

From Hot to Cold Nuclear Matter: Heavy-Ion Collisions and the EIC

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36th Winter Workshop
on Nuclear Dynamics

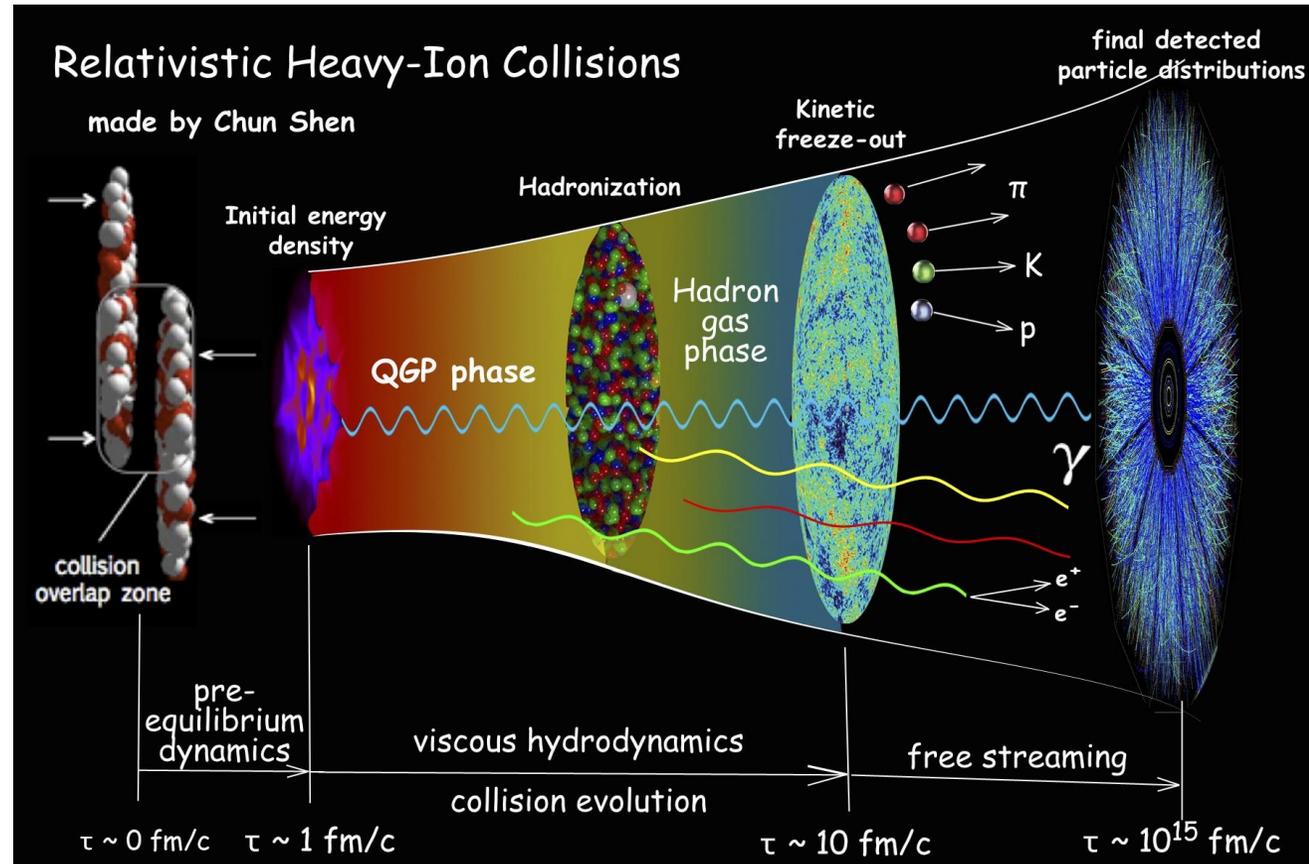
Mar. 5, 2020

In Hot Nuclear Matter, Geometry is King

For a nice historical perspective, see R. Belmont talk

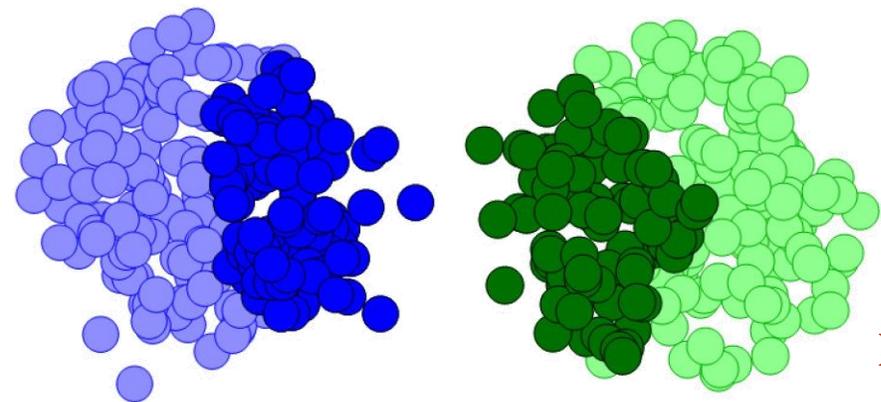
The Standard Model of Heavy-Ion Collisions

- $\tau = 0$: Lorentz-contracted nuclei collide as **shockwaves of energy**
- $0 < \tau < 1 \text{ fm}$: Pre-equilibrium interactions lead to onset of **“emergent hydrodynamics”**
- $1 \text{ fm} < \tau < 10 \text{ fm}$: Nearly-ideal **hydrodynamic flow** of quark-gluon plasma
- Condensation back into **confined hadrons** and eventual **freeze-out**



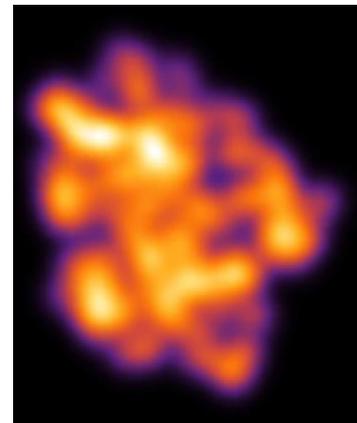
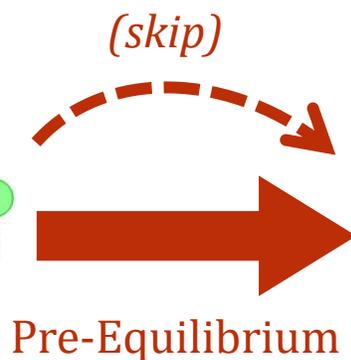
Workflow of Heavy-Ion Collisions

Nuclear Monte Carlo

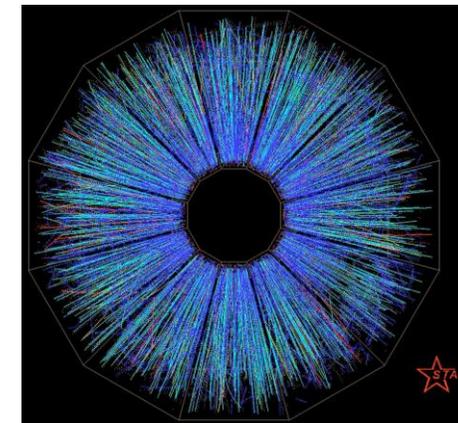
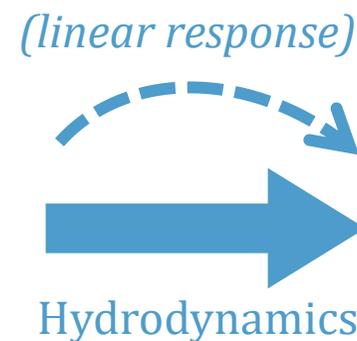


$$\tau = 0$$

Hydro Initialization



$$\tau \sim 1 \text{ fm}$$



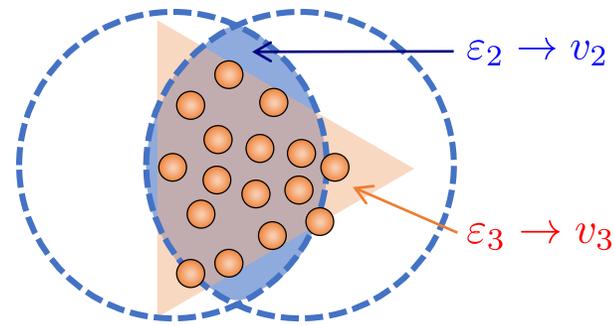
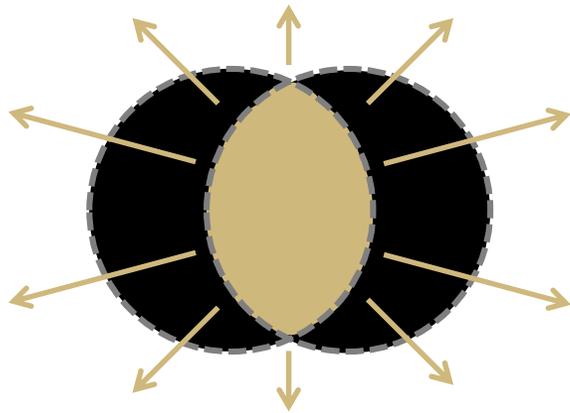
$$\tau > 10 \text{ fm}$$

- **Before collision:**
 - **Pre-equilibrium:**
- **“Initial state”:**
 - **Hydrodynamics:**

Event-by-event fluctuating nuclear geometry
Classical Yang-Mills, kinetic theory, AdS-CFT...

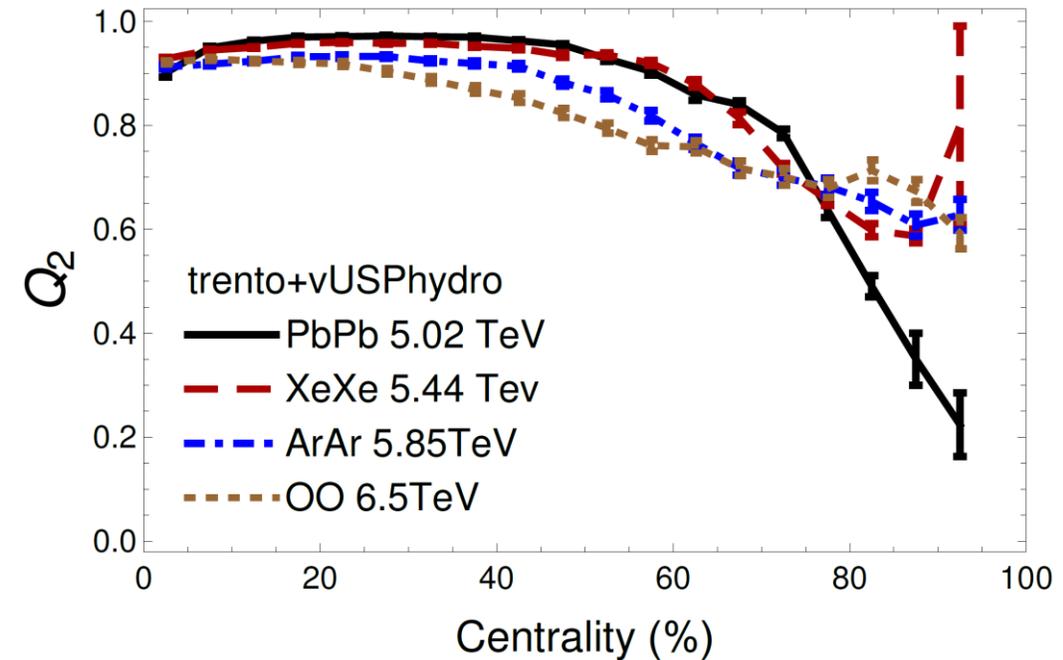
Energy (entropy) deposited at onset of hydrodynamics
Deterministic response to its initial conditions

Collective Flow as a Response to Geometry



$$Q_2 = \frac{\text{Re} \langle \vec{\epsilon}_2 | \vec{v}_2 \rangle}{|\vec{\epsilon}_2| |\vec{v}_2|}$$

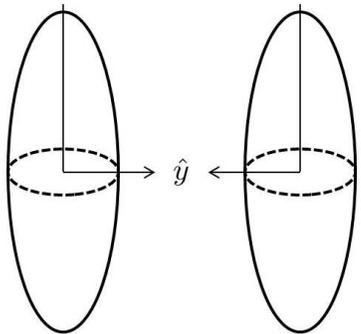
- Defining signature of **collectivity**:
 - **Many-body** response to initial **geometry**
 - Final flow harmonics exhibit **quasi-linear response** to initial eccentricities
- Critical role of **event-by-event fluctuations**
 - **Triangularity**
 - Cumulants



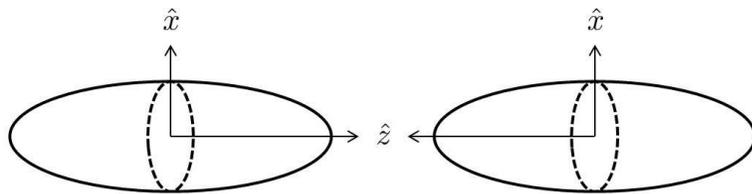
M.D.S. and J. Noronha-Hostler, Phys. Rev. C100 (2019)

Geometry Response: More than Just Impact Parameter

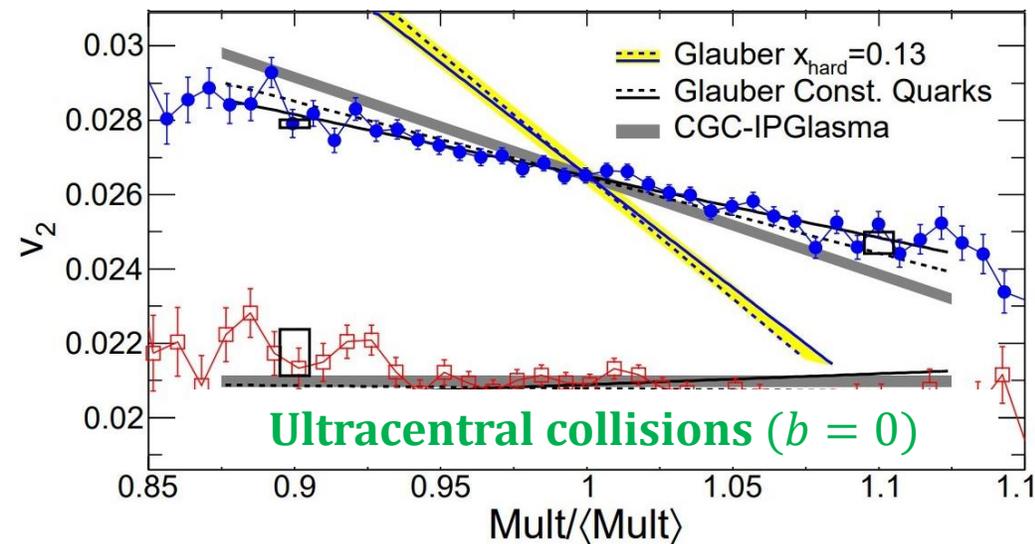
$b = 0$, side-on
Largest Mult.



$b = 0$, tip-on
Largest v_2



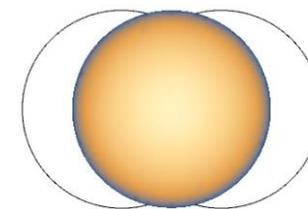
See S. Huang talk



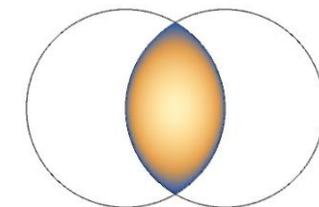
STAR, Phys. Rev. Lett. 115 (2015)

- The strongest geometrical signal is the **elliptical overlap region** based on **impact parameter b**
- **Deformed nuclei** have additional structure, even for $b = 0$
- ❖ **Rules out** entropy deposition for **binary collision density**
 - Sensitivity to some kind of **sub-nucleonic structure?**

pp entropy deposition:



Binary collision:
Same for all b



Overlap region:
 b -dependent

The Unsettling Question of Geometry in Small Systems

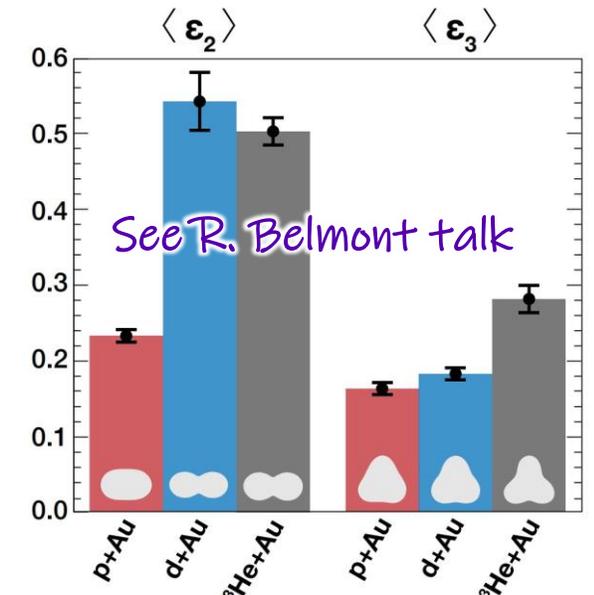
- **Unexpectedly good description** of hydrodynamic response to the geometry of **few-nucleon small systems**.

➤ PHENIX small-system geometry scan:

$$v_2^{(p)} < v_2^{(d)} \sim v_2^{(He)}$$

$$v_3^{(p)} \sim v_3^{(d)} < v_3^{(He)}$$

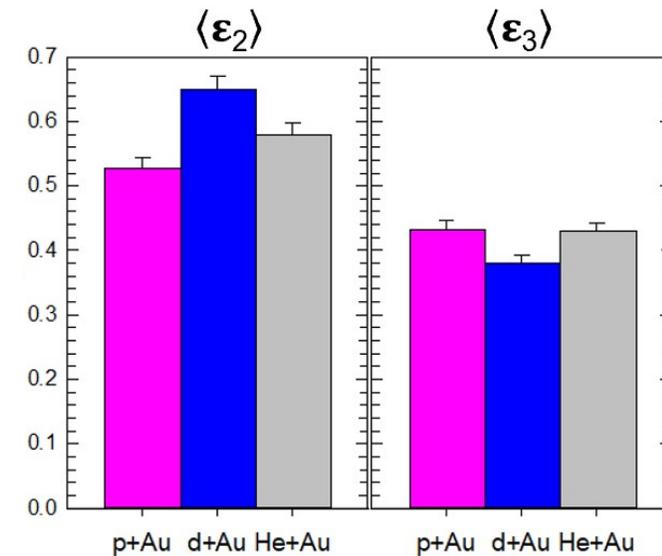
PHENIX, Nature Phys. 15 (2019)



- **But:** the inclusion of **sub-nucleonic structure** substantially changes this picture

R. Lacey, QM2019

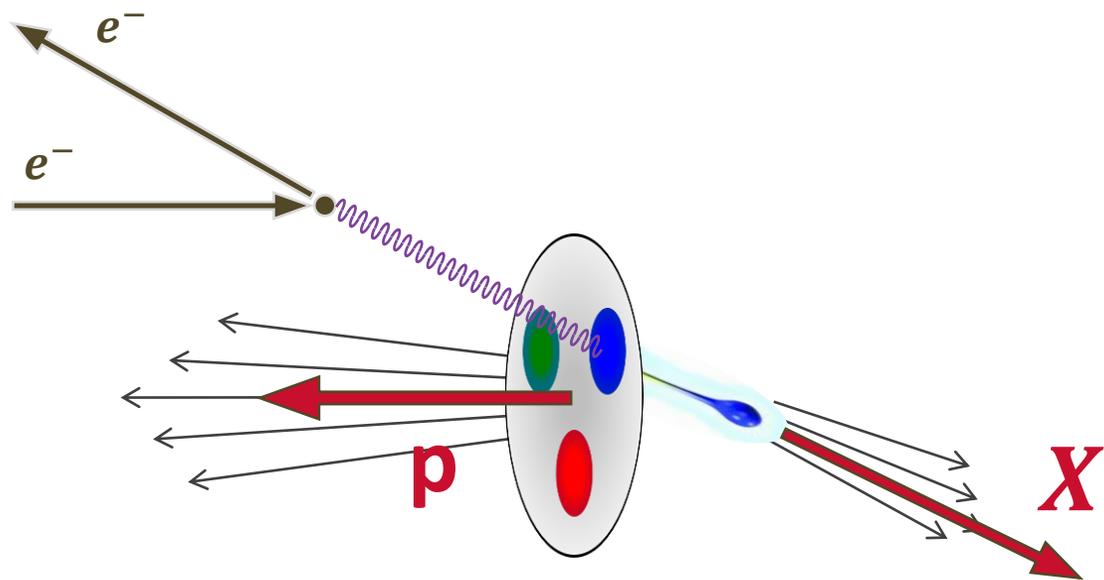
- **Dilutes geometry** which exists at **nucleon level**
- Generates **new geometry** which did not exist before



- ❖ Uncomfortably sensitive to all the **“messy details of QCD”**

Extracting Hadronic Structure from Cold Nuclear Matter

DIS: Imaging the Messy Details of QCD

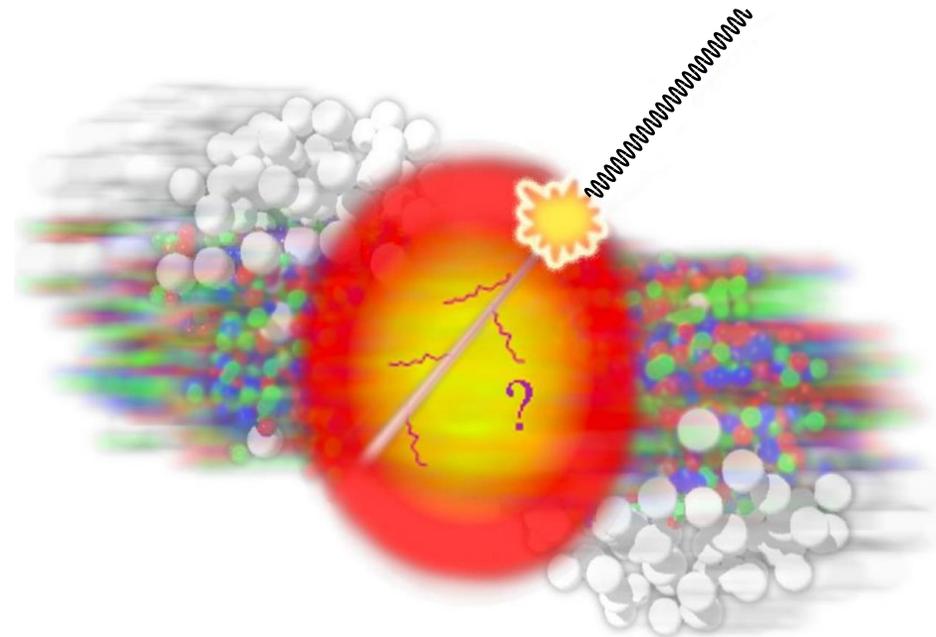


Deep Inelastic Scattering (DIS)

$$\left\{ \begin{array}{l} e + p/A \Rightarrow e + X \\ (\gamma^* + p/A \Rightarrow X) \end{array} \right.$$

Semi-Inclusive DIS

$$\gamma^* + p/A \Rightarrow h + X$$



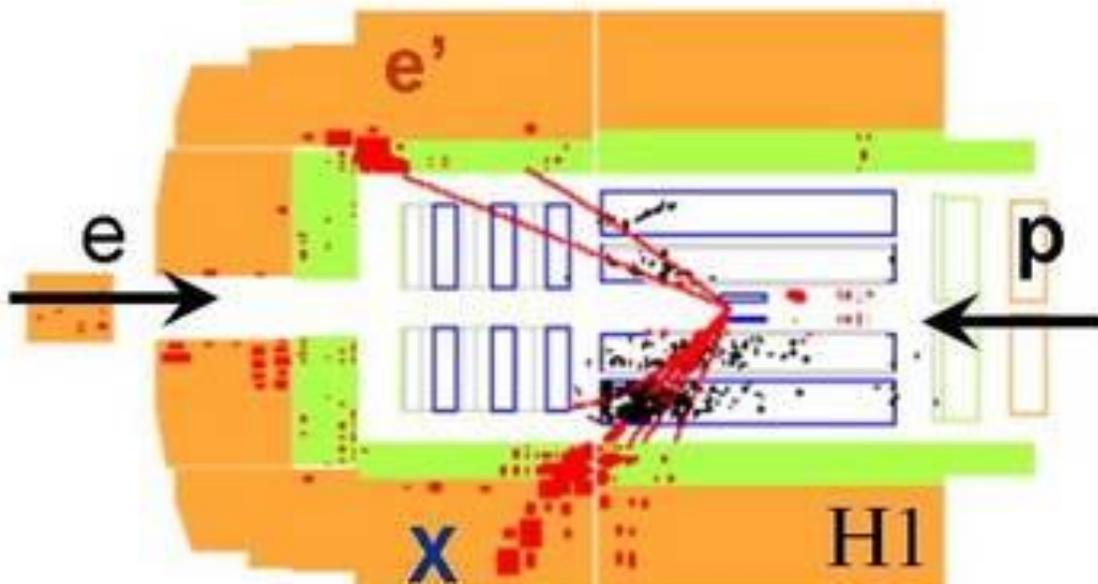
See A. Ewigleben talk

An analogy: γ + jet correlations

$$A + A \Rightarrow \gamma + \text{jet} + X$$

The Past and Future of DIS

HERA: the Electron – Proton Collider



EIC: the Electron – Ion Collider



A. Accardi et al., Eur. Phys. J. A52 (2016)

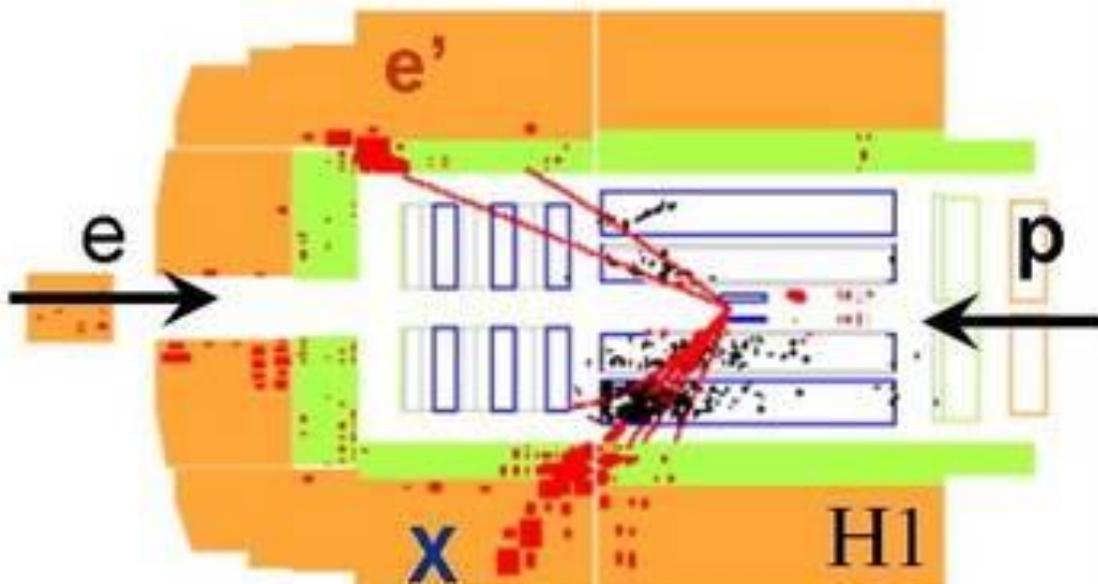
- DIS at HERA: 1992 - 2007

- DIS at the EIC: 2030 ~ 2050

The Golden Channel of Hadronic Structure

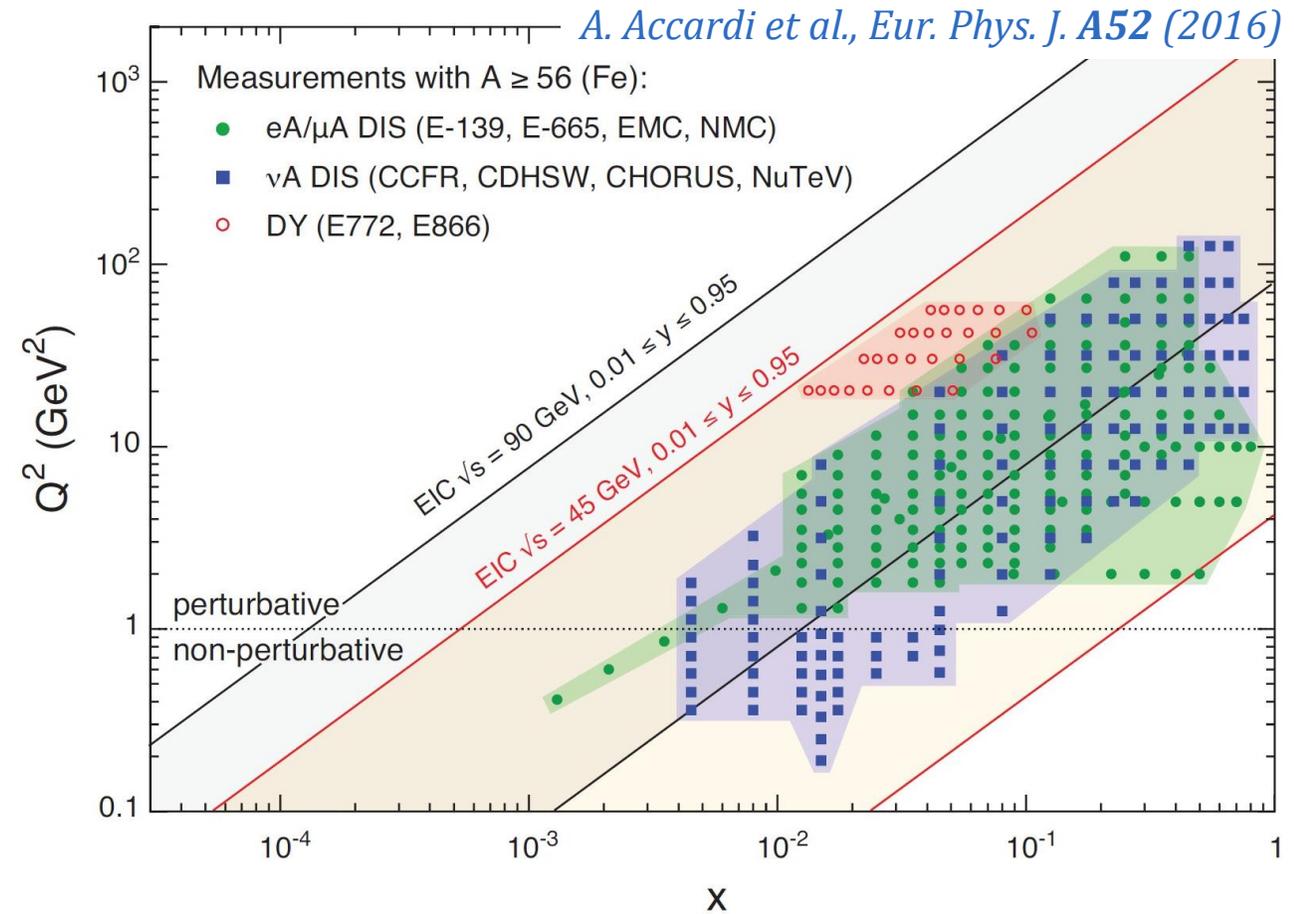
Hard electron recoil Q^2

➤ short-distance pQCD



$$Q^2 = -(\ell_e - \ell'_e)^2$$

$$x = Q^2 / (s_\gamma + Q^2)$$

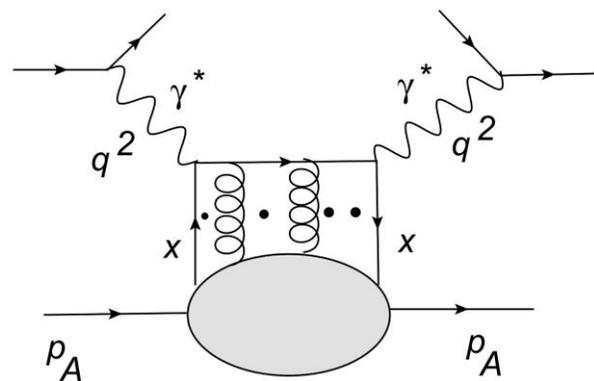


Clean EM measurement of partonic structure
 ➤ Protons and Nuclei

QCD Factorization: An Anchor to Quantum Field Theory

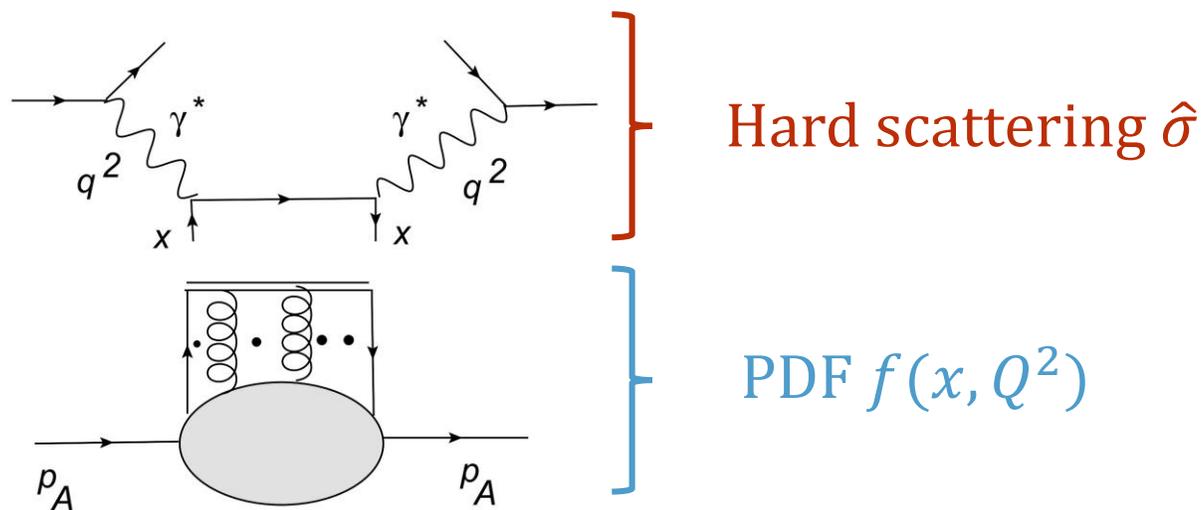
Figures from L. Szymanowski, PoS QNP2012 (2012)

General QCD diagram



$Q^2 \rightarrow \infty$

Factorization of Nonperturbative Physics



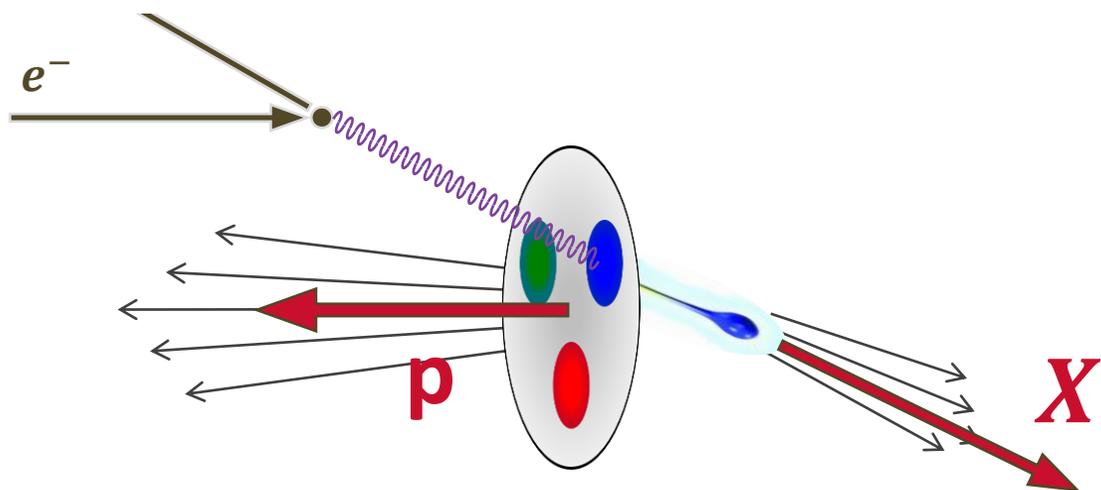
$$\frac{d\sigma}{dx dy} = \frac{2\pi y \alpha_{EM}^2}{Q^4} L^{\mu\nu} W_{\mu\nu}$$

$$W^{\mu\nu} = \sum_a \int_x^1 \frac{dz}{z} f_a(z, Q^2) \hat{\sigma}^{\mu\nu} + \mathcal{O}\left(\frac{1}{Q^2}\right)$$

$$f(x, Q^2) = \int \frac{dr^-}{2\pi} e^{ixp^+ r^-} \langle p | \bar{\psi}(0) \frac{\gamma^+}{2} \mathcal{U}[0, r] \psi(r) | p \rangle$$

Unfolding Hadronic Structure: Momentum Space

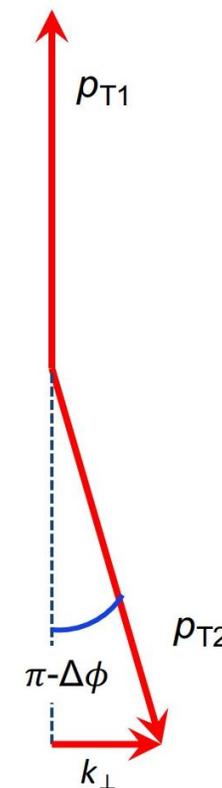
Semi-Inclusive DIS $\gamma^* + p/A \Rightarrow h + X$



“Acoplanarity”:

Sensitive to
intrinsic
transverse
momentum \vec{k}_T

See S. Mohapatra talk

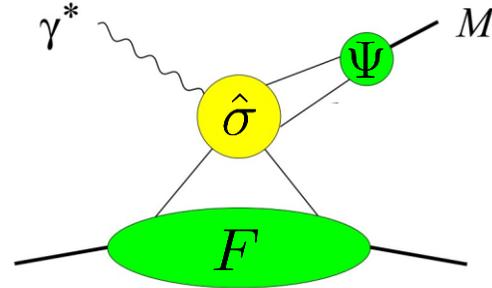
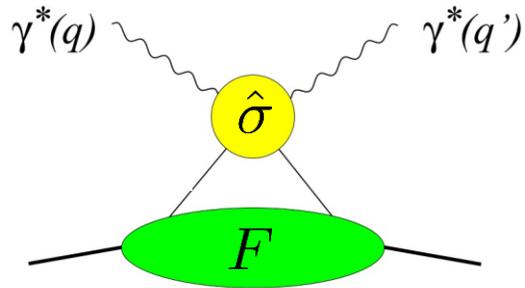


SIDIS: Tag not just on **recoil photon**, but also on **one identified hadron**
(two scales)

➤ **Transverse-Momentum Dependent (TMD)**
parton distribution functions

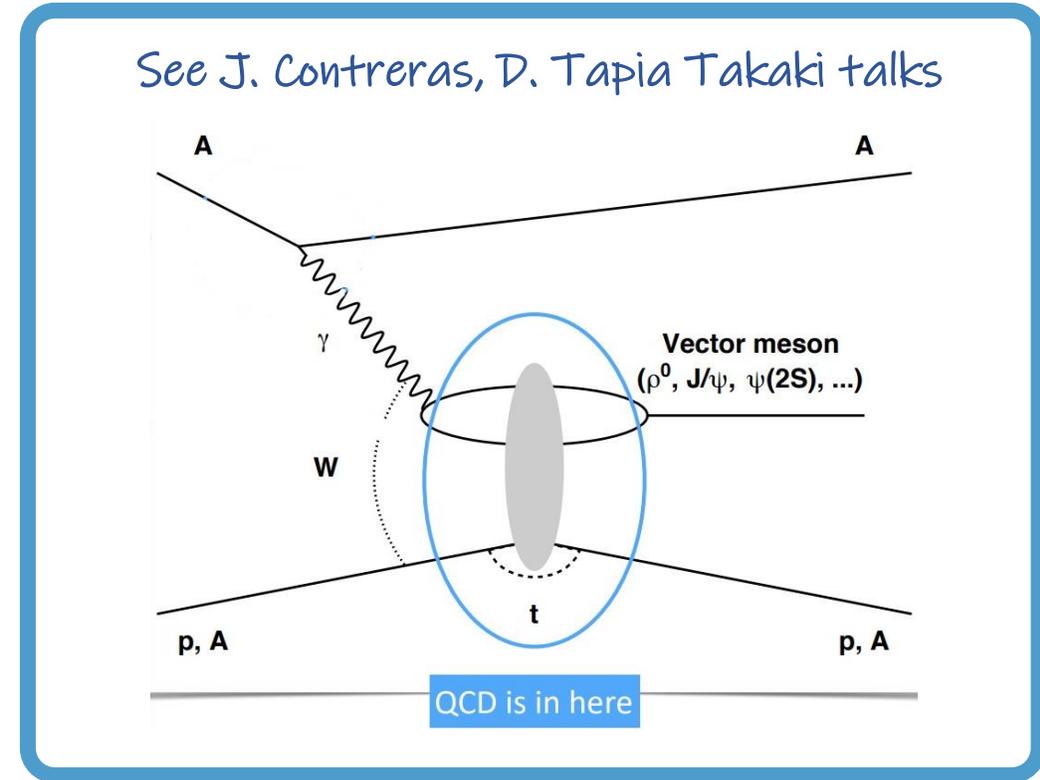
$$\vec{k}_T = \vec{k}_T^{(PDF)} + \vec{k}_T^{(FF)}$$

Unfolding Hadronic Structure: Coordinate Space



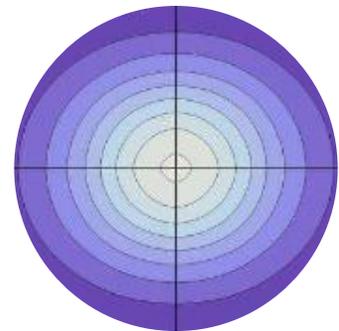
M. Diehl, Phys. Rept. 388 (2003)

- **Hard exclusive $\gamma^* + h$ processes** can be factorized at the **amplitude level**
 - Deeply virtual Compton scattering
 - Deeply virtual meson production



$$\mathcal{A}^{DVMP} = \frac{1}{Q} \int_{-1}^1 dx \int_0^1 dz \hat{\sigma} F(x, \xi, t; Q^2) \Psi^{(VM)}(z) + \mathcal{O}\left(\frac{1}{Q^2}\right)$$

- **Generalized Parton Distributions (GPDs)**
 - **Spatial distribution** of partons = Fourier transform of t –dependence



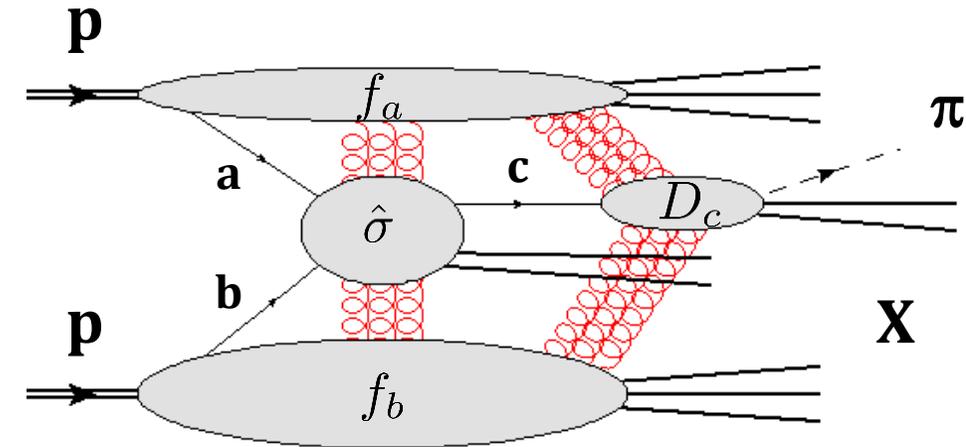
The Delicate Game of Structure for Hadrons and Heavy Ions

Factorization is the Exception, Not the Rule

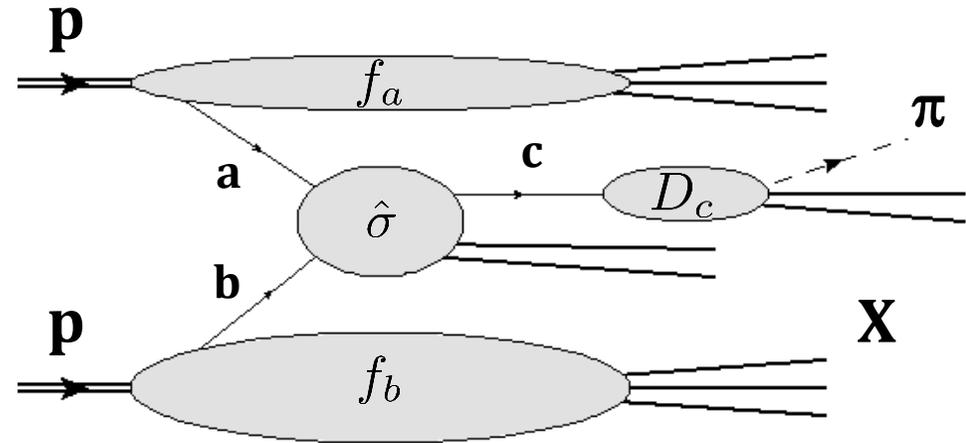
- **Hadronic collisions** (e.g. $p + p \rightarrow \pi + X$) are among the **most complicated processes in QCD**
 - **Soft, nonperturbative radiation entangles** projectile + target and initial + final state
 - **No *a priori* hope of factorization, universality**

$$E \frac{d\sigma}{d^3p} = \sum_{abc} \int_0^1 dx_a dx_b \frac{dz}{z^2} f_a(x, p_T^2) f_b(x, p_T^2) \hat{\sigma}_{ab \rightarrow c} D_c(z, p_T^2)$$

- Only for **sufficiently inclusive (or exclusive) observables** do the dangerous **spectator interactions cancel** to recover factorization



J. Collins, Camb. Monog. Part. Phys. Nucl. Phys. Cosmol. 32 (2011)

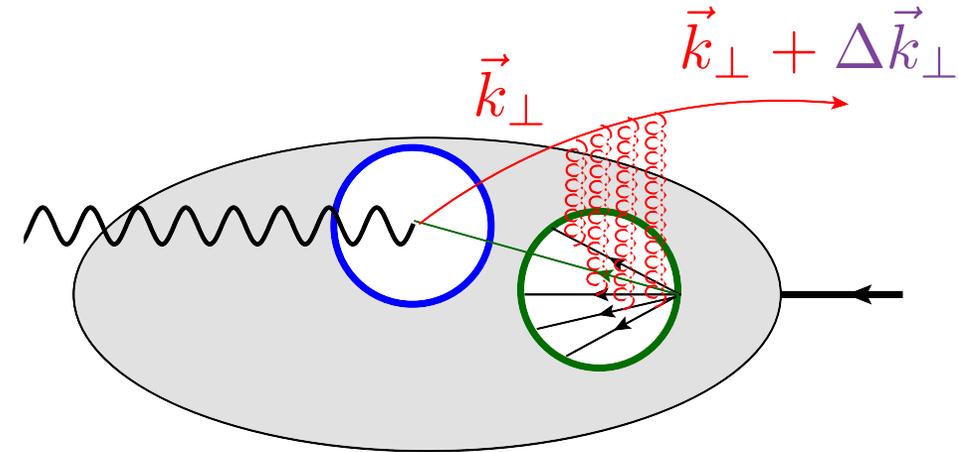


3D Structure is Even More Fragile

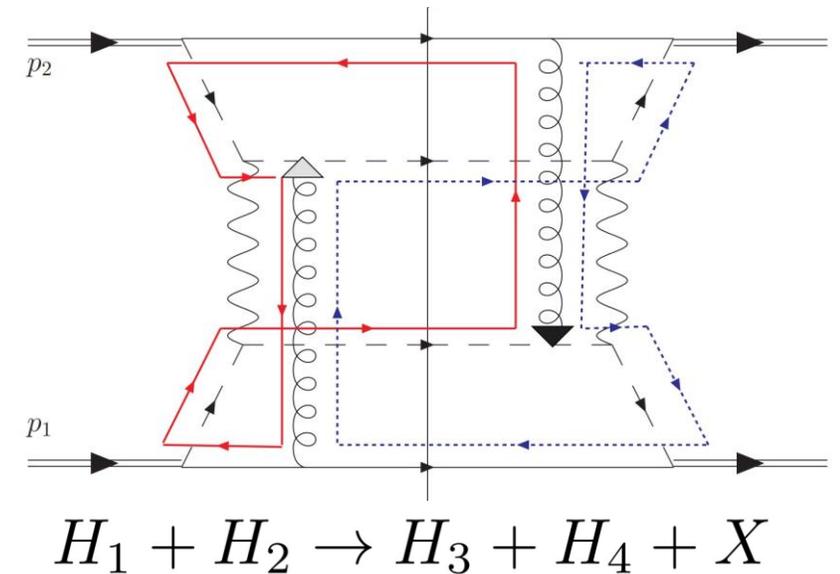
$$f(x, Q^2) \sim \mathcal{FT}_{1D} \langle p | \bar{\psi}(0) \frac{\gamma^+}{2} \mathcal{U}[0, r] \psi(r) | p \rangle$$

$$f(x, \vec{k}_T; Q^2) \sim \mathcal{FT}_{3D} \langle p | \bar{\psi}(0) \frac{\gamma^+}{2} \mathcal{U}[0, r] \psi(r) | p \rangle$$

- Seemingly trivial to **generalize PDFs from 1D to 3D...**
 - Only factorize for a few special processes
- Intrinsic transverse momentum (i.e., “initial flow”) is **warped by final-state interactions**
 - Controlled **non-universality: sign change!**
- Even worse, hadronic collisions are explicitly **color entangled!**



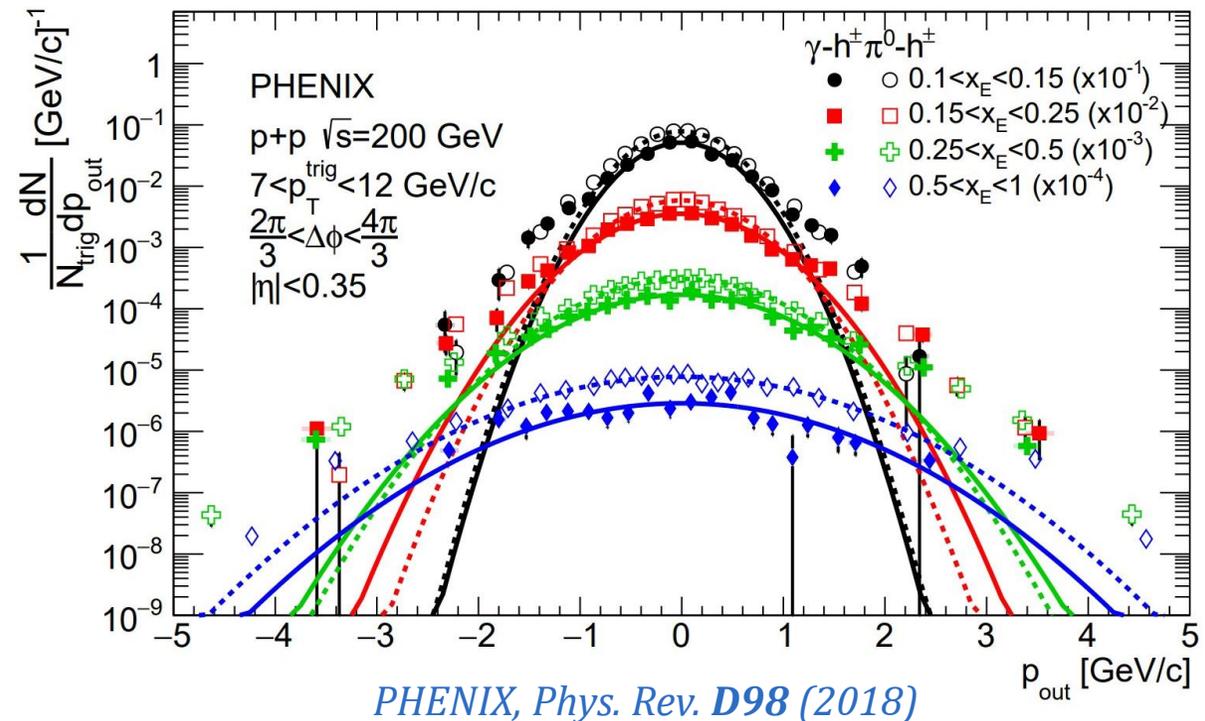
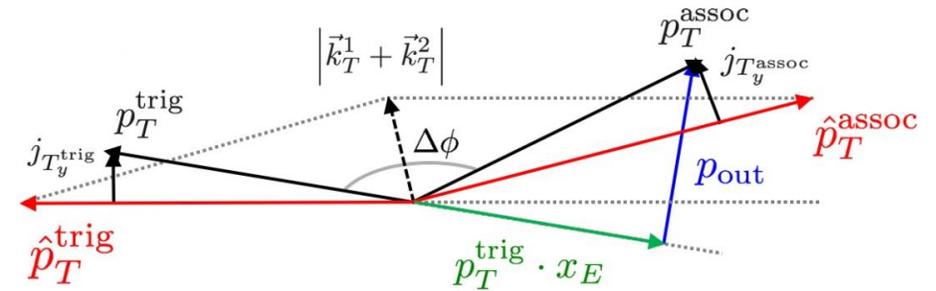
T. Rogers and P. Mulders, Phys. Rev. D81 (2010)



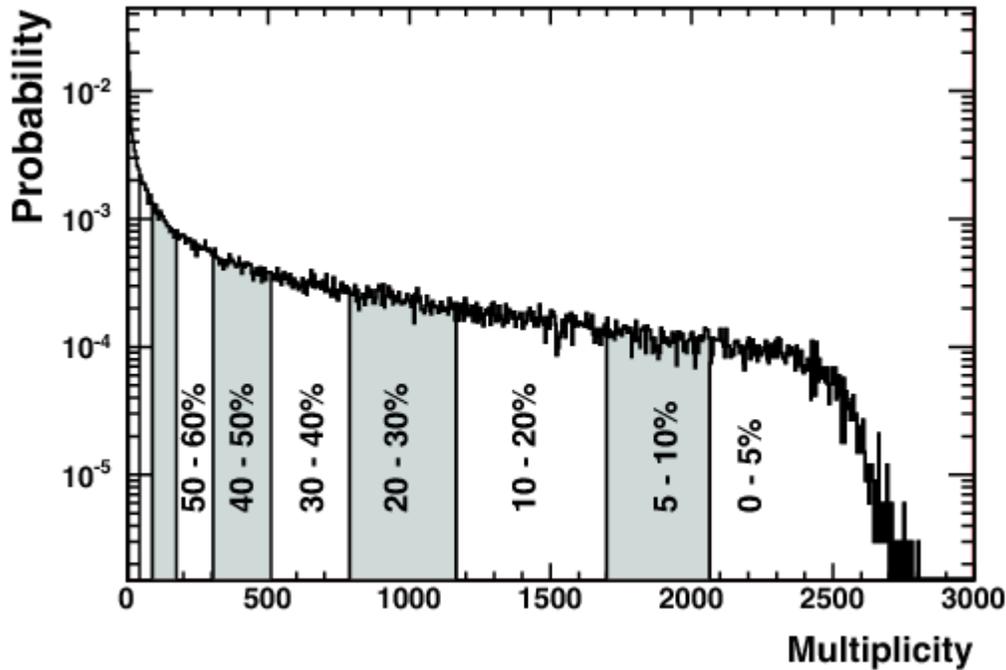
In Heavy Ions, We Wouldn't Let That Stop Us

- Even if factorization breaking is present, **what can we learn from it?**
 - Is it numerically large?
 - Entanglement physics in QCD?
- PHENIX used dihadron and γ -hadron correlations to **try to measure factorization breaking**

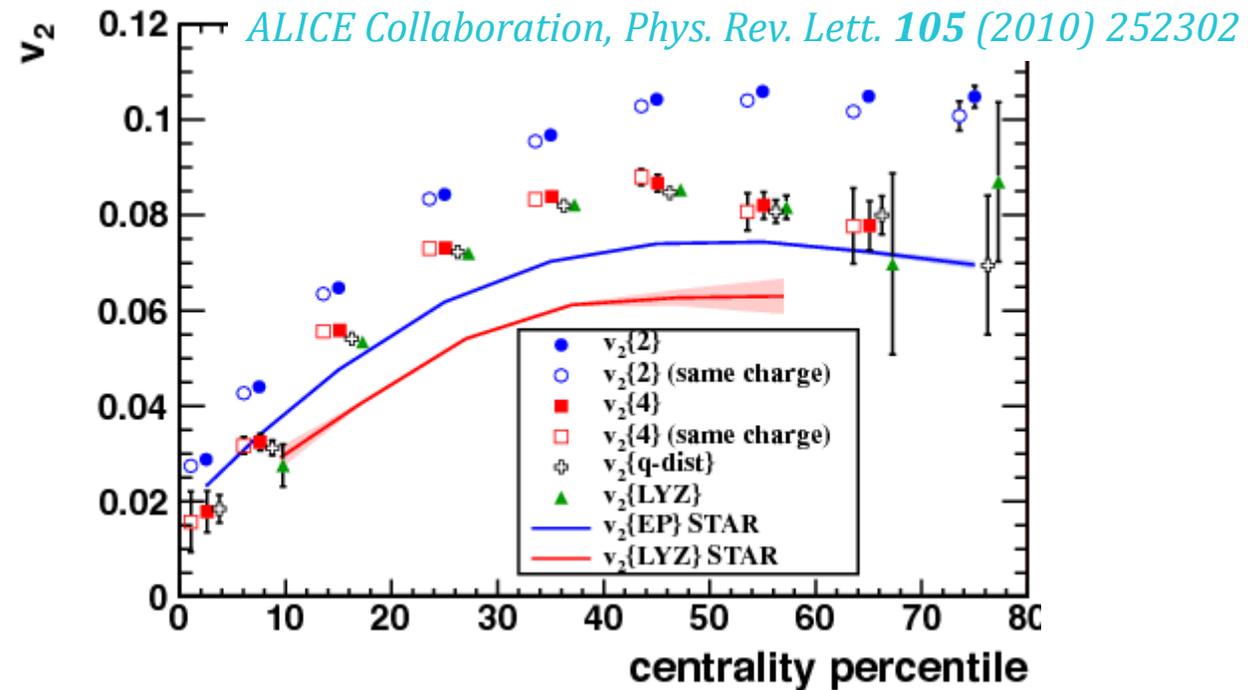
For the time being, the only obvious way to quantify factorization breaking effects is to **compare data in processes that are predicted to violate factorization and calculations assuming factorization holds**. Such calculations are **not available at this time**, largely due to the fact that even for unpolarized observables TMD PDFs and TMD FFs are not yet well constrained due to a **lack of data**.



Flow is the Most Non-Factorizing Observable Imaginable



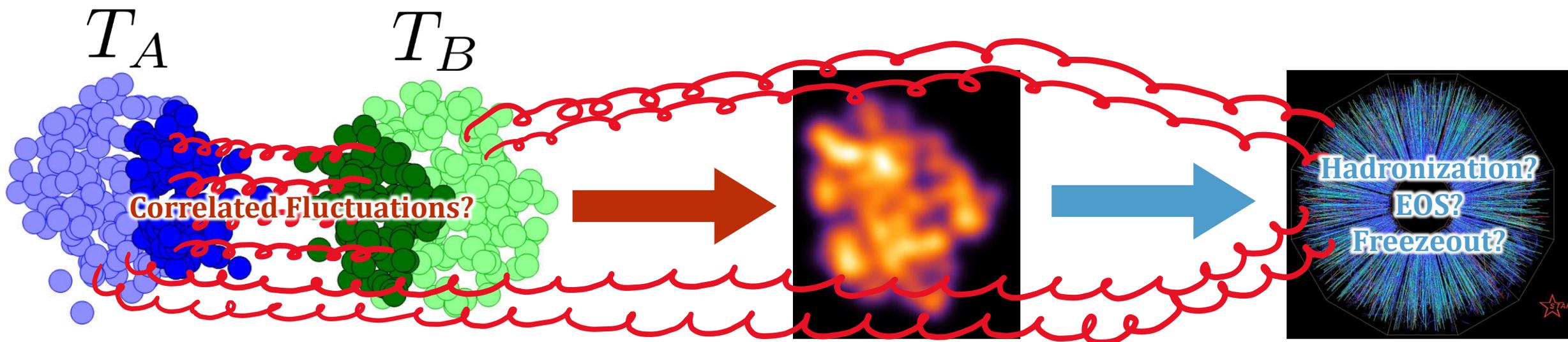
- Many-hadron correlations
- Soft sector with no hard scale
- Selection cuts: centrality, event engineering...



*“Twenty years ago, the challenge in heavy ion physics was to find the QGP. Now, the challenge is **not** to find it.”*

- Jurgen Schukraft, QM2017

Factorization Breaking for Heavy Ions?



- **Implicit assumptions of factorization and universality** are pervasive
 - **Demonstrably false** in QCD – even just for $v_2\{2\}$ in $p + p$
- **Projectile / target entanglement** – a nucleus depends on its partner?
 - **Different “Au”** in each case: $AuAu \neq CuAu \neq dAu \neq eAu$
- **Initial state / hadronization entanglement?**

Dialogue Between Hot and Cold Nuclear Matter*

* ...and a little self-promotion

The Opening Statement of a Long Conversation

EIC → Heavy Ions

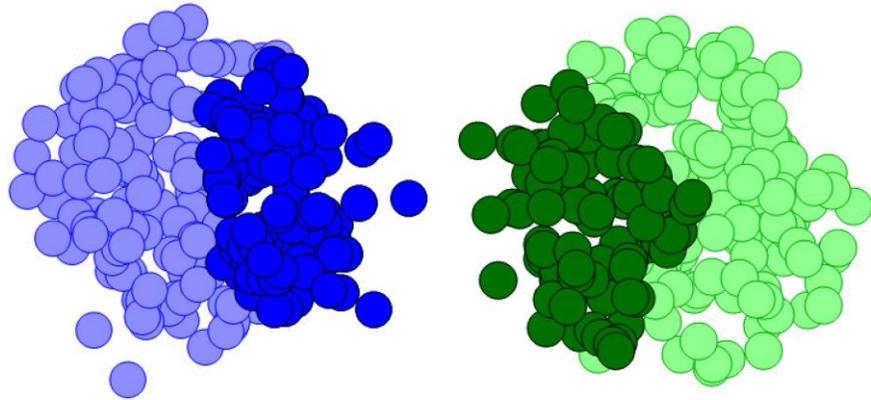
- Spatial imaging (GPDs) ?
- Nuclear modification (nPDFs) ?
- Nuclear deformation ?
- **Partonic chemistry ?**
- Fluctuating proton structure ?
- Quantum small system engineering ?

Heavy Ions → EIC

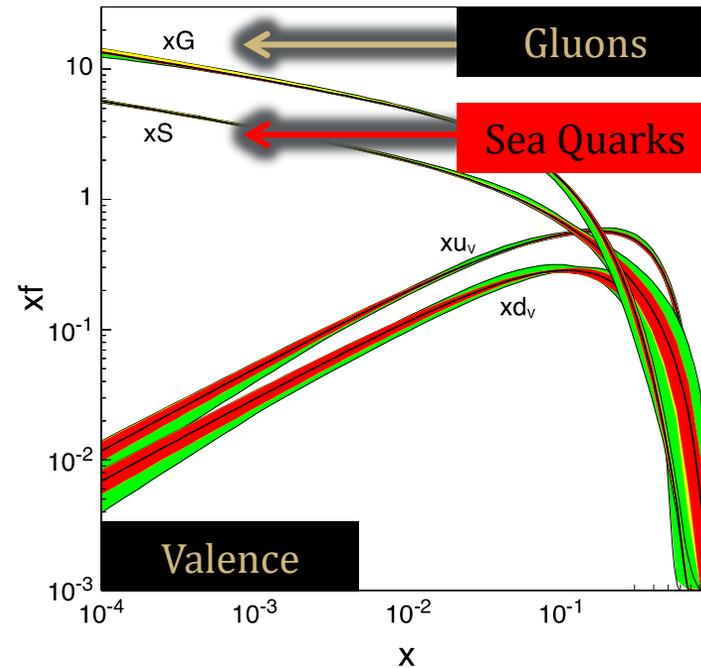
- Fluctuation dominance !
- UPCs: preview of the EIC
- Collectivity in small systems ?

Chemistry of the Initial State: More than Just Gluons

Nuclear Monte Carlo



$$\tau = 0$$



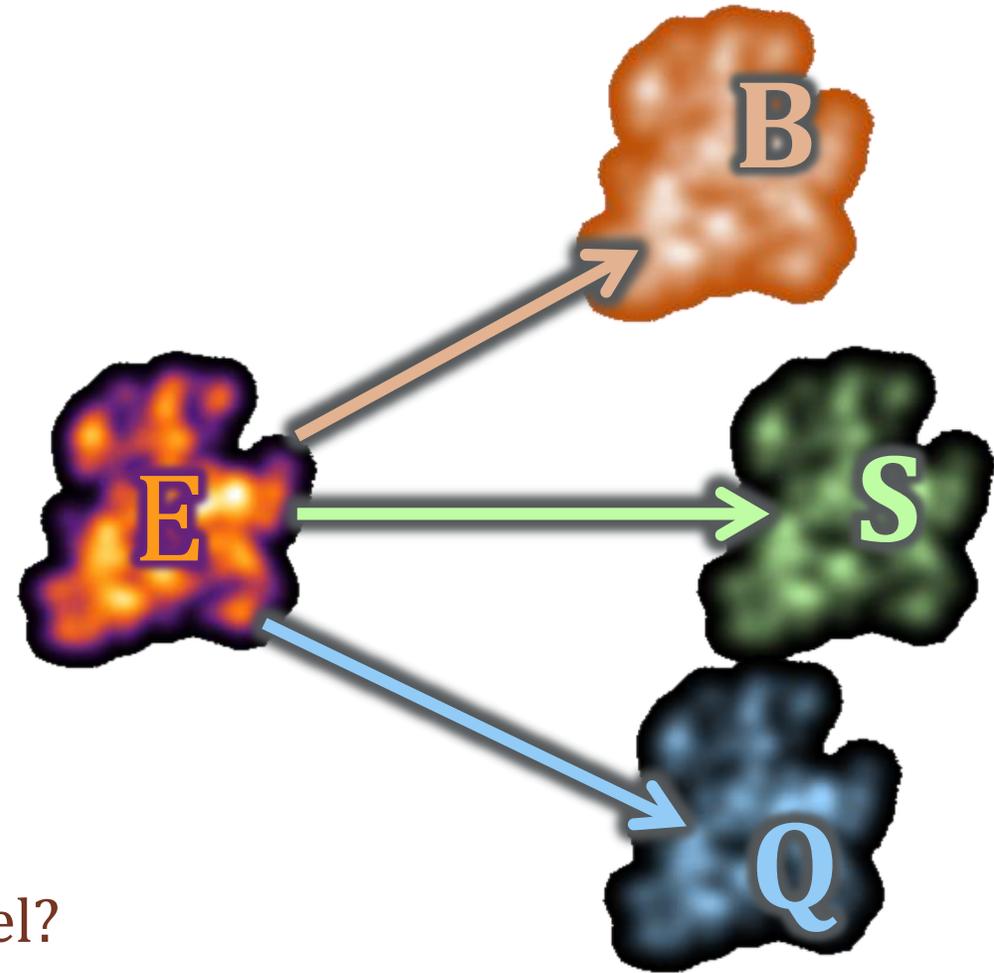
$$\frac{xS}{xG} \sim 30\%$$

*H1 and ZEUS Collaborations,
JHEP 1001 (2010) 109*

- The conventional wisdom that **charge transport is only accessible at low energies** is based on **mean-field (optical Glauber) logic**
- While the **net charge is zero** at top collider energies, the **spatial fluctuations from $q\bar{q}$ pairs** are abundant

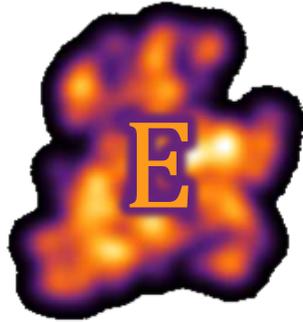
A Module to Generate Initial Conserved Charges

- **Pair production of quarks** will lead to spatially-fluctuating **domains of charge**
- **Initial conditions of conserved charges**
 - Baryon number
 - Strangeness
 - Electric Charge
- How are these **charge domains correlated** with the shape of the **energy density**?
- Can we **produce these charges from the energy directly**, without making another initial-state model?

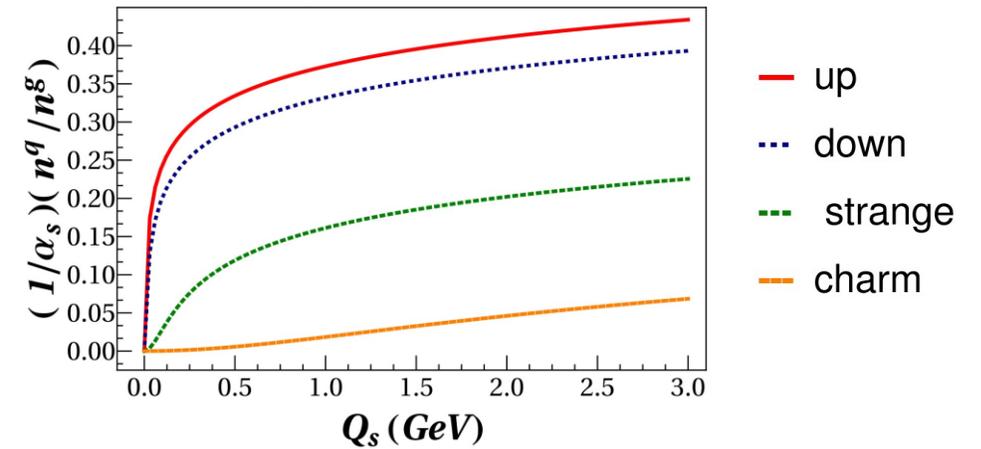


A Resampling Strategy

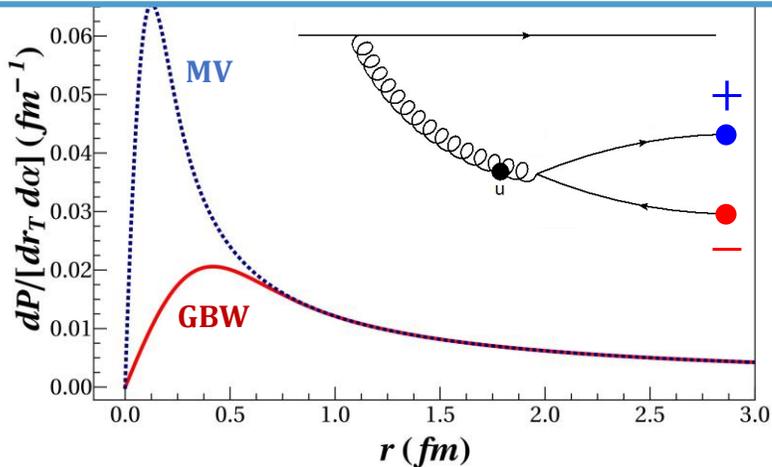
Input: Initial Energy



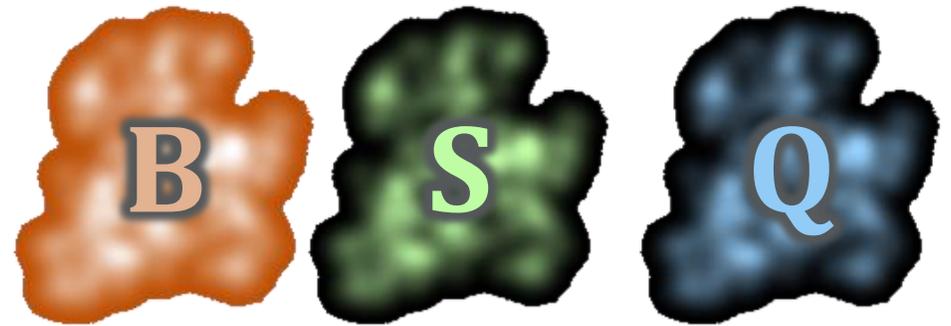
Step 1: Sample the Chemistry



Step 2: Sample the Splitting



Output: Baryon #, Strangeness, Charge

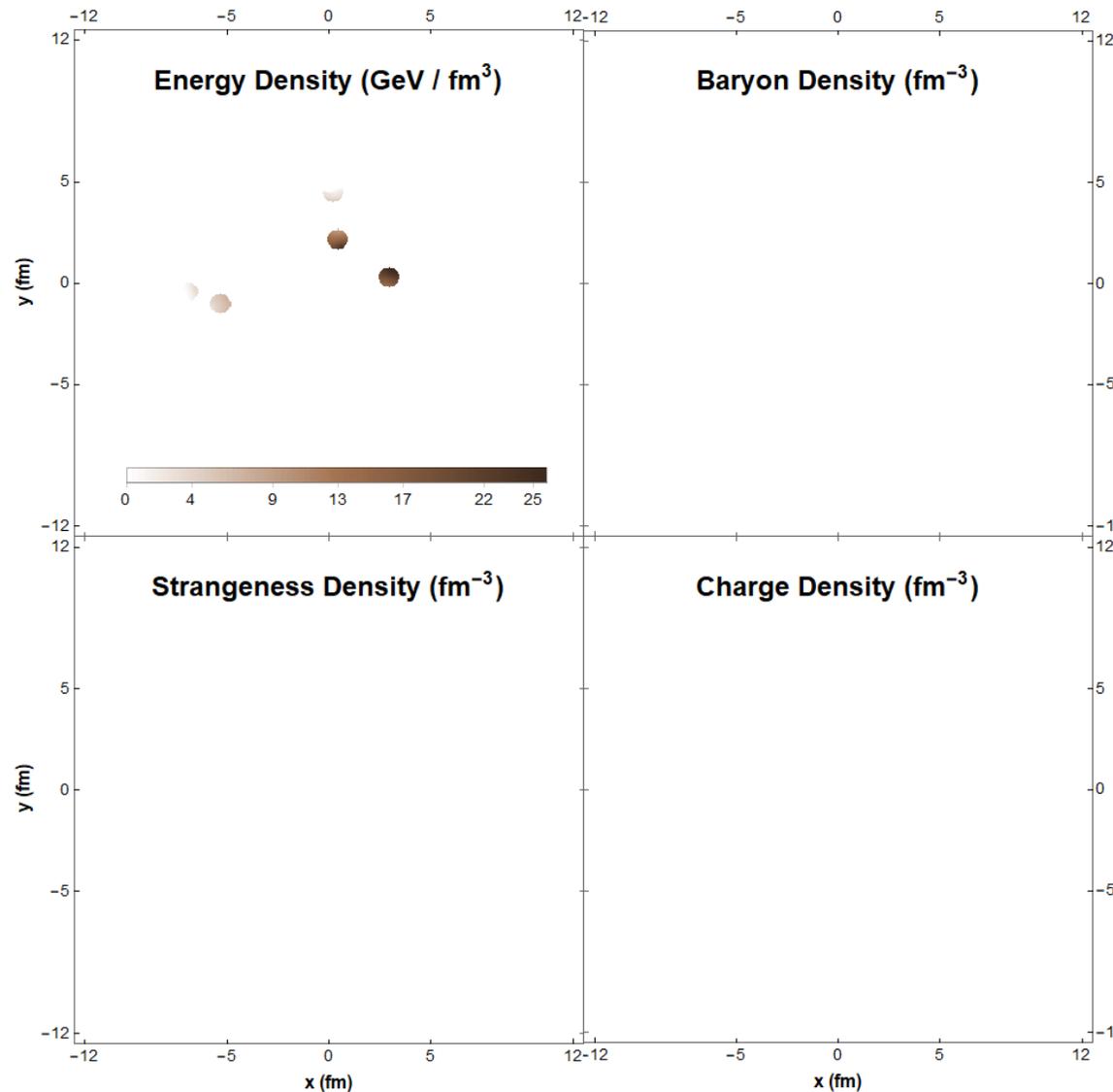


The Algorithm in Action

*M.D.S. et al,
arXiv: 1911.10272,
arXiv:1911.12454*

Mass threshold:

**Strange quarks
couple to hot
spot geometry**

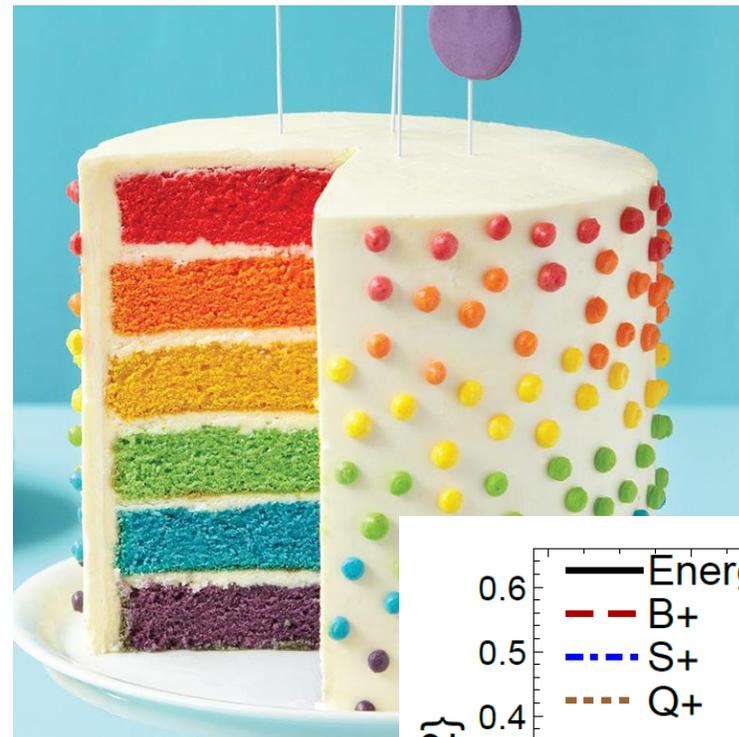
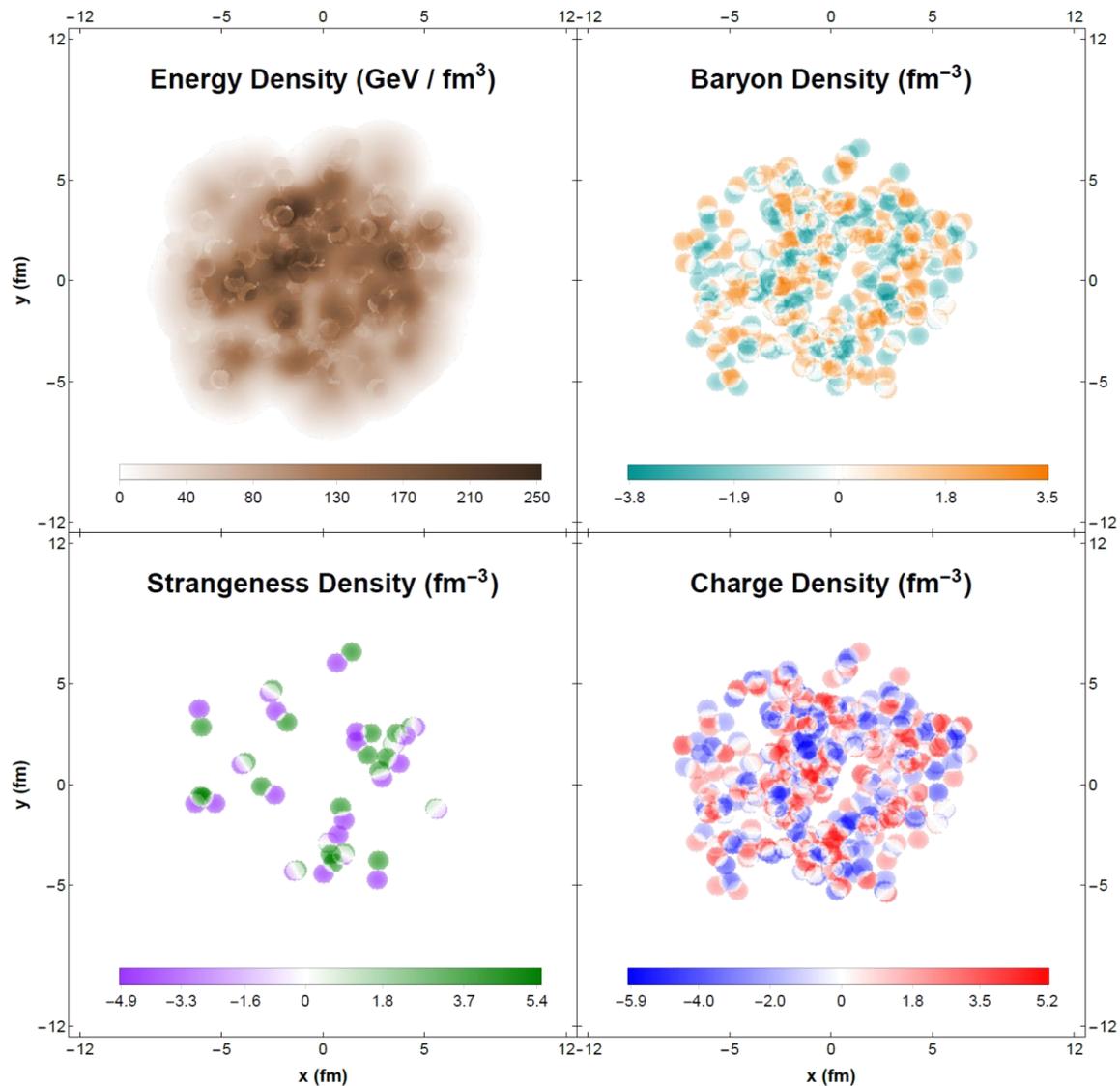


see S. Pratt talk

CGC details didn't
matter after all...

...Could we take
PDF chemistry
directly instead?

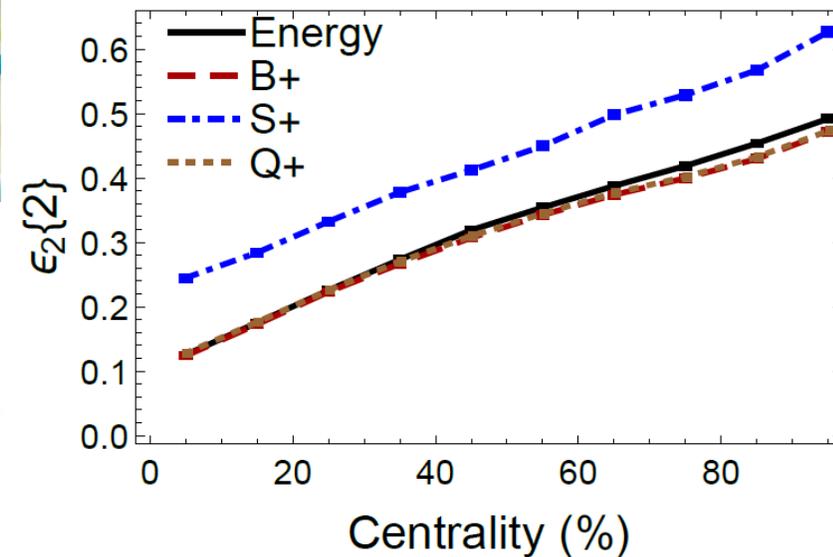
ICcing: Initial Conserved Charges in Nuclear Geometry



E+BSQ:

A "Layer Cake" of Structure

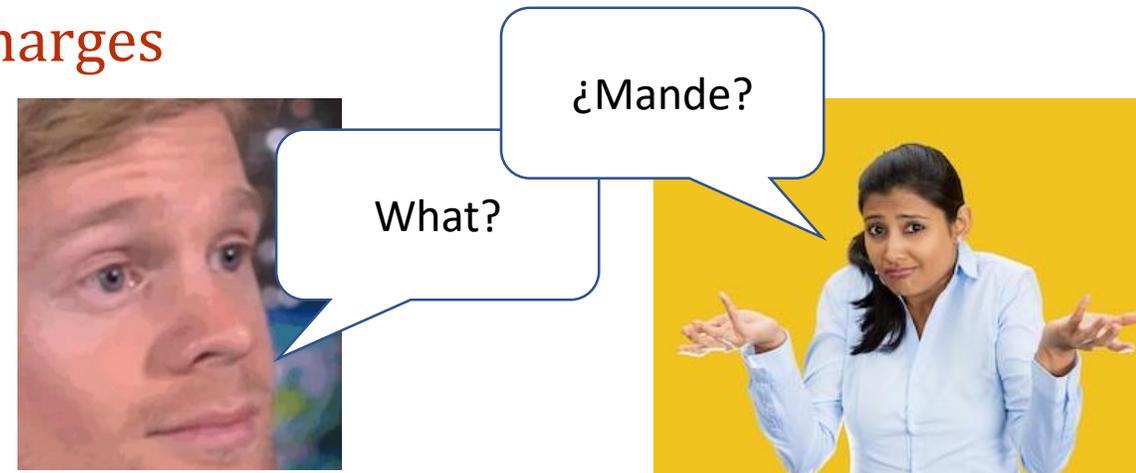
Strangeness can select on hot spots!



Conclusion and Outlook

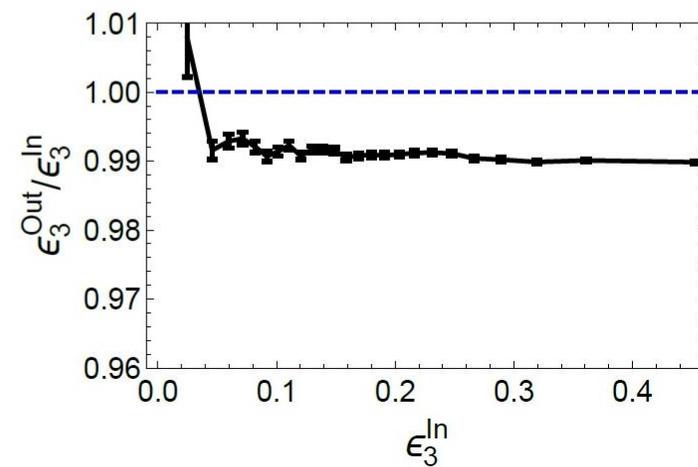
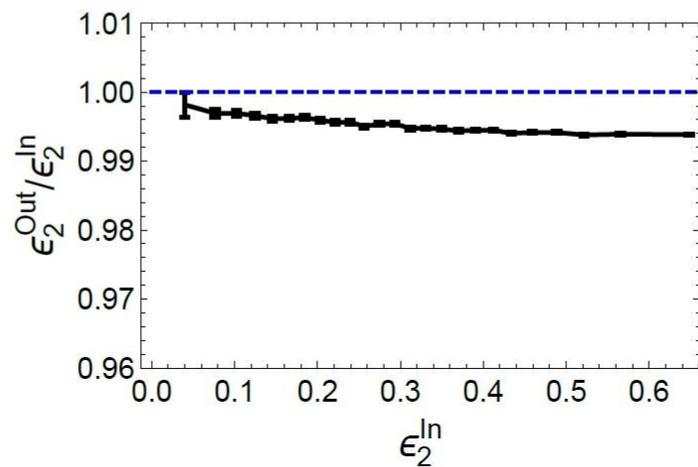
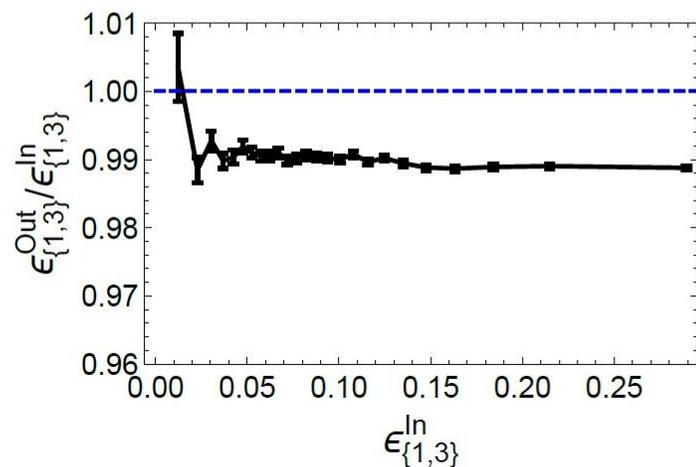
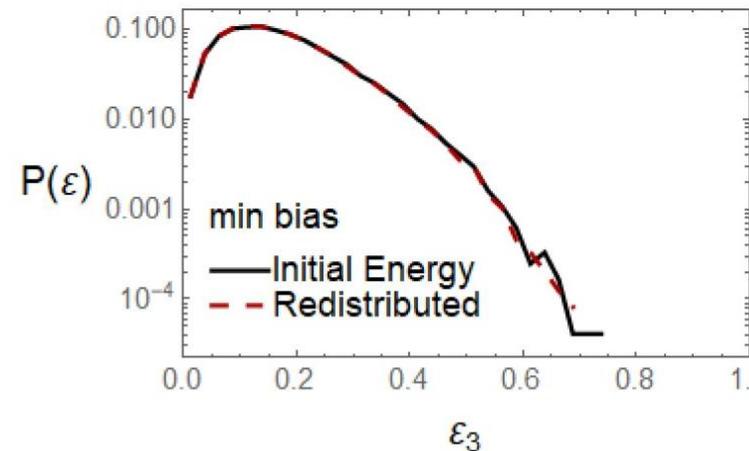
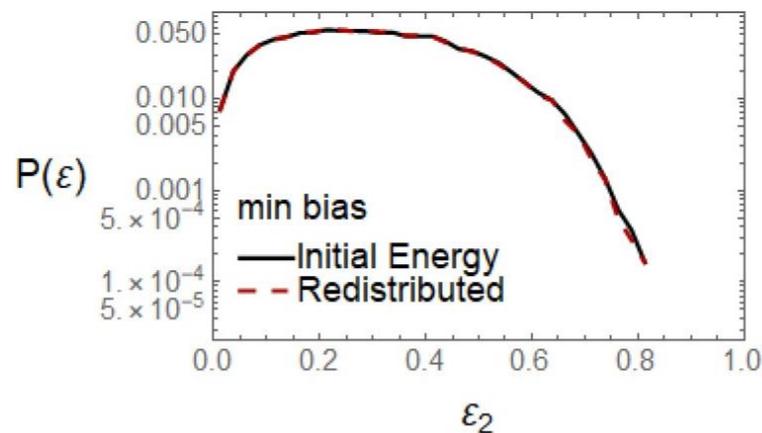
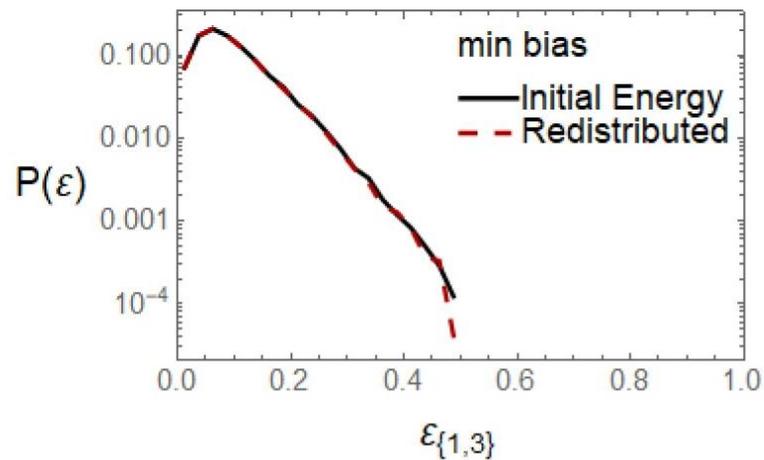
“True Conversation is About Going on a Journey”

- Hot and cold nuclear physics see through very different paradigms:
 - Heavy Ions: Data-driven, geometry response, fluctuation-centric
 - Cold QCD: Anchored in QFT, limited observables, mostly mean field
- An opportunity for dialogue:
 - EIC → Heavy Ions: Partonic chemistry, imaging hadronic structure, ...
 - Heavy Ions → EIC: Fluctuations, UPCs, small systems, ...
- ICcing: Initial Conditions of Conserved Charges
 - Initial conditions for BSQ-Hydro
 - Flexible input – PDF chemistry?
- **The EIC is on the way! The time to break down the language barrier is now.**



Backup

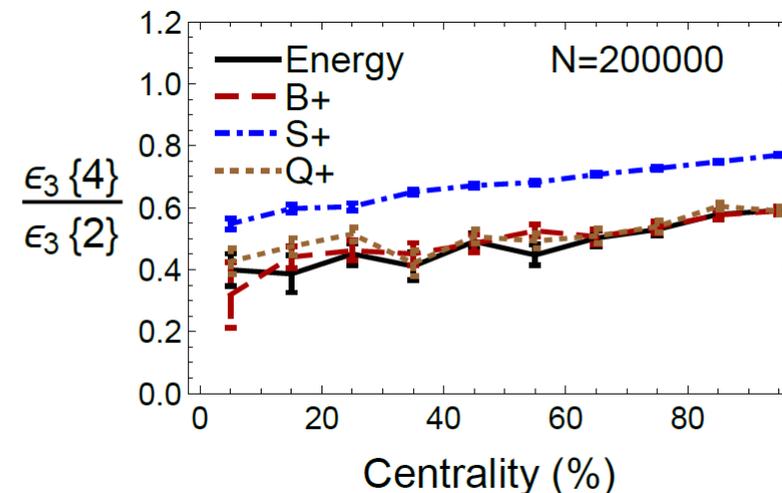
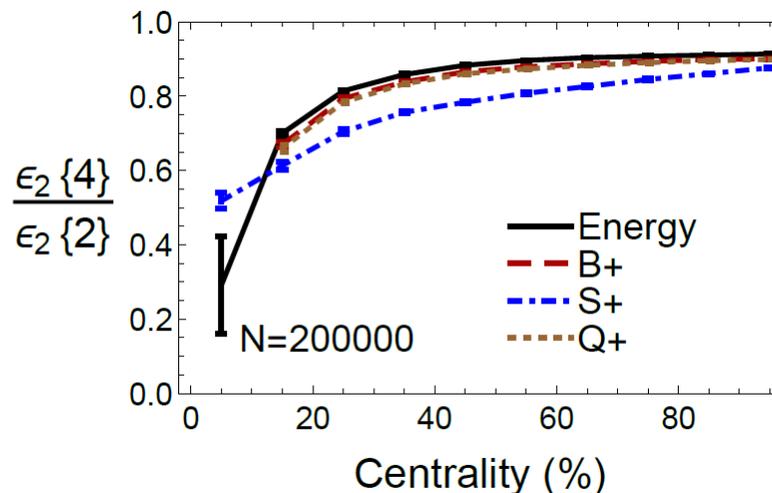
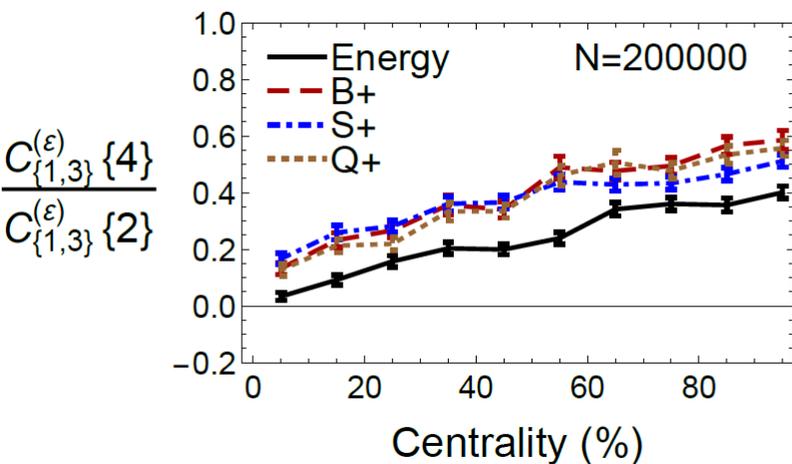
Does ICCING Disturb Existing Fits to Bulk Observables?



$\varepsilon_n\{4\}$: the Fluctuating Eccentricities

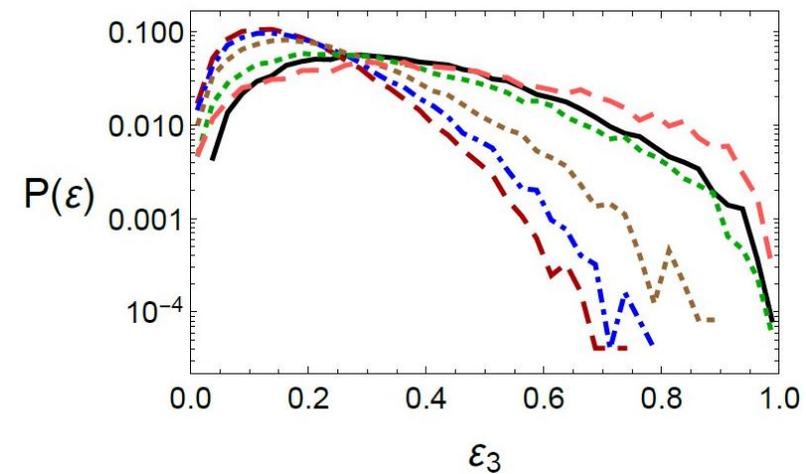
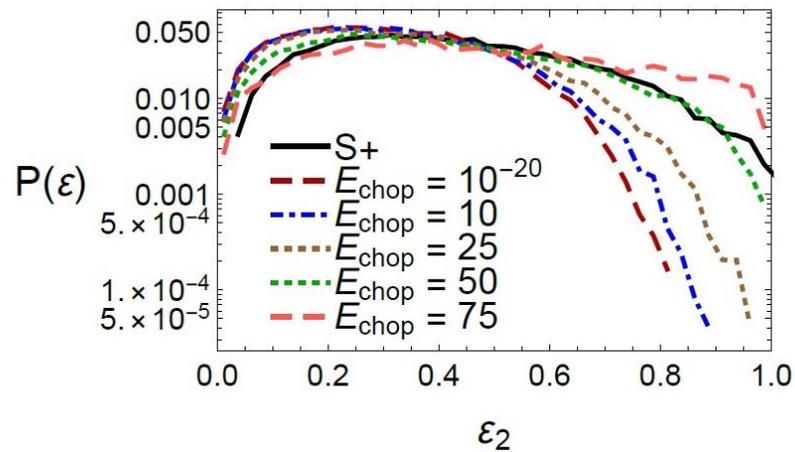
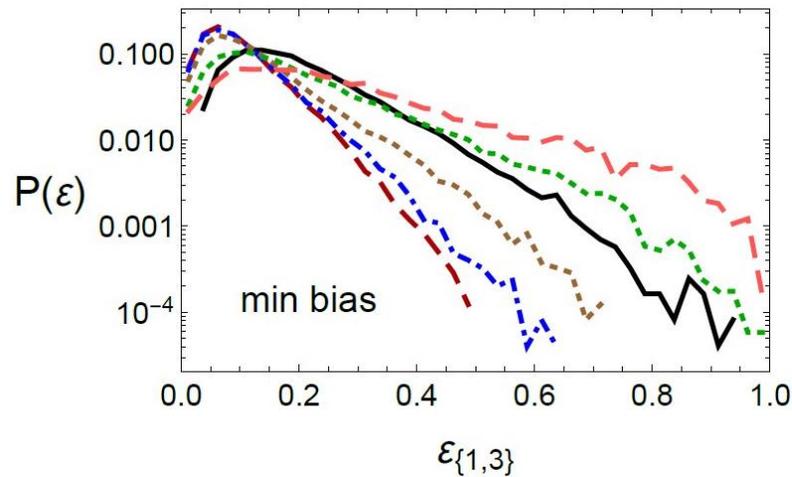
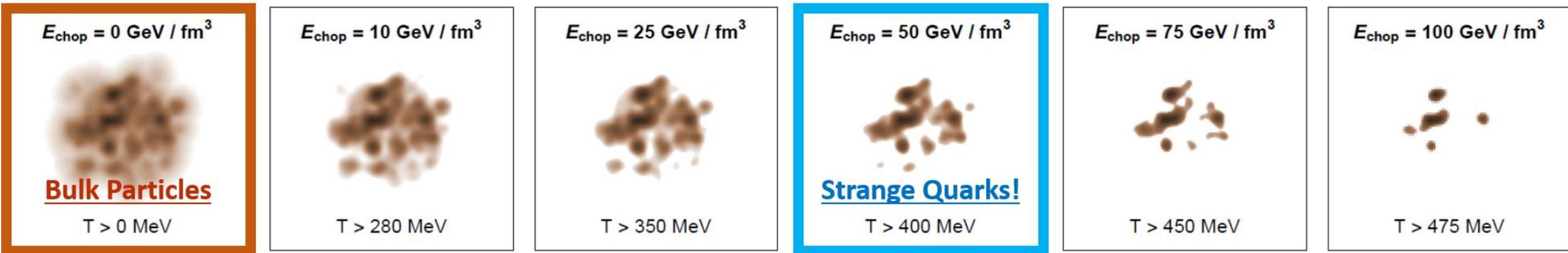
$$\frac{v_n\{4\}}{v_n\{2\}} = \sqrt[4]{\frac{C_n\{4\}}{C_n\{2\}}}$$

$$\frac{v_n\{4\}}{v_n\{2\}} = \sqrt[4]{1 - \frac{\text{Var}(v_2^2)}{\langle v_2^2 \rangle^2}}$$



- **Bulk / B / Q** eccentricities are **dominated** by **elliptical overlap** region
 - **Few fluctuations** in **peripheral** collisions (large elliptical signal)
 - **Many fluctuations** in **central** collisions (small / vanishing elliptical signal)
- **Strangeness fluctuations** are much **less sensitive** to the elliptical background

Hot Spot Grooming of the Initial State

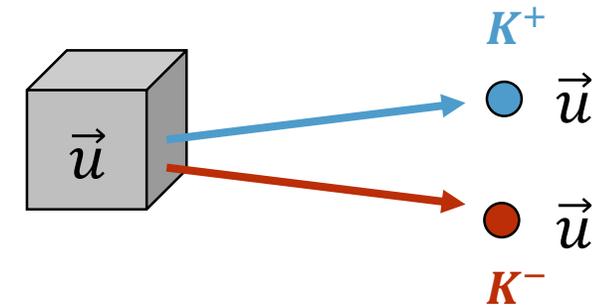
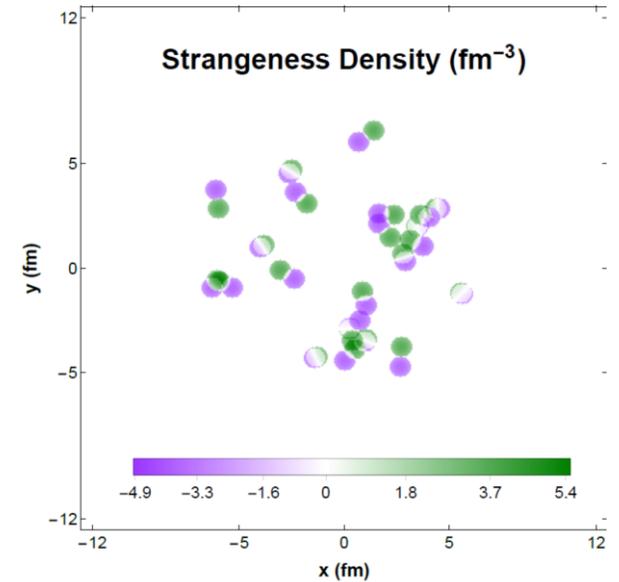


- **Strangeness geometry** corresponds to a groomed **hot spot geometry**

$T \sim 400 \text{ K} (?)$

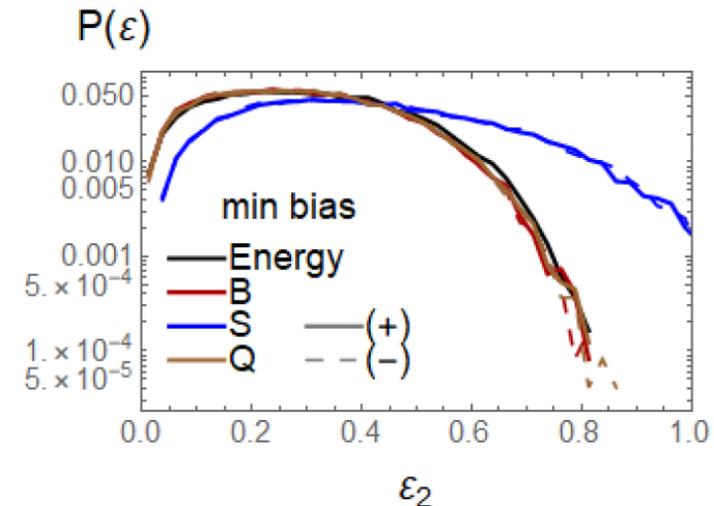
Initial vs. Thermal Quark Production

- Quarks produced in the **initial state** constitute only a **minority** of the overall production rates
 - Final yields consistent with **chemical equilibrium**
- Does this mean the **hot spot effect** will be **washed out**?
 - Not necessarily
- **Strange pairs** produced in the **final state** will flow with the **same fluid velocity**
 - **Spatially-separated domains** in the initial state can flow **differently**



Selecting the Right Observables

- Hot-spot production of strangeness in the initial state probably will **not significantly affect** overall v_n of kaons
- Looking at a **C-odd difference** in flow between K^+ and K^- should enhance sensitivity to the **initial state**
- **Caution:** Need to look on an **event-by-event basis**
 - **Not** $v_n\{2\}$ of K^+ versus $v_n\{2\}$ of K^- (*difference of RMS*)
 - **Rather:** $v_n\{2\}$ of $(K^+ - K^-)$ (*RMS of the difference*)
- **Caution:** Correlations with one kaon? Or two?



A Full Answer Requires Full BSQ-Hydro

- For now, **no hydrodynamics code exists** that can evolve **all three conserved charges**

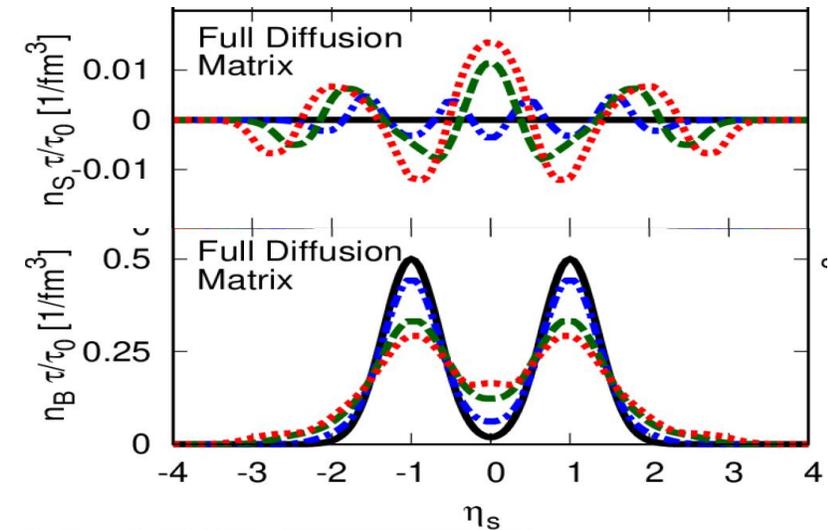
- **One charge is not sufficient:**

- Different charges affect each other
- Mixed transport coefficients

M. Greif et al., Phys. Rev. Lett. 120 (2018)

- For now: **quantify the initial state** with candidate **estimators** for final-state flow

- In progress: develop a full-fledged simulation of **“BSQ-Hydro”**



J. Fotakis, Quark Matter 2019

Embracing Agnosticism

- Despite trying to include *ab initio* CGC theory input, the results **aren't very sensitive** to these details
 - Dominated by **mass thresholds**
 - Correlations driven by **light-front wave functions**
- The downside:
 - Not a good test of CGC or gluon saturation
- The upside:
 - Hot spot effect is **robust** based on **elementary QCD**
- The vision is to provide ICCING as an **agnostic module** that can be run on **any initial energy profile**, with any choice of **quark chemistry** and **correlations**

