Heavy ion collisions at the LHC

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LI - International Meeting on Fundamental Physics
Benasque - September 2024

Yocto/LHC
Yoctosecond imaging of QCD collectivity using jet observables
An ERC Advanced Grant 2019 · 2024
erc European Research Council
Established by the European Commission
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25 1999 2024
CENTROS CIGUS
EXCELENCIA MARÍA DE MAEZTU 2024-2029

QCD and collectivity

Standard Model built/discovered looking for the **highest possible degree of simplicity**

All particle content and interactions of the Standard Model discovered using this principle
— greatest success of the reductionistic approach in Physics

Also very successful — **Complex systems with emerging behavior**

[Strongly-coupling many body systems; quantum entanglement with many d.o.f…]

Region of transition — largely unknown

QCD — rich dynamical content, with emerging dynamics
that happens at scales easy to reach in collider experiments

Best available tool to study the first levels of complexity

Equilibrium AND non-equilibrium dynamics

QCD phase diagram

QCD — rich dynamical content, with emerging dynamics
that happens at scales easy to reach in collider experiments — e.g. EoS

Experimental tools

High-energy heavy-ion coll. [high T, low n_B]

LHC — pp, pPb, PbPb, XeXe, (other lighter ions under study)

RHIC — pp, dAu, AuAu, CuCu, UU,…

Medium energies HIC [moderate T, high n_B]

RHIC Beam Energy Scan

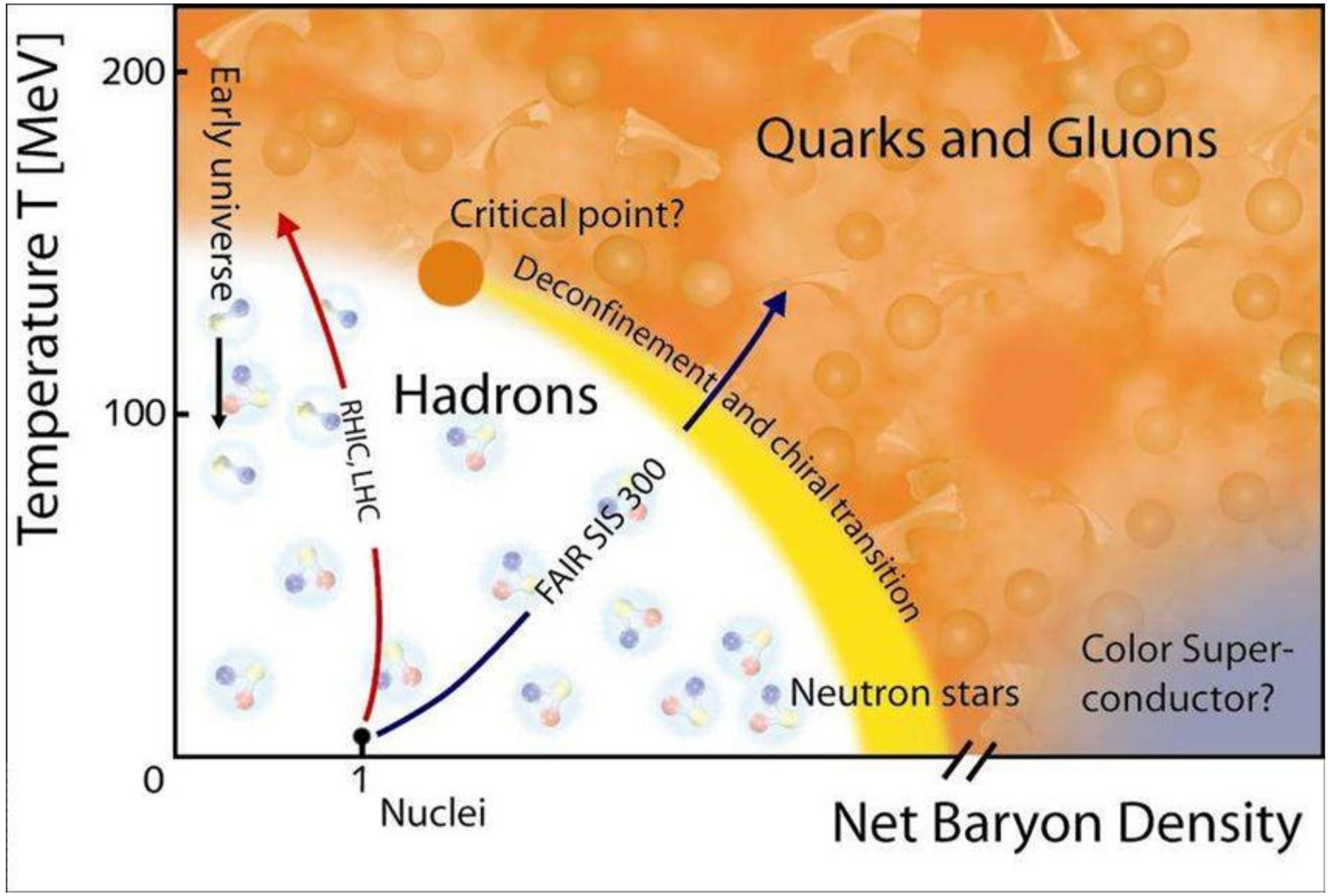
FAIR at GSI

NICA at Dubna

Cosmological observations — notably GWs

Neutron star coalescence - **low T, high n_B**

Future — access to QCD transition in early Universe?



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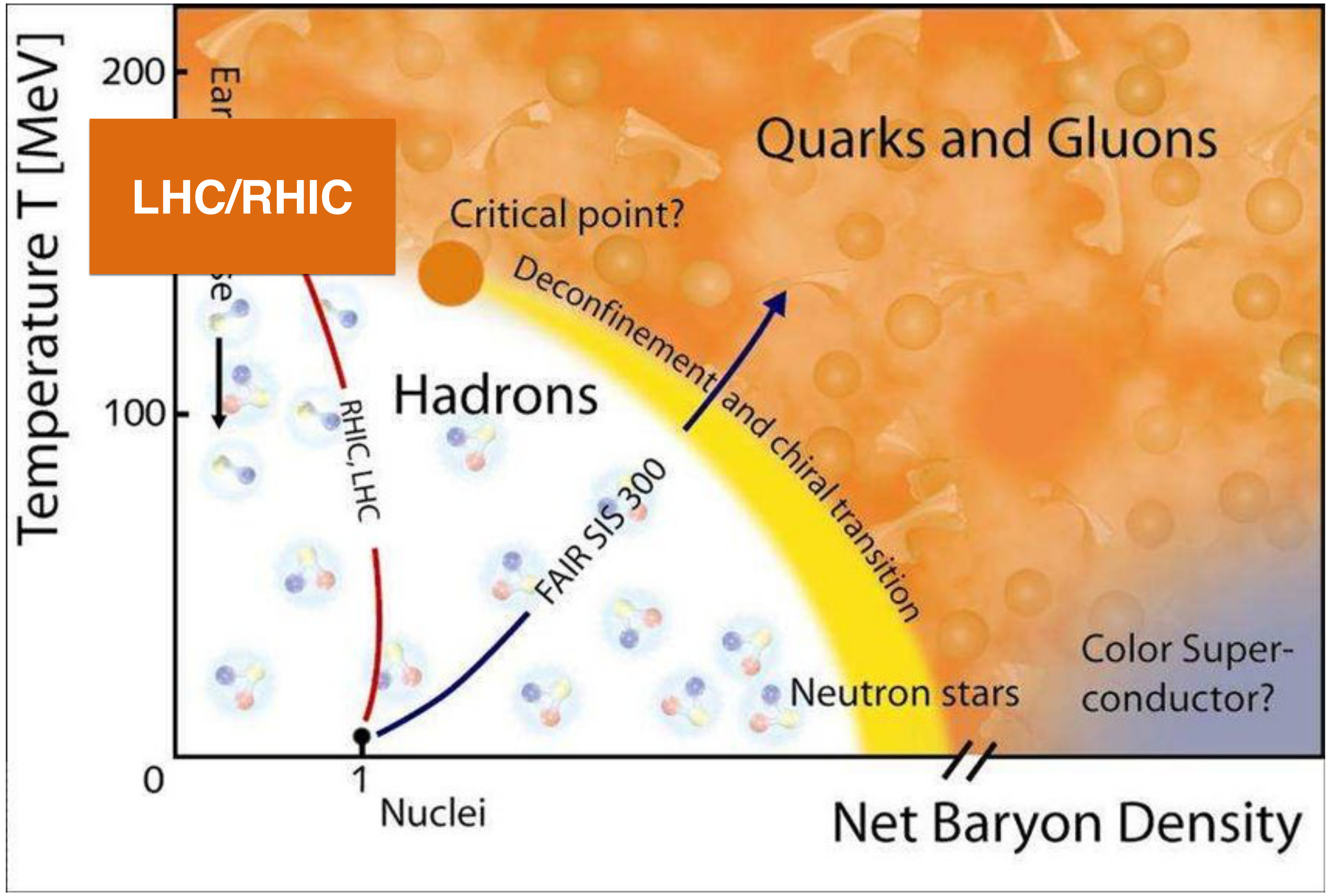

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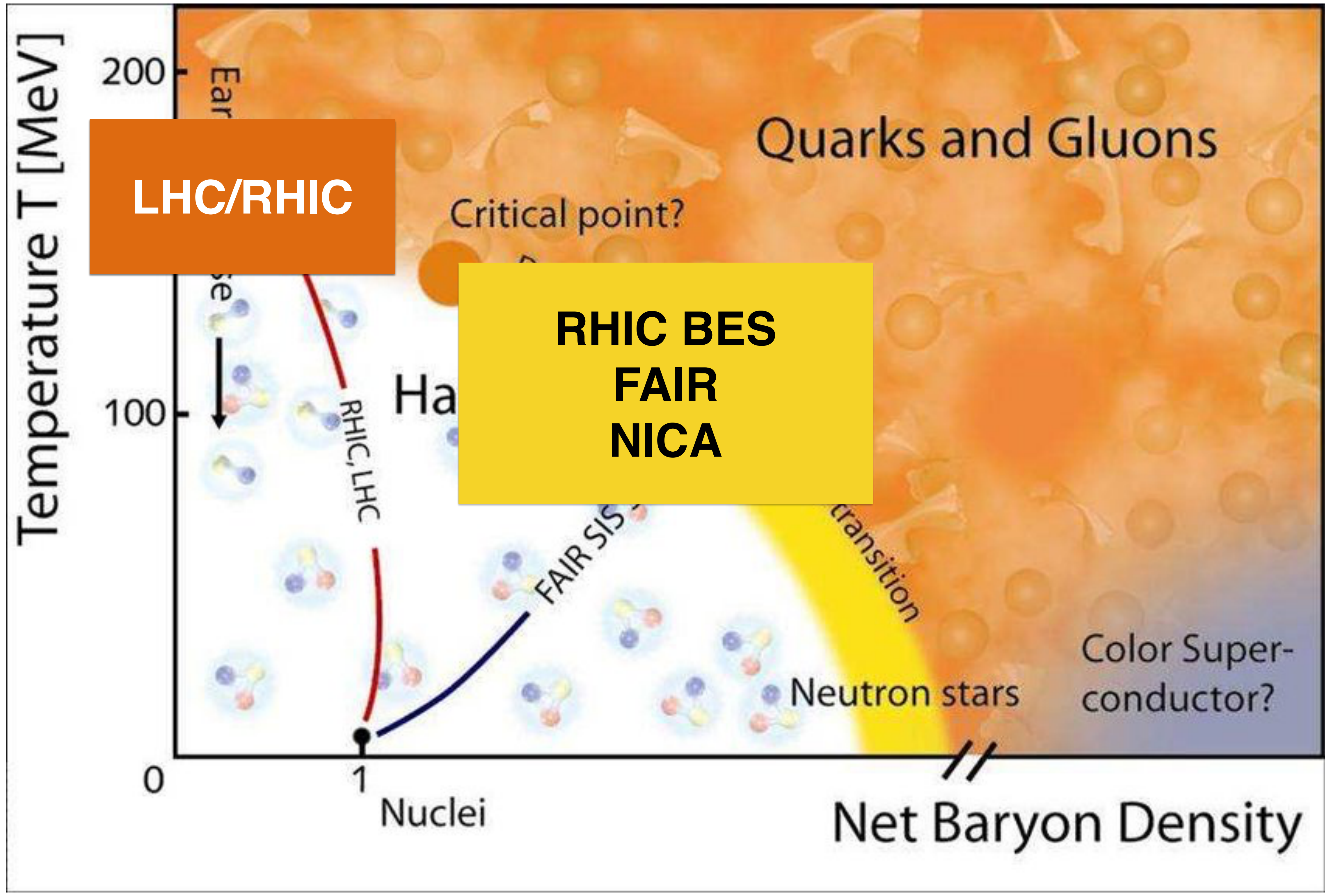

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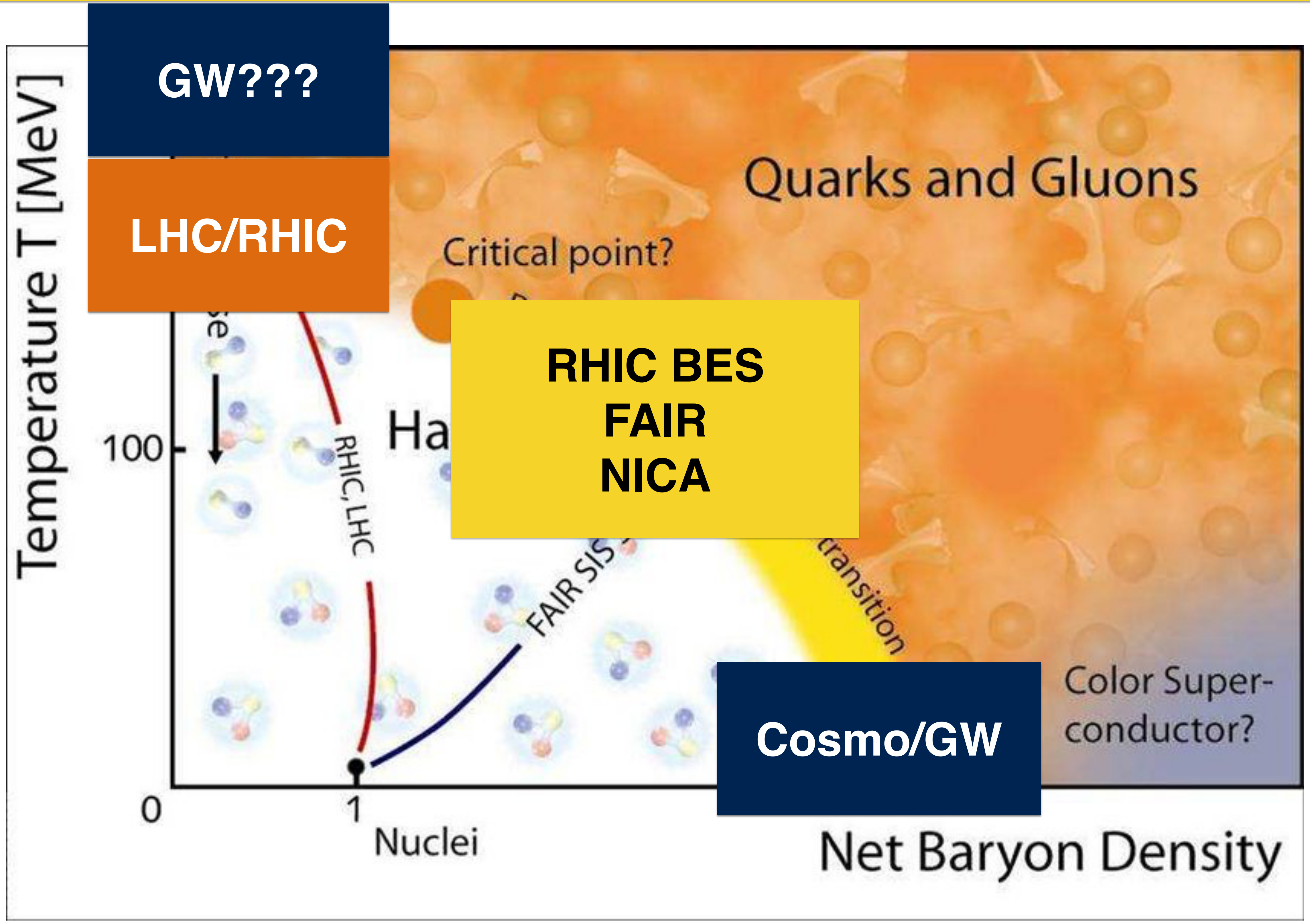
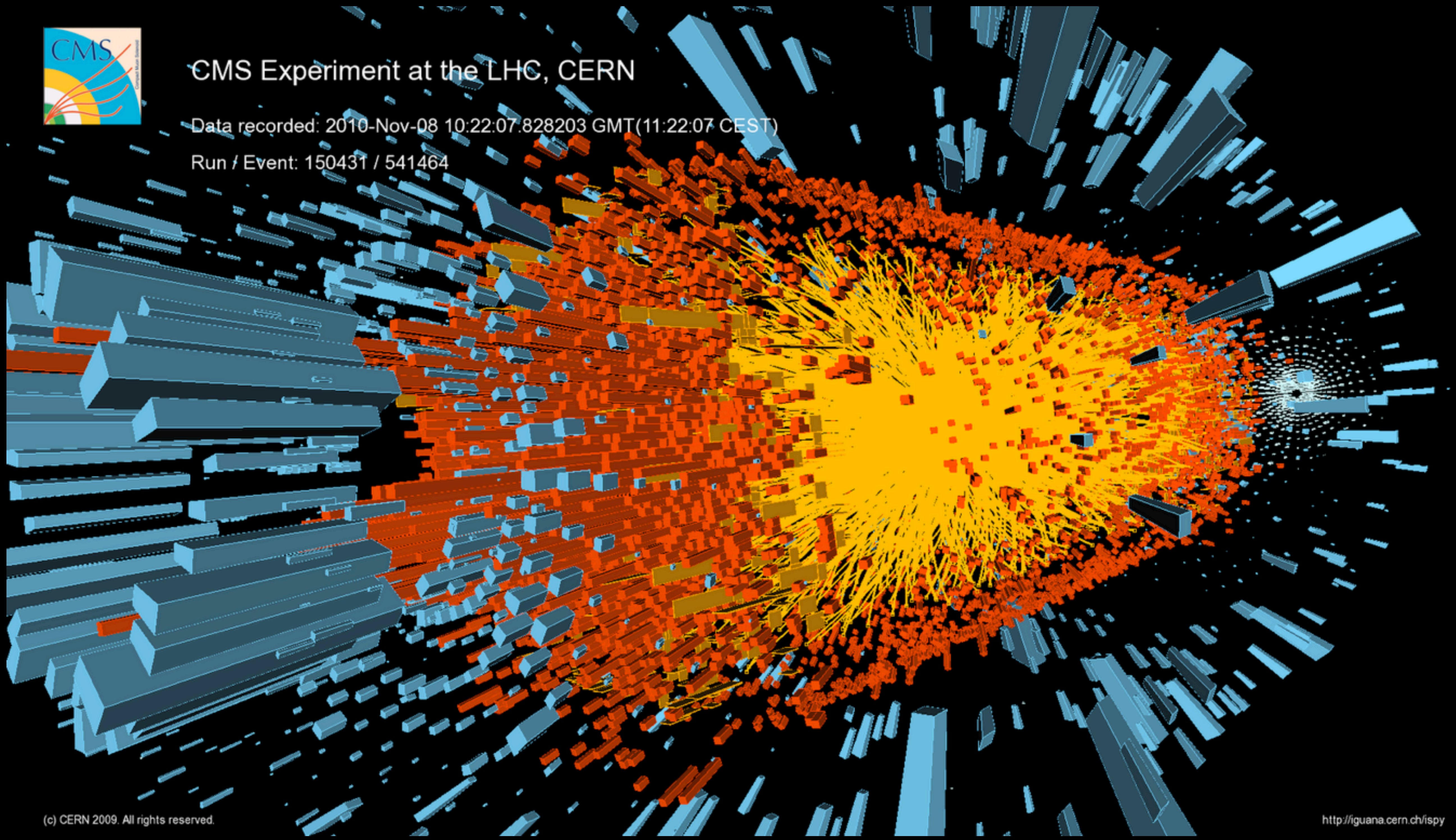


High energy heavy ion collisions:



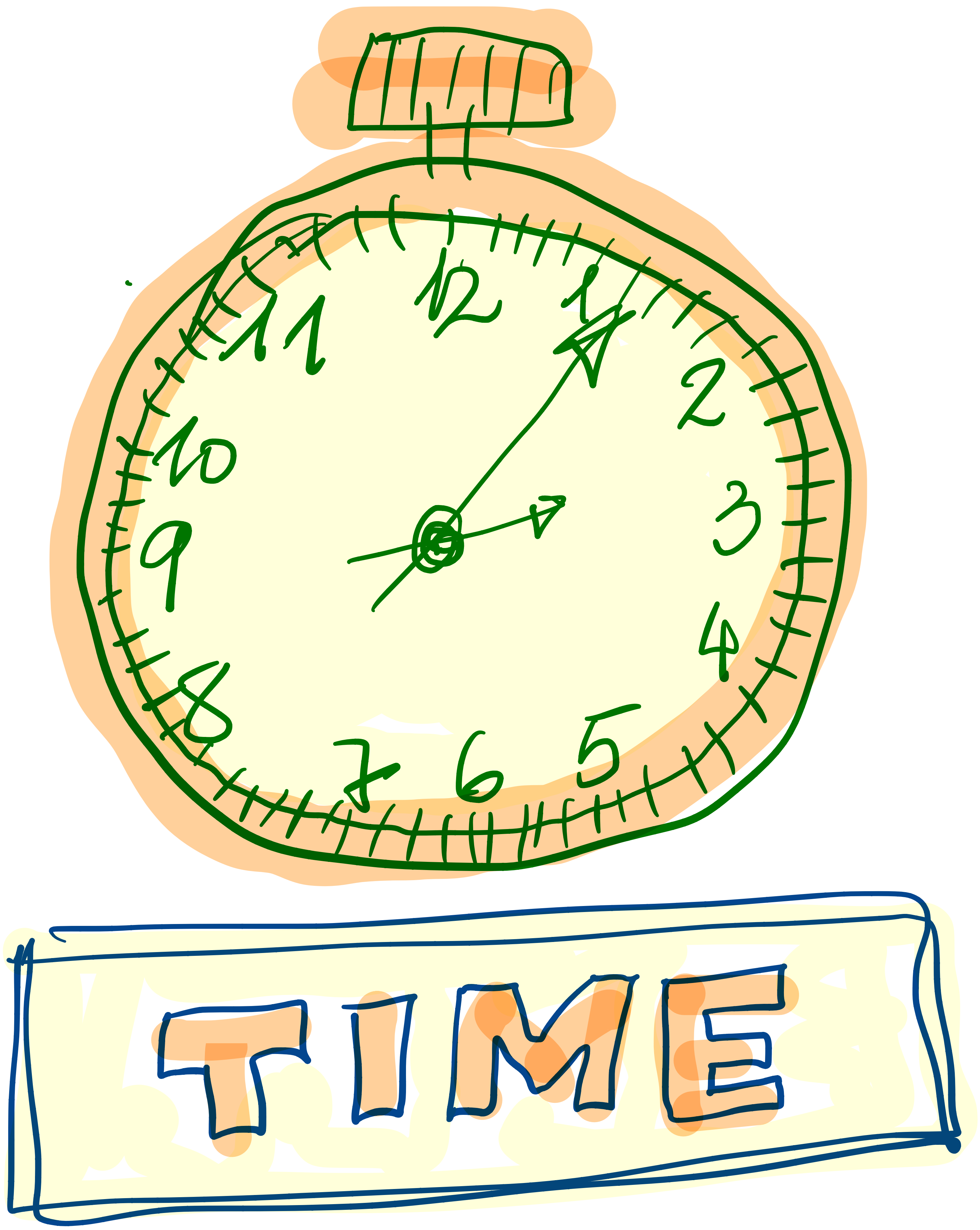
Produce "large" objects

↳ Macroscopic in QCD scale

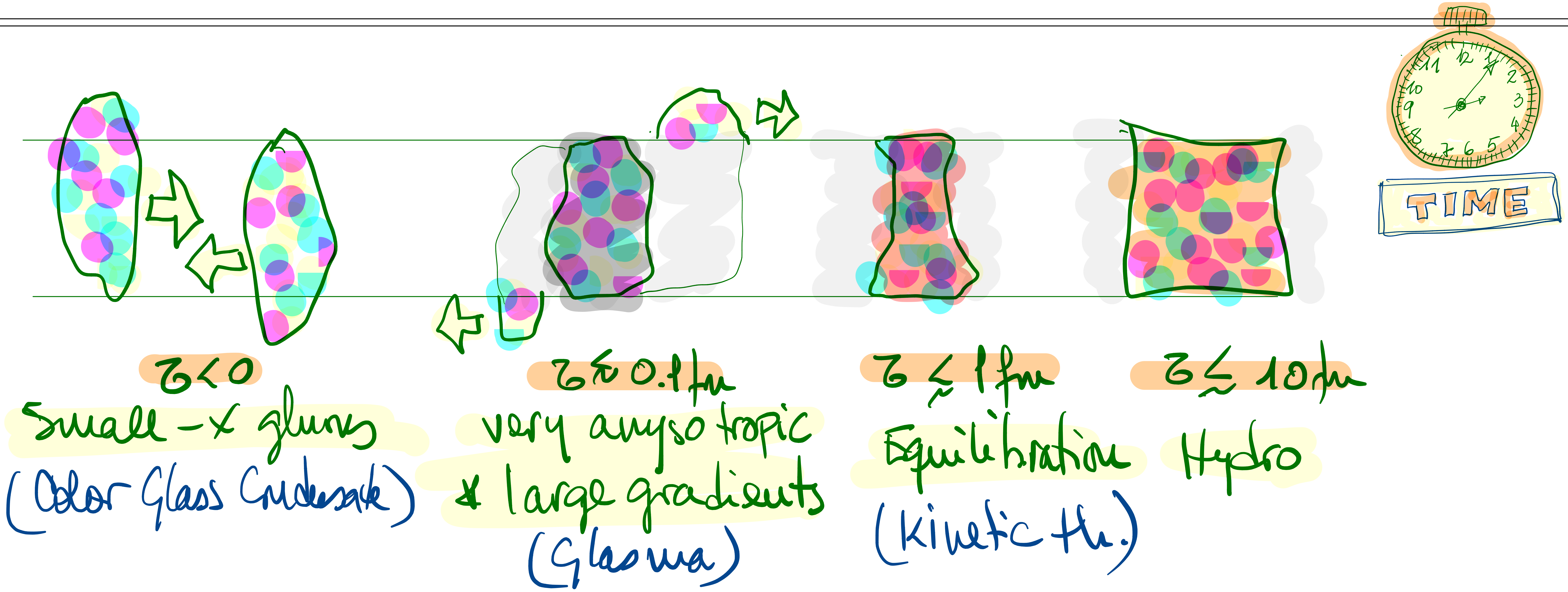
Collide heavy nuclei

How do we extract QGP properties from data?

But also…



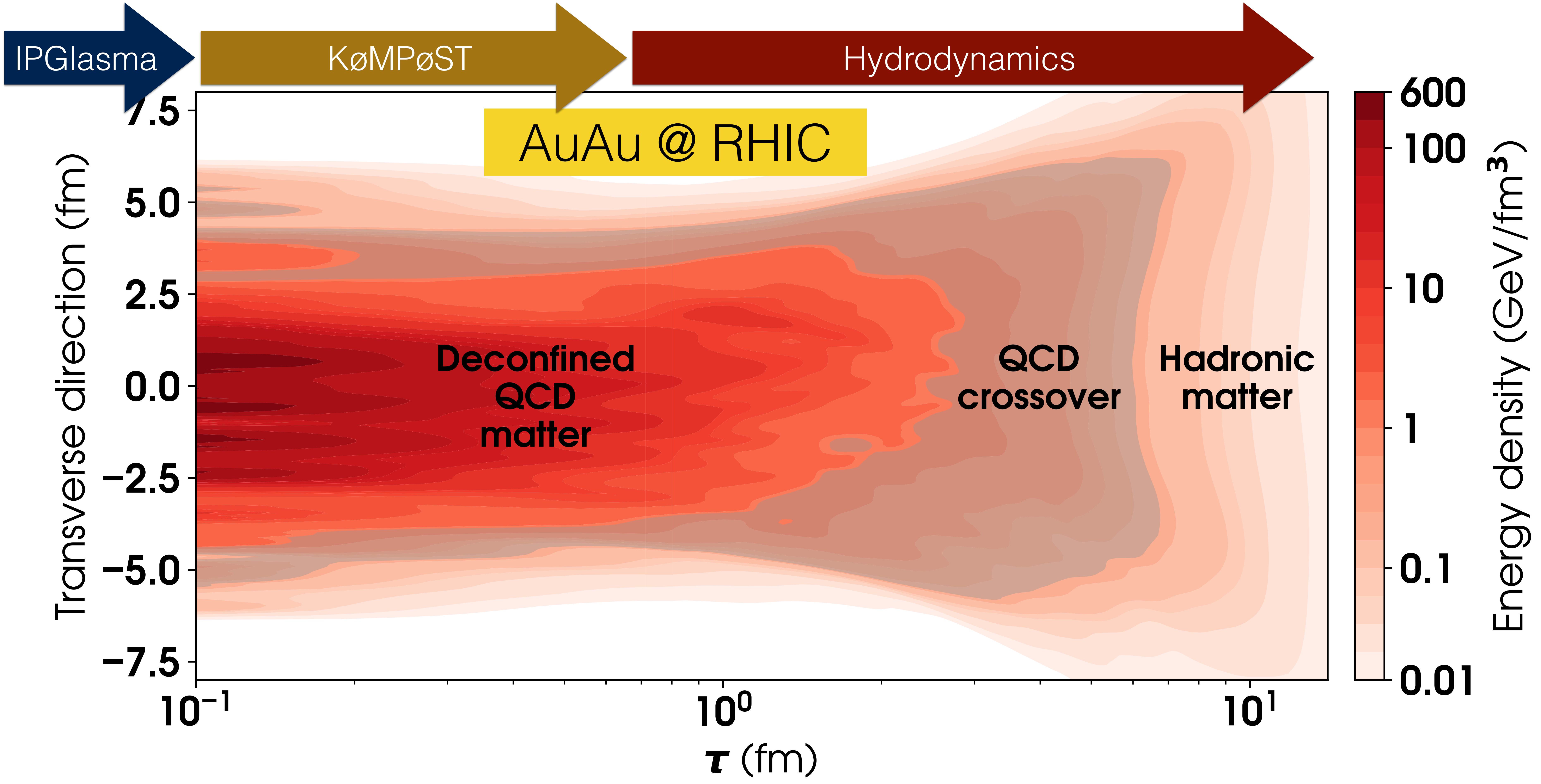
(A possible) Time evolution of a HIC



In contrast to usual HEP, **time and distance are relevant variables** in heavy-ion collisions

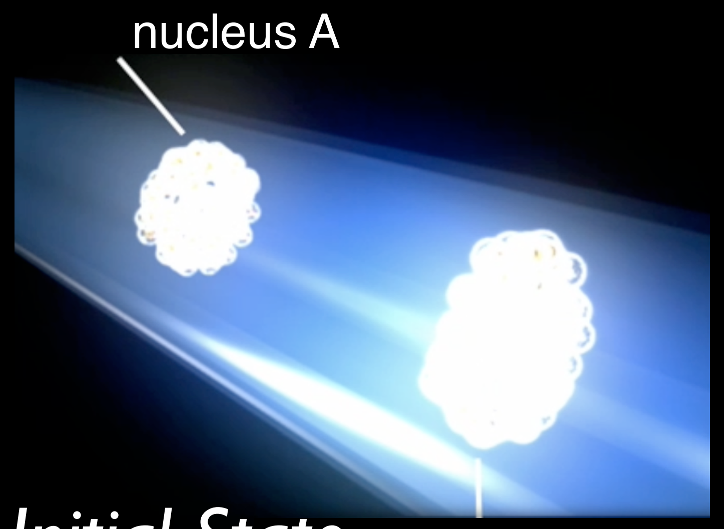
Building collectivity in extended (macroscopic) systems

(A possible) Time evolution of a HIC



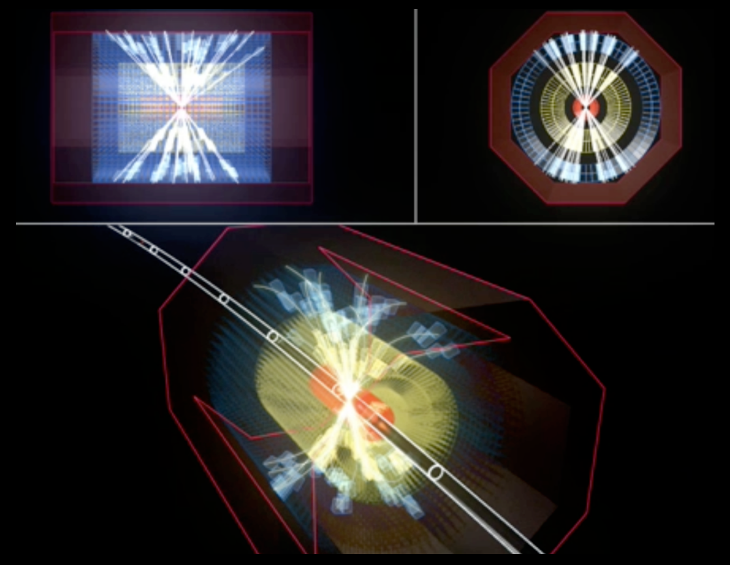
[Jean-François Paquet - talk at Initial Stages 2021]

Questions accessible in HIC



Initial State

Final State



What is the structure of the colliding objects?

- Small-x region of the nuclear (hadron) wave function
- Fix <u>out-of-equilibrium</u> initial stages with well-controlled theoretical framework

What is the dynamics at the initial stages after the collision?

- Mechanism of isotropization/equilibration/thermalization — classical/quantum
- When/how/why hydrodynamics apply?

What are the properties of the produced medium?

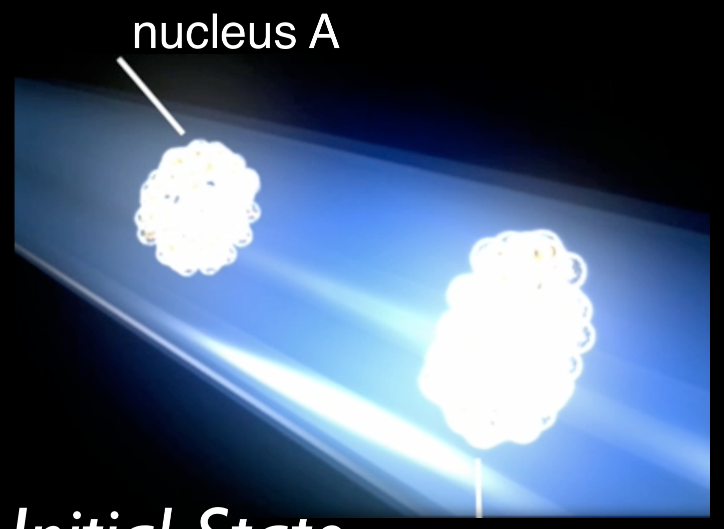
- identify signals to characterize the medium with well-controlled observables
- what are the building blocks and how they organize?
- is it strongly-coupled? quasiparticle description? phases?

Out of equilibrium

Towards equilibrium

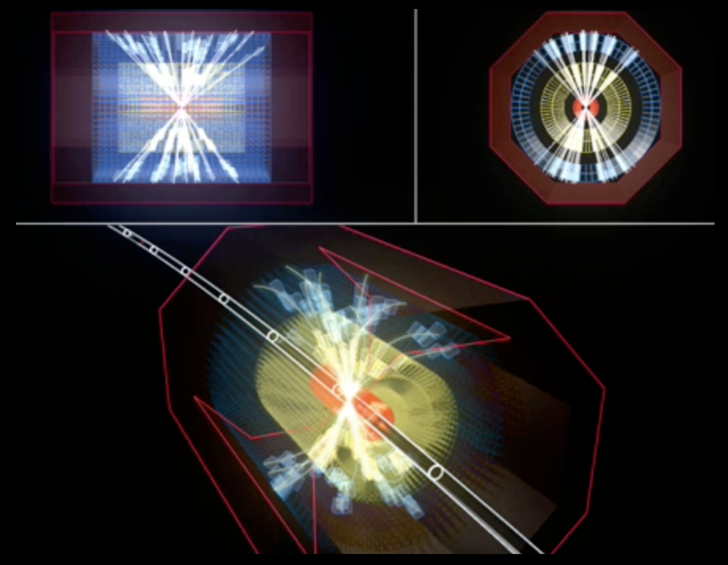
Local equilibrium

Questions accessible in HIC



Initial State

Final State



First ~5 yoctoseconds or 1.5fm/c

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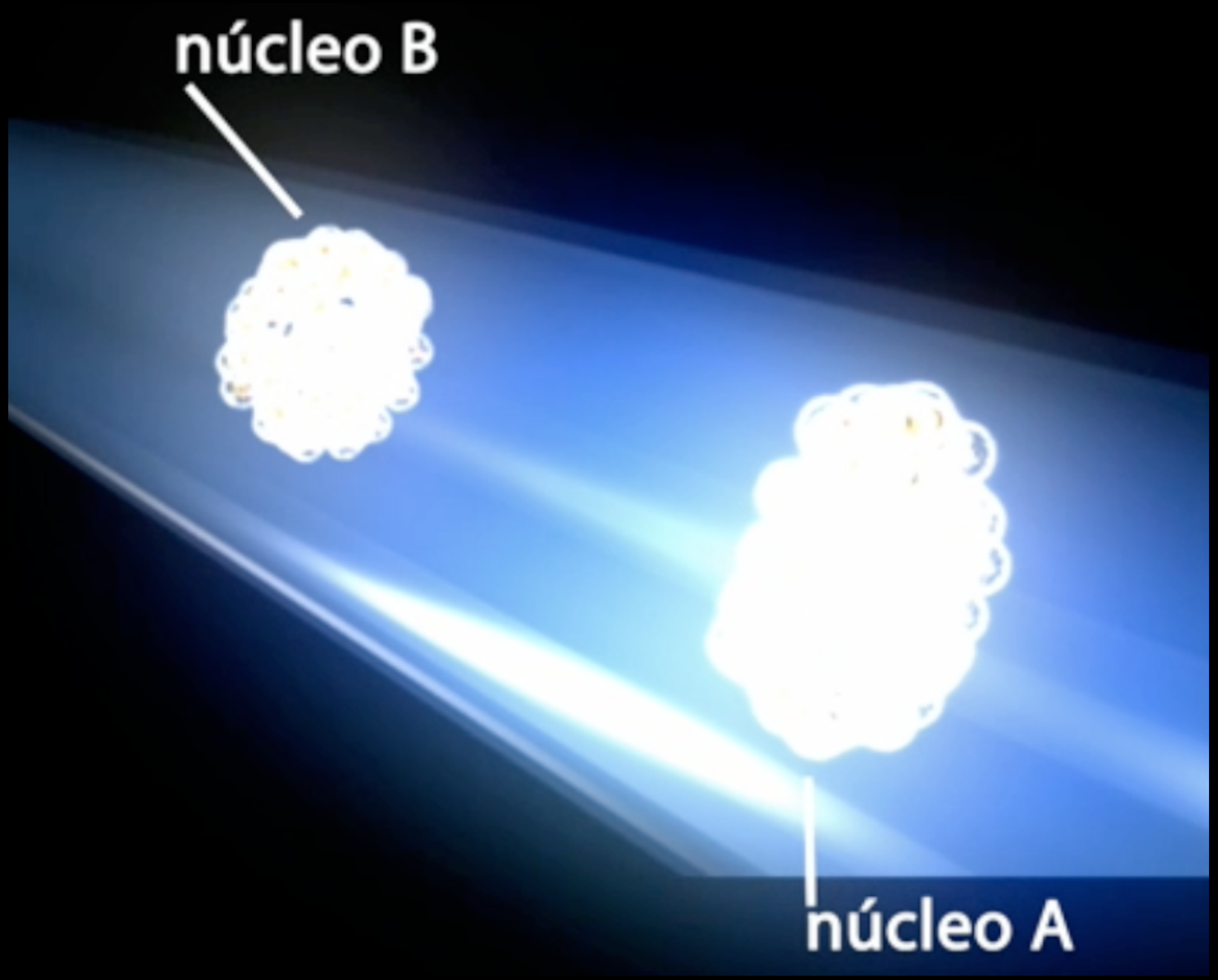


Initial state Partonic densities & Multiparticle Production

Processes with large virtualities probe the inner part of the nucleons as usual — nuclear PDFs — **Dilute regime**

At smaller scales, however, the partons are densely packed — **Dense regime** — this regime **determines the production of the dense system**

“Dilute” regime - usual DGLAP

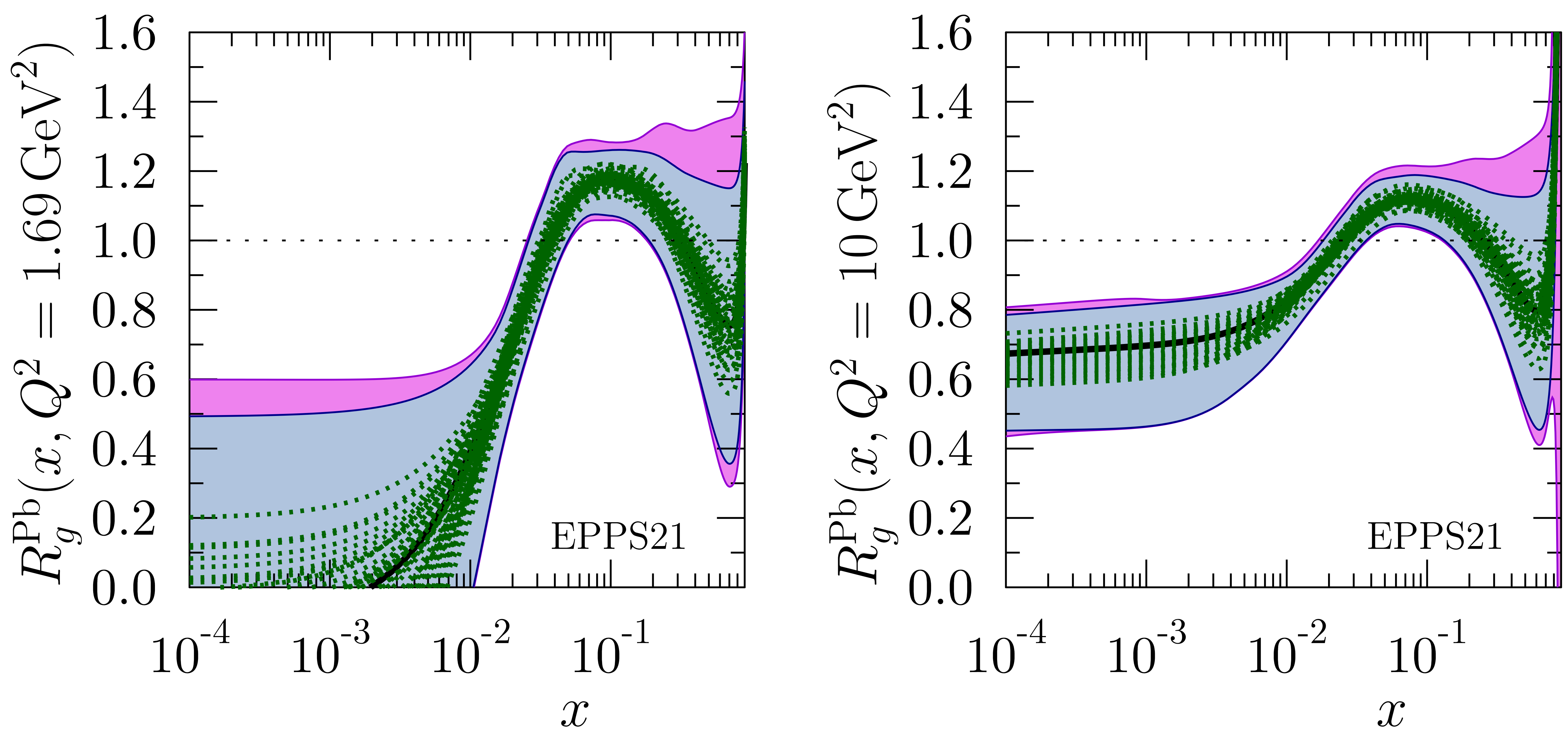
Nuclear PDFs extracted in DGLAP global fits - as usual proton PDFs
[Normally ratios w.r.t. proton PDFs fitted]

$$f_i^{\mathrm{p}/A}(x,Q^2) = R_i^{\mathrm{p}/A}(x,Q^2)\, f_i^{\mathrm{p}}(x,Q^2)\,.$$

$$\frac{\partial q_i}{\partial \log\mu^2} = \frac{\alpha_s}{2\pi}\left[P_{qq}\otimes q_i + P_{qg}\otimes g\right]$$

$$\frac{\partial g}{\partial \log\mu^2} = \frac{\alpha_s}{2\pi}\left[P_{gq}\otimes q + P_{gg}\otimes g\right]$$

[Fit I.C. with experimental data]



Excellent description of data (not shown) **- universality of nuclear PDFs**

“Dilute” regime - usual DGLAP

Nuclear PDFs extracted in DGLAP
[Normally ratios w.r.t. proton PDFs

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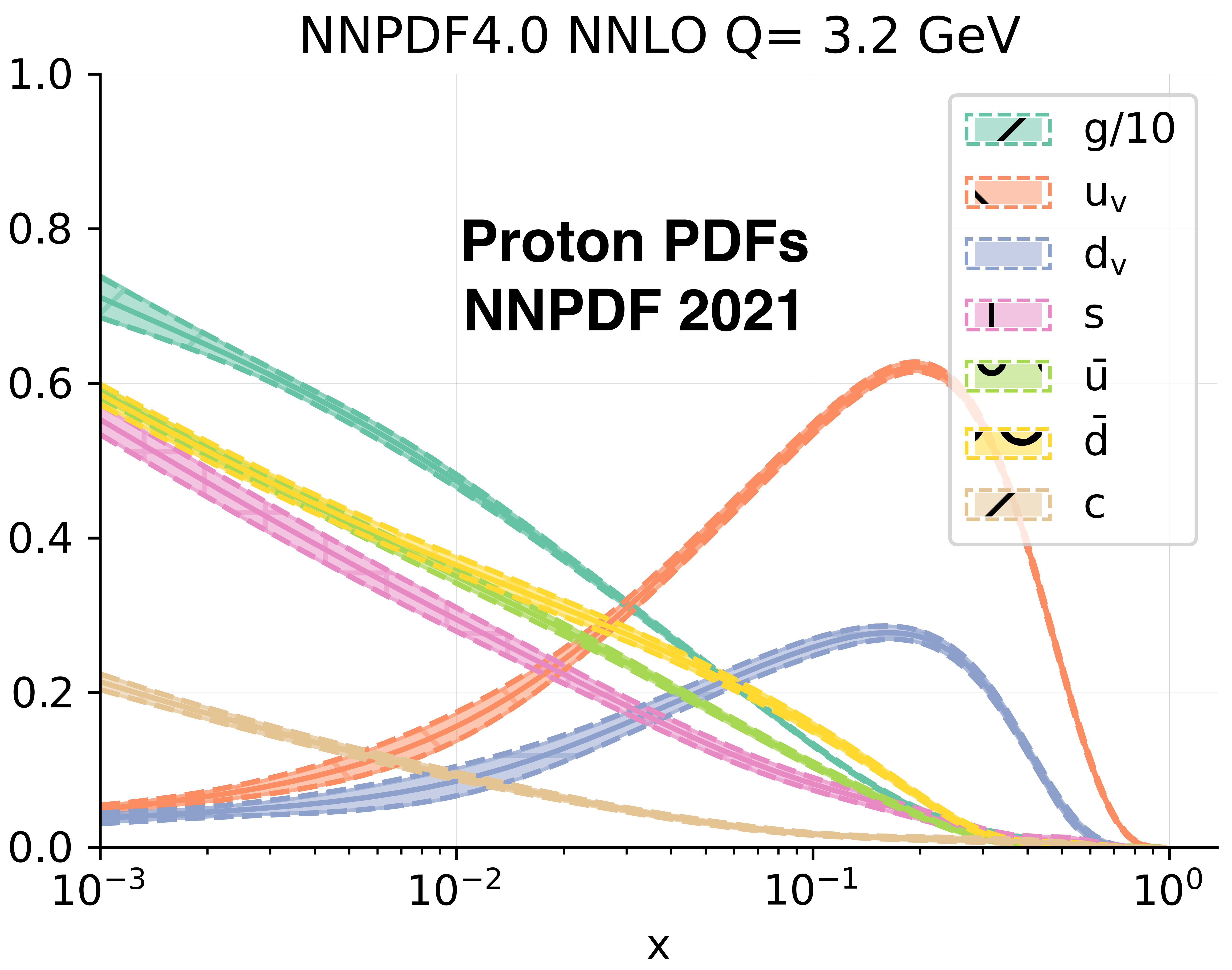
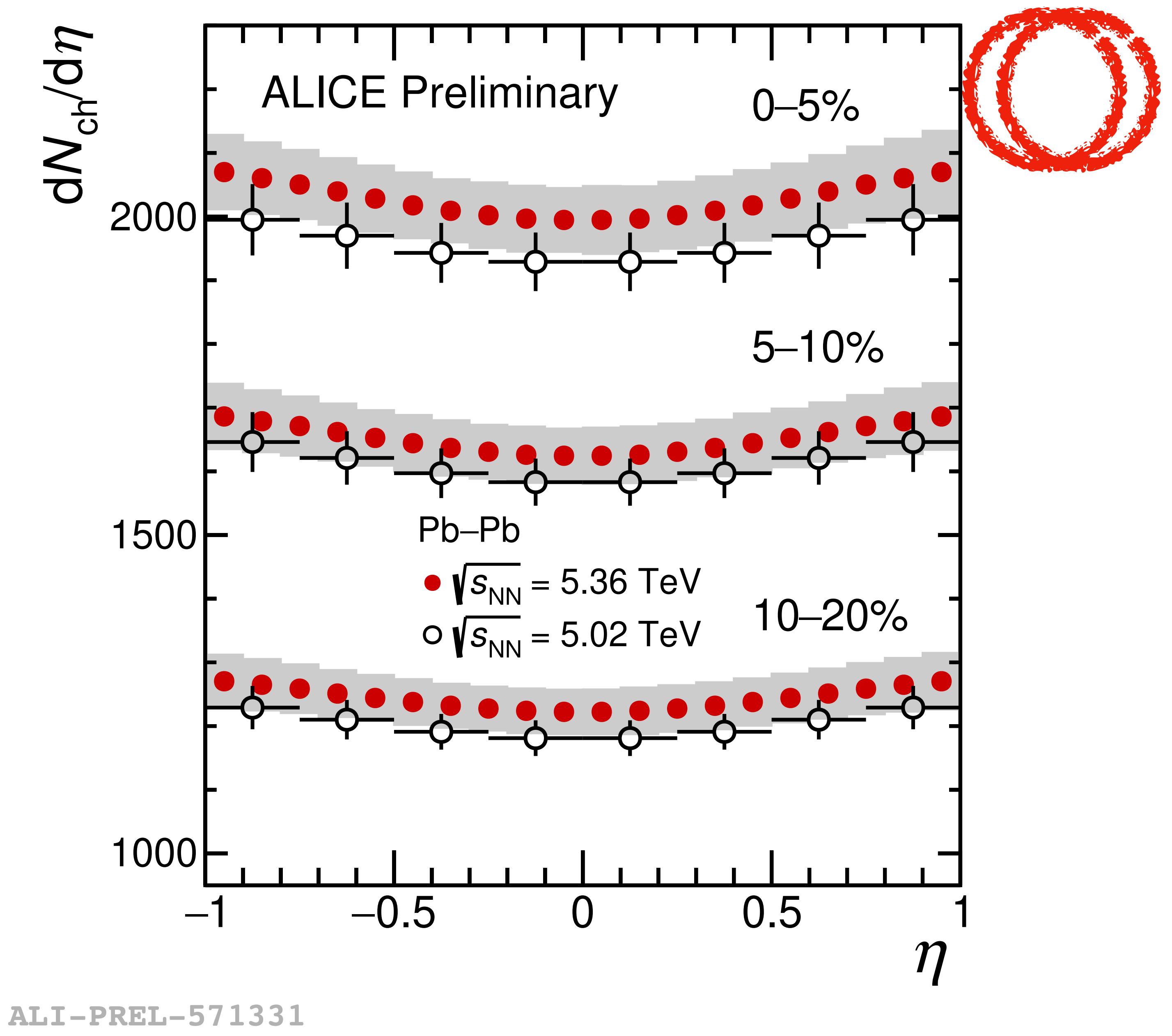


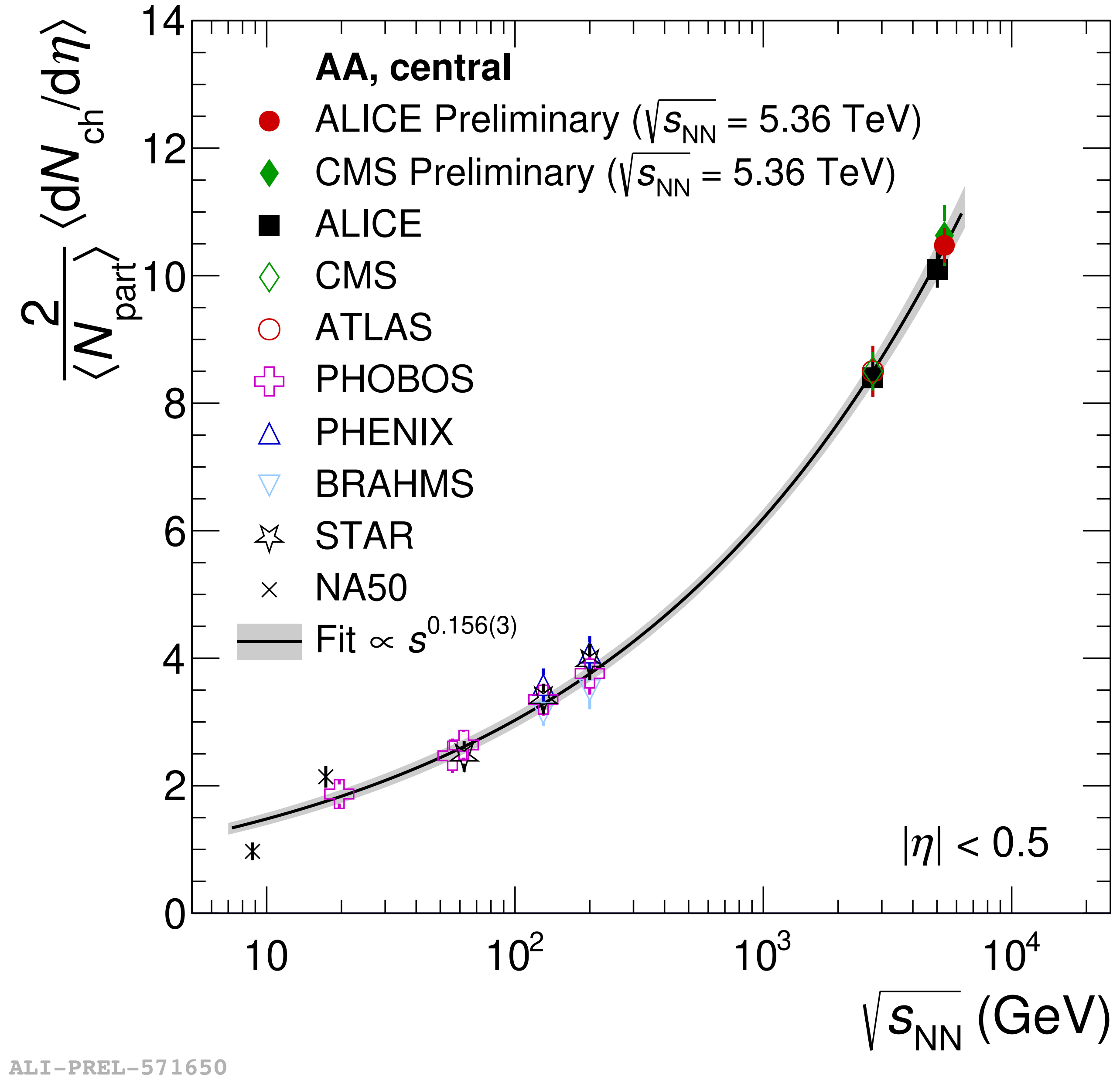
“Dense” regime - non-linear needed

Experimental data from ALICE in “centrality” and energy

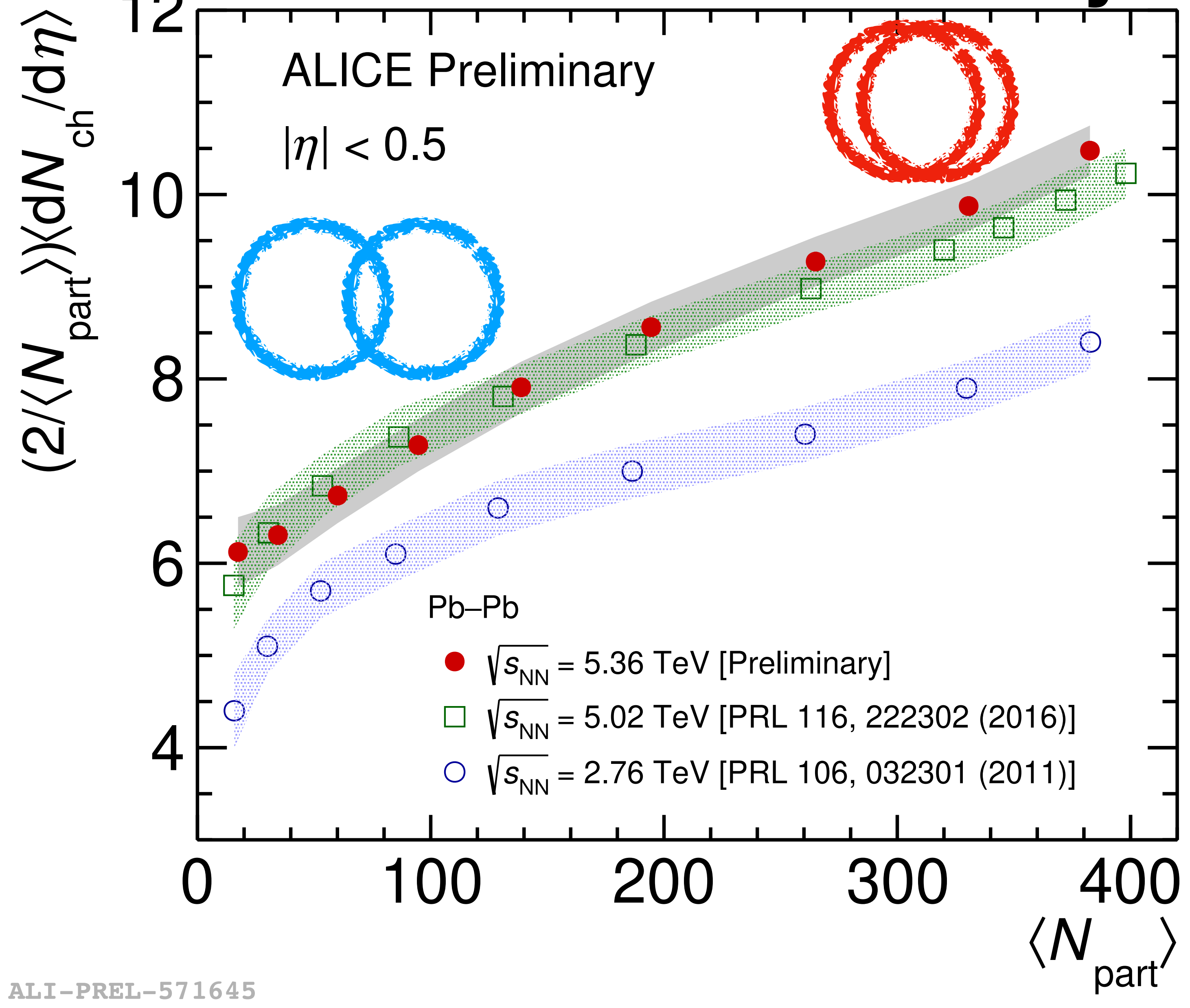
[N. Jacazio ICHEP2024]



Evolution with energy

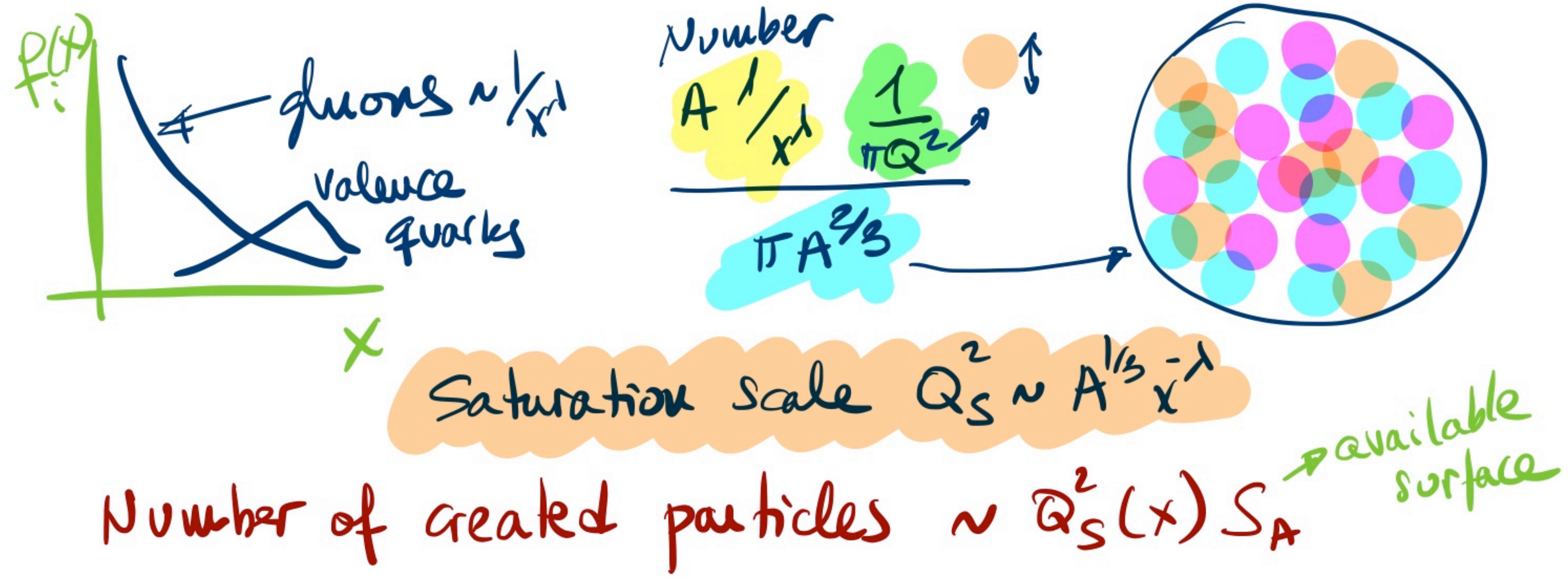


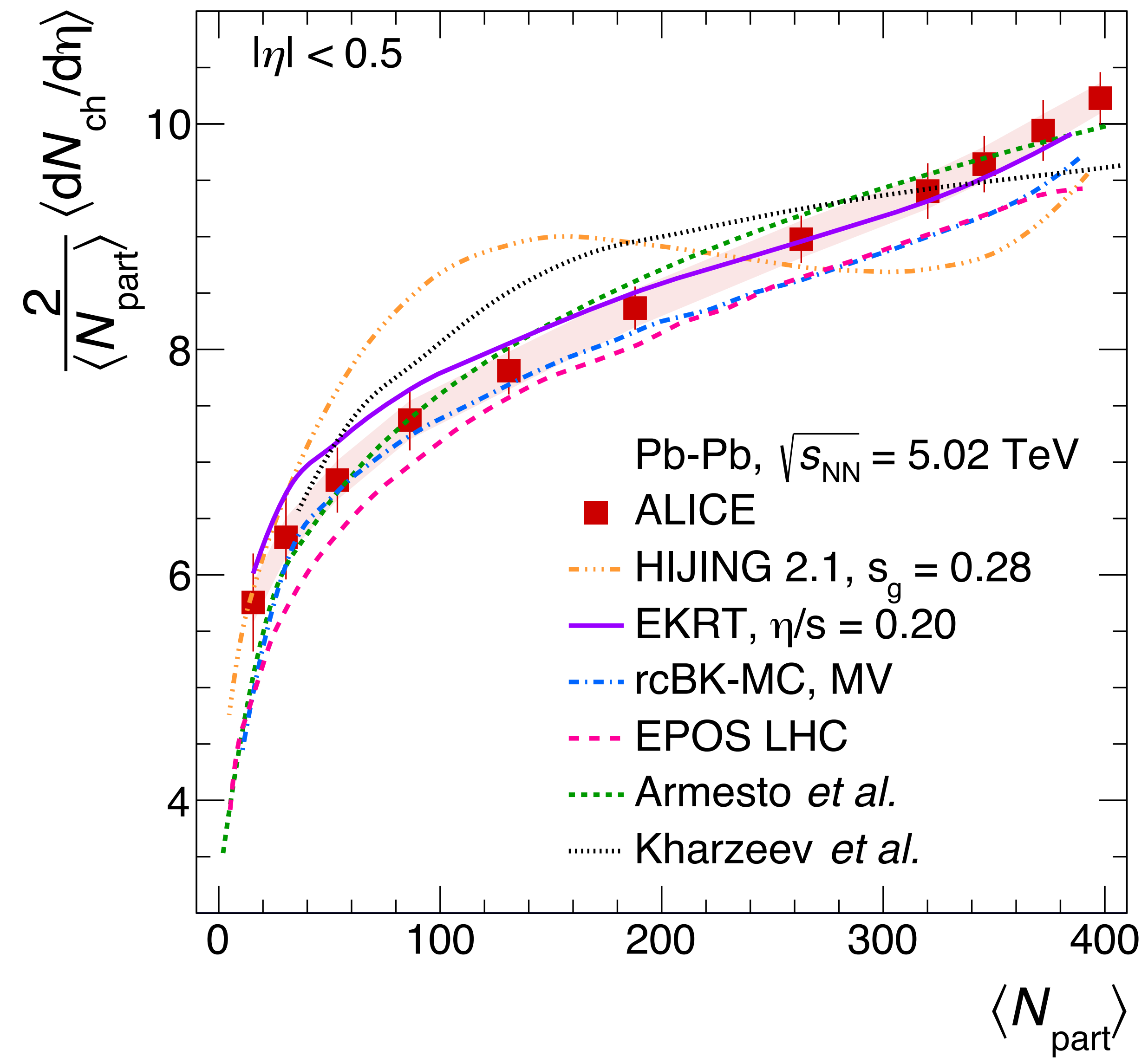
Evolution with centrality



Huge multiplicities for central PbPb collisions

Saturation - Color Glass Condensate



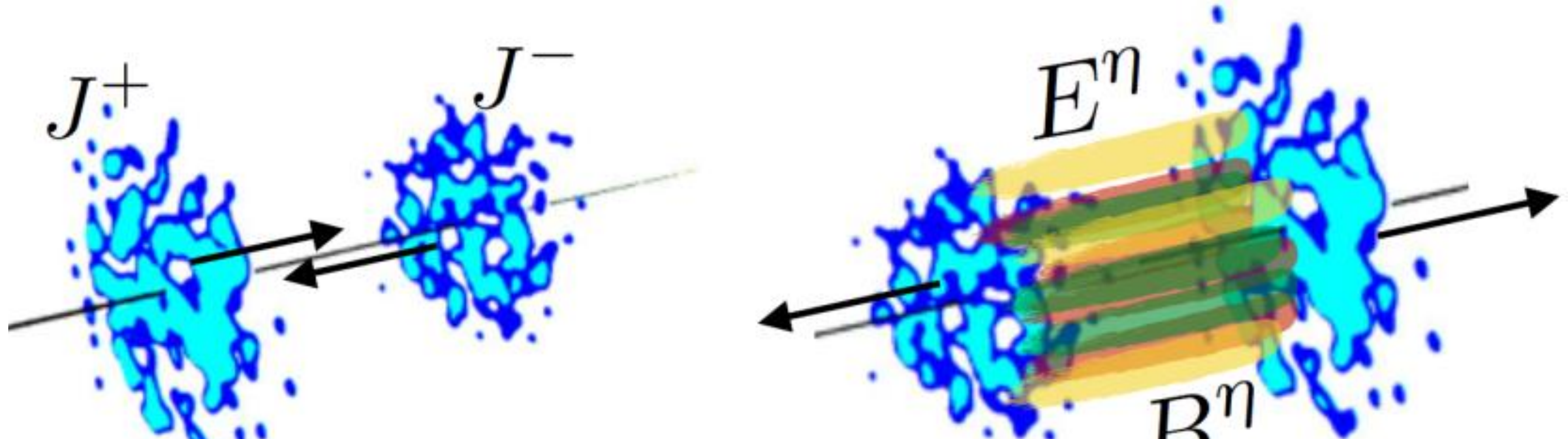


Color Glass Condensate

Large occupation numbers - classical fields

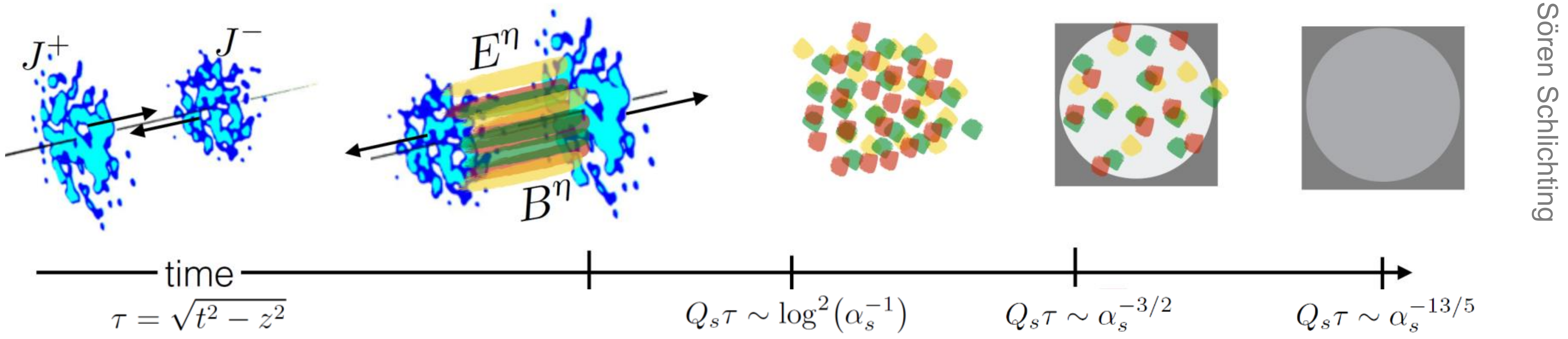
Quantum Corrections - evolution eqs.

Color Glass Condensate provides a general framework to compute initial stages



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

A picture for equilibration



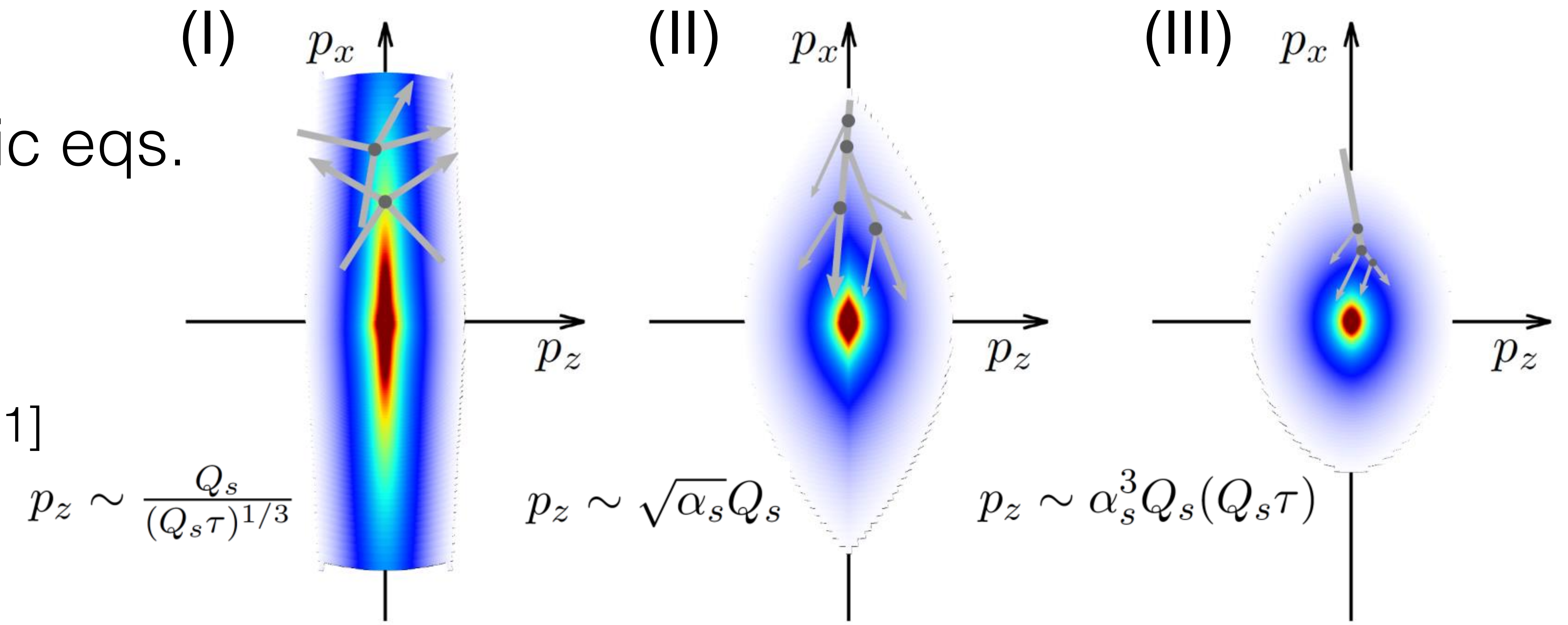
[Classical statistical/lattice gauge theory…]

Evolution of boost-invariant system with kinetic eqs.

$$p^\mu \partial_\mu f(x,p) = \mathcal{C}_{2\leftrightarrow 2}[f] + C_{1\leftrightarrow 2}[f]$$

[Bottom-up thermalization — Baier, Mueller, Schiff, Son 2001]

[Arnold, Moore, Yaffe 2001; Kurkela, Zhu 2015; Keegan, Kurkela, Mazeliauskas, Teaney 2016; Kurkela Mazeliauskas, Paquet, Schlichting, Teaney 2019…]



Hydrodynamics $\partial_\mu T^{\mu\nu} = 0$

$$T^{\mu\nu} = (\epsilon + p) u^\mu u^\nu - p g^{\mu\nu} + \text{viscosity corrections}$$

$(+ \text{ Equation of State})$

+ initial time
+ freeze-out temperature

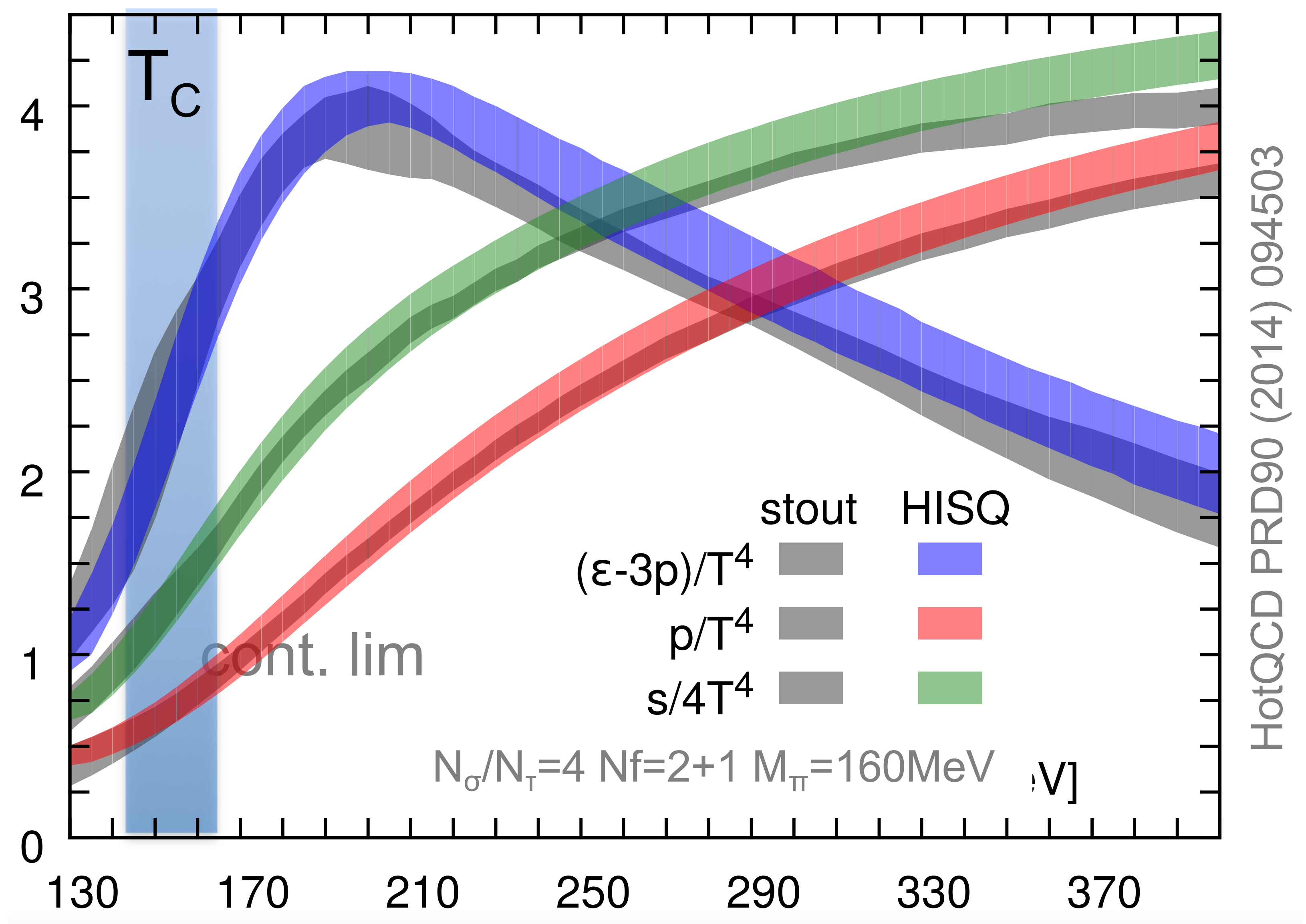
Far from equilibrium initial state needs to equilibrate fast (~1 fm or less)

Most of the theoretical progress in the last years:

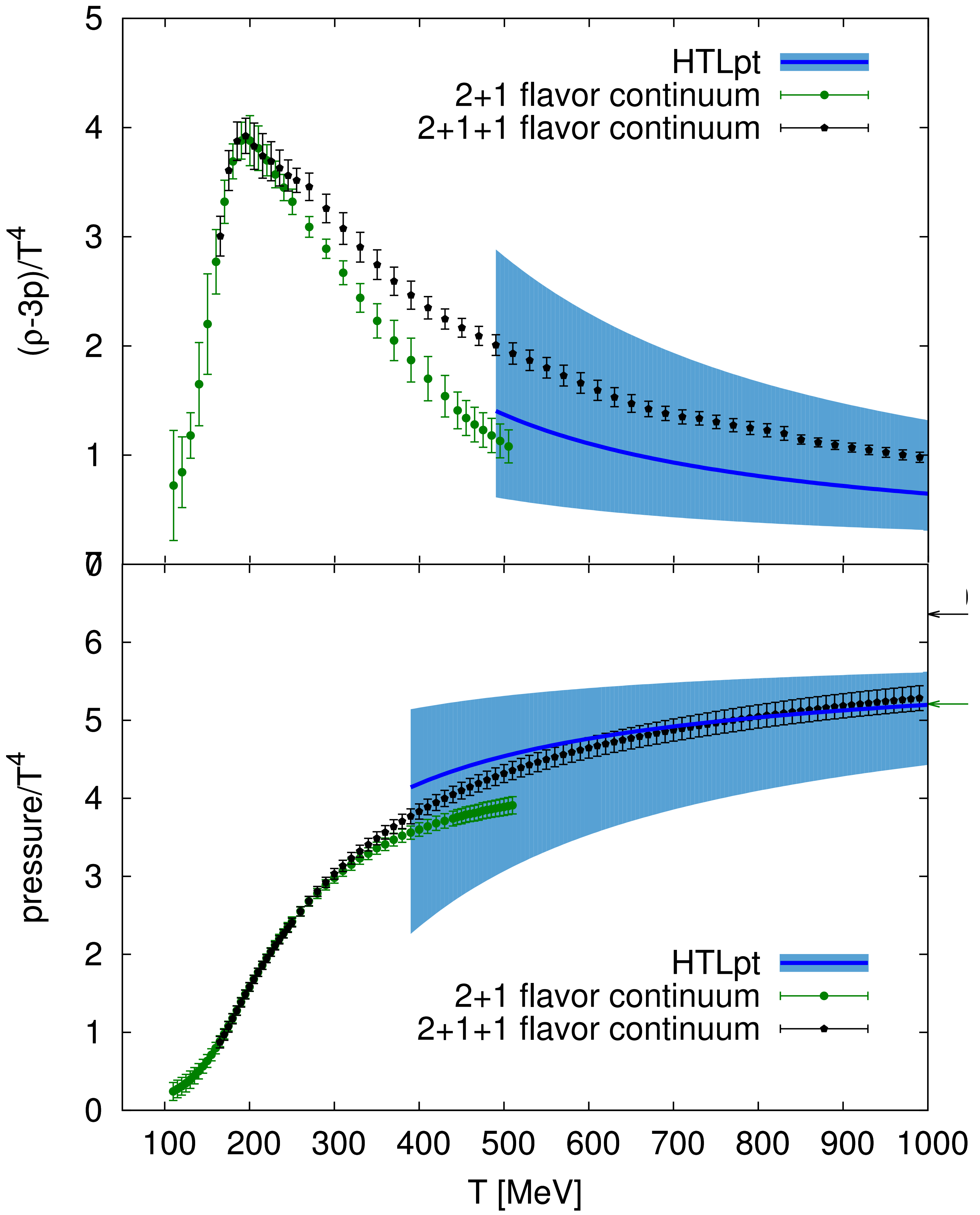
- Viscosity corrections and consistency
- Fluctuations in initial conditions
- Emergence of hydro from kinetic eqs, holography, etc…

EoS — high temperature

Equation of state at $\mu_B = 0$ is rather well known by lattice at moderate temperature — reasonably good matching with perturbative at $T \lesssim 1 GeV$



[Included in hydro simulations]



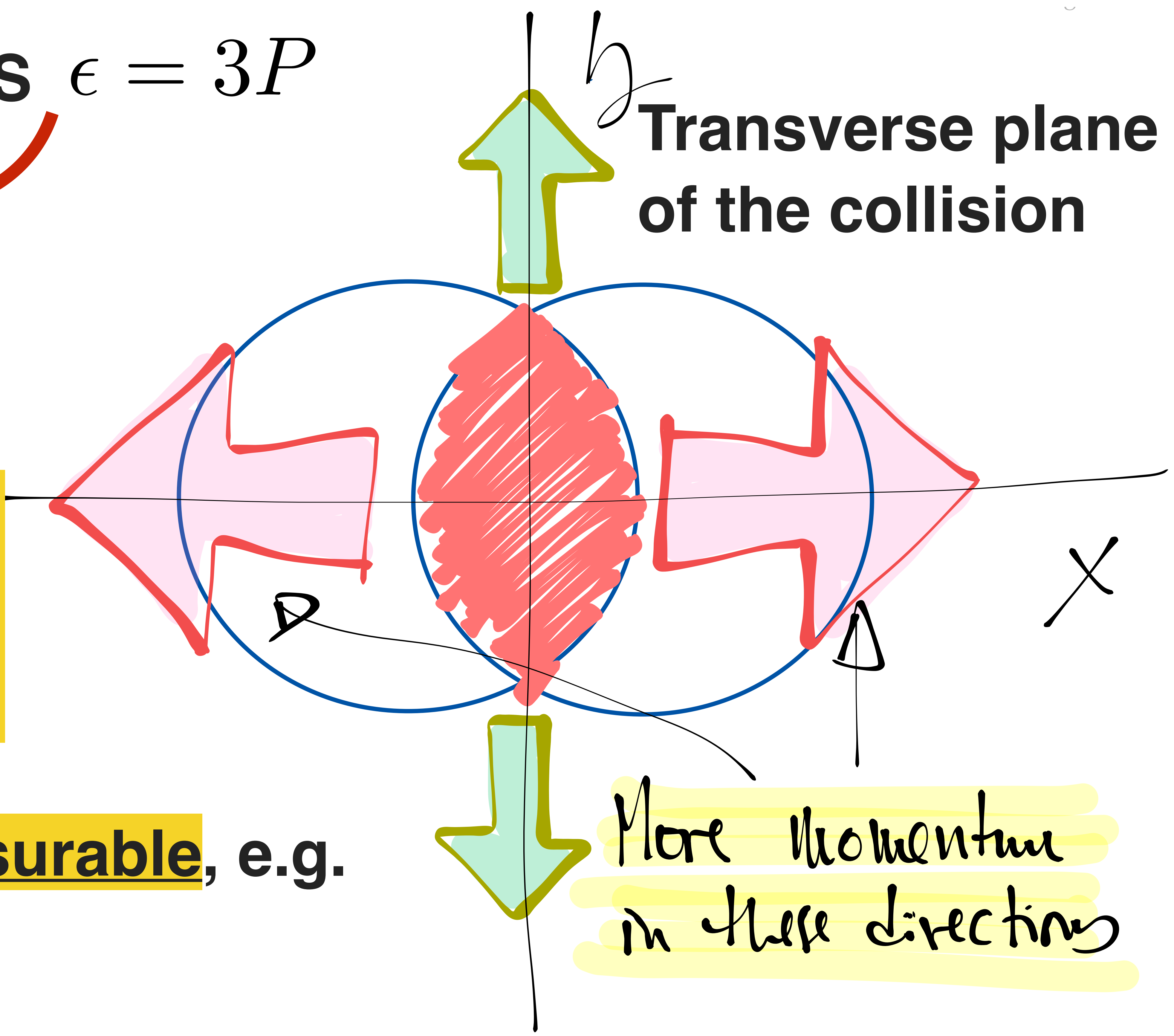
[Borsanyi et al Nature 539 (2016) no.7627, 69-71]

Harmonics: the golden measurement

[simplified discussion]

Remember the Euler eqs. — and use conformal EoS $\epsilon = 3P$

$$\frac{\partial \beta}{dt} = -\frac{c^2}{\epsilon + P}\nabla P \propto -\nabla \epsilon$$



Initial state <u>spatial</u> anisotropies → **Final state <u>momentum</u> anisotropies**

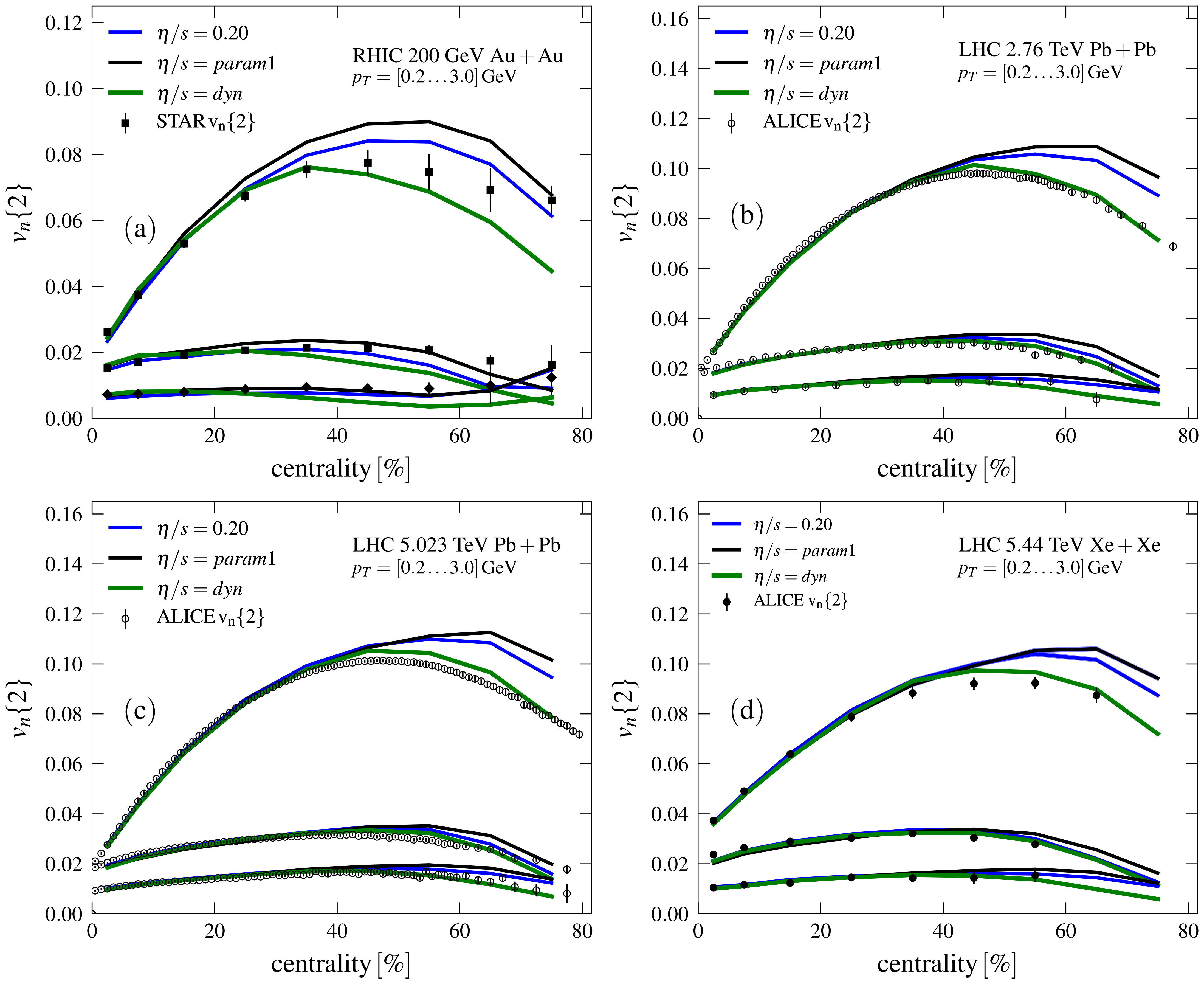
These final state momentum anisotropies are <u>measurable</u>, e.g.

$$\frac{dN}{d\phi} \propto 1 + 2 v_2 \cos 2\phi$$

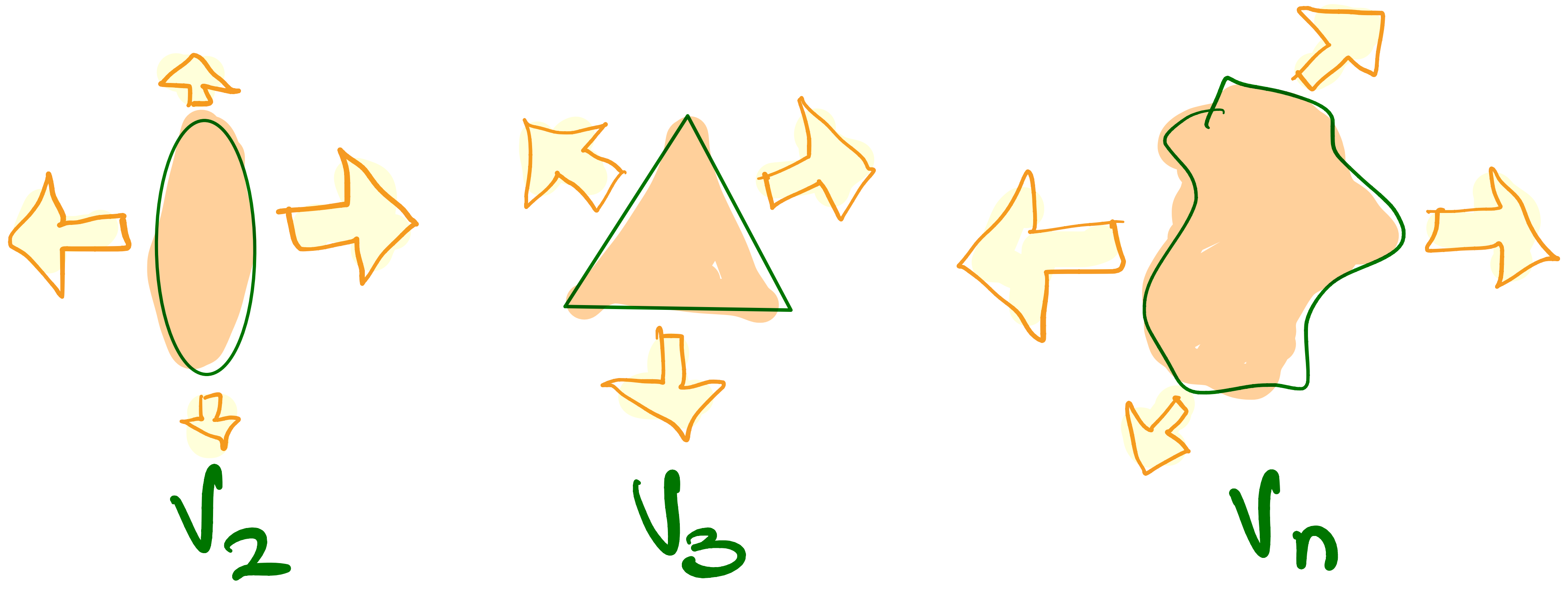
v_2 → Elliptic Flow

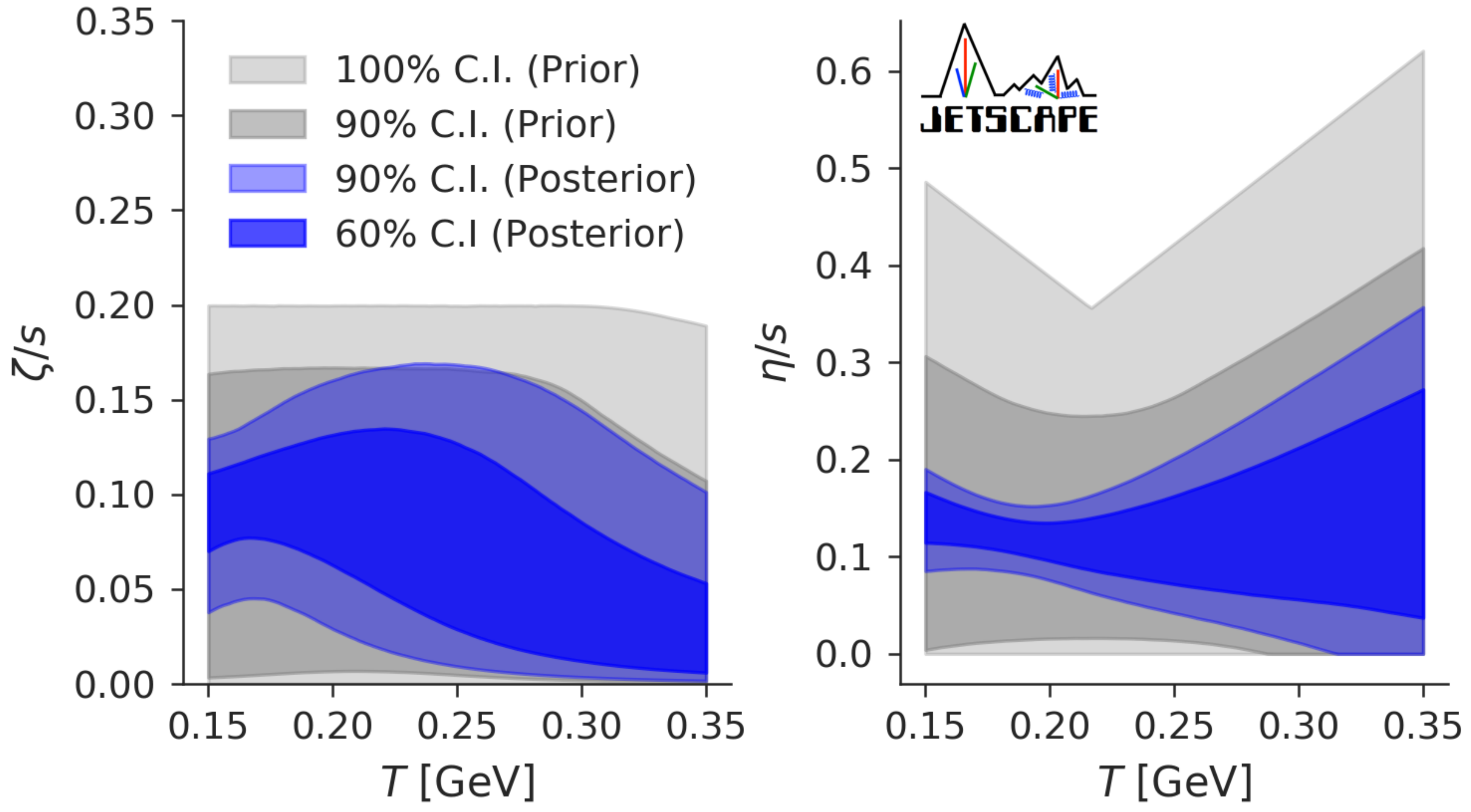
Description of data and viscosity

[Hirvonen, Eskola, Niemi 2022]



Fluctuation in I.C. generate higher harmonics





[Everett et al. 2021]

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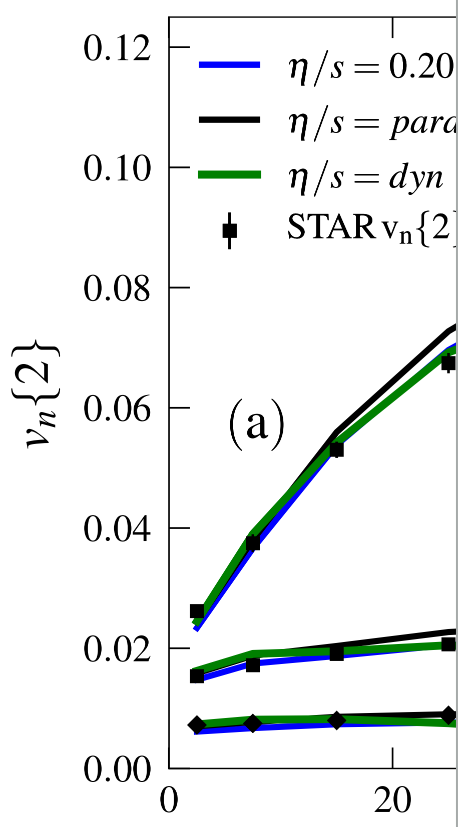
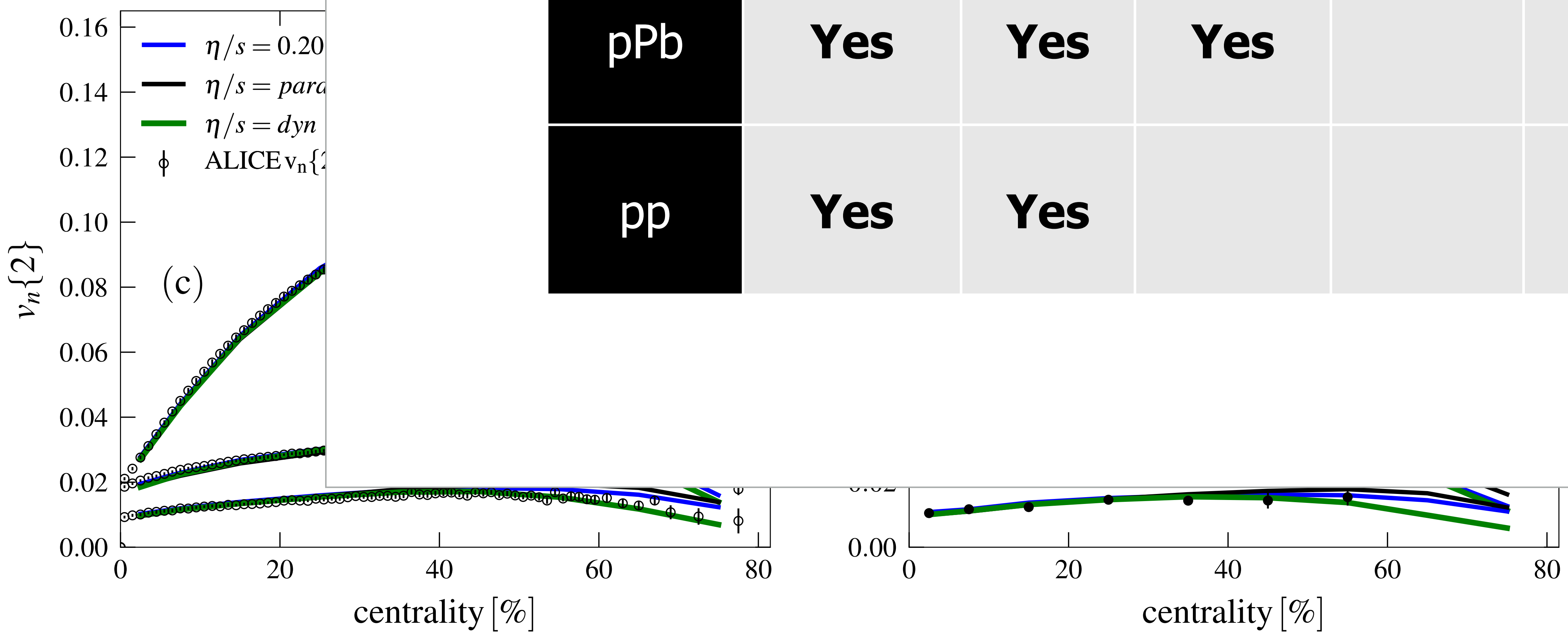


Shengquan Tuo parallel 08/07

Do we see flow signals?

	Charged hadron	Strange	Prompt J/Ψ	b→ J/ψ	Prompt D⁰	b→ D⁰	Υ(1S/2S)	Dijet	Z boson
PbPb	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**No**	**Yes**	**No**
pPb	**Yes**	**Yes**	**Yes**		**Yes**	**No**	**No**		
pp	**Yes**	**Yes**			**Yes**				



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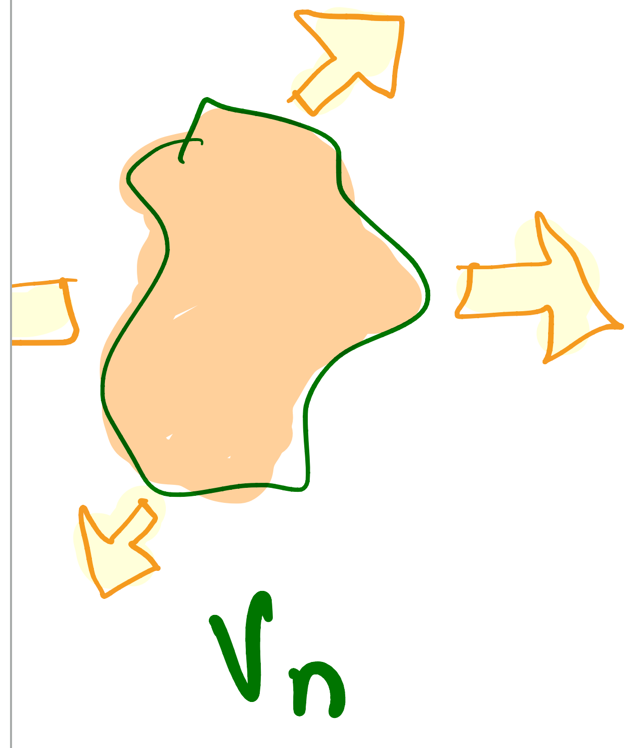
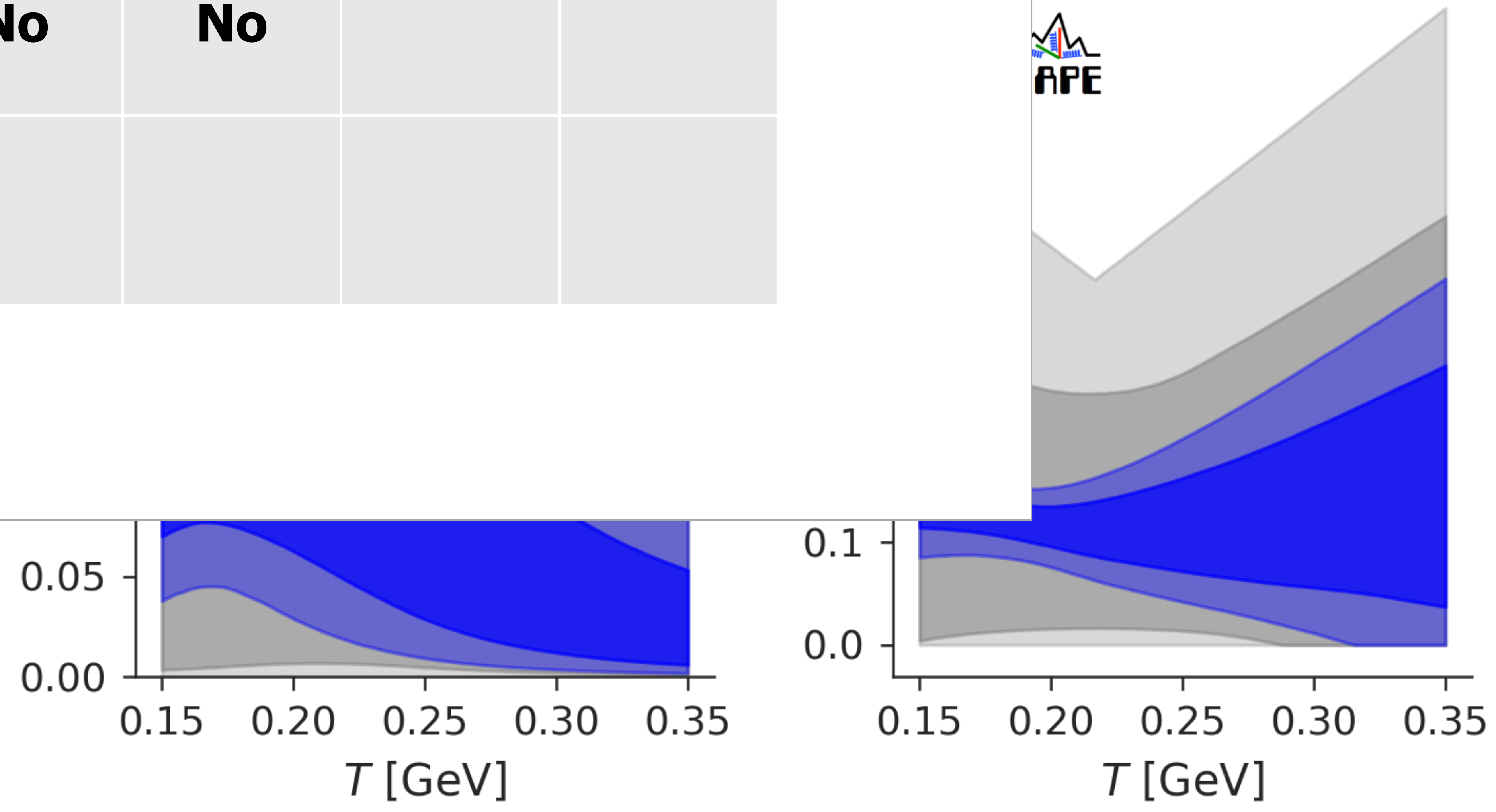
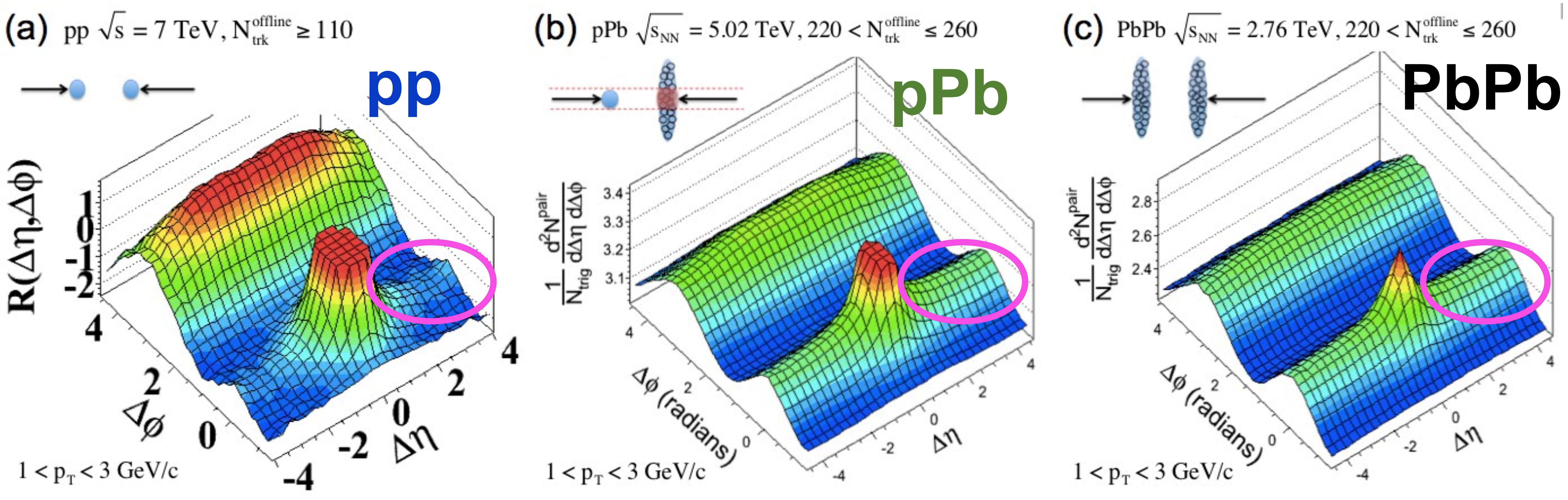
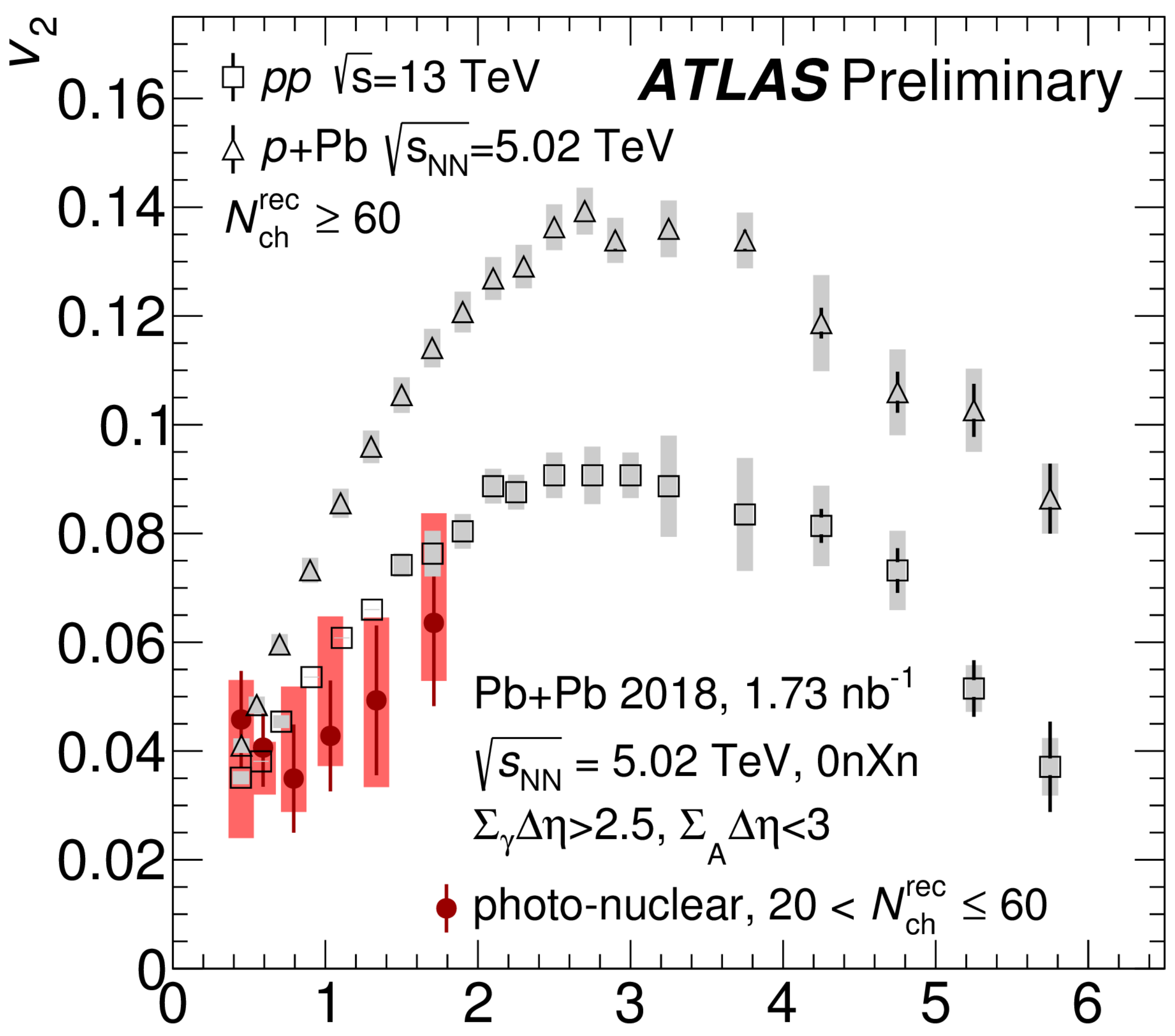




[Everett et al. 2021]

Hydro works in all systems from small to large ??





Hydro models able to describe the harmonics from these data

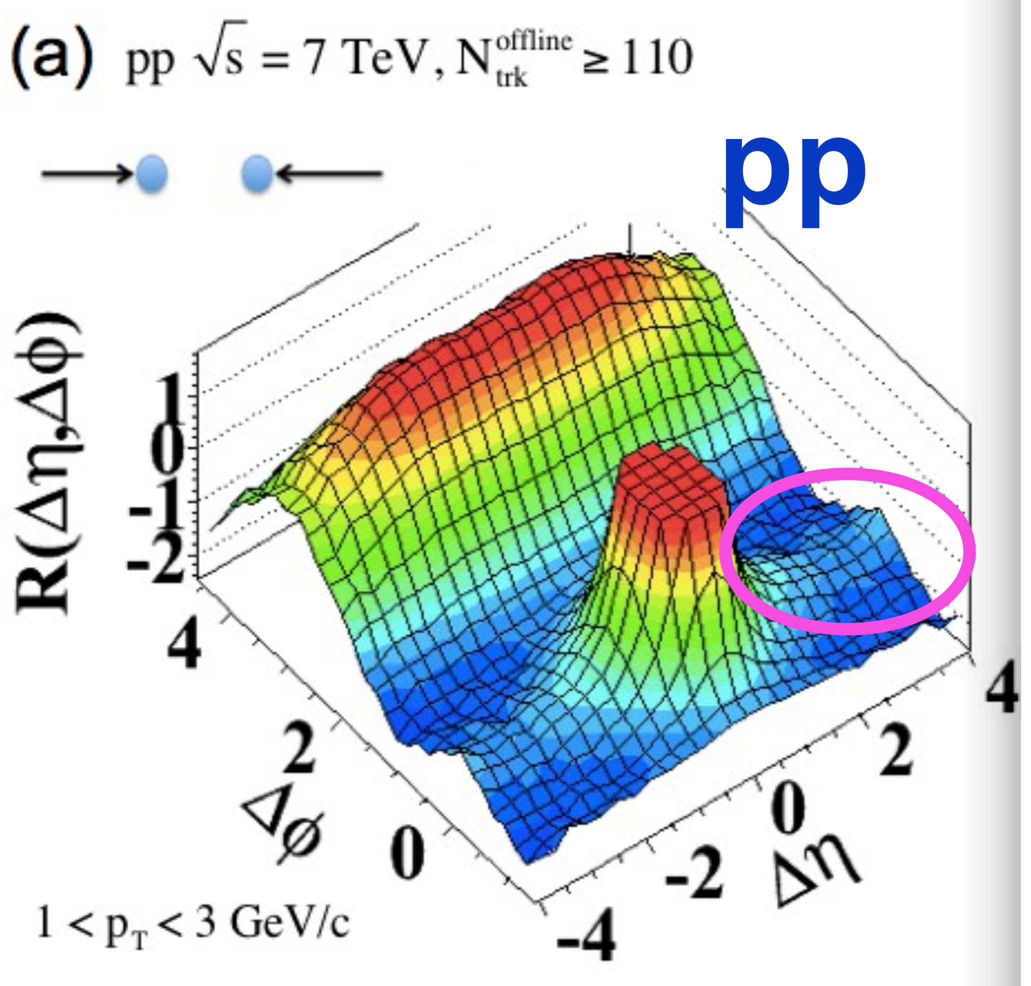
Hydrodynamics seem to work (too) well in all colliding systems for large multiplicities

But time scales and occupancies in small systems are small

For some classes of problems hydro equations have attractors

[universal solutions, independent on initial conditions]

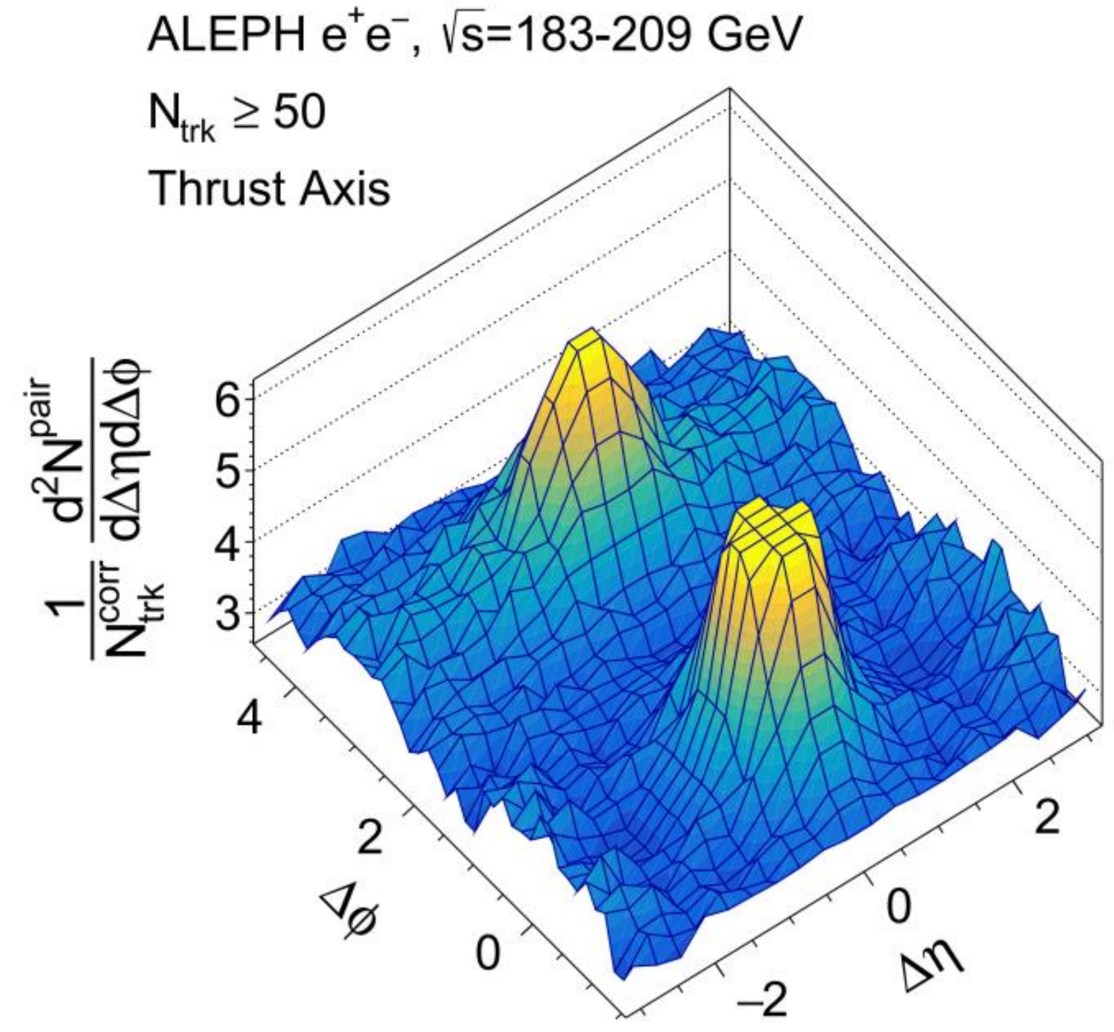
Hydro works in all systems from small to large ??



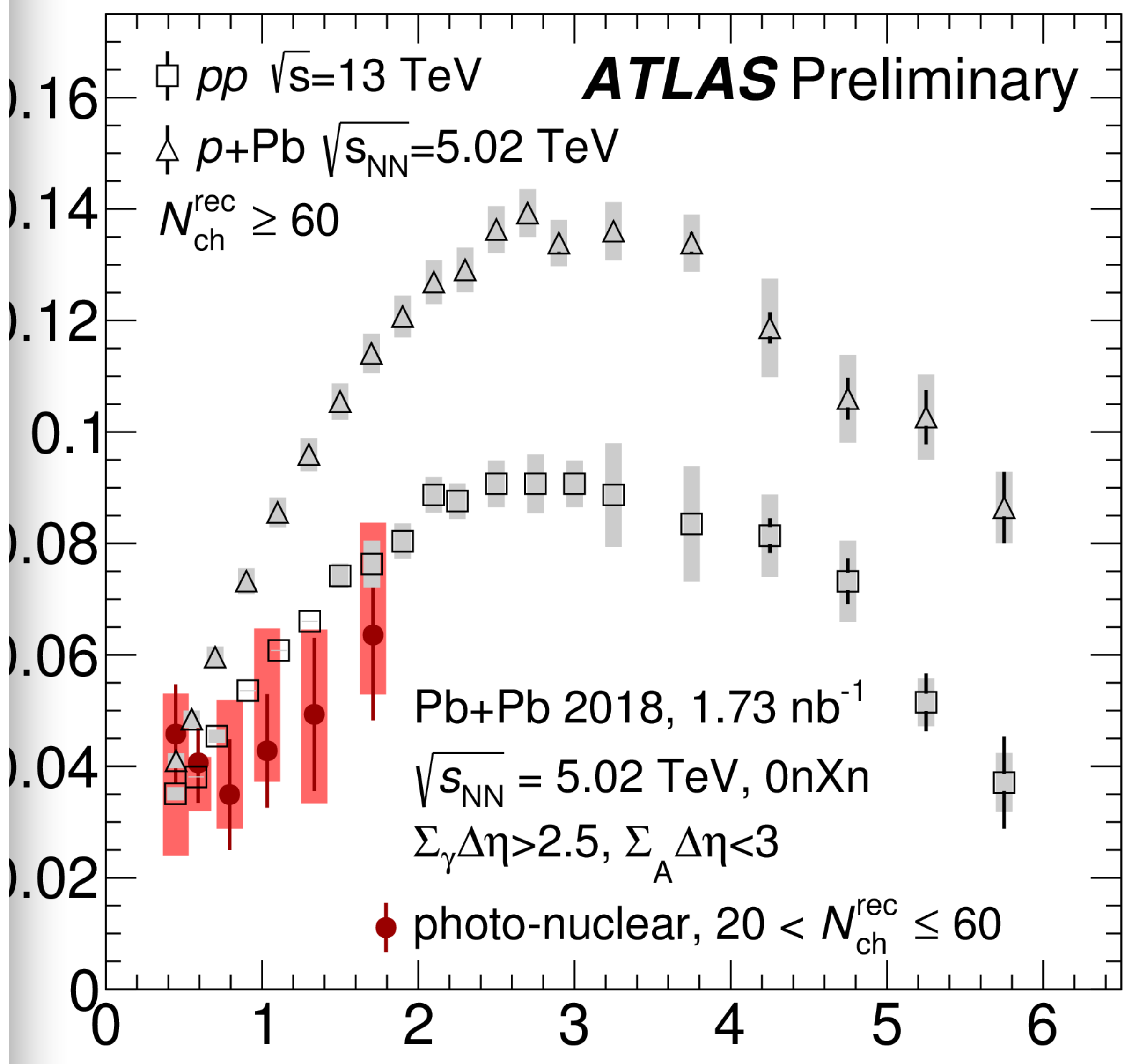
Hydro models able

Yen-Jie Lee Parallel 09/07

Hits of a ridge in (reanalysed) high multiplicity ALEPH data?



What does it mean?

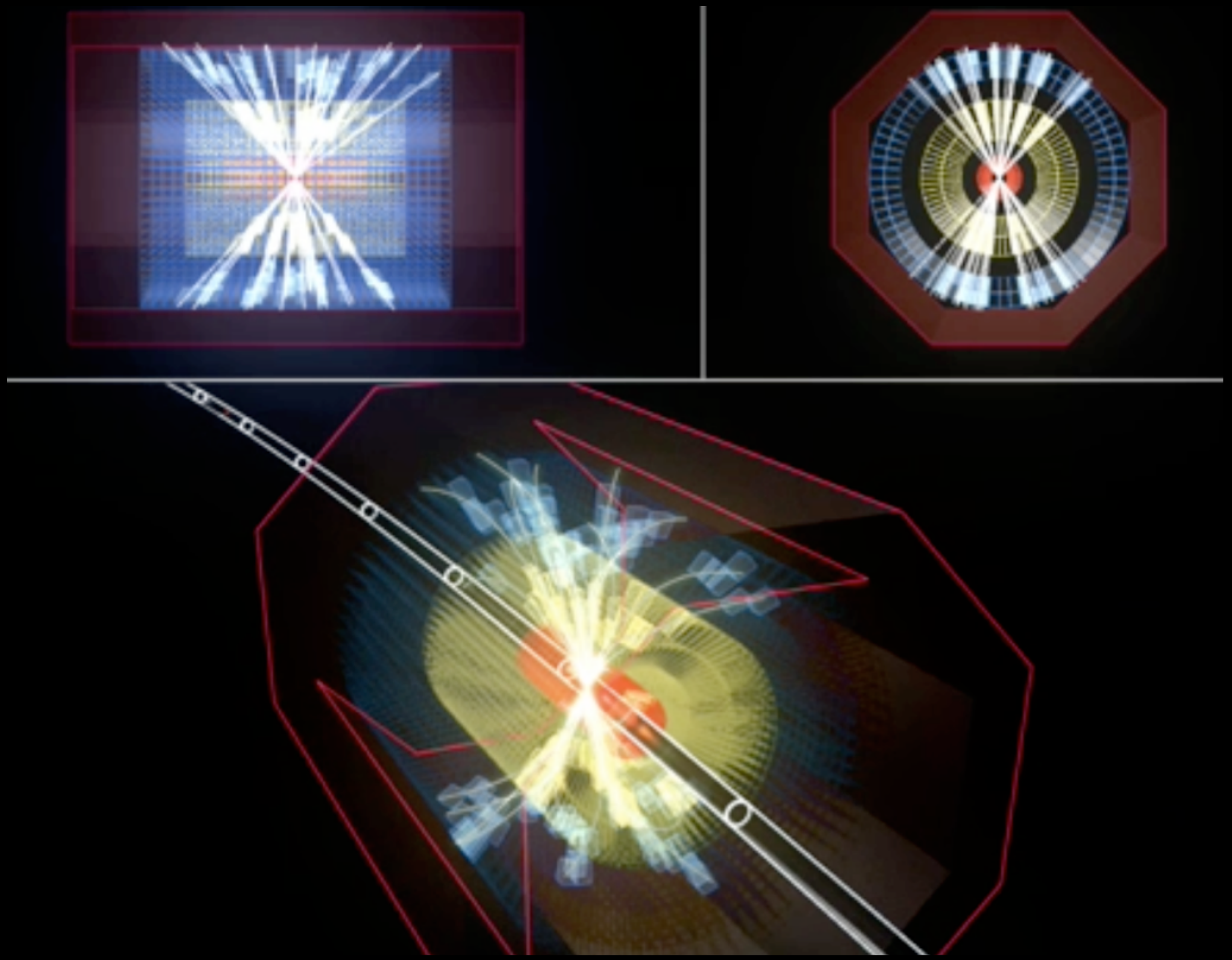


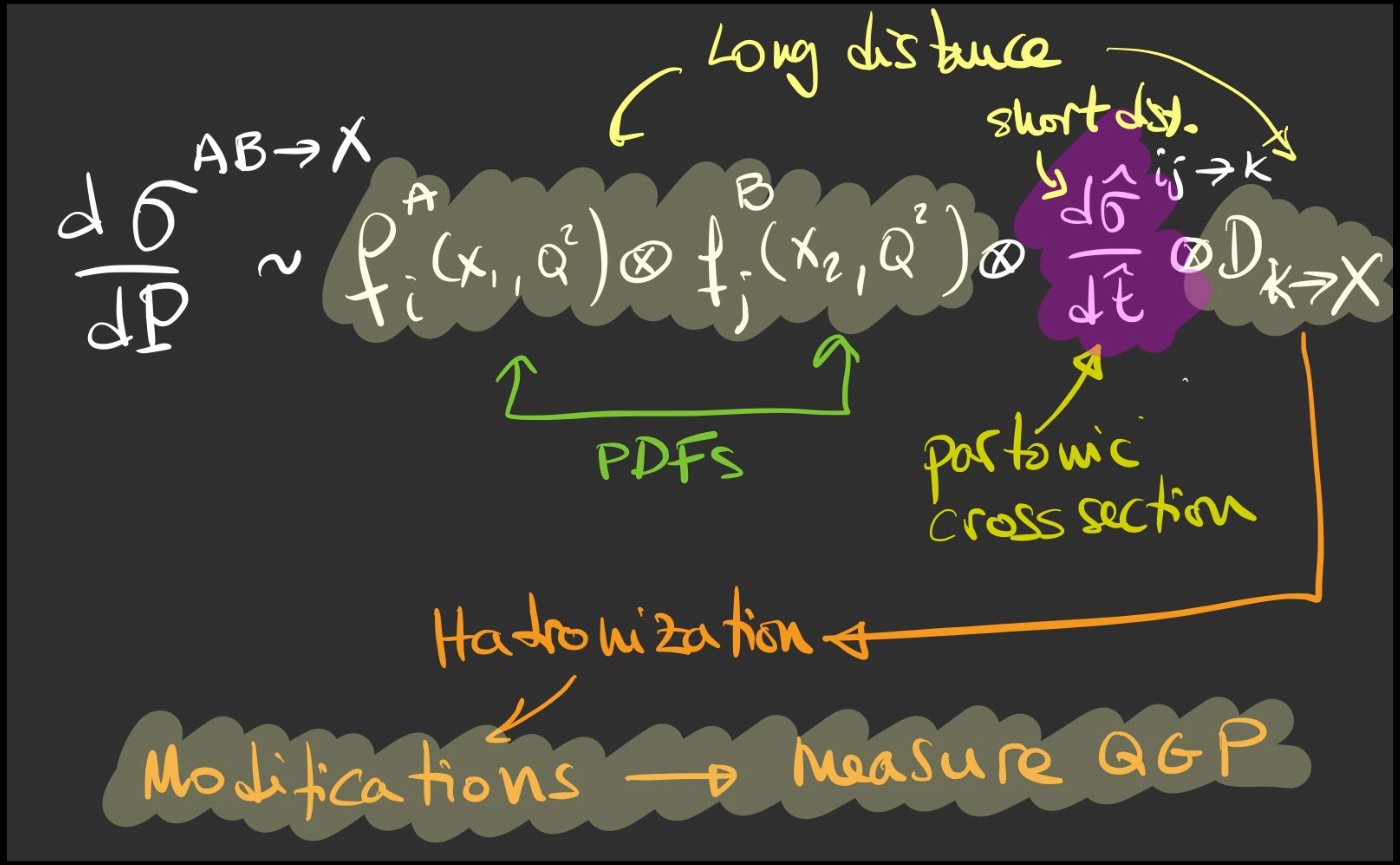
Hydrodynamics se ... large multiplicities

For some classes of problems hydro equations have attractors

[universal solutions, independent on initial conditions]

HARD PROBES

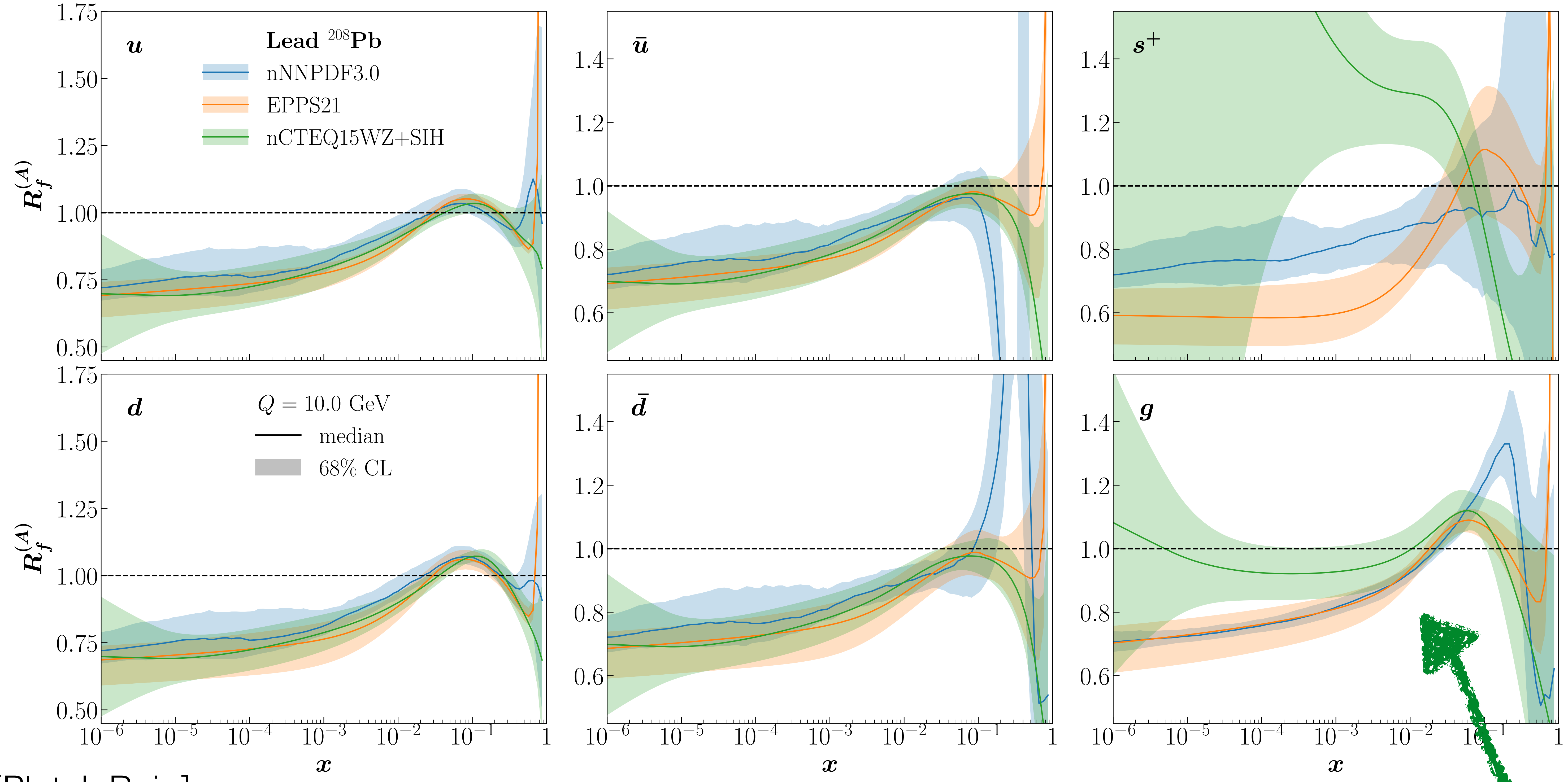




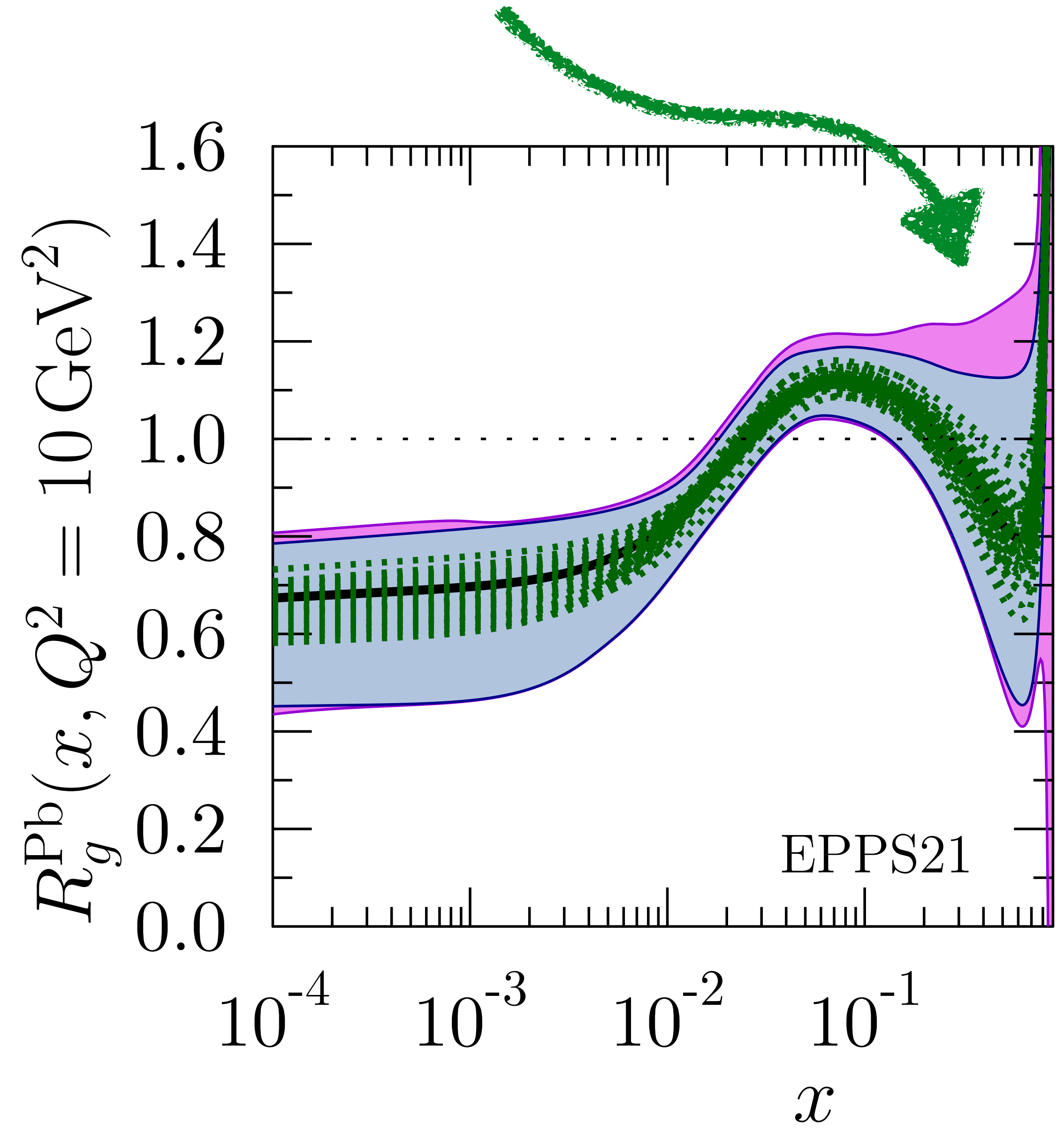
- Jet quenching
- Quarkonia suppression
- Open heavy flavor
- EW probes

Nuclear Parton Distribution Functions II

Two new analyses EPPS21, nNNPDF3.0 **Proton PDF uncertainties**



[Plot J. Rojo]



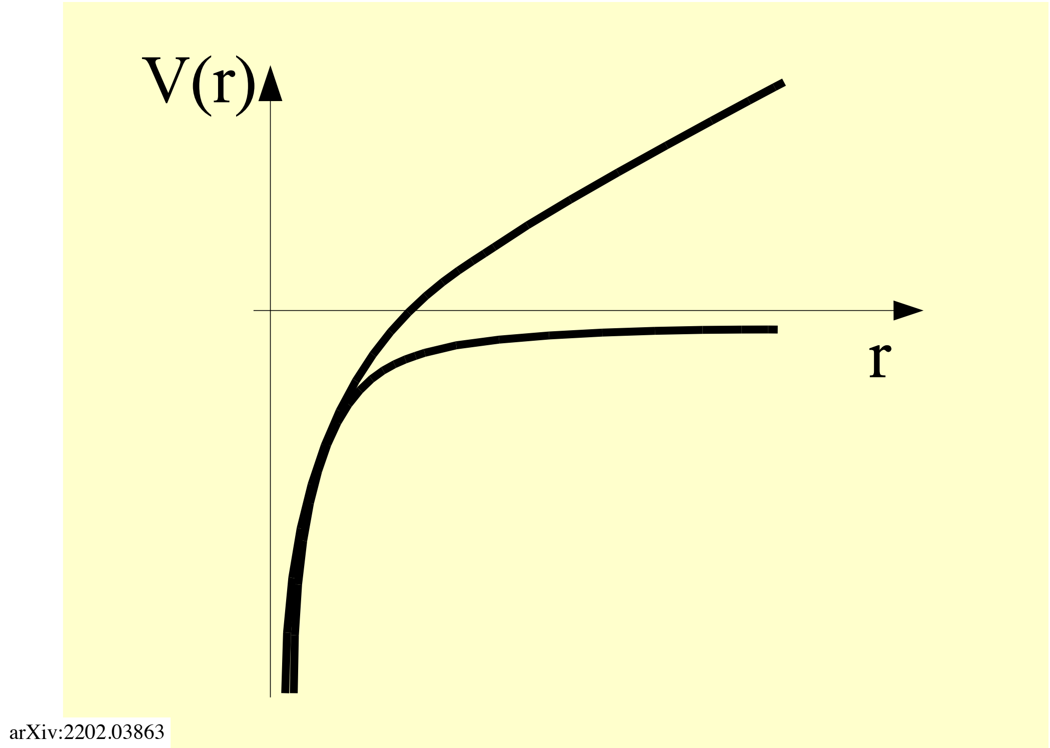
D's LHCb
dijets CMS
pPb

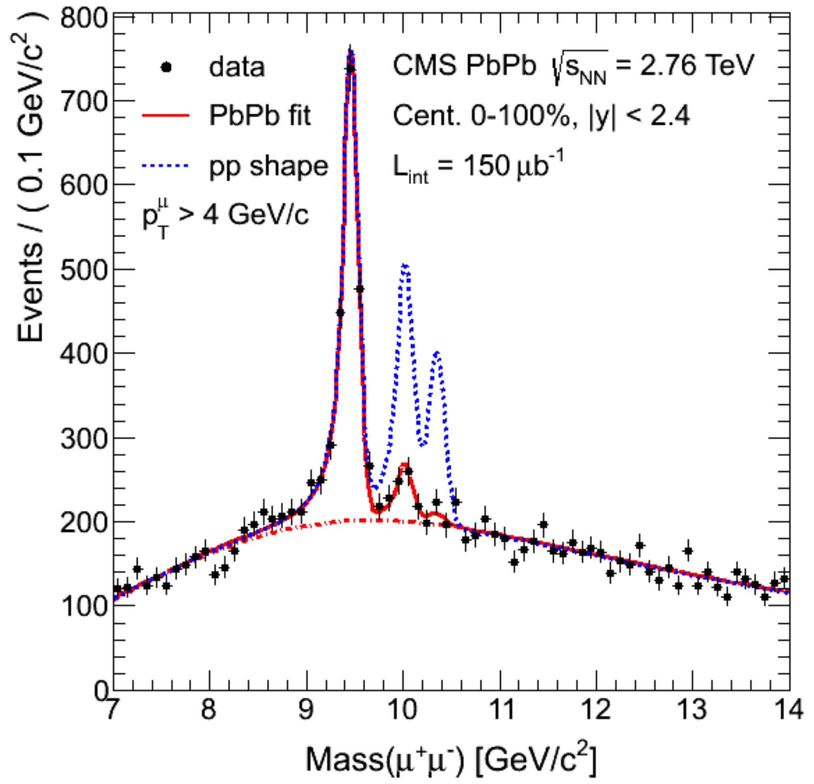
[Several different teams: EPPS, nNNPDF, nCTEQ, TUJU, DSSZ, HKN, KA]

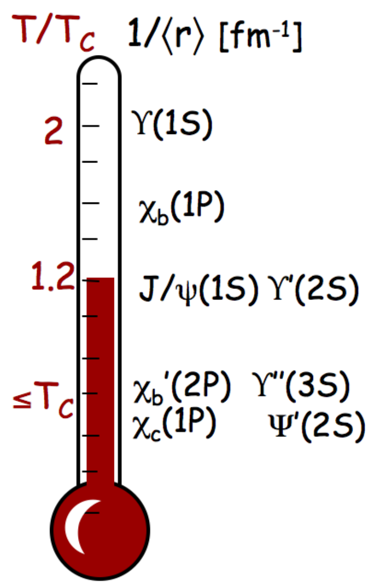
Quarkonia suppression

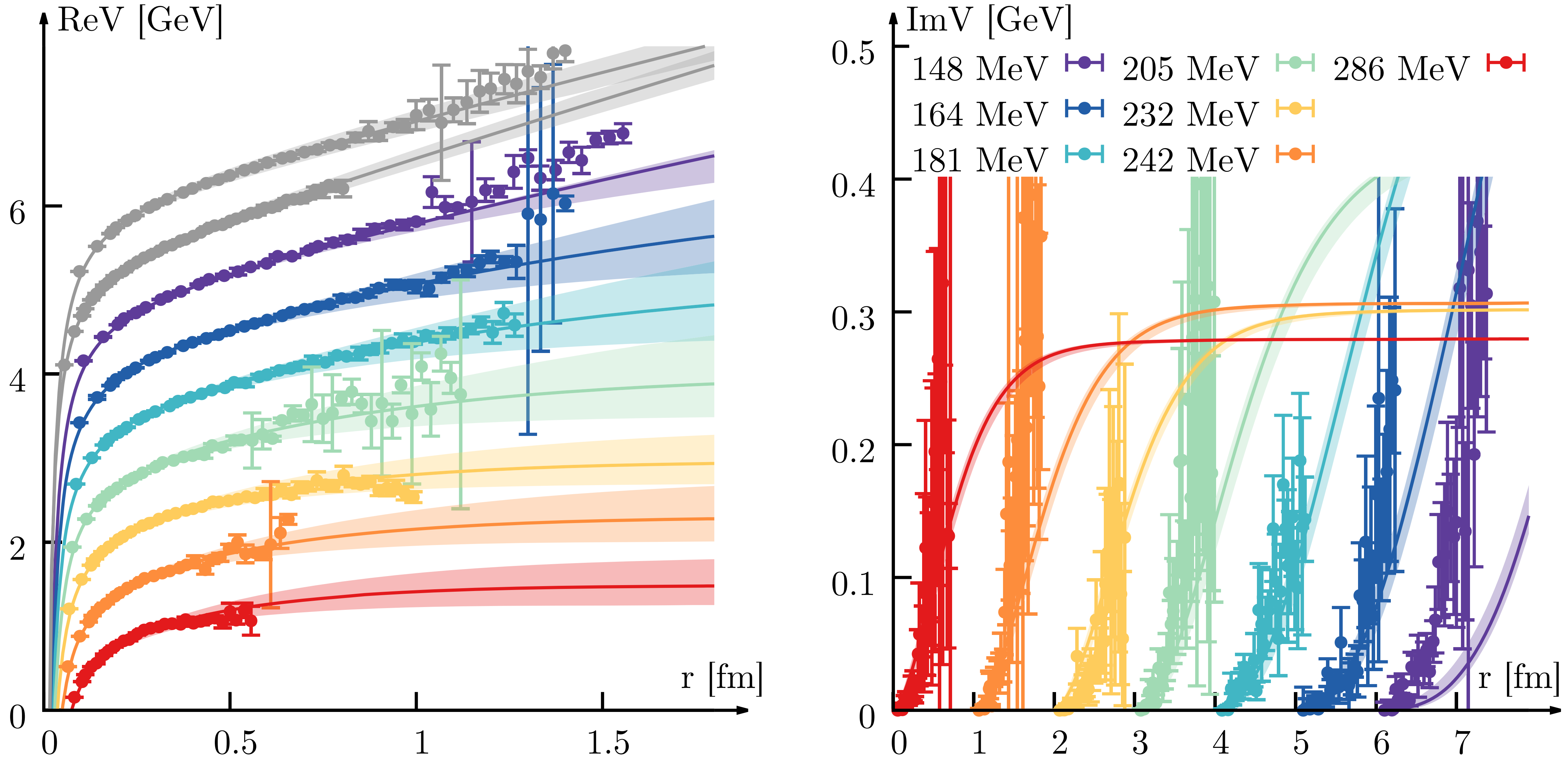
Simple intuitive picture [Matsui & Satz 1986]

- Potential screened at high-T
- Quarkonia suppressed
- Sequential suppression of excited states
- **Quarkonia as a thermometer**









[Lafferty, Rothkopf 2020]

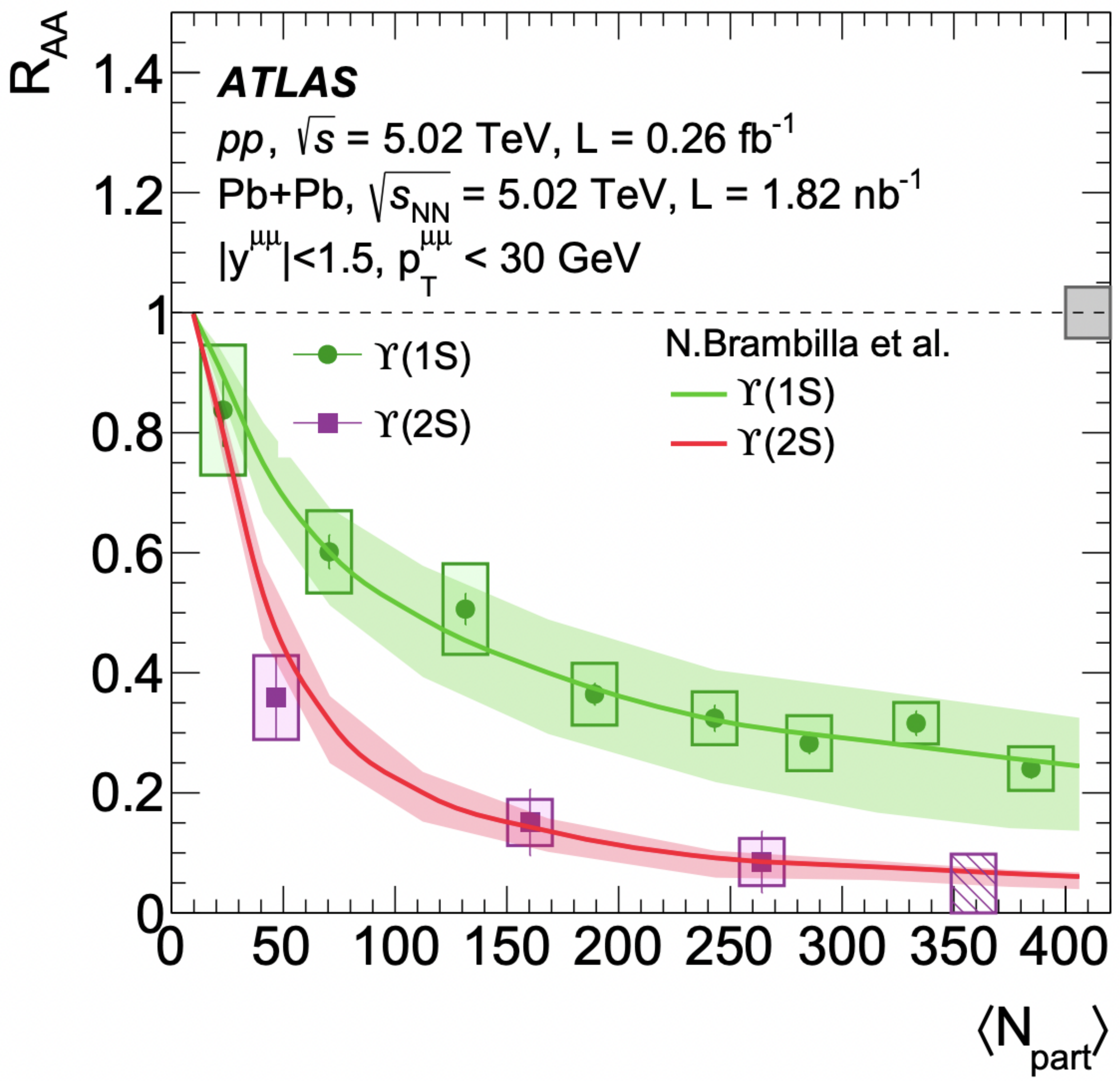
Dynamical picture:

- different effects:
  - screening / rescattering / recombination
- Induced transition between quarkonia states

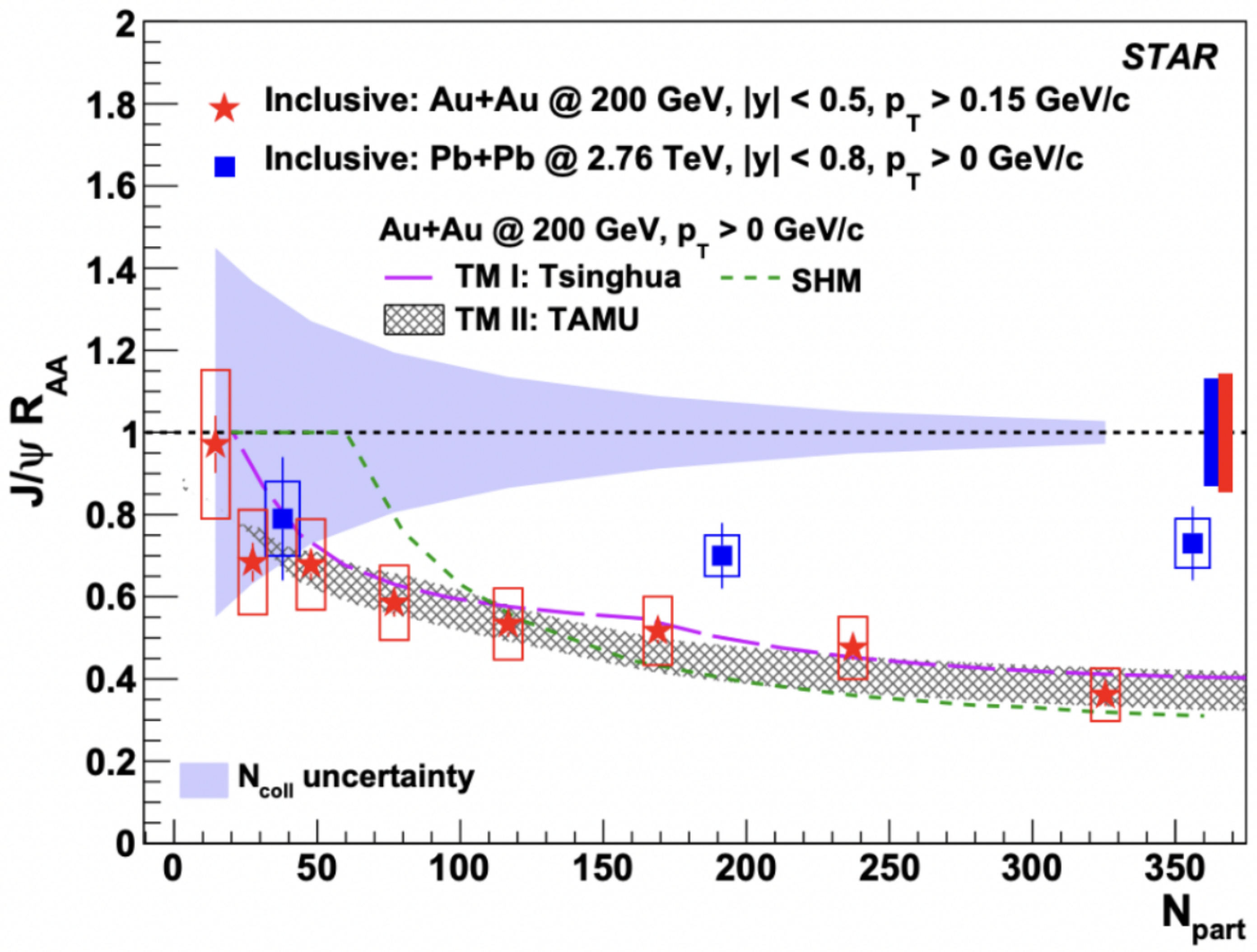
Quarkonia as an open quantum system

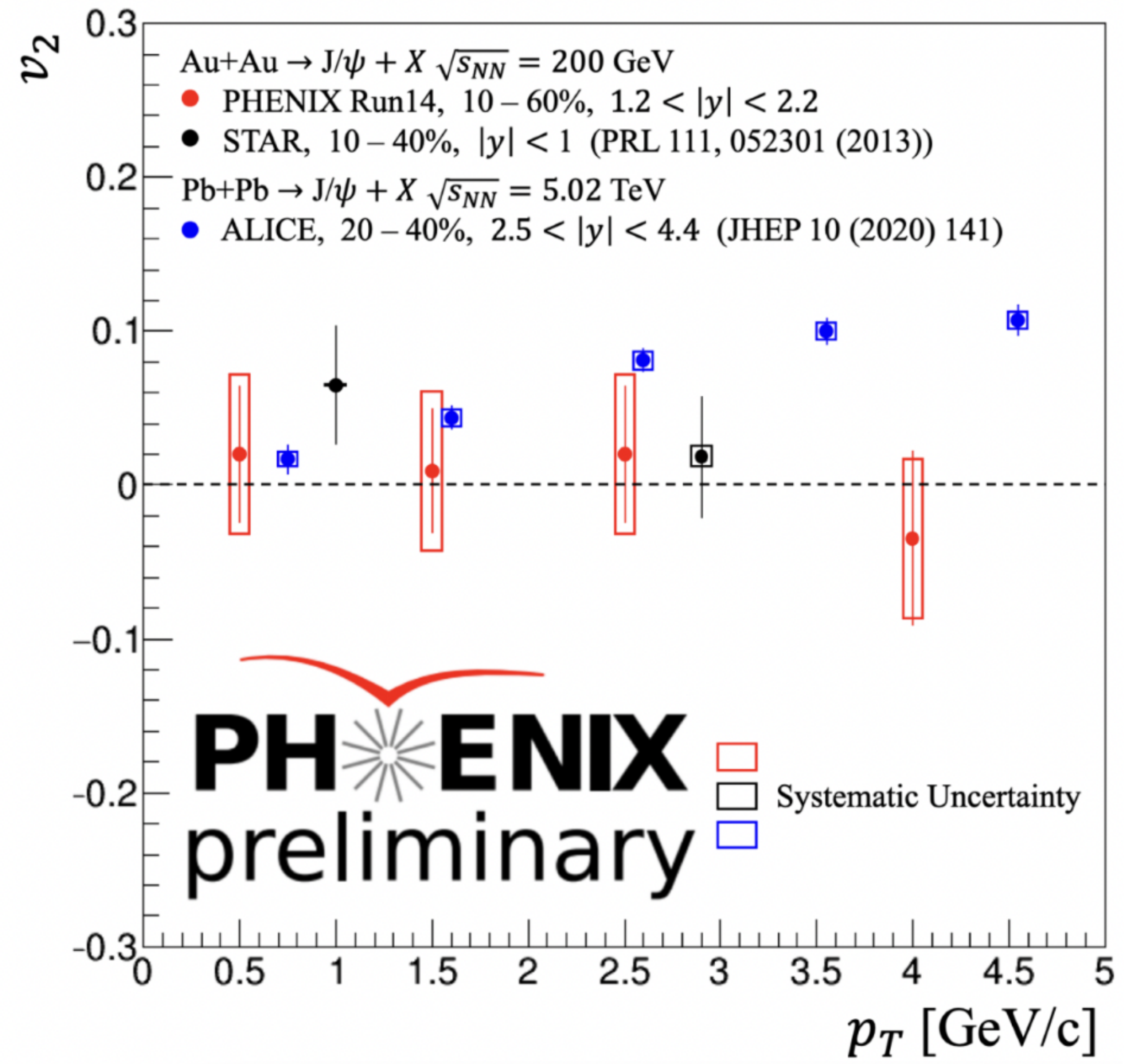
[Bambrilla, Soto, Escobedo, Vairo, Ghiglieri, Petreczky, Strickland, Blaizot, Rothkopf, Kaczmarek, Asakawa, Katz, Gossiaux, Kajimoto, Akamatsu, Borghini …]

Quarkonia suppression

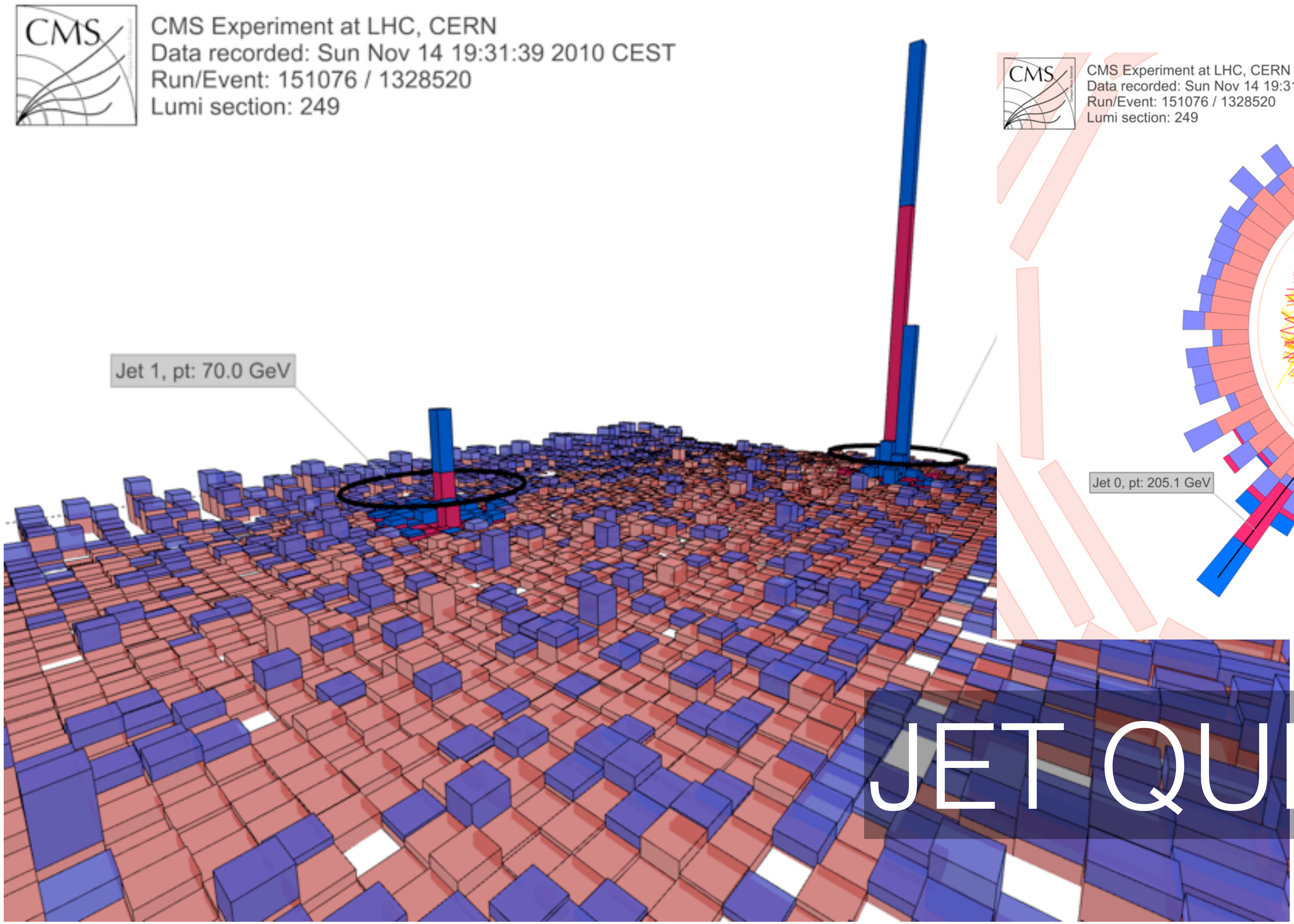


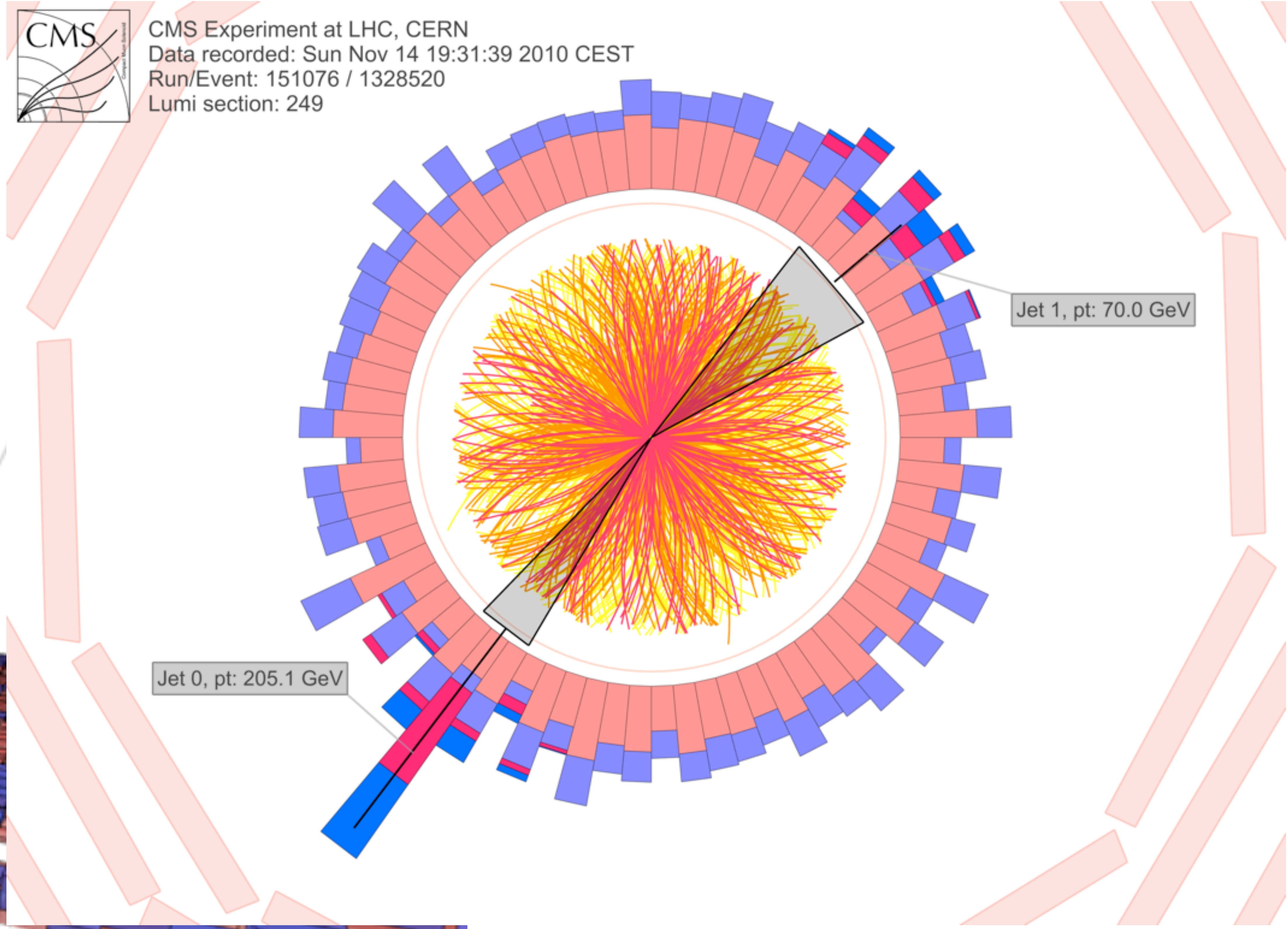
Bottomonia
sequential suppression





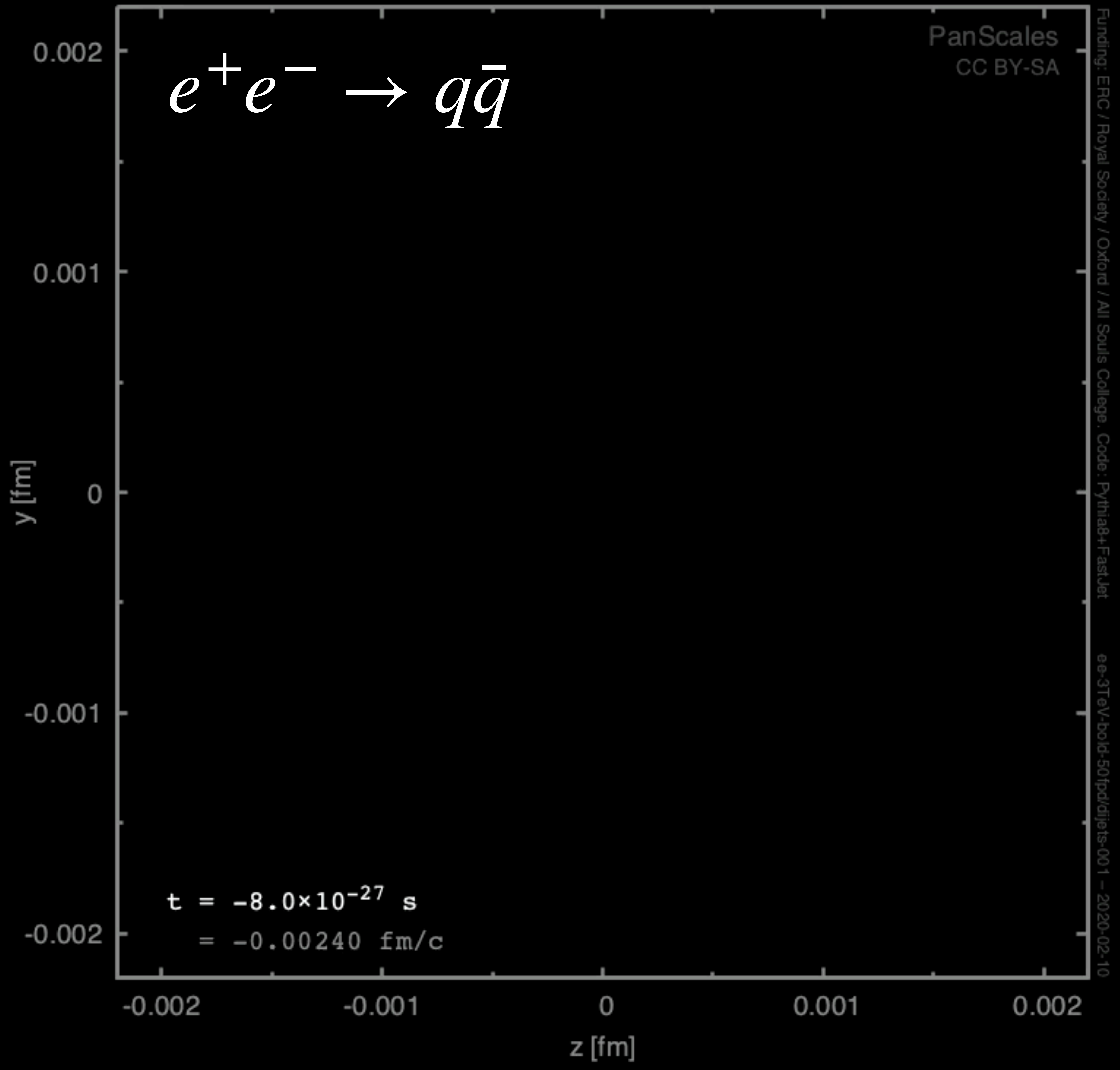
Charmonia
Mass is small enough so that many charm quarks are produced and almost thermalize. Charmonia is “regenerated”





JET QUENCHING

https://gsalam.web.cern.ch/gsalam/panscales/videos.html



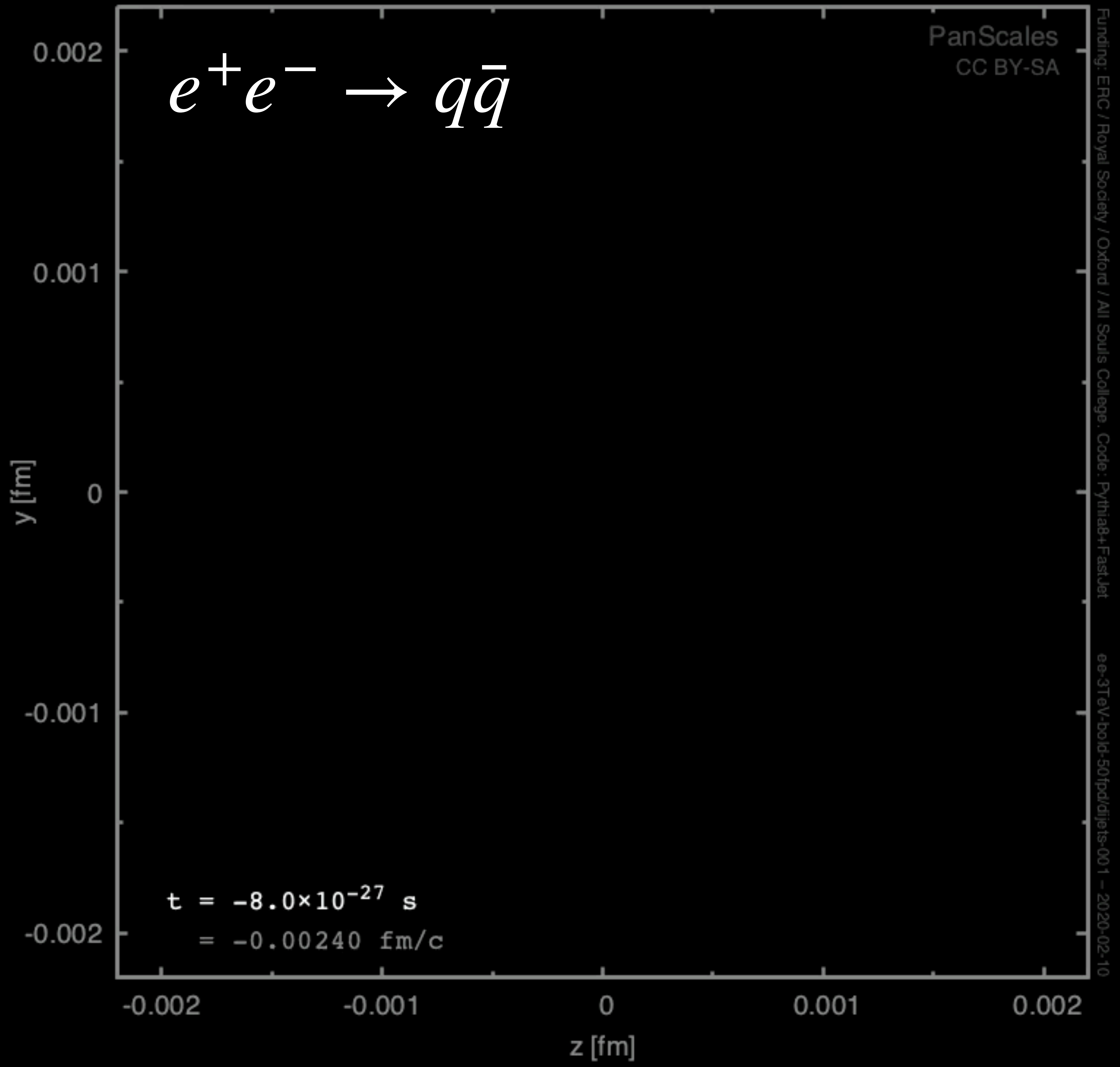
JETS

3TeV e^+e^- events

Initial particles in yellow
Intermediate particles in blue
Final particles in red

[Simulation of the events are produced with Pythia 8 times estimated by clustering algorith - see details in the web page]

https://gsalam.web.cern.ch/gsalam/panscales/videos.html



JETS

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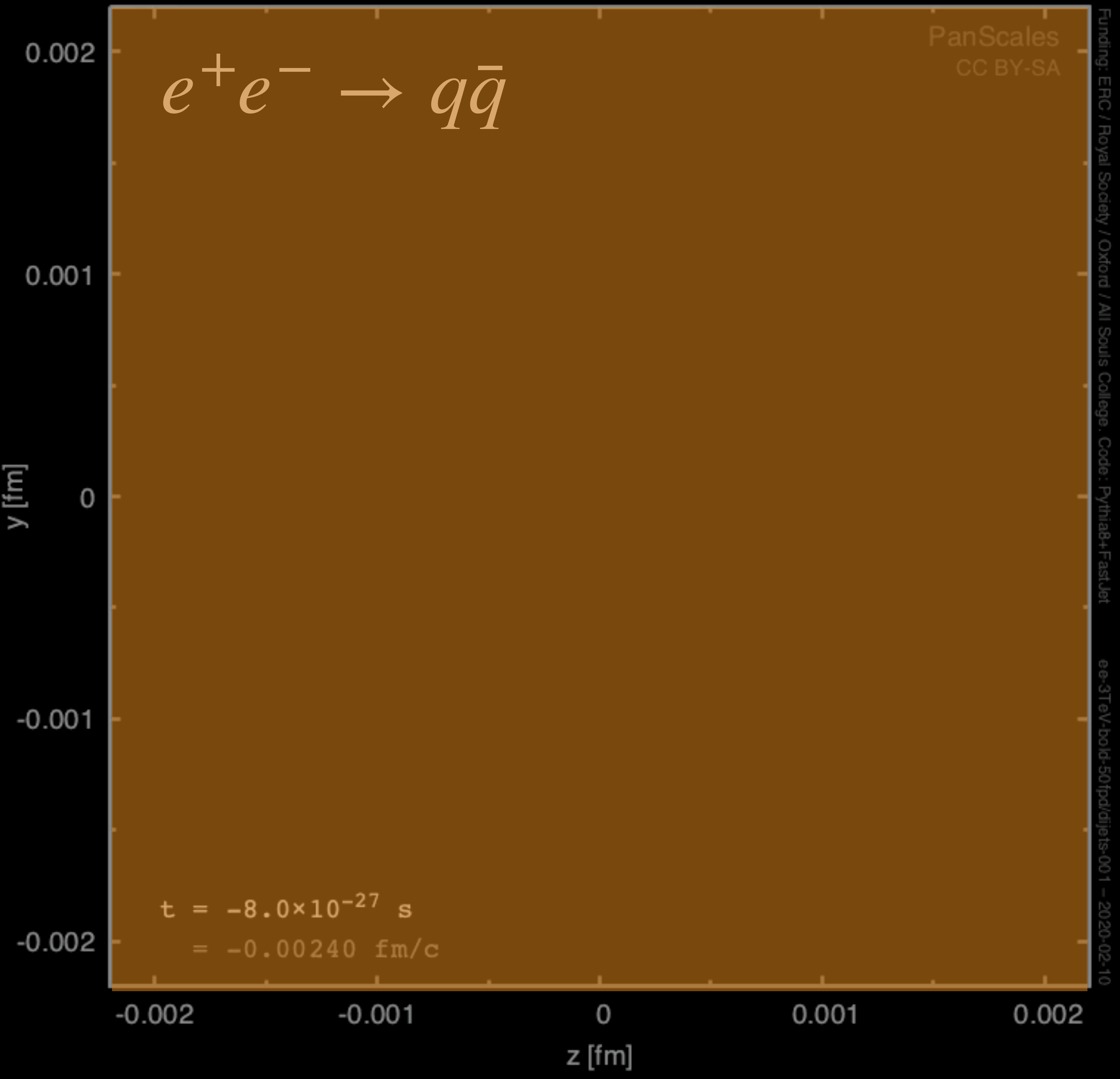


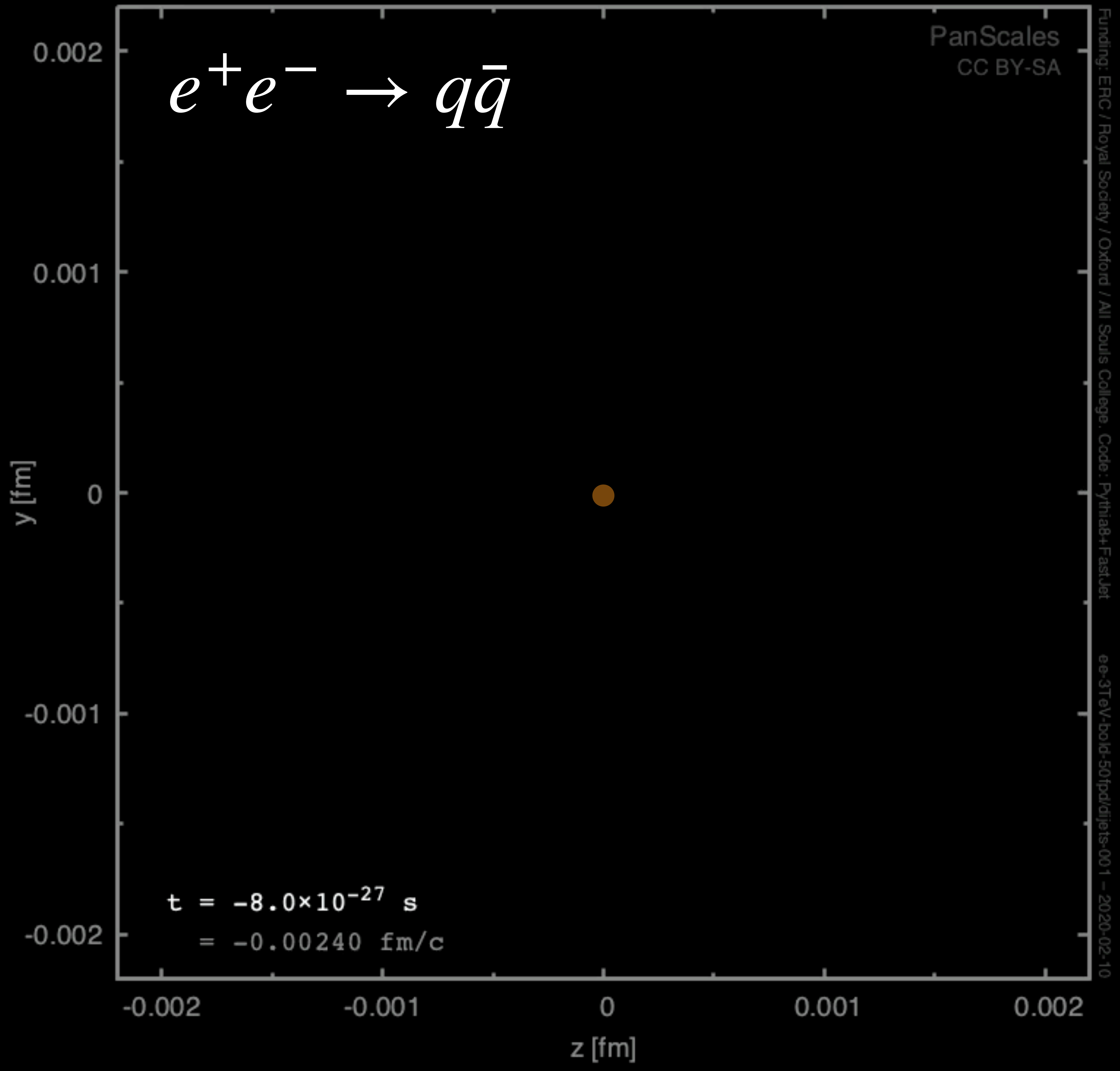
A QCD jet evolving in the medium

The size of the medium is ~10fm

Most of the jet evolution happens **inside the medium**

Most of the structure decided in the **initial times**

https://gsalam.web.cern.ch/gsalam/panscales/videos.html



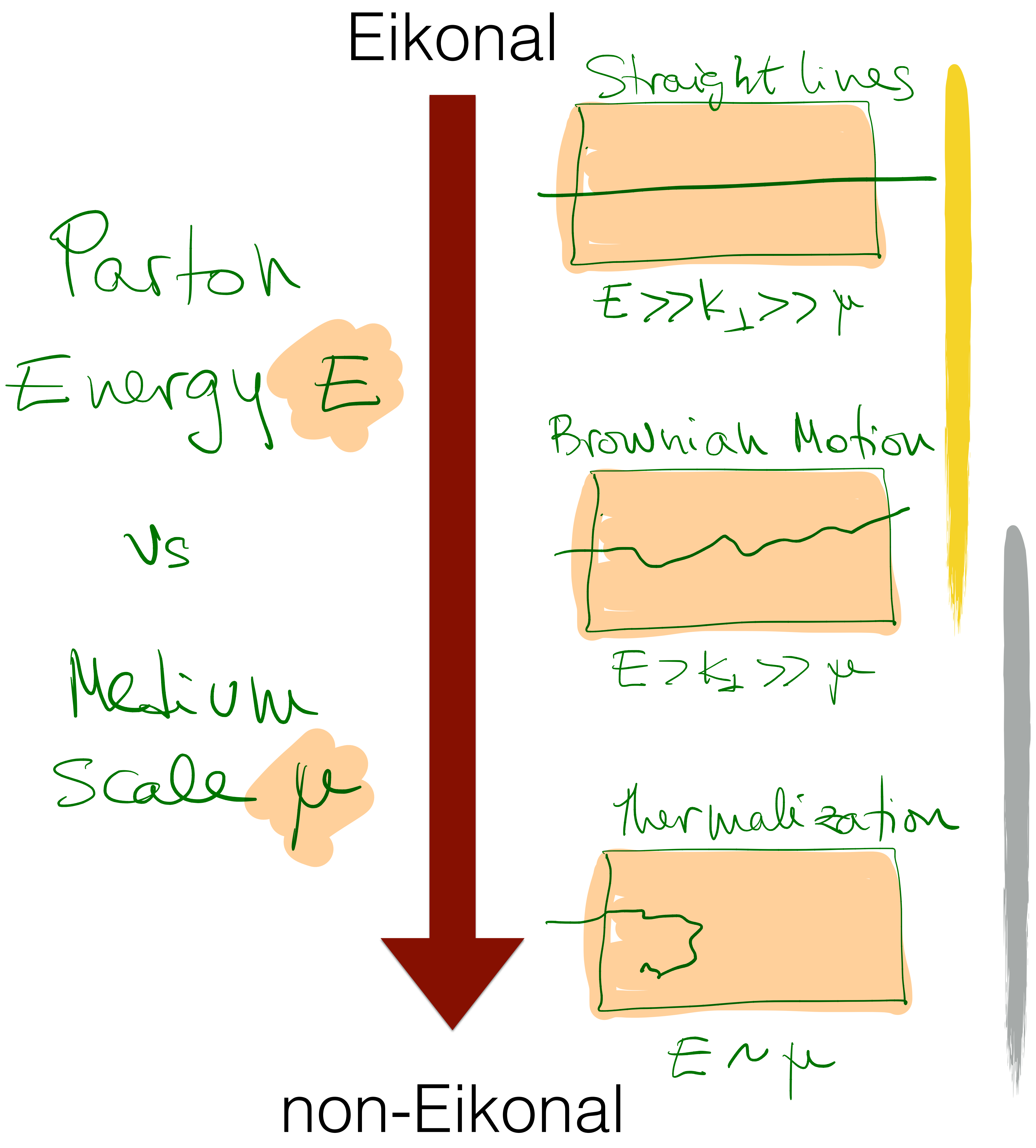
A QCD jet evolving in the medium

The size of the medium is ~10fm

Most of the jet evolution happens **inside the medium**

Most of the structure decided in the **initial times**

In-medium parton propagation

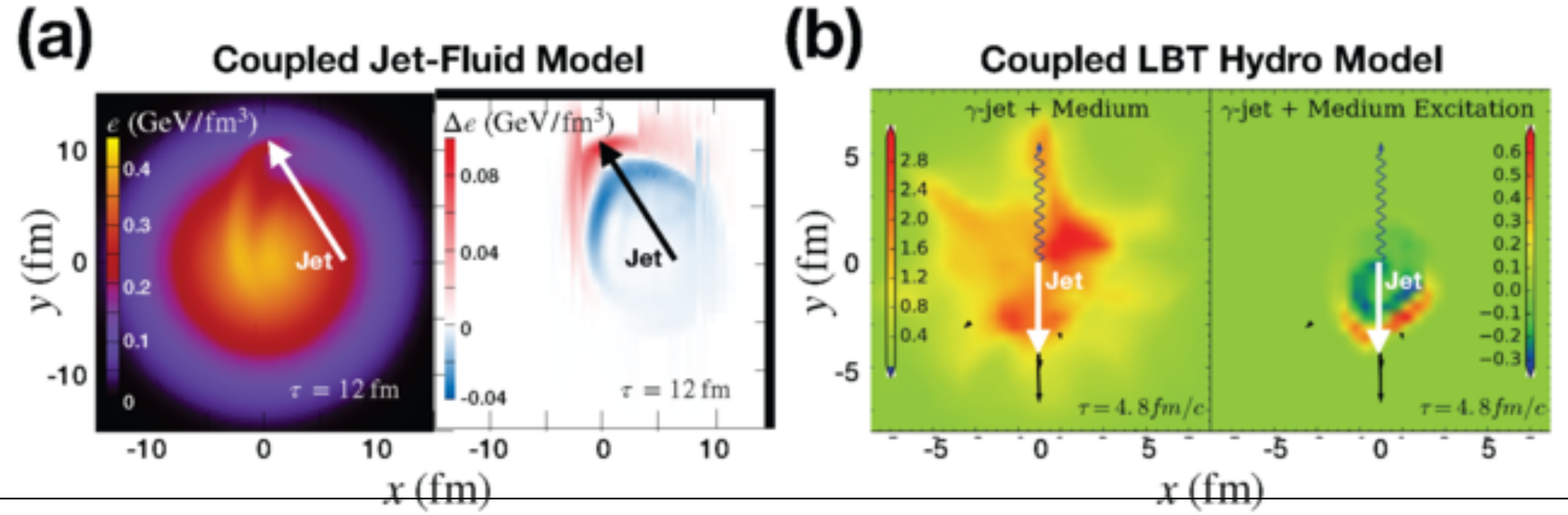


Medium is a background field: color rotation
[Energy of the parton unmodified]

$$W(x_\perp) = \mathcal{P}\exp\left\{ig\int d\xi\, n\cdot A(\xi, x_\perp)\right\}$$

$$G(x_\perp; y_\perp) = \mathcal{P}\int \mathcal{D}\mathbf{r}\exp\left\{i\frac{E}{2}\int d\xi\left[\frac{d\mathbf{r}}{d\xi}\right]^2 + ig\int d\xi\, n\cdot A(\xi, \mathbf{r})\right\}$$

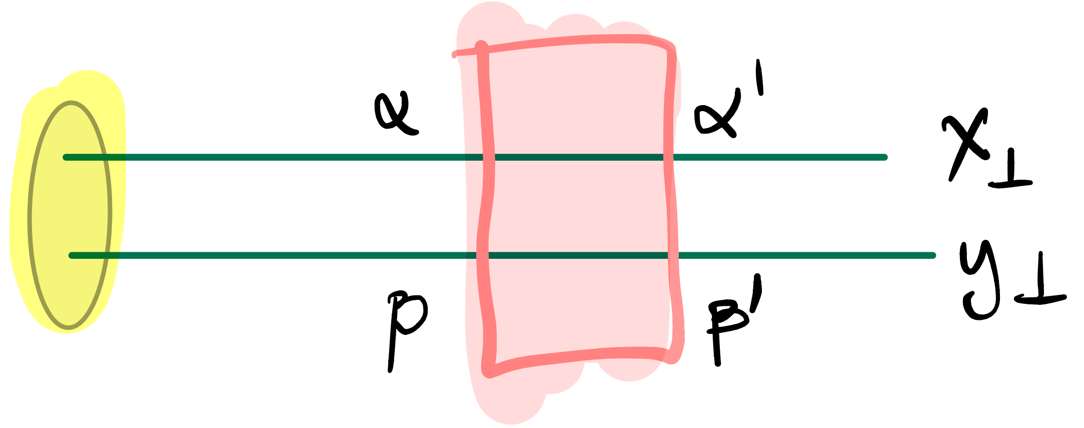
Medium is **dynamical**
[Energy exchanged with the medium]



[Tachibana 2019]

Scattering amplitudes

Color dipole - The simplest configuration



Background field
Color Rotation

S-Matrix

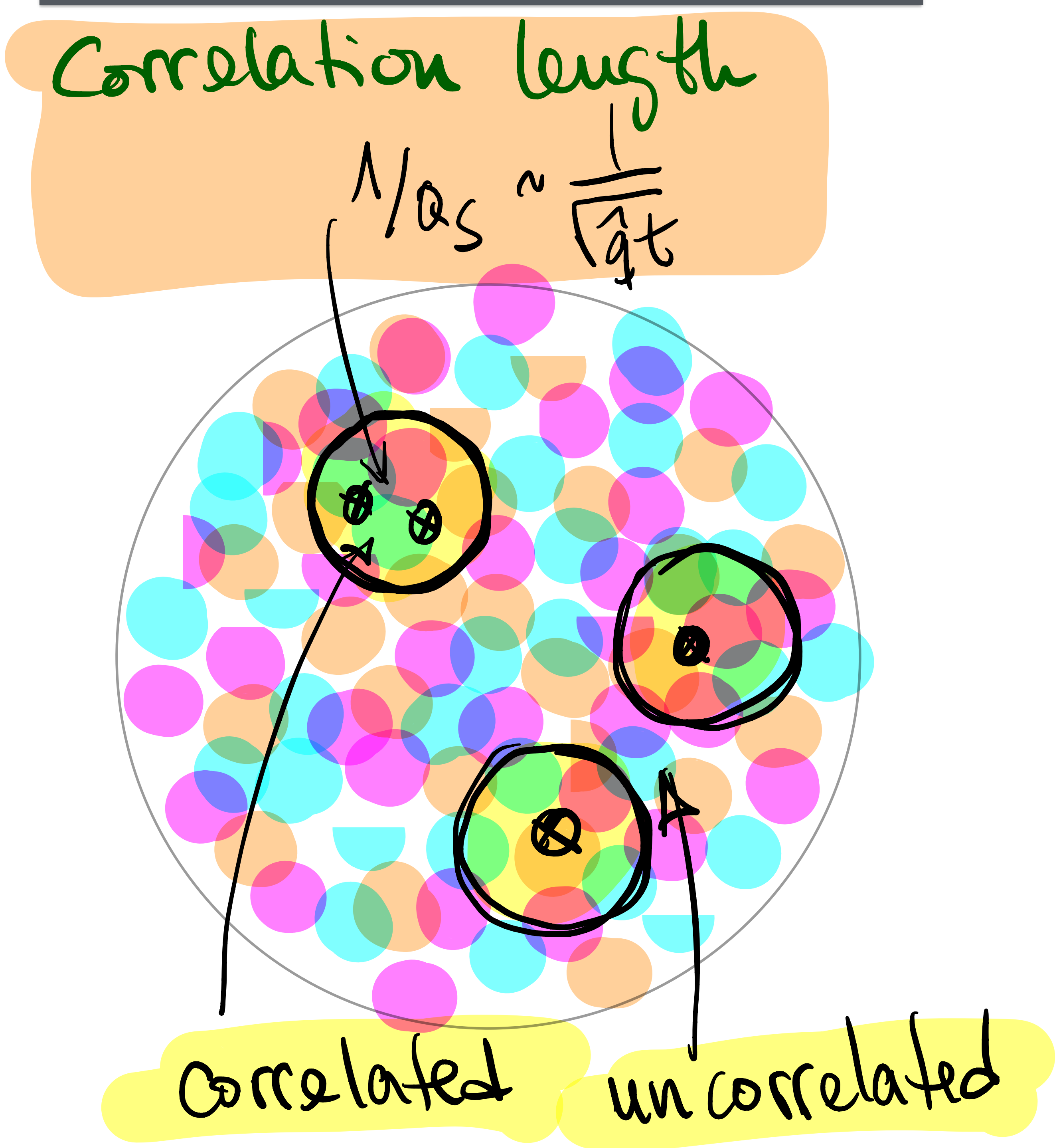
$$|\alpha'\beta'\rangle = S_{\alpha'\beta'\alpha\beta}|\alpha\beta\rangle = W_{\alpha'\alpha}(x_\perp)\,W^\dagger_{\beta'\beta}(y_\perp)|\alpha\beta\rangle$$

Survival Probability —

$$S(x_\perp, y_\perp) = \frac{1}{N_c}\,\mathrm{tr}\left[W(x_\perp)\,W^\dagger(y_\perp)\right]$$

Average over Configurations $\frac{1}{N_c}\langle \mathrm{tr}\left(W(x_\perp)W^\dagger(y_\perp)\right)\rangle_{med}$

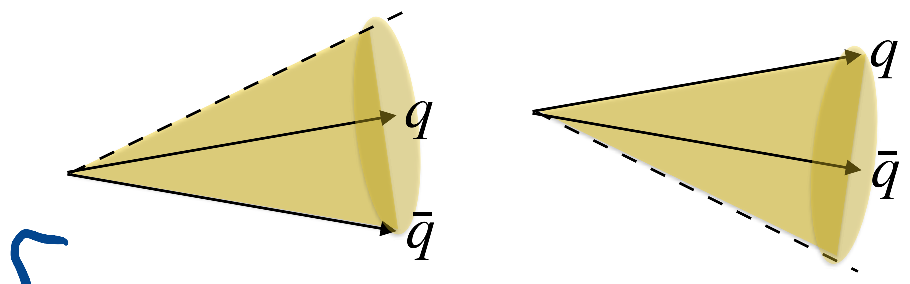
A useful picture: color domains in transverse plane

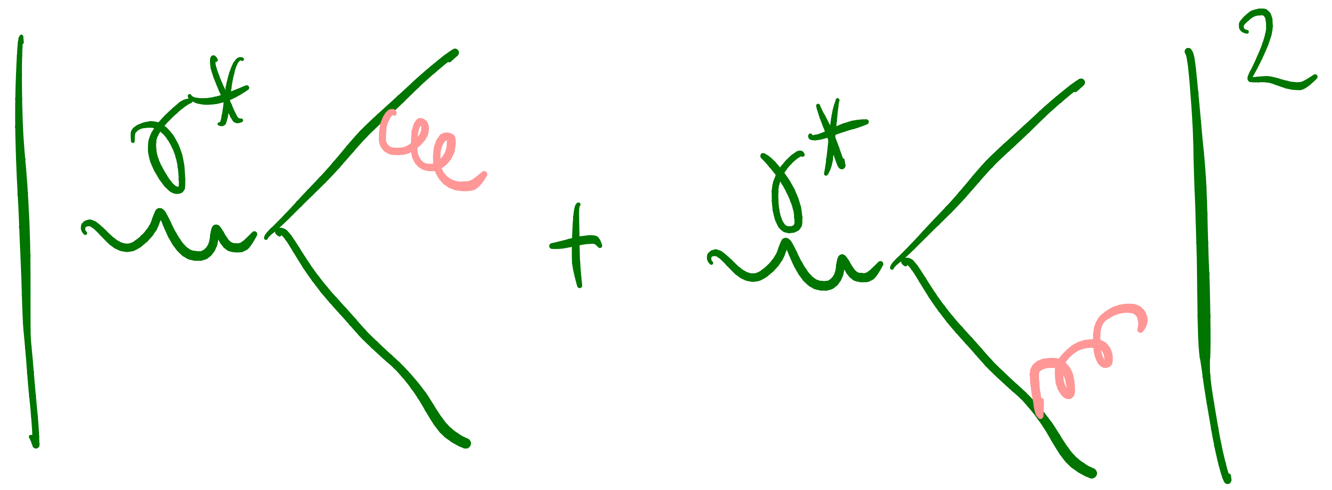


Intra-jet color coherence

[Mehtar-Tani, Salgado, Tywoniuk; Iancu, Casalderrey-Solana, … 2010-]

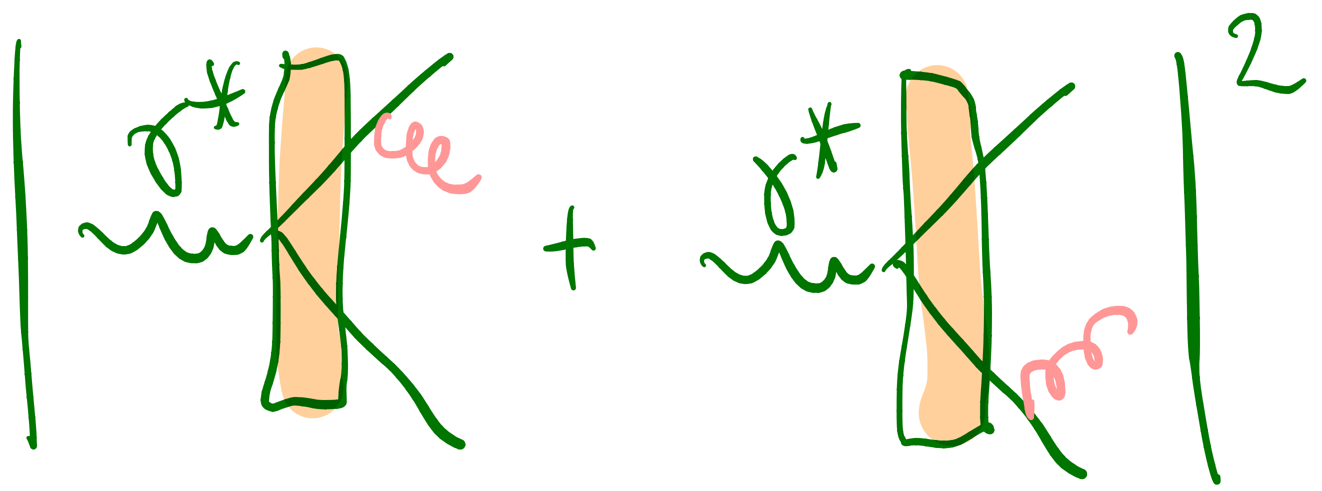
QCD antenna - classical calculation including color coherence *[angular ordering]*





$$\omega \frac{dN}{d\omega\, d\theta} \sim \alpha_s C_F \left[R_q - J + R_{\bar q} - J \right]$$

The QCD medium can break color coherence - independent color rotation of q and qbar



$$\omega \frac{dN}{d\omega\, d\theta} \sim \alpha_s C_F \left[R_q - S_{q\bar q} J + R_{\bar q} - S_{q\bar q} J \right]$$

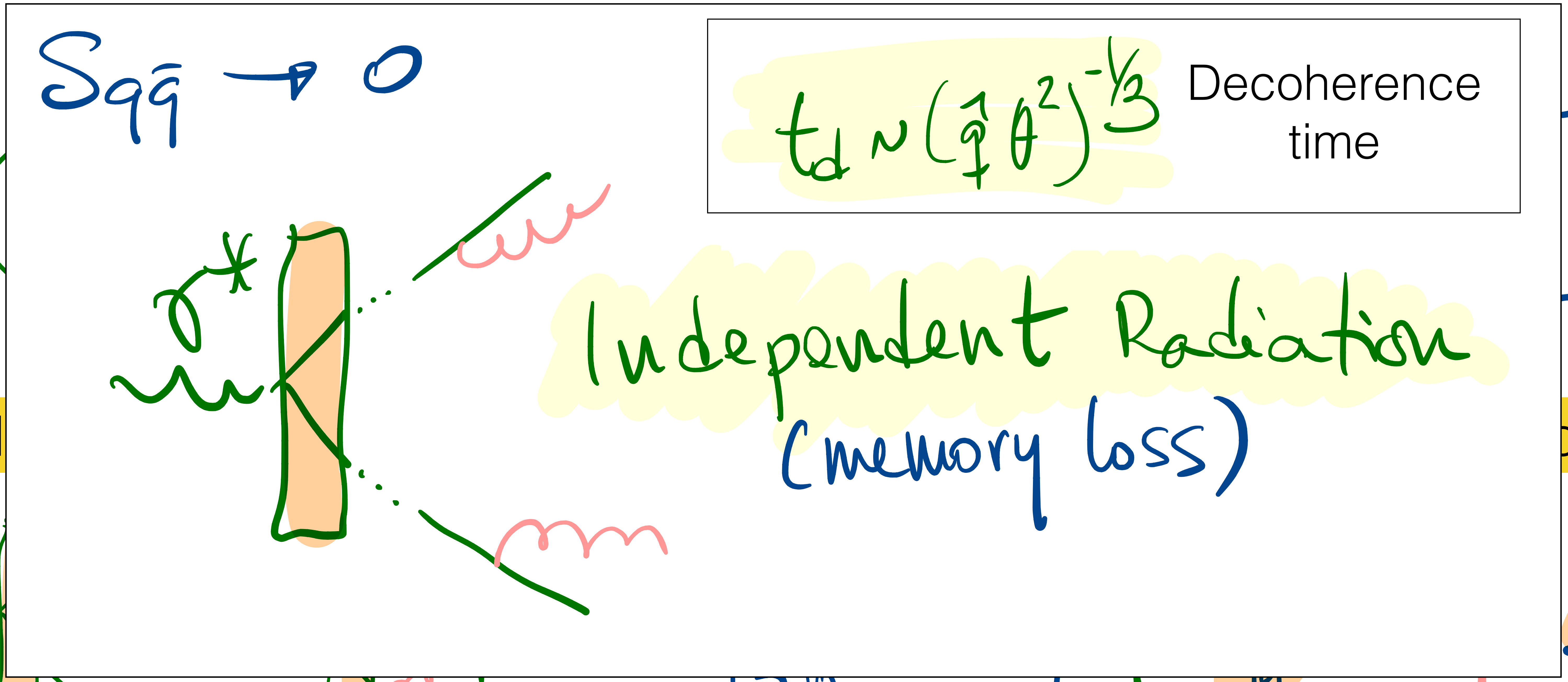
$$S(x_\perp, y_\perp) \equiv \frac{1}{N_c^2 - 1} \mathrm{Tr} \left\langle W(x_\perp) W^\dagger(y_\perp) \right\rangle_{\mathrm{med}} \simeq \exp\left\{ -\frac{1}{4} \hat{q}\, \theta_{q\bar q}^2\, L^3 \right\}$$

Survival probability
$\hat{q}$ - jet quenching parameter

Intra-jet color coherence

[Mehtar-Tani, Salgado, Tywoniuk; Iancu, Casalderrey-Solana, … 2010-]

QCD antenna - classical calculation including color coherence *[angular ordering]*



The QCD med … of q and qbar

$$S(x_\perp, y_\perp) \equiv \frac{1}{N_c^2-1}\mathrm{Tr}\,\langle W(x_\perp)W^\dagger(y_\perp)\rangle_{\mathrm{med}} \simeq \exp\left\{-\frac{1}{4}\hat{q}\,\theta_{q\bar{q}}^2\,L^3\right\}$$

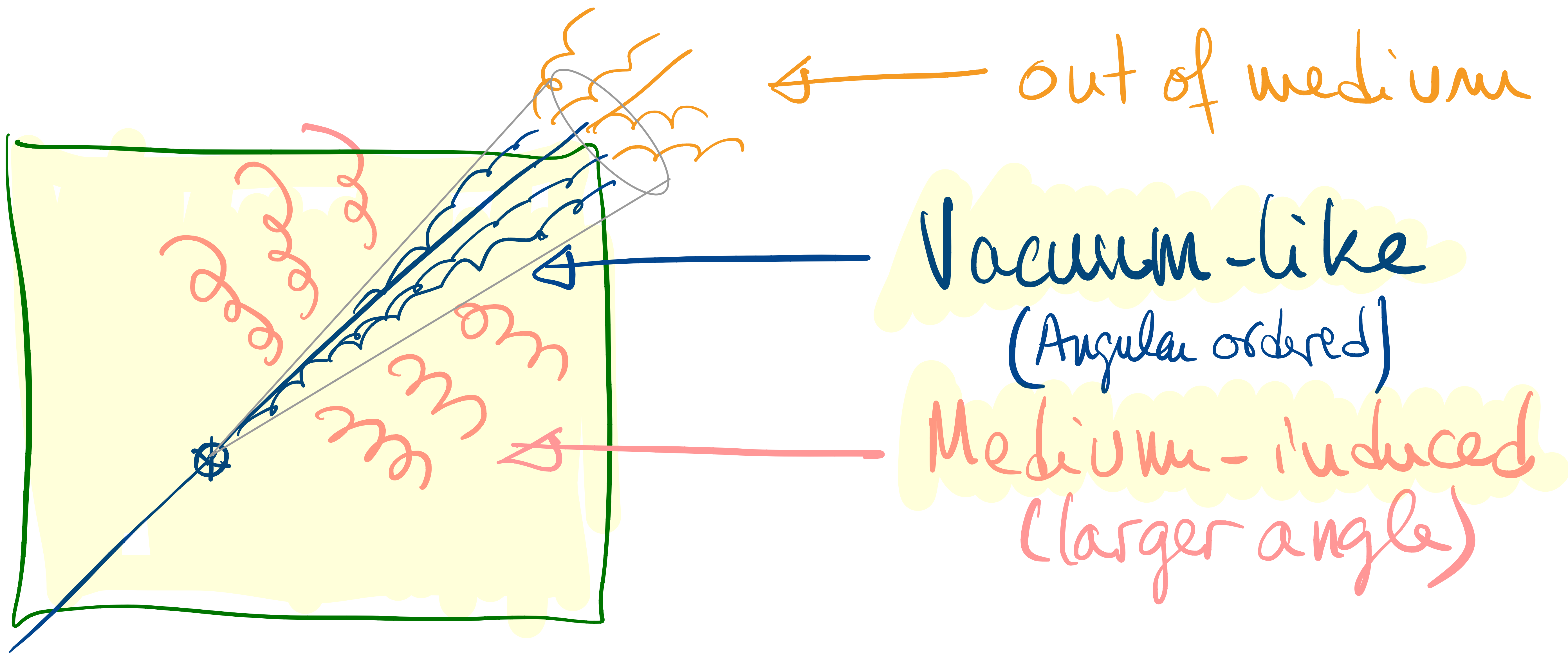
Survival probability

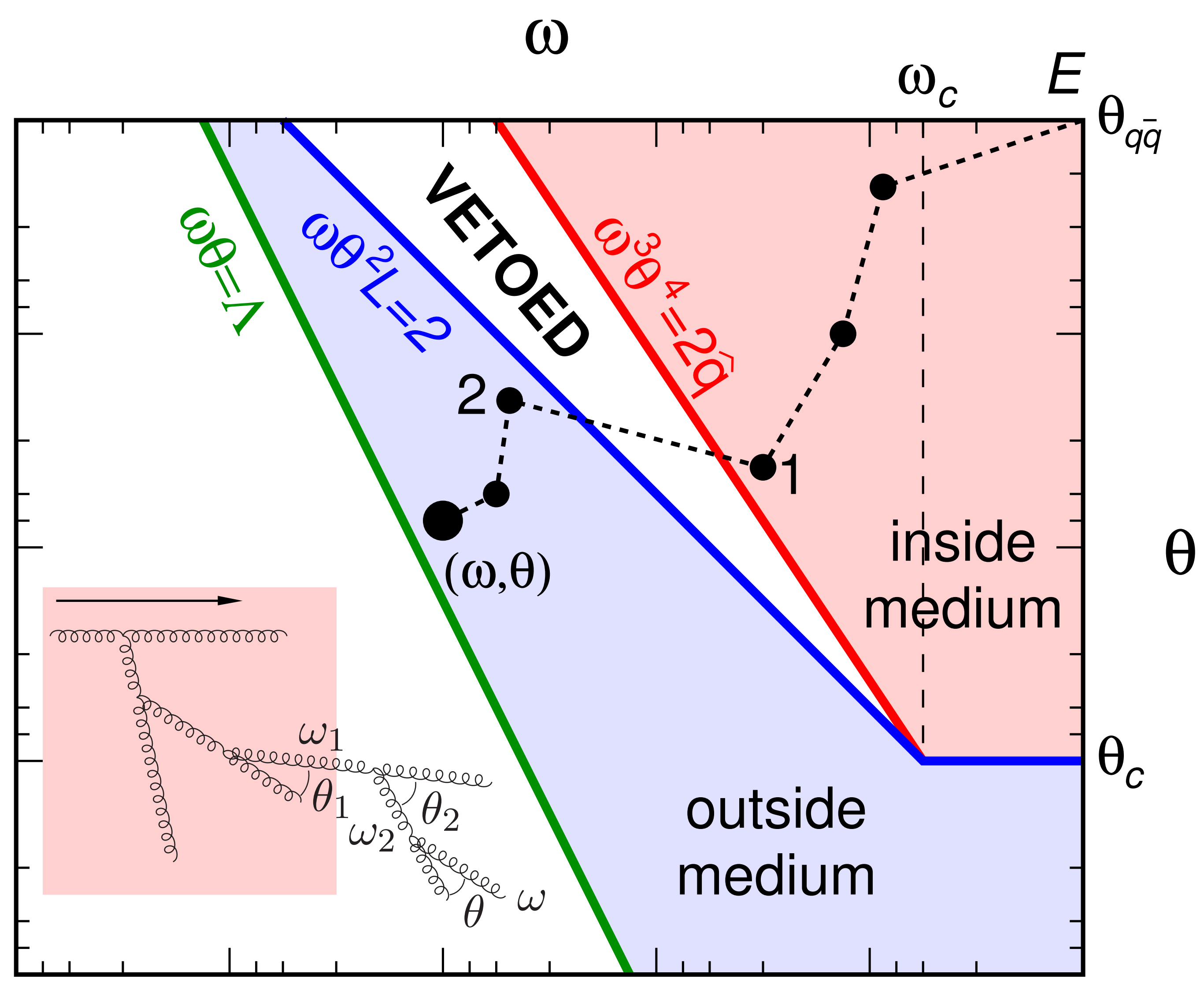
$\hat{q}$ - jet quenching parameter

Vacuum-like emissions

Hard splittings with small formation time $t_f \ll t_d$ cannot be resolved by the medium

First hard splitting + DLA — **most of the cascade is vacuum-like** (with energy loss on top)





[Caucal, Iancu, Mueller, Soyez 2018]

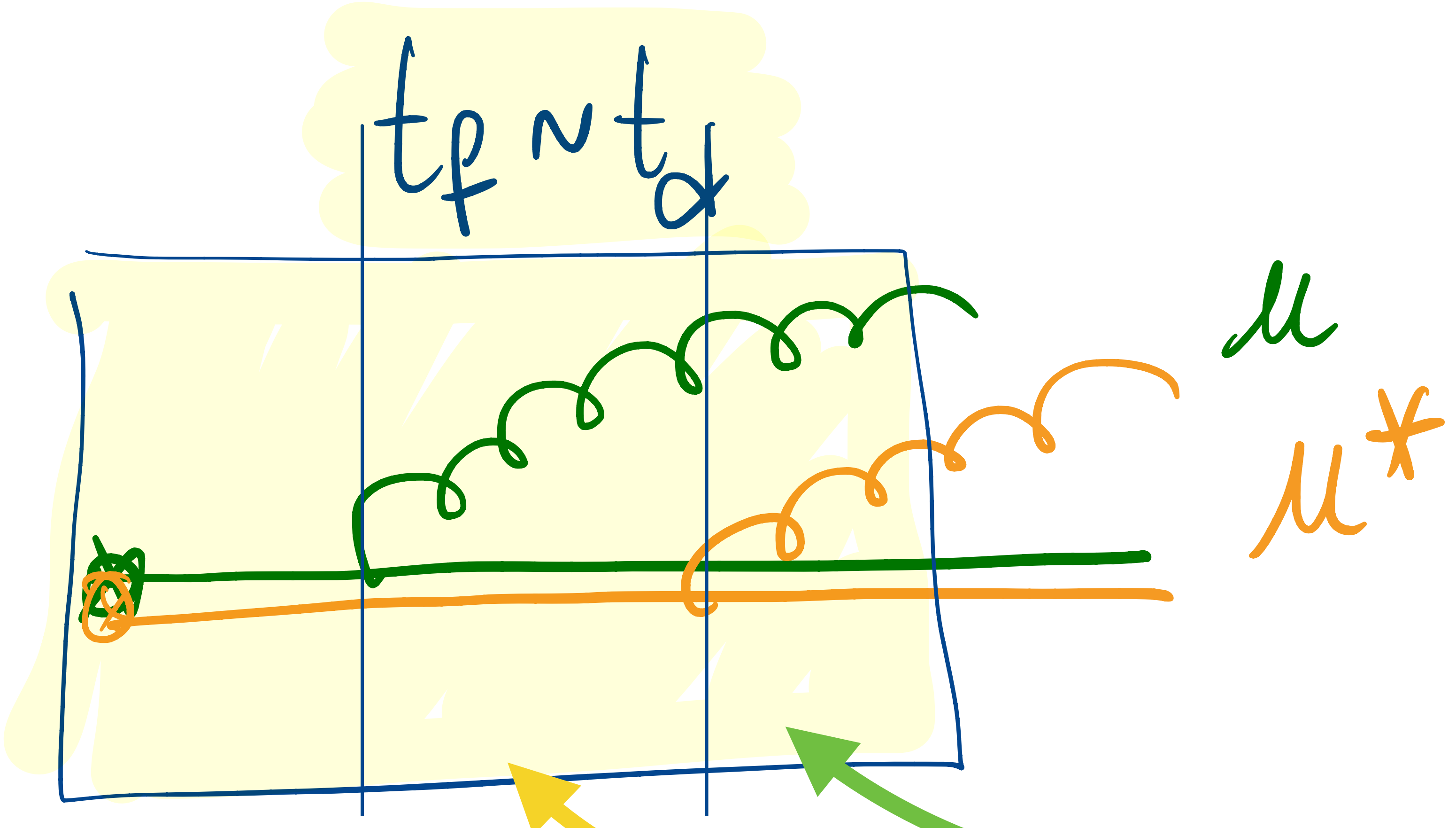
Color coherent sub-jets provide organizational principle for in-medium cascade

[Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk 2012]

Medium-induced radiation

[Zakharov, Baier, Dokshitzer, Mueller, Peigne, Schiff, Wiedemann, Gyulassy, Levai, Vitev, and many others… starting in the mid-90's]

For fluctuation with $t_f \sim t_d$ the gluon is resolved: **medium-induced radiation**



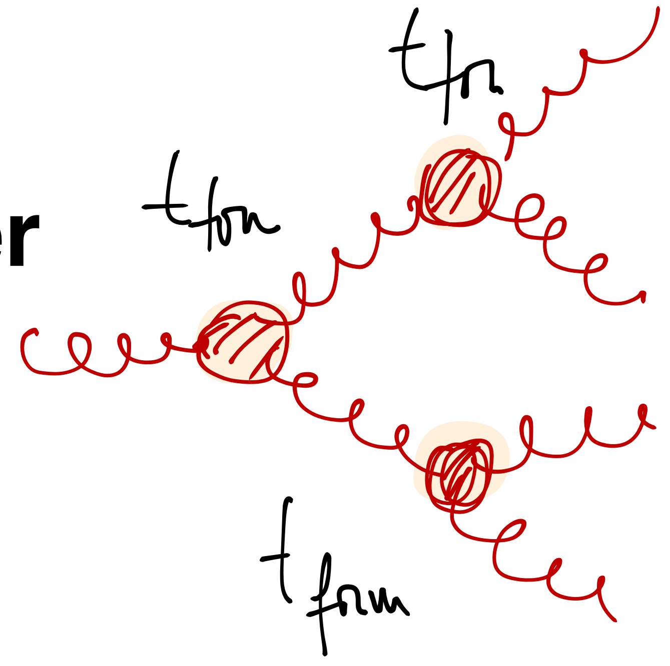
$$\omega \frac{dN}{d\omega d^2\mathbf{k}} \sim \frac{\alpha_s C_R}{\omega^2} \mathrm{Re} \int_{t',t} \int_{\mathbf{p},\mathbf{q}} \mathbf{p}\cdot\mathbf{q}\,\tilde{\mathcal{K}}(t',\mathbf{q};t,\mathbf{p})\,\mathcal{P}(L,\mathbf{k};t',\mathbf{q})$$

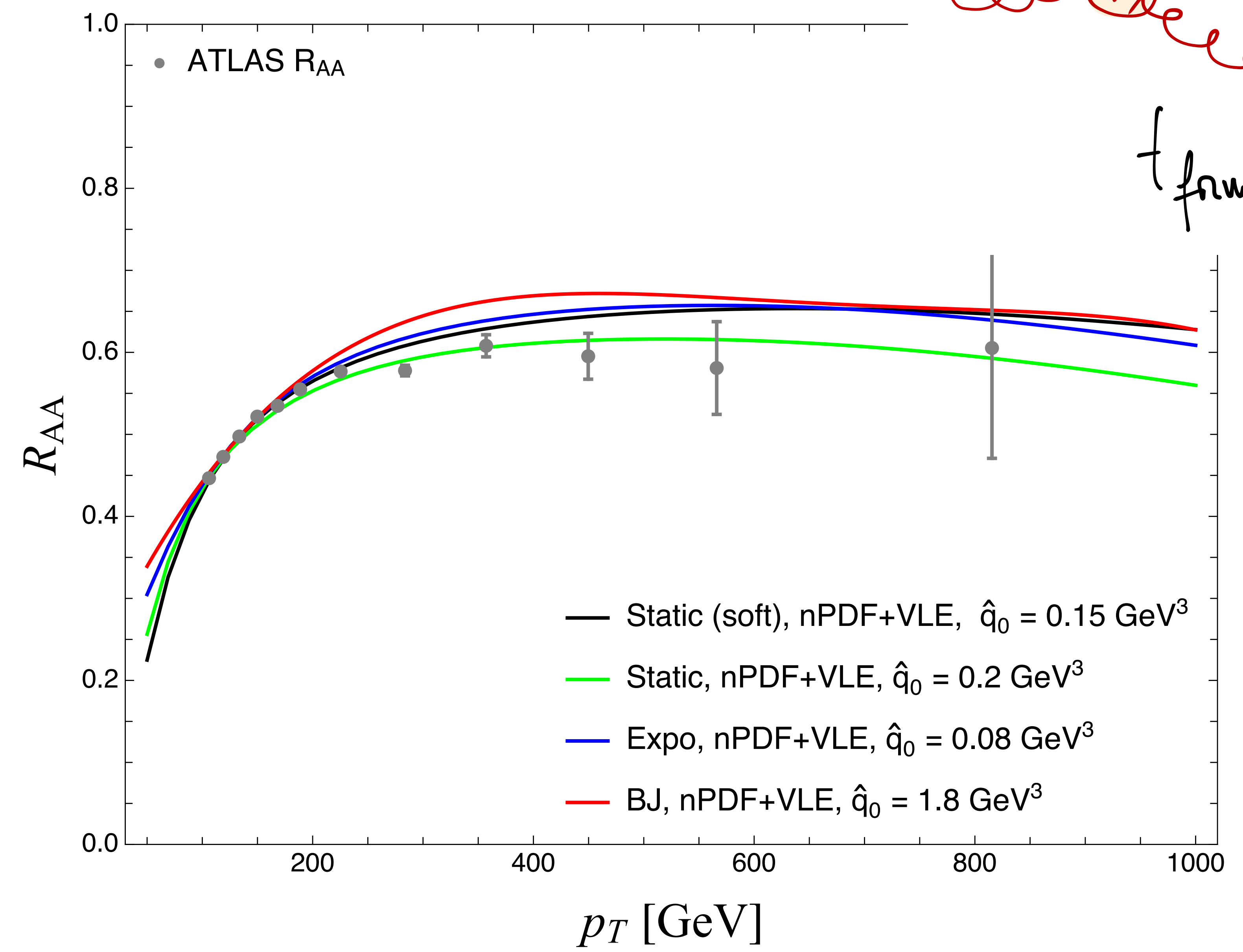
$$\mathcal{K}(t',\mathbf{z};t,\mathbf{y}) = \int \mathcal{D}\mathbf{r}\, \exp\left[\int_t^{t'} ds \left(\frac{i\omega}{2}\dot{\mathbf{r}}^2 - \frac{1}{2}n(s)\sigma(\mathbf{r})\right)\right]$$

$t_f \sim t_d \ll L$: democratic branching

[Balizot, Dominguez, Iancu, Mehtar-Tani 2013; Jeon, Moore 2005]

Probabilistic treatment:
In-medium parton shower





[Adhya, Salgado, Spousta, Tywoniuk 2022]

Medium-induced radiation

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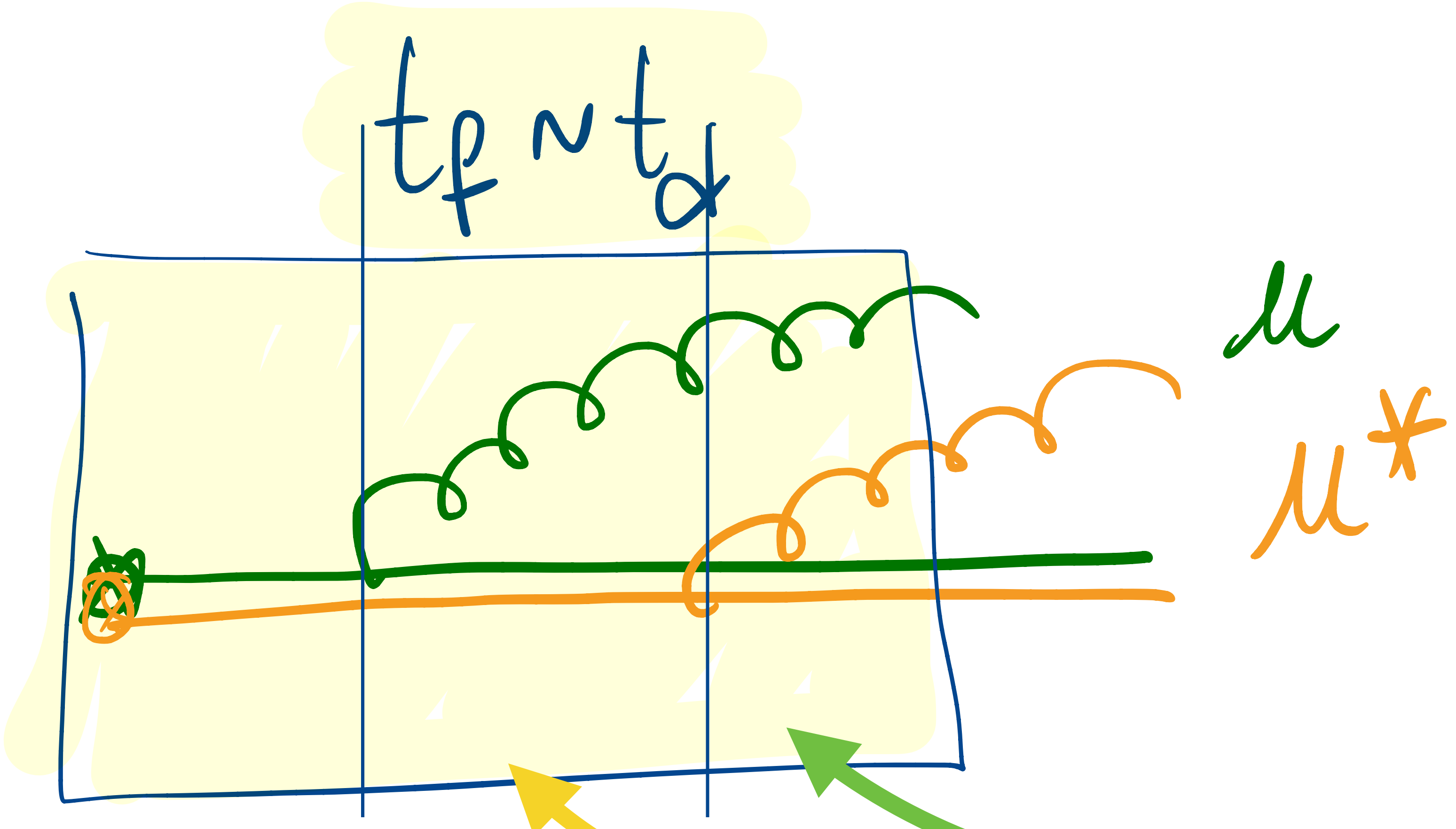

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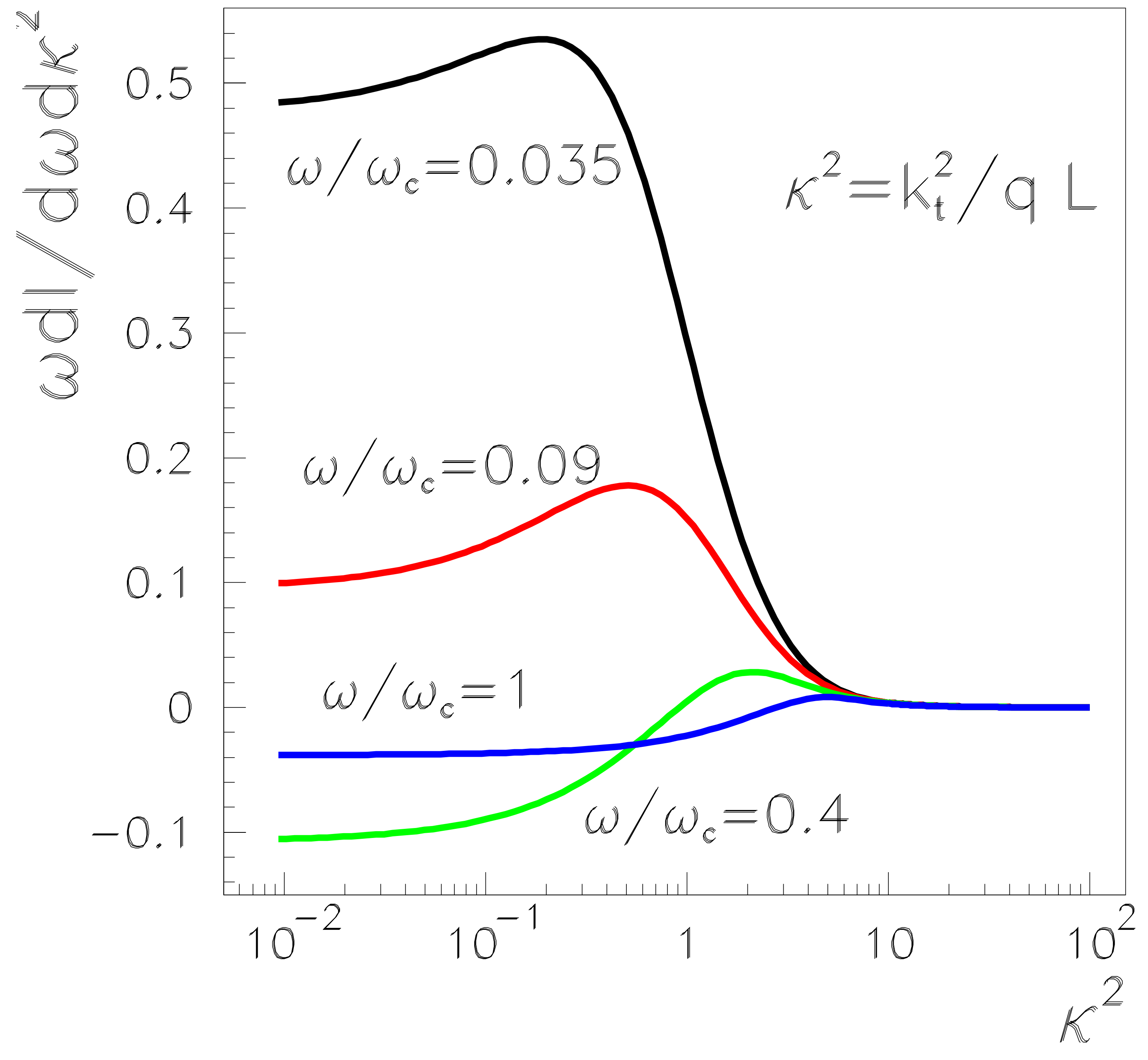
For fluctuation with $t_f > t_d$

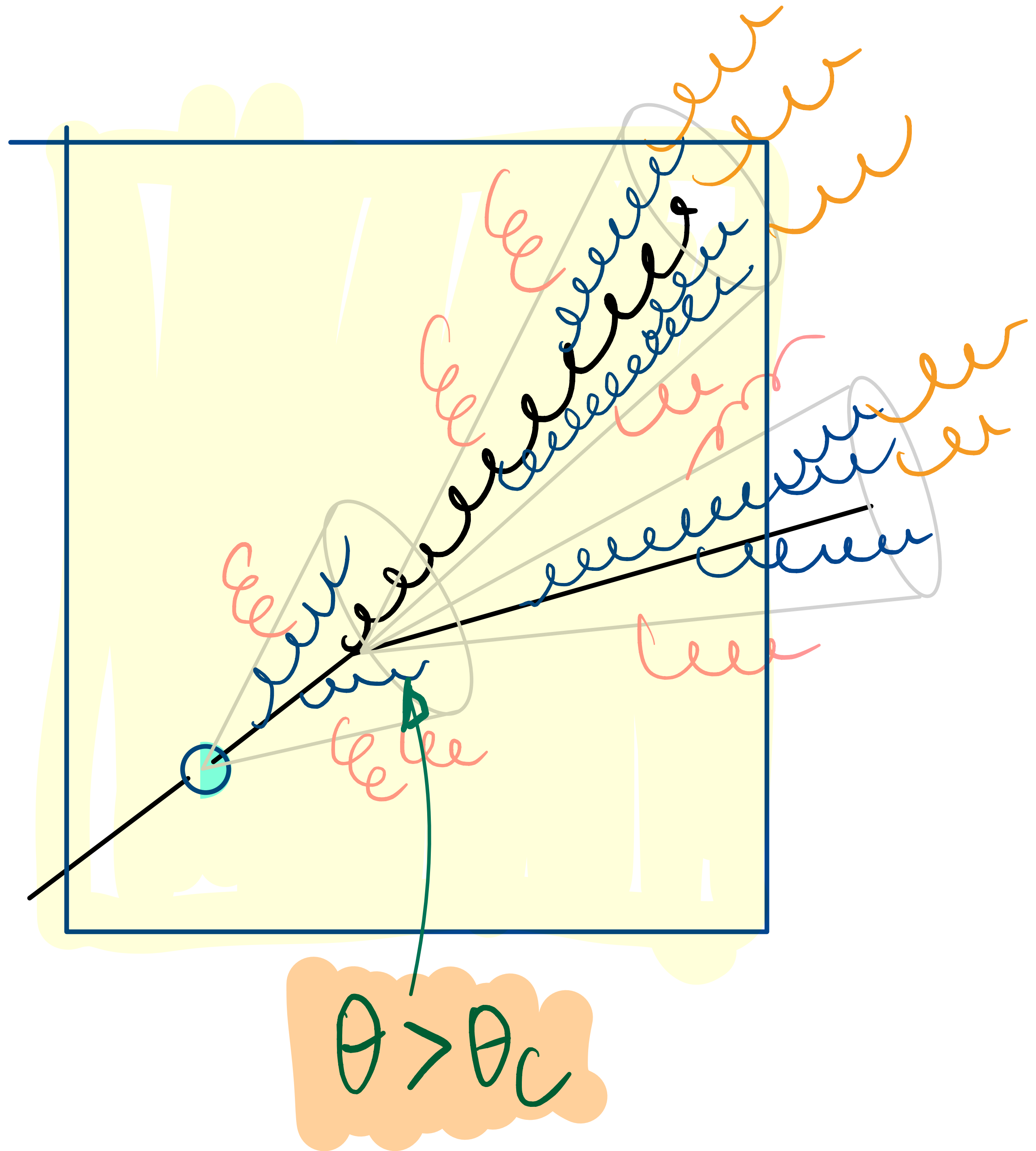
LPM suppression



A picture of in-medium jets

[Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk 2012]

Color coherence provides a clean picture of parton shower in medium
Medium induced radiation by **subjets** defined by **resolution scale** of the medium



$$S(r_\perp) = e^{-\frac{1}{4}\int dt\, \hat{q}\, r^2(t)}$$

$$r(t) = \theta t \Rightarrow \theta_c \sim \frac{1}{\sqrt{\hat{q} t^3}}$$

Resolution power

$$\Lambda_\perp \sim \frac{1}{\sqrt{\hat{q} t}} \equiv \frac{1}{Q_s}$$

Inner core of the jet (subjet) is mildly modified

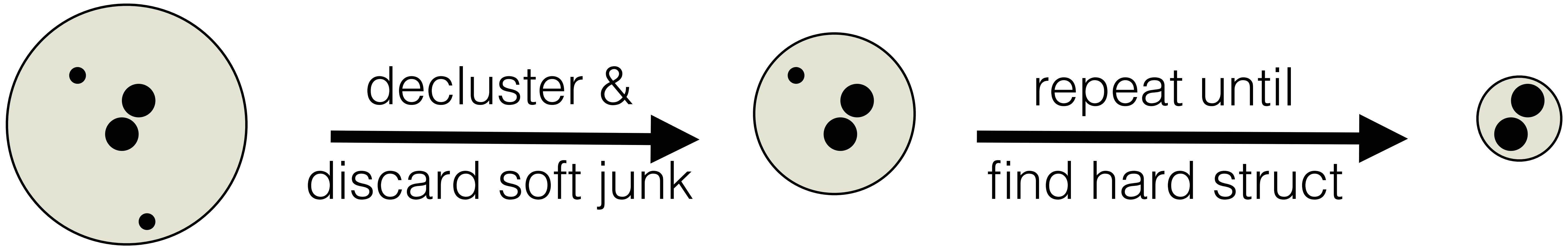
Medium-induced radiation at **large angles**

In agreement with experimental findings

Subjets are effective emitters

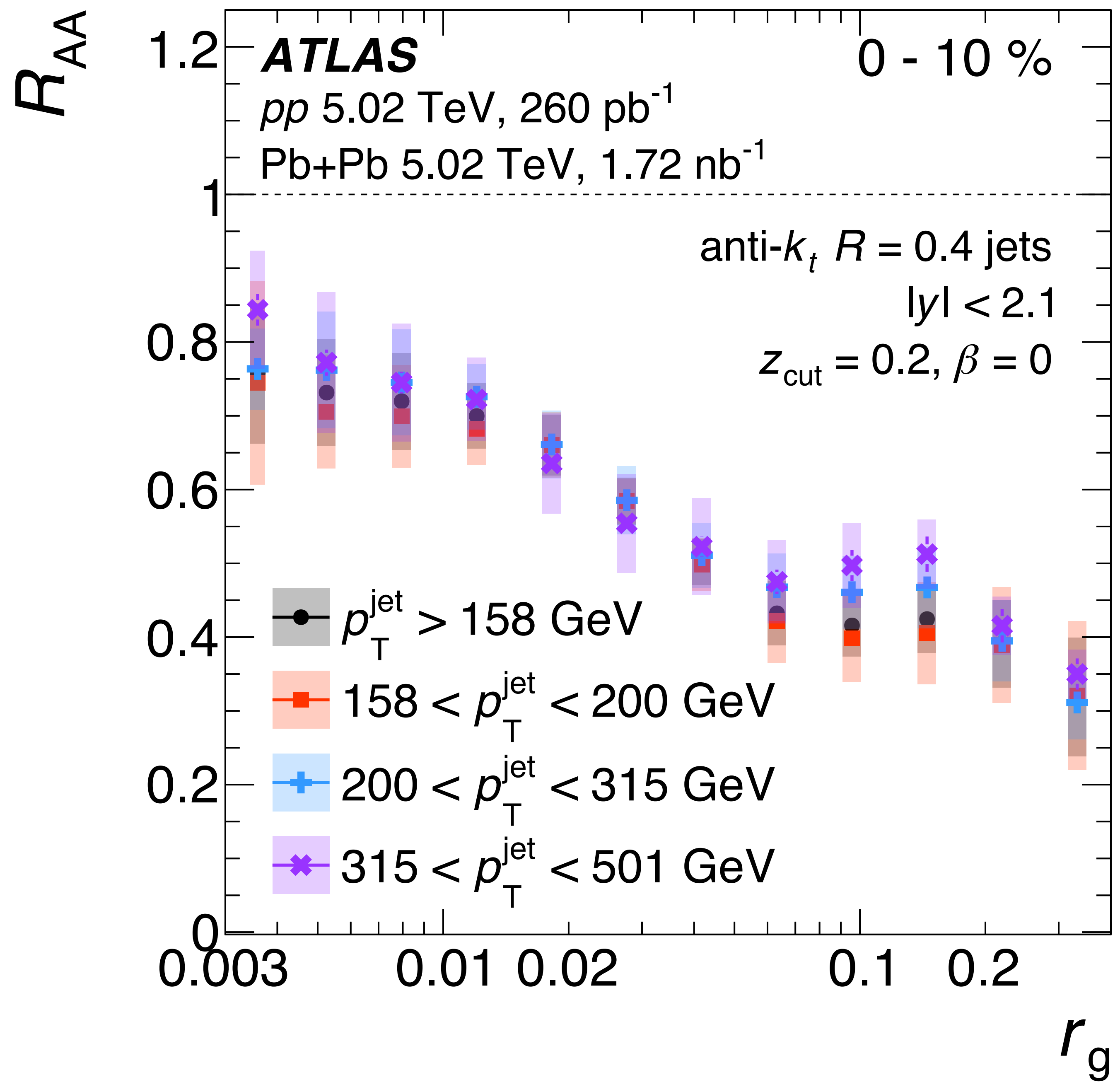
Jet substructure

Softdrop



[Dasgupta, Fregoso, Marzani, Salam 2013]
[Fig from G Salam]

[ATLAS 2023]



Interpretation in terms of color coherence

Smaller angle r_g

- Subjet has a small number of effective emitters - smaller suppression

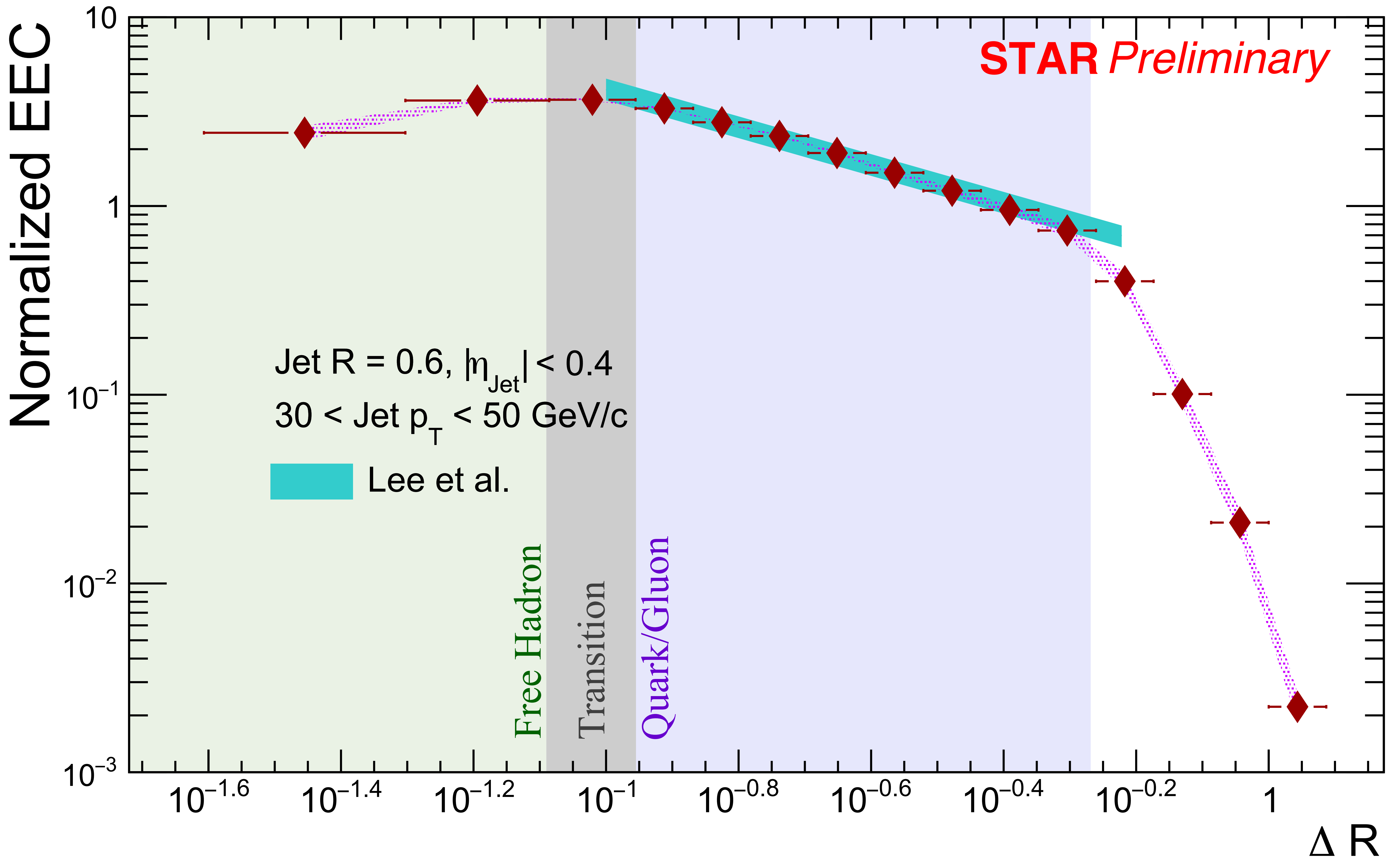
Larger angle r_g

- Subjet has a larger number of effective emitters - larger suppression

Energy-Energy Correlators

$$\frac{\langle \mathcal{E}^n(\boldsymbol{n}_1)\mathcal{E}^n(\boldsymbol{n}_2)\rangle}{Q^{2n}} = \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma_{ij}}{d\boldsymbol{n}_i d\boldsymbol{n}_j}\frac{E_i^n E_j^n}{Q^{2n}}\delta^{(2)}(\boldsymbol{n}_i - \boldsymbol{n}_1)\delta^{(2)}(\boldsymbol{n}_j - \boldsymbol{n}_2)$$

CMS-PAS-HIN-23-004



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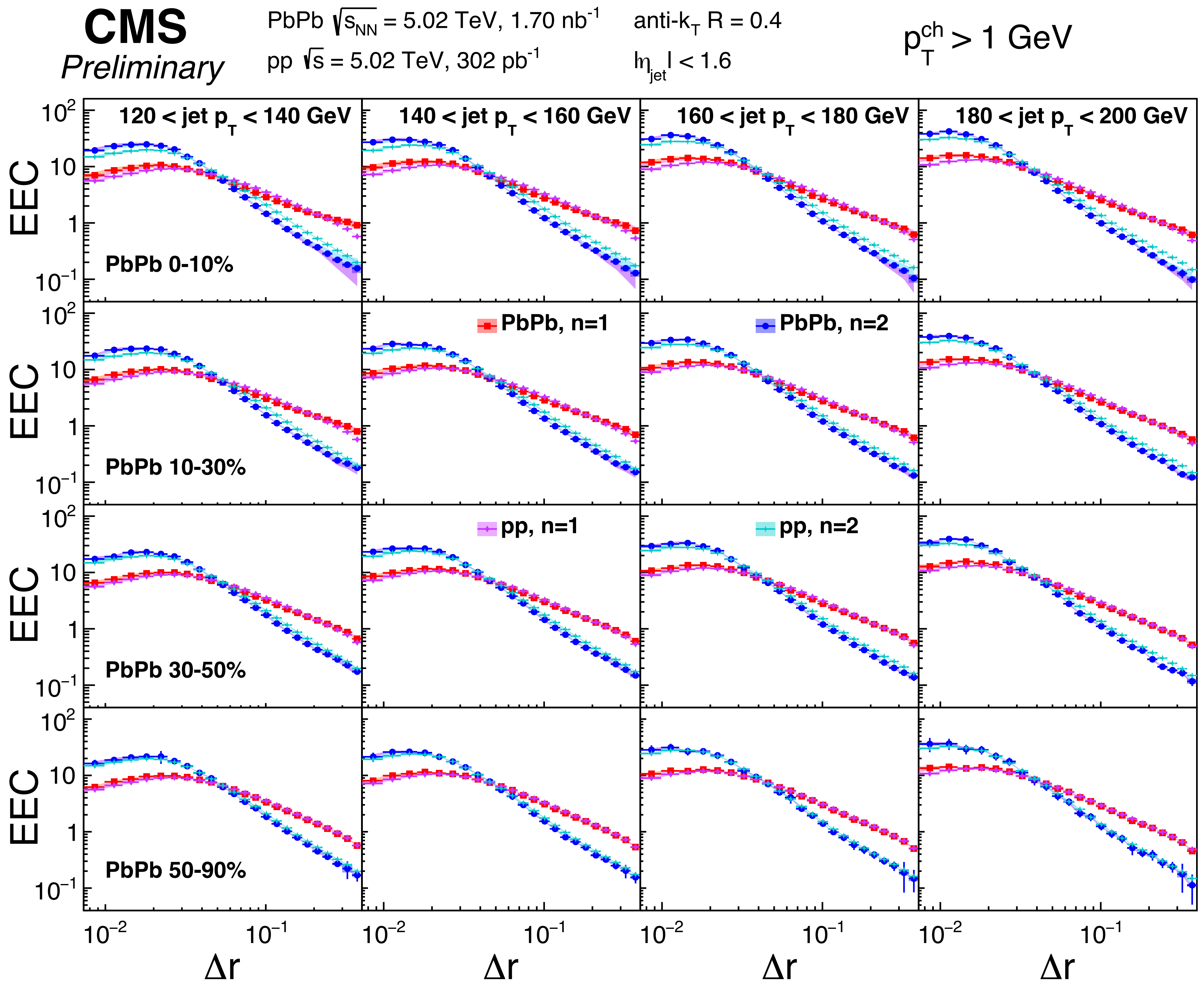
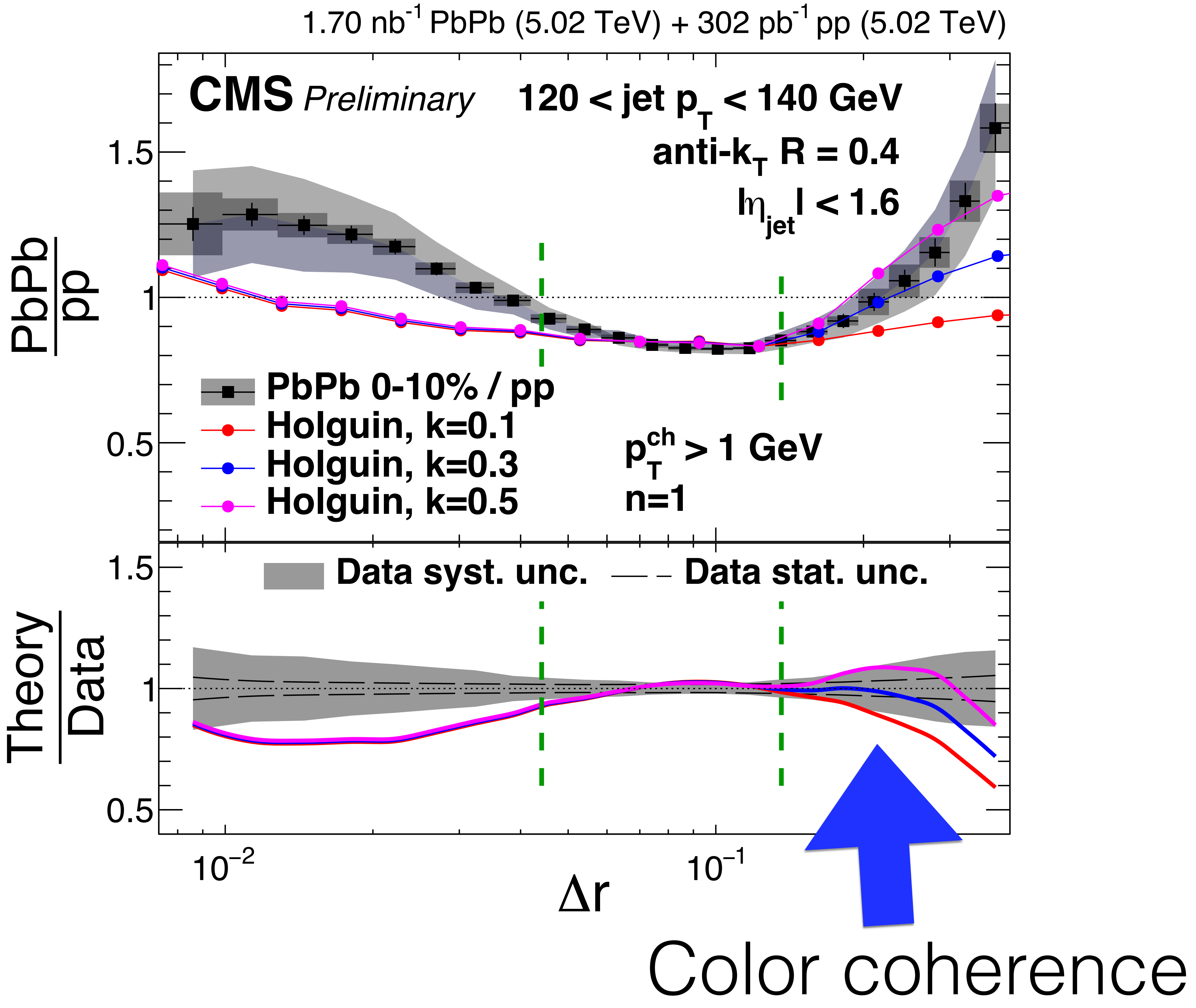
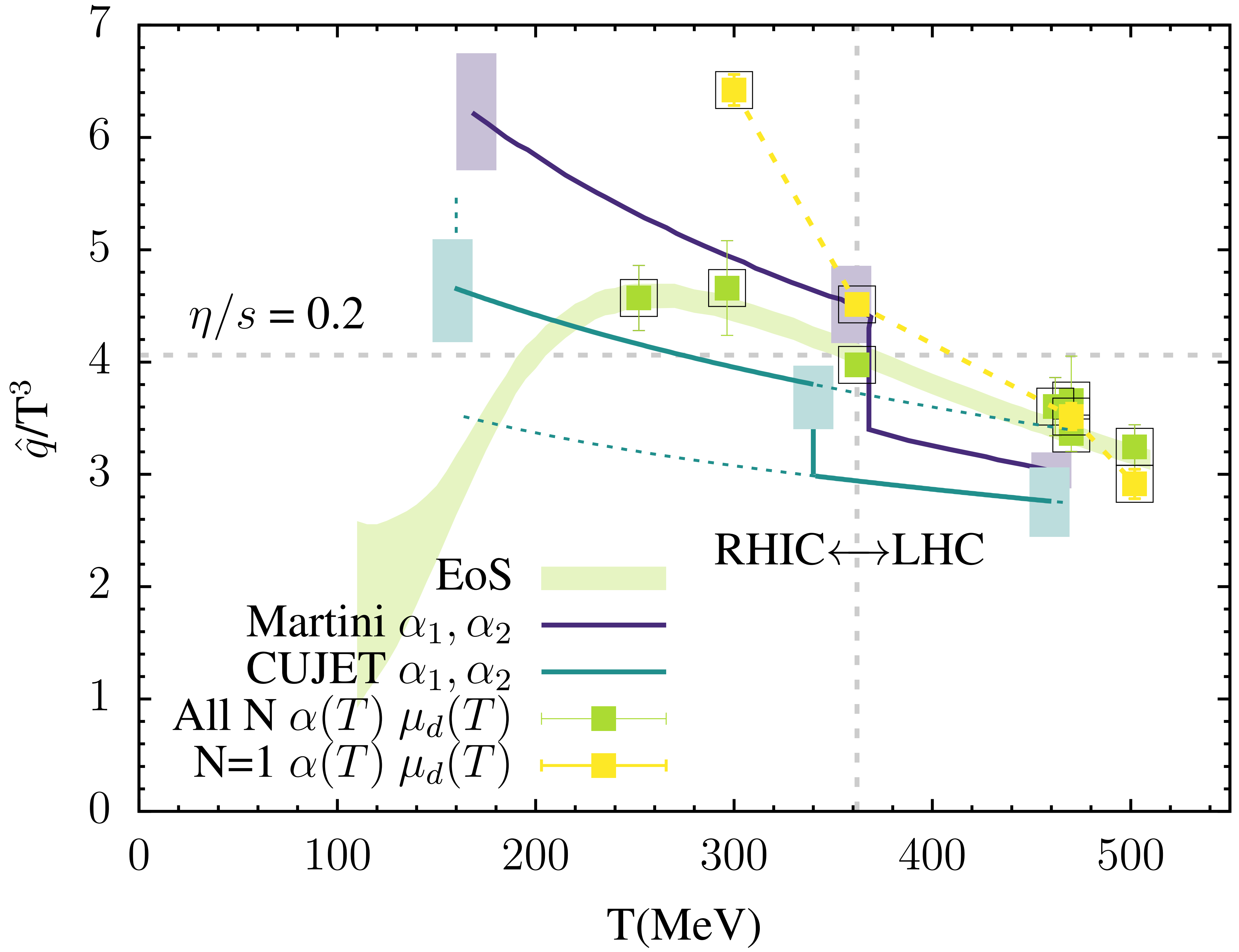
CMS-PAS-HIN-23-004

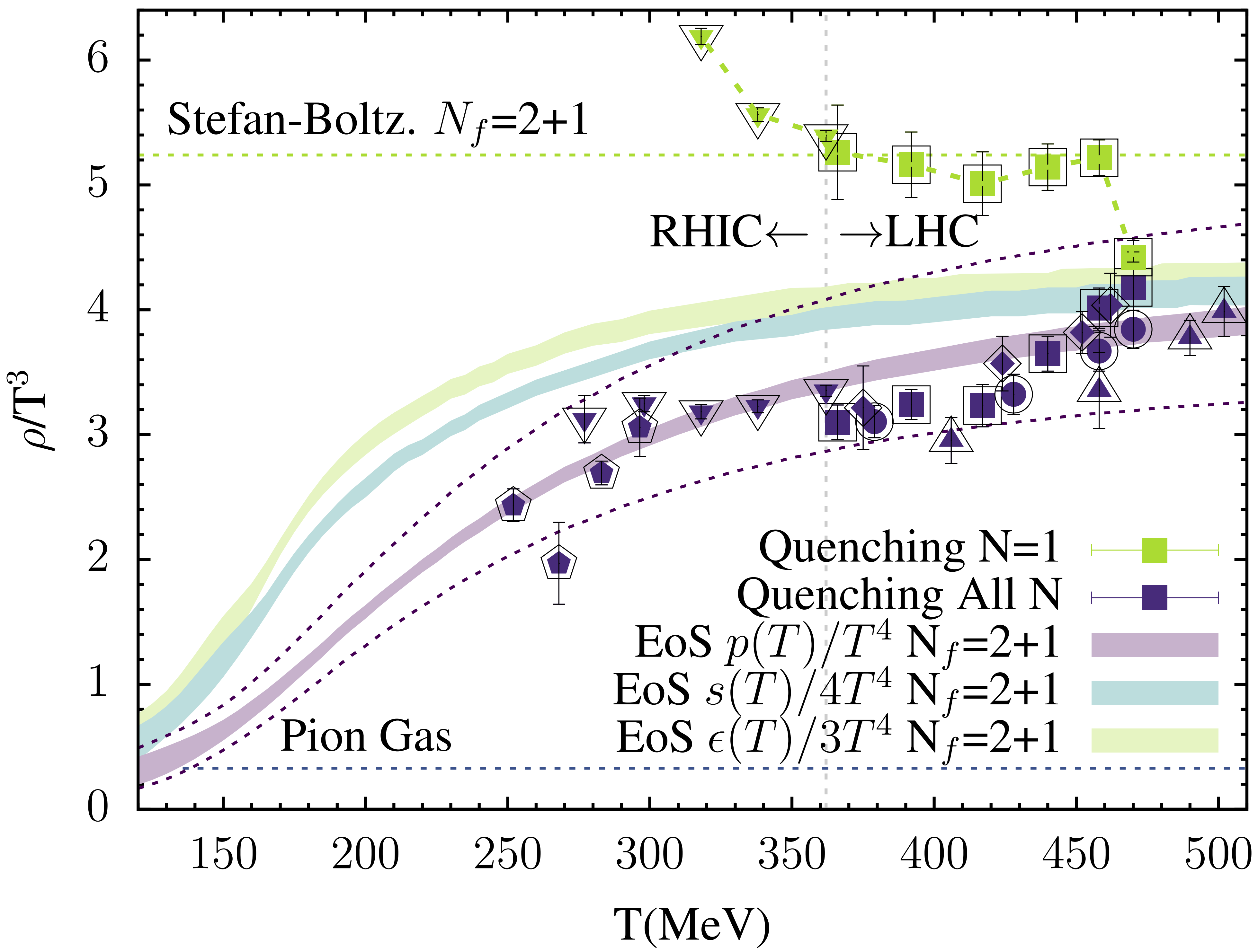




Jet quenching parameter

Information about the medium properties usually encoded in the jet quenching parameter $\hat{q}$

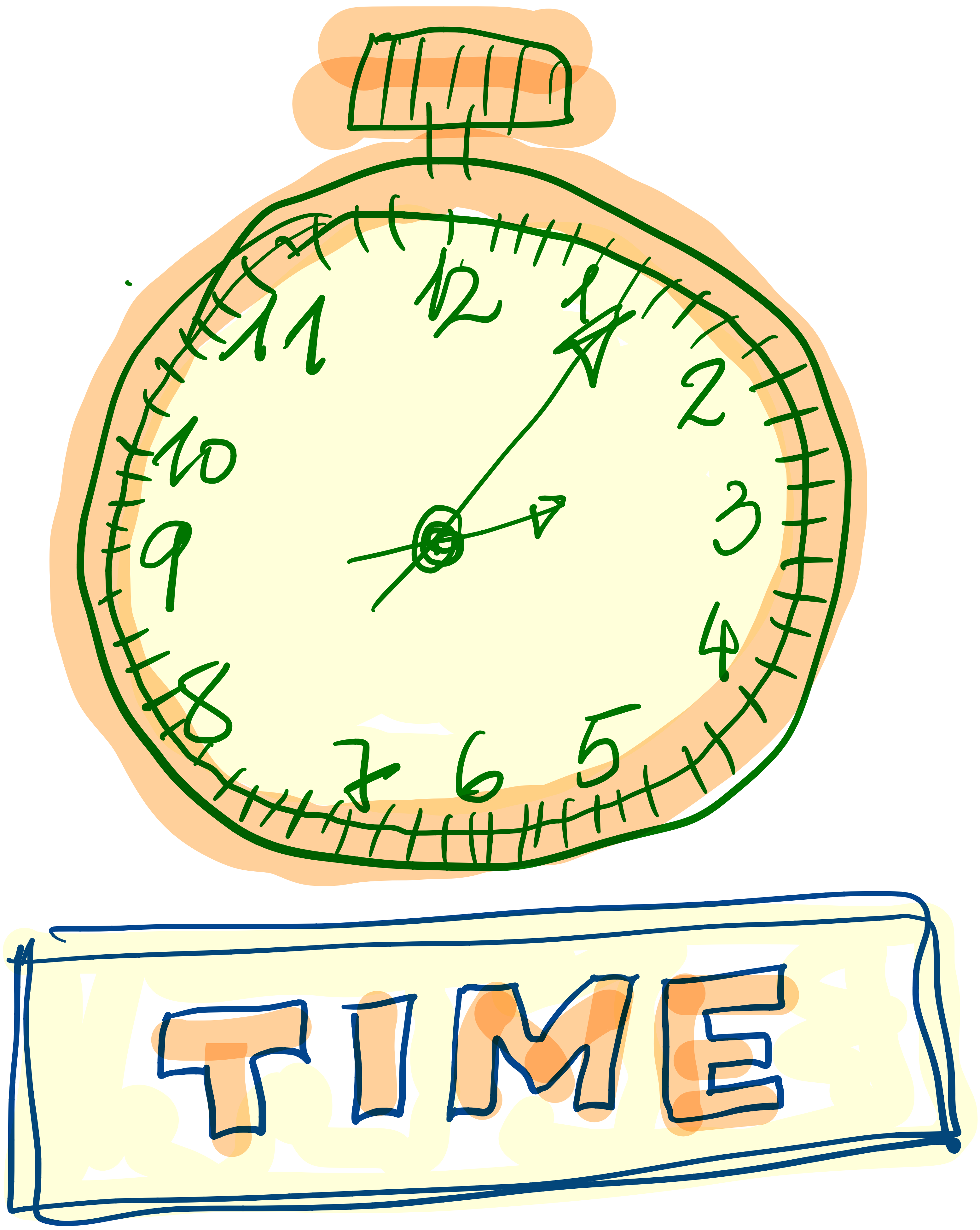




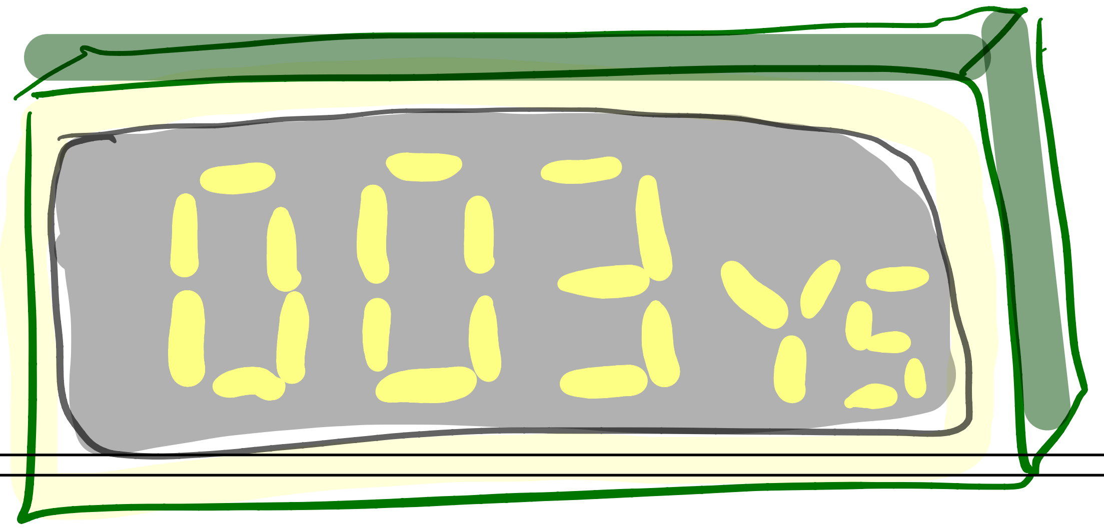
[Feal, Salgado, Vazquez 2019]

Agreement with cross sections from thermal-QCD — resummation of multiple scatterings needed

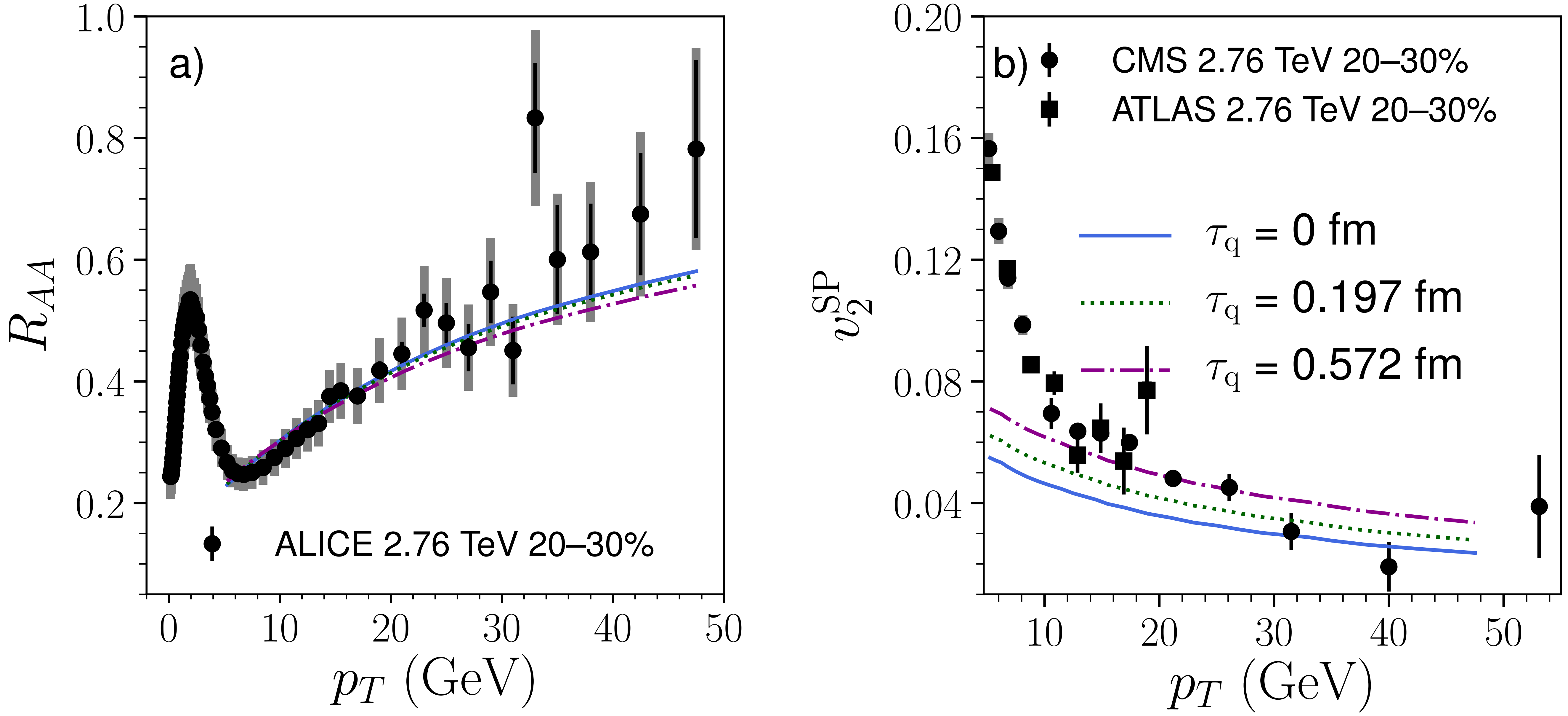
But also…

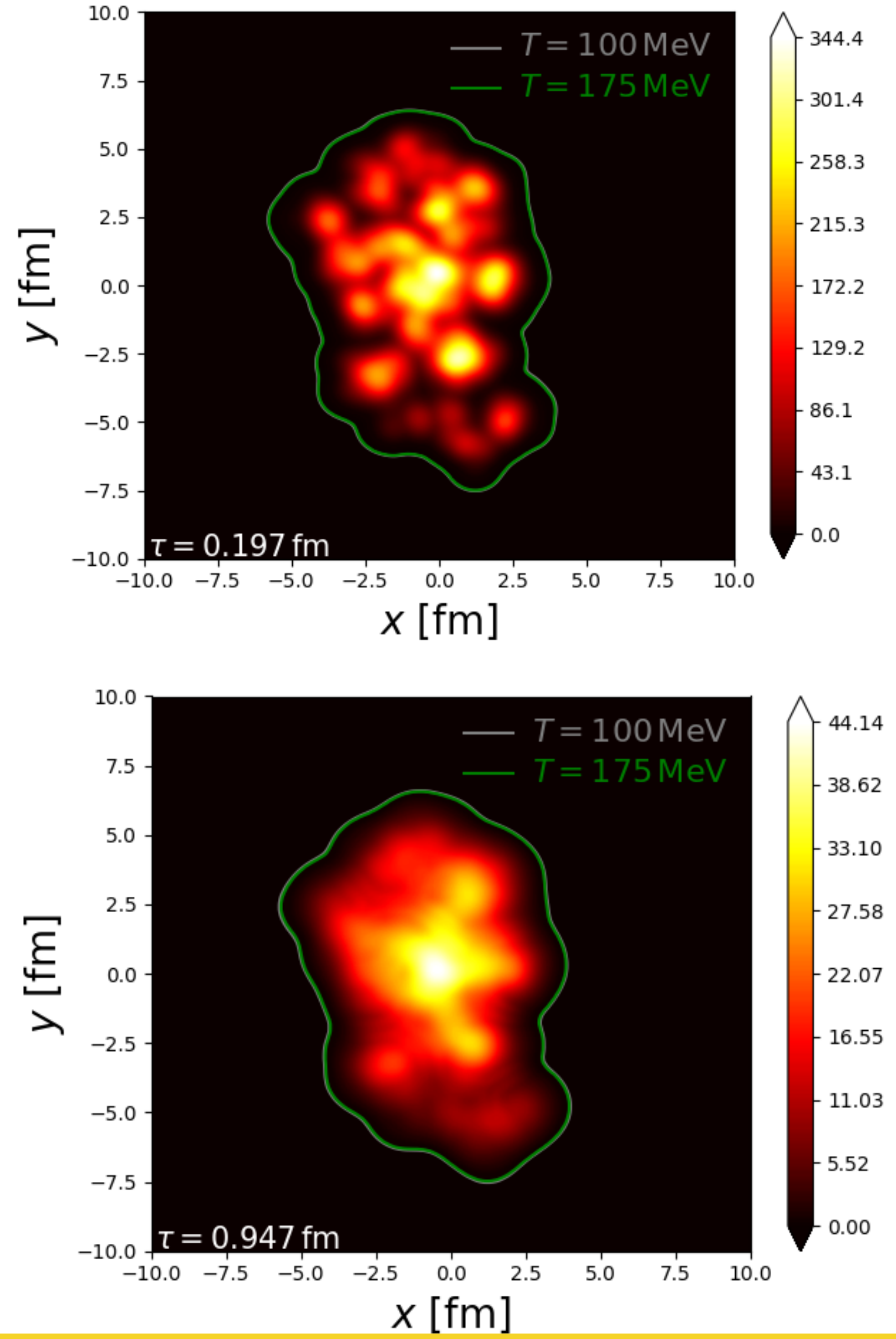


First ~3ys…



Main question - can we access the initial stages with jet quenching?





[Andres, Armesto, Niemi, Paatelainen, Salgado 2019]

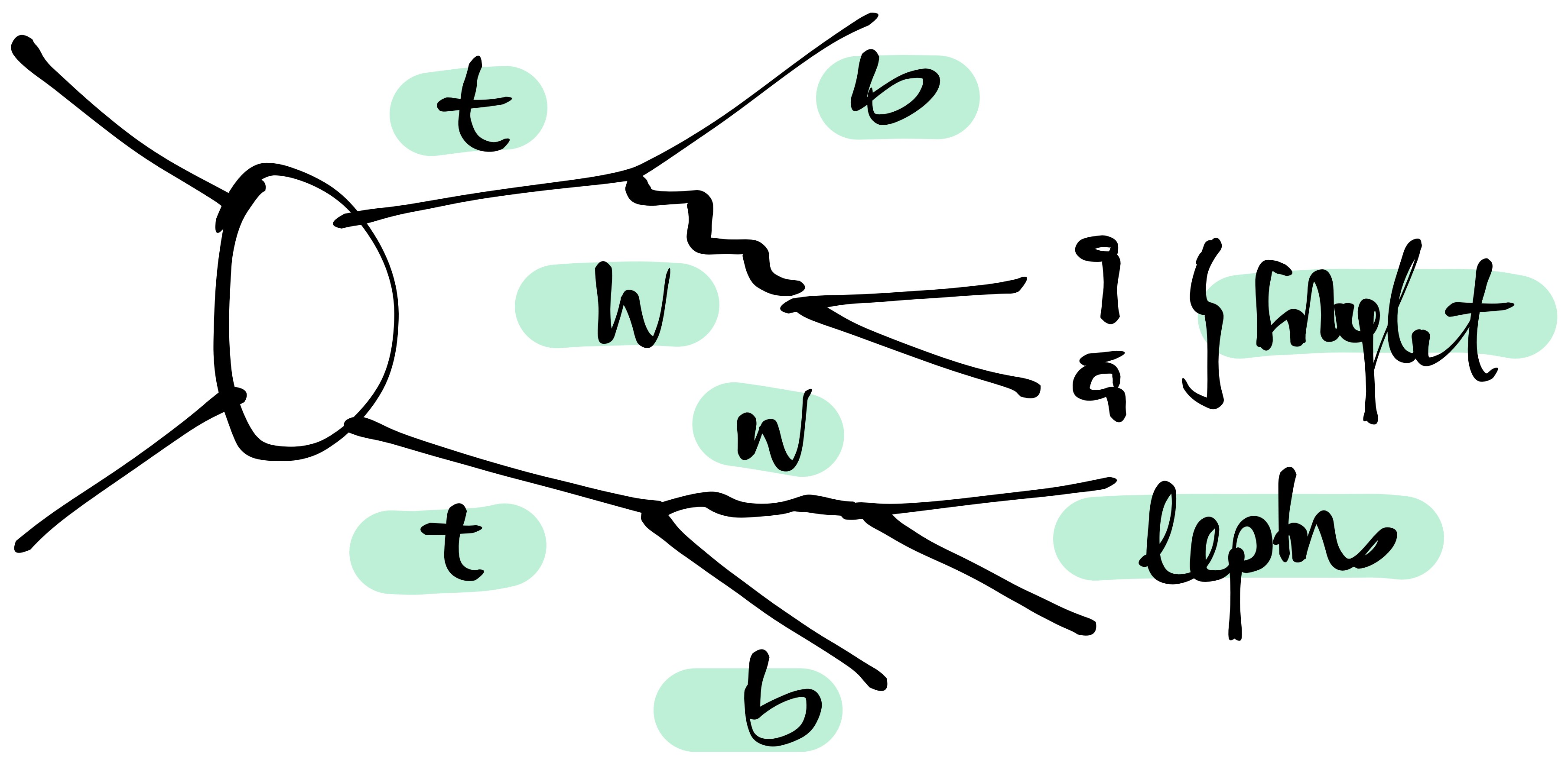
Initial stages (thermalisation period) affect jet quenching -
Opens completely new possibilities - study early times with jet observables

A yoctosecond chronometer

[late times]

Can we **more directly measure the space-time development with jet observables?**

[Apolinario, Milhano, Salgado, Salam 2019]



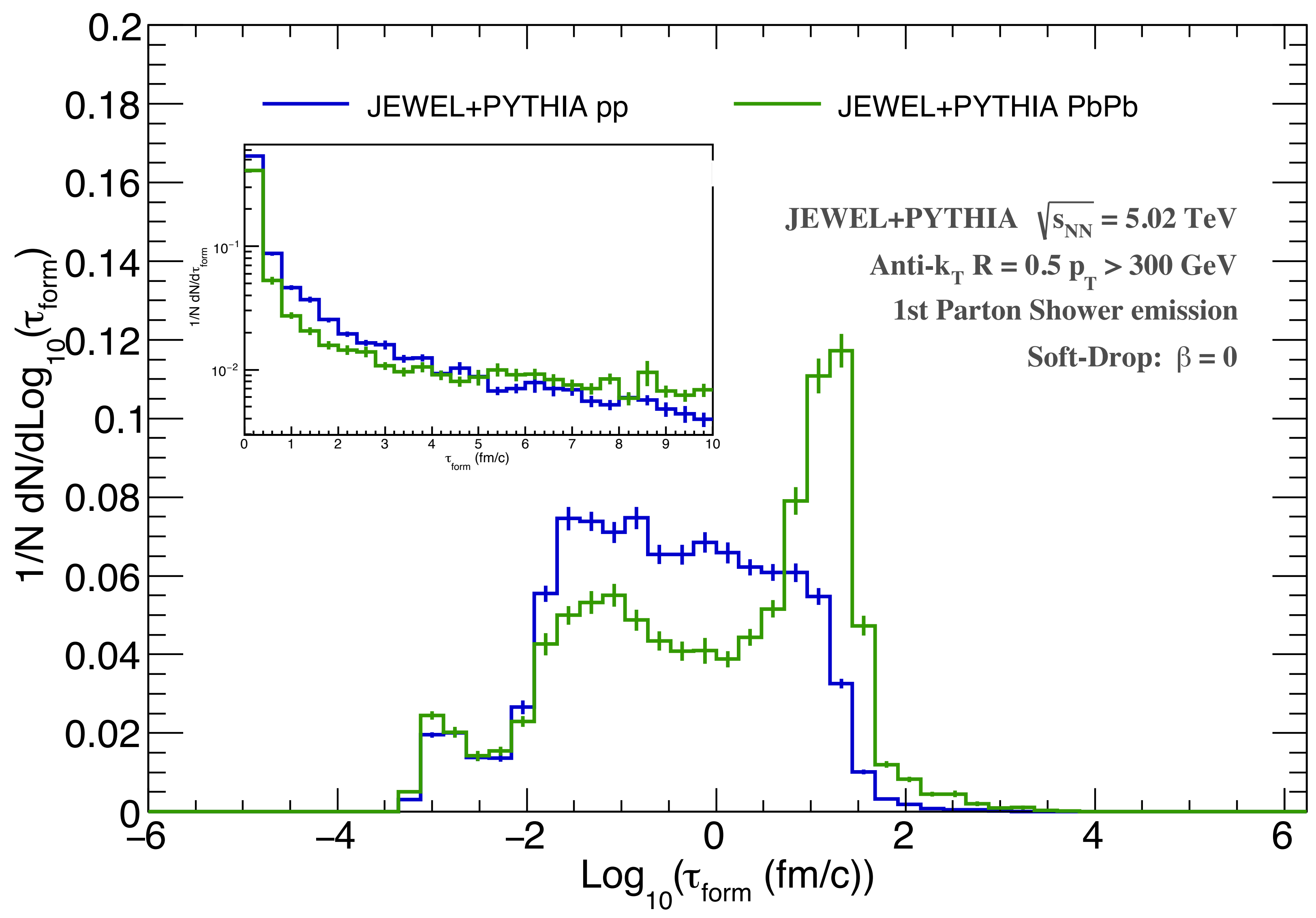
Boosted tops

Difficult with LHC PbPb luminosity - lighter ions?

Charm/Bottom quarks? [Attems, et al 2022]

New time reclustering algorith

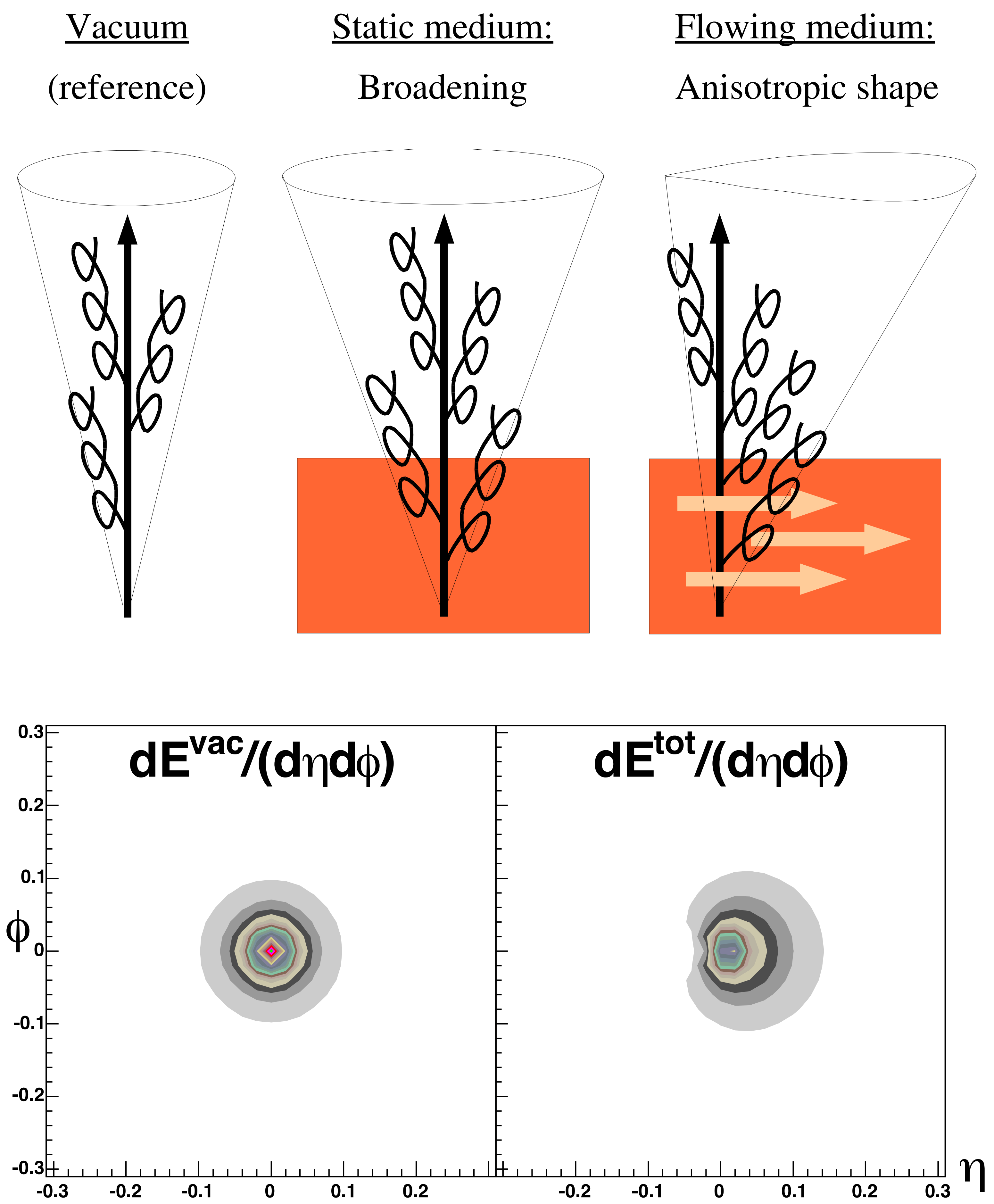
Very promising

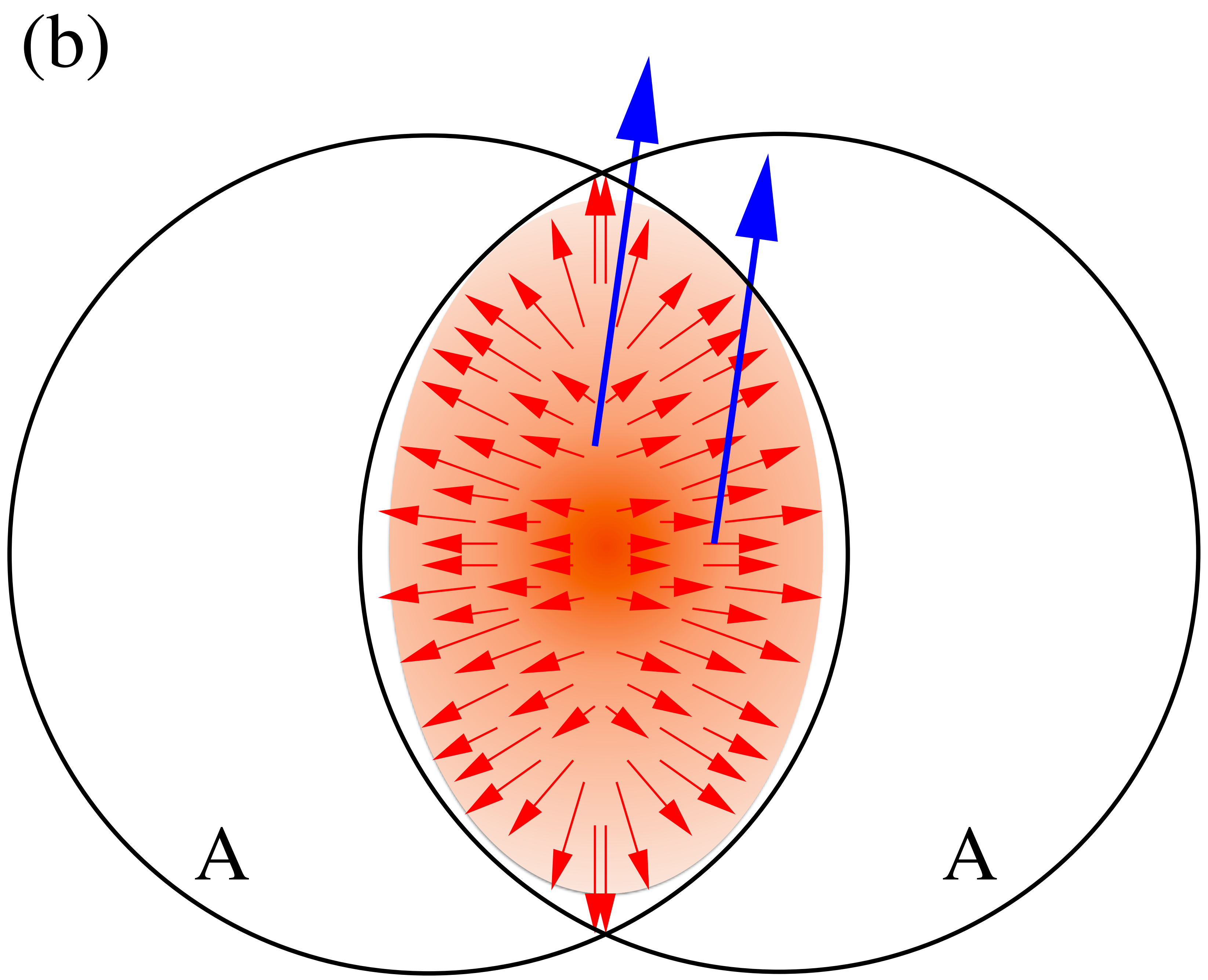


[Apolinario, Cordeiro, Zapp 2021]

Coupling jet-hydro

[Armesto, Salgado, Wiedemann 2004]

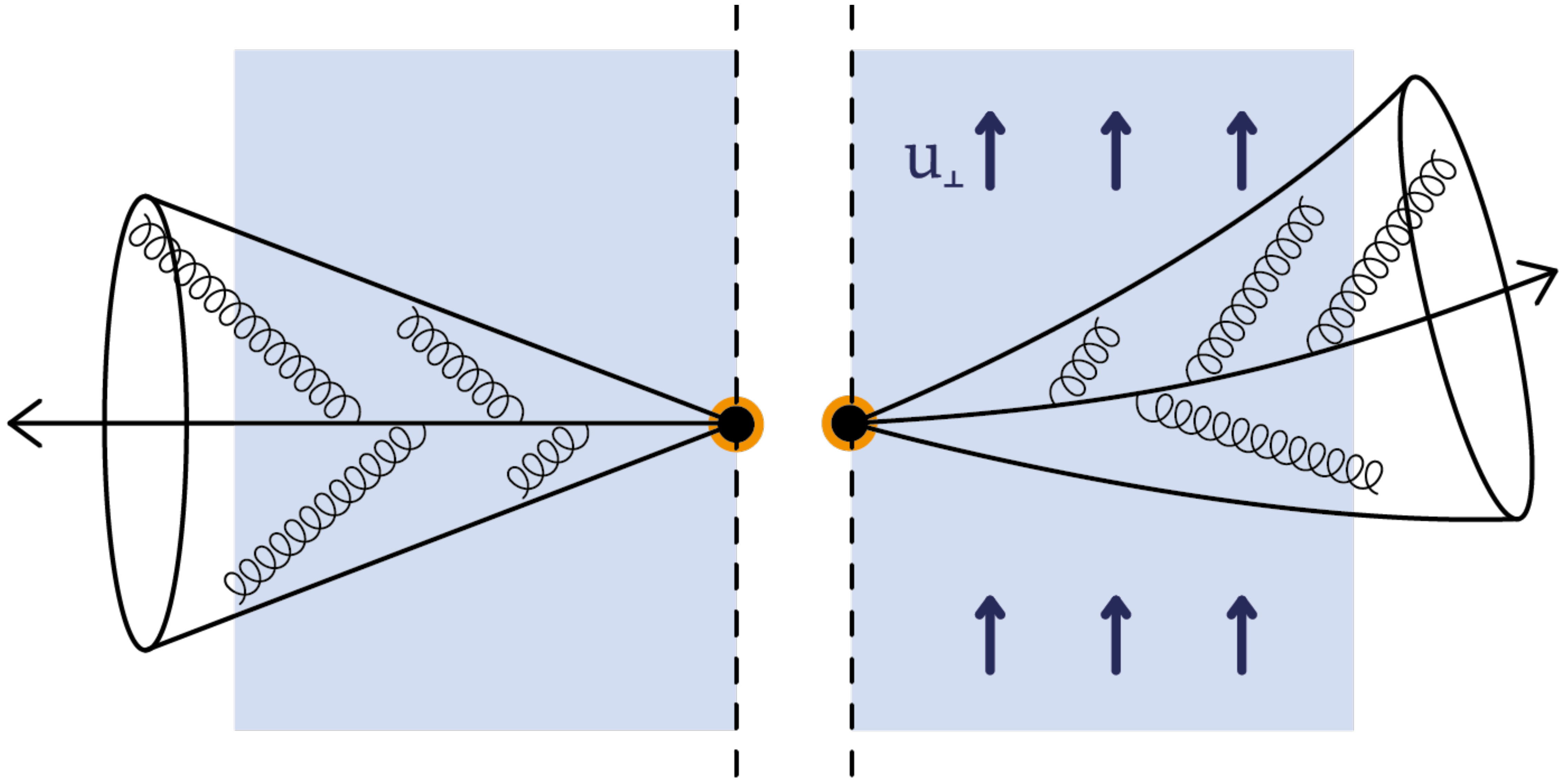


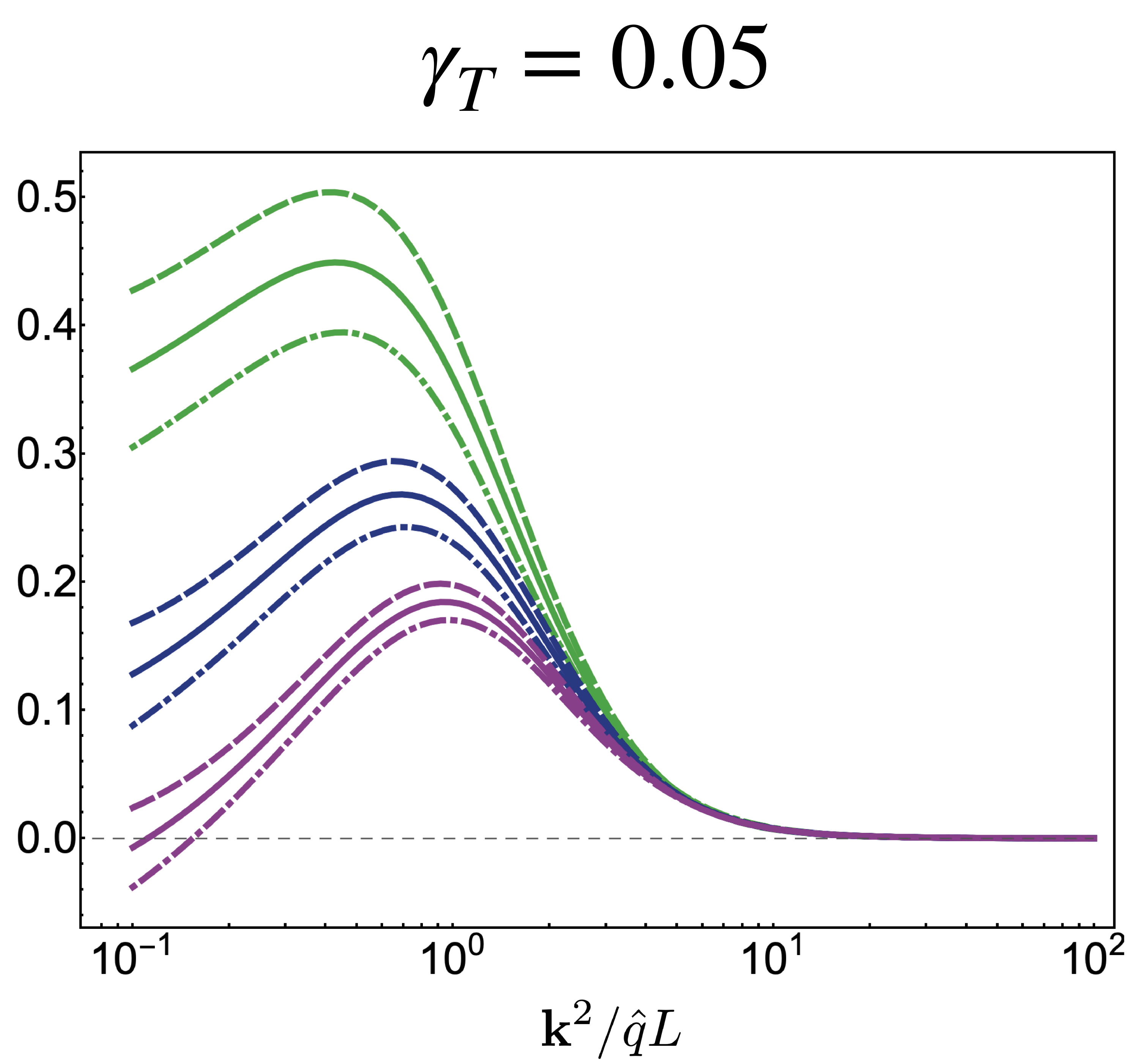


What is the effect of the velocity fields and the (density/temperature) gradients in jet quenching observables?

Anisotropic radiation

Radiation follows the anisotropies (gradients and/or flow)





[Barata, Mayo, Sadofyev, Salgado 2022]

Where the gradient parameter $\gamma_T = |\nabla T/T^2|$

To be confirmed experimentally - direct measurement of velocity fields!

Conclusions

QCD provides a very powerful laboratory to understand how the first levels of complexity emerge from a fundamental (and non-abelian) theory

- **QCD has a rich dynamical content well within experimental reach**
- Branches to other very active fields in Physics, including Cosmology or Condense Matter where equilibration, role of quantum entanglement, etc…

Impressive progress in several theoretical areas of heavy ion collisions

- Initial stages, parton saturation and thermalization
- Hydrodynamics
- Hard Probes: jet quenching and quarkonia (also heavy-flavor)
- … **and connections between them**

New data from LHC and RHIC

- Continuous progress on the characterization of the QGP and Yoctosecond Chronometer
- **Completely new opportunities — initial stages / small systems — directly access time evolution**

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Acknowledgements

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CENTROS CiUS

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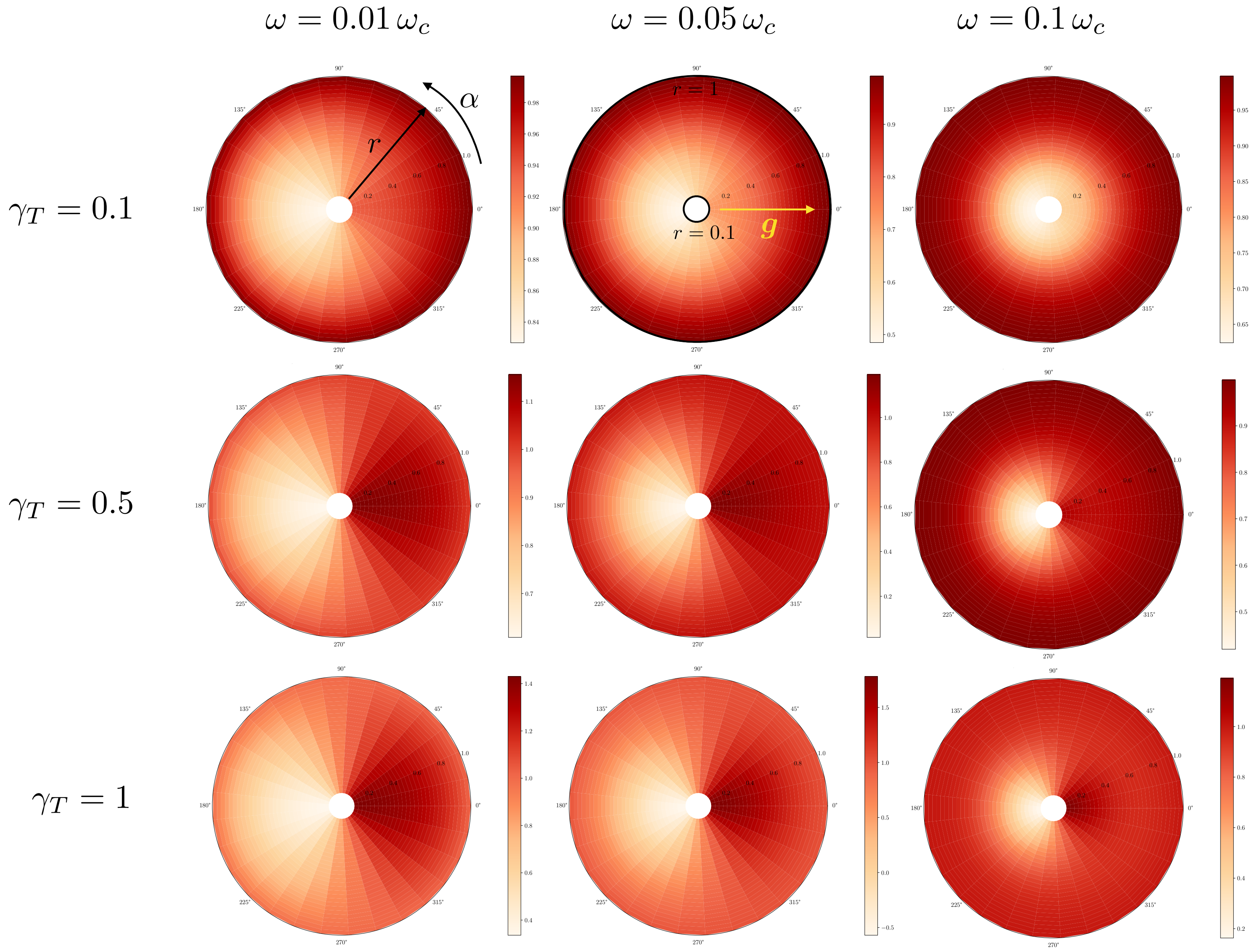
Fondos Europeos

erc European Research Council Established by the European Commission

EXCELENCIA MARÍA DE MAEZTU 2024-2029

Anisotropic jet angular distributions

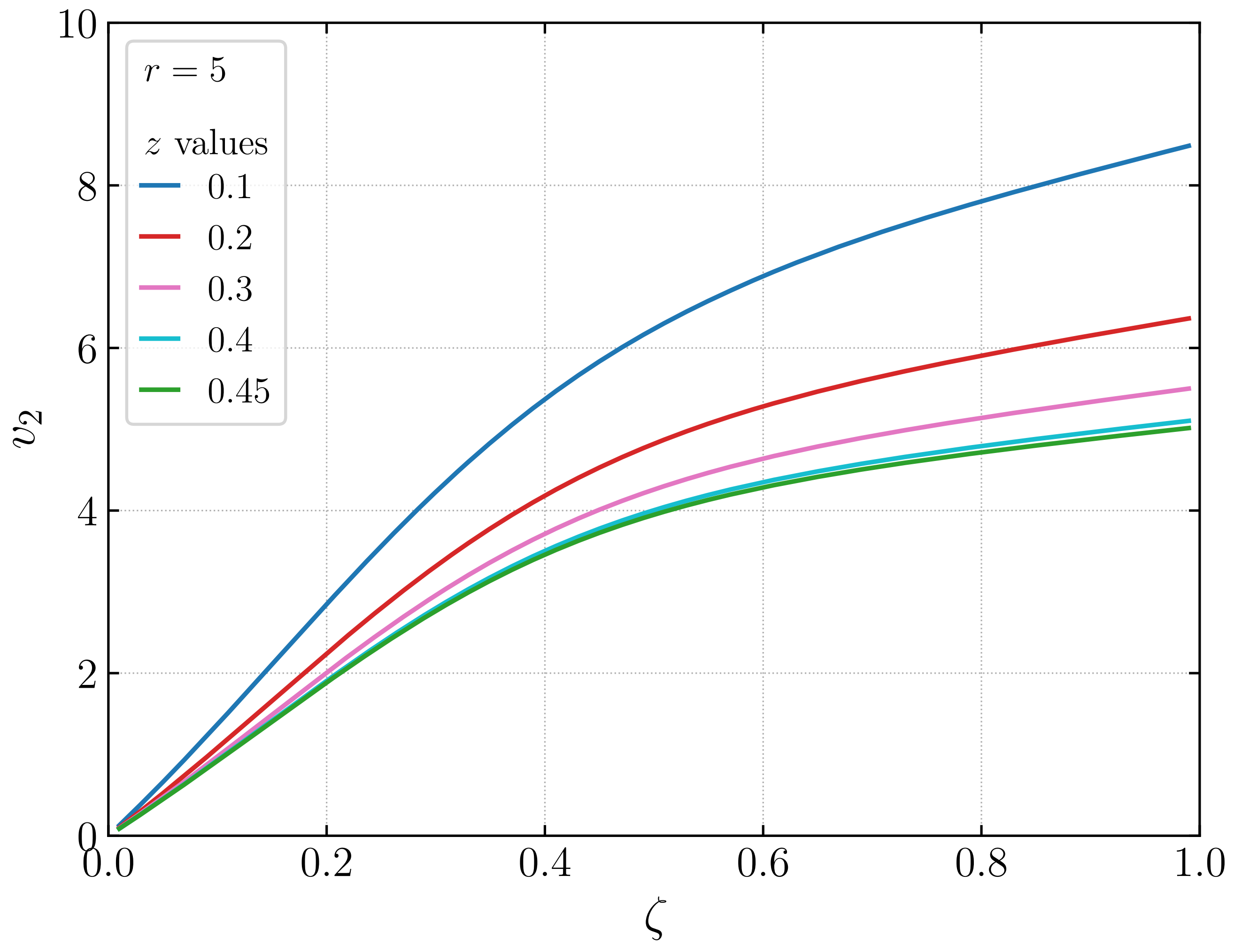
Jet shapes



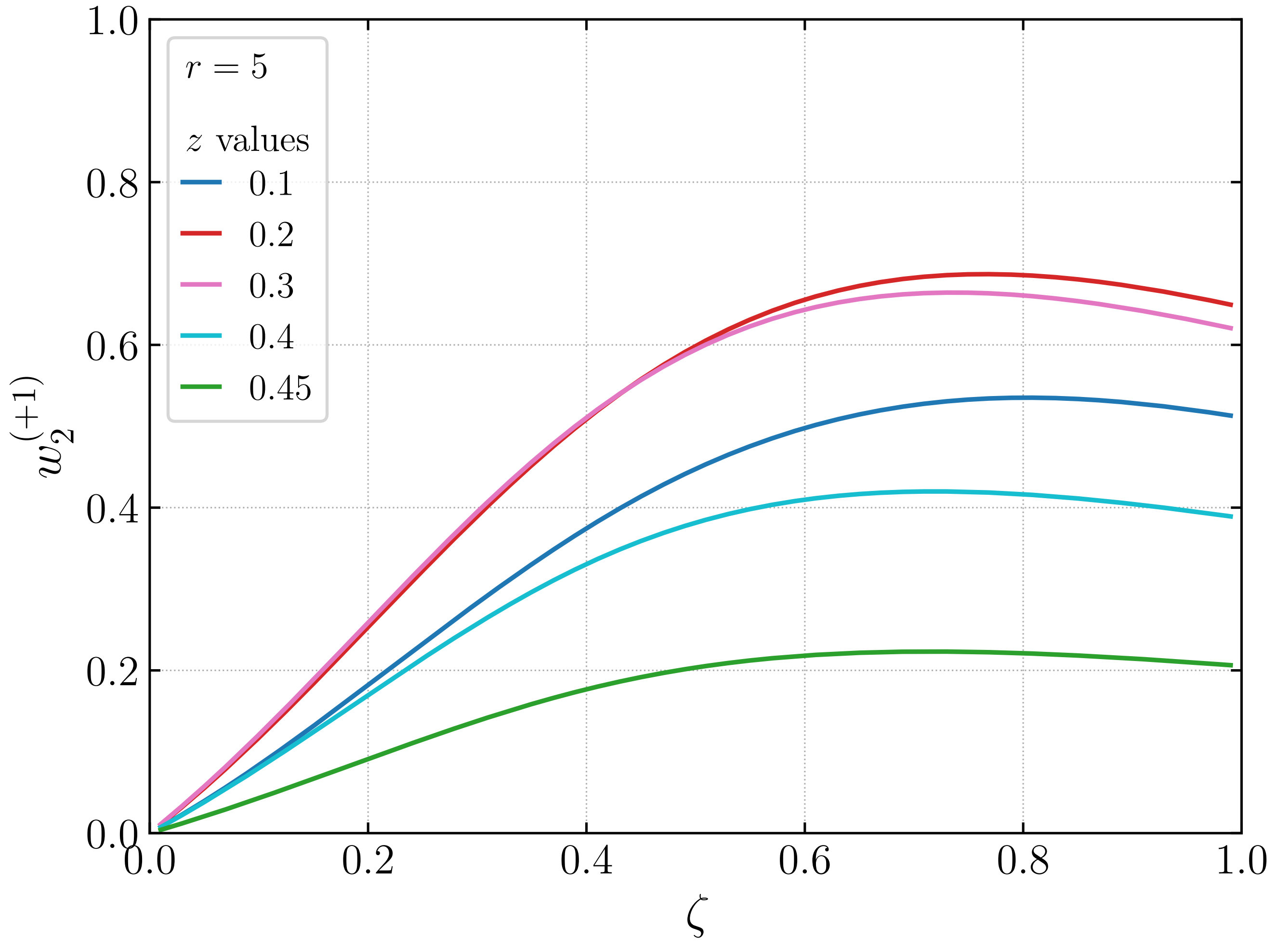
[Barata, Milhano, Sadofyev 2023]

Intra-jet v2 (and w2)

[Barata, Salgado, Silva 2024]



v2 large due to jet anisotropy



w2 correction due to spin in a $q\bar{q}$ antenna