Quantum Parton Shower with Kinematics

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August 21, 2024

QCHSC 24 @ Cairns

Based on PRA 2024 (arXiv: 2310.19881 [hep-ph])

Cristian W. Bauer
(Berkeley)

So Chigusa
(Berkeley → MIT)

(also Chigusa + MY 2204.12500
Bauer + de Jong + Nachman + Provasoli 1904.03196)

Today:

Quantum Veto Parton Shower

Today:

veto algorithm

Quantum Veto Parton Shower

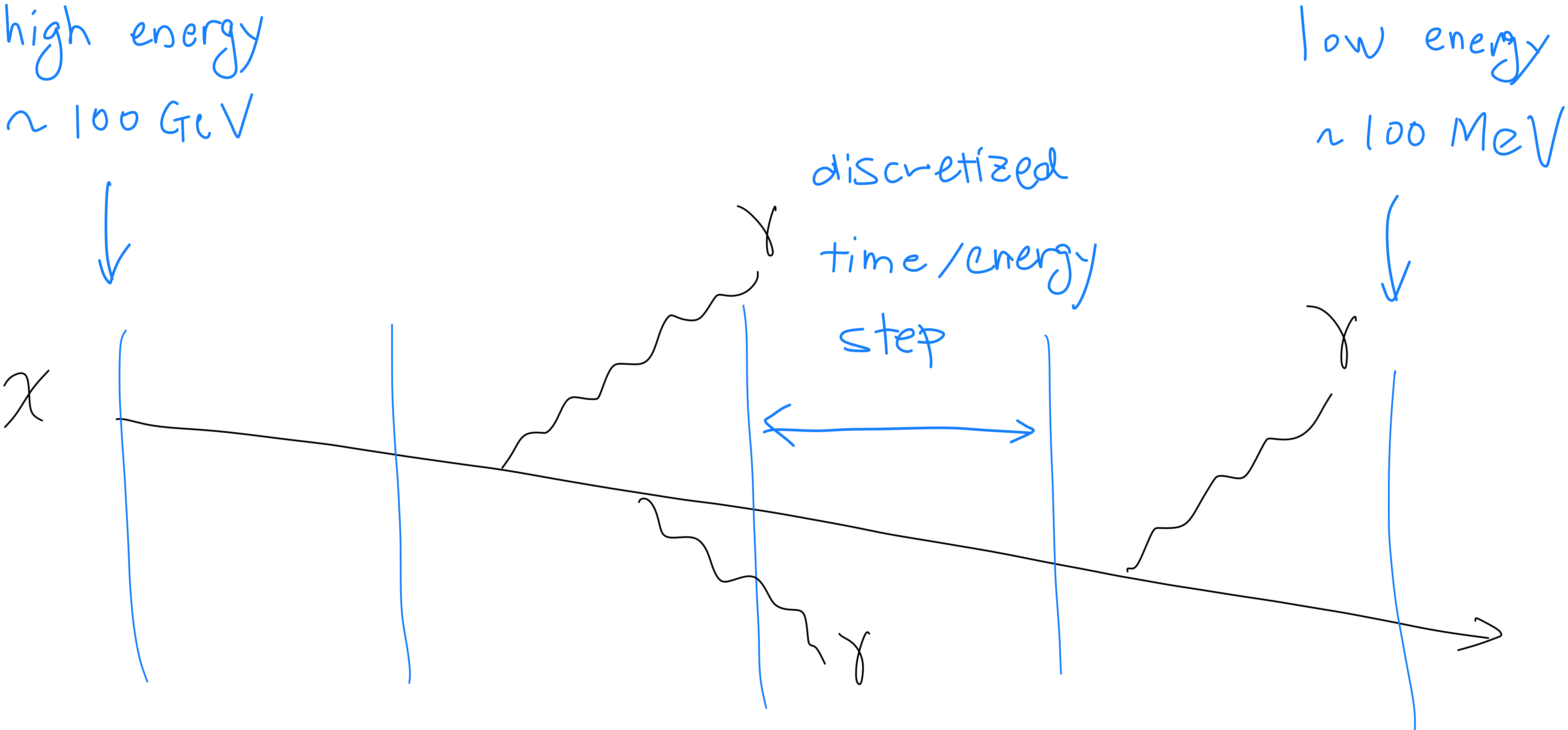
quantum / classical hybrid

QCD / BSM

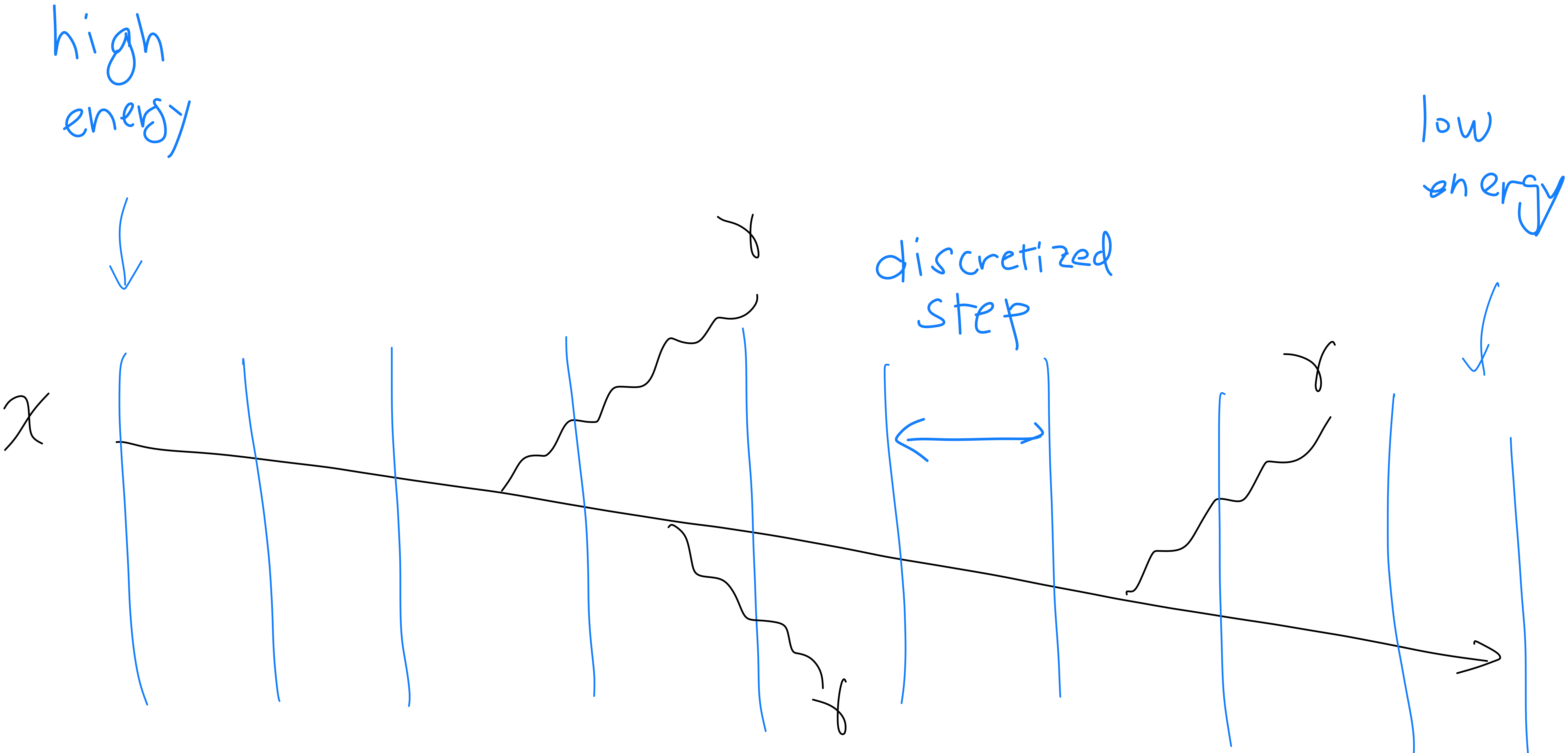
Porton Shower

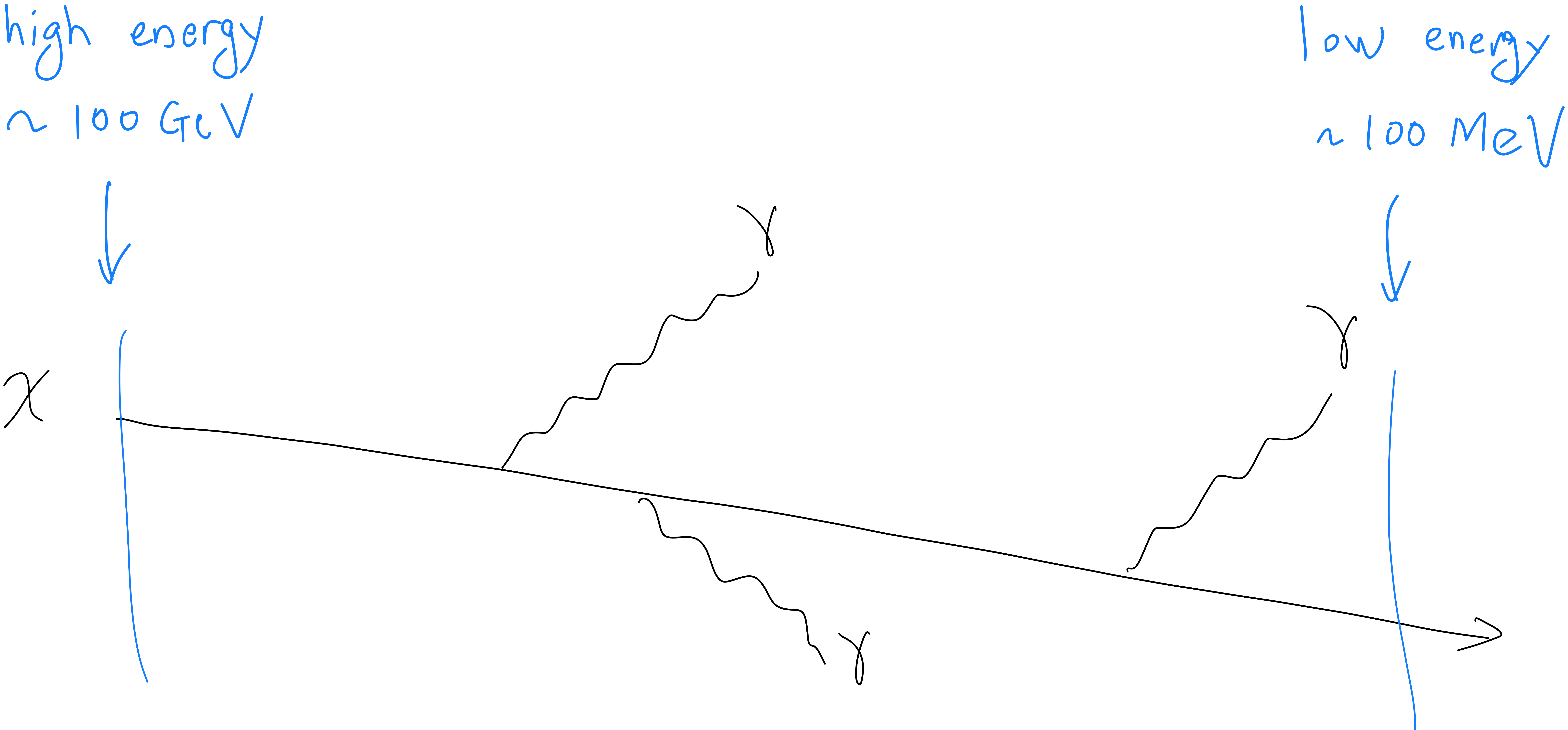

"dark photon"
emission
γ
χ
"dark
fermion"


"dark photon"
emission
γ
χ
γ
"dark
fermion"
γ

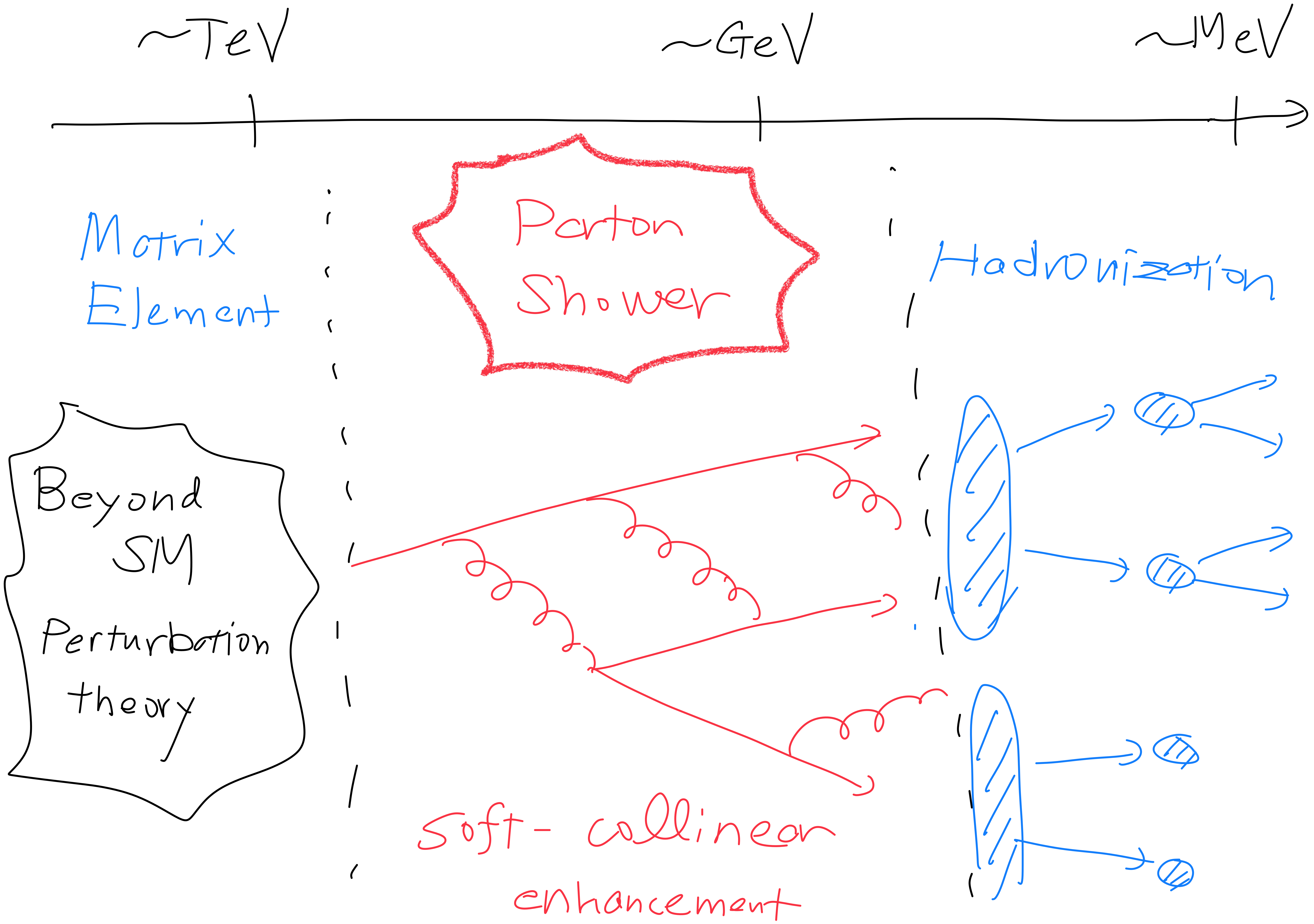


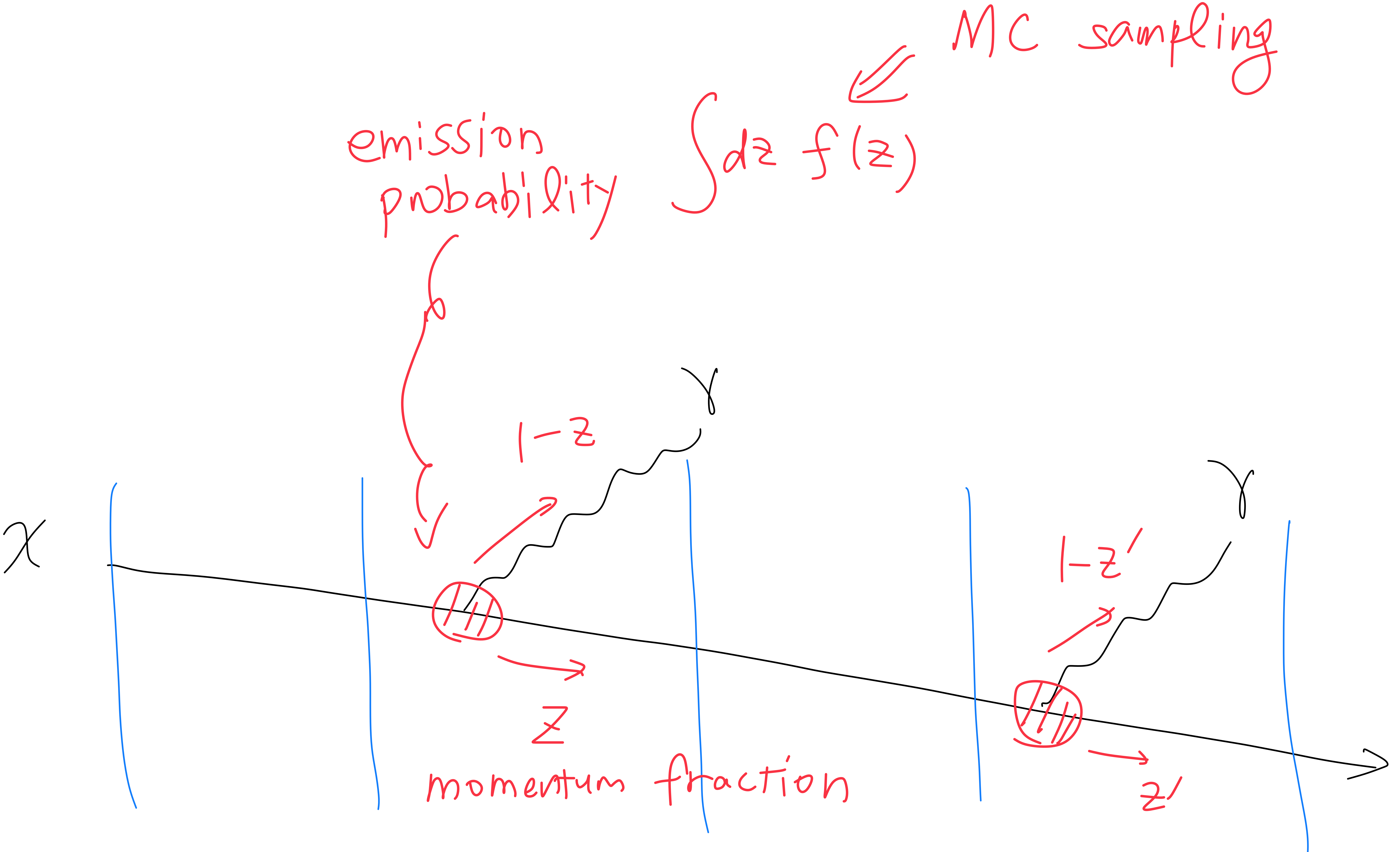
high energy
~ 100 GeV
low energy
~ 100 MeV
discretized
time/energy
step
χ
γ
γ
γ


high energy
low energy
discretized step
χ
γ
γ
γ


high energy
~ 100 GeV
low energy
~ 100 MeV
χ
γ
γ
γ

"EFT / Factorization"





MC sampling
emission probability
$\int dz\, f(z)$
x
γ
$1-z$
z
momentum fraction
γ
$1-z'$
z'

$\mathcal{O}(10{,}000)$ papers in PS

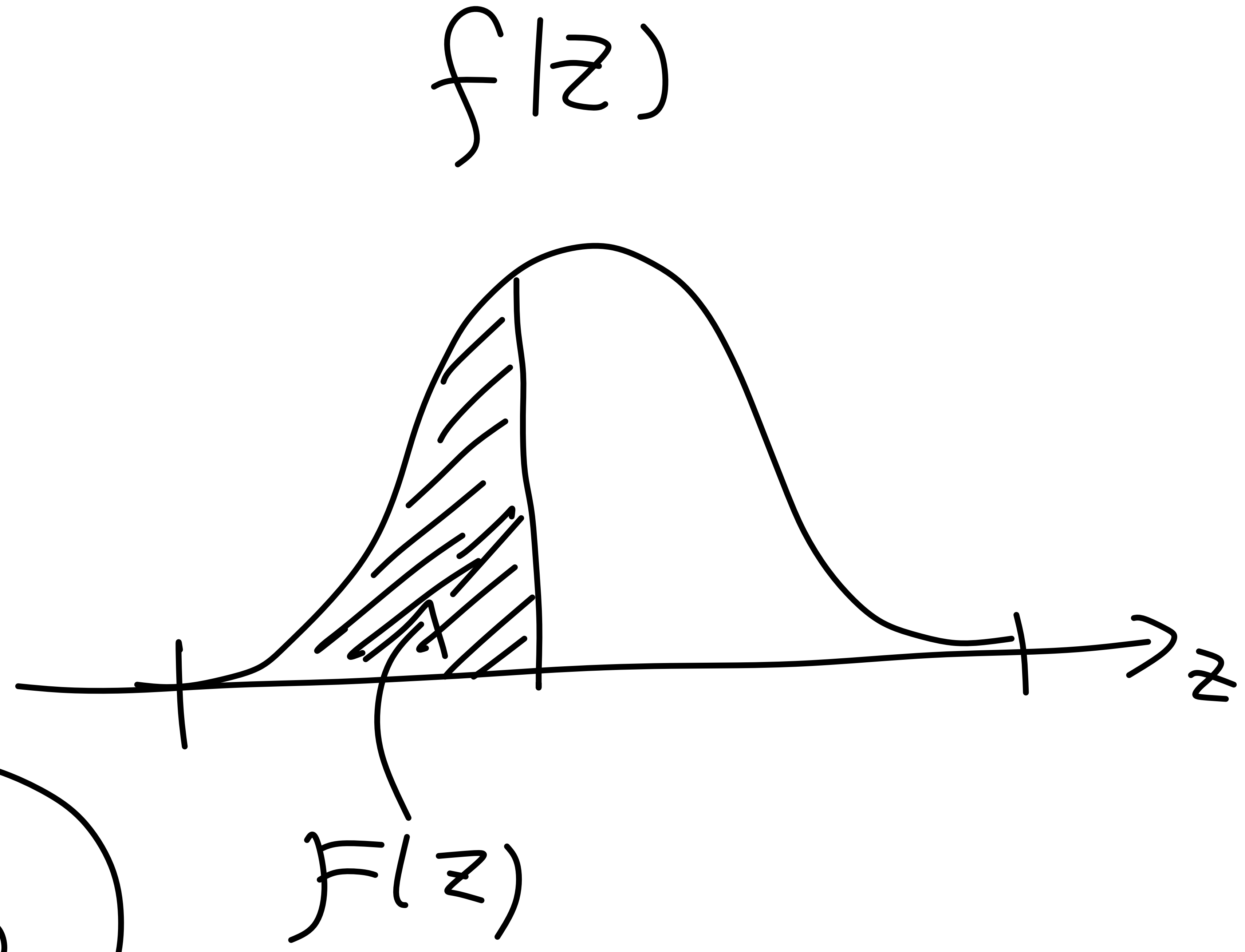
MC sampling

emission probability $\int dz\, f(z)$

Sample z by

$$z = F^{-1}(R)$$

(R: uniform distribution)

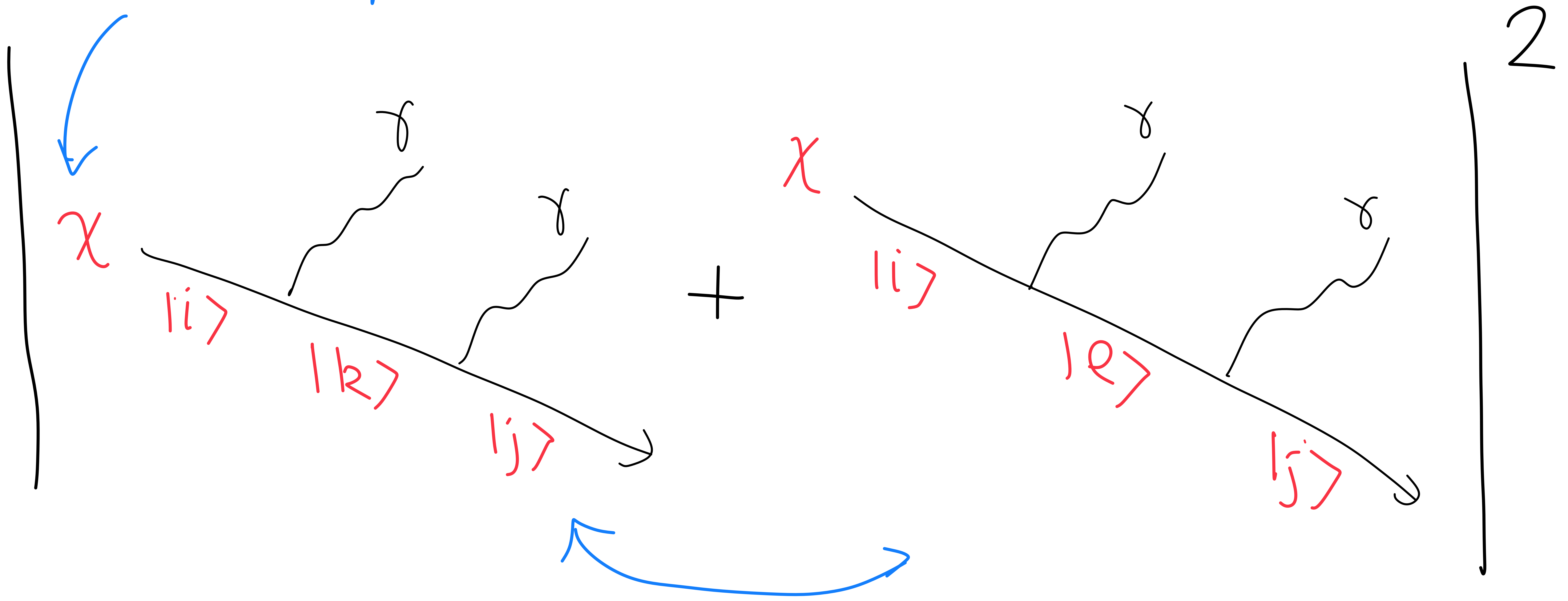


$$F(z) := \int^{z} dz'\, f(z') \quad \text{s.t.,} \quad f(z)\,dz = dR$$

Quantum Parton Shower

quantum interference

* multiple quantum states



cross term w/ $k \neq \ell$

Simplified BSM Model

$\mathcal{O}(100)$ papers

dark fermion $\chi_{i=1\sim N_f}$ (N_f flavors)

dark photon $U(1)$ A'_μ

$$\mathcal{L}_{dark} = \sum_i \bar{\chi}_i (i\not{\partial} - m_{\chi_i})\chi_i + \sum_{ij} g'_{ij} \bar{\chi}_i \not{A}' \chi_j \quad \leftarrow \text{off-diagonal}$$

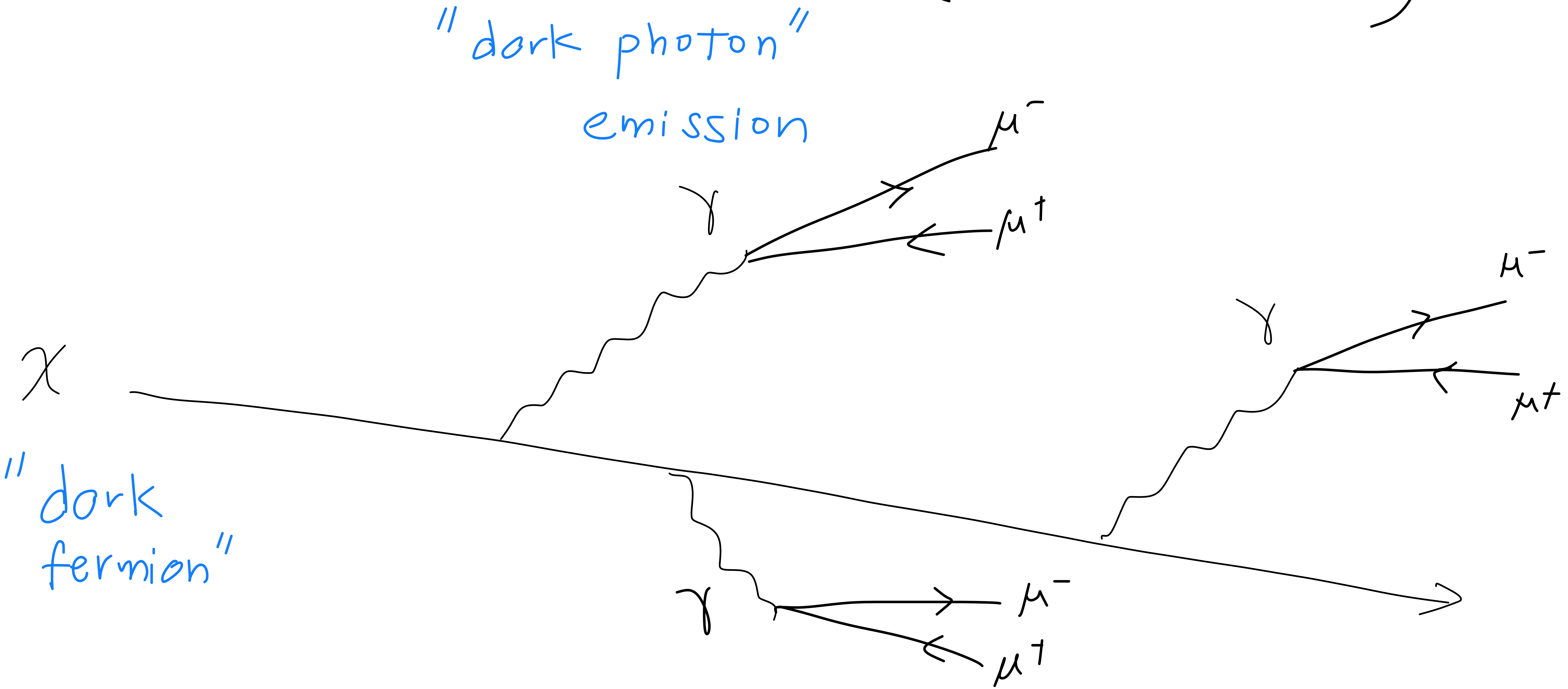
$$- \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{1}{2} m_{A'} A'_\mu A'_\mu$$

※ cosmological motivations

(dark-matter self-interaction / SIDM)

※ collider signatures

(2n - μ event)



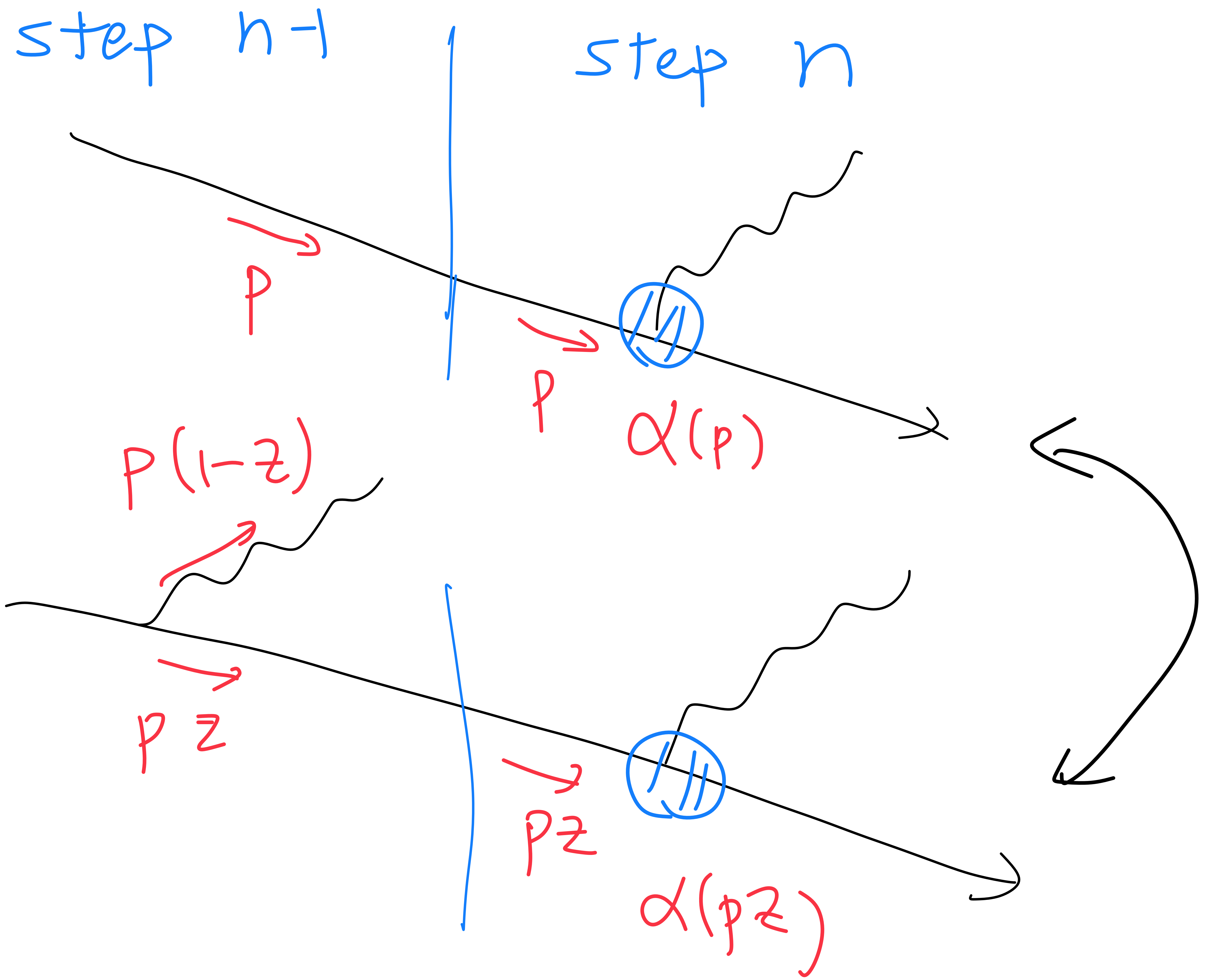
Quantum Matters! Simplified Analysis [Chigusa-MY '22]

$N_f = 1 \rightsquigarrow N_f = 2 \rightsquigarrow N_f = 4$

Huge enhancements for n large (2n-μ event)

More Complete Algorithm?

kinematics: requires quantum/classical hybrid



differences in history matters

$$\begin{pmatrix} \text{* quantum state } |q\rangle \\ \text{* classical data } \mathbb{C} \end{pmatrix}$$

($\mathbb{C}$ ← history)

↓

$$\begin{pmatrix} \text{parameter } z \\ \text{from prob. dist.} \\ f(q, \mathbb{C}, z) \ll 1 \end{pmatrix}$$

$$f_{tot}(q, \mathbb{C}) = \int dz \; f(q, \mathbb{C}, z) \quad \leftarrow \text{emission}$$

$$f_{no}(q, \mathbb{C}) = 1 - f_{tot}(q, \mathbb{C}) \quad \leftarrow \text{no emission}$$

* quantum state $|\psi\rangle$
* classical data $\mathbb{C}$ ← history

↓

parameter z from prob. dist. $f(\psi, \mathbb{C}, z) \ll 1$ ⇝ sample z from $p(\mathbb{C}, z) = \sum_{\psi} \alpha_{\psi}^{2} f(\psi, \mathbb{C}, z)$

↑ exponentially-many terms!

$f_{tot}(\psi, \mathbb{C}) = \int dz\, f(\psi, \mathbb{C}, z)$ ← emission

$f_{no}(\psi, \mathbb{C}) = 1 - f_{tot}(\psi, \mathbb{C})$ ← no emission

* quantum state $|q\rangle$
* classical data $\mathbb{C}$ ← history

↓

parameter z from prob. dist. $f(q, \mathbb{C}, z) \ll 1$

⇝ sample z from $p(\mathbb{C}, z) = \sum_q \alpha_q^2 f(q, \mathbb{C}, z)$

(sum over q: exponentially-many terms!)

inverse needed for $P(\mathbb{C}, z) = \int^z dz' \, p(\mathbb{C}, z')$ (sum of prob. dist.)

$$f_{tot}(q, \mathbb{C}) = \int dz \, f(q, \mathbb{C}, z) \quad \leftarrow \text{emission}$$

$$f_{no}(q, \mathbb{C}) = 1 - f_{tot}(q, \mathbb{C}) \quad \leftarrow \text{no emission}$$

Veto Algorithm

$$f^{over}(\mathbb{C}, z) \geq f(\mathfrak{q}, \mathbb{C}, z) \quad \forall \mathfrak{q}$$

Veto Algorithm

$$f^{over}(\Phi, z) \geq f(q, \Phi, z) \quad \forall q$$

↓

replace $p(\Phi, z) = \sum_q \alpha_q^2 f(q, \Phi, z)$

by $P_{over}(\Phi, z) = \sum_q \alpha_q^2 f_{over}(\Phi, z)$

$= f_{over}(\Phi, Z)$

w/ simple $\int P_{over}(\Phi, z)\, dz$

Veto Algorithm

$$f^{over}(\Phi, z) \geq f(q, \Phi, z) \quad \forall q$$

replace $p(\Phi, z) = \sum_q \alpha_q^2 f(q, \Phi, z)$

by $P_{over}(\Phi, z) = \sum_q \alpha_q^2 f_{over}(\Phi, z)$

$= f_{over}(\Phi, z)$

w/ simple $\int P_{over}(\Phi, z)\, dz$

Veto

reject if

$$\frac{f(q, \Phi, z)}{f_{over}(\Phi, z)} < R$$

$R \in [0, 1]$

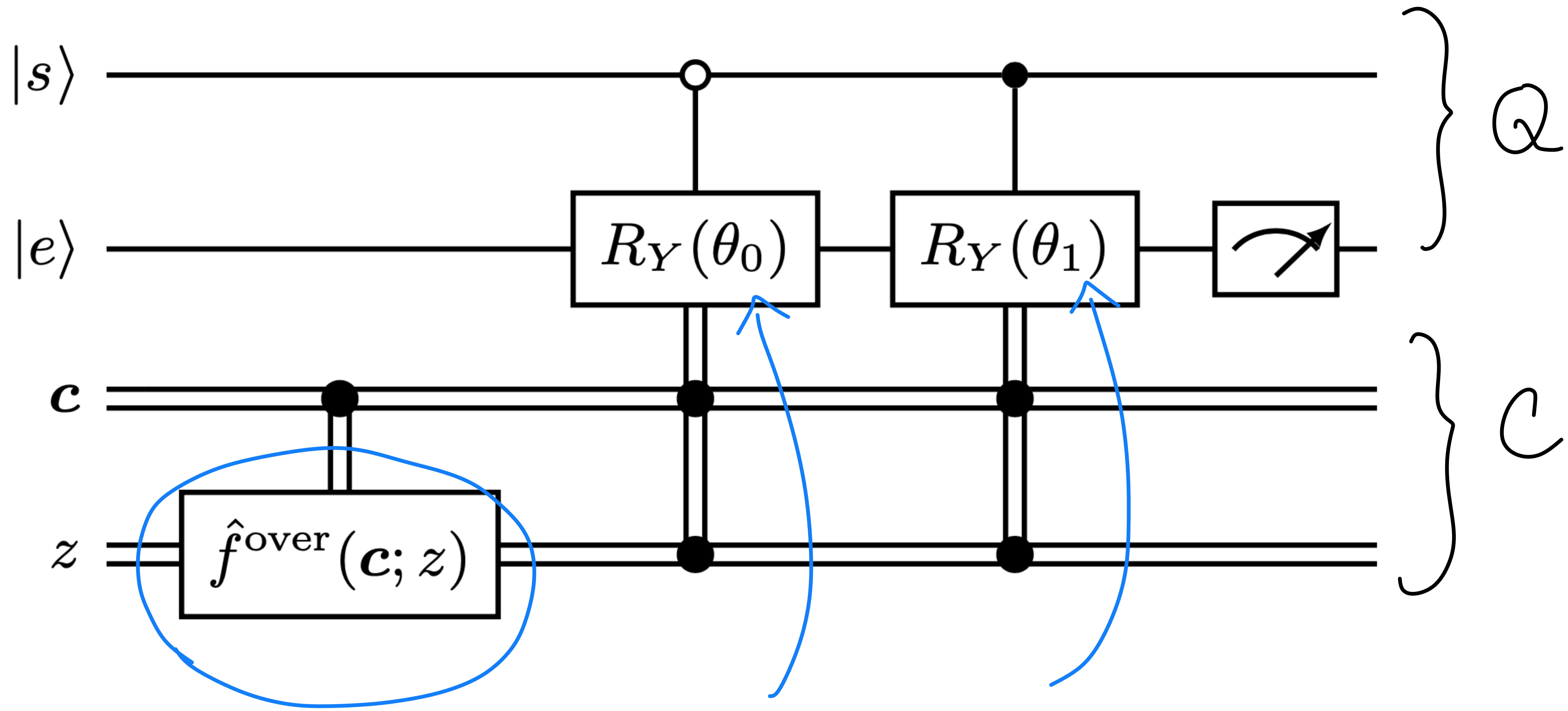
Classical veto dangerous due to quantum entanglement

⇒ implement veto inside quantum circuit

Quantum Circuit Implementation

state $\alpha_0|0\rangle + \alpha_1|1\rangle$ →

emission →

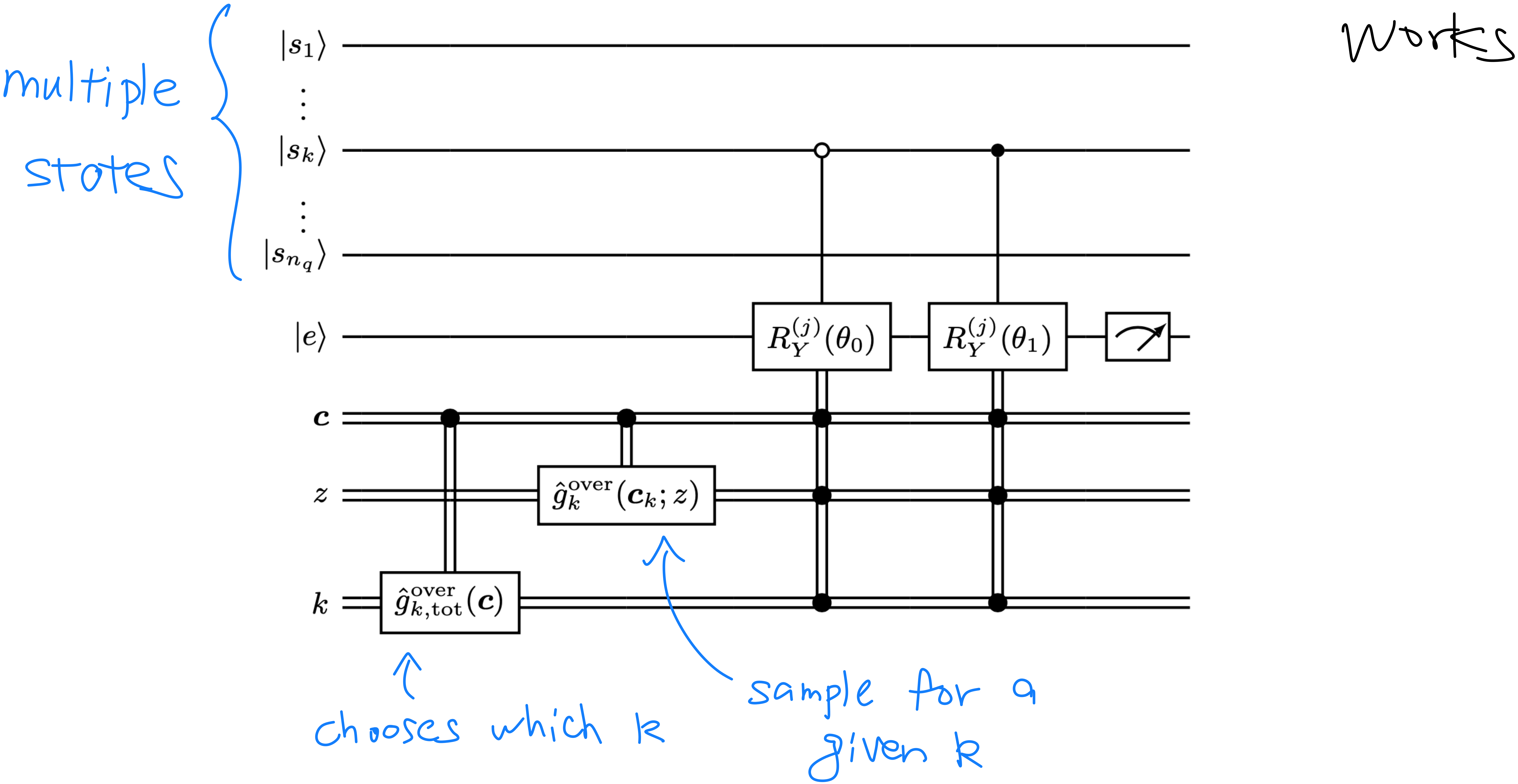


(works for $f \ll 1$)

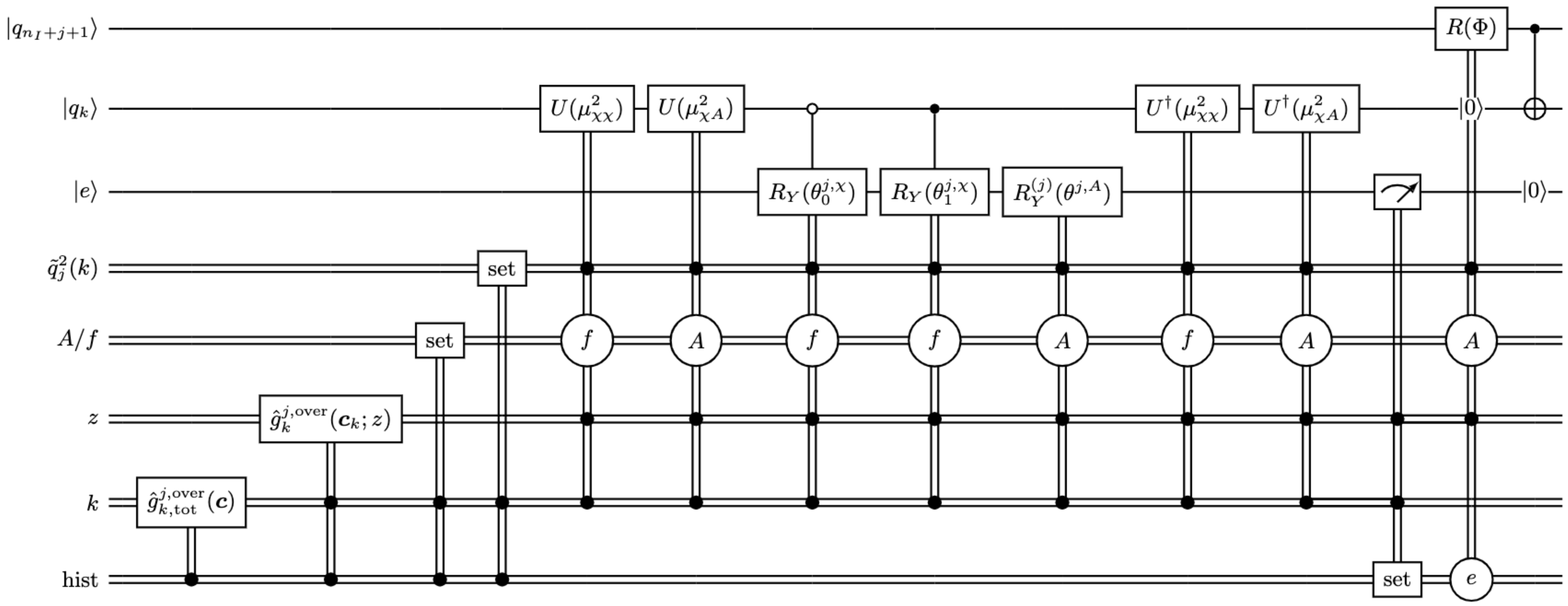
$$\left(\theta_q = 2 \arcsin \sqrt{\frac{f(q, c, z)}{\hat{f}_{over}(c, z)}} \right)$$

↑ normalized fover

* multiple MC steps / multiple q-state works



※: can be upgraded to full quantum PS

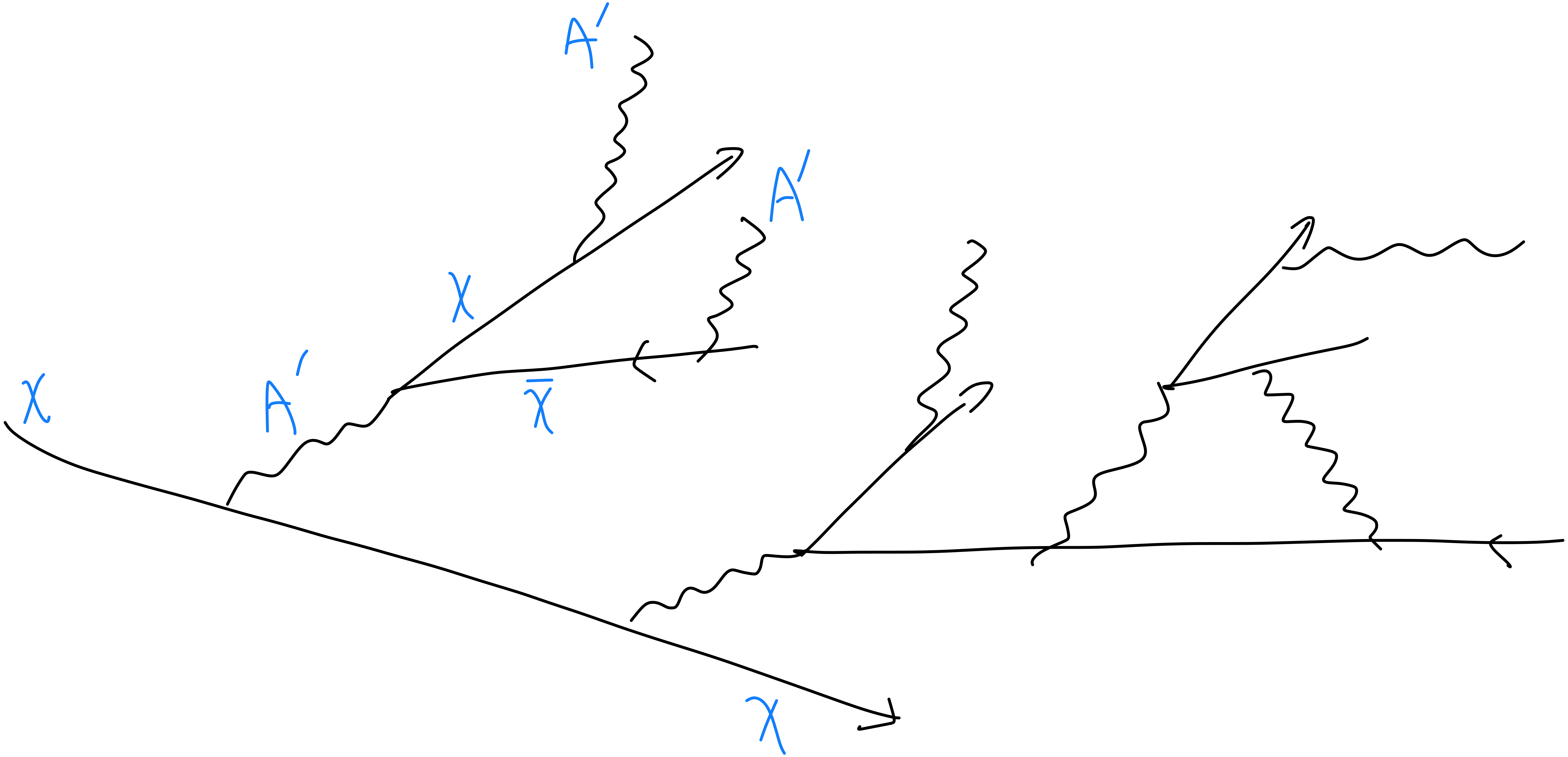


$\#(\text{qubit}) \sim (\log_2 N_f)\, N$

$\#\begin{pmatrix}\text{2Q} \\ \text{gates}\end{pmatrix} \sim \mathcal{O}(N_f^2 N)$

emission history is complicated in general

"f": $\chi \to \chi A'$ "A": $A' \to \chi \bar{\chi}$



* if $\mathcal{U}$ is a product state

classically simulated, with error $\sim N_{step}$

$$|S\rangle = \bigotimes_k \left(\sum_{q_k=0,1} \alpha_{k,q_k} |q_k\rangle \right)$$

$$p_k(z;c) = \sum_{q_k=0,1} |\alpha_{k,q_k}|^2 f(q_k, c_k; z)$$

↑ only 2 terms

Summary

* Quantum Veto Algorithm for Quantum Parton Shower

* Much more efficient than previous algorithms sometimes classically simulated

Q : More examples for

Quantum Vetos in MC ?

Q : Serious search in colliders ?

Q : Detailed model building ?

“Focus Week on Non-equilibrium Dynamics,”
Sep. 30 - Oct.4, 2024, Kavli IPMU, Tokyo, Japan

Organizers: H. Katsura, Y. Miao, M. Oshikawa, M. Yamazaki

KAVLI IPMU
KAVLI INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

“High-Energy Physics in the Quantum Era,”
Dec. 2-4, 2024, KEK, Japan

Organizers: D. Grabowska, R. Harnak, S. Hashimoto,
M. Honda, R. Kitano, M. Yamazaki

KEK
Insight through Accelerators.

“Exact Solvability and Quantum Information,”
Aug. 4-29, 2025, Les Houches, France

Organizers: S. Ouvry, T. Prosen, D. Serban, M. Yamazaki

ÉCOLE DE PHYSIQUE DES HOUCHES