Jet quenching and quantum algorithms

Felix Ringer

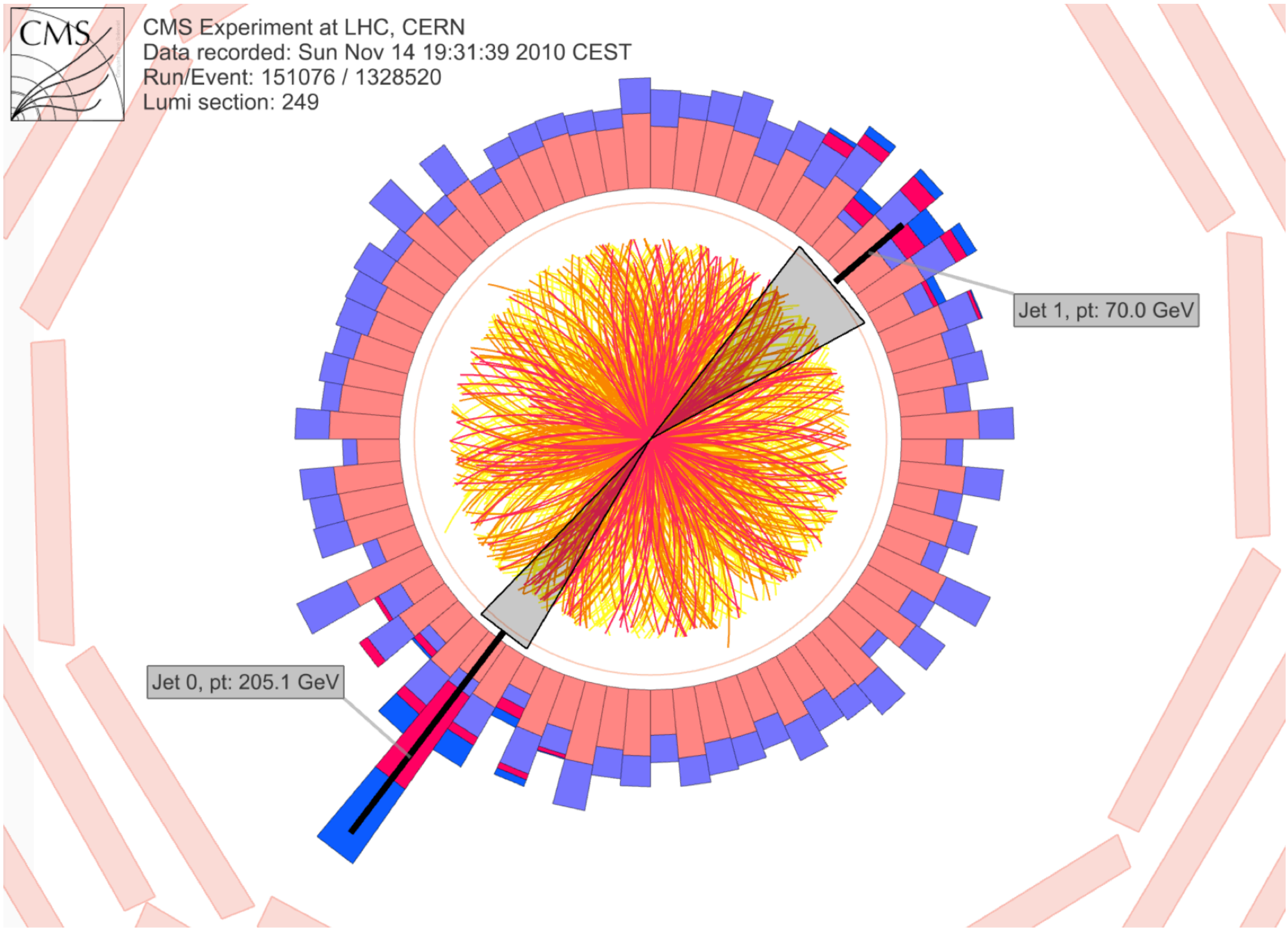
YITP, Stony Brook University

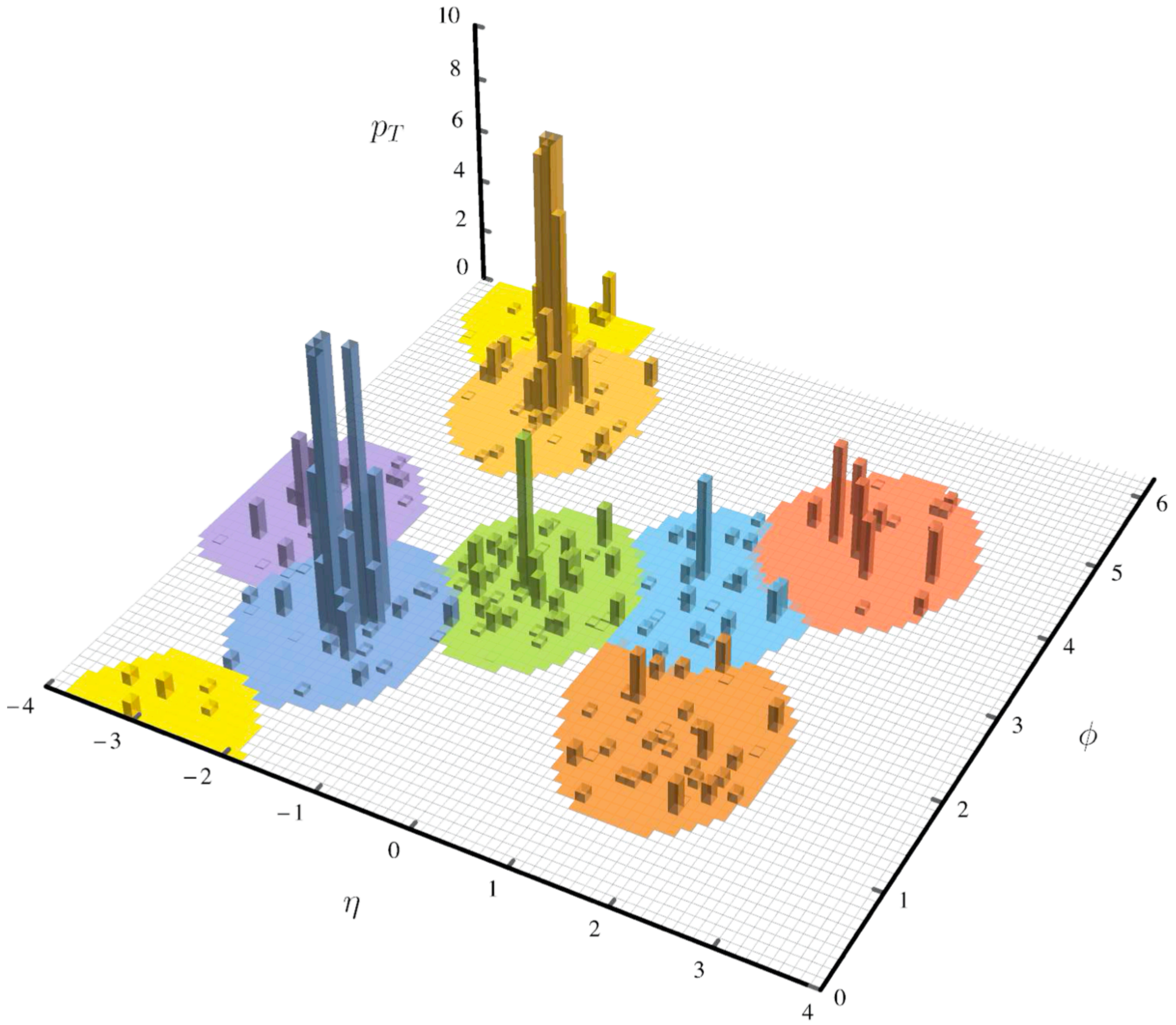
The Quantumness of Hard Probes, MITP, Mainz, 01/19/22

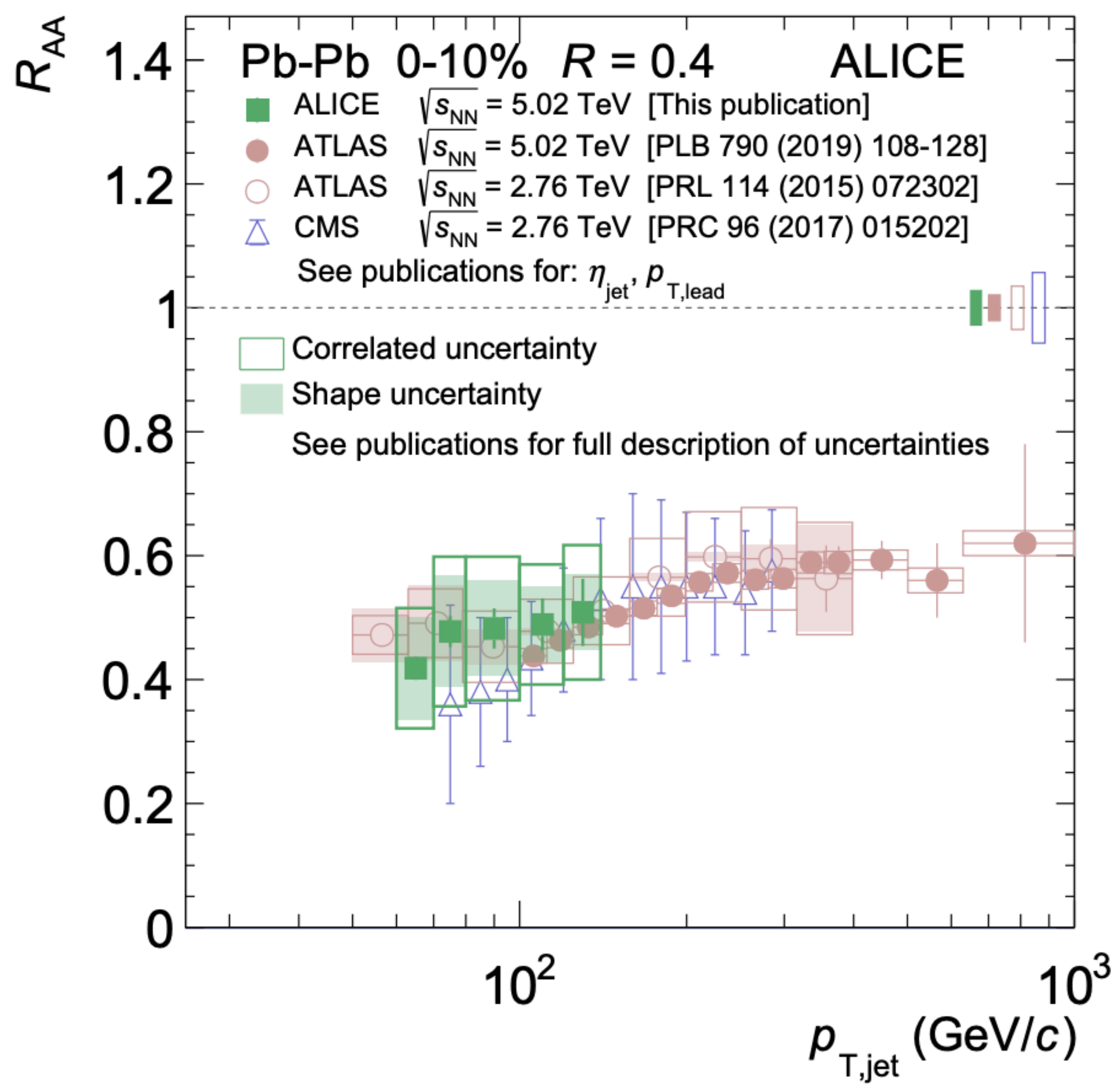
Stony Brook University

SIMONS FOUNDATION

Jet quenching and energy loss







ALICE, PRC 101 (2020) 034911

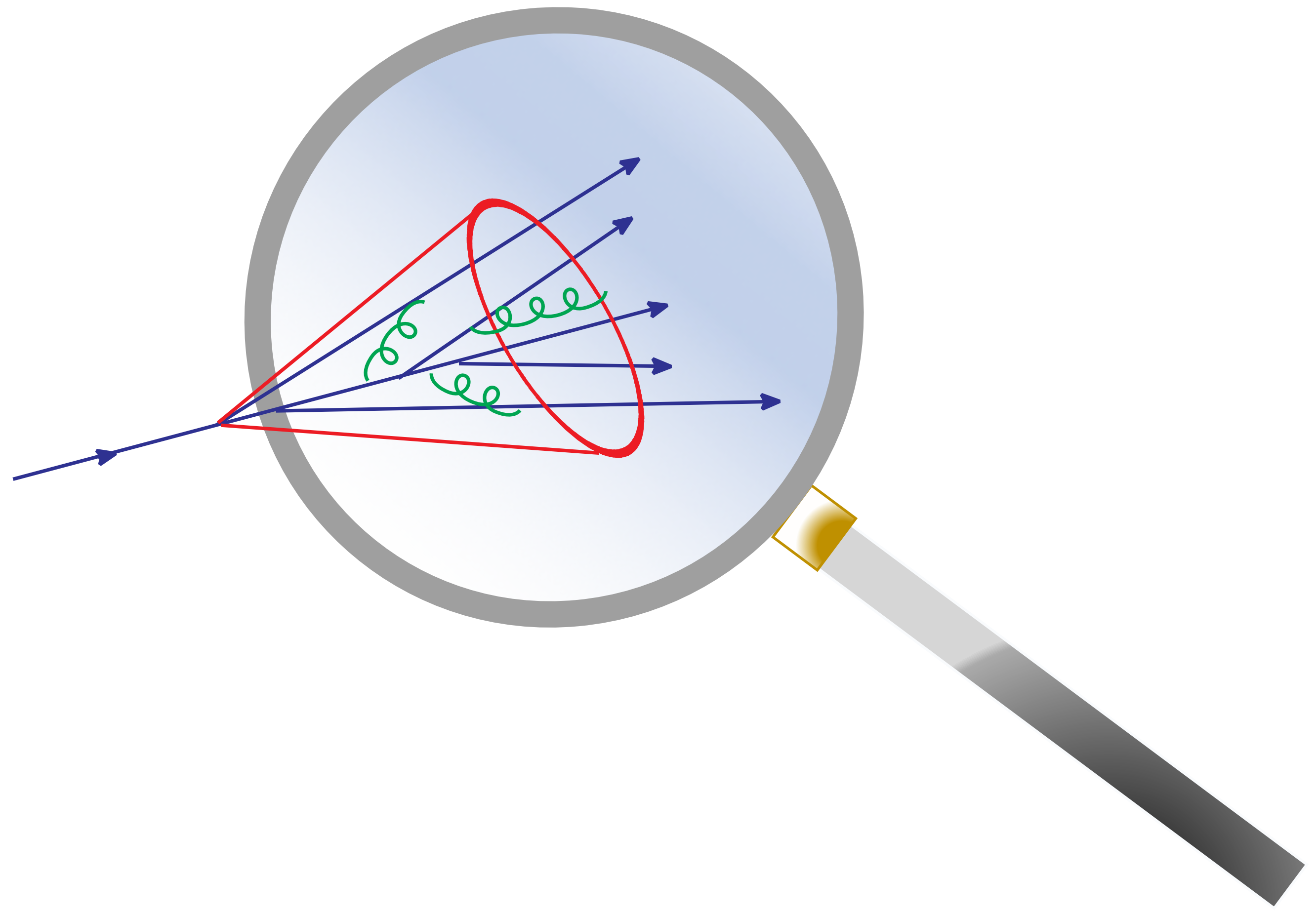
see talks by Yacine Mehtar-Tani and Varun Vaidya

Factorization in heavy-ion collisions

- Test of factorization & universality
- Extension of vacuum factorization theorems to the medium case
- In-medium jet functions

$$\frac{d\sigma_{pp\to \mathrm{jet}+X}}{d\eta dp_T} = \sum_{ijk} f_{i/p} \otimes f_{j/p} \otimes H_{ijk} \otimes \boxed{J_k^{\mathrm{med}}}$$

Applications to jet substructure?

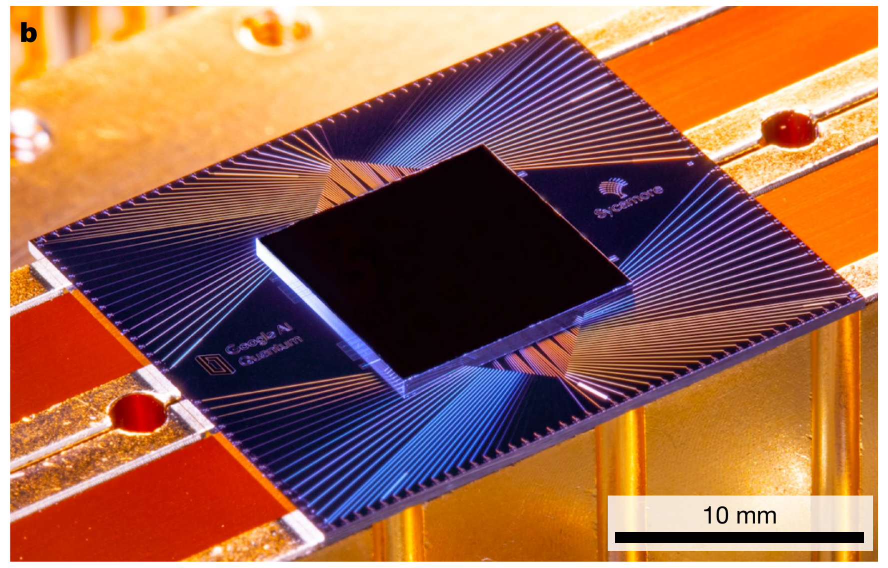


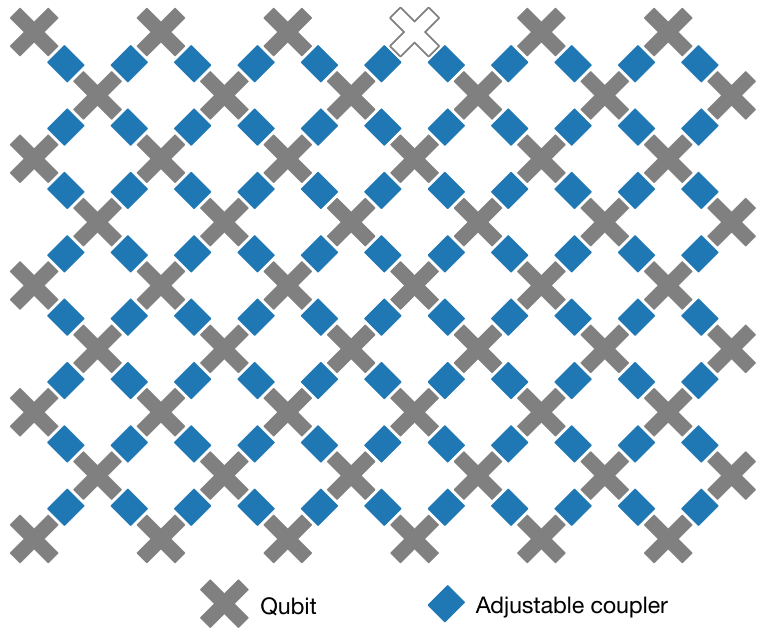
Applications of quantum computing

Google

Article

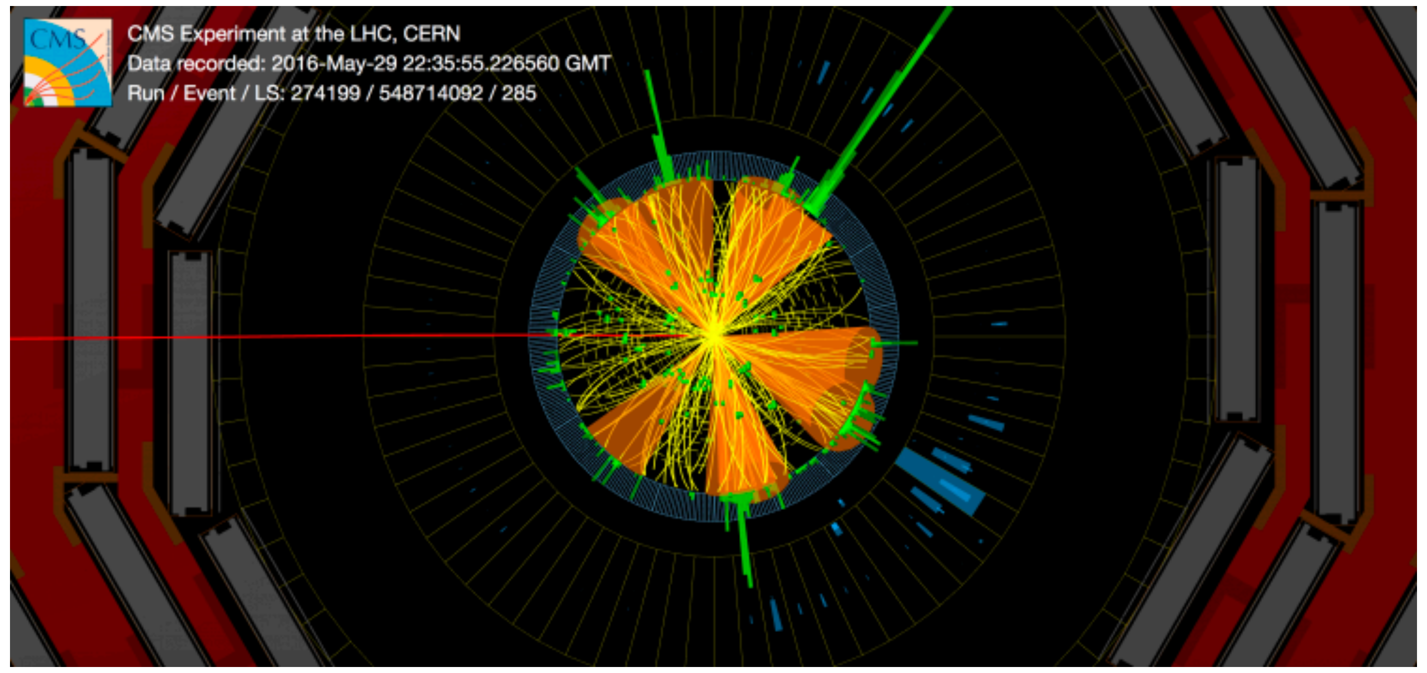
Quantum supremacy using a programmable superconducting processor





Random circuit sampling *Martinis et al. `19*

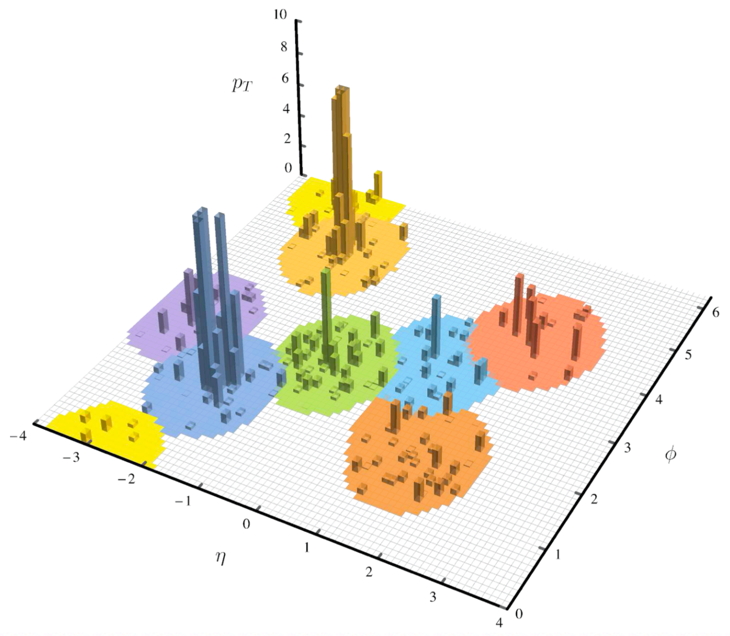
Universal simulations of QCD from first principles?



Outline

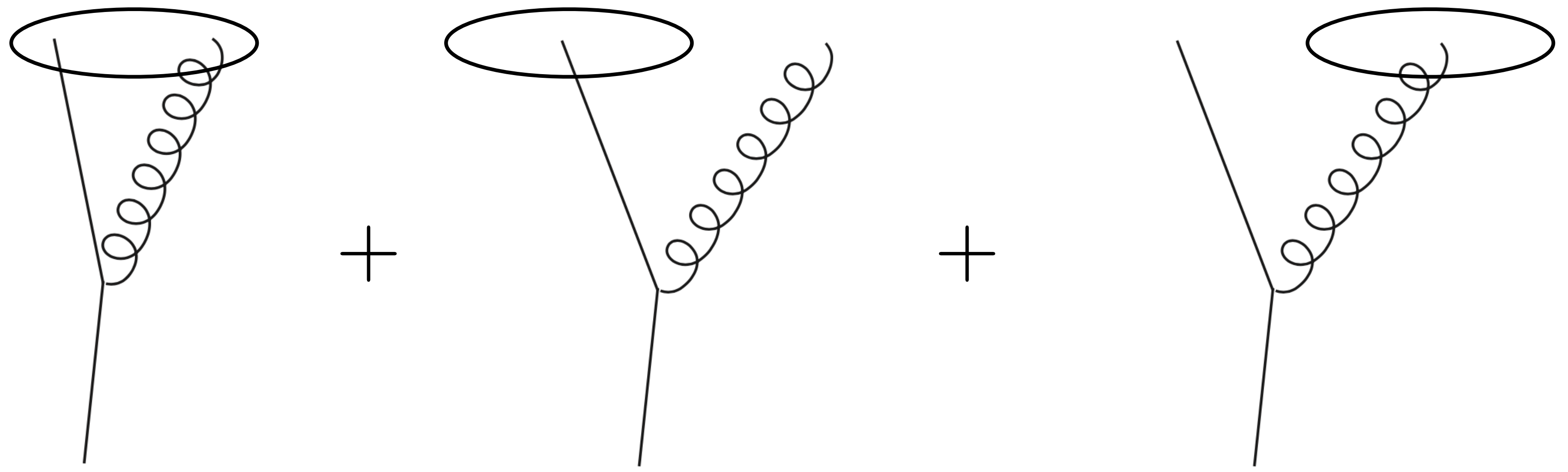
- Introduction
- QCD factorization in heavy-ion collisions
- Quantum simulations of open quantum systems
- Conclusions

Inclusive jet cross sections

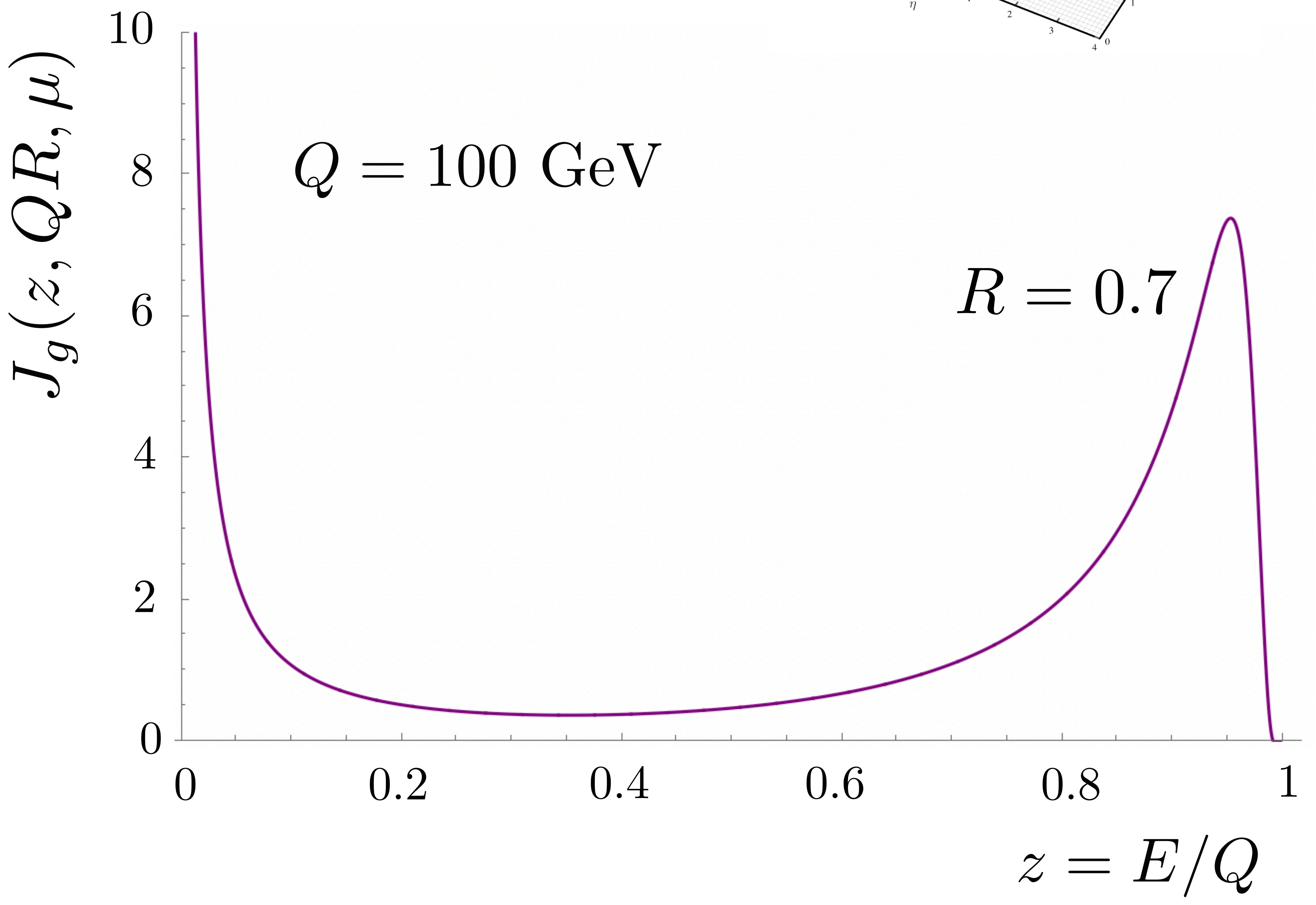


- **NLO** $J_i(z, QR, \mu)$

$z = E/Q$

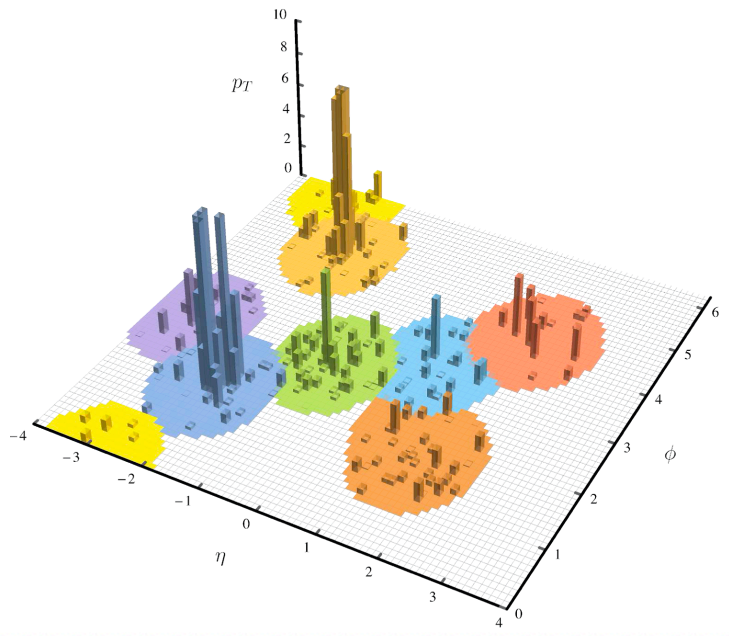


$$J_q(z, QR, \mu) = \delta(1-z) + \frac{\alpha_s}{2\pi}\left(\ln\left(\frac{\mu^2}{Q^2R^2}\right) - 2\ln z\right)[P_{qq}(z) + P_{gq}(z)] \; + \; \ldots$$



Dasgupta, Dreyer, Salam, Soyez `14
Kaufmann, Mukherjee, Vogelsang `15
Kang, Ringer, Vitev `16
Dai, Kim, Leibovich `16
Liu, Moch, Ringer `18, `19

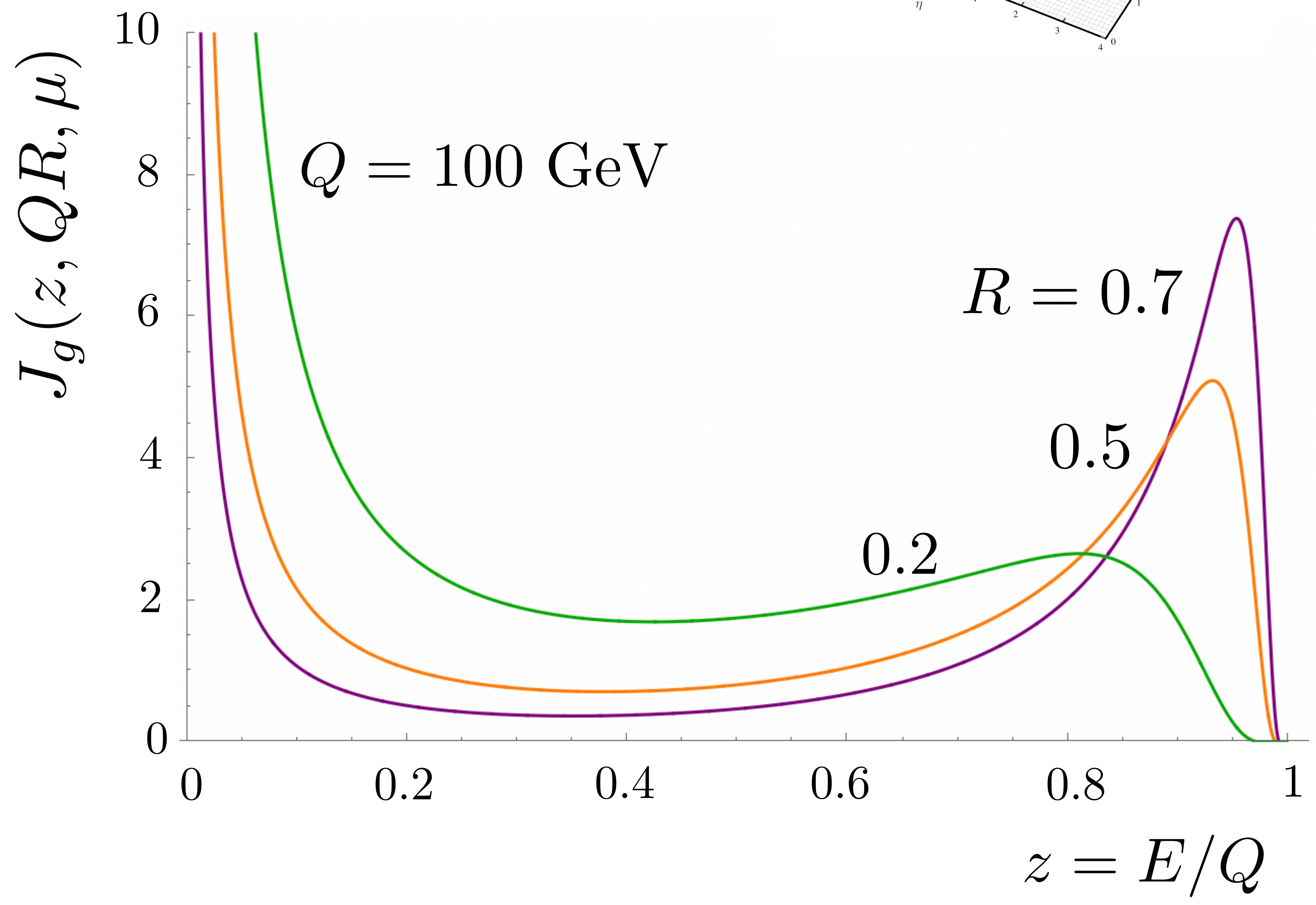
Inclusive jet cross sections

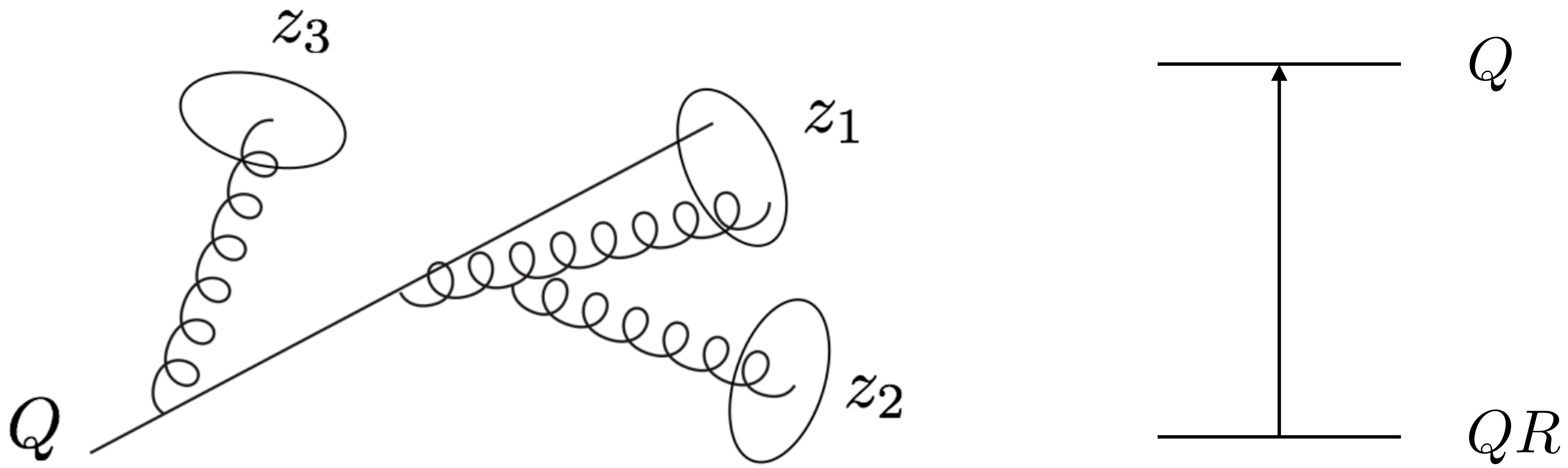


- **NLO** $J_i(z, QR, \mu)$

- **QCD evolution** $$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} J_i = \frac{\alpha_s}{2\pi} \sum_j P_{ji} \otimes J_j$$

DGLAP like hadron fragmentation functions





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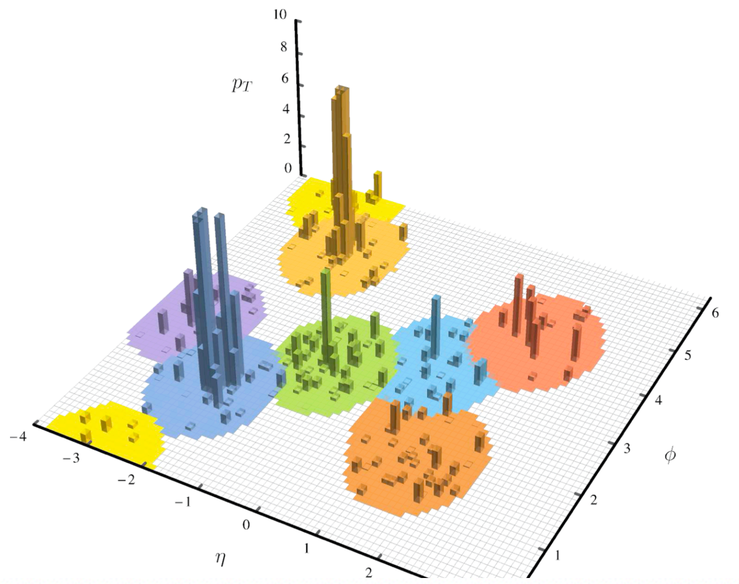
Inclusive jet cross sections



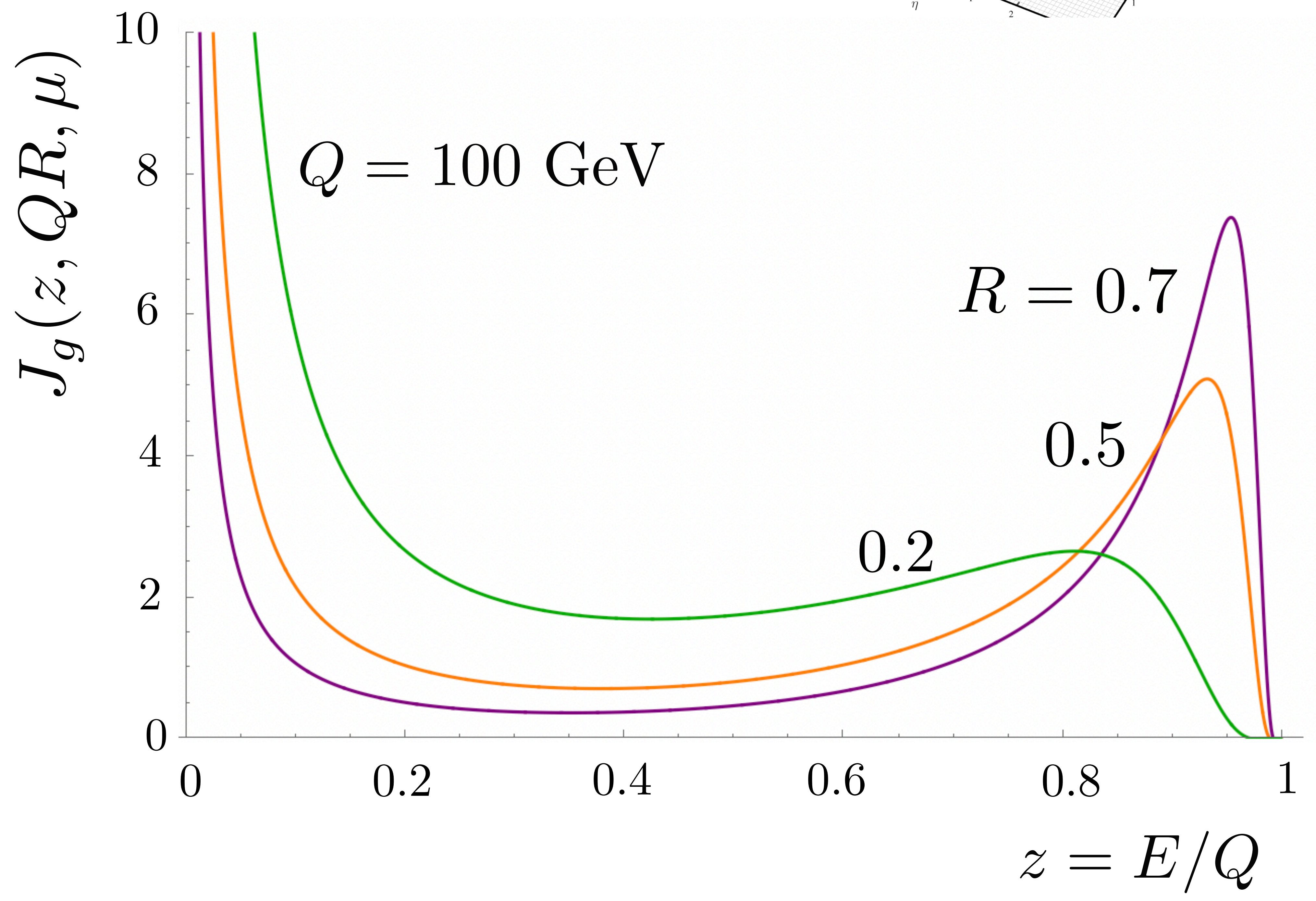
- **NLO** $J_i(z, QR, \mu)$

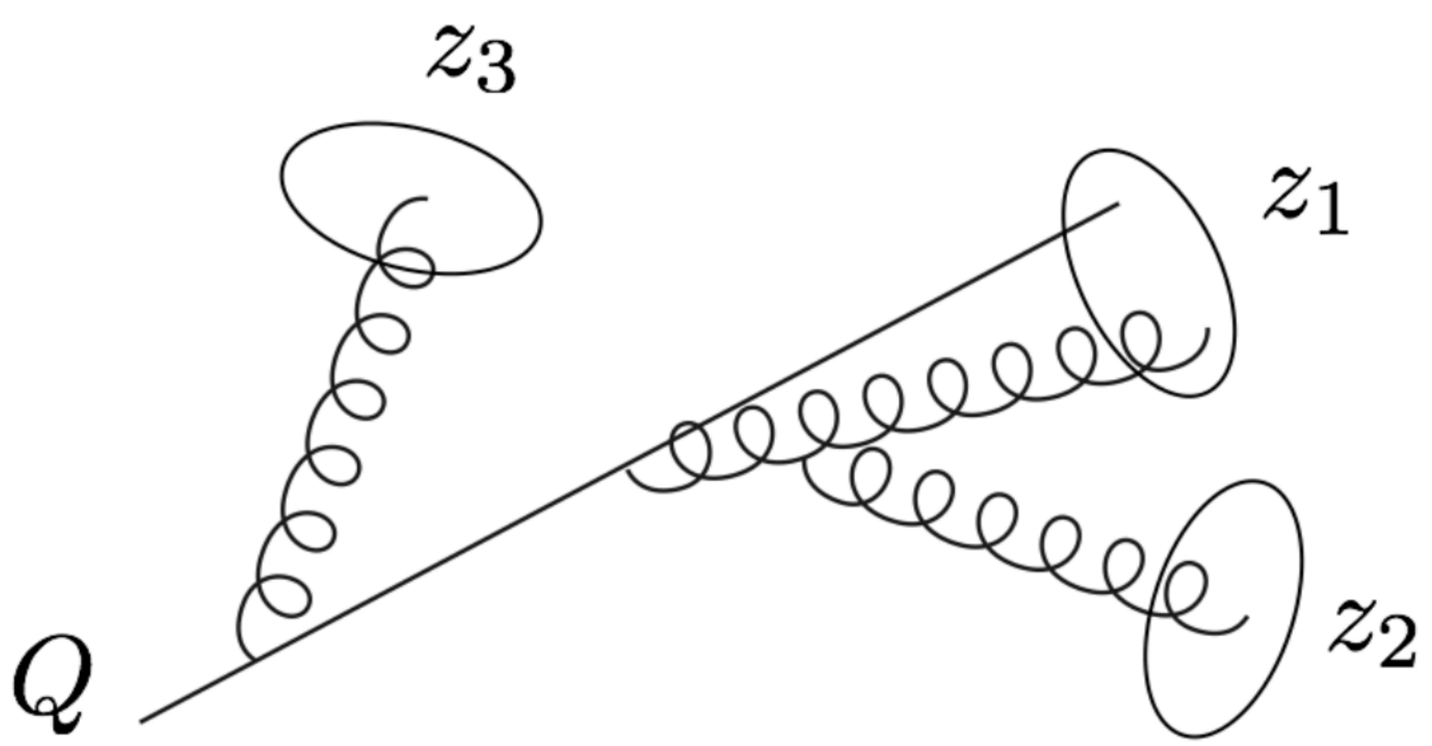
- **QCD evolution**

$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} J_i = \frac{\alpha_s}{2\pi} \sum_j P_{ji} \otimes J_j$$

- **Factorization**

$$\frac{\mathrm{d}\sigma_{pp\to \mathrm{jet}+X}}{\mathrm{d}\eta \mathrm{d}p_T} = \sum_{ijk} f_{i/p} \otimes f_{j/p} \otimes H_{ijk} \otimes J_k$$





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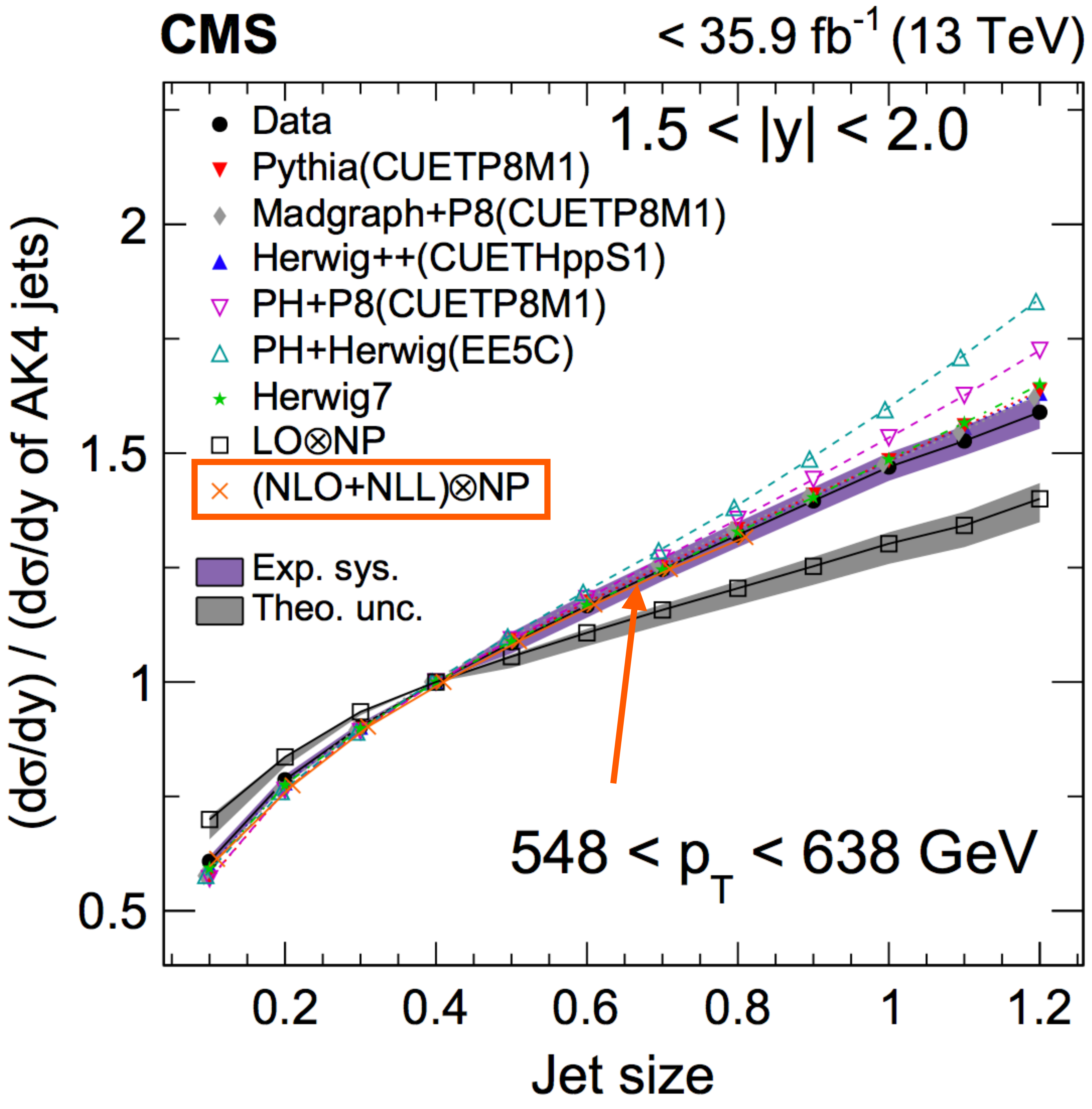
Inclusive jet cross sections

- Phenomenology

- Jet substructure

$$f_q\, J_q(\theta_g) + f_g\, J_g(\theta_g)$$



Liu, Moch, FR `17, 18

CMS, JHEP 12 (2020) 82
see also recent results from ALICE

Inclusive jets in heavy-ion collisions

- Factorization - can we systematically extend vacuum factorization theorems in vacuum to heavy-ion collisions?

$$\frac{\mathrm{d}\sigma_{pp\to\mathrm{jet}+X}}{\mathrm{d}\eta\mathrm{d}p_T} = \sum_{ijk} f_{i/p} \otimes f_{j/p} \otimes H_{ijk} \otimes J_k$$

→ Heavy-ion collisions

- Universality - consistent description of multiple observables?

$$f_q\, J_q(\theta_g) + f_g\, J_g(\theta_g)$$

- Phenomenological approach first

Inclusive jets in heavy-ion collisions

Qiu, FR, Sato, Zurita `19

- Proton-proton

$$\frac{d\sigma^{pp\to \text{jet}+X}}{dp_T d\eta} = \sum_{a,b,c} f_{a/p} \otimes f_{b/p} \otimes H_{ab}^c \otimes J_c$$

$$\mu^2 \frac{d}{d\mu^2} J_i = \sum_j P_{ji} \otimes J_j$$

- Heavy-ion

$$\frac{d\sigma^{AA\to \text{jet}+X}}{dp_T d\eta} = \sum_{a,b,c} f_{a/A} \otimes f_{b/A} \otimes H_{ab}^c \otimes J_c^{\text{med}}$$

$$\mu^2 \frac{d}{d\mu^2} J_i = \sum_j P_{ji} \otimes J_j + \frac{1}{\mu^2} \Gamma \otimes T$$

Initial state e.g. nPDFs

Medium jet functions

see also Kang, FR, Vitev `16

- Modified evolution not considered here
- Could be constrained phenomenologically

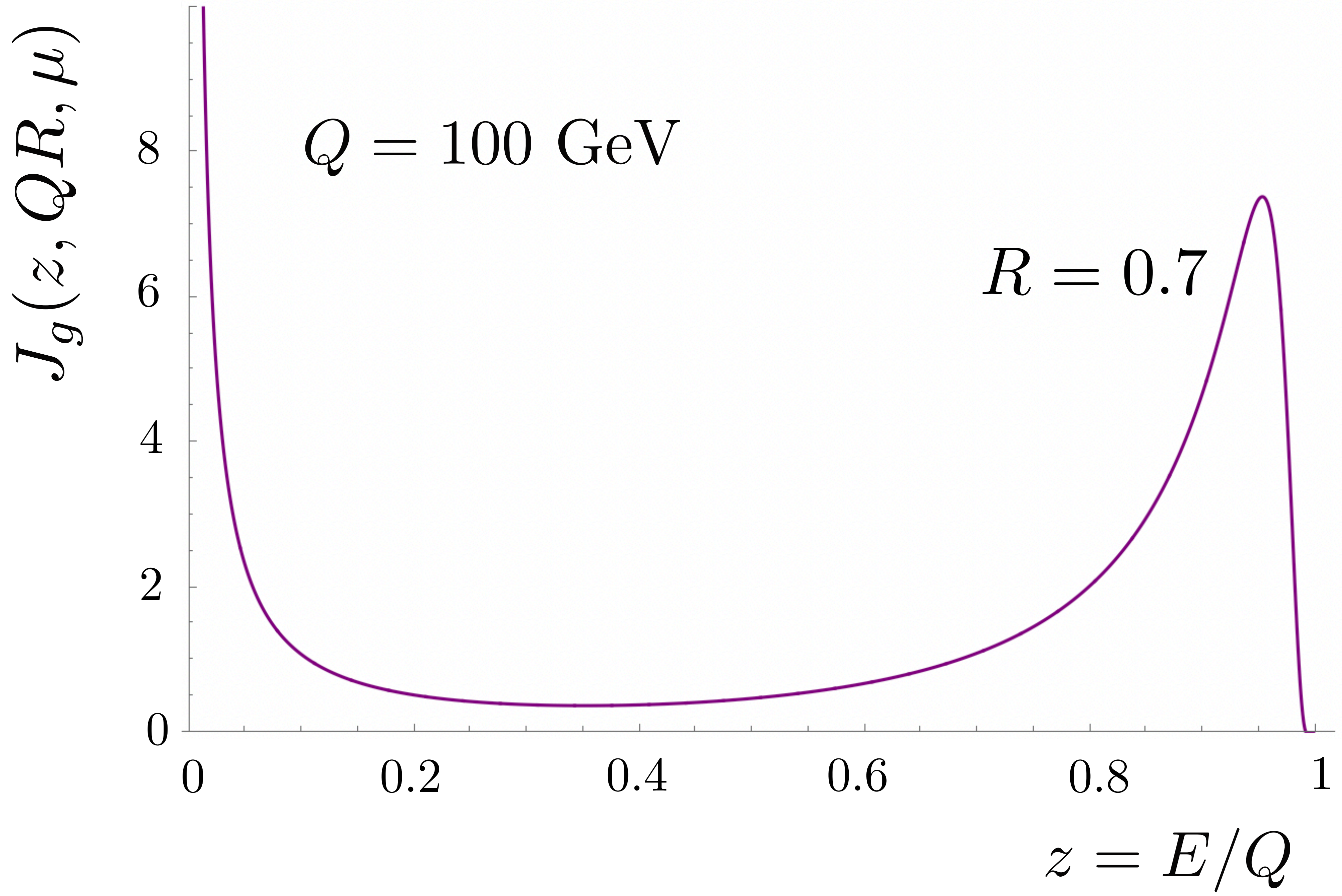
Inclusive jets in heavy-ion collisions

Qiu, FR, Sato, Zurita `19

- Introduce medium modified jet function at the jet scale

$$J_c^{\rm med}(z, p_T R, \mu_J) = W_c(z) \otimes J_c(z, p_T R, \mu_J)$$

$$W_c(z) = \epsilon_c \delta(1-z) + N_c\, z^{\alpha_c}(1-z)^{\beta_c}$$



- Momentum sum rule

$$\int_0^1 dz\, z\, J_c(z, p_T^c R, \mu) = 1$$

- Monte Carlo sampling approach

NNPDF `17, JAM `16

nPDFs	*Eskola, Paakkinen, Paukkunen, Salgado `17, Kovarik et al. `16* *de Florian, Sassot, Zurita, Stratmann `12*
nFFs	*Sassot, Stratmann, Zurita `10*

Inclusive jets in heavy-ion collisions

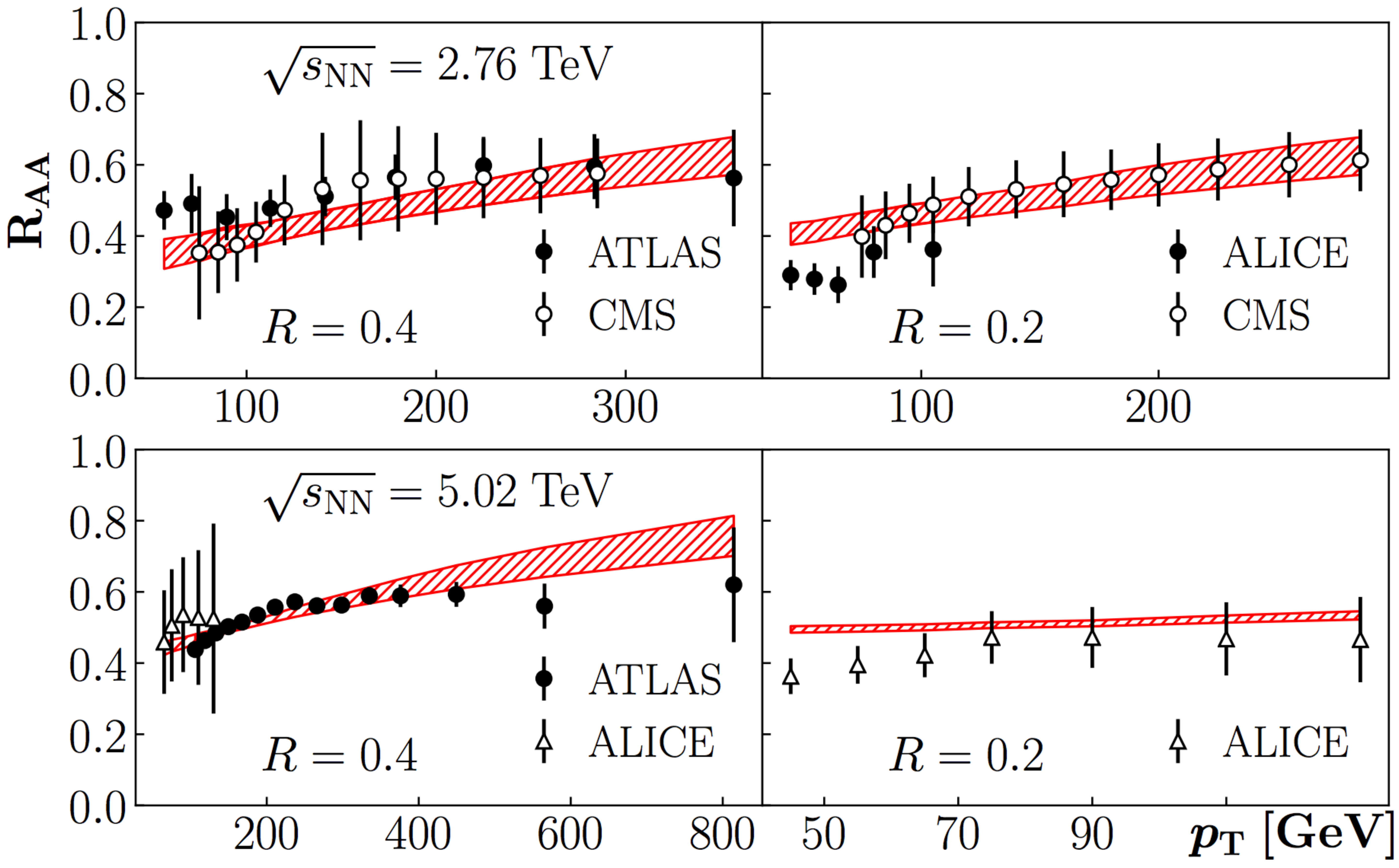
Qiu, FR, Sato, Zurita `19

$\sqrt{s_{\rm NN}} = 2.76$ TeV

$\chi^2/\text{d.o.f.} = 1.1$

$\sqrt{s_{\rm NN}} = 5.02$ TeV

$\chi^2/\text{d.o.f.} = 1.7$



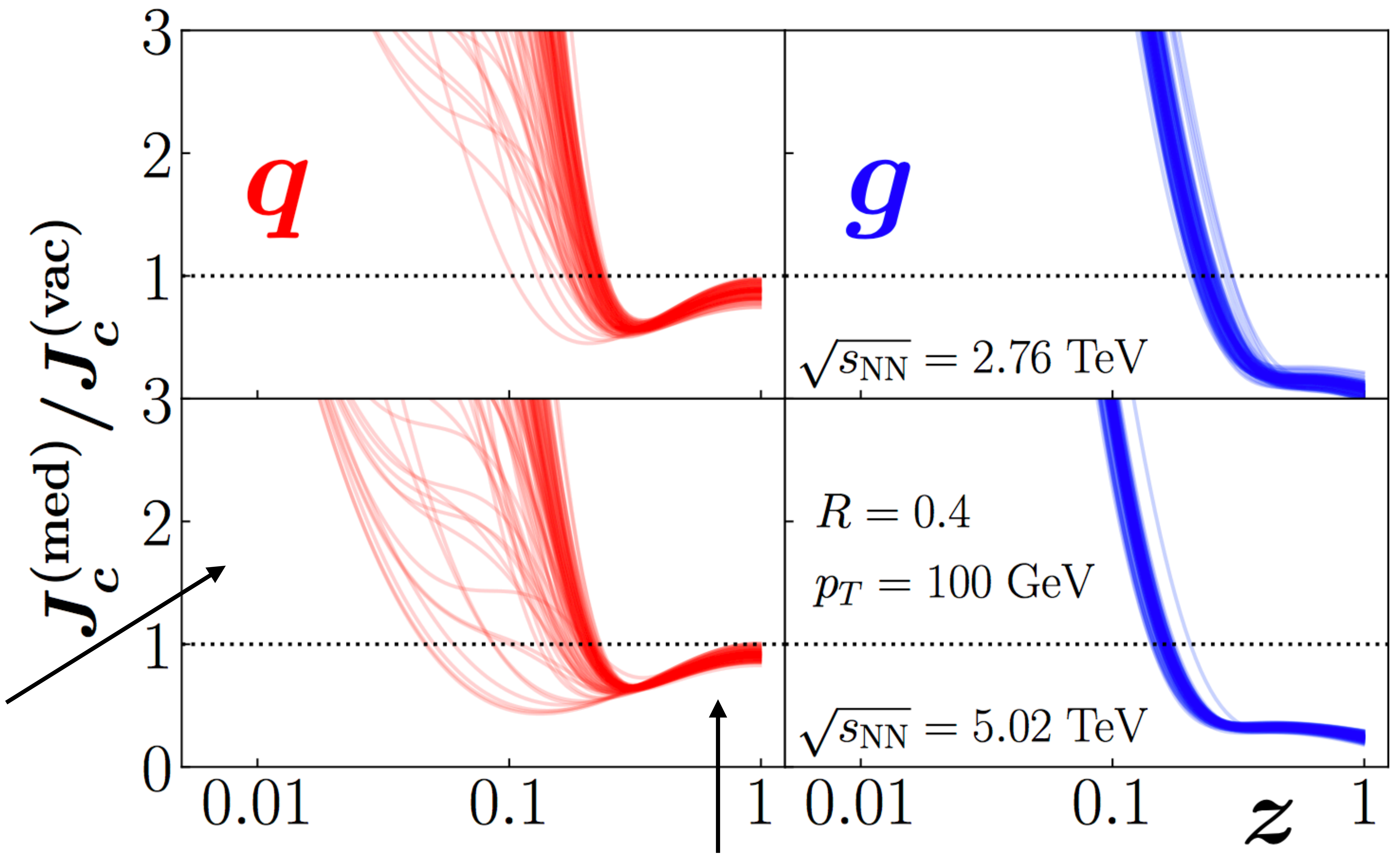
- Fit to data similar to PDFs and fragmentation functions

ALICE, PLB 746 (2015) 1
ATLAS, PRL 114 (2015) 072302
CMS, PRC 96 (2017) 015202
ALICE preliminary
ATLAS, PLB 790 (2019) 108

In-medium jet functions

Qiu, FR, Sato, Zurita `19

- Suppression at large-z compensated for by enhancement at small-z



Small-z region generally less constrained

Potentially requires threshold resummation for $z \to 1$

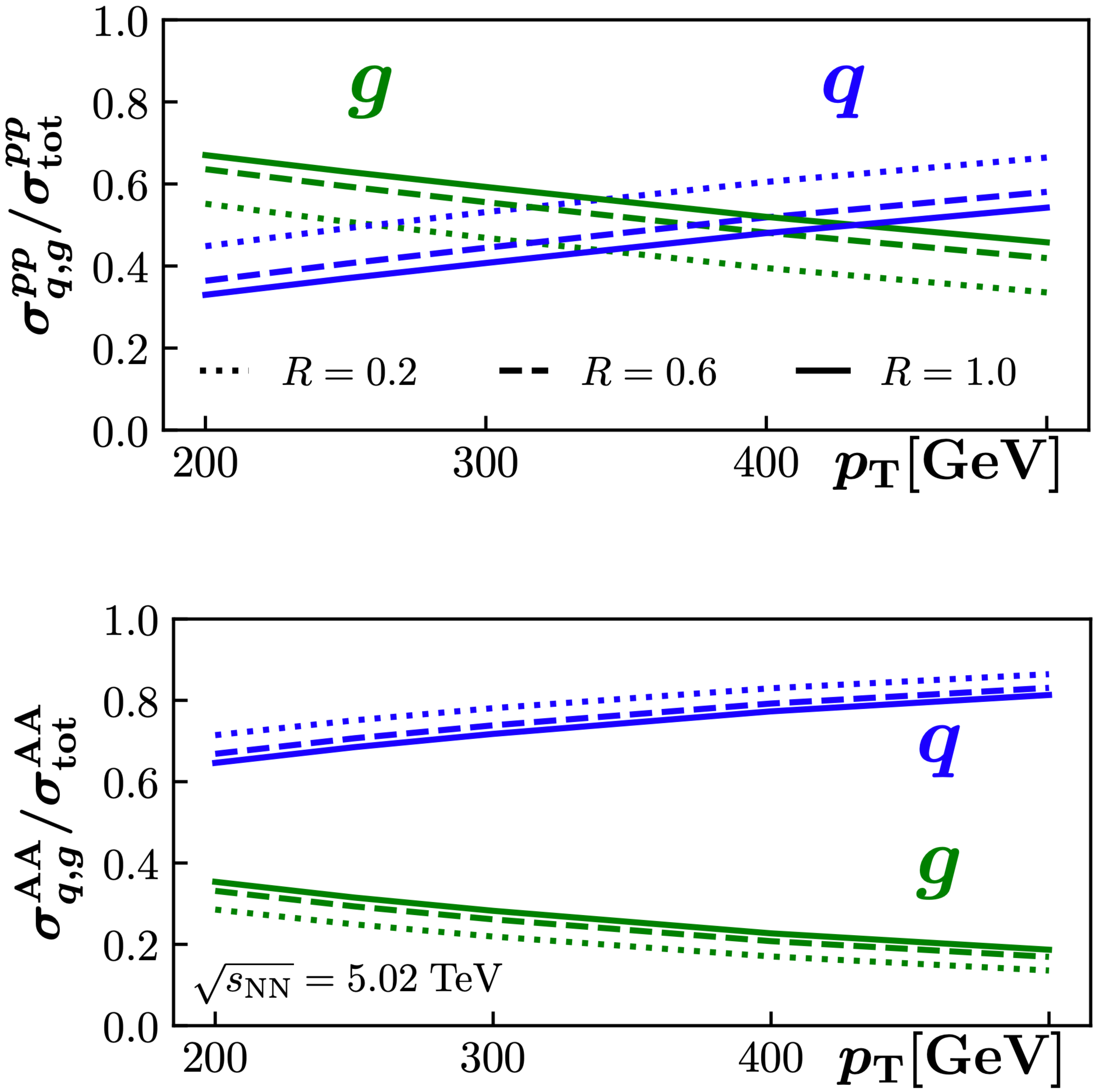
In-medium quark/gluon fractions

- Quark/gluon fractions defined at leading power in R^2

- Significant shift toward quark jets in the medium

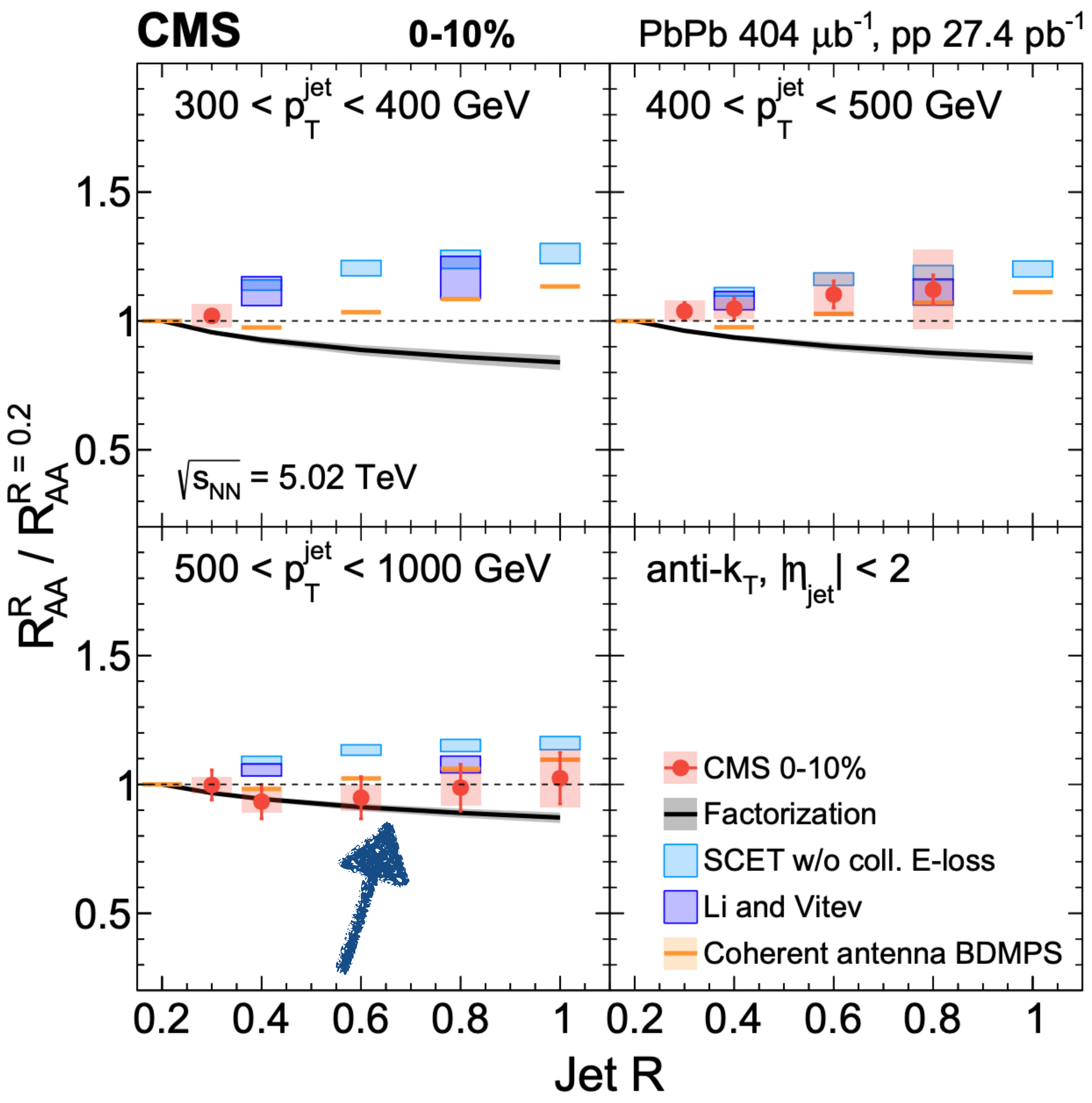
- Should be the same for all JSS observables measured on an inclusive jet sample

$$f_q\, J_q(\theta_g) + f_g\, J_g(\theta_g)$$



Inclusive jet R_{AA} - radius dependence

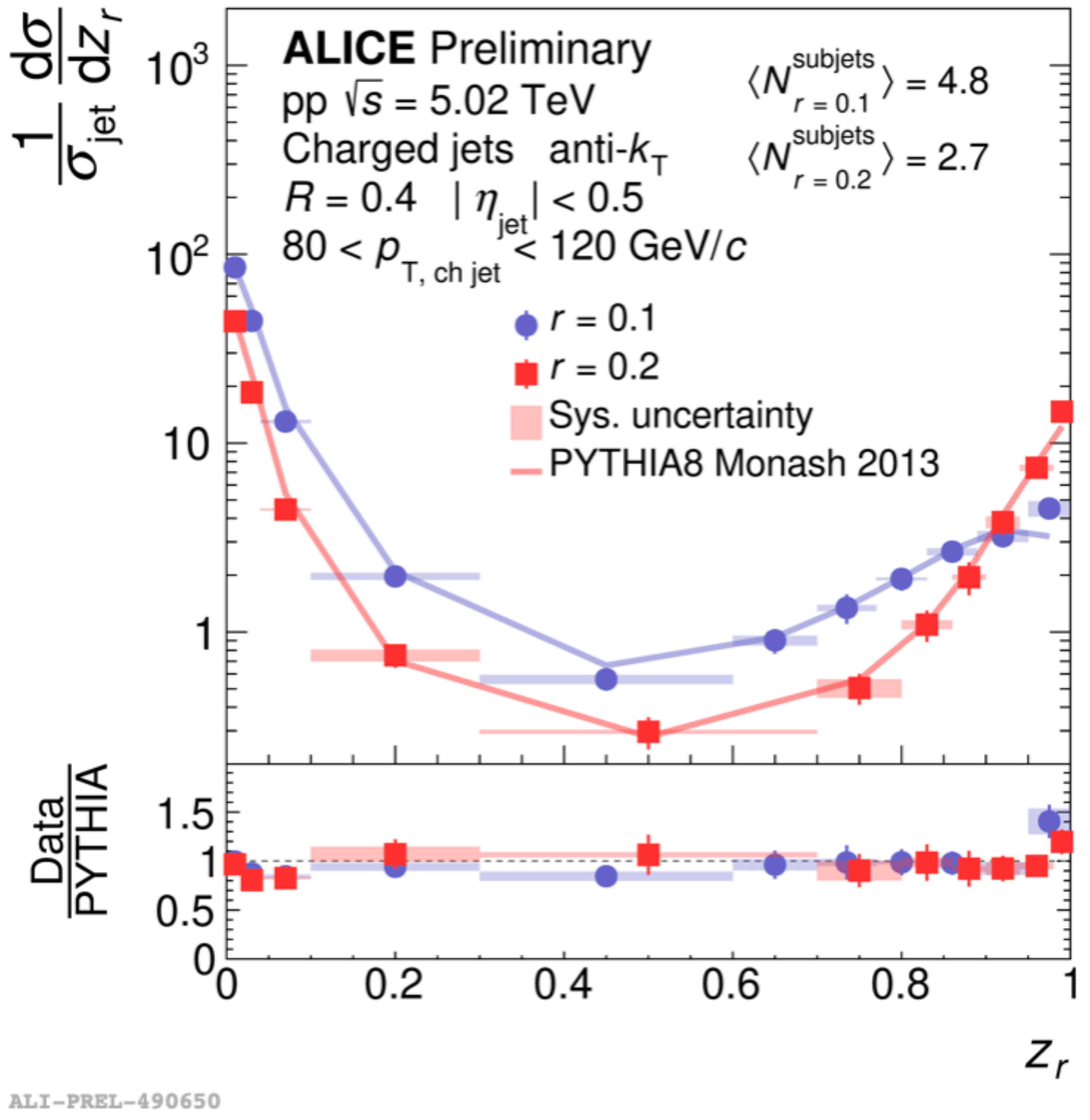
- CMS measurement
- Hadron R_{AA} for $R \to 0$
- Could be included in an updated fit

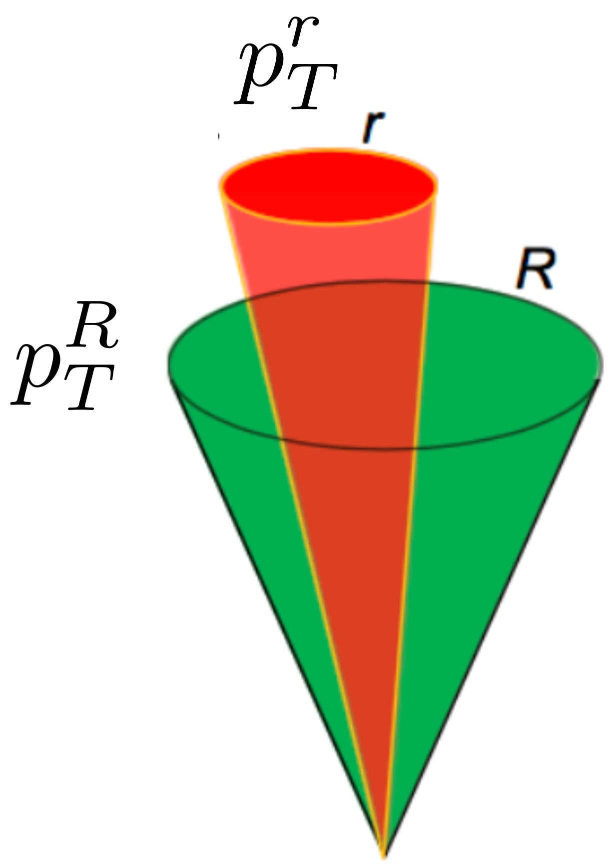


CMS, JHEP 05 (2021) 284

Applications to jet substructure

- Leading & inclusive subjets in pp





$$z_r = p_T^r / p_T^R$$

see Dai, Kim, Leibovich `16
Kang, FR, Waalewijn `17
Neill, FR, Sato `21

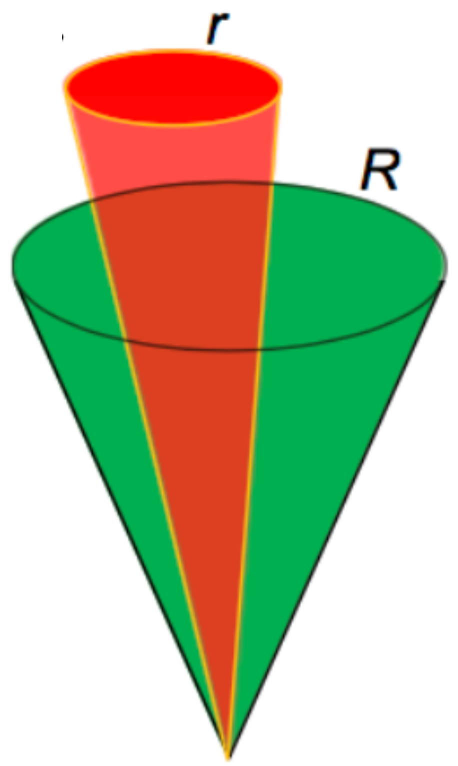
https://alice-figure.web.cern.ch/node/19990 *Figures from J. Mulligan, LHCP `21*

Applications to jet substructure

- Subjet modification in AA

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_T \mathrm{d}\eta \mathrm{d}z_r} \sim \sum_{abcd} f_a \otimes f_b \otimes H_{abc} \otimes J_{cd}^{\mathrm{med}} \times J_d^{\mathrm{med}}(z_r)$$

$$z_r = p_T^r / p_T^R$$



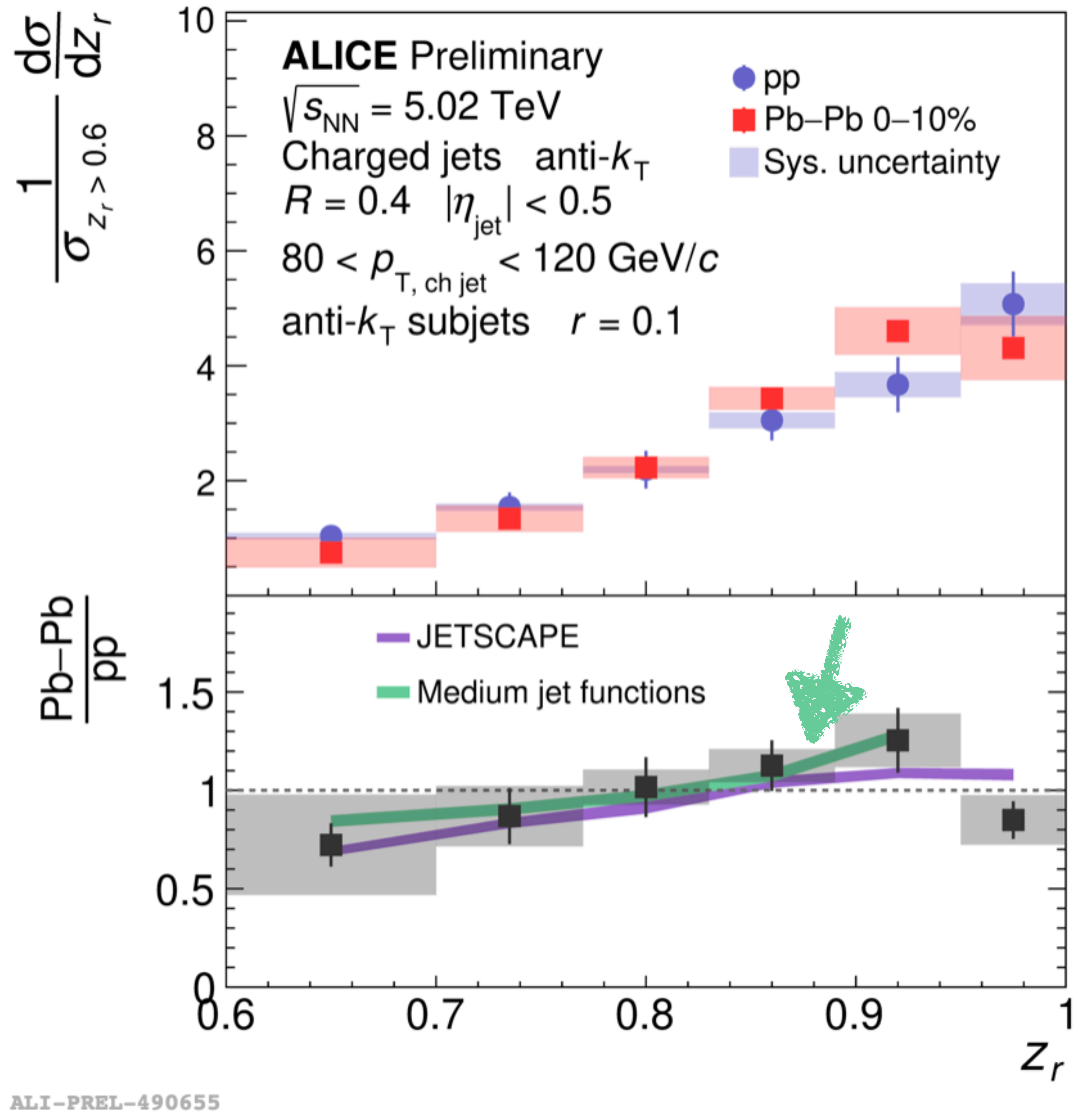
- Extracted from inclusive jet data alone
- Test of universality

Applications to jet substructure

- Subjet modification in AA

$$\frac{d\sigma}{dp_T d\eta dz_r} \sim \sum_{abcd} f_a \otimes f_b \otimes H_{abc} \otimes J_{cd}^{\rm med} \times J_d^{\rm med}(z_r)$$

- Extracted from inclusive jet data alone
- Test of universality

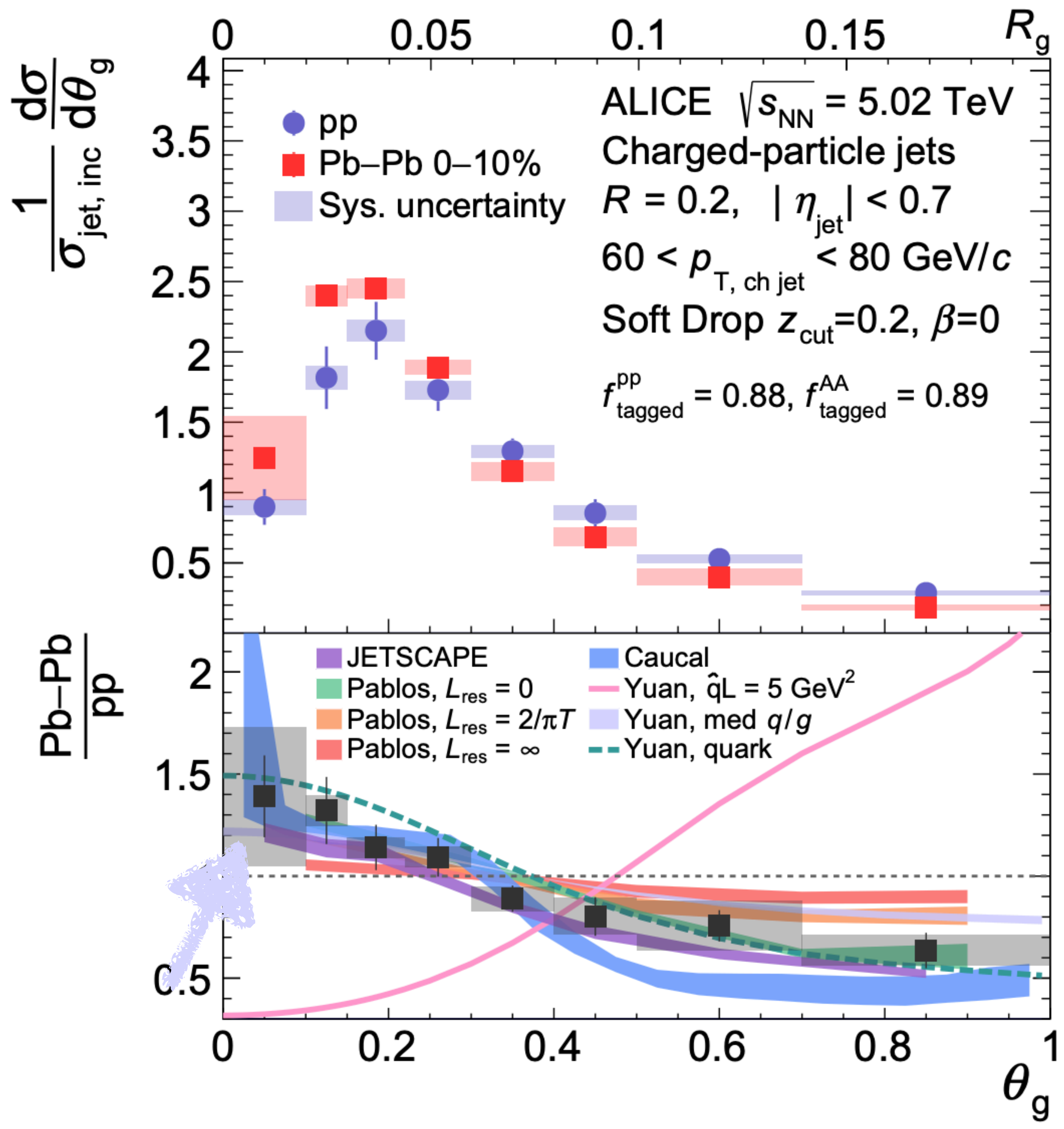


https://alice-figure.web.cern.ch/node/19990

Figure from J. Mulligan, LHCP `21

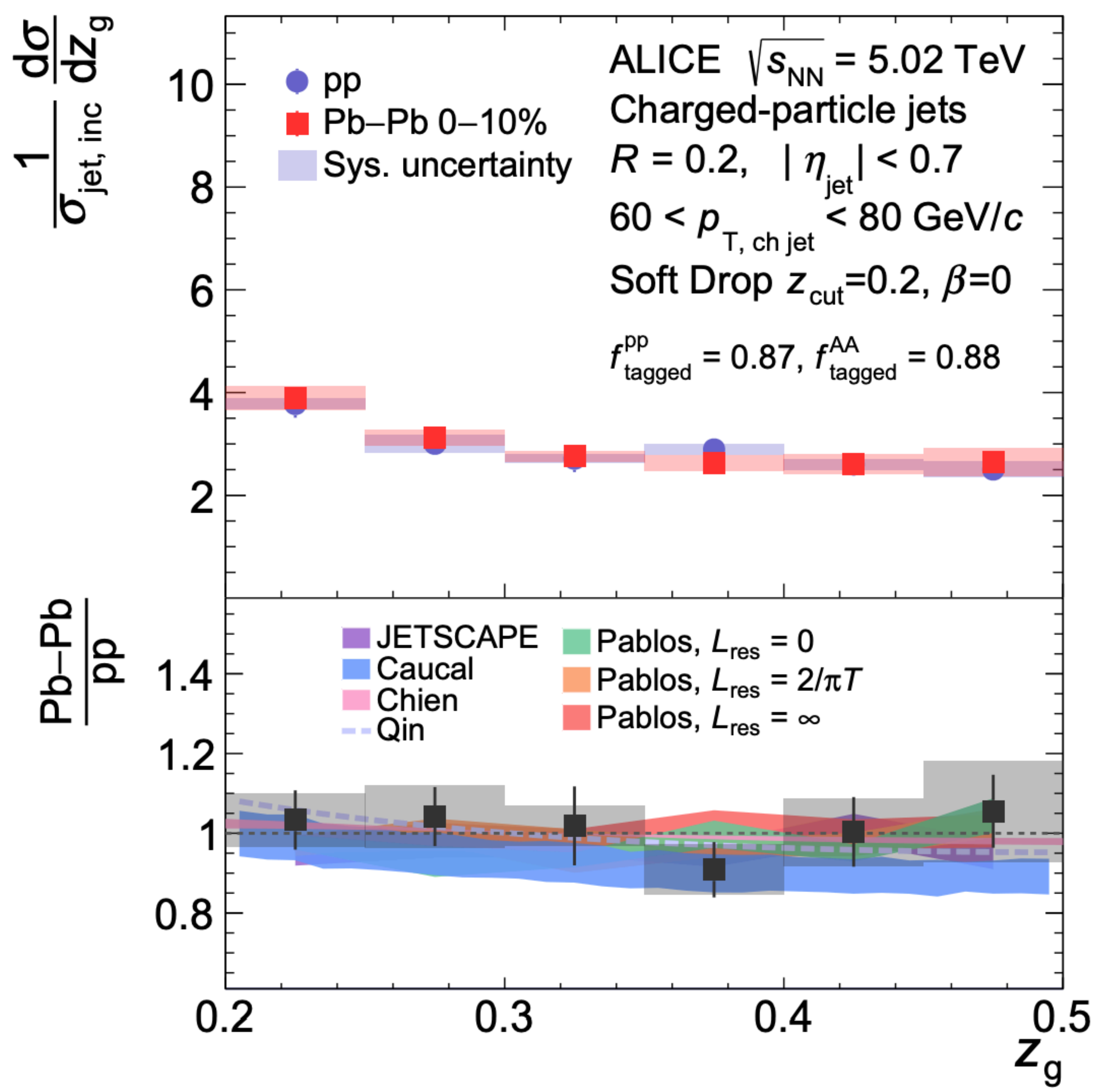
Applications to jet substructure

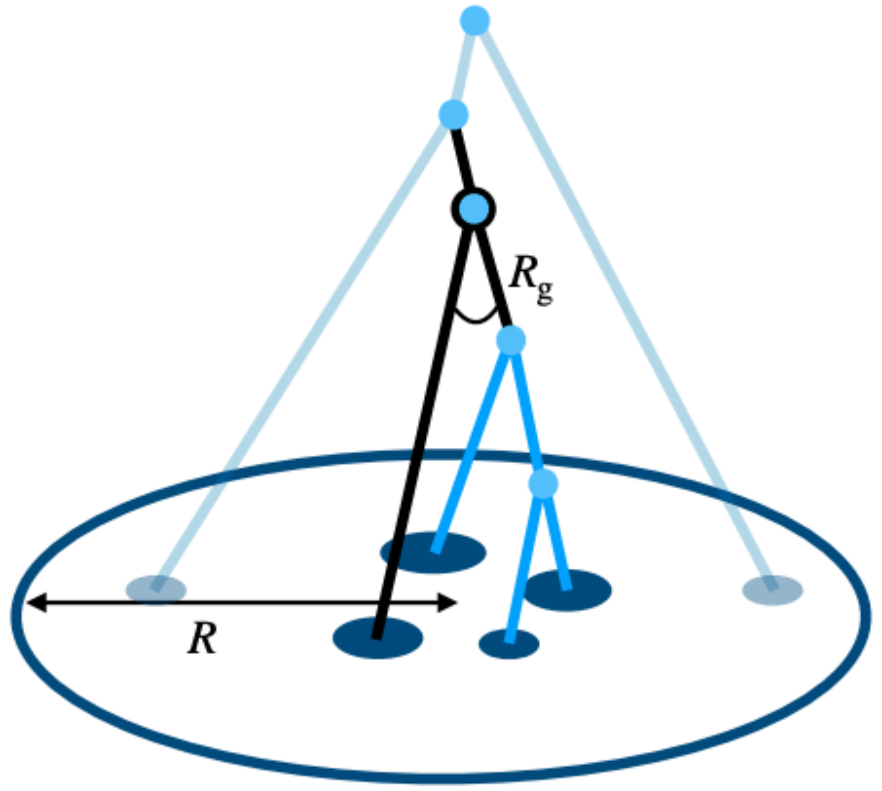
- Groomed radius R_g, medium jet functions and p_T broadening



ALICE, 2107.12984

- Momentum sharing fraction z_g, no sensitivity to medium jet functions





Factorization

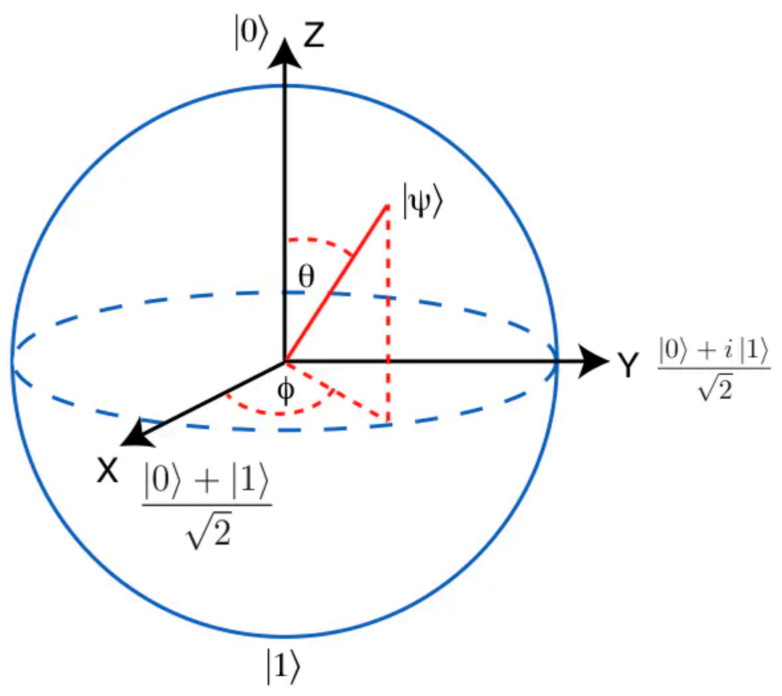
$$f_q\, J_q(\theta_g) + f_g\, J_g(\theta_g)$$

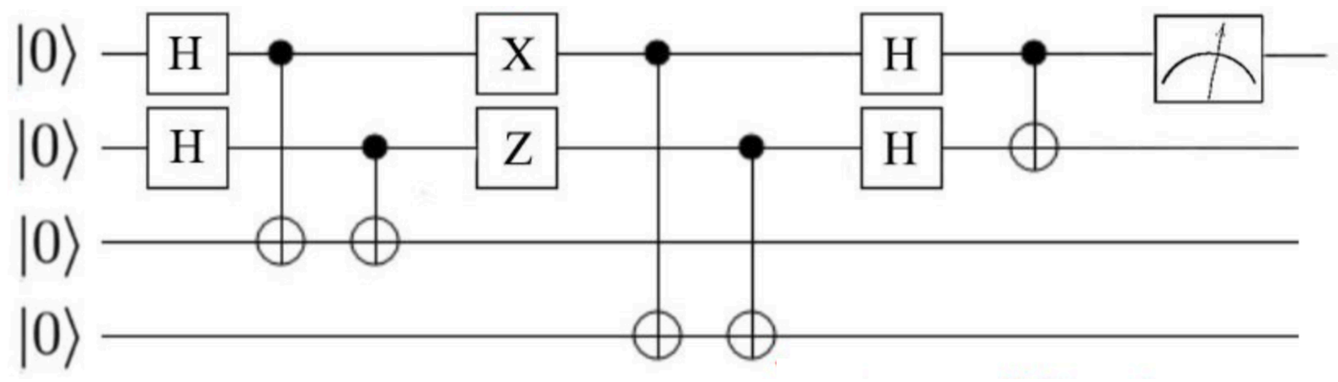
Outline

- Introduction
- QCD factorization in heavy-ion collisions
- Quantum simulations of open quantum systems
- Conclusions

Quantum computing

- Universal gate set: single-qubit rotations and CNOT

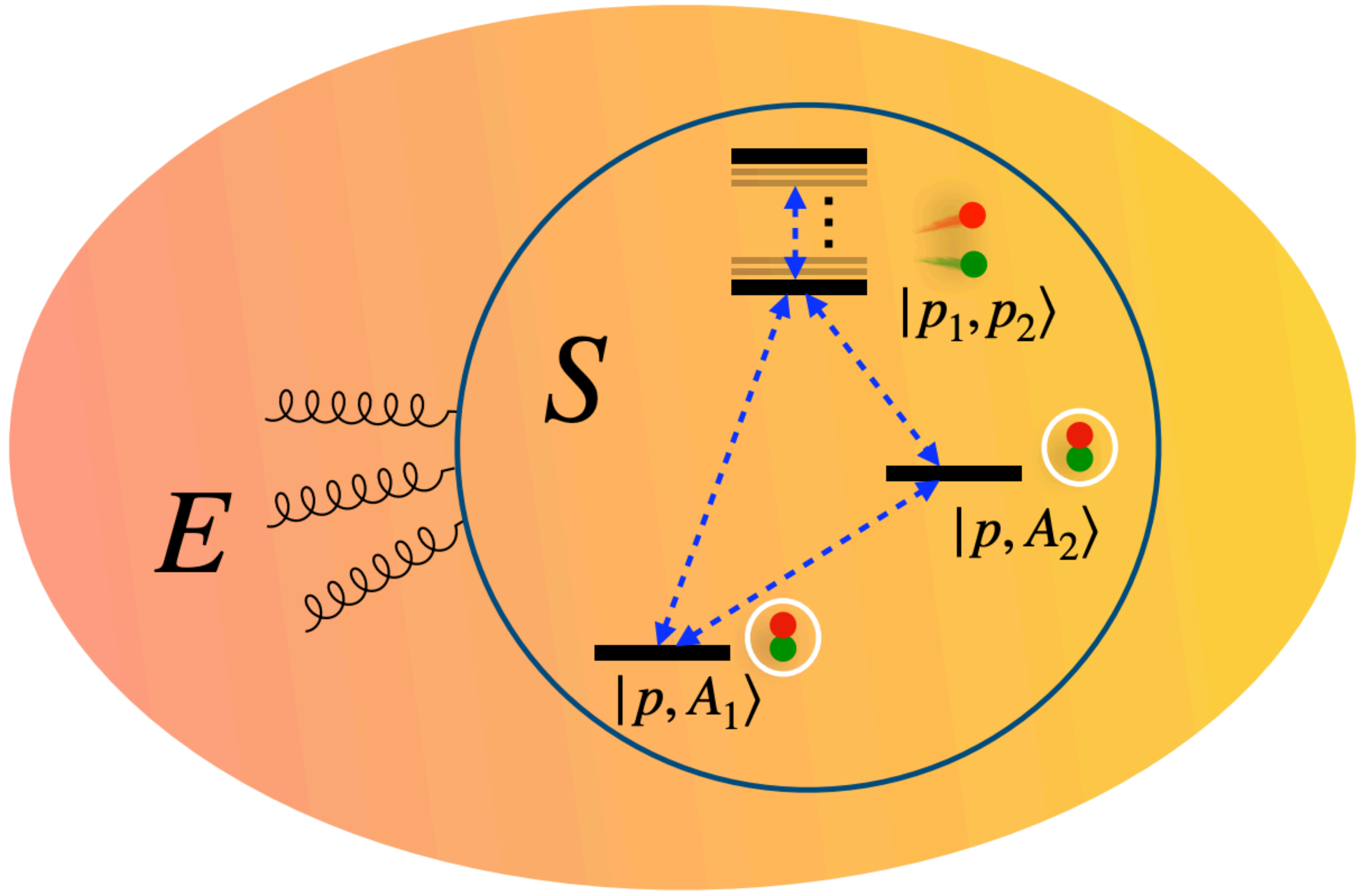




IBM Q, rigetti, Google, IONQ, Honeywell, Microsoft

…

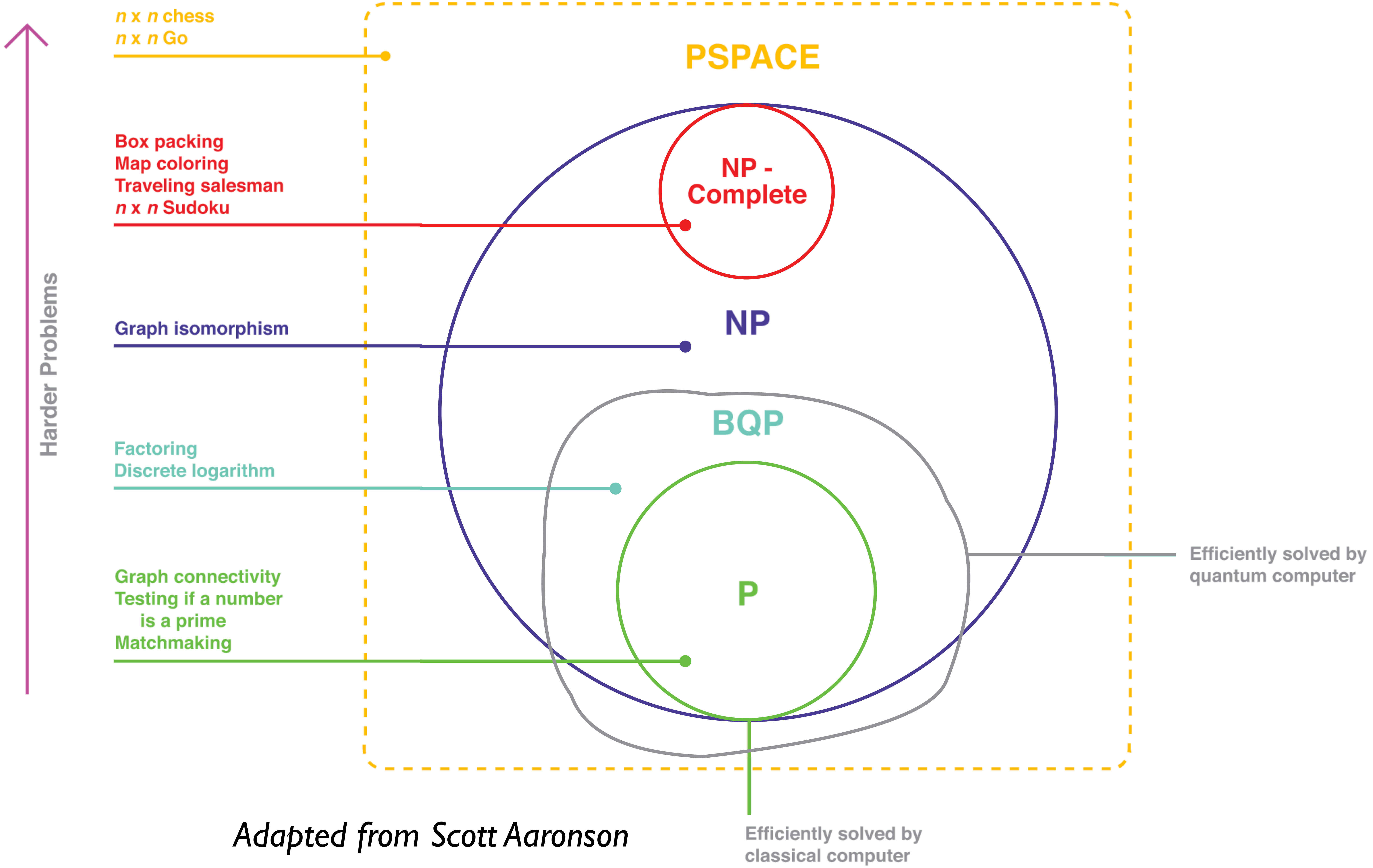
- Simulation of open quantum systems
- Extension of 2-level system



see talk by Bert de Jong

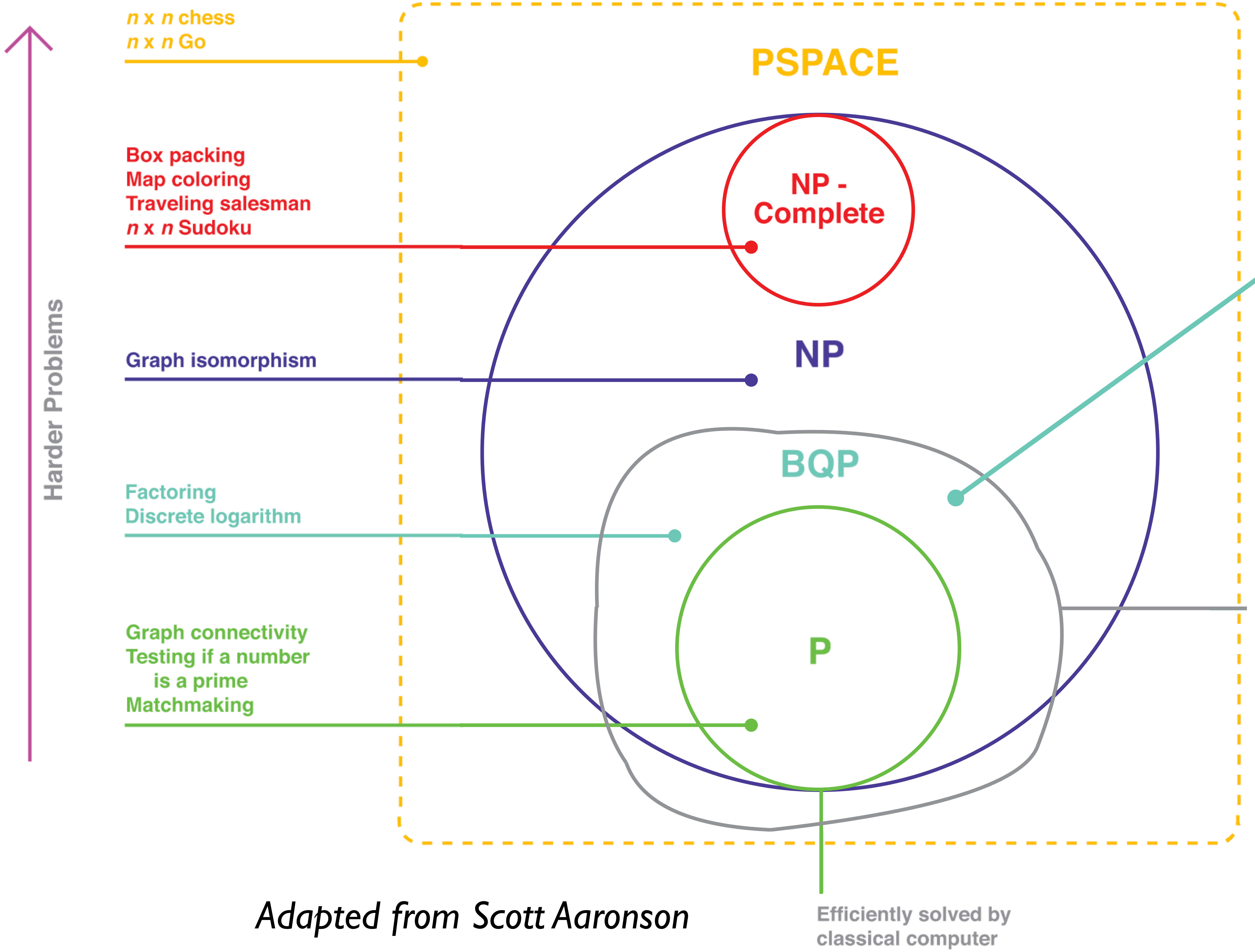
See also e.g. Cohen, Lamm, Lawrence, Yamauchi `21, Barata, Salgado `21

Computational complexity



Adapted from Scott Aaronson

Computational complexity



Adapted from Scott Aaronson

- Standard Model/QCD?
- Scalar field theory

  Jordan, Lee, Preskill `10-`14

$$|\langle X|U(t,t_0)|AA\rangle|^2$$

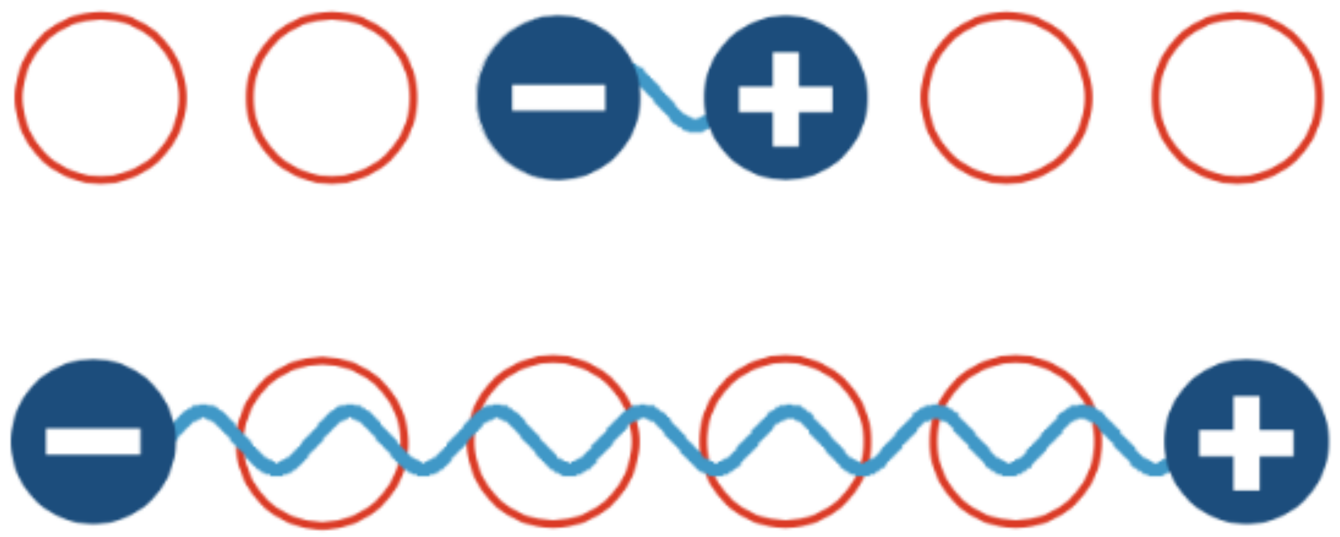
→ Significant resources at high energies

→ Focus on isolated phase space, jets, and low energy

Schwinger model

- 1+1 dimensional version of QED *Schwinger `62*
- Simplest field theory with fermions and a U(1) gauge field
- Spontaneous chiral symmetry breaking
- Confining potential $\sim r$
- Model for hadronization & string breaking in QCD e.g. Pythia
- Anomalous soft photon production

Loshaj, Kharzeev `13



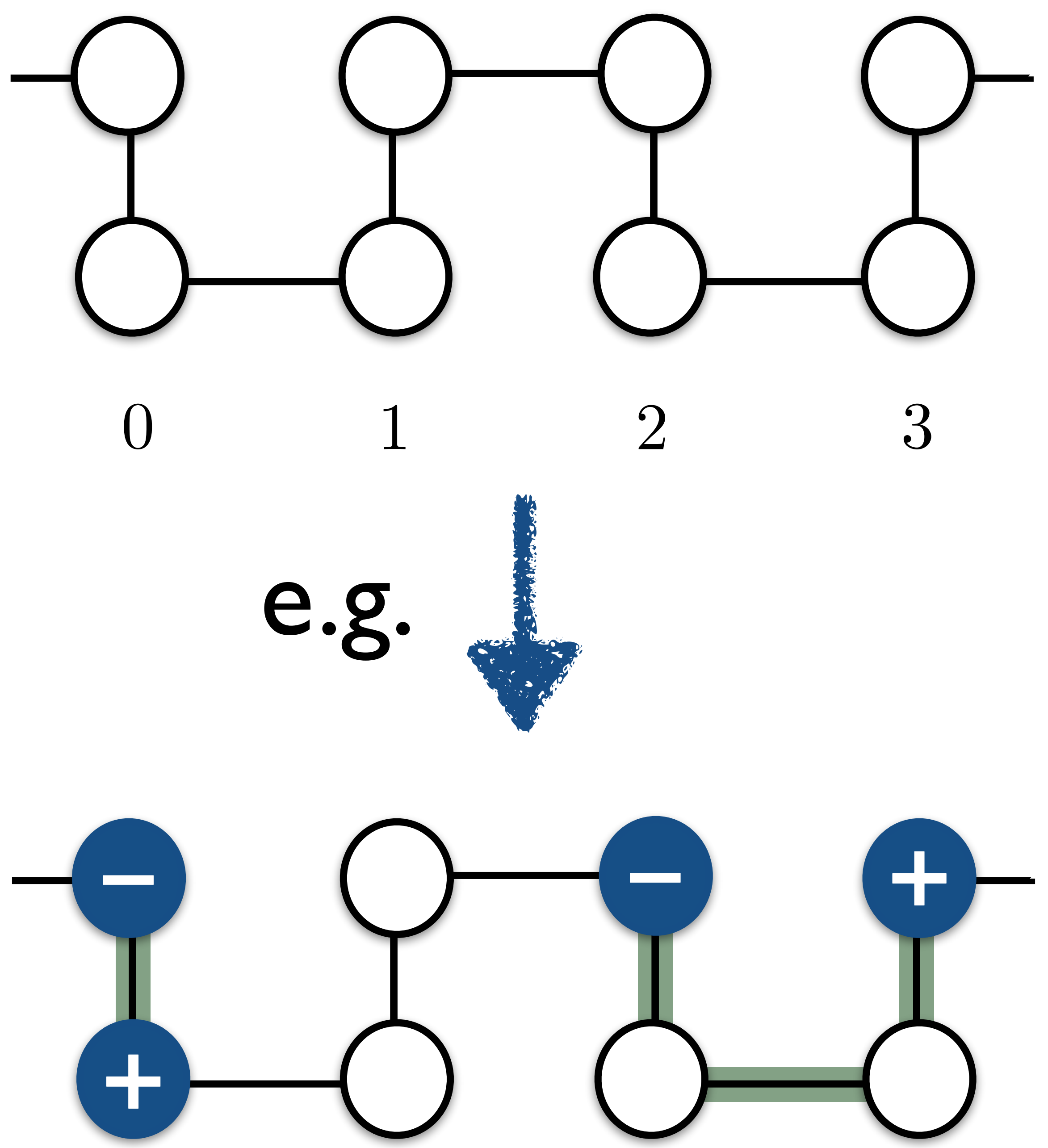
$$\mathcal{L} = \overline{\psi}(i\not{D} - m)\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

Hamiltonian of the Schwinger model

Kogut, Susskind `70s

- Time continuous, 1-dimensional spatial lattice $x = na$
- Continuum limit $a \to 0$

$$H_S = \frac{1}{2a}\sum_{n=0}^{N_f-1}\left(\sigma^+(n)L_n^-\sigma^-(n+1) + \sigma^+(n+1)L_n^+\sigma^-(n)\right)$$
$$+\sum_{n=0}^{N_f-1}\left(\frac{ae^2}{2}\ell_n^2 + m(-1)^n\frac{\sigma_z(n)+1}{2}\right)$$



- Study real-time evolution

$$|\psi(t)\rangle = U|\psi(0)\rangle = e^{-iH_S t}|\psi(0)\rangle$$

Hamiltonian of the Schwinger model

Kogut, Susskind `70s

- Time continuous, 1-dimensional spatial lattice $x = na$
- Continuum limit $a \to 0$

$$
H_S = \frac{1}{2a}\sum_{n=0}^{N_f-1}\left(\sigma^+(n)L_n^-\sigma^-(n+1)+\sigma^+(n+1)L_n^+\sigma^-(n)\right)
+\sum_{n=0}^{N_f-1}\left(\frac{ae^2}{2}\ell_n^2+m(-1)^n\frac{\sigma_z(n)+1}{2}\right)
$$

Different constraints e.g. zero momentum $\mathbf{k}=0,\ N=4$

Savage et al. `18

$$
H_S^{\mathbf{k}=\mathbf{0},+} =
\begin{pmatrix}
-4m & \frac{\sqrt{2}}{a} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{\sqrt{2}}{a} & \frac{ae^2}{2}-2m & \frac{1}{a} & \frac{1}{\sqrt{2}a} & \frac{1}{\sqrt{2}a} & \frac{1}{\sqrt{2}a} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{1}{a} & ae^2 & 0 & 0 & 0 & \frac{1}{2a} & \frac{1}{a} & \frac{1}{2a} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{1}{\sqrt{2}a} & 0 & ae^2 & 0 & 0 & 0 & 0 & \frac{1}{\sqrt{2}a} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{1}{\sqrt{2}a} & 0 & 0 & ae^2 & 0 & 0 & \frac{1}{\sqrt{2}a} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{1}{\sqrt{2}a} & 0 & 0 & 0 & ae^2 & 0 & 0 & \frac{1}{\sqrt{2}a} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{1}{2a} & 0 & 0 & 0 & \frac{3}{2}ae^2-2m & 0 & 0 & \frac{1}{2a} & \frac{1}{2a} & \frac{1}{2a} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{1}{a} & 0 & \frac{1}{\sqrt{2}a} & 0 & 0 & \frac{3}{2}ae^2+2m & 0 & \frac{1}{2a} & 0 & \frac{1}{2a} & \frac{1}{a} & 0 & 0 & 0 & 0 & 0 & 0 \\
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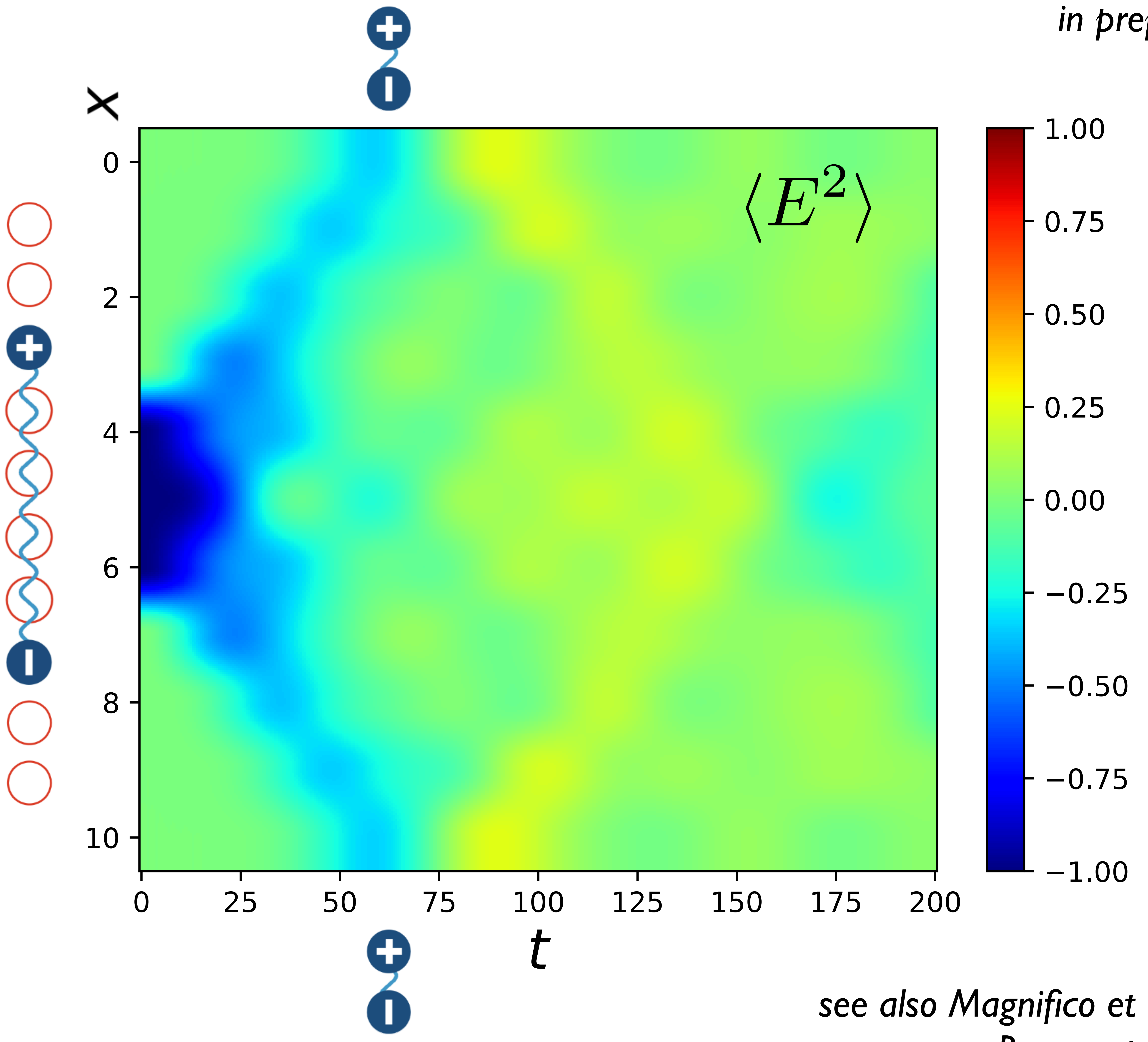
0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{2a} & 0 & \frac{1}{2a} & 0 & 2ae^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{2a} & \frac{1}{2a} & 0 & 0 & 0 & 2ae^2 & 0 & \frac{1}{2a} & \frac{1}{2a} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{a} & 0 & 0 & 0 & 0 & 2ae^2+4m & 0 & \frac{1}{a} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{2a} & 0 & \frac{1}{2a} & 0 & \frac{5}{2}ae^2-2m & 0 & \frac{1}{2a} & & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{2a} & 0 & \frac{1}{2a} & \frac{1}{a} & 0 & \frac{5}{2}ae^2+2m & \frac{1}{a} & \frac{1}{\sqrt{2}a} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{2a} & \frac{1}{a} & 3ae^2 & 0 & \frac{1}{a} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{\sqrt{2}a} & 0 & 3ae^2 & \frac{1}{\sqrt{2}a} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{a} & \frac{1}{\sqrt{2}a} & \frac{7}{2}ae^2-2m & \frac{1}{a} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{a} & 4ae^2-4m
\end{pmatrix}
$$

The string-breaking mechanism

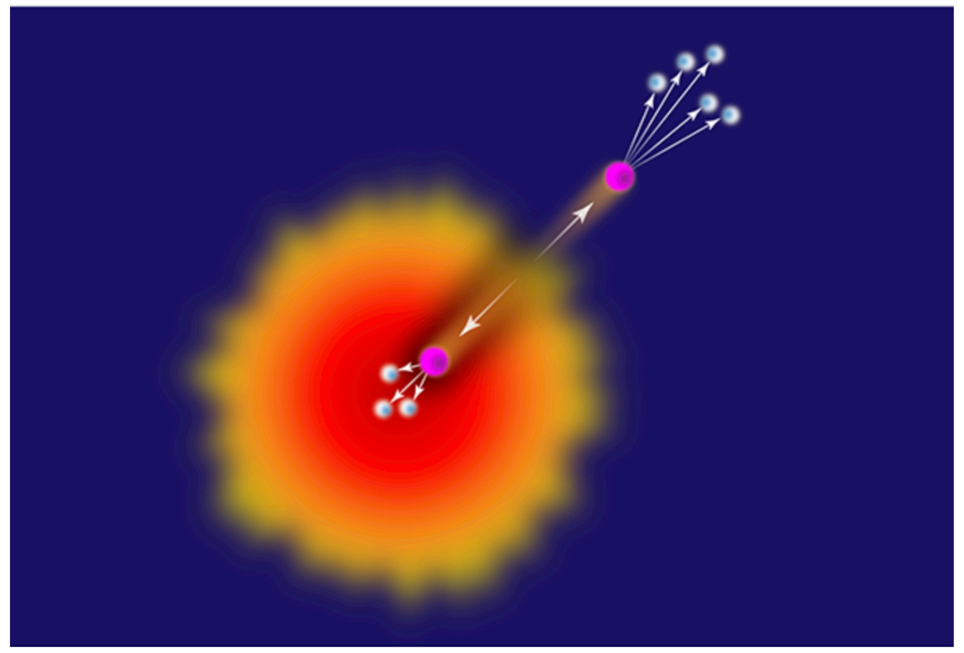
- Model of the hadronization
- Real-time evolution
- Vacuum evolution
- Study as an OQS *in progress*

in preparation



see also Magnifico et al.
Berges et al.

Open quantum systems



- Couple system to a thermal environment
- Schwinger model + thermal scalar field theory
- Yukawa-type interaction
- Non-equilibrium dynamics
- Eventually approximates thermalization

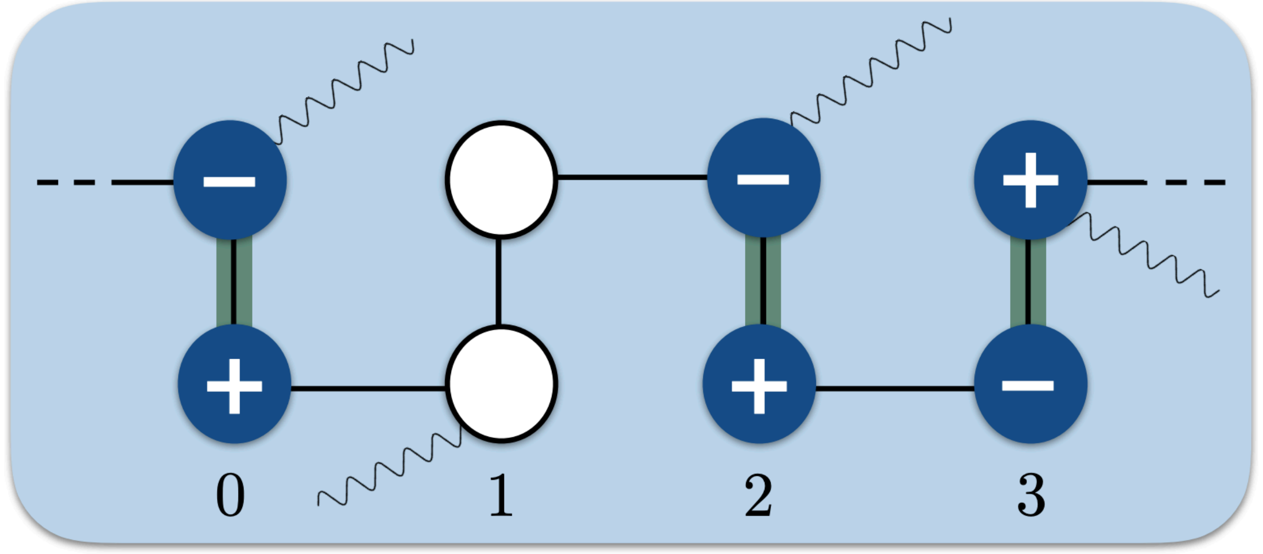
$$H = H_S + H_E + H_I \quad \text{where}$$

$$H_E = \int \mathrm{d}x \left[\frac{1}{2}\Pi^2 + \frac{1}{2}(\nabla\phi)^2 + \frac{1}{2}m_\phi^2\phi^2 + \frac{1}{3!}g\phi^3 \right]$$

$$H_I = \lambda \int \mathrm{d}x\, \phi(x)\overline{\psi}(x)\psi(x) = \int \mathrm{d}x\, O_E(x)O_S(x)$$

where $O_E(x) = \lambda\phi(x)$

$O_S(x) = \overline{\psi}(x)\psi(x)$



Jong, Lee, Mulligan, Ploskon, FR, Yao `21

Open quantum systems

see talks by Yukinao Akamatsu, Nora Brambilla, Michael Strickland

- Time evolve the density matrix - von Neumann equation

$$\rho = \sum_n p_n |\psi_n\rangle\langle\psi_n| \qquad \frac{\mathrm{d}\rho(t)}{\mathrm{d}t} = -i\big[H, \rho(t)\big]$$

- Trace out environmental degrees of freedom $\rho_S^{(\mathrm{int})}(t) = \mathrm{Tr}_E\big(\rho^{(\mathrm{int})}(t)\big)$

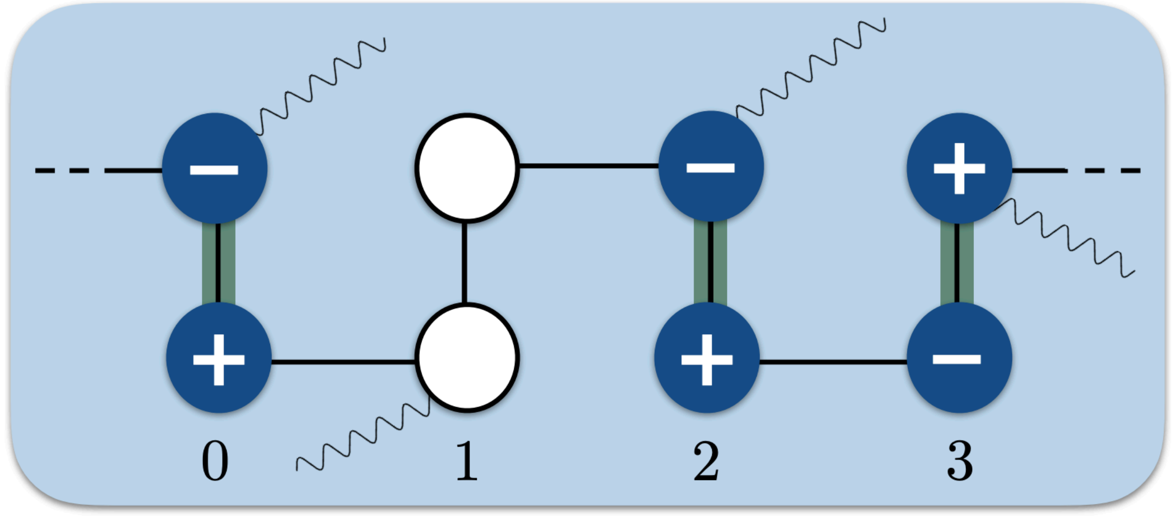
- Assume environment is in thermal equilibrium $\rho_E^{(\mathrm{int})}(t) = \rho_E = \dfrac{e^{-\beta H_E}}{\mathrm{Tr}_E e^{-\beta H_E}}$

- Can be formally solve as $\rho_S^{(\mathrm{int})}(t) = \mathrm{Tr}_E\big(U(t)\rho^{(\mathrm{int})}(0)U^\dagger(t)\big)$

with $U(t) = \mathcal{T}\exp\Big(-i\int_0^t H_I^{(\mathrm{int})}(t')\,\mathrm{d}t'\Big)$

Hamiltonian of the Schwinger model

Jong, Lee, Mulligan, Ploskon, FR, Yao `21



- Work in the Quantum Brownian Motion limit

$\tau_R \gg \tau_E \quad \longrightarrow \quad$ Markovian approximation

$\tau_S \gg \tau_E \quad \longrightarrow \quad$ Valid if $\quad T \gg H_S$

- Lindblad equation for $\mathbf{k} = 0$

$$\frac{\mathrm{d}\rho_S(t)}{\mathrm{d}t} = -i\big[H_S, \rho_S(t)\big] + L\rho_S(t)L^\dagger - \frac{1}{2}\{L^\dagger L, \rho_S(t)\}$$

with $\quad L = \sqrt{aN_f D(k_0 = 0, k = 0)}\Big(O_S - \frac{1}{4T}[H_S, O_S]\Big)$

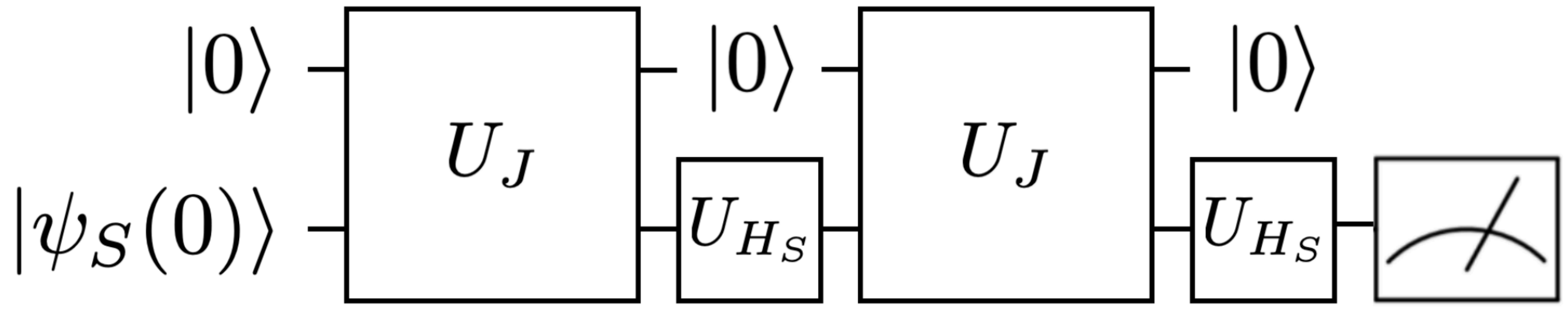
Quantum algorithm for non-unitary evolution

Jong, Lee, Mulligan, Ploskon, FR, Yao `21

- Time evolve the density matrix instead of pure states

$$\frac{\mathrm{d}\rho_S(t)}{\mathrm{d}t} = -i\big[H_S, \rho_S(t)\big] + L\rho_S(t)L^\dagger - \frac{1}{2}\{L^\dagger L, \rho_S(t)\}$$

- Stinespring dilation theorem



where

$$U_J = e^{-iJ\sqrt{\Delta t}}$$

$$J = \begin{pmatrix} 0 & L^\dagger \\ L & 0 \end{pmatrix}$$

$$U_{H_S} = e^{-iH_S\sqrt{\Delta t}}$$

- Time-irreversible
- Evolve for N_{cycle} in small time steps Δt

see also e.g. Cleve, Wang `16
Hu, Xia, Kais `20
Jong, Metcalf, Mulligan, Ploskon, FR, Yao `20
Metcalf, Kemper, Jong et al. `21

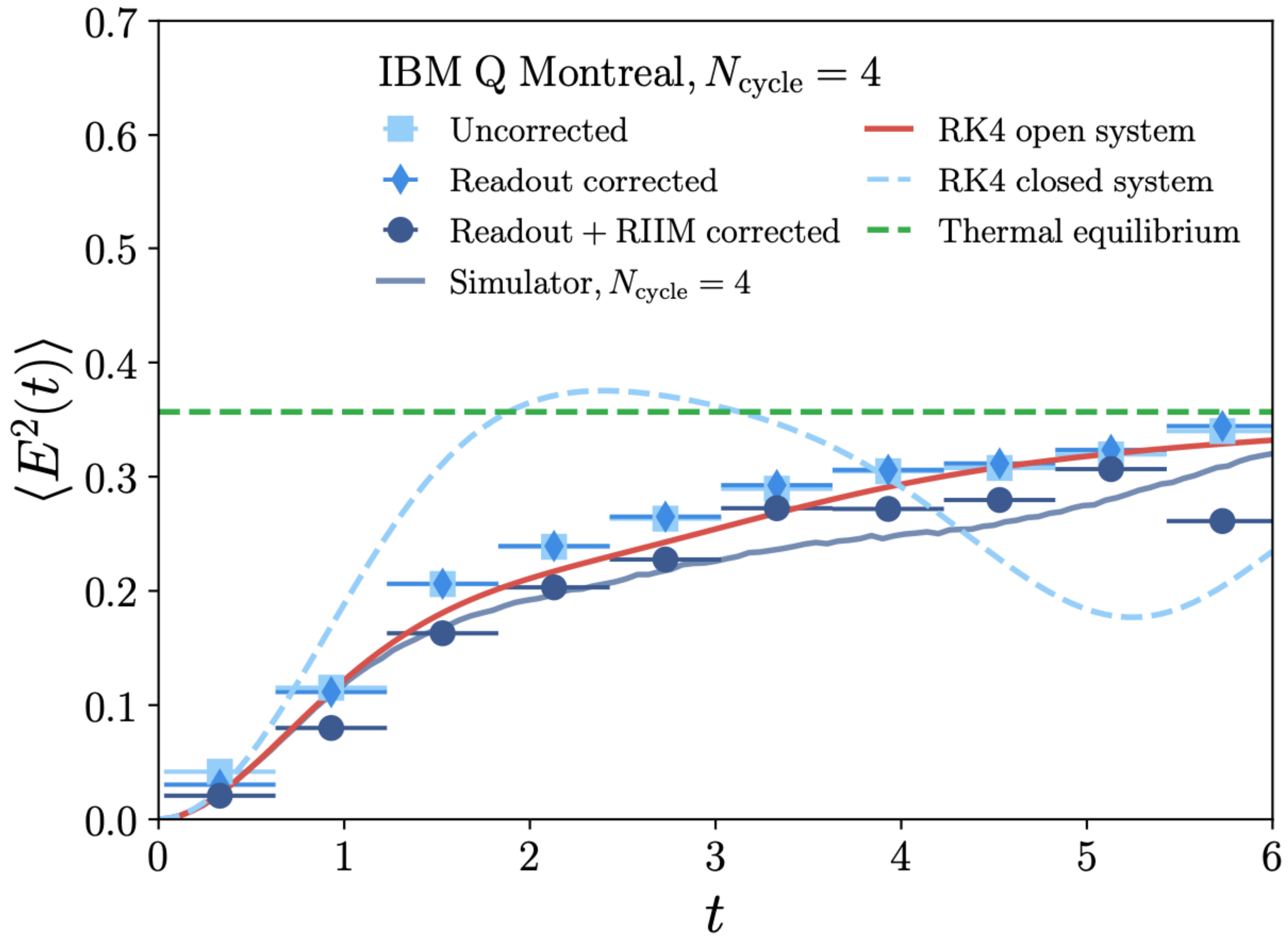
Simulation on IBMQ

Jong, Lee, Mulligan, Ploskon, FR, Yao `21

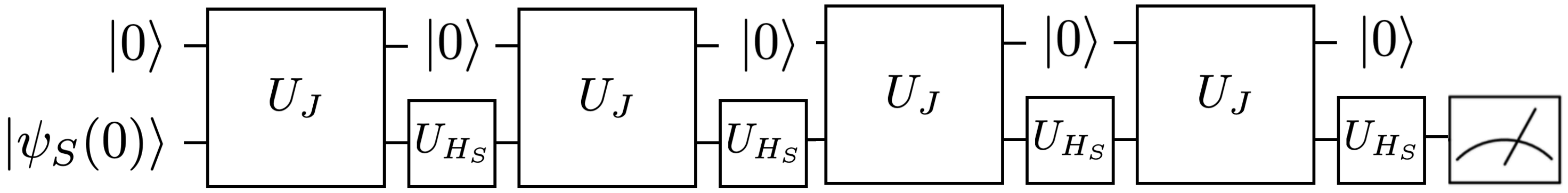
- Vacuum fluctuations
- Readout and gate error mitigation

  see talk by Bert de Jong

- 6 qubits with up to 200 CNOT and 500 single-qubit gates
- Approximate preparation of thermal state from non-equilibrium dynamics



Electric field



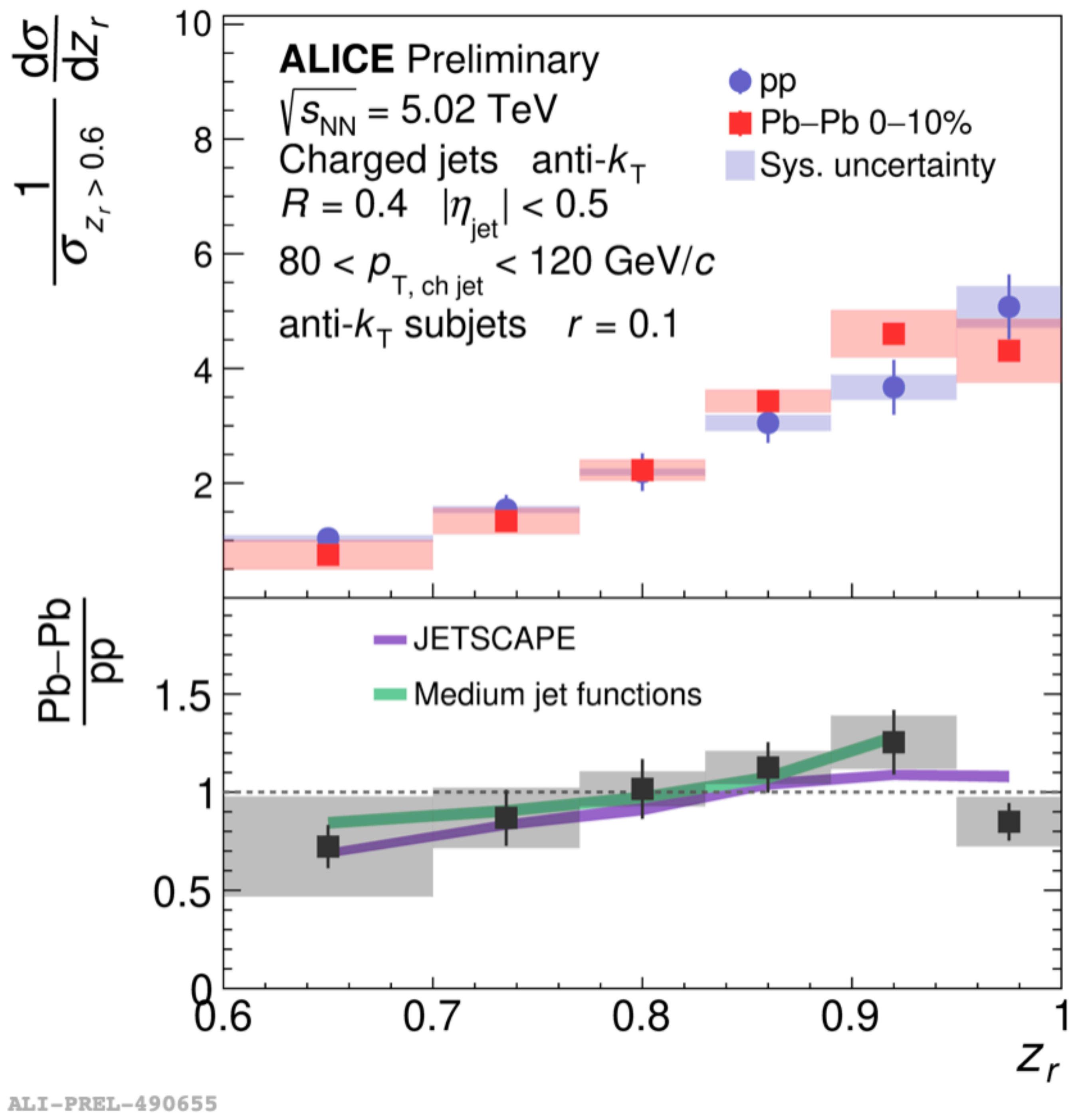
Outline

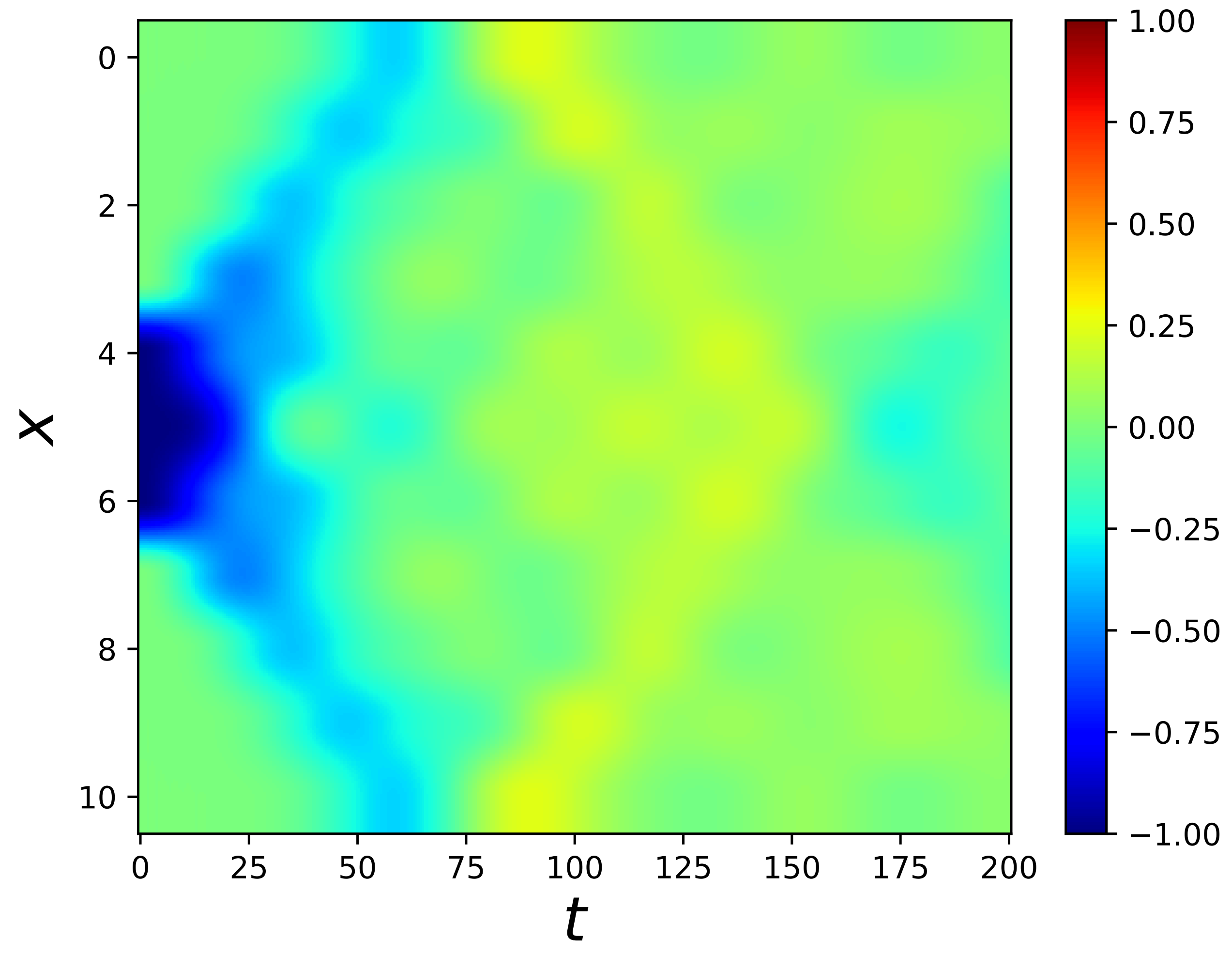
- Introduction
- QCD factorization in heavy-ion collisions
- Quantum simulations of open quantum systems
- Conclusions

Conclusions

- Exploration of QCD factorization in heavy-ion collisions
- Medium jet functions
- Motivates further theory studies

- Quantum computing may allow for first principles simulations of QCD scattering
- Open quantum systems
- Development in early stages

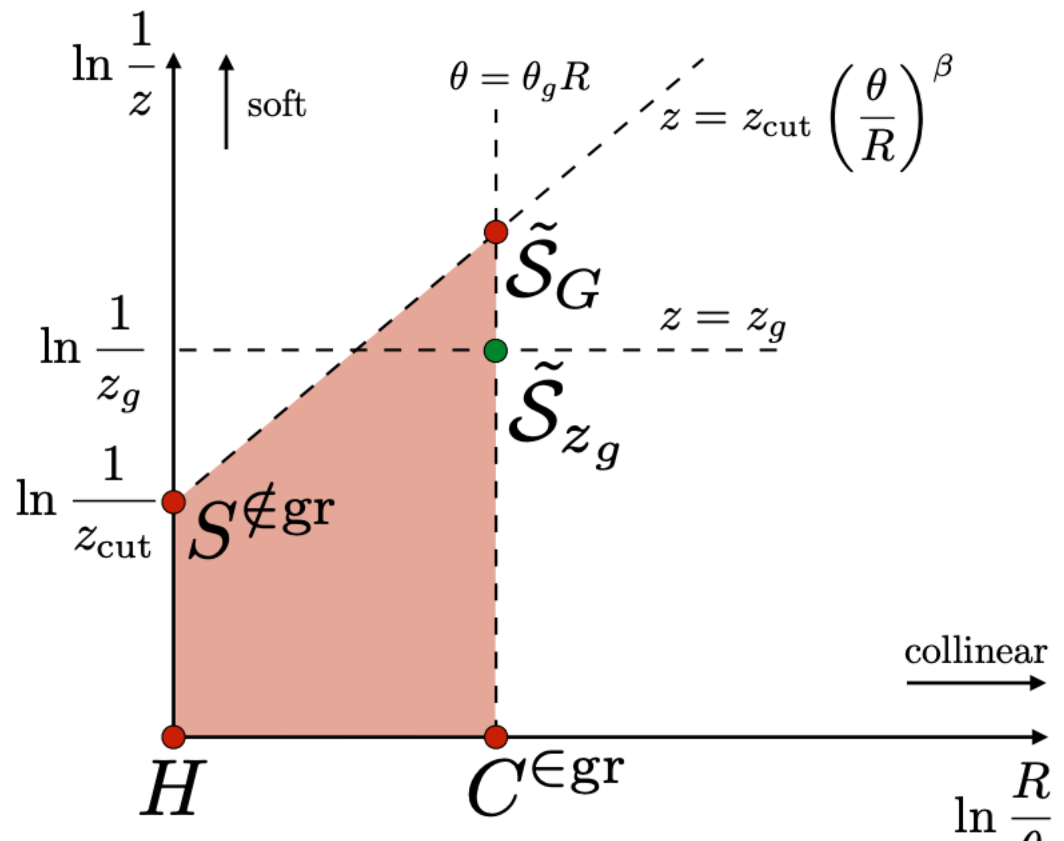




Factorization for z_g

Cal, Lee, FR, Waalewijn `21

$$\frac{d\sigma}{dp_T\, d\eta\, dz_g\, d\theta_g} = \sum_i f_i(p_T, \eta, R, \mu) \times \tilde{\mathcal{G}}_i(z_g, \theta_g, p_T R, z_{\rm cut}, \beta, \mu)$$



with $$\tilde{\mathcal{G}}_i = \Theta(1/2 > z_g > z_{\rm cut}\theta_g^\beta)\tilde{H}_i(p_T R, \mu)\, C_i^{\in \rm gr}(\theta_g p_T R, \mu) \times S_i^{\notin \rm gr}(z_{\rm cut} p_T R, \beta, \mu)\, \tilde{S}_G(z_{\rm cut}\theta_g^{1+\beta} p_T R, \beta, \mu) \times S_i^{\rm NG}(z_{\rm cut})\Big[\frac{d}{dz_g}\frac{d}{d\theta_g}\tilde{S}_{z_g}(z_g\theta_g p_T R, \mu) + \tilde{S}_{i,1}^{\prime \rm NG}(z_g\theta_g, z_g) + \tilde{S}_{i,2}^{\prime \rm NG}\Big(z_g\theta_g, \frac{z_g}{z_{\rm cut}\theta_g^\beta}\Big)\Big]$$