Heavy Ion Theory

Carlos A. Salgado
Universidade de Santiago de Compostela

2016 Aspen Winter Conference on Particle Physics
ACP Aspen, CO - January 2016

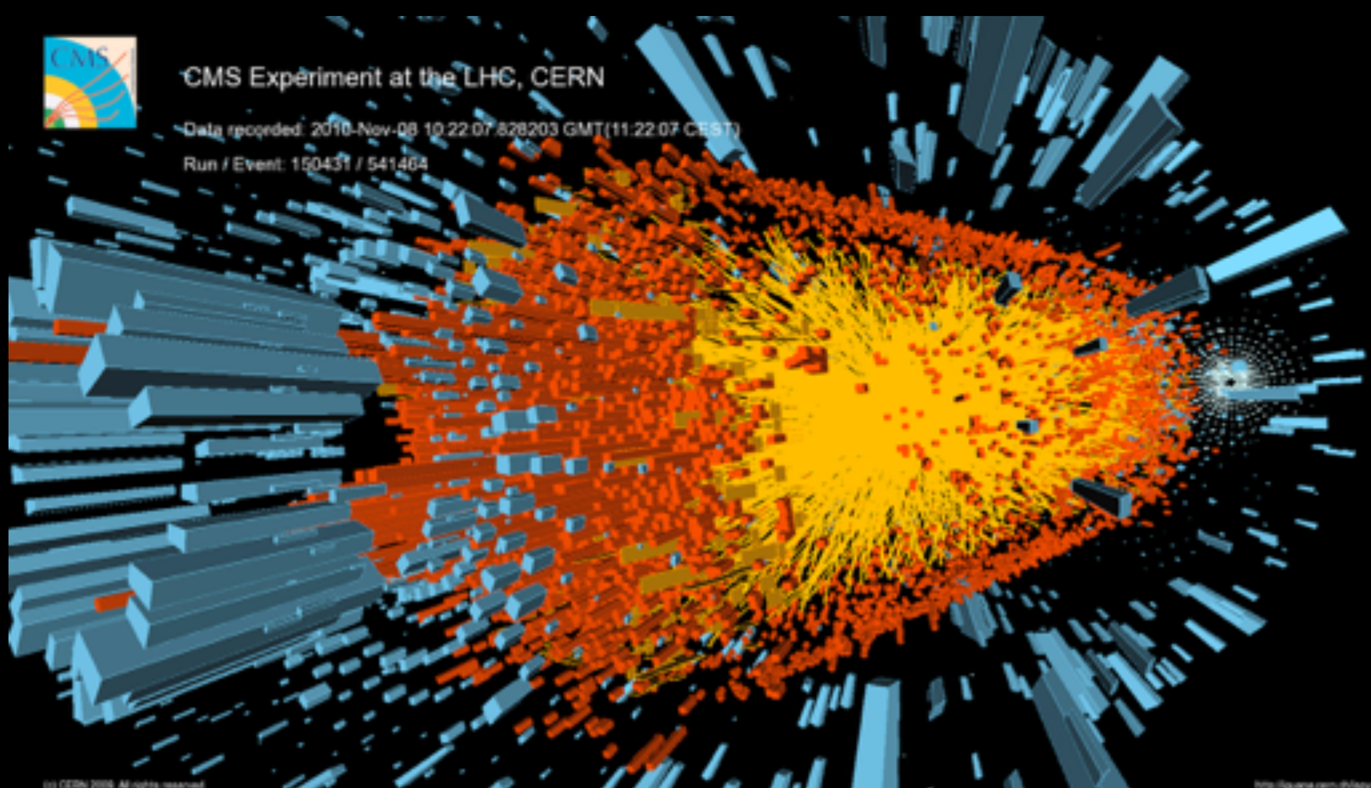
@CASSalgado   @HotLHC

European Research Council
Established by the European Commission

QCD: An apparently simple lagrangian hides a wealth of **emerging phenomena**

Asymptotic freedom; confinement; chiral symmetry breaking;
mass generation; new phases of matter; a rich hadronic spectrum; etc

High-energy nuclear collisions are the experimental tools to access (some of) these collective properties - high density states of matter

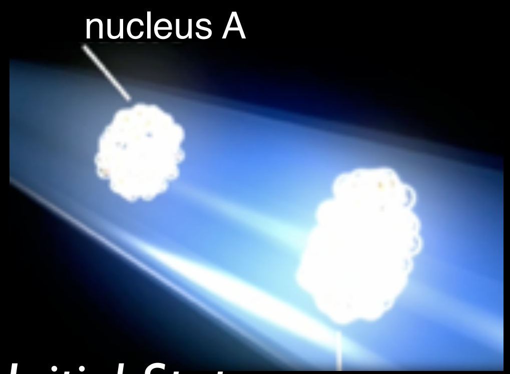


Produce "large" objects

↳ Macroscopic in QCD scale

Collide heavy nuclei

Some of the questions accessible with heavy-ion collisions



Initial State

Final State

What is the structure of hadrons/nuclei at high energy?

— *color coherence effects in the small-x partonic wave function*

— *fix the initial conditions in well-controlled theoretical framework*

Is the created medium thermalized? How?

— *presence of a hydrodynamical behavior*

— *what is the mechanism of thermalization in a non-abelian gauge theory?*

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?*

Newest questions

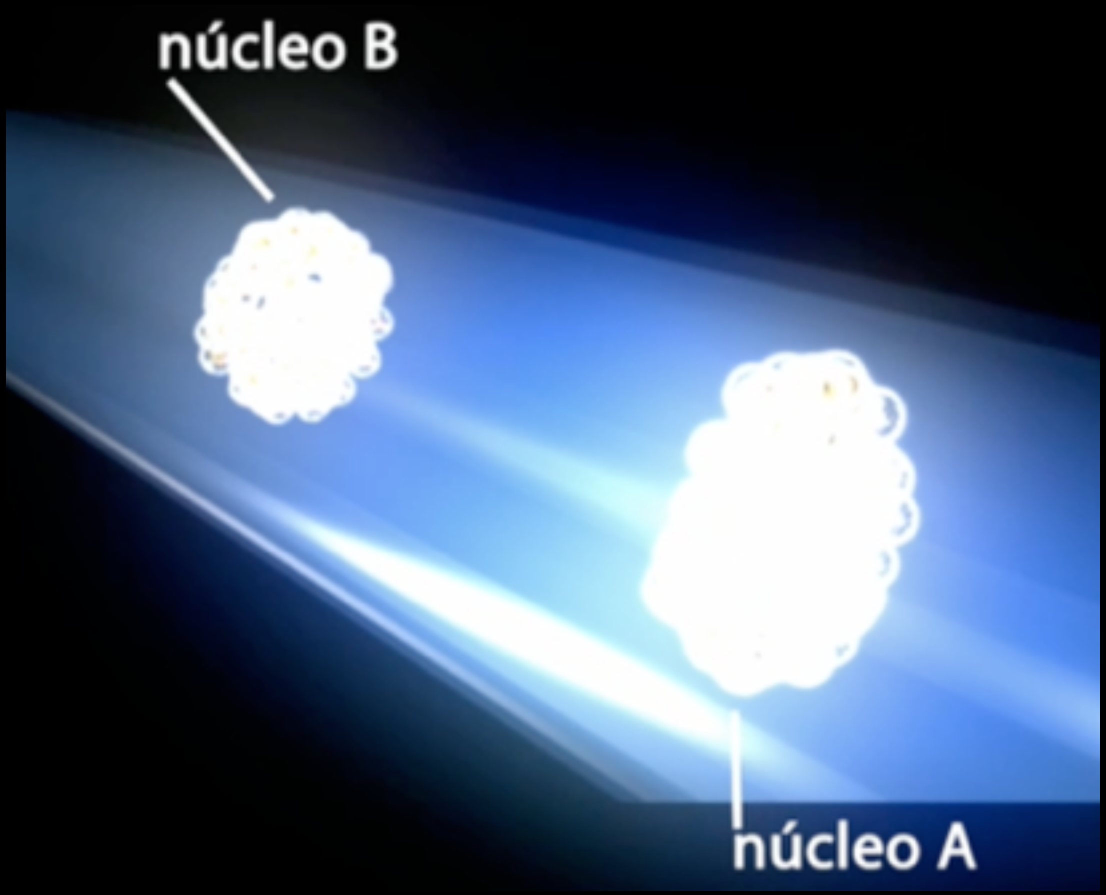
How large is "large"?

↳ Study "Small Systems"

Proton - nucleus collisions

(original main goal: benchmarking)

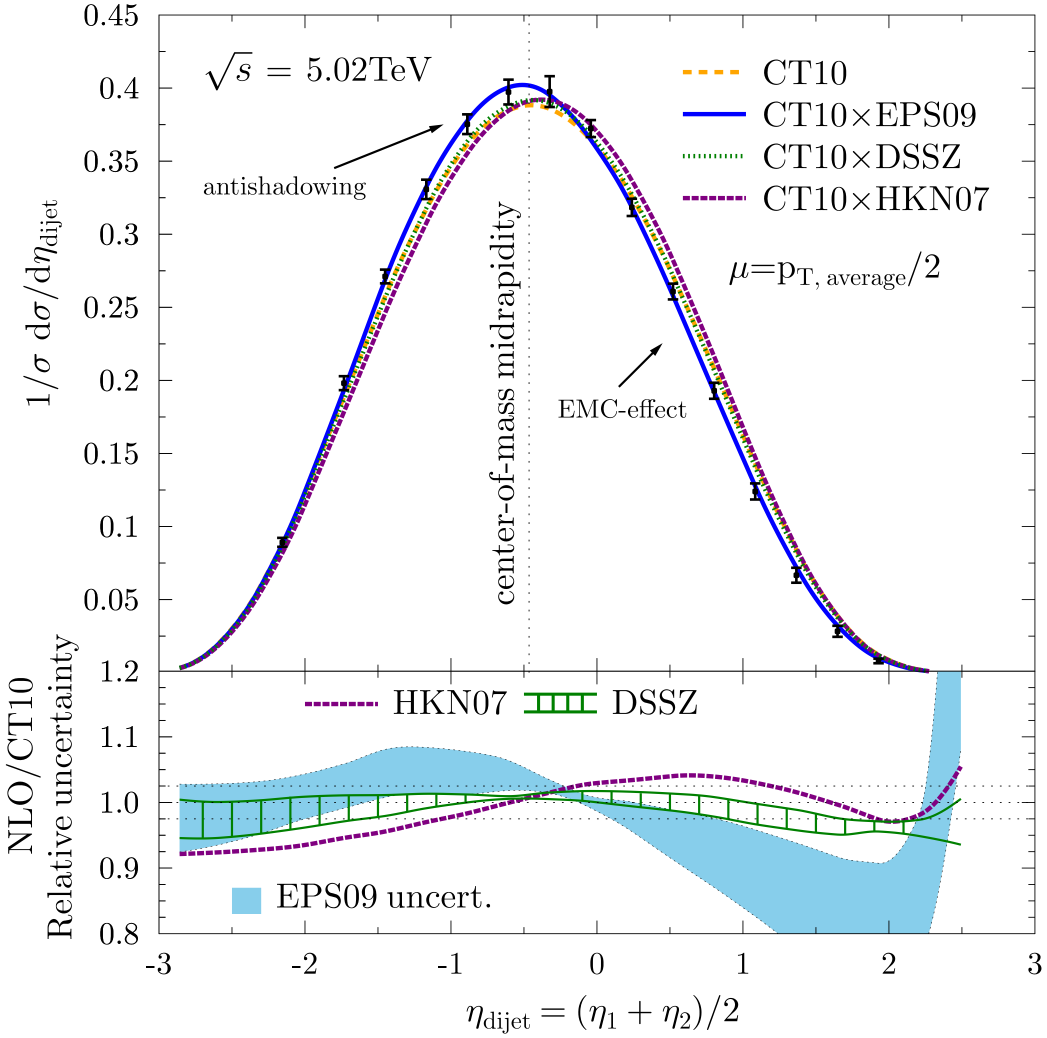
Initial state
Partonic densities
&
Multiparticle Production



Nuclear PDFs

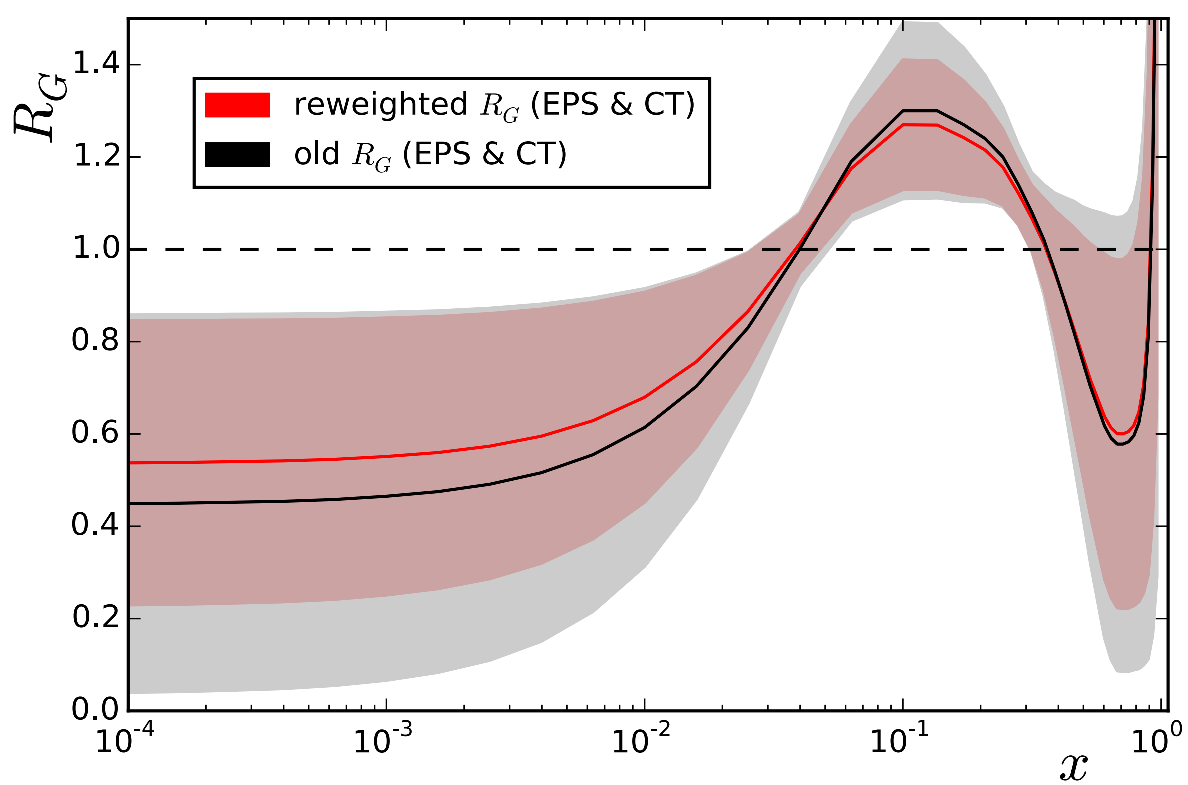
Nuclear PDFs extracted from global fits / DGLAP

- New constraints from the proton-lead run at the LHC



Reweighting

[Andres et al arxiv:1512.01528]



Excellent description of pPb LHC data by existing sets [RHIC data already in fits]

- Better control on systematic uncertainties needed for stronger constraints on nPDFs

From Dilute to Dense

Parton Saturation

Color Correlation in the transverse plane → $1/Q_{sat}$

Color Glass Condensate → General framework

$$Q_{sat}^2 \sim \frac{xg(x, Q_{sat}^2)}{\pi R^2} \sim \frac{A^{1/3}}{x^\lambda}$$

Non-linear eqs. - Multiparticle production

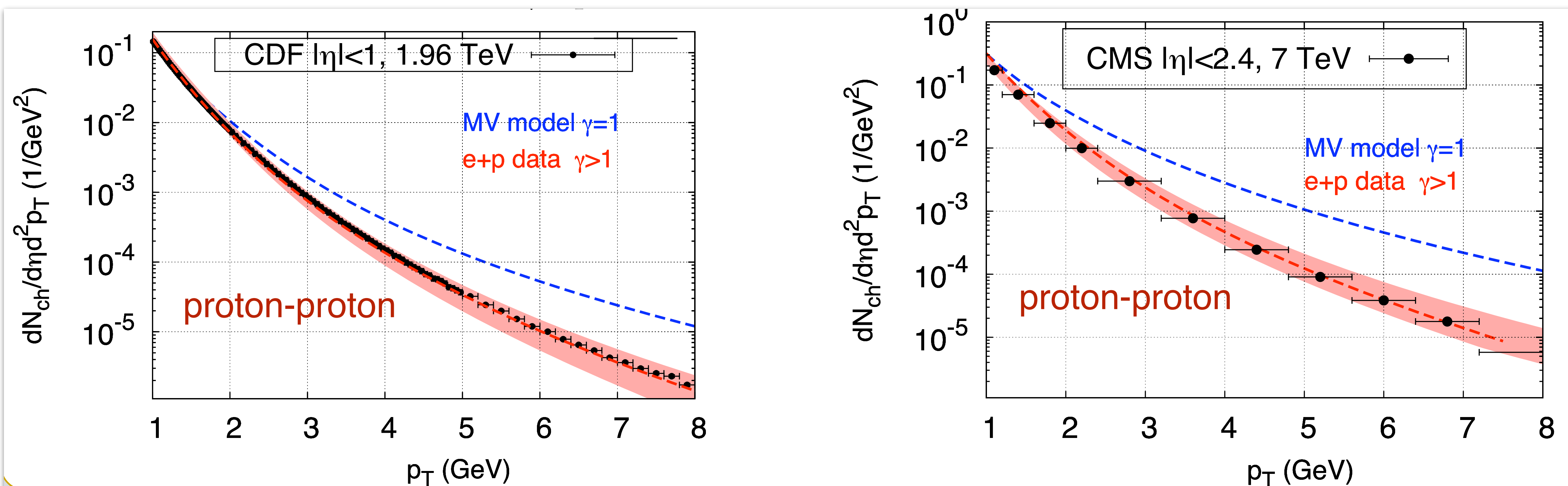
⇛ Screening leads to non-linear terms. E.g. Balitsky-Kovchegov eqs.

$$\frac{\partial \phi(x,k_t)}{\partial \log(x/x_0)} \approx \mathcal{K} \otimes \phi(x,k_t) - \phi(x,k_t)^2$$

Splitting [BFKL] Merging [restores unitarity]

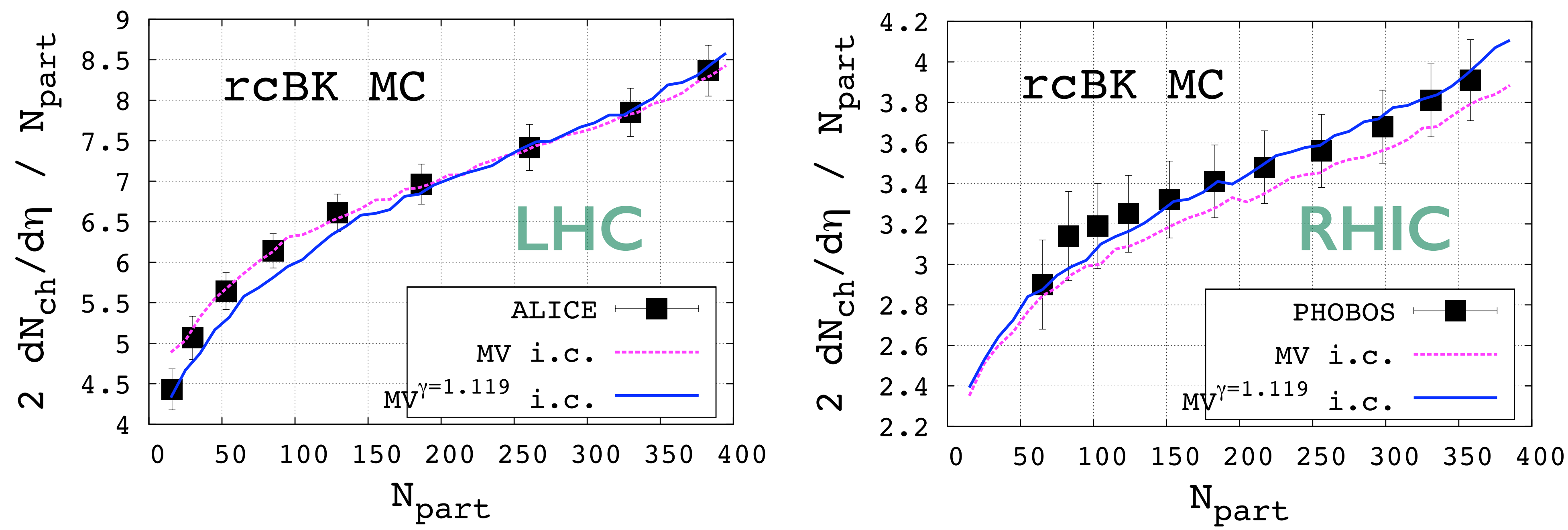
⇛ (unintegrated) gluon distributions fitted to HERA data reproduce pp

[Albacete, Dumitru 2011]

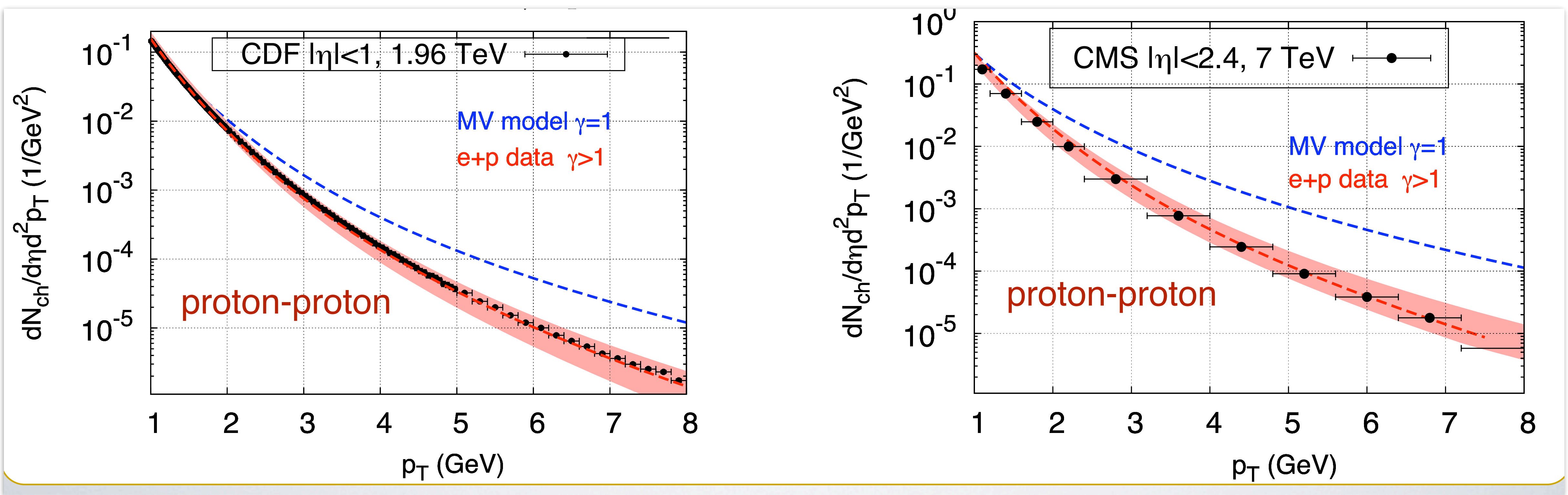


Non-linear eqs. - Multiparticle production

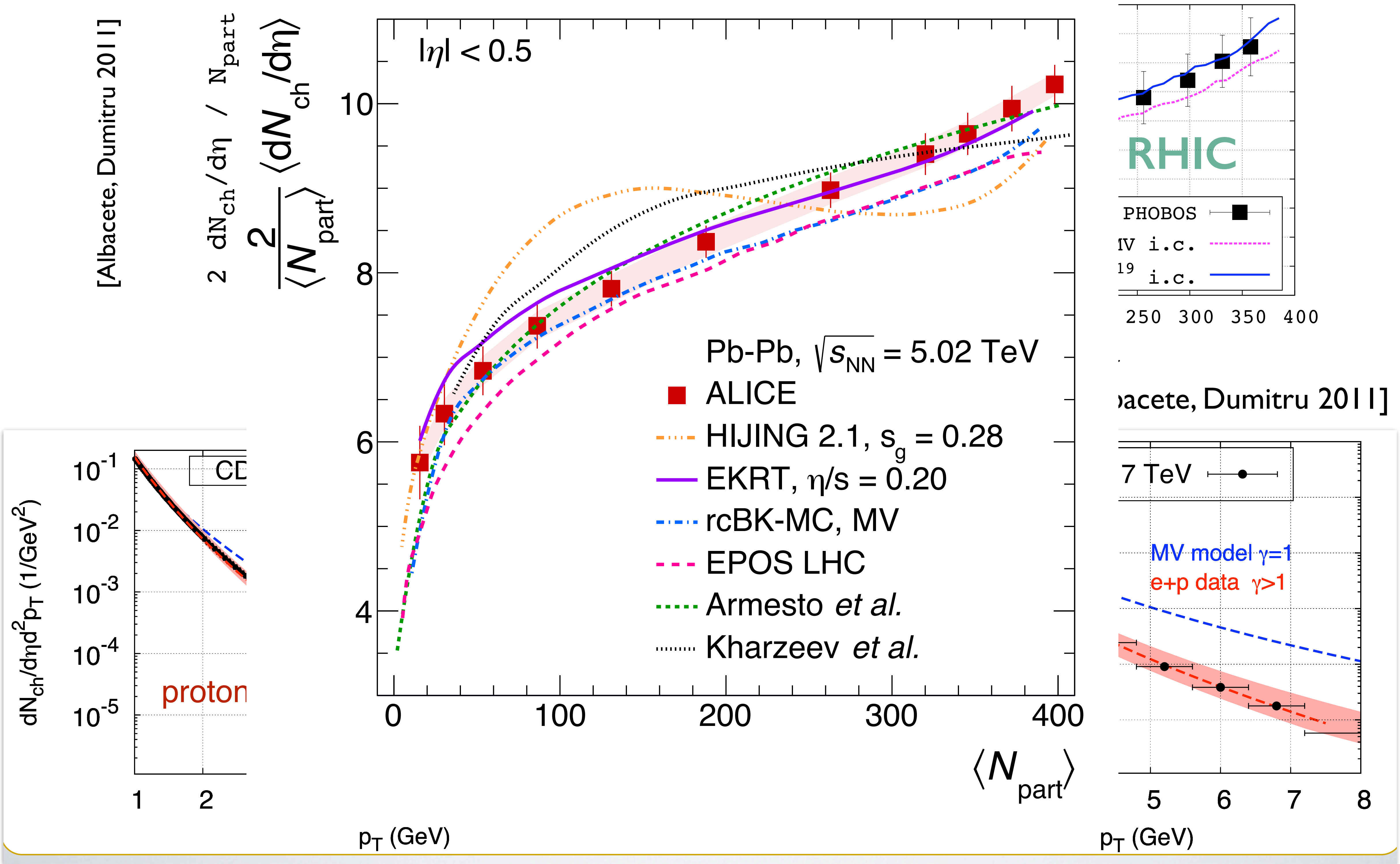
[Albacete, Dumitru 2011]



[Albacete, Dumitru 2011]



Non-linear eqs. - Multiparticle production



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

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

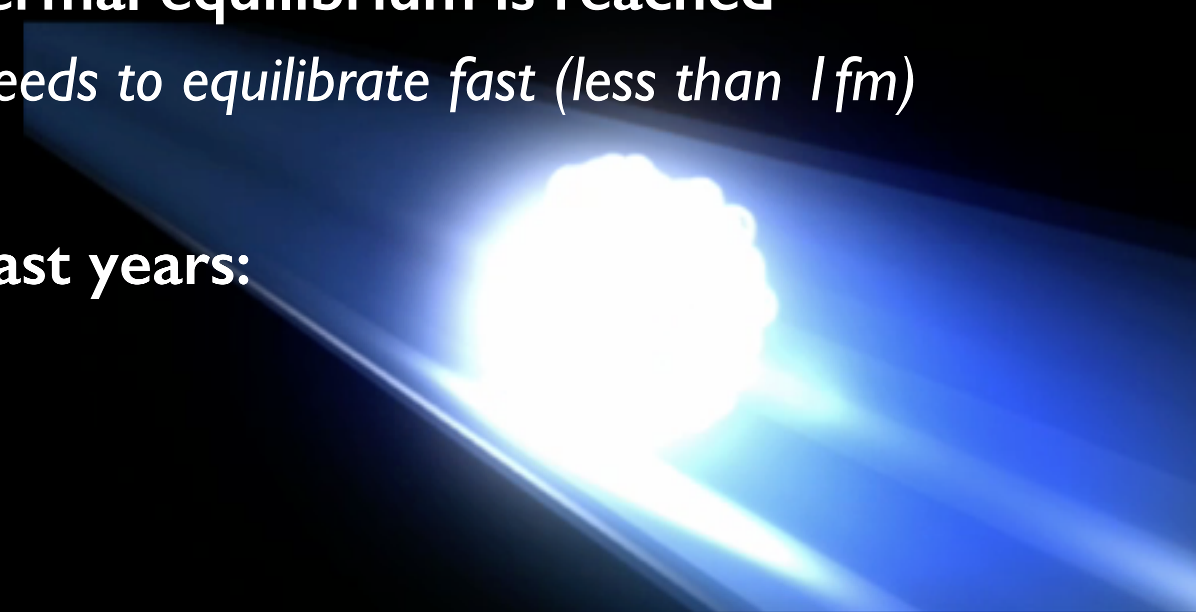
(+ Equation of State)

Does not address the question on **how thermal equilibrium is reached**

- *Far from equilibrium initial state needs to equilibrate fast (less than 1fm)*

Most of the theoretical progress in the last years:

- *Viscosity corrections*
- *Fluctuations in initial conditions*



Elliptic flow - a strong signal of hydro behavior

Remember the Euler eq.

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

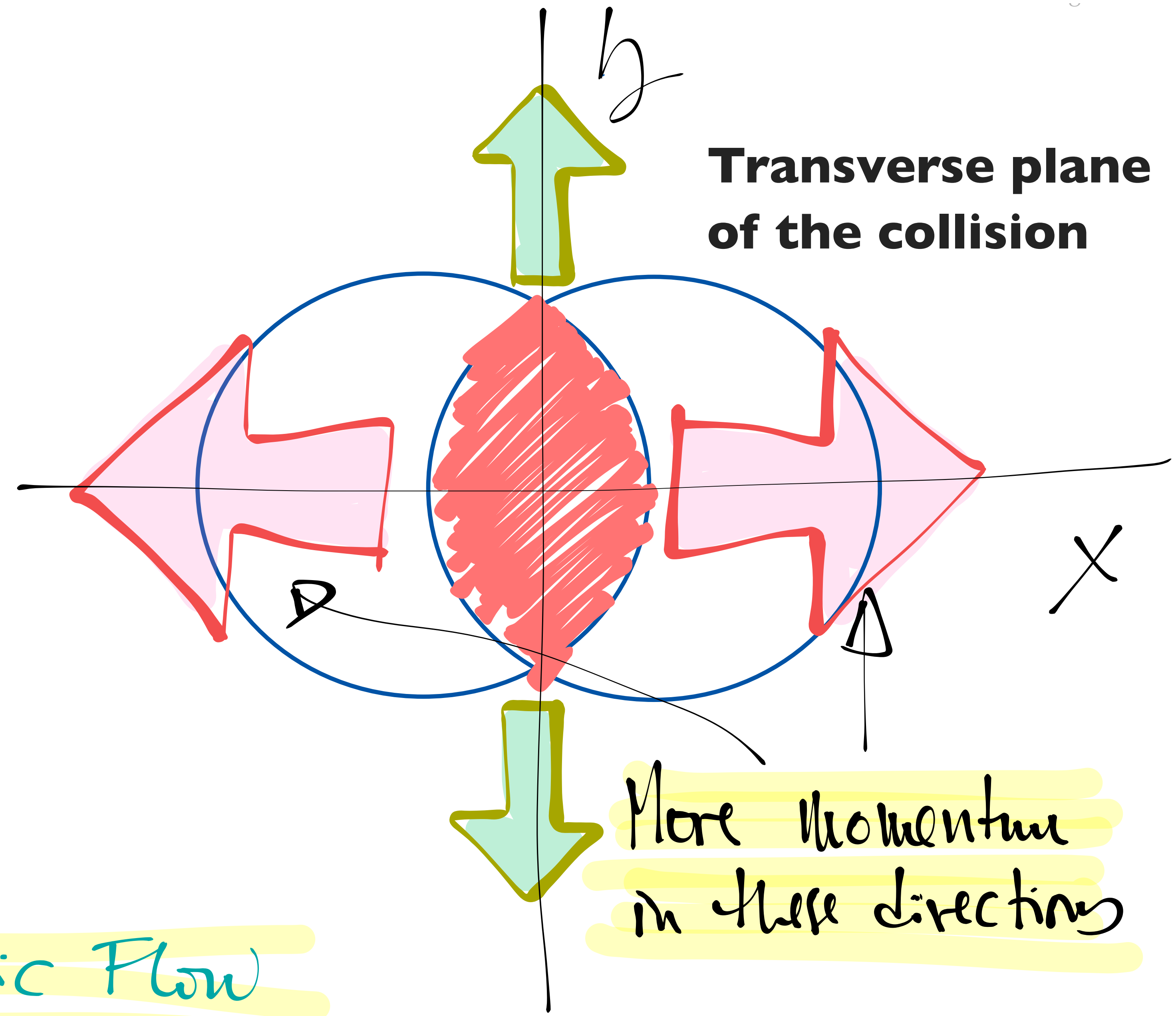
$$\epsilon = 3P \implies \partial_x P > \partial_y P$$

Make a Fourier decomposition

- Elliptic flow is the second component

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

→ Elliptic Flow

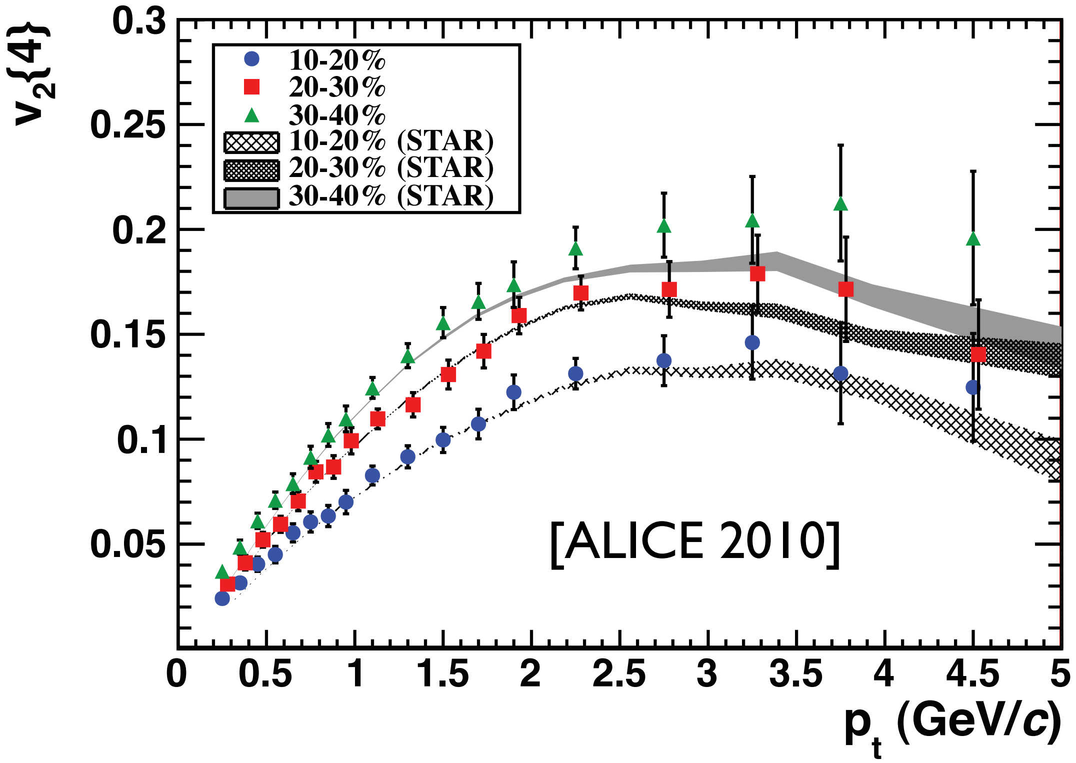


Anisotropies in the initial spacial distributions - <u>geometry</u> - translate into anisotropies in the momentum distributions

- Impossible with instantaneous, point-like, interactions unless initial- or final-state correlations

Fluid behavior from hydro: viscosity of the QGP

LHC flow similar to RHIC



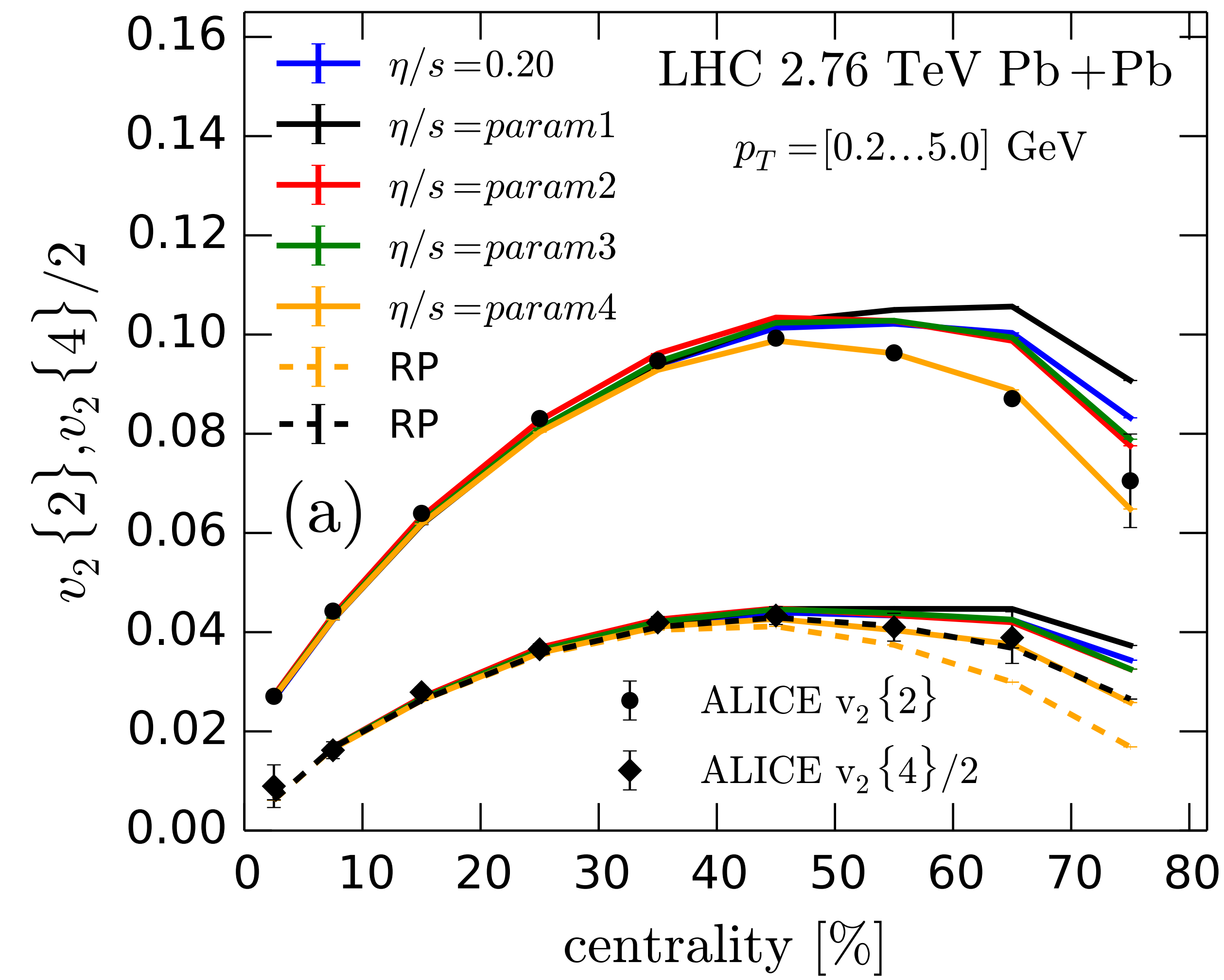
Lowest viscosity known

- "Perfect liquid": sQGP
- AdS/CFT bound

$$\frac{\eta}{s} \geq \frac{1}{4\pi}$$

[Policastro, Son, Starinets, 2001]

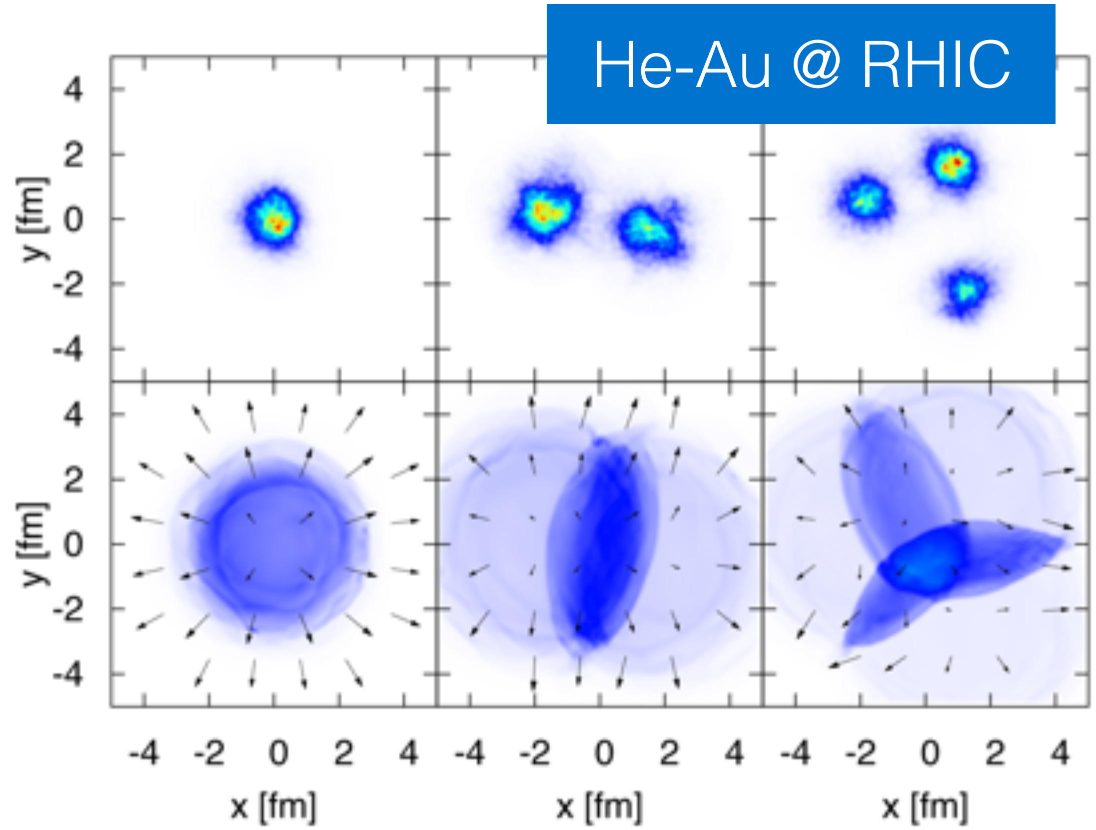
Well described by hydro



[Niemi, Eskola, Paatelainen 2015]

Higher harmonics and event-by-event fluctuations

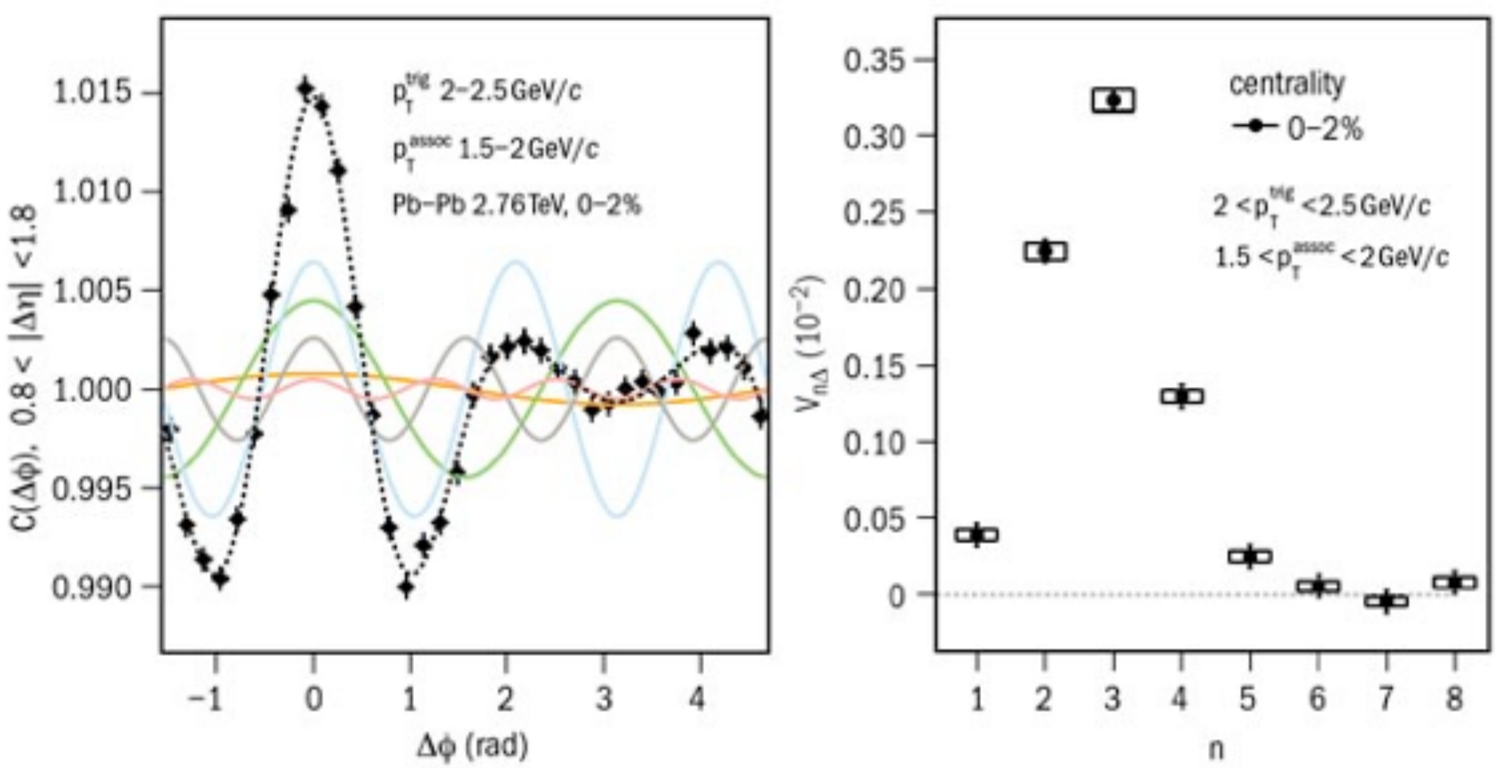
$$\frac{dN}{d\phi} \propto 1 + 2 \sum_n v_n \cos n\phi$$

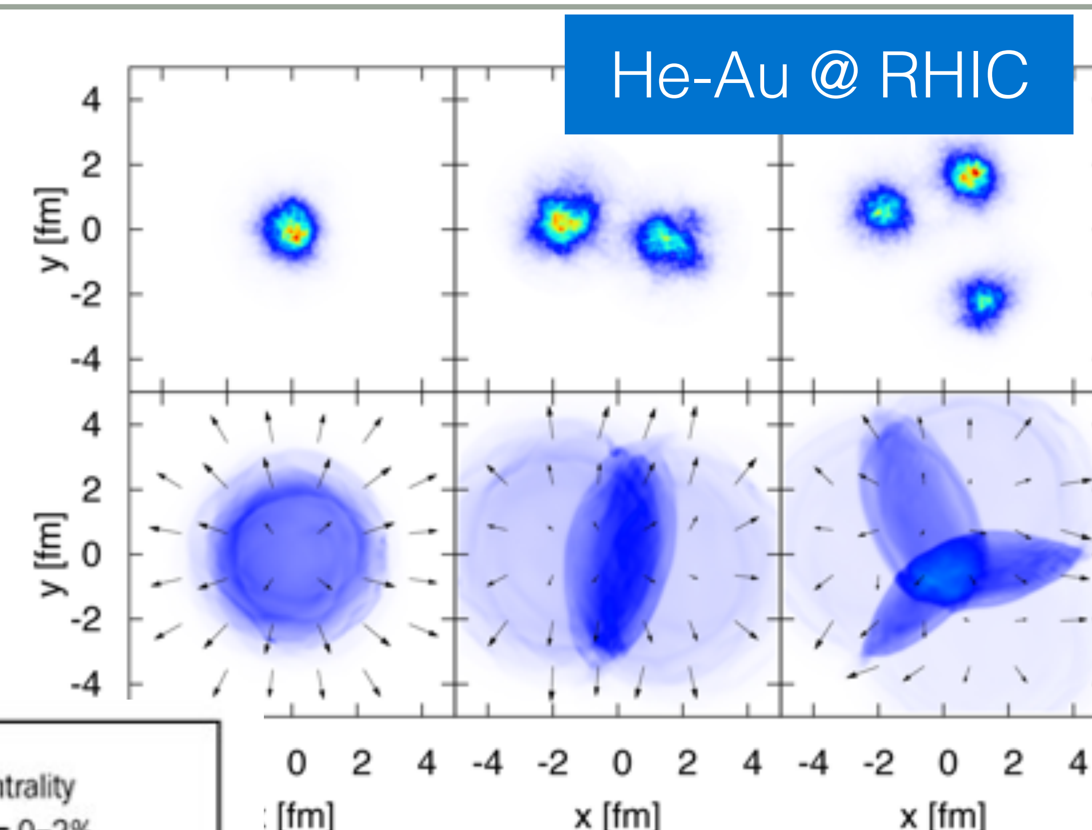


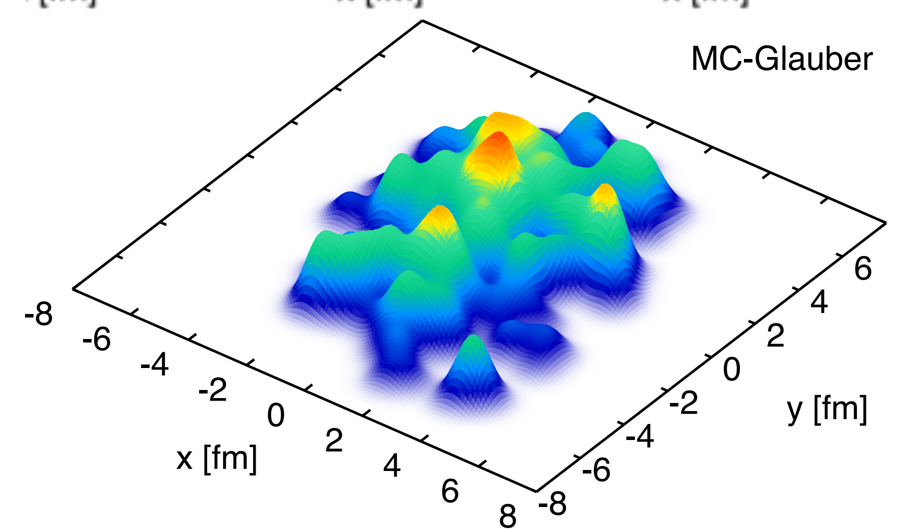
Higher harmonics and event-by-event fluctuations

$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos n\phi$$

[ALICE 2011]





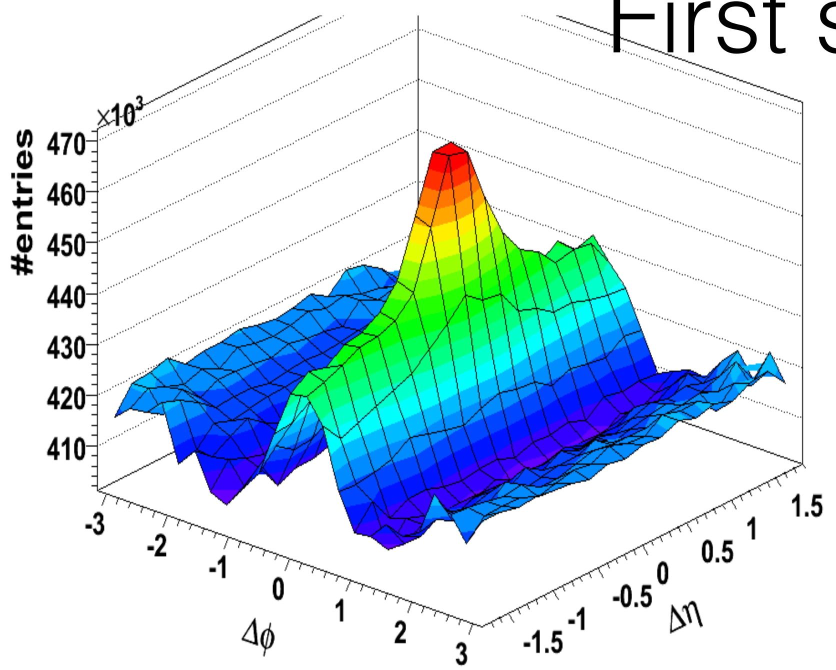


[Gale, Jeon, Schenke]

Anisotropic initial conditions : all harmonics (in particular odd) present

The ridge

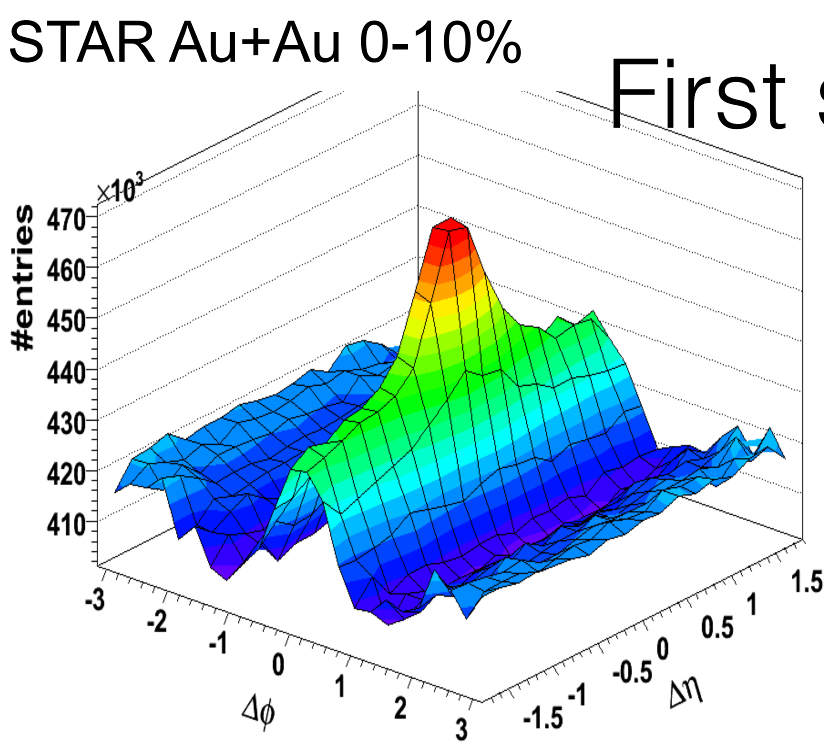
STAR Au+Au 0-10%



First seen (2008) in AuAu, STAR @ RHIC. Generated lot of discussion

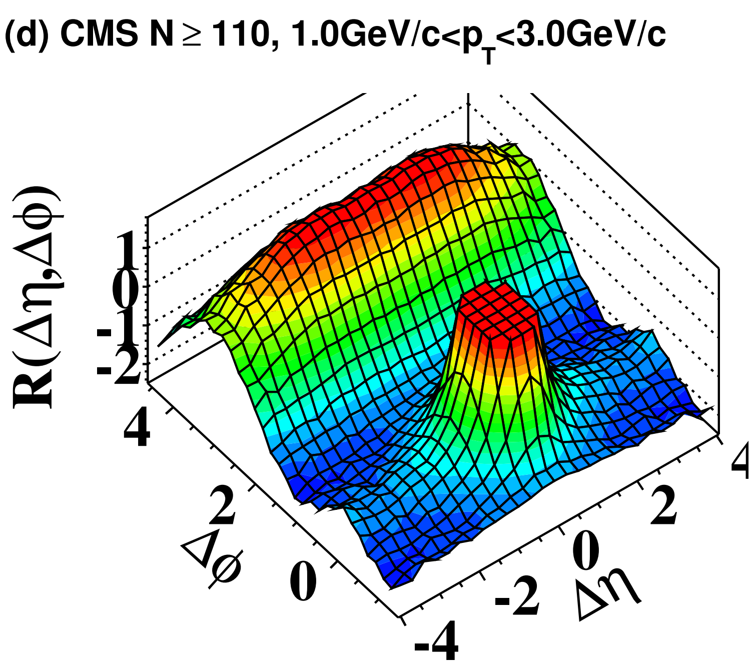
- Long-range (in rapidity) angular correlations indicates collective phenomena

The ridge

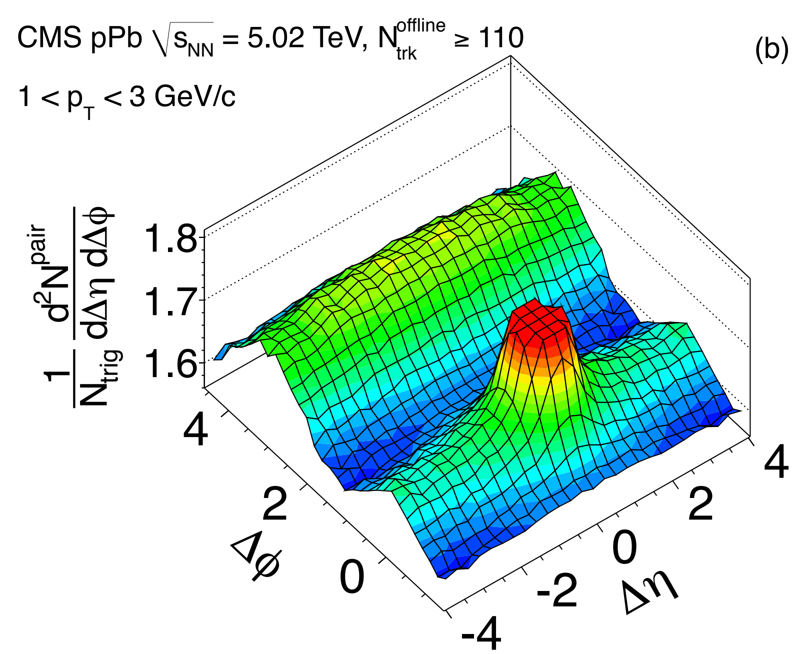


First seen (2008) in AuAu, STAR @ RHIC.
Generated lot of discussion

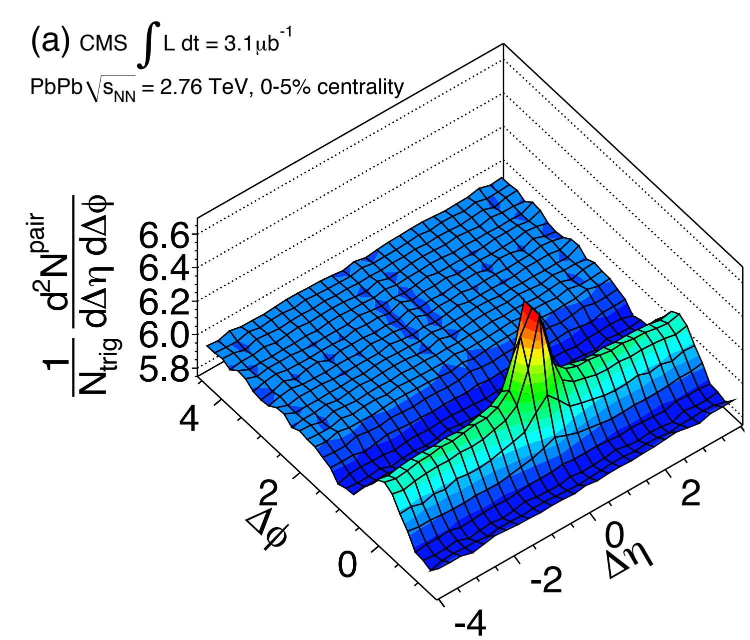
- Long-range (in rapidity) angular correlations indicates collective phenomena



high multiplicity pp

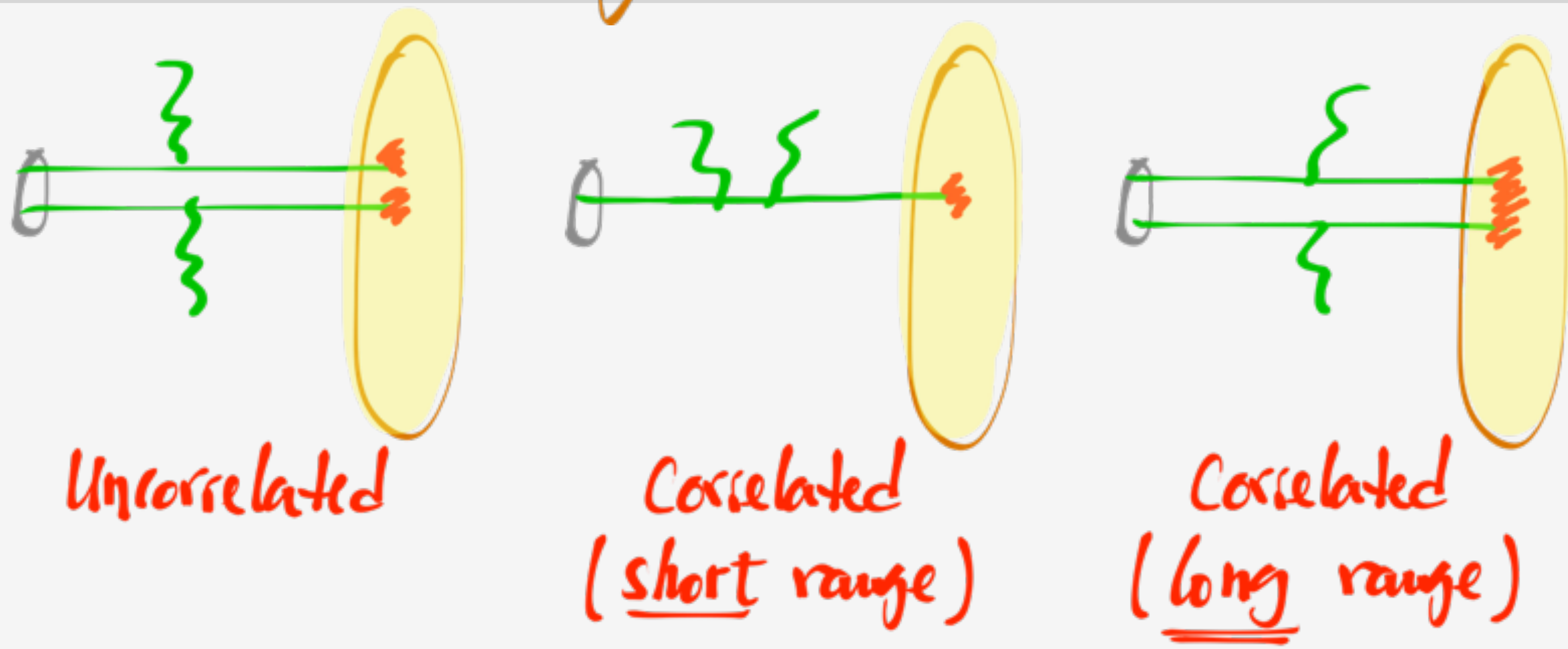


high multiplicity pPb



everywhere in PbPb

The Ridge & the CGC



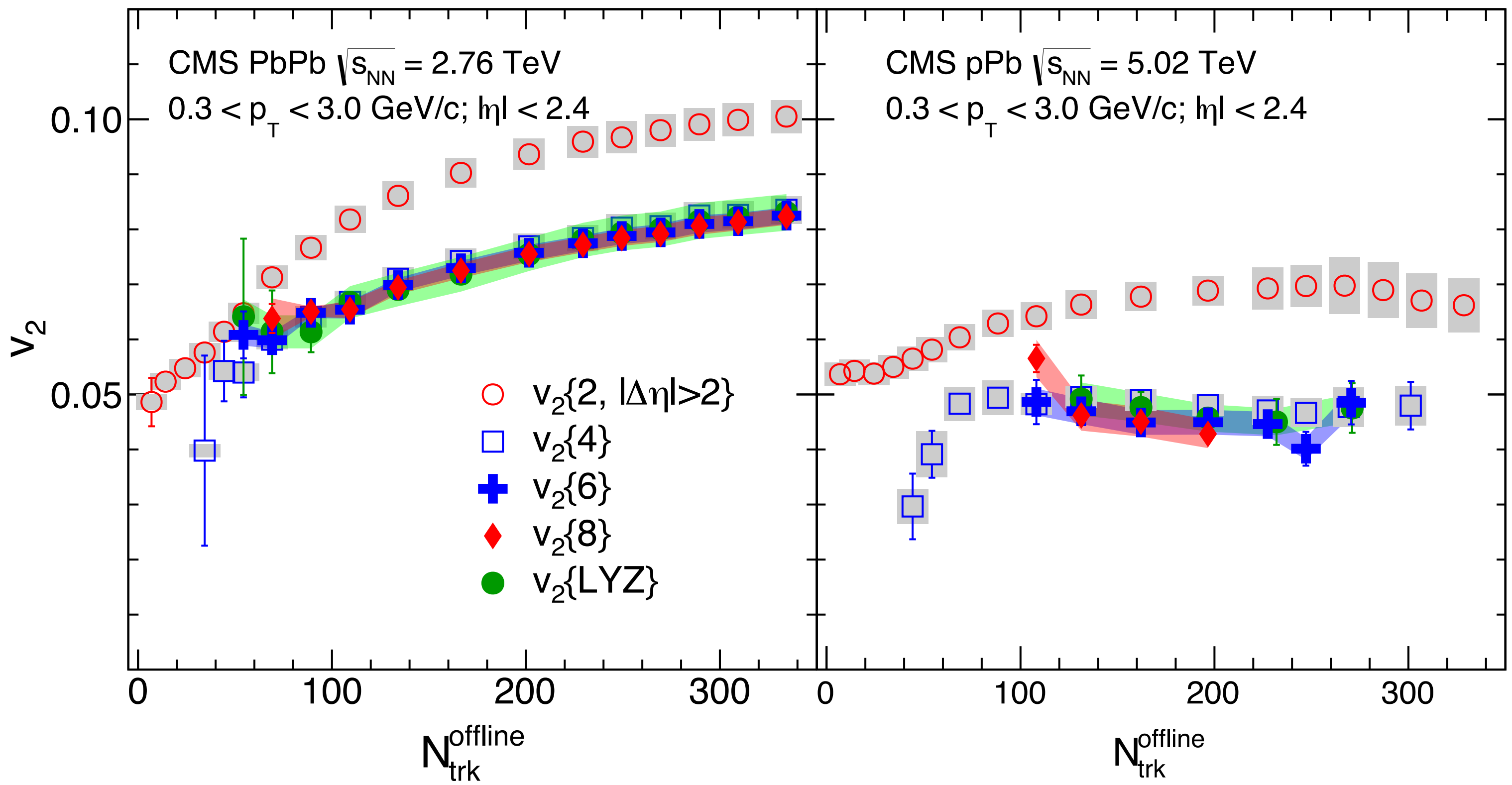
COLOR correlations in transverse plane ~ Q_{sat}^{-1}

The Ridge & the CGC

COLOR correlations in transverse plane ~ Q_{sat}^{-1}

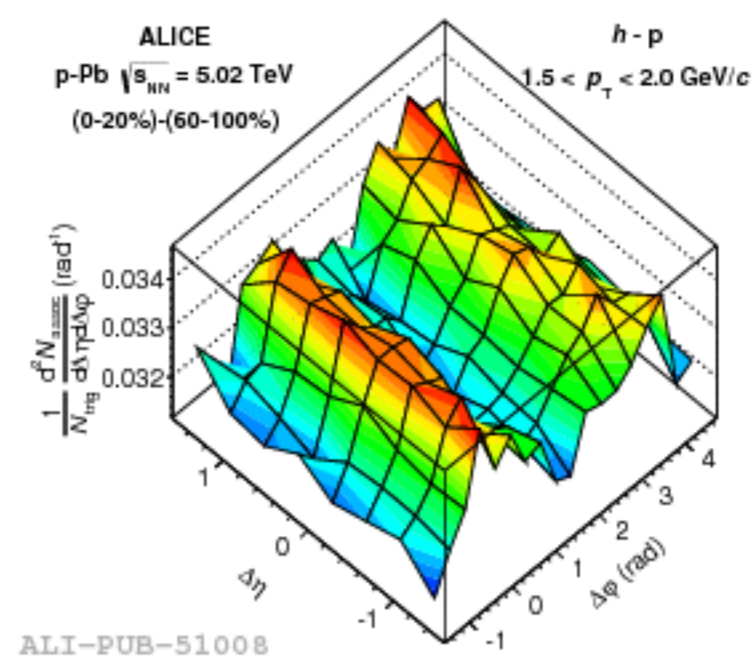
Is the Ridge Initial State / Final State / Both?

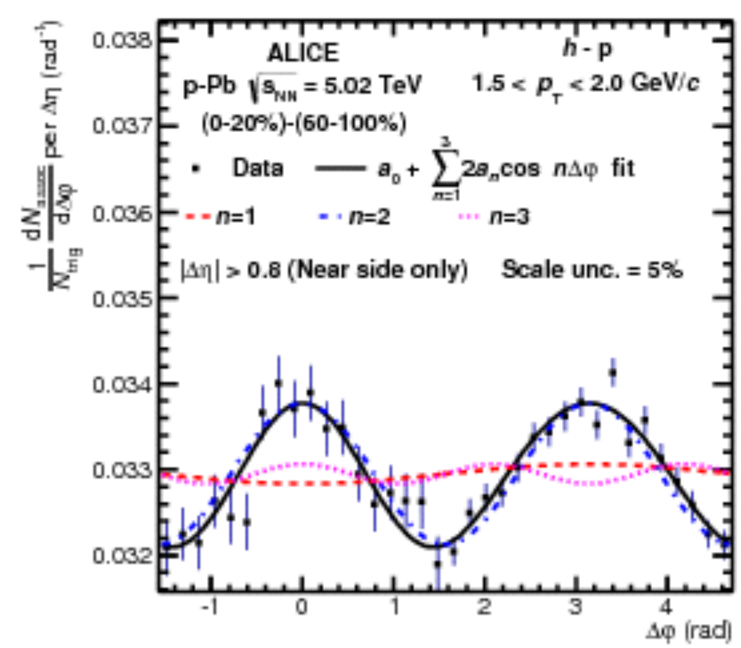
Characterizing the ridge



Factorization - natural in hydro difficult to compute in CGC

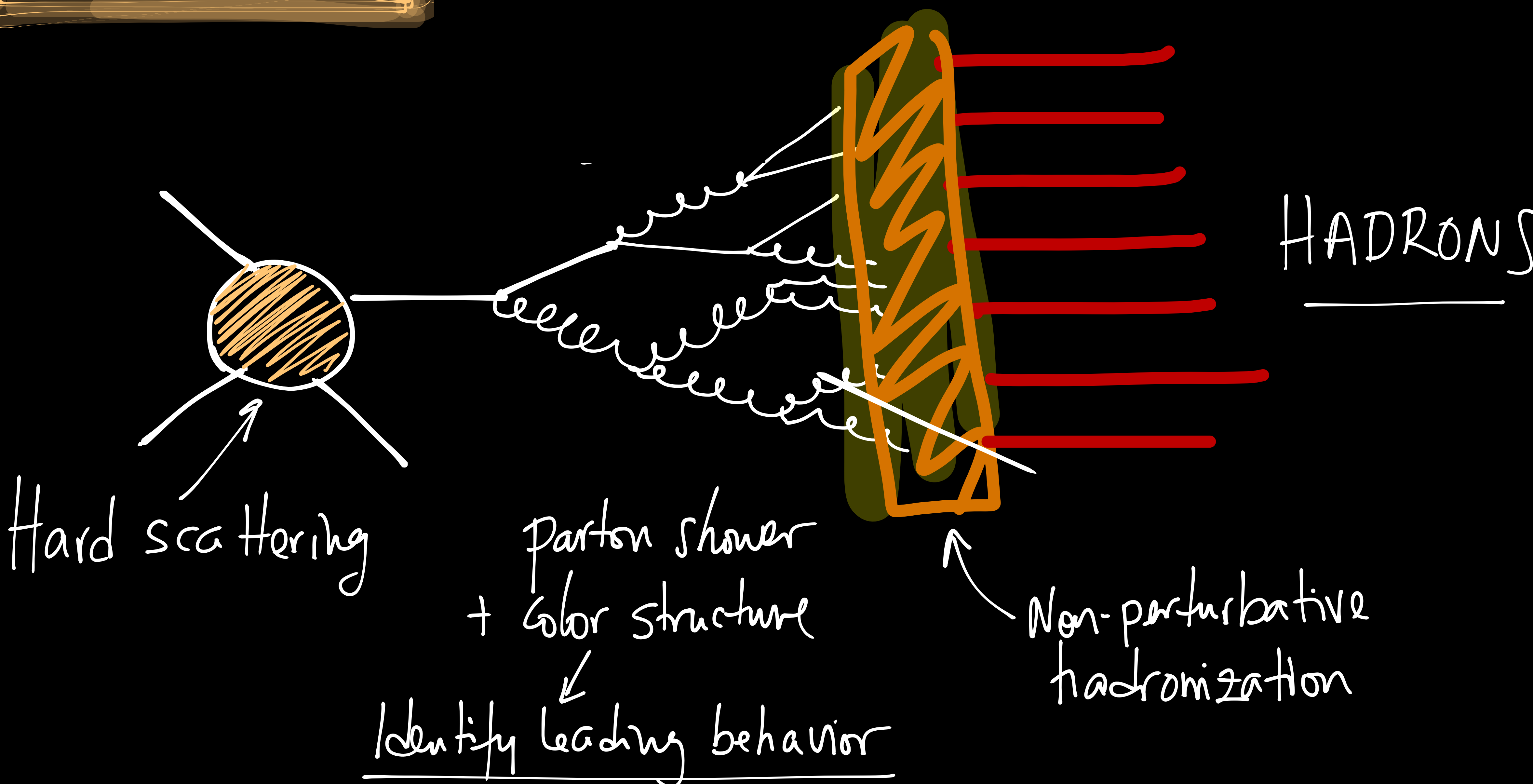
Double-ridge predicted in CGC
[Kovchegov, Wertepny / Dusling, Venugopalan]
also natural in hydro





Jets in medium

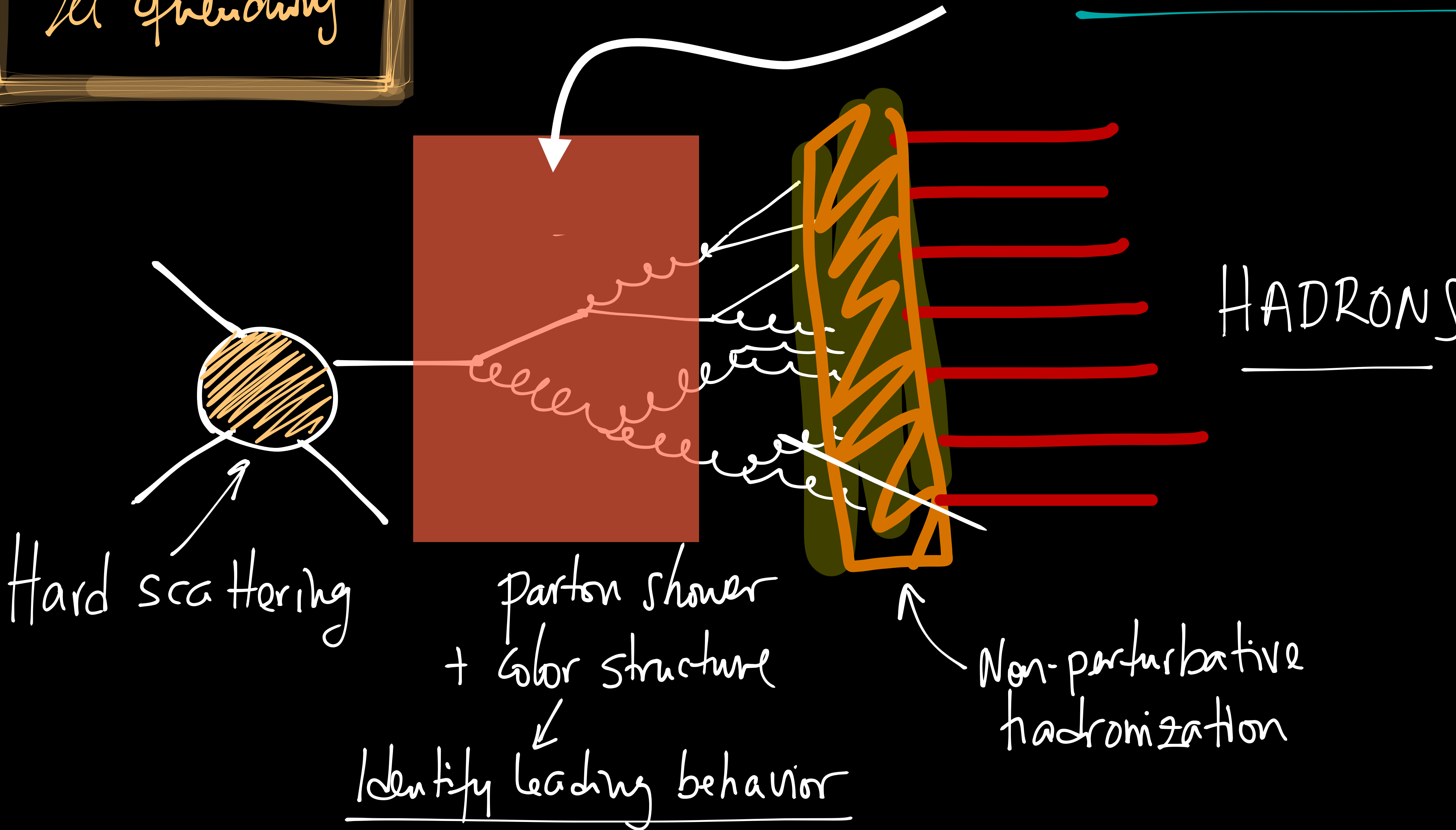
Jet quenching



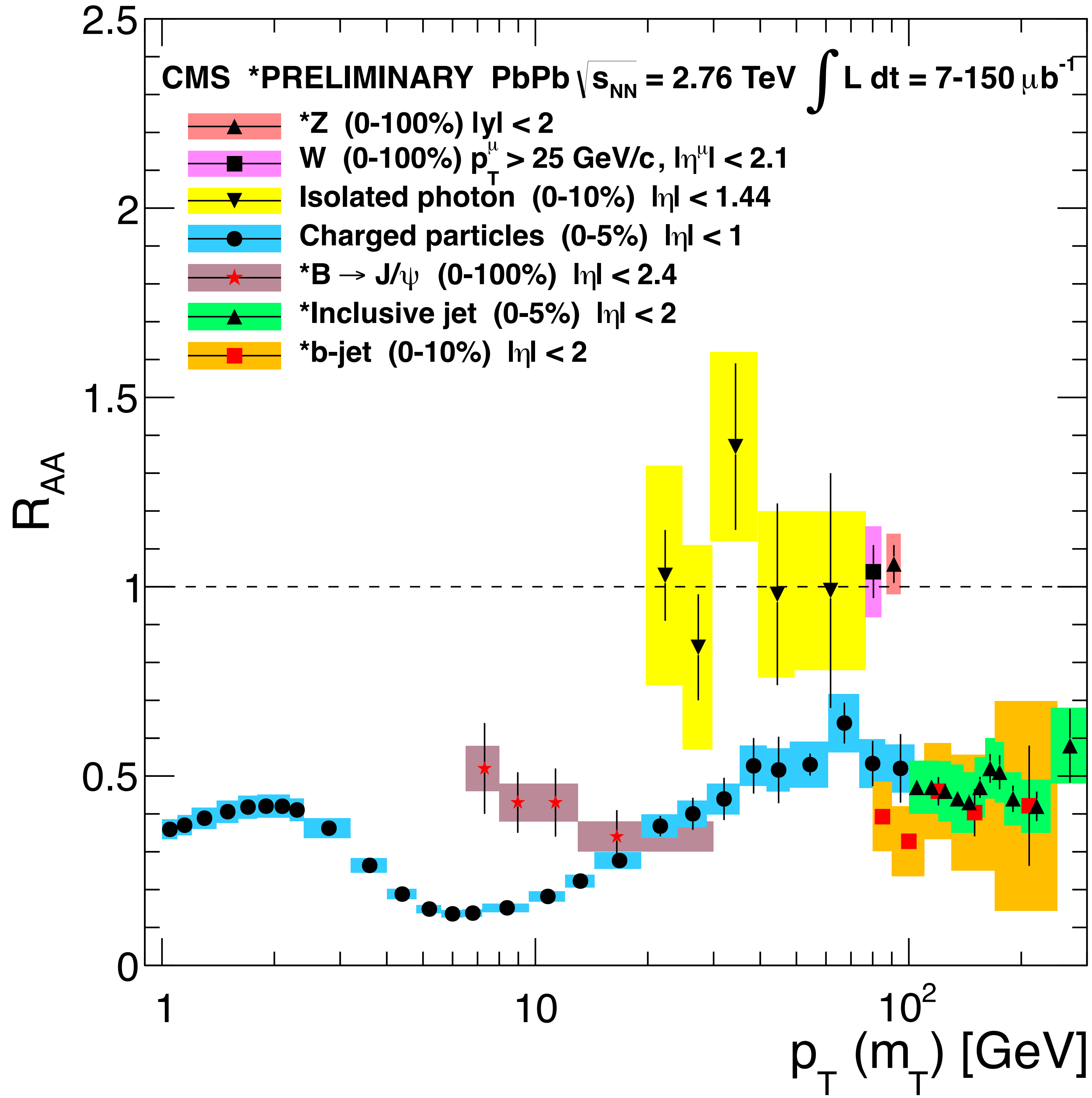
Jets in medium

Jet quenching

Put now a medium here

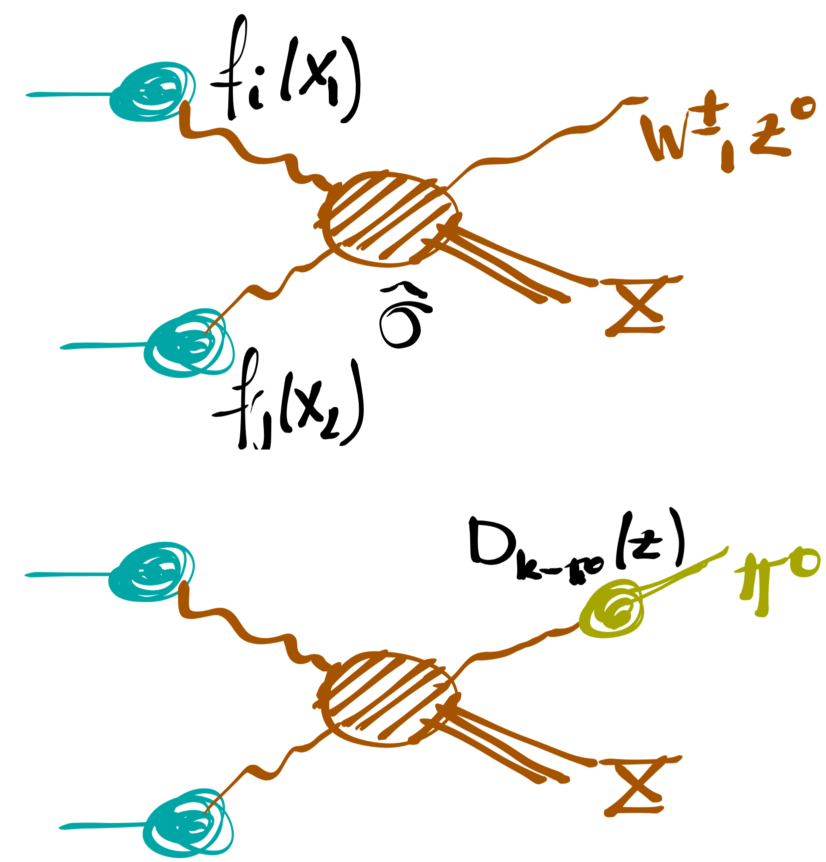


Suppression in one plot (LHC)

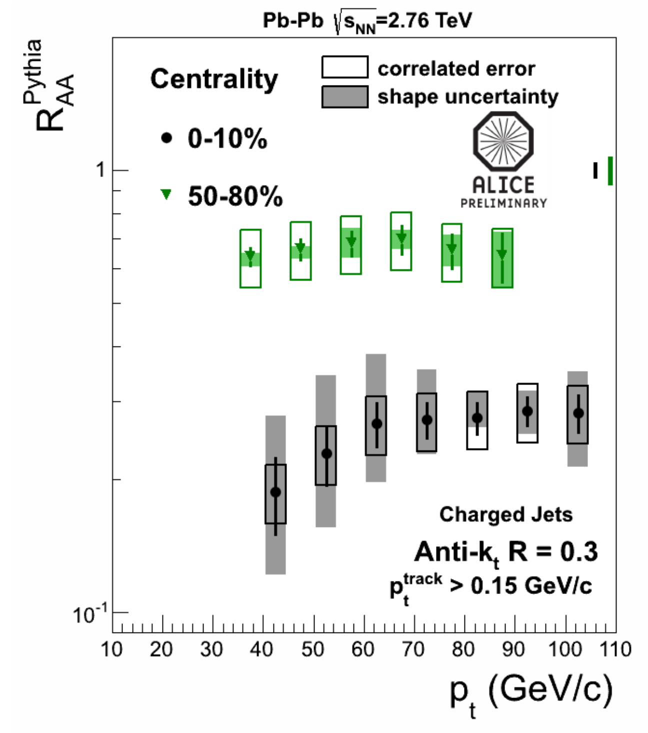


[A. Florent - Hard Probes 2013]

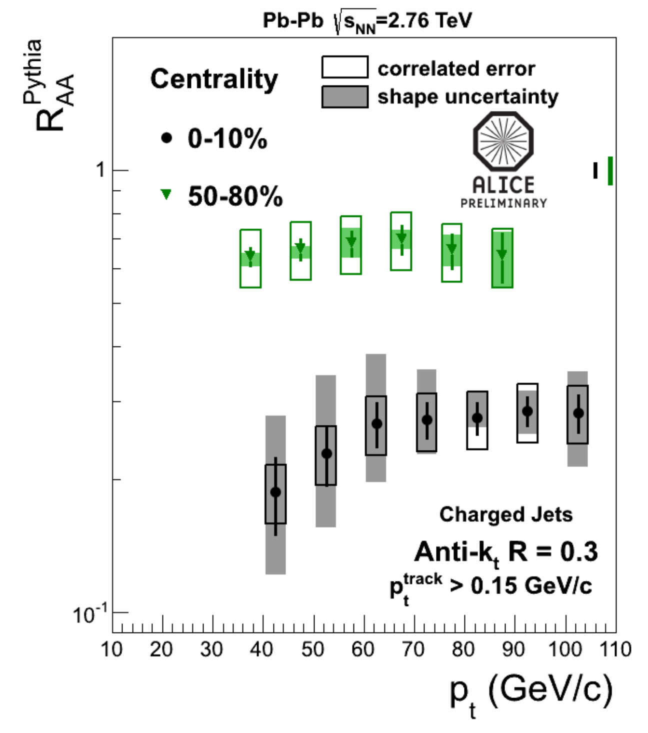
$$R_{AA} = \frac{dN^{AA}/dp_t}{\langle N_{coll}\rangle dN^{pp}/dp_t}$$

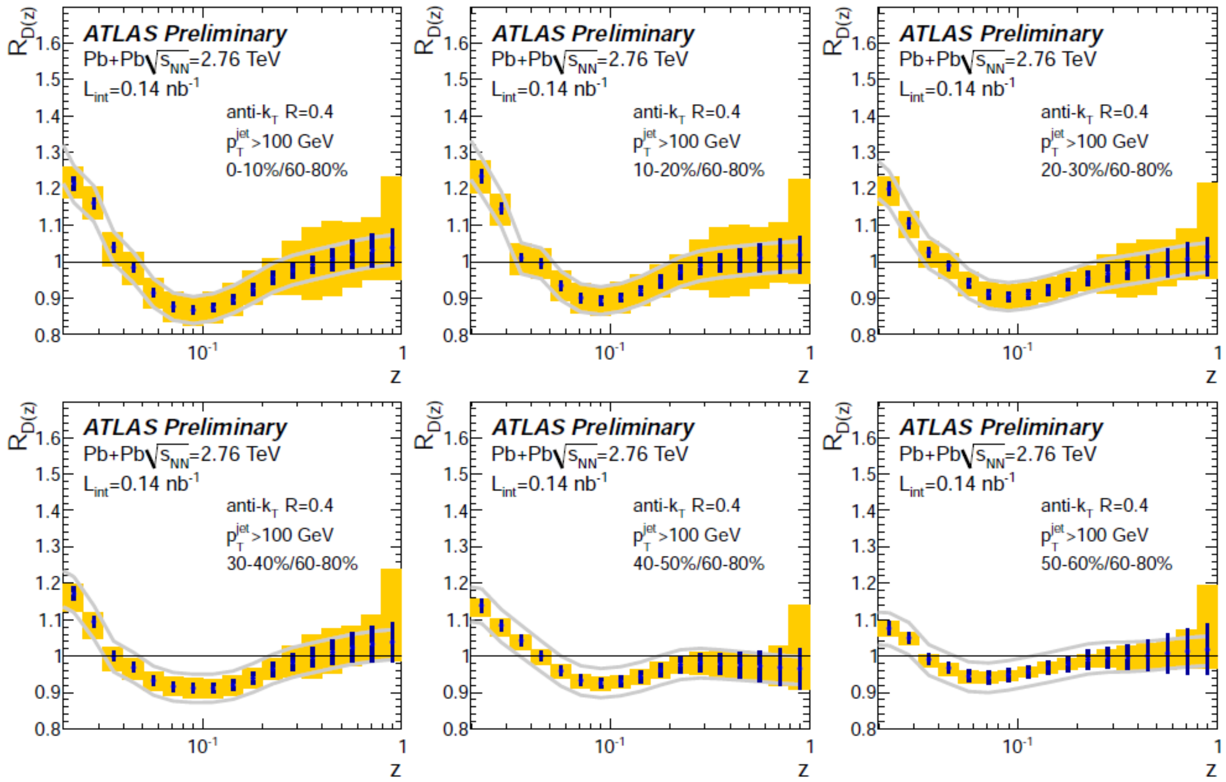


Reconstructed jets - plenty of data now

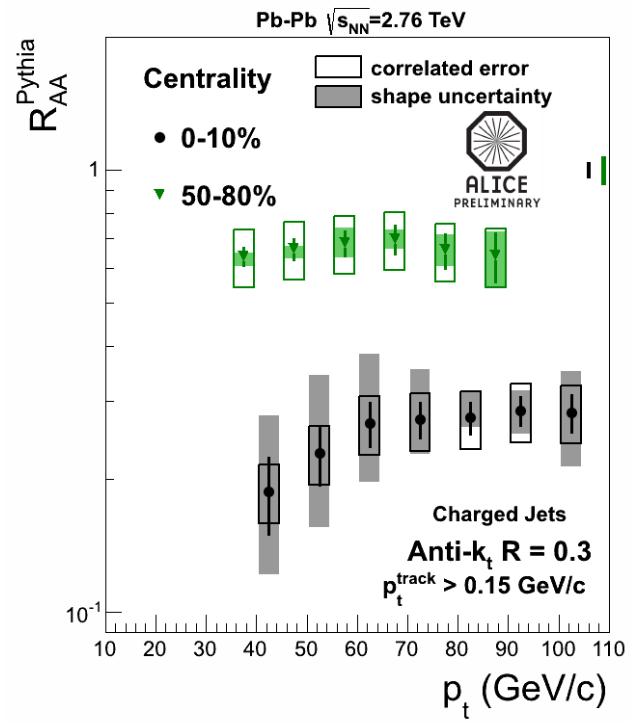


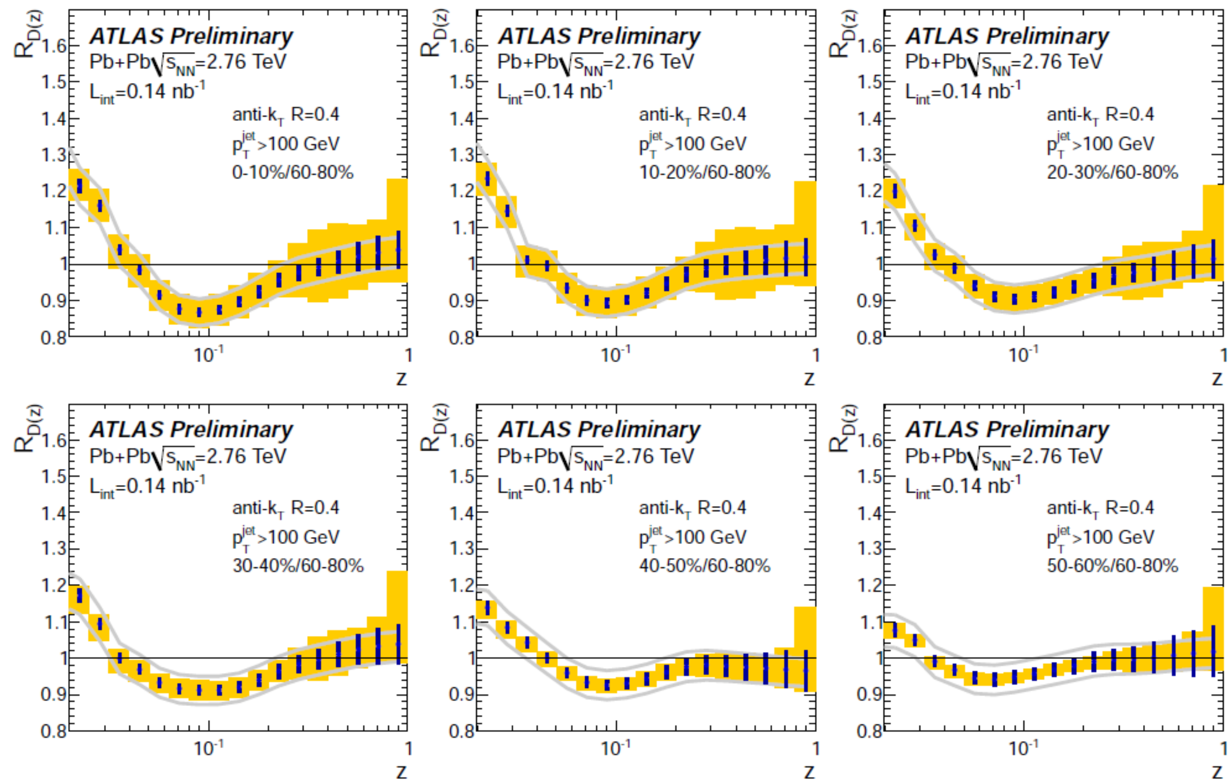
Reconstructed jets - plenty of data now

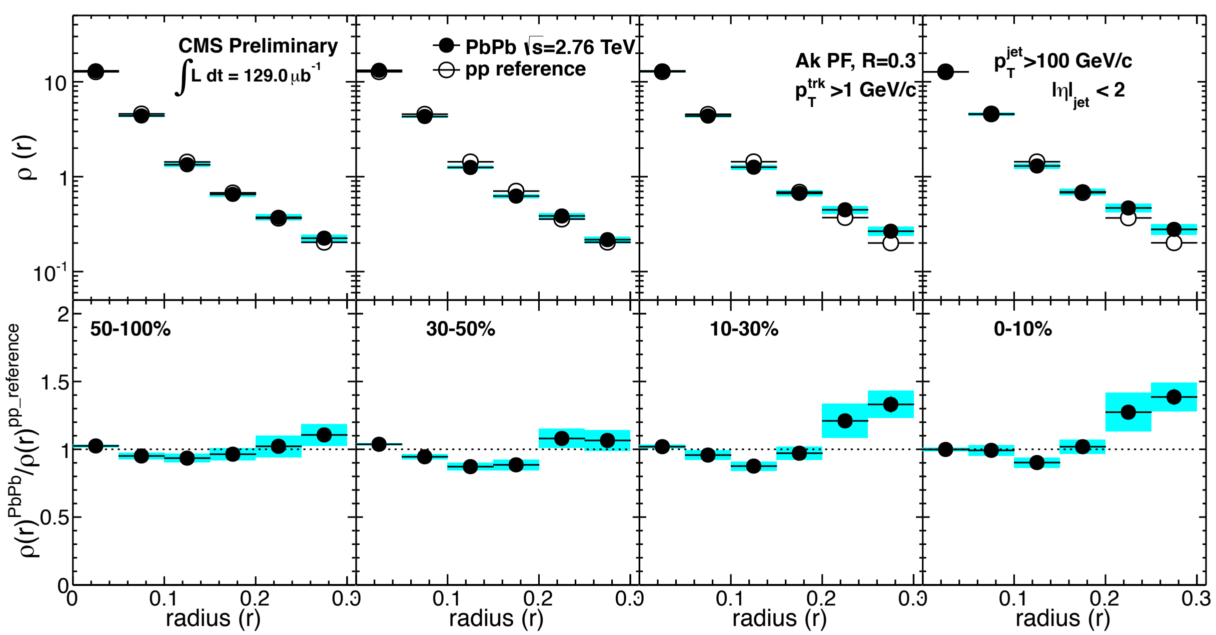




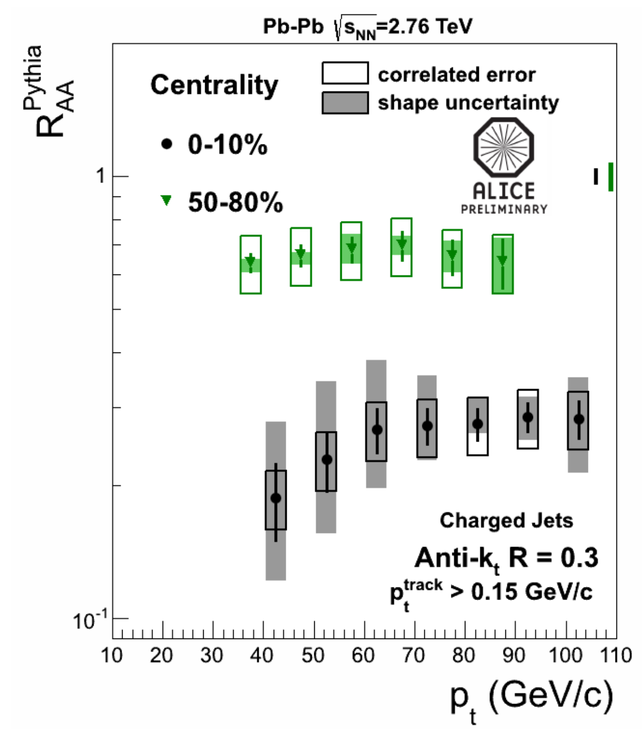
Reconstructed jets - plenty of data now

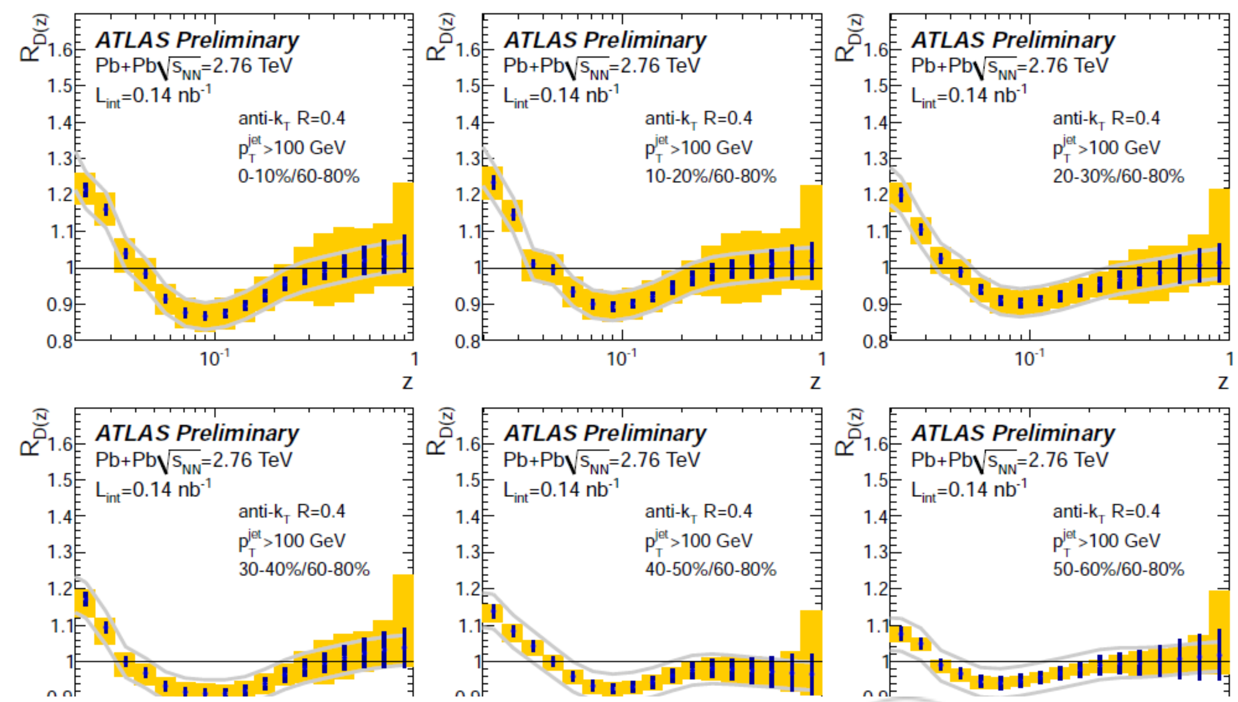


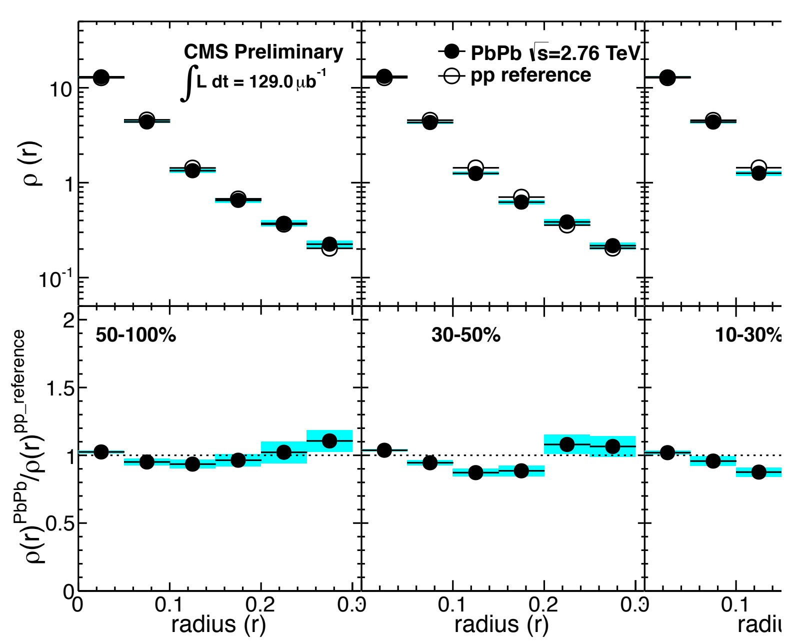


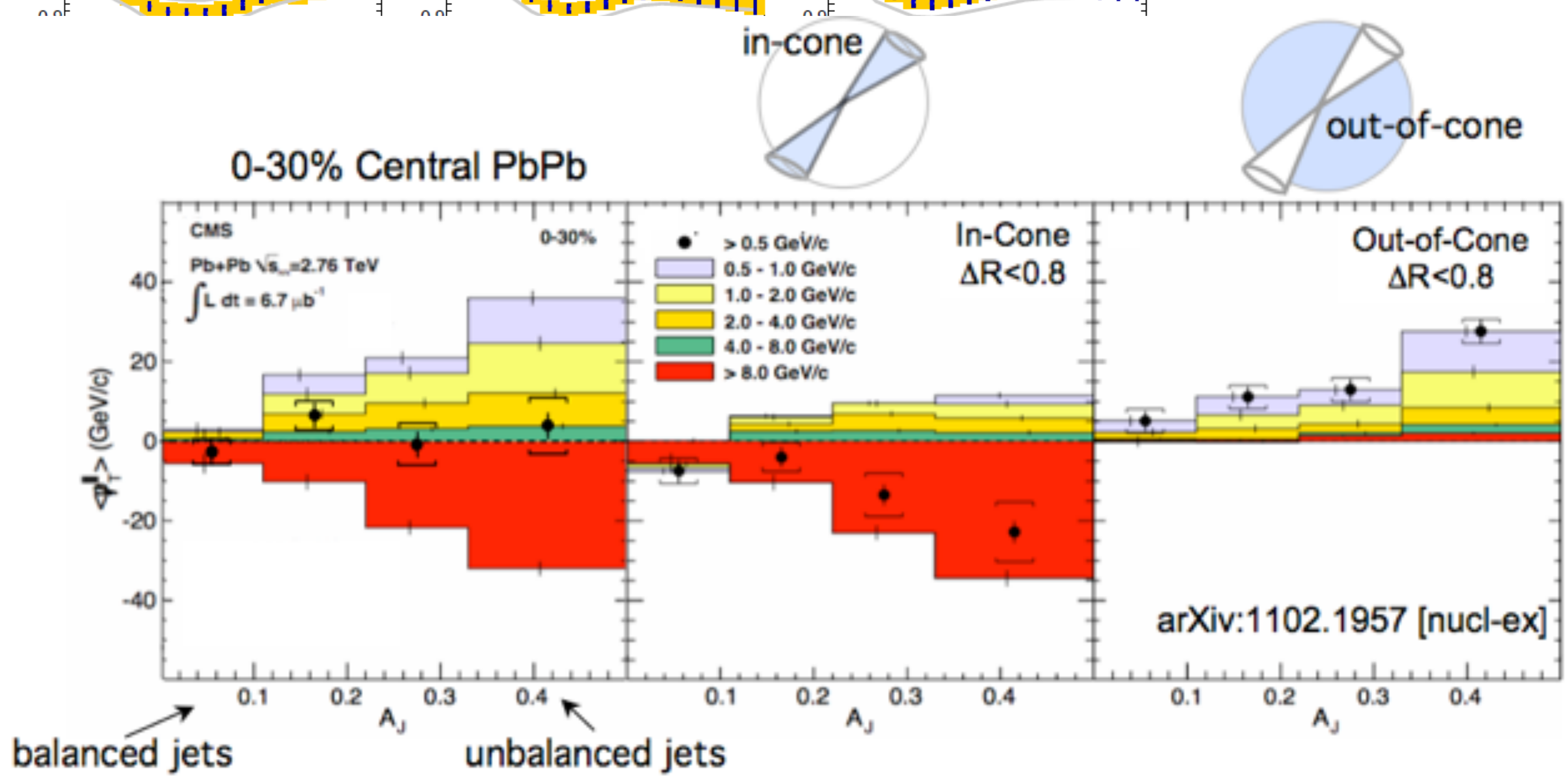


Reconstructed jets - plenty of data now

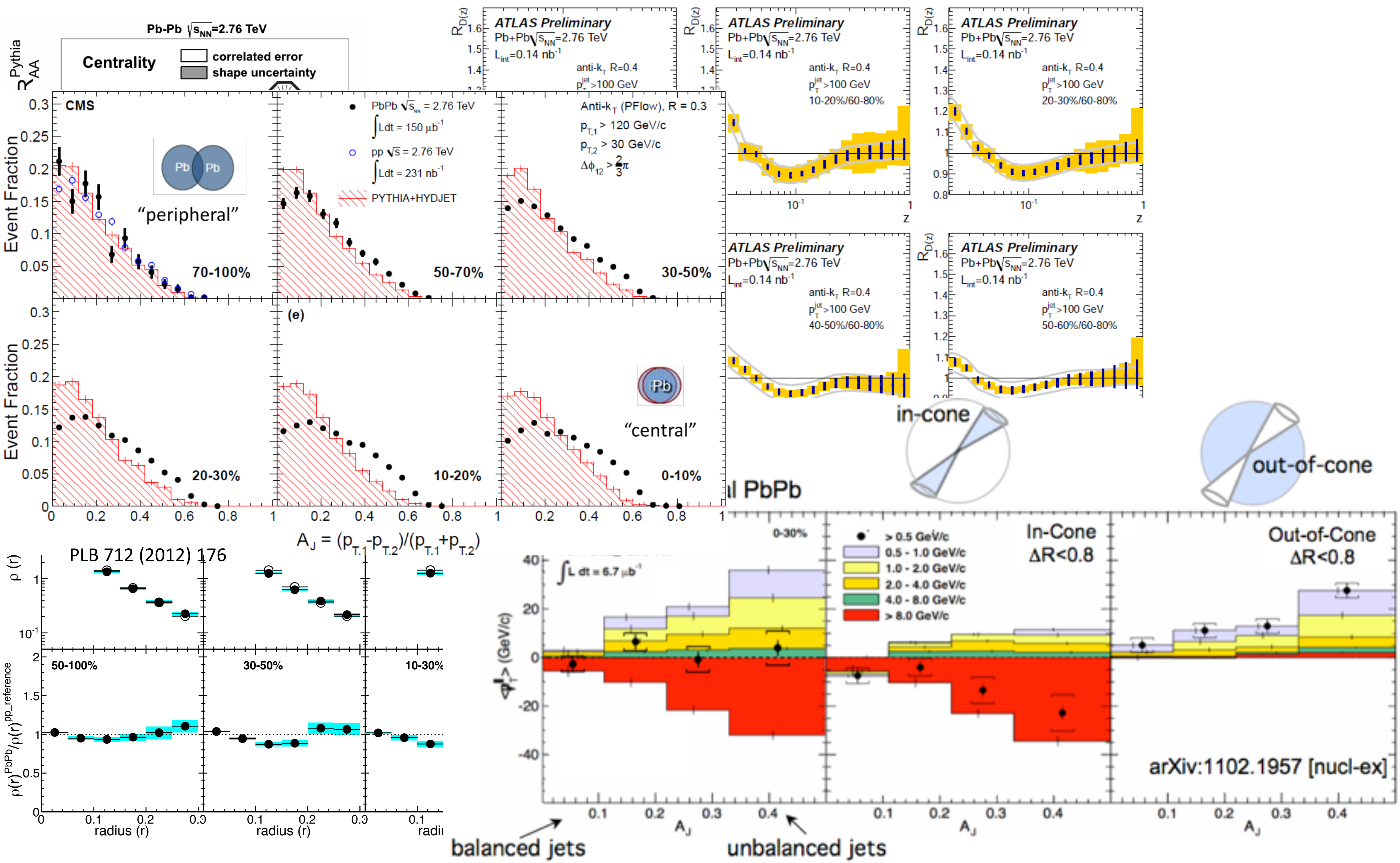




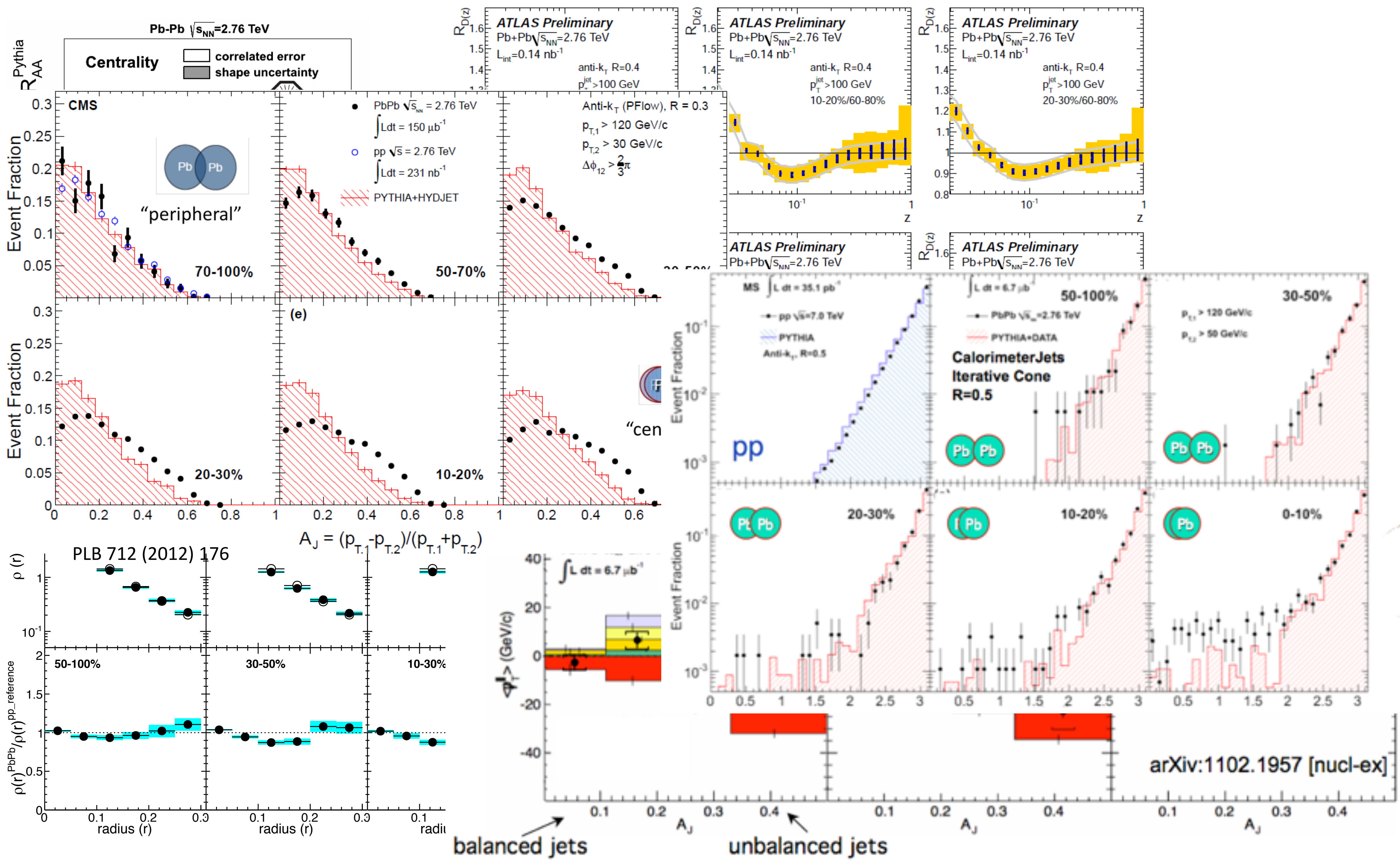




Reconstructed jets - plenty of data now



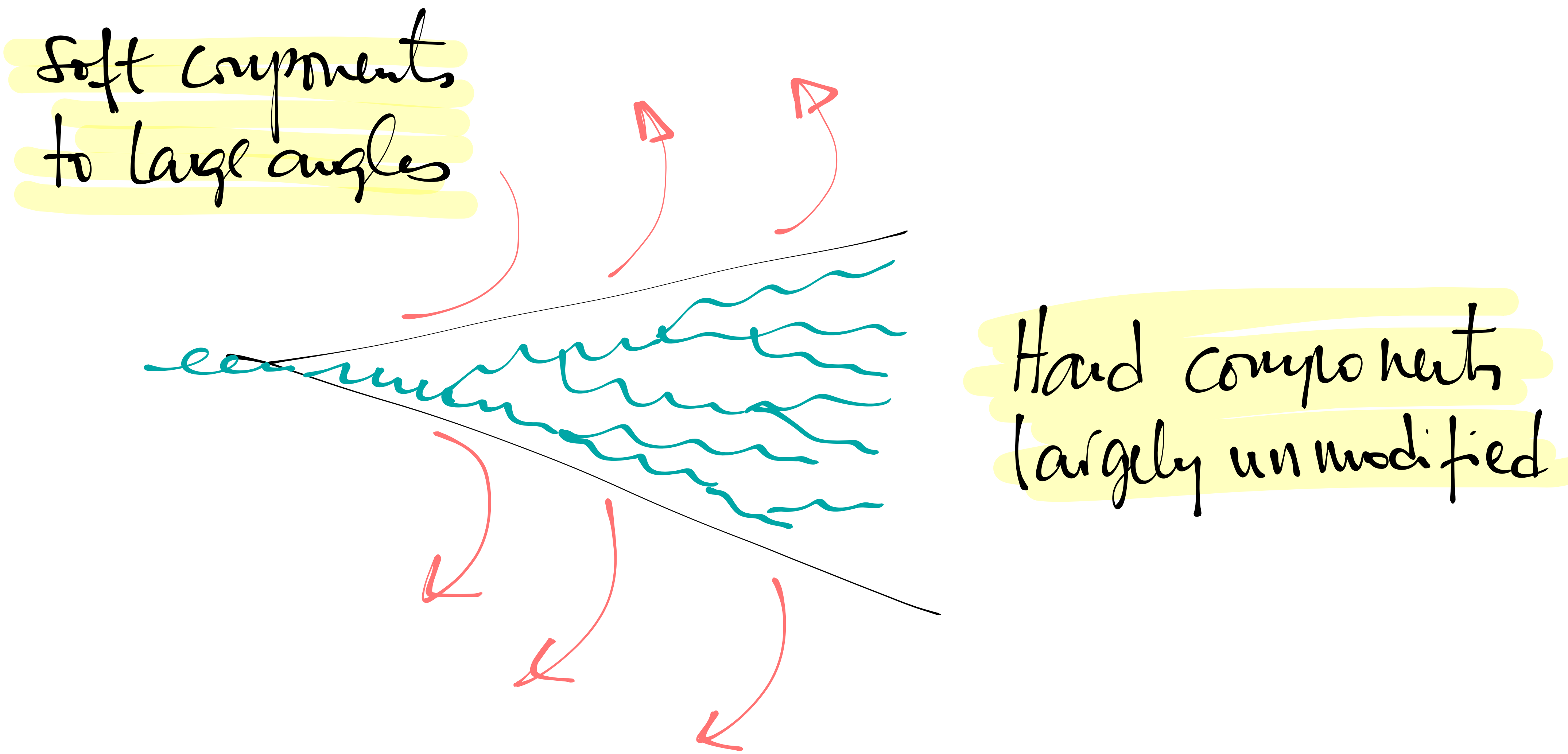
Reconstructed jets - plenty of data now



Qualitative description: jet collimation

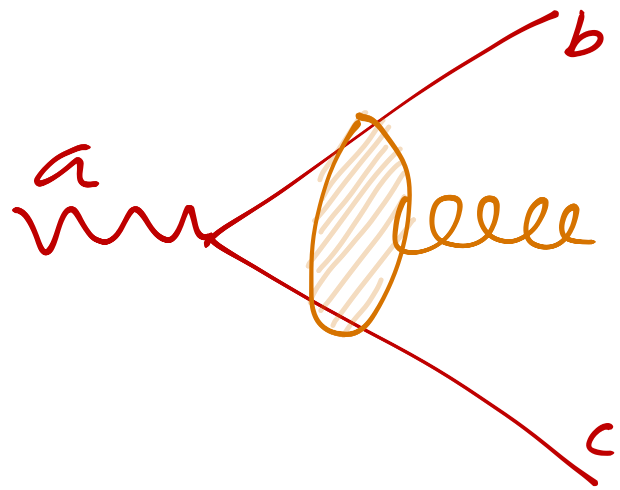
Lessons from experimental data on jet reconstruction

- Suppression similar to inclusive hadrons for similar pT
- Fragmentation functions are mildly modified - more in soft
- Jet shapes have mild modifications
- Azimuthal decorrelation of di-jets as in proton-proton
- Energy taken by soft particles at large angles



Coherence and decoherence in the antenna

Antenna in the vacuum



$$r_\perp \sim \Theta\, t_{\rm form} \sim \frac{\Theta}{\theta^2 \omega}$$

$$\lambda_\perp \sim \frac{1}{k_\perp} \sim \frac{1}{\omega\theta}$$

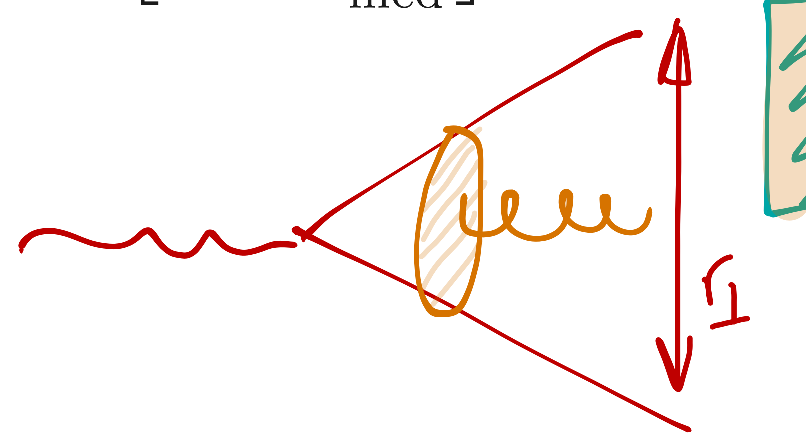
$$r_\perp > \lambda_\perp \iff \Theta > \theta$$

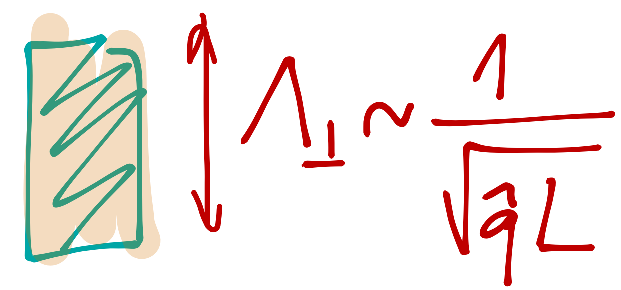
Coherent emission

Antenna in the medium

- Decoherence parameter

$$\Delta_{\rm med} = 1 - \exp\left[-\frac{1}{12}\frac{r_\perp^2}{\Lambda_{\rm med}^2}\right]$$





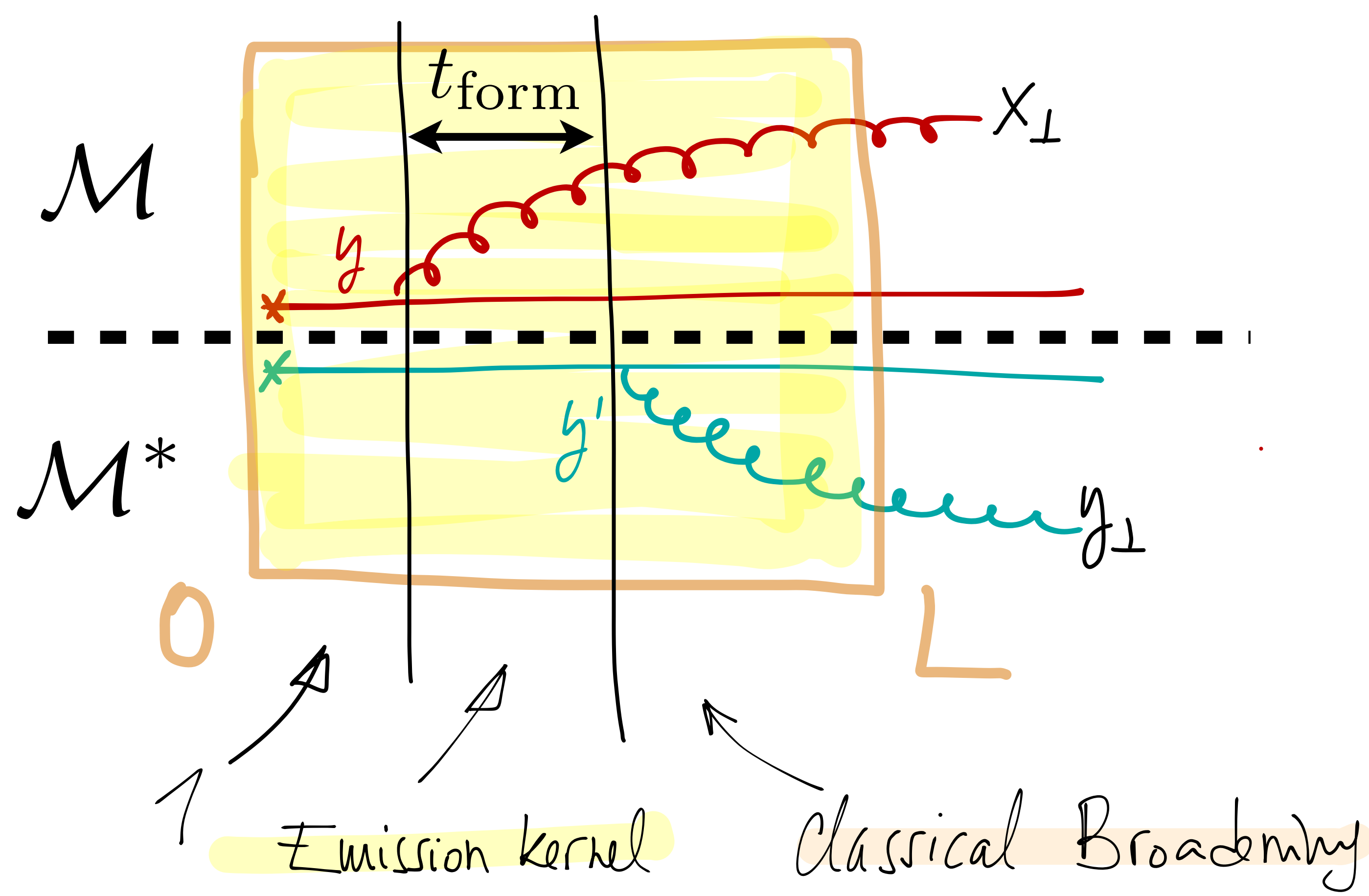
$$r_\perp \sim \Theta L$$

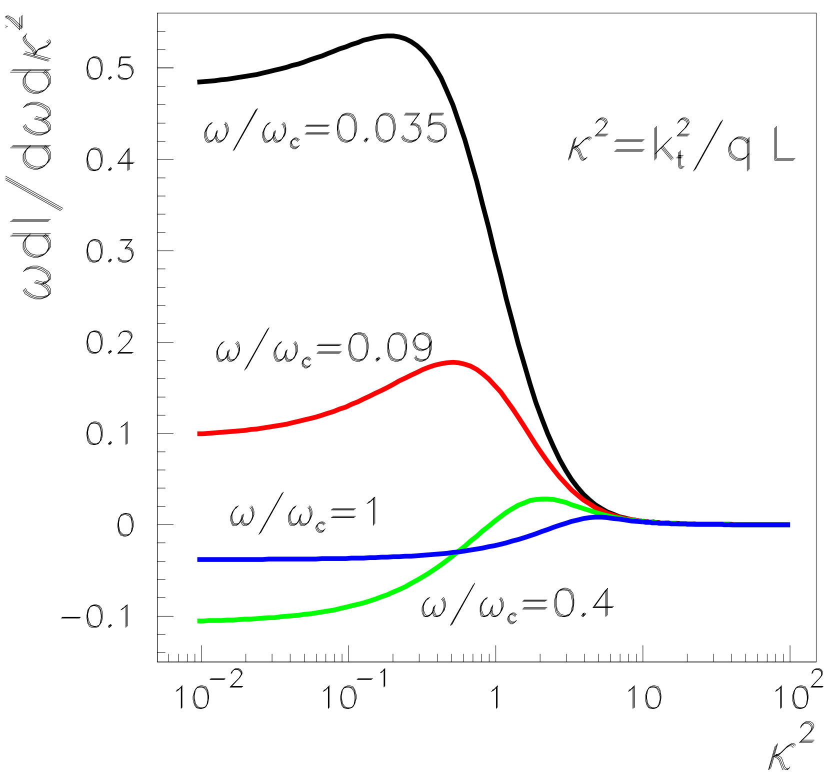
$$\Lambda_{\rm med} \sim \frac{1}{\sqrt{\hat{q} L}}$$

- The medium color-rotates the antenna which eventually looses color coherence

Medium-induced gluon radiation

$$\omega \frac{dI}{d\omega d\mathbf{k}} \sim \alpha_s C_R \int dy \int dy' \int d\mathbf{u}\, \mathrm{e}^{i\mathbf{k}\cdot\mathbf{u}}\, \partial_{\mathbf{u}} \cdot \partial_{\mathbf{y}} \mathcal{K}(y', \mathbf{u}; y, \mathbf{y}) \Big|_{\mathbf{y}=0} \tilde{\mathcal{P}}(L, y'; \mathbf{u})$$



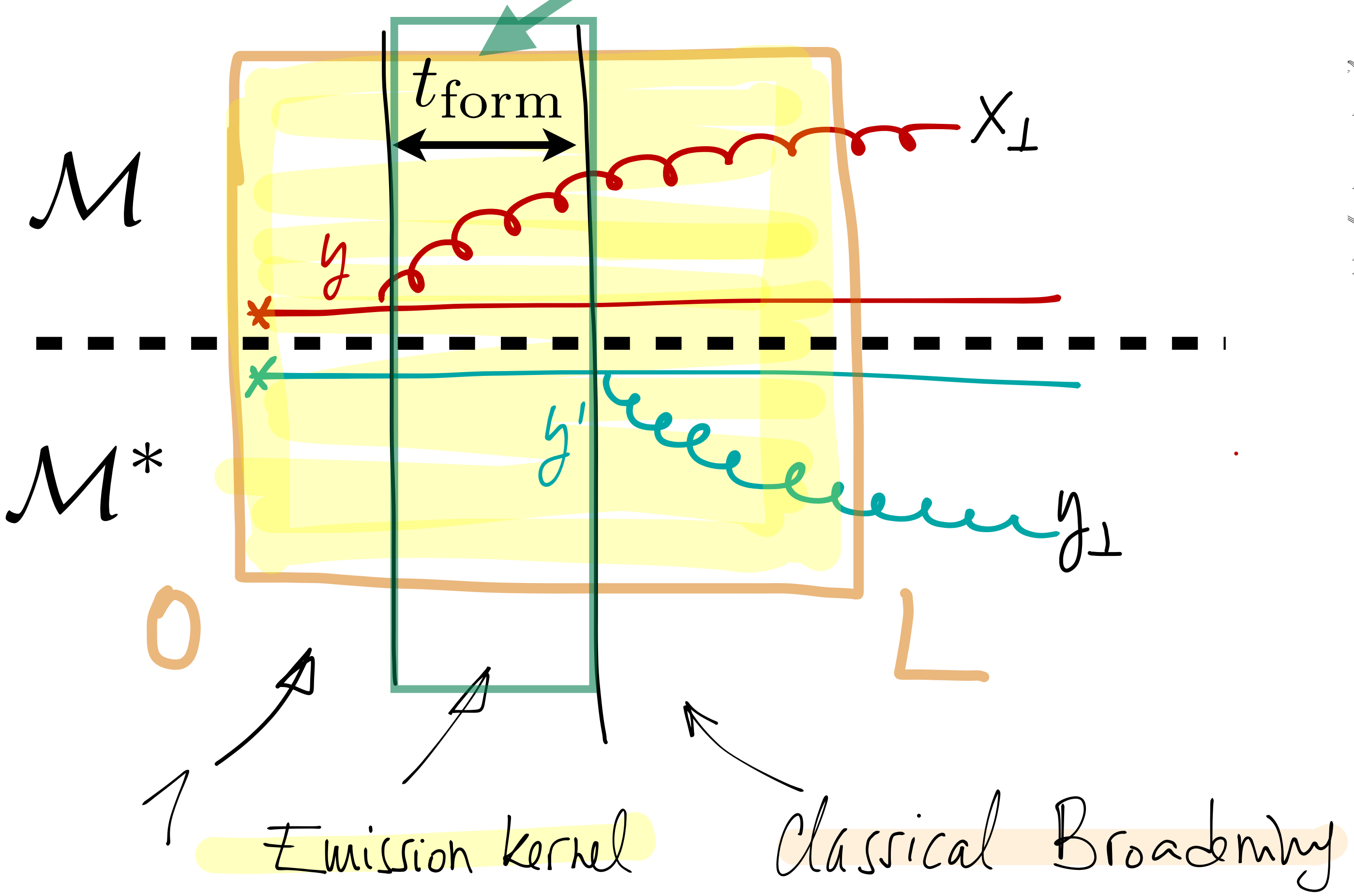


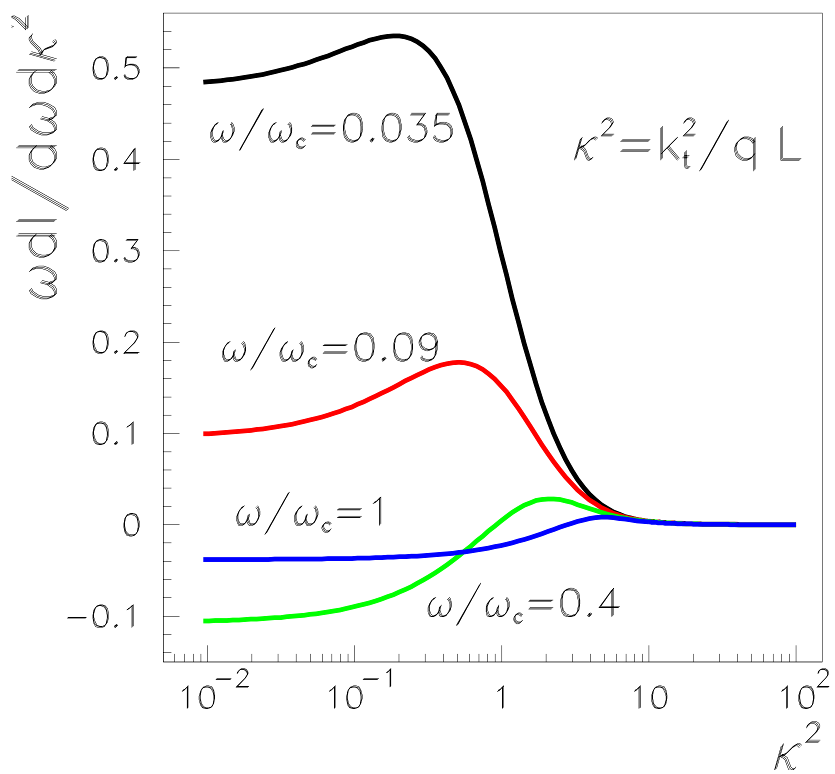
$$\mathcal{K}(y', \mathbf{u}; y, \mathbf{y}) = \int_{\mathbf{y}(y)}^{\mathbf{u}(y')} \mathcal{D}\mathbf{r} \exp\left\{ i\frac{\omega}{2} \int d\xi \left(\frac{d\mathbf{r}(\xi)}{d\xi} \right)^2 \right\} \tilde{\mathcal{P}}(y', y, \mathbf{r})$$

[Zakharov, Baier, Dokshitzer, Mueller, Peigne, Schiff, Wiedemann, Gyulassy, Levai, Vitev, and many others...]

Medium-induced gluon radiation

$$\omega \frac{dI}{d\omega d\mathbf{k}} \sim \alpha_s C_R \int dy \int dy' \int d\mathbf{u}\, e^{i\mathbf{k}\cdot\mathbf{u}}\, \partial_{\mathbf{u}} \cdot \partial_{\mathbf{y}} \mathcal{K}(y', \mathbf{u}; y, \mathbf{y})\Big|_{\mathbf{y}=0} \tilde{\mathcal{P}}(L, y'; \mathbf{u})$$



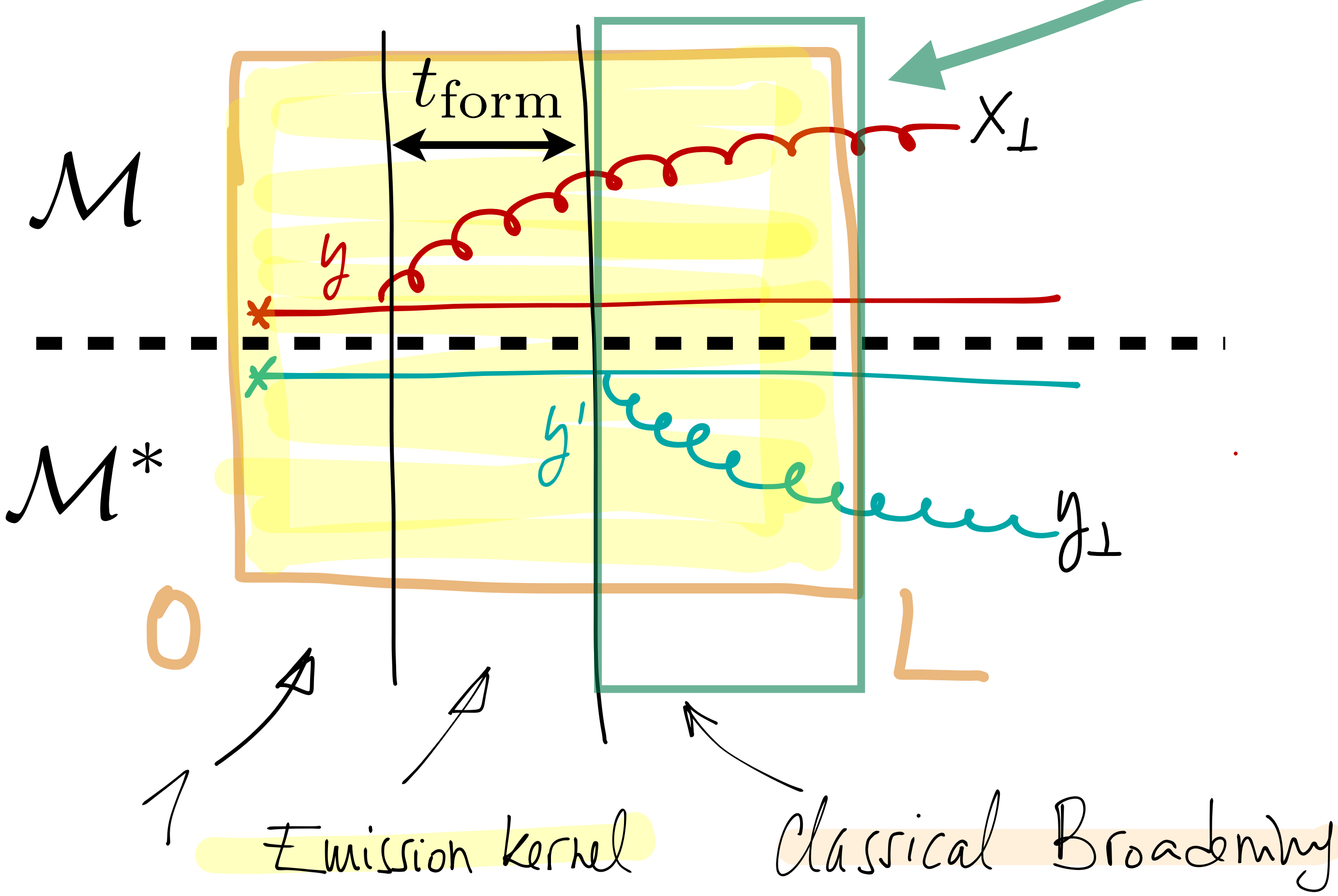


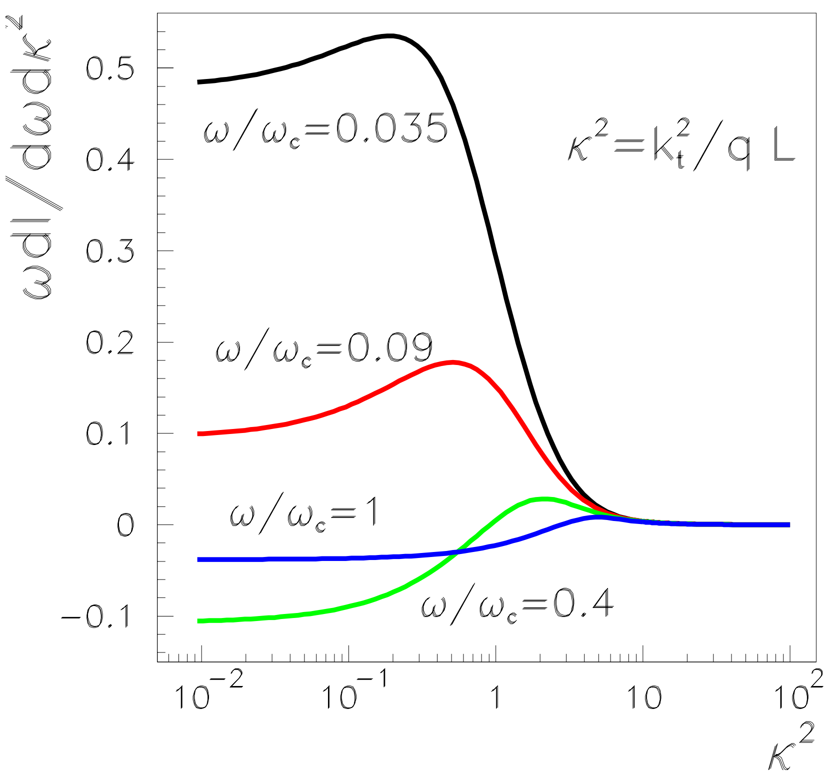
$$\mathcal{K}(y', \mathbf{u}; y, \mathbf{y}) = \int_{\mathbf{y}(y)}^{\mathbf{u}(y')} \mathcal{D}\mathbf{r} \exp\left\{ i\frac{\omega}{2} \int d\xi \left(\frac{d\mathbf{r}(\xi)}{d\xi} \right)^2 \right\} \tilde{\mathcal{P}}(y', y, \mathbf{r})$$

[Zakharov, Baier, Dokshitzer, Mueller, Peigne, Schiff, Wiedemann, Gyulassy, Levai, Vitev, and many others...]

Medium-induced gluon radiation

$$\omega \frac{dI}{d\omega d\mathbf{k}} \sim \alpha_s C_R \int dy \int dy' \int d\mathbf{u}\, \mathrm{e}^{i\mathbf{k}\cdot\mathbf{u}}\, \partial_{\mathbf{u}} \cdot \partial_{\mathbf{y}} \mathcal{K}(y', \mathbf{u}; y, \mathbf{y})\Big|_{\mathbf{y}=0} \tilde{\mathcal{P}}(L, y'; \mathbf{u})$$





$$\mathcal{K}(y', \mathbf{u}; y, \mathbf{y}) = \int_{\mathbf{y}(y)}^{\mathbf{u}(y')} \mathcal{D}\mathbf{r} \exp\left\{ i\frac{\omega}{2} \int d\xi \left(\frac{d\mathbf{r}(\xi)}{d\xi}\right)^2 \right\} \tilde{\mathcal{P}}(y', y, \mathbf{r})$$

[Zakharov, Baier, Dokshitzer, Mueller, Peigne, Schiff, Wiedemann, Gyulassy, Levai, Vitev, and many others...]

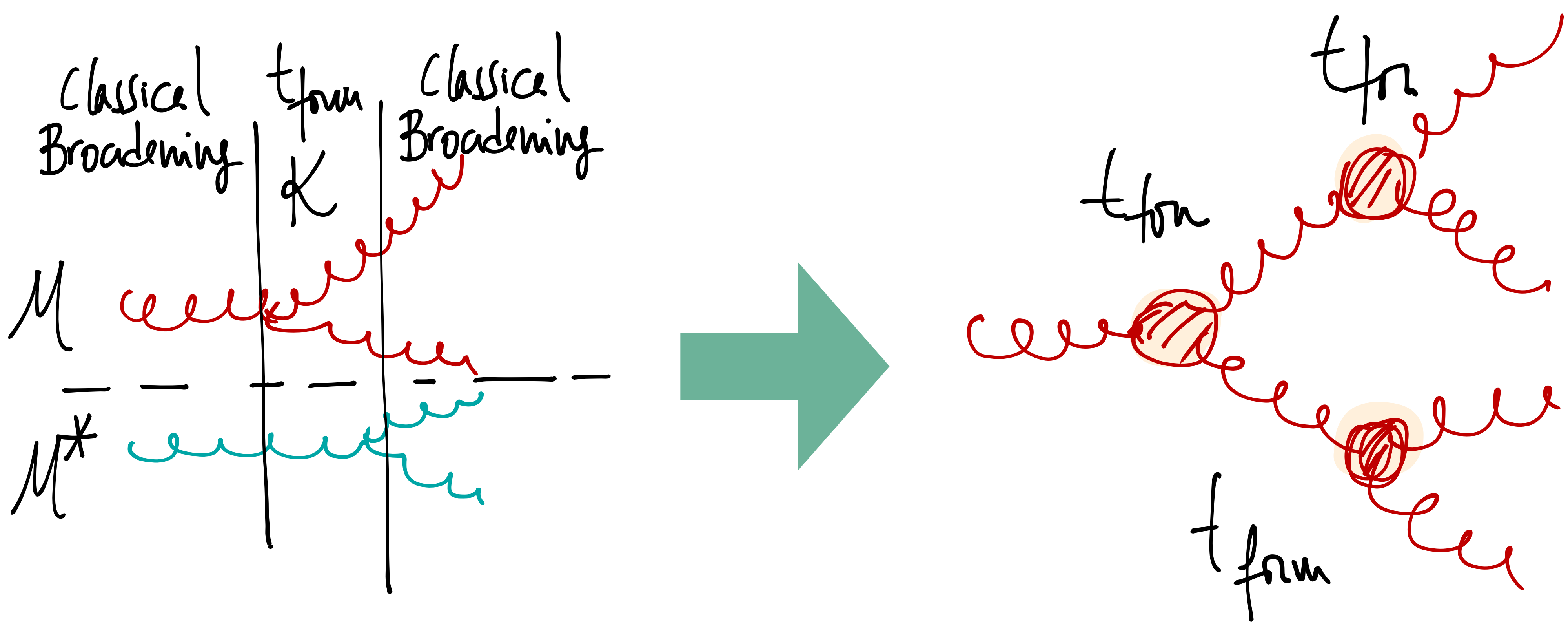
A resummation scheme

Factorization possible for $t_{\mathrm{form}} \ll L$

[Blaizot, Dominguez, Iancu, Mehtar-Tani]

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega_{k_a}\mathrm{d}\Omega_{k_b}} = 2g^2 z(1-z)$$
$$\times \int_{t_0}^{t_L} \mathrm{d}t \int_{\boldsymbol{p}_0,\boldsymbol{q},\boldsymbol{p}} \mathcal{P}(\boldsymbol{k}_a - \boldsymbol{p}, t_L - t)\,\mathcal{P}(\boldsymbol{k}_b - \boldsymbol{q} + \boldsymbol{p}, t_L - t)$$
$$\times \mathcal{K}(\boldsymbol{p} - z\boldsymbol{q}, z, p_0^+)\,\mathcal{P}(\boldsymbol{q} - \boldsymbol{p}_0, t - t_0)\,\frac{\mathrm{d}\sigma_{hard}}{\mathrm{d}\Omega_{p_0}},$$

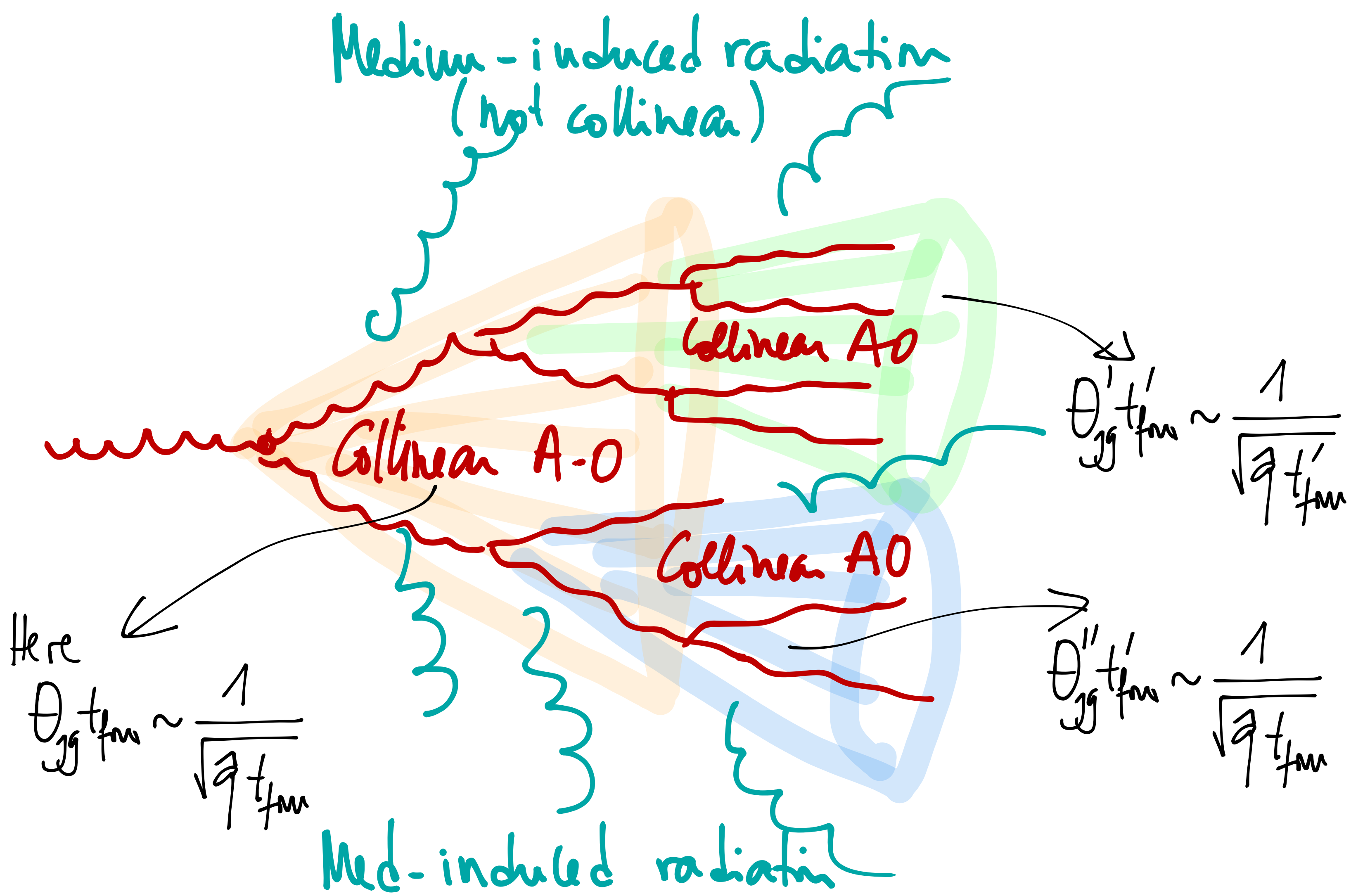
Simple probabilistic interpretation - rate equations



A new picture of jet quenching

The parton shower is composed of **un-modified subjets** (vacuum-like)

- **With a typical radius given by the medium scale**
- For medium-induced radiation **each subject is one single emitter**

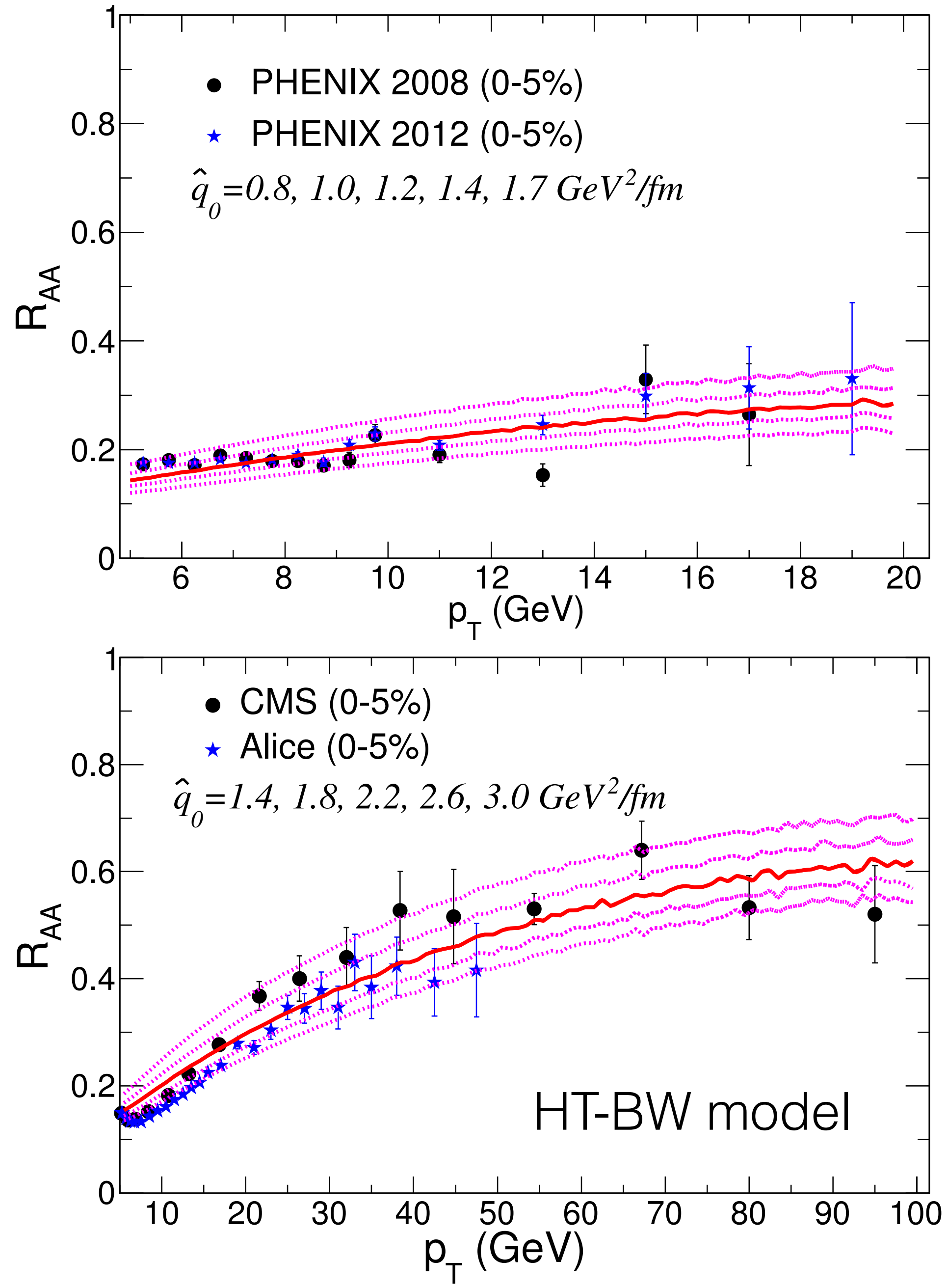


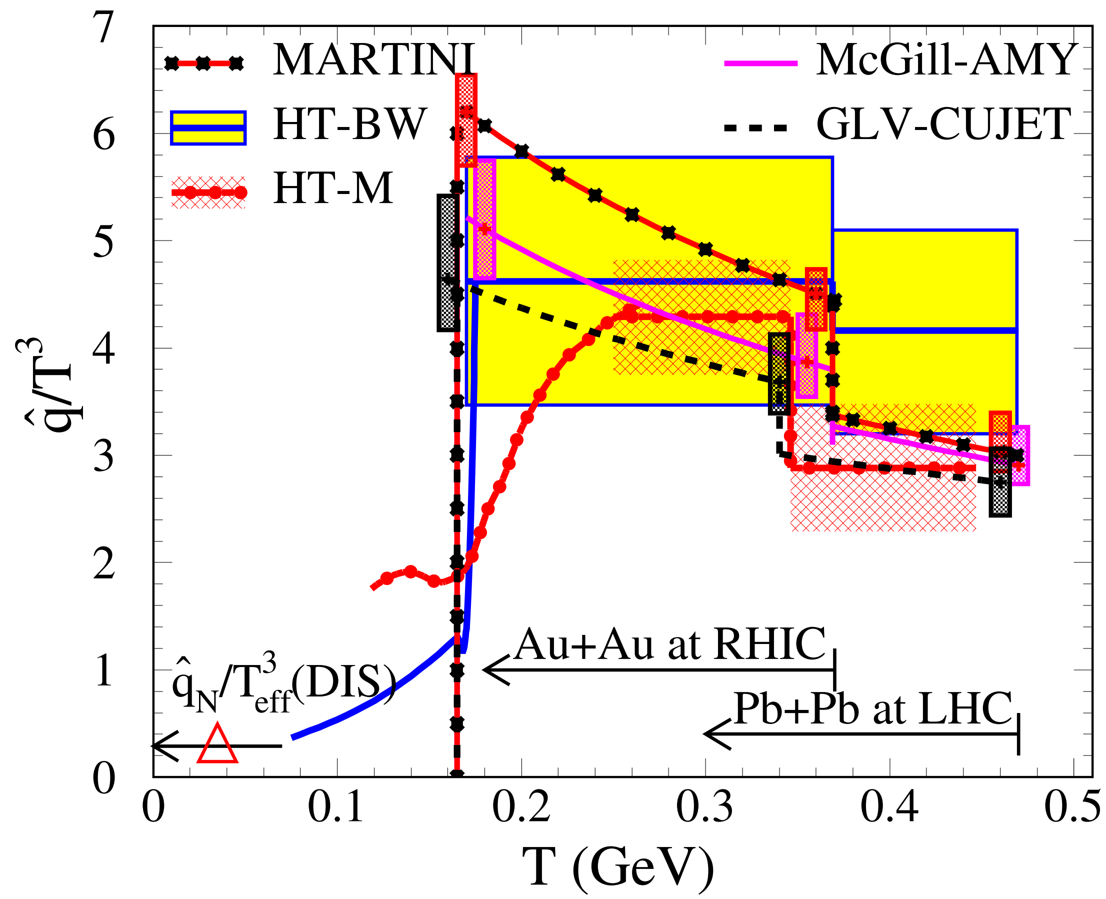
Also, 1st calculation of 1->3 splitting performed in SCET and 1st order in opacity expansion

- [Fickinger, Ovanesyan, Vitev] - [also Arnold, Iqbal 2015; Casalderrey-Solana, Pablos, Tywoniuk 2015]

Extracting the jet quenching parameter from data

Different modeling of the splitting probability and the multi-gluon emission studied by the JET Collaboration to extract qhat





[Jet Collaboration 2013]

Summary

Nucleus-nucleus data

- *Good description by hydrodynamical models - viscosity*
- *Remarkable progress on the theory of jet quenching*
- *Many other observables not covered here - see next talks*

New questions open by the proton-lead run *(small systems)*

- *Soft regime presents AA features - thermal system? Initial state? both?*
- *Hard processes in good agreement with nuclear PDFs*
- *Fully consistent picture still missing - strong activity at present*
- ***From a dilute system to a hot and dense medium***