Ultimate Quantum Precision Limits at Colliders: Conditions and Case Studies

Jia Liu (刘佳)
Peking University

Collaborators: Tengyu Ai, Qi Bi, Yuxin He and Xiao-Ping Wang
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Outlines

- Motivation and Background
- General Framework
- Case Studies
- Outlook and Discussions

The Central Question

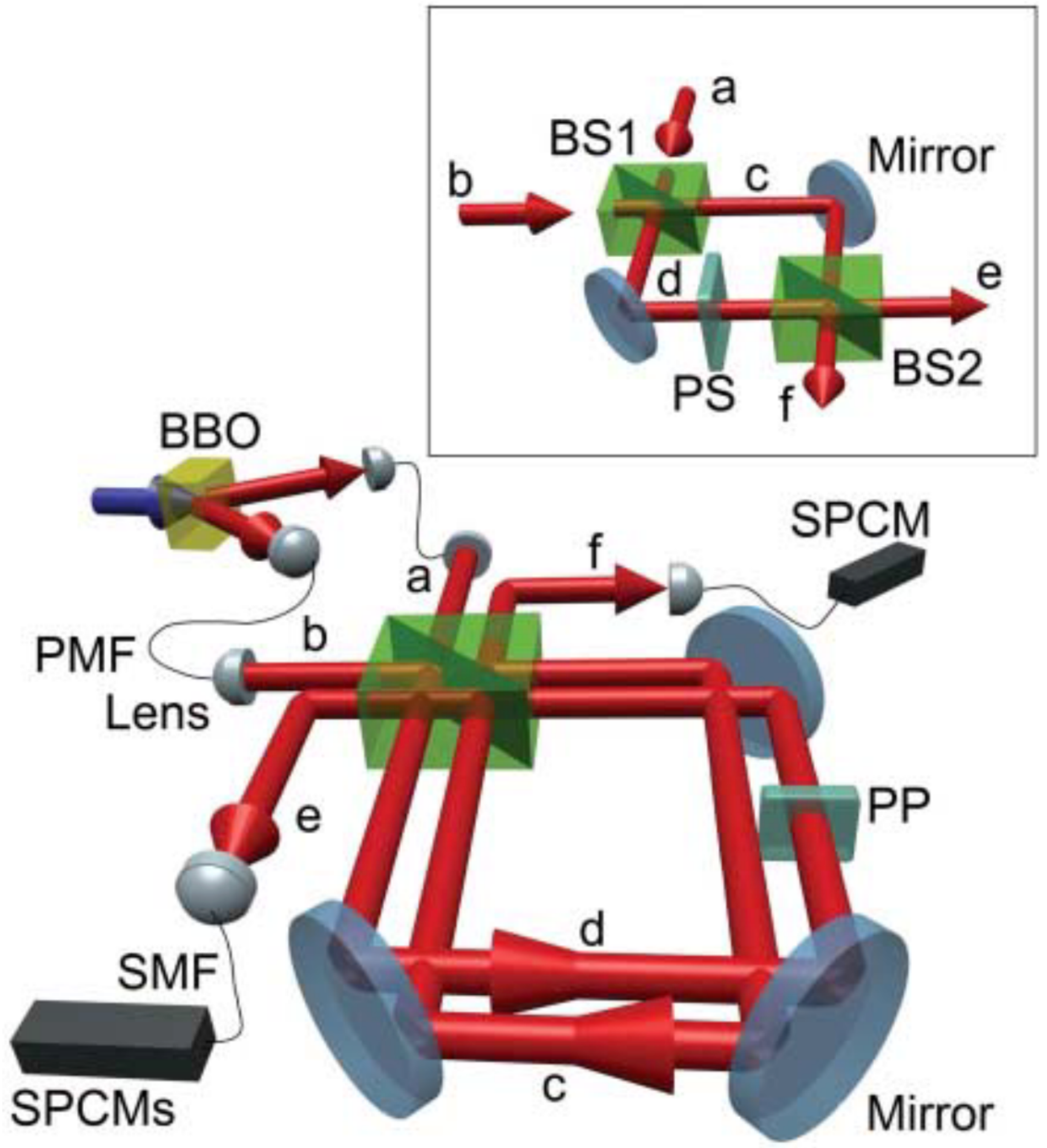
- We have heard news like the following in AMO physics

REPORTS

Beating the Standard Quantum Limit with Four-Entangled Photons

TOMOHISA NAGATA, RYO OKAMOTO, JEREMY L. O'BRIEN, KEJI SASAKI, AND SHIGEKI TAKEUCHI Authors Info & Affiliations

SCIENCE • 4 May 2007 • Vol 316, Issue 5825 • pp. 726-729 • DOI: 10.1126/science.1138007



- Can collider experiments reach the Ultimate Quantum Limit?

- Challenge: colliders only access to classical observables (momenta)

Conventional Collider Physics analysis

- QFT, M. Peskin, Section 3 $|\text{out}\rangle = iT|\text{in}\rangle = \int d\{\vec{p}\}\ M(\{\vec{p}\})\ |\{\vec{p}\}\rangle$

- Starting from the scattering amplitude M

- Next, calculate amplitude square $|M|^2$ $|M|^2 \propto \langle \text{out}|\text{out}\rangle$

- The model provides differential Xection $\dfrac{d\sigma}{d\{\vec{p}_1, \vec{p}_2\cdots\}}$

- For parameter X, exists best observable $O_X(d\sigma/d\{p\})$ (Classical Optimal Measurement)

Quantum Information & Collider Physics interplay

- QFT, M. Peskin, Section 3

$$|\text{out}\rangle = iT|\text{in}\rangle = \int d\{\vec{p}\}\ M(\{\vec{p}\})\ |\{\vec{p}\}\rangle$$

- Starting from the scattering amplitude M
- Next, calculate amplitude square $|M|^2$

$$|M|^2 \propto \langle \text{out}|\text{out}\rangle$$

- The model provides differential Xection $\frac{d\sigma}{d\{\vec{p}_1, \vec{p}_2 \cdots\}}$

$$\rho = |\text{out}\rangle\langle\text{out}|$$

- For parameter X, exists best observable $O_X(d\sigma/d\{p\})$ (Classical Optimal Measurement)

Measure & Analysis

Start with Classical Fisher Information (CFI)

- CFI: quantifies how much information an observable random variable carries about an unknown parameter d on which its probability distribution $f(x, d)$ depends
- $F_c(d) = \int dq\, f(q \mid d) \left[\frac{\partial}{\partial d} \log f(q \mid d) \right]^2$
- Cramér–Rao Bound: for any classical observable O_d for parameter d
  $\mathrm{Var}(O_d) \geq \left(\partial_d \langle O_d \rangle_\pi \right)^2 / F_c(d)$
- Only classical optimal observable O_d^{opt} reaches equality
- The larger CFI, the better the precision

Classical Fisher Information (CFI)

- Classical optimal observable reaching CFI
  - In perturbative sense: $f(q\,|\,d) = f_0 + d \cdot f_1 + \mathcal{O}(d^2)$
- Classical optimal observable $O_d^{\text{opt}} = f_1/f_0$
  - Saturating CR bound: $F_c(d) = \int dq\, f_0 \left(O_d^{\text{opt}}\right)^2$
- E.g. BELLE search of τ Electric Dipole Moments PLB2003, JHEP04(2022)110
- E.g. machine learning techniques at colliders are optimizing sensitivities towards CFI

Quantum Fisher Information (QFI)

- QFI $F_q(d)$: quantum precision limit for estimating parameters d encoded in quantum density matrix ρ_d
- Consider small parameter d (perturbative sense): $\rho_d = \rho_0 + d \cdot \rho_1 + \mathcal{O}(d^2)$
  - There exists Symmetric Logarithmic Derivative (SLD) operator $\hat{Q}^{\mathrm{opt}}$: $\rho_1 = \frac{1}{2}\left\{\rho_0, \hat{Q}^{\mathrm{opt}}\right\}$
  - QFI in a perturbative form: $F_q(d) = \mathrm{Tr}\left[\rho\left(\hat{Q}^{\mathrm{opt}}\right)^2\right] \simeq \mathrm{Tr}\left[\rho_0\left(\hat{Q}^{\mathrm{opt}}\right)^2\right]$
- **QFI** provides the **best achievable precision** for a given quantum state.
- CFI always loses information comparing with QFI: $F_q(d) \geq F_c(d)$

Ultimate Quantum Limit: Quantum Cramér–Rao bound

- Quantum Cramér–Rao bound: for any quantum operator $\hat{Q}$ for measuring d

$$\mathrm{Var}\left(\hat{Q}\right) \geq \frac{\left(\partial_d \langle \hat{Q} \rangle\right)^2}{F_q(d)}$$

- Mean $\langle \hat{Q} \rangle$ and Variance $\mathrm{Var}\left(\hat{Q}\right)$

- A higher QFI corresponds to a more precise measurement limit

- QFI saturation ⇔ projective measurements $\hat{\Pi}_i = |\psi_i\rangle\langle\psi_i|$ in SLD $\hat{Q}^{\mathrm{opt}} = \sum_i \lambda_i \hat{\Pi}_i$ eigenbasis

(S. L. Braunstein et al *Phys.Rev.Lett*. 1994)

(J. Liu, H. Yuan, X.-M. Lu, and X. Wang, *J. Phys.A* 2020)

The generalized quantum measurement at colliders

- Suppose a fermion decay $A \to BC$, with decay amplitude $M(A_\alpha \to BC)$

- Colliders perform classical measures on momenta of particles $|\vec{p}\rangle$

- But particle decay can serve as generalized quantum measurement

  - Its decay perform a measurement to spin density matrix: $\rho_A \to M\rho_A M^\dagger \propto \rho_A^{\text{post}}$

  - Generalized measurement : $\hat{D}_{\alpha\alpha'} \equiv N_D^{-1} M(A_\alpha \to BC) M^\dagger(A_{\alpha'} \to BC)$

    - Completeness condition: $\mathbf{I} = \int d\Omega_B \hat{D}(p_B)$

    - Normalized differential distribution and conservation:

$$1 = \text{Tr}[\rho_A] = \int d\Omega_B \text{Tr}[\rho_A \hat{D}(p_B)] = \int d\Omega_B \text{Tr}[\rho_A^{\text{post}}] = \int d\Omega_B f(p_B)$$

Q. Wang et al, 2402.16574, CPL
C.F. Qiao et al, 2002.04284, PRD
R. Ashby-Pickering et al, 2209.13990, JHEP

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τ pair decay as Quantum Measurements

- $\tau^+\tau^-$ entanglement production and spin density matrix:

$$\rho_{\alpha\alpha';\beta\beta'}(\hat{k}) = \frac{1}{|\overline{M}|^2} \overline{\sum_{\text{initial}}} M(\text{initial} \to \tau^+_\alpha(\hat{k})\tau^-_\beta(-\hat{k}))M^*(\text{initial} \to \tau^+_{\alpha'}(\hat{k})\tau^-_{\beta'}(-\hat{k}))$$

  - Introduce spin density matrix $\rho_d = \rho_0 + d \cdot \rho_1 + \mathcal{O}(d^2)$

- Two-body τ decay: $\tau^\pm \to \pi^\pm \overset{(-)}{\nu}$

  - Single τ spin measurement operator

$$\hat{D}^\pm_{\alpha\alpha'}(\hat{q}_\pm) = \frac{f_\pi^2}{2m_\tau^3|q|} M(\tau^\pm_{\alpha'} \to \pi^\pm(\hat{q}_\pm)X)M^*(\tau^\pm_\alpha \to \pi^\pm(\hat{q}_\pm)X)$$

τ Decay with maximal spin analyzing power

- Single τ spin measurement operator for general decay

$$\hat{D}^{\pm}_{\alpha\alpha'}(\hat{q}_{\pm}) = \frac{1}{2}(\mathbf{I}_2 \mp a\hat{q}_{\pm} \cdot \vec{\sigma})_{\alpha\alpha'}$$

  - With $0 \leq |a| \leq 1$, $|a| = 1$ maximal spin analyzing power; $|a| = 0$ no spin analyzing power

- Two-body τ decay: $\tau^{\pm} \to \pi^{\pm} \overset{(-)}{\nu}$
  - Maximal spin analyzing power $\to \mathrm{Rank}[\hat{D}] = 1$
  - Projector: $\hat{D} = |\hat{q}\rangle\langle\hat{q}|$, $|\hat{q}\rangle = \{\cos(\theta/2), \sin(\theta/2)e^{i\phi}\}$
  - Properties: $\mathrm{Tr}[\hat{D}^{\pm}] = 1, \quad (\hat{D}^{\pm})^2 = \hat{D}^{\pm}, \quad \int d\Omega_{\pm}\hat{D}^{\pm}(\hat{q}_{\pm}) = 2\pi\mathbf{I}_2$

- We take projector measurement, and leave Positive Operator-Valued Measure (POVM) for future study

Collider Reality: Separable (local) Measurements

- $\tau^+\tau^-$, each decays independently
  $M^{\rm tot}_{\alpha\beta} \propto M(\text{ini} \to \tau^+_\alpha(k_+)\tau^-_\beta(k_-)) \times M(\tau^+_\alpha(k_+) \to \pi^+\bar{\nu})M(\tau^-_\beta(k_-) \to \pi^-\nu)$

- Their decay forms separable quantum measurements

  - $\hat{E}_{\alpha\alpha';\beta\beta'}(\hat{q}_+, \hat{q}_-) = \hat{D}^+_{\alpha\alpha'}(\hat{q}_+) \otimes \hat{D}^-_{\beta\beta'}(\hat{q}_-)$

  - Properties:
    $\text{Tr}[\hat{E}] = 1, \quad \hat{E}^2(\hat{q}_+, \hat{q}_-) = \hat{E}(\hat{q}_+, \hat{q}_-), \quad \frac{1}{4\pi^2}\int d\Omega_+ d\Omega_- \hat{E}(\hat{q}_+, \hat{q}_-) = \mathbf{I}_4 \, .$

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- General collider measurements *cannot* access entangled states

Reaching QFI at collider is very difficult

- Recall to saturate QFI, one should measure with all four optimal projectors $\hat{\Pi}_i = |\psi_i\rangle\langle\psi_i|$, with orthonormal eigenstates $|\Psi_i\rangle$ of SLD $\hat{Q}^{\text{opt}}$

- Collider separable (non-entangled) measurements: $\hat{E} = |\hat{q}_+, \hat{q}_-\rangle\langle\hat{q}_+, \hat{q}_-|$

  - Define first measurement: $|E_1\rangle = |\hat{q}_+, \hat{q}_-\rangle \equiv |\hat{q}_+\rangle \otimes |\hat{q}_-\rangle$

  - The other orthonormal separable measurements are forced to be
    $|E_2\rangle = |-\hat{q}_+, \hat{q}_-\rangle, \;\; |E_3\rangle == |\hat{q}_+, -\hat{q}_-\rangle, \;\; |E_4\rangle == |-\hat{q}_+, -\hat{q}_-\rangle$

- Conditions for QFI saturation:
  $[\hat{Q}, \hat{E}_j] = 0 \quad \Leftrightarrow \quad \hat{Q}|E_j\rangle = \lambda_j|E_j\rangle$

Reaching QFI at collider is very difficult

- Conditions for QFI saturation: $[\hat{Q}, \hat{E}_j] = 0 \quad \Leftrightarrow \quad \hat{Q}\,|\,E_j\rangle = \lambda_j\,|\,E_j\rangle$

- $\hat{Q}^{\mathrm{opt}}$ from production is independent with the measurement $\hat{E}$
  - If eigenstate $|\,\psi_i\rangle$ is entangled $\rightarrow$ *cannot* reach quantum optimal at colliders

- Schmidt Condition to be separated:
  - $|\,\psi\rangle = a\,|\uparrow\uparrow\rangle + b\,|\uparrow\downarrow\rangle + c\,|\downarrow\uparrow\rangle + d\,|\downarrow\downarrow\rangle$
    $|\,\psi\rangle$ separable $\longleftrightarrow ad - cb = 0$
  - Zero measure, very difficult to satisfy

Rank-deficient ρ saves the Day

- If ρ_0 is not full-rank, SLD is not unique——Most general form of SLD:

$$\hat{Q} = \sum_{\substack{i,j \\ p_i + p_j \neq 0}} \frac{\langle p_i | \rho_1 | p_j \rangle}{p_i + p_j} |p_i\rangle\langle p_j| + \sum_{\substack{i,j \\ p_i = p_j = 0}} r_{ij} |p_i\rangle\langle p_j|$$

- $|p_i\rangle$: the eigenstate of ρ_0 with eigenvalue (probability) p_i
- r_{ij} : arbitrary complex numbers satisfying $r_{ij} = r_{ji}^*$

- Null space freedom provides the flexibility of $\hat{Q}$, *which provides hope to match* $\hat{E}_m(\hat{q}) = \hat{\Pi}_m(r)$

$$F_q(d) \xleftarrow{\hat{Q}^{\text{opt}}} \rho_d \xrightarrow{\hat{\Pi}_m(r)=\hat{E}_m(\hat{q}_+,\hat{q}_-)} \frac{df_m}{d\Omega_+ d\Omega_-} \xrightarrow{O_d^{\text{opt}}(\hat{q}_+,\hat{q}_-)} f_c(d)$$

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Three scenarios

- Higgs decay with CP-violating coupling: $h \to \tau^+\tau^-$
  - $$\mathscr{L}_{\text{CPV}} = -\frac{m_\tau}{v} h\, \bar{\tau} \left[\cos\delta_h + i\gamma_5 \sin\delta_h\right] \tau$$
- τ Magnetic/Electric Dipole Moment: $e^+e^- \to \tau^+\tau^-$
  - $$\mathscr{L}_{\text{MDM/EDM}} = \frac{1}{2} F_{\mu\nu}\, \bar{\tau}\sigma^{\mu\nu} \left[-\frac{e}{2m_\tau} a_\tau - i\gamma_5 d_\tau \right] \tau$$
- We use helicity basis for spin density matrix

Higgs CP-violating scenario

- Spin density matrix perturbatively: $\rho_0 = \frac{1}{2}\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}, \quad \rho_1 = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & -i & 0 \\ 0 & i & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$

- Most simple and direct SLD: $Q_h = 2\rho_1$,
  - easy to check $\rho_1 = \frac{1}{2}\{\rho_0, Q_h\}$, and QFI: $F_q(\delta_h) = 4$

- Q_h is rank 2, with two entangled eigenstates:
$\hat{\Pi}_1 = \frac{1}{\sqrt{2}}(i|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle), \hat{\Pi}_2 = \frac{1}{\sqrt{2}}(-i|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$

- $\hat{\Pi}_{1,2}$ cannot match to collider measurements

Higgs CP-violating scenario

- Most general SLD satisfying $\rho_1 = \frac{1}{2}\{\rho_0, \hat{Q}^{\rm gen}\}$:

$$\hat{Q}^{\rm gen}(r) = \begin{pmatrix} r_{44} & -\frac{r_{43}}{\sqrt{2}} & \frac{r_{43}}{\sqrt{2}} & r_{42} \\ -\frac{r_{34}}{\sqrt{2}} & \frac{r_{33}}{2} & -\frac{r_{33}}{2}-2i & -\frac{r_{32}}{\sqrt{2}} \\ \frac{r_{34}}{\sqrt{2}} & -\frac{r_{33}}{2}+2i & \frac{r_{33}}{2} & \frac{r_{32}}{\sqrt{2}} \\ r_{24} & -\frac{r_{23}}{\sqrt{2}} & \frac{r_{23}}{\sqrt{2}} & r_{22} \end{pmatrix}$$

- Scan all solutions across the auxiliary variables r's and particle momentum choices $\hat{q}_+$ and $\hat{q}_-$
  - to match $\hat{\Pi}_{1,2,3,4}(r) = \hat{E}_{1,2,3,4}(\hat{q}_+, \hat{q}_-)$

Higgs CP-violating scenario

- We found $\hat{\Pi}_{1,2,3,4}(r) = \hat{E}_{1,2,3,4}(\hat{q}_+, \hat{q}_-)$ for Higgs CPV scenario!

- Collider accessible SLD: $Q_h^{\text{opt}} = \frac{2}{\sin\varphi} \begin{pmatrix} -\cos\varphi & 0 & 0 & e^{-i\Phi} \\ 0 & -\cos\varphi & e^{-i\varphi} & 0 \\ 0 & e^{i\varphi} & -\cos\varphi & 0 \\ e^{i\Phi} & 0 & 0 & -\cos\varphi \end{pmatrix} \neq Q_h^{\text{old}} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & -2i & 0 \\ 0 & 2i & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$

- With $\varphi = \phi_1 - \phi_2$ and $\Phi = \phi_1 + \phi_2$; $\phi_{1,2}$ are free phase parameters

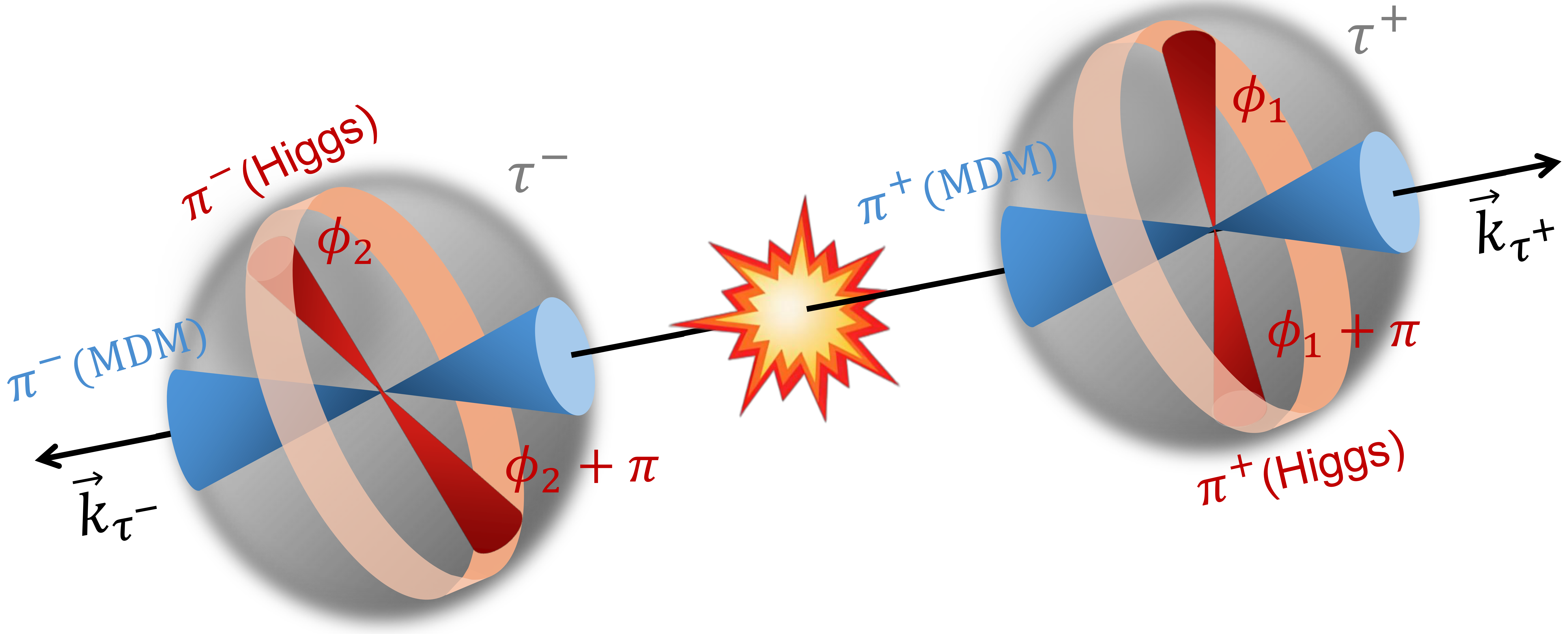
Quantum optimal collider measurements $\hat{E}_{1,2,3,4}$

CPV h	θ_+	θ_-	ϕ_+	ϕ_-
$\lvert E_1\rangle$	$\pi/2$	$\pi/2$	ϕ_1	ϕ_2
$\lvert E_2\rangle$	$\pi/2$	$\pi/2$	$\phi_1+\pi$	ϕ_2
$\lvert E_3\rangle$	$\pi/2$	$\pi/2$	ϕ_1	$\phi_2+\pi$
$\lvert E_4\rangle$	$\pi/2$	$\pi/2$	$\phi_1+\pi$	$\phi_2+\pi$

$\theta_\pm$: polar angle of $\hat{q}_\pm$

$\phi_\pm$: azimuthal angle of $\hat{q}_\pm$

Optimal collider measurements: four sets of directions



MDM scenario

- The spin density matrix for MDM:

$$\rho_0 = c_0 \begin{pmatrix} \frac{1}{2}(\cos 2\theta + 3) & -\frac{im}{\sqrt{s}}\sin 2\theta & -\frac{im}{\sqrt{s}}\sin 2\theta & -\sin^2\theta \\ \frac{im}{\sqrt{s}}\sin 2\theta & \frac{4m^2}{s}\sin^2\theta & \frac{4m^2}{s}\sin^2\theta & \frac{im}{\sqrt{s}}\sin 2\theta \\ \frac{im}{\sqrt{s}}\sin 2\theta & \frac{4m^2}{s}\sin^2\theta & \frac{4m^2}{s}\sin^2\theta & \frac{im}{\sqrt{s}}\sin 2\theta \\ -\sin^2\theta & -\frac{im}{\sqrt{s}}\sin 2\theta & -\frac{im}{\sqrt{s}}\sin 2\theta & \frac{1}{2}(\cos 2\theta + 3) \end{pmatrix}$$

$$\rho_1 = (1 - \frac{4m^2}{s})c_0^2 \begin{pmatrix} -2\sin^2\theta(\cos 2\theta + 3) & -\frac{ic_1\sqrt{s}}{4m}\sin 2\theta & -\frac{ic_1\sqrt{s}}{4m}\sin 2\theta & 4\sin^4\theta \\ \frac{ic_1\sqrt{s}}{4m}\sin 2\theta & 2\sin^2\theta(\cos 2\theta + 3) & 2\sin^2\theta(\cos 2\theta + 3) & \frac{ic_1\sqrt{s}}{4m}\sin 2\theta \\ \frac{ic_1\sqrt{s}}{4m}\sin 2\theta & 2\sin^2\theta(\cos 2\theta + 3) & 2\sin^2\theta(\cos 2\theta + 3) & \frac{ic_1\sqrt{s}}{4m}\sin 2\theta \\ 4\sin^4\theta & -\frac{ic_1\sqrt{s}}{4m}\sin 2\theta & -\frac{ic_1\sqrt{s}}{4m}\sin 2\theta & -2\sin^2\theta(\cos 2\theta + 3) \end{pmatrix}$$

MDM and EDM scenarios

- Quantum optimal collider-accessible SLD for MDM:

$$\hat{Q} = 2\left(\frac{s}{4m^2} - 1\right) c_0 \begin{pmatrix} -\frac{8m^2}{s}\sin^2\theta & 0 & 0 & 0 \\ 0 & \cos 2\theta + 3 & 0 & 0 \\ 0 & 0 & \cos 2\theta + 3 & 0 \\ 0 & 0 & 0 & -\frac{8m^2}{s}\sin^2\theta \end{pmatrix}$$

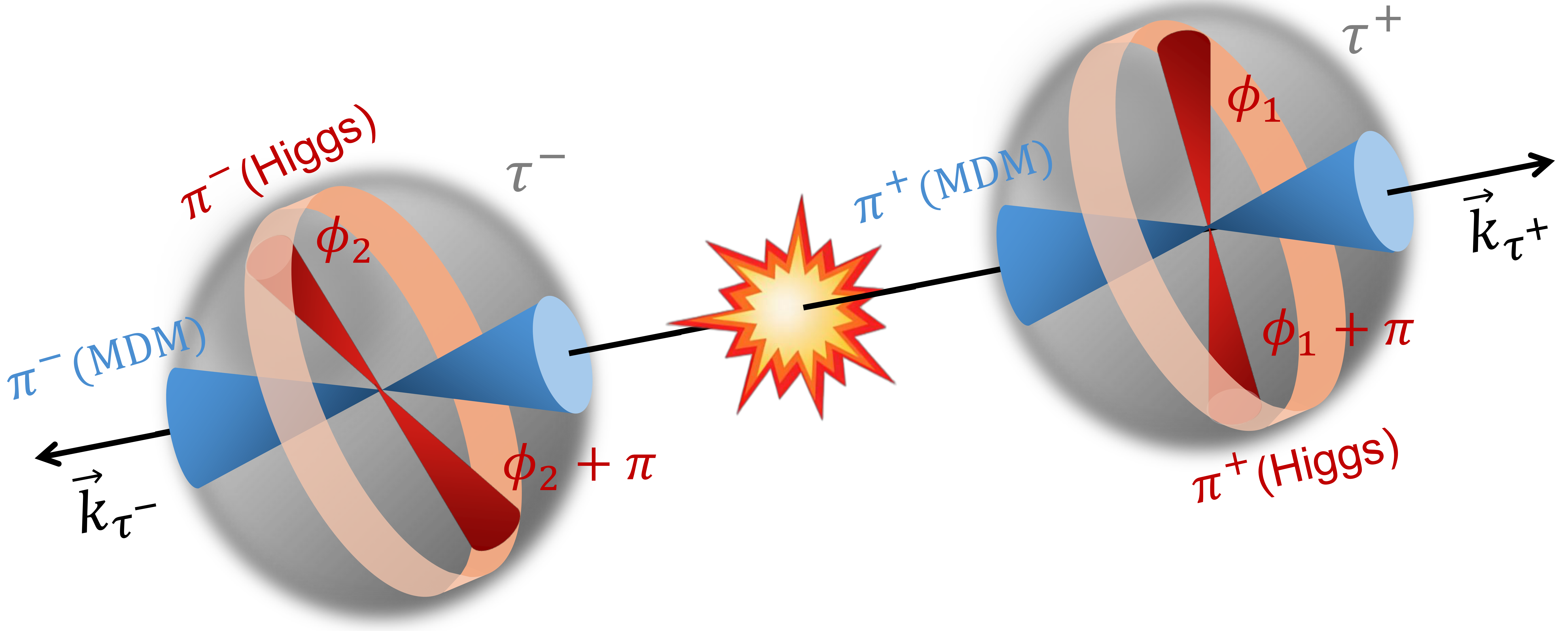
$$F_q^{\mathrm{MDM}}(\theta) = \frac{2s\sin^2\theta\,(\cos 2\theta + 3)\left(s - 4m^2\right)^2}{m^2\left(8m^2\sin^2\theta + s\cos 2\theta + 3s\right)^2}$$

- Corresponding classical optimal collider measurements:

MDM	θ_+	θ_-	ϕ_+	ϕ_-
$\lvert E_1\rangle = \lvert\downarrow\downarrow\rangle$	π	π	$-$	$-$
$\lvert E_2\rangle = \lvert\downarrow\uparrow\rangle$	π	0	$-$	$-$
$\lvert E_3\rangle = \lvert\uparrow\downarrow\rangle$	0	π	$-$	$-$
$\lvert E_4\rangle = \lvert\uparrow\uparrow\rangle$	0	0	$-$	$-$

- EDM has no solution

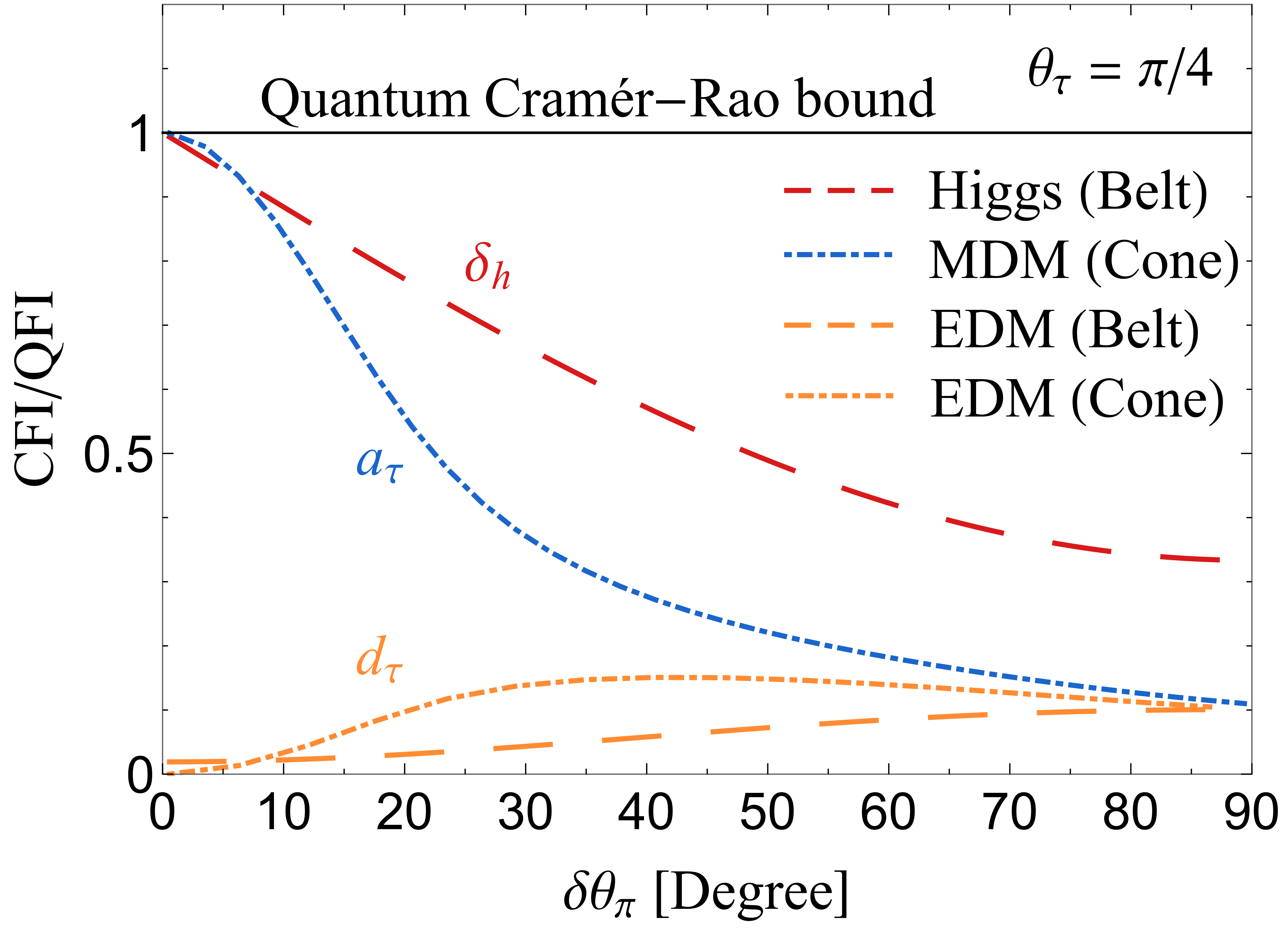
Optimal collider measurements: four sets of directions

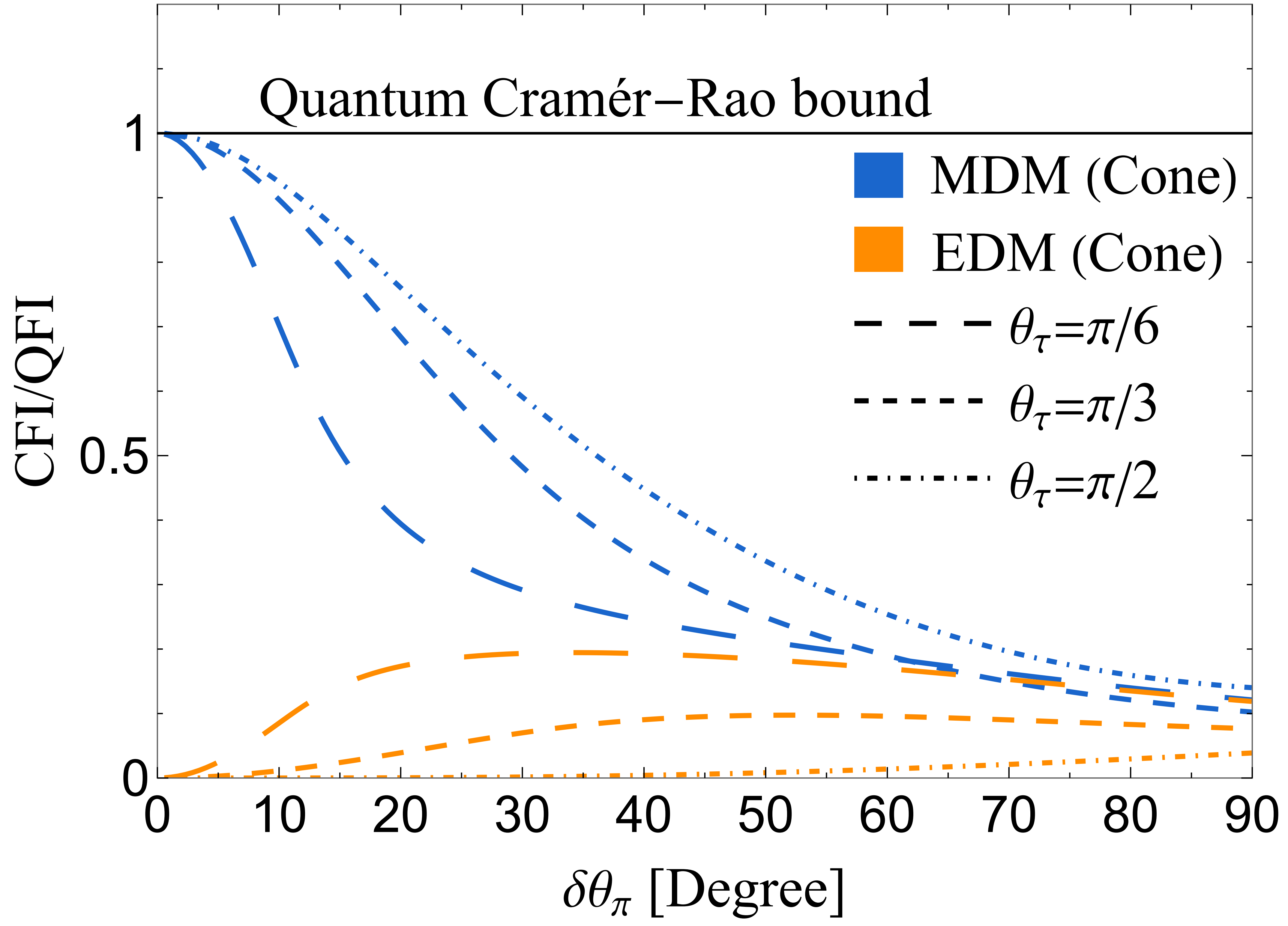


Collider Strategy: Phase-Space Restricted PS

- Expand each optimal direction into a cone of angular size $\delta\theta_\pi$
  - Allowing non-zero events
  - CFI asymptotic saturates QFI

$$F_c(d) = \int d\mathrm{PS}_{\mathrm{Belt/Cone}} \times \frac{\Sigma_1^2}{\Sigma_0}$$





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Summary and Outlook

- QFI represents the ultimate precision limit in parameter estimating, QFI ≥ CFI

- Quantum measurement connect quantum states to classical distribution
  Particle decay serves as generalized quantum measurements

- Collider measurements can only access separable projectors $\hat{E} = \hat{D}(q_+) \otimes \hat{D}(q_-)$

- Condition for QFI saturation: (specific directions)

$$F_q(d) \xleftarrow{\hat{Q}^{\rm opt}} \rho_d \xrightarrow{\hat{E}_m(\hat{q}_+,\hat{q}_-)=\hat{\Pi}_m(r)} \frac{df_m}{d\Omega_+ d\Omega_-} \xrightarrow{O_d^{\rm opt}(\hat{q}_+,\hat{q}_-)} f_c(d)$$

  - Rank deficiency of $\rho \longrightarrow$ Flexibility of SLD

- QFI saturation is achievable for Higgs CPV decay and MDM cases, but not for EDM

- Framework easily applicable to other entangled biparticle systems:
  $t\bar{t}$ from ee, $t\bar{t}$ pseudo-scalar resonance, baryon pairs $(\Delta, \Lambda, \Lambda_b)$, gauge boson pairs
  also general $b\bar{b}$ system

Summary and Outlook

Tools from
Quantum Information Science

New analyzing tools

New quantum states

Treasures coded in the
S-matrix of QFT

$$|\text{out}\rangle = iT|\text{in}\rangle$$

Probabilities
in differential distributions

$$P = \Big|\langle \text{measured}|\text{out}\rangle\Big|^2$$

Thanks you!

Backup slides