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

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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
- ⋮

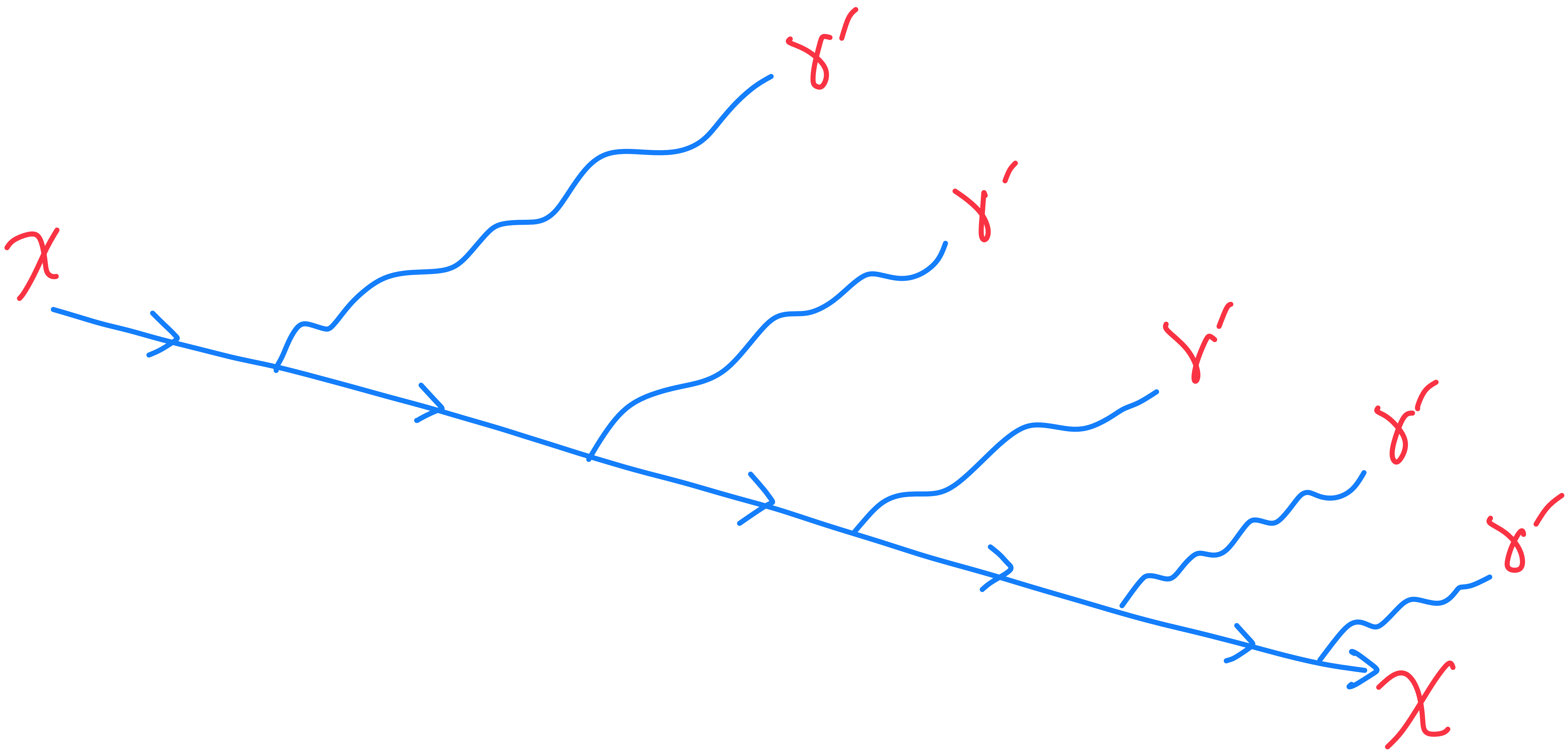
Today

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

dark photon $U(1)_D$ γ'

$$\mathcal{L}_{dark} = \sum_i \bar{\chi}_i (i\not{\partial} - m_{\chi_i})\chi_i + \sum_{ij} i g'_{ij} \bar{\chi}_i \not{A}' \chi_j - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu$$

Dark sector jets ($N_f = 1$)



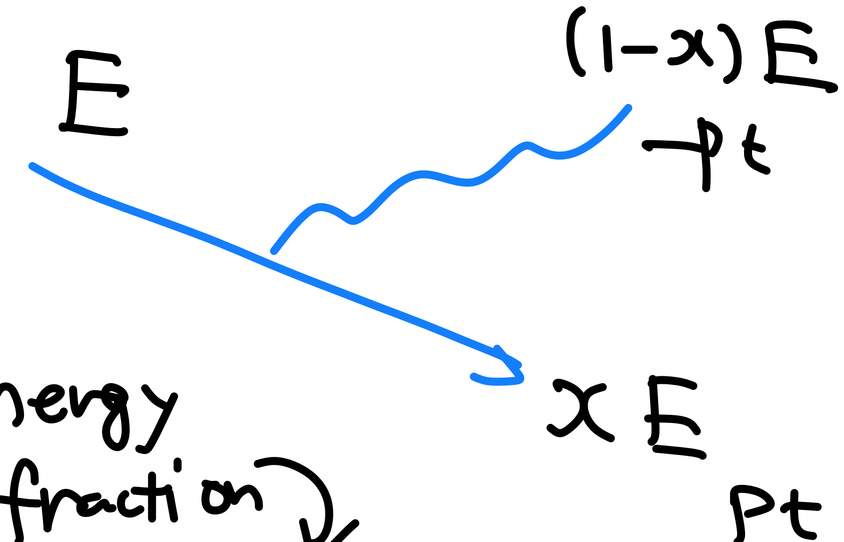
dramatic effects, e.g. @ H-L LHC?

[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 → x

virtuality → t

$$P_{\chi\to\chi} = \frac{1+x^2}{1-x} - \frac{2(m_\chi^2 + m_{A'}^2)}{t}$$

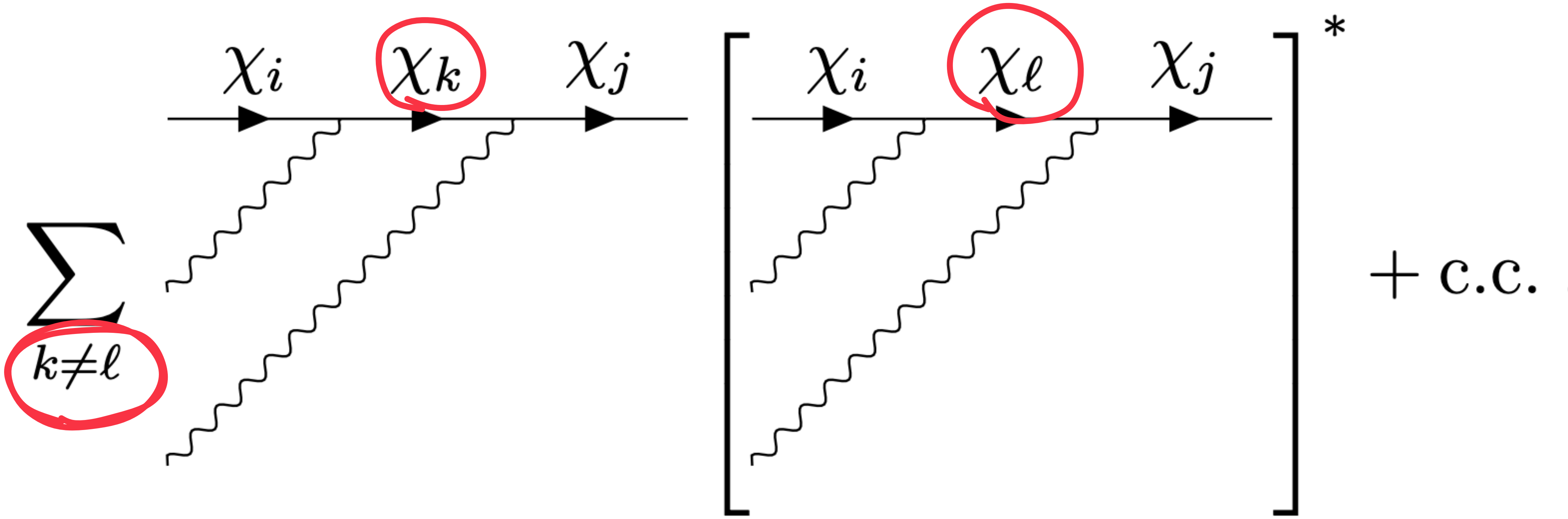
virtuality $t \leftrightarrow p_t$

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

We can do MC for each t-step

However, quantum interference

among different flavors ($N_f > 1$)



NOT in classical parton shower

(except e.g. in large N_c approximation)

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

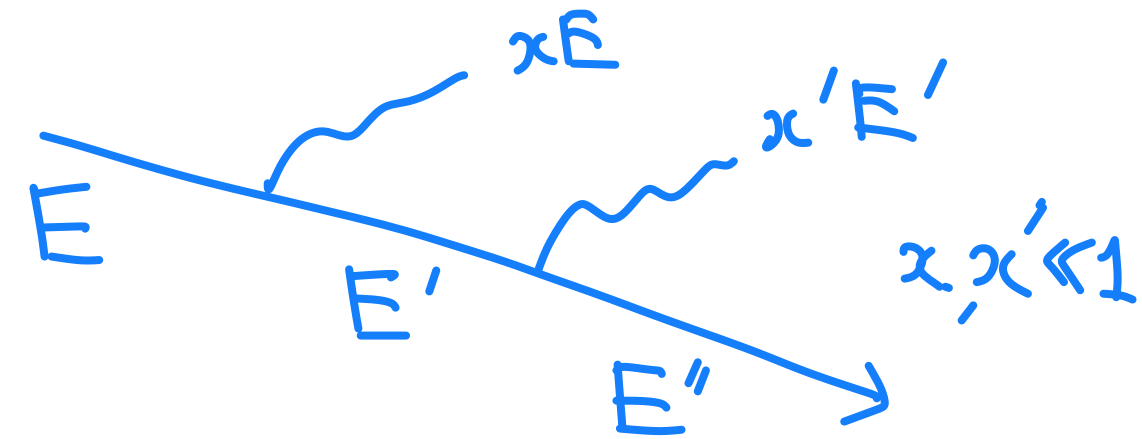
quantum algorithm for quantum PS

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

⋮

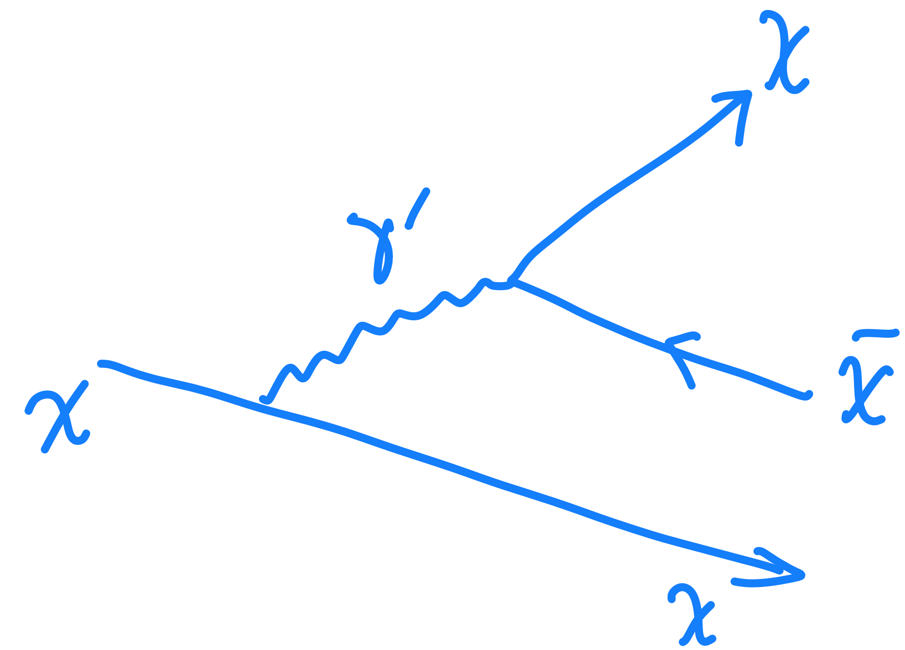
Today: simplifying assumptions

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



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

otherwise

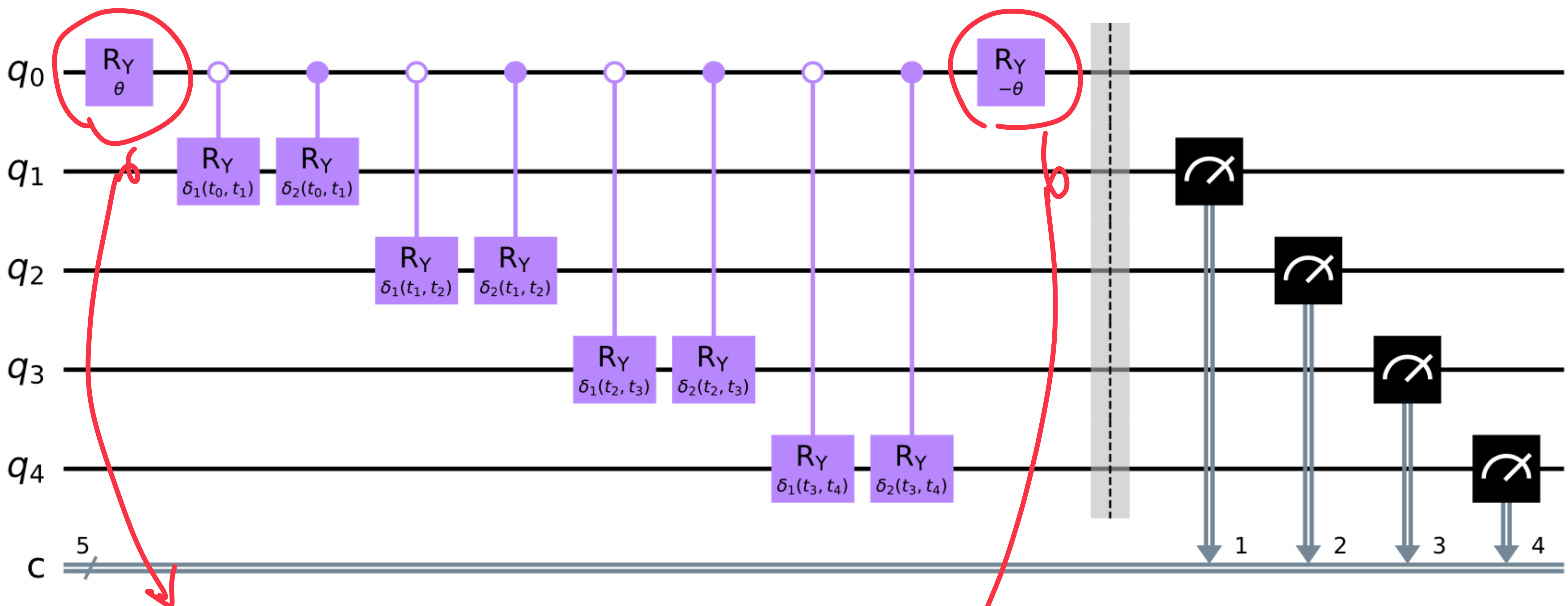


3. running of α' ignored

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

⇝ only # (dark photons)

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

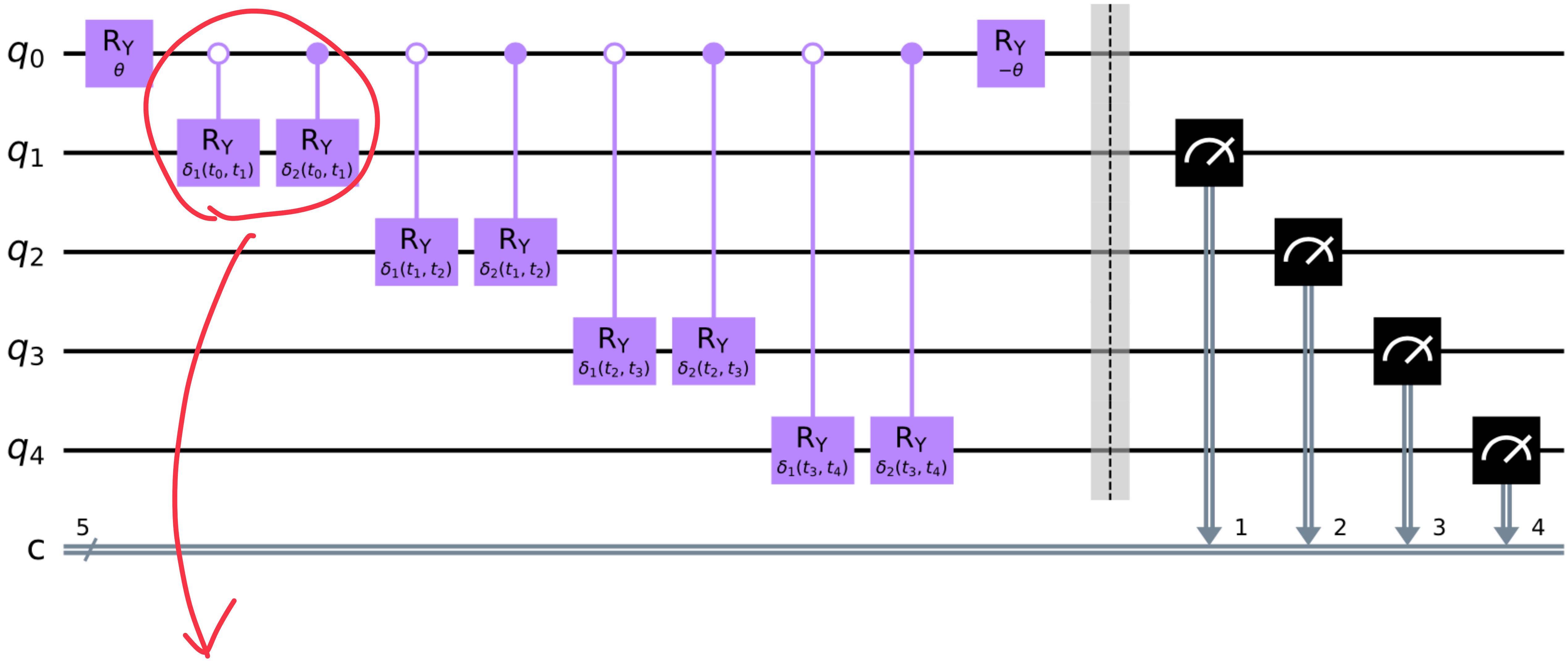


rotate the state into gouge-diagonal basis

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

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

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

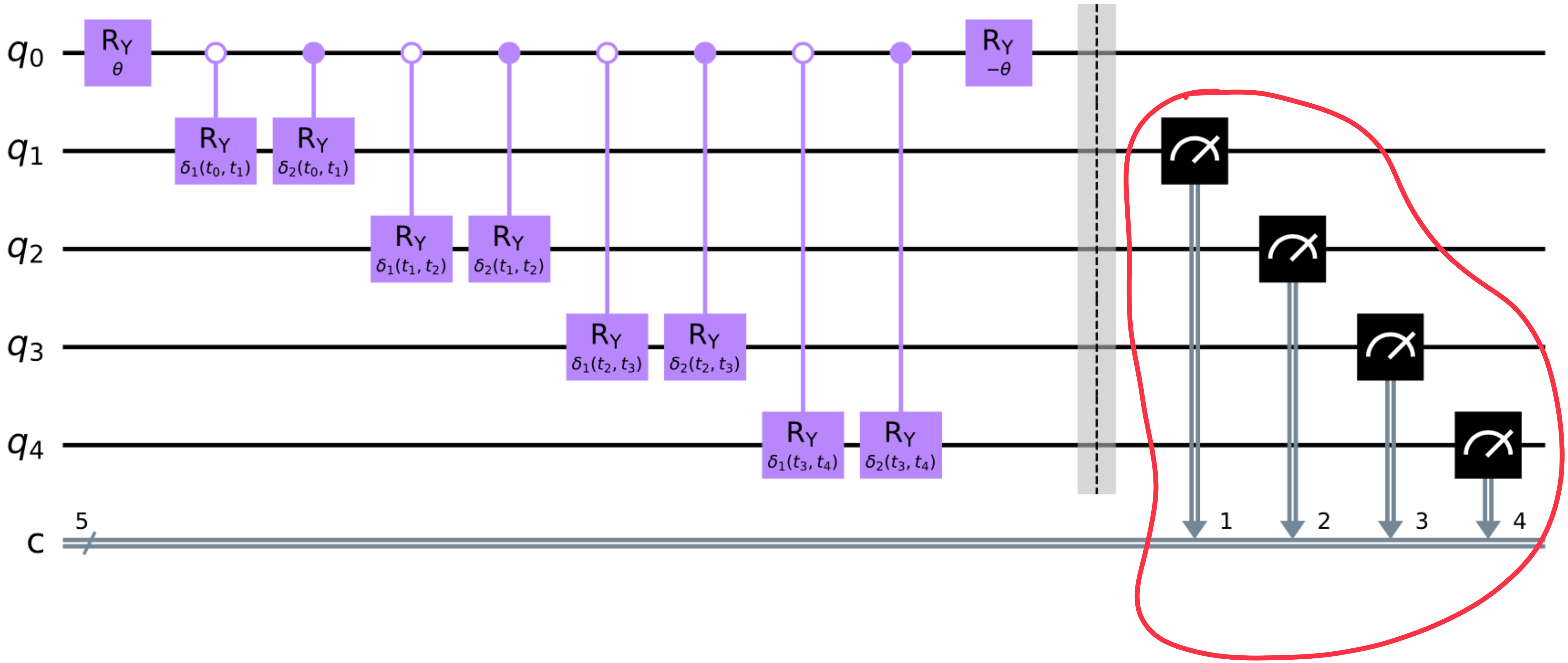


depending on the q_0
we emit particles
with different probabilities

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

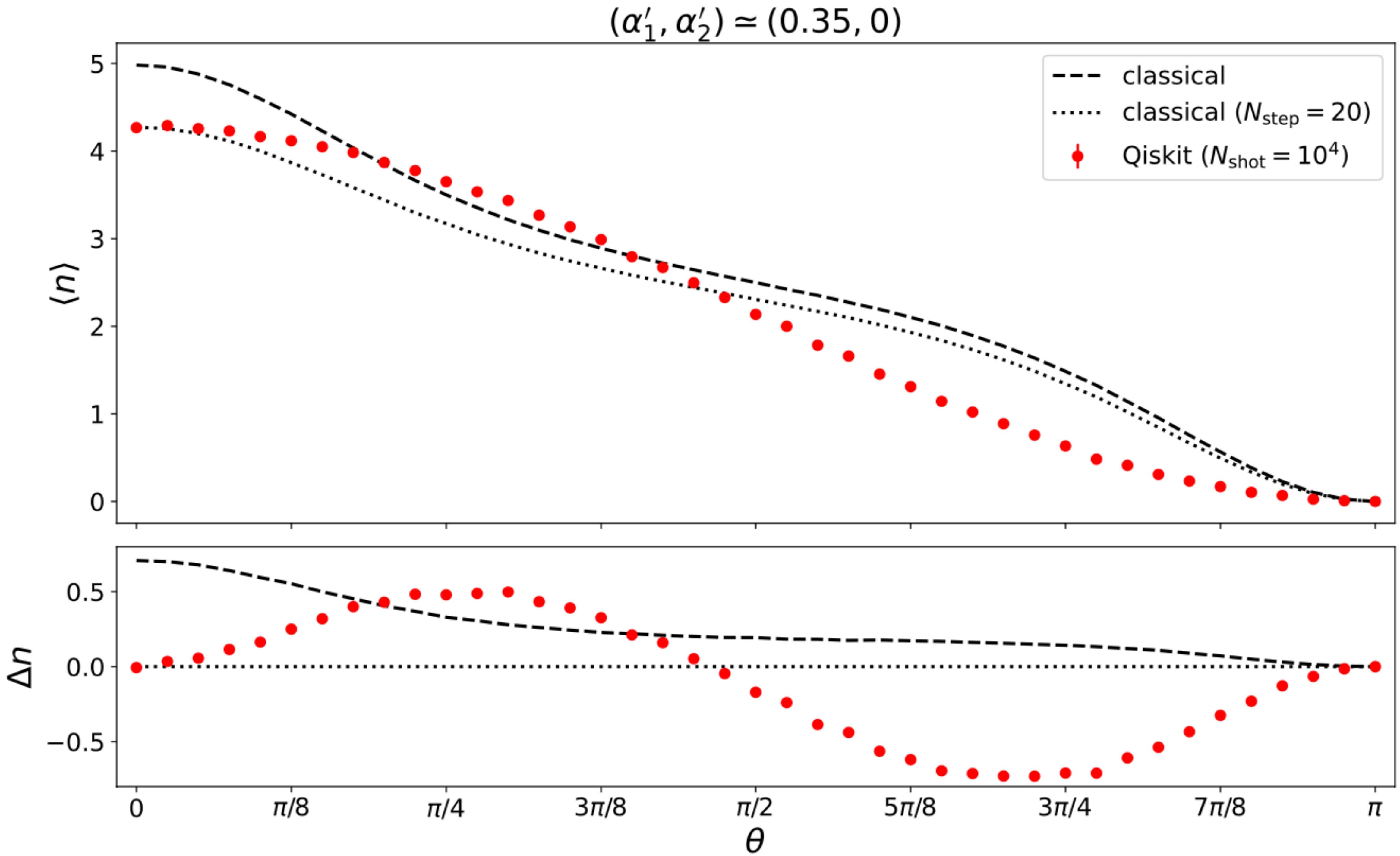
$$\Delta_i = \exp\left[-N_f \int R(t)\right]$$

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



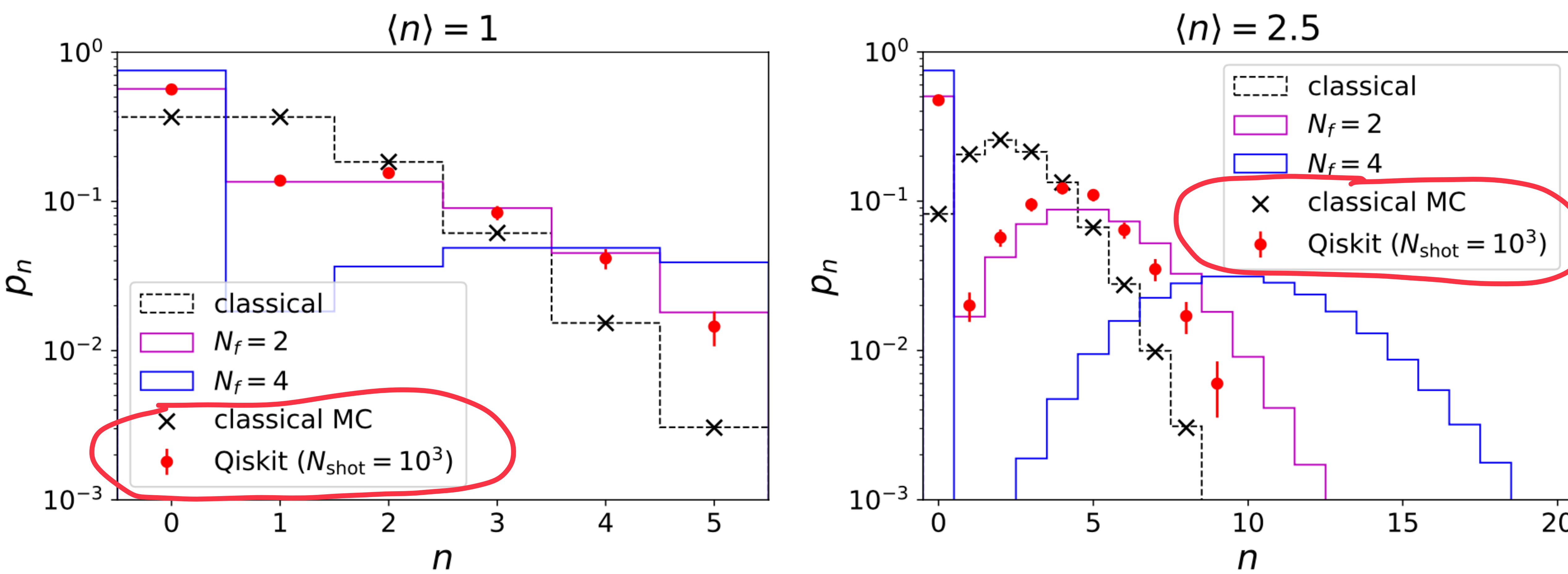
measure # of γ'

Results



$(\alpha'_1, \alpha'_2) \simeq (0.35, 0)$
classical
classical ($N_{\mathrm{step}} = 20$)
Qiskit ($N_{\mathrm{shot}} = 10^4$)
$\langle n \rangle$
Δn
0
1
2
3
4
5
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

  ⟿ Dark Sector Jets ☺

- Quantum Interference among flavors

  studied by quantum algorithm
  quantum simulator

  ⟿ enhancement for
  many-γ' events ☺ ☺

Outlook

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

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