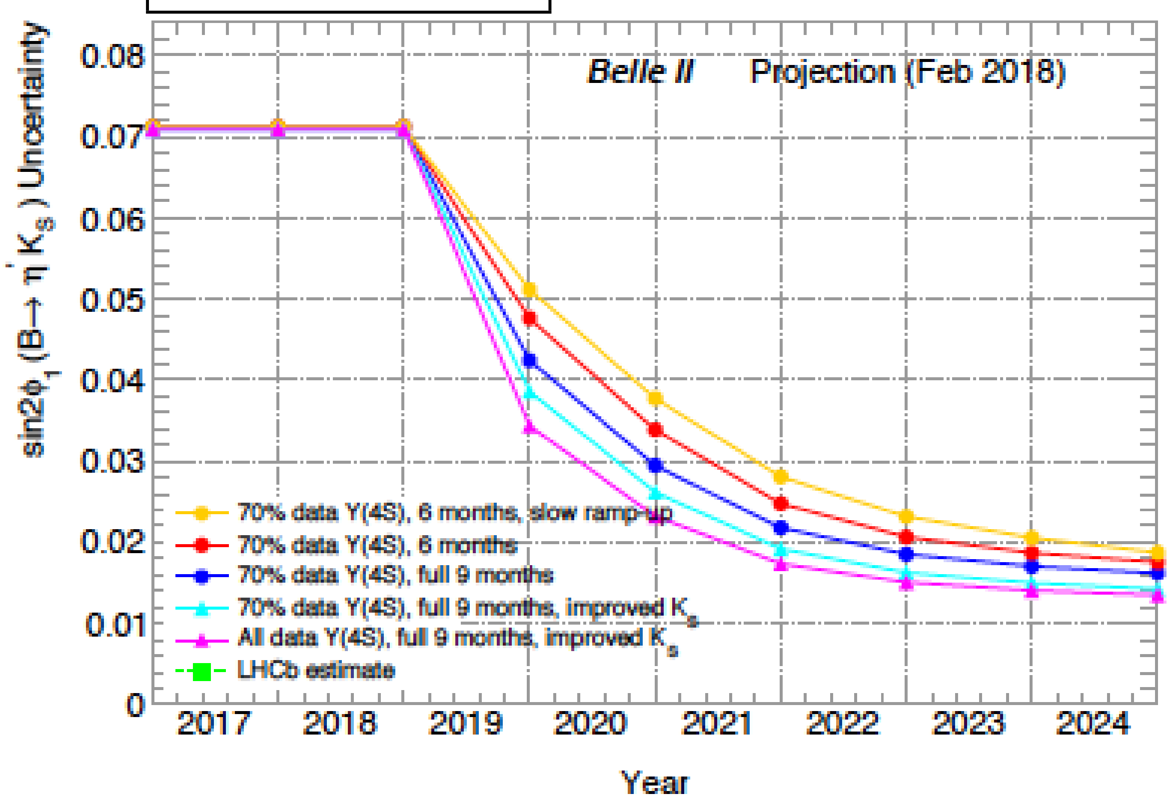
$B \to J/\psi\, K_S$



$B \to \phi\, K_S$

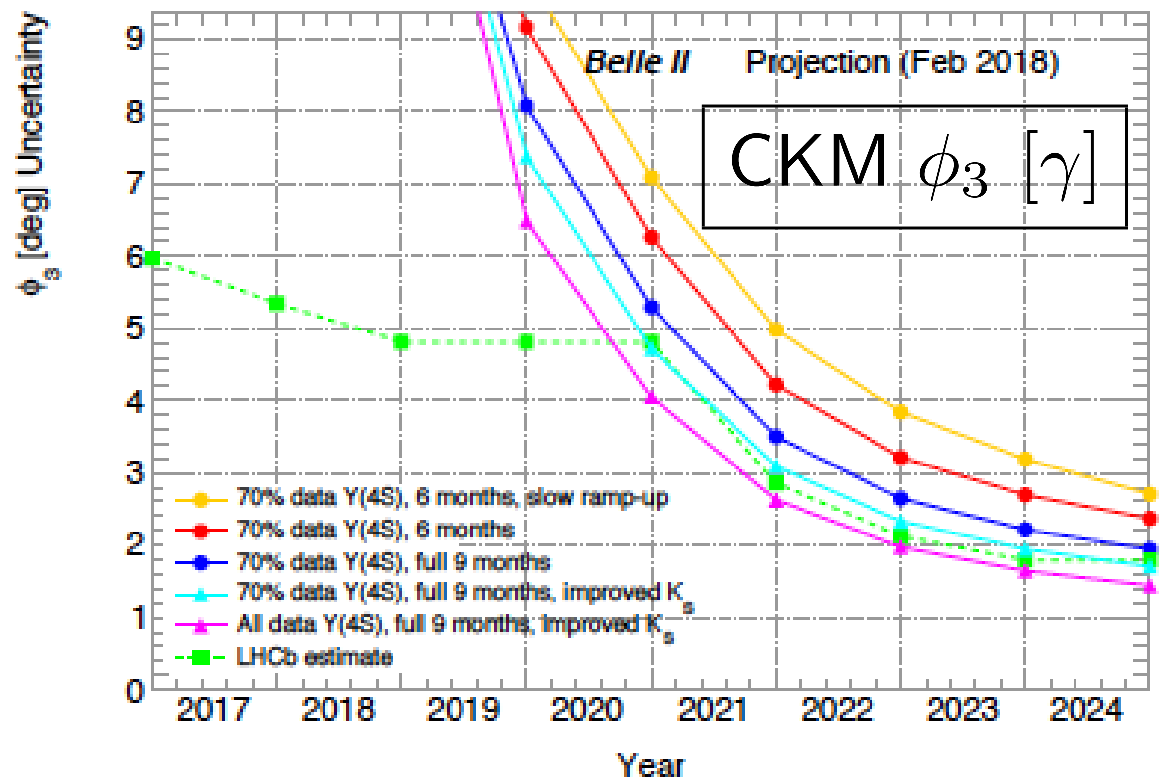


$B \to \eta'\, K_S$

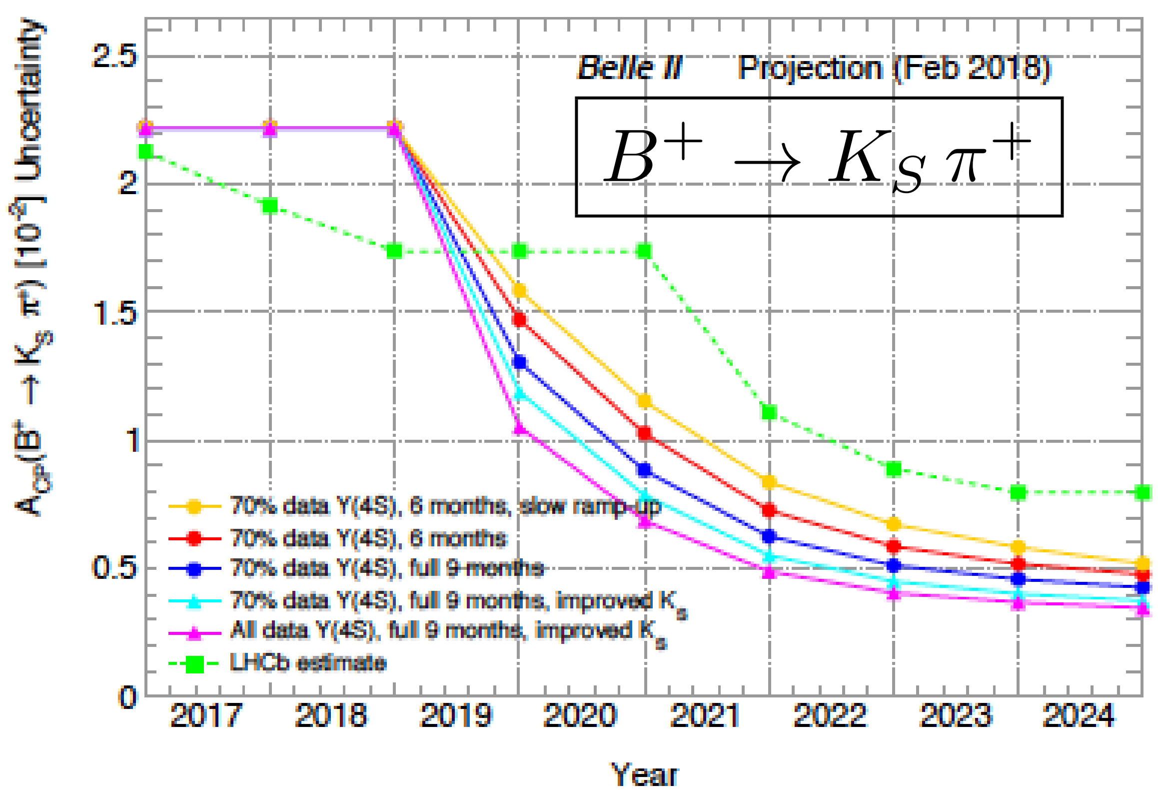


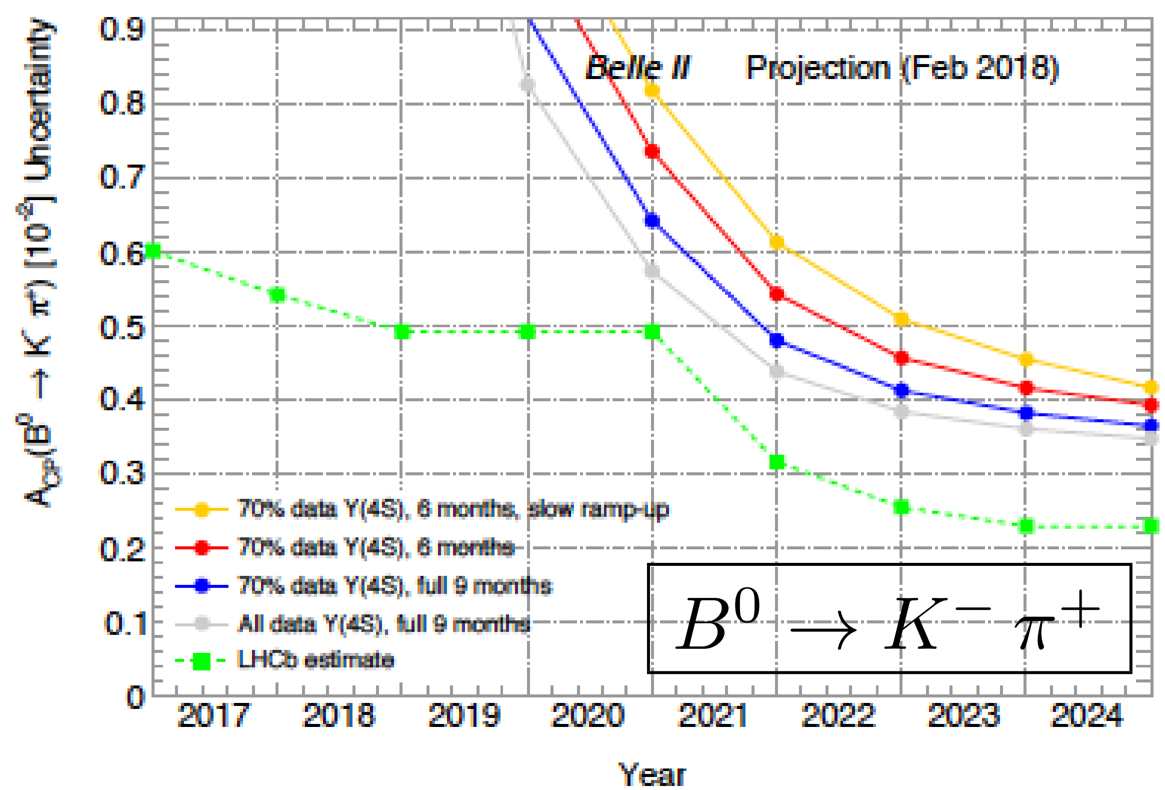
using publicly available LHCb projections

Belle II direct CP sensitivity projections

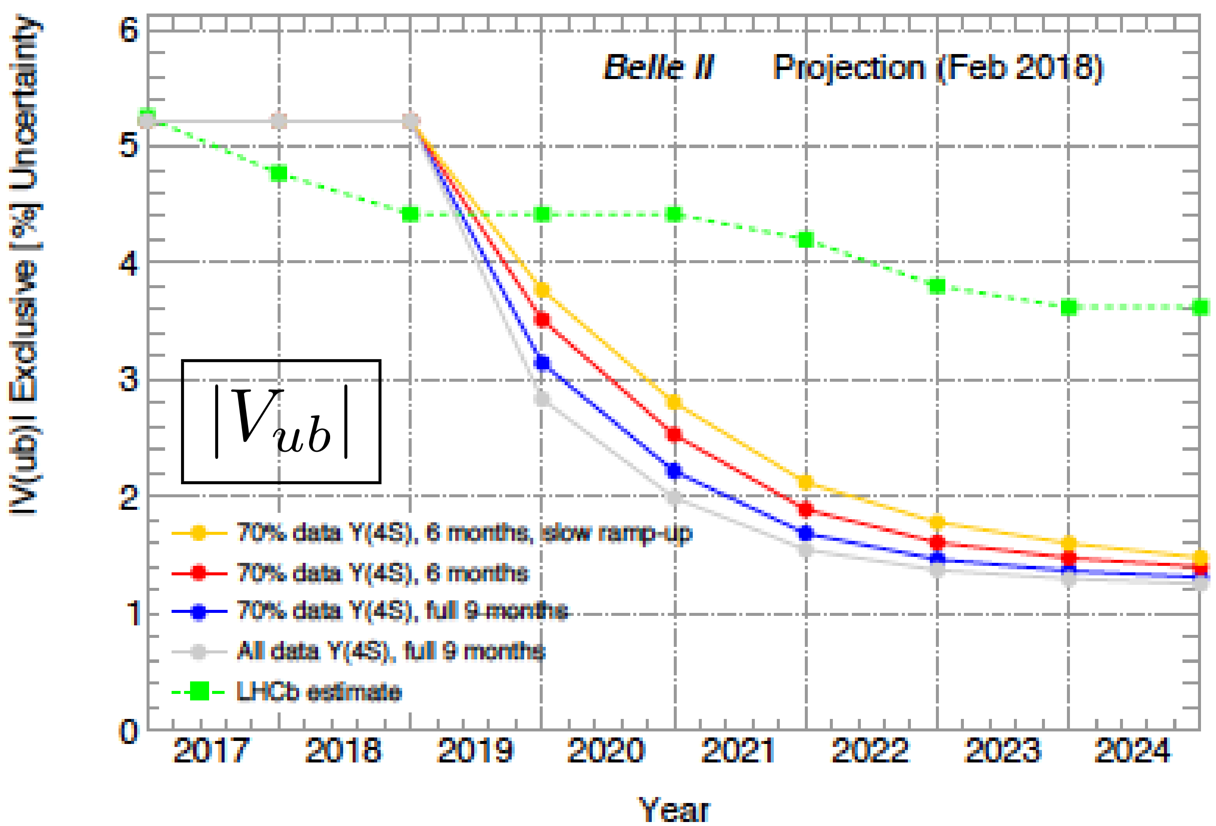


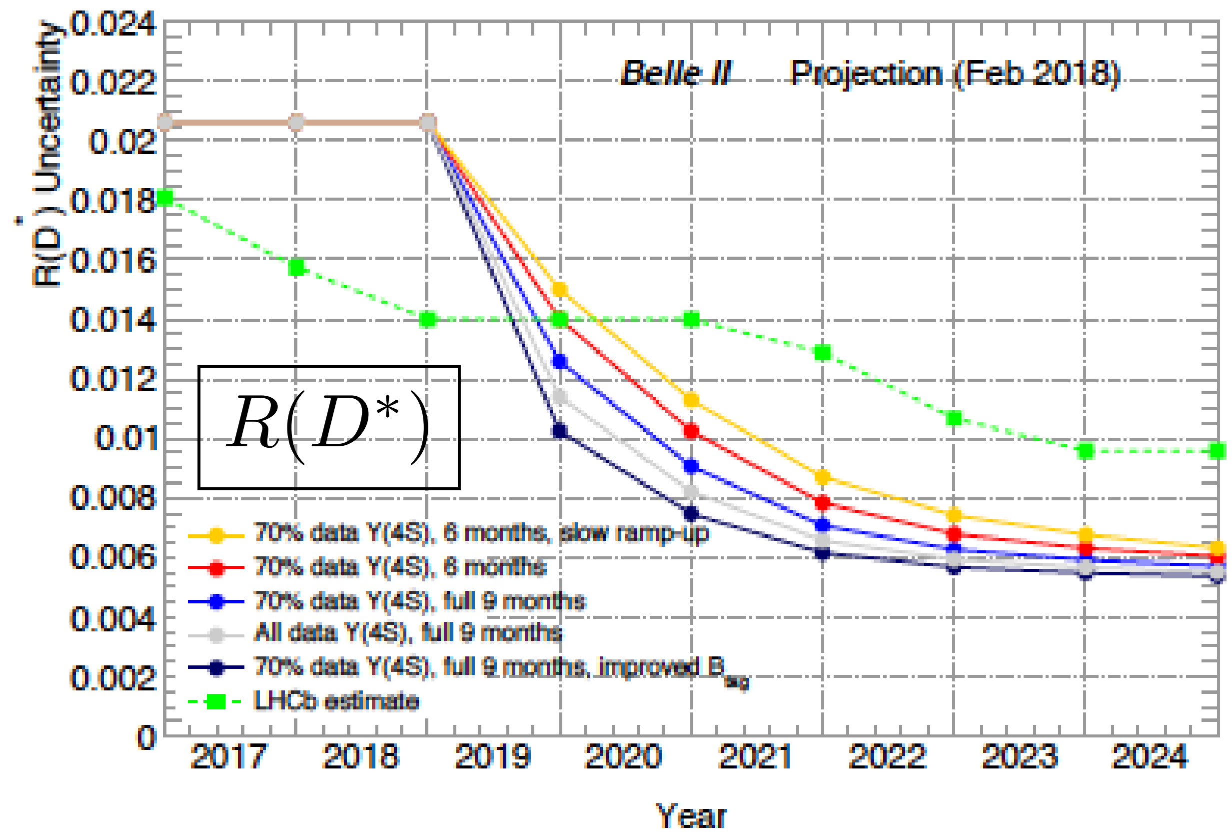
using publicly available LHCb projections

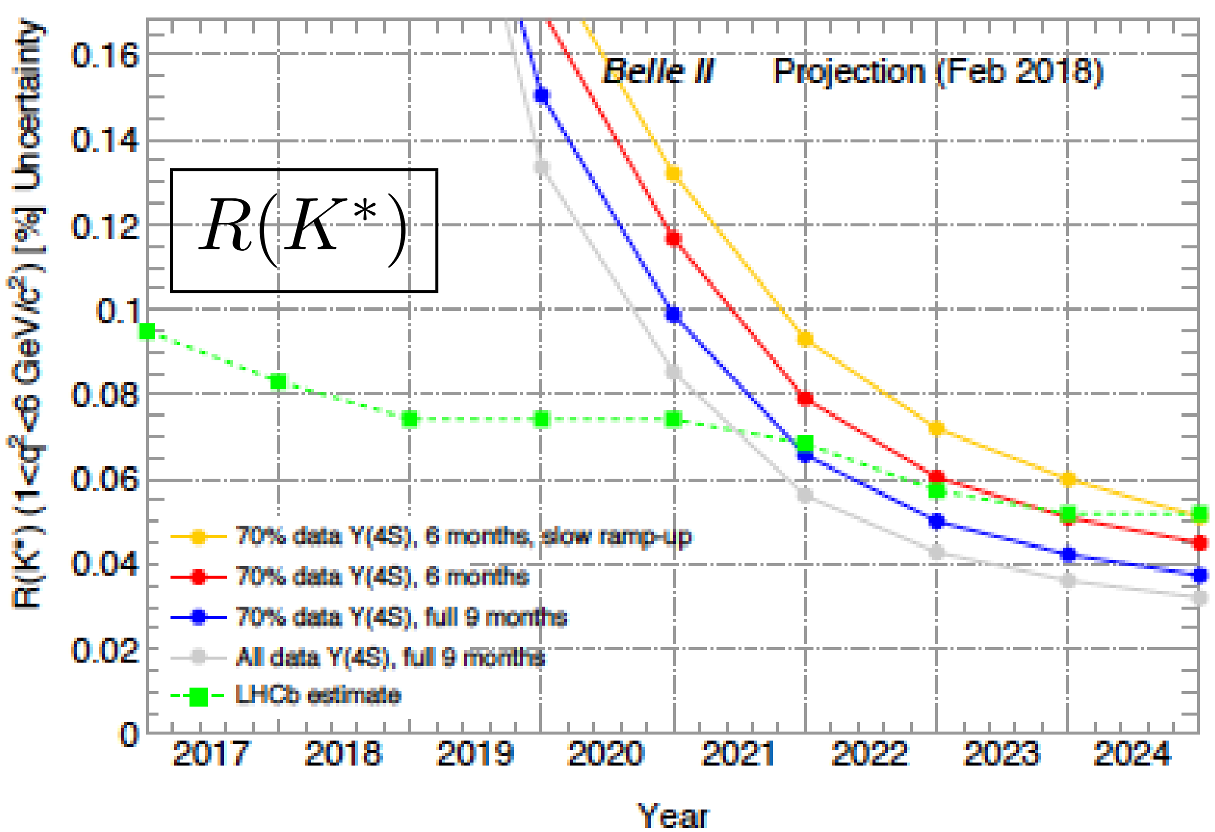




Belle II semileptonic-decay sensitivity projections



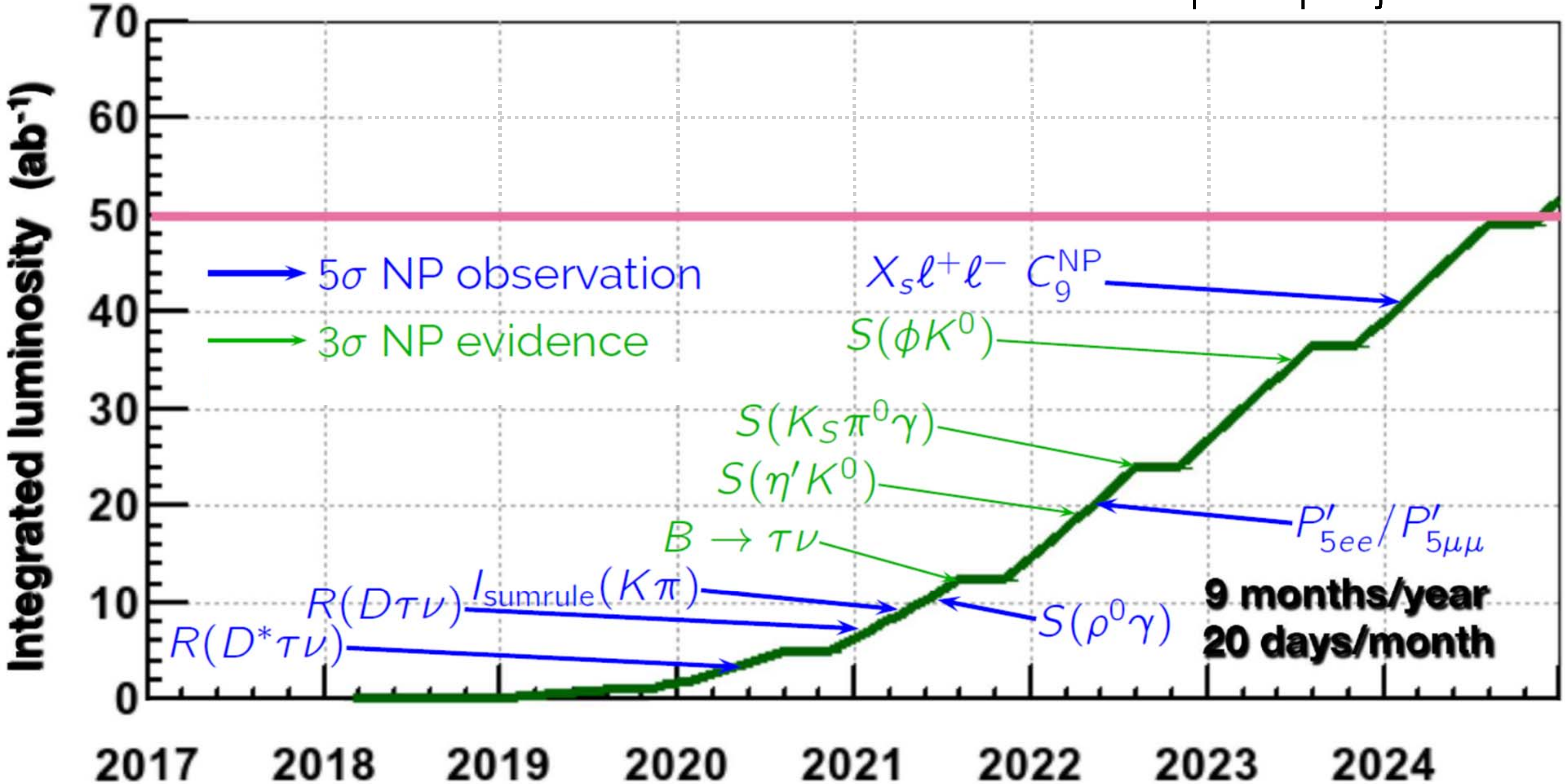




using publicly available LHCb projections

Belle II new-physics prospects vs time

based on HFLAV 2017 + B2TiP report projections



Summary

- Belle II will explore New Physics and make precision measurements of SM physics with 50x more data than Belle.
- Belle II Physics Book (arXiv:1808.10567) provides a wealth of detail on the machine, detector, analysis tools and physics.
- Belle II will be complementary to LHCb. Any NP measurement in one will have to be confirmed in some way by the other. “Symbiotic”
- The world is waiting for your results!

Animations from the Belle II virtual reality app: see www.phys.vt.edu/~piilonen/VR/

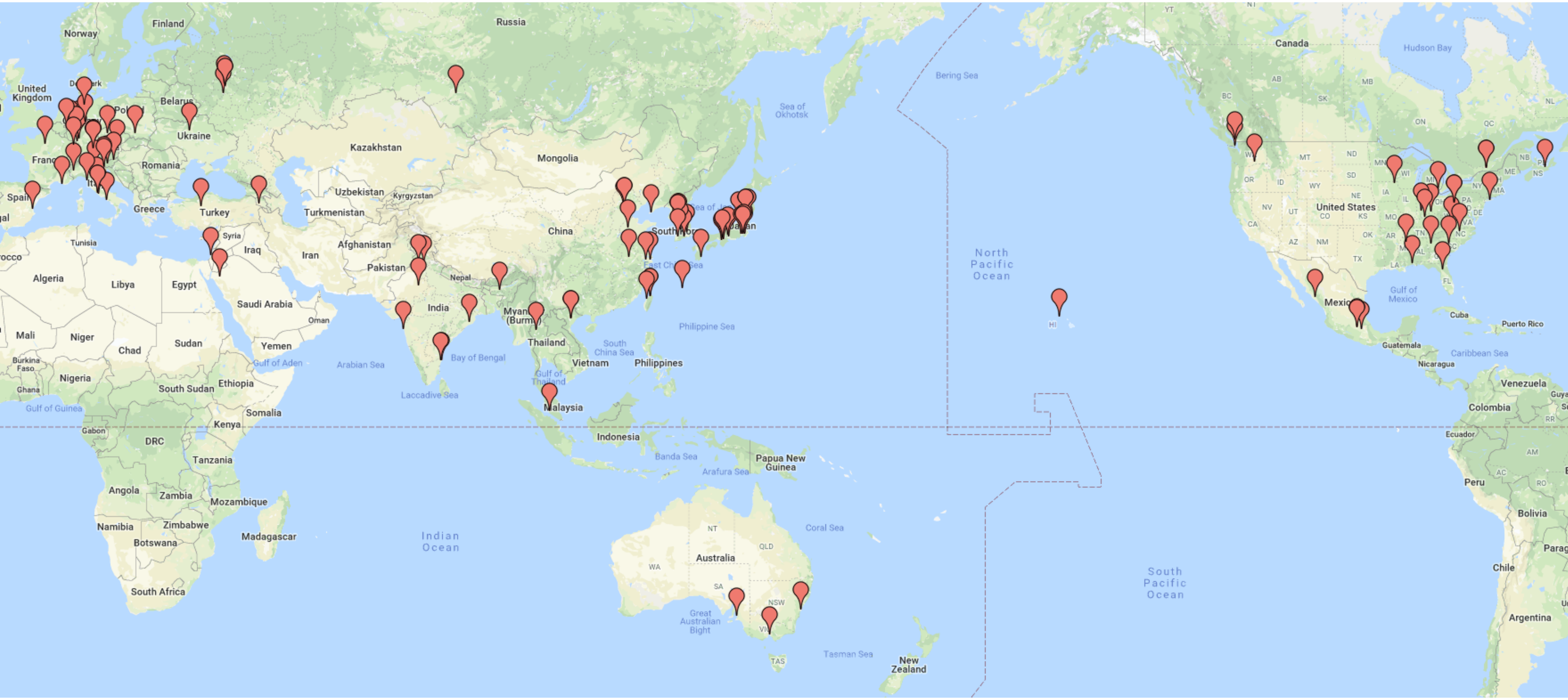
Backup

Machine Parameters

2017/September/1	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	():zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	3.20×10^{-4}	4.55×10^{-4}		
σ_δ	$7.92(7.53)\times10^{-4}$	$6.37(6.30)\times10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6(4.7)	5(4.9)	mm	():zero current
ν_s	-0.0245	-0.0280		
ν_x/ν_y	44.53/46.57	45.53/43.57		
U_0	1.76	2.43	MeV	
$\tau_{x,y}/\tau_s$	45.7/22.8	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	8×10^{35}		$cm^{-2}s^{-1}$	

Belle II collaboration

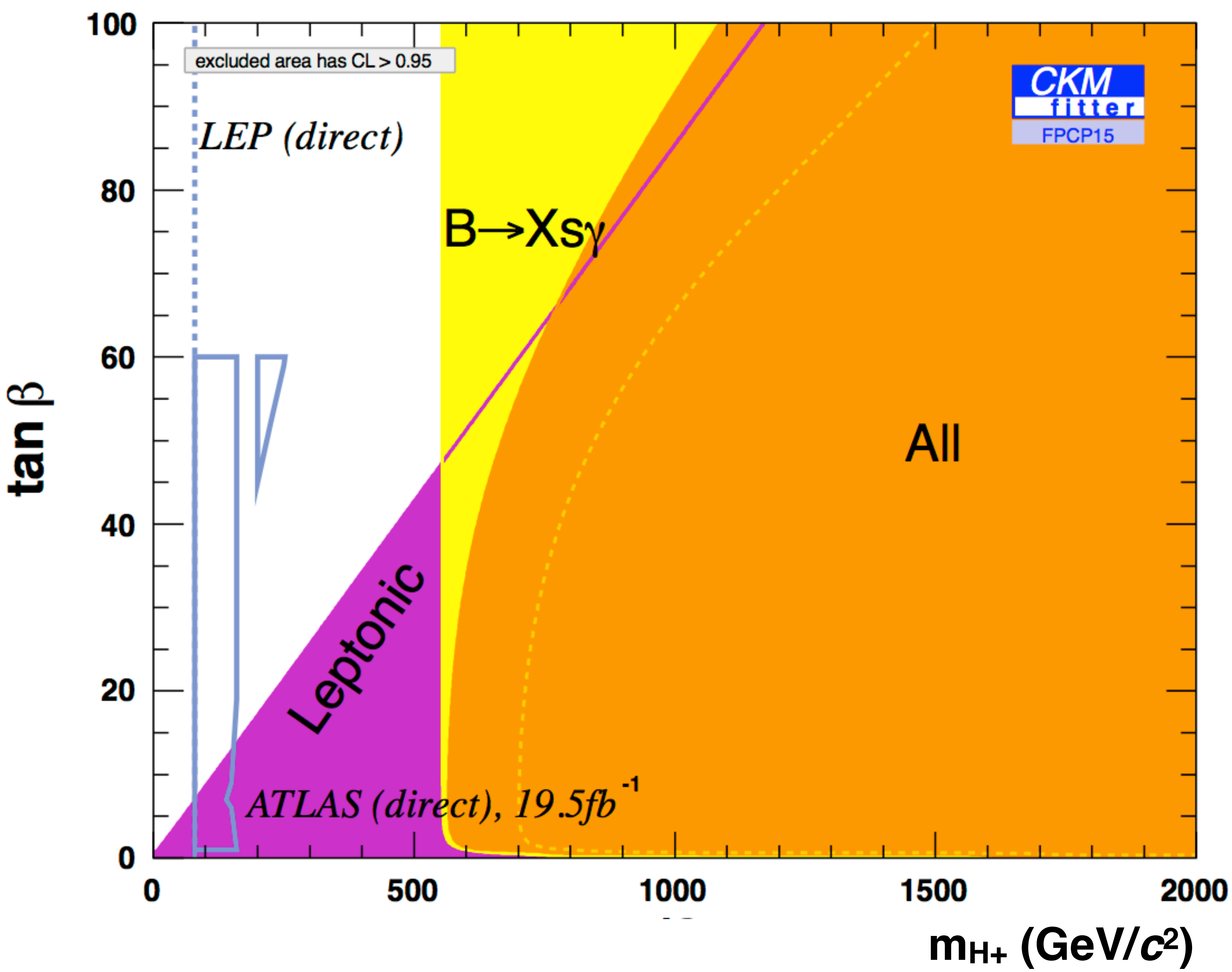
- 948 collaborators, of whom 15% are women and 32% are graduate students
- 115 institutions
- 25 countries/regions

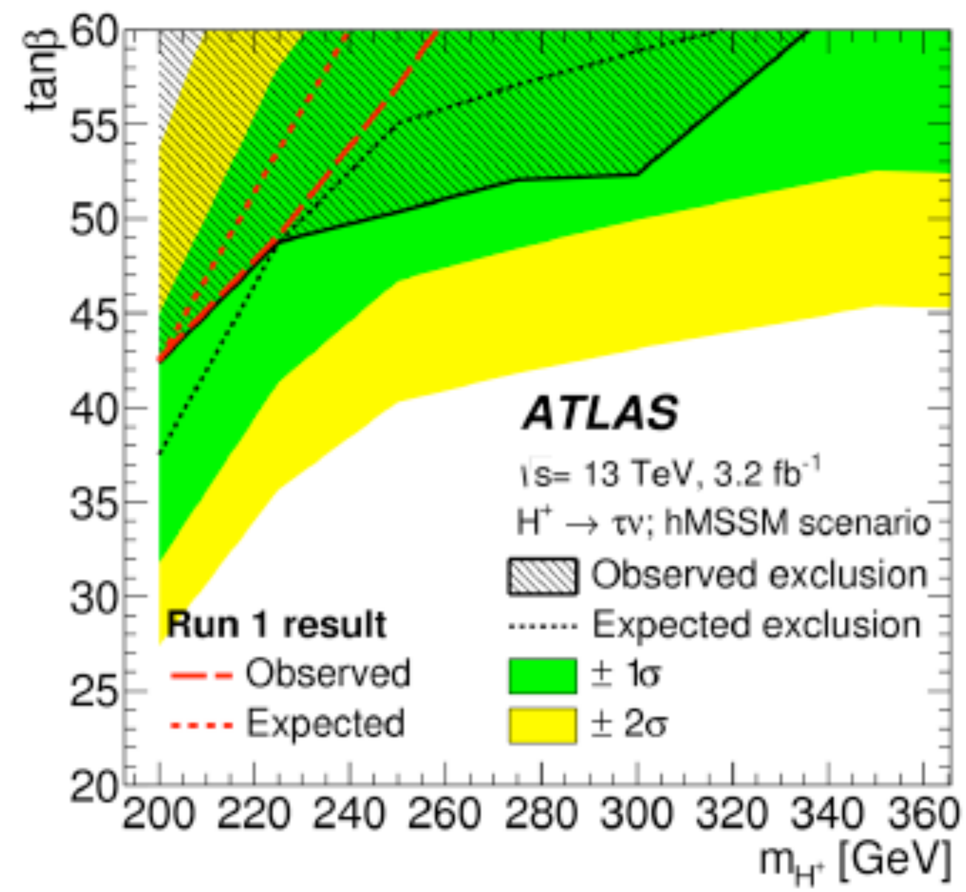


Complementarity of $e^+ e^-$ and LHC for MSSM

Thanks to Luis Pesantez and Phil Urquijo

The current combined $B \to \tau\nu$ limit places a stronger constraint than direct searches from LHC experiments for next few years.





Currently, $B \to X_s\gamma$ rules out m_{H+} below ~480 GeV/c² at 95% CL (for any tanβ), M. Misiak *et al.* (assuming no other NP) – arxiv: 1503.01789

Adapted from Adrian Bevan

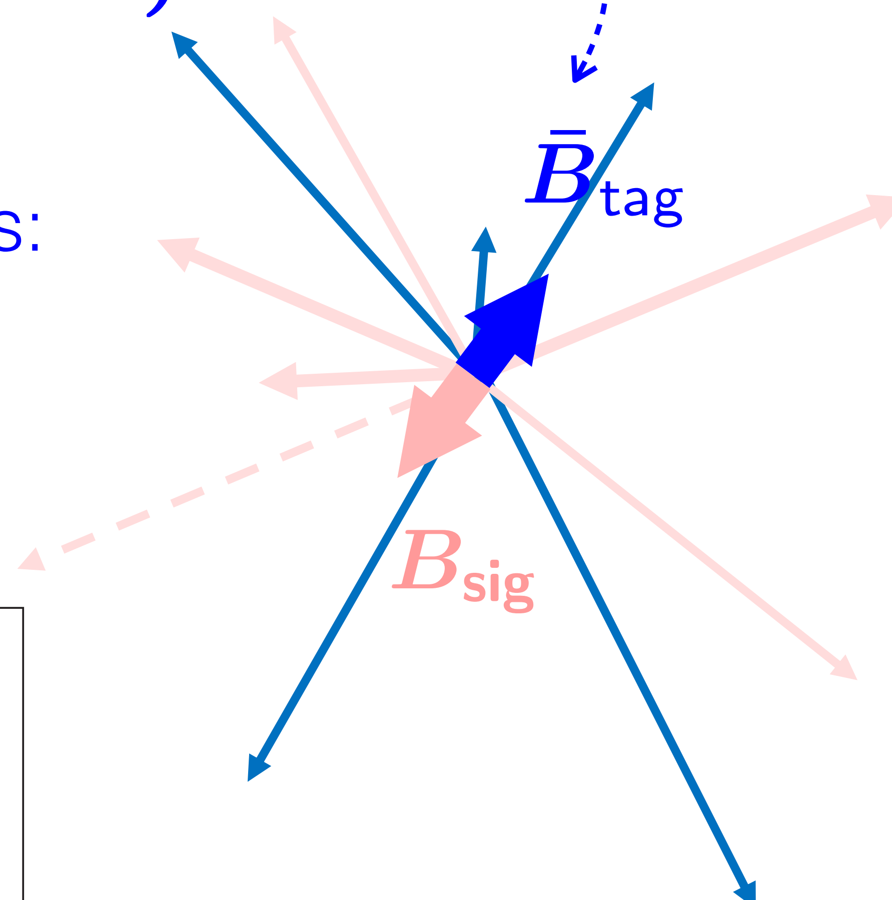
Full-reconstruction tag for missing-energy B decays

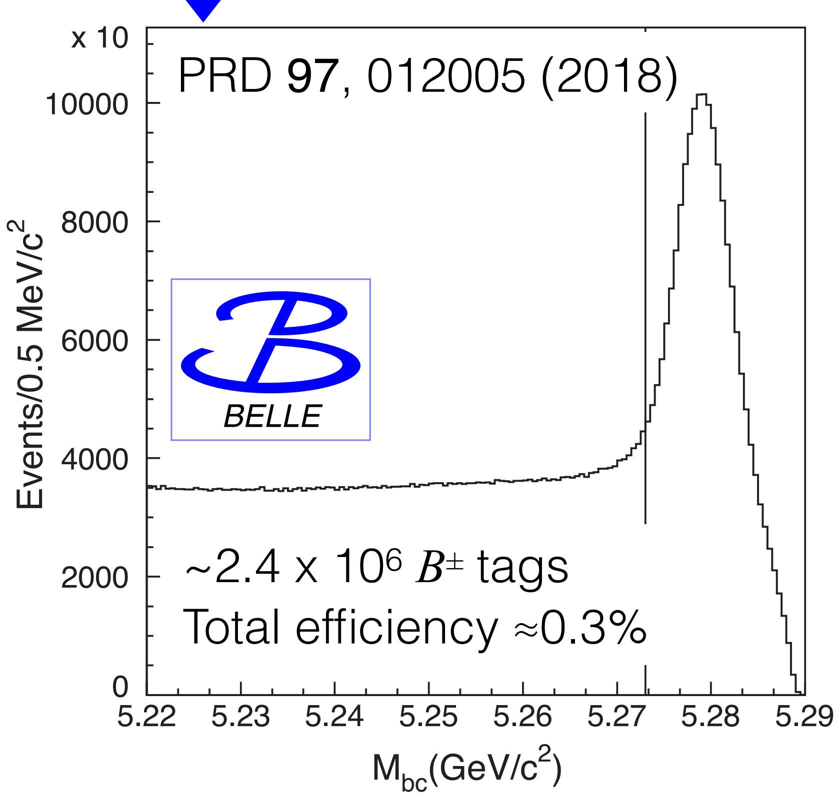
$$E_{\text{tag}} = \sum_{i,\text{tag}} E_i \quad (= E_{\text{beam}})$$

$$\vec{\mathbf{p}}_{\text{tag}} = \sum_{i,\text{tag}} \vec{\mathbf{p}}_i$$

Beam-constrained mass:

$$M_{\text{bc}} = \sqrt{E_{\text{beam}}^2 - |\vec{\mathbf{p}}_{\text{tag}}|^2}$$



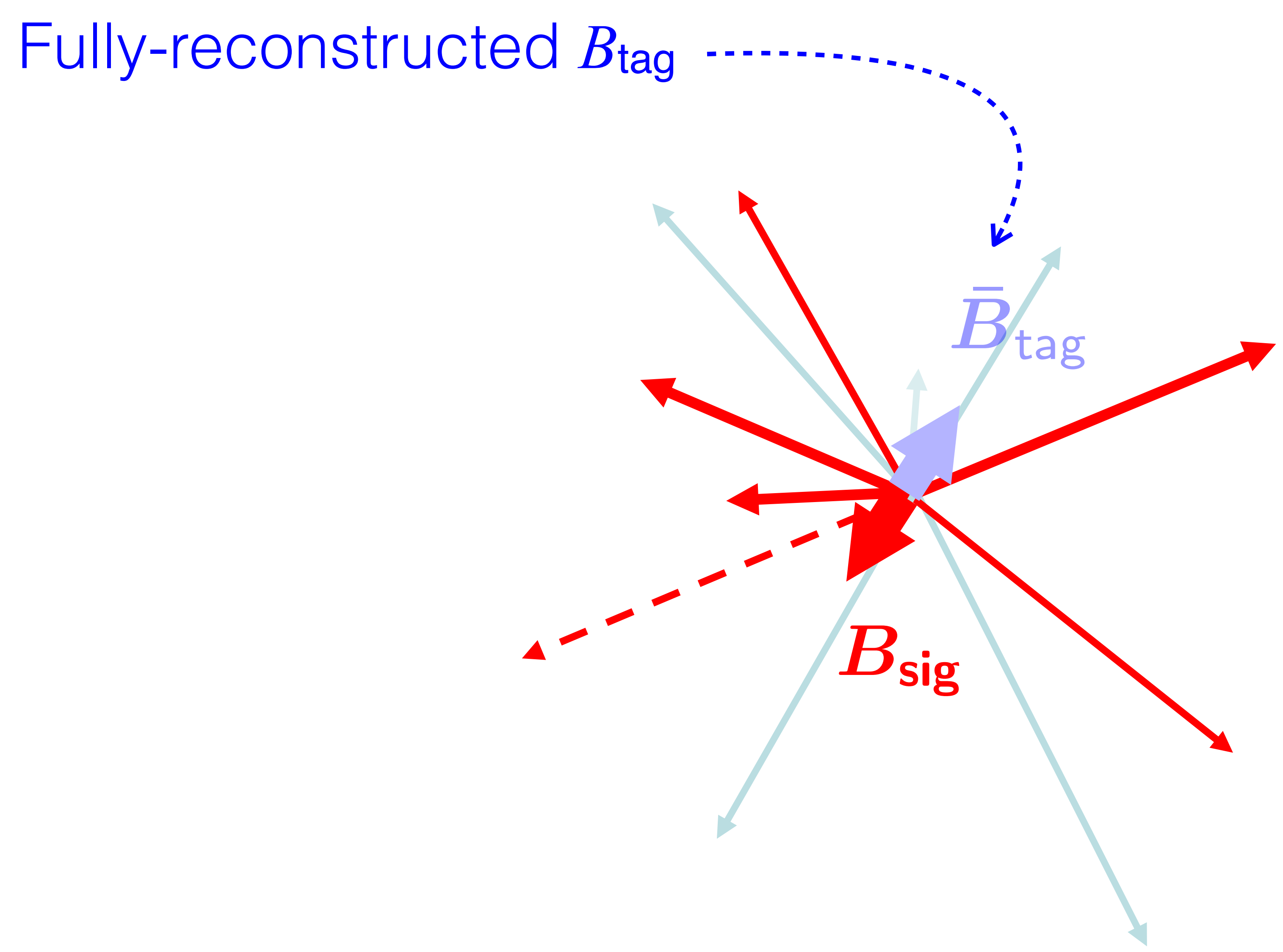


>5000 distinct decay modes

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

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

Full-reconstruction tag for missing-energy B decays



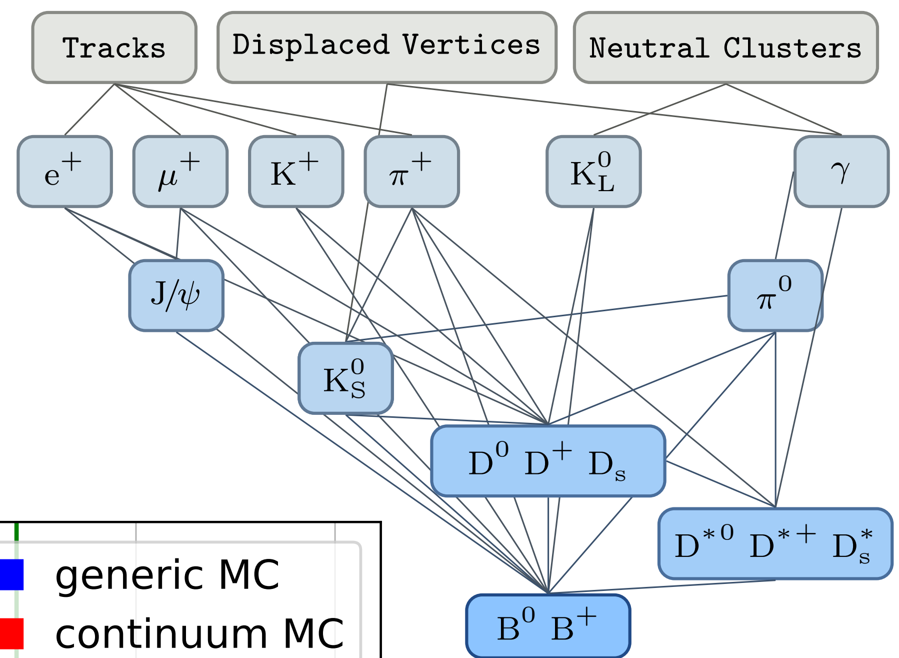
All remaining particles *(detected or not)* belong to B_{sig}

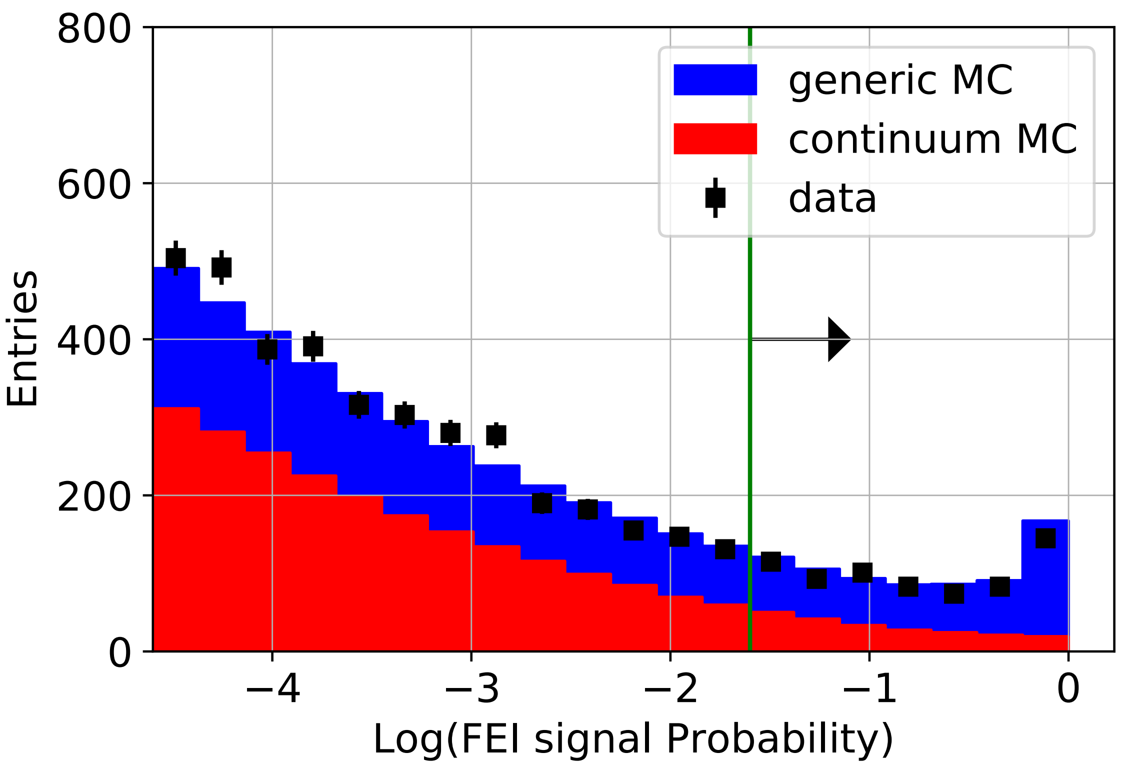
$$E_{\text{sig}} = E_{\text{beam}} \qquad \vec{\mathbf{p}}_{\text{sig}} = -\vec{\mathbf{p}}_{\text{tag}}$$

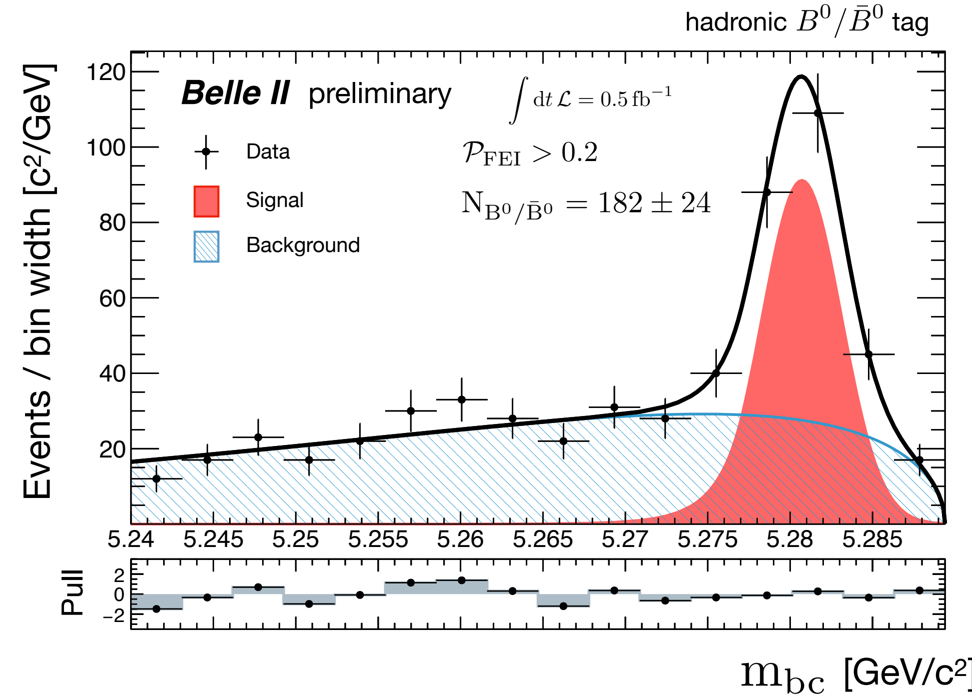
➠ missing-energy decays, absolute branching fractions, inclusive rates, …

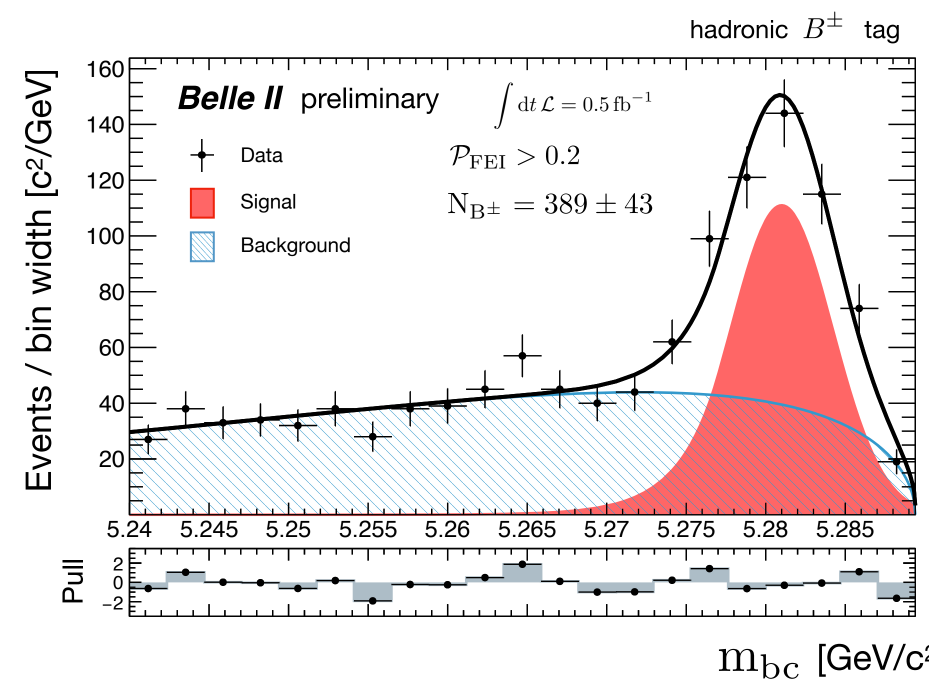
B-full reconstruction in 2018

- Recursive reconstruction algorithm (FEI):
  > 5000 B decay modes!
- Boosted decision tree classifier.









Consumer's Guide to the Charged Higgs

- *Higgs doublet of type I* (ϕ_1 couples to upper (u-type) and lower (d-type) generations. No fermions couple to ϕ_2)

- *Higgs doublet of type II* (ϕ_u couples to u type quarks, ϕ_d couples to d-type quarks, u and d couplings are different; $\tan(\beta) = v_u/v_d$) [favored NP scenario e.g. MSSM, generic SUSY]

- *Higgs doublet of type III* (not type I or type II; anything goes.
  "FCNC hell"→many FCNC signatures)

Thanks to theorist Xerxes Tata