# Quantum & Classical Algorithms for Parton Showers


KAVLI IPMU

Masahito Yamazaki

THE UNIVERSITY OF TOKYO


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So Chigusa (Berkeley) + MY, arXiv: 2204.12500 [hep-ph]

Christian W. Bauer, So Chigusa + MY [In Progress]

# Quantum in HEP?

- # qubits $\gg 30 \sim 40$
  quantum advantage?
- rapid progress on hardware

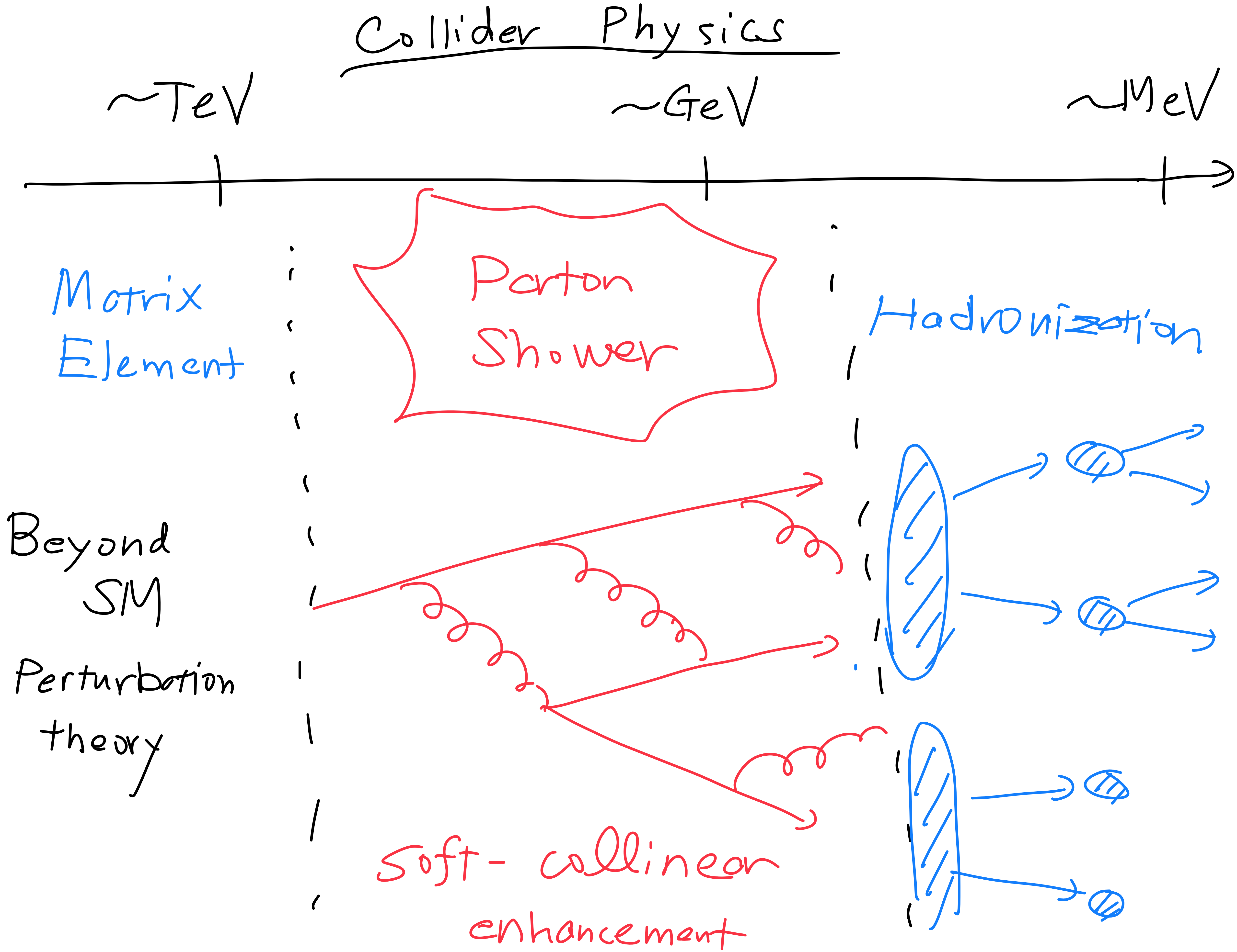
- Noisy
- Hard to prove quantum advantage
- Not enough qubits?

# Wish List

* quantum effects important (e.g. interference)

* small-scale problem $\subset$ full-scale problem

* simplified model + extra layers


Collider Physics
~TeV
~GeV
~MeV
Matrix Element
Parton Shower
Hadronization
Beyond SM
Perturbation theory
soft-collinear enhancement

# Simplified Model

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

photon $U(1)$ $A'_\mu$

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

# Simplified Model

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

dark photon $U(1)$ $A'_\mu$

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

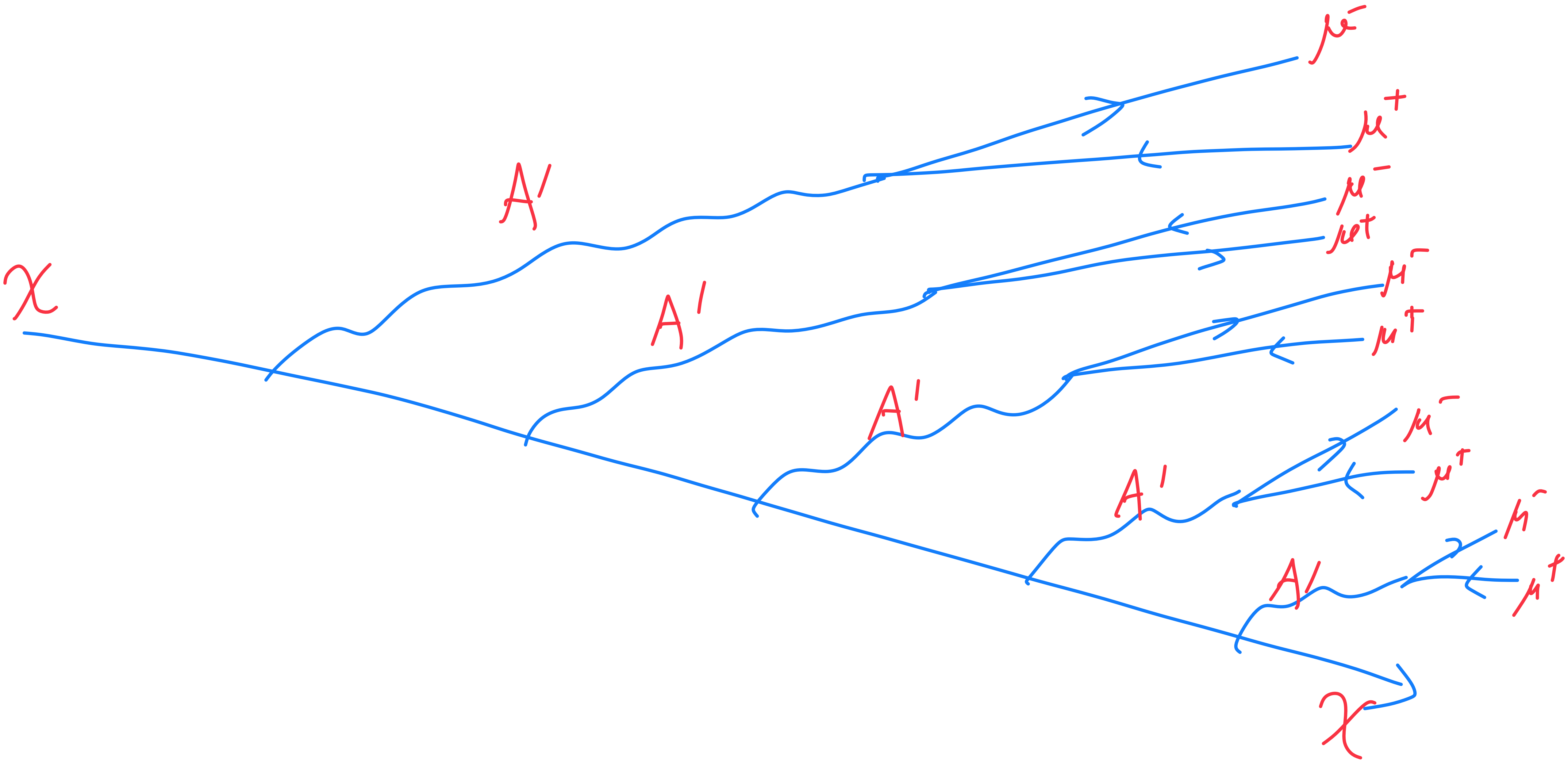
$$- \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{1}{2} m_{A'}^2 A'_\mu A'_\mu$$

※ dark sector model [many papers]

mediator for dark-matter self-interactions

↑ cosmology

# Dark Sector Jets

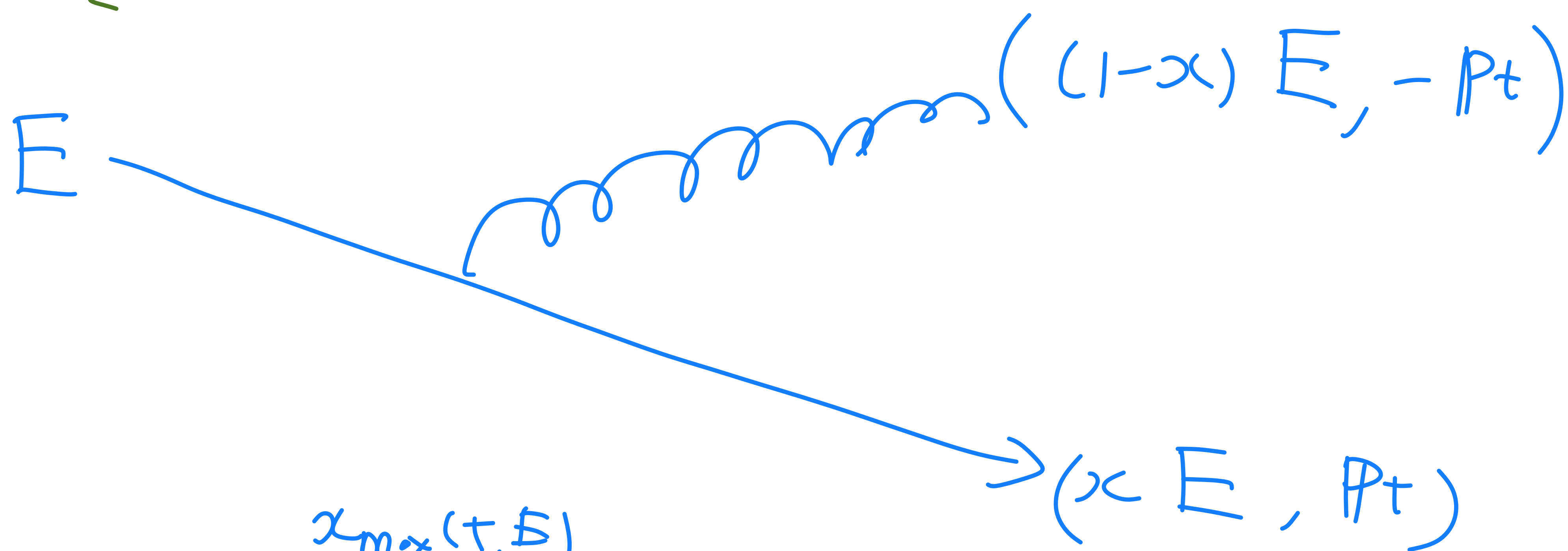



dramatic event e.g. @ HL-LHC

[many papers]

# Standard : classical Monte Carlo

[many programs, e.g. Pythia, Herwig, Sherpa, ...]




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

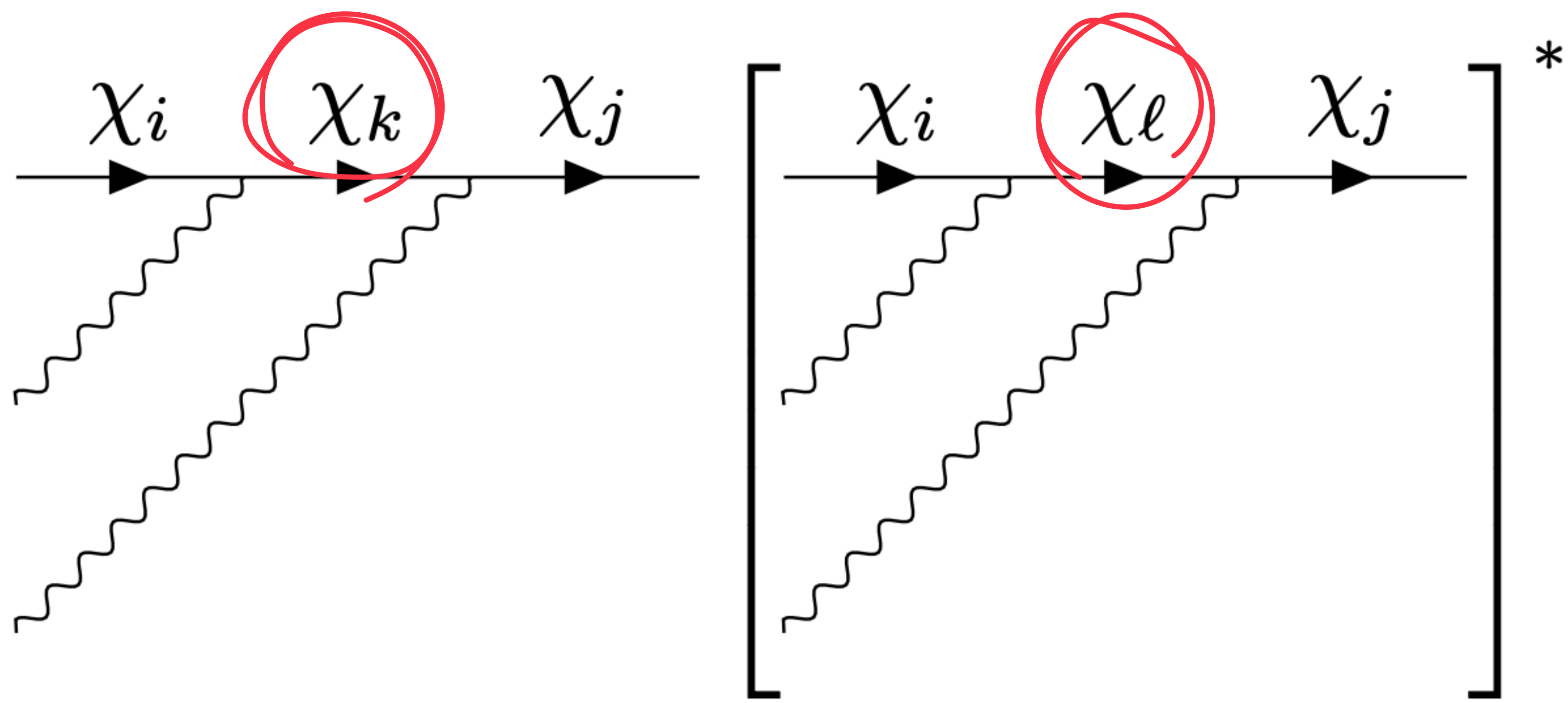
energy fraction → $x$

virtuality ↔ $p_t$ → $t$

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

## Quantum interference between flavors ($N_f > 1$)

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

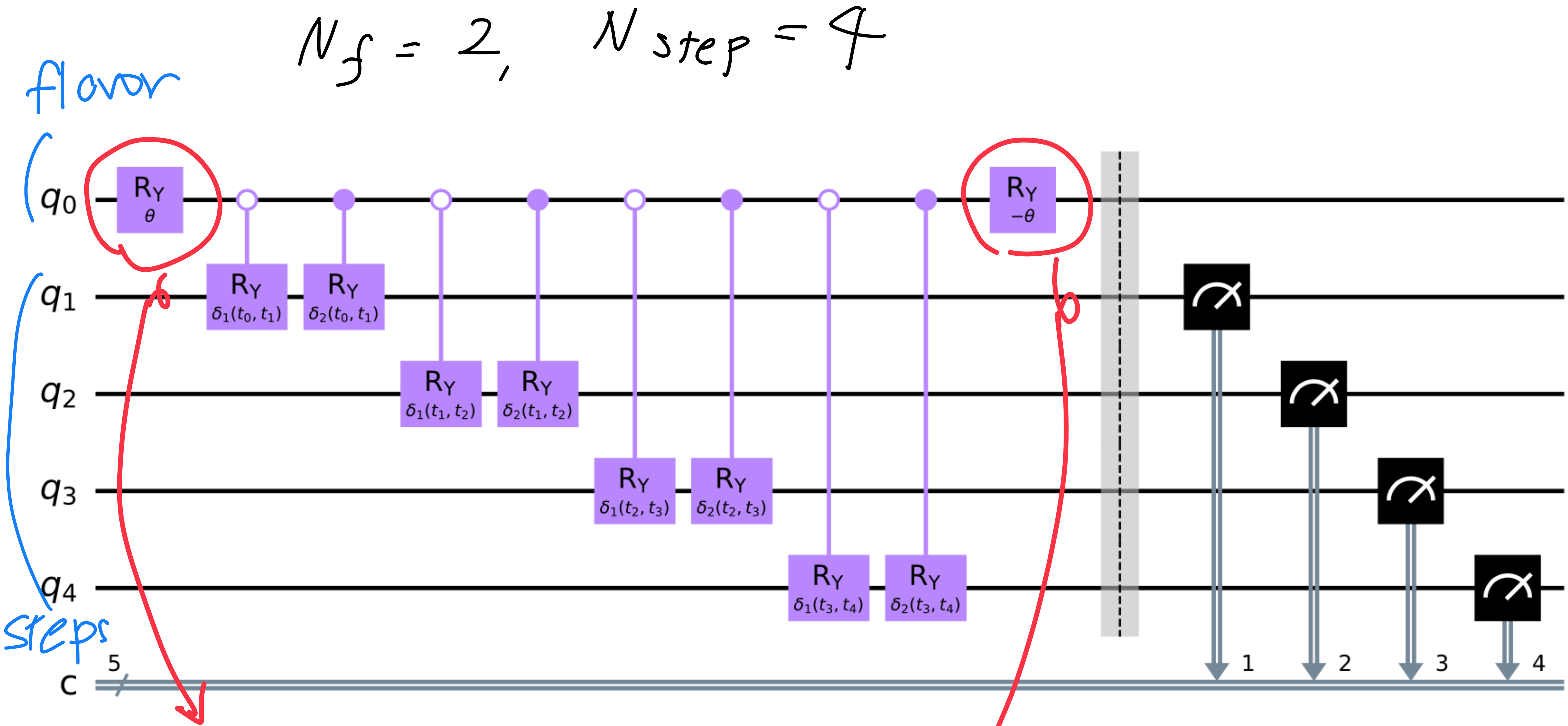



$$+ \text{c.c.} \,,$$

Not in classical Monte Carlo

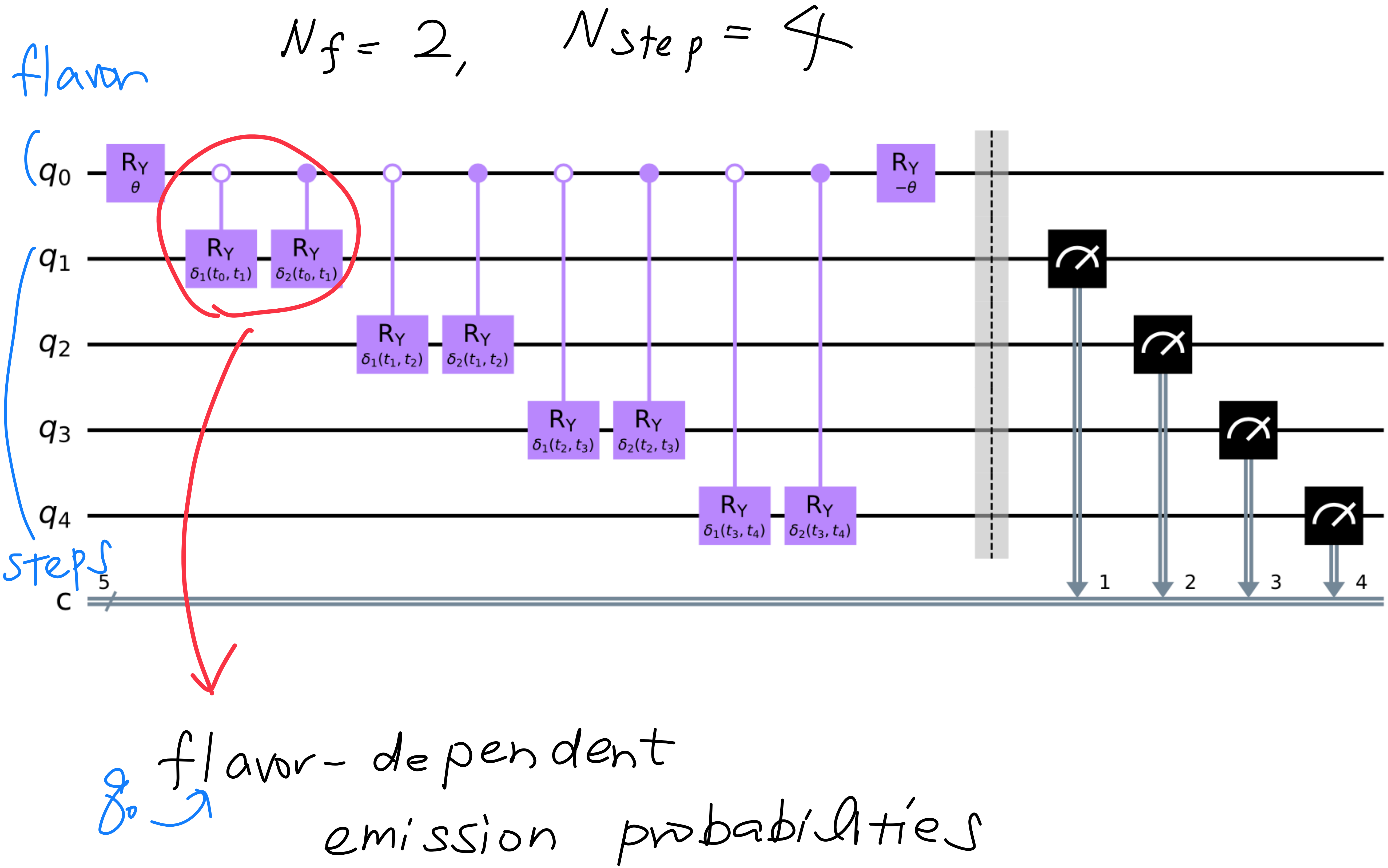
(except in large $N_c$ approximation)

# Simplified Quantum Circuit

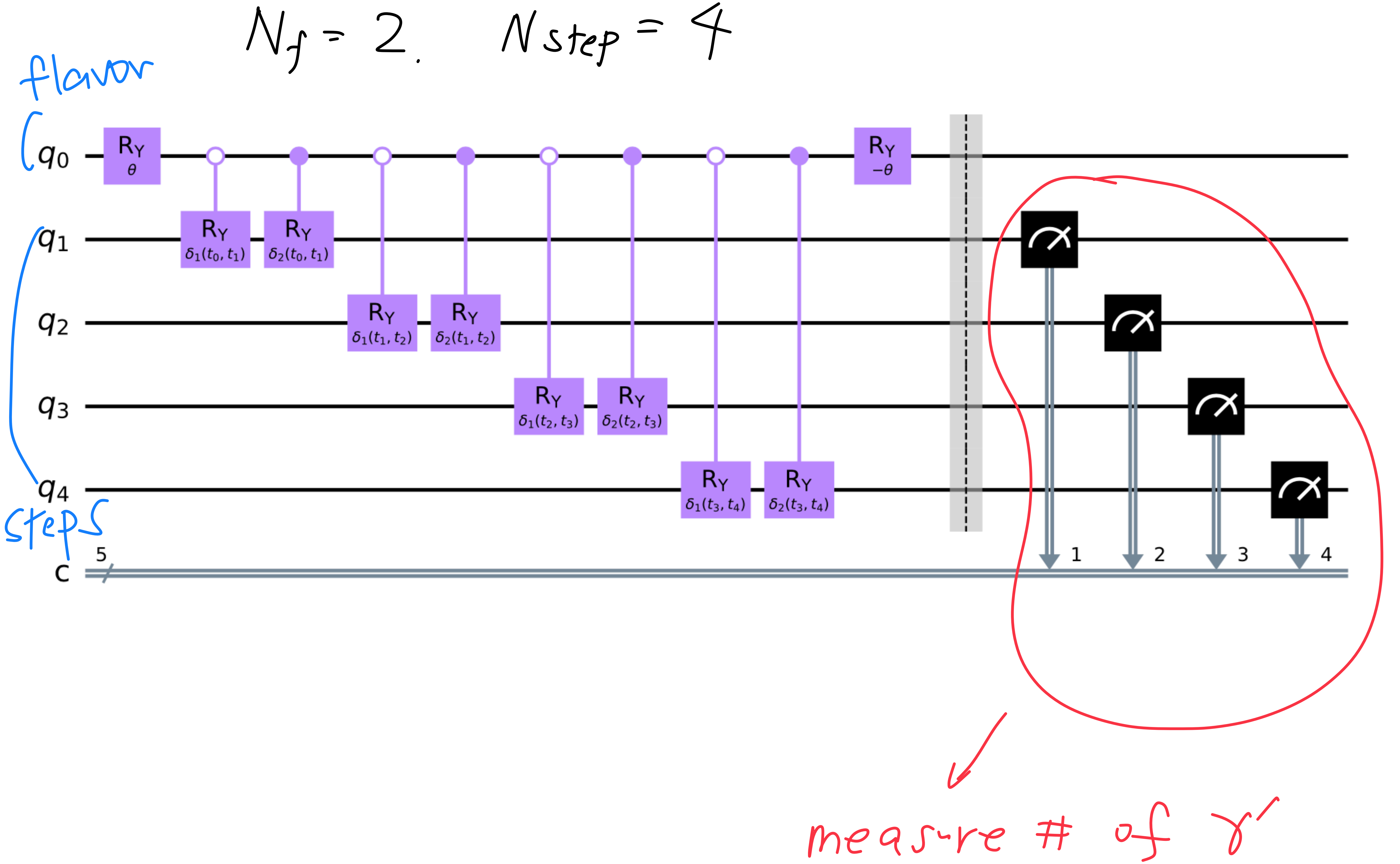



rotate states into gauge-diagonal basis

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



Nf = 2, Nstep = 4
flavor
steps
q0
q1
q2
q3
q4
c
5
RY θ
RY δ1(t0, t1)
RY δ2(t0, t1)
RY δ1(t1, t2)
RY δ2(t1, t2)
RY δ1(t2, t3)
RY δ2(t2, t3)
RY δ1(t3, t4)
RY δ2(t3, t4)
RY −θ
1
2
3
4
flavor-dependent emission probabilities



Nf = 2. Nstep = 4
flavor
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q0
q1
q2
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q4
c
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RY θ
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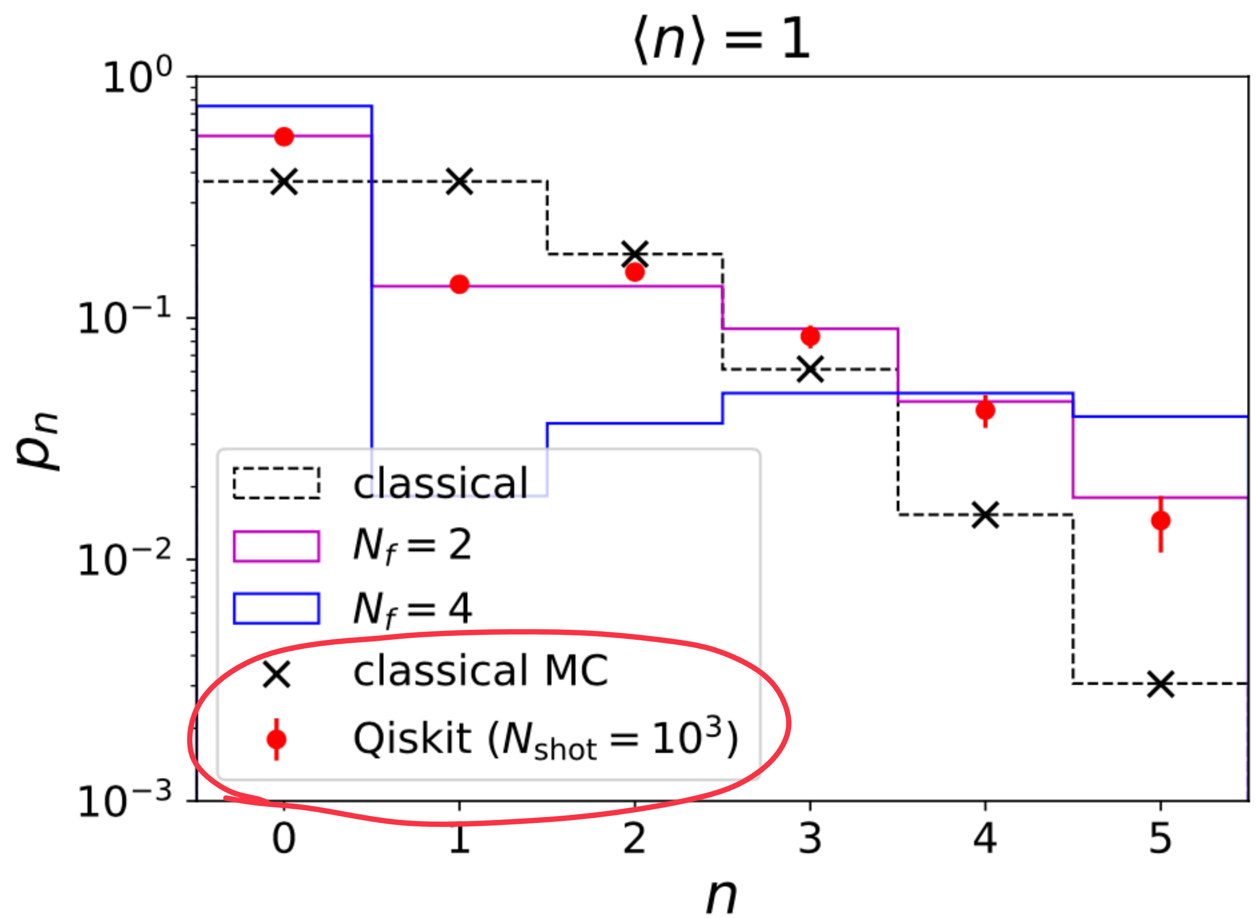
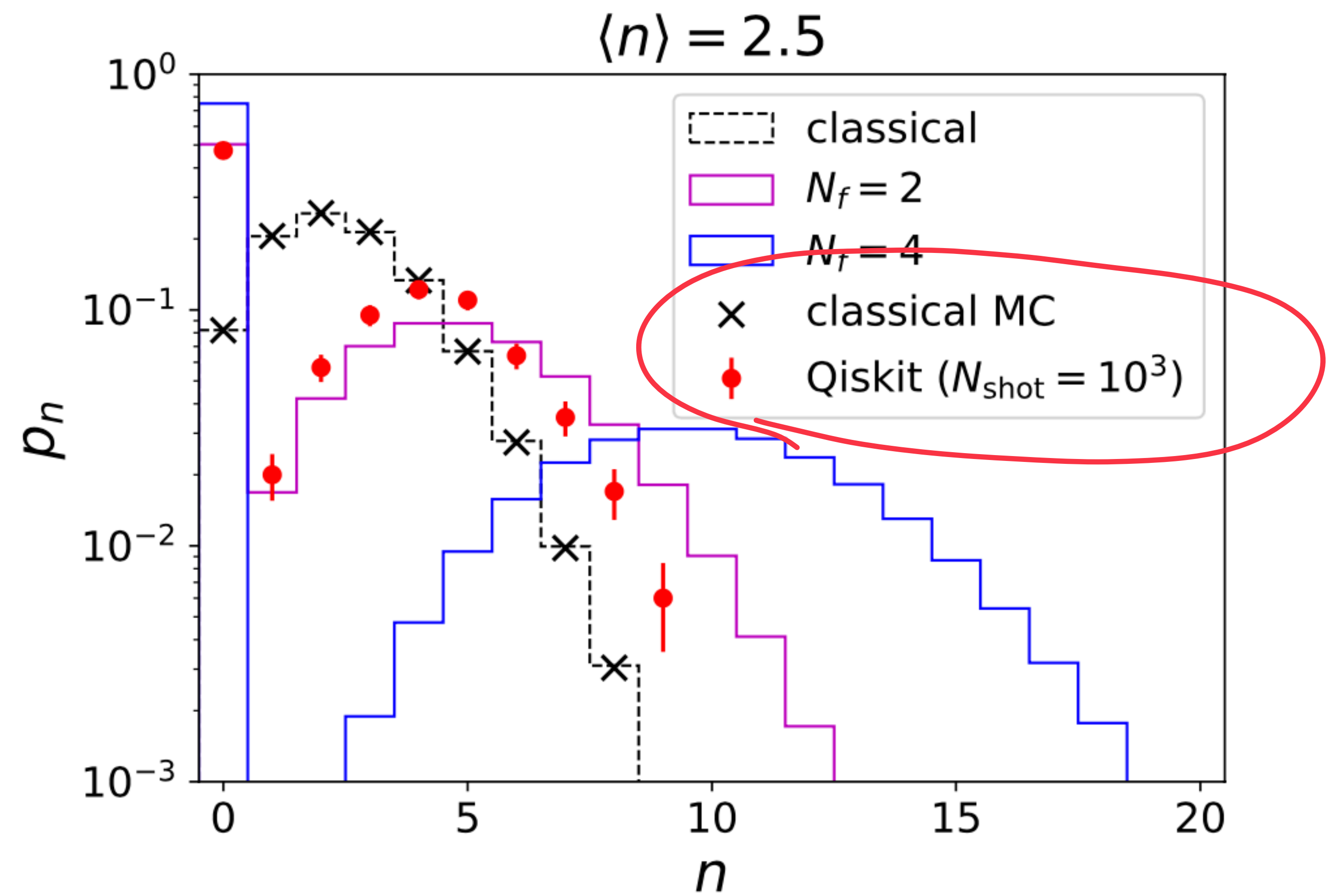
RY δ2(t0, t1)
RY δ1(t1, t2)
RY δ2(t1, t2)
RY δ1(t2, t3)
RY δ2(t2, t3)
RY δ1(t3, t4)
RY δ2(t3, t4)
RY −θ
1
2
3
4
measure # of γ'

# Results (in simplified analysis)

[ Chigusa–MY '22 ]




huge enhancement

for n (# emissions) large!!

# In Progress

- incorporate kinematics, RG-flow

↑ quantum-classical hybrid [Bauer-Chigusa-MY] ↓

- incorporate Veto algorithm

  mid-circuit measurement

Quantum Monte Carlo in general?