

Non-perturbative quark production and evolution in the dynamic glasma from WAGASHI

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Papers: 2608.13393 [hep-ph] and work in-progress

https://home.hiroshima-u.ac.jp/njbenoit/

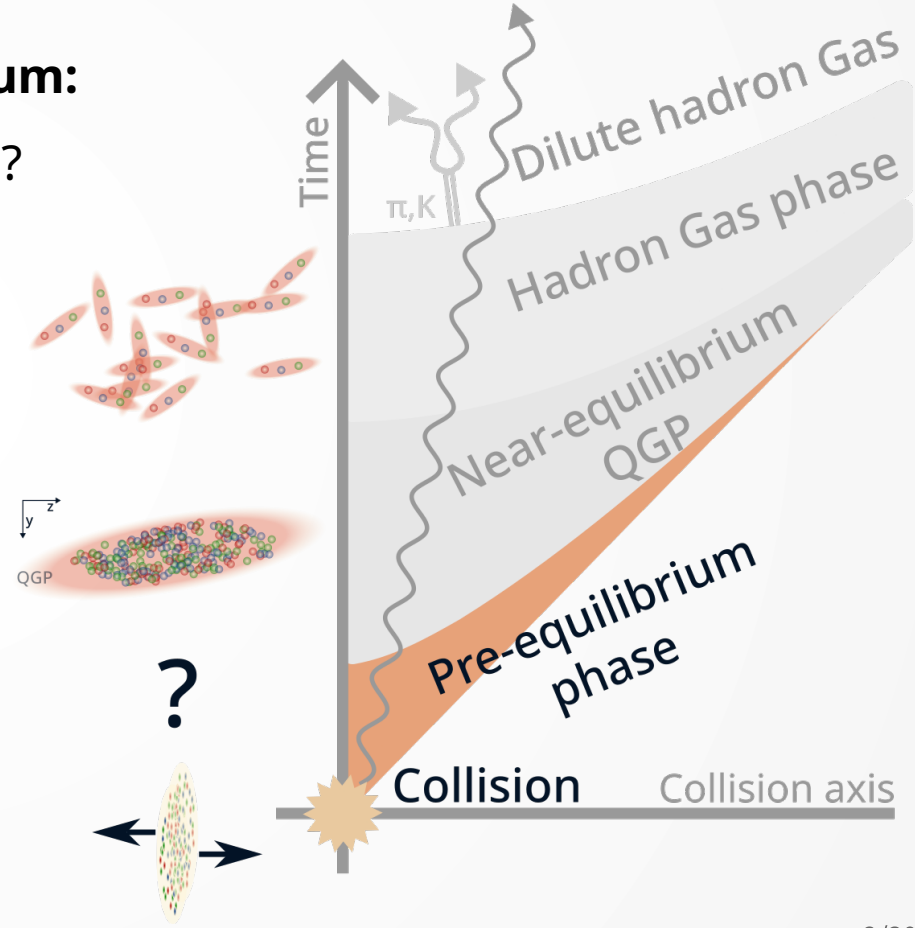
Relativistic heavy-ion collision modeling

After the collision, things are far from equilibrium:

How is energy and charge converted into QGP?

Model approaches:

- Dense gluon field (glasma)
- Dilute gluon gas (kinetic)
- Parton cascade
- etc.



Relativistic heavy-ion collision modeling

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How is energy and charge converted into QGP?

Our approach:

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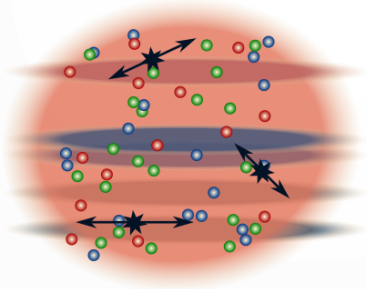
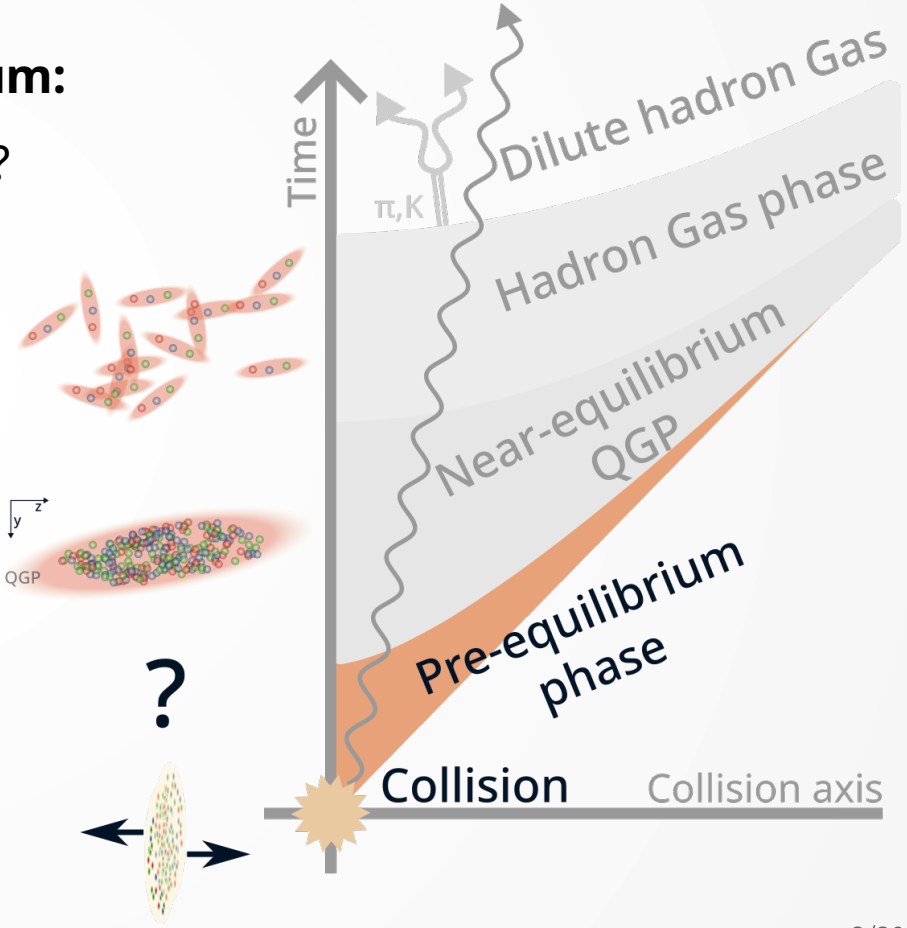
- Parton cascade
- etc.

Goal:

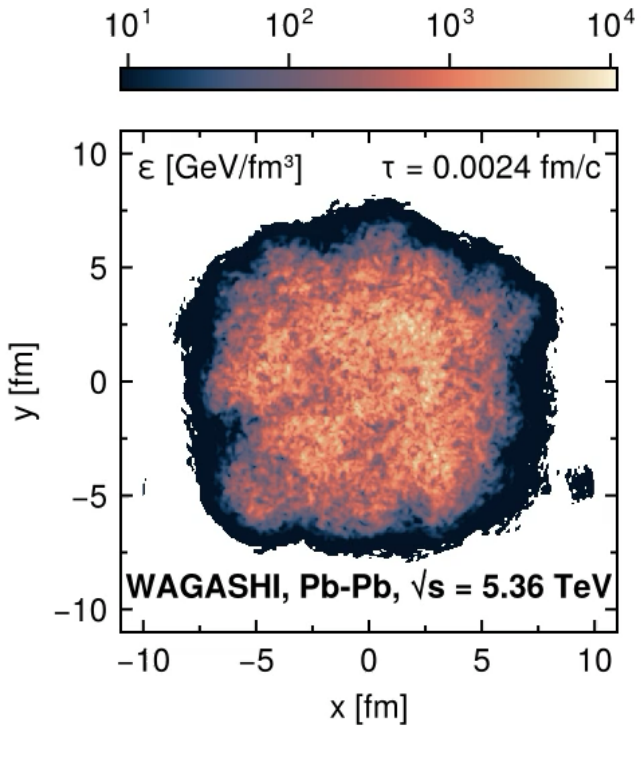
- Quantitative model for charge (spin) from the glasma





WAGASHI (和菓子 , traditional Japanese sweets)

W = Wong-precessing, A = Anisotropic, G = Glasma, A = And, SH = Schwinger-produced, I = Initial-conditions



WAGASHI is a cPIC model

- Classical Yang-Mills + Wong baseline
- Tested p-Pb, O-O, Au-Au, and Pb-Pb
- Available now for download (later fully open source)

+ more new physics:

- Dynamically produces quarks with Schwinger mechanism
- BMT equations for spin transport

Other approaches ignore quarks (IP-glasma)
or quarks are introduced by hand

[**NJB**, C. Nonaka, H. Taya; 2608.13393 [hep-ph] and https://home.hiroshima-u.ac.jp/~njbenoit/wagashi/]

Introducing WAGASHI



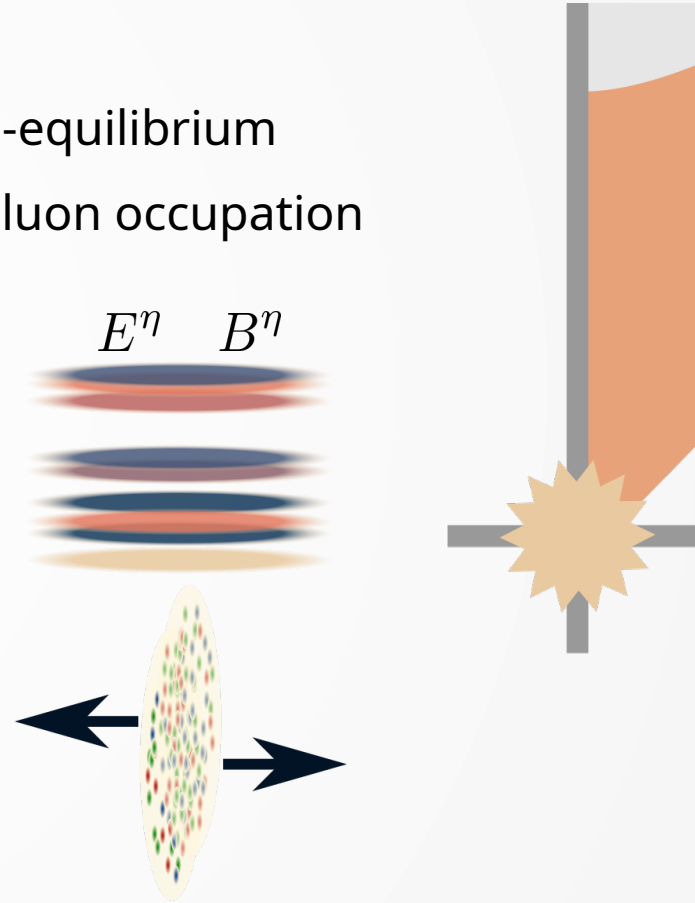
From: A.P. KALWEIT, PoS (EPS-HEP2023) 027

Right after the collision

The glasma for the time evolution

- Many gluons are liberated from the ions and are far-from-equilibrium
- Region is highly energetic (weakly coupled) with a large gluon occupation

Proper time in Milne coordinates $\tau > 0, \qquad \frac{1}{\alpha_s} \gg 1$



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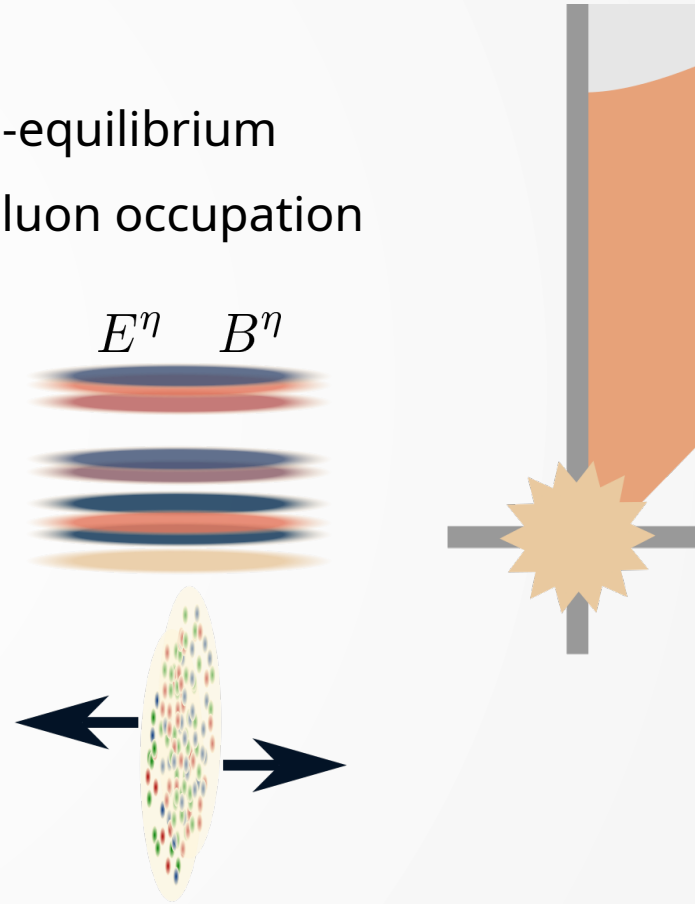
Proper time in Milne coordinates $\tau > 0, \qquad \frac{1}{\alpha_s} \gg 1$

- Valid regime of classical SU(N) Yang-Mills theory

$$D_\mu F^{\mu\nu} = 0$$

- The **glasma** is characterized by **strong**, **coherent** color **electric and magnetic fields**

$$F_{\mu\nu} \equiv F^a_{\mu\nu} t^a = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + ig\left[A^a_\mu, A^a_\nu\right]$$



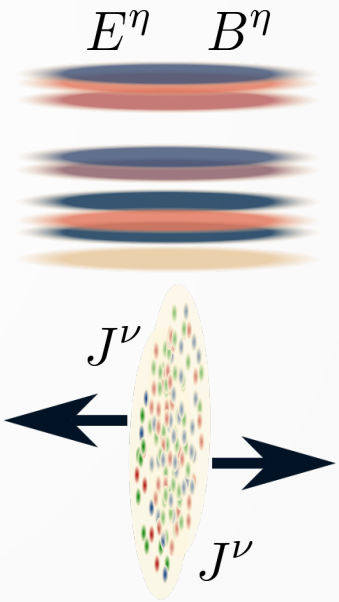
2+1D Boost invariant glasma

WAGASHI is partly a real-time lattice solver

- Well established method that captures the non-linear evolution, gauge conditions, and conservation conditions

[D. Müller, 1904.04267]
[K. Fukushima and F. Gelis,1106.1396]
[A. Krasnitz and R. Venugopalan, hep-ph/9809433]
[A. Krasnitz, Y. Nara and R. Venugopalan, hep-ph/0108092]
[T. Lappi, hep-ph/0505095]
etc.

- WAGASHI is 2+1D, so only the transverse plane (x,y) & proper time (τ) are discretized





Calculates the time evolution of the glasma's strong, coherent color electric and magnetic fields

Initial condition for the glasma (saturation physics)

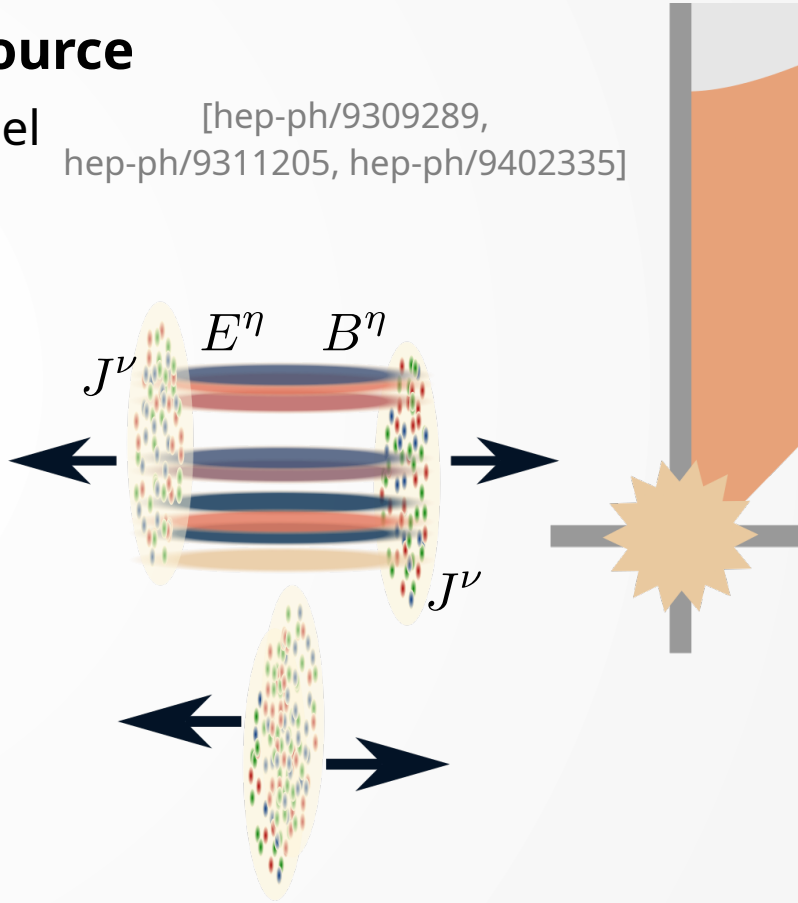
Color glass condensate EFT provides an initial source

- WAGASHI uses the McLerran Venugopalan (MV) model

[hep-ph/9309289, hep-ph/9311205, hep-ph/9402335]

Classical YMs with source term

$$D_\mu F^{\mu\nu} = J^\nu$$
$$= \delta^{\nu\pm}\rho^a(\tau, x_T)t^a$$



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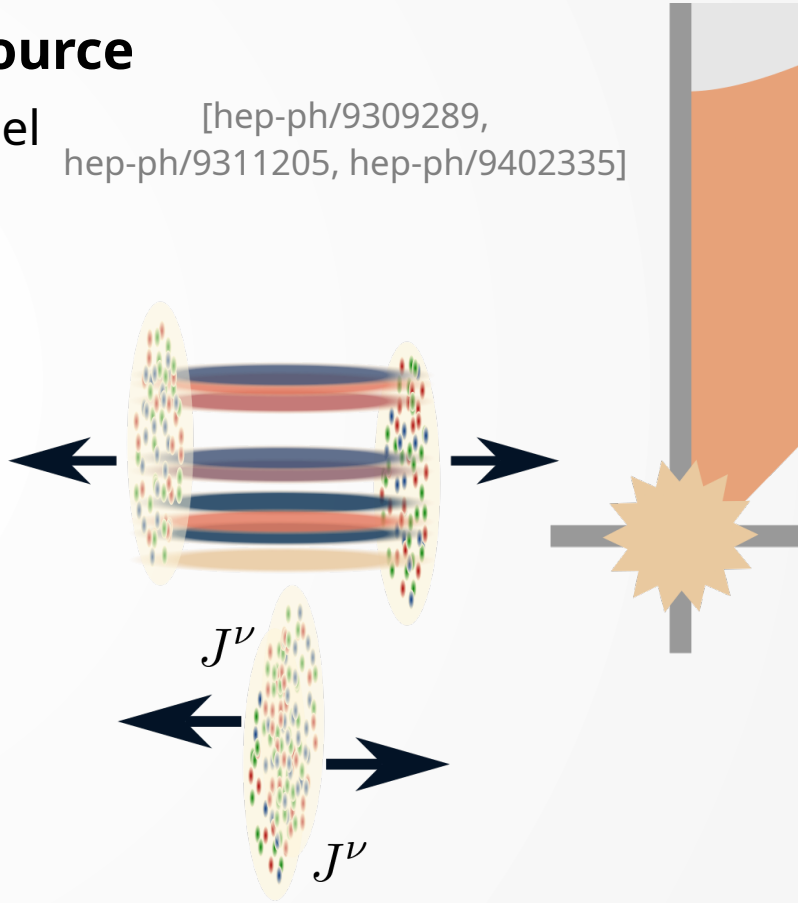
Classical YMs with source term

$$D_\mu F^{\mu\nu} = J^\nu$$
$$= \delta^{\nu\pm}\rho^a(\tau, x_T)t^a$$

- Transverse plane dependent color charge density, that allows for finite sized ions

$$\langle \rho^a(x_T)\rho^b(x'_T)\rangle = g^2\mu^2(x_T)\delta^{ab}\delta^2(x_T - x'_T)$$

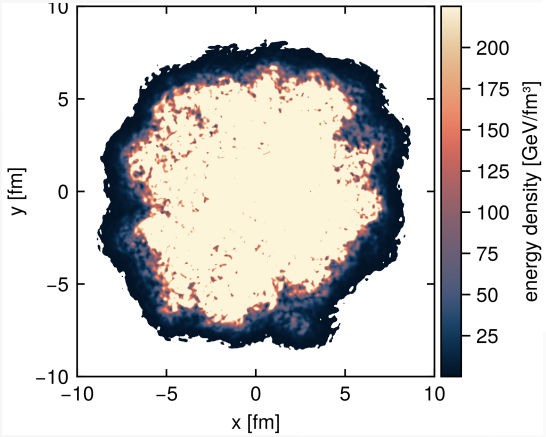
- Source term is only at initial time $\tau \to 0$
- Color charges are assumed to be uncorrelated + normally distributed

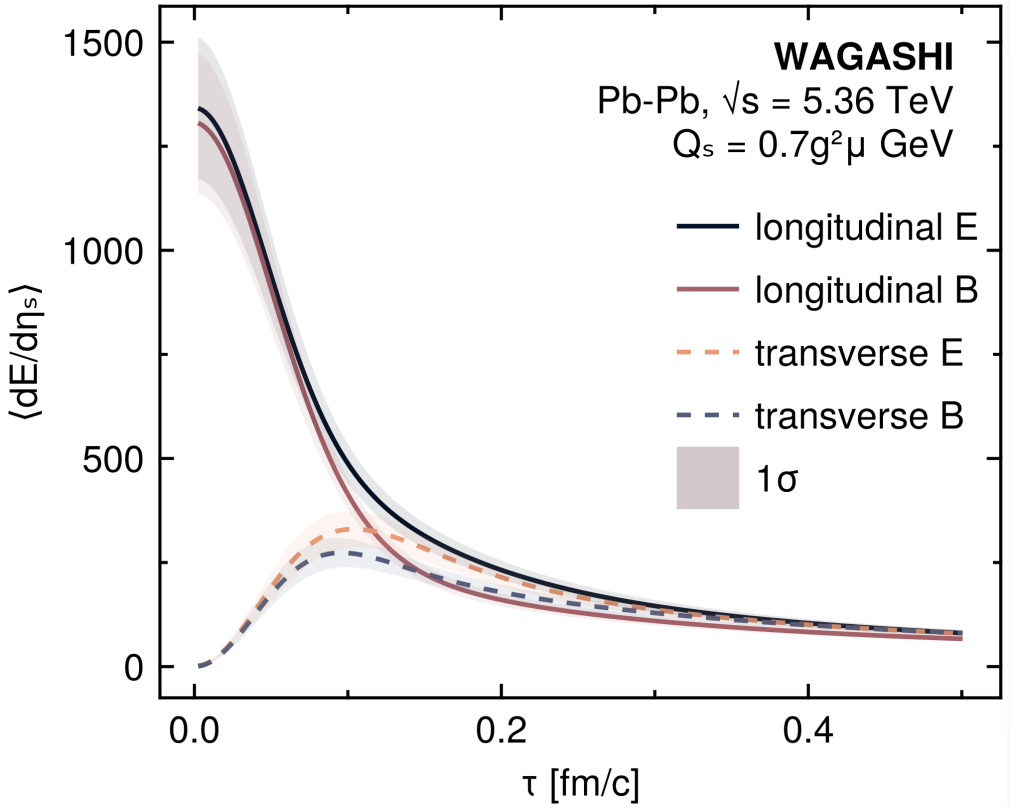


After running on the lattice

Early times

- longitudinally dominated
- “flux tubes”



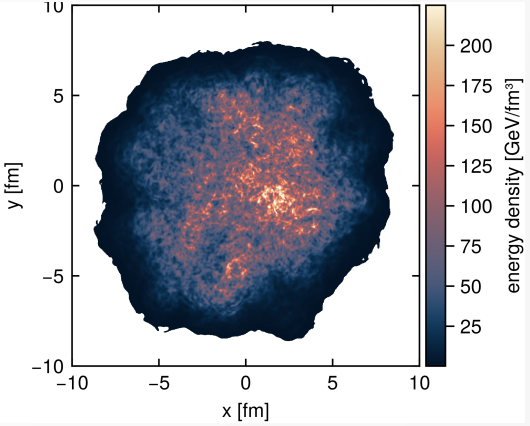


Strong color EM fields are formed

$$gF^{\mu\nu} \gg m^2_{\text{up, down, strange}}$$

Later times

- Equal energy in longitudinal and transverse



Why strong fields matter

Non-linear and non-perturbative effects become important

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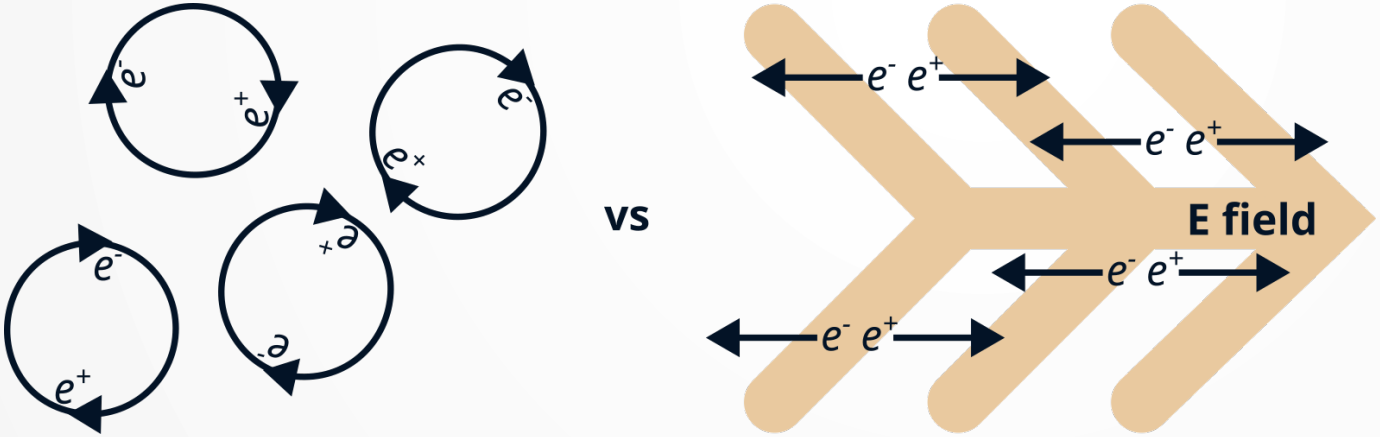
Schwinger pair production [Schwinger P.R. 1951], [For review: H. Taya, 2603.07847]

- Vacuum fluctuations are torn apart by the strong EM field



Never been observed “New Physics”

$$n_{q,\bar{q}}(x,p,t) \propto \exp\left[-\pi \frac{m_T^2}{gE}\right]$$

Pair production rate in a constant electric field

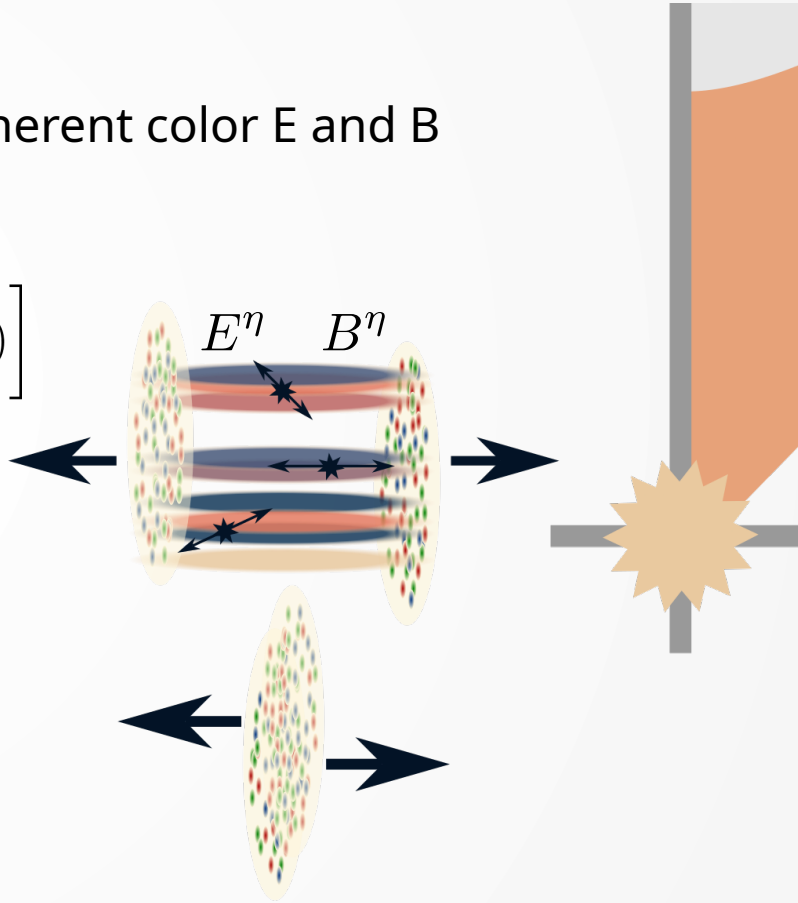
Schwinger pair production in the glasma

LCFA Schwinger production in WAGASHI

- WAGASHI uses the time evolution of the strong, coherent color E and B fields to calculate the pair-production

$$n_{q,\bar{q}}(x,p,t) \propto \sum_{s=\pm 1/2} \sum_{n=0}^{\infty} \exp\left[-\pi \frac{m^2}{g\mathcal{E}}\right] \exp\left[-\pi \frac{\mathcal{B}}{\mathcal{E}}(2n+1\mp 2s)\right]$$

- We used locally-constant-field approximation (LCFA) and Landau quantization for the B field



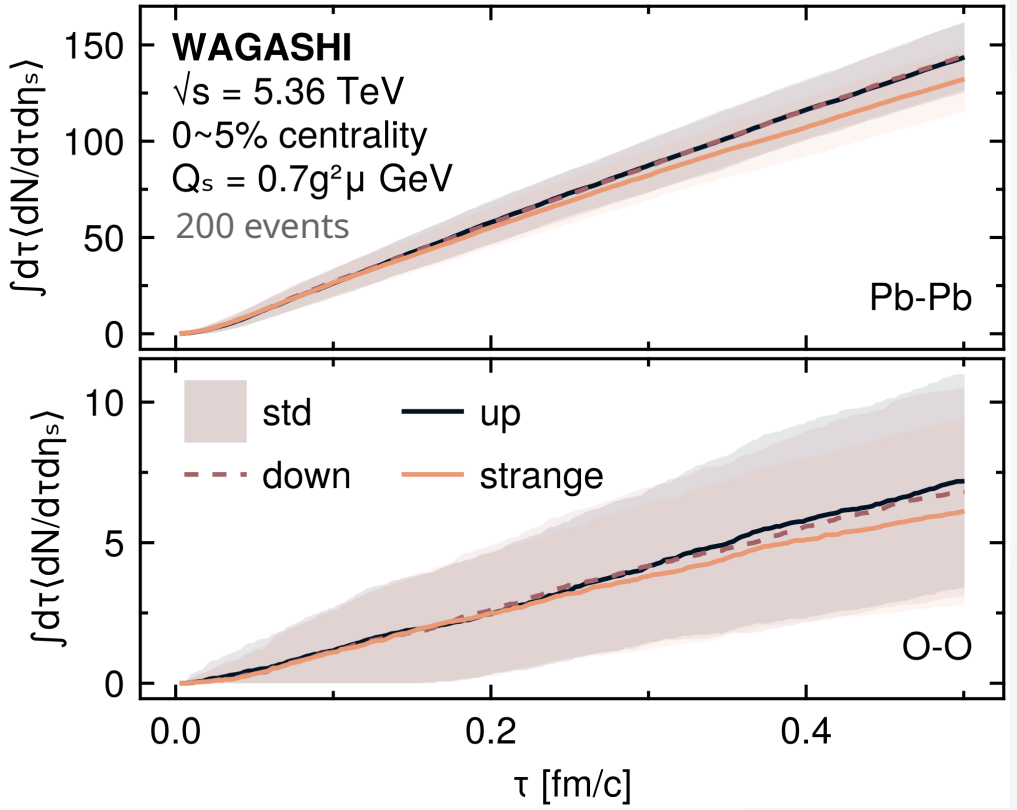
Production of quarks and antiquarks in WAGASHI

Accumulated Schwinger pairs over time

- Production of all 3 flavors starts very early $\tau < 0.1\ \mathrm{fm}/c$
- Complimentary to perturbative calculations after $\tau \sim Q_s^{-1}$

[Recent work: Barrera Cabodevila, et al., PLB 2025]

Close to ~450 (anti)quarks before 0.5 fm/c!



[**NJB**, C. Nonaka, H. Taya; 2608.13393]

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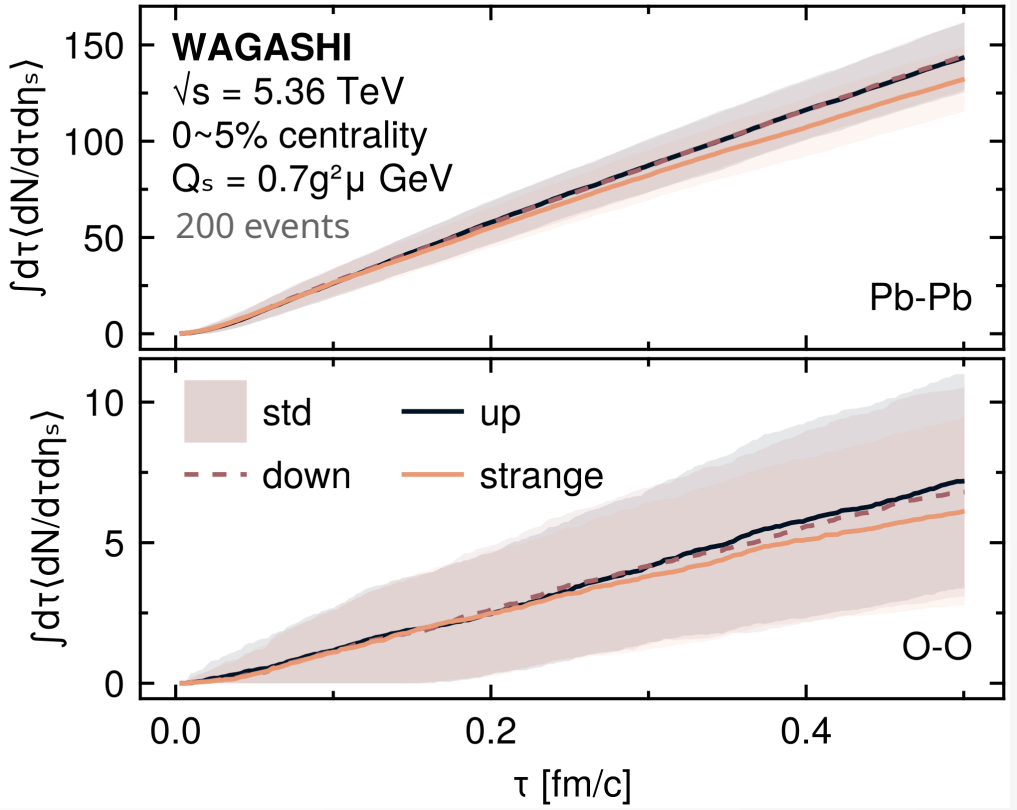
Close to ~450 (anti)quarks before 0.5 fm/c!

- Approximately linear growth vs time
- Strange production is suppressed because of mass difference

$$n_s \propto \exp\left[-\pi \frac{m^2}{gE}\right]$$



[**NJB**, C. Nonaka, H. Taya; 2608.13393]

Evolution in a colored background (cPIC)

After production the quarks do not sit still

- They are in a medium, glasma, and pushed by a color Lorentz force

$$m\frac{dx^\mu}{d\tau} = p^\mu, \qquad m\frac{dp^\mu}{d\tau} = gQ^a F_a^{\mu\nu} p_\nu,$$

WAGASHI is a colored Particle in cell (cPIC) solver [D. Avramescu, et al., 2303.05599]

- Semi-classical transport equations for particles in a Yang-Mills background (Wong equations + spin) [S. K. Wong; Nuovo Cim. A 65, 689 (1970)], [For review, H. Elze and U. Heinz; PR 1989]

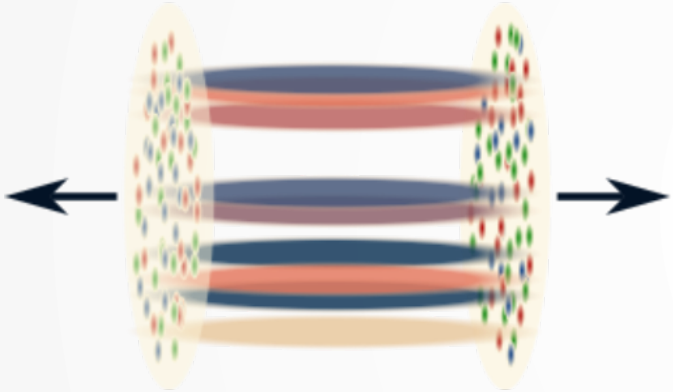
Color rotation $$m\frac{dQ^a}{d\tau} = -gf_{abc}p^\mu A_\mu^b Q^c + \mathcal{O}(\hbar)$$

Spin precession [BMT, PRL 2, 435 (1959)] $$m\frac{dS^\mu}{d\tau} = gQ^a F_a^{\mu\nu} S_\nu + \mathcal{O}(\hbar)$$

[Other method using QKT: H. Sung, B. Müller, D.L. Yang, 2507.23210]

WAGASHI (putting it all together)

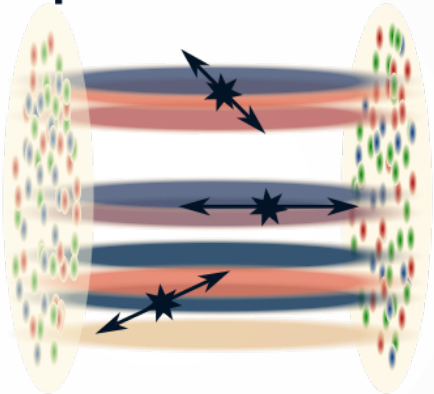
CGC + Glasma



Impact parameter dependent MV Model (CGC)

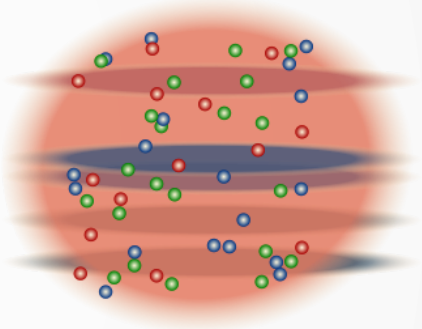
Real-time lattice 2+1D glasma (Classical Yang-Mills solver)

Schwinger pair production



Schwinger formula for pair production from color E&B fields (Poisson sampler)

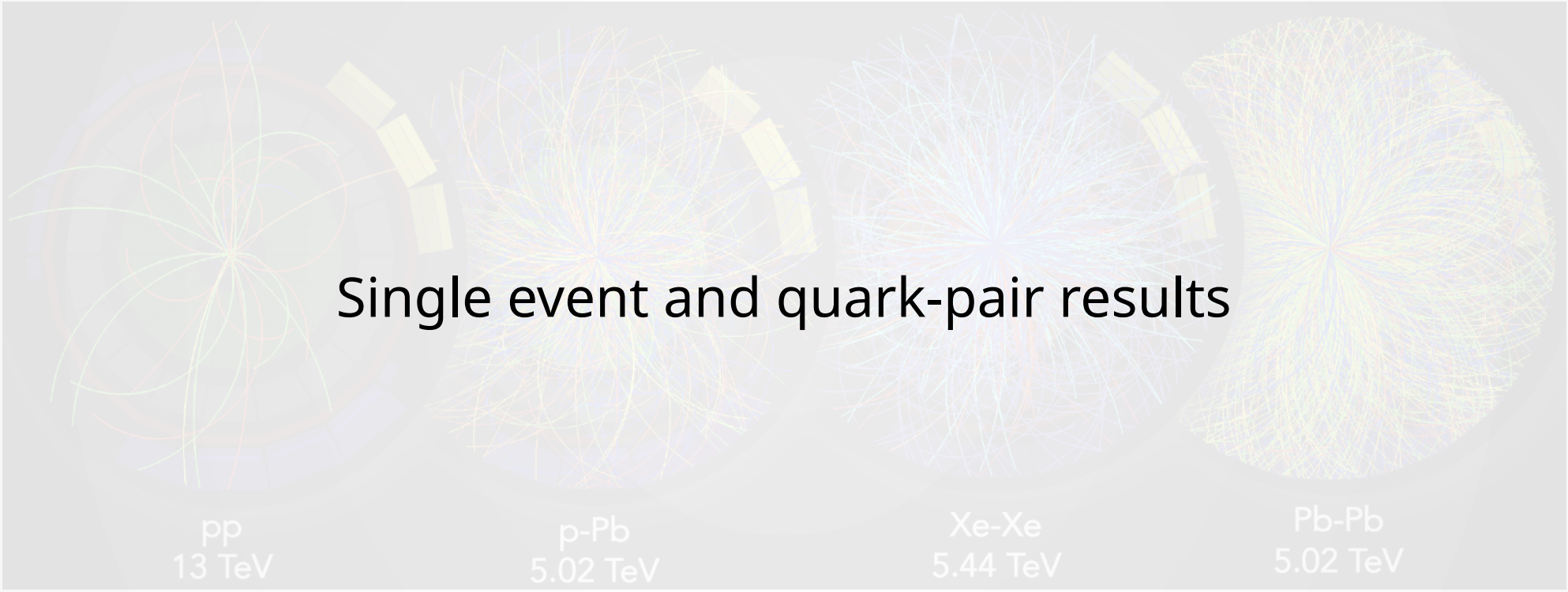
Wong equations with spin



Colored particle-in-cell for quark time evolution (Wong equations + spin)

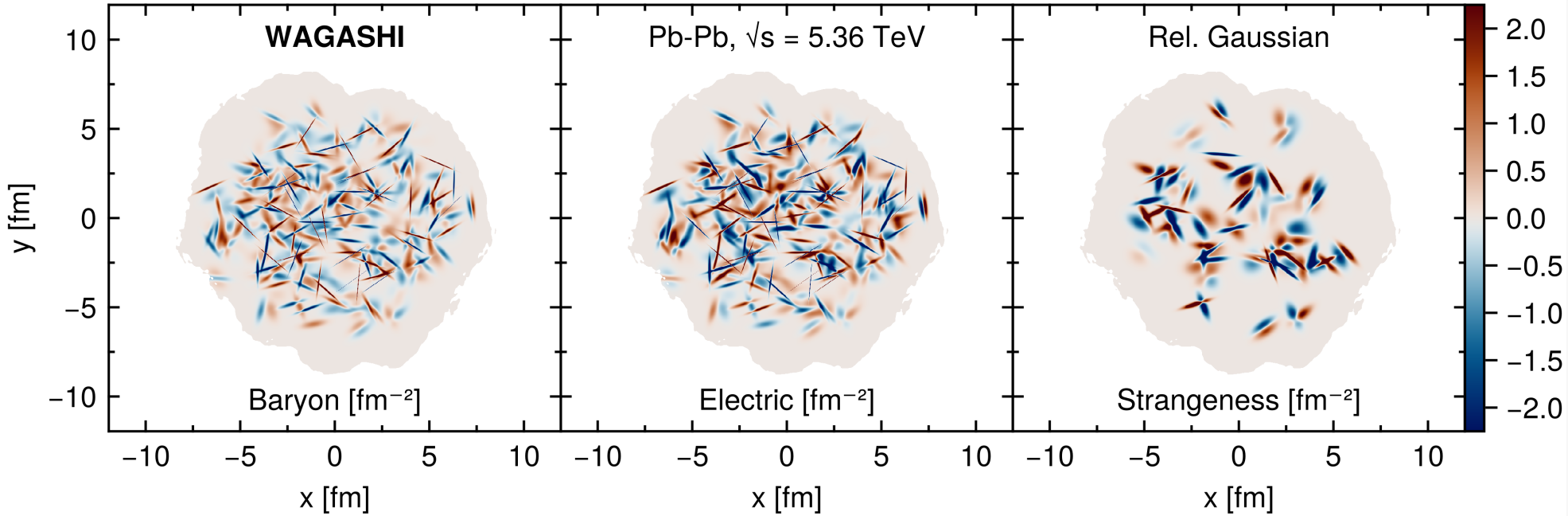
Final time Gaussian smoothing on particles for connecting to QGP

Single event and quark-pair results



From: A.P. KALWEIT, PoS (EPS-HEP2023) 027

Single event, charge densities at mid-rapidity



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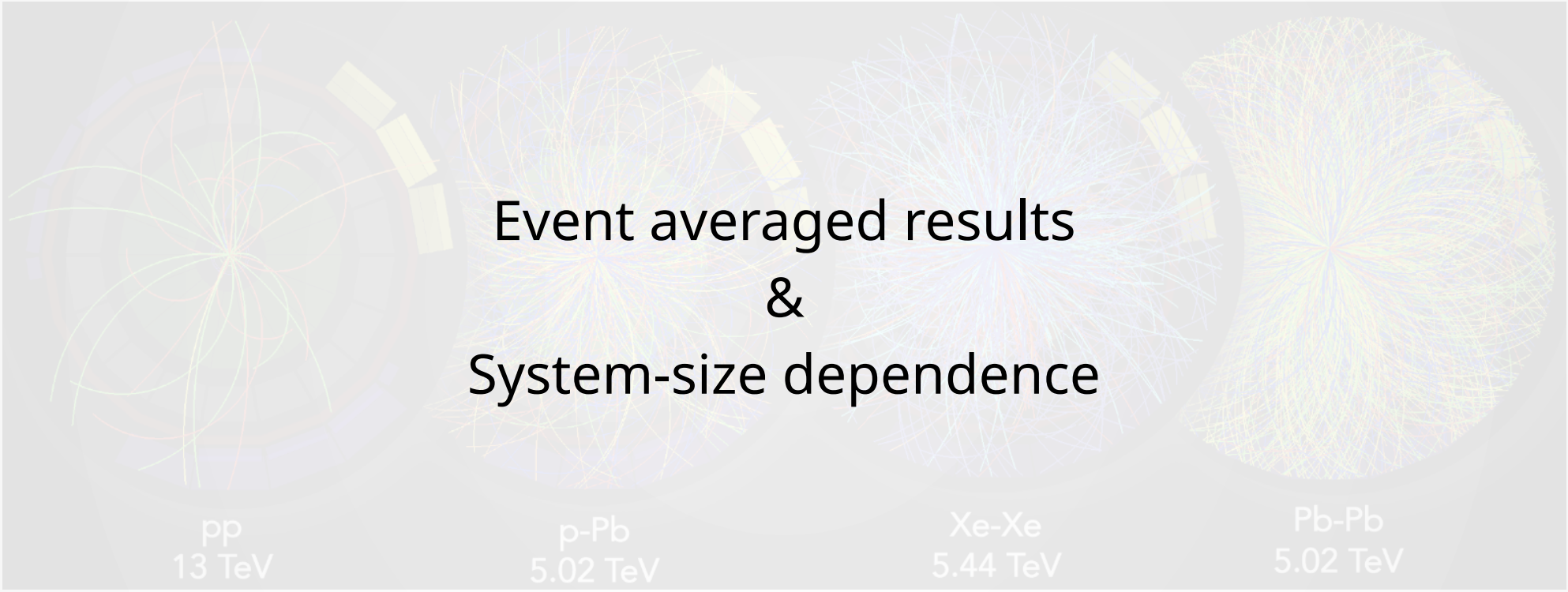
Anisotropy from the color-EM field non-perturbative decay and glasma interactions

These anisotropies may survive the hydrodynamic evolution.
Estimate a 5~10 reduction for ideal hydrodynamics. [ICCING; 1911.12454]

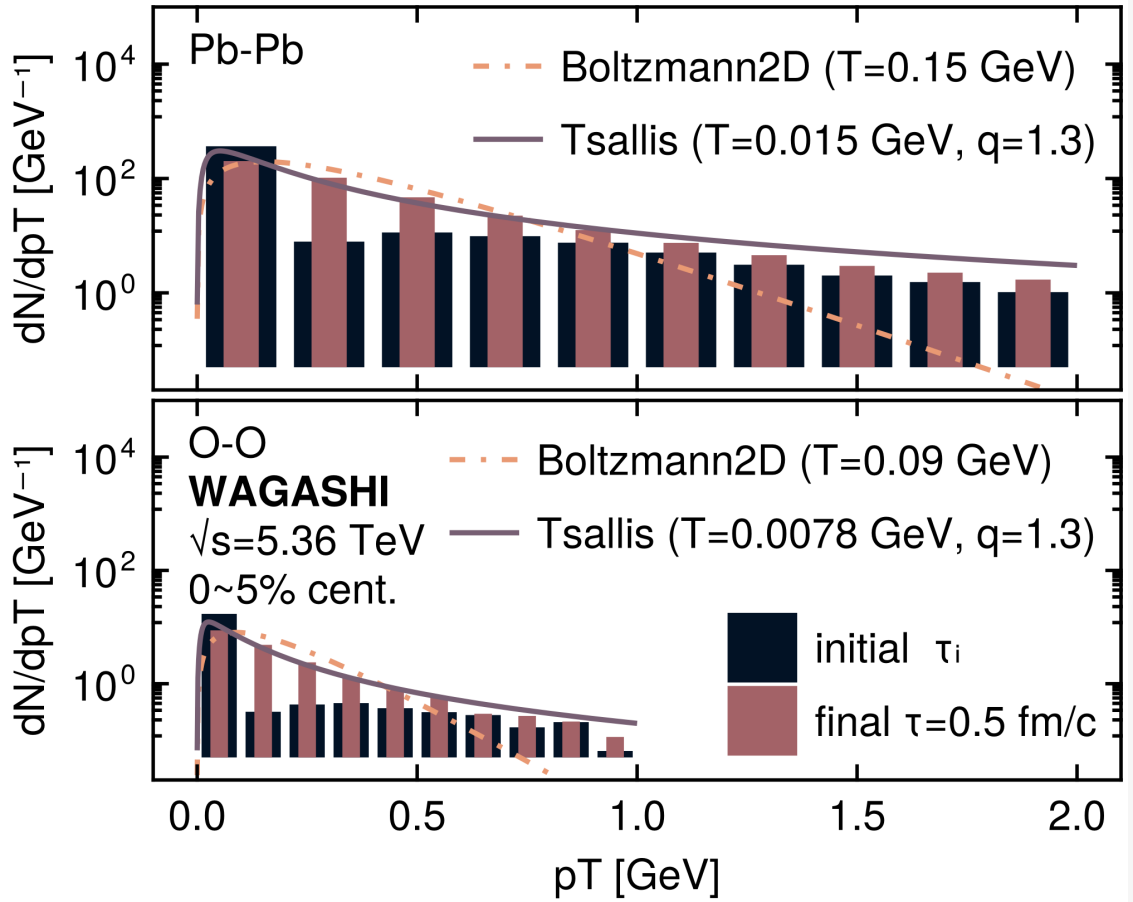
Event averaged results
&
System-size dependence



From: A.P. KALWEIT, PoS (EPS-HEP2023) 027

Quark transverse-momentum (400 events)

- Initial momentum is concentrated near $p_T \sim 0$ GeV (LLL)
  - Landau quantization by the strong color B field



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Quark transverse-momentum (400 events)

- Initial momentum is concentrated near $p_T \sim 0$ GeV (LLL)
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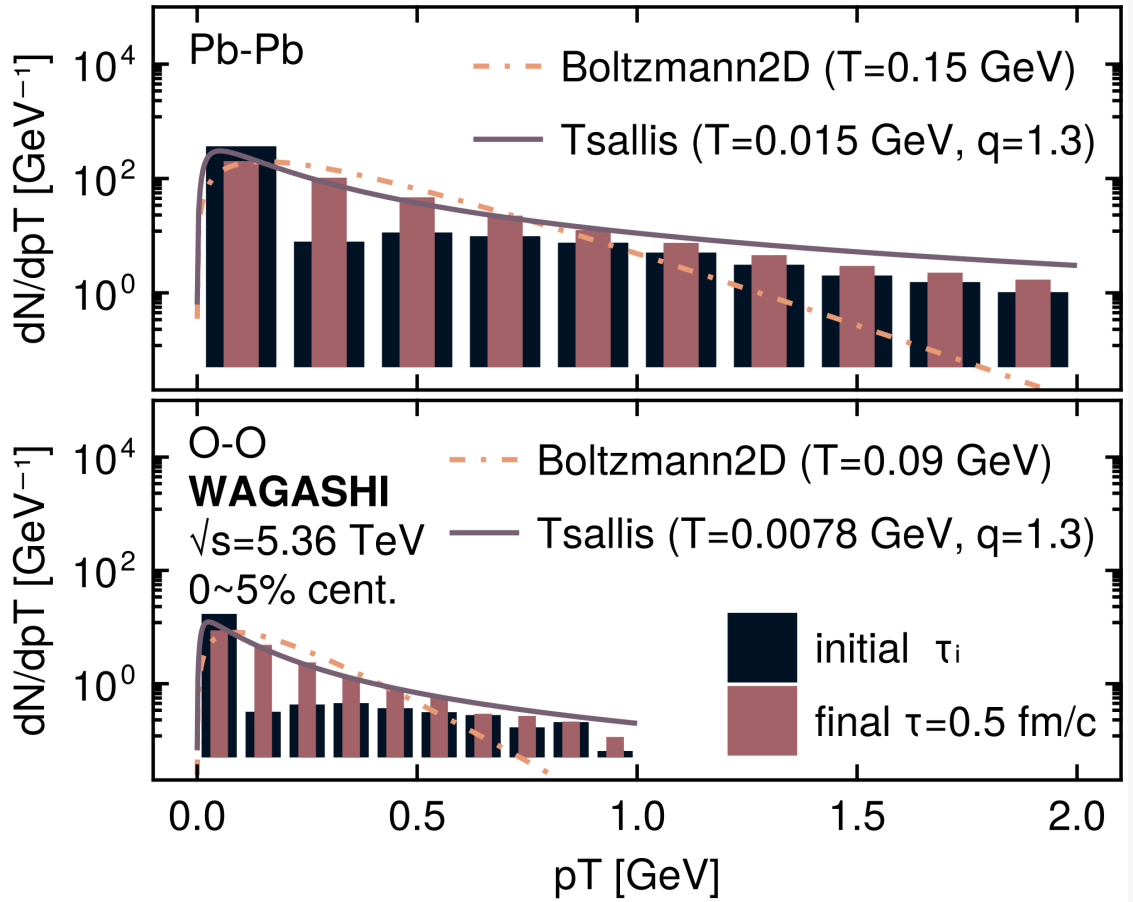
- Interacting with the glasma broadens the spectrum
- This is a transfer of the produced quarks from soft to hard modes
- This broadening is independent of system size (Pb vs O)



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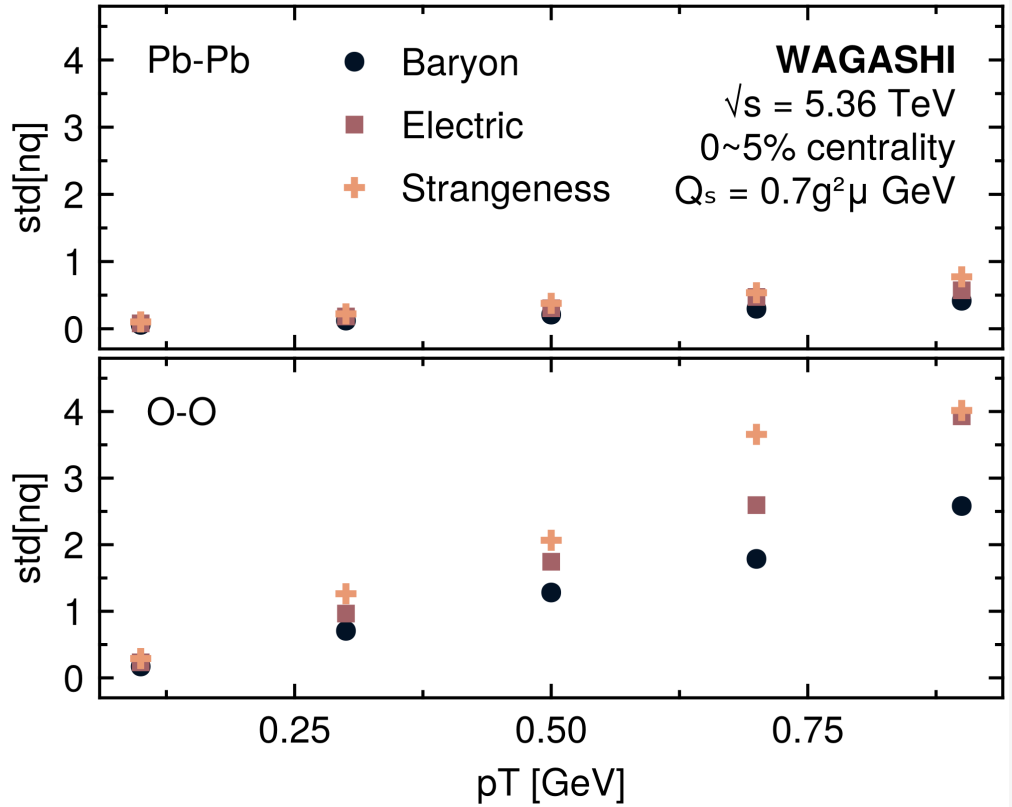
Conserved charge fluctuations (400 events)

- Conserved charge densities are highly fluctuating in the transverse plane
  - random fields of the glasma
- Fluctuations also appear in momentum space
  - Sort charges by p_T bins

$$\mathrm{std}[n_q(p_T)] \equiv \frac{\sqrt{\langle n_q^2(p_T)\rangle}}{\langle N(p_T)\rangle}$$



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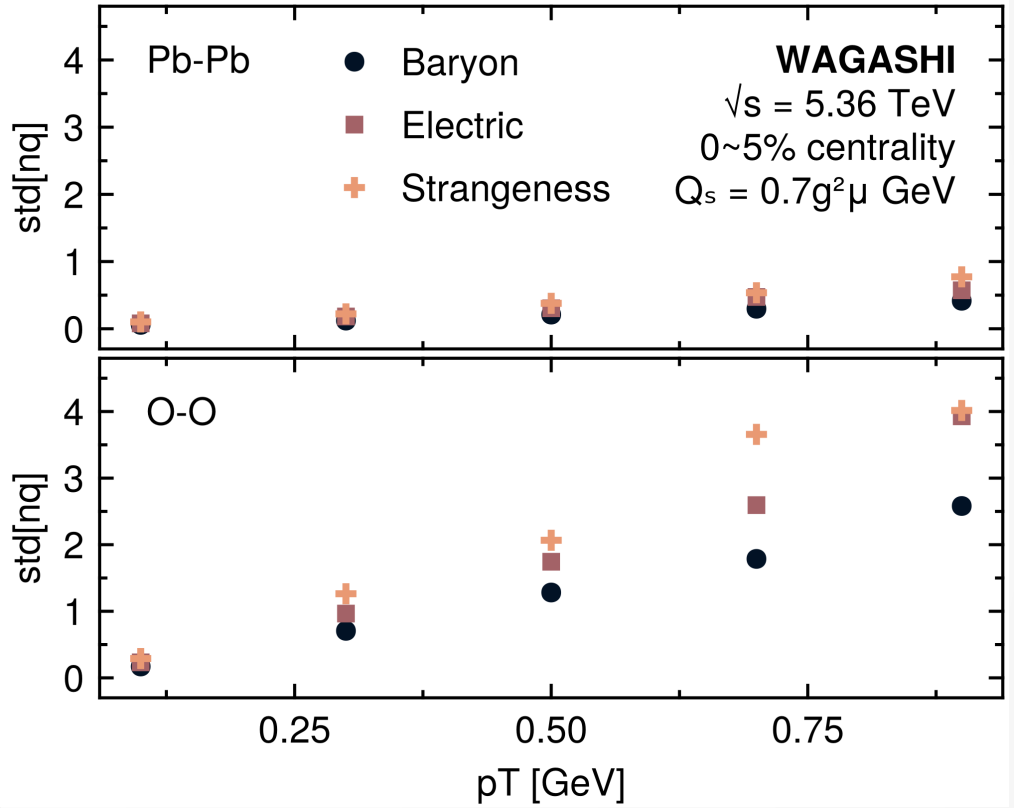
$$\mathrm{std}[n_q(p_T)] \equiv \frac{\sqrt{\langle n_q^2(p_T)\rangle}}{\langle N(p_T)\rangle}$$

- Glasma interactions cause the pair to acquire different momenta
- Fluctuations stronger in O-O (smaller total)



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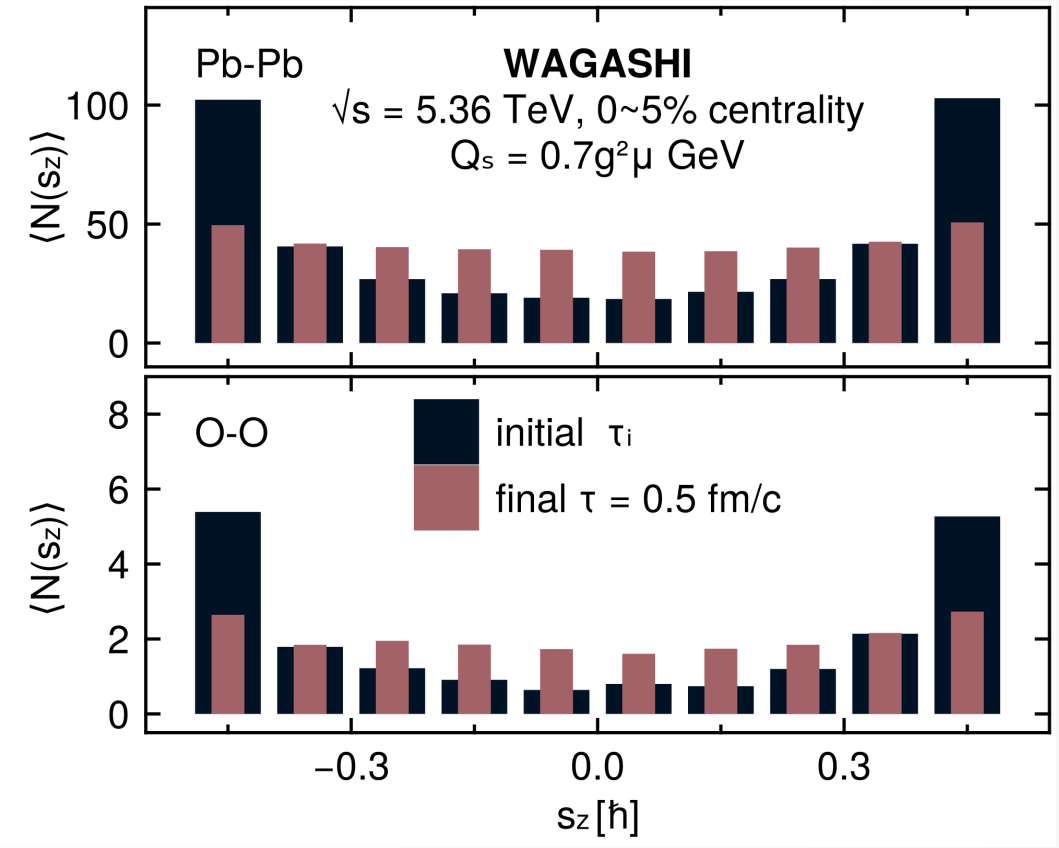
Spin polarization of quarks

- Initially, strongly polarized along the beam direction
  - Landau quantization by the strong color B field
- Interaction with the glasma via the colored-BMT equation randomizes the final spins
  - analogous to the momentum broadening

- The randomization occurs independent of system size (Pb vs O)



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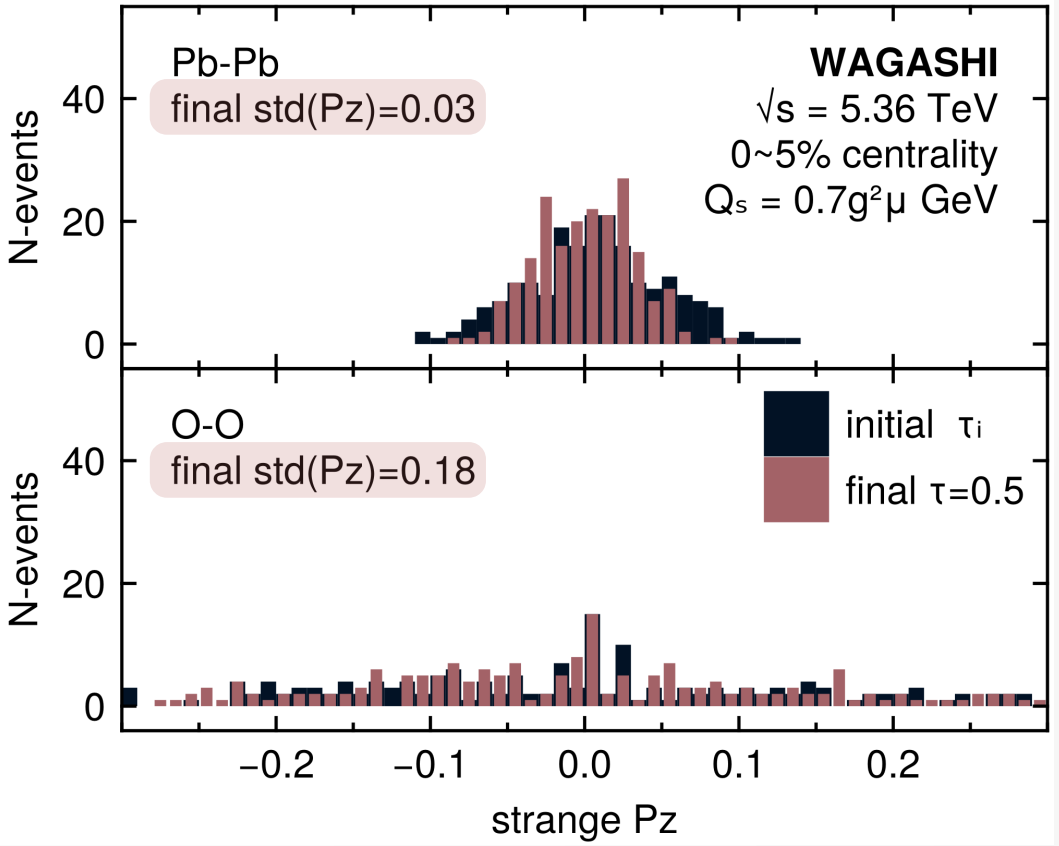
Spin polarization of quarks

- Spin polarization also has sizeable event-by-event fluctuations in the transverse plane
  - Mean is zero

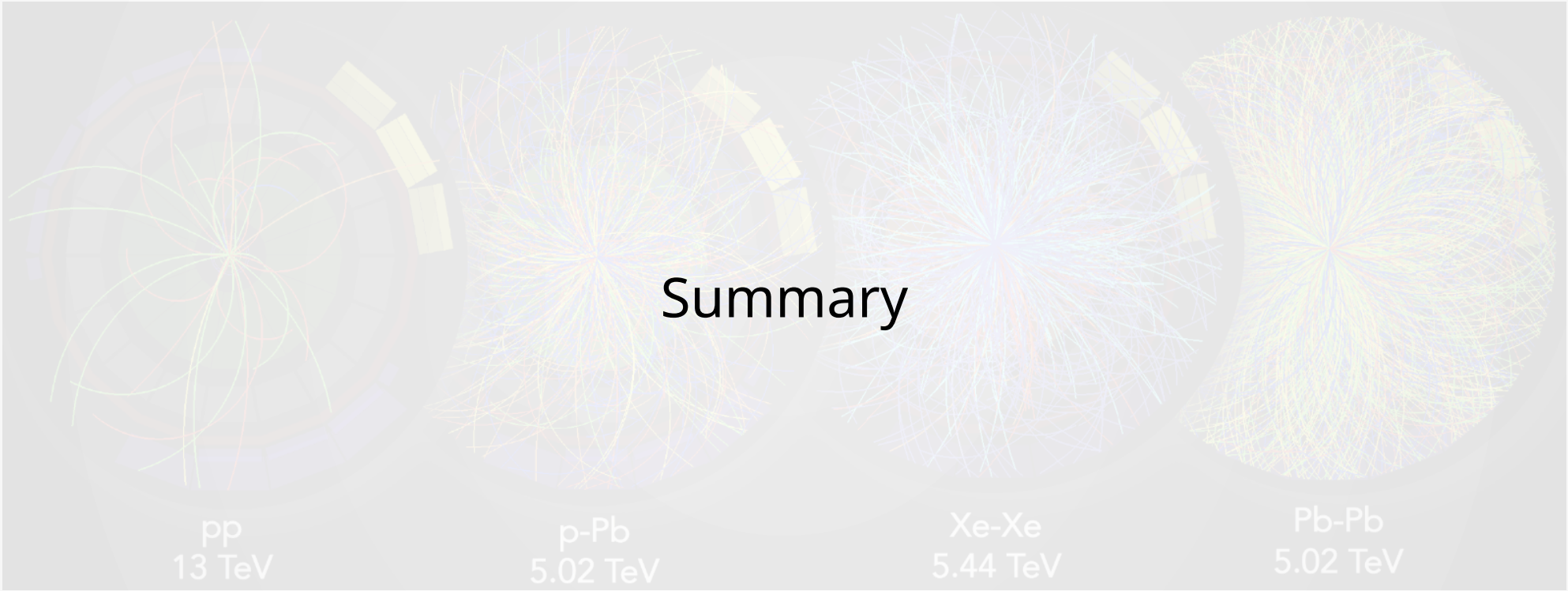
$$\mathrm{std}(\mathcal{P}_z) \equiv \sqrt{\langle \mathcal{P}_z^2 \rangle} = \sqrt{\left\langle \left(\frac{1}{N} \sum_{n=1}^{N} s_z^n \right)^2 \right\rangle}$$

- Pb-Pb fluctuation is comparable to the Glauber-model estimate
- O-O has stronger fluctuations (smaller total # of quarks)

[G. Giacalone and E. Speranza; 2502.13102]



Summary



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Summary

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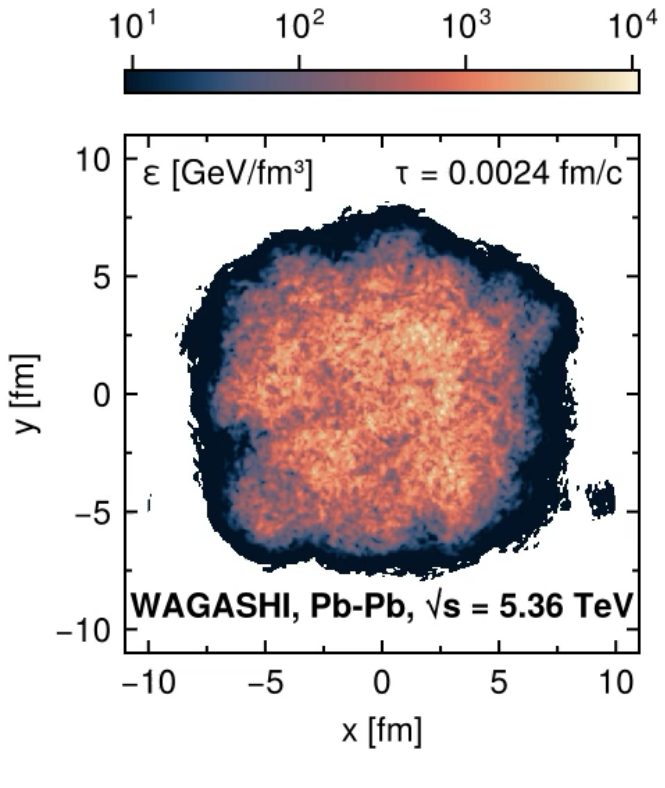

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- Available now for download (later fully open source)

+ more new physics:

- Dynamically produces quarks with Schwinger mechanism
- BMT equations for spin transport

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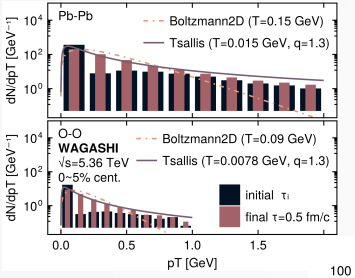
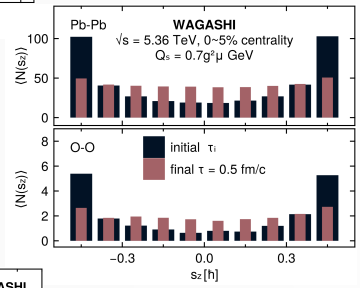
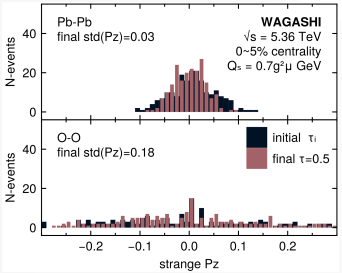
Summary & Thank you!







Landau quantization by the strong color B field

- Initial momentum is concentrated near pT ~ 0 GeV
- Spin starts strongly polarized along the beam direction

Interaction with the glasma

- broadens the p_T spectrum (soft → hard)
- randomizes the final quark spins

Fluctuations are key

- Conserved charges fluctuate in momentum space
- Spin polarization fluctuates event-by-event

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Backup

Schwinger pair production (non-perturbative)

LCFA Schwinger production

- We used locally-constant-field approximation (LCFA) and Landau quantization for the B field

$$n_{q,\bar{q}}(x,p,t) \propto \sum_{s=\pm 1/2} \sum_{n=0}^{\infty} \exp\left[-\pi \frac{m^2}{g\mathcal{E}}\right] \exp\left[-\pi \frac{\mathcal{B}}{\mathcal{E}}(2n+1\mp 2s)\right]$$

- That equation requires,

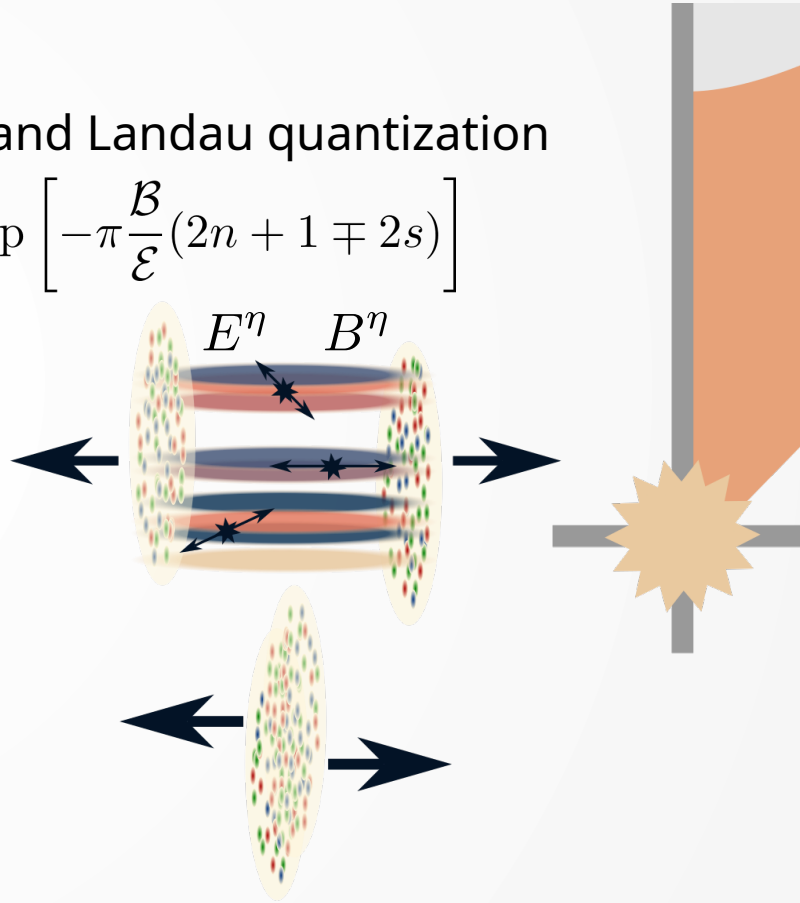
$$\Omega^{-1} \gg \frac{m}{gE}, \qquad \Omega^{-1} \gg \frac{1}{\sqrt{gB}}$$

transverse size of the wave function from Landau quantization

- Where, the glasma scale is estimated from the gluon saturation [A. Dumitru, Y. Nara, and E. Petreska; arXiv:1302.2064]

$$\Omega^{-1} \sim Q^{-1} = 1.0 \sim 2.5 \text{ GeV}$$

B-field condition is only marginally satisfied, but if the lowest Landau level dominates LCFA is a reasonable first approximation



Schwinger pair production (non-perturbative)

LCFA Schwinger production

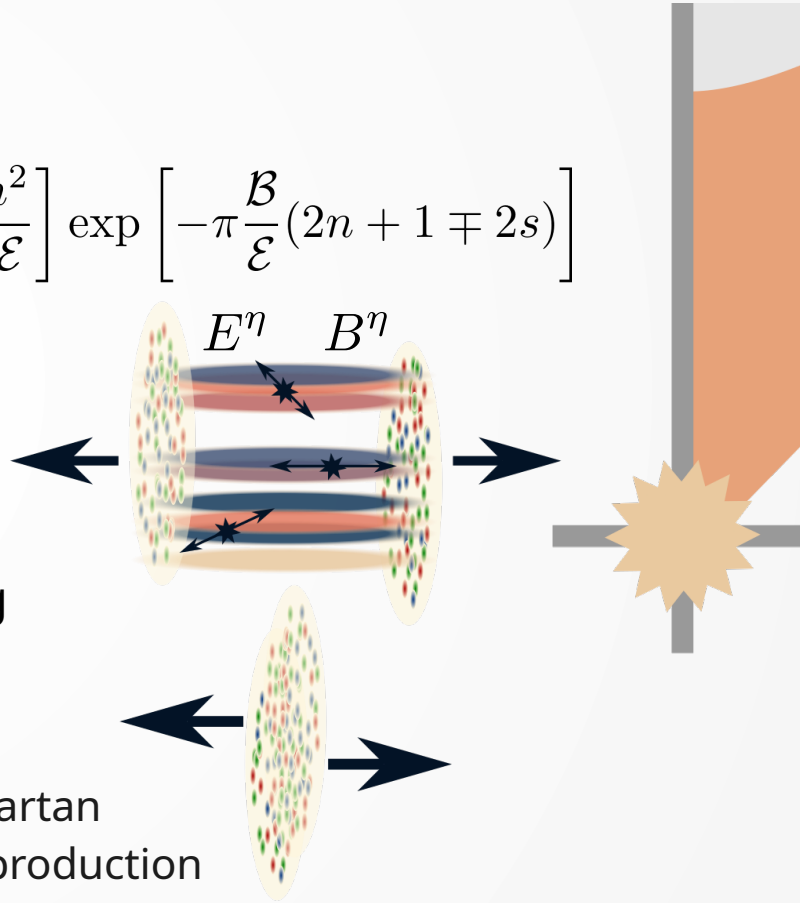
- We solved for this equation with Abelian fields

$$n_{q,\bar{q}}(x,p,t) \propto \sum_{s=\pm 1/2} \sum_{n=0}^{\infty} \exp\left[-\pi \frac{m^2}{g\mathcal{E}}\right] \exp\left[-\pi \frac{\mathcal{B}}{\mathcal{E}}(2n+1\mp 2s)\right]$$

Glasma is strongly non-Abelian

- We use an Abelian projection and suppress the off-diagonal components with gauge fixing to the maximally Abelian gauge (MAG)
- On the Lattice this is the same as globally maximizing the squares of the diagonal of each gauge link

[M. Schröck and H. Vogt; arXiv:1212.5221]



MAG does not guarantee the E&B fields have maximum Cartan components, which gives us a lower bound for the Schwinger production

Schwinger pair production in the glasma

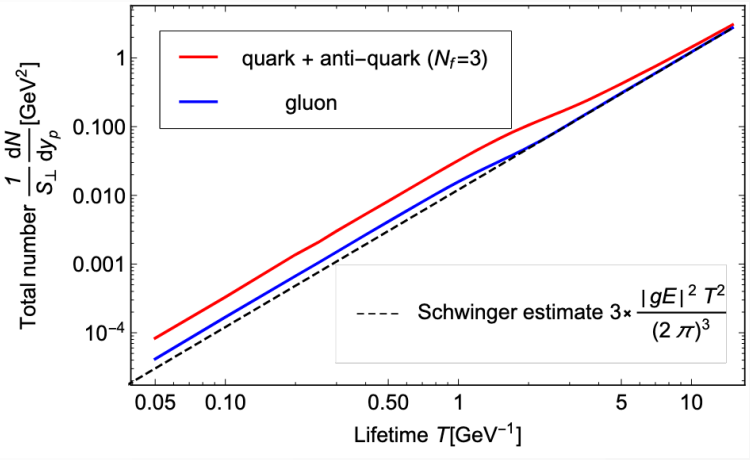
Studies show Schwinger pair production should occur in the glasma

- Flux tube models predict rapid production
  - On the order of ~500 quarks and anti quarks

[K. Kajantie and T. Matsui; PLB 164, 373 (1985)]
[G. Gatoff, A. K. Kerman, and T. Matsui; PRD 36, 114 (1987)]
[N. Tanji: arXiv:0810.4429, 1002.3143, 1506.08442]
etc.

- Related works have numerically solved the Dirac equation for pair production in the glasma
  - Found similar rapid production as flux tube models

[F. Gelis, K. Kajantie, and T. Lappi; hep-ph/0409058 and hep-ph/0508229]



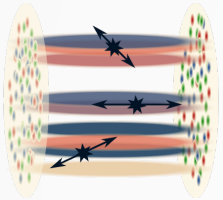
[H. Taya; 1609.06189]

None of those works have addressed the early-time charge, flavor, and spin dynamics of the quarks

Single event, polarization at mid-rapidity

Anisotropic spin distribution

- Initial spin fixed by Landau quantization of the Schwinger production



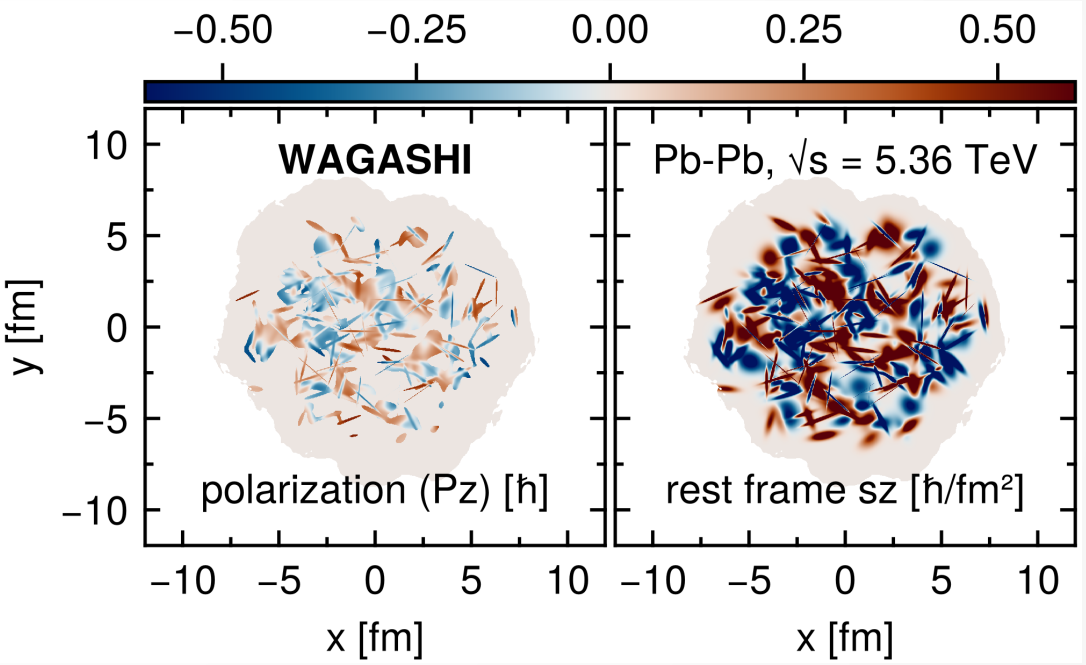
$$g\mathcal{B}(2n+1\mp 2s)$$

- Spin precesses after coupling to local color EM-fields (Wong + BMT spin)

$$m\frac{dS^{\mu}}{d\tau} \simeq gQ^{a}F_{a}^{\mu\nu}S_{\nu}$$

- Different source of polarization than initial nucleons

[G. Giacalone and E. Speranza; 2502.13102]



[**NJB**, C. Nonaka, H. Taya; 2608.13393]

Quark SU(3) classical color charge (120 events)

Final state is randomized (Preliminary)

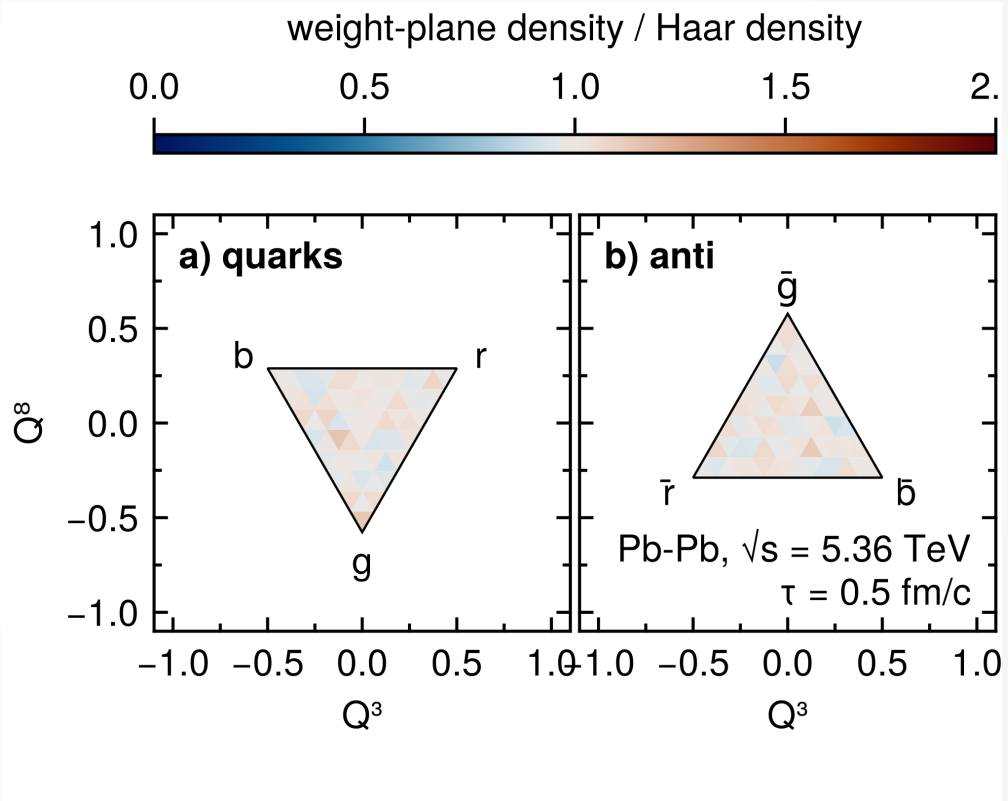
- Initial color is assigned as (b, r, g)
- Glasma rotates the quark SU(3) color charge (Wong + BMT spin)

$$m\frac{dQ^a}{d\tau} = -gf_{abc}p^\mu A^b_\mu Q^c$$

- Baseline: Haar density used as a uniform probability distribution over all possible 3×3 unitary matrices with determinant 1

[D. Avramescu, et al., 2303.05599],

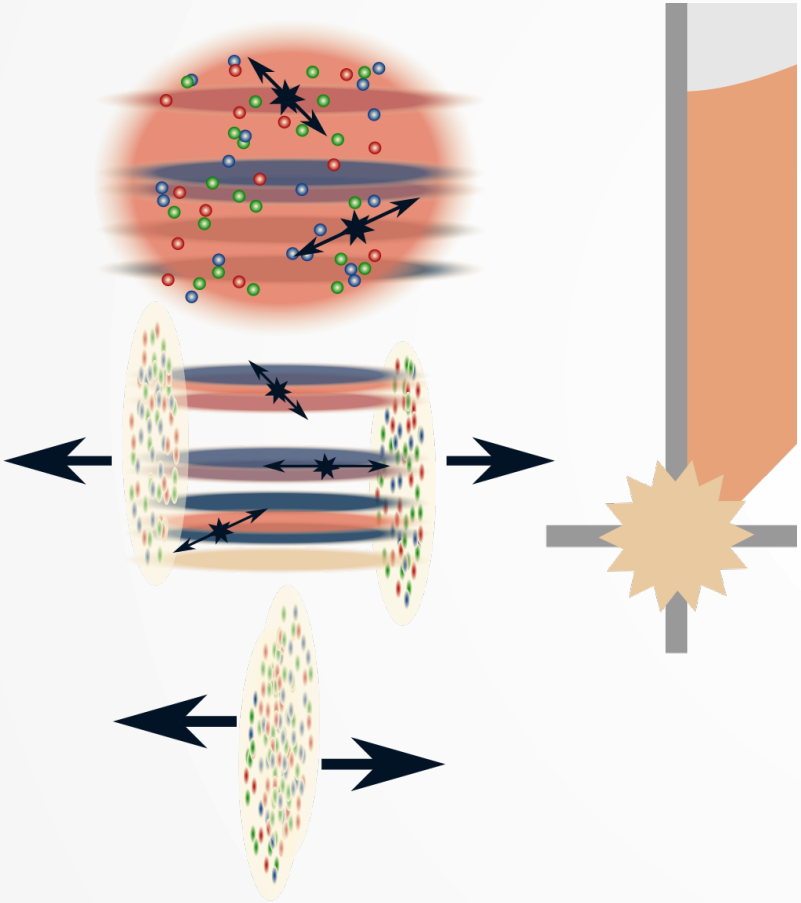
[P. F. Kelly, et al., hep-ph/9406285]



Complete randomization

Wong equations + spin precession

[S. K. Wong, Nuovo Cim. A 65, 689 (1970)]



Particle evolution in a colored background (cPIC)

[D. Avramescu, et al., 2303.05599]

Semi-classical transport equations for particles in a Yang-Mills background (Wong equations + spin)

Spacetime evo $$m\frac{dx^\mu}{d\tau} = p^\mu$$

Color rotation $$m\frac{dQ^a}{d\tau} = -g f_{abc} p^\mu A^b_\mu Q^c + \mathcal{O}(\hbar)$$

Spin precession [BMT, PRL 2, 435 (1959)] $$m\frac{dS^\mu}{d\tau} = g Q^a F^{\mu\nu}_a S_\nu + \mathcal{O}(\hbar)$$

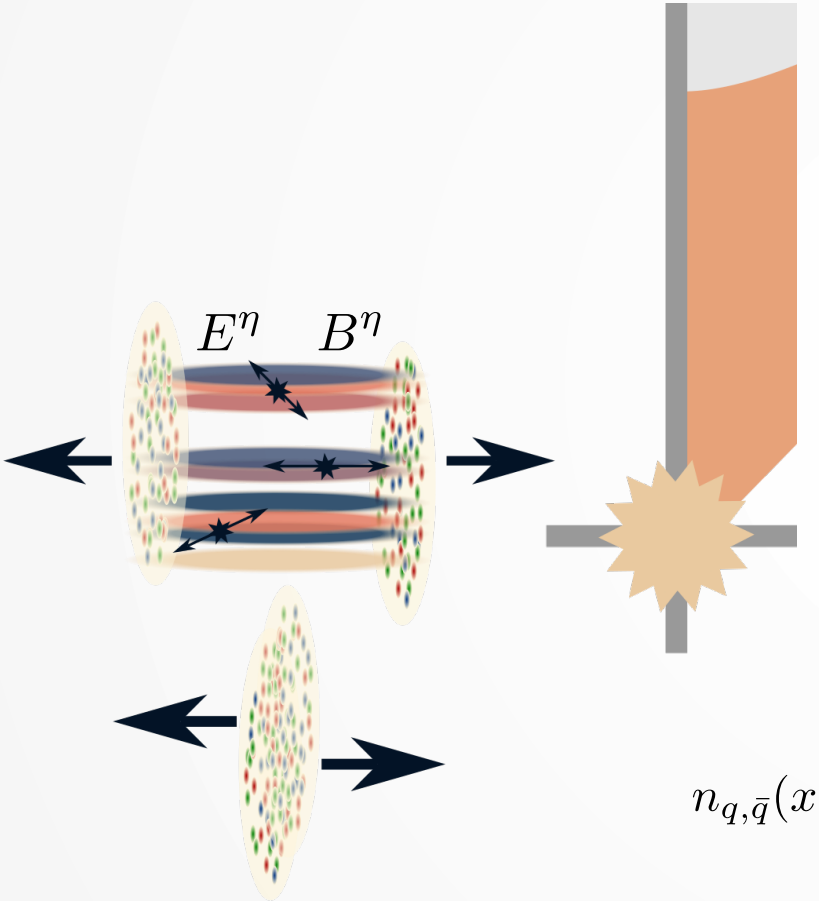
Momentum evo $$m\frac{dp^\mu}{d\tau} = g Q^a F^{\mu\nu}_a p_\nu + \mathcal{O}(\hbar)$$

[For review, H. Elze and U. Heinz, Physics Reports 1989]

[Other method using QKT: H. Sung, B. Müller, D.L. Yang, 2507.23210]

Schwinger pair production (non-perturbative)

[Schwinger P.R. 1951]



Poisson sampling and gauge fixing

- During the glasma time evolution we sample the color *E&B* fields

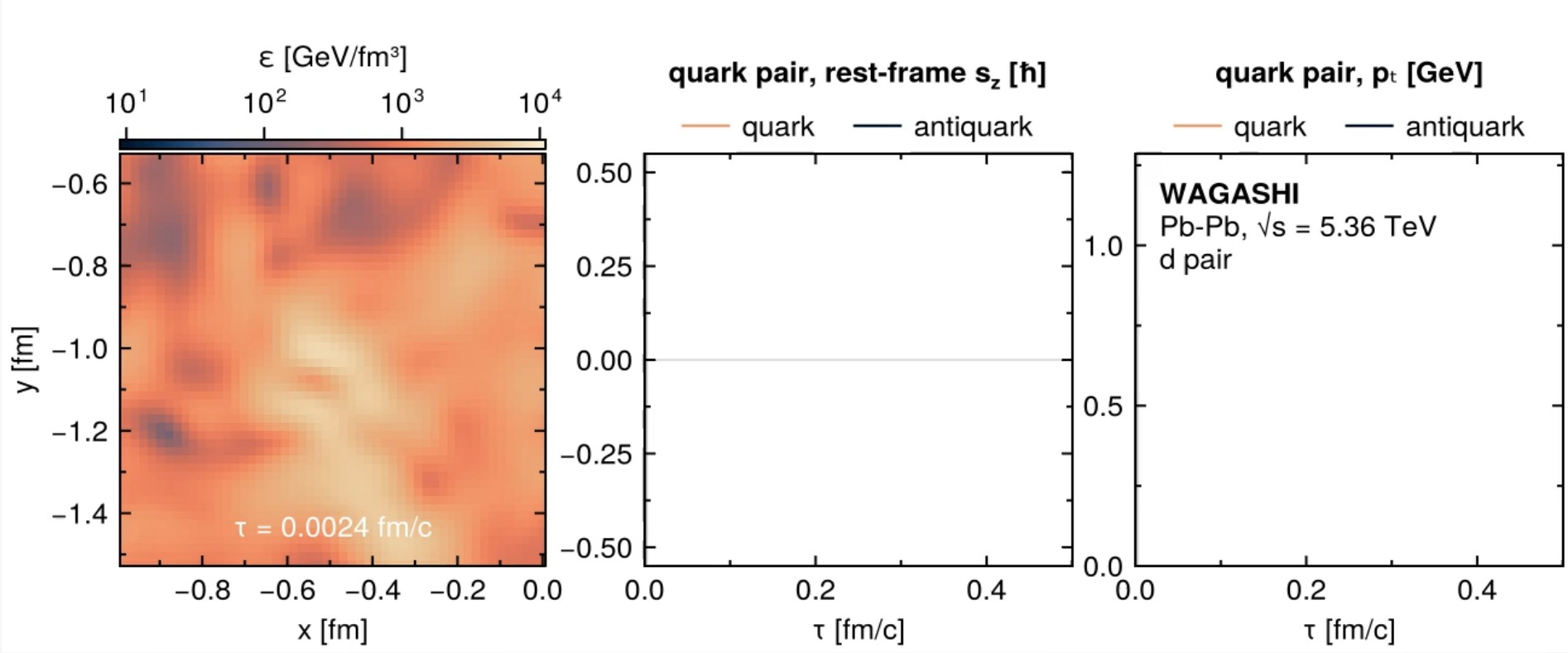
$$P(N,x,p,t) = \frac{[n_{q,\bar{q}}(x,p,t)]^N e^{-n_{q,\bar{q}}(x,p,t)}}{N!}$$

- Mean of the distribution is the LCFA Schwinger formula for pair production
- Gauge fixing to maximally Abelian gauge

$$n_{q,\bar{q}}(x,p,t) \propto \sum_{s=\pm 1/2} \sum_{n=0}^{\infty} \exp\left[-\pi \frac{m^2}{g\mathcal{E}}\right] \exp\left[-\pi \frac{\mathcal{B}}{\mathcal{E}}(2n+1\mp 2s)\right]$$

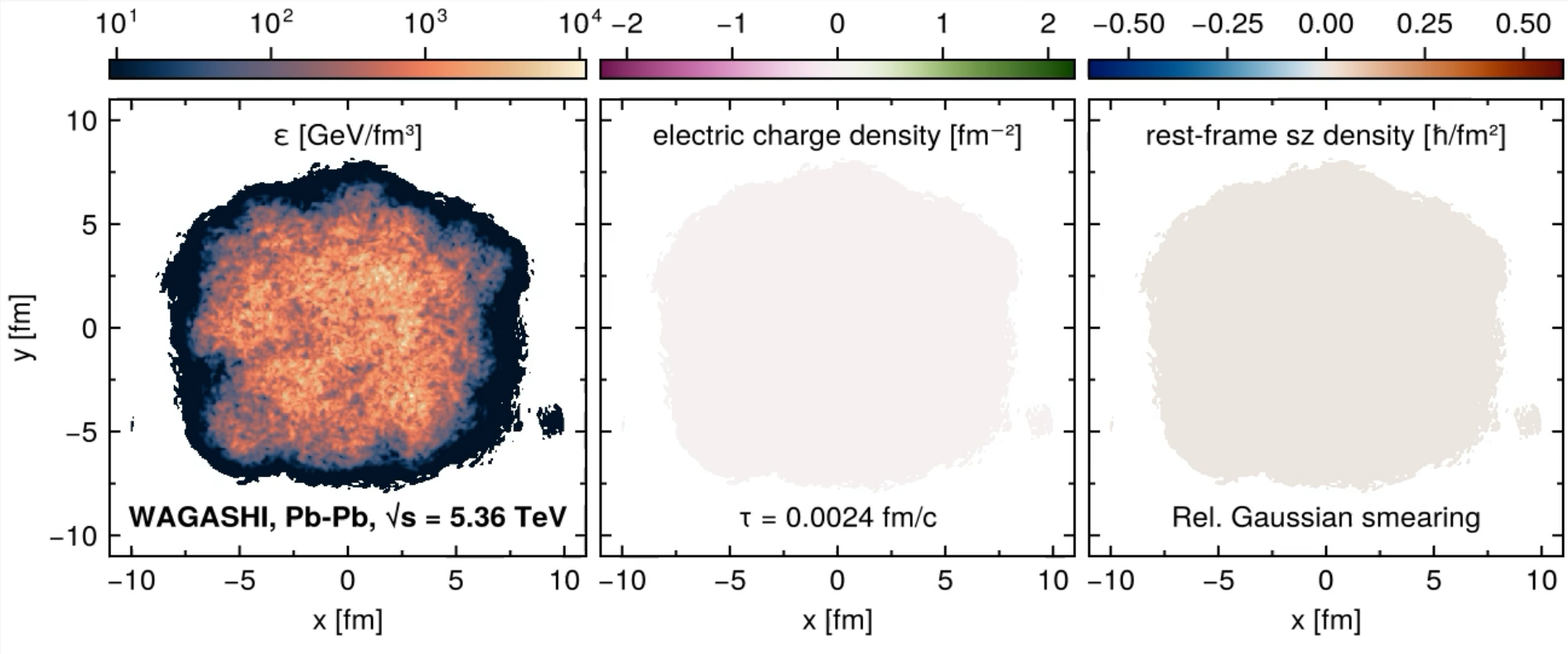
Quark-pair spin and momentum

After production pairs do not follow the same world-line



WAGASHI (和菓子 , traditional Japanese sweets)

W = Wong-precessing, A = Anisotropic, G = Glasma, A = And, SH = Schwinger-produced, I = Initial-conditions



[**NJB**, C. Nonaka, H. Taya; 2608.13393 [hep-ph] and https://home.hiroshima-u.ac.jp/~njbenoit/wagashi/]

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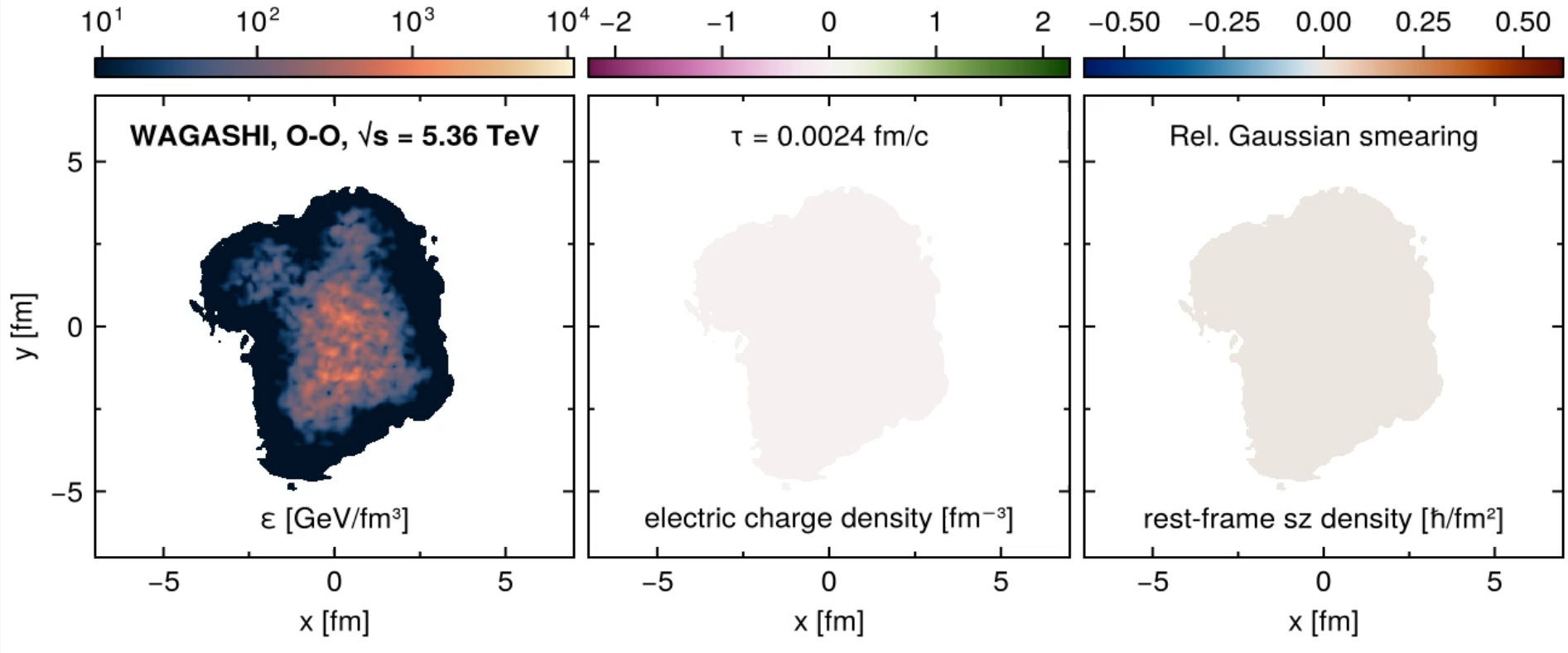

WAGASHI (和菓子 , traditional Japanese sweets)
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Schwinger effect with back-reaction

Back-reaction requires extending the classical Yang-Mills

- Back-reaction is an induced current built from two parts

$$D_\mu F^{\mu\nu} = J^\nu_{\rm ind} = J^\nu_{\rm cond} + J^\nu_{\rm pol}$$

[G. Gatoff, A. K. Kerman, T. Matsui; Phys. Rev. D 1951]

- Conduction current is driven from the convective flow of particles

$$J^\mu_{\rm cond} = \sum_i^{N_{\rm tot}} g_i \int \frac{d^3p}{(2\pi)^3 p_0} f(x,p)$$

Usual current for a evolving system of particles

- New current that appears if there is a particle source term (i.e., Schwinger effect)
  - Comes from the time-evolution of particle number

$$\partial_\mu J^\mu_{\rm cond} = \sum_i^{N_{\rm tot}} \partial_\mu j^\mu_i + \partial_\mu \left[\sum_i^{N_{\rm tot}} \right] j^\mu_i$$

Schwinger effect with back-reaction

Back-reaction requires extending the classical Yang-Mills

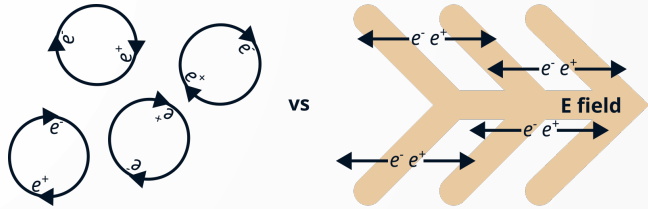
- Back-reaction is an induced current built from two parts

$$D_\mu F^{\mu\nu} = J^\nu_{\rm ind} = J^\nu_{\rm cond} + J^\nu_{\rm pol}$$

[G. Gatoff, A. K. Kerman, T. Matsui; Phys. Rev. D 1951]

- Schwinger effect causes a time dependent dipole (pair-production), which is a polarized current
- Should be fixed by charge conversation

$$J^\mu_{\rm pol} \sim \left(\partial^0 N\right) d$$



- Polarization current has been calculated in QFT for constant electric fields and Abelianized classical color fields [N. Tanji; 1002.3143]

Abelian back-reaction

Full 3+1 solver by collaborator Hidetoshi Taya

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Our model

✔ **Consists of 4 steps:** [Benoit, Nonaka, HT, arXiv: 2608.XXXXX]

(1) Schwinger pair production

- Based on LCFA and Poisson sampling (similar to WarpX)
- Momentum & spin resolved (new)
- No macroscopic particles (new)
- Quantum interference (new)

(2) Particle pusher

- Use Lorentz equation to evolve X and P (same as standard PIC)
- Also BMT equation to evolve S (new)

(3) Calculate current

- Calculate conduction current (same as standard PIC)
- Also polarization current ⇐ essential for charge consv. (new)

(4) EM-field pusher

- Solve Maxwell equation (same as standard PIC)
- Polarization is essential for backreaction = energy-momentum consv. (new)

