Initial state and thermalization in p+A and A+A

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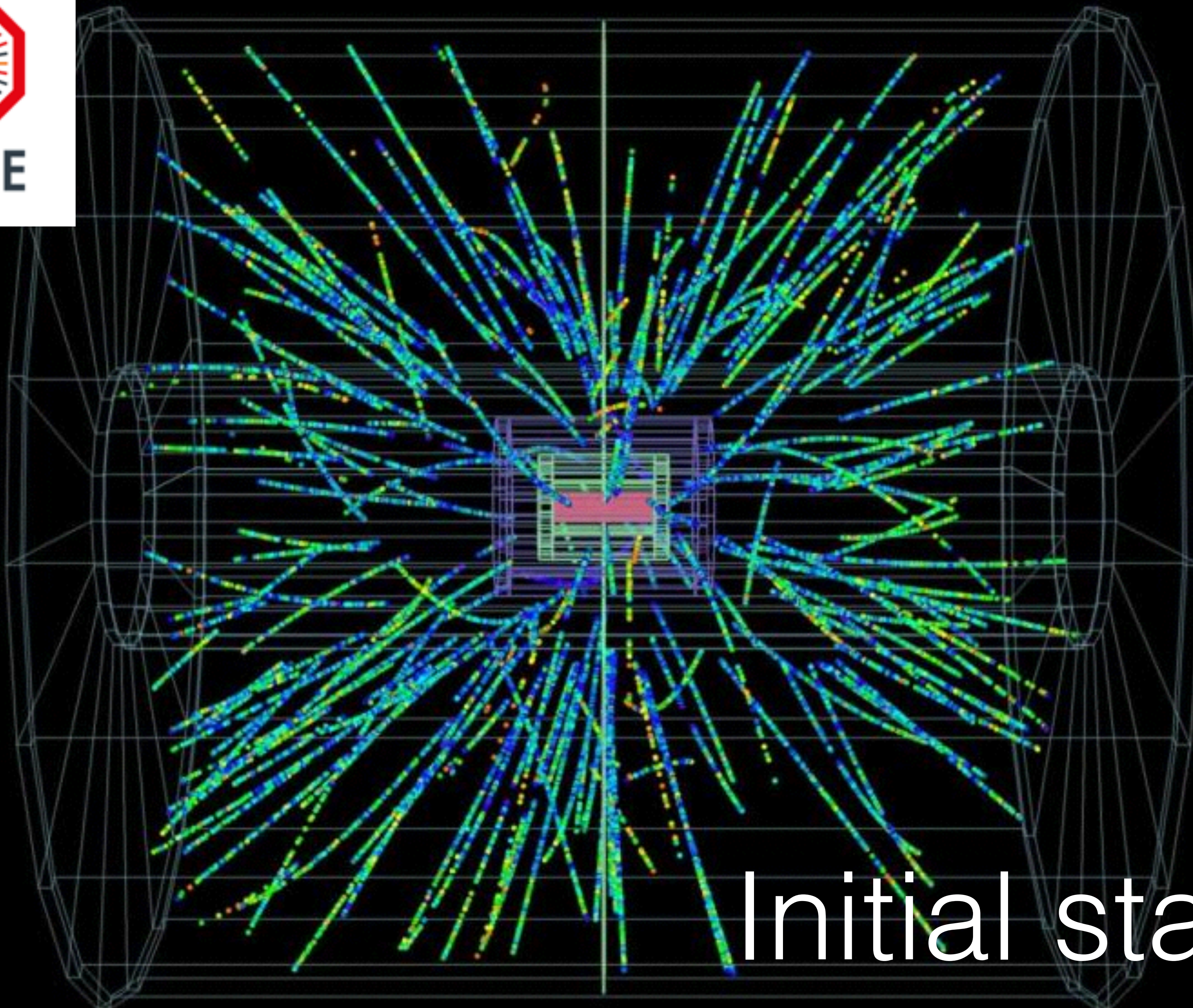
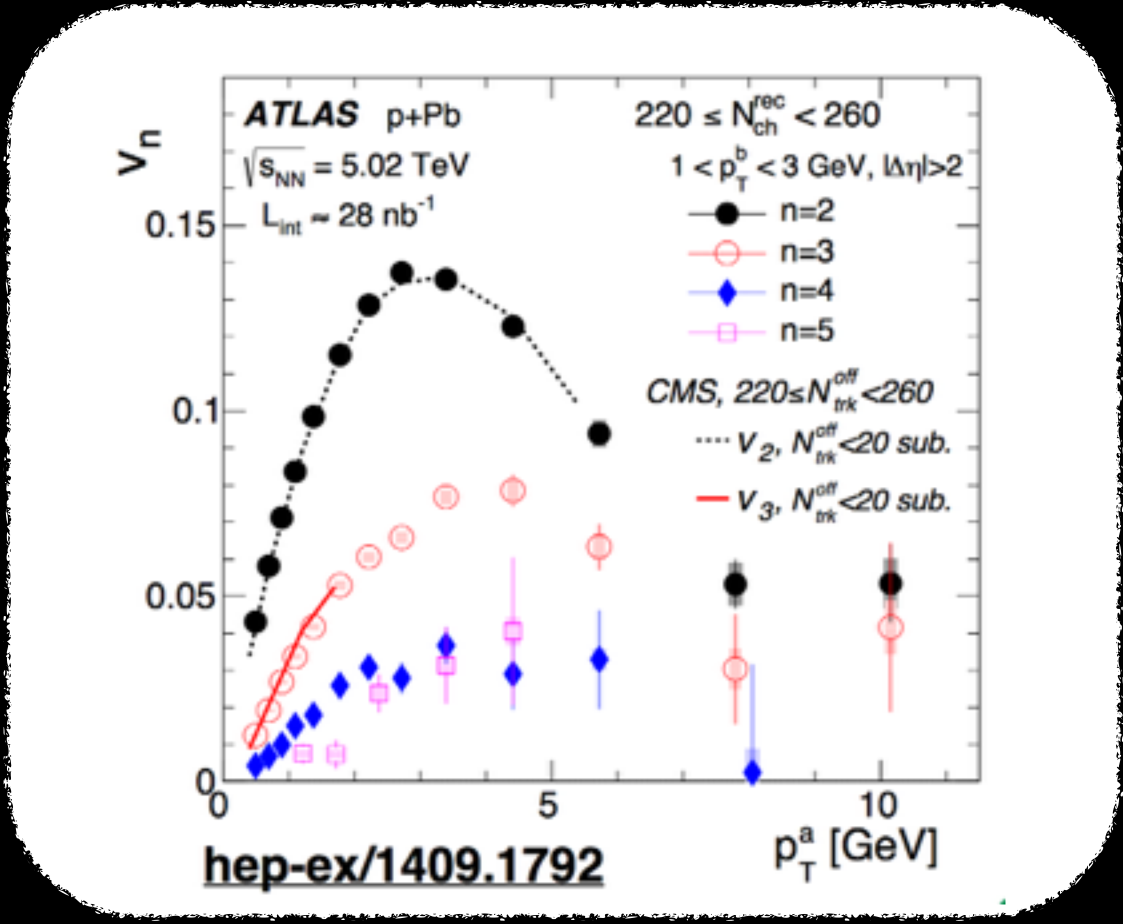
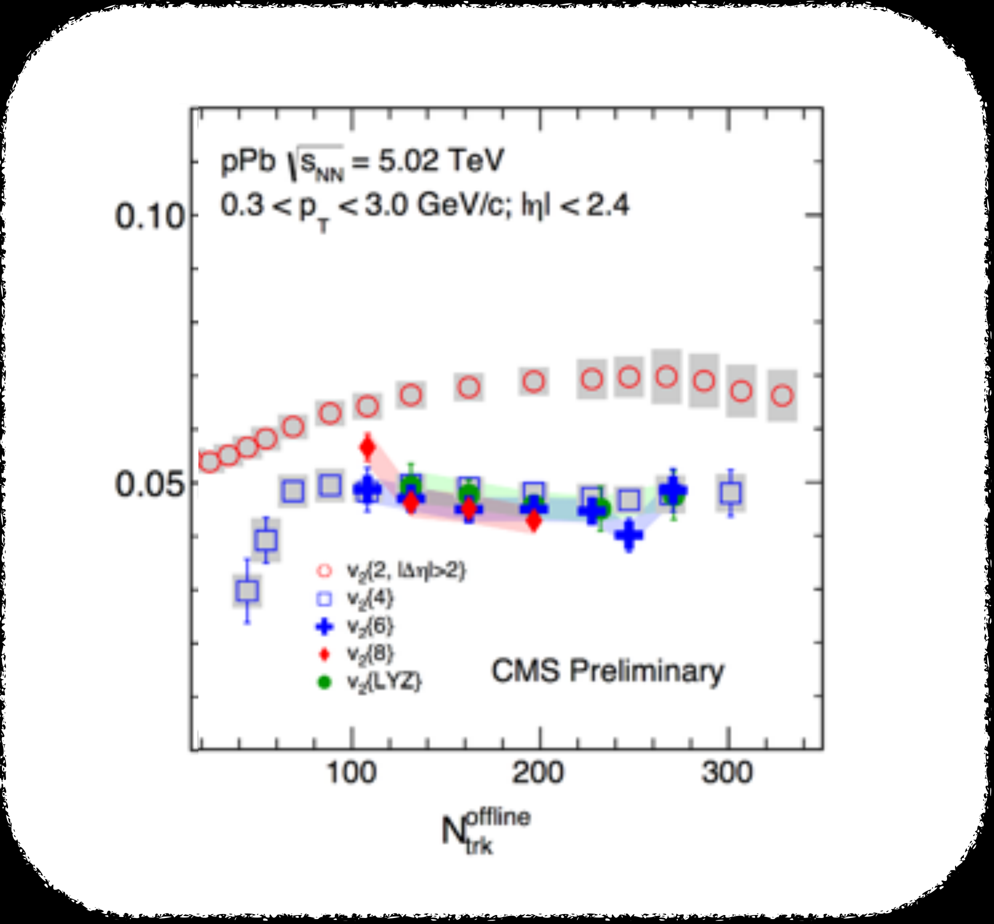


Initial state in p+A collisions

p+A collisions

- Surprise at LHC: particle production appears to be anisotropic on an event-by-event basis





- Correlation between many particles (>8) observed

-> Spontaneous breaking of rotational symmetry event-by-event

p+A collisions

Different mechanisms have been proposed to explain the data:

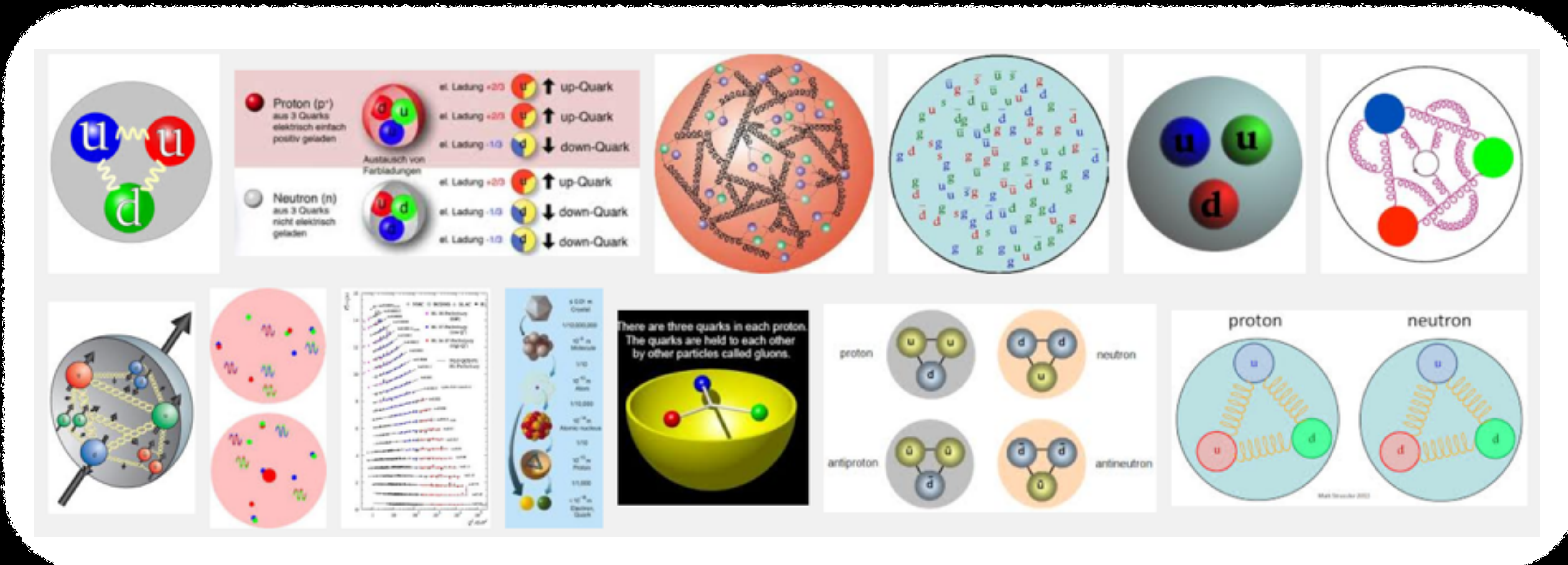
- ***Initial state interactions*** ***and/or***
- ***Initial state geometry + final state interactions***

Irrespective of the mechanism, one needs to understand

I) Nucleon structure and fluctuations on sub-nucleonic scales

II) Initial state dynamics up to $\tau \sim 1$ fm/c

Origin of non-trivial geometry

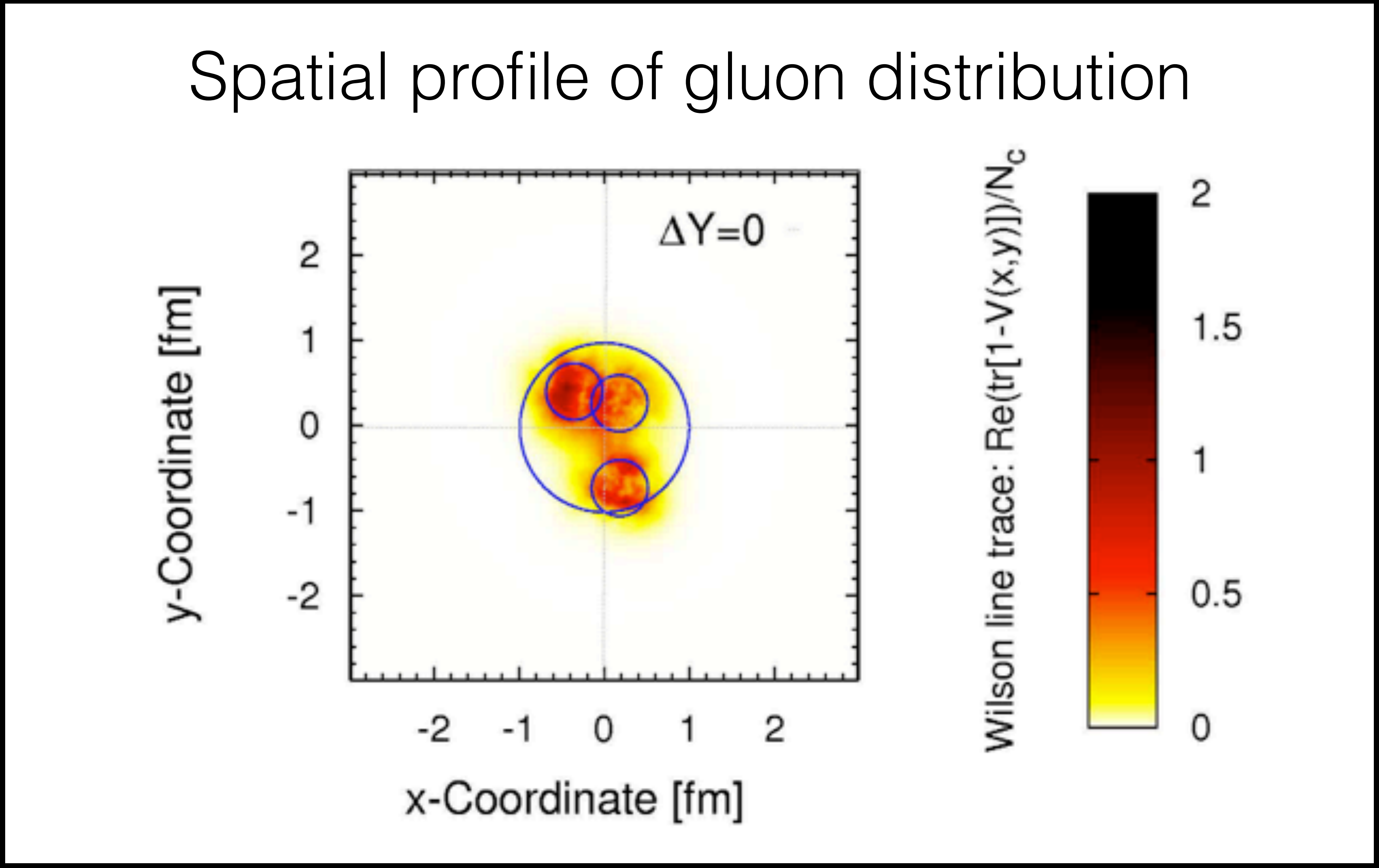


- Large x structure may well give rise to event-by-event fluctuations of the protons geometry

How does this affect the small x evolution? What to expect for typical values of x probed in p+A collisions?

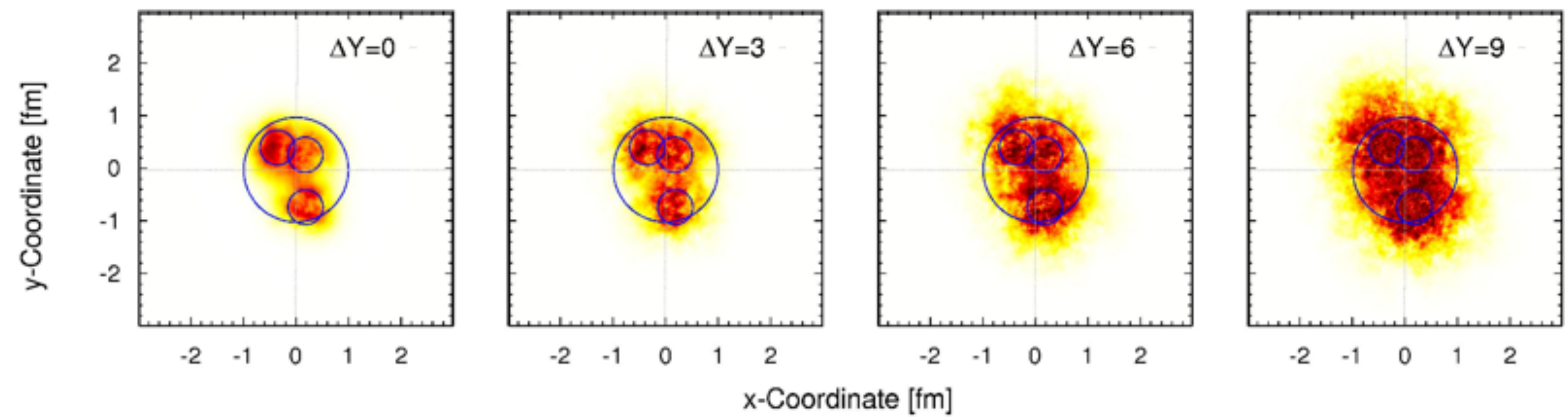
Evolution of fluctuations

Consider fluctuating initial state at moderately small value of x
— inspired by constituent quark models



(SS, Schenke PLB 739 (2014) 313-319)

Evolution of fluctuations



- Small scale fluctuations become finer and finer (Q_S grows)

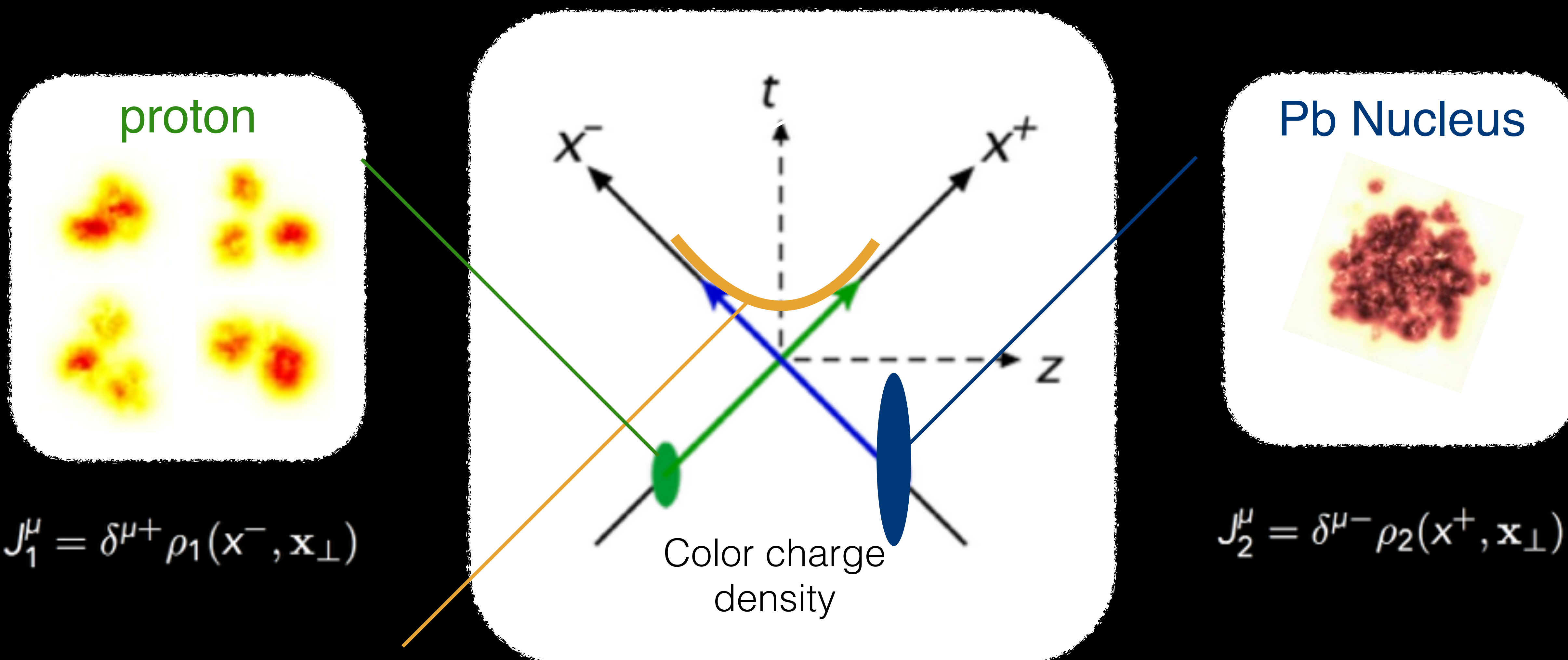
- Hadron radius increases linearly with rapidity — 'Gribov diffusion'

-> Nucleon shape remains in tact even after evolution over several units of rapidity

(SS, Schenke PLB 739 (2014) 313-319)

p+A collisions

- High-energy p+A collision in the CGC framework

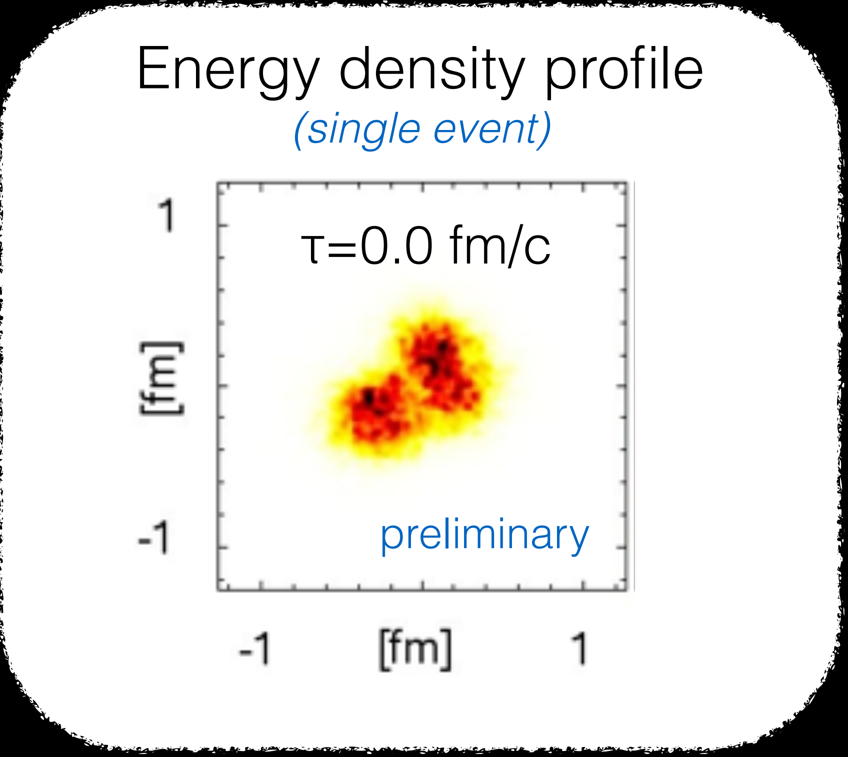


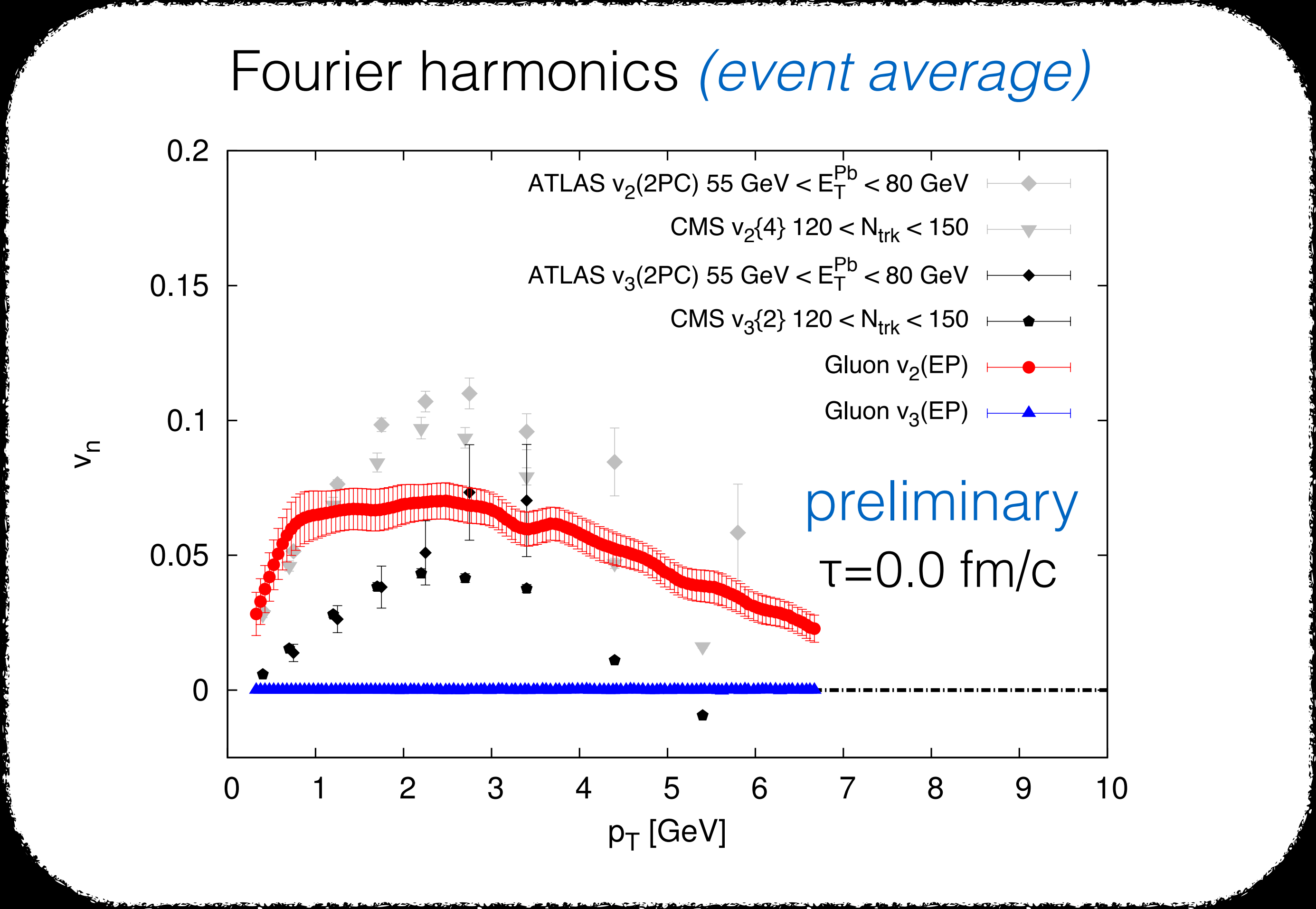
Initial state (τ=0+) and pre-equilibrium dynamics described by the solution of classical Yang-Mills equations to leading order in α_s

(Kovner,McLerran,Weigert,Krasnitz, Venugopalan,Lappi …)

Initial state in p+A

- Initial state properties immediately after the collision ($\tau=0^+$)



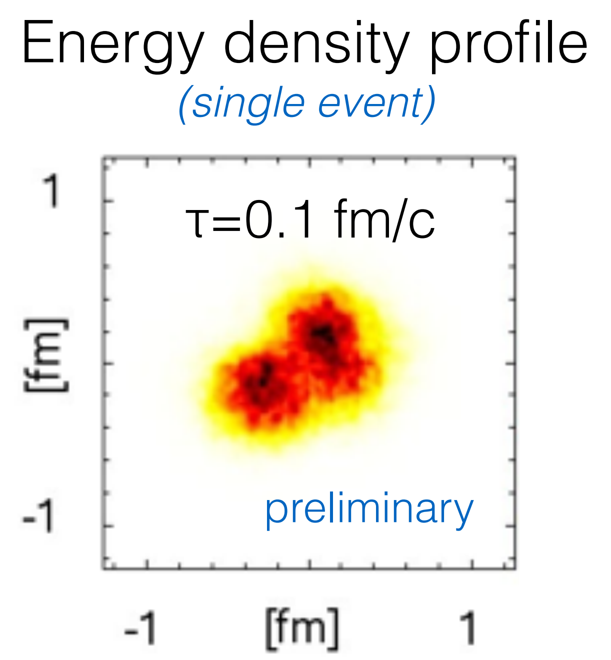


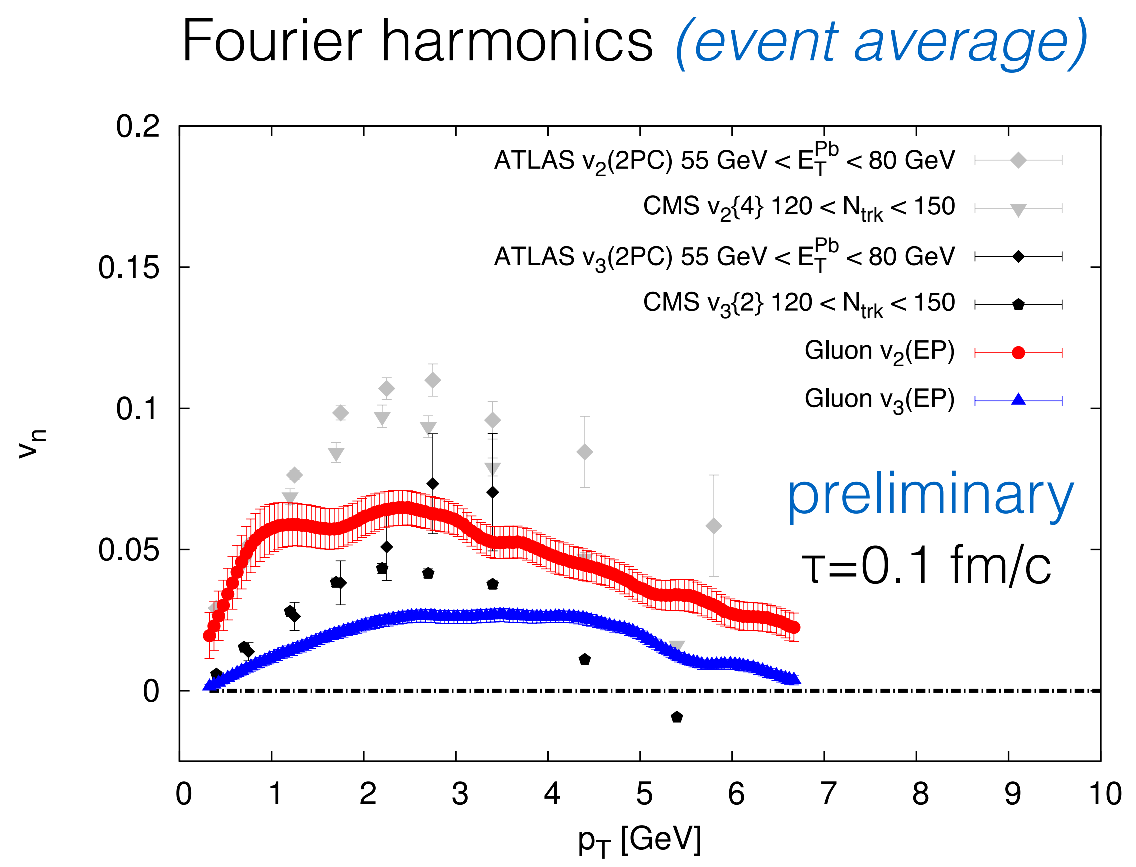
(SS, Schenke, Venugopalan work in progress)

-> No odd harmonics for gluons without final-state interactions.

Evolution in p+A collisions

- Classical (2+1D)Yang-Mills evolution after the collision — includes re-scattering of produced gluons



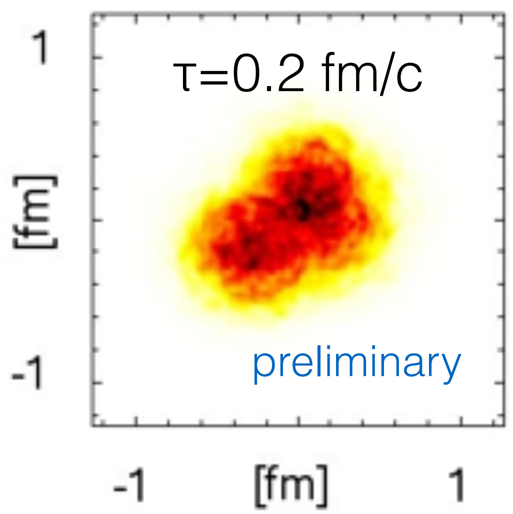


(SS, Schenke, Venugopalan work in progress)

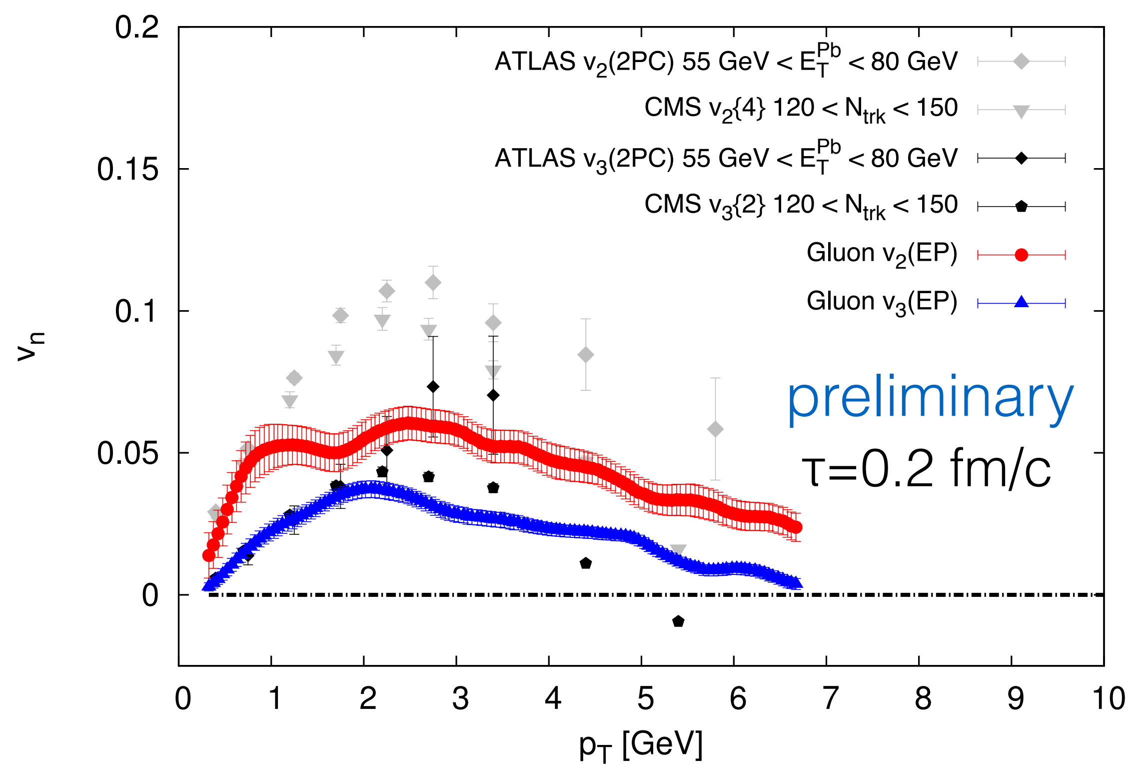
Evolution in p+A collisions

- Classical (2+1D)Yang-Mills evolution after the collision — includes re-scattering of produced gluons

Energy density profile
(single event)



Fourier harmonics *(event average)*



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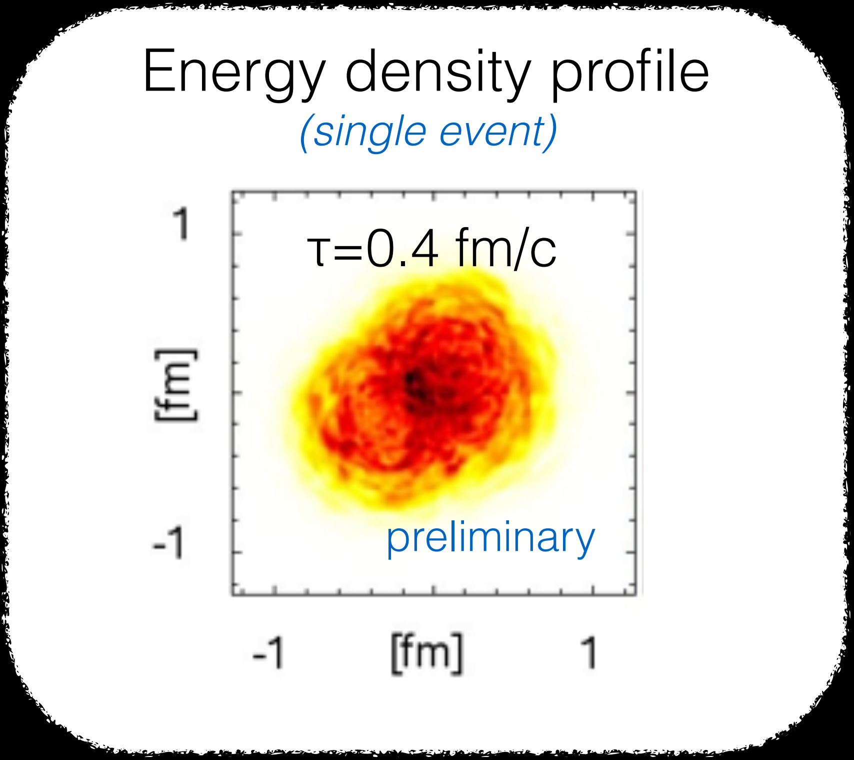
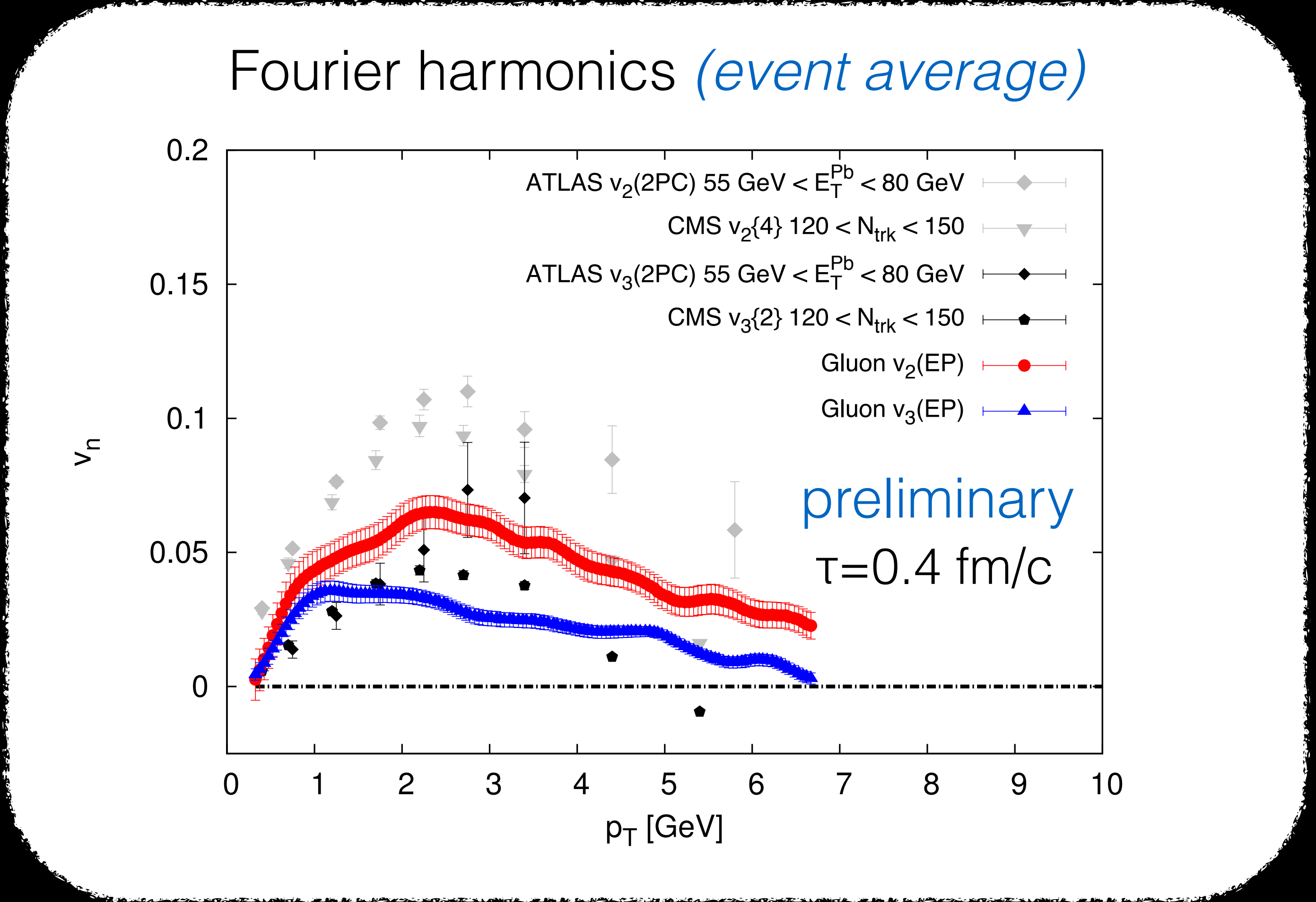
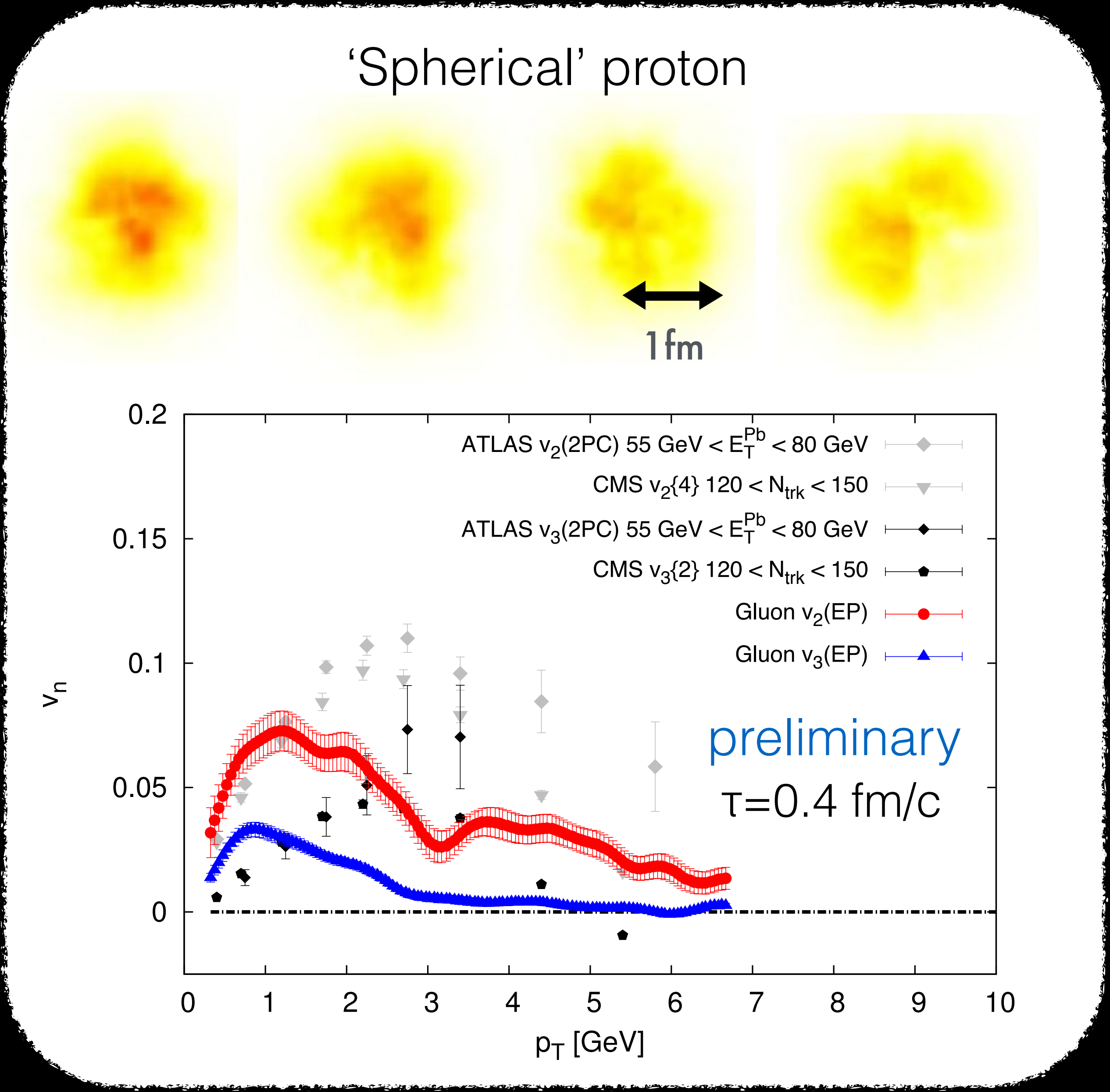


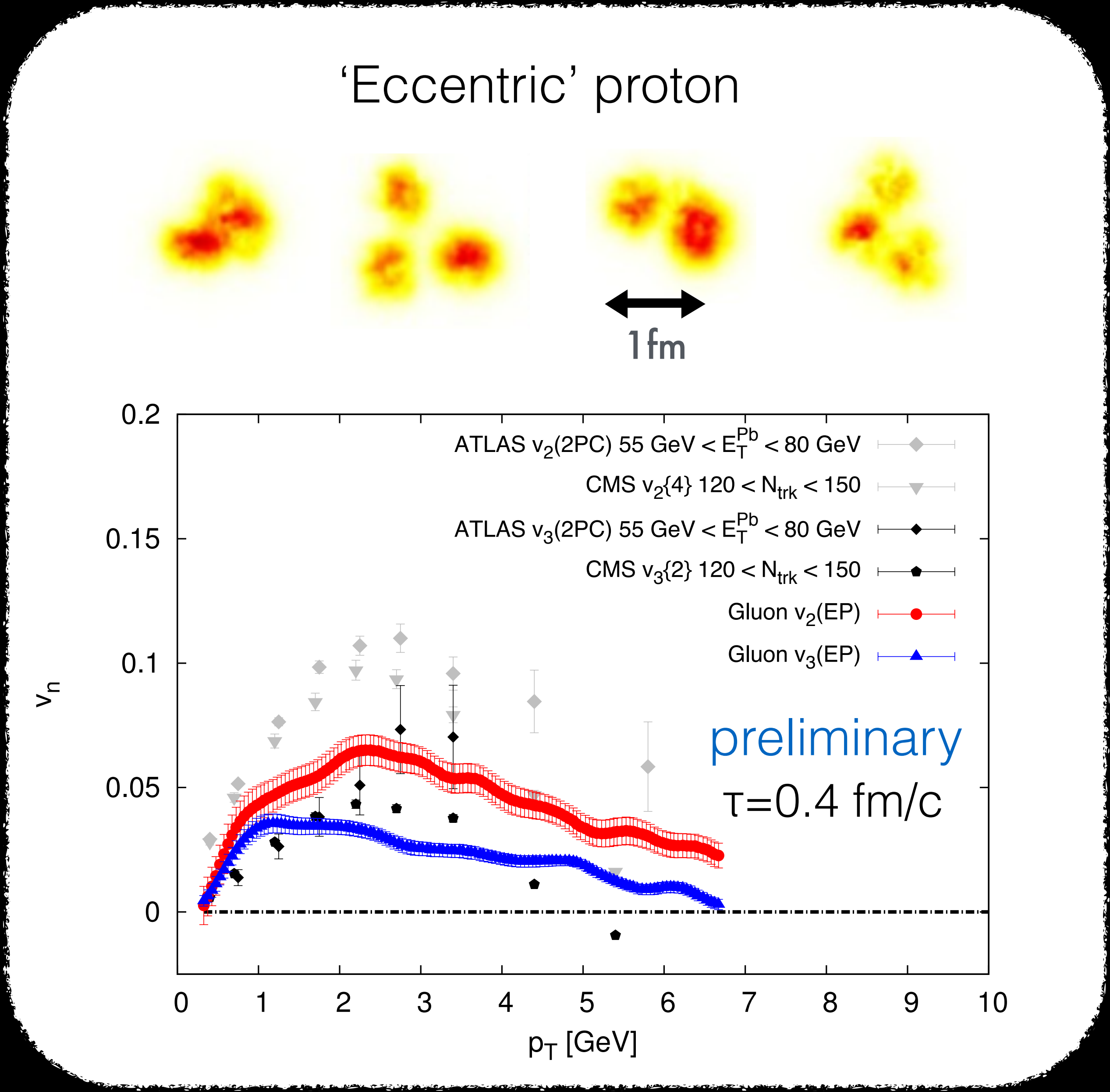


(SS, Schenke, Venugopalan work in progress)

-> Sizeable odd harmonics for gluons generated by pre-equilibrium dynamics

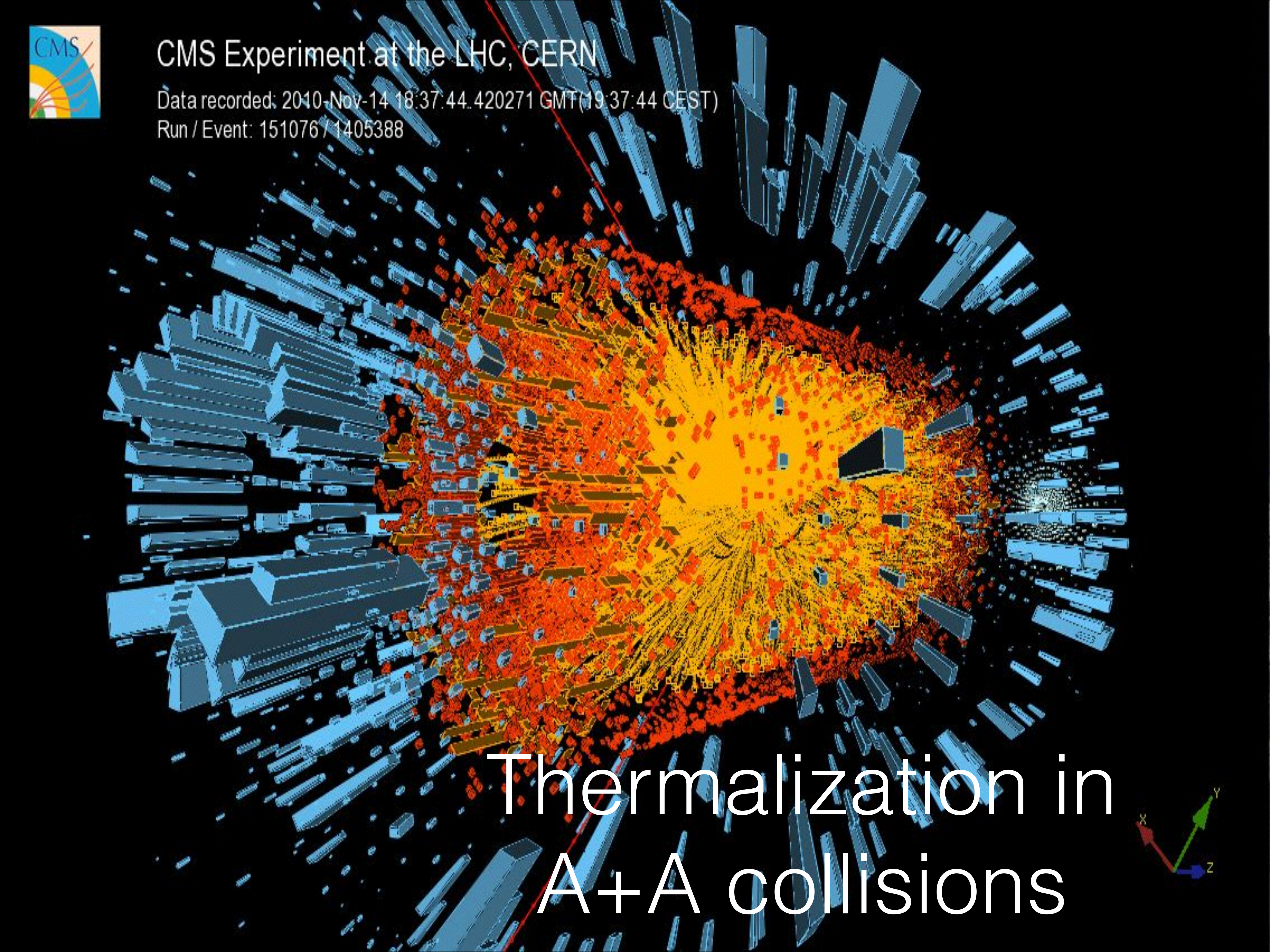
Sensitivity to proton structure





(SS, Schenke, Venugopalan work in progress)

Conversions to hadrons? Constraints from e+p?



Thermalization in A+A collisions

Thermalization from the CGC perspective

Classical Yang-Mills dynamics leads to (2+1)D boost-invariant solution

- No thermalization at leading order in α_s

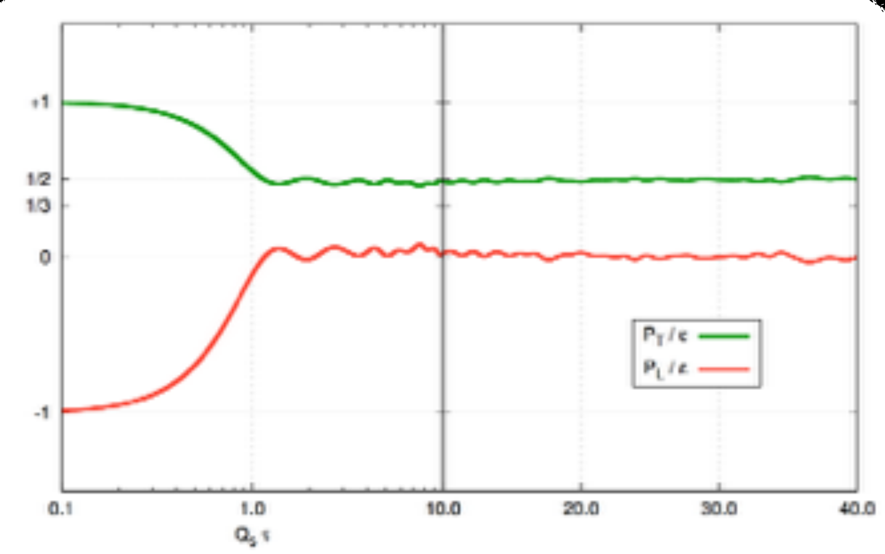


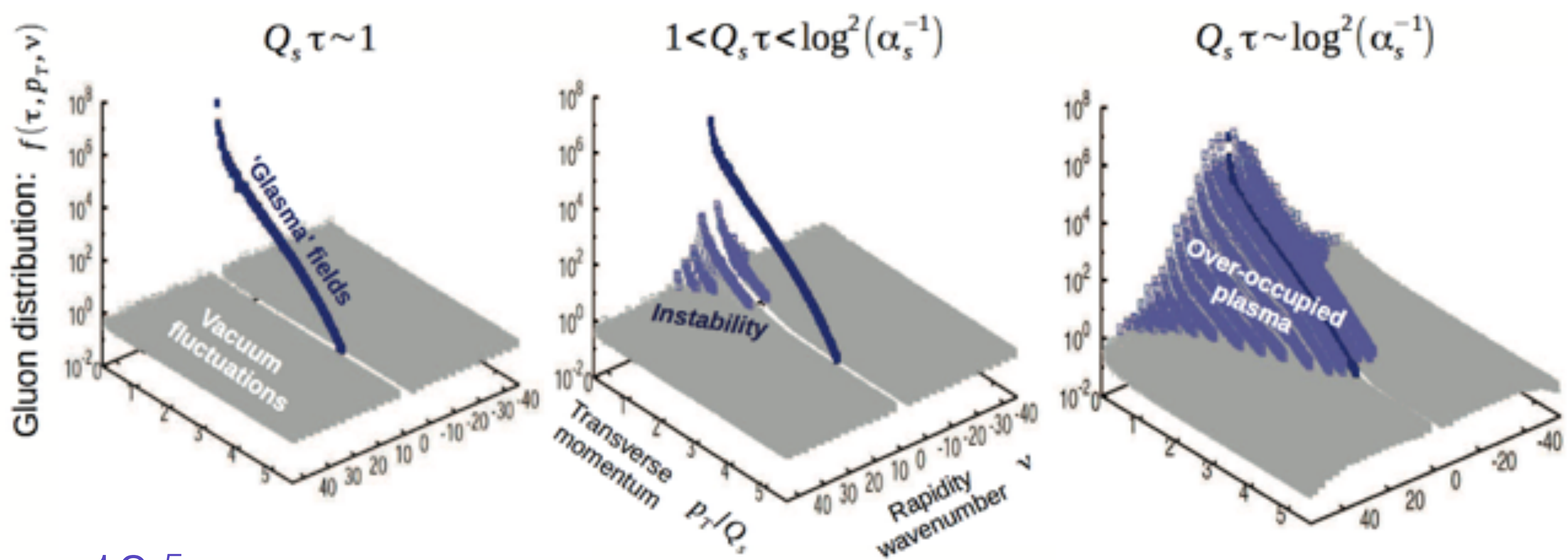
Fig by T. Epelbaum

At next-to-leading order quantum fluctuations break boost invariance and thermalization becomes possible

- Spectrum of fluctuations derived within CGC formalism (Epelbaum,Gelis)

The CGC @ NLO

At next-to leading order plasma instabilities lead to an exponential growth of quantum fluctuations.



$\alpha_s \sim 10^{-5}$

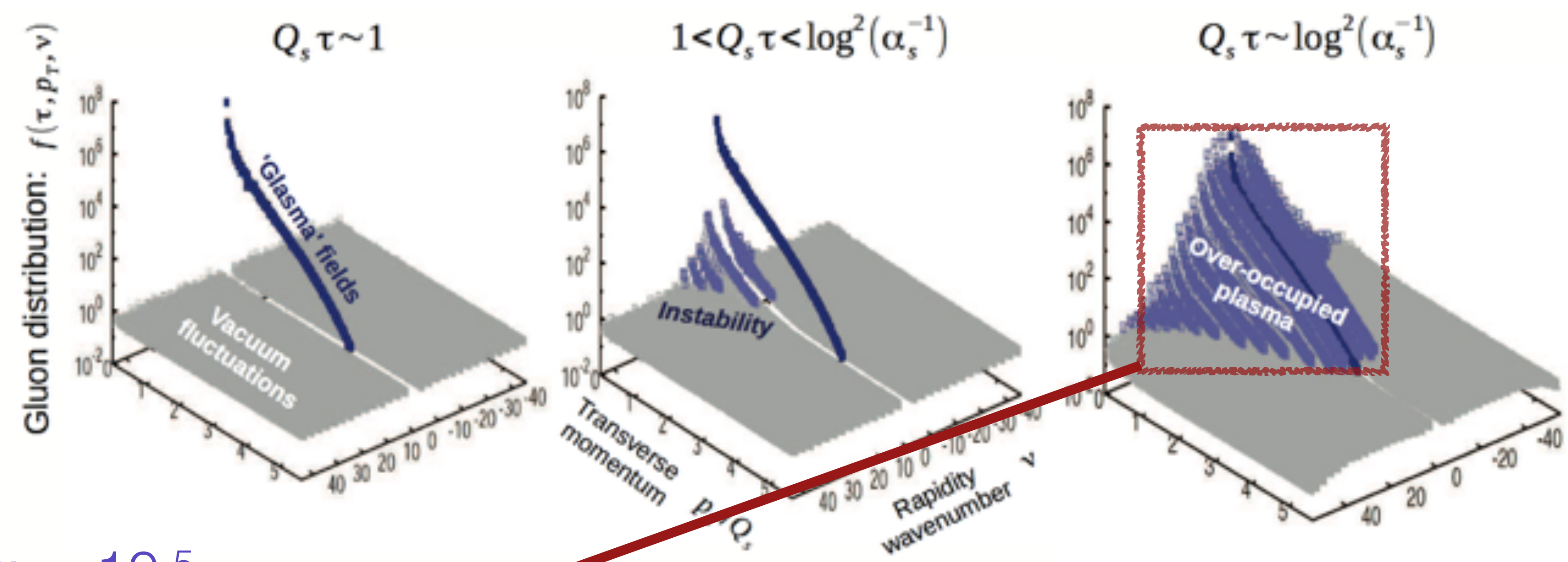
Berges, Schenke, SS, Venugopalan arXiv:1409.1638

-> ***Subset of corrections*** becomes as important as the leading order. *Breakdown of the naive power-counting.*

Correct strategy — Identity ***subset of unstable modes*** and perform classical-statistical resummation (Son, Klebnikov, Tkachev,… work in progress)

Caution — Classical-statistical resummation of complete NLO results in non-renomalizability of the theory (Epelbaum, Gelis, Wu)

Thermalization process



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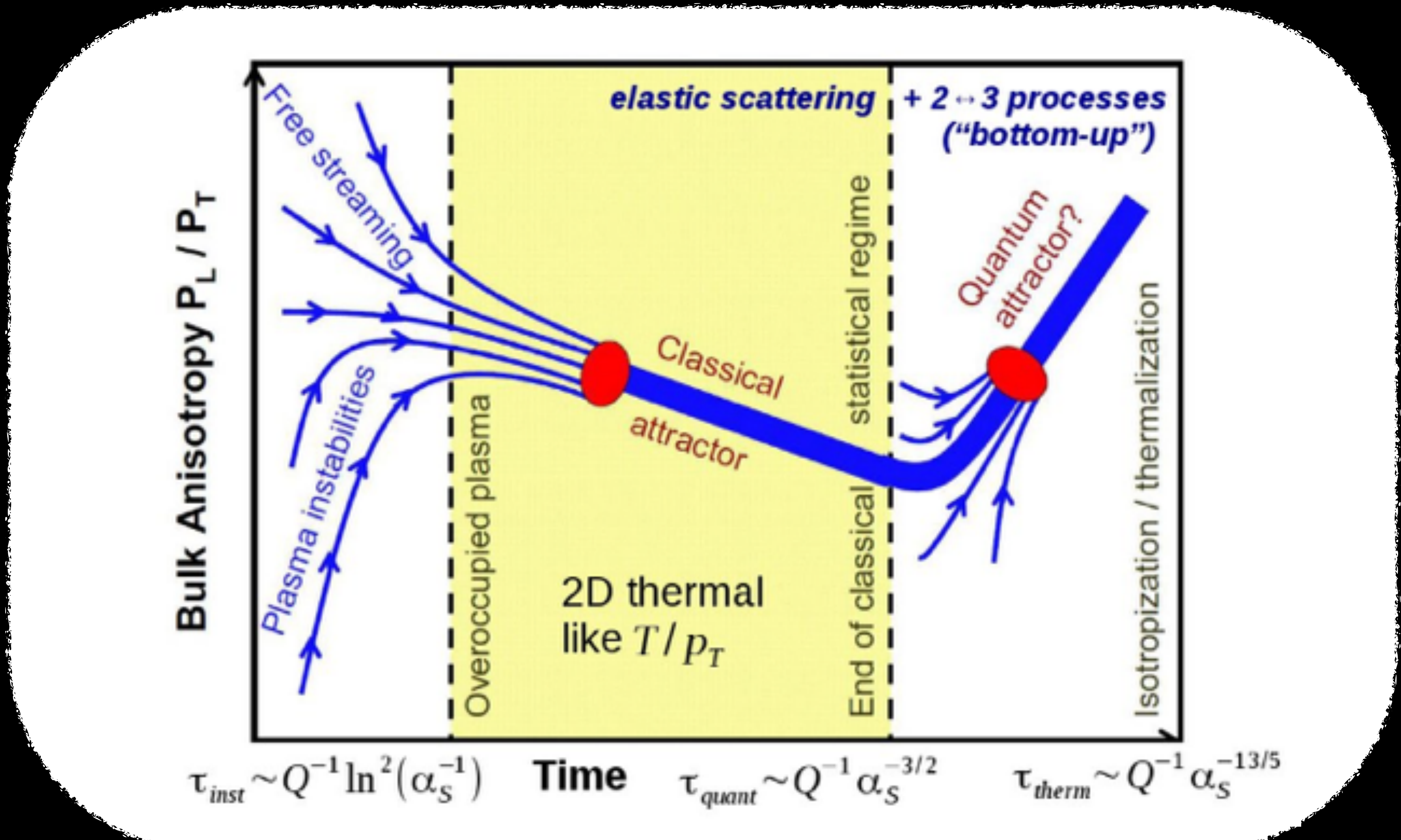
Even without a detailed matching one can understand the thermalization process on a qualitative level by considering the over-occupied plasma as a starting point

Thermalization process

Thermalization scenario based on classical-statistical and kinetic theory simulations

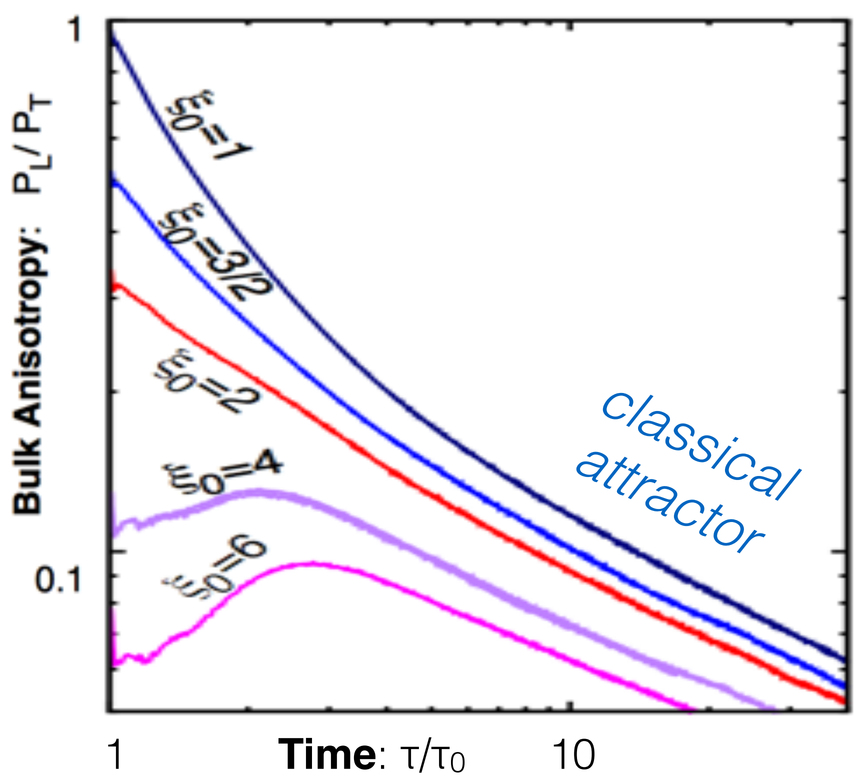


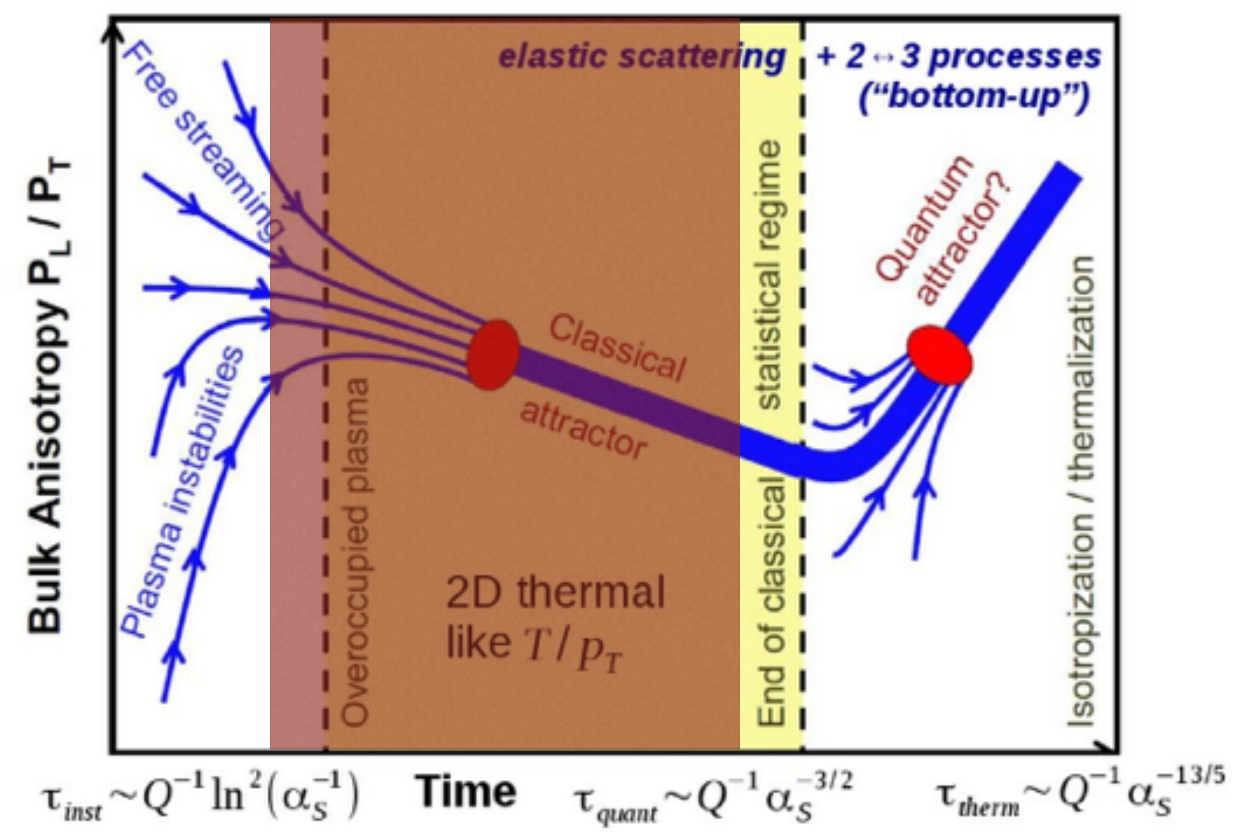
(Berges,Boguslavski,SS,Venugopalan PRD 89 (2014) 074011; 89 (2014) 114007)

Thermalization process

Classical-statistical regime (f>>1) until $\tau \sim Q_s^{-1} \alpha_s^{-3/2}$

Classical-statistical lattice simulations





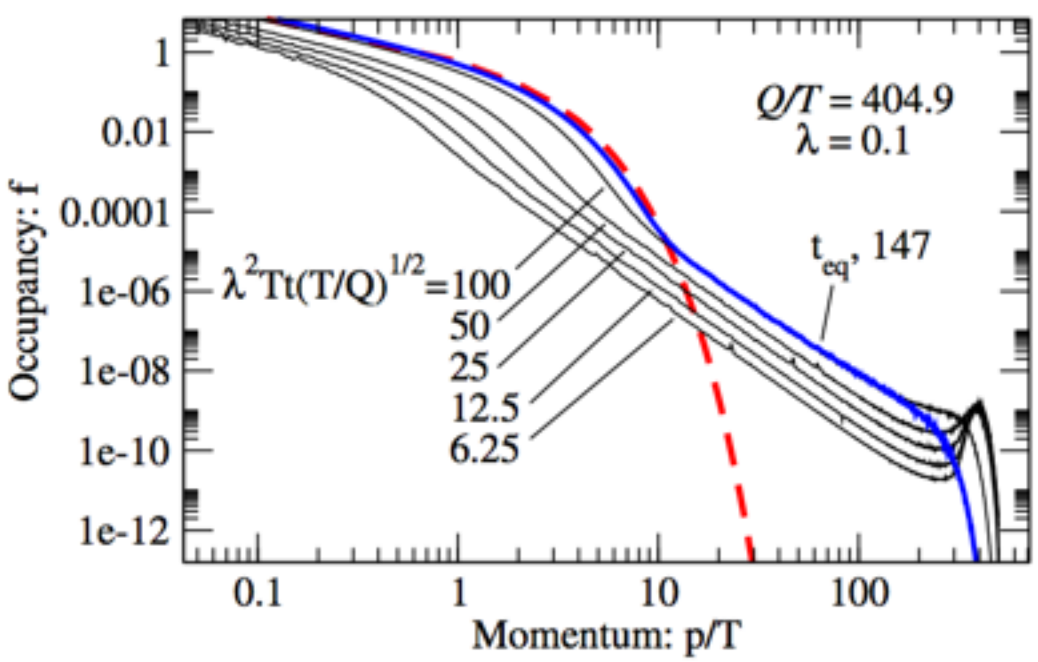
-> Dynamics becomes insensitive to details of initial conditions. Consistent with onset of 'bottum-up' thermalization.

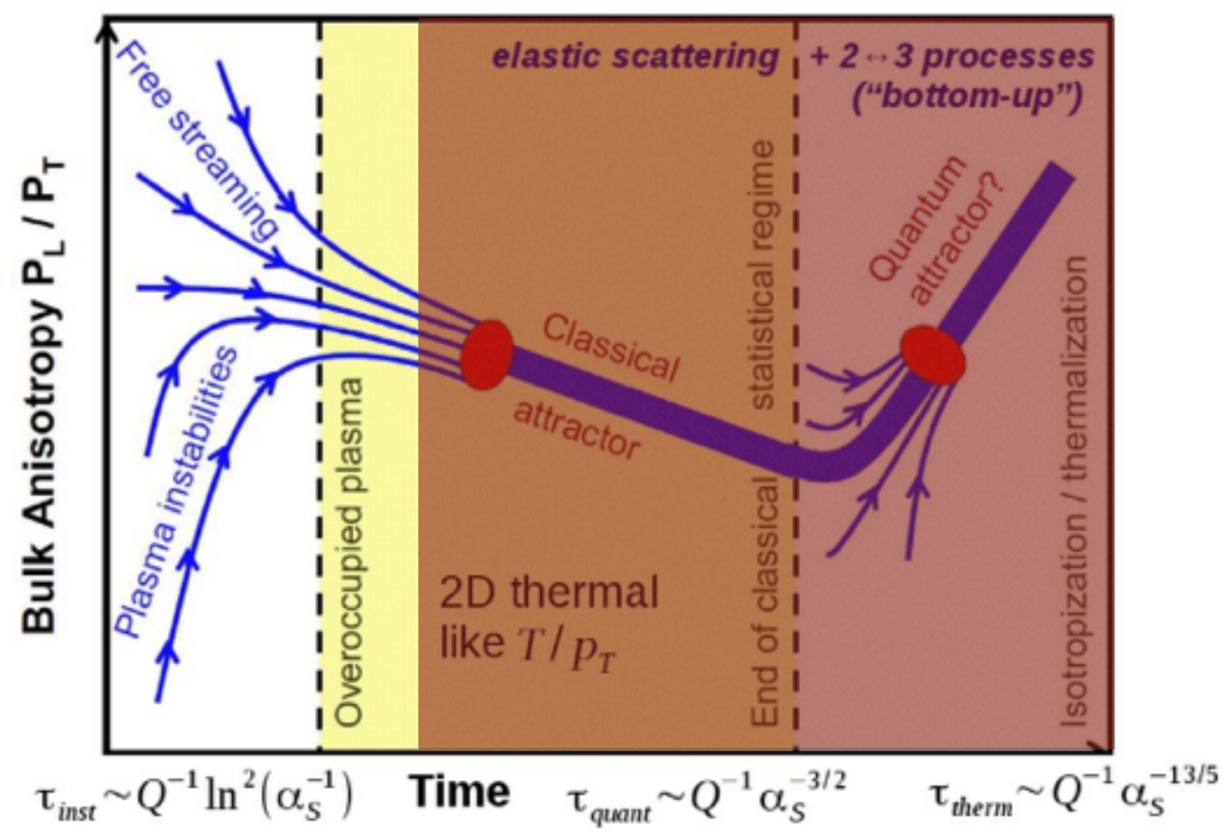
(Berges,Boguslavski,SS,Venugopalan PRD 89 (2014) 074011; 89 (2014) 114007)

Thermalization process

Classical-statistical regime (f>>1) until $\tau \sim Q_s^{-1}\, \alpha_s^{-3/2}$

Kinetic theory simulations





-> Thermalization via 'radiative breakup' a la 'bottum up'.
Quantitative estimate of the thermalization time τ~0.2- 2 fm/c.

(Kurkela,Lu,Moore,York PRD89 (2014) 074036 Kurkela, Lu PRL 113 (2014) 18, 182301)

Summary & Conclusions

- Event by event fluctuations of the protons sub-nucleonic structure are consistent with small-x evolution and may play an important role in our understanding of p+A collisions at the LHC.

- Initial state effects and early time dynamics (τ<0.4 fm/c) can lead to flow-like behavior with sizable even ($v_{2,4,...}$) and odd harmonics ($v_{3,5,...}$) up to fairly large p_T.

Still many open questions how to transition to final state
— Hydro? No Hydro? Hadronization?

- Thermalization process in A+A can now be computed from an interplay of methods