Flavour challenges from Belle II and LHCb to Tera-Z

Future Colliders @ DESY meeting

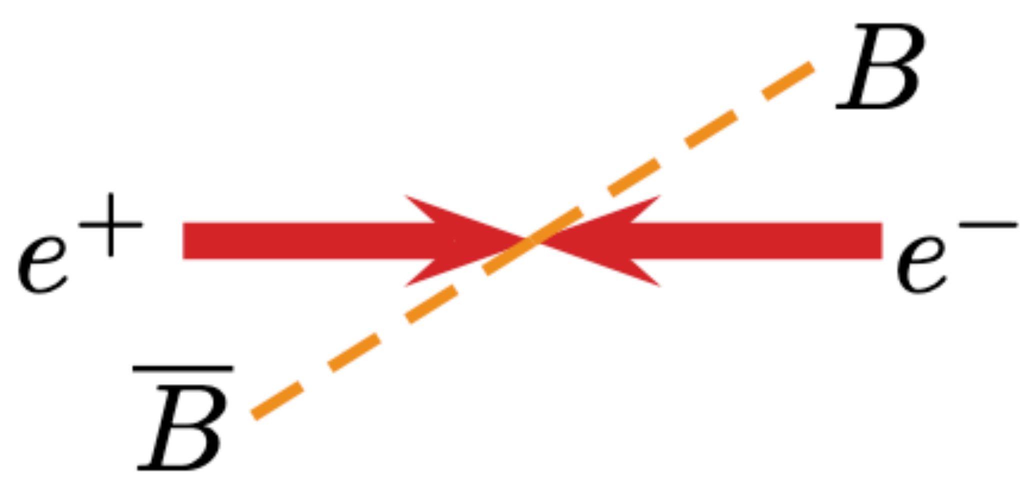
Most numbers from: [Belle II physics book](), [Physics case for LHCb Upgrade II](), [FCC-ee CDR V2](), [PRD102(2020)056023]().

Thibaud Humair, 21 June 2024

Outline

- Status and challenges in flavour physics:
  - Today: LHCb and Belle II
  - In the future: Tera-Z at FCC-ee
- Focus on B physics
- Focus on some subjects that are important or that I like, not necessarily what FCC-ee can do best

Belle II



Clean: only 1 B-$\bar{B}$ pair,

Constrained kinematics: known $E_{\text{CMS}}(B)$

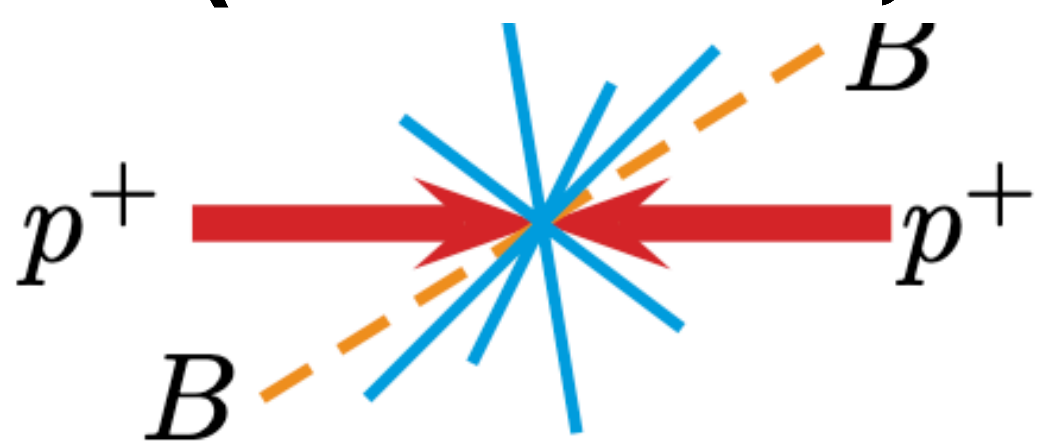
~ 60 B's per sec, $\sim 1/4$ of total events
high reconstruction efficiency, "no" trigger

Ideal for decays with π^0, γ, ν

Today: 700 (Belle) + 400 fb^{-1} (Belle II)
$\Rightarrow \sim 1.2 \times 10^9$ BB pairs

$p(B) \sim 1.5$ GeV
flight distance ~ 0.1 mm
$\Rightarrow$ decay-time resolution ~ 0.30 ps

LHCb (also ATLAS, CMS)



B hadrons + $\mathcal{O}(100)$ charged particles

Unconstrained kinematics

$\sim 20'000$ B's per sec., 1% of total events
low reconstruction efficiency, need trigger

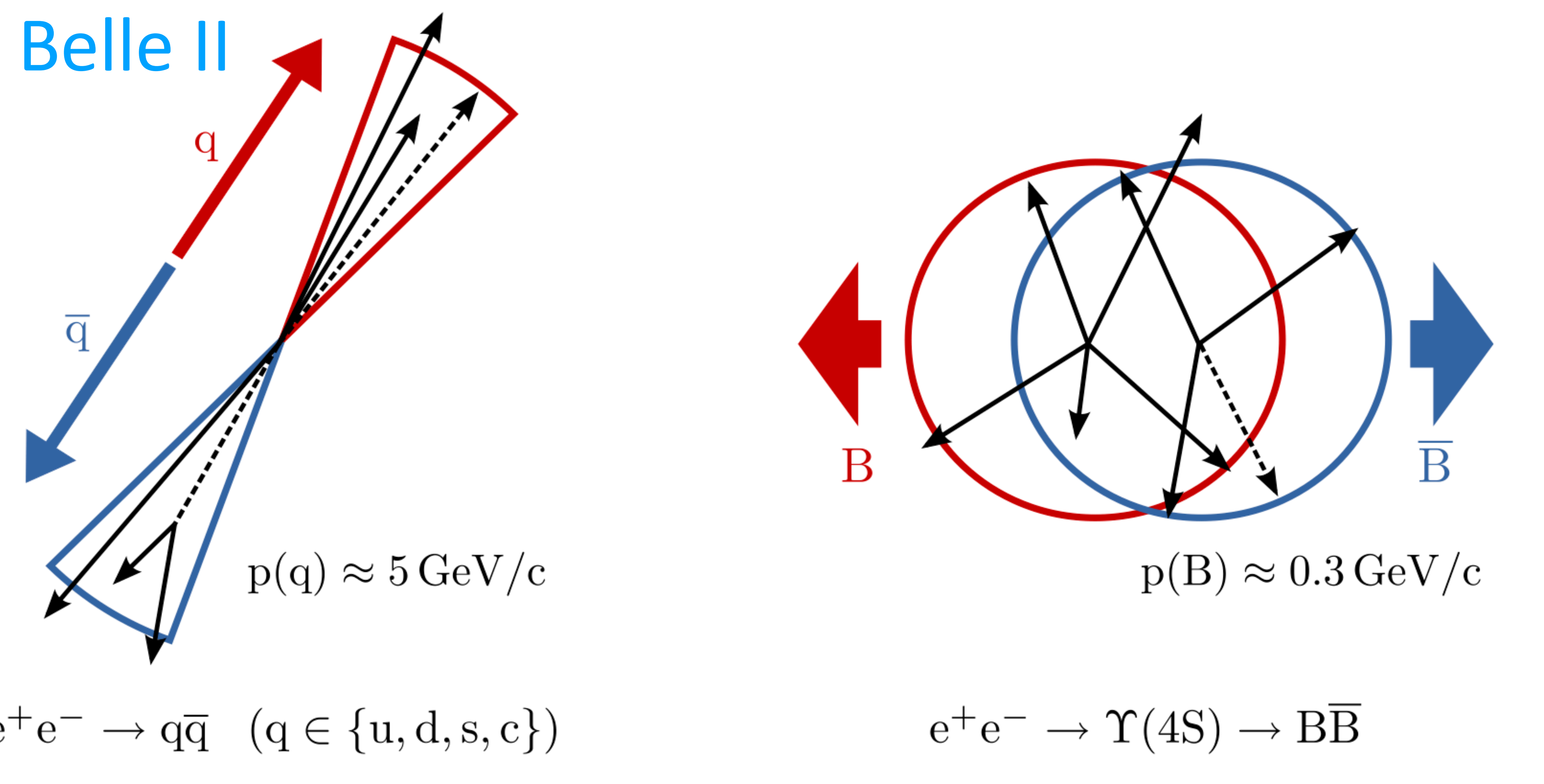
Ideal for very rare decays to charged particles

Today: 3 (Run I) +6 fb^{-1} (Run II)
$\sim 10^{12}$ $b\bar{b}$ jet pairs in acceptance

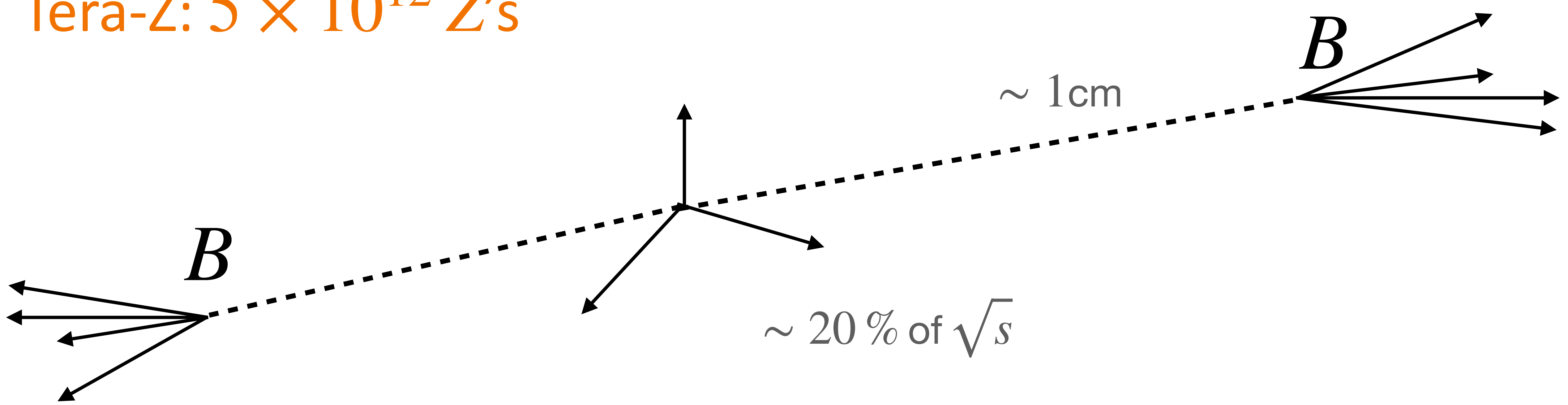
$p(B) \sim 100$ GeV
flight distance ~ 1 cm
$\Rightarrow$ decay-time resolution ~ 0.05 ps

LHCb vs Belle II vs Tera-Z environments

Belle II

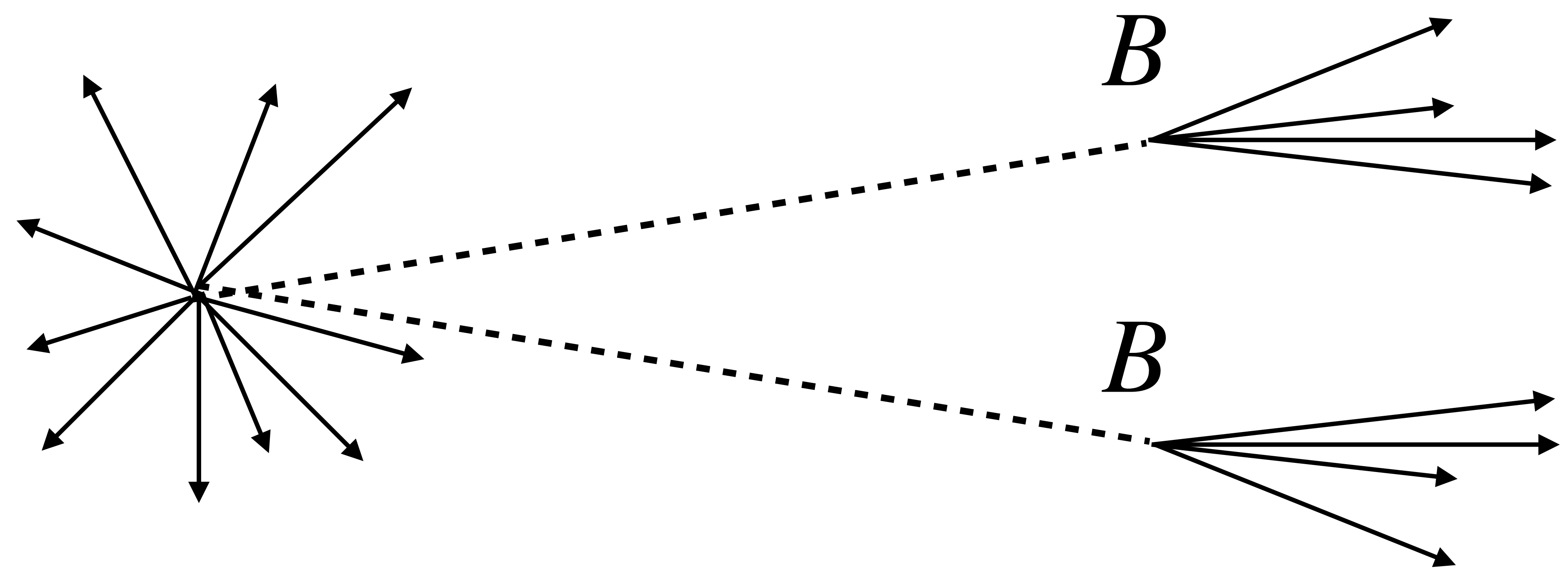


Tera-Z: 5×10^{12} Z's



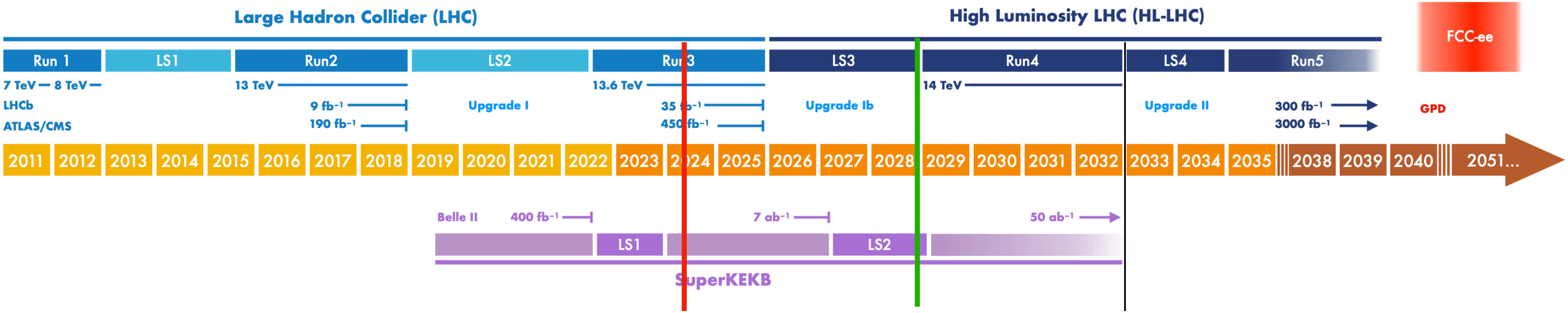
Particle species	B^0	B^+	B_s^0	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$)	310	310	75	65	1.5	600	170

LHC



Attribute	Belle II	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

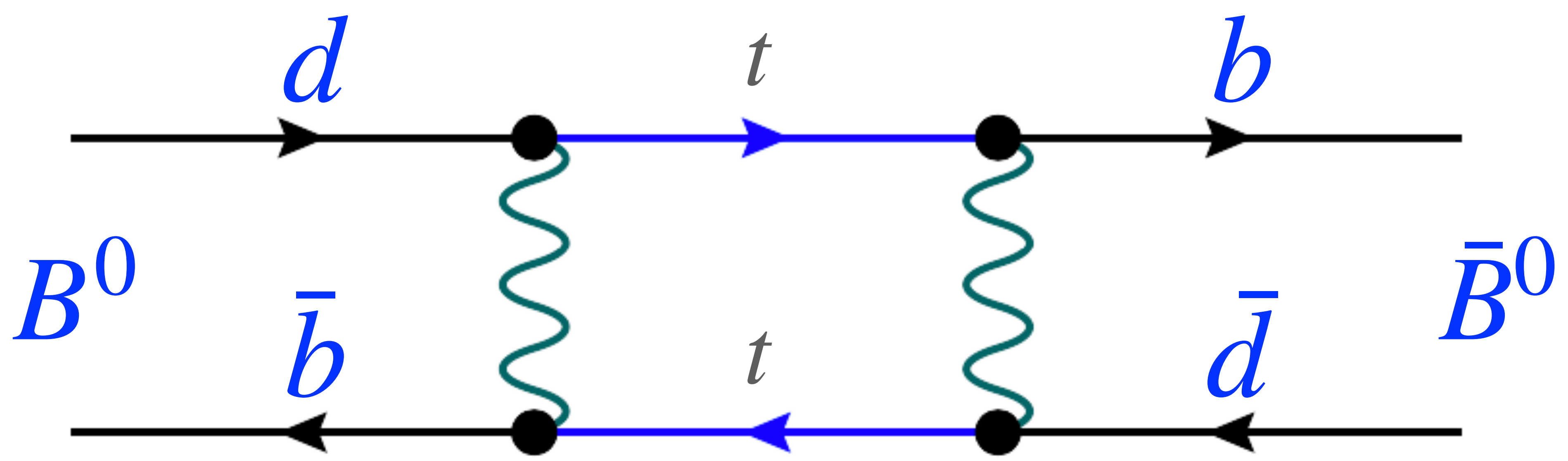
Timeline (outdated)

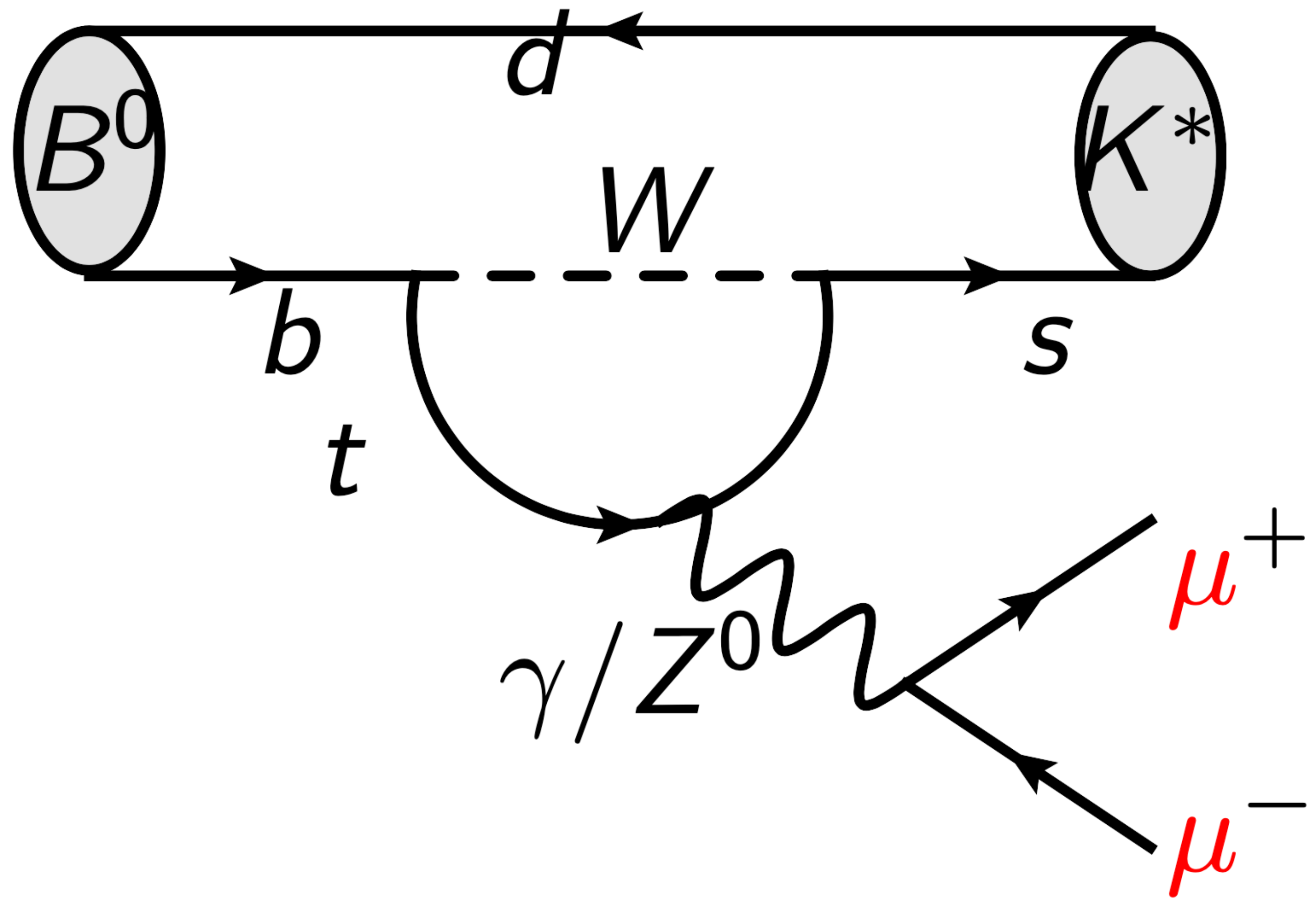


- Today: LHCb running ~ stable (upstream tracker + vertex detector seem OK)
  Belle II re-started in February, pixel detector off due to beam losses
- Direct future (~2028): LHCb $\sim 30\,\mathrm{fb}^{-1}$ and Belle II $\sim 5\,\mathrm{ab}^{-1}$
- early 2030s: LHCb $\sim 50\,\mathrm{fb}^{-1}$ and Belle II $\sim 50\,\mathrm{ab}^{-1}$
- late 2030s: LHCb upgrade II $\sim 300\,\mathrm{fb}^{-1}$ and Belle III $\sim 250\,\mathrm{ab}^{-1}$
- 2040s FCC-ee : Tera-Z: $5 \times 10^{12}\, Z$ decays

How B physics works

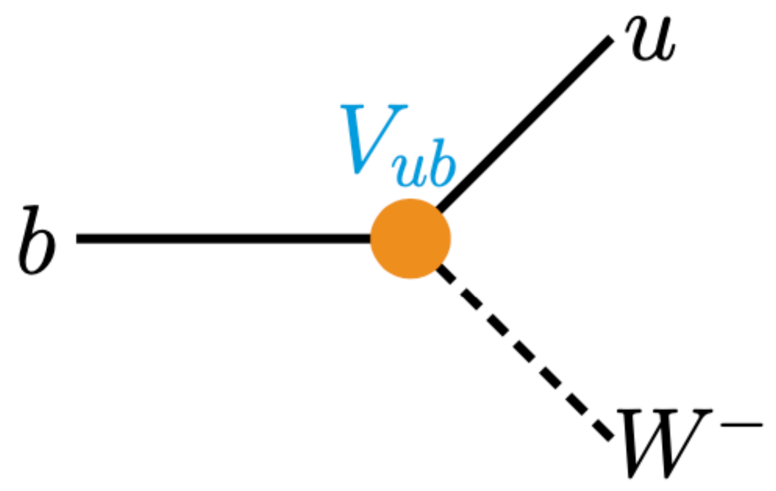
- We mostly perform precision measurement of processes that aren't tree level:
  - Box diagrams that appear in B^0-$\bar{B}^0$ and B_s^0-$\bar{B}_s^0$ mixing
  - Penguin diagrams mediating some B hadron decays
- New physics, even heavy, could interfere with these diagrams, modifying observables
  - Example: Argus observed substantial B^0-$\bar{B}^0$ mixing $\Longrightarrow$ means the top quark is *very* heavy

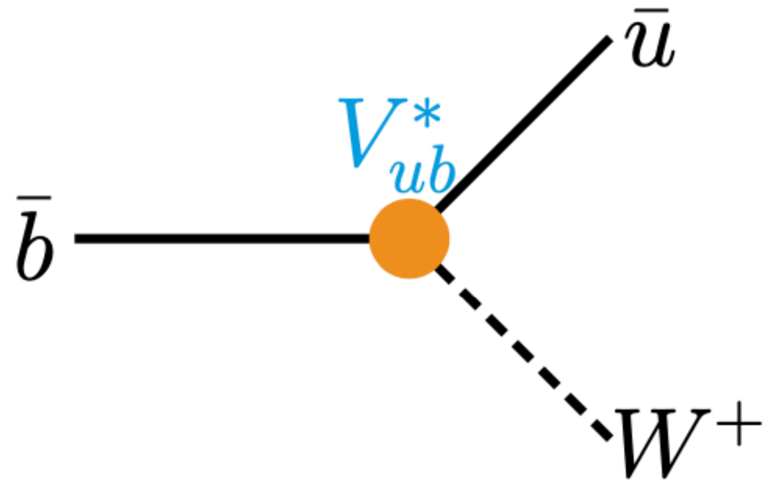




The CKM matrix

CKM matrix: rotate down-type quarks from mass to flavour basis

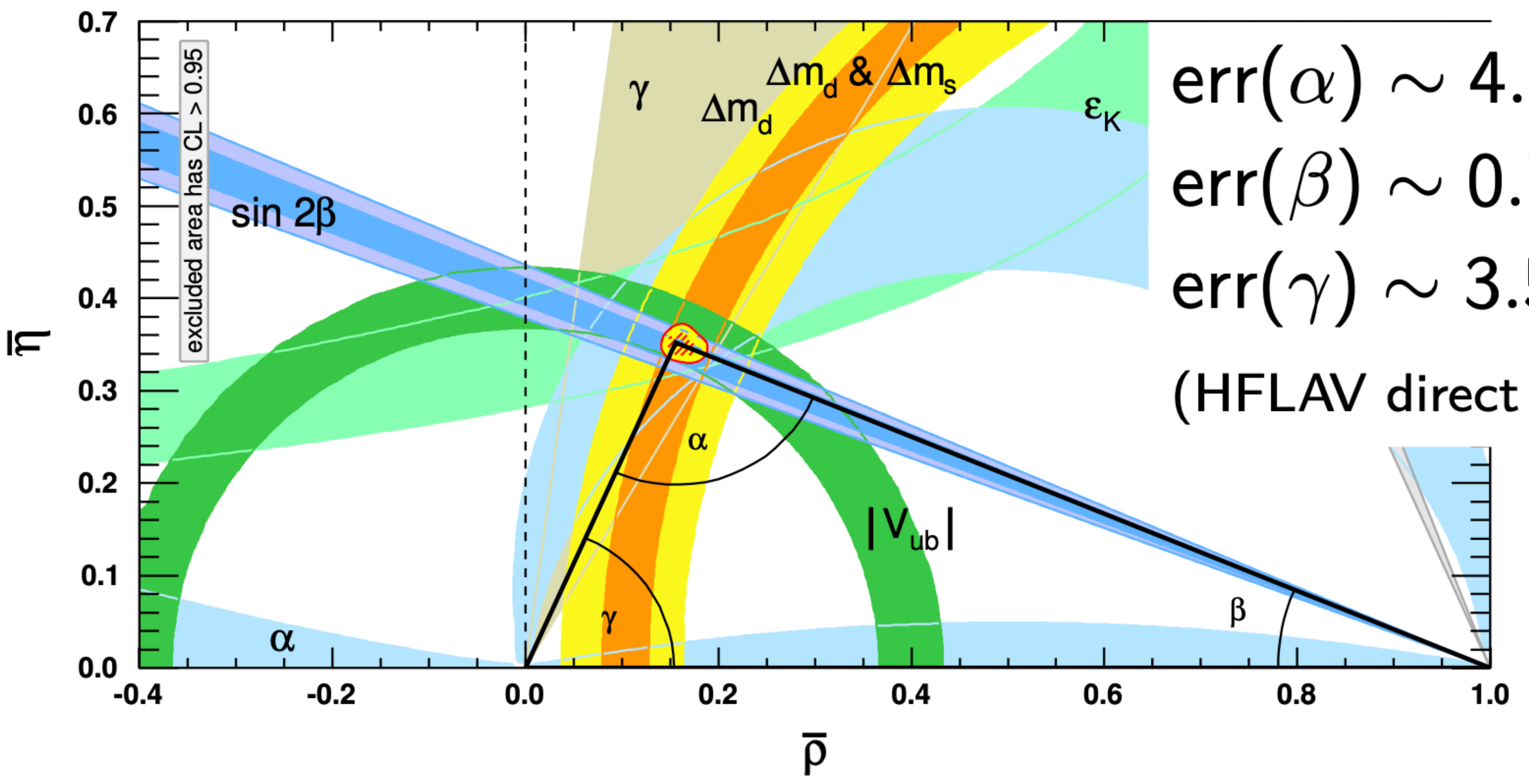




$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 0.97 & 0.22 & 0.004e^{1.1i} \\ 0.22 & 0.99 & 0.04 \\ 0.008e^{0.4i} & 0.04 & 1.00 \end{pmatrix}$$

$$V_{td} = |V_{td}|e^{i\beta} \quad V_{ub} = |V_{ub}|e^{i\gamma}$$

Constraints best visualised as unitary triangle in complex plane



$\mathrm{err}(\alpha) \sim 4.5°$

$\mathrm{err}(\beta) \sim 0.7°$

$\mathrm{err}(\gamma) \sim 3.5°$

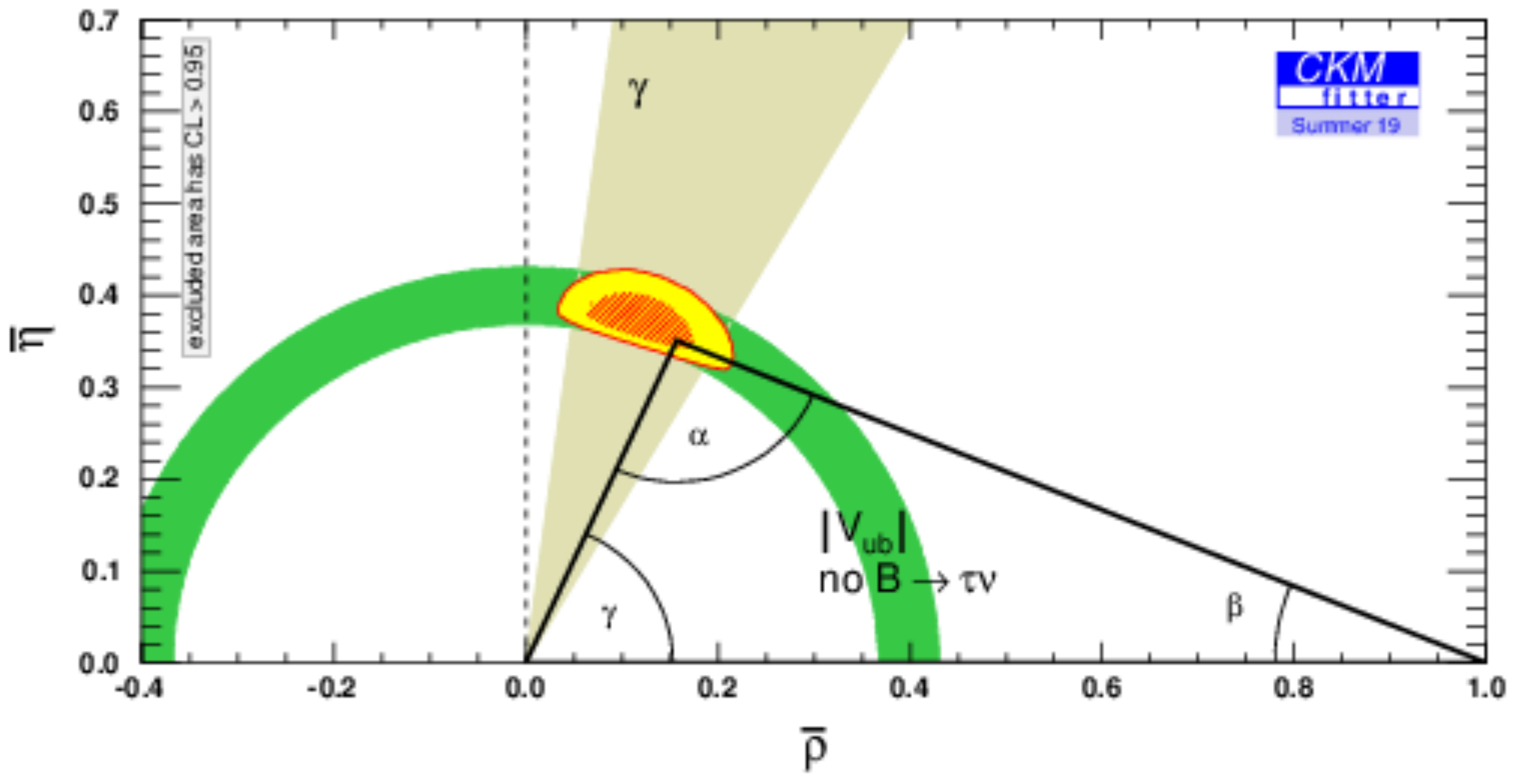
(HFLAV direct meas.)

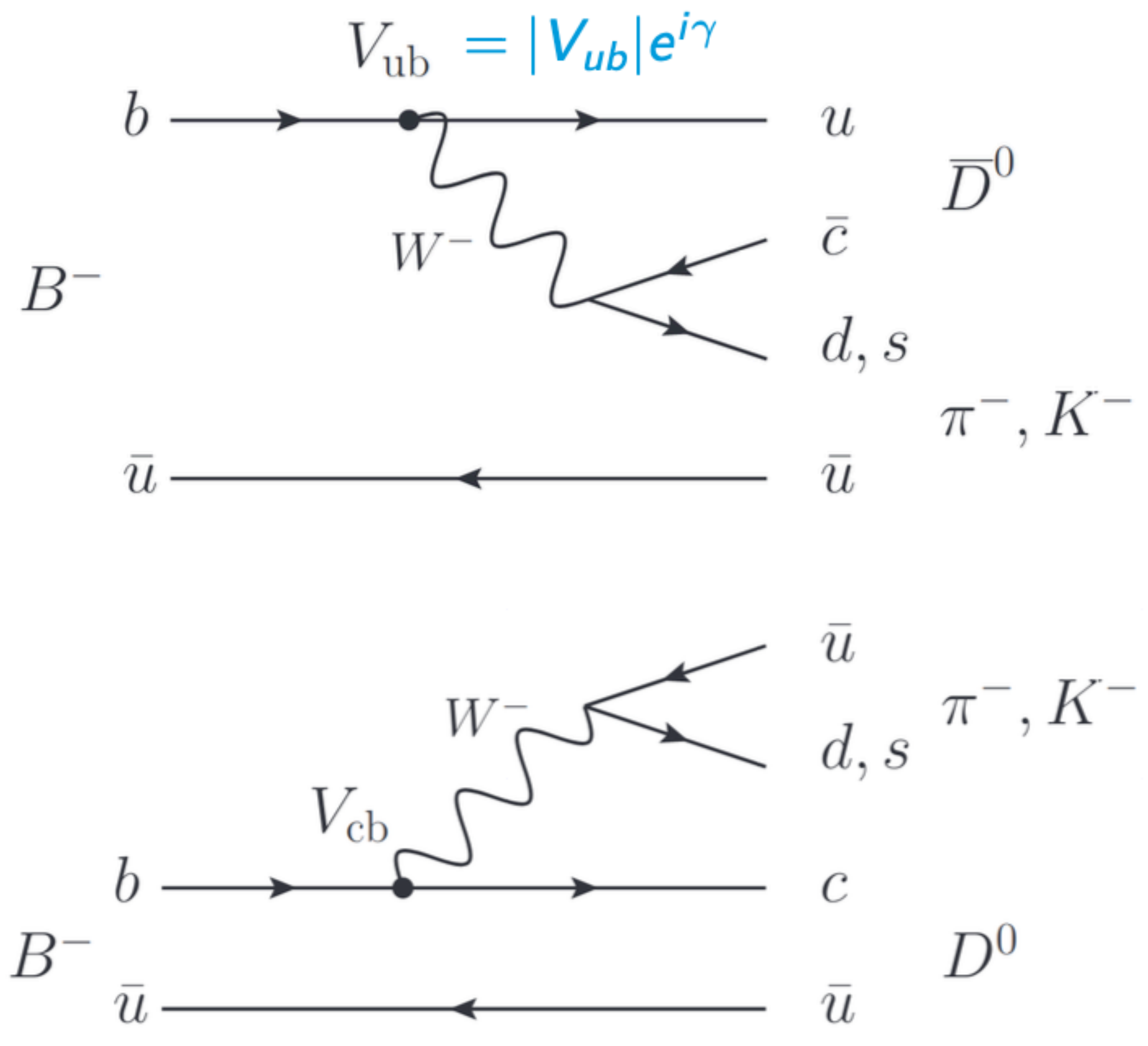
SM standard candles

Left side and γ depend on tree-level decays
→ “standard candles” for apex position

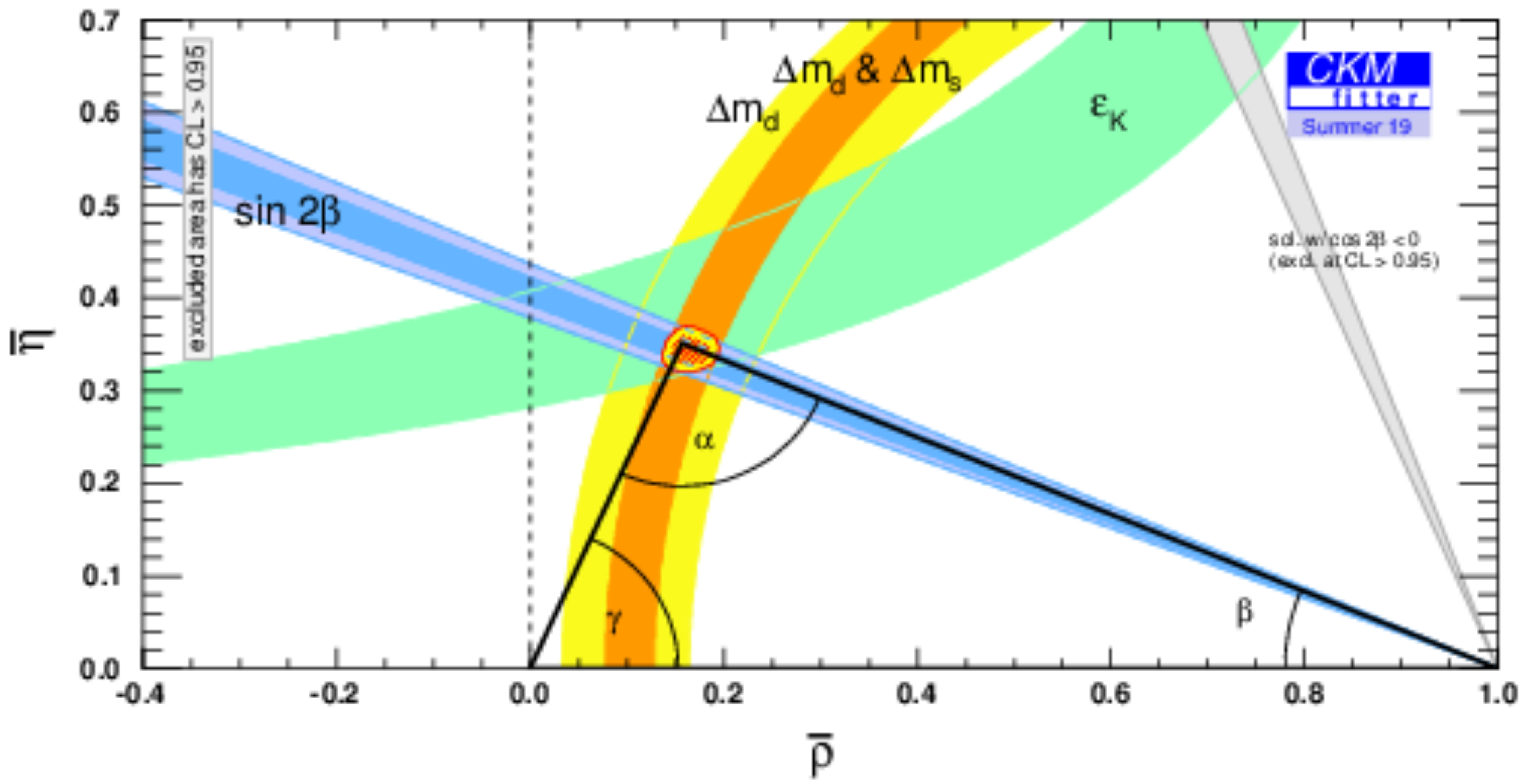
- $|V_{ub}|$ and $|V_{cb}|$ from rates of $B \to \pi\ell\nu$ and $B \to D\ell\nu$ decays

- γ from (direct) CP-asymmetry between $B^+ \to D^0K^+$ and $B^- \to D^0K^-$ decays (or similar)





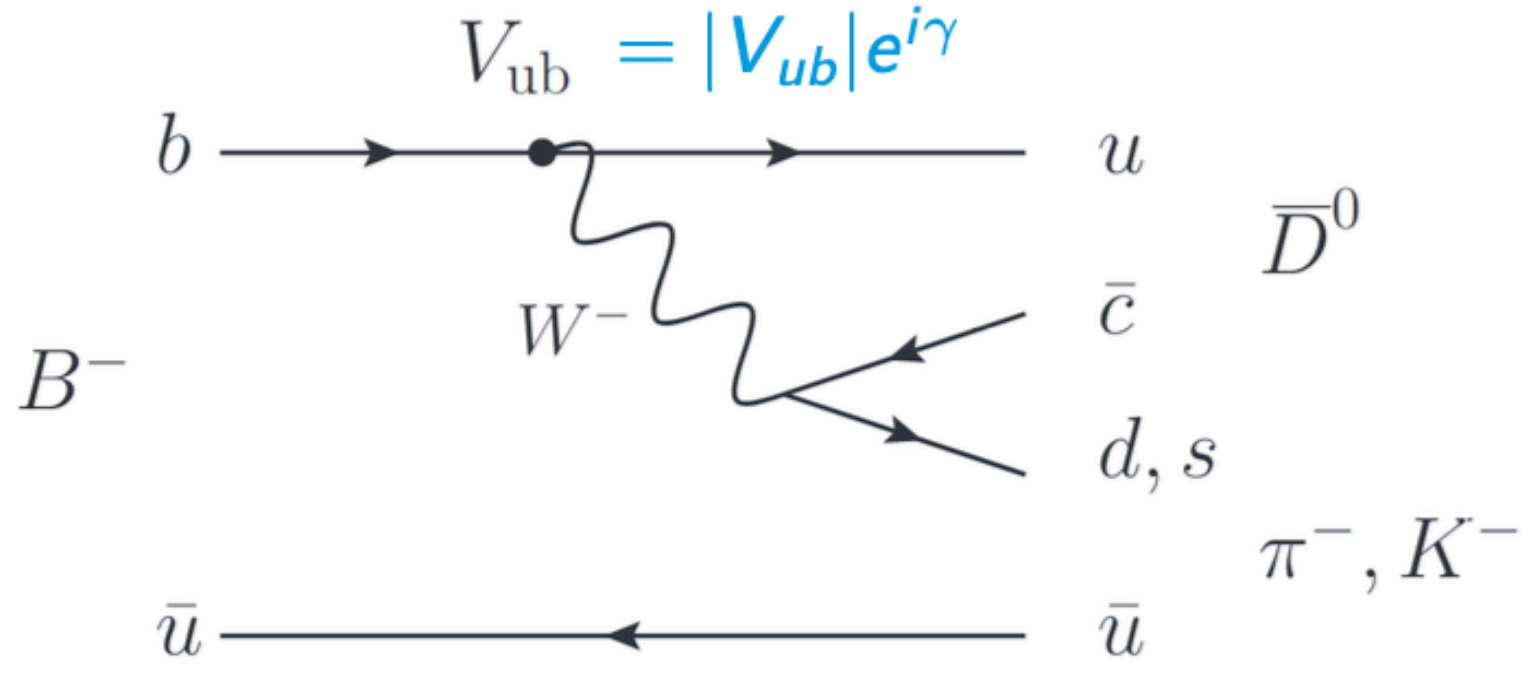
SM standard candles

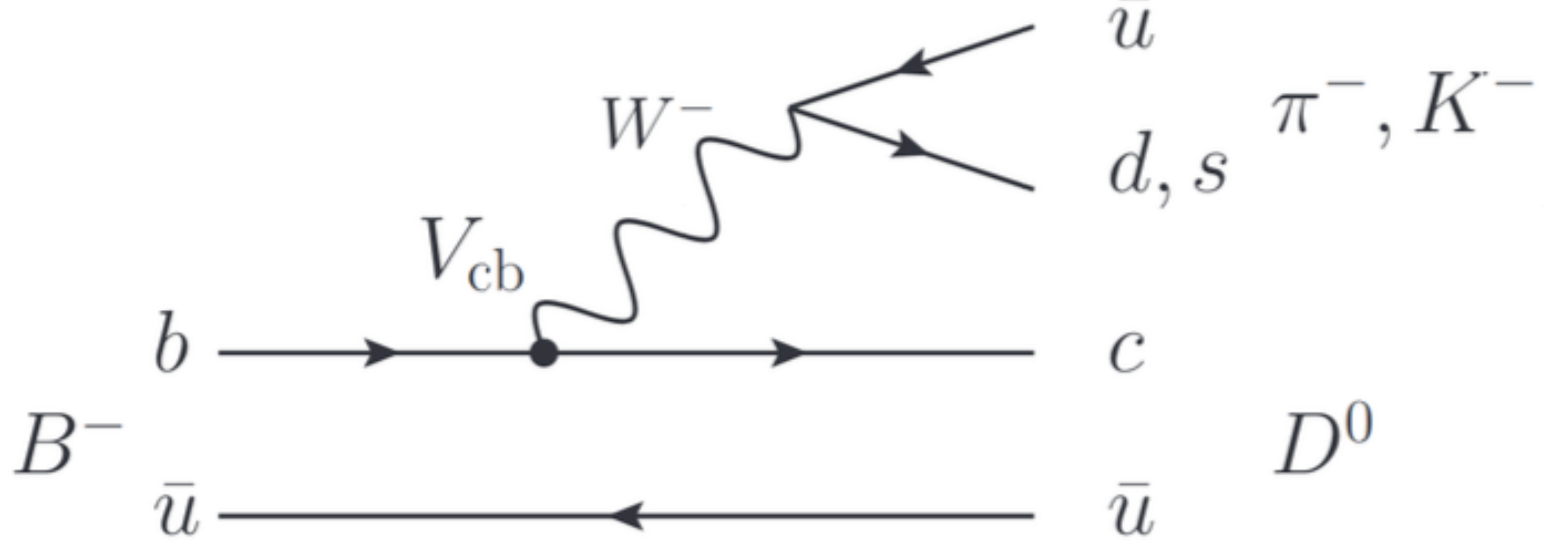


Left side and γ depend on tree-level decays
→ "standard candles" for apex position

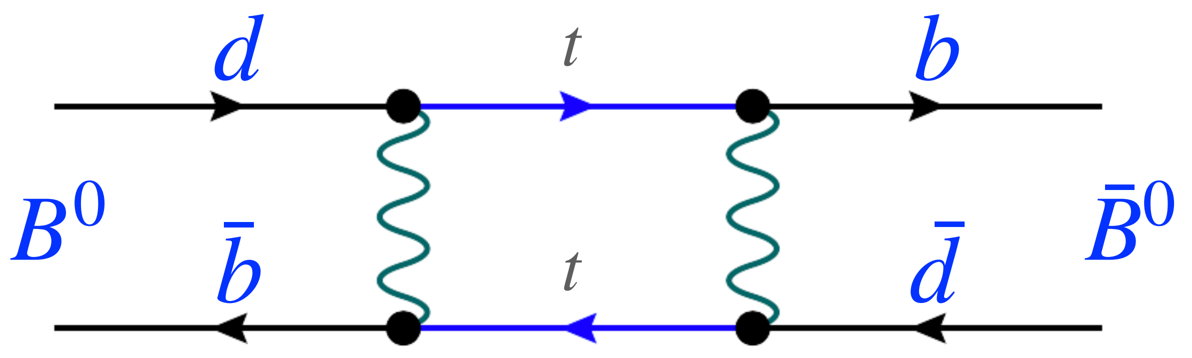
- $|V_{ub}|$ and $|V_{cb}|$ from rates of $B \to \pi\ell\nu$ and $B \to D\ell\nu$ decays

- γ from (direct) CP-asymmetry between $B^+ \to D^0K^+$ and $B^- \to D^0K^-$ decays (or similar)





All other constraints involve the box diagram



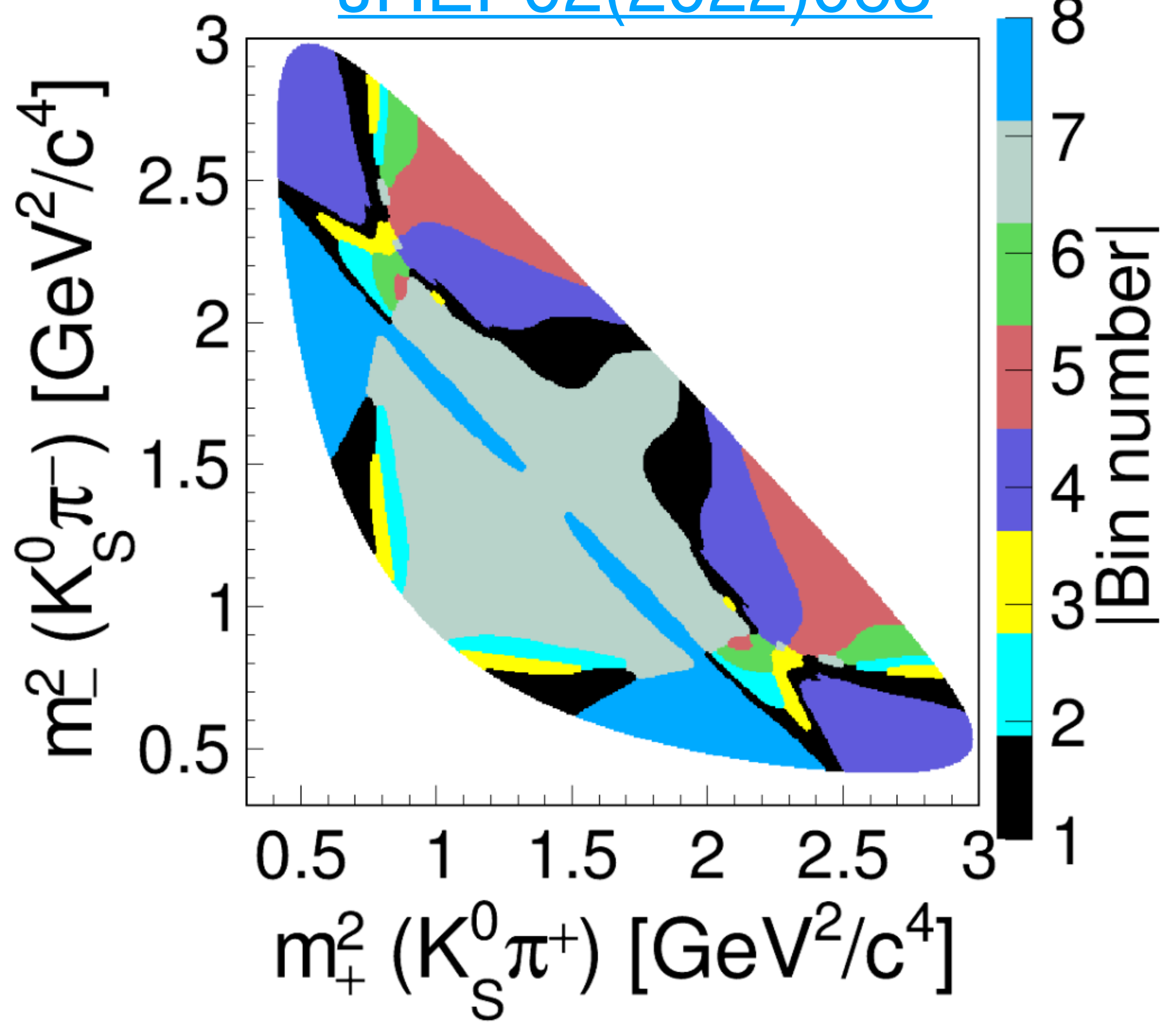
Gamma: today

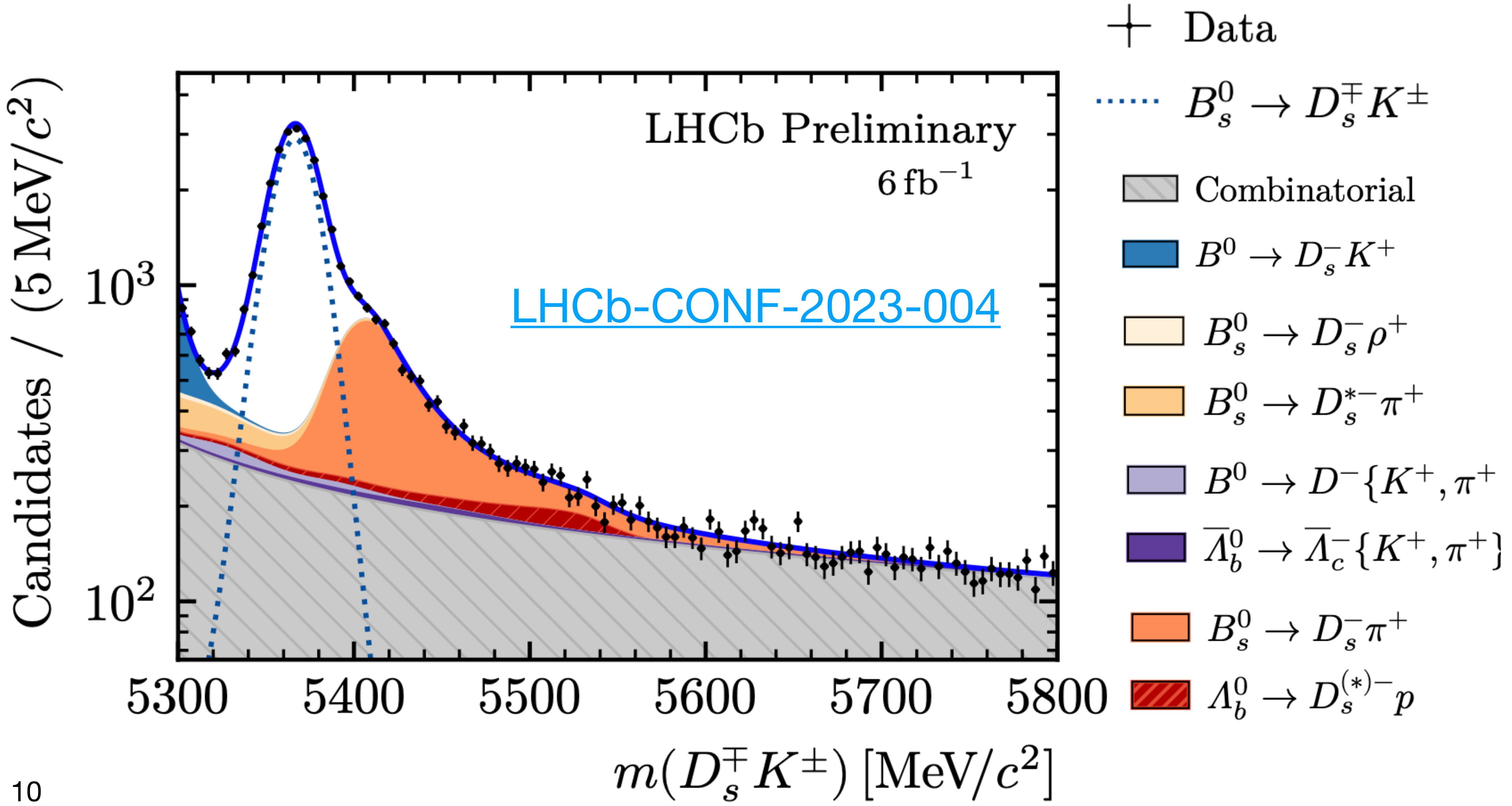
Most precise method today:
→ use $B^+ \to D^0 K^+$ with D^0 3- or 4-body decay
→ measure A_{CP} in bins of D^0 Dalitz plane
→ use BESIII inputs from $e^+e^- \to D^0\bar{D}^0$ to get γ

Other methods exist (less precise today):
→ $B^+ \to D^0 K^+$ with D^0 2-body decays
→ $B_s^0 \to D_s^- K^+$ decay-time-dependent

- LHCb comb.: $\gamma = 65.4^{+3.8}_{-4.2}$ JHEP12(2021)141
- Belle I+II comb.: $\gamma = 78.6^{+7.2}_{-7.3}$ arXiv:2404.12817

Belle + Belle II
JHEP02(2022)063





Gamma: future

- sub-degree precision will be reached from combination of different methods
- no systematic bottleneck expected
- LHCb expected to drive the precision, both in medium-term future and with HL-LHC

Belle $50\,\mathrm{ab}^{-1}$	LHCb $50\,\mathrm{fb}^{-1}$	LHCb $300\,\mathrm{fb}^{-1}$	FCC-ee
$\sim 1.5\,\mathrm{deg}$	$\sim 1.0\,\mathrm{deg}$	$\sim 0.35\,\mathrm{deg}$	$\sim 0.25\,\mathrm{deg}$

$|V_{cb}|$ & $|V_{ub}|$: today

Exclusive measurements:

$|V_{ub}|$ & $|V_{cb}|$@Belle (II): $B \to \pi\ell\nu$, $B \to D^{(*)}\ell\nu$

$|V_{ub}|/|V_{cb}|$@LHCb: e.g. $\Lambda_b^0 \to p^+\ell\nu/\Lambda_b \to \Lambda_c\ell\nu$

Inclusive measurements: $B \to X_c\ell\nu$, $B \to X_u\ell\nu$

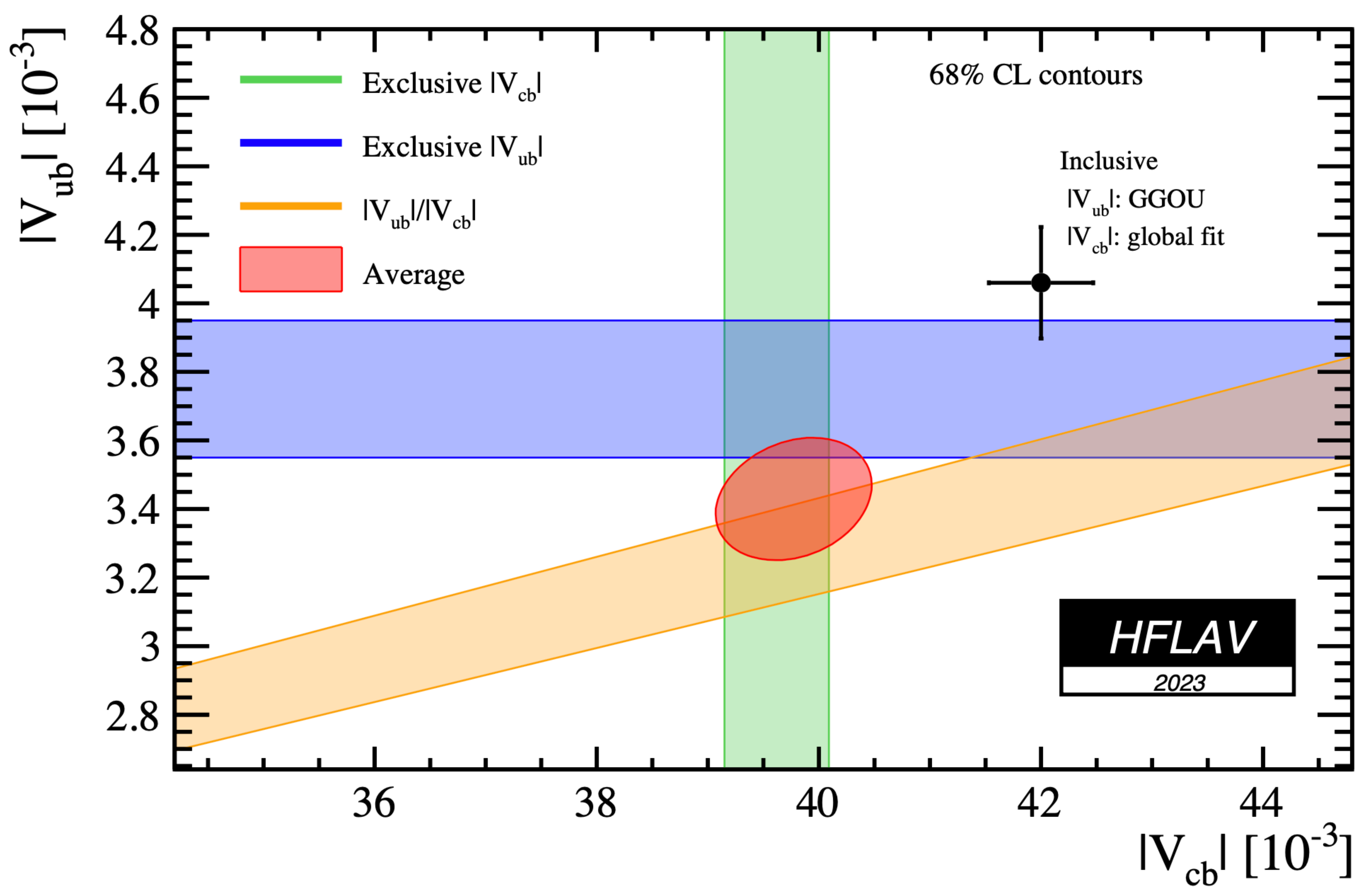
→ Impossible in hadronic environment: need known kinematics and full event reconstruction

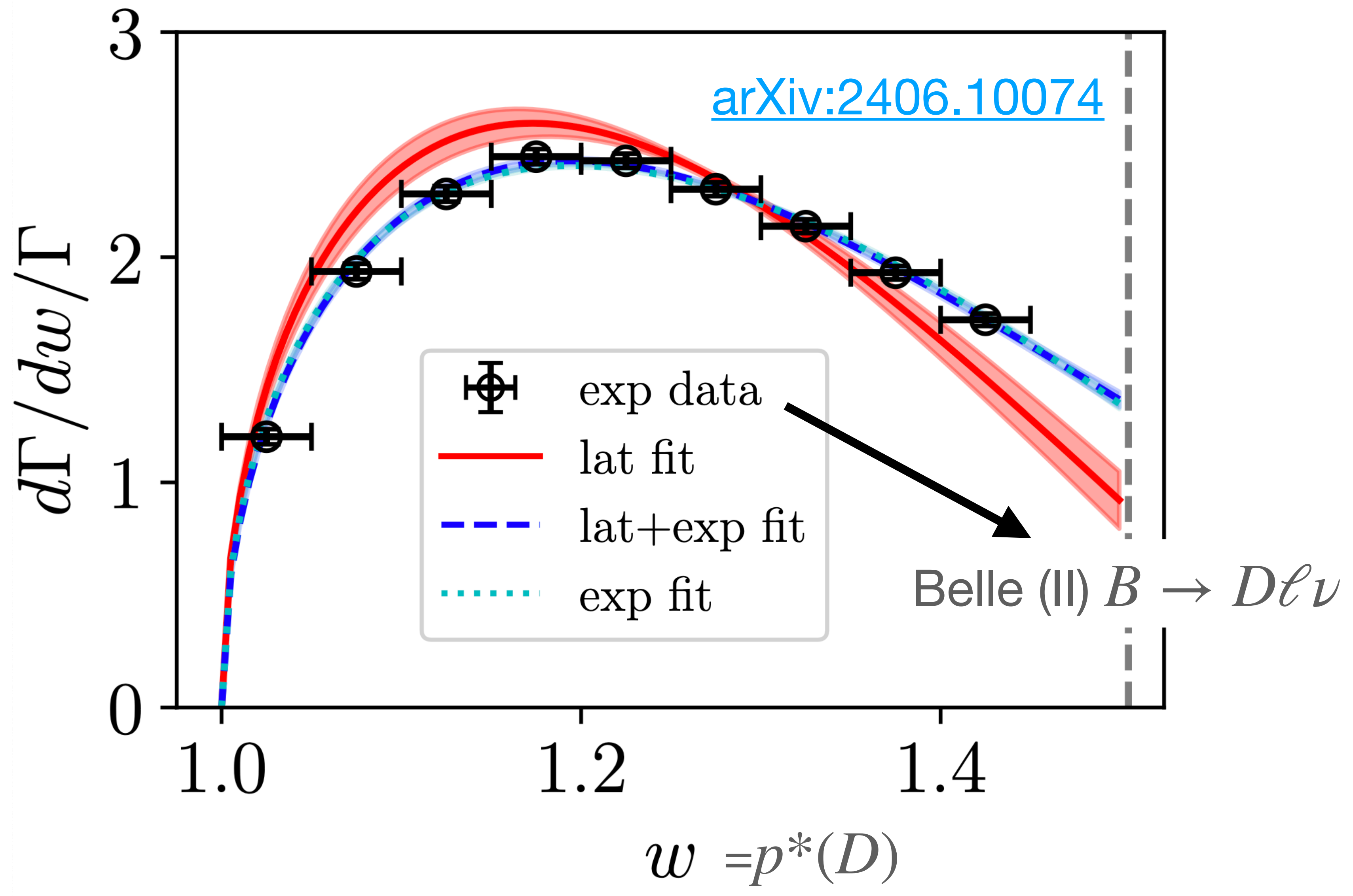
Different frameworks for excl. and incl. predictions (lattice vs HQET)

Tension between inclusive and exclusive:

→ Precise studies of QCD parameterisations using unfolded kinematic distributions

→ Improving understanding of various peaking backgrounds that may bias the result



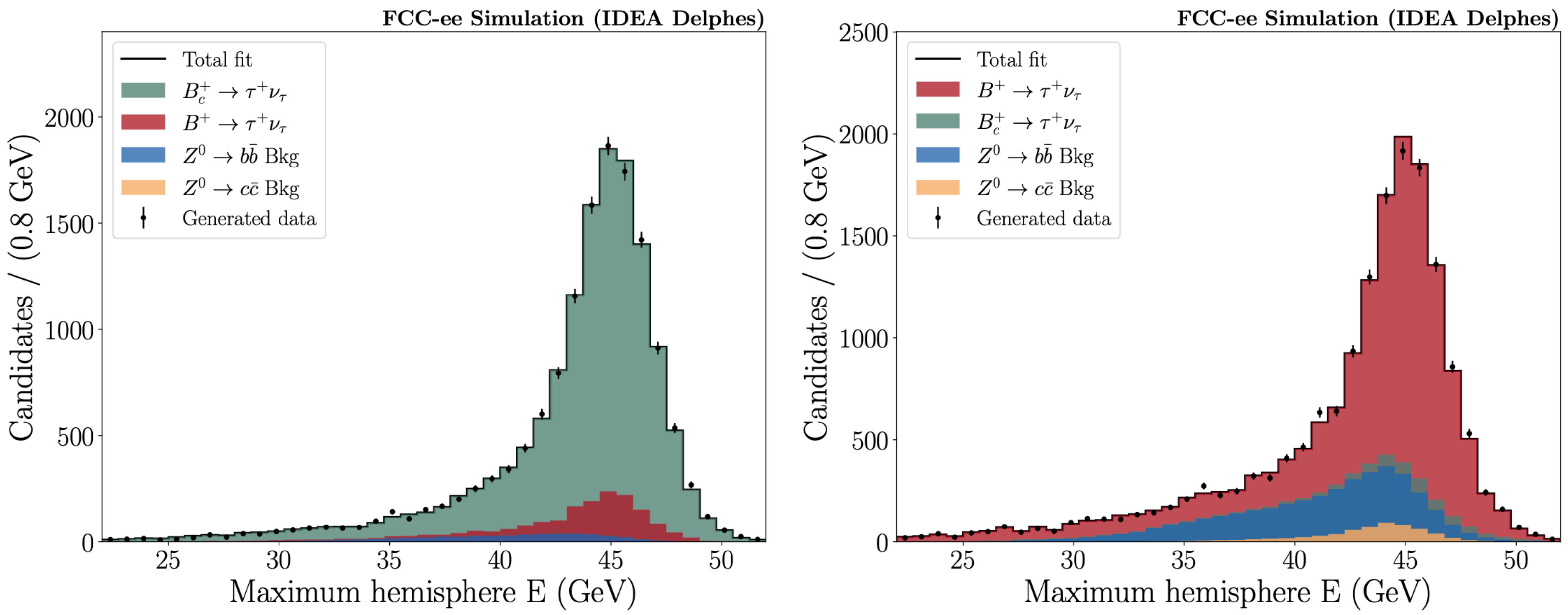


$|V_{cb}|$ & $|V_{ub}|$: future

FCC-ee could measure $|V_{ub}|$ with $B^+ \to \tau^+\nu$
→ only decay constant as theory input

FCC-ee can also measure $B_c^+ \to \tau^+\nu$
→ precision on V_{cb} limited by knowledge $b \to B_c$ fragmentation fraction
→ (also important to investigate $R_{D^{(*)}}$ anomaly)

Real benefit @ FCC-ee: $|V_{cb}|$ from $W^+ \to c\bar{b}$
→ $\sim 0.5\,\%$ precision, 3X better than SL decays at HL-LHC or Belle II

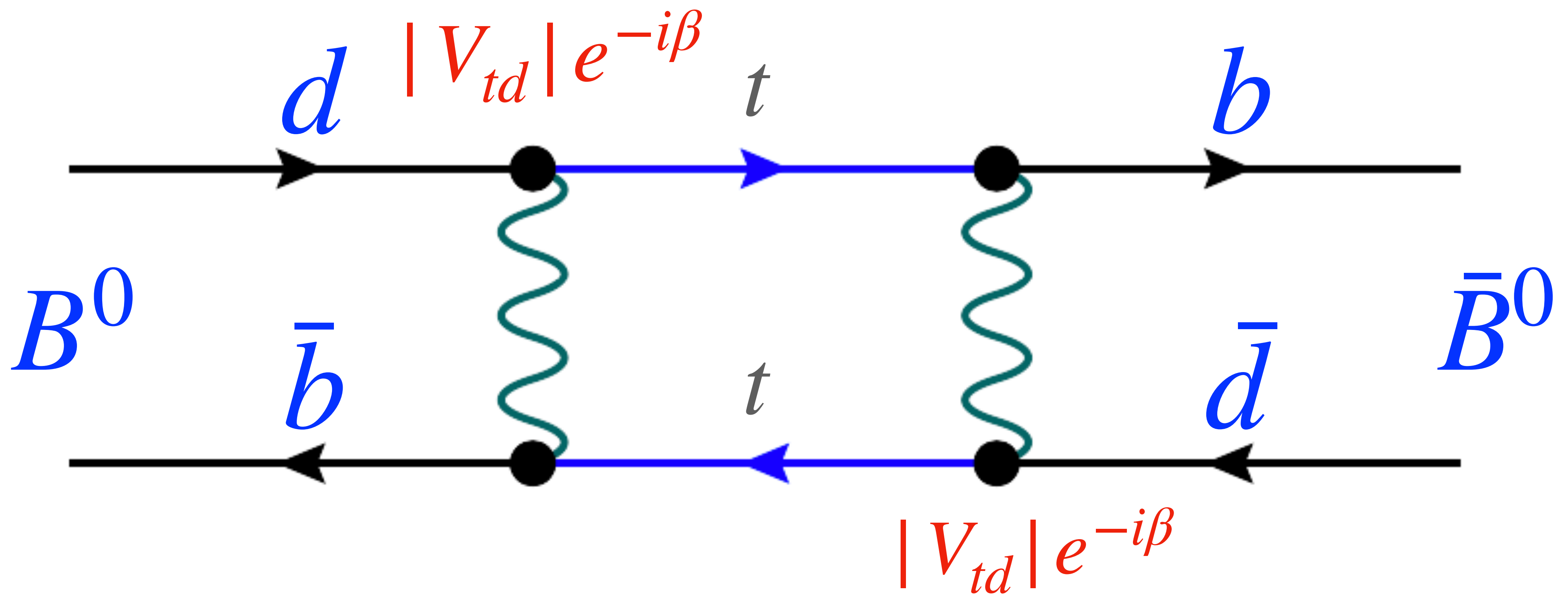


Can separate B_c and B^+ well, as B_c has a shorter lifetime
arXiv:2305.02998

	Belle $50\,\mathrm{ab}^{-1}$	FCC-ee	th
V_{ub} SL	1-3%	$\sim 1\%$	$\sim 1\%$
V_{ub} $B^+ \to \tau^+\nu$	$\sim 3\%$	$\sim 2\%$	$\sim 2\%$

Mixing diagram and mixing frequency

Other measurements in the CKM triangle are related to the B^0-$\bar{B}^0$ mixing box diag.
→ suppressed, sensitive to new physics

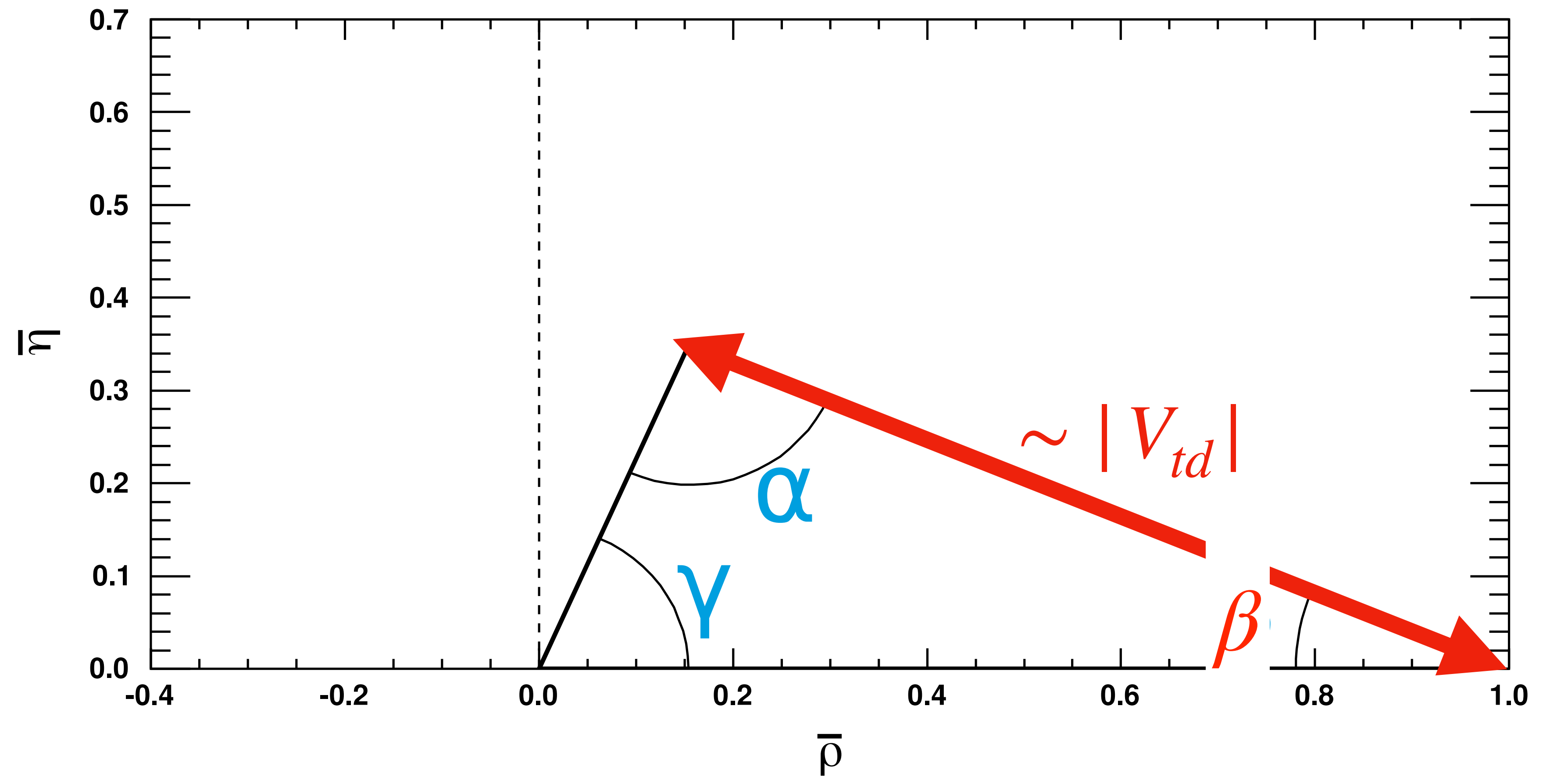


|box| ~ $|V_{td}|^2$ ~ B^0-$\bar{B}^0$ osc. freq. Δm_d:

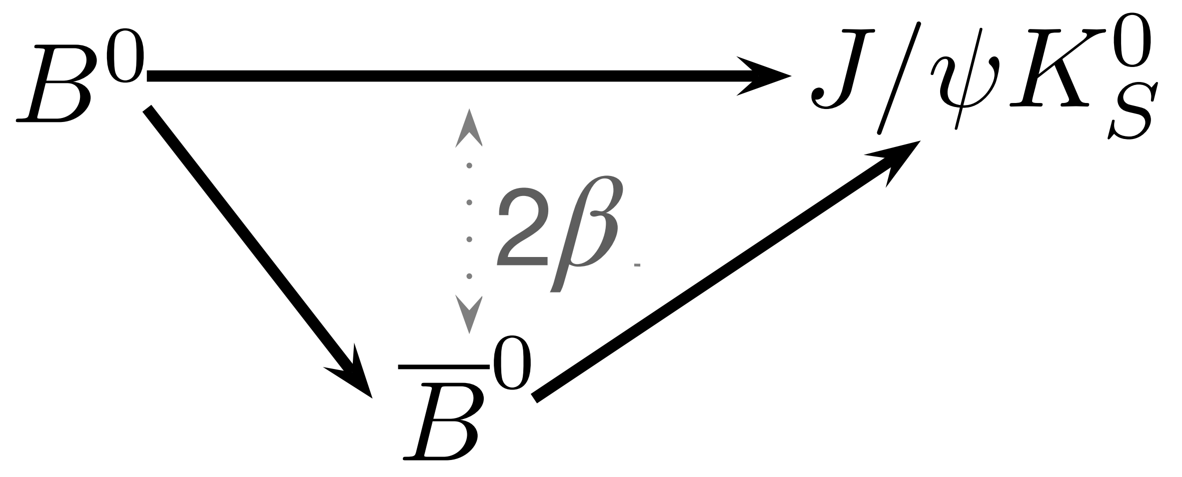
$$N\left(B^0 \to \bar{B}^0(t) \text{ or } \bar{B}^0 \to B^0(t)\right) \sim 1 - \cos(\Delta m_d t)$$

Accuracy dominated by LHCb using $B^0 \to D^{*-}\mu^+\nu$

But: theory prediction (lattice) $10\times$ less accurate than measurement, even worse for B_s^0-$\bar{B}_s^0$

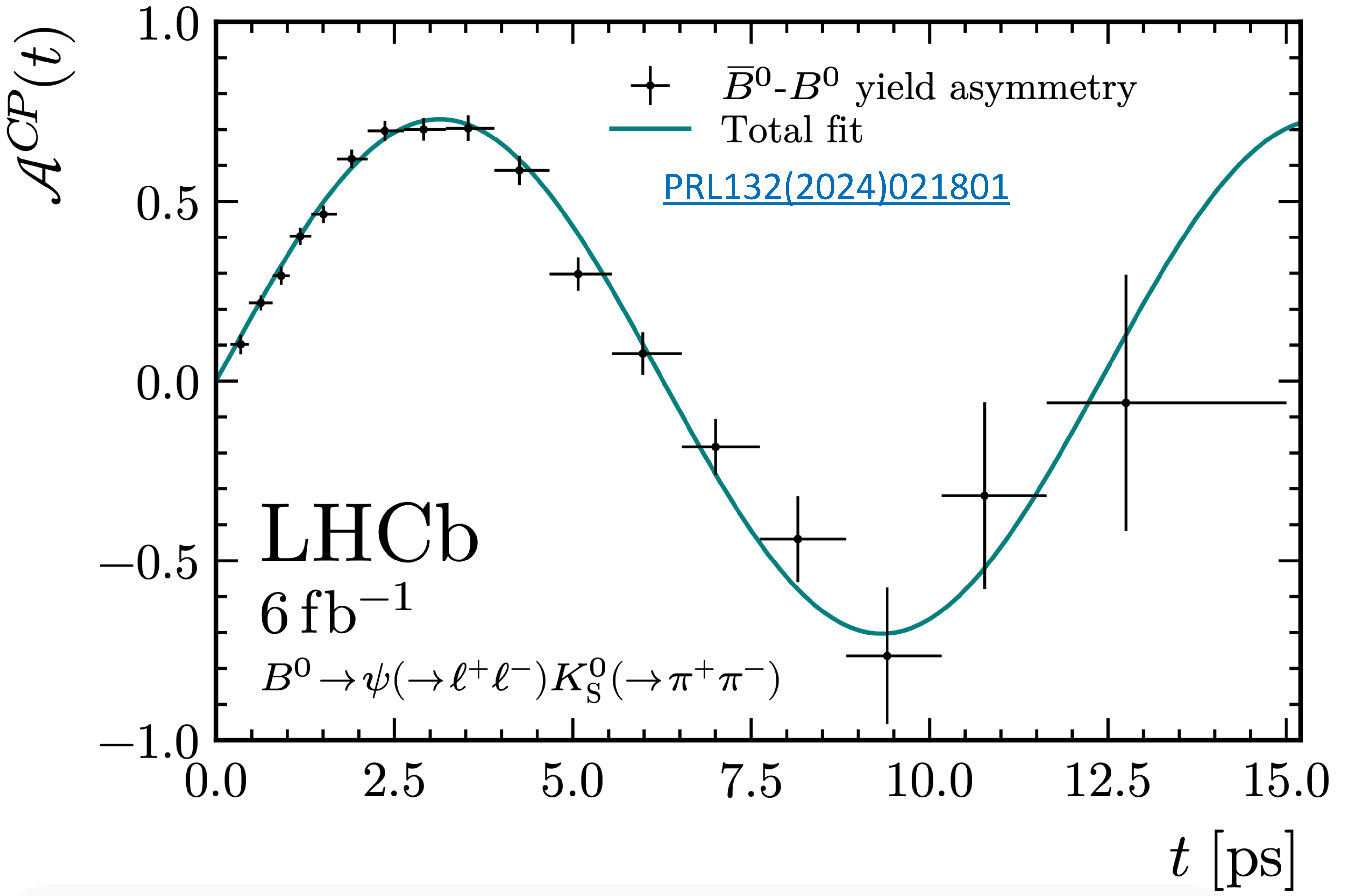


Mixing phase and $\sin 2\beta$



Historical flagship at LHCb & Belle II:

$$\frac{N(B^0 \to J/\psi K_S)(t) - N(\bar{B}^0 \to J/\psi K_S)(t)}{N(B^0 \to J/\psi K_S)(t) + N(\bar{B}^0 \to J/\psi K_S)(t)} = \sin 2\beta \sin \Delta m_d t$$



Best known angle, future accuracy will depend on how much we control:

→ time resolution

→ flavour tagger calibration

→ interference with penguin decays, can be constrained from the data (using e.g. $B^0 \to J/\psi\pi^0$)

Marginal improvements from FCC-ee (maybe in the study of penguin-free modes?)

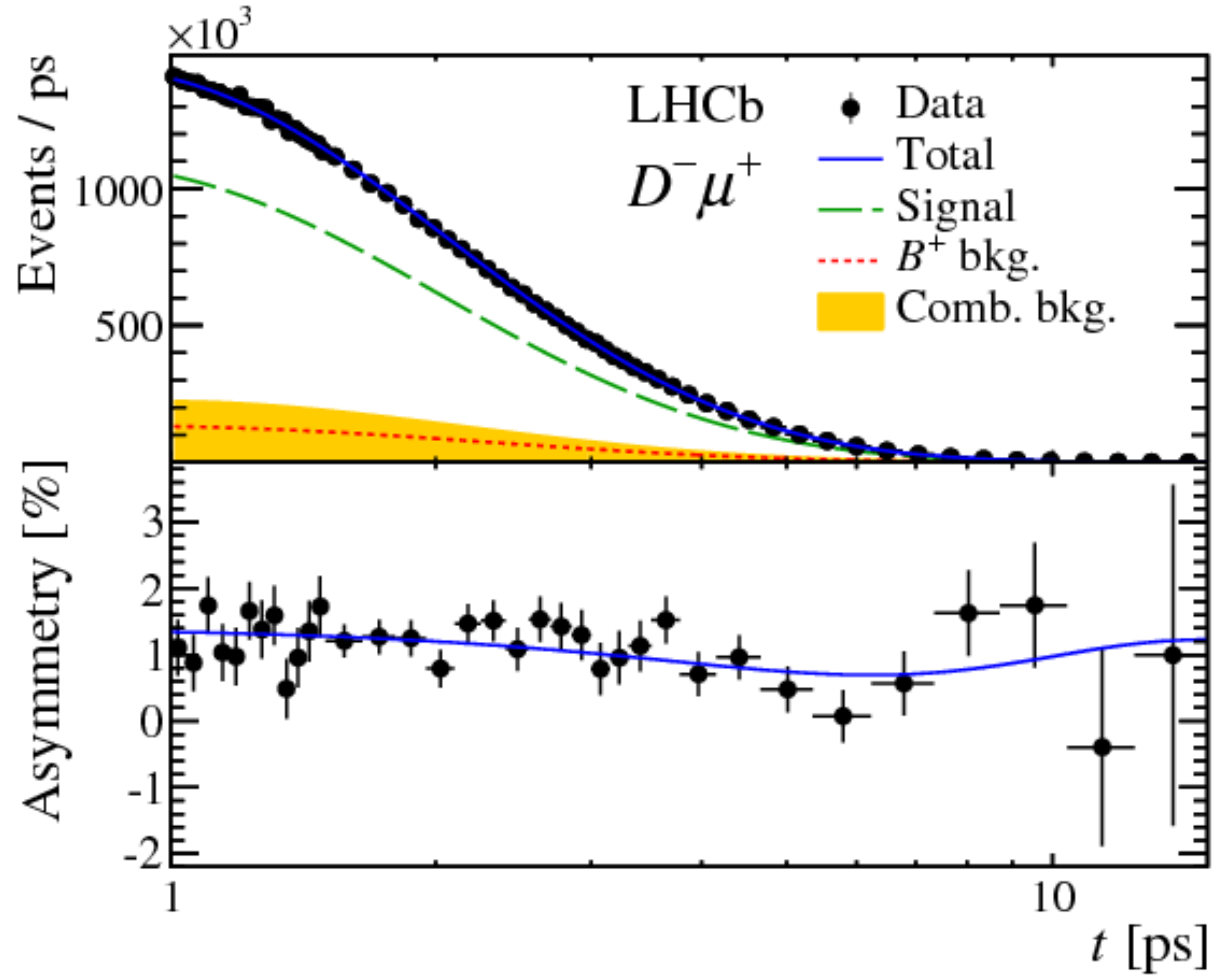
Belle now	LHCb now	Belle $50\,\mathrm{ab}^{-1}$	LHCb $300\,\mathrm{fb}^{-1}$
20.9 ± 1.0 deg	23.1 ± 0.6 deg	$\pm \sim 0.3$ deg	$\pm \sim 0.1$ deg

LHCb: more data
Belle II: better tagging

Semileptonic asymmetries

PRL114(2015)041601

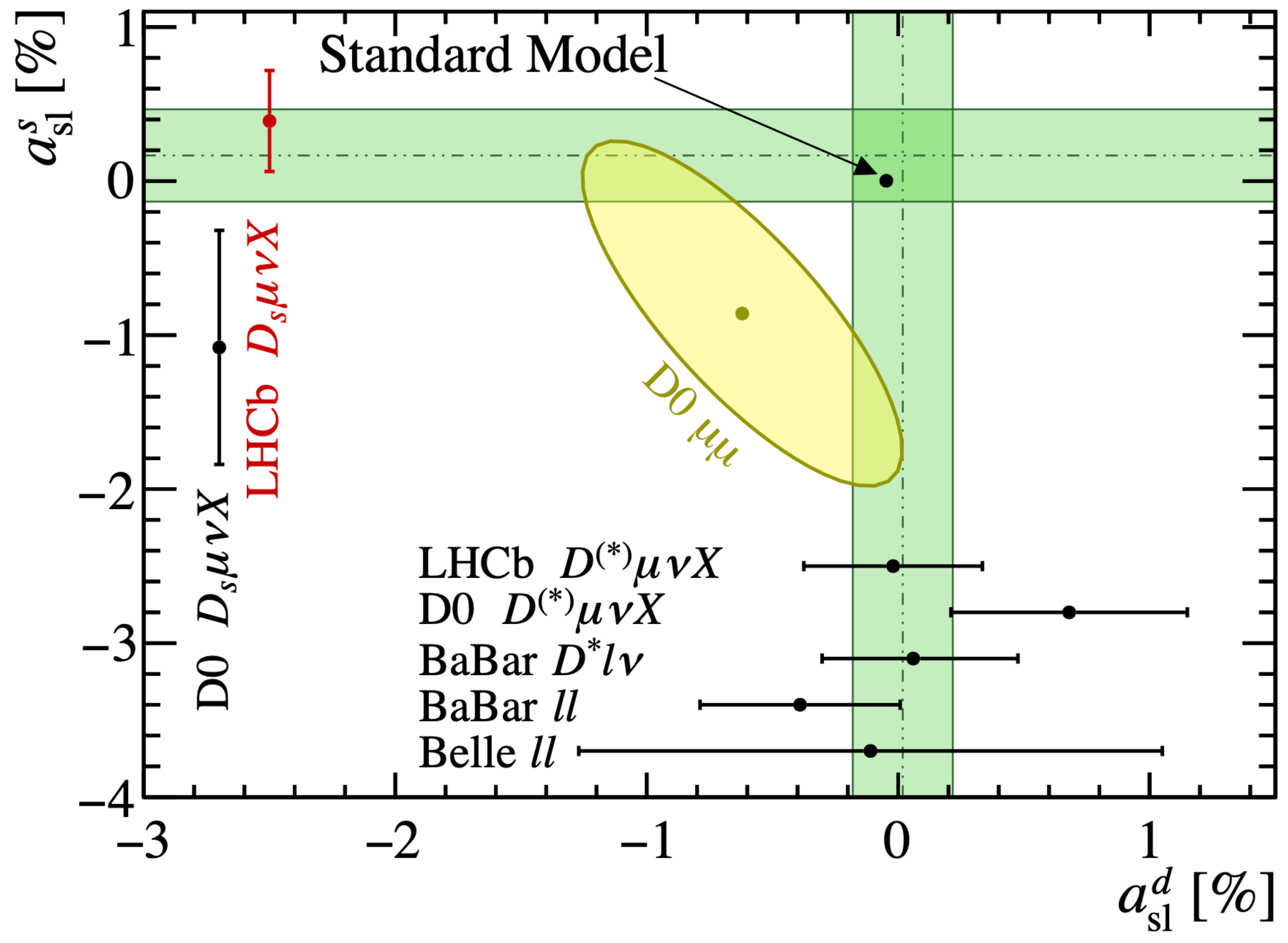
$$a_{sl} = \frac{N(\bar{B}^0 \to B^0) - N(B^0 \to \bar{B}^0)}{N(\bar{B}^0 \to B^0) + N(B^0 \to \bar{B}^0)}$$



unlike mixing freq., clean theory prediction

LHCb: decay time shape in $B \to D^{(*)-}\mu^+\nu$ vs $B \to D^{(*)+}\mu^-\nu$ decays

Challenges: to control:
→ Production asymmetry
→ Detection asymmetries (calibrated with D decays)
→ Backgrounds



FCC-ee with similar analysis ⇒ best precision

	LHCb now	LHCb 300fb^{-1}	FCC-ee	theo
δa_{sl}^d $[10^{-4}]$	36	2	0.25	0.6
δa_{sl}^s $[10^{-4}]$	33	3	0.25	0.03

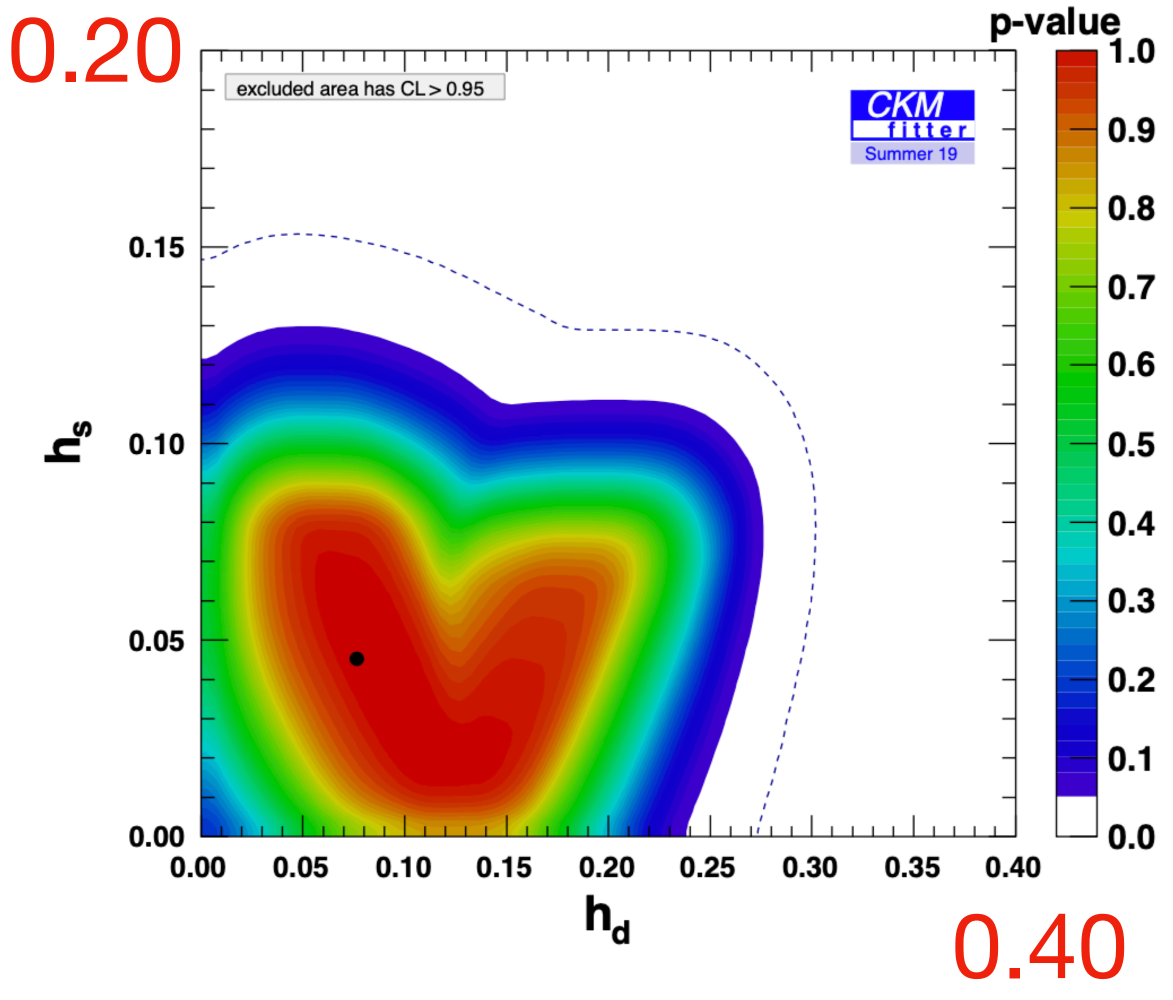
Summary

[PRD102(2020)056023](PRD102(2020)056023)

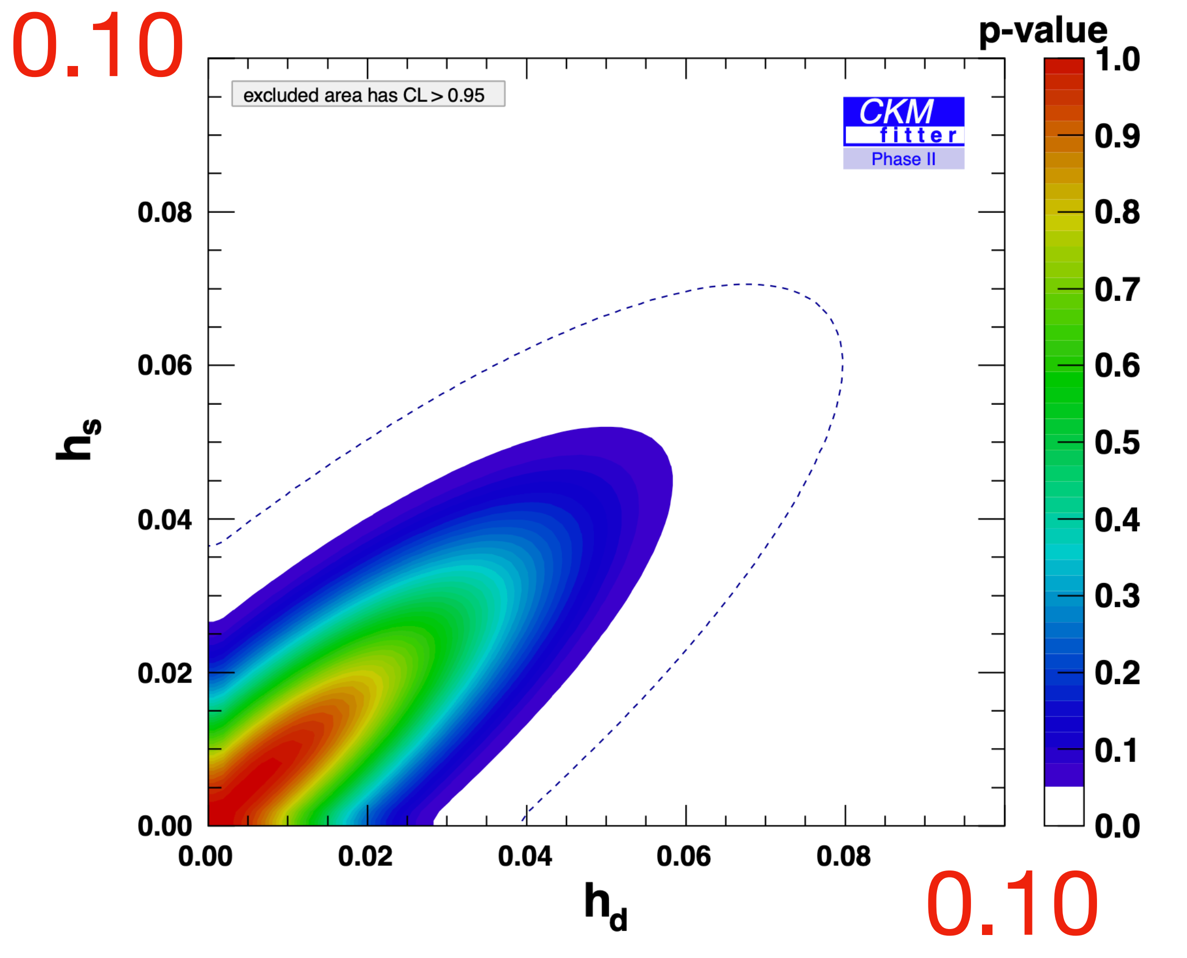
Fit the CKM triangle measurements with parameterisation:

$$A_{box} = A_{box}^{SM} \cdot \left(1 + h_{s,d}\, e^{i\sigma_{s,d}}\right)$$

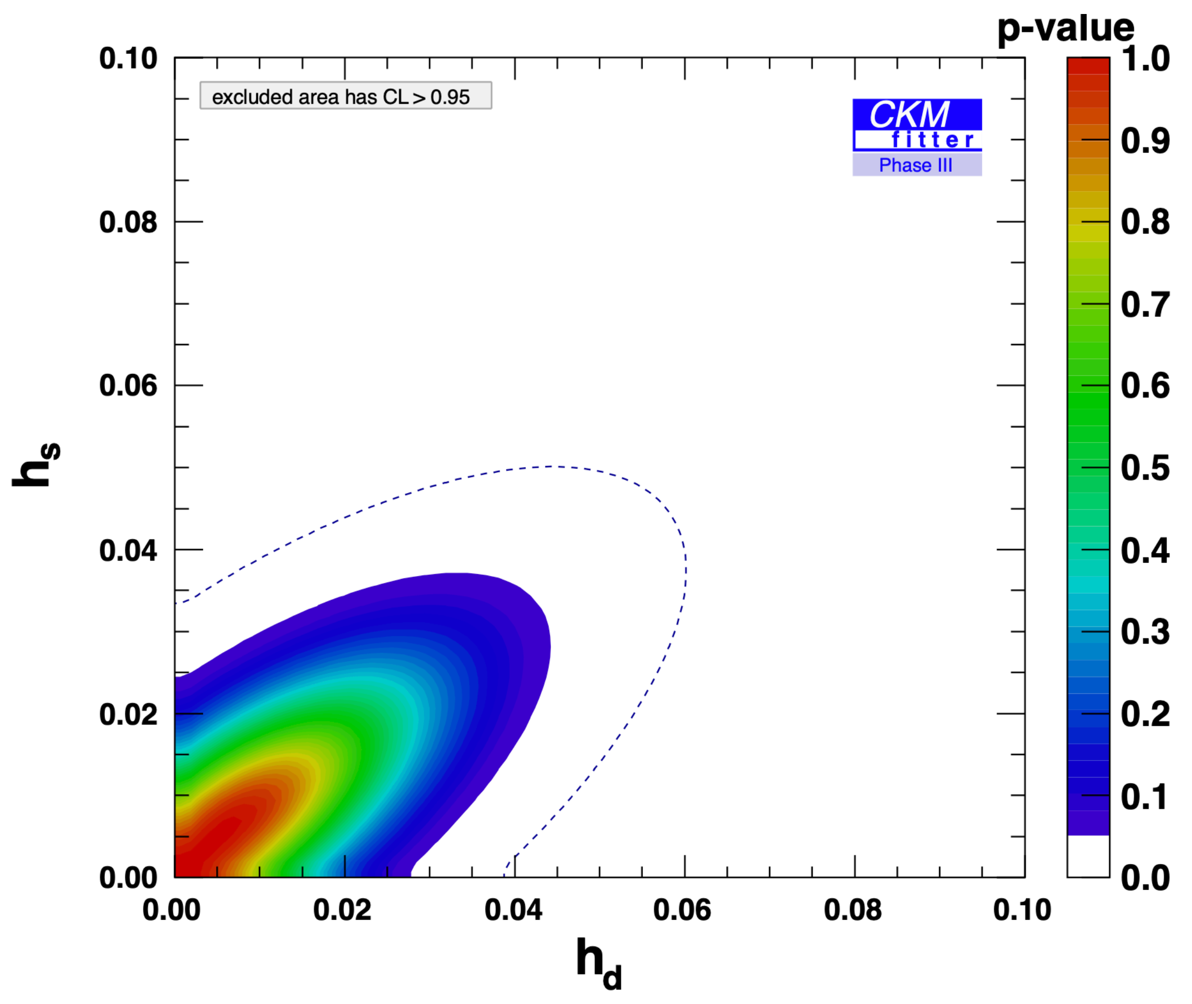
- Today, $h_{s,d} < \sim 15\,\%$
- Would reduce to $\sim 3\,\%$ with FCC-ee, HL-LHC, Belle II
- Control of theory uncertainties critical to reach this precision



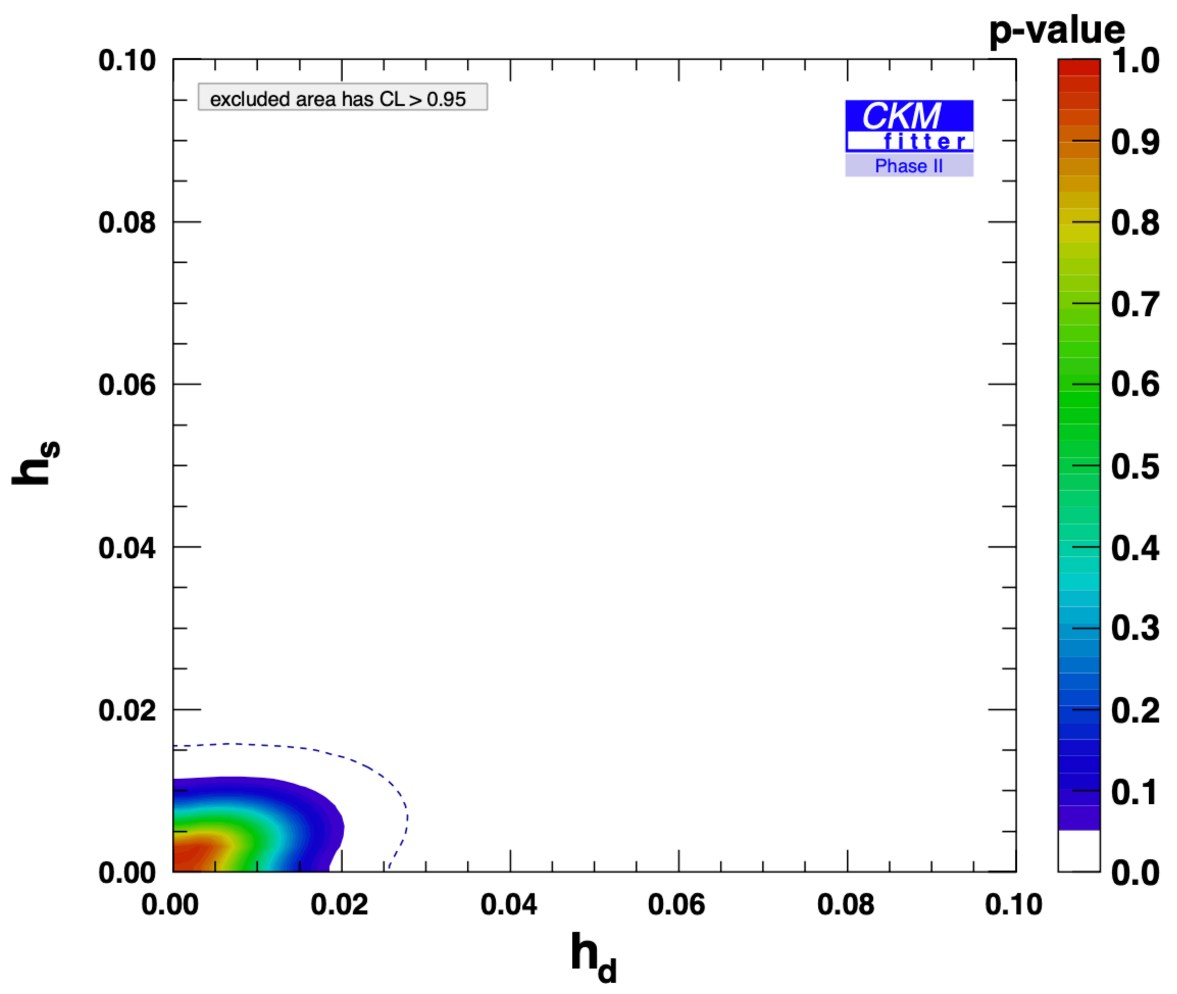
Today



LHCb 300 fb^{-1}, Belle III 300 ab^{-1}



LHCb 300 fb^{-1}, Belle III 300 ab^{-1}, FCC-ee

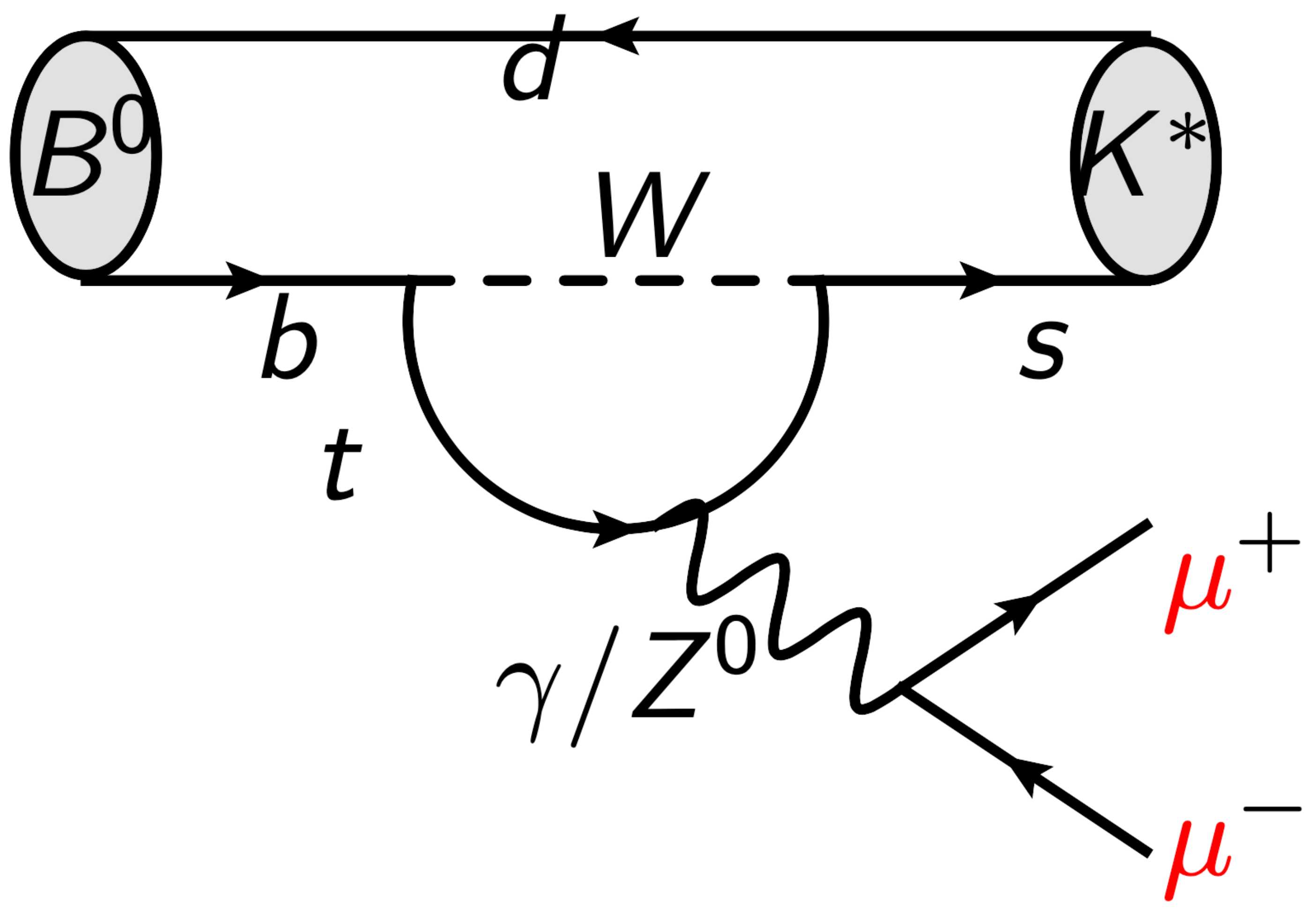


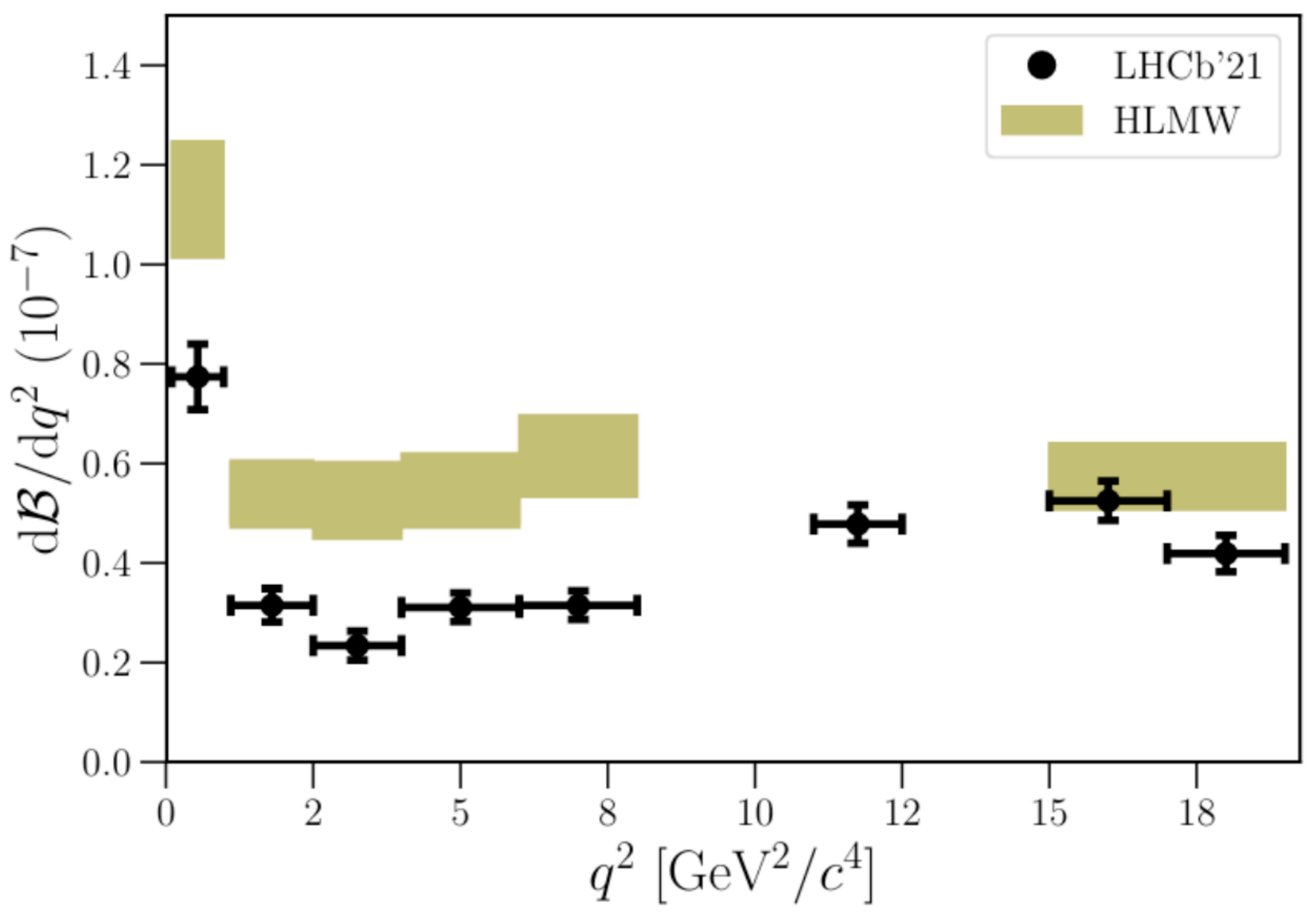
LHCb 300 fb^{-1}, Belle III 300 ab^{-1}, theoretical uncert. removed

$b \to s\ell\ell$ penguins

- Penguin-mediated $b \to s\ell\ell$ transitions suppressed in SM and very sensitive to NP

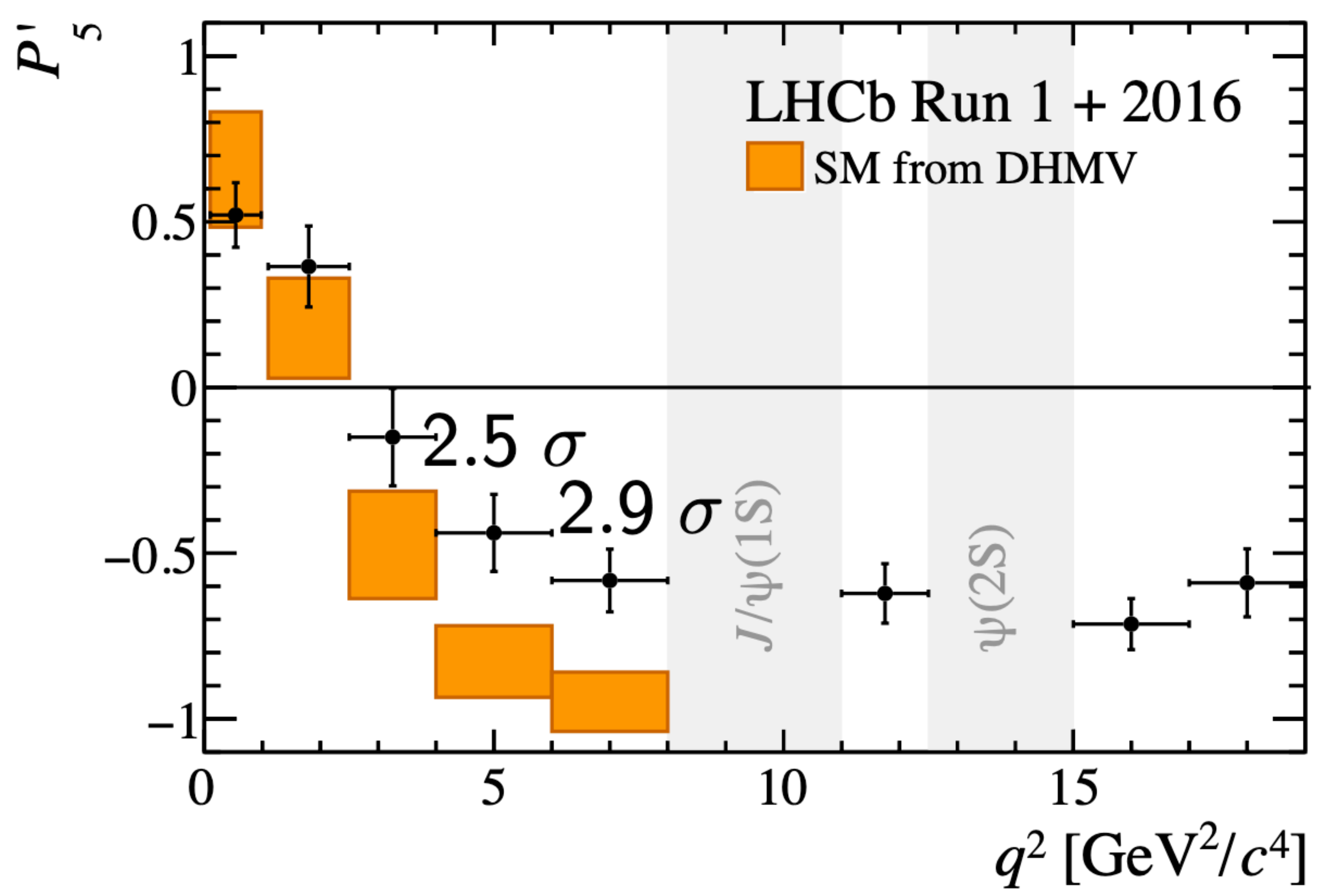
- Angular observables and BF for $b \to s\mu\mu$ decays ($B \to K^{(*)}\mu\mu, B_s \to \phi\mu\mu$) are off





Branching fraction in $B_s^0 \to \phi\mu\mu$

PRL127(2021)151801



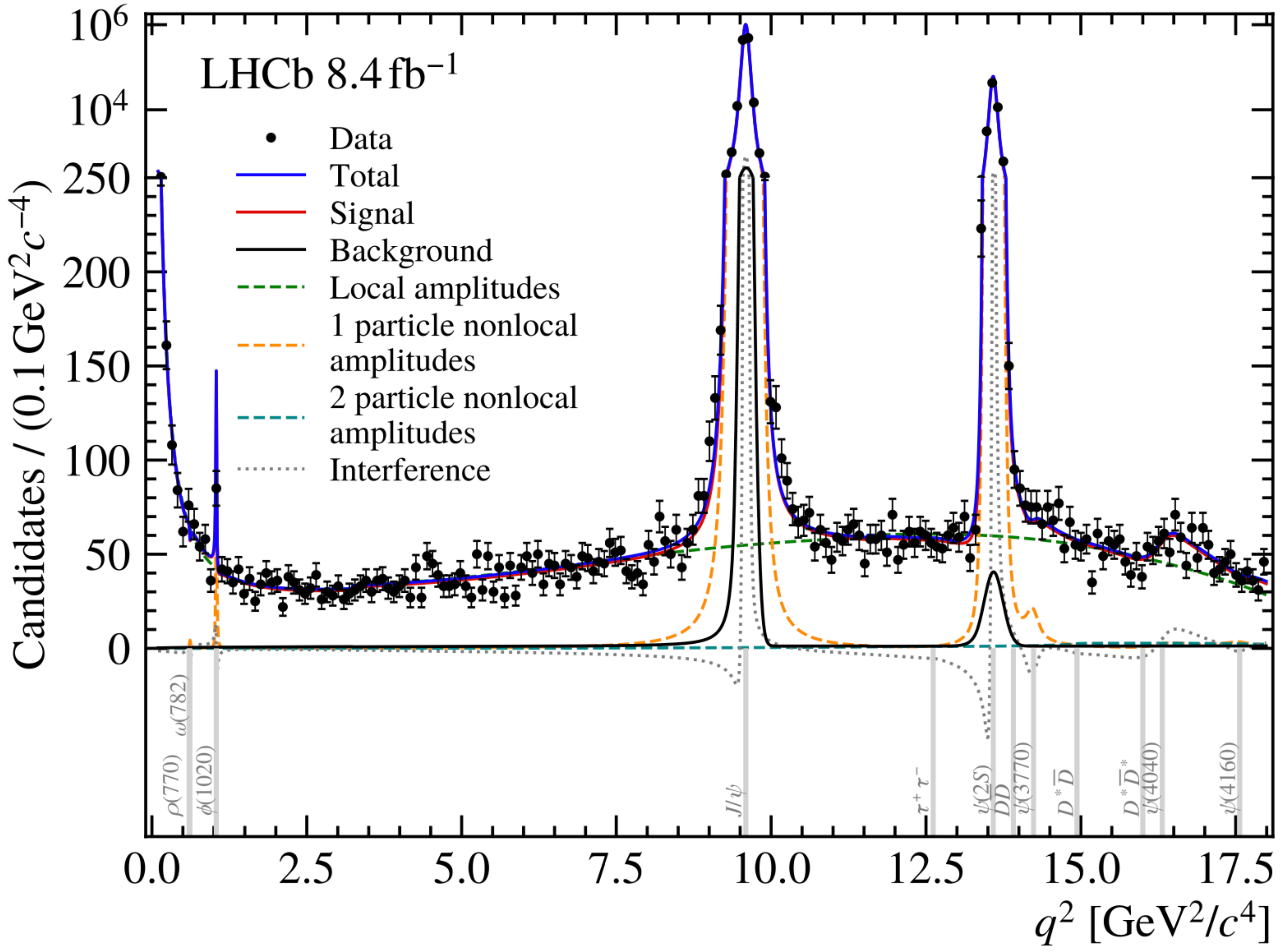
Angular distributions in $B^0 \to K^*\mu^+\mu^-$

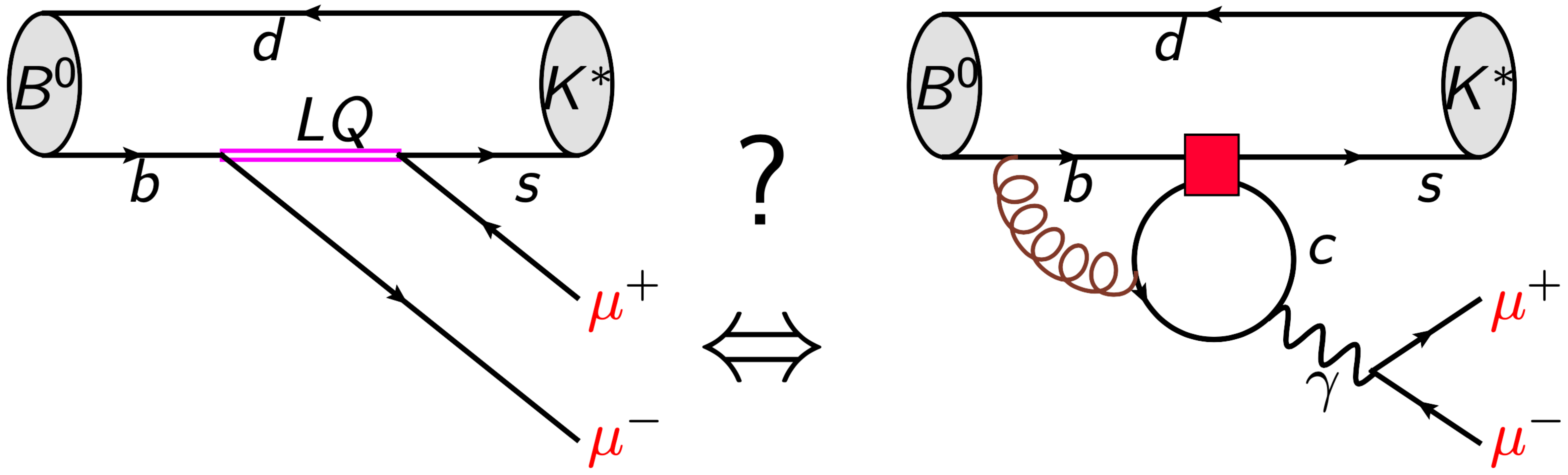
PRL125(2020)011802

Charm loops in $b \to s\ell\ell$

- NP or charm loops?
- LHCb attempts to control charm loop contributions from the data
- Tension with SM at the level of $\sim 2.1\,\sigma$, but mostly free of QCD inputs

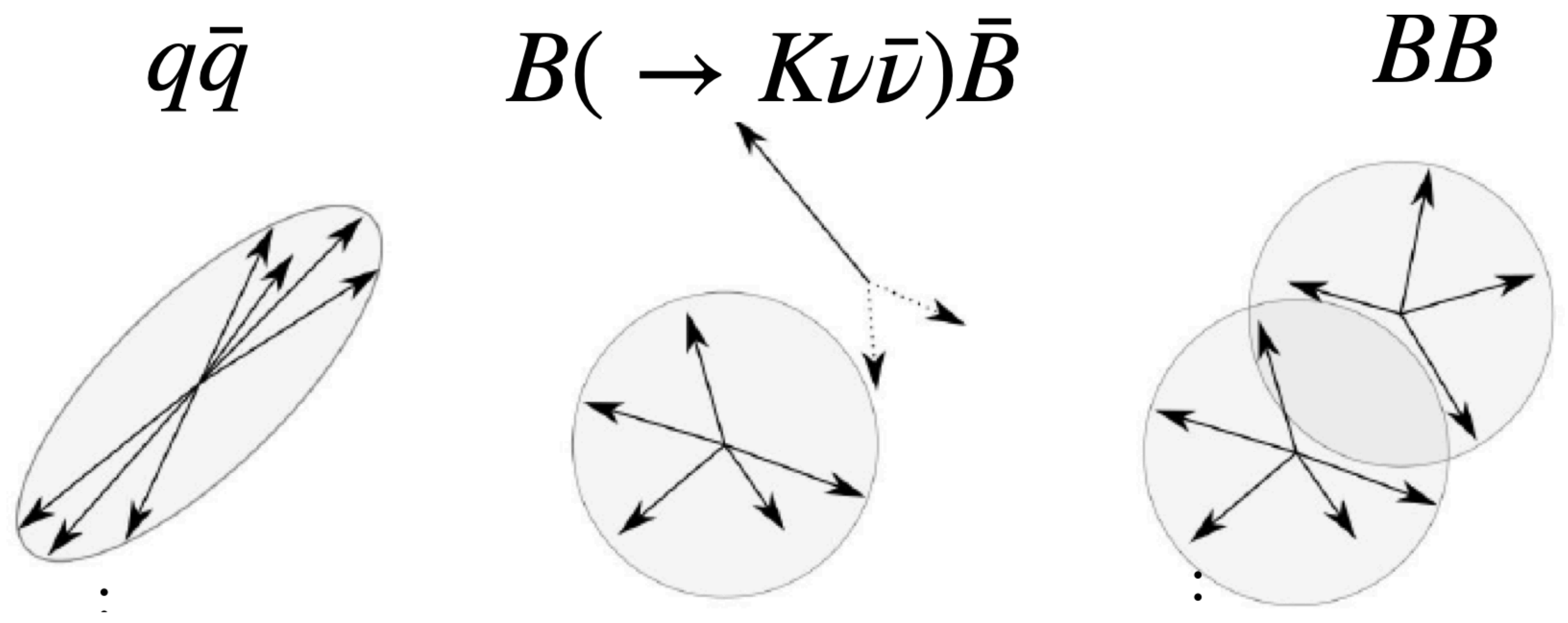
[arXiv:2405.17347](https://arxiv.org/abs/2405.17347)

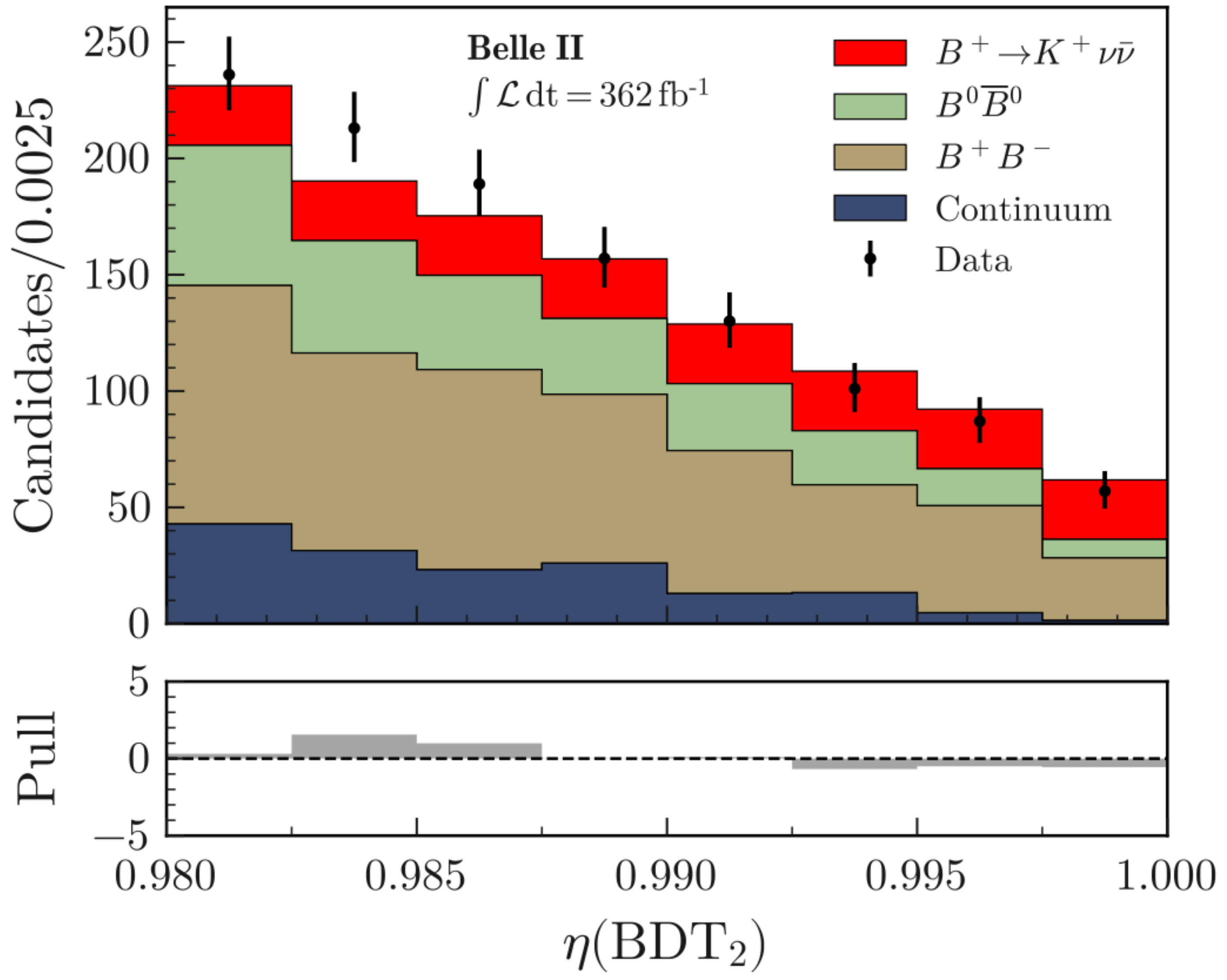




$B \to K\nu\nu$: present

- If NP is in $b \to s\mu\mu$, also expect it in $b \to s\nu\nu$
- Theoretically clean: no charm loops!
- Belle II $B^+ \to K^+\nu\nu$ analysis with 2 techniques:
    - Exclusive: reconstruct other B in $ee \to BB$ to infer missing energy
    - Inclusive: detect large momentum K^+, train classifier based on event topology/occupancy
- Observe an excess: $3.6\,\sigma$ wrt background only,
  $2.8\,\sigma$ above SM.





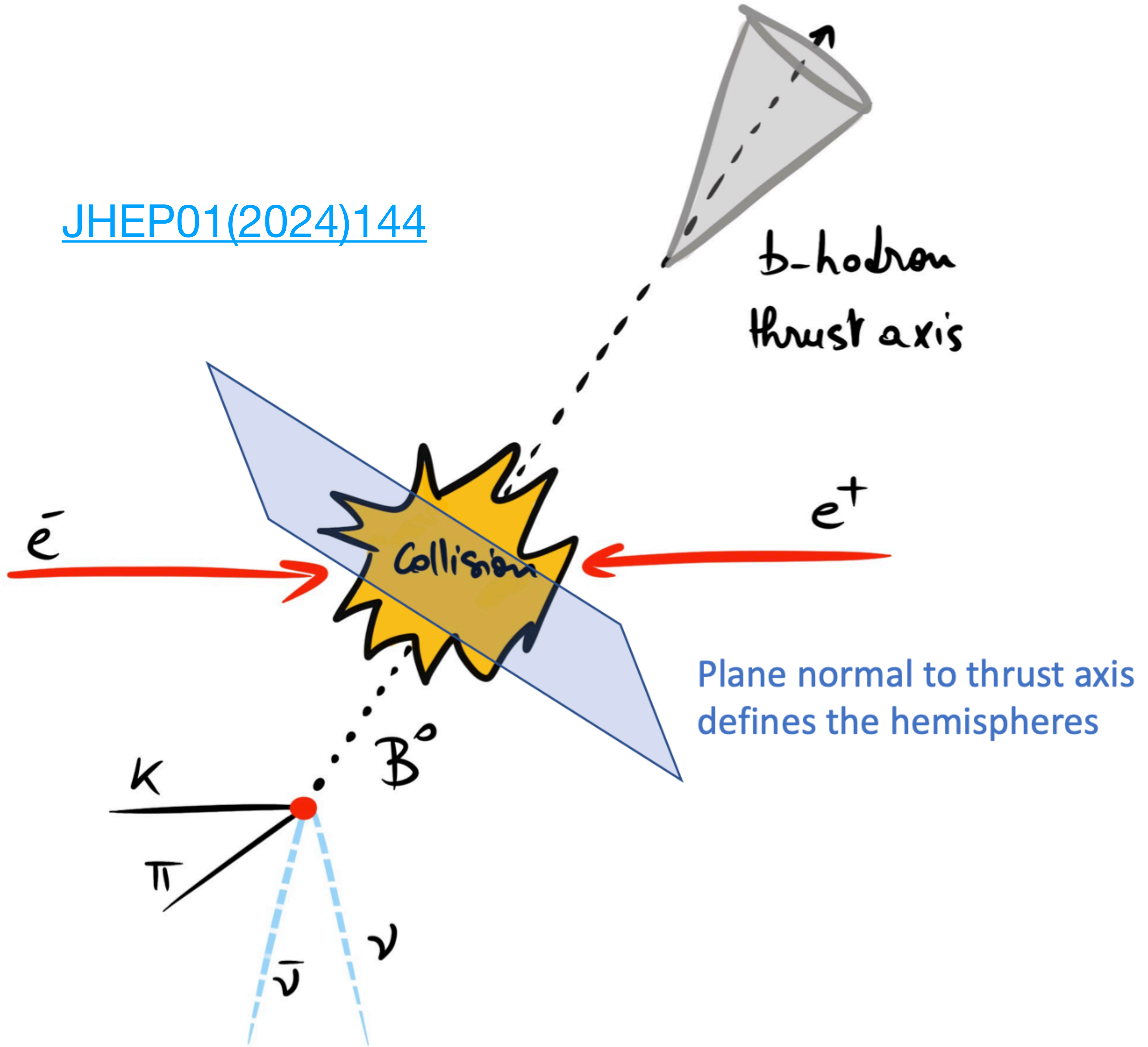
$B \to K\nu\nu$: future

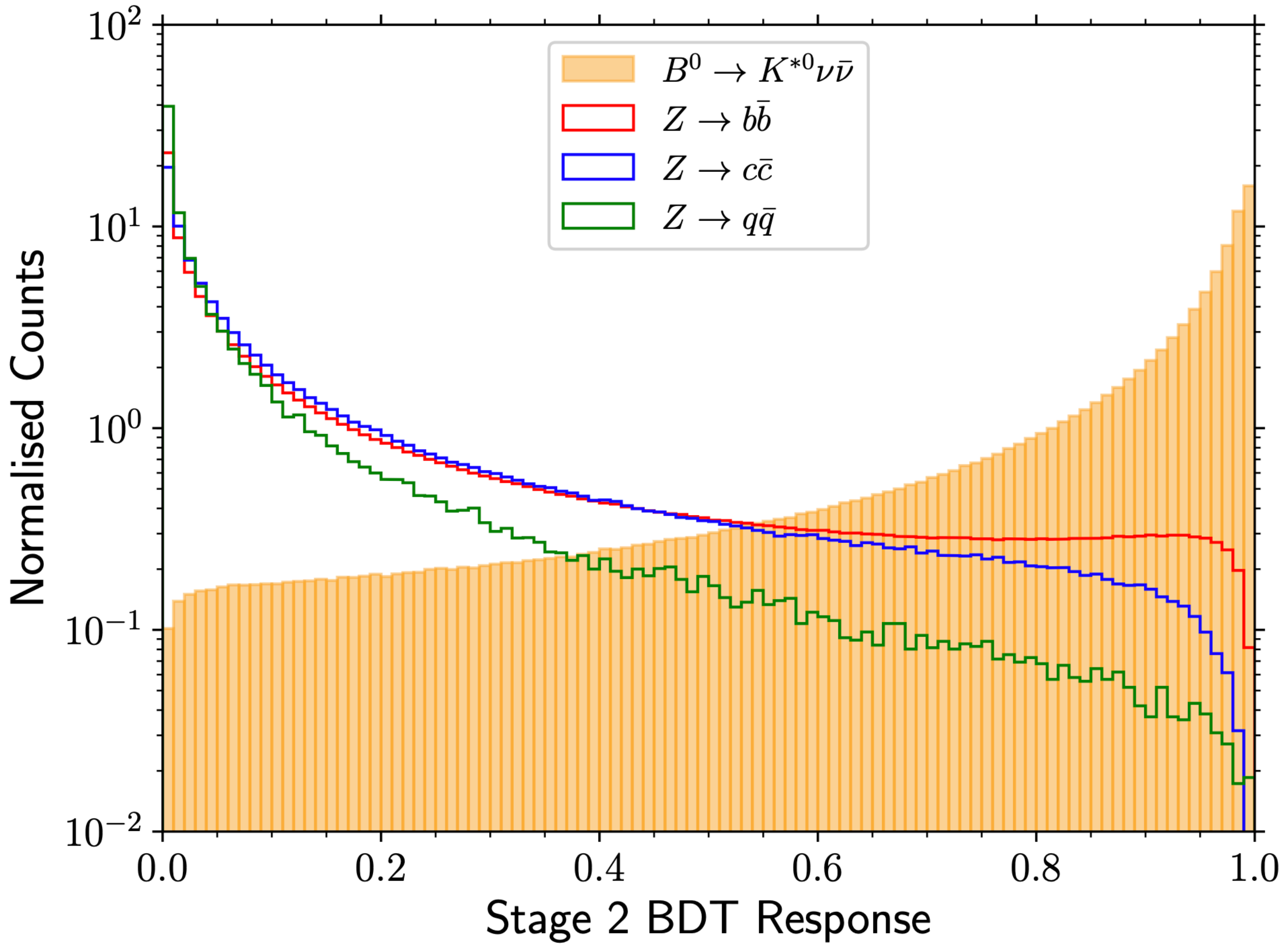
- FCC-ee sensitivity study for $B^0 \to K^+\pi^-\nu\nu$
- Discriminate from backgrounds using mainly:
  - detached $K^+\pi^-$ vertex
  - missing energy in hemisphere
- Expected precisions on BF:

$$\begin{array}{ll} \text{Belle II } 50\,\text{ab}^{-1} & \sim 10\% \\ \text{FCC-ee:} & \sim 0.5\% \end{array}$$

  - Would allow more refined analysis to extract additional observables (f_L)
- Similar situation for $B_s \to \phi\nu\nu$, $\Lambda_b \to pK\nu\nu$

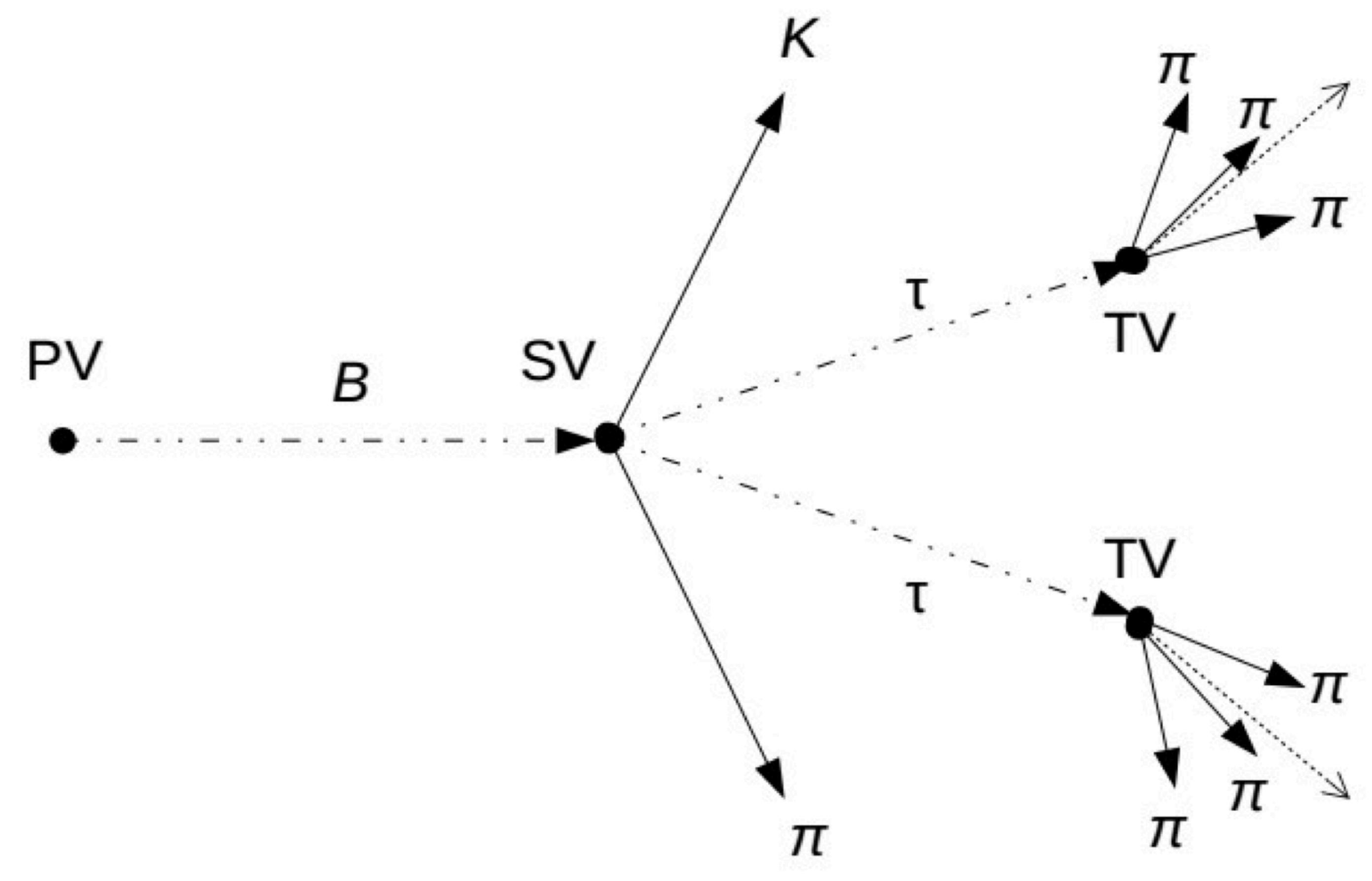
JHEP01(2024)144



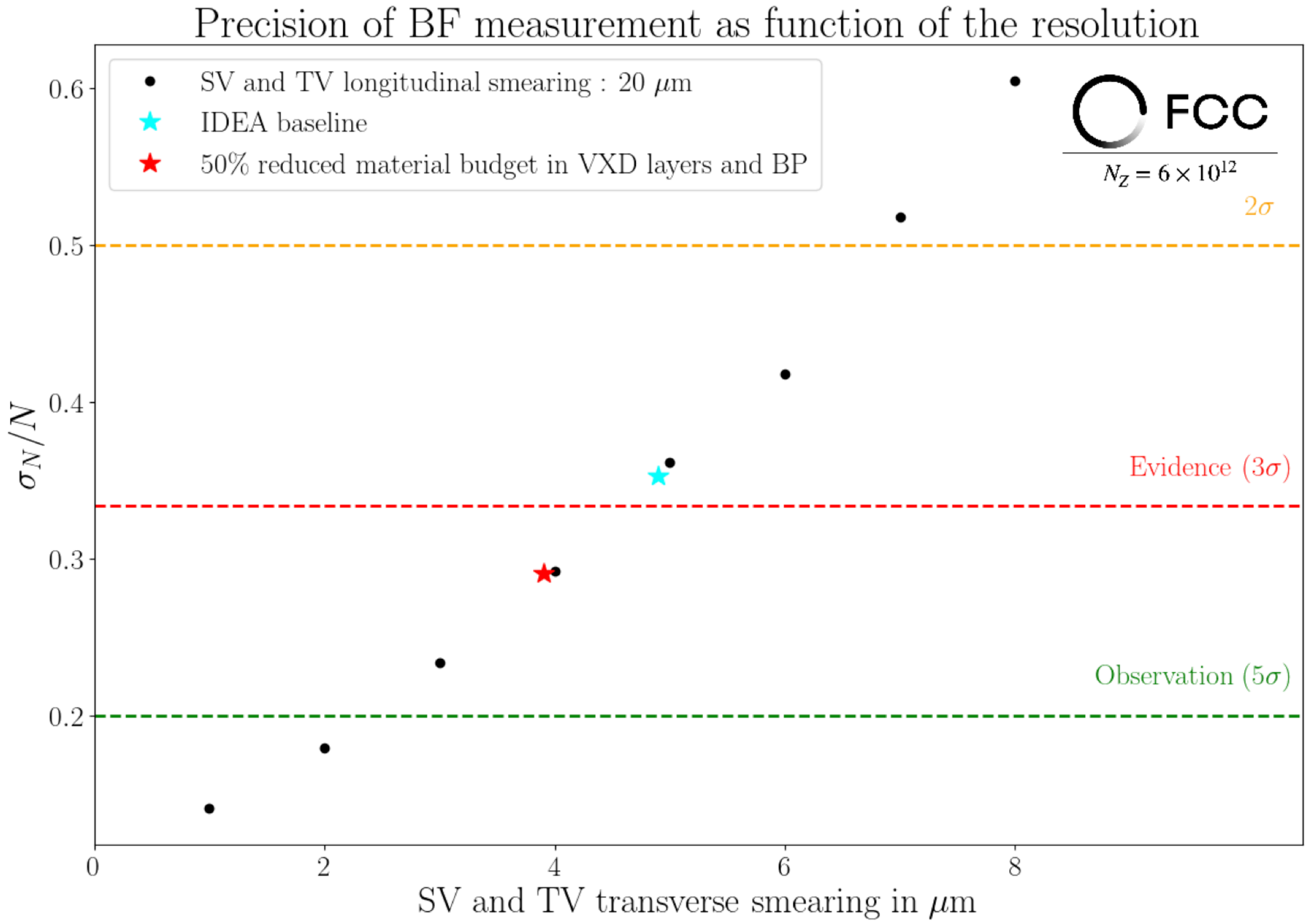


$b \to s\tau\tau$

- Similarly, $b \to s\tau\tau$ also sensitive to NP
- Very difficult to see, as tau leptons always decay to at least 1 neutrino
- At Belle II, no real hope of observing it
- [Recent study]() for a $B^0 \to K^{*-}\tau^+\tau^-$ search at FCC-ee:
  - using $\tau \to 3\pi\nu$ decays
  - sensitivity depends strongly on vertex resolution, $3\,\sigma$ evidence not guaranteed



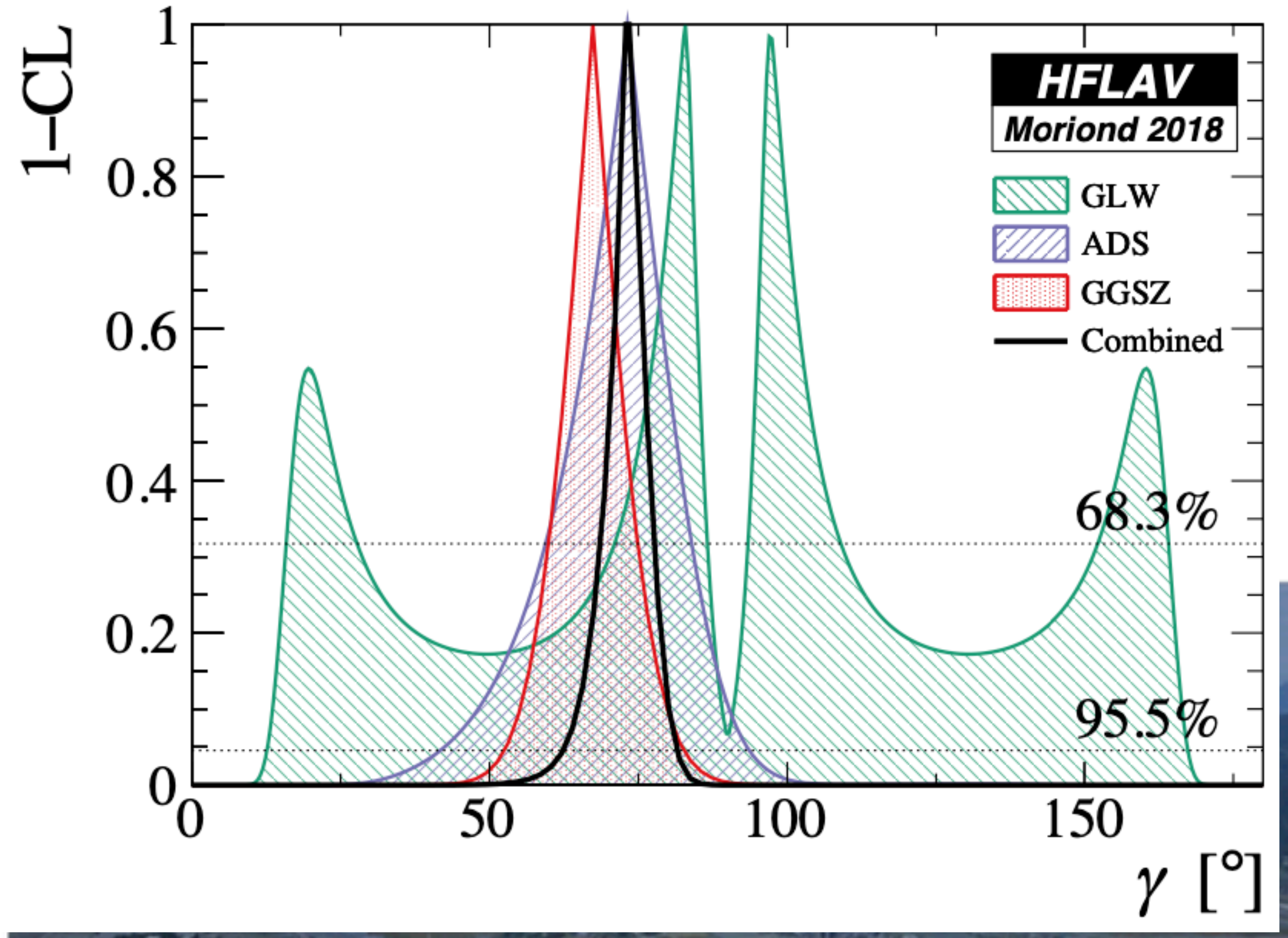
Decay topology

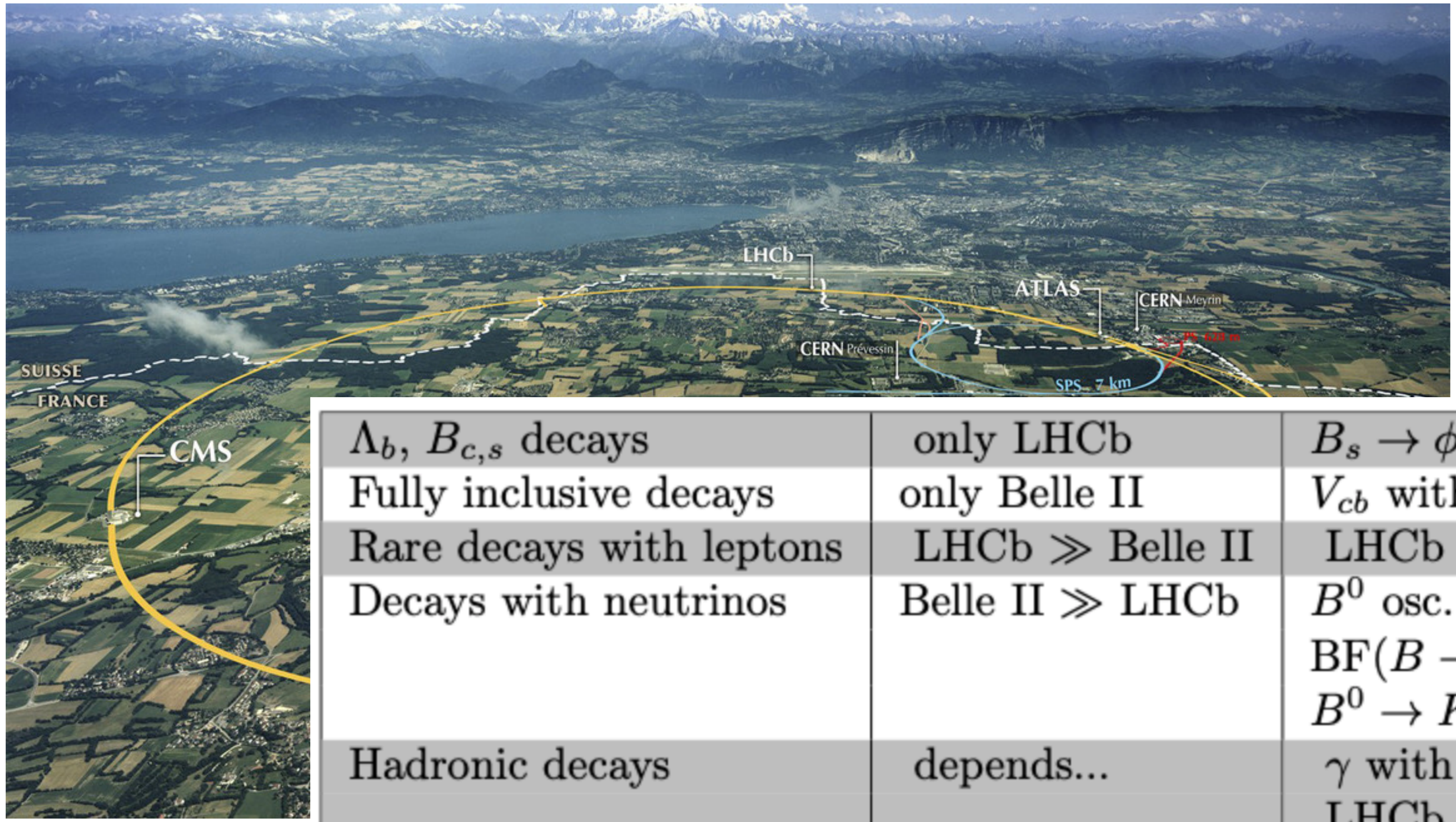


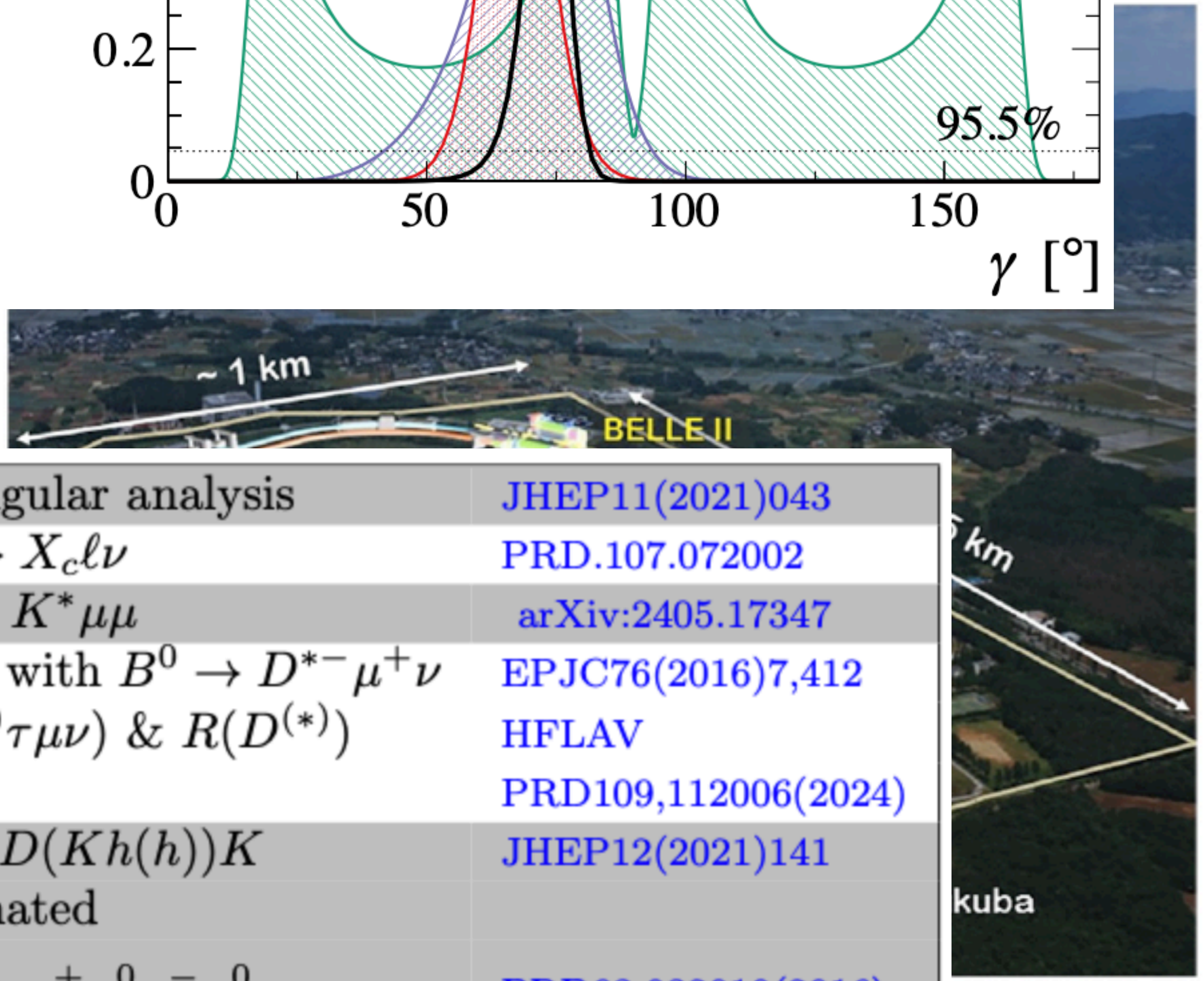
Conclusions

- I have shown prospects in studies of the CKM triangle and penguin decays (esp. with missing energy), and what Tera-Z can bring
- FCC-ee can do more than what I discussed:
  - B physics: polarised Λ_b, lepton flavour violating decays, $2\beta_{(s)} + \gamma$ (with $B_s \to D_s K$), α with $B \to \pi\pi$, etc.
  - D physics: not much explored, quite some activities now at Belle II
  - τ physics, and Z couplings to leptons
- How much Tera-Z brings also depends on how HL LHCb, Belle II perform and on progress in theory predictions

LHC vs superKEKB







Λ_b, $B_{c,s}$ decays	only LHCb	$B_s \to \phi\mu\mu$ angular analysis	JHEP11(2021)043
Fully inclusive decays	only Belle II	V_{cb} with $B \to X_c \ell\nu$	PRD.107.072002
Rare decays with leptons	LHCb $\gg$ Belle II	LHCb $B^0 \to K^* \mu\mu$	arXiv:2405.17347
Decays with neutrinos	Belle II $\gg$ LHCb	B^0 osc. freq. with $B^0 \to D^{*-}\mu^+\nu$ $\mathrm{BF}(B \to D^{(*)}\tau\mu\nu)$ & $R(D^{(*)})$ $B^0 \to K^+\nu\nu$	EPJC76(2016)7,412 HFLAV PRD109,112006(2024)
Hadronic decays	depends...	γ with $B \to D(Kh(h))K$ LHCb dominated α with $B^0 \to \pi^+\pi^0\pi^-\pi^0$ Belle dominated	JHEP12(2021)141 PRD93,032010(2016)

Alpha