Quantum Simulations of Dark Sector Showers

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Based on collaboration with So Chigusa (UC Berkeley)
arXiv: 2204.12500 [hep-ph]

cf. in progress with
So Chigusa and Christian Bauer (UC Berkeley)

Beyond Dark Matter?

Let's assume we have Dark Matter in the dark sector

Beyond Dark Matter?

Let's assume we have Dark Matter in the dark sector

Q: Dark sector beyond dark matter ??

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motivation:

self-interaction of DM (SIDM) via dark mediators

- galaxy core cusp problem
- positron excess in cosmic ray — PAMELA, AMS, Fermi-LAT
- galatic center GeV excess — Fermi-LAT

⋮

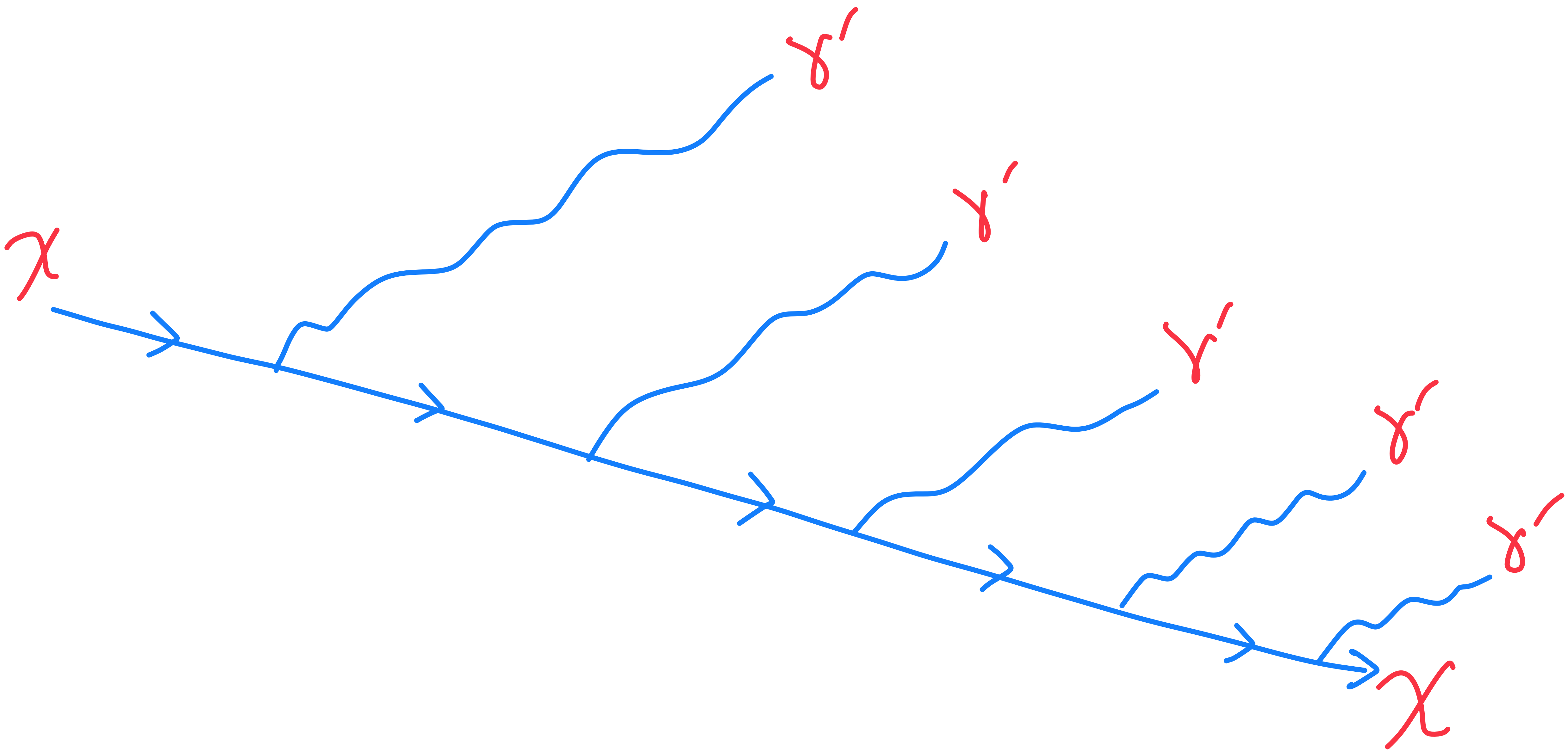
Today

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

dark photon $U(1)_D$ γ'

$$\mathcal{L}_{dark} = \sum_i \bar{\chi}_i (i\cancel{\partial} - m_{\chi_i})\chi_i + \sum_{ij} i g_{ij} \bar{\chi}_i \cancel{A}' \chi_j - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu$$

Dark sector jets ($N_f = 1$)



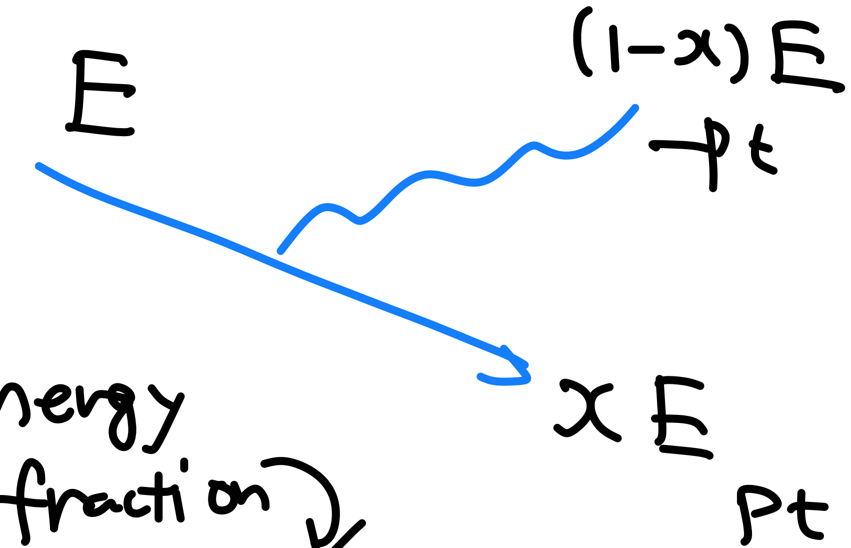
dramatic effects, e.g. @ H-L LHC?

[many papers]

standard : classical parton shower

[Pythia, Herwig, Sherpa, … cf. Krauss's talk]

emission probability density



$$R(t) = \int_{x_{min}(t,E)}^{x_{max}(t,E)} dx \, \frac{g^2}{8\pi} \, \frac{1}{t} \, P_{\chi \to \chi}(x, t)$$

energy fraction

Virtuality

$t \leftrightarrow p_t$

$$P_{\chi \to \chi} = \frac{1+x^2}{1-x} - \frac{2\left(m_\chi^2 + m_A^2\right)}{t}$$

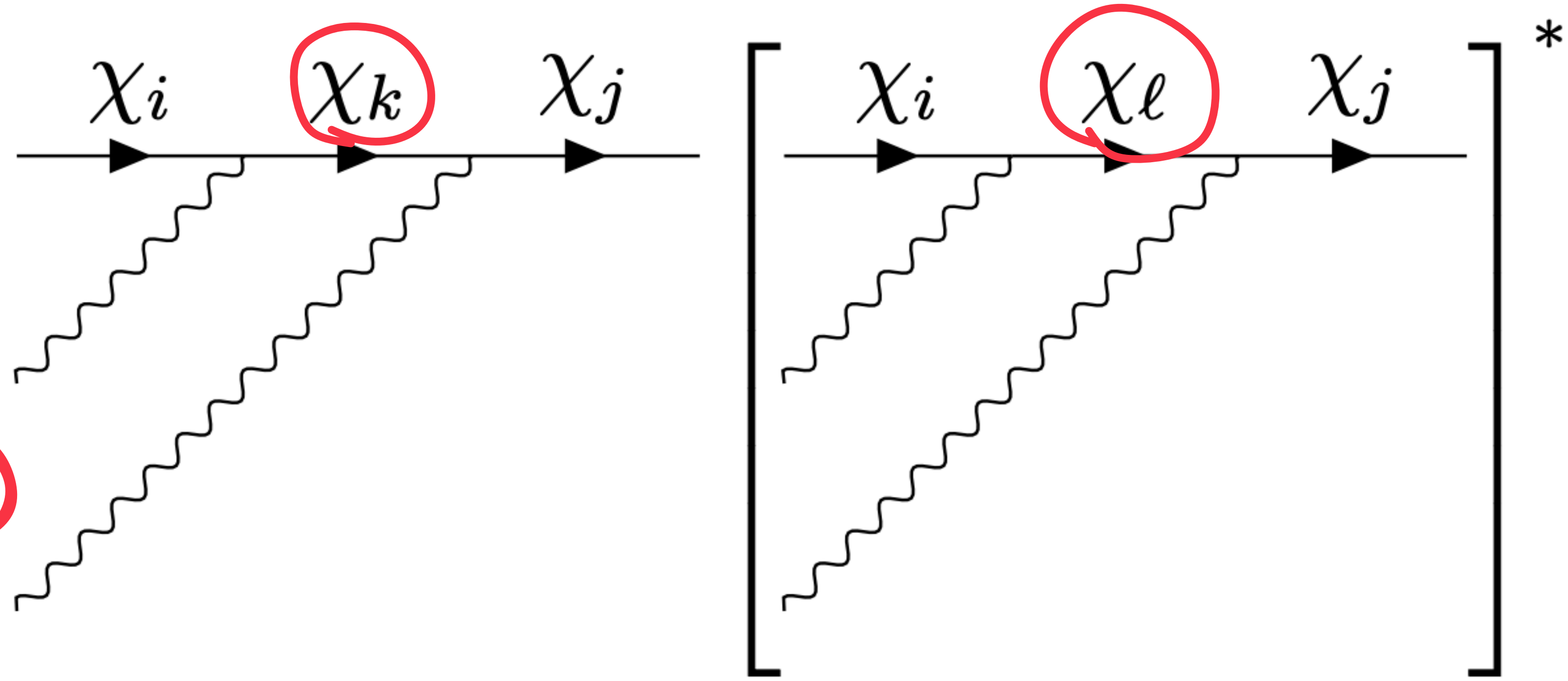
[cf. Chen-Ko-Li^2-Yokoya '18]

We can do MC for each t-step

However, quantum entanglement

among different flavors ($N_f > 1$)

$$\sum_{k \neq \ell}$$



$+ \text{c.c.}$,

NOT in classical parton shower

(except e.g. in large N_c approximation)

If the problem in quantum,
why not use quantum computer?

quantum algorithm for quantum PS

[see also Bauer, de Jong, Nachman, Provasoli ('19)
Bepari, Malik, Spannowsky, Williams ('20)]

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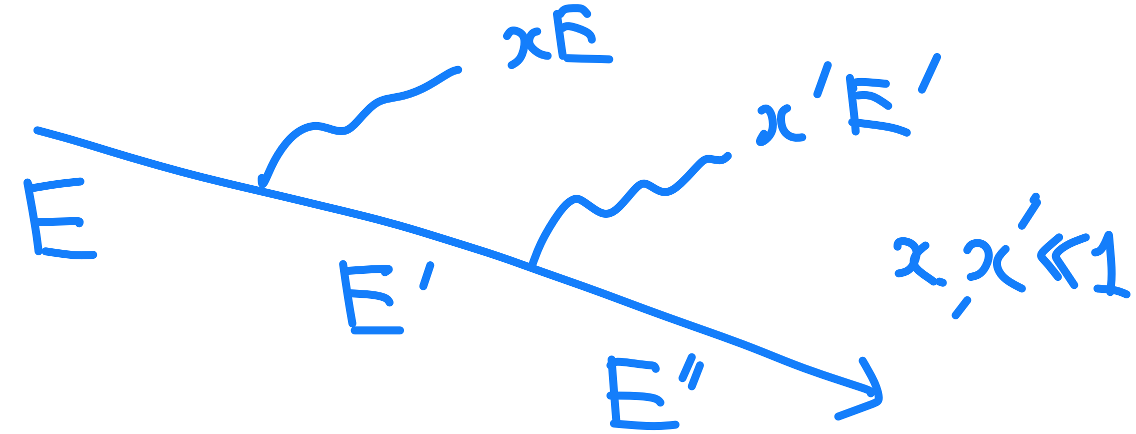
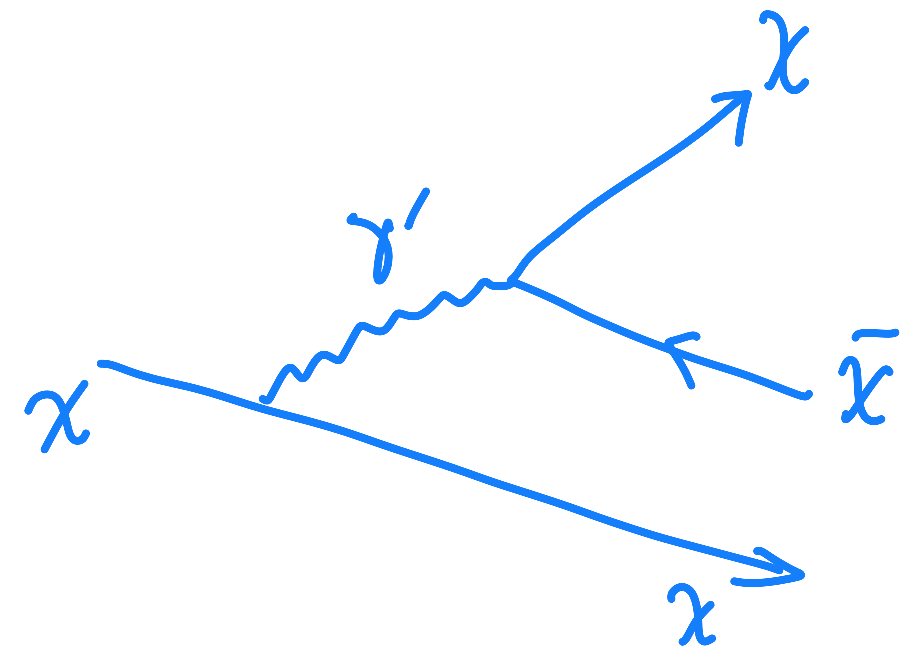
Today: simplifying assumptions

1. $E \sim E' \sim E'' \sim E_0$



2. $m_{A'} < 2 m_\chi$

otherwise

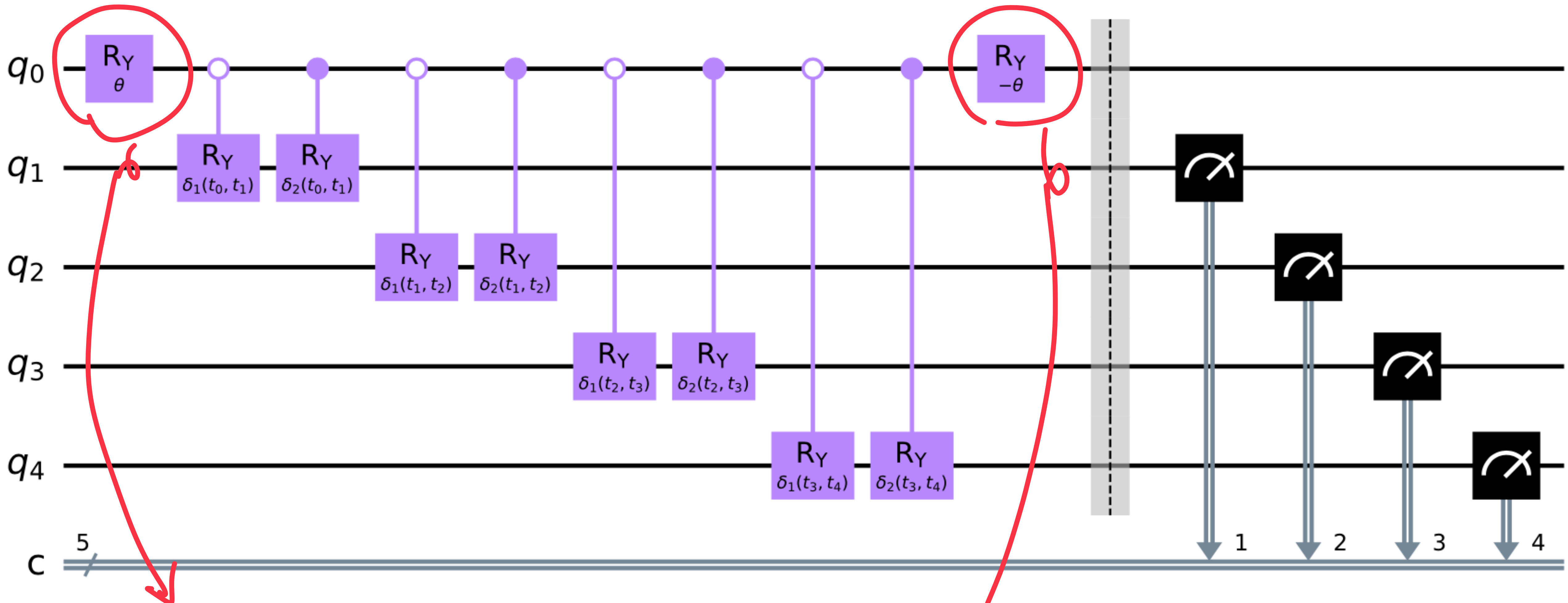


3. running of α' ignored

(e.g. $E_0 = 500$ GeV, $m_\chi = m_{A'} = 0.4$ GeV)

$\rightsquigarrow$ only # (dark photons)

$N_f = 2, \quad N_{step} = 4$



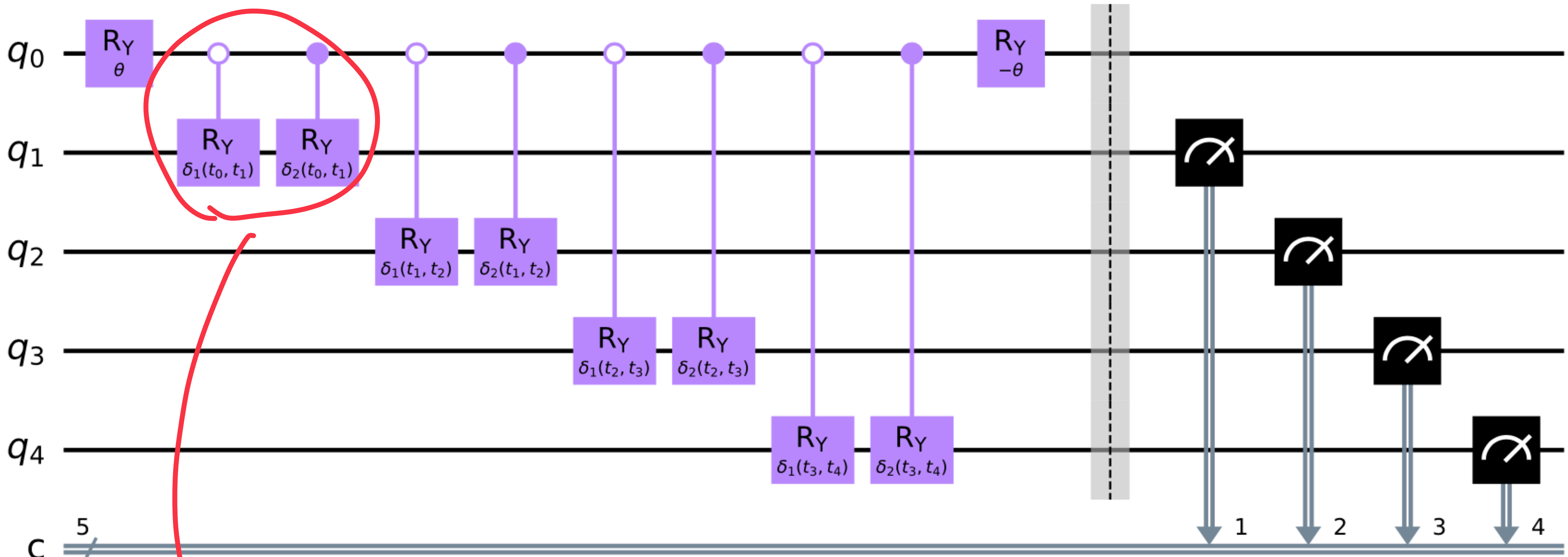
rotate the state into

gauge-diagonal basis

$$\begin{pmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{pmatrix} = R_Y(\theta)^\dagger \begin{pmatrix} g_1' & 0 \\ 0 & g_2' \end{pmatrix} R_Y(\theta)$$

$$R_Y(\theta) = \begin{pmatrix} \cos\frac{\theta}{2} & -\sin\theta/2 \\ \sin\frac{\theta}{2} & \cos\theta/2 \end{pmatrix}$$

$N_f = 2, \quad N_{step} = 4$



depending on the q_0

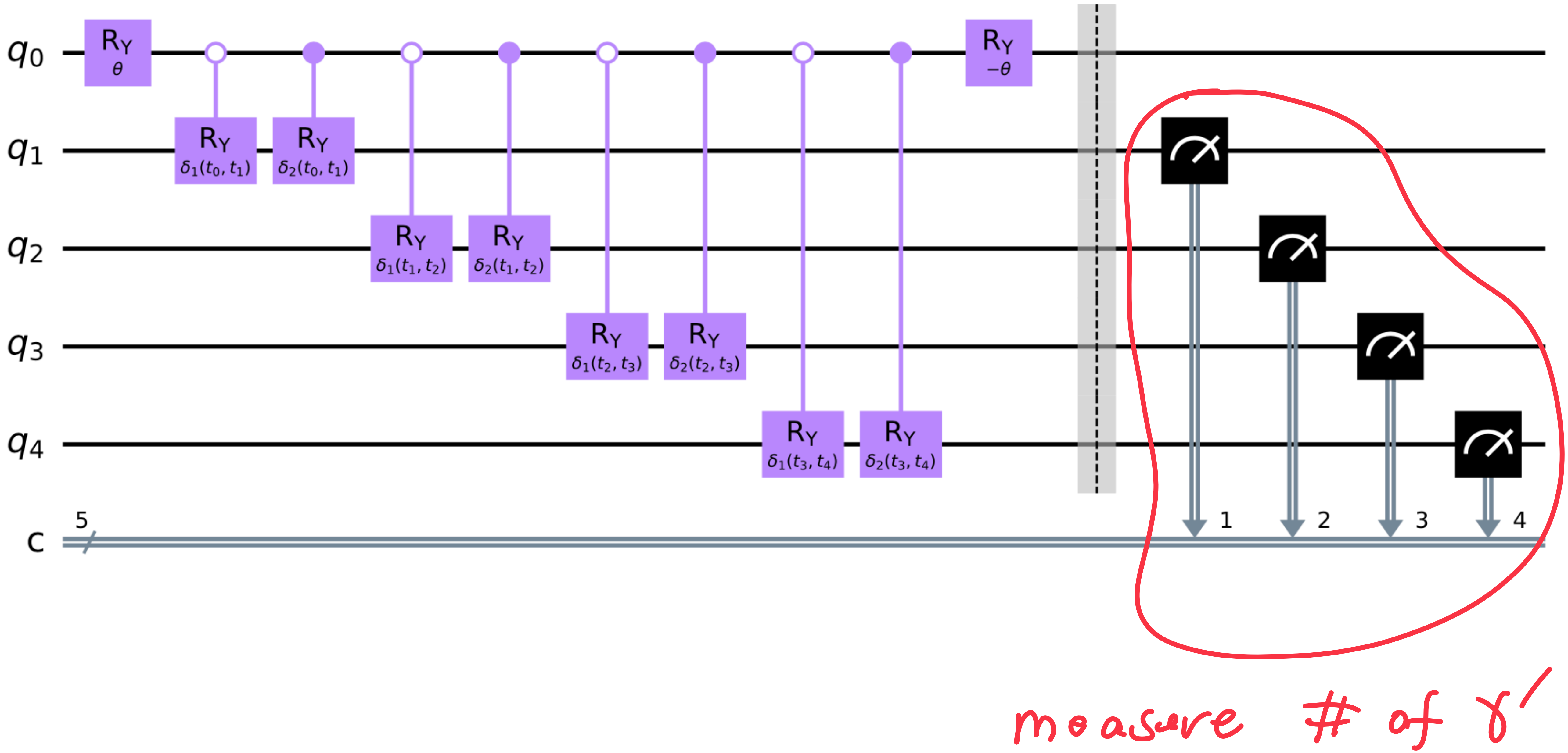
we emit particles

with different probabilities

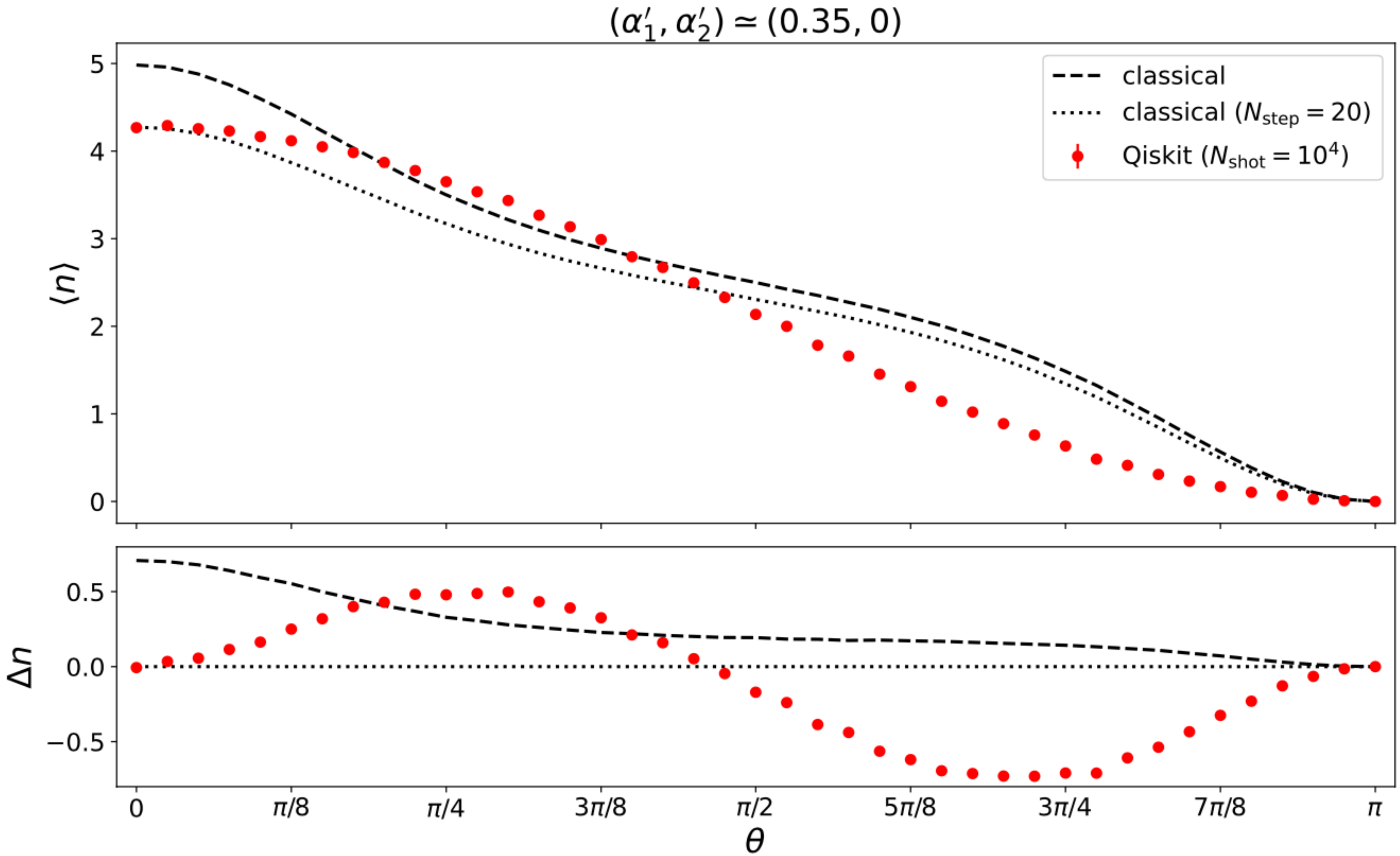
$$\tan\frac{\delta_i}{2} = \sqrt{\frac{1-\Delta_i}{\Delta_i}}$$

$$\Delta_i = \exp\left[-N_f \int R(t)\right]$$

$N_f = 2, \quad N_{step} = 4$

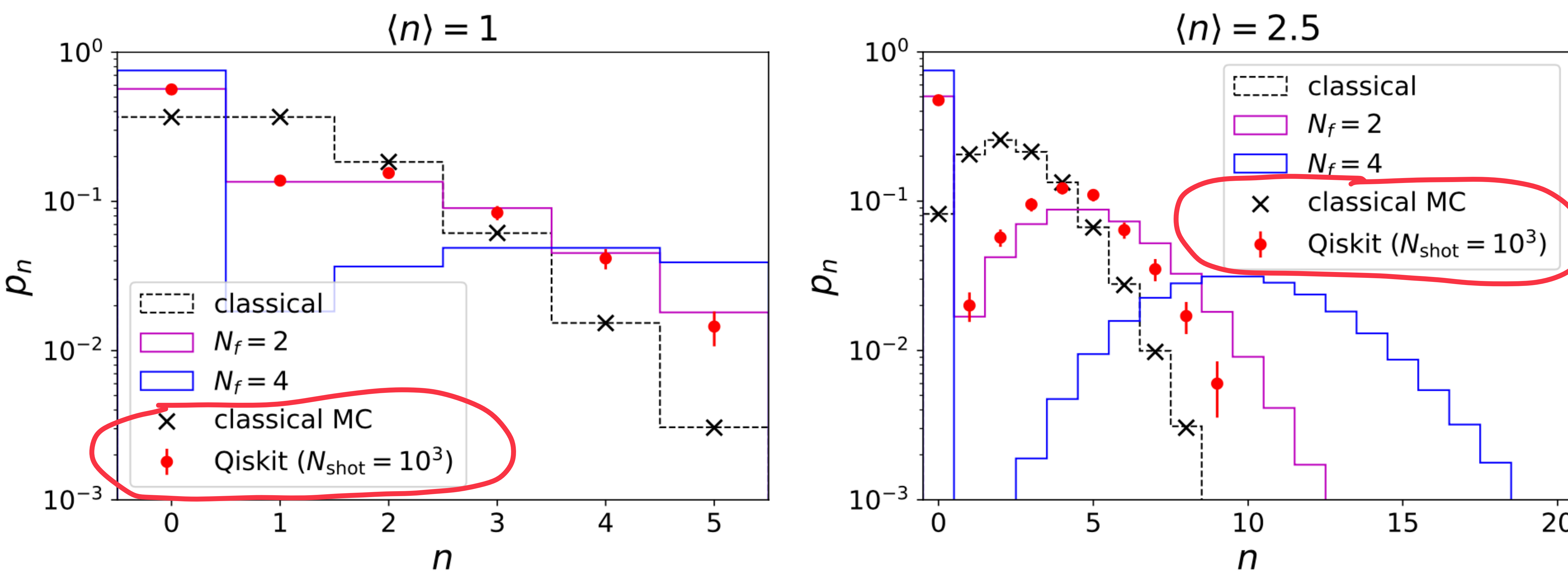


Results



$(\alpha_1', \alpha_2') \simeq (0.35, 0)$
classical
classical ($N_{\text{step}} = 20$)
Qiskit ($N_{\text{shot}} = 10^4$)
$\langle n \rangle$
Δn
5
4
3
2
1
0
0.5
0.0
−0.5
0
π/8
π/4
3π/8
π/2
5π/8
3π/4
7π/8
π
θ

Results



huge enhancements for p_n with n large!!

(but $\langle n \rangle$ the same for cases above)

Summary

- Dark Photon γ' + Dark Fermion χ

  $\rightsquigarrow$ Dark Sector Jets ☺

- Quantum Interference among flavors

  studied by quantum algorithm
  quantum simulator

  $\rightsquigarrow$ enhancement for
  many-γ' events ☺ ☺

Outlook

- Incorporate kinematics
- More detailed model building
- simulations and error mitigations on real quantum devices

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