Prospect for Measurement of CKM Angle γ in $B_s^0 \to D_s^{\mp} K^{\pm}$ Decays at CEPC

[arXiv:2502.11172]

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Outline

- **Why CKM Angle γ Matters:**

  CP violation, CKM matrix, and measurement methods

- **Why We Need a Future Flavor Factory:**

  CEPC experiment

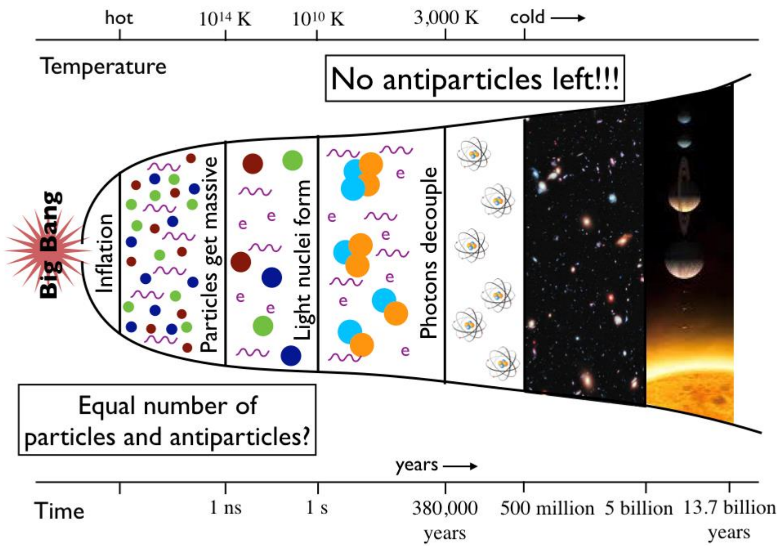
- **Prospect for γ Measurement in $B_s^0 \to D_s^{\mp} K^{\pm}$ at CEPC:**

  Strategy, simulation, reconstruction, flavor tagging, time resolution, fitting, and projections

- **Conclusion**

Why matter dominates the universe?

- Big Bang: matter = antimatter
- Today: matter ≫ antimatter
- Sakharov conditions (1967)：
  - Baryon number violation
  - C /CP violation [Sakharov, JETP Lett. 5 (1967) 24]
  - Departure from thermal equilibrium



- CKM matrix is the only source of CP violation in the SM

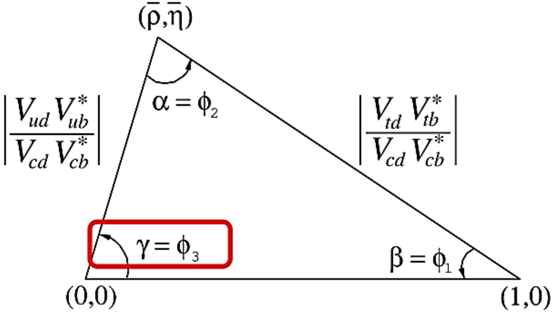
CKM matrix

- CKM matrix describes quark mixing in the SM

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} + O(10^{-3}) =$$

- Unitarity of the CKM matrix ⇒ the unitarity triangles (UTs)
  - Indirect search of BSM physics

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

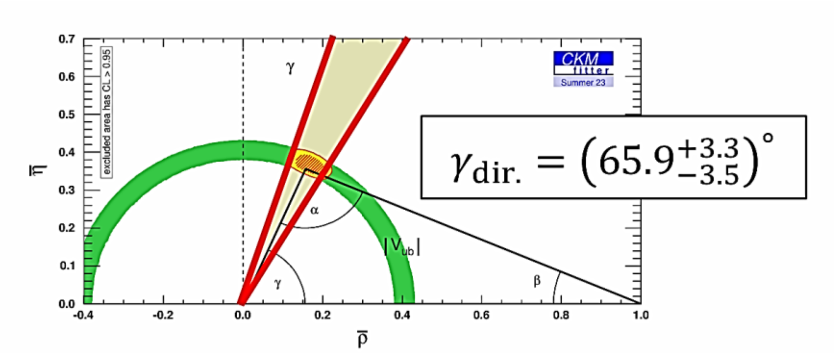


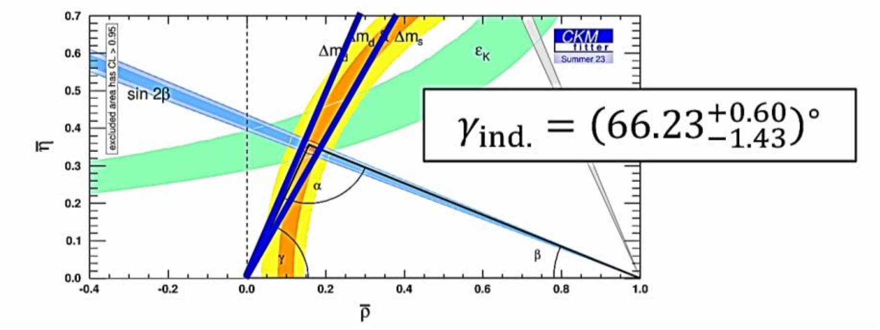
$$\left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right| \qquad \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right|$$

CKM angle γ

- Free of top quark by definition ⇒ accessible via tree-level
- Negligible theoretical uncertainty ⇒ SM benchmark [JHEP 01 (2014) 051]
- Probe γ via interference between $b \to u\bar{c}s$ and $b \to c\bar{u}s$ transitions
- Search for new physics： direct vs. indirect measurement

$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

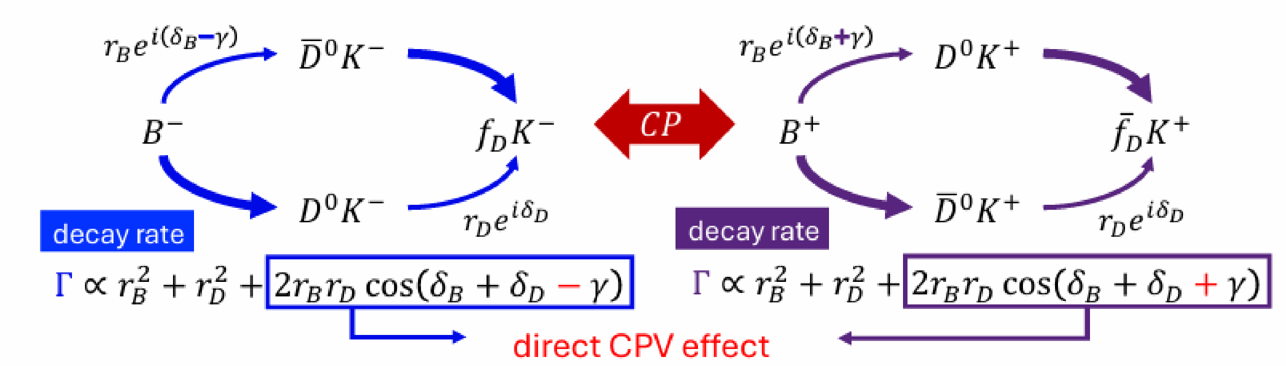




[CKMfitter-2023]

Time integrated method

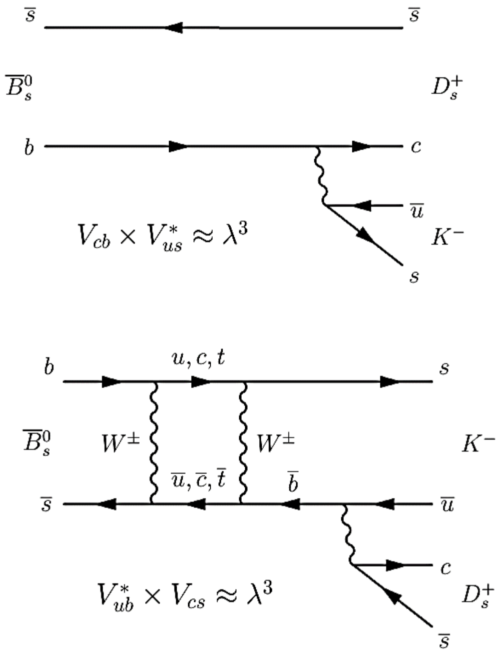
- Most commonly used decays： $\boldsymbol{B^{\pm} \to DK^{\pm}, D \to f}$

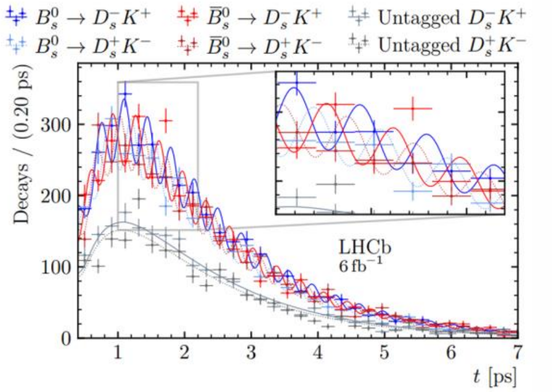


- Different methods based on D decay modes:
  - GLW method: CP eigenstates， e.g. $D \to KK$， $D \to \pi\pi$ [Phys. Lett. B 253 (1991) 483] [Phys. Lett. B 265 (1991) 172]
  - ADS method： CF or DCS decays, e.g. $D \to K\pi$ [Phys. Rev. Lett. 78 (1997) 3257] [Phys. Rev. D 63 (2001) 036005]
  - BPGGSZ method： Self-conjugate 3-body final states， e.g. $D \to K_S^0\pi\pi$ [Phys. Rev. D 68 (2003) 054018]

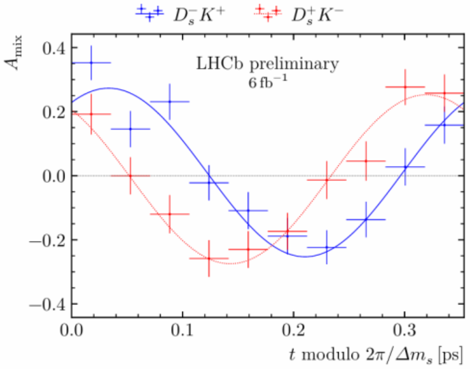
Time dependent method

- Another golden channel: $B_s^0 \to D_s^{\mp} K^{\pm}$
  - Time-dependent study
  - CPV in $B_s^0 - \bar{B}_s^0$ mixing and decay
  - Larger interference: $r_B^{D_s K}$ $(\sim 0.4) > r_B^{DK^{\pm}}$ (~ 0.1)





Decay-time-dependent decay rate



Mixing asymmetry

[LHCb-PAPER-2024-020]

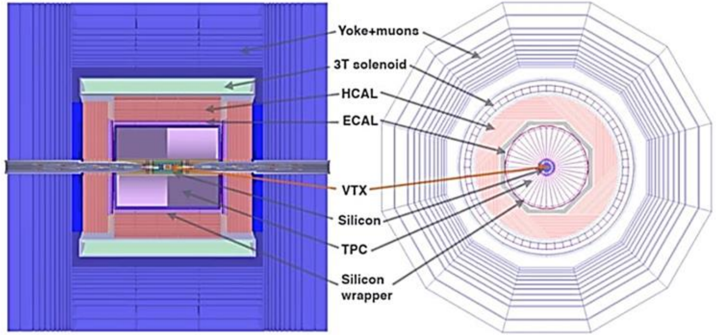
Why we need a future flavor factory?

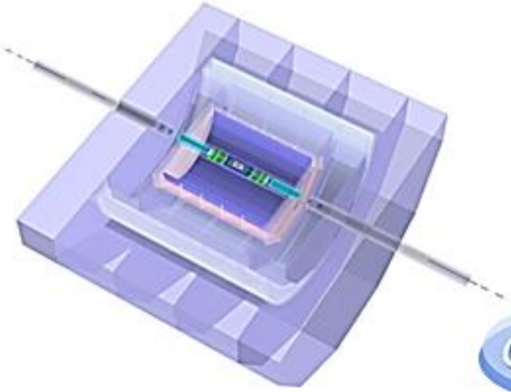
- Current measurements (e.g. angle γ) limited by:
  - Statistics
  - Systematics
  - Decay modes
- Future high-luminosity colliders ⇒ much better precision

Experiment	Type	Features	Ref.
CEPC	e^+e^- @ Z pole	Clean, low background, high precision	[arXiv:1811.10545]
FCC-ee	e^+e^- @ Z pole	Similar to CEPC	[arXiv:1901.02648]
LHCb Upgrade II	pp	High stats, complex background	[arXiv:1808.08865]
Belle II	e^+e^- @ Υ(4S)	Very clean, no B_s	[arXiv:1808.10567]

CEPC experiment

- CEPC (Circular Electron Positron Collider)
- Designed as a future **Higgs / W / Z factory**
- Runing at e^+e^- @ Z pole ⇒ Tera-Z factory
- Baseline Detector Highlights:
  - Vertex resolution: μm-level silicon detector
  - PID: ToF + ECAL + Muon
- Advantages:
  - High statistics from high-luminosity collisions
  - Low background from clean e^+e^- environment





Strategies

Goal: Estimate CEPC's sensitivity to CKM angle $\boldsymbol{\gamma}$ via $\boldsymbol{B_s^0} \to \boldsymbol{D_s^{\mp} K^{\pm}}$, assuming CEPC baseline detector and **4.1×10^{12} Z** events (Tera-Z)

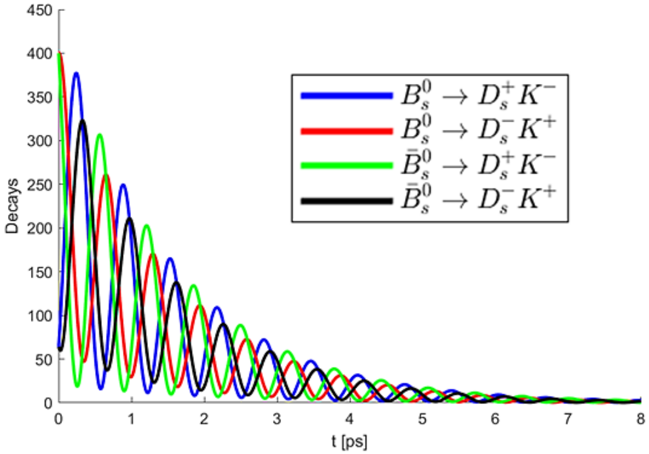
Steps:

1. Monte Carlo samples:
   - Signal and inclusive background samples
2. Detector effects:
   - Full simulation applied
   - Flavor tagging efficiency from truth-level estimation
3. Reconstruction & Selection:
   - Vertex, decay time, invariant mass
4. Fit & Sensitivity Projection:
   - Mass–Time fit to extract statistical precision on $\boldsymbol{\gamma}$
   - Extrapolate to full dataset for final sensitivity

Decay rates

- **5 CP observables**： C， D_f， $D_{\bar{f}}$， S_f， $S_{\bar{f}}$
- Depend on amplitude ratio r_{D_sK}、 strong phase δ、weak phase $\gamma - 2\beta_s$
- $-2\beta_s$ as input from independent measurement， γ can be precisely extracted

$$\begin{pmatrix} P_{B_s^0\to D_s^+K^-}(t) \\ P_{\bar{B}_s^0\to D_s^+K^-}(t) \\ P_{B_s^0\to D_s^-K^+}(t) \\ P_{\bar{B}_s^0\to D_s^-K^+}(t) \end{pmatrix} \propto e^{-\Gamma_s t} \begin{pmatrix} 1 & -C & D_{\bar{f}} & -S_{\bar{f}} \\ 1 & C & D_{\bar{f}} & S_{\bar{f}} \\ 1 & C & D_f & -S_f \\ 1 & -C & D_f & S_f \end{pmatrix} \begin{pmatrix} \cosh\left(\frac{\Delta\Gamma_s}{2}t\right) \\ \cos(\Delta m_s t) \\ \sinh\left(\frac{\Delta\Gamma_s}{2}t\right) \\ \sin(\Delta m_s t) \end{pmatrix}$$



$$C = \frac{1 - r_{D_sK}^2}{1 + r_{D_sK}^2},$$

$$D_f = \frac{-2\, r_{D_sK} \cos(\delta - (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}, \qquad D_{\bar{f}} = \frac{-2\, r_{D_sK} \cos(\delta + (\gamma - 2\beta_s))}{1 + r_{D_sK}^2},$$

$$S_f = \frac{2\, r_{D_sK} \sin(\delta - (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}, \qquad S_{\bar{f}} = \frac{-2\, r_{D_sK} \sin(\delta + (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}.$$

Full MC simulation

Signal:

- Simulate $B_s^0 \to D_s^- (\to K^- K^+ \pi^-) K^+$
- Generator: **Whizard 1.95** for $Z \to b\bar{b} \to B_s^0 X$
- **Pythia8** for B_s^0 decays (with latest measured parameters)
- Detector simulation: **MokkaC**
- Corresponds to 5.3% statistics across three D_s^- decay modes of full 4.1Tera-Z

Background:

- Generated inclusive $Z \to q\bar{q}$ events under the same setup
- Used to model background distributions in mass and decay time

Branching ratios	Values
$\mathcal{B}(B_s^0 \to D_s^\mp K^\pm)$	$(2.25 \pm 0.12) \times 10^{-4}$ [45]
$\mathcal{B}(D_s^- \to K^- K^+ \pi^-)$	$(5.37 \pm 0.10) \times 10^{-2}$ [45]
$\mathcal{B}(D_s^- \to K^- \pi^+ \pi^-)$	$(6.20 \pm 0.19) \times 10^{-3}$ [45]
$\mathcal{B}(D_s^- \to \pi^- \pi^+ \pi^-)$	$(1.08 \pm 0.04) \times 10^{-2}$ [45]

Parameters	Values
$\tau(B_s^0) = 1/\Gamma_s$	1.520 ± 0.005 [ps] [139]
$\Delta\Gamma_s$	$+0.084 \pm 0.005$ [ps^{-1}] [139]
Δm_s	17.765 ± 0.006 [ps^{-1}] [139]
$-2\beta_s$	-0.039 ± 0.016 [rad] [140]
$r_{D_s K}$	$0.318^{+0.035}_{-0.033}$ [141]
δ	$(347.6^{+6.2}_{-6.1})^\circ$ [141]
γ	$(66.2^{+3.4}_{-3.6})^\circ$ [139]

Reconstruction & Selection

Vertex Reconstruction:

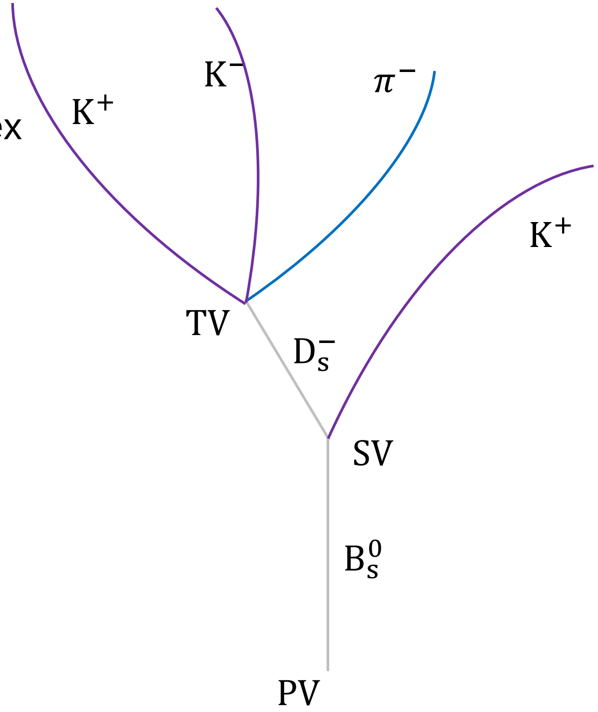
- **TV:** Reconstruct $\boldsymbol{D_s^- \to K^- K^+ \pi^-}$ with mass-constrained fit
- **SV**: Combine $\boldsymbol{D_s^-}$ pseudo-track with $\boldsymbol{K^+}$ to reconstruct $\boldsymbol{B_s^0 (\overline{B}_s^0)}$ vertex

Selection Cuts:

- Mass windows:
  - M(D_s^-) $\in$ [1.96,1.98]GeV/c^2
  - M(B_s^0) $\in$ [5.28,5.46]GeV/c^2
- Vertex fit： $\chi^2_{TV} < 9$
- PV - SV > 0.1 mm, PV - TV > 0.5 mm

Efficiencies:

- Signal selection efficiency: 80%
- PID efficiency: K: 98.5%, π: 97.7% [arxiv:2411.06939]



(*PV*: Primary Vertex, *SV*: Secondary, *TV*: Tertiary)

Flavor tagging

Goal: Determine initial B_s^0 or $\bar{B}_s^0$ flavor

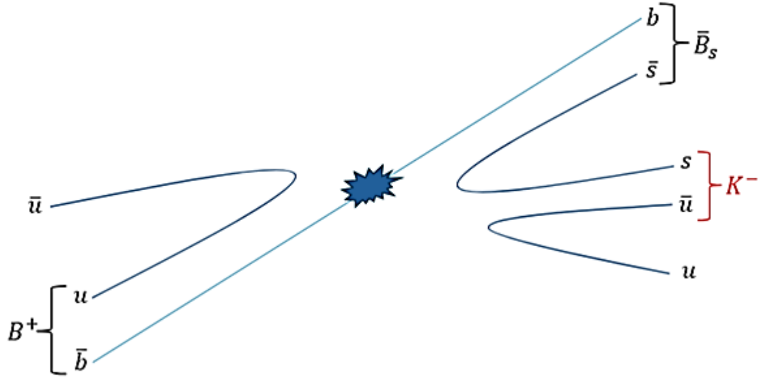
Tagging Strategy:

- Choose **the leading Kaon** (highest energy)
- Same-Side Kaon (SSK): Kaon aligned with B_s^0 direction
- Opposite-Side Kaon (OSK): Kaon opposite to B_s^0

Classification:

- Right (R) : tag matched true flavor (+ or -)
- Wrong (W) : tag is opposite
- Untagged (U) : tag = 0

Result: $\epsilon_{\text{eff}} = 23.6\%$



$B^+ \to \bar{D}^0 \to K^+$

Methods	ϵ_{tag}	ω	ϵ_{eff}
Leading SSK (%)	57.45	19.96	20.73
Leading OSK (%)	72.41	31.36	10.06
Combined (%)	72.12	21.39	23.60

Tagging efficiency: $\epsilon_{tag} = \frac{R+W}{R+W+U}$

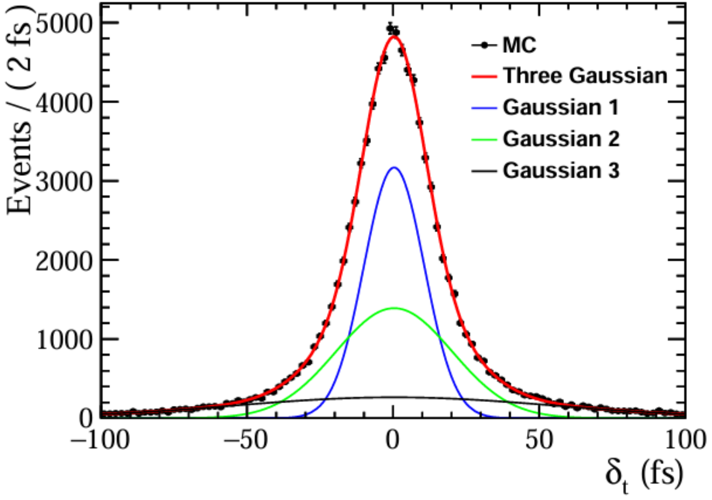
Mistag rate: $\omega = \frac{W}{R+W}$

Tagging power: $\epsilon_{\text{eff}} = \epsilon_{tag}(1-2\omega)^2$

Time resolution and acceptance

Time resolution:

- Proper decay time: $t = \frac{m\, l_{xy}}{p_T}$
- Time residual: $\delta_t = t_{\text{reco}} - t_{\text{sim}}$
- Modeled with a triple Gaussian fit
- Effective time resolution: σ_t = 26 fs



Time acceptance:

- Modeled by an empirical acceptance function a(t)

$$\frac{d\Gamma^{\text{acc}}(t)}{dt} = \frac{d\Gamma(t)}{dt} \times a(t). \qquad a(t) = \frac{(\alpha t)^\beta}{1+(\alpha t)^\beta}(1-\xi t).$$

Signal parameterization

- Flavor tagging divides the samples into 6 categories:

$$B^0_{s,+} \to D_s^+ K^-, \quad B^0_{s,-} \to D_s^+ K^-, \quad B^0_{s,0} \to D_s^+ K^-,$$

$$B^0_{s,+} \to D_s^- K^+, \quad B^0_{s,-} \to D_s^- K^+, \quad B^0_{s,0} \to D_s^- K^+.$$

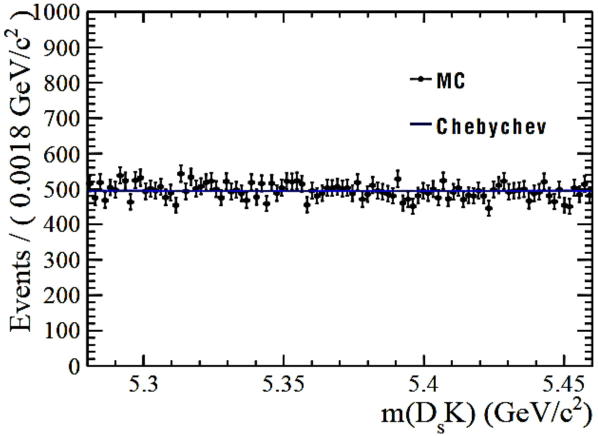
$B^0_{s,+}$: tag as B^0_s
$B^0_{s,-}$: tag as $\bar{B}^0_s$
$B^0_{s,0}$: untagged

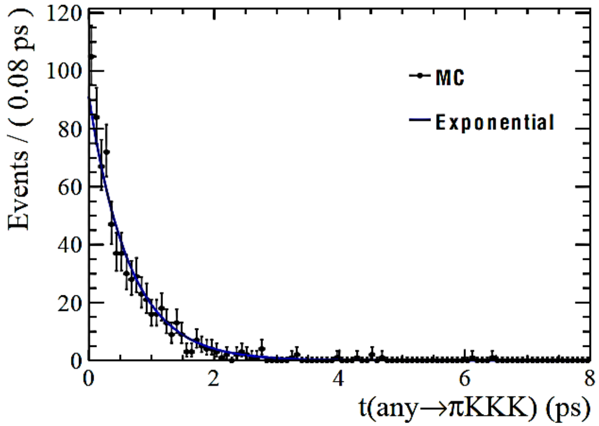
- **Mass distribution** modeled by a Double-Sided Crystal Ball (DSCB) function
- **Time distribution** based on the ideal model with corrections for:
  - Flavor tagging effects,
  - Time resolution,
  - Time acceptance

$$\begin{pmatrix} P_{B^0_{s,+}\to D_s^+K^-}(t) \\ P_{B^0_{s,-}\to D_s^+K^-}(t) \\ P_{B^0_{s,0}\to D_s^+K^-}(t) \\ P_{B^0_{s,+}\to D_s^-K^+}(t) \\ P_{B^0_{s,-}\to D_s^-K^+}(t) \\ P_{B^0_{s,0}\to D_s^-K^+}(t) \end{pmatrix} \propto \underbrace{\begin{pmatrix} 1-\omega & \omega & 0 & 0 \\ \omega & 1-\omega & 0 & 0 \\ \epsilon_{\rm tag}^{-1}-1 & \epsilon_{\rm tag}^{-1}-1 & 0 & 0 \\ 0 & 0 & 1-\omega & \omega \\ 0 & 0 & \omega & 1-\omega \\ 0 & 0 & \epsilon_{\rm tag}^{-1}-1 & \epsilon_{\rm tag}^{-1}-1 \end{pmatrix}}_{\text{Tagging matrix}} \underbrace{\left[\begin{pmatrix} P_{B^0_s\to D_s^+K^-}(t) \\ P_{\bar{B}^0_s\to D_s^+K^-}(t) \\ P_{B^0_s\to D_s^-K^+}(t) \\ P_{\bar{B}^0_s\to D_s^-K^+}(t) \end{pmatrix} \theta(t)\right]}_{\text{Ideal PDF}} \otimes \underbrace{Res(t,\sigma_1,\sigma_2,\sigma_3)\cdot a(t)}_{\text{Detector effects}}$$

Background treatment

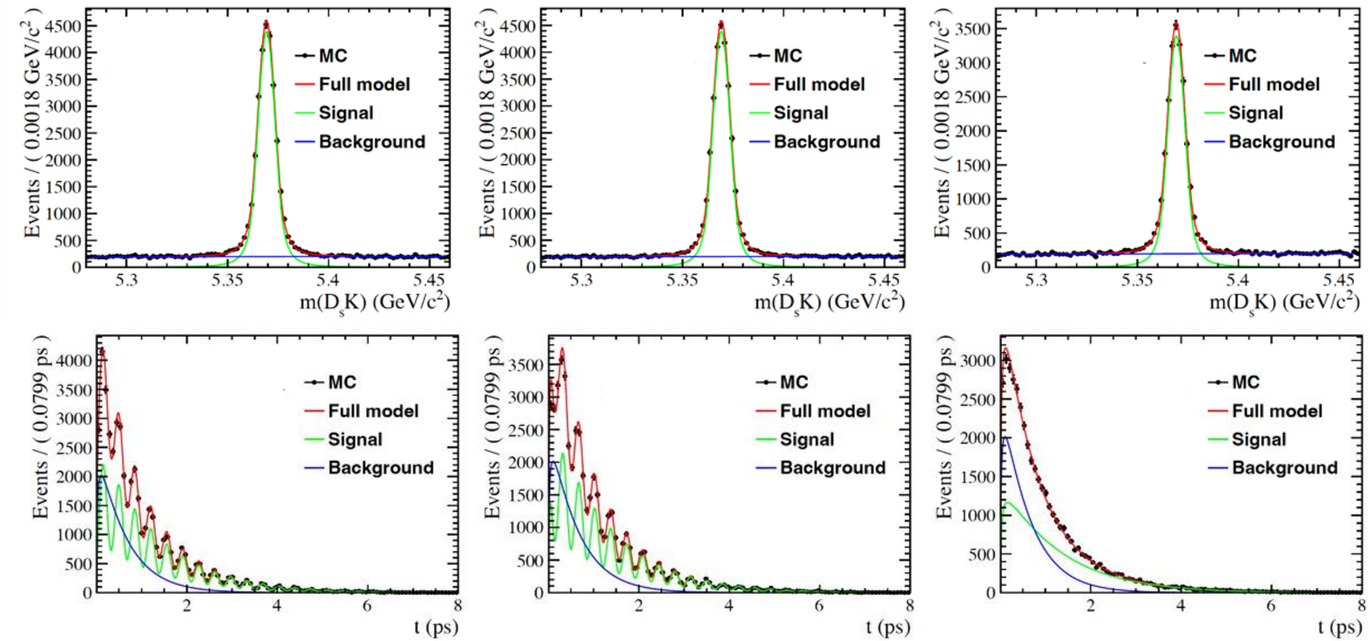
- **Ideal case**: Use large $Z \to q\bar{q}$ samples to extract mass/time distributions
- **Real life:** Limited full simulation samples ⇒ use alternative modeling methods
  - **Mass:** Fake B_s^0 by combining K and D_s^- in $Z \to q\bar{q}$ samples; fit with Chebyshev polynomial
  - **Time:** Use $Z \to q\bar{q} \to \{\pi, K, K, K\}$ samples; fit with exponential functions
  - All subsamples share the same shape and background yields





Mass-Time fit

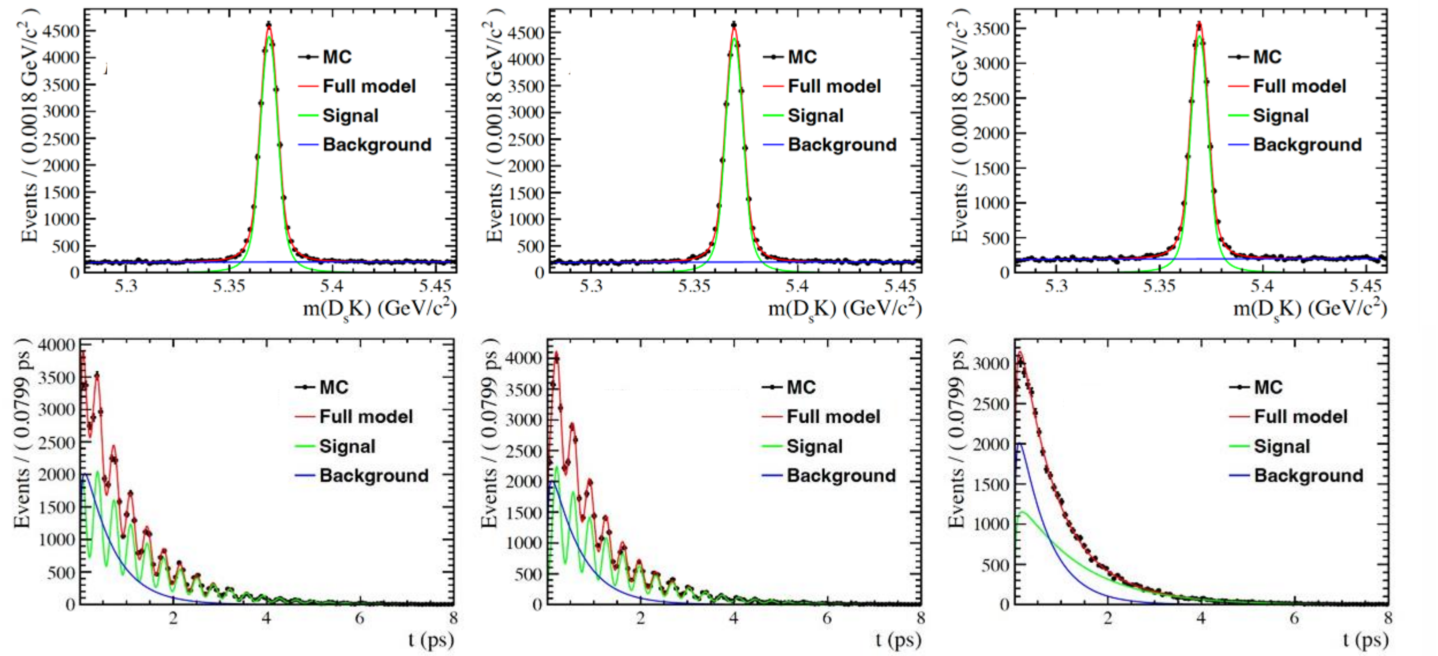
Parameters fixed: Γ_s, $\Delta\Gamma_s$, Δm_s and $-2\beta_s$



$B^0_{s,+} \to D_s^+ K^-$ $B^0_{s,-} \to D_s^+ K^-$ $B^0_{s,0} \to D_s^+ K^-$

Mass-Time fit

Parameters fixed: Γ_s, $\Delta\Gamma_s$, Δm_s and $-2\beta_s$



$B^0_{s,+} \to D_s^- K^+$ $B^0_{s,-} \to D_s^- K^+$ $B^0_{s,0} \to D_s^- K^+$

Fit results & Discussion

Fit result:

- γ **= (66.43 ± 3.01)°** (Statistical uncertainty only, based on 5.3% of full dataset, compatible with input value of γ = 66.2°)

Projected final precision:

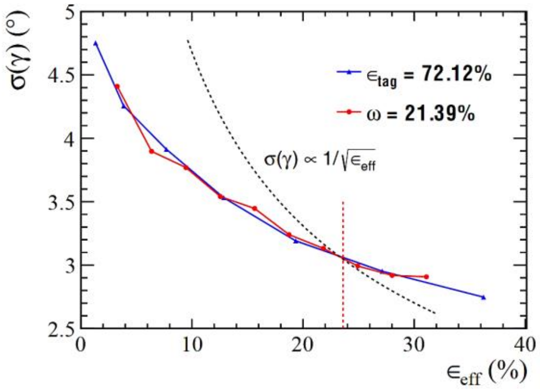
- **σ(γ) = 0.69°** (Using all three D_s^- decay modes, 4.1 Tera-Z)

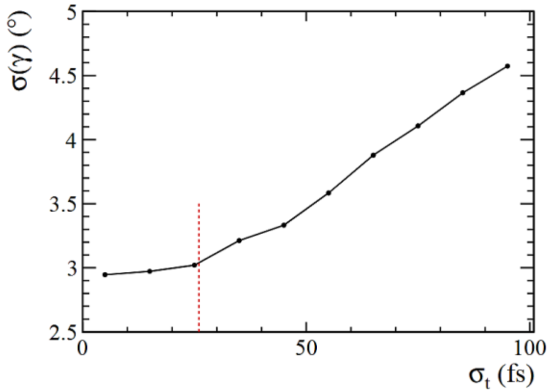
σ(γ) vs. $\boldsymbol{\epsilon_{\mathrm{eff}}}$:

- Red & blue curves overlap: $\boldsymbol{\epsilon_{\mathrm{eff}}}$ effectively summarizes tagging performance
- Clear deviation from $\mathbf{1}/\sqrt{\boldsymbol{\epsilon_{\mathrm{eff}}}}$: Untagged events also carry γ information

σ(γ) vs. $\boldsymbol{\sigma_t}$:

- Current σ_t = 26 fs is sufficient for high-precision γ measurement





Further optimization directions

A scale factor encapsulates all contributions affecting the γ resolution:

$$\zeta = \left[N_{b\bar{b}} \cdot \mathcal{B} \cdot \epsilon \cdot (\epsilon_{\mathrm{eff}} + \mathcal{D}) \cdot e^{-\mathcal{F} \cdot \Delta m_s^2 \sigma_t^2} \right]^{-1/2}$$

Effective Statistics: Include additional D_s^- decay modes, e.g. with π^0

Selection Efficiency: Use machine learning to further improve selection

Tagging Power: Apply advanced tagging algorithms, e.g. ParticleNet

Time resolution: Optimize vertex reconstruction methods

Conclusion

- Based on the CEPC Baseline detector, under 4.1 Tera-Z conditions, the projected statistical precision on the CKM angle γ from $B_s^0 \to D_s^\mp K^\pm$ decay is $\sigma(\gamma) = 0.69°$ [arXiv:2502.11172]
- In comparison, LHCb Upgrade I / II expects: 2.5°/1.0° precision for the same decay channel [arXiv:1808.08865]
- CEPC shows competitive performance with LHCb Upgrade II in this channel
- CEPC opens new opportunities for precision flavor physics exploration

Thanks