Correlation Function/Wilson Loop Duality in QCD from SCET

Zhaoyan Pang (Peking University)

SCET 2026

Based on [2510.07377] with
Hao Chen (MIT), Pier Francesco Monni (CERN), Gherardo Vita (CERN), and Hua Xing Zhu (PKU)

Main Result

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$j^{\mu}(x) = \bar{\psi}\gamma^{\mu}\psi(x)$ EM current

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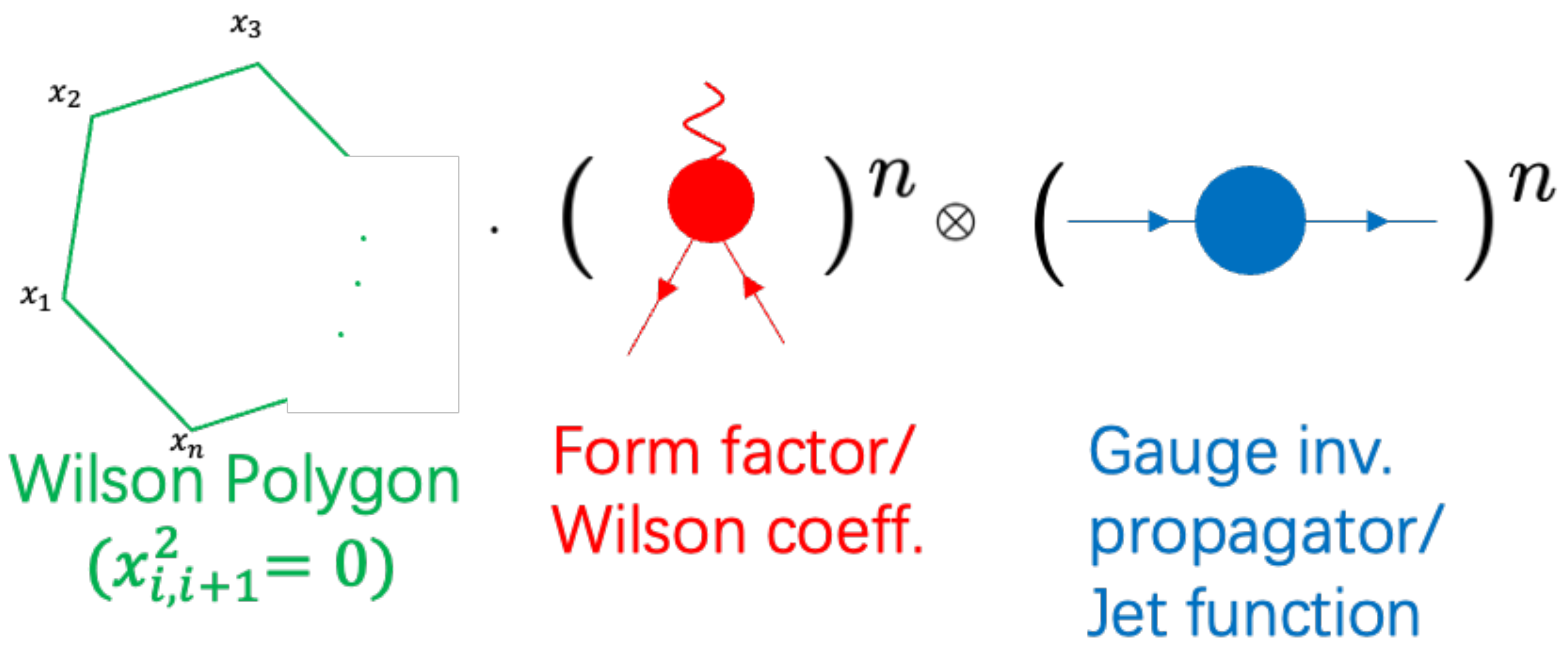

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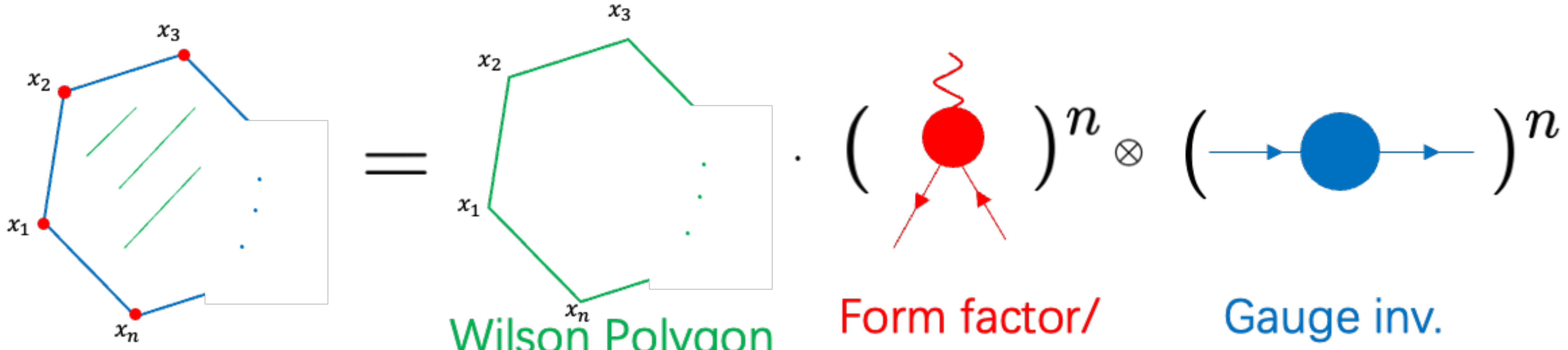

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- $x_{i,i+1}^2 \to 0^-$ (Sequential Light-cone Limit)

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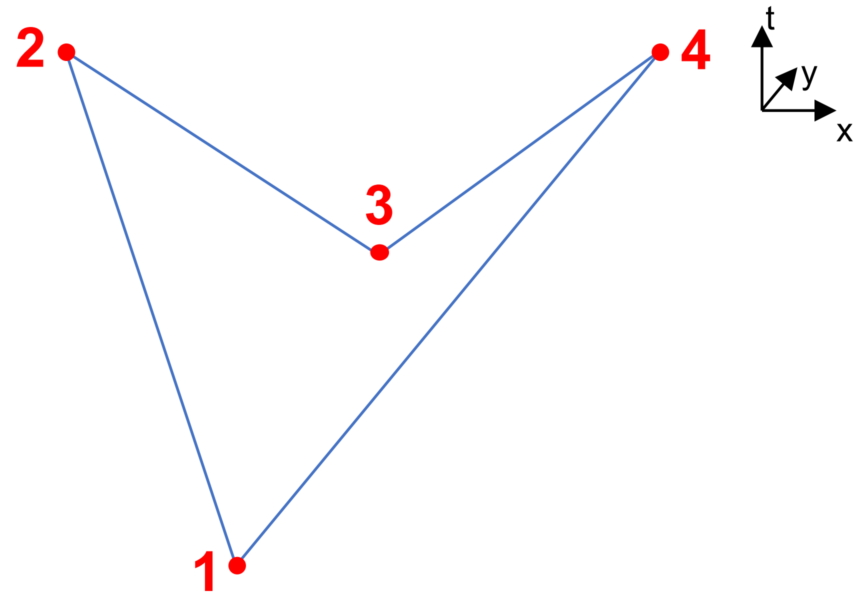
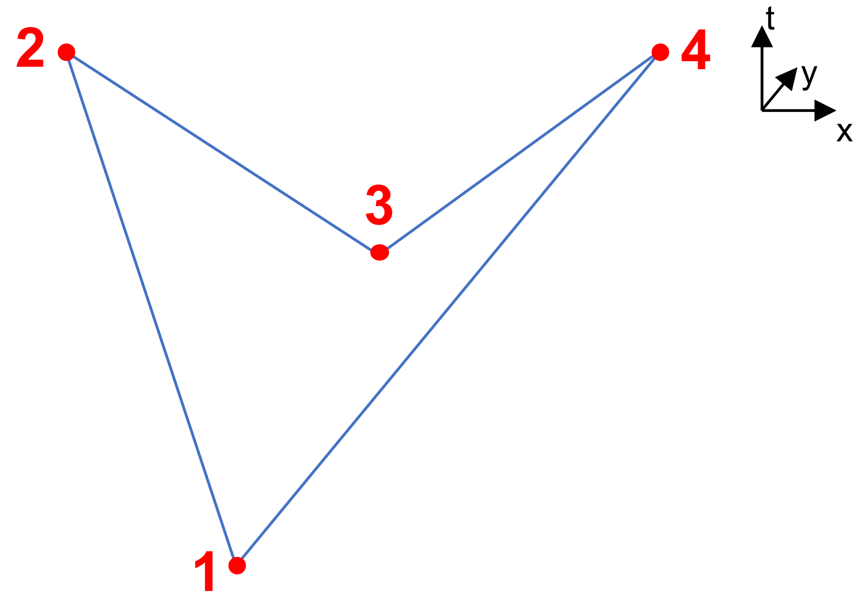
  ➡ Similar duality in $\mathcal{N} = 4$ SYM **[Alday, Eden, Korchemsky, Maldacena, Sokatchev, 1007.3243]**

$$x_{i,i+1}^2 \to 0^-$$



$$x^2_{i,i+1} \rightarrow 0^-$$



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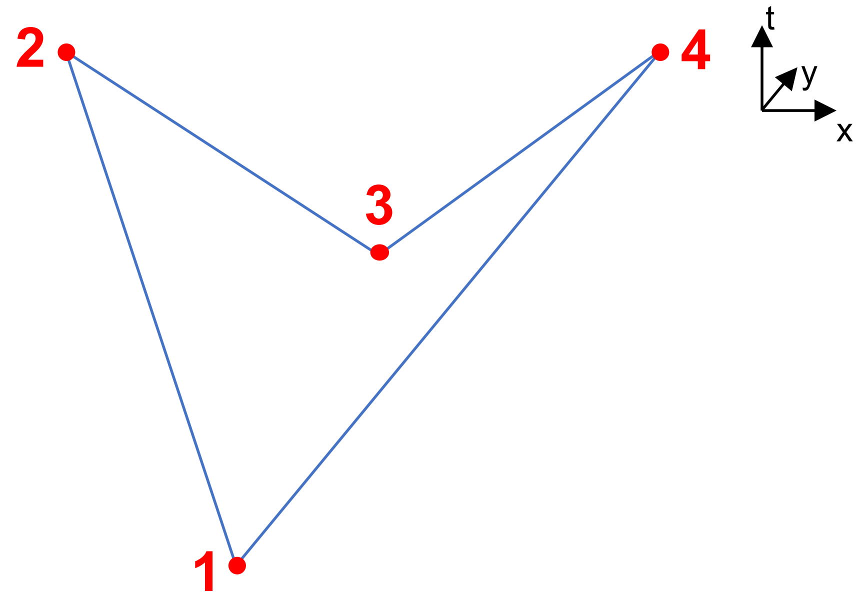

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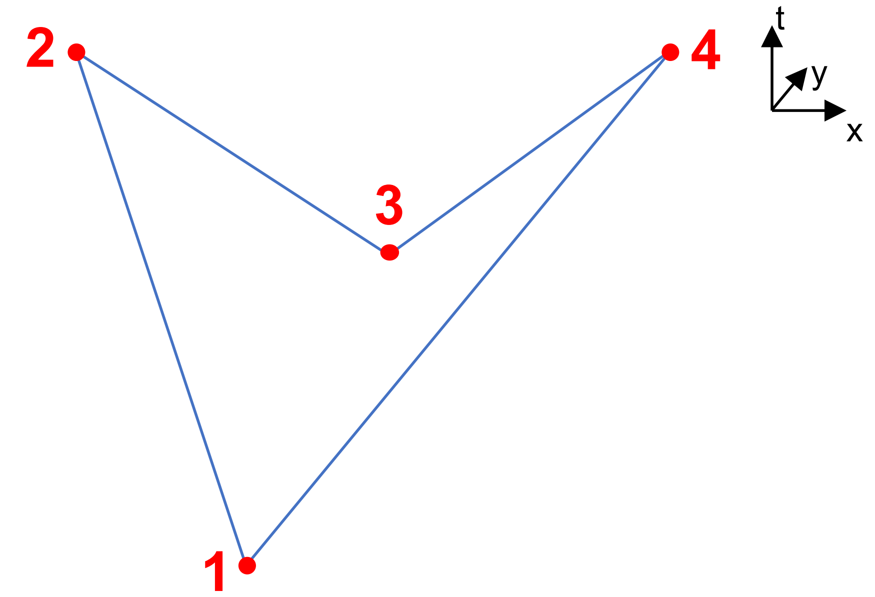

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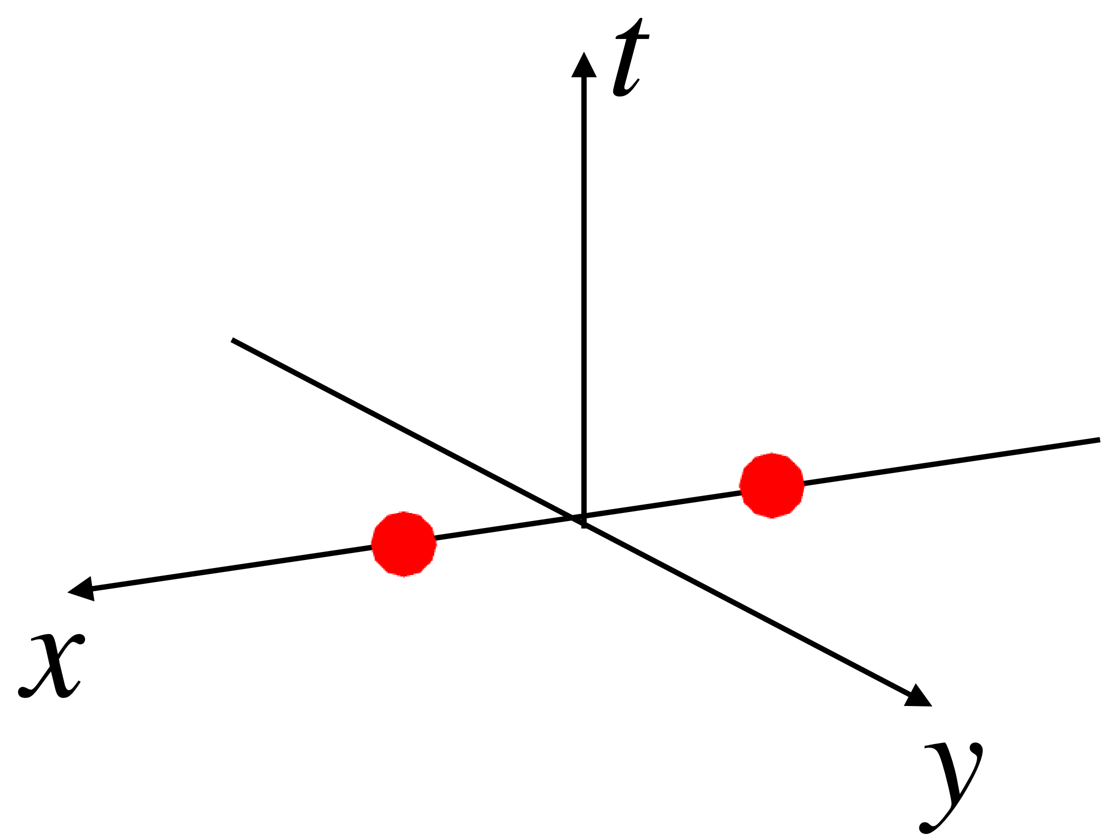

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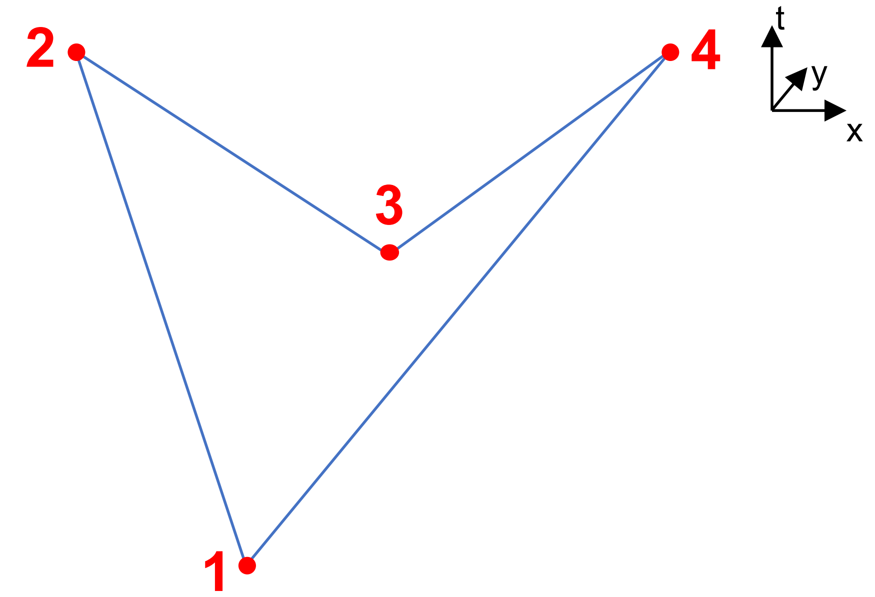

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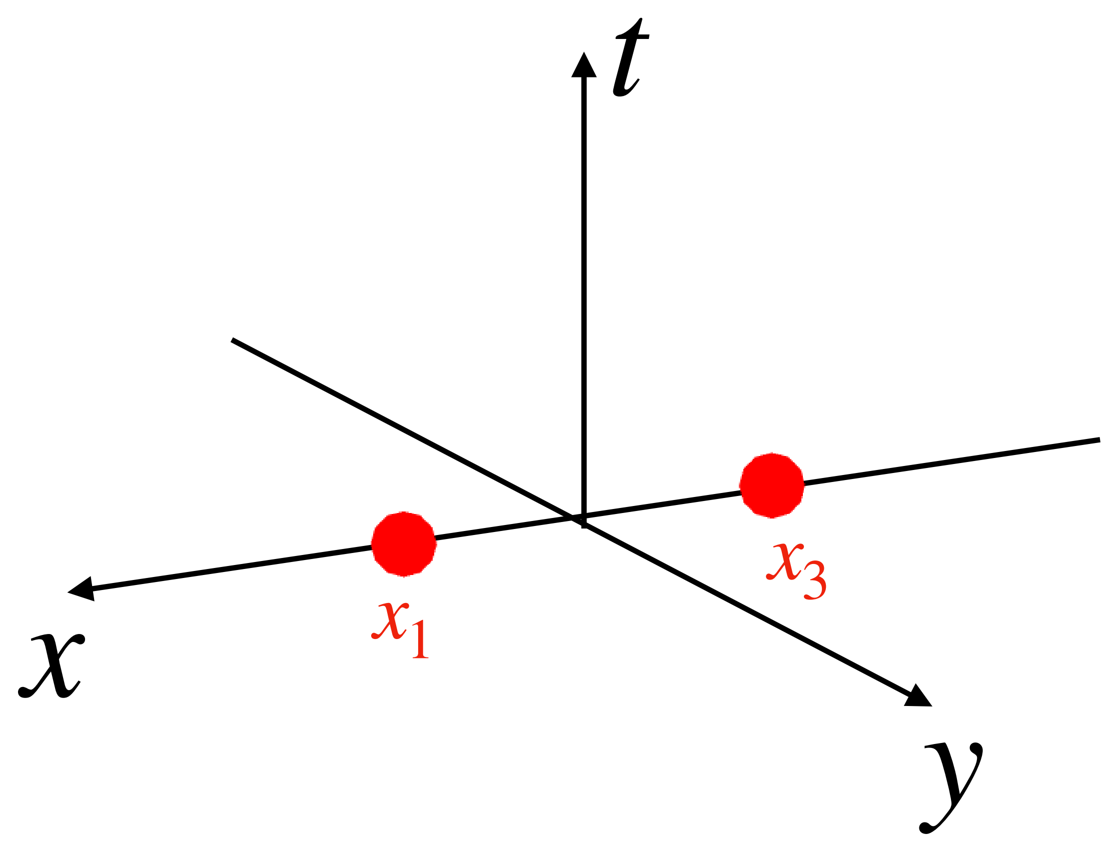

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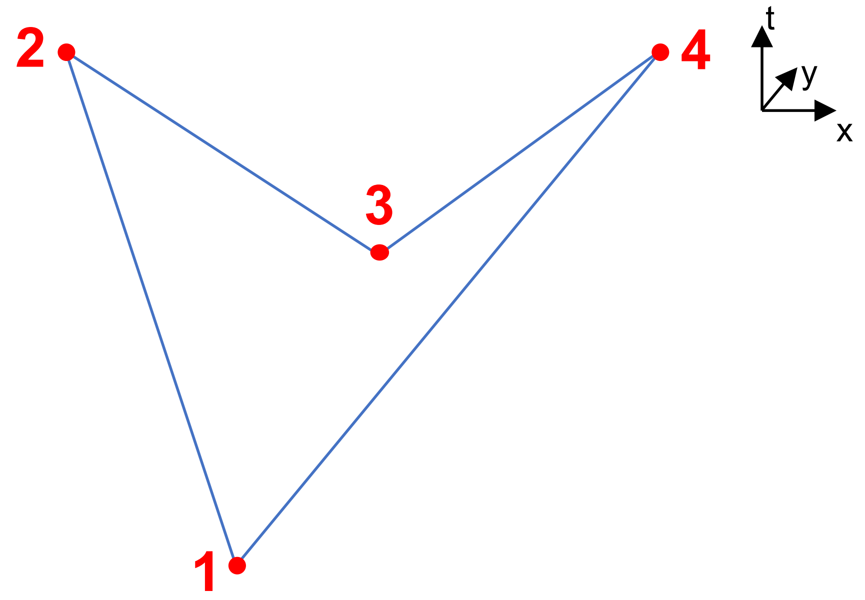

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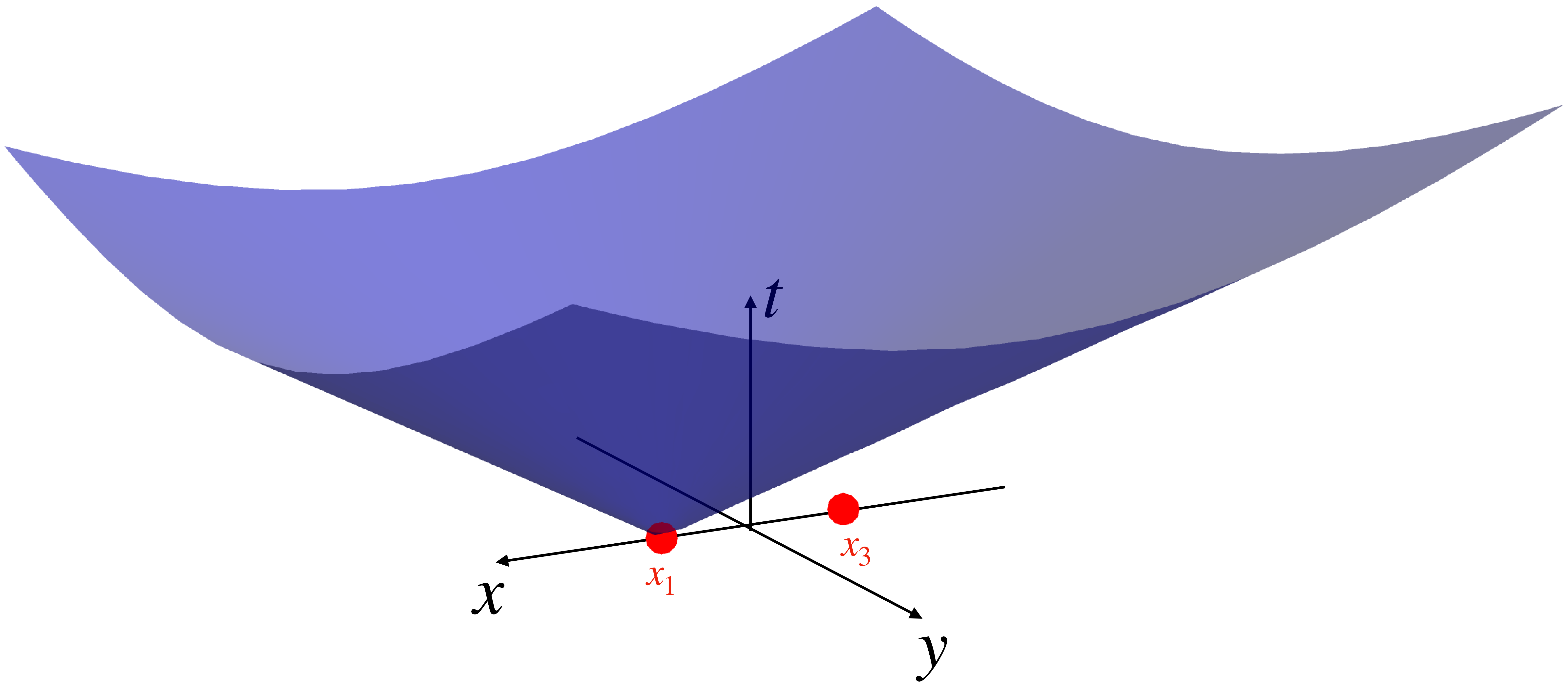

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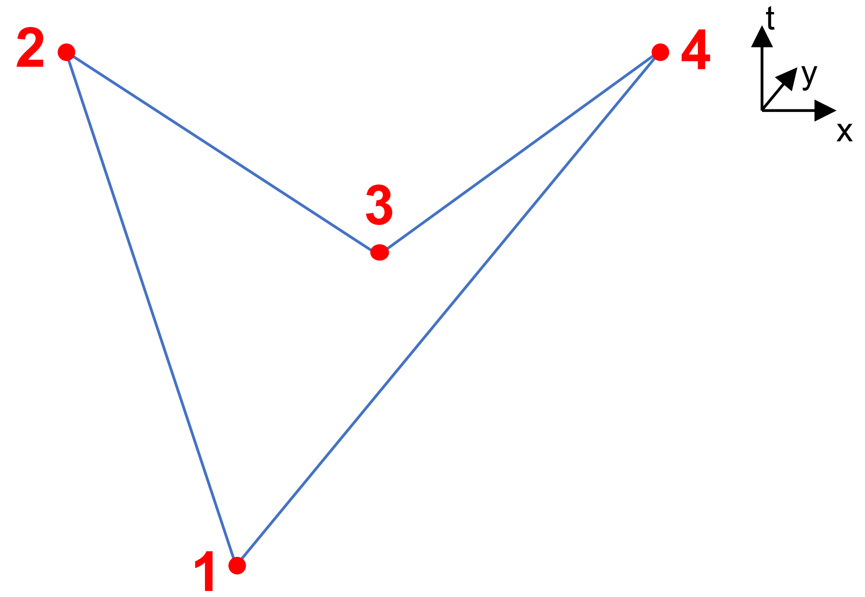

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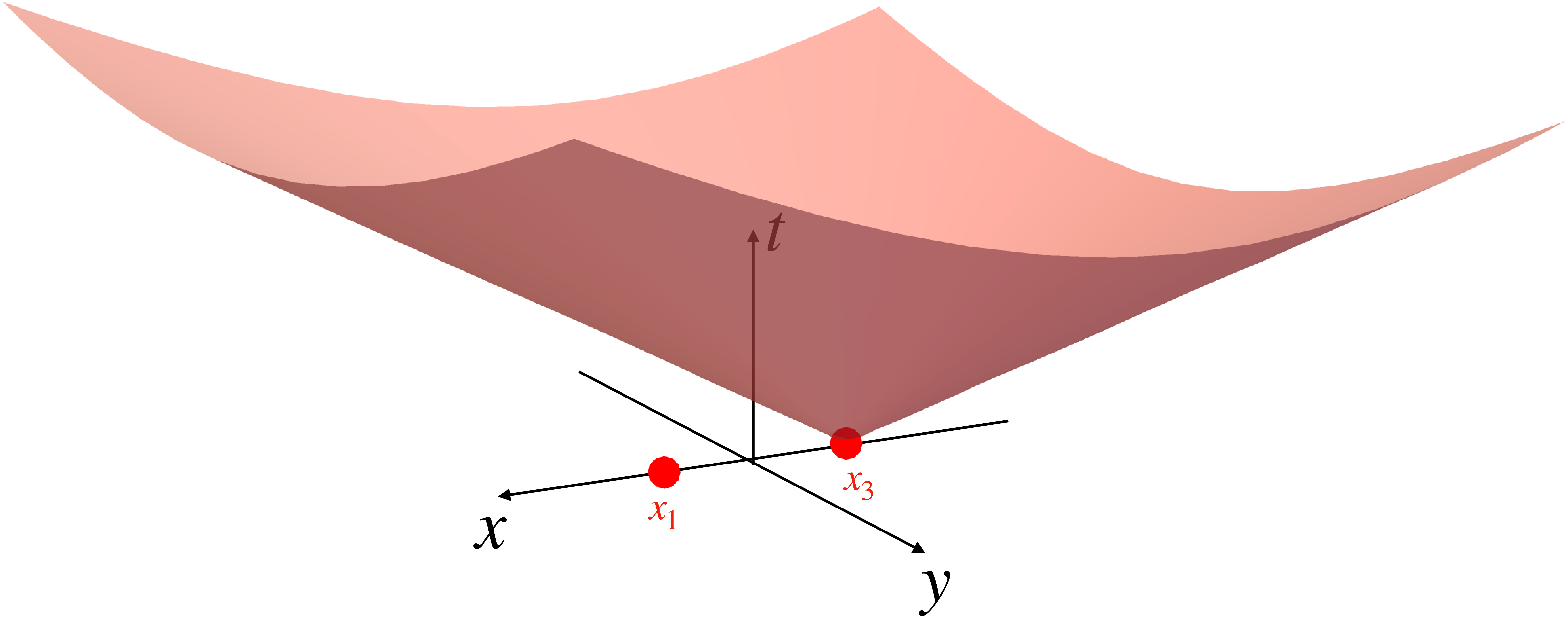

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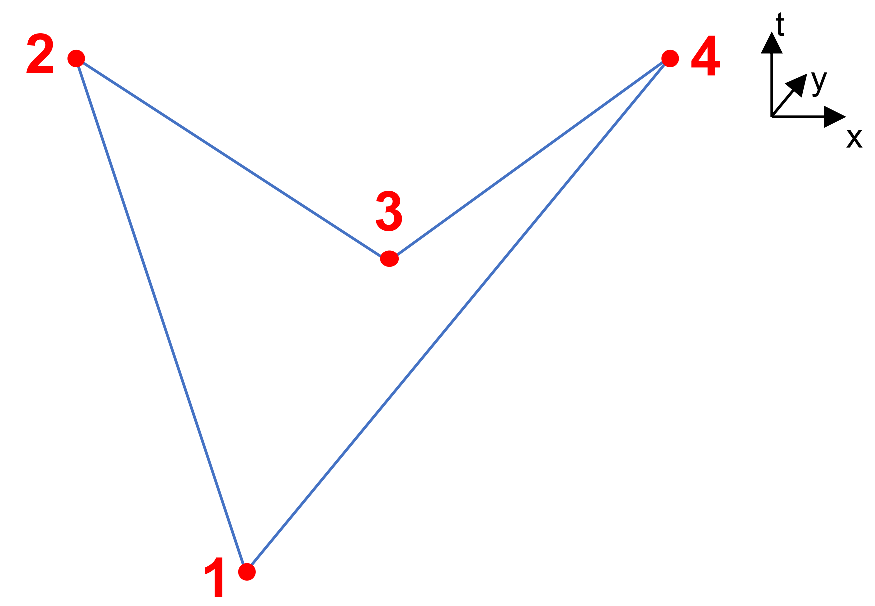

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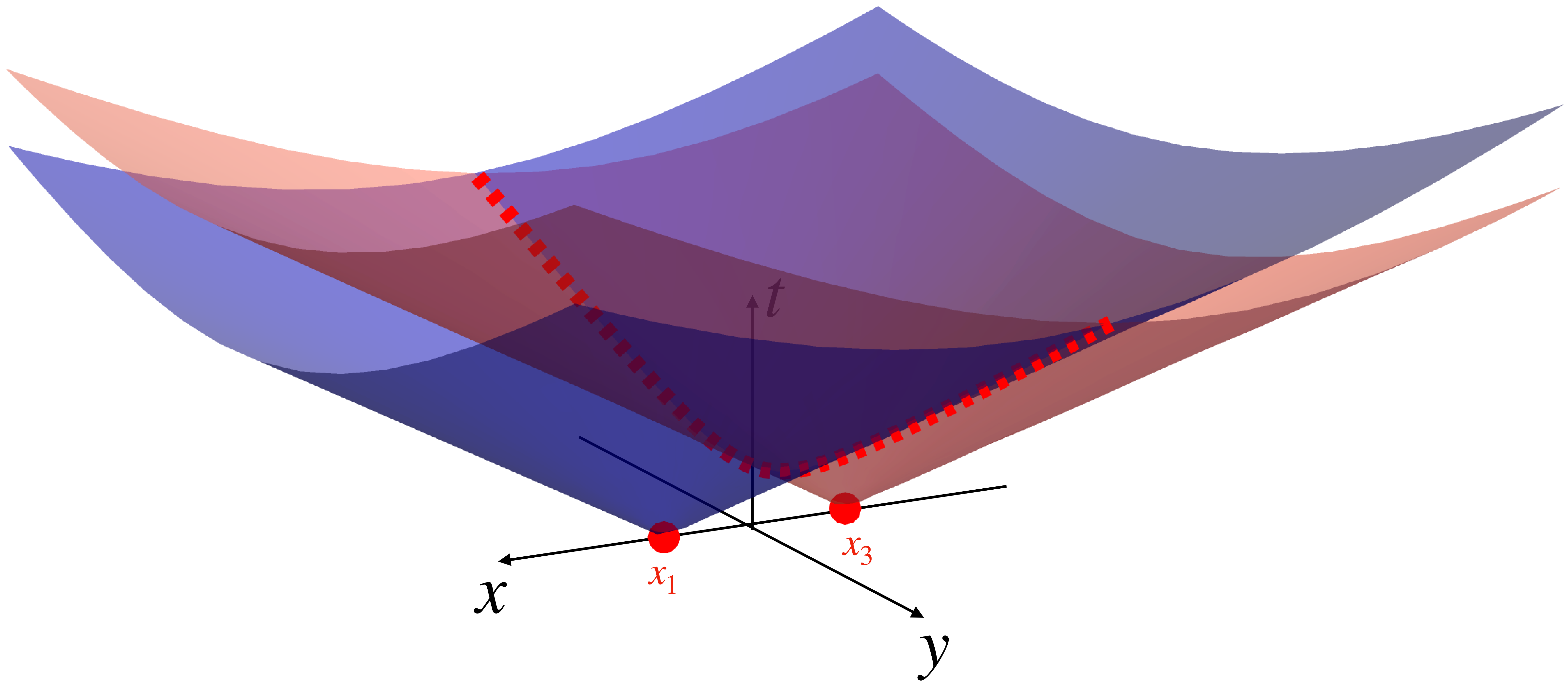

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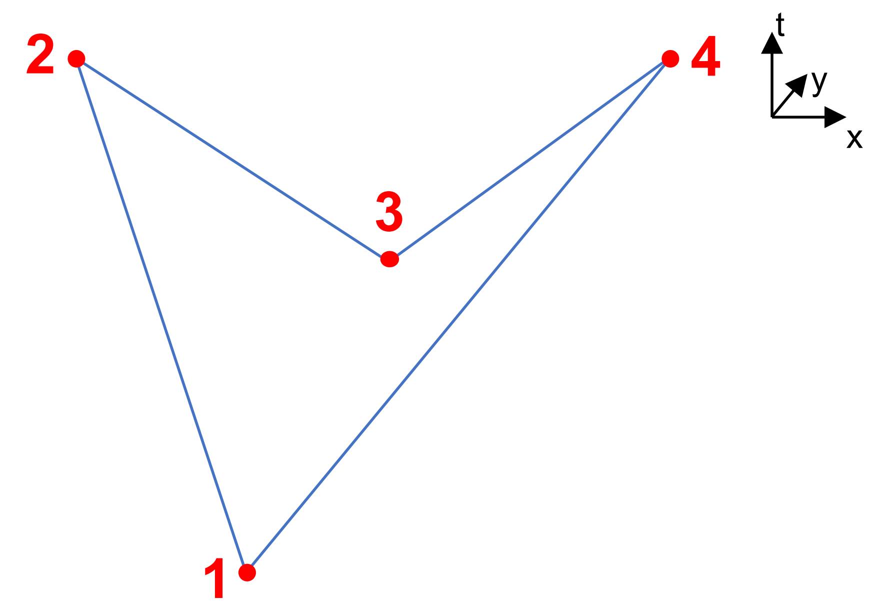

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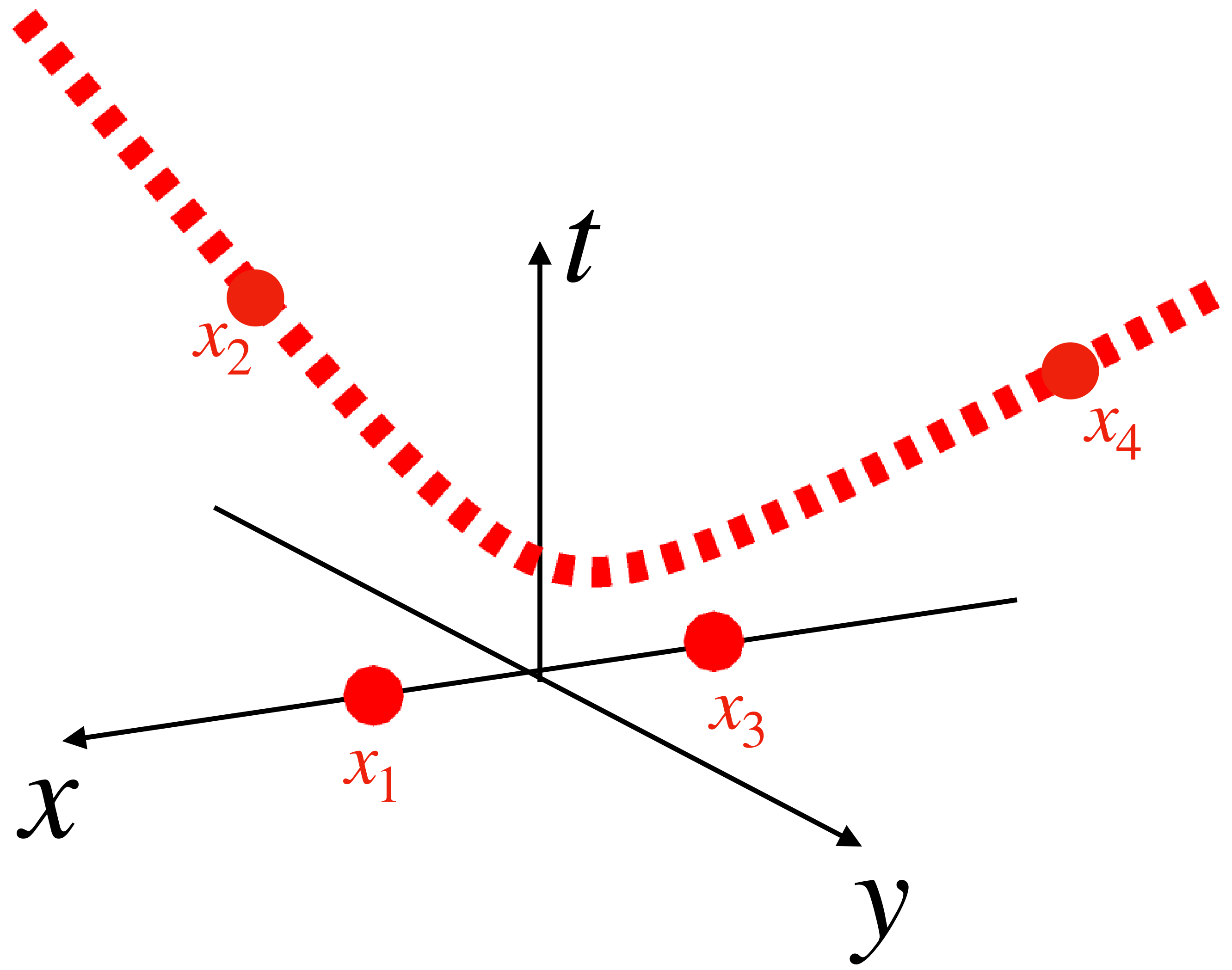

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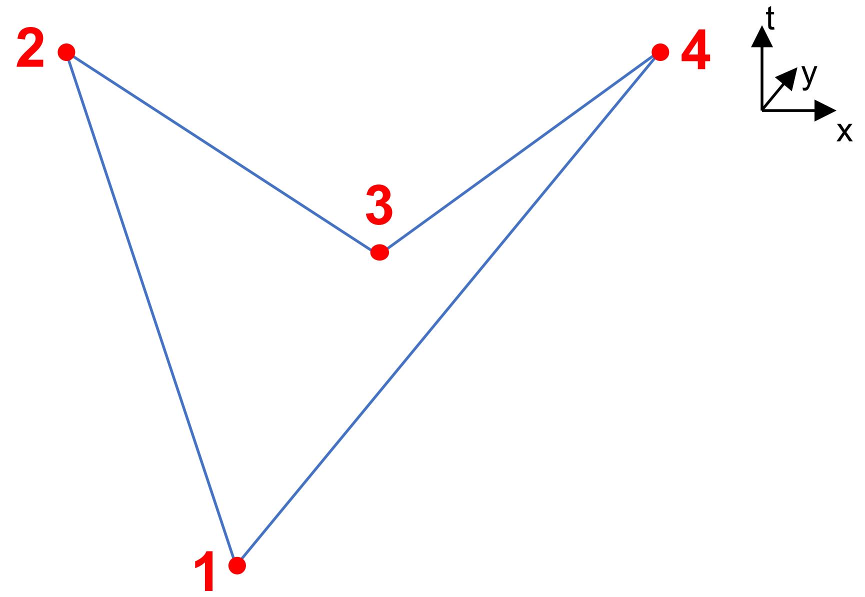

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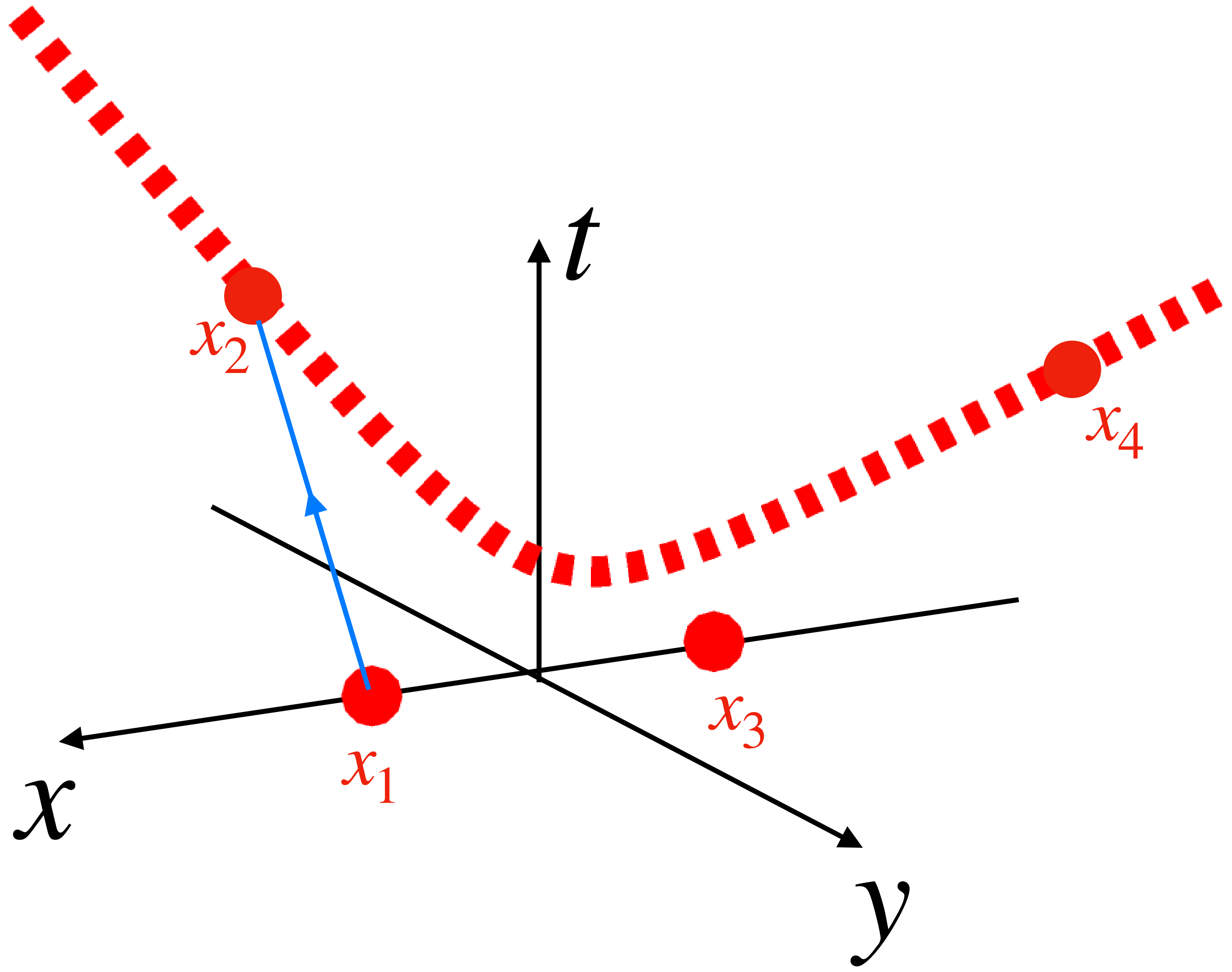

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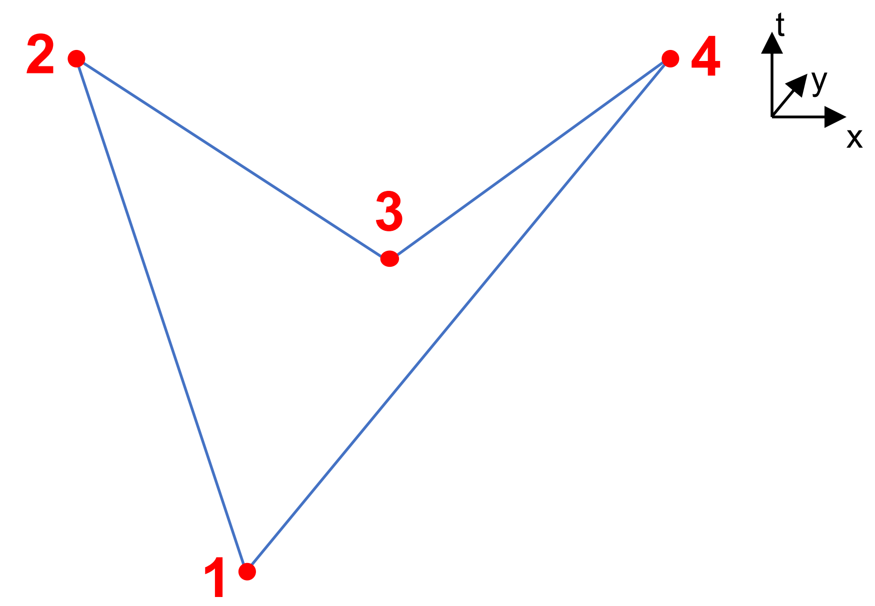

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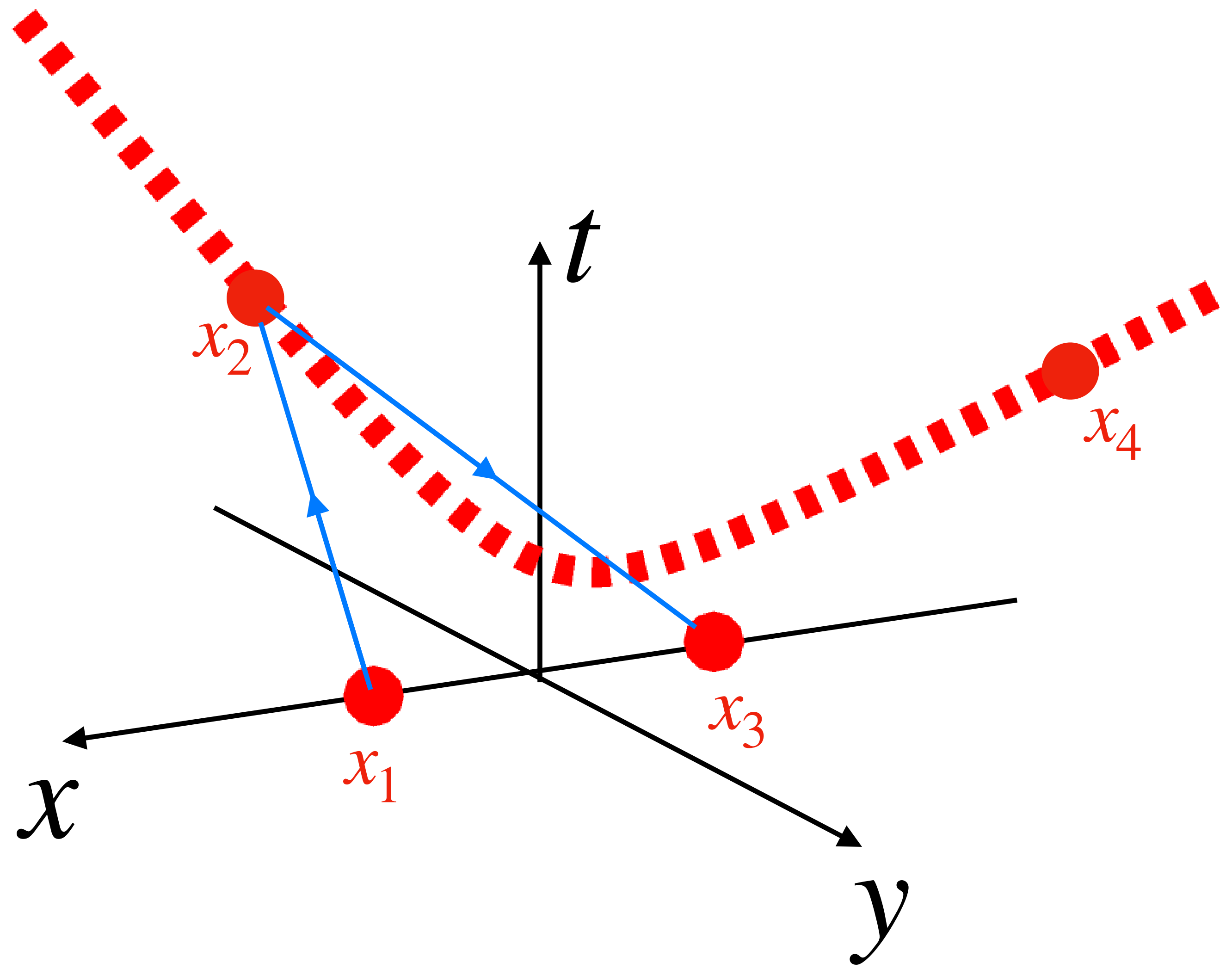

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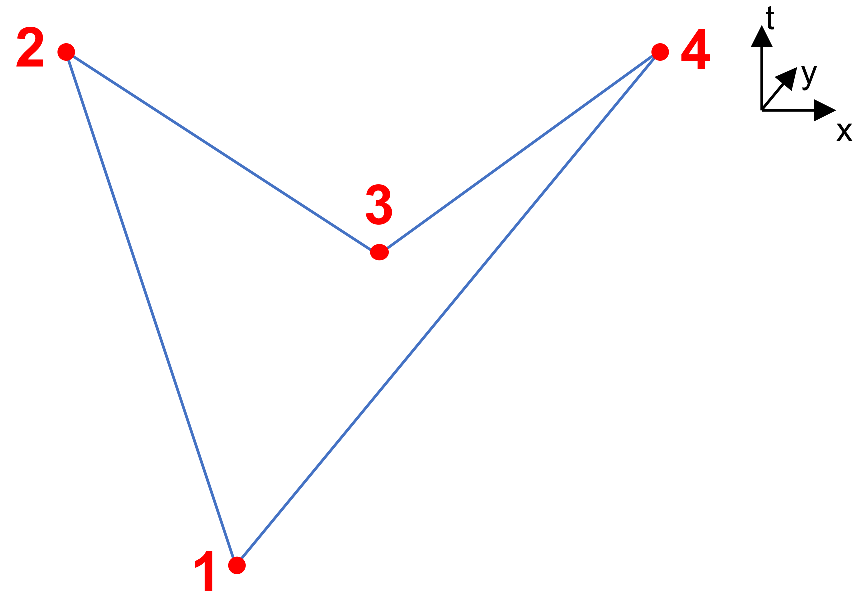

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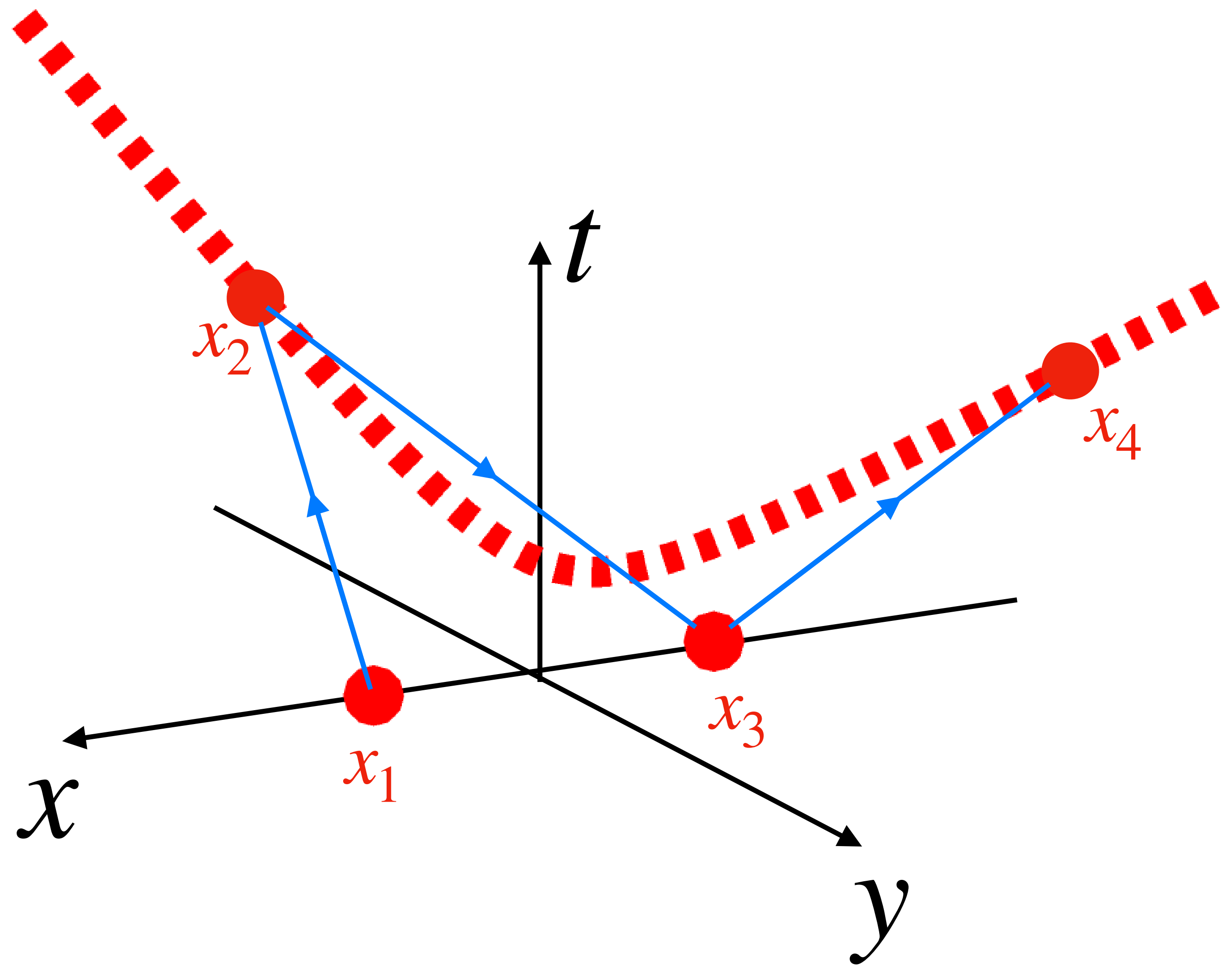

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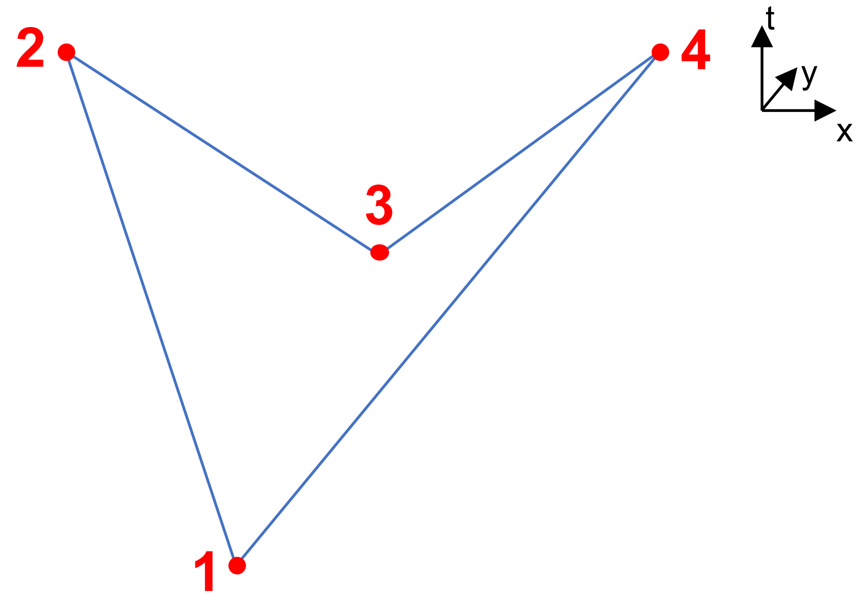

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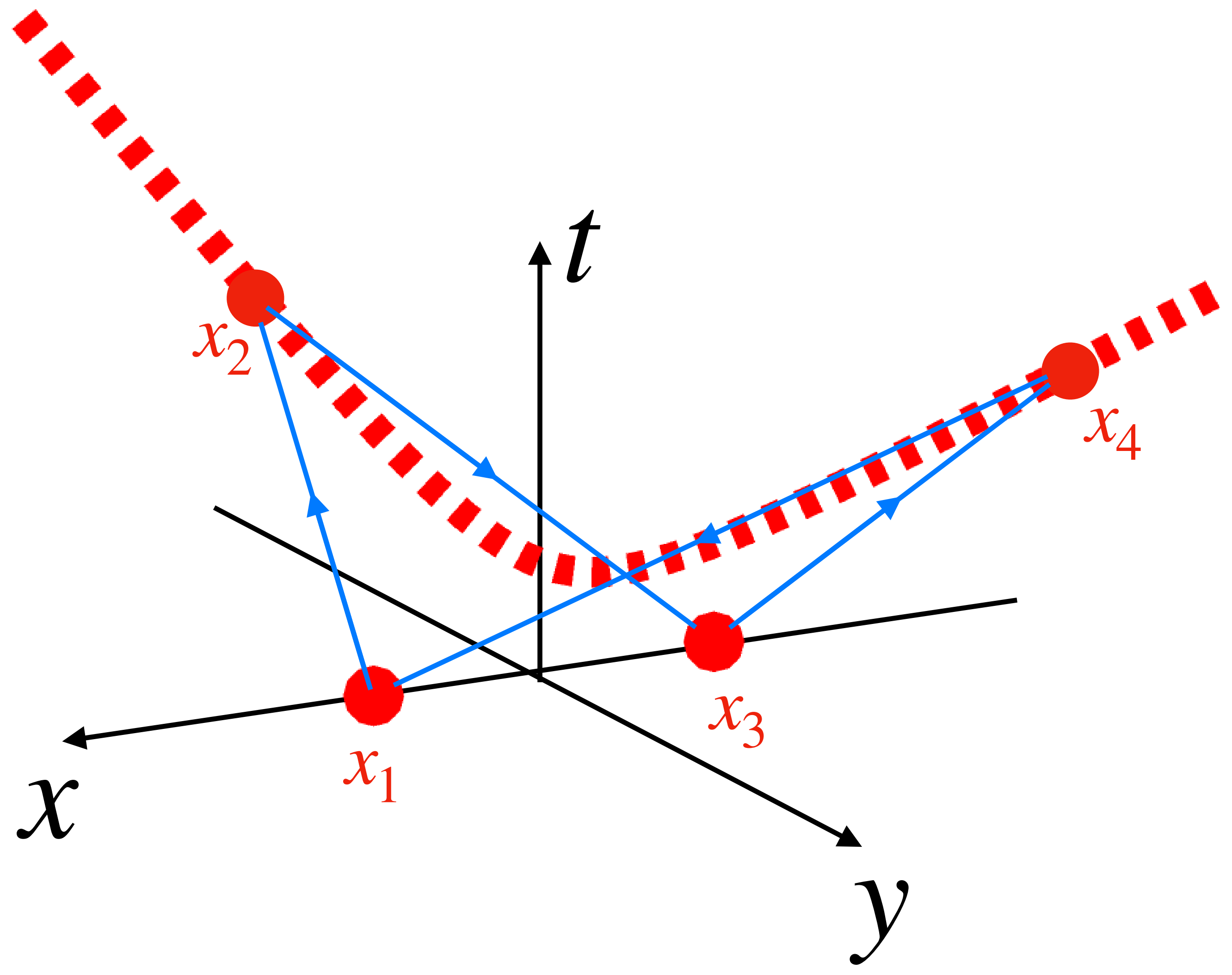

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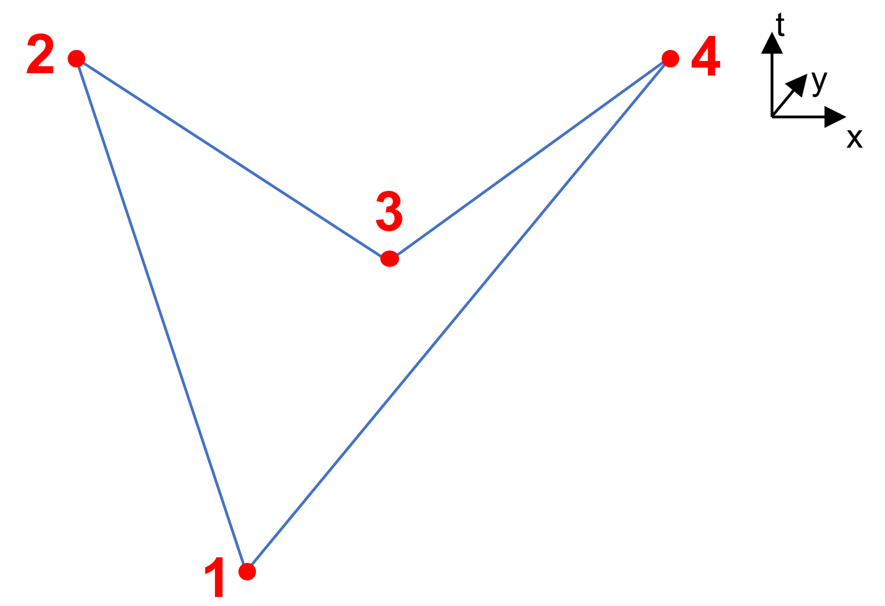

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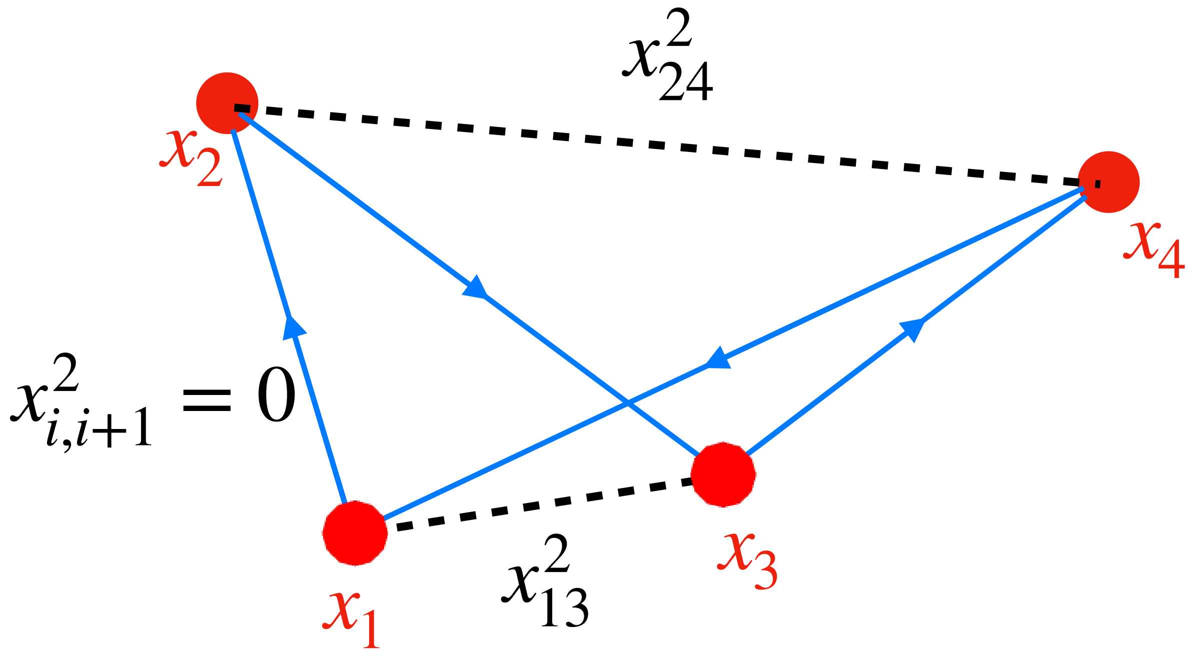

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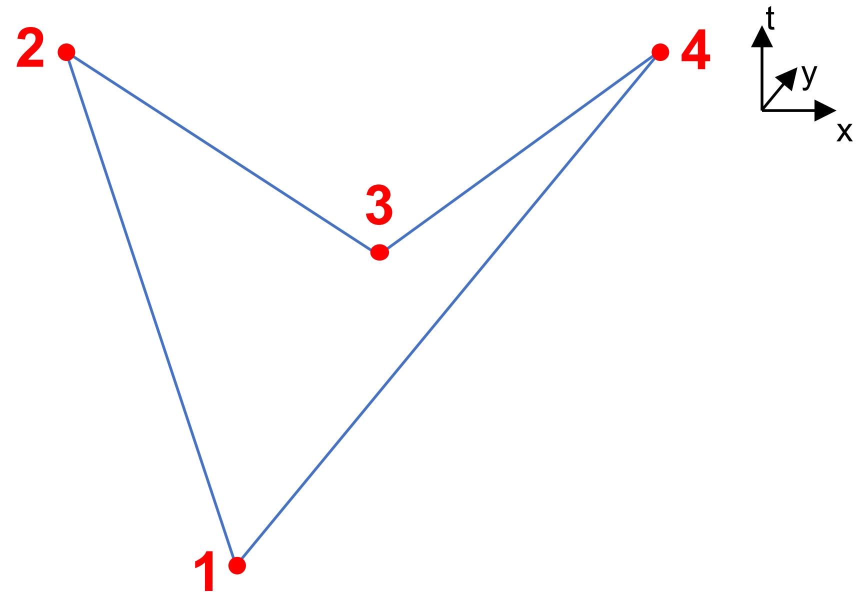

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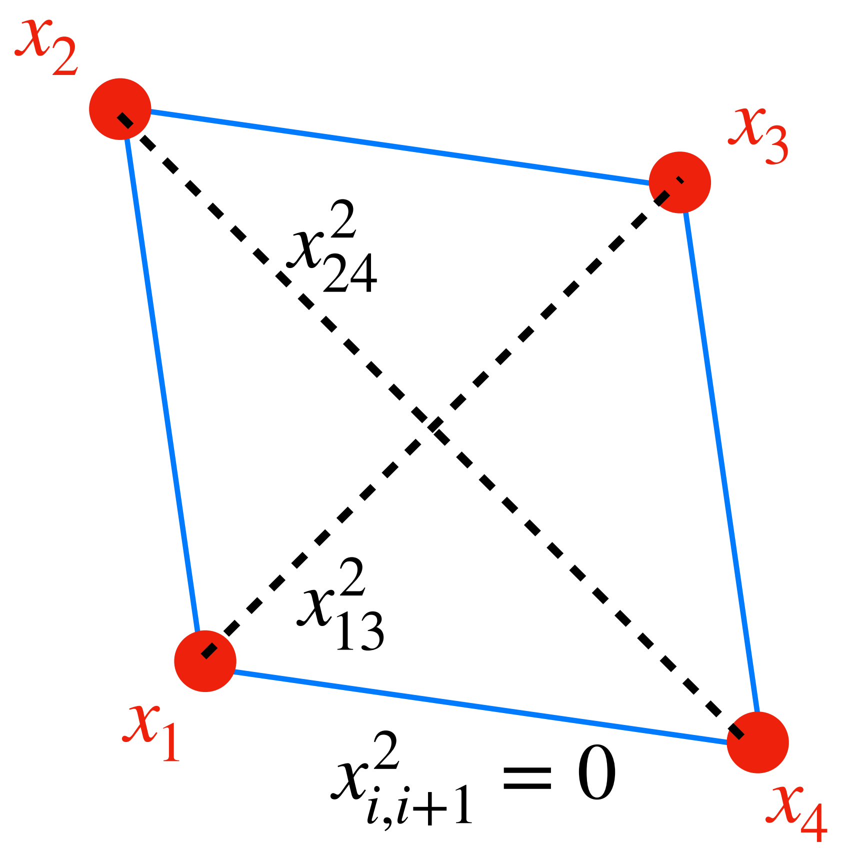

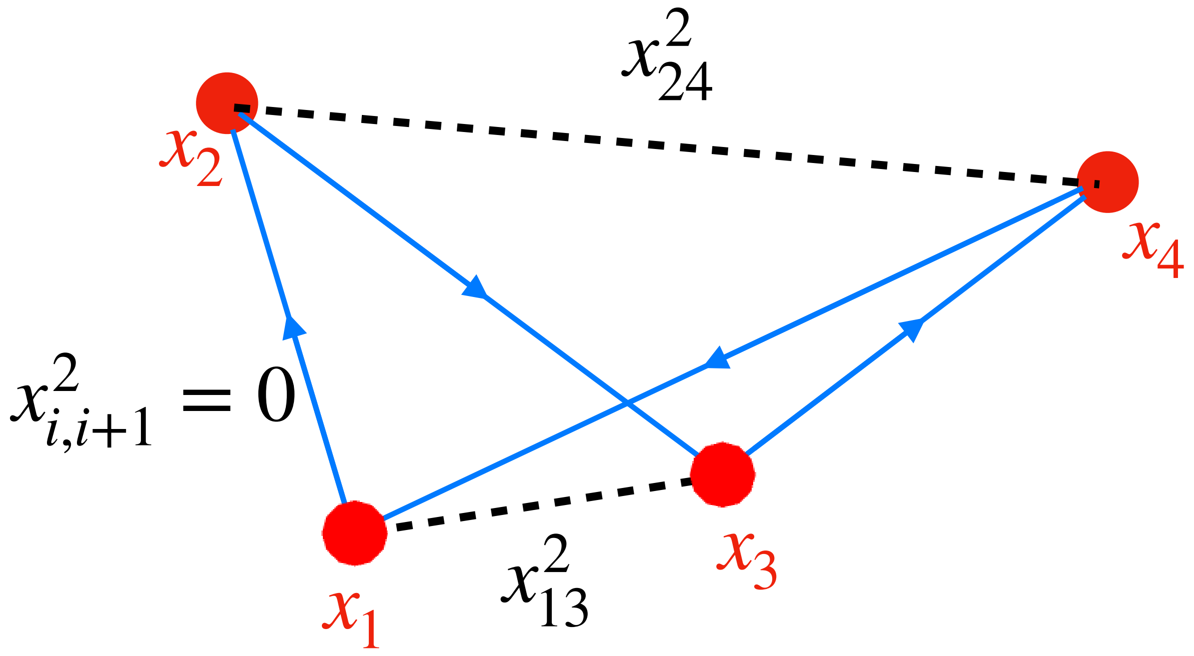

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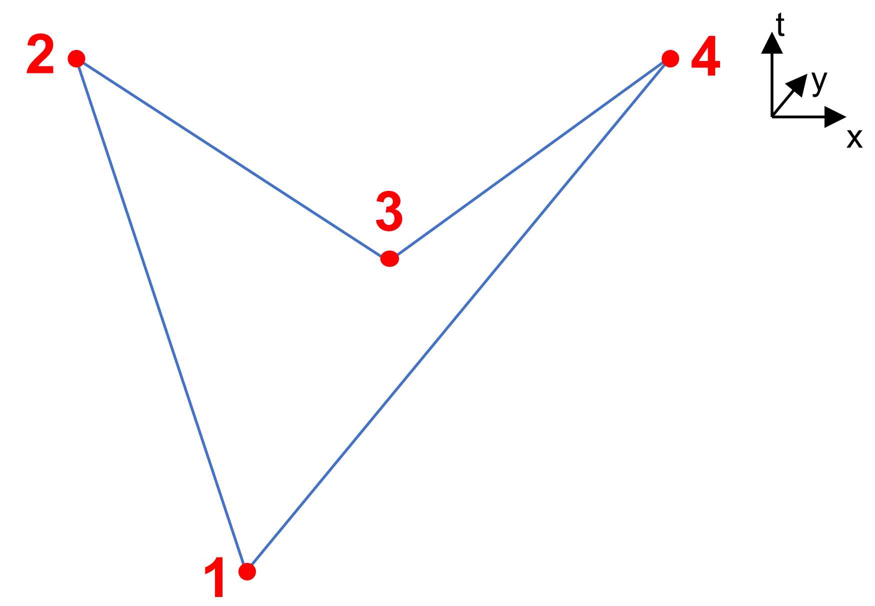

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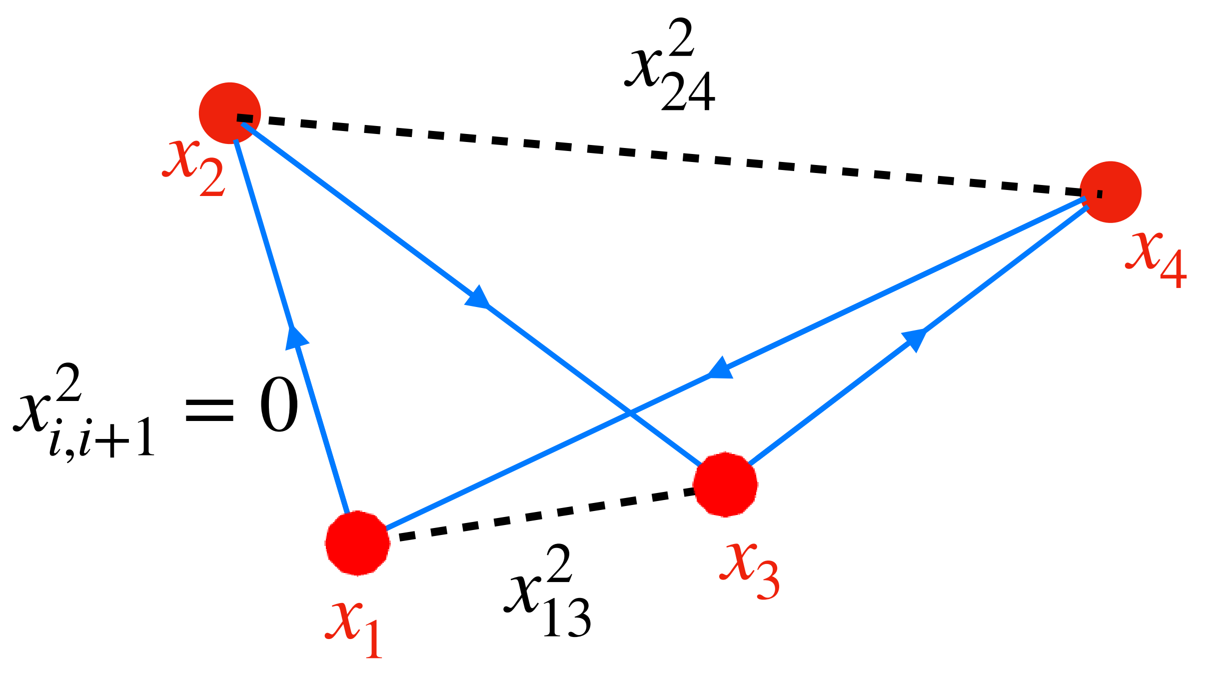

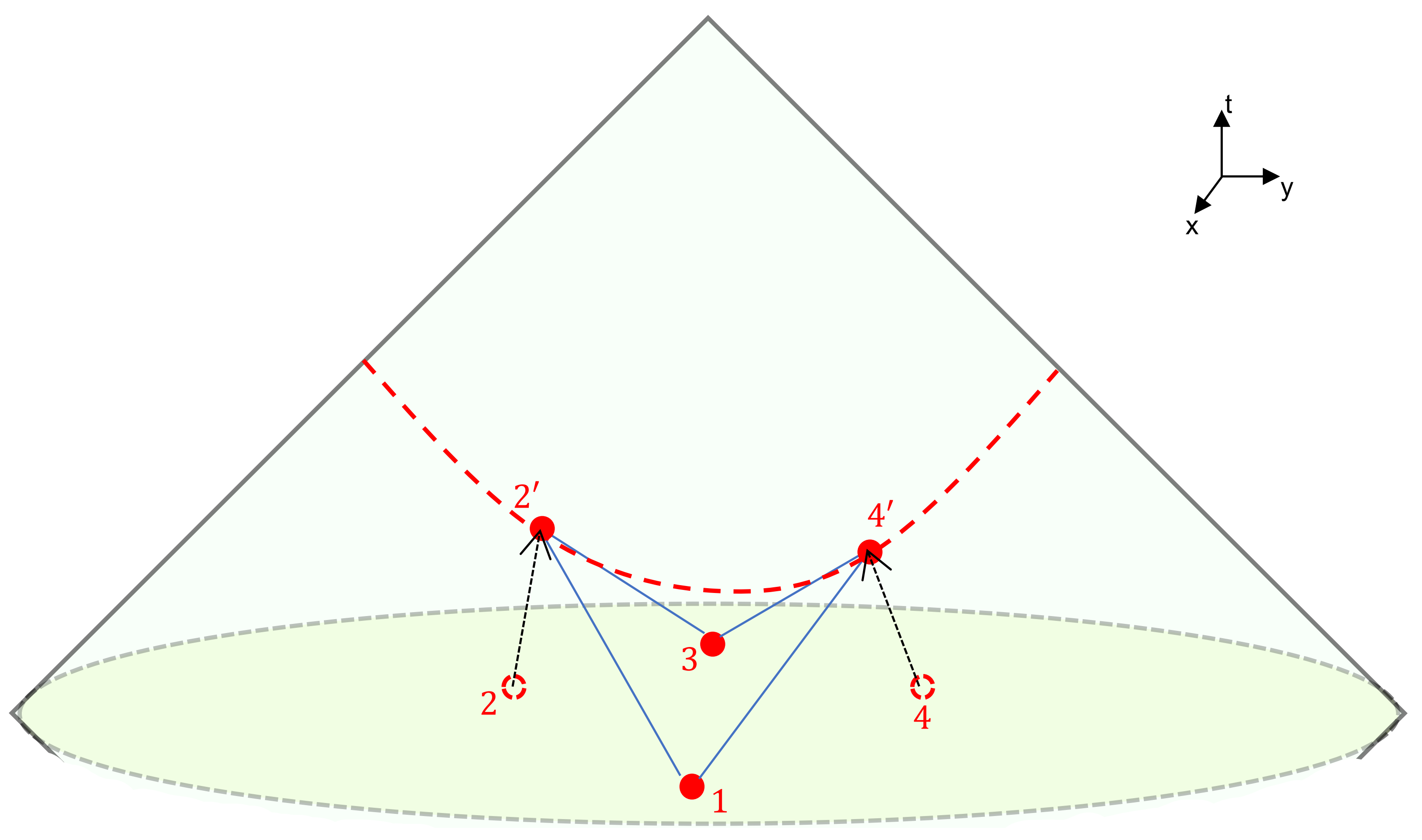

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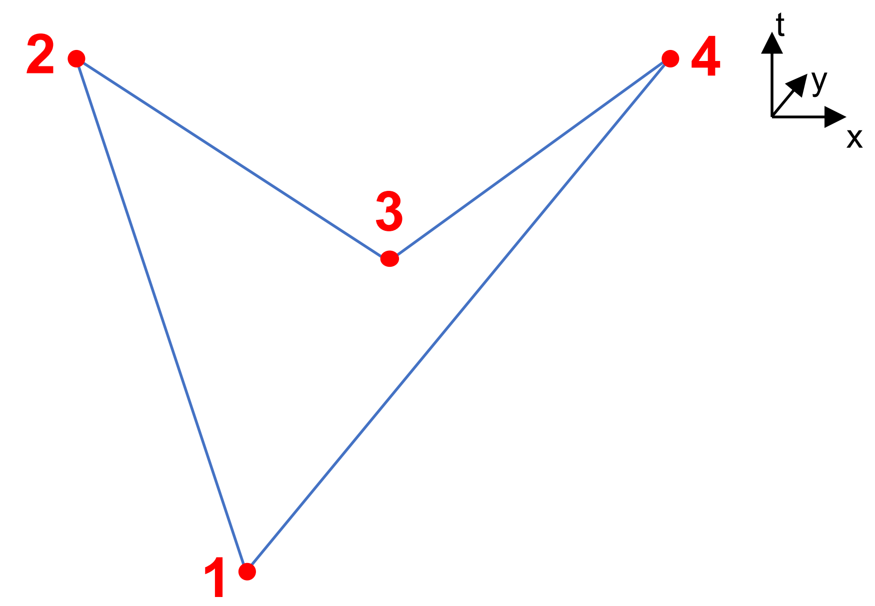

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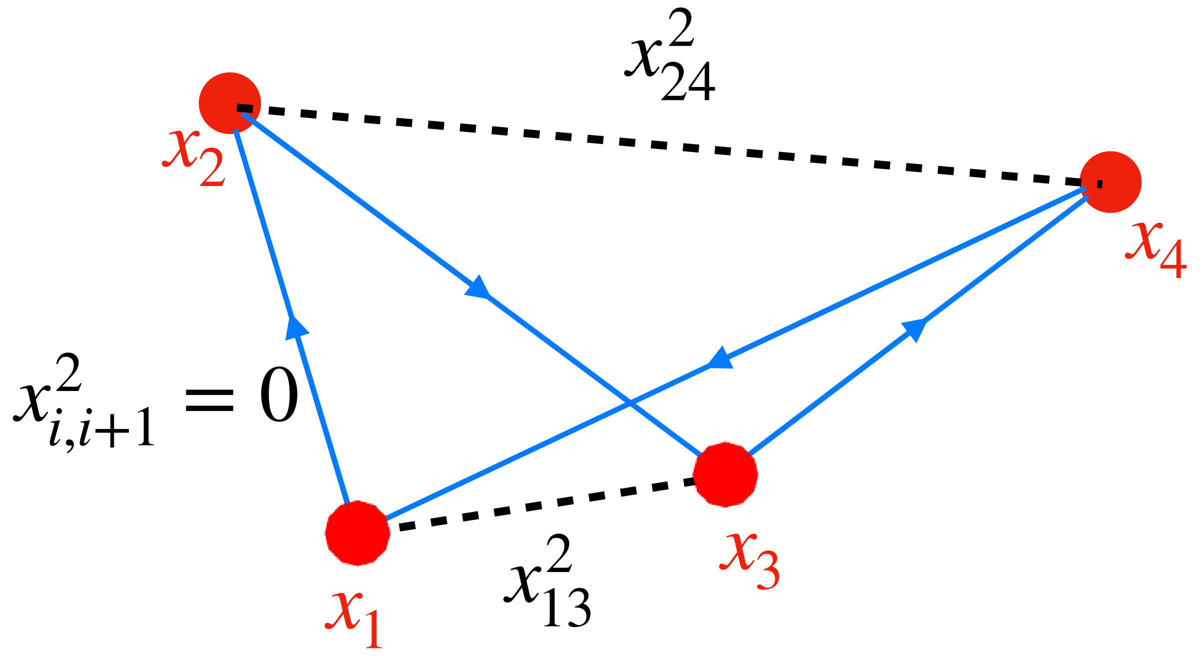

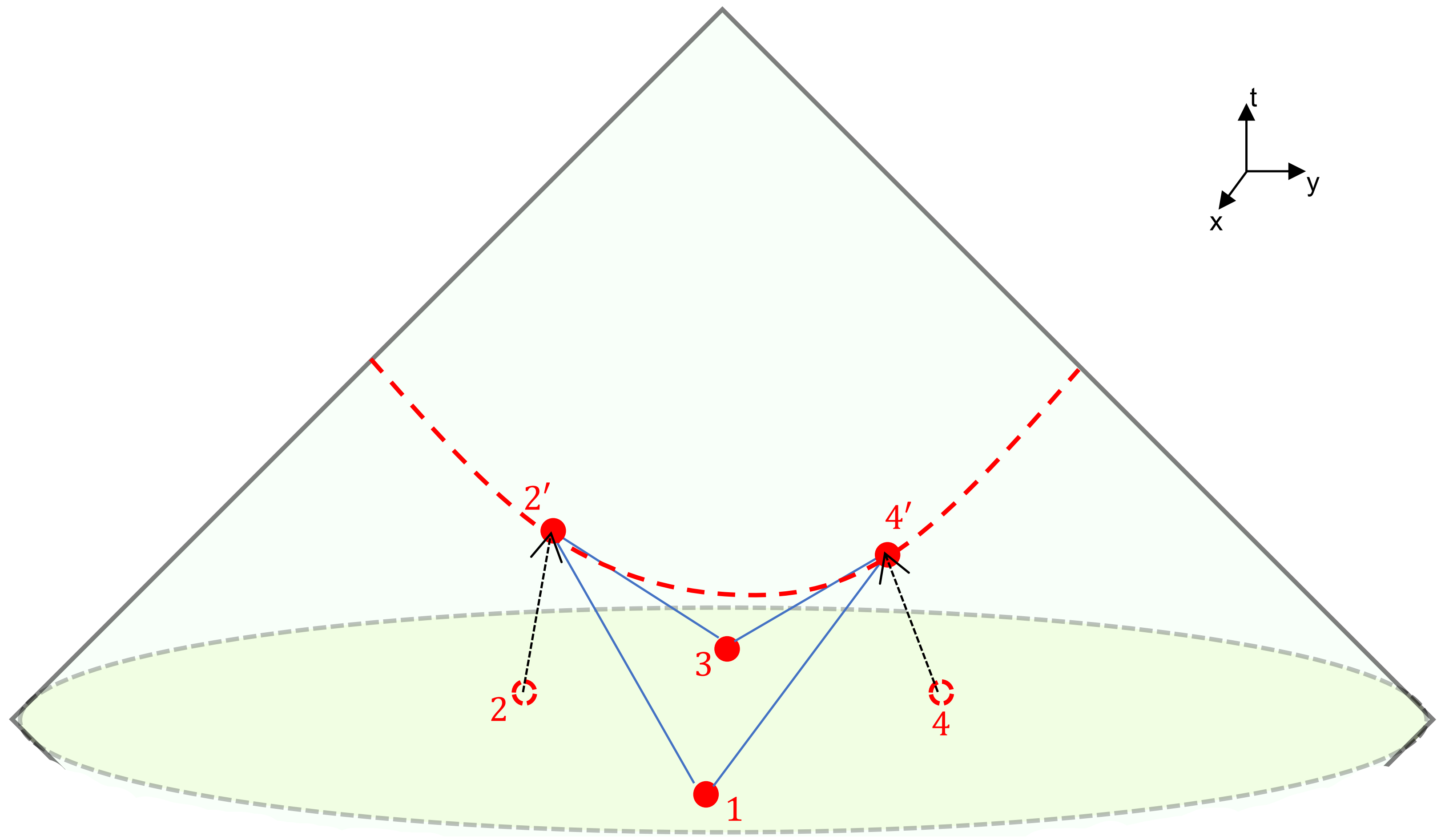

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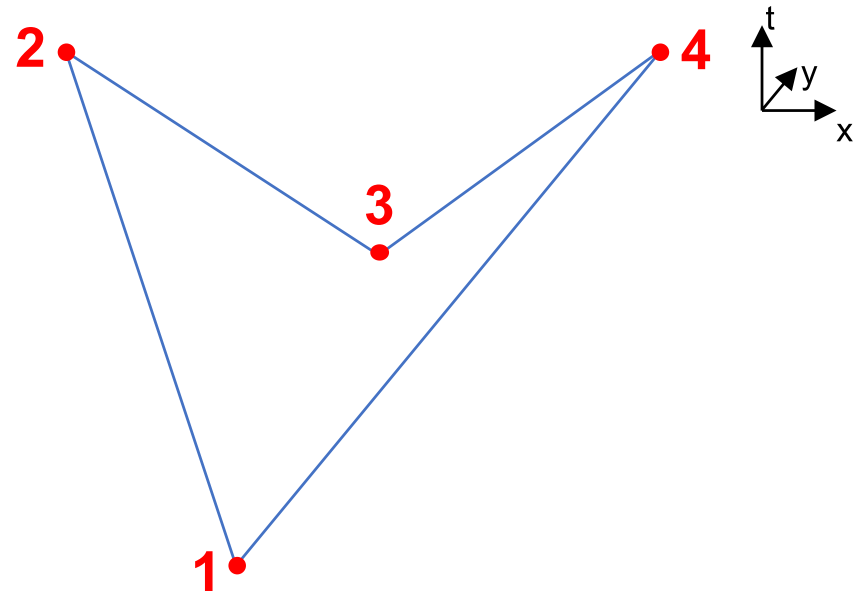

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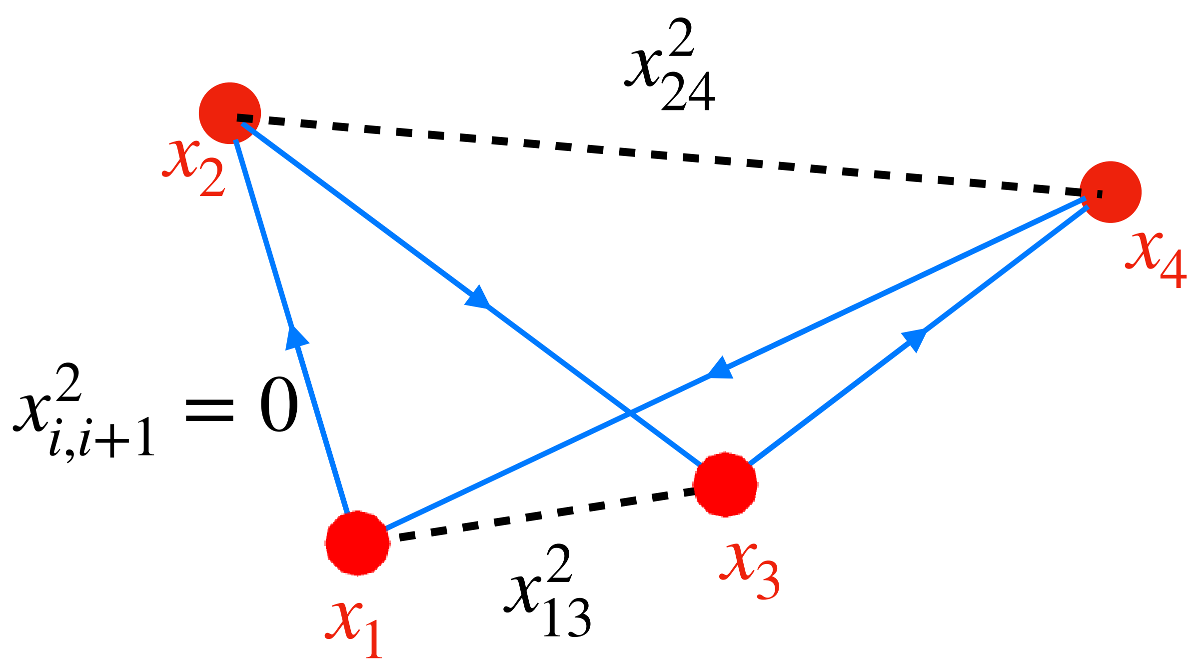

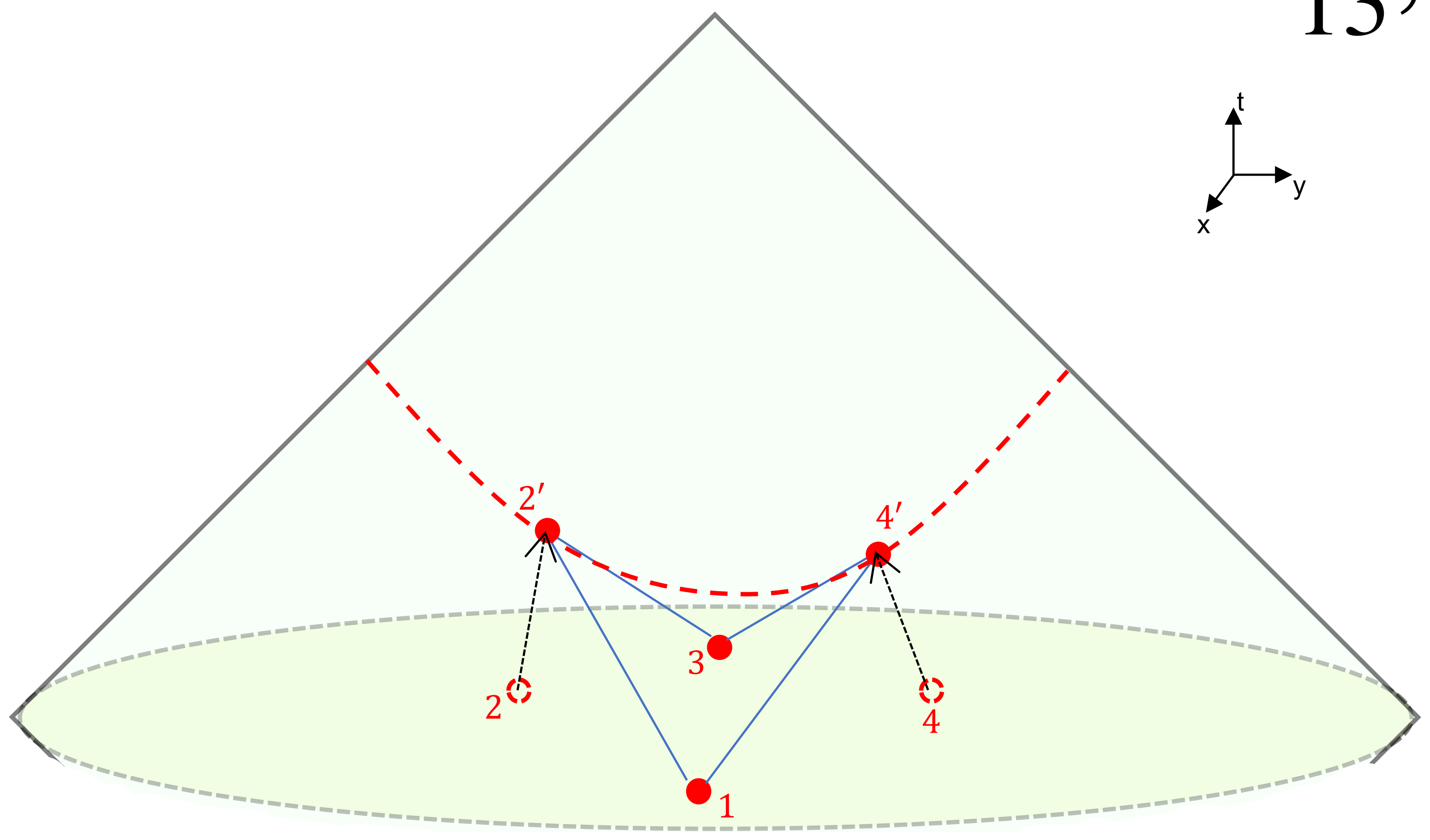

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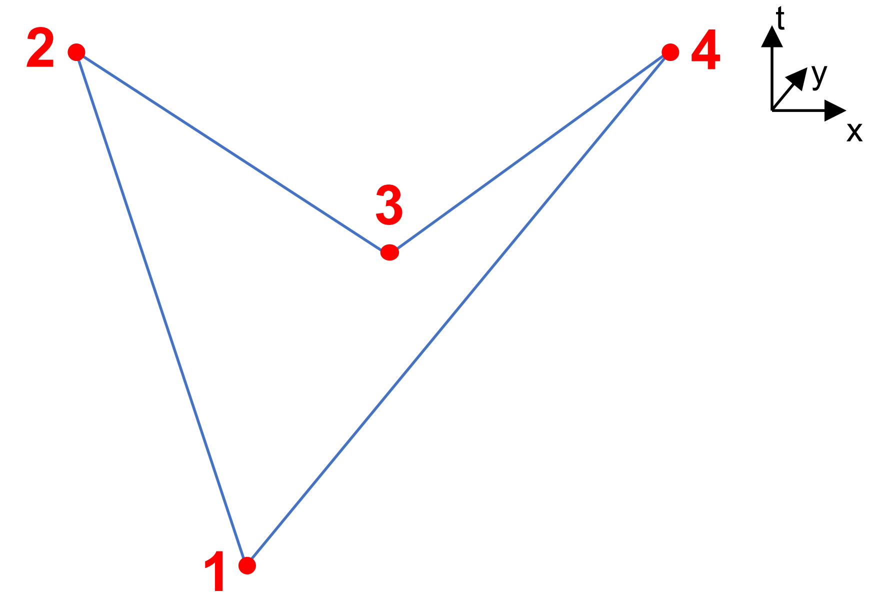

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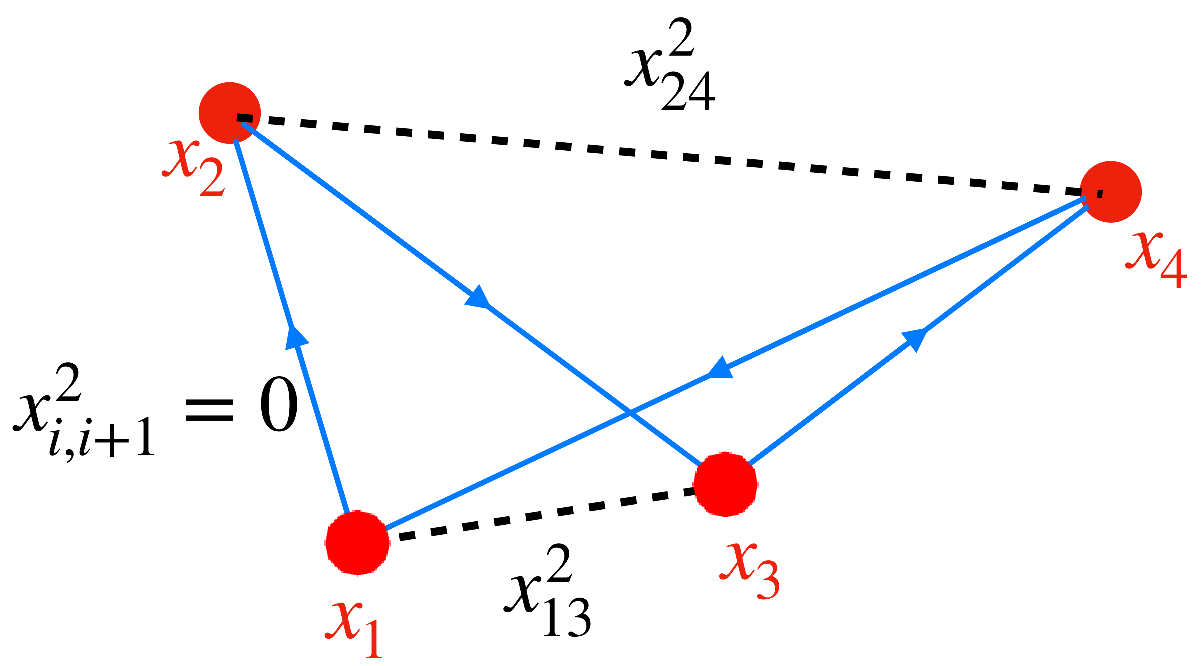

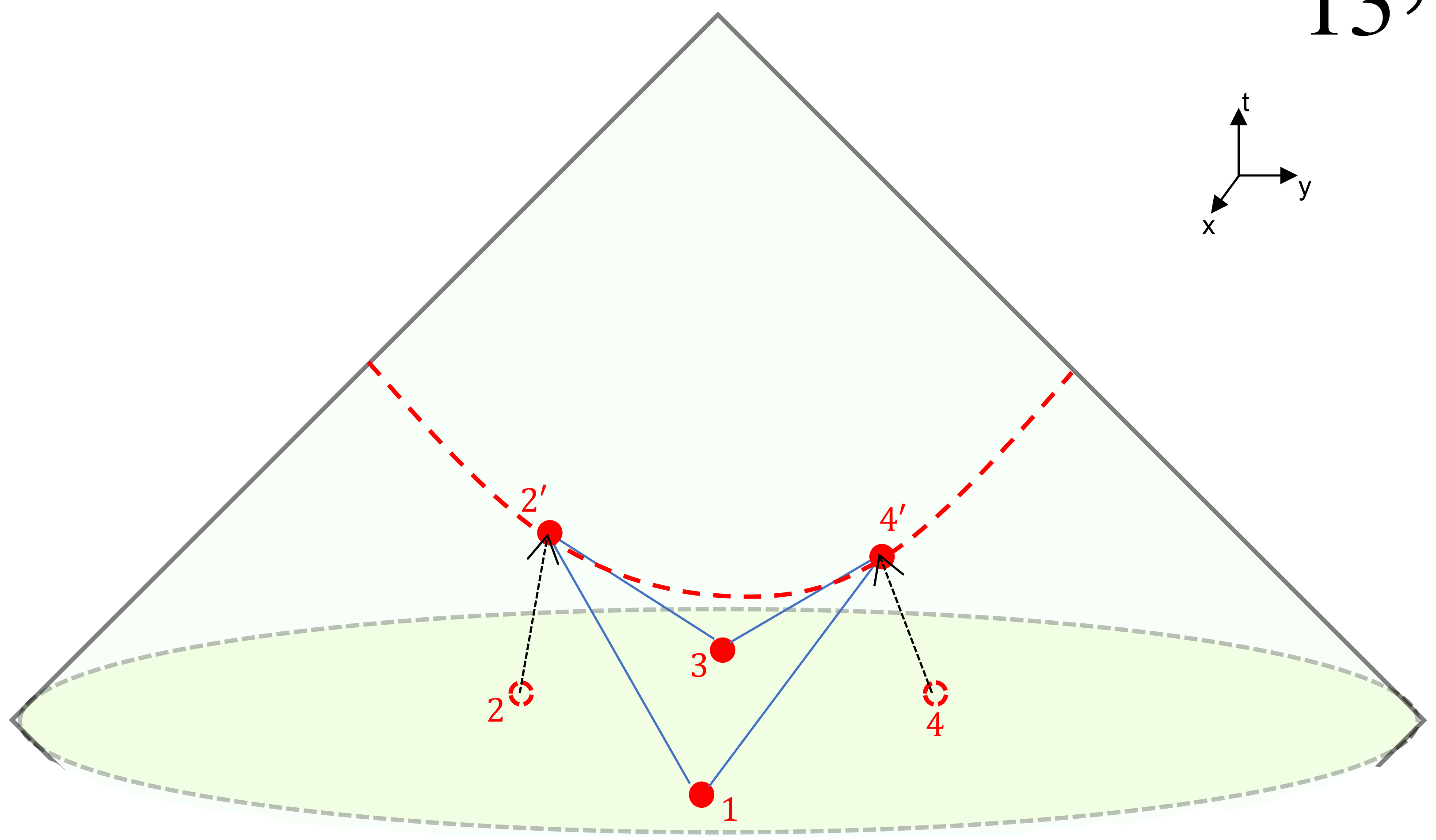

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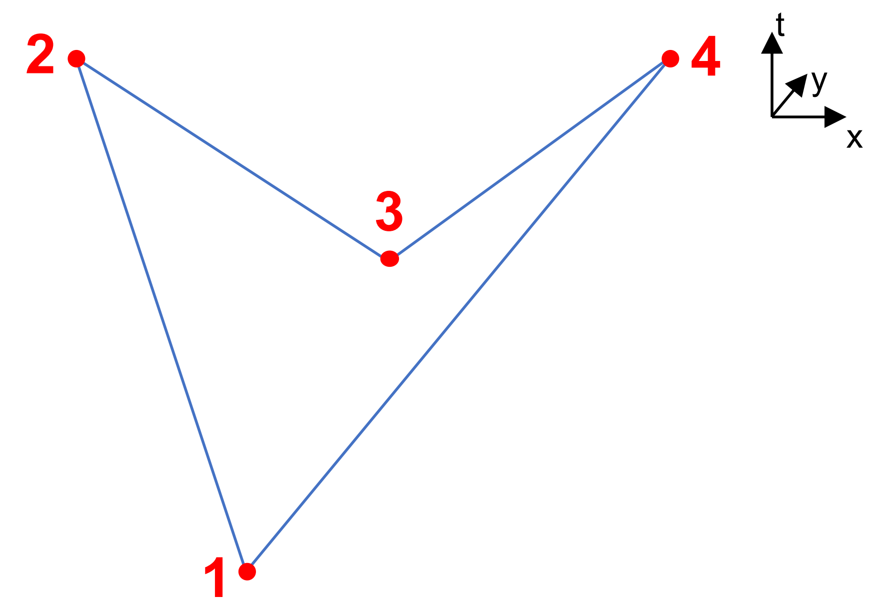

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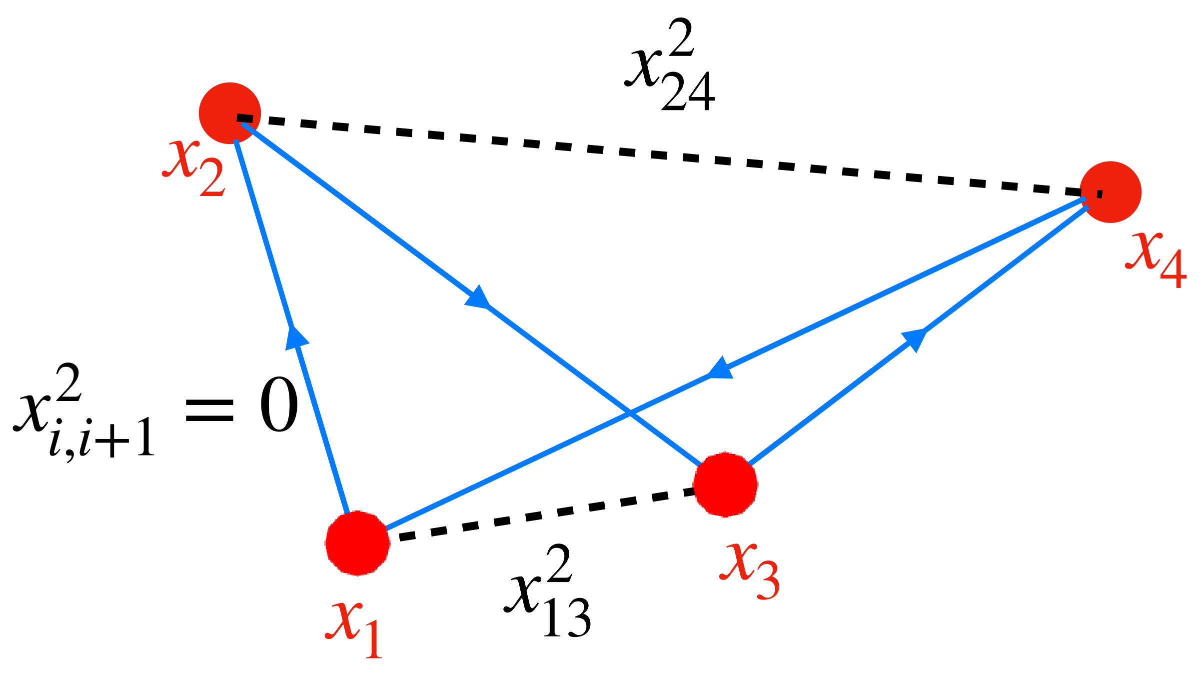

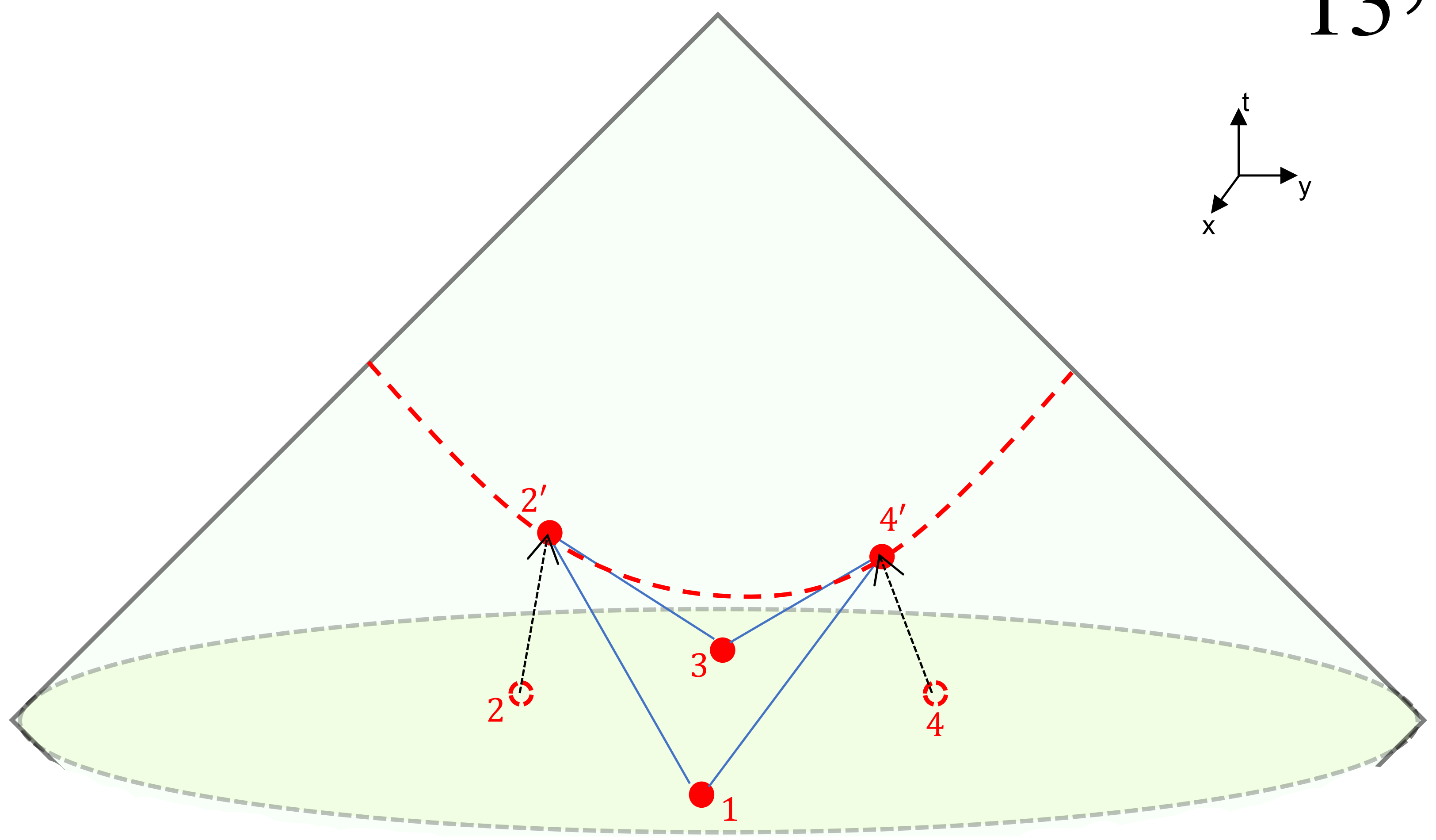

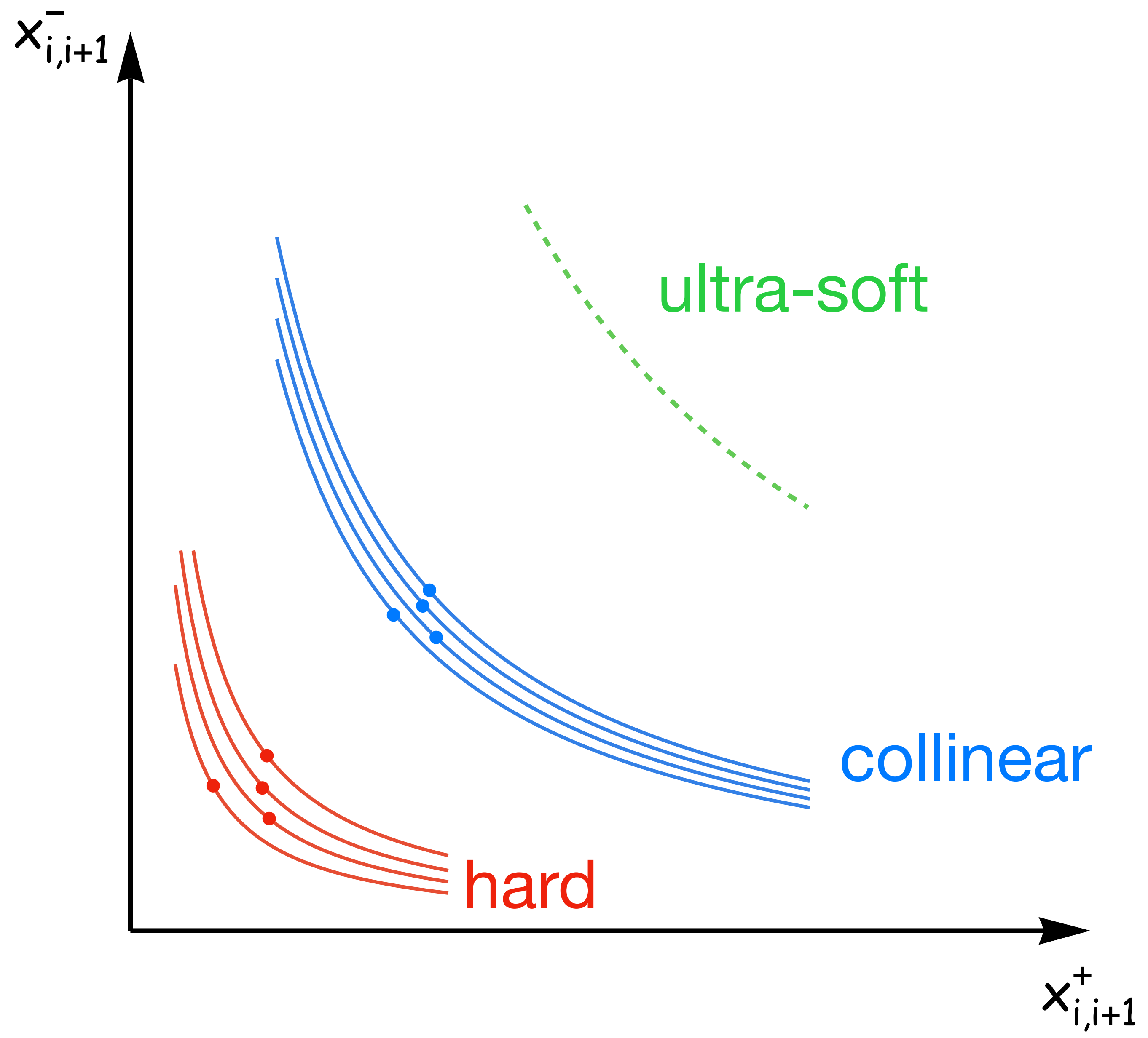

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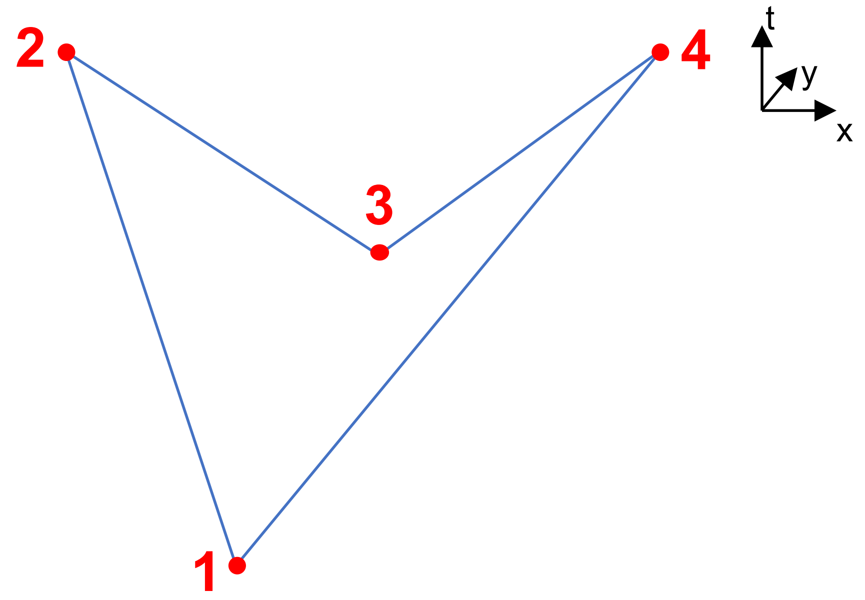

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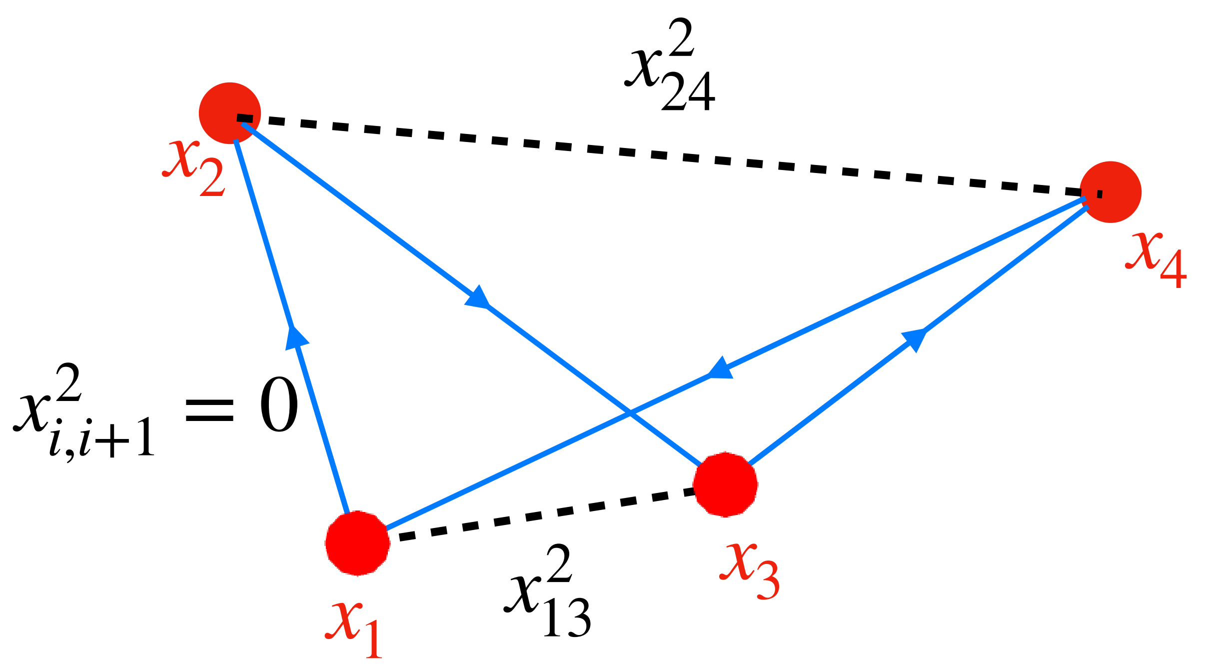

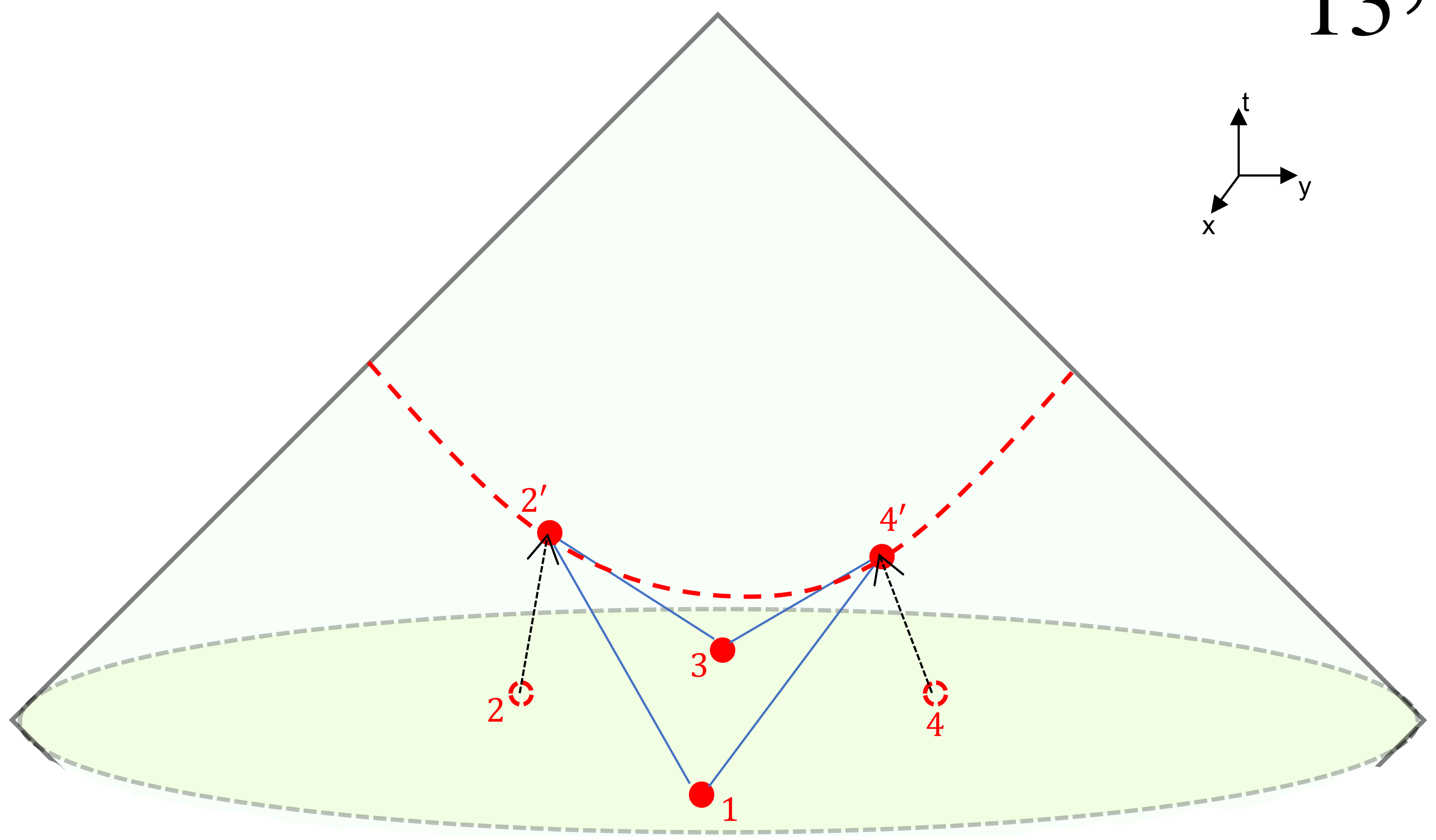

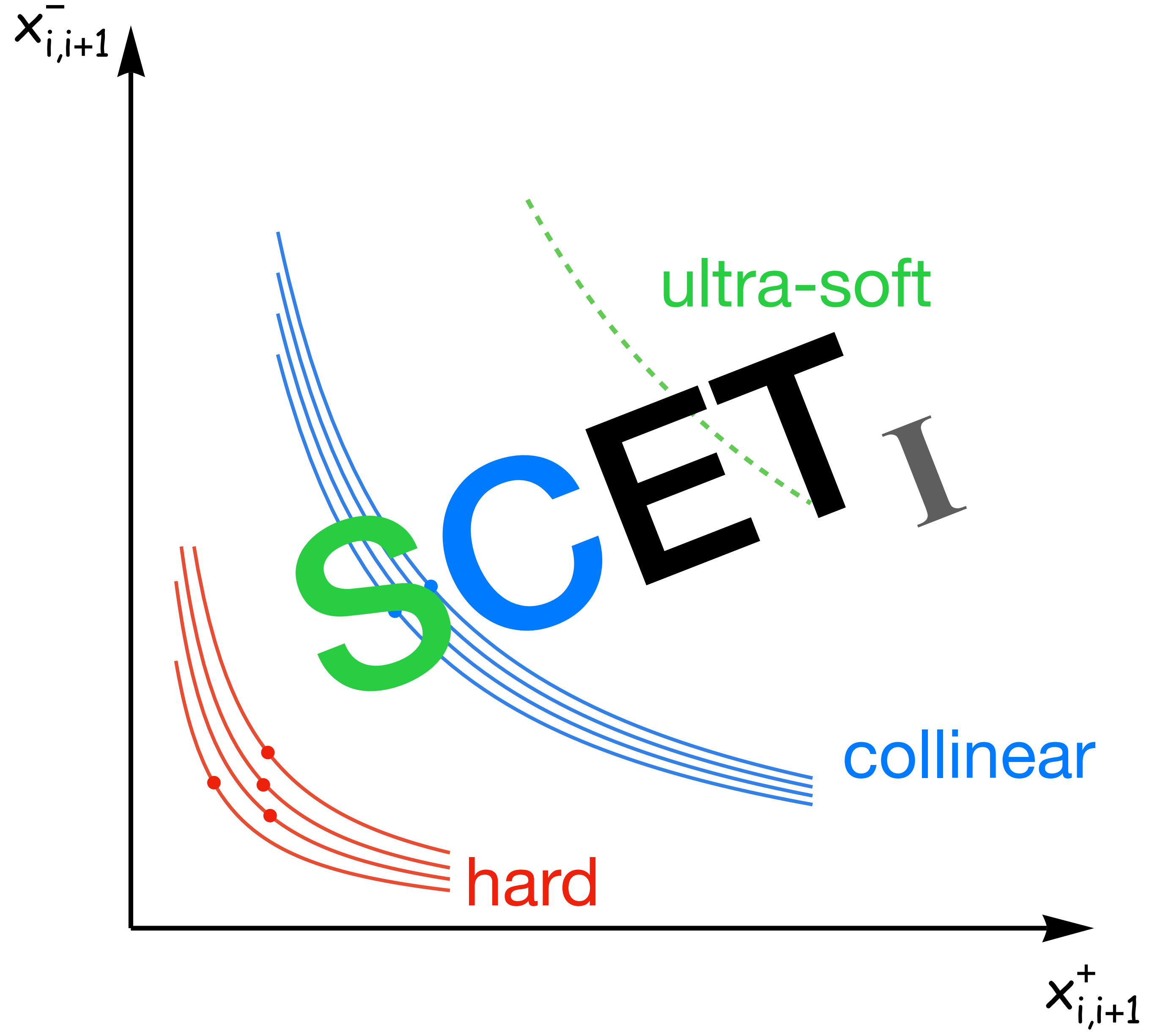

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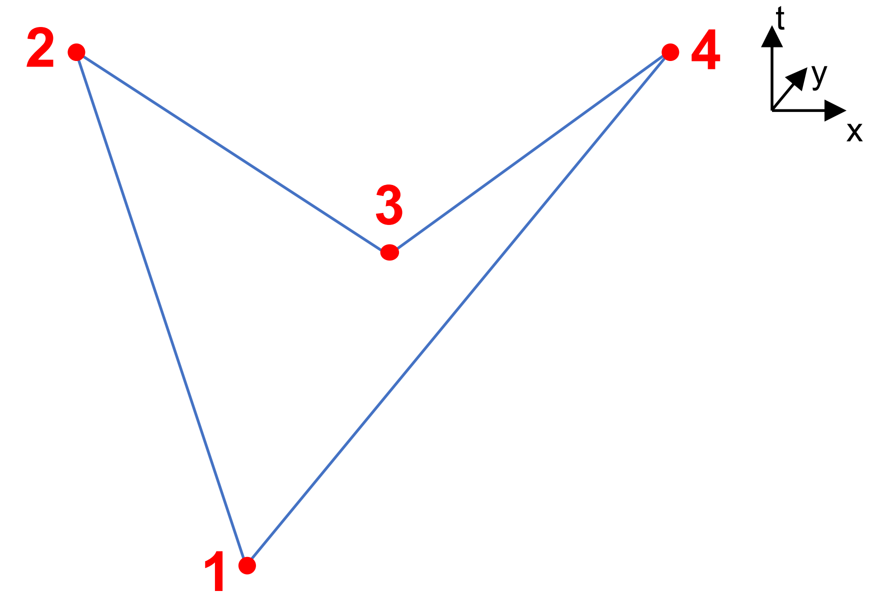

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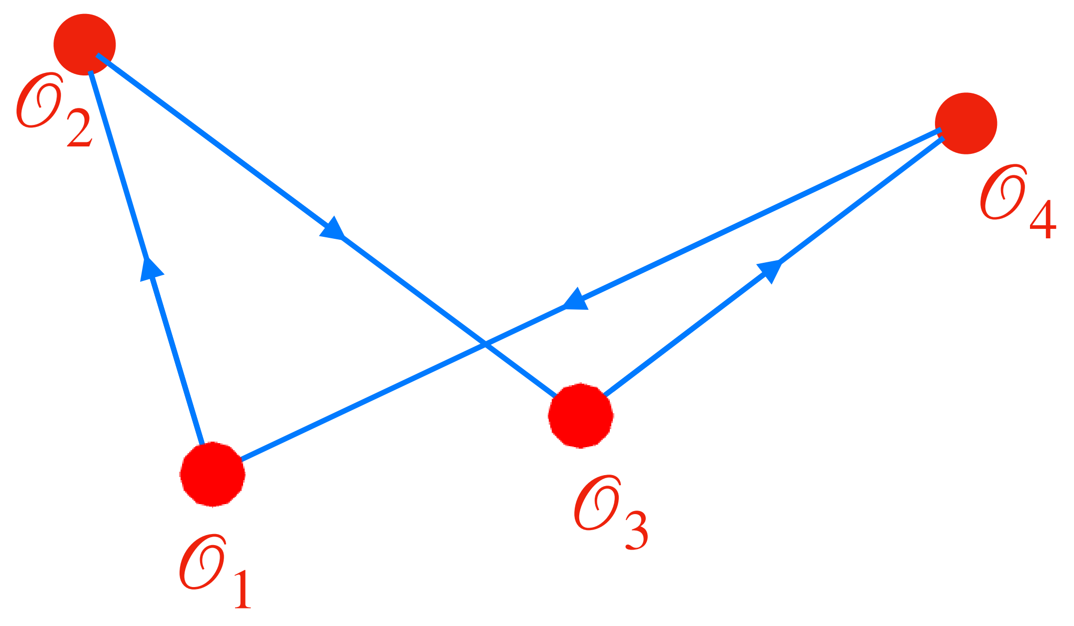
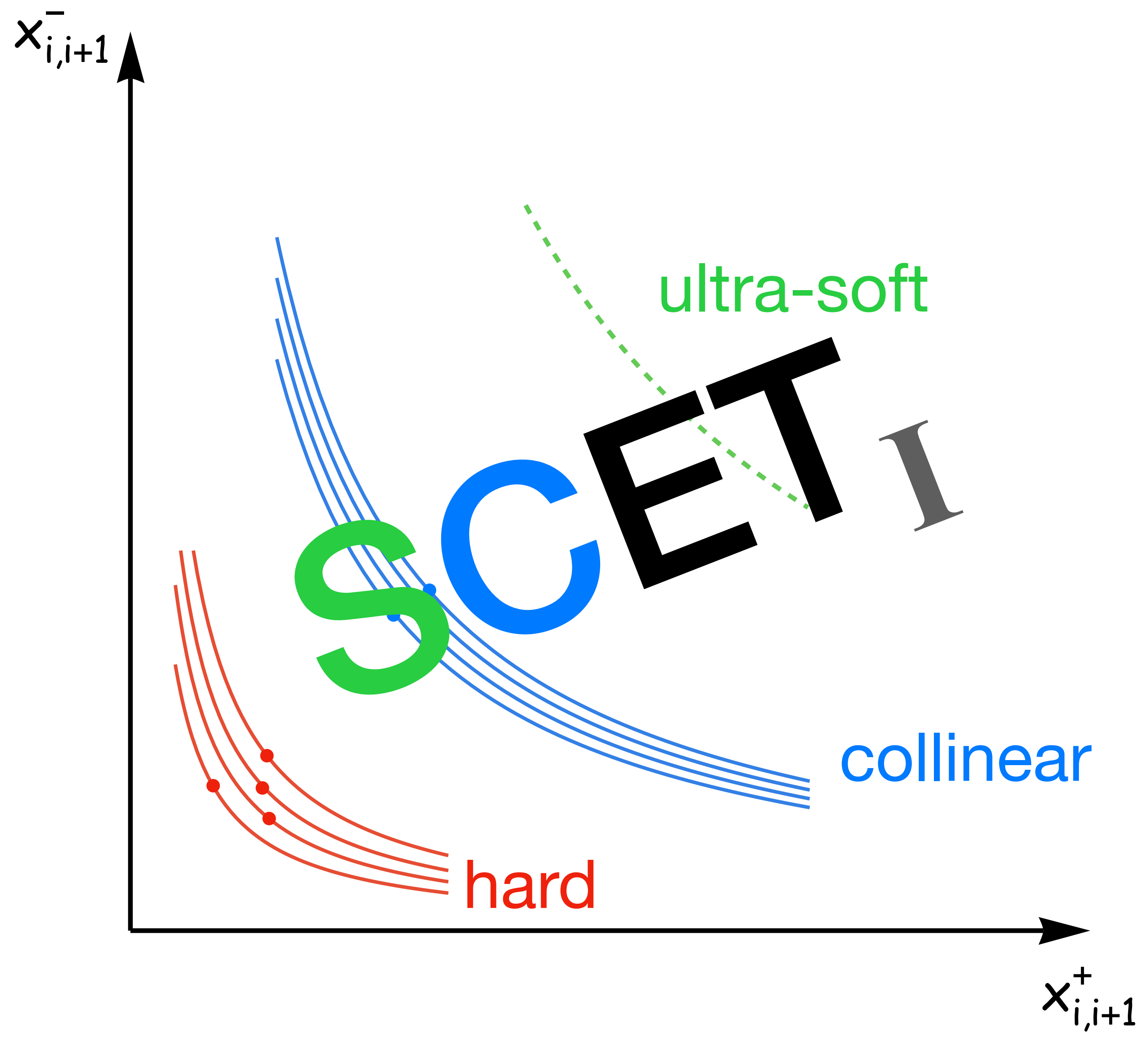
- $\langle 0|\mathcal{O}_1\mathcal{O}_2\mathcal{O}_3\mathcal{O}_4|0\rangle \overset{x^2_{i,i+1}\to 0^-}{\sim}$ $SCET_I$





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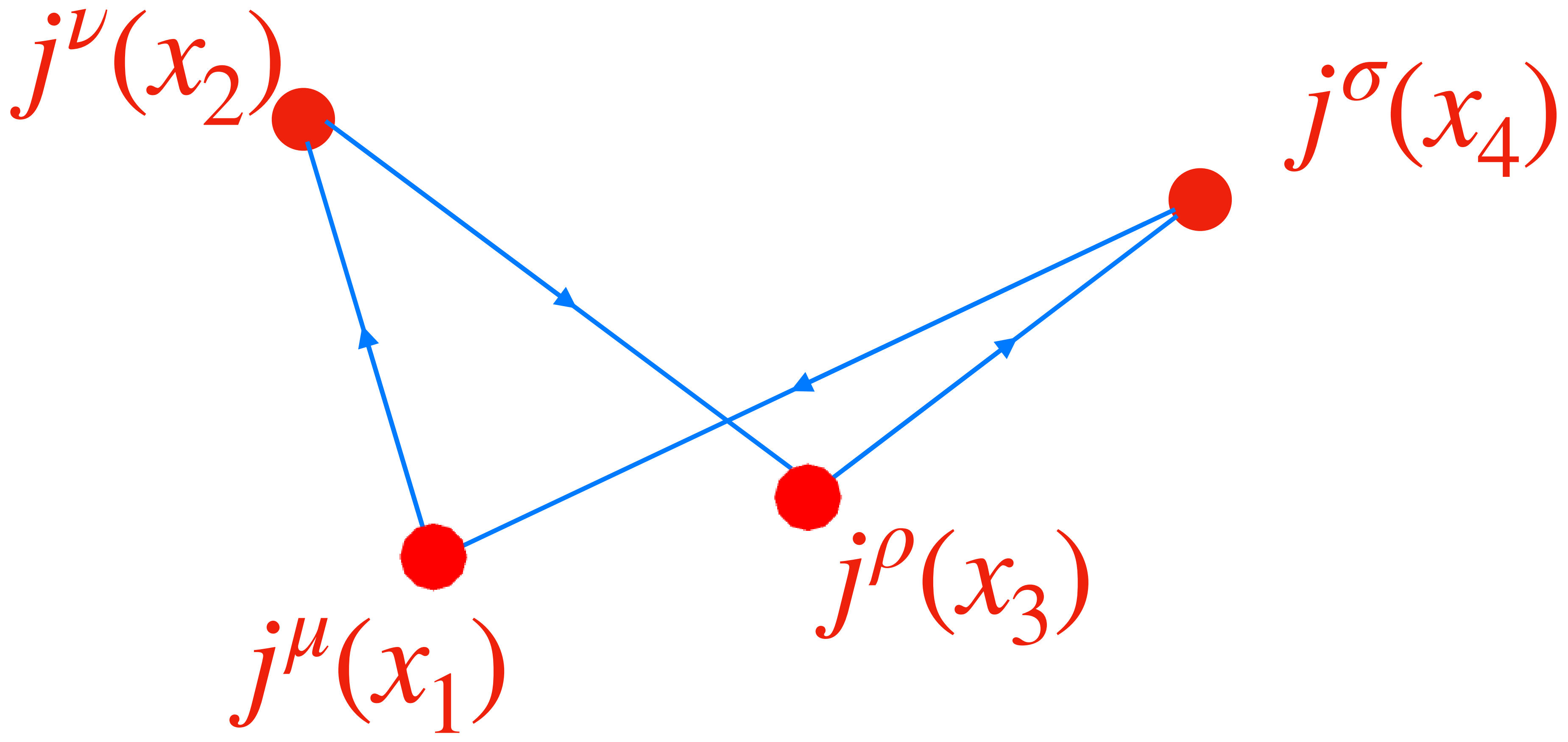
- A Wightman correlation function ~~time-ordered correlation function~~

$$\langle 0 | j^\mu(x_1) j^\nu(x_2) j^\rho(x_3) j^\sigma(x_4) | 0 \rangle$$

- A Wightman correlation function ~~time-ordered correlation function~~
- In the $x_{i,i+1}^2 \to 0$ limit, it looks like:



$$\langle 0|j^{\mu}(x_1)j^{\nu}(x_2)j^{\rho}(x_3)j^{\sigma}(x_4)|0\rangle$$

- Up to an analytic continuation, the operator ordering can be changed to

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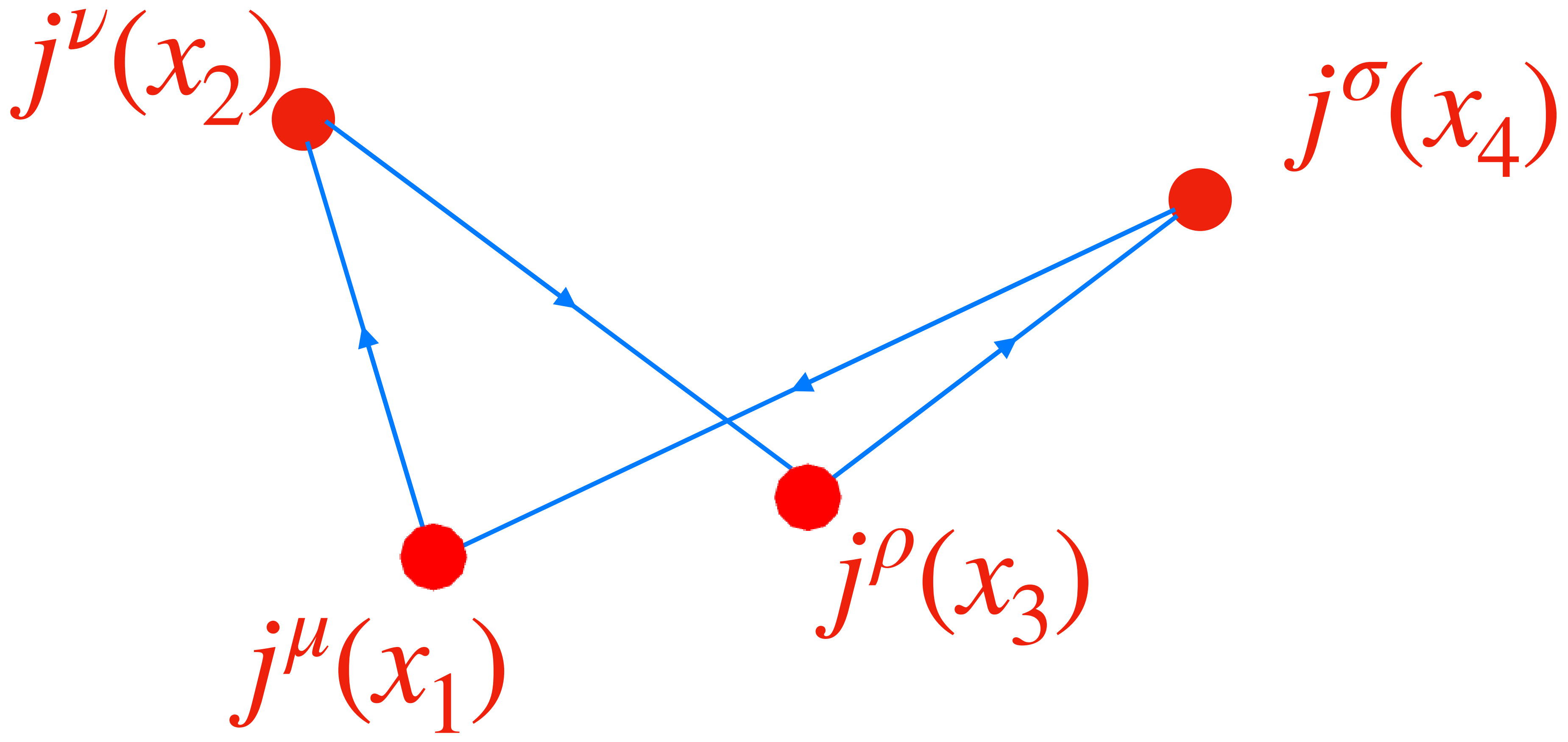

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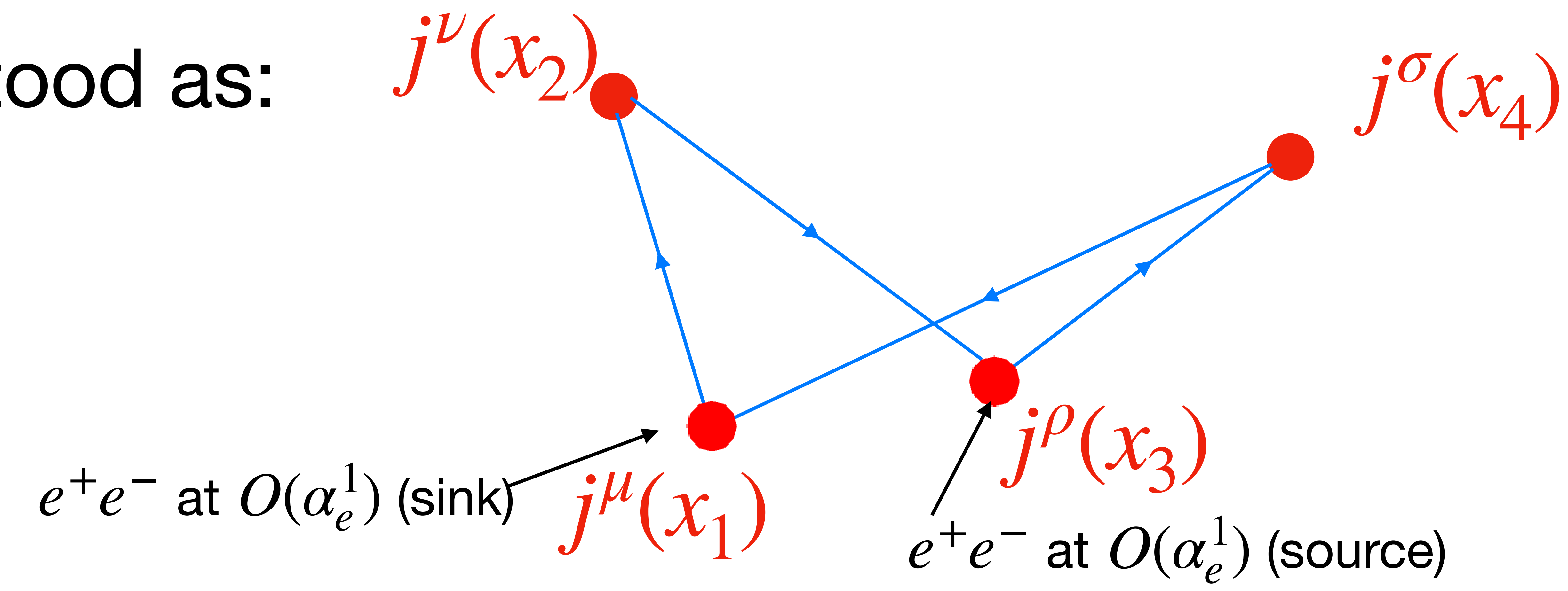

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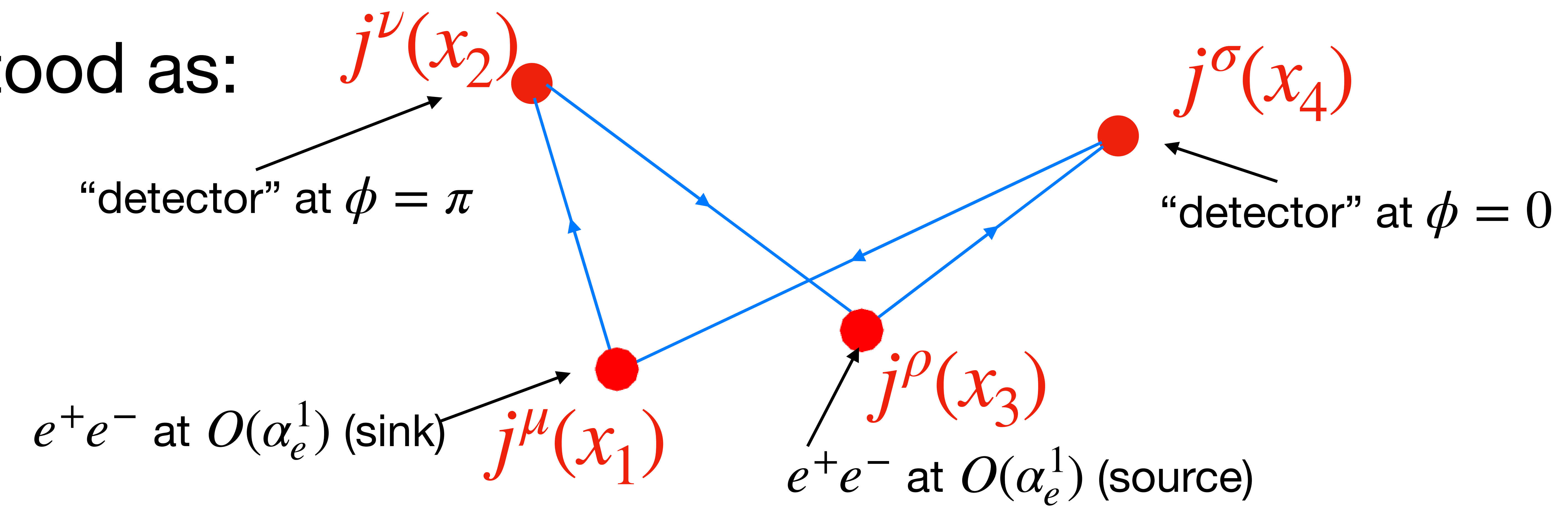

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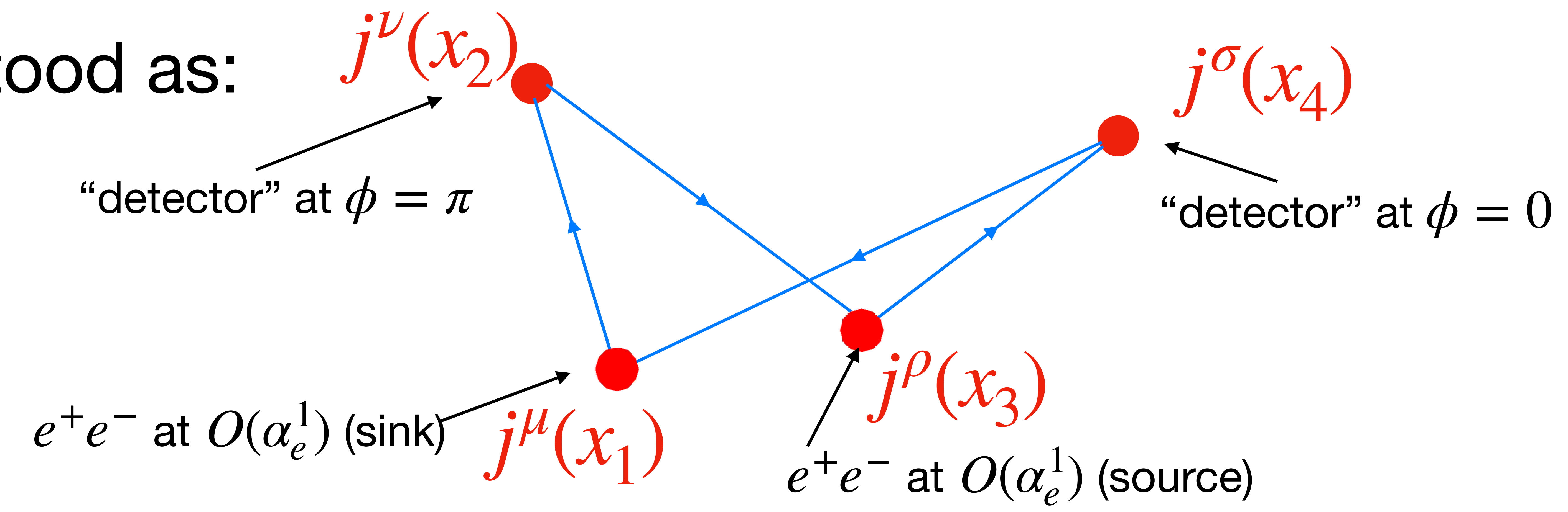
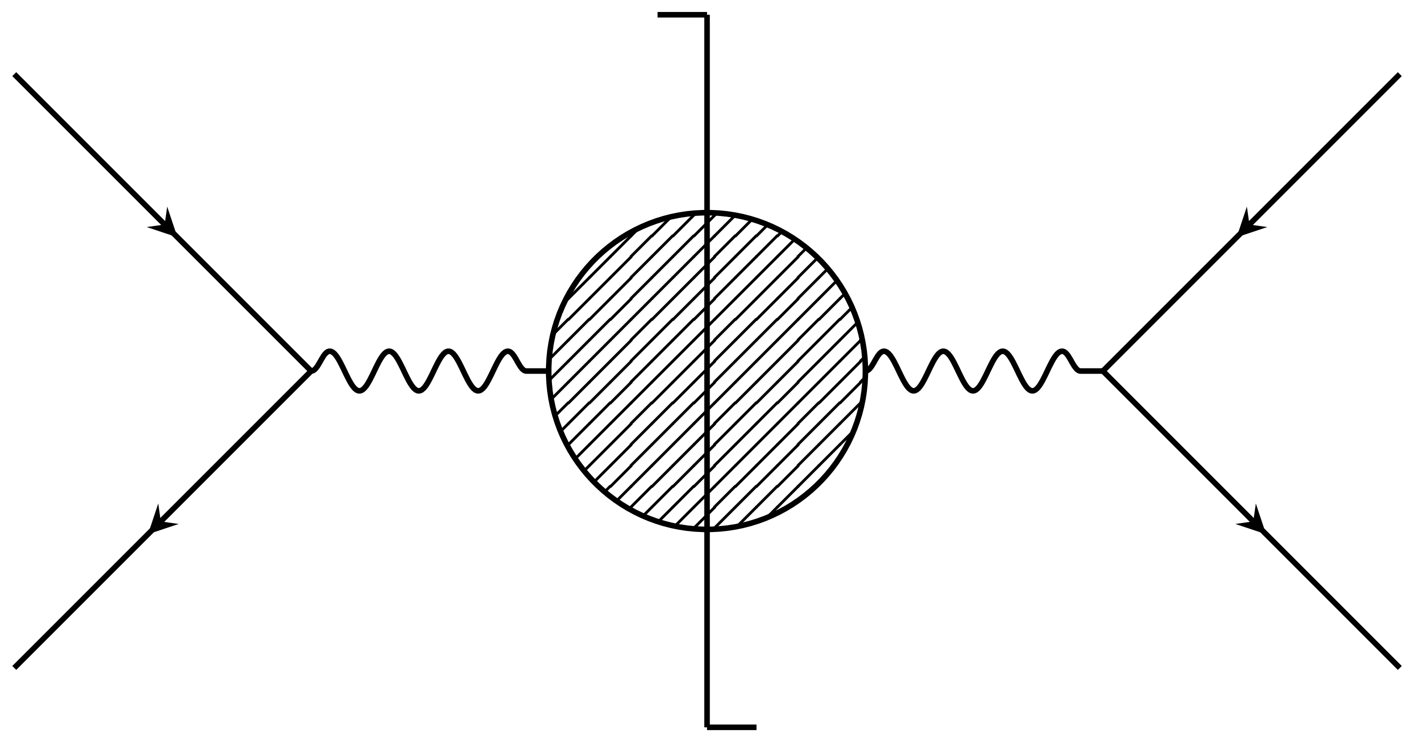


- Why?

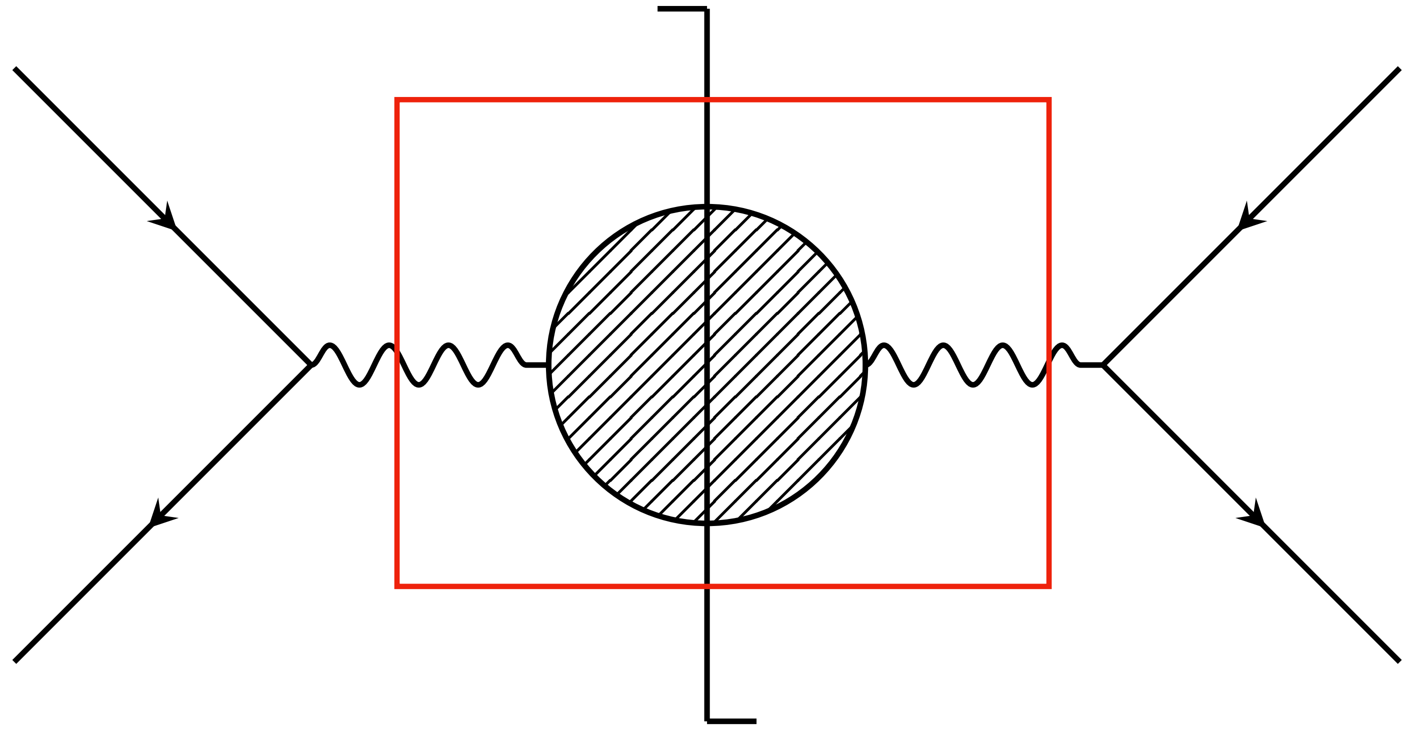
$$\langle 0 | j^{\mu}(x_1) j^{\nu}(x_2) j^{\rho}(x_3) j^{\sigma}(x_4) | 0 \rangle$$



e^+e^- annihilation at $O(\alpha_e)$

$\langle 0|j^{\mu}(x_1)j^{\nu}(x_2)j^{\rho}(x_3)j^{\sigma}(x_4)|0\rangle$

- $\sigma_{tot}(e^+e^-) \sim \mathscr{F}(\langle 0\,|\,j^\mu(x)j_\mu(0)\,|\,0\rangle)$ at $O(\alpha_e)$
- $\langle 0\,|\,j^\mu(x)j_\mu(0)\,|\,0\rangle = \sum_X \langle 0\,|\,j^\mu(x)\,|\,X\rangle\langle X\,|\,j_\mu(0)\,|\,0\rangle$



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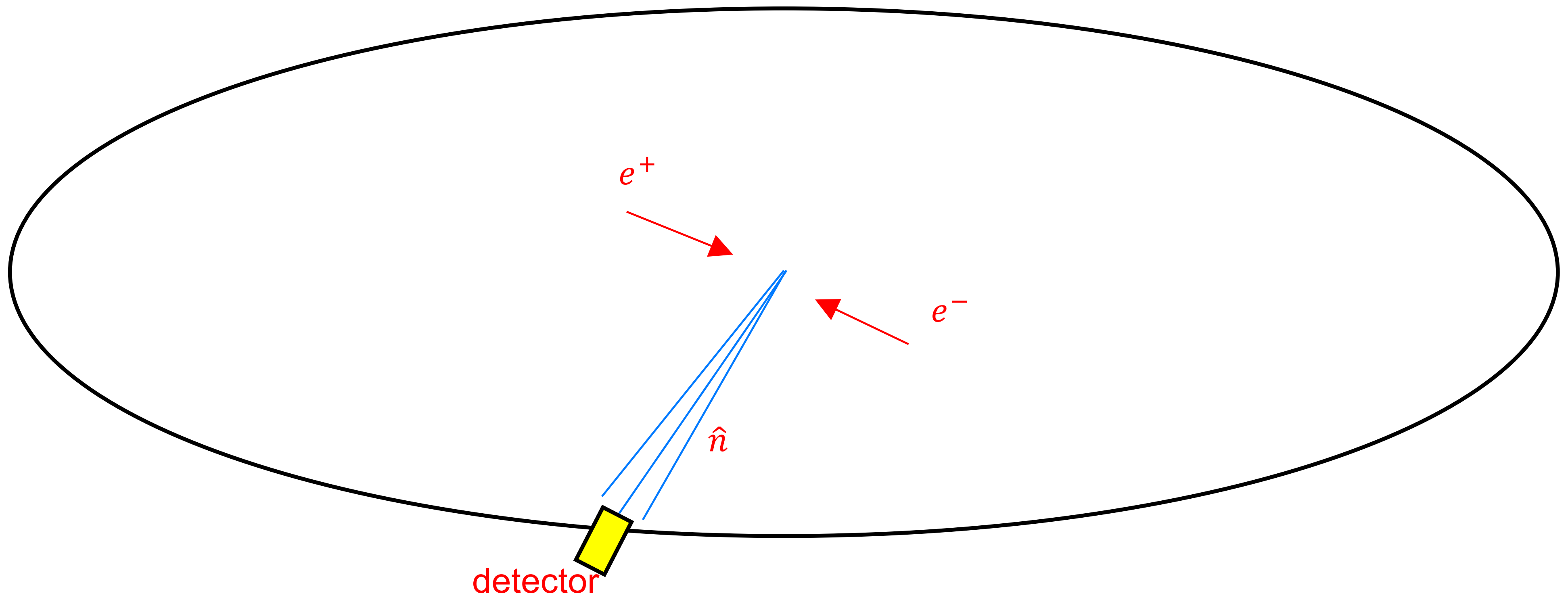
- Measure the number of hadron h along the direction $\hat{n}$: $\sum_X \langle 0 | j^{\mu}(x) | X, \boxed{h(\hat{n})} \rangle \langle X, \boxed{h(\hat{n})} | j_{\mu}(0) | 0 \rangle$



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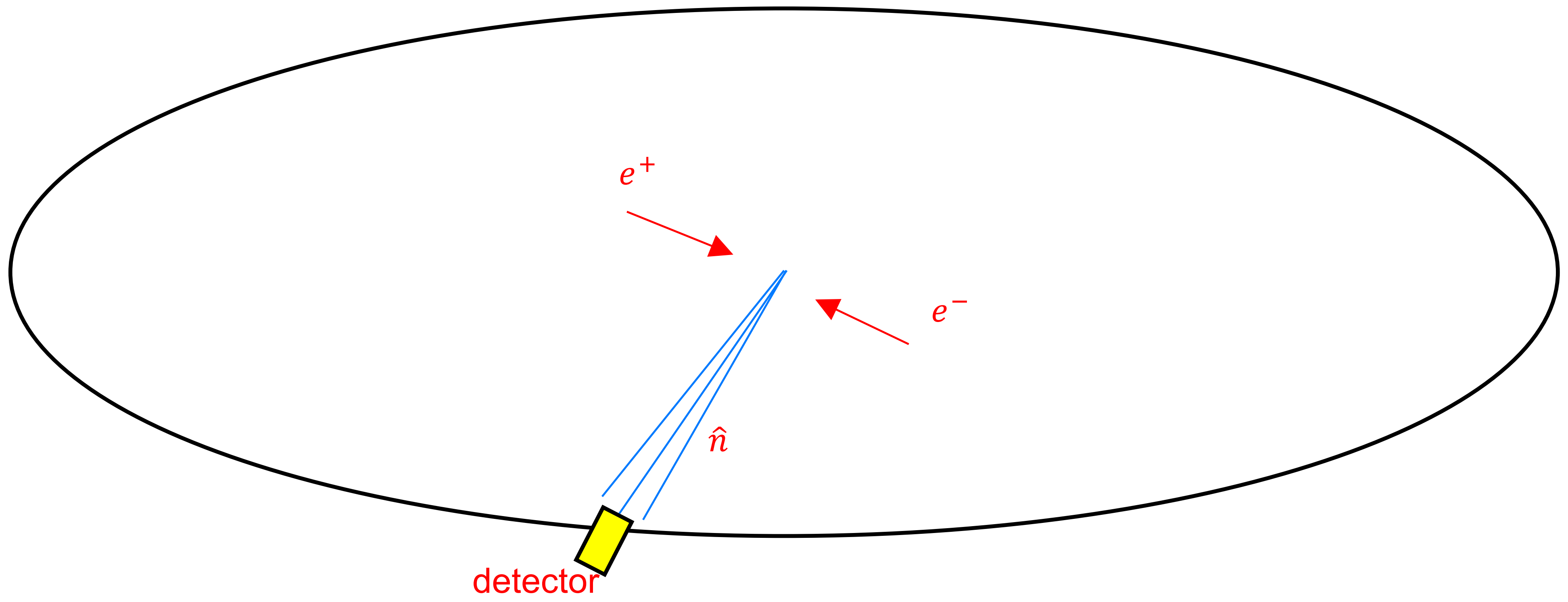

- Count the quantum number q (energy, charge) along the direction $\hat{n}$:
$$\sum_h \sum_X \langle 0|j^\mu(x)|X, h(\hat{n})\rangle \boxed{q_h} \langle X, h(\hat{n})|j_\mu(0)|0\rangle$$

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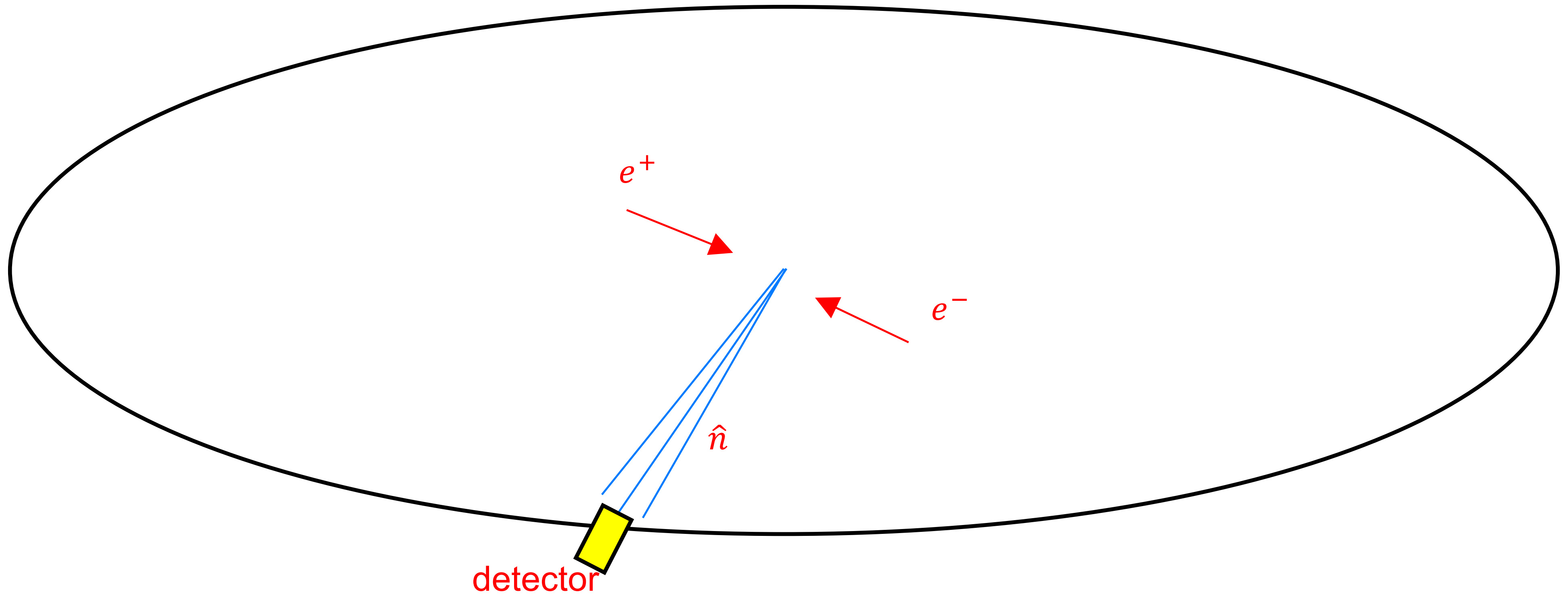

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non-local

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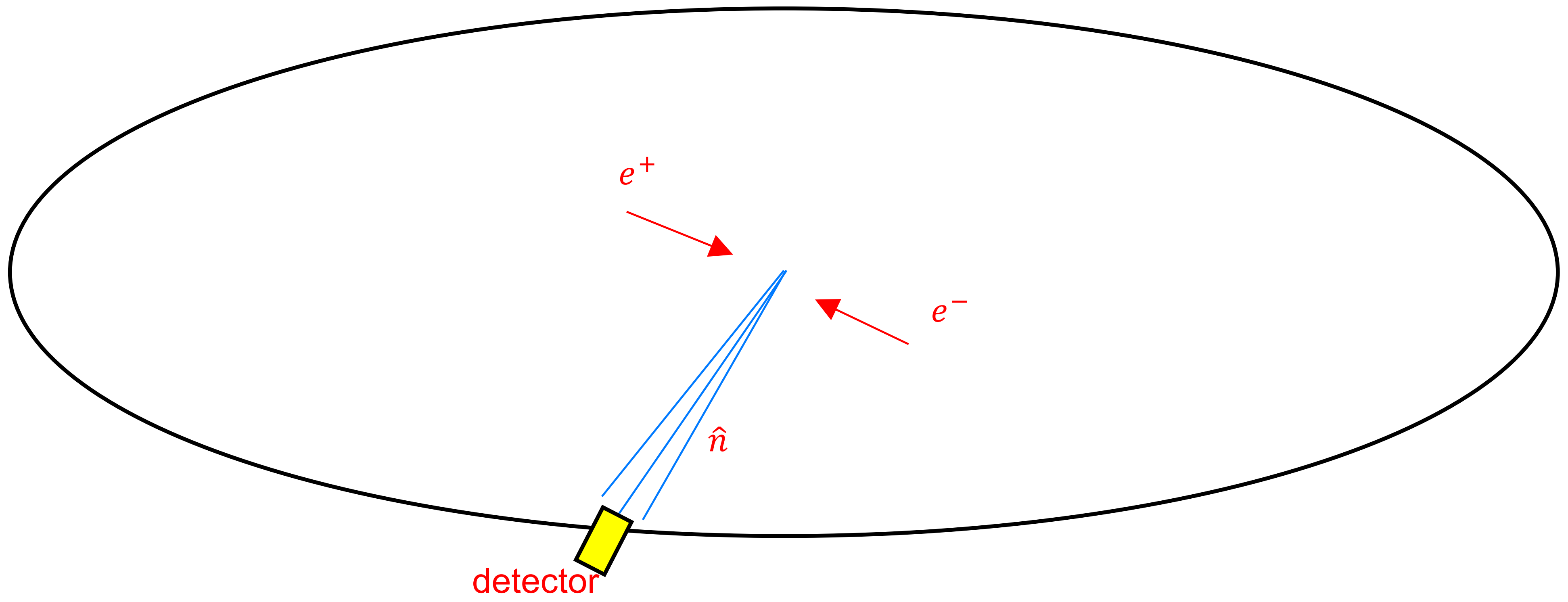

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- A famous example: count the energy $\langle 0|j^\mu(x)\mathscr{E}(\hat{n})j_\mu(0)|0\rangle$ [Sterman, 1975]

➡ "energy flow operator"/"calorimeter"/"ANEC operator" $\mathcal{E}(\hat{n}) = \lim_{r\to\infty} r^2 \int_0^\infty dt \vec{n}_i T^{0i}(t, r\vec{n})$

[Sveshnikov, Tkachov, hep-ph/9512370]
[Tkachov, hep-ph/9601308]

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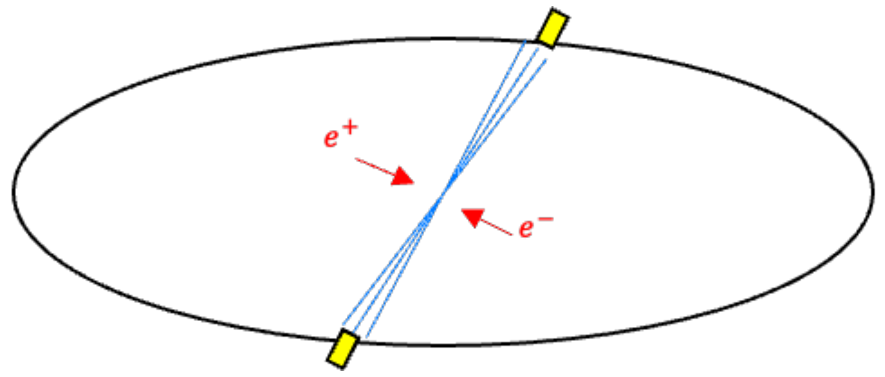

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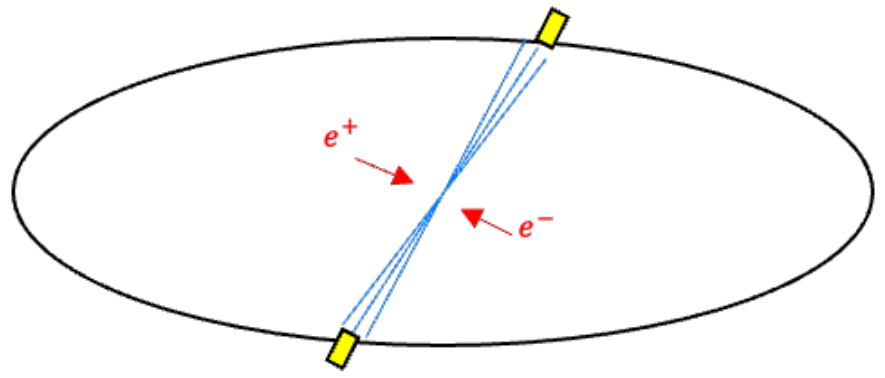

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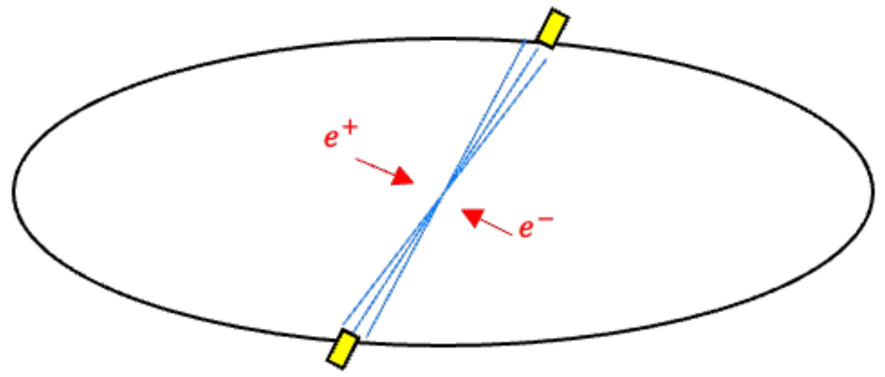

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[Chen, Luo, Moult, Yang, Zhang, Zhu, 1912.11050]
[Chen, Moult, Zhu, 2011.02492]
[Yan, Zhang, 2203.04349]
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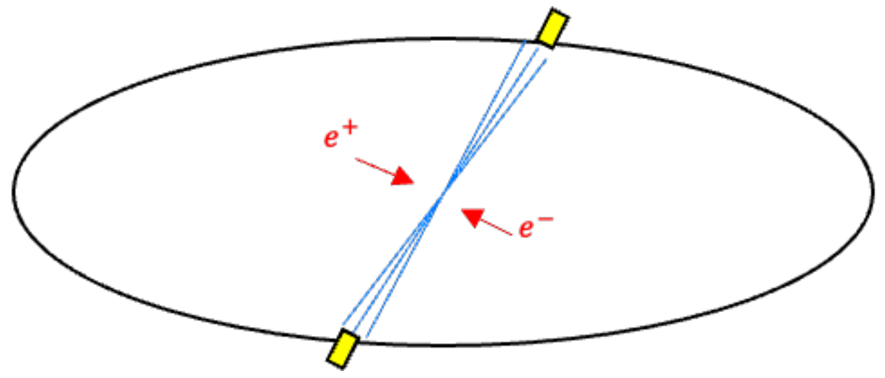

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Review [Moult, Zhu, 2506.09119]

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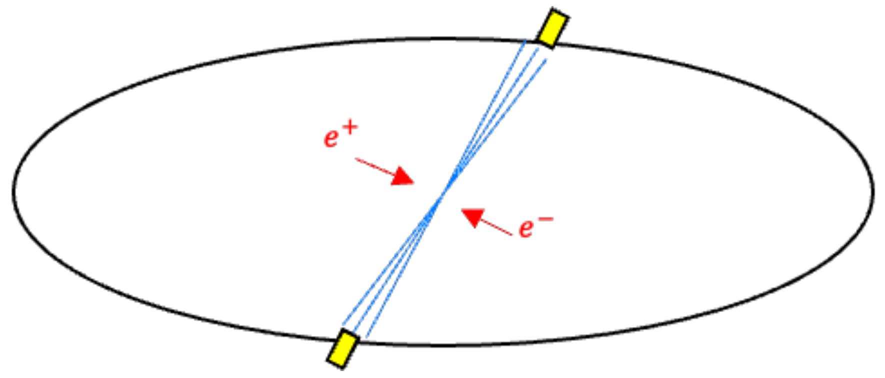

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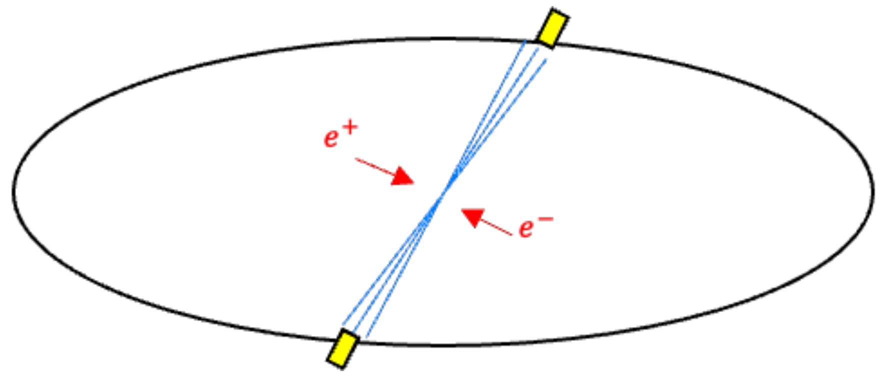

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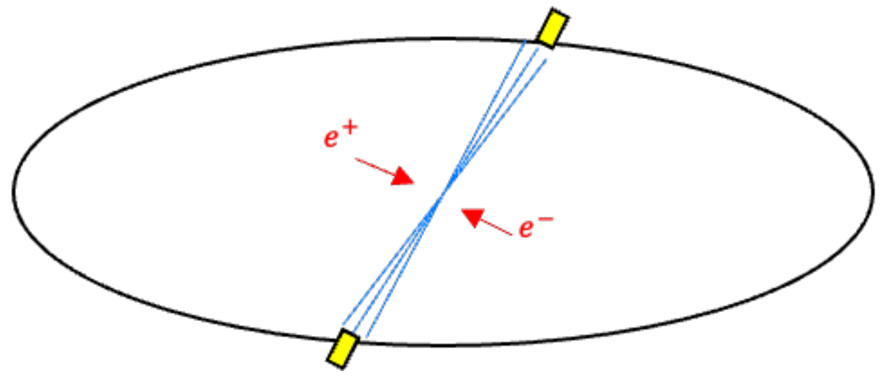

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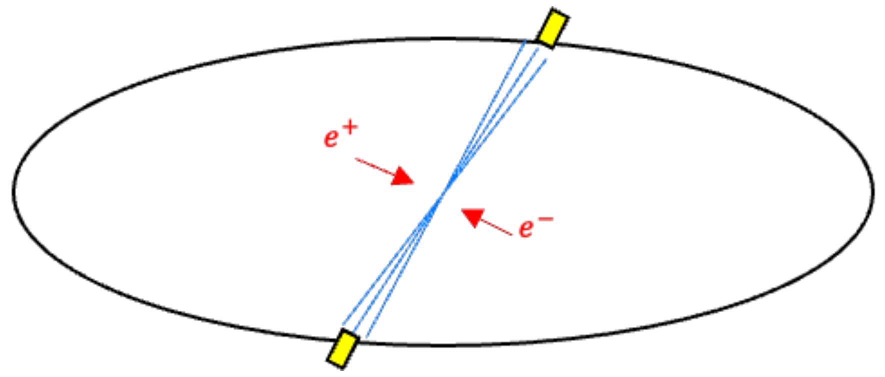

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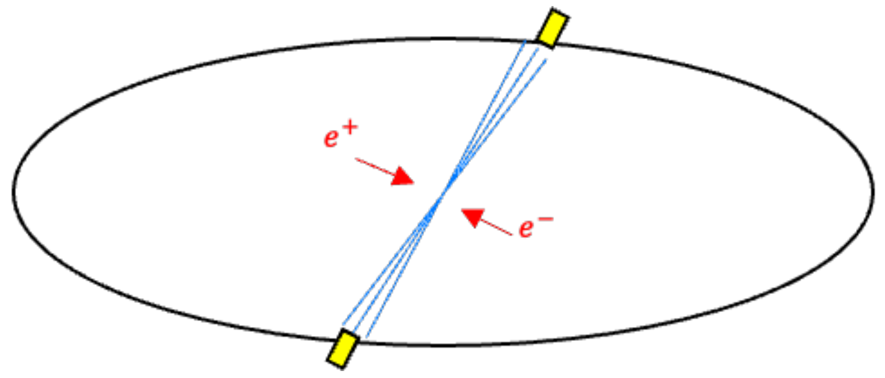

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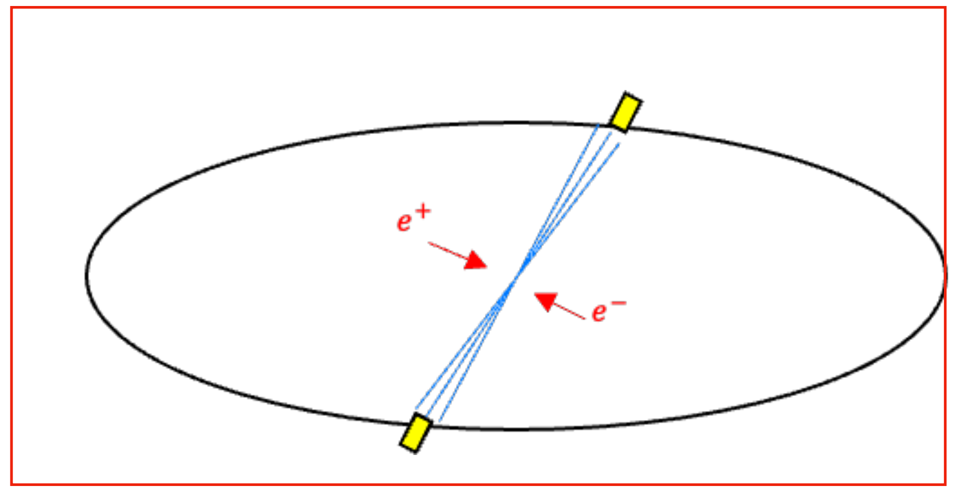

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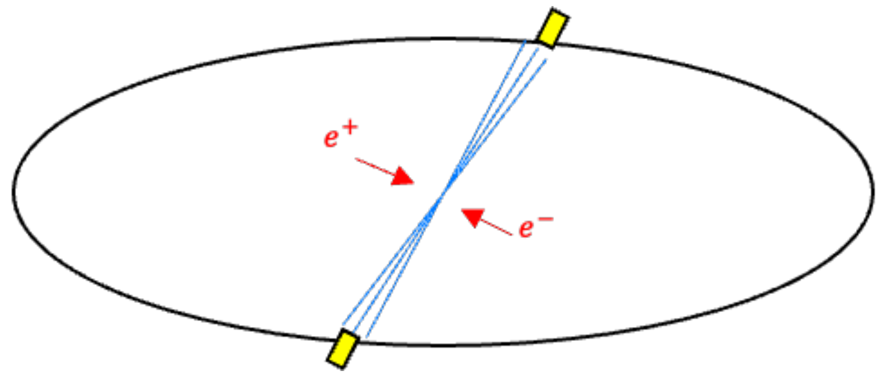

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IRC safe in the back-to back limit

[Monni, Vita, Xu, Zhu, 2508.00977]

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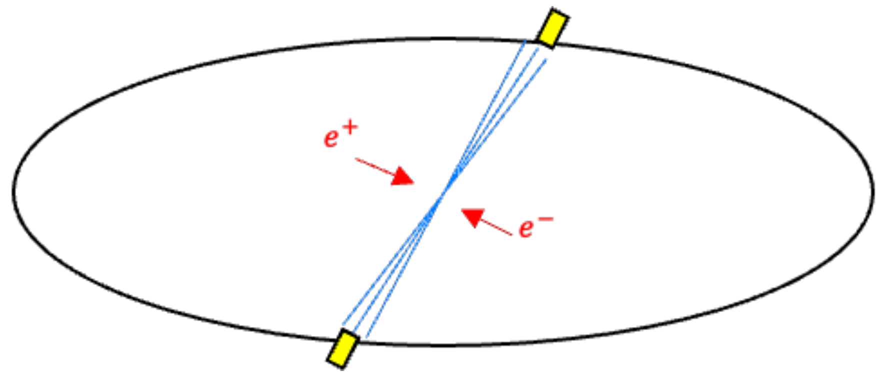

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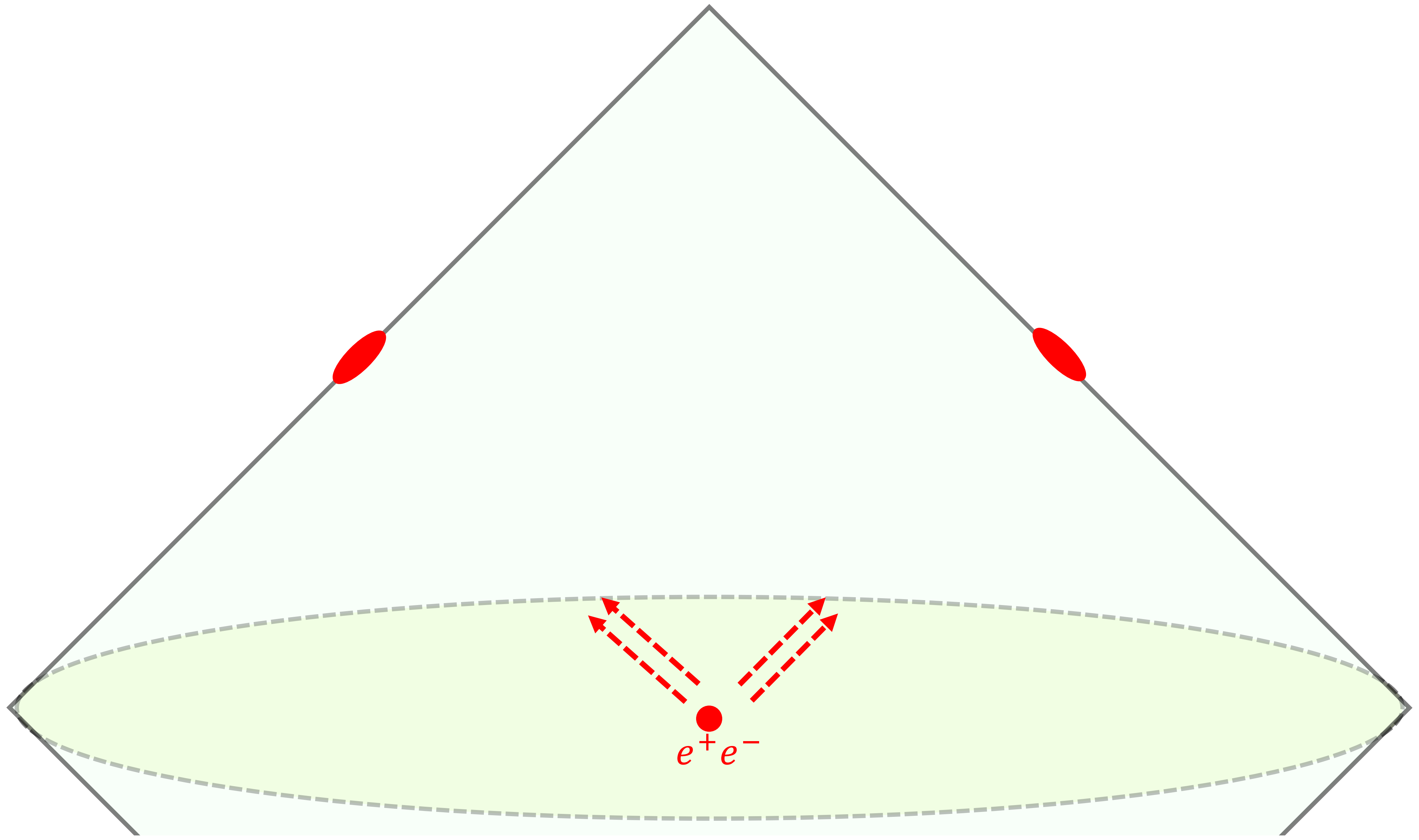

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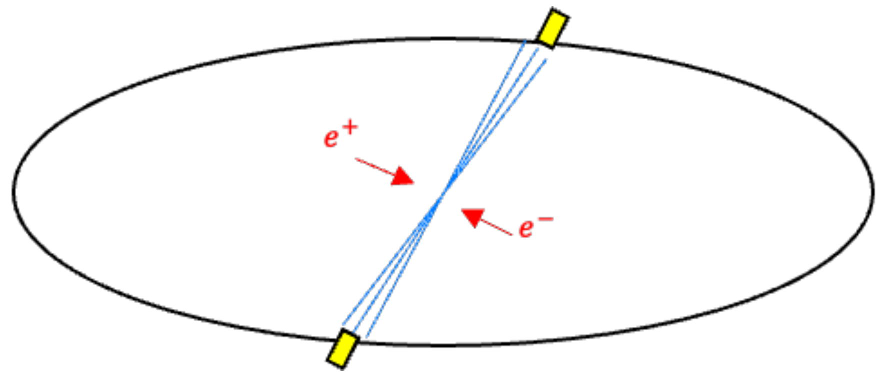

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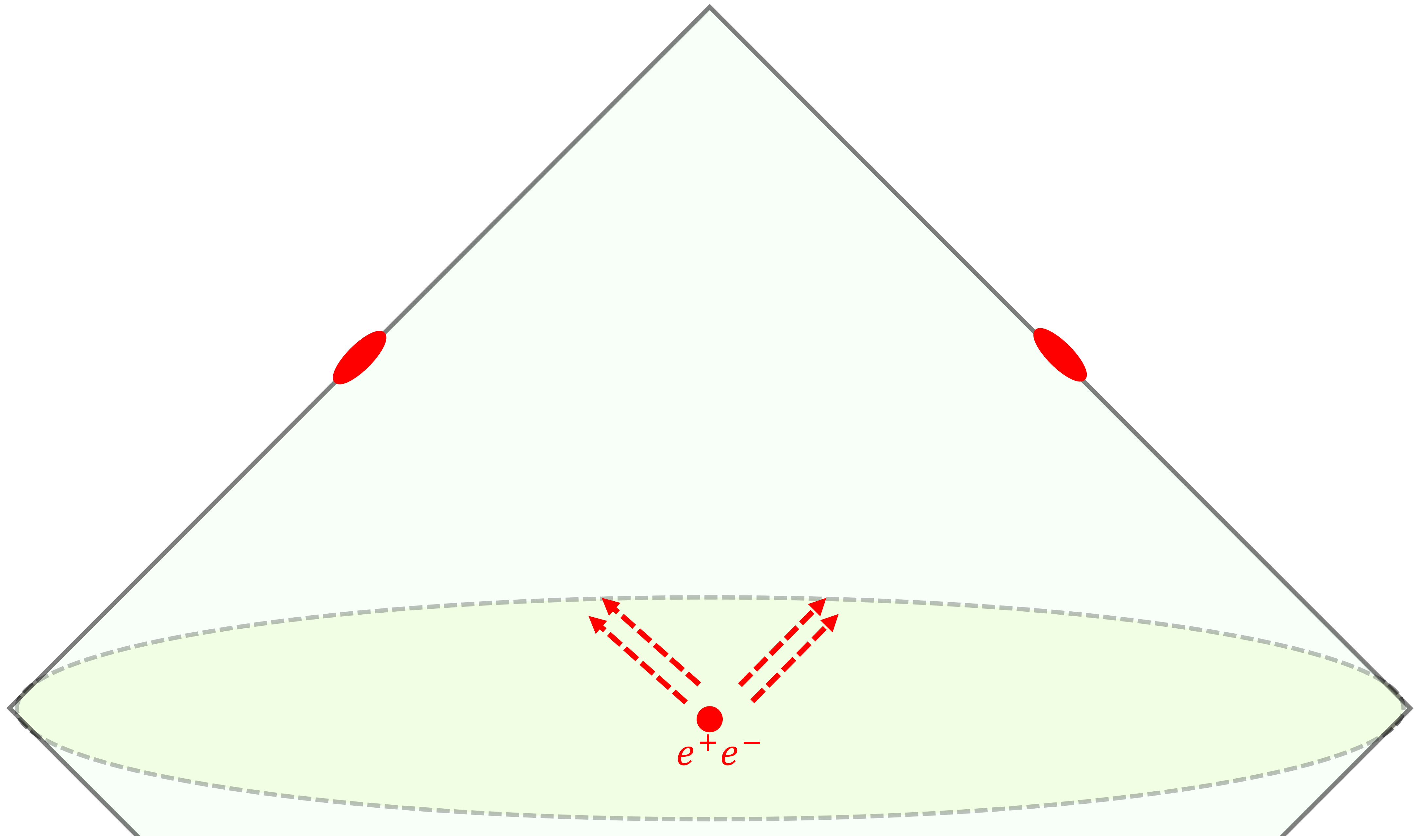
CFT
[Korchemsky, 1905.01444]
[Chen, Zhou, Zhu, 2301.03616]

- $\langle 0|\mathcal{O}(x_1)\,T(x_2)\,T(x_4)\,\mathcal{O}(x_3)|0\rangle$ in this configuration determines the "energy-energy correlator" in the back-to-back limit in CFT



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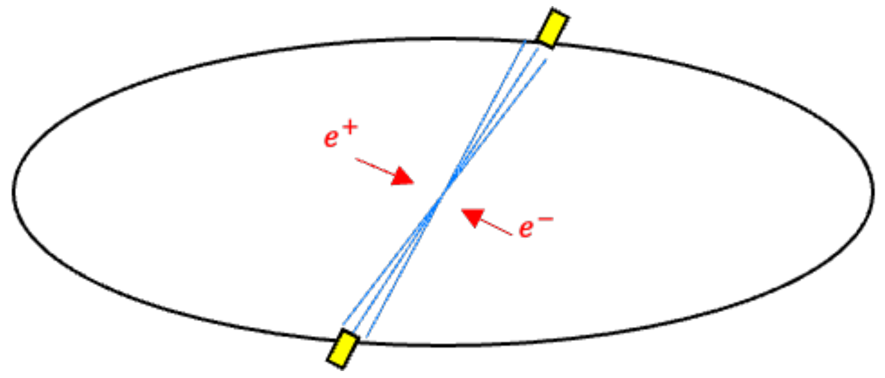

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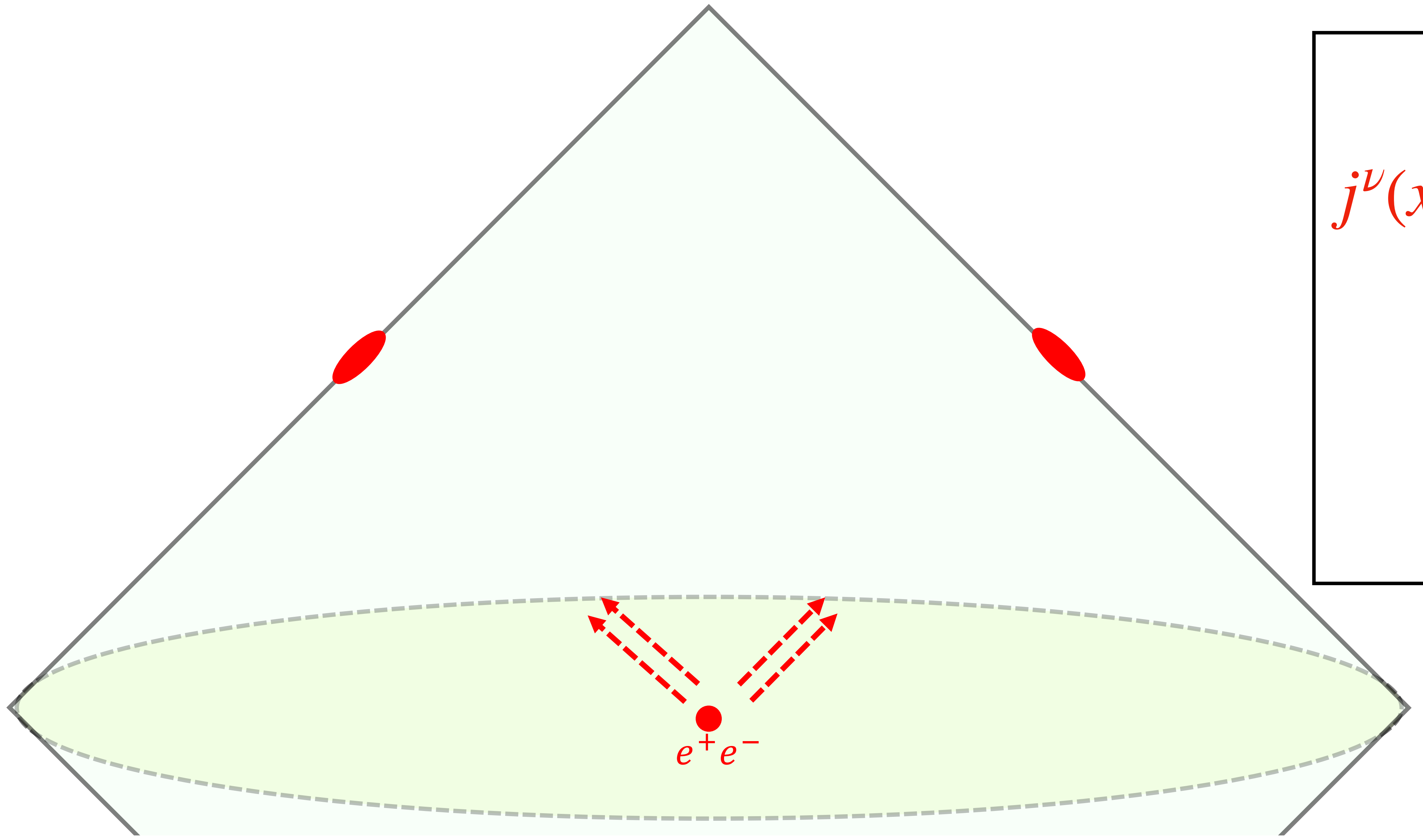
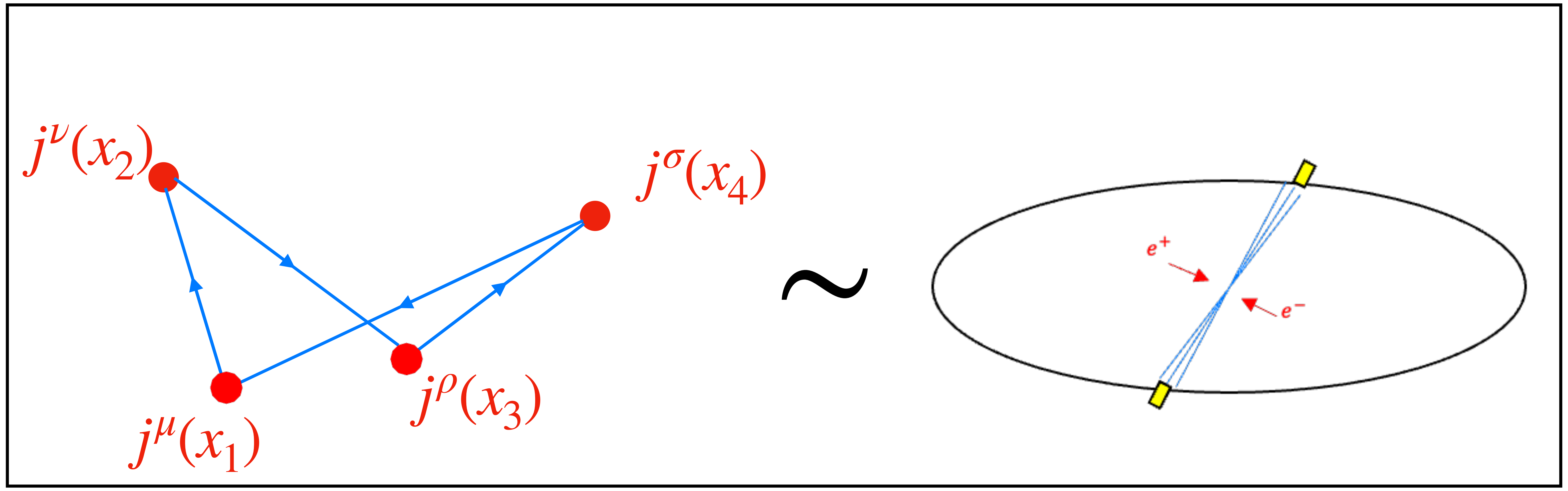
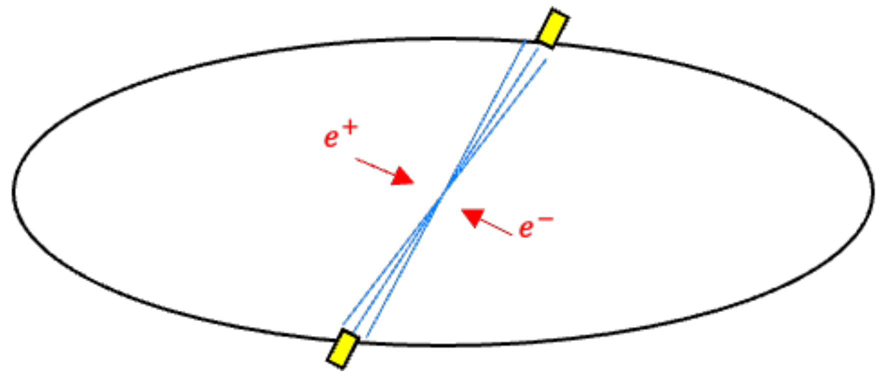
CFT
[Korchemsky, 1905.01444]
[Chen, Zhou, Zhu, 2301.03616]

- $\langle 0 | \mathcal{O}(x_1)\, T(x_2)\, T(x_4)\, \mathcal{O}(x_3) | 0 \rangle$ in this configuration determines the "energy-energy correlator" in the back-to-back limit in CFT





$\langle 0|j^{\mu}(x_1)j^{\nu}(x_2)j^{\rho}(x_3)j^{\sigma}(x_4)|0\rangle$



- $\langle 0\,|\,j^{\mu}\left(x_1\right)j^{\nu}\left(x_2\right)j^{\sigma}\left(x_4\right)j^{\rho}\left(x_3\right)|\,0\rangle$ determines $\langle 0\,|\,j^{\mu}(x)\mathcal{Q}(\hat{n}_1)\mathcal{Q}(\hat{n}_2)j_{\mu}(0)\,|\,0\rangle$

- $x^2_{i,i+1} \to 0^-$ (sequential light-cone limit) is related to "back-to-back" limit

- $x^2_{i,i+1} \to 0^- \sim SCET_I$

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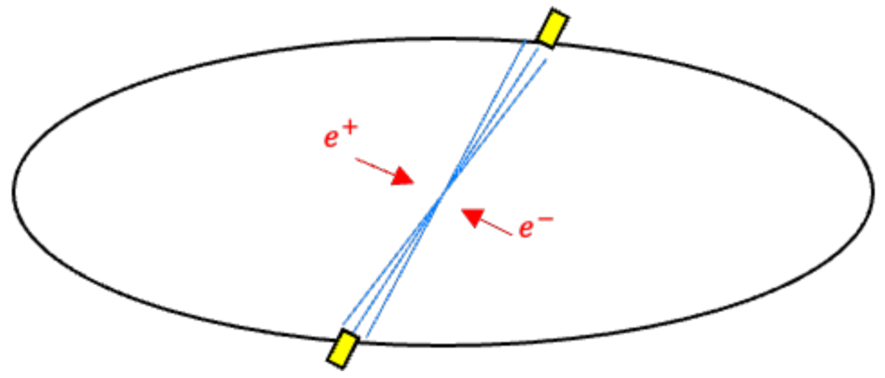

- $\langle 0\,|\,j^{\mu}(x_1)\,j^{\nu}(x_2)\,j^{\sigma}(x_4)\,j^{\rho}(x_3)\,|\,0\rangle$ determines $\langle 0\,|\,j^{\mu}(x)\mathcal{Q}(\hat{n}_1)\mathcal{Q}(\hat{n}_2)j_{\mu}(0)\,|\,0\rangle$
- $x_{i,i+1}^2 \to 0^-$ (sequential light-cone limit) is related to "back-to-back" limit
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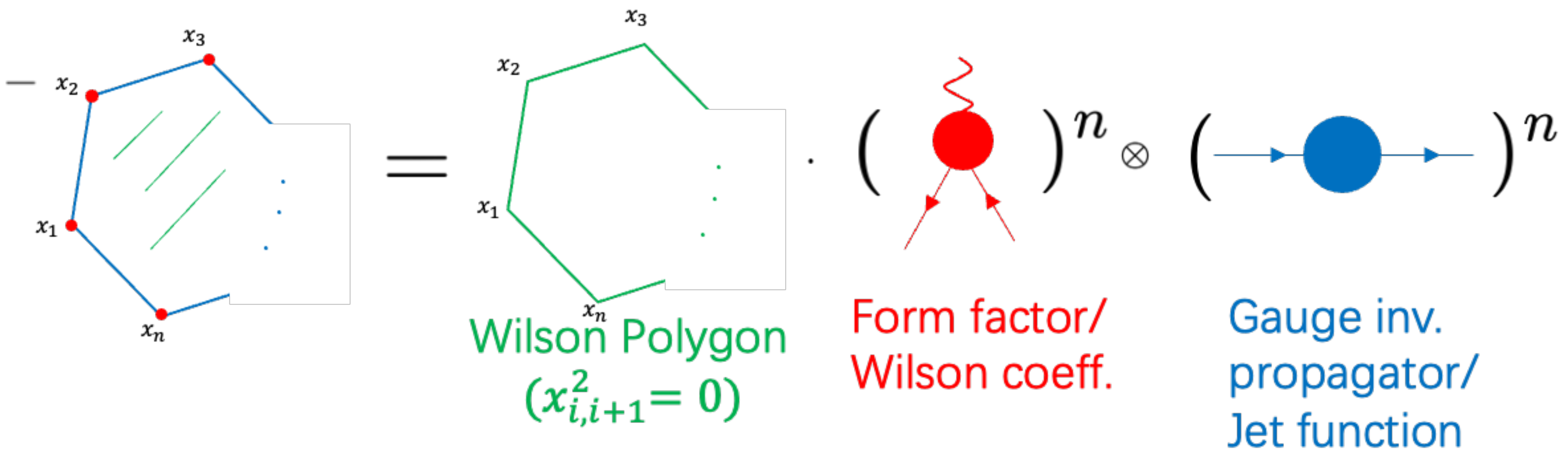
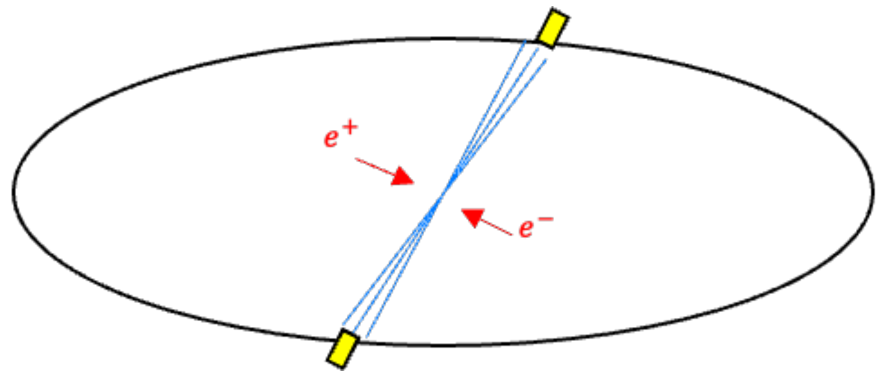
$$\langle 0|j^{\mu}(x_1)\ldots j^{\sigma}(x_n)|0\rangle \overset{x_{i,i+1}^2\to 0^-}{\sim}$$



$$\langle 0 | j^{\mu}(x_1) j^{\nu}(x_2) j^{\rho}(x_3) j^{\sigma}(x_4) | 0 \rangle$$



$$W \cdot H \otimes J = W \cdot \int \prod_{i=1}^{n} dp_i^- \tilde{C}_V \left(\frac{2p_i^-}{\mu^2} p_{i+1}^- x_{i,i+1}^- \right) \tilde{j} \left(\ln \left(\frac{2p_i^-}{\mu^2} \right) \right) e^{-\frac{x_{i+1,i}^2}{2} p_i^-}$$

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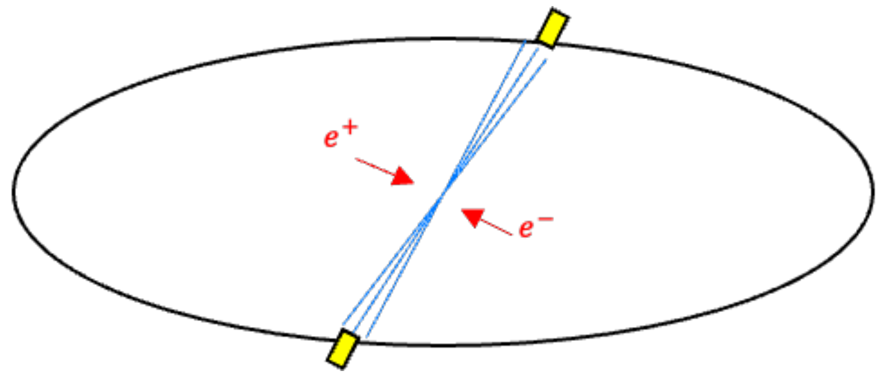

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- “Jet functions” in SCET

[Becher, Neubert, hep-ph/0603140]

- $\mathscr{J} \sim \mathscr{F}[\langle \chi_{\bar{c}} \bar{\chi}_c \rangle]$

- $J_{SCET} \sim \text{Im}[\mathscr{J}]$

- $j \sim \int_0^{Q^2} J(p^2)$

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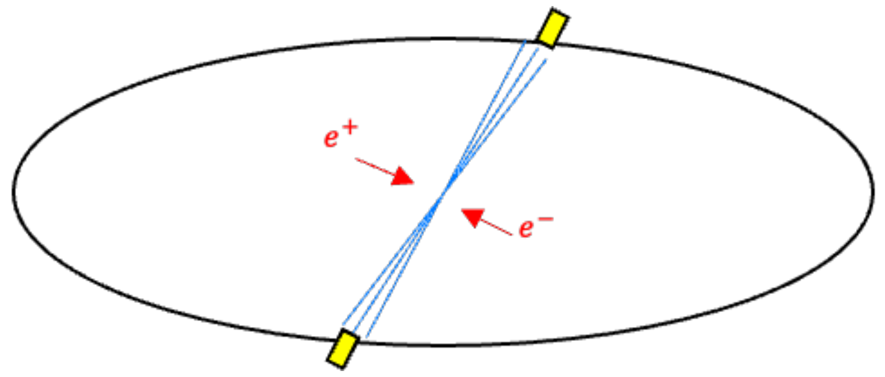

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[Neubert, hep-ph/0506245]

are polynomials of degree n. For our purposes we need the first four of them, which are

$$I_1(x)=x\,,\qquad I_3(x)=x^3+\frac{\pi^2}{2}x-2\zeta_3\,,$$
$$I_2(x)=x^2+\frac{\pi^2}{6}\,,\qquad I_4(x)=x^4+\pi^2x-8\zeta_3\,x+\frac{3\pi^4}{20}\,. \tag{17}$$

We now define functions $\tilde{s}$ and $\tilde{j}$ by the following replacement rules:

$$\tilde{j}(L,\mu)\equiv j(L,\mu)\Big|_{L^n\to I_n(L)}\,,\qquad \tilde{s}(L,\mu)\equiv s(L,\mu)\Big|_{L^n\to I_n(L)}\,. \tag{18}$$

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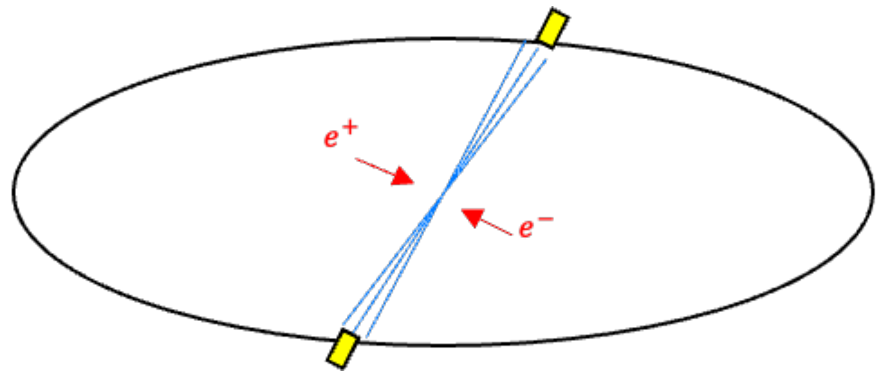

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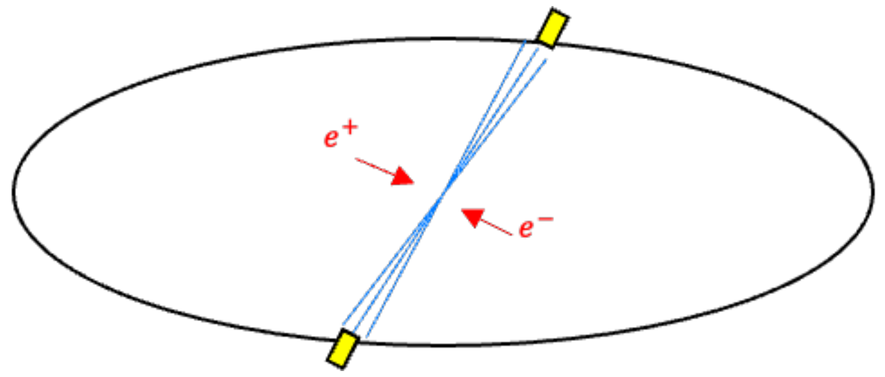

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$\tilde{j}$ satisfies local RG

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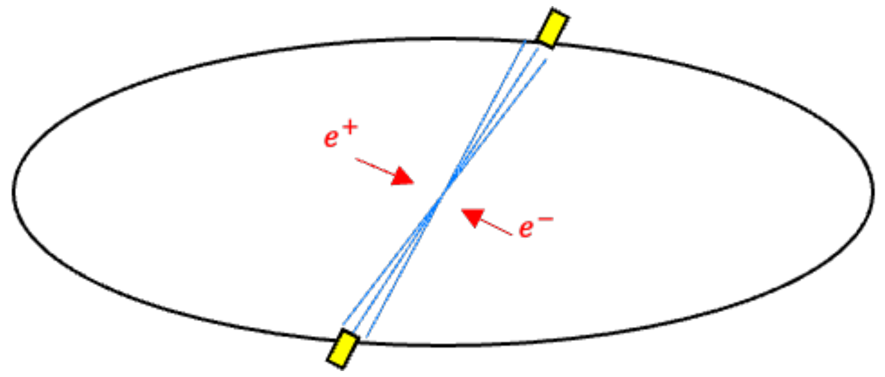

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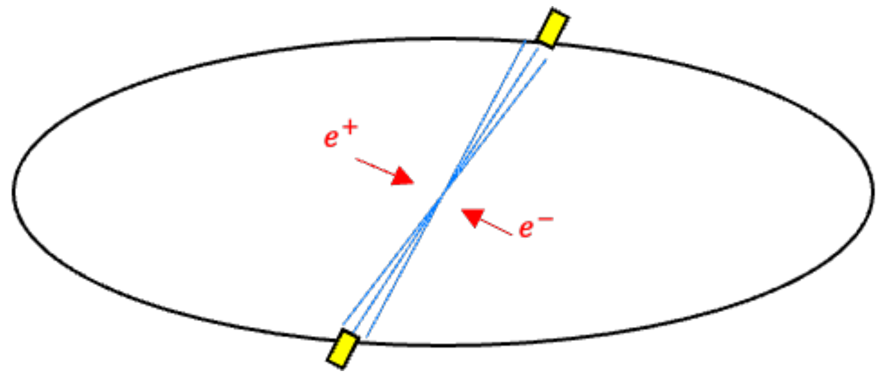
- 2-loop result & 3-loop singular terms

[Chicherin, Henn, Sokatchev, Yan, 2001.10806]

$$\frac{G_4}{G_4^{\text{tree}}} = 1 + \frac{\alpha_s}{4\pi}C_F(\ldots) + \left(\frac{\alpha_s}{4\pi}\right)^2\times$$
$$\left(f_{\text{conformal}}\ (u,v;C_F^2,C_FC_A,C_Fn_f) + \beta_0\cdot r_{\text{non-conf.}}\left(\frac{x_{13}^2}{x_{24}^2},u,v,\ldots\right)\right)+\ldots$$

$$\langle 0|j^\mu(x_1) j^\nu(x_2) j^\rho(x_3) j^\sigma(x_4)|0\rangle$$



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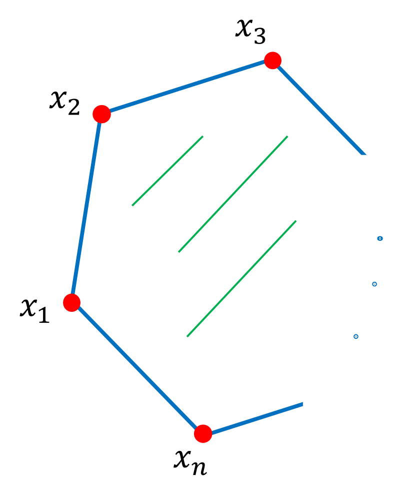
$$\Bigg(\int \begin{aligned} R_2 = C_F^2 \Big[&- 28\zeta_2 - 48\zeta_3 + 116\zeta_4 + L_u (8 - 2L_{uv}) L_v + 2L_u^2 L_v^2 + \left(4\zeta_2 - \frac{7}{2}\right) L_{uv}^2 + \left(4\zeta_2 - 24\zeta_3 + \frac{5}{2}\right) L_{uv} \Big] \\ &+ C_F C_A \left[\frac{68\zeta_2}{9} + \frac{28\zeta_3}{3} - 16\zeta_4 + L_u L_v \left(4\zeta_2 - \frac{11 L_{uv}}{6} - \frac{235}{18}\right) + \frac{11 L_{uv}^2}{12} + \left(-\frac{112\zeta_2}{3} + 12\zeta_3 + \frac{221}{18}\right) L_{uv} \right] \\ &+ C_F n_f \left[-\frac{8\zeta_2}{9} + \frac{8\zeta_3}{3} + L_u \left(\frac{L_{uv}}{3} + \frac{17}{9}\right) L_v + \left(\frac{16\zeta_2}{3} - \frac{13}{9}\right) L_{uv} - \frac{L_{uv}^2}{6} \right] + 16\left(C_F^2 - \frac{1}{2} C_F C_A\right) \\ &+ \frac{1}{2}\beta_0 R_1 \ln \frac{x_{13}^2 x_{24}^2 \mu^4}{16} + C_F \beta_0 \left[r_2(L_{uv}, x) + r_2\left(L_{uv}, \frac{1}{x}\right) + \frac{L_{13}^2}{4} + \frac{L_{24}^2}{4} + \ln(x) L_{13} L_{24} - \frac{1}{2}\left(L_v L_{13}^2 + L_u L_{24}^2\right) \right], \end{aligned} \quad , \ldots \Bigg) \Bigg) + \ldots$$

$$r_2(L_{uv}, x) = 2\text{Li}_3(-x) - 2\ln(x)\text{Li}_2(-x) - \frac{1}{4} L_{uv} \ln^2(x) - \frac{1}{2}(6\zeta_2 + \ln^2(x)) \ln \frac{(1+x)^2}{x} + \frac{1}{4}\ln^2(x) . \qquad (18)$$

Correlation function/Wilson loop duality



- Similar duality was established in $\mathcal{N} = 4$ SYM:

$$\frac{G_n}{G_n^{\text{tree}}} = e^{-\frac{\mathrm{r}^{\text{adj}}_{\text{cusp}} \sum_{i=1}^n \log \frac{x^2_{i-1,i}}{x^2_{i-1,i+1}} \log \frac{x^2_{i,i+1}}{x^2_{i-1,i+1}} + \frac{\tilde{g}(\lambda)}{2} \sum_{i=1}^n \log u_{i,i+1}}{x^2}} W^{\text{adj}}_{\text{ren}} \mathcal{J}$$

$$\mathcal{J} = \int \prod_{i=1}^n d\hat{\sigma}_i C_i\left(\hat{\sigma}_i, \hat{\sigma}_{i+1}\right) \left|\psi_0\left(-\hat{\sigma}_i\right)\right|^2 e^{\frac{1}{2}\Gamma^{\text{adj}}_{\text{cusp}} \sum_{i=1}^n \hat{\sigma}_i \log u_{i,i+1}}$$

[Alday, Eden, Korchemsky,
Maldacena, Sokatchev, 1007.3243]

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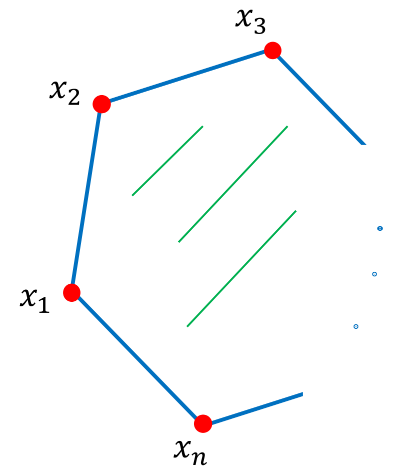

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"energy"

$$\mathcal{J} = \int \prod_{i=1}^{n} d\hat{\sigma}_i C_i\left(\hat{\sigma}_i, \hat{\sigma}_{i+1}\right) \left|\psi_0\left(-\hat{\sigma}_i\right)\right|^2 e^{\frac{1}{2}\Gamma_{\rm cusp}^{\rm adj} \sum_{i=1}^{n} \hat{\sigma}_i \log u_{i,i+1}}$$

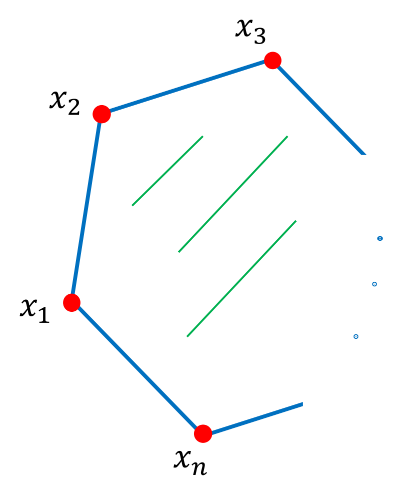
all order in perturbation theory
[Alday, Bissi, 1305.4604]

"wavefunction"

"The amplitude that the operator creates a pair of particles"

[Alday, Eden, Korchemsky, Maldacena, Sokatchev, 1007.3243]

Correlation function/Wilson loop duality



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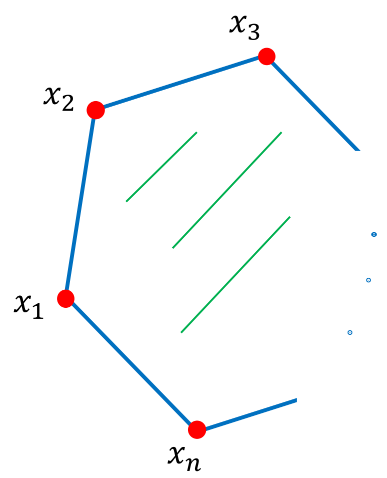
- Although the result seems similar, the argument is different.

Let us now turn to the second effect that is related to the modification of the propagation of the particles in Figure 6 (d) due to their interaction with the color flux. There are two sources of corrections. The first is that the energy of the particles can be modified. Instead of being precisely 1, it can be slightly bigger or smaller. If that were the only effect, it would be very easy to take it into account. One would need to change the propagator $e^{-\Delta\tau_{i,i+1}}$ to $e^{-(1+\tilde{g})\Delta\tau_{i,i+1}}$. Using the formulas in (4.5) applied to points $i-1, i, i+1, i+2$ we find that

$$\Delta\tau_{i,i+1} \sim -\frac{1}{2}\log\frac{x^2_{i+1,i+2}x^2_{i-1,i}}{x^2_{i,i+2}x^2_{i-1,i+1}} \equiv -\frac{1}{2}\log u_{i,i+1}\,. \tag{4.8}$$

[Alday, Eden, Korchemsky, Maldacena, Sokatchev, 1007.3243]

Correlation function/Wilson loop duality



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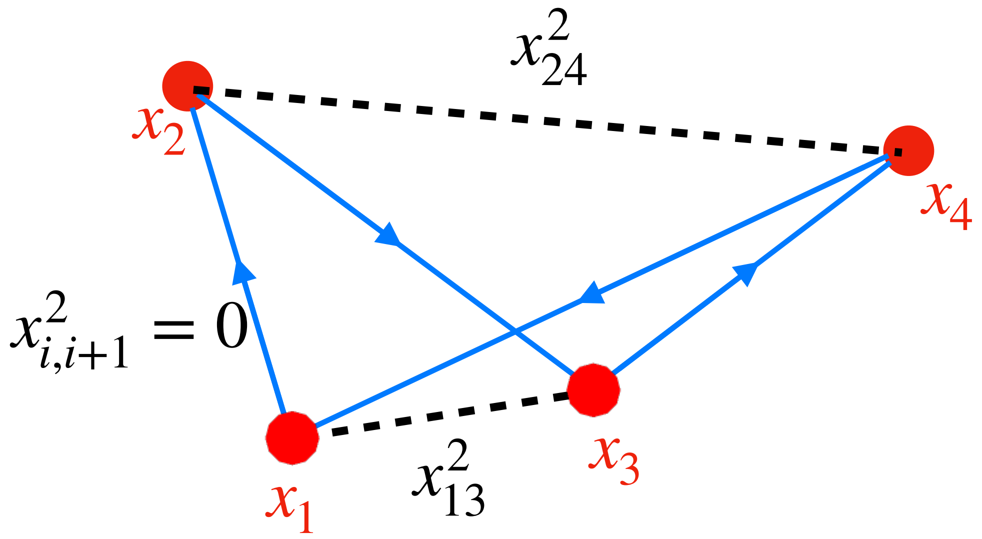
Summary

- $x_{i,i+1}^2 \to 0^-$



  ➡ $SCET_I$

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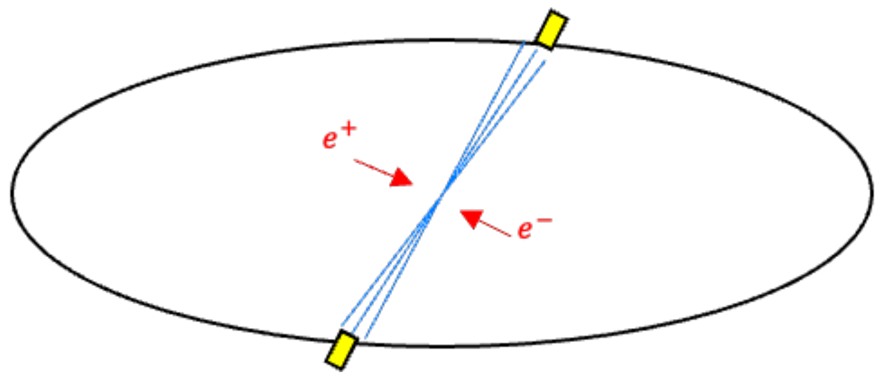

  ➡ $\langle \mathcal{Q}(\hat{n}_1) \mathcal{Q}(\hat{n}_2) \rangle_j$

- Correlation function/Wilson loop duality