

Title: QUANTUM LATENTS: DISTINGUISHING CAUSAL SCENARIOS WITH INDISTINGUISHABLE CLASSICAL ANALOGS

Speakers: Daniel Centeno Díaz

Collection/Series: Causalworlds

Subject: Quantum Foundations, Quantum Information

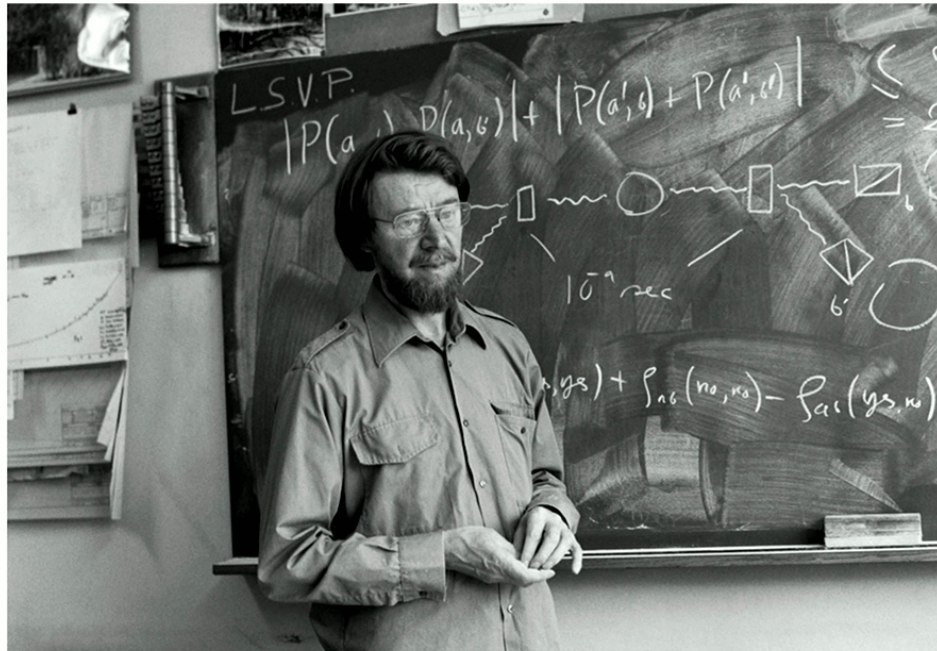
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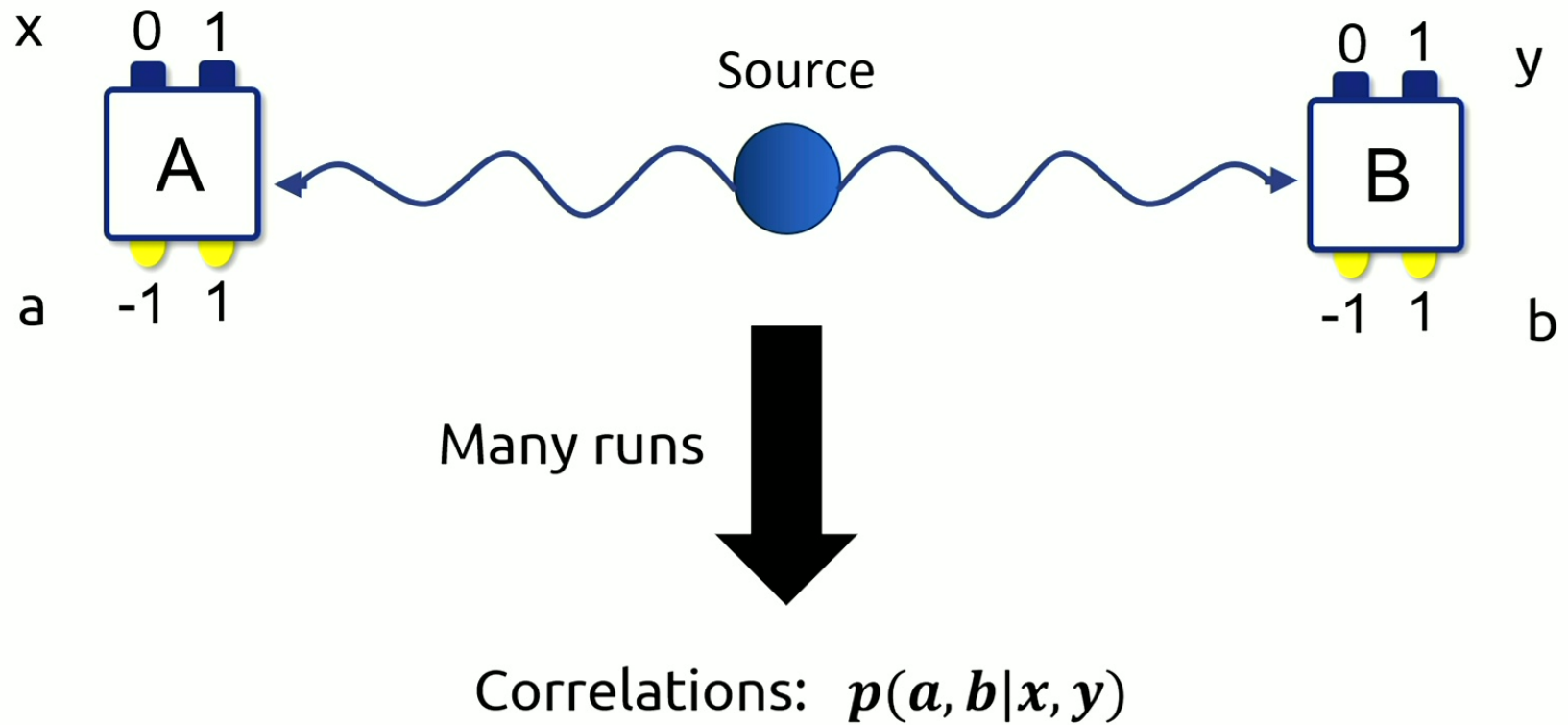
Quantum latents: distinguishing causal scenarios with indistinguishable classical analogs

Bell nonlocality

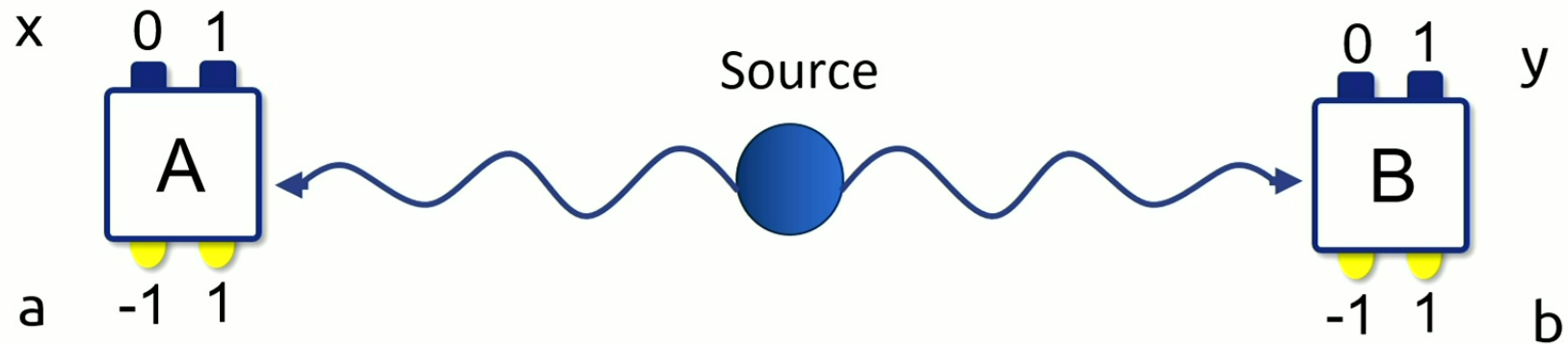
- 1964: "If a hidden-variable theory is local it will not agree with quantum mechanics, and if it agrees with quantum mechanics it will not be local."



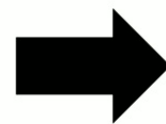
Bell nonlocality



Bell nonlocality



No interaction faster
than light

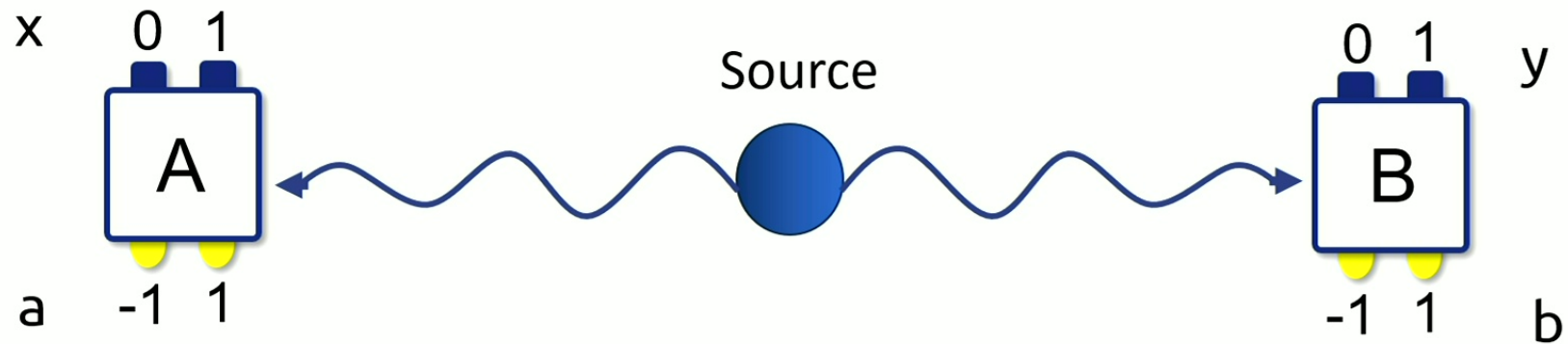


No-signalling

$$p(a|x, y) = p(a|x)$$

$$p(b|x, y) = p(b|y)$$

Bell nonlocality

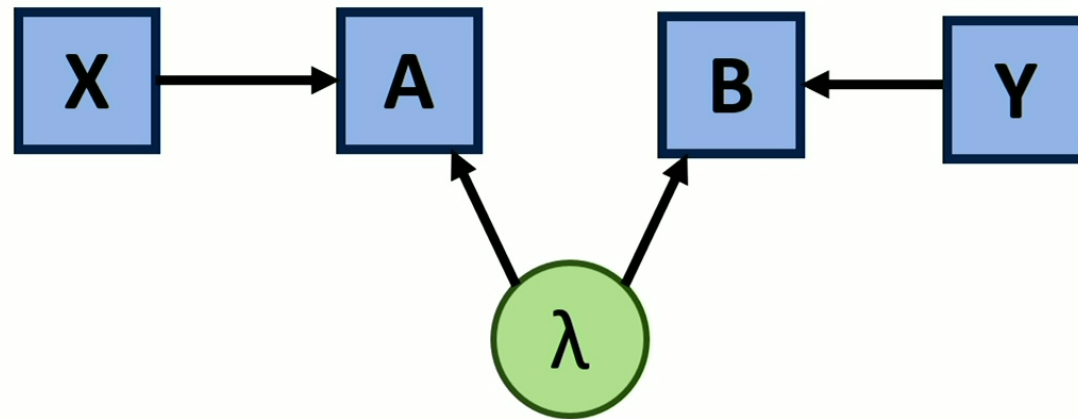


$$CHSH = \langle A_0 B_0 \rangle + \langle A_0 B_1 \rangle + \langle A_1 B_0 \rangle - \langle A_1 B_1 \rangle$$

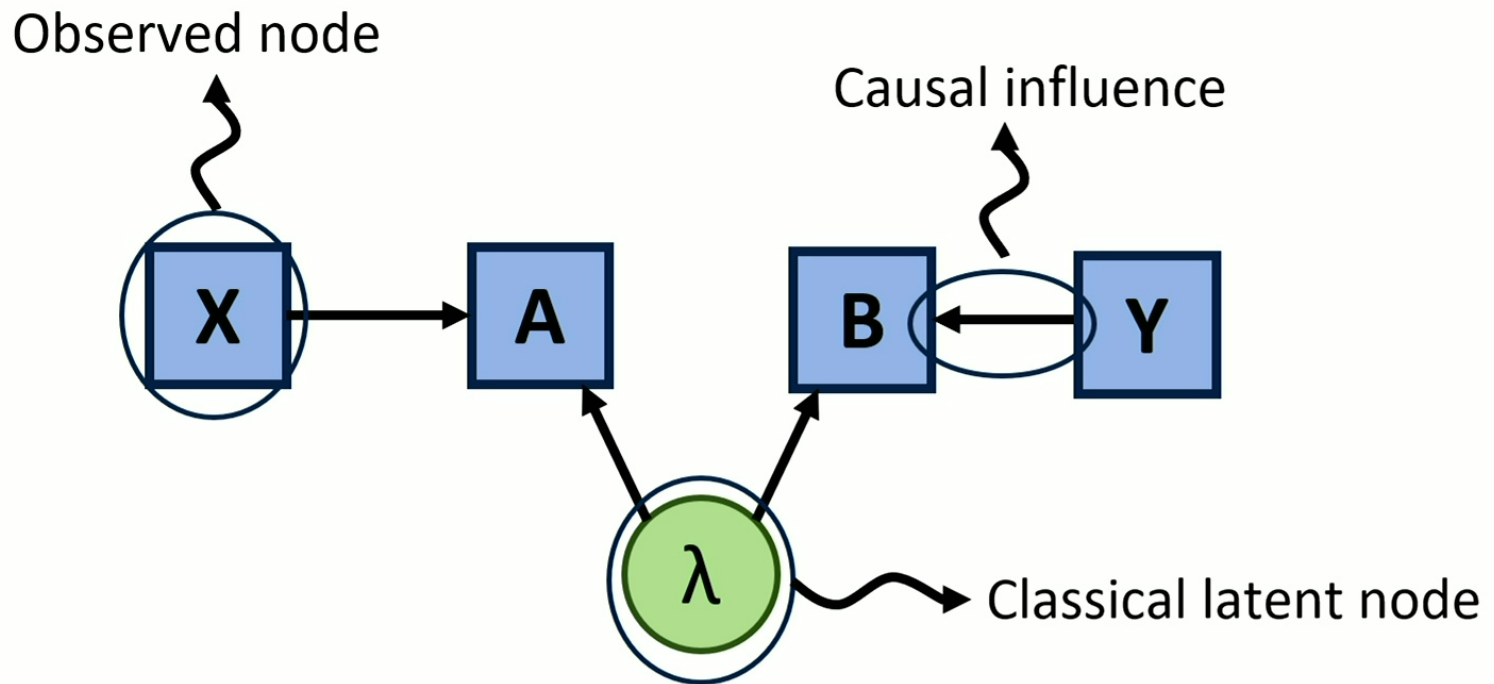
$$CHSH \leq 2 \leq 2\sqrt{2} \leq 4$$

Classical Quantum OPT

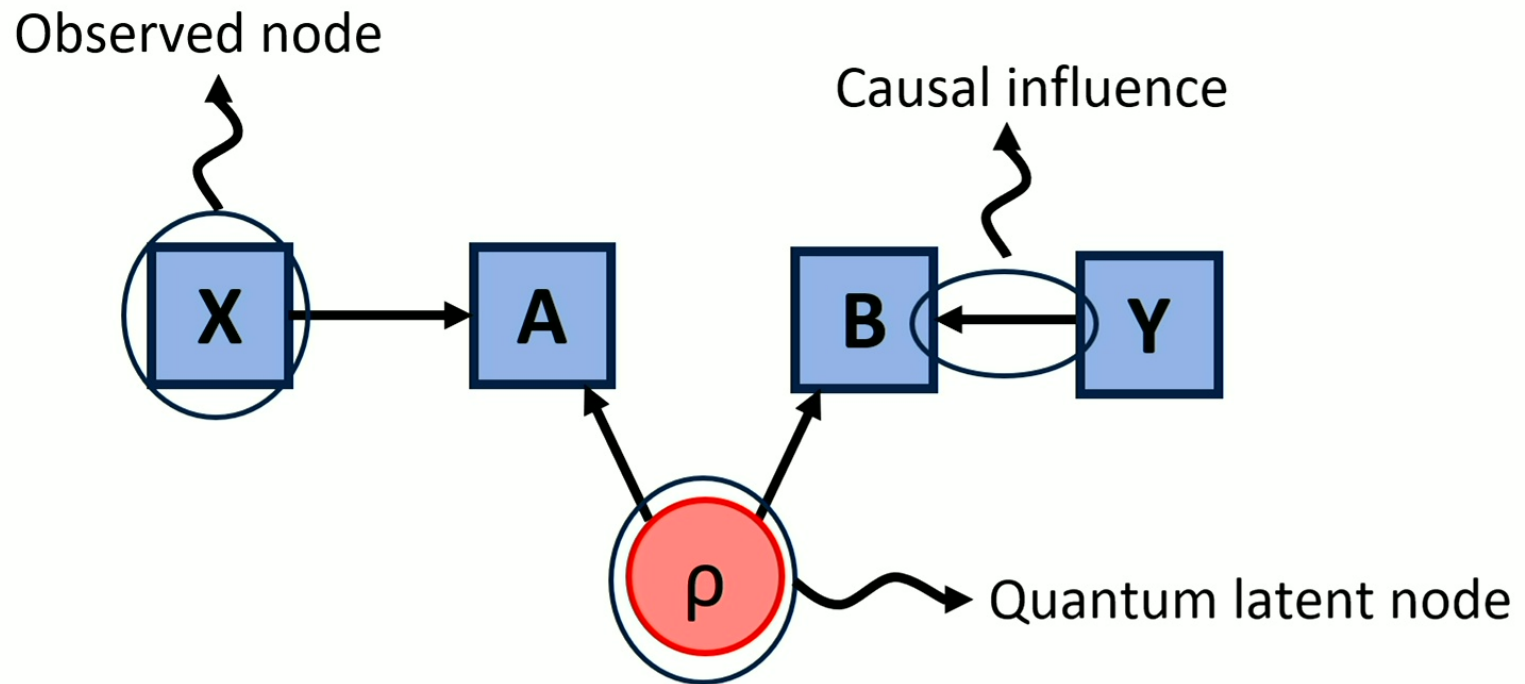
Causal inference



Causal inference

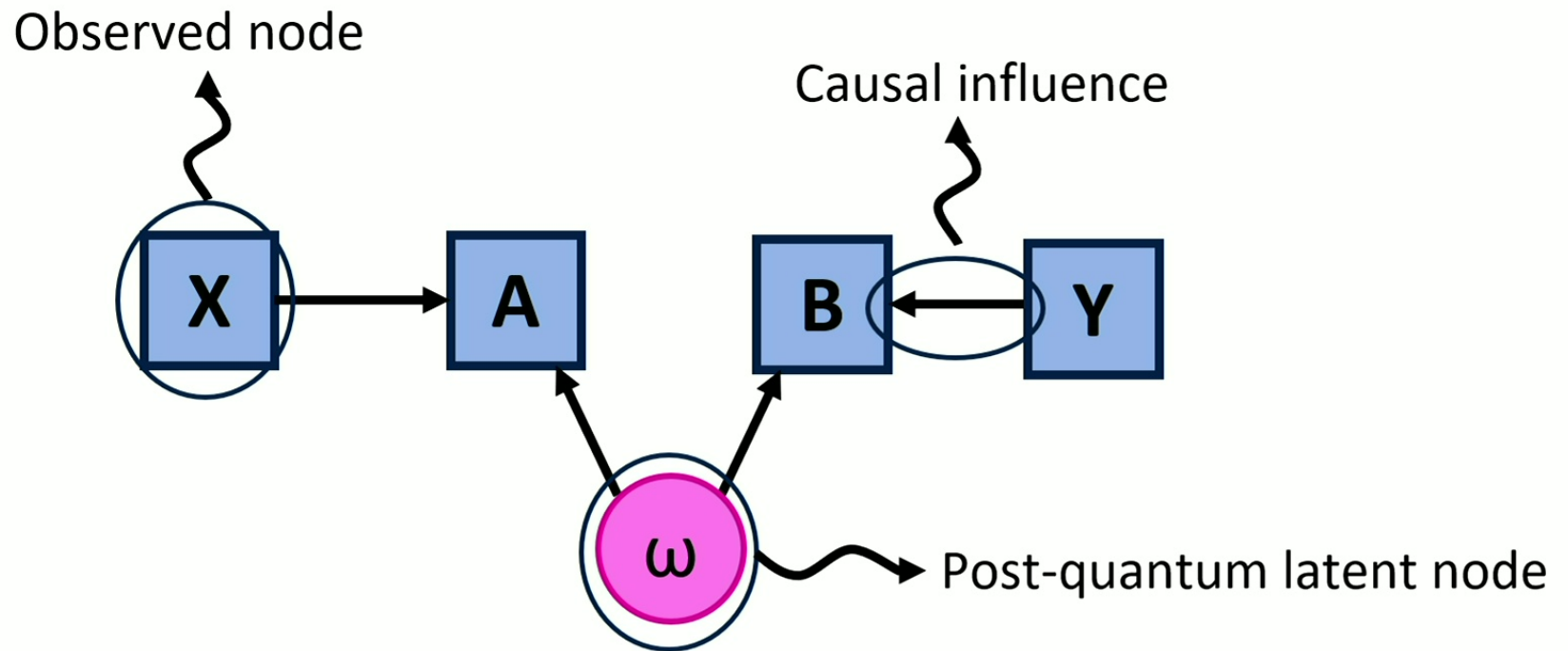


Causal inference



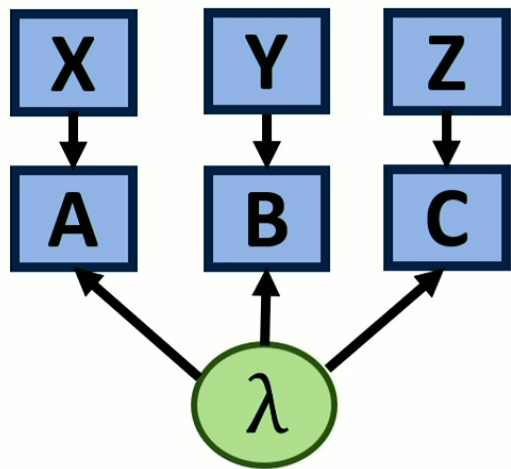
$$p(a, b|x, y) = \text{Tr}\{(A_a^x \otimes B_b^y)\rho\}$$

Causal inference

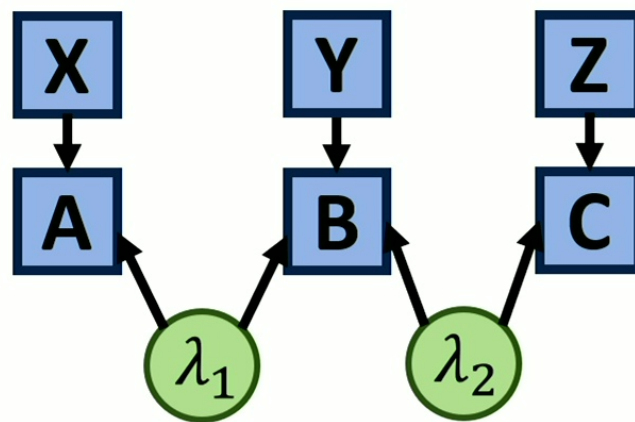


$p(a, b|x, y)$ satisfying no-signalling

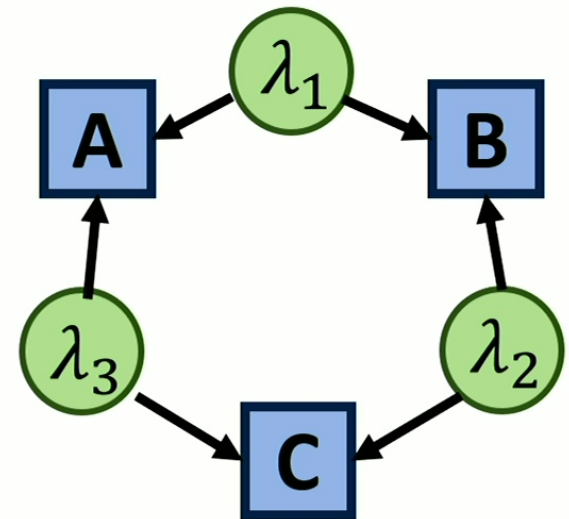
Beyond standard scenario



Tripartite Bell scenario



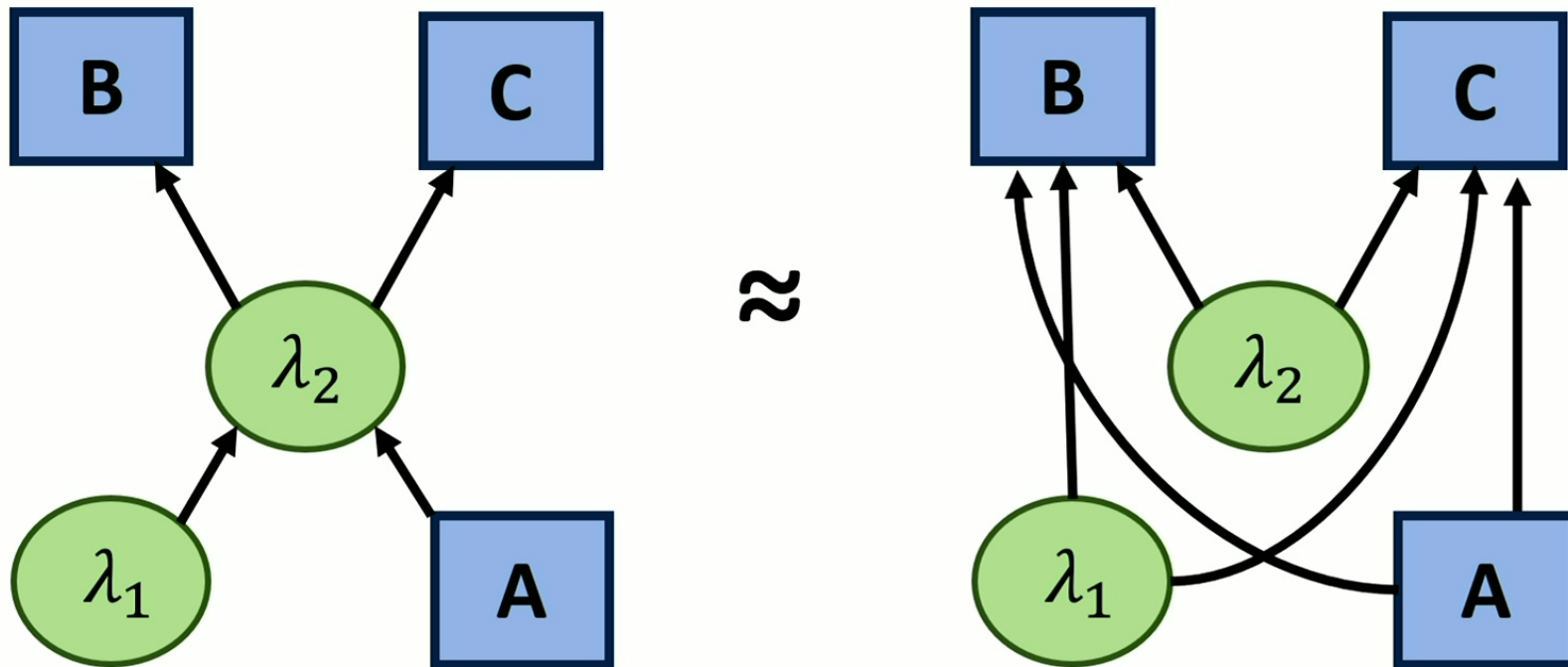
Bilocality scenario



Triangle scenario

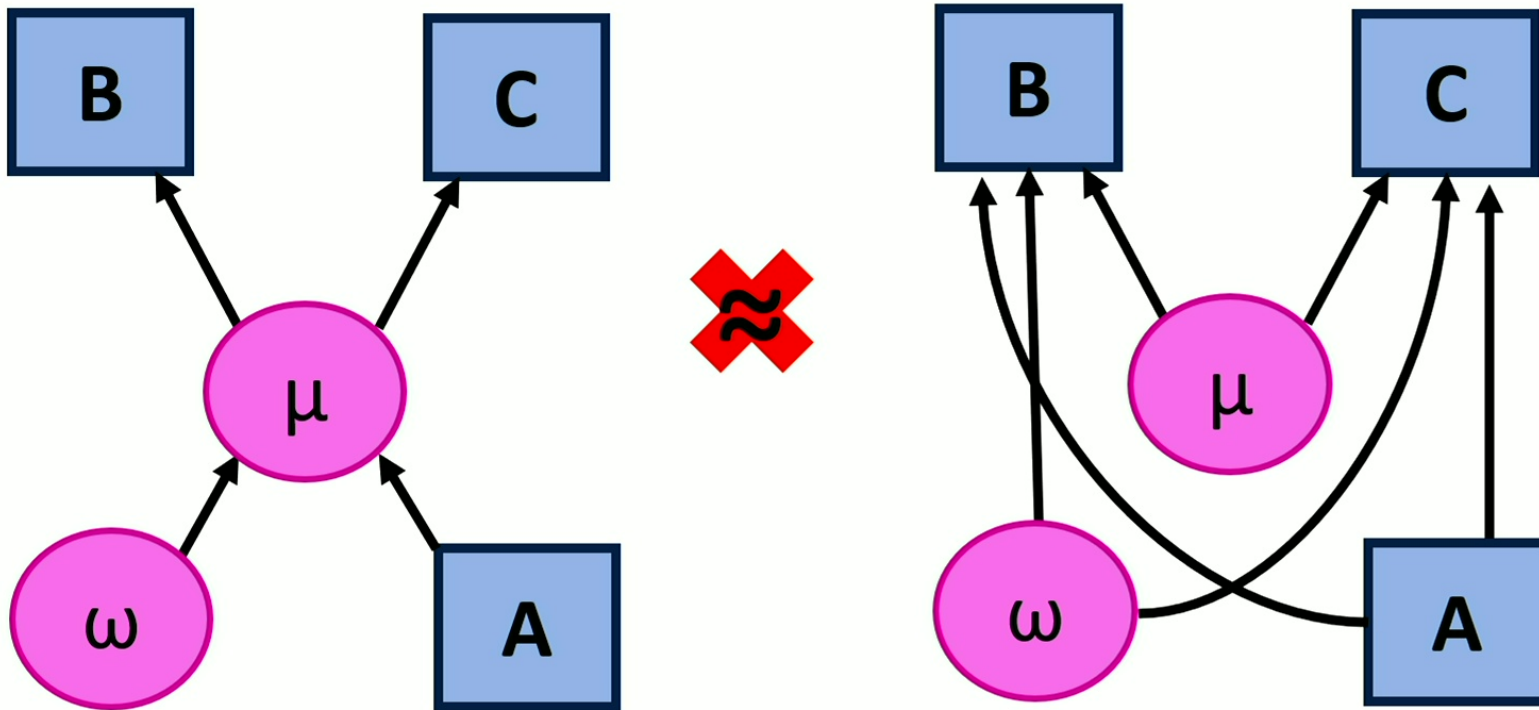
Exogenization

- Classically valid but invalid for non-classical theories



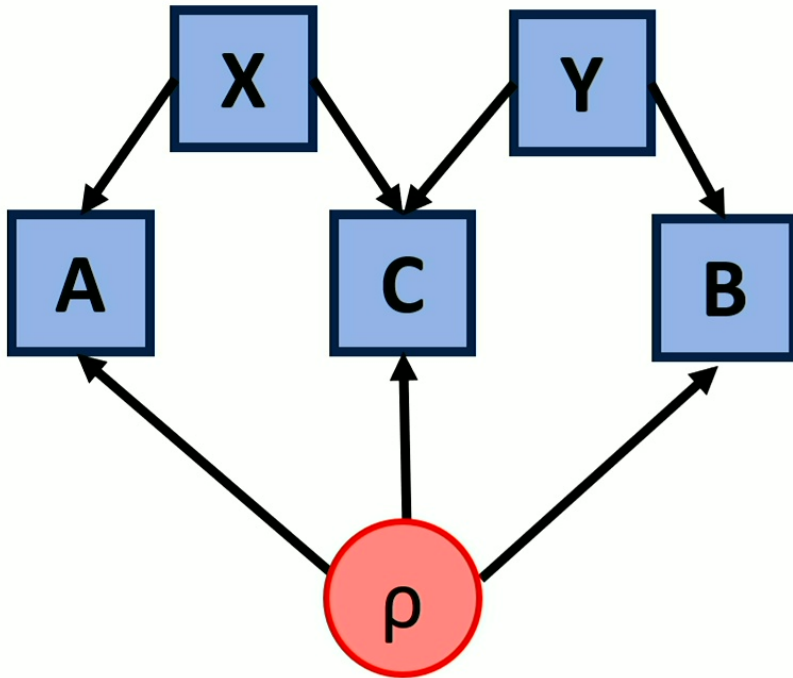
Exogenization

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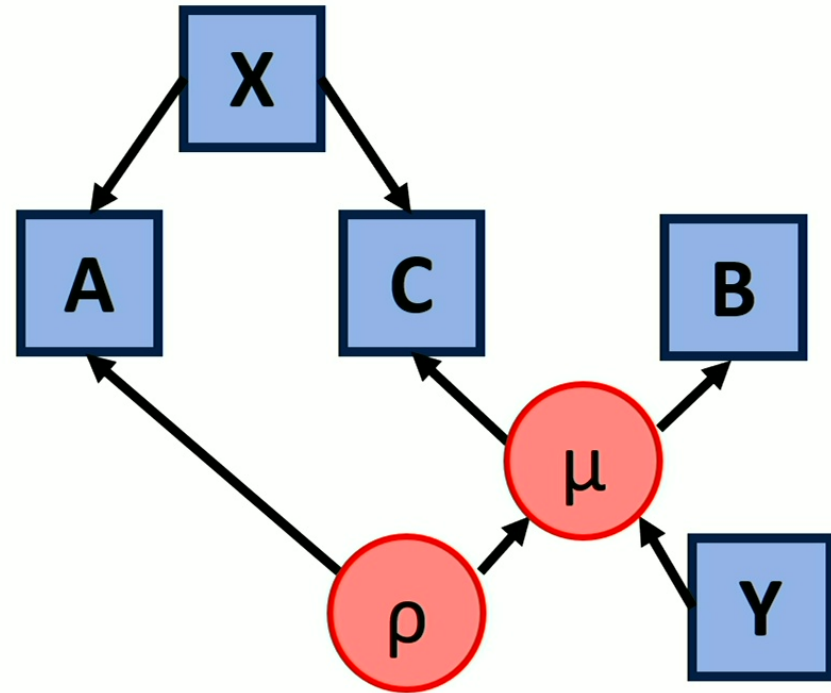
Concepts

1-layer scenarios: no latents with latent parents



$$p(a, b, c|x, y) = \text{Tr}\{(A_a^x \otimes B_b^y \otimes C_c^{xy})\rho\}$$

Multilayer scenarios: latents pointing to latents



$$\begin{aligned} p(a, b, c|x, y) \\ = \text{Tr}\{(A_a^x \otimes B_b^y \otimes C_c^{xy})(\text{Id}_A \otimes \mu_{BC}^y)\rho\} \end{aligned}$$

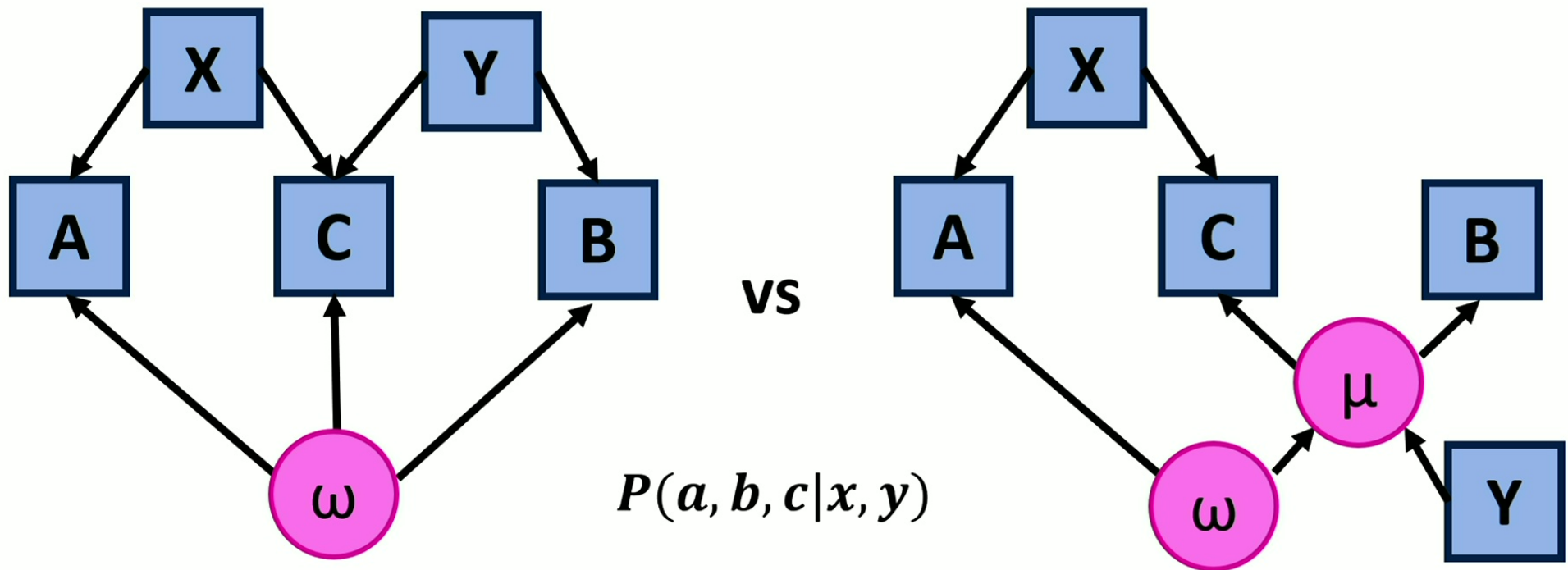
Goal

- Study the features that arise when considering multilayer versions of causal scenarios.

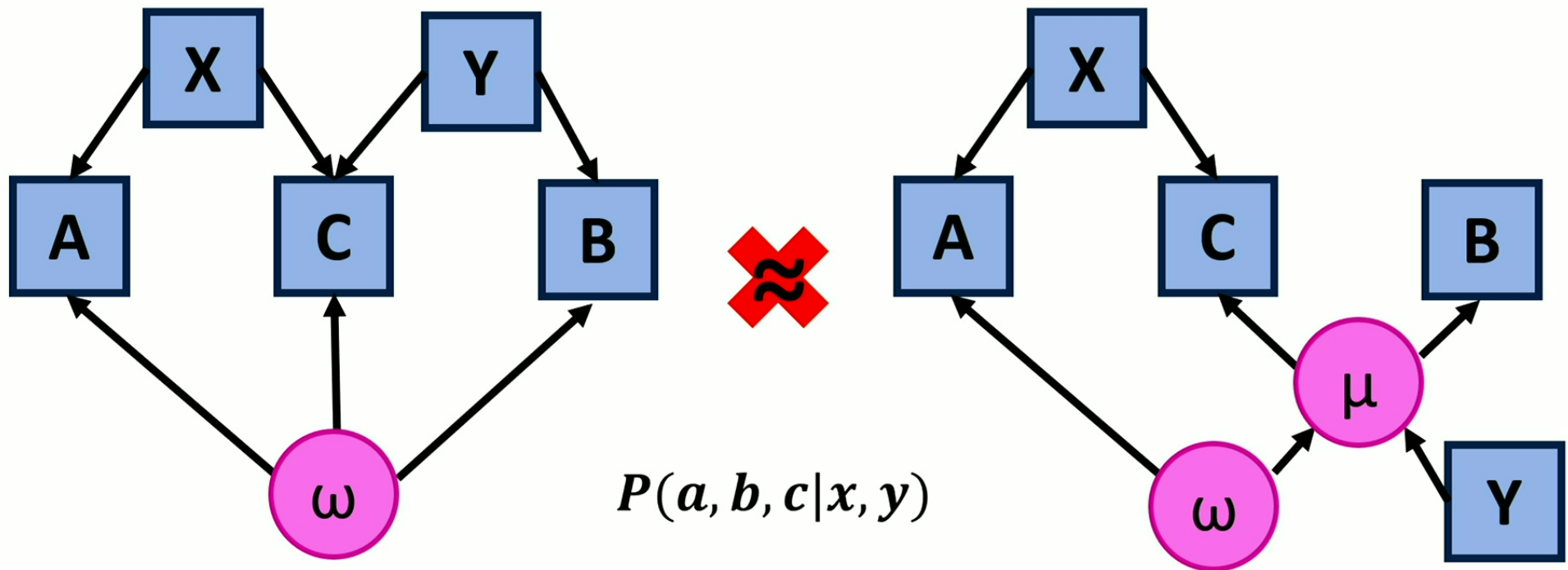


- Observational differences between 1-layer and multilayer scenarios
- Different versions of multilayer scenarios coming from a 1-layer causal structure
- Classicality vs non-classicality of intermediate latent

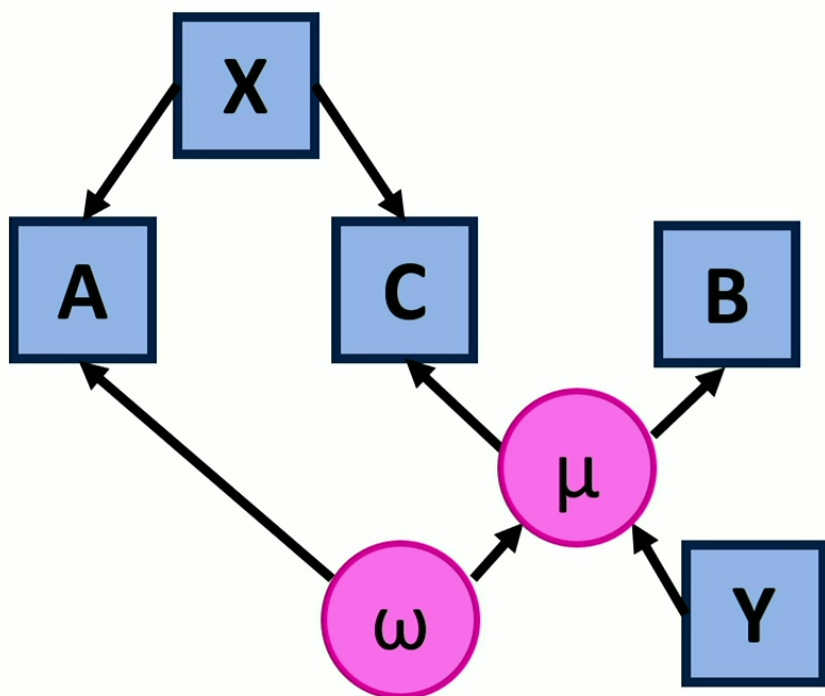
Observational difference



Observational difference



Observational difference

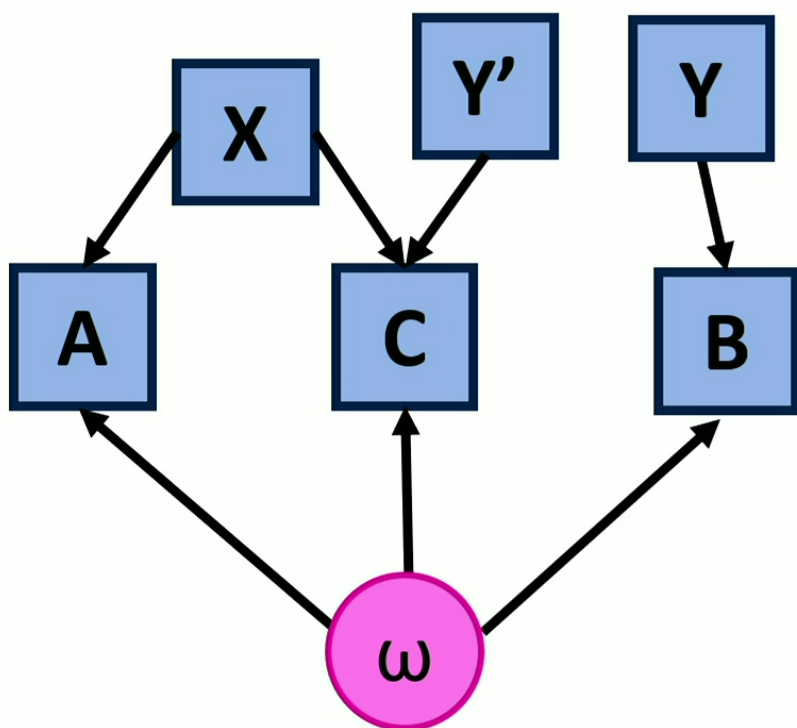


Protocol:

- ω : Resource needed to violate CHSH
- A and μ perform measurements to violate CHSH according to settings x and y
- μ sends the outcome to B and C

$$P^*(a, b, c|x, y) = P_{CHSH \geq 2}(a, b|x, y)\delta_{b,c}$$

Observational difference



Infeasibility with 1-layer scenario:

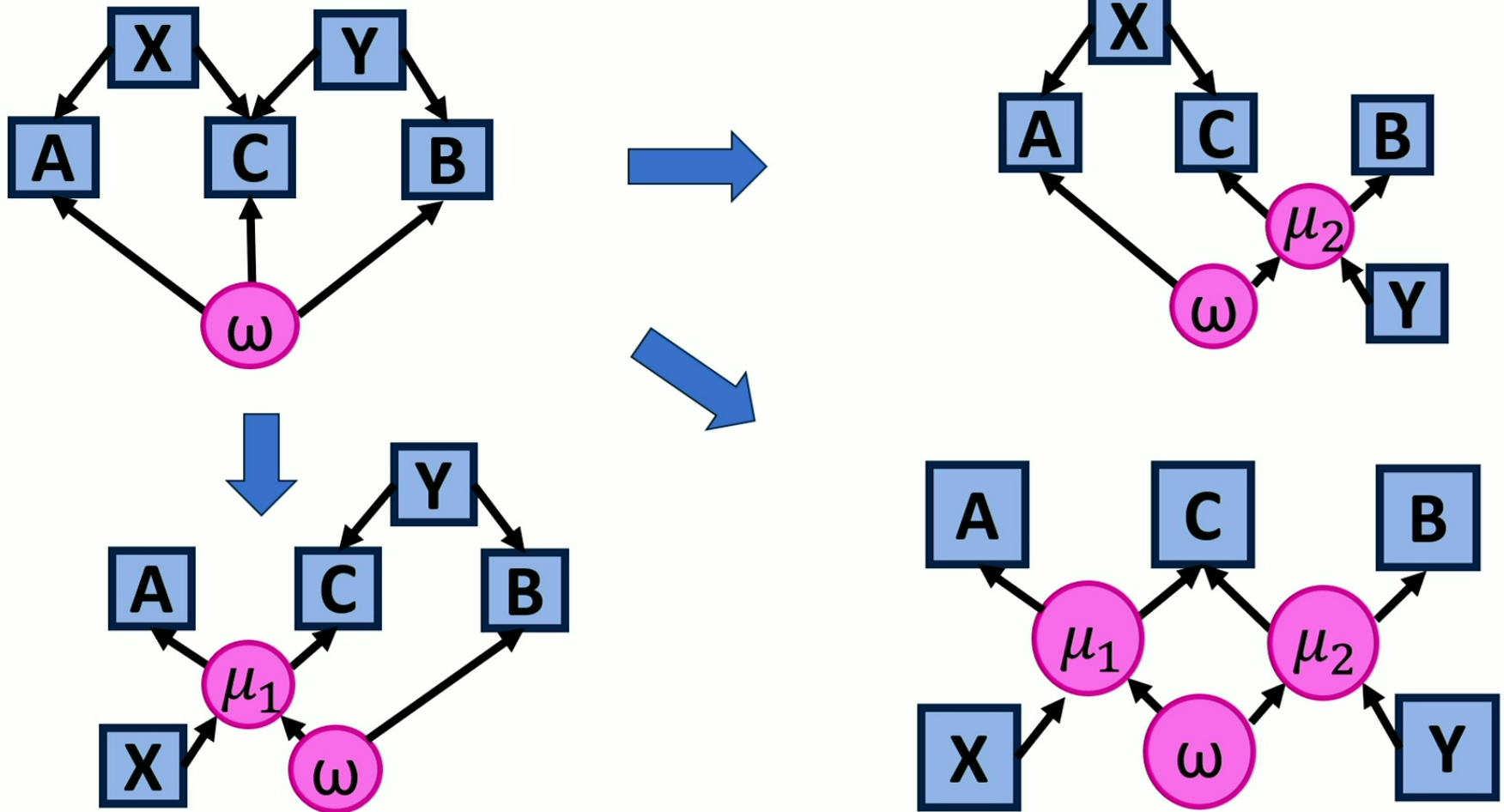
- Intervened DAG allowing for different values of y
- Require no-signalling and $P(a, b, c|x, y, y' = y) = P^*(a, b, c|x, y)$

$$CHSH_{(A,B|X,Y)} + 2\langle B_Y C_{XY} \rangle \leq 4$$

Goal

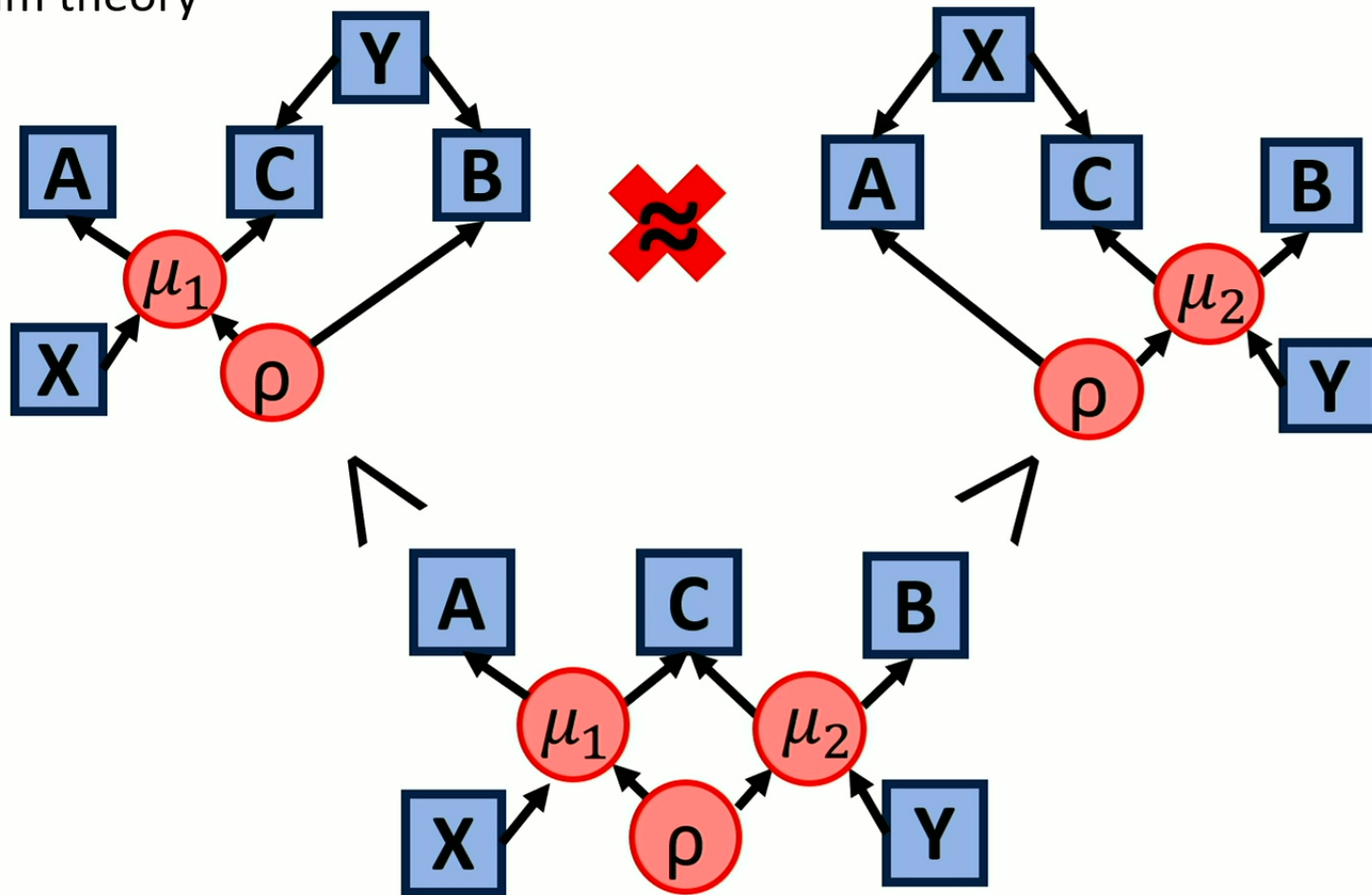
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Different multilayer scenarios



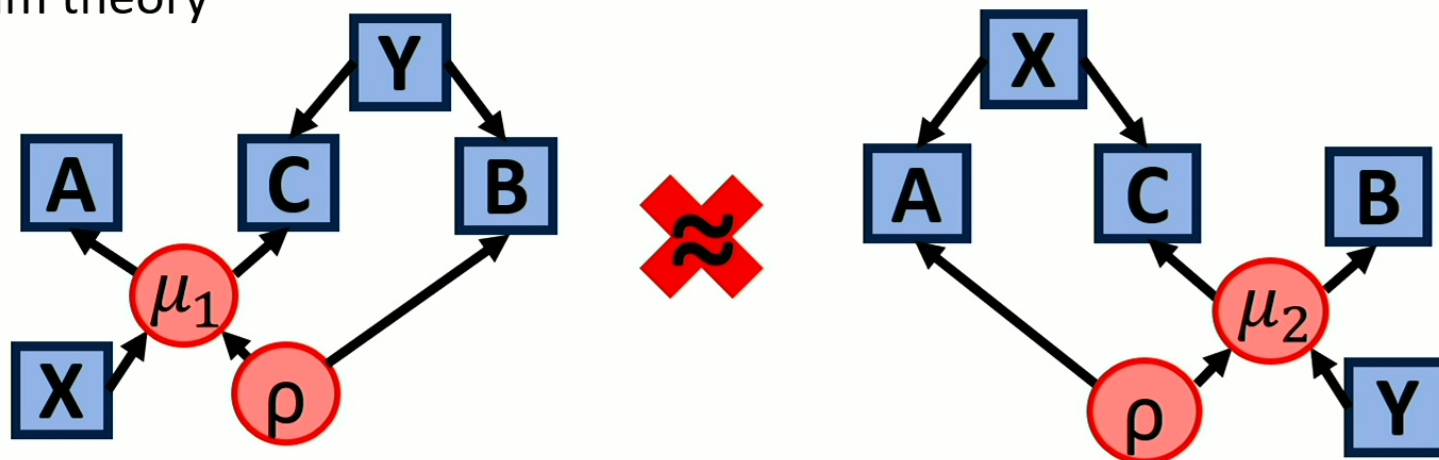
Different multilayer scenarios

Quantum theory



Different multilayer scenarios

Quantum theory

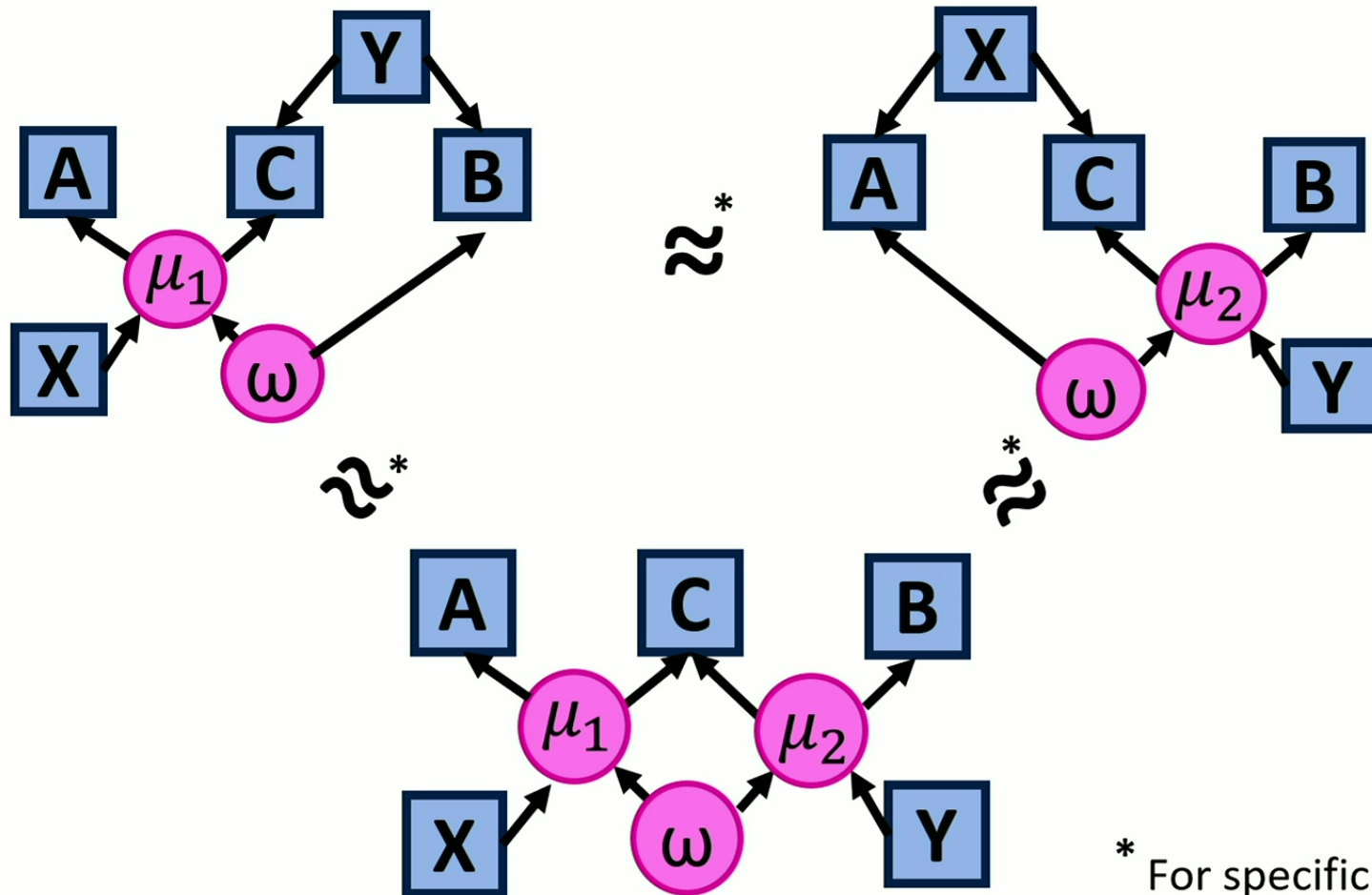


Proof sketch:

- Using previous protocol: $P^*(a, b, c|x, y) = P_{CHSH \geq 2}(a, b|x, y)\delta_{b,c}$ on the right-hand-side DAG
- Use NPA hierarchy to show the incompatibility of $P^*(a, b, c|x, y)$ with the left-hand-side DAG
- Analogously from left to right

Different multilayer scenarios

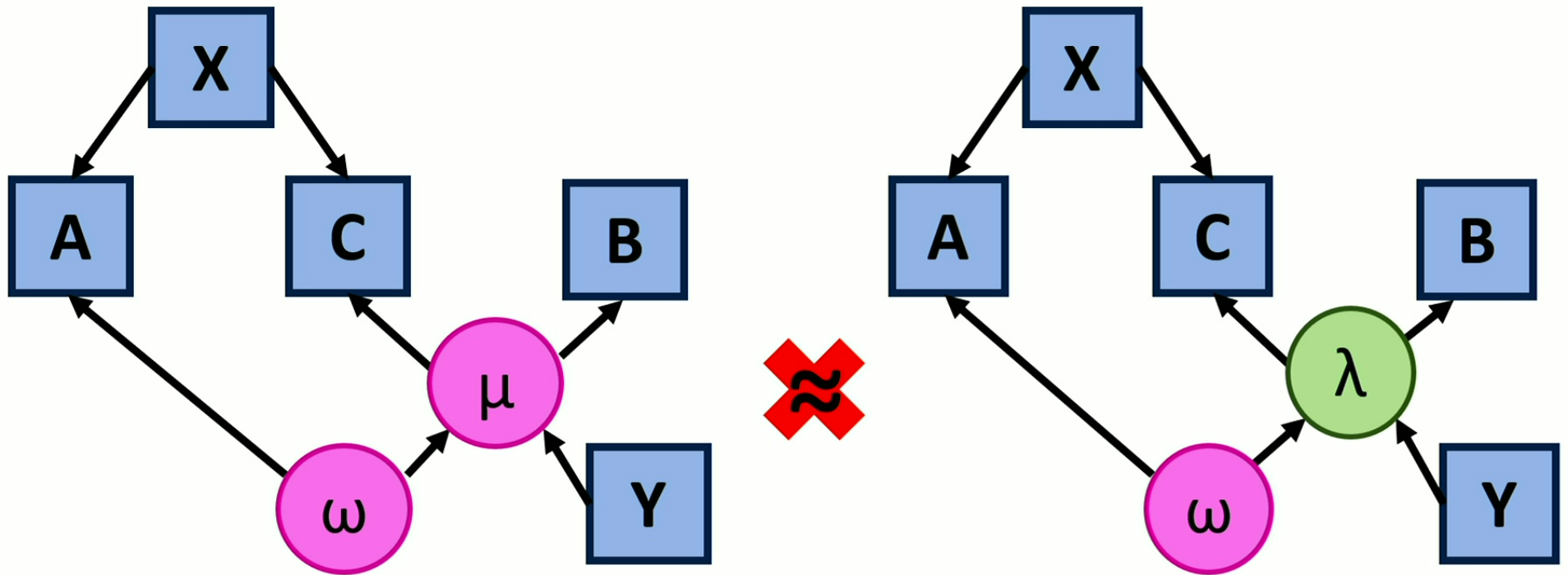
OPTs



Goal

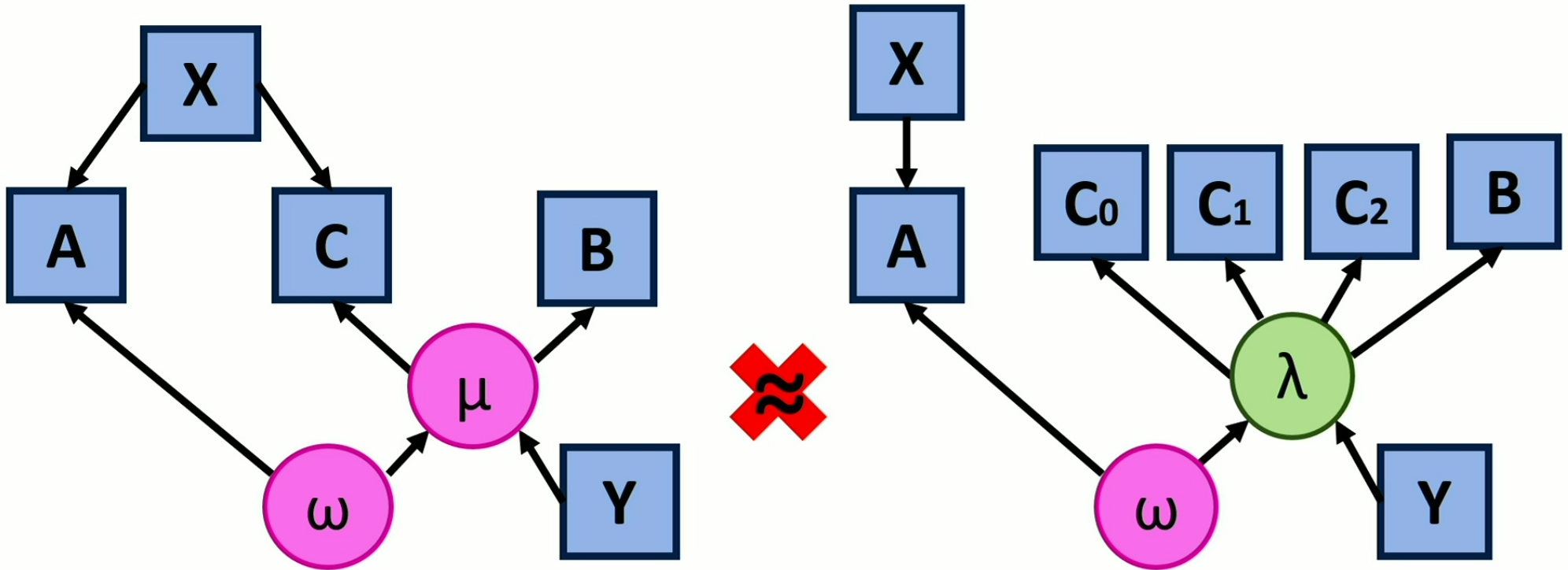
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Classicality vs non-classicality of intermediate latent



$$|A|=|B|=|C|=|X|=|Y|=3$$

Classicality vs non-classicality of intermediate latent



$$|A|=|B|=|C|=|X|=|Y|=3$$

Unpacking

$$p(a, b, c_i | x, y) = p(a, b, c | x = i, y)$$

Conclusions

- Causal inference is a precise framework for Bell nonlocality
- Multilayer scenarios were overlooked because of the origins of causal inference (exogenization procedure)
- Multilayer scenarios are observationally different of their 1-layer versions when introducing non-classical sources
- Different multilayer versions of the same 1-layer scenario may differ
- The classicality or non-classicality of the intermediate nodes is relevant



Different multilayer scenarios

Quantum theory

