Understanding heavy-ion data

Carlos A. Salgado
Universidade de Santiago de Compostela

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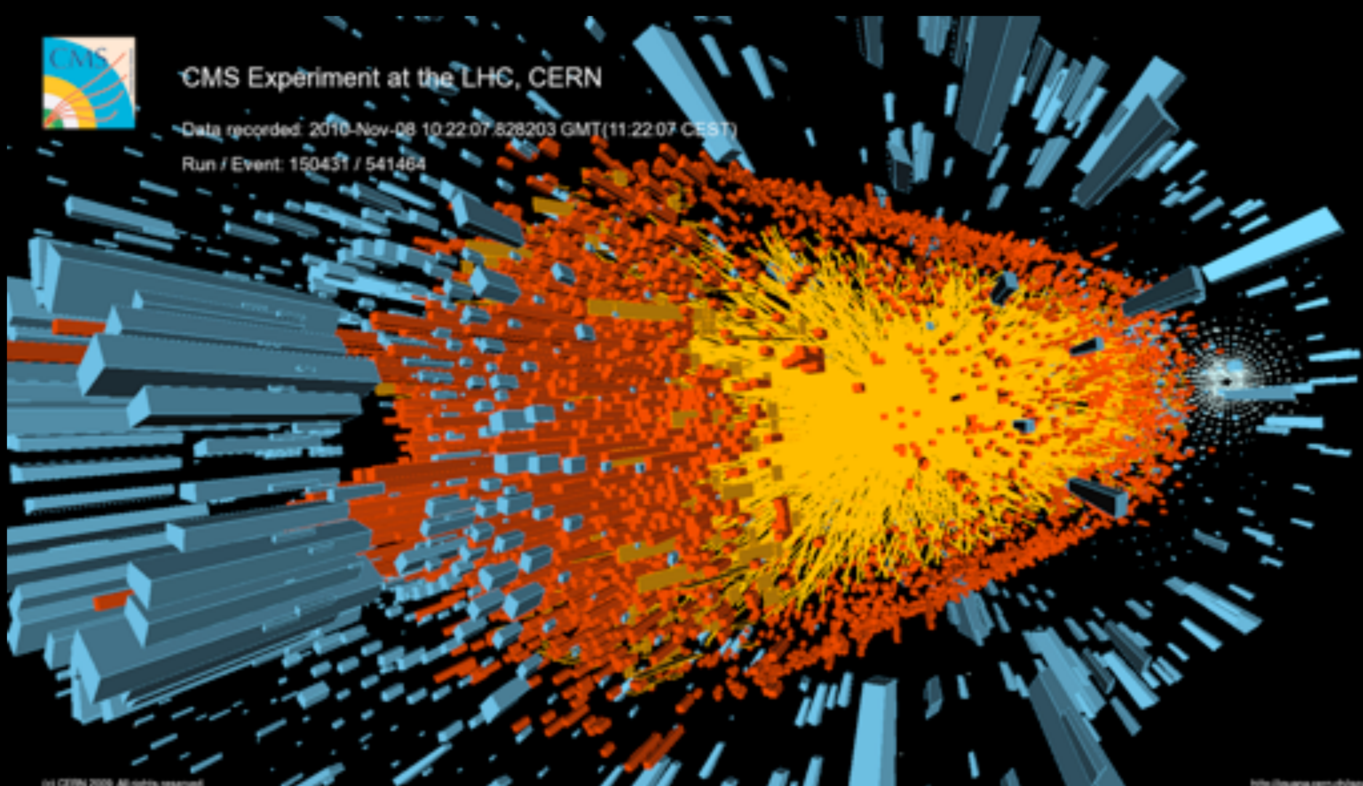
QCD: An apparently simple lagrangian hides a wealth of **emerging phenomena**

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

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"?

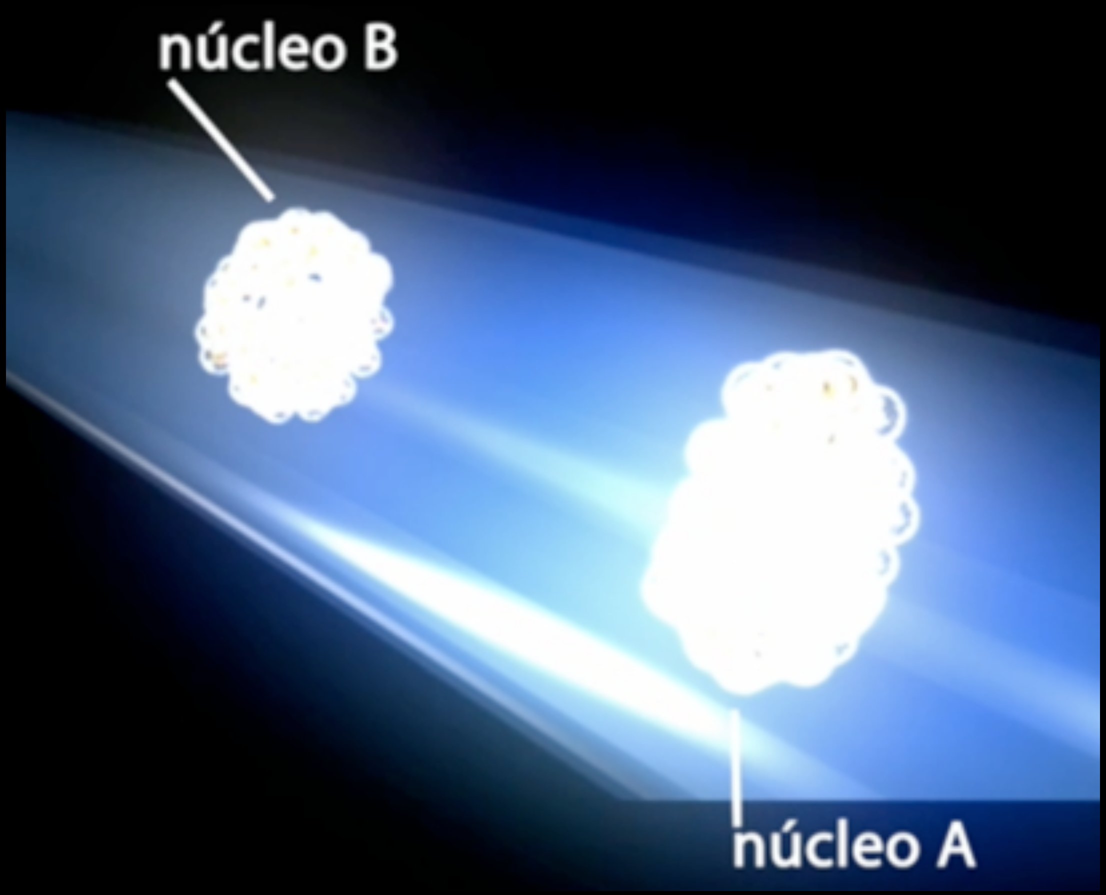
↳ Several talks at this conference

Proton-nucleus collisions

(original main goal: benchmarking)

[see I. Lokhtin talk in this session]

Initial state
Partonic densities
&
Multiparticle Production

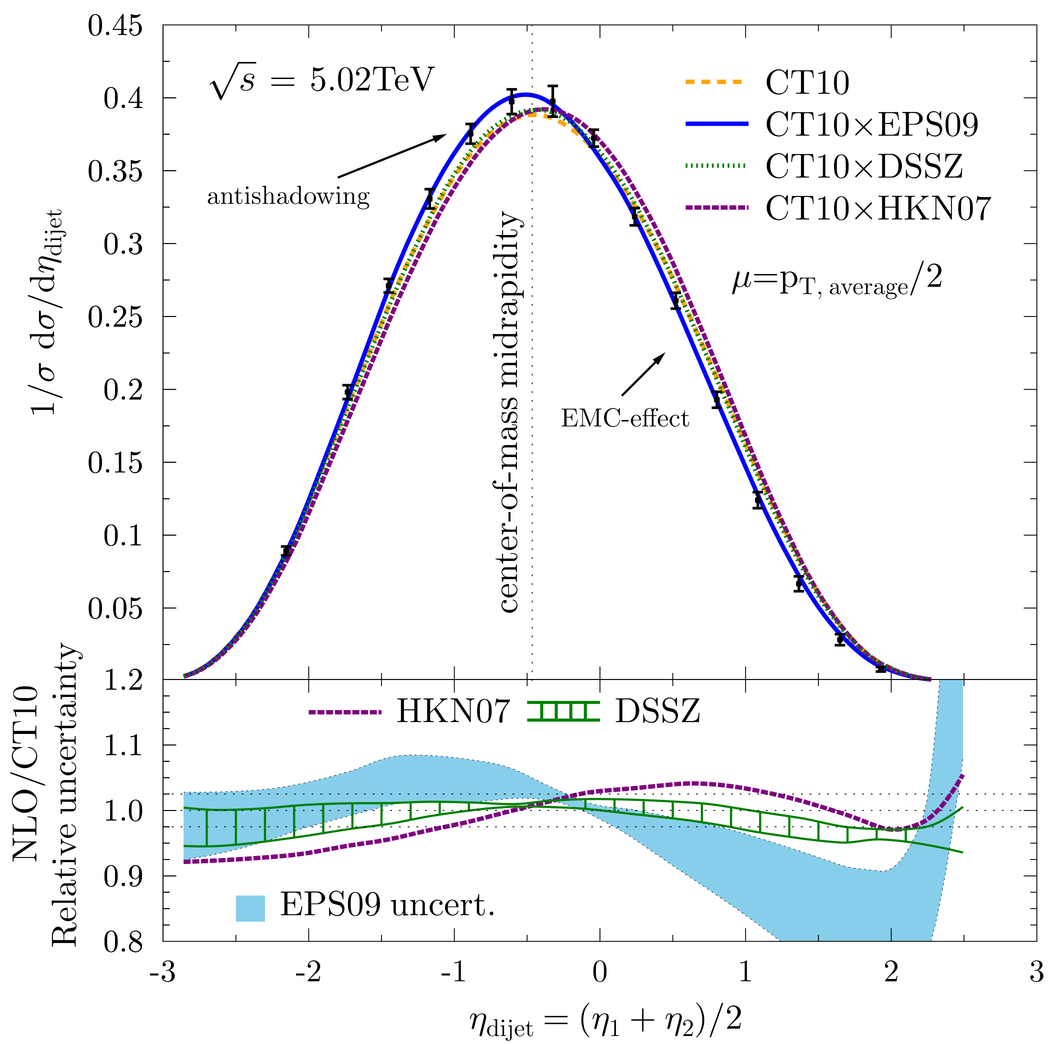


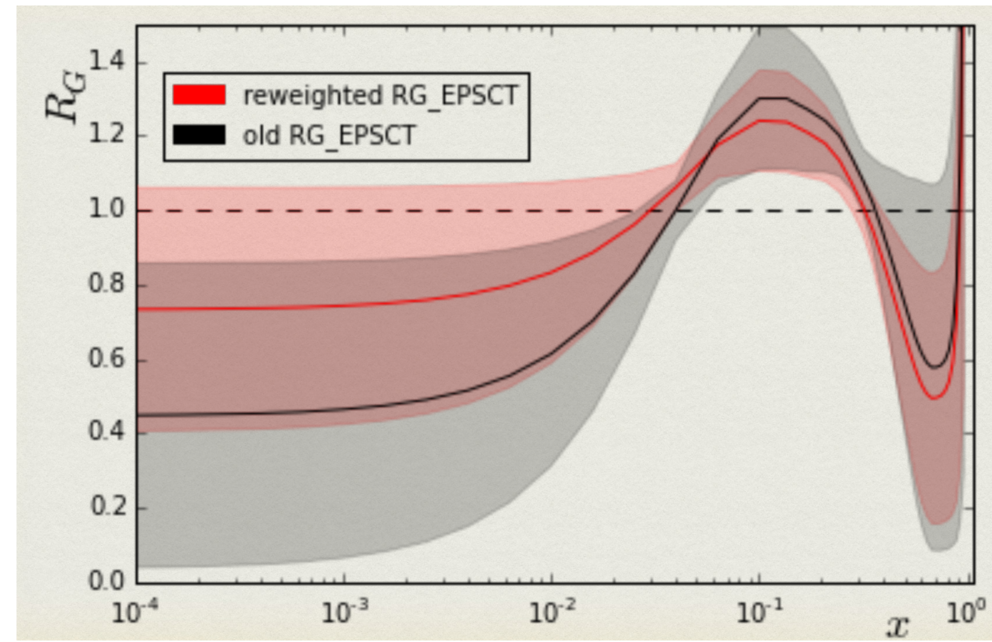
Nuclear PDFs

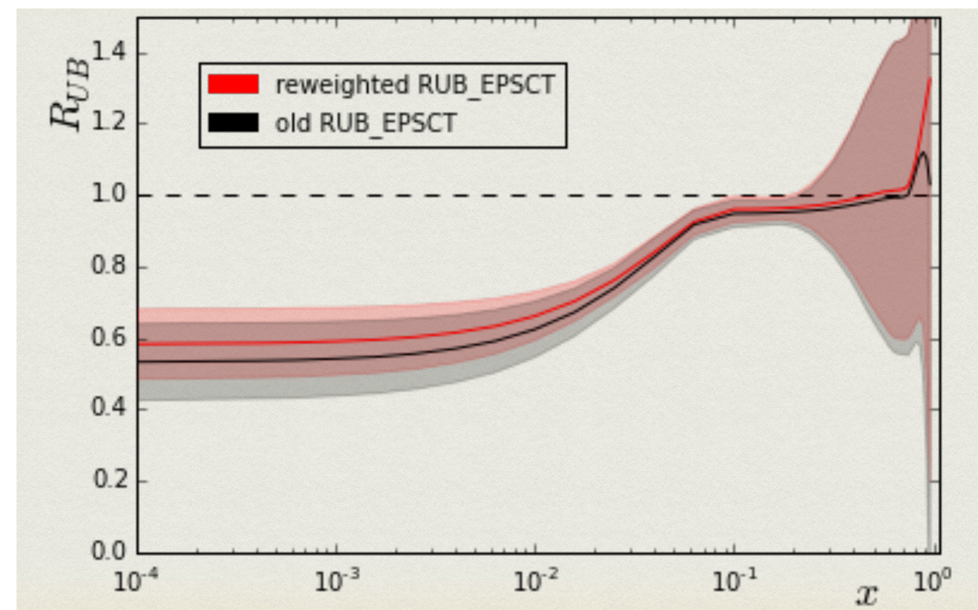
Nuclear PDFs extracted from global fits / DGLAP

[Zurita, Paukkunen et al]

- New constraints from the proton-lead run







Large uncertainties in the gluon distributions at small-x

- Relevant to pindown the relevance of non-linear effects

[see talk by A Sidoti]

From Dilute to Dense

Parton Saturation

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

Color Glass Condensate → General framework

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

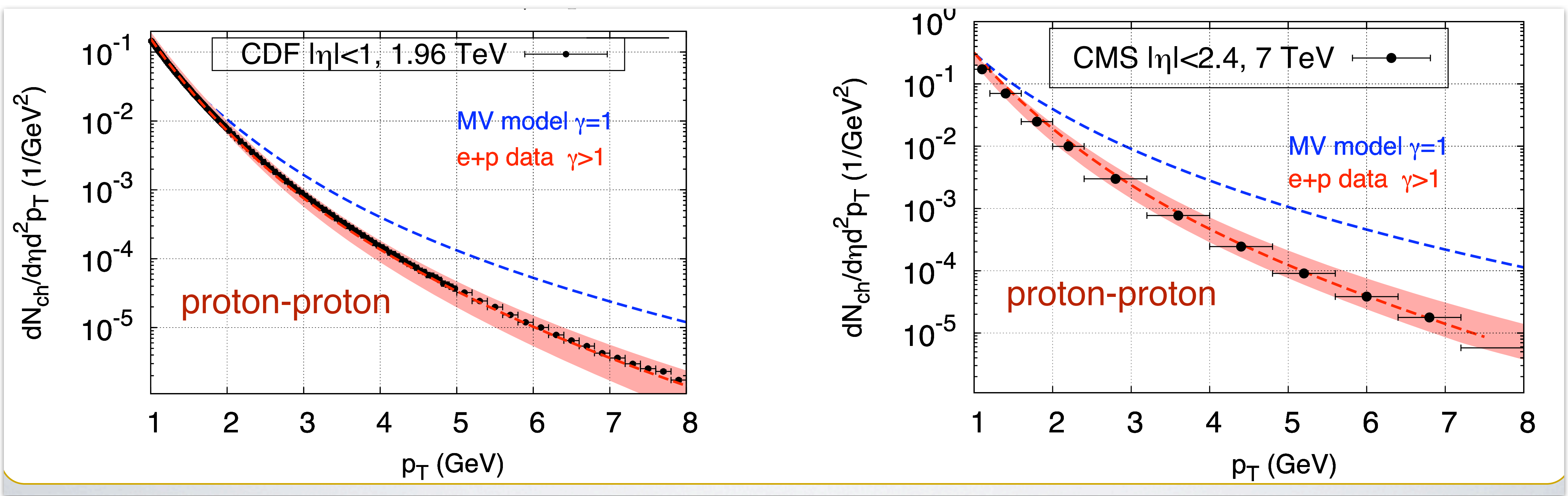
⇛ Screening leads to non-linear terms. E.g. Balitsky-Kovchegov eqs.

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

Splitting [BFKL] Merging [restores unitarity]

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

[Albacete, Dumitru 2011]



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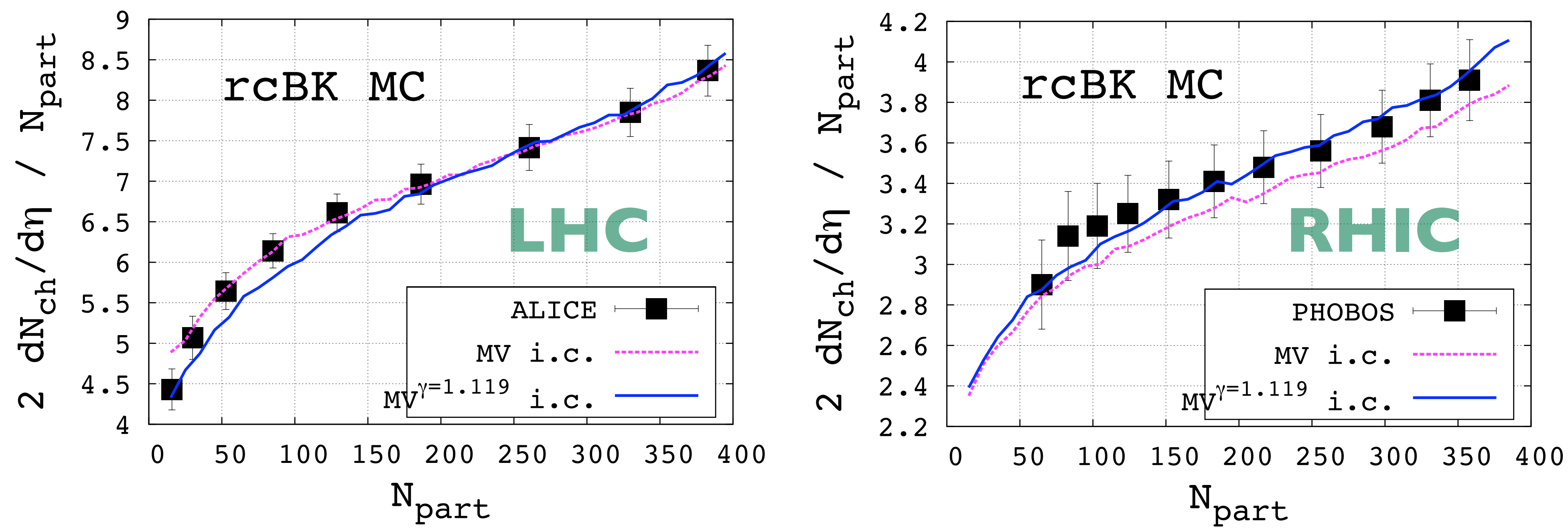

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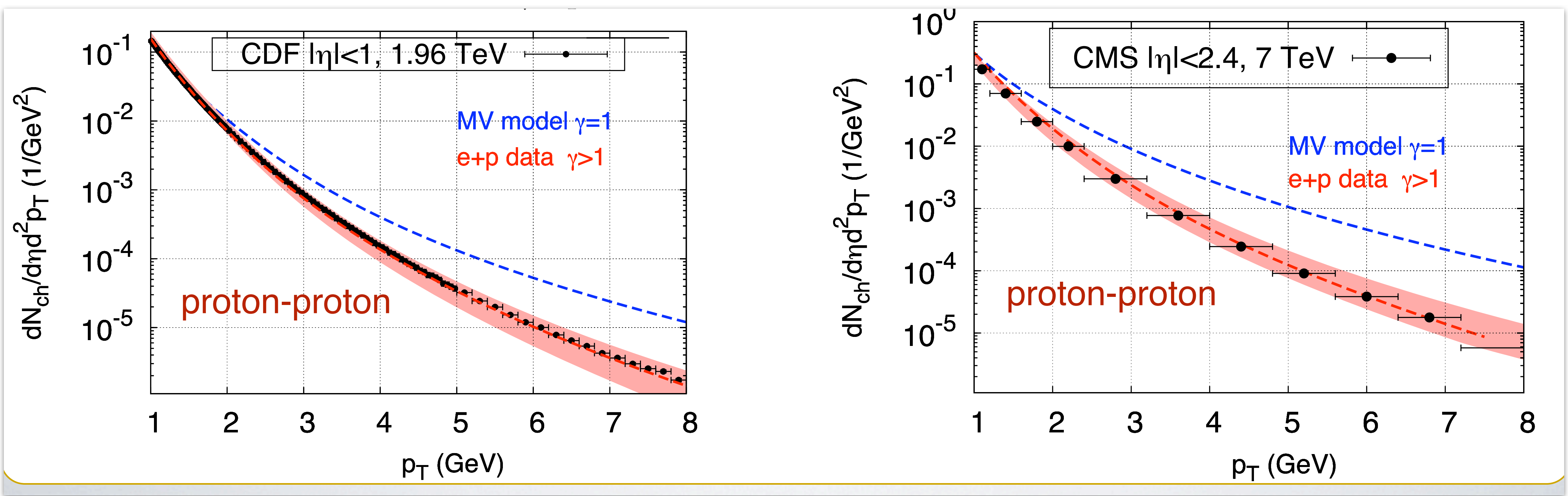


Hydrodynamics & Harmonics

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

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

+ 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.

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

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

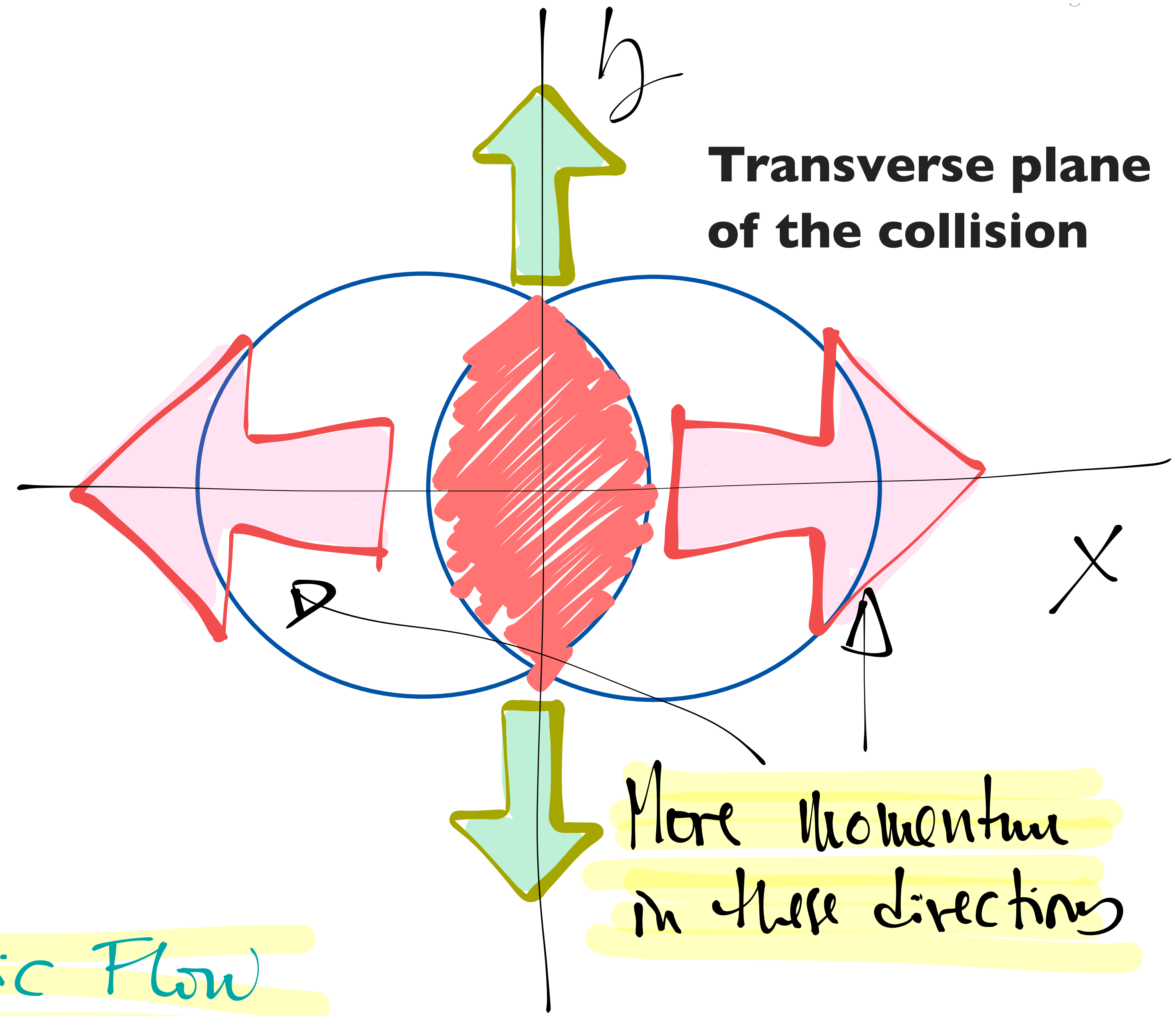
Make a Fourier decomposition

- Elliptic flow is the second component

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

↳ Elliptic Flow

Transverse plane of the collision

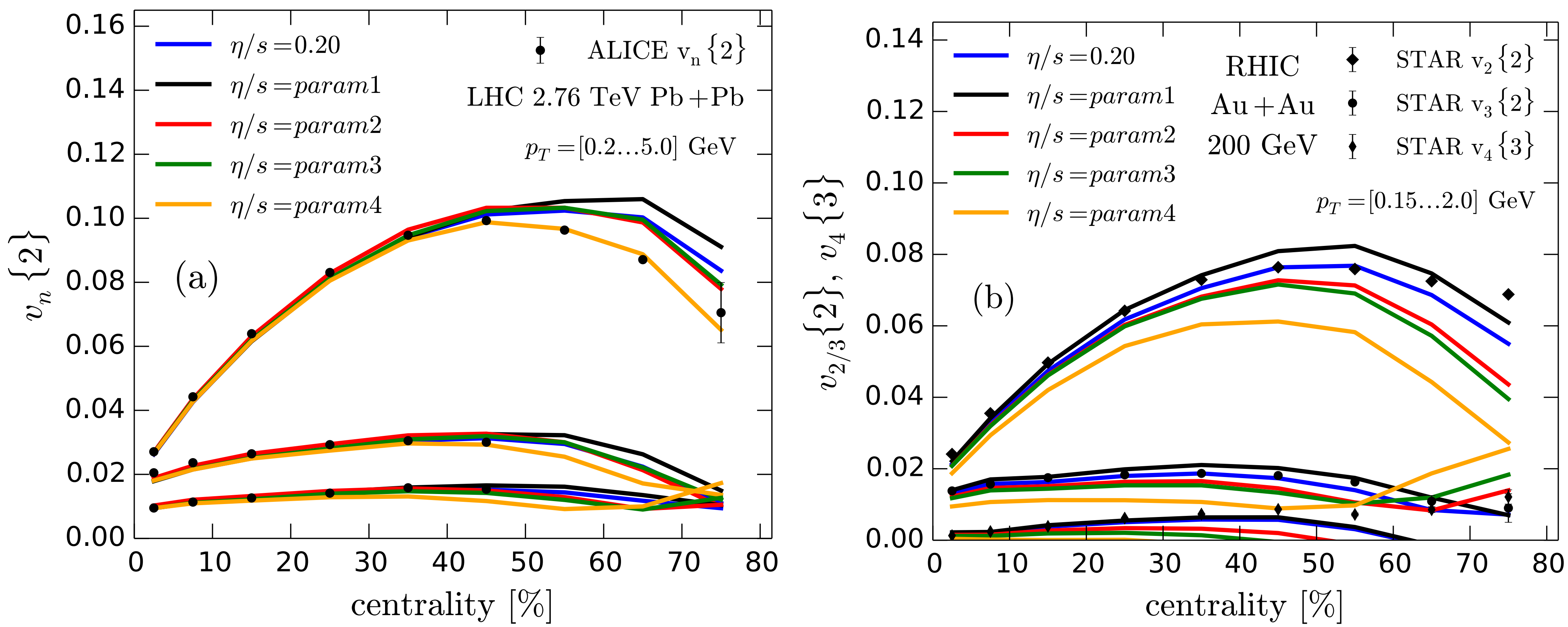


Anisotropies in the initial spacial distributions - <u>geometry</u> - translate into anisotropies in the momentum distributions

Fluid behavior from hydro: viscosity of the QGP

Hydro models provide excellent description of data

- Initial conditions of the (partial differential) equations needed
- Data constrain the value of the **viscosity** of the medium



[Niemi, Eskola, Paatelainen 2015]

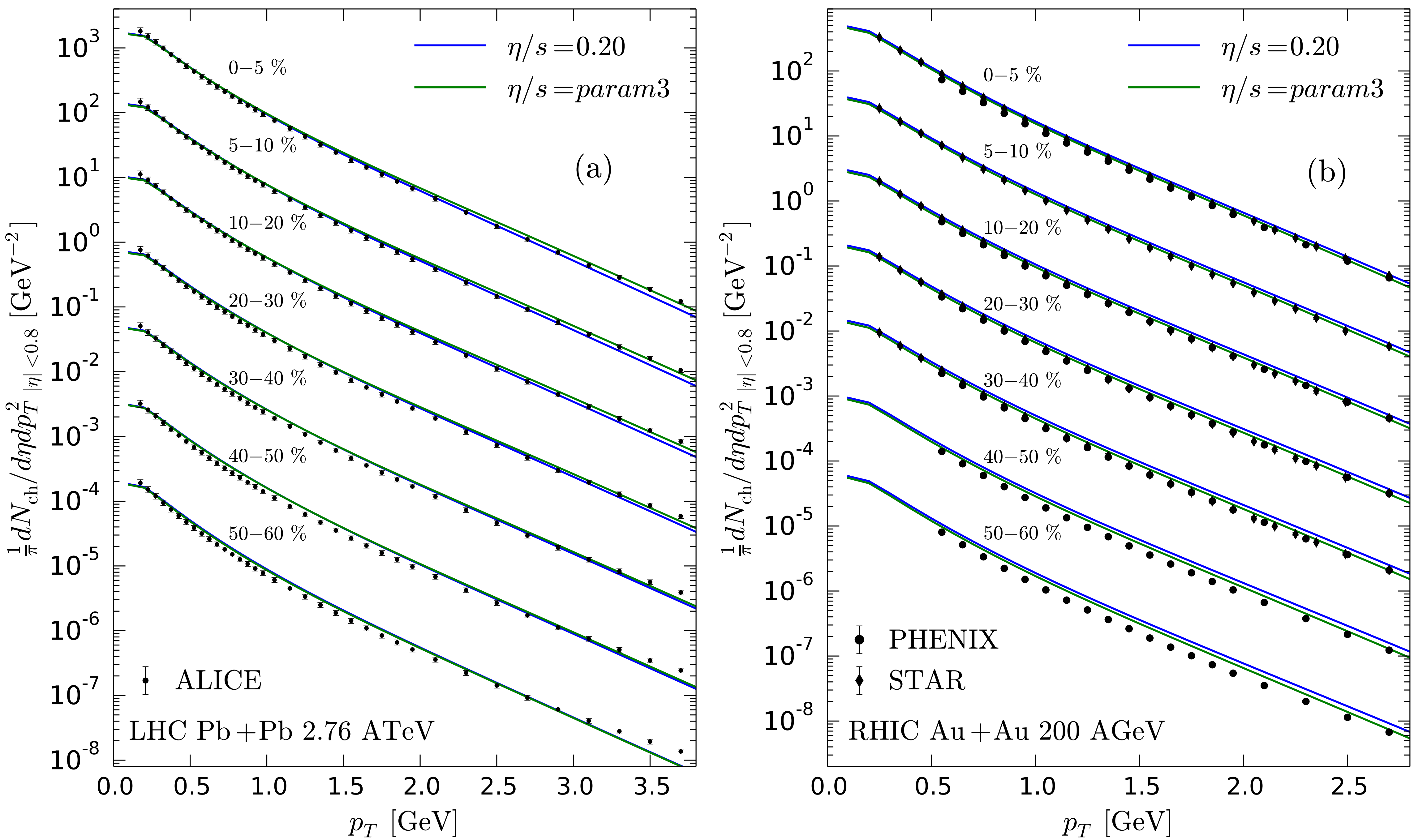
Lowest viscosity known - *perfect liquid sQGP*

- AdS/CFT bound [Policastro, Son, Starinets, 2001]

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

[See talks by R Preghenella; I Altsybeev]

Hydro: description of the data

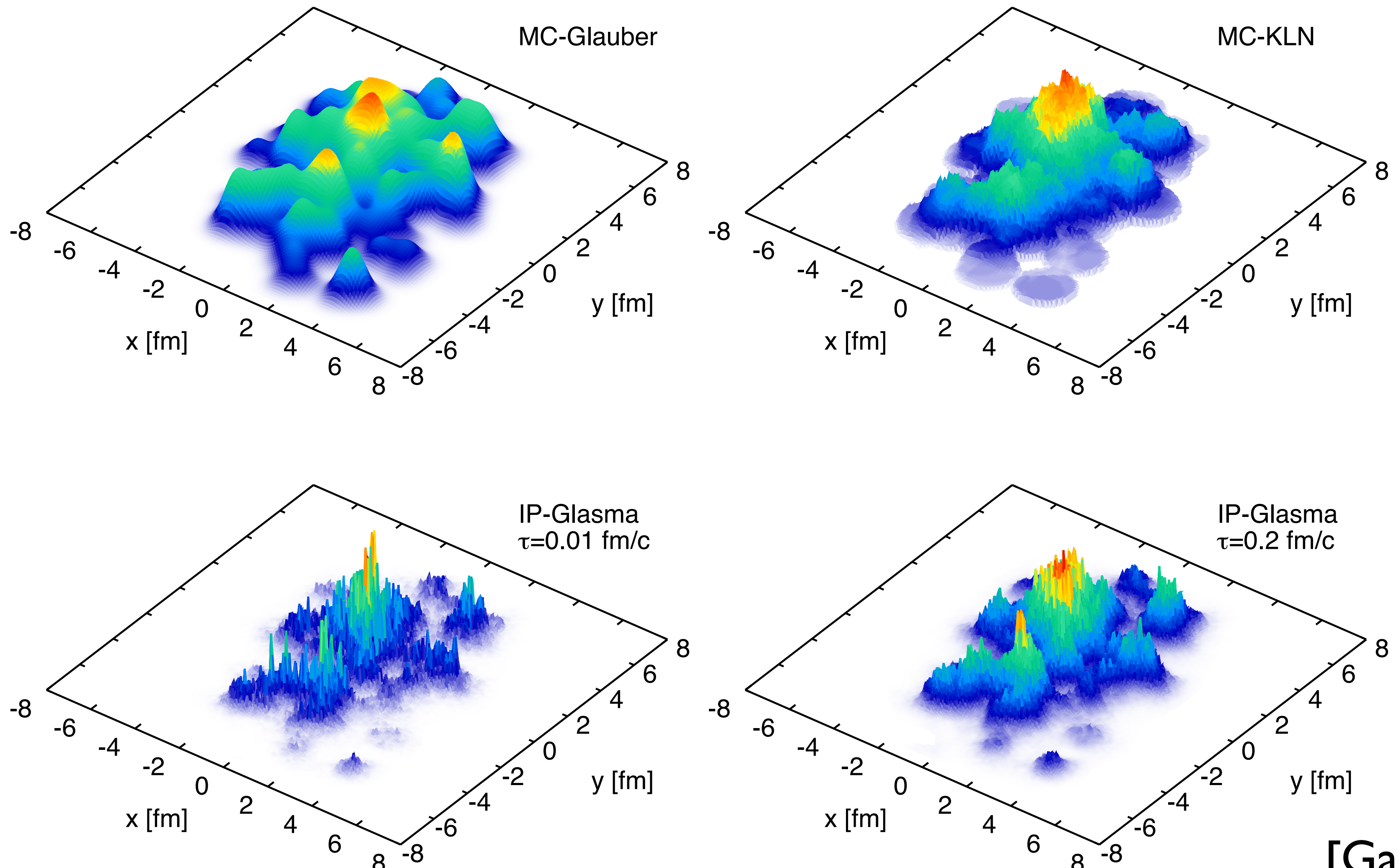


[Niemi, Eskola, Paatelainen 2015]

Event-by-event fluctuations

[See talk by G Herten]

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



[Gale, Jeon, Schenke 2013]

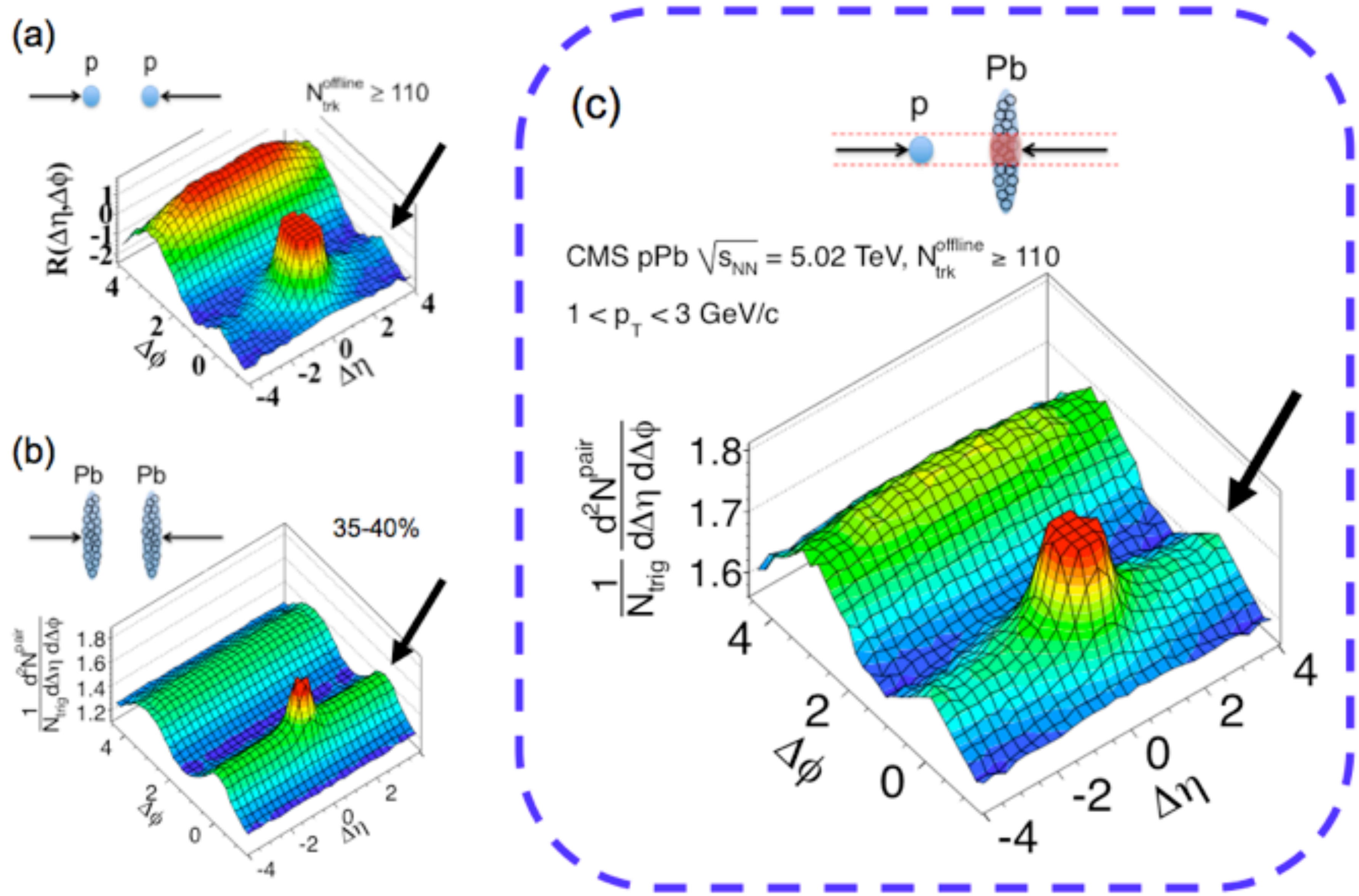
A useful tool to study the initial conditions and thermalization

- Role of saturation of partonic densities intensively investigated

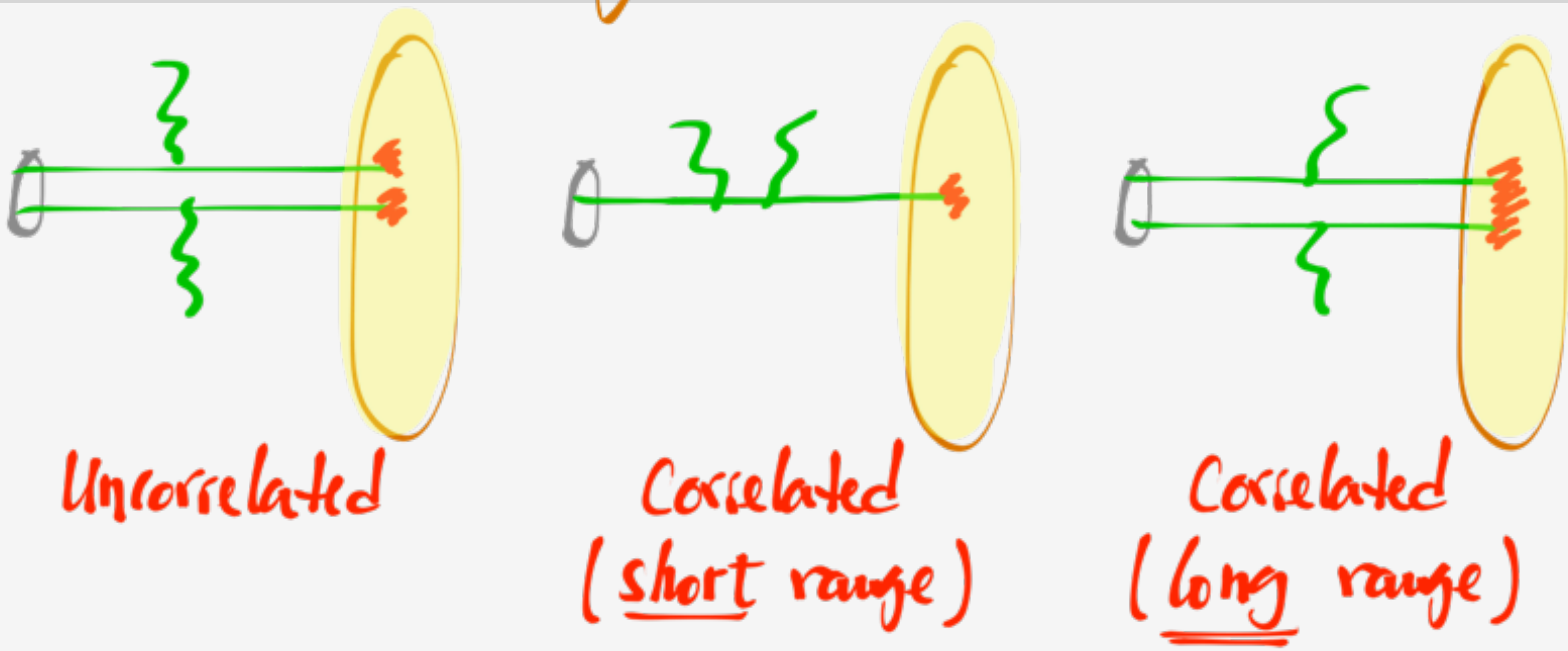
[See talk by A Ohlson]

Fluctuations produce also long-range rapidity correlations

- The ridge observed in high-multiplicity proton-proton, proton-lead, and lead-lead
- **Common origin??** - role of thermalization?



The Ridge & the CGC



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

The Ridge & the CGC

Uncorrelated

Correlated (short range)

Correlated (long range)

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

Is the Ridge Initial State / Final State / Both ?

Hard Probes

Long distance terms modified by the presence of medium

- *Nuclear PDFs and new (non-linear) evolution equations*
- *Modification of hadronization probes the medium properties*
- *EW processes (no hadronization) used as benchmark*

$$\sigma^{AB\to h} = f_A^i(x_1, Q^2) \otimes f_B^j(x_2, Q^2) \otimes \sigma(ij \to k) \otimes D_{k\to h}(z, Q^2)$$

Nuclear PDFs

Hadronization

J/Ψ paradigmatic example

Hard Probes

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Nuclear PDFs

Hadronization

J/Ψ paradigmatic example

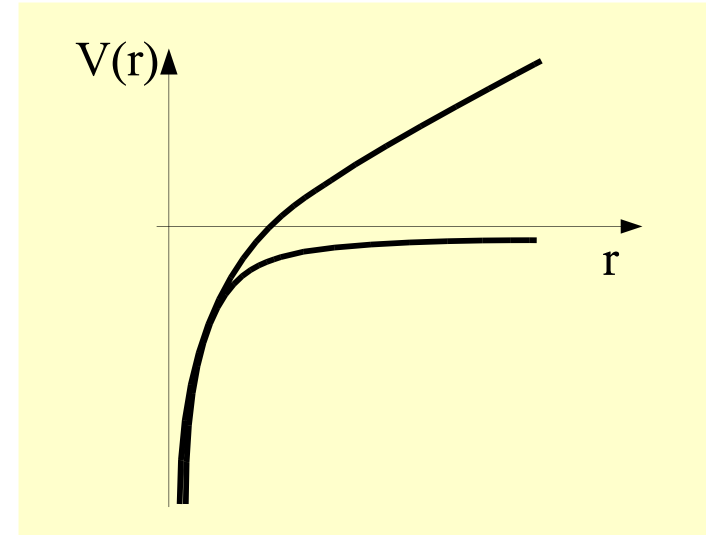
Background subtraction of "cold" nuclear matter effects

- *proto-nucleus needed: nuclear PDFs badly constrained at small-x*

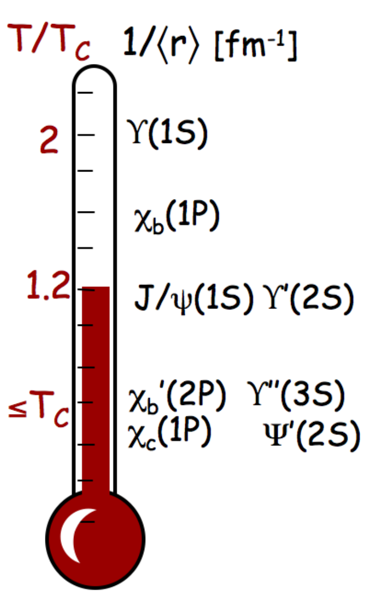
Quarkonia suppression

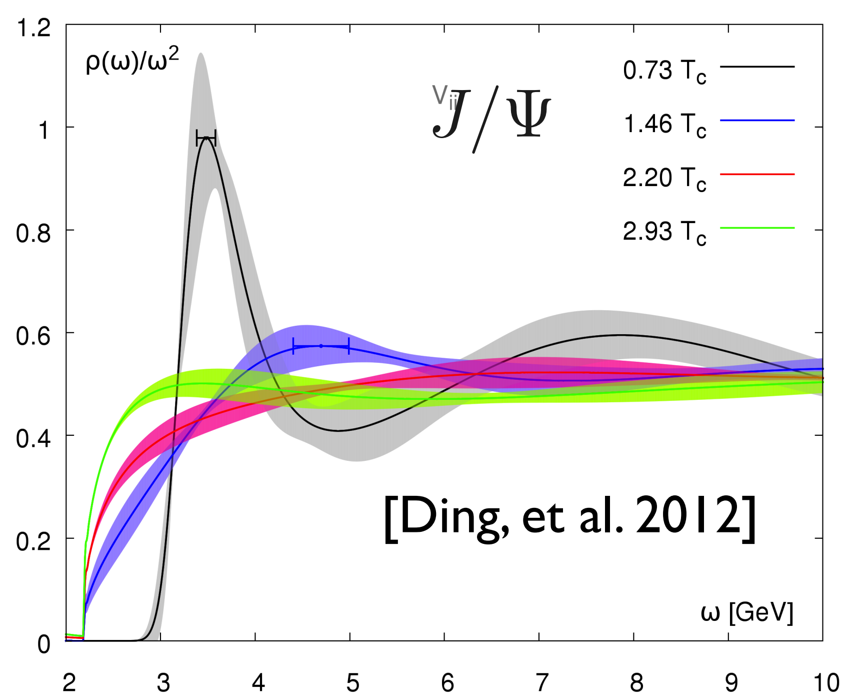
Simple intuitive picture [Matsui & Satz 1986]

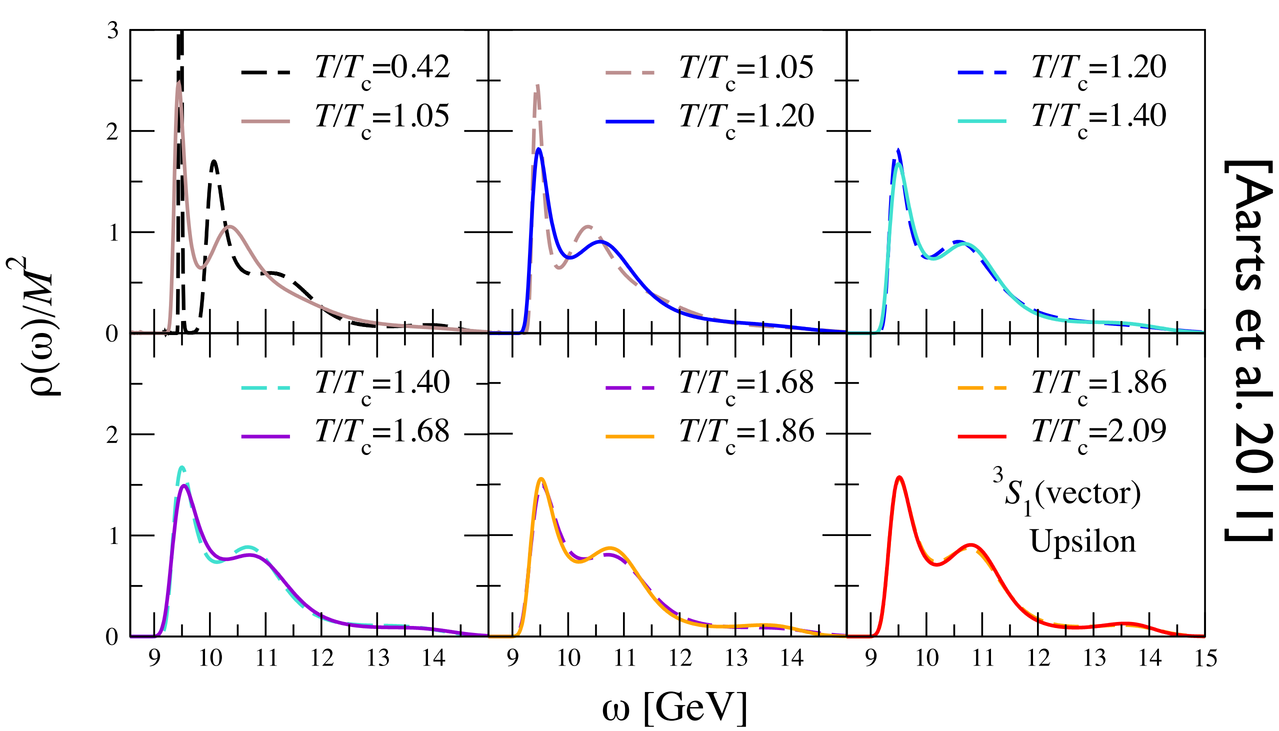
- *Potential screened at high-T*
- *Bound states not possible*
- *Suppression of J/Psi in nuclear collisions*
- *Sequential suppression of excited states*



Interpretation of the data traditionally difficult



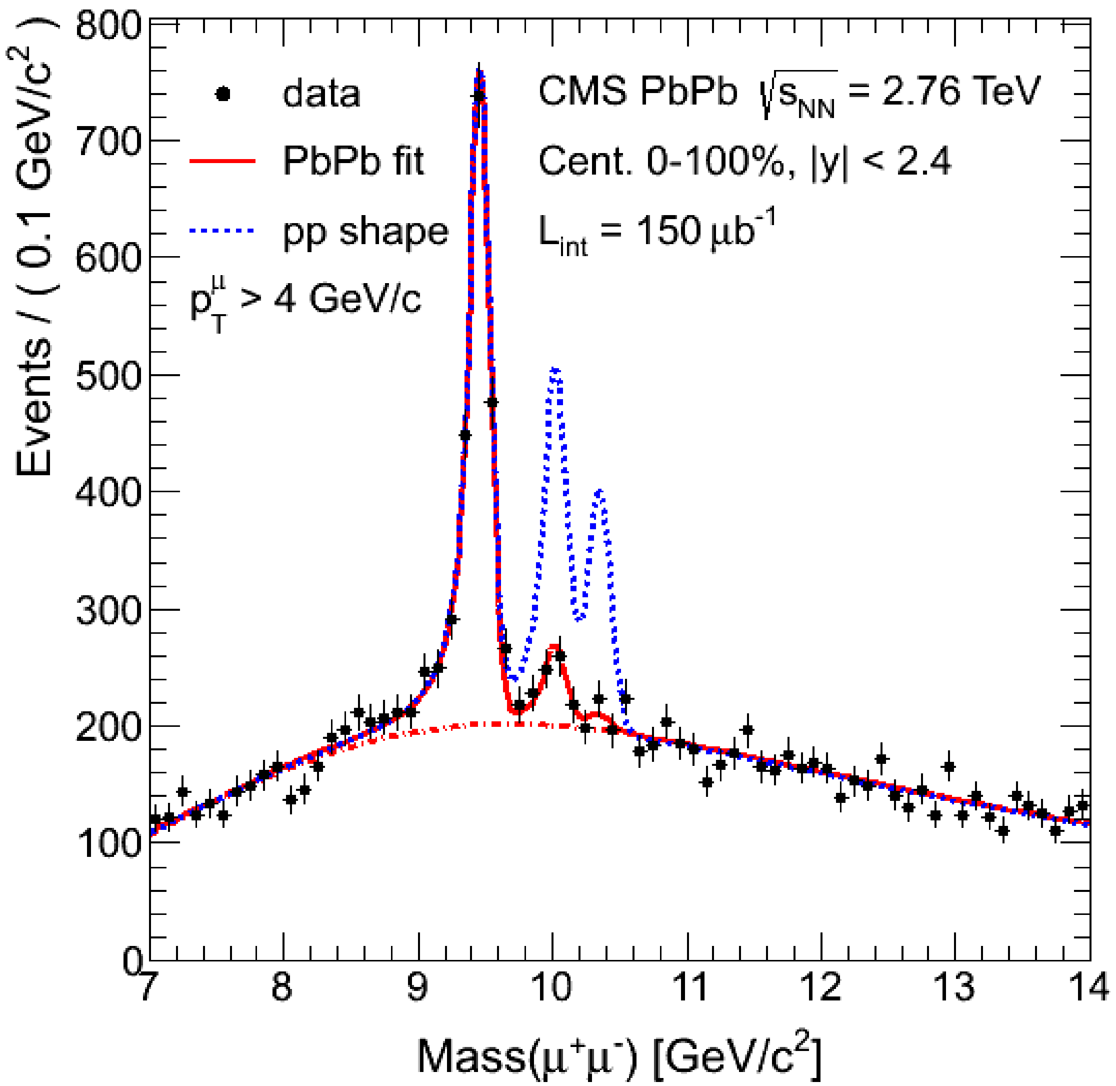


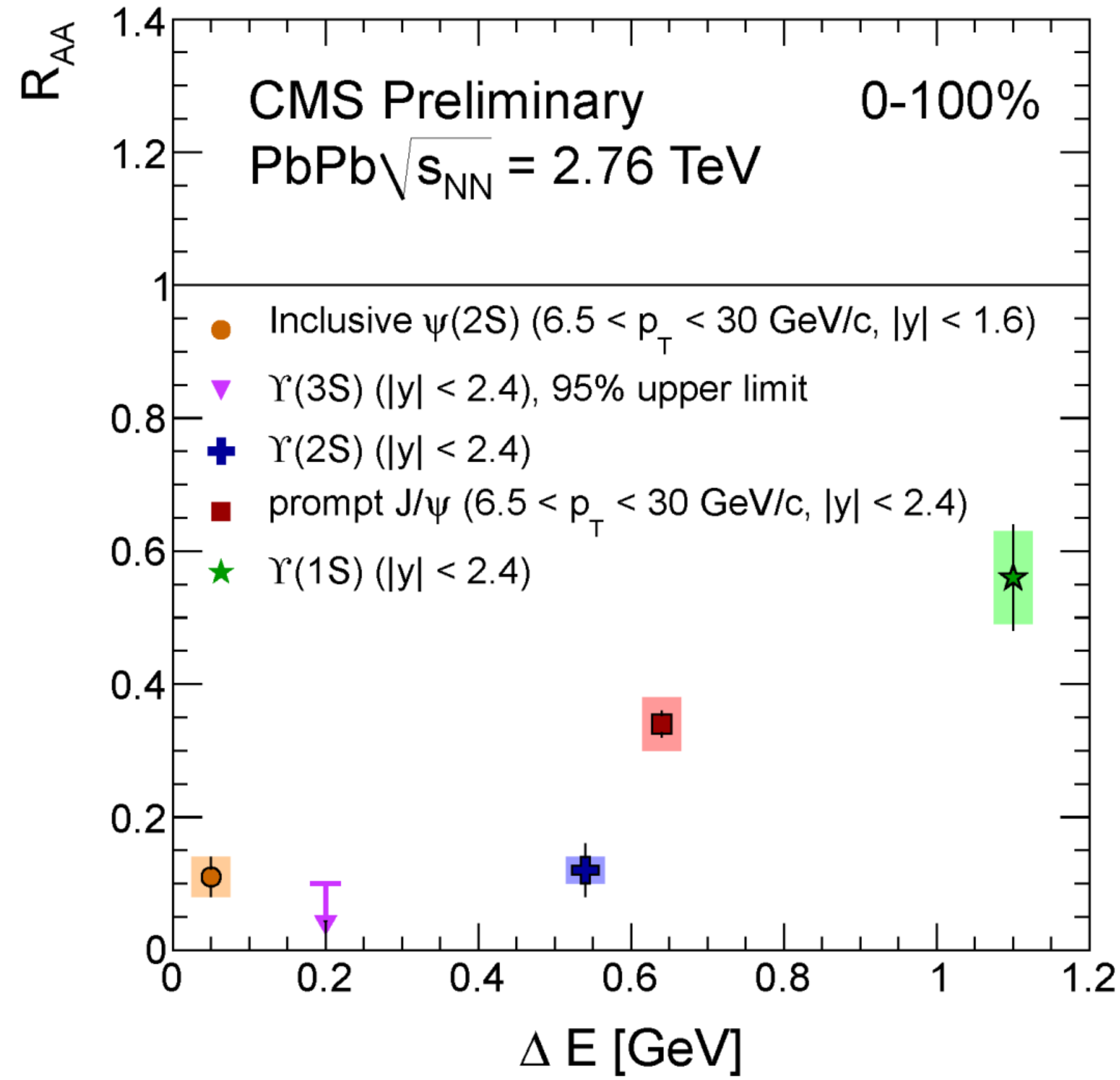


Lattice results for spectral functions

Suppression of quarkonia

[see talks by I Lakomov and G Bruno]



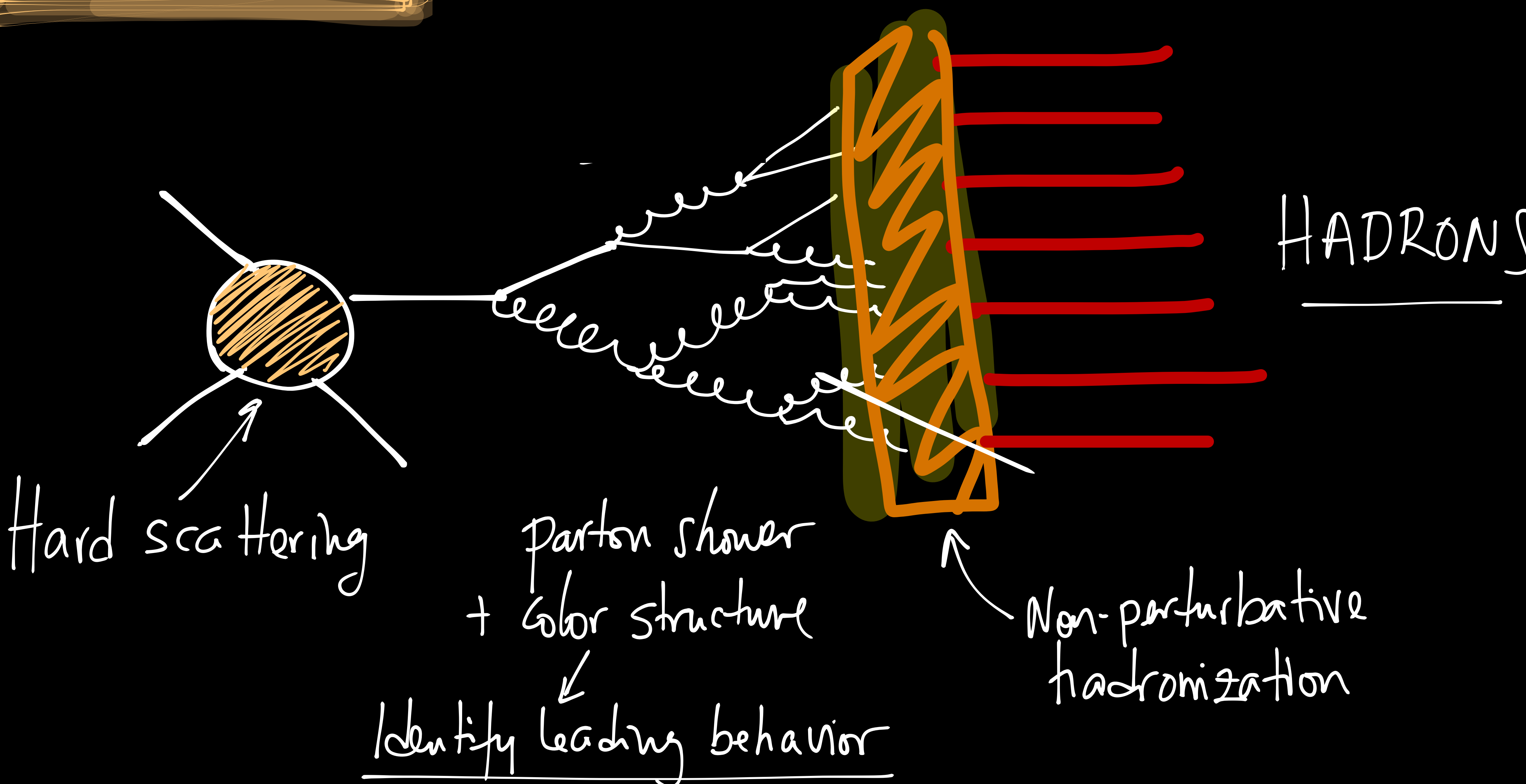


Suppression ordered by binding energy

- **Quarkonia as a termometer**

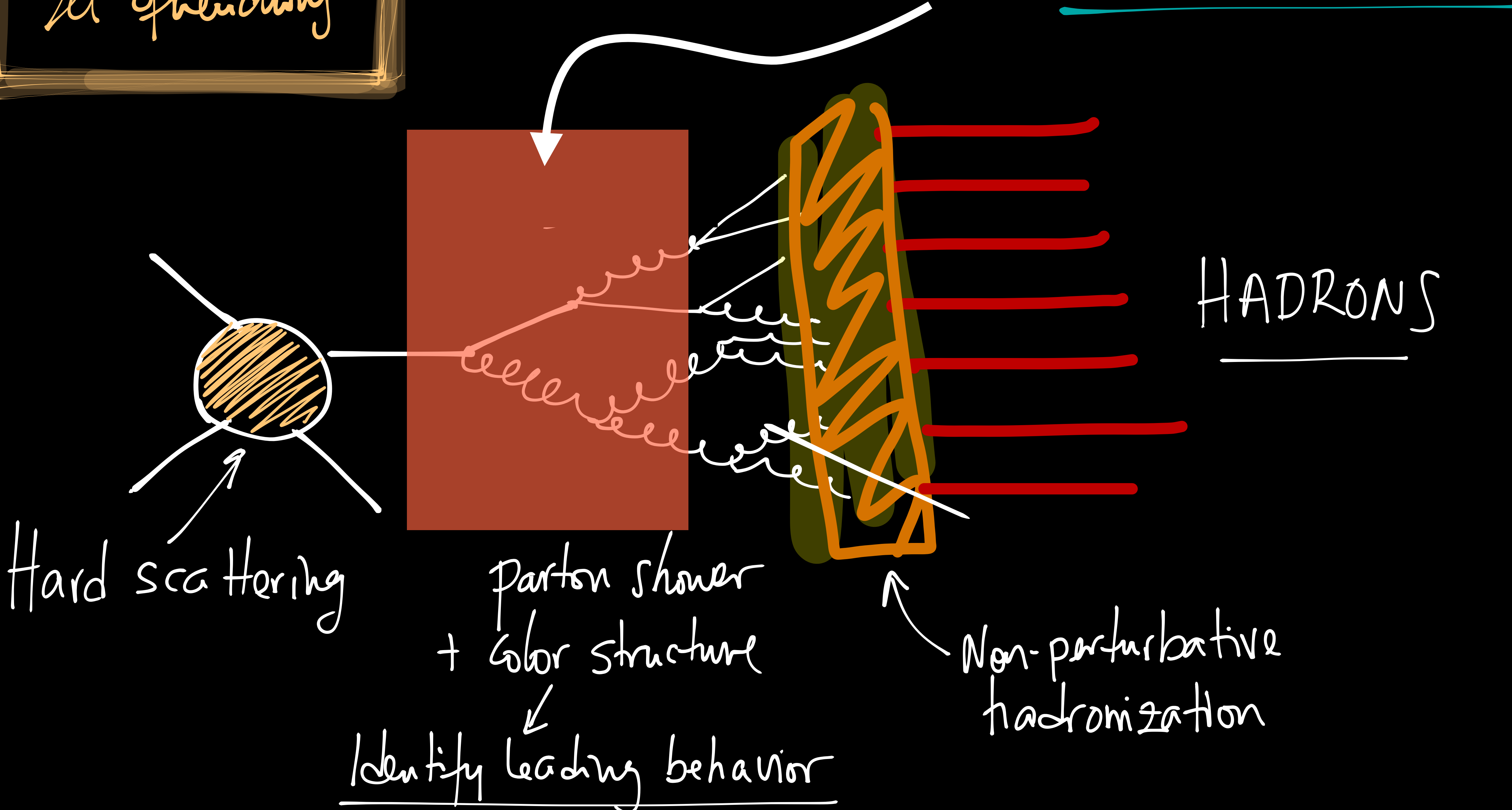
[J Velkovska Hard Probes 2013]

Jets in medium
Jet quenching

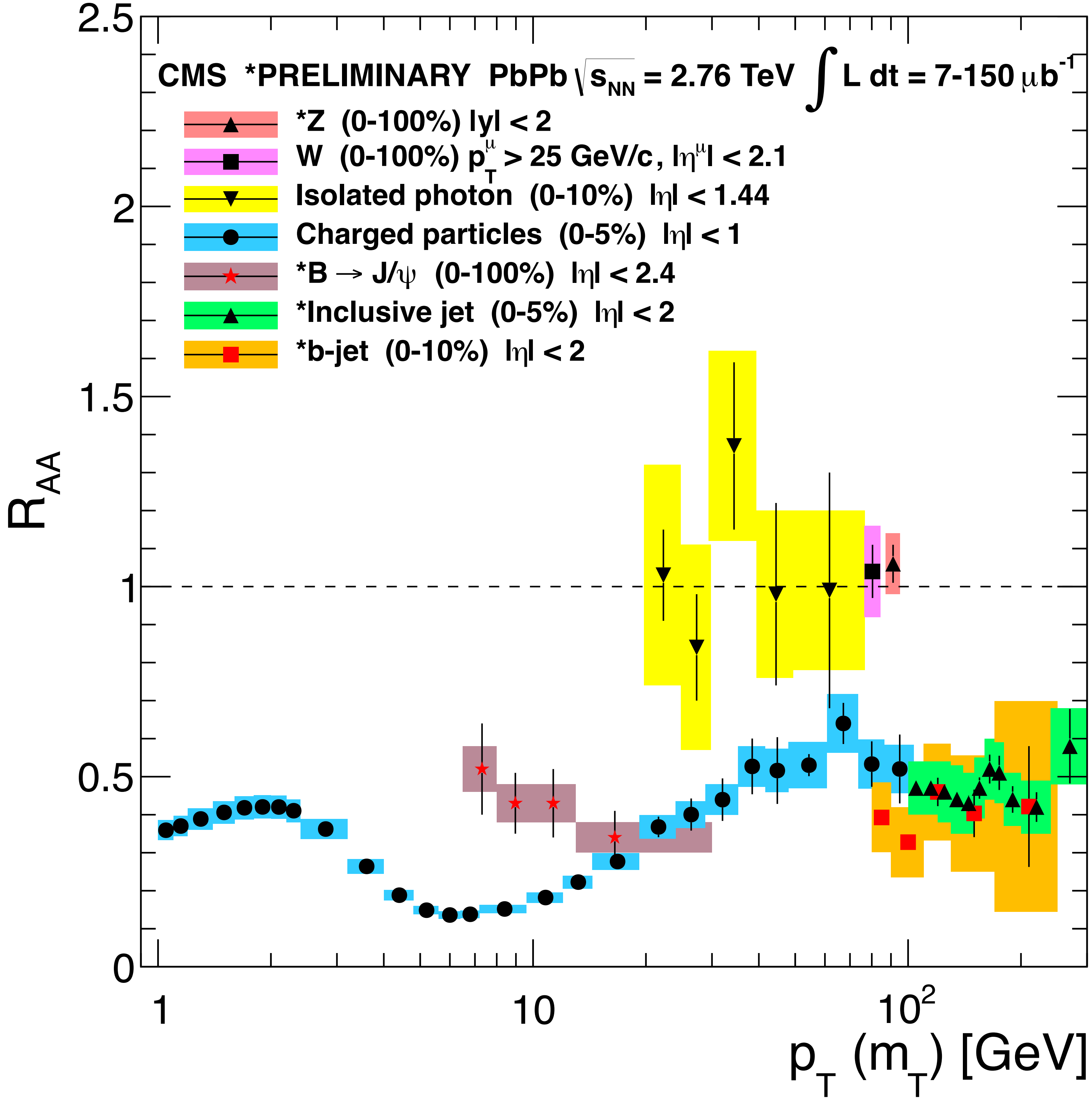


Jets in medium
Jet quenching

Put now a medium here

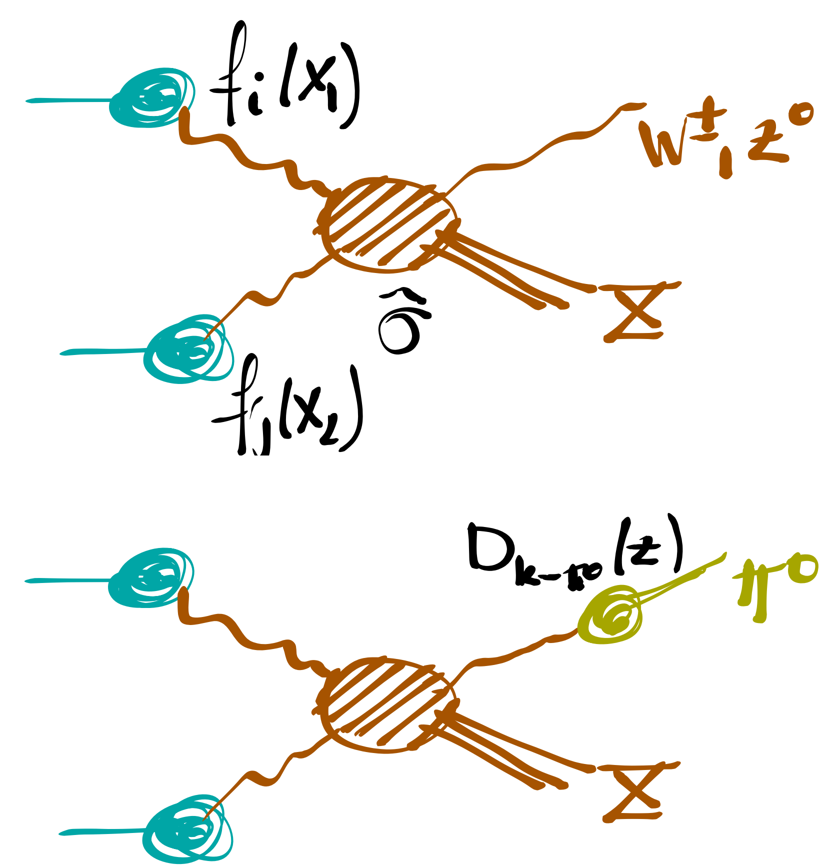


Suppression in one plot



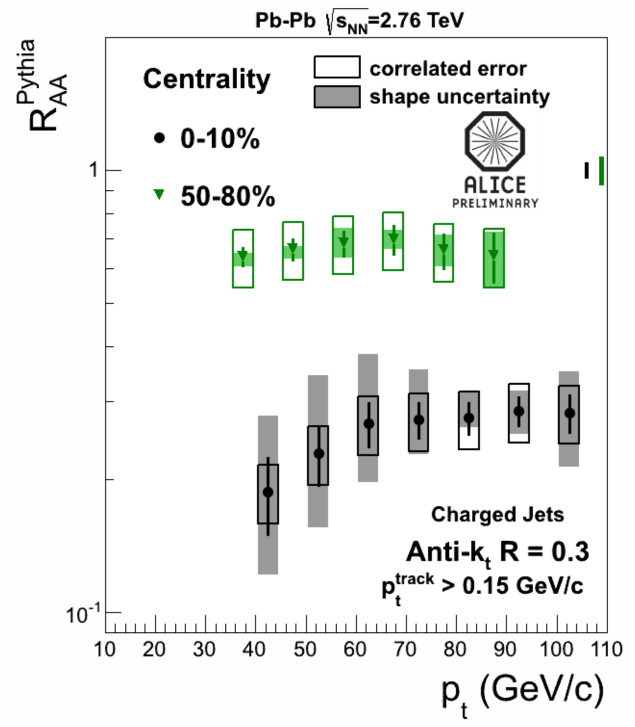
[A. Florent - Hard Probes 2013]

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



Reconstructed jets

[see talks by A Sidoti; L Cunqueiro and G Bruno]



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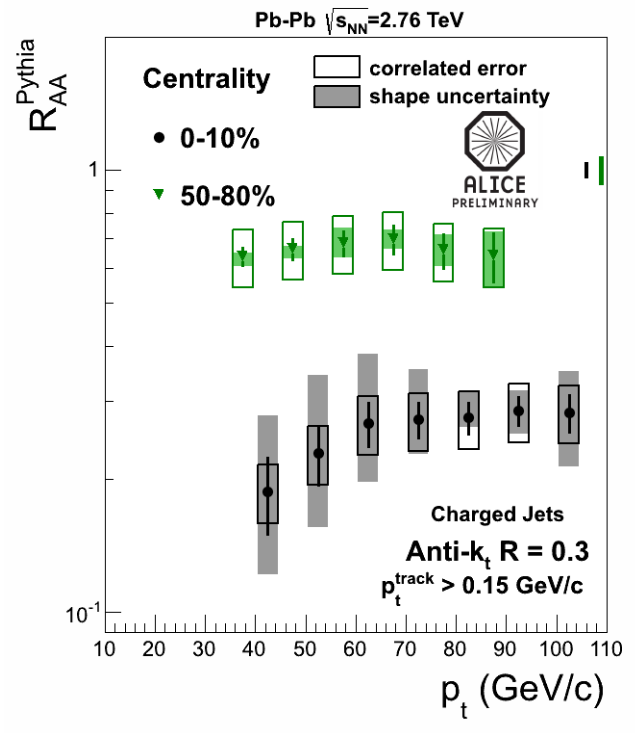

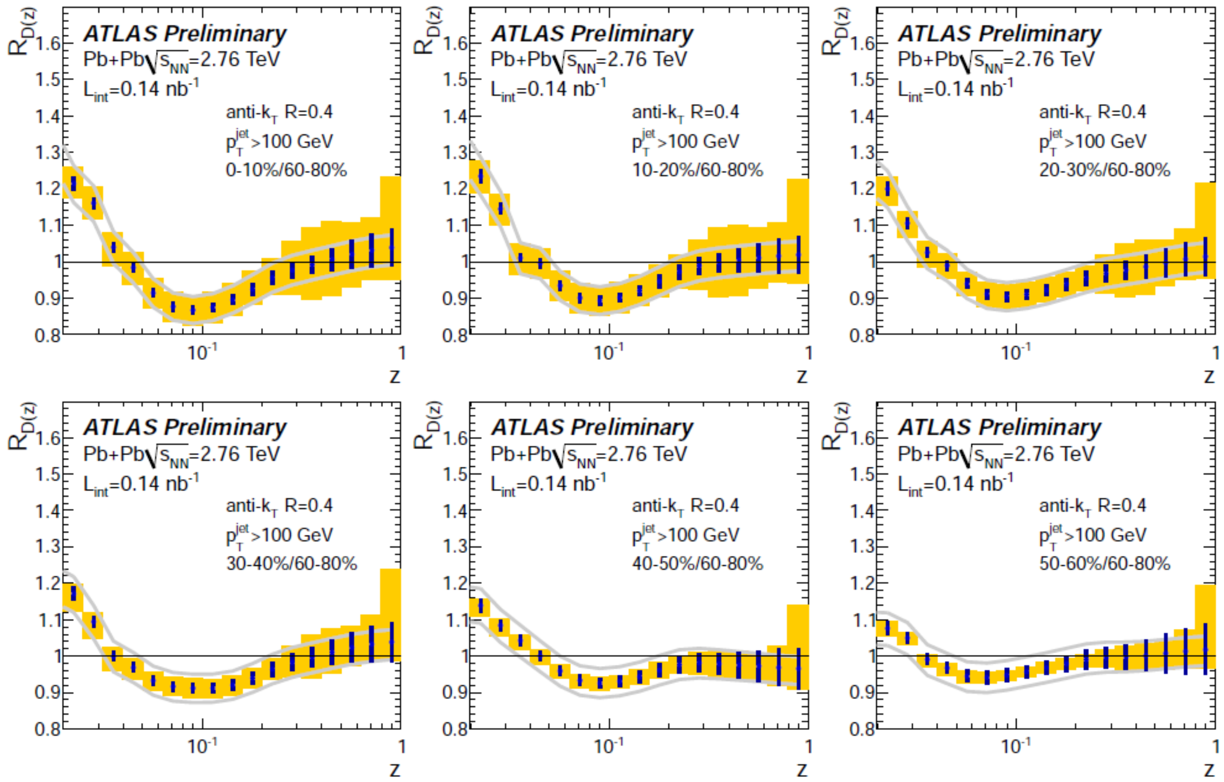

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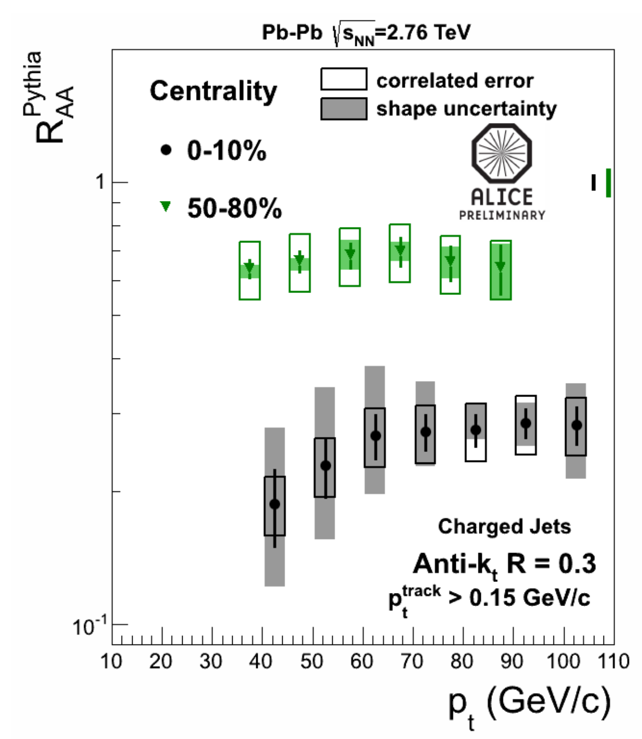

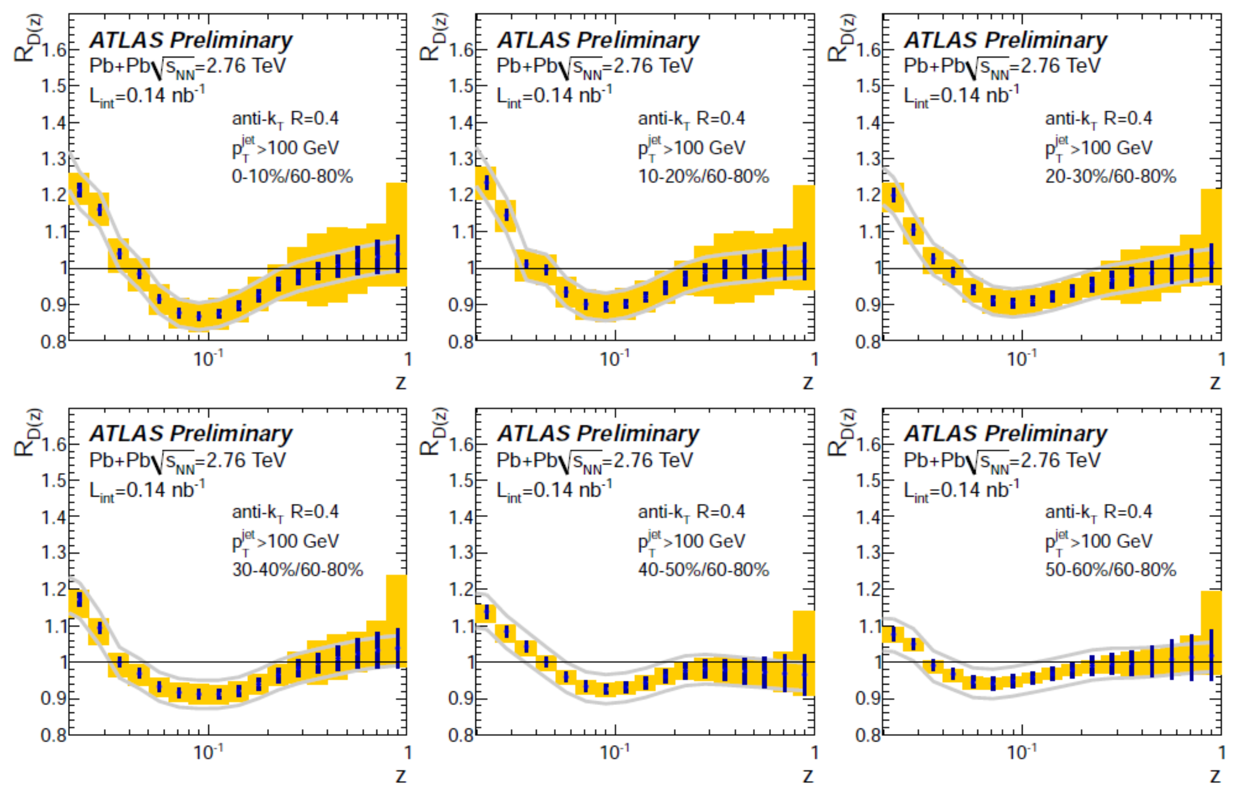

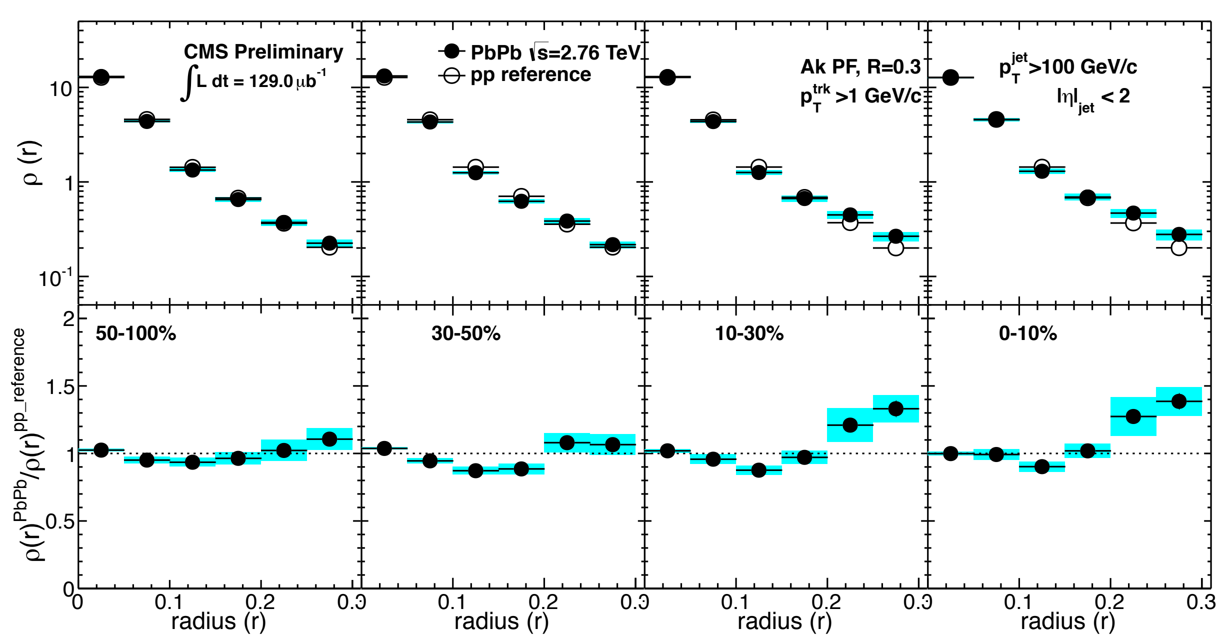

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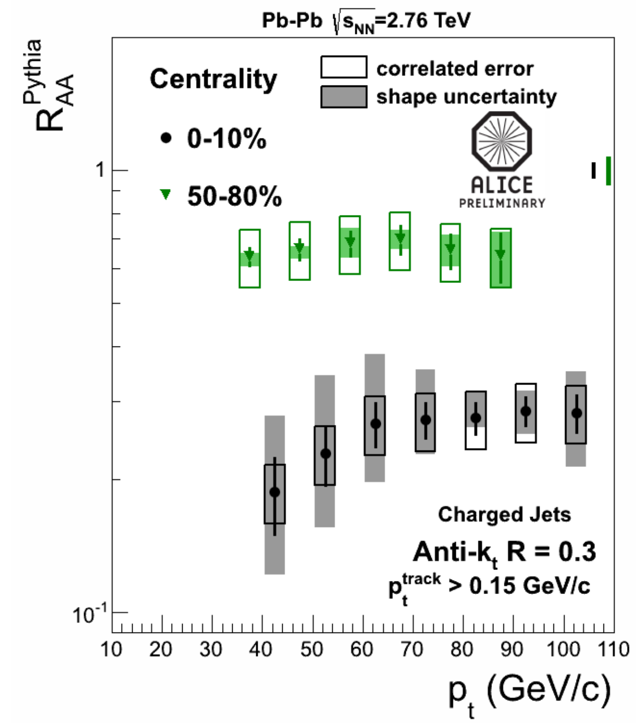

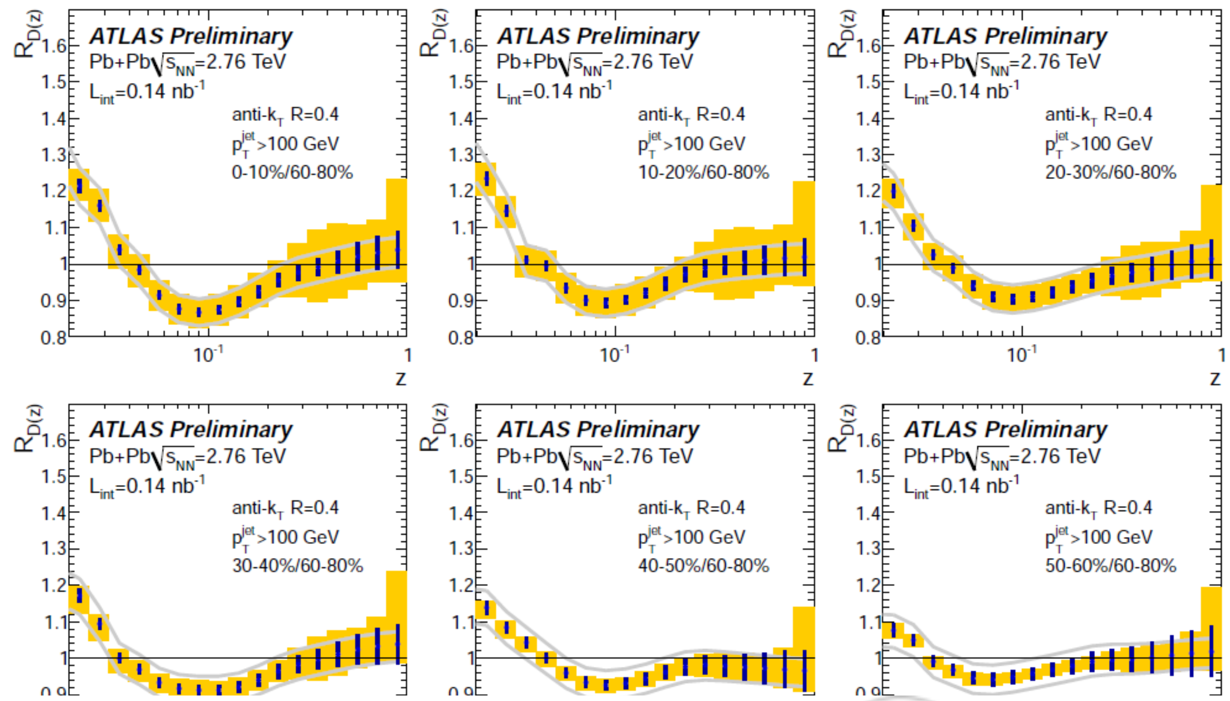

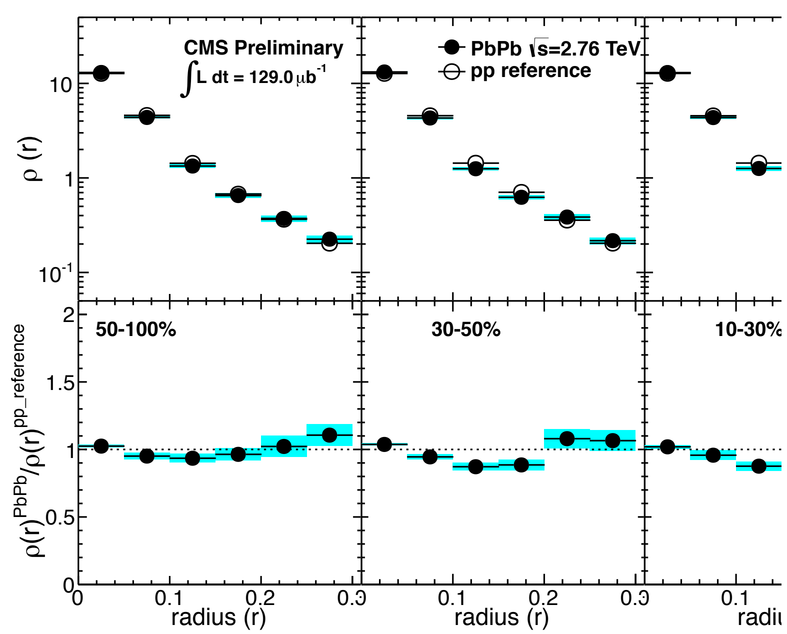

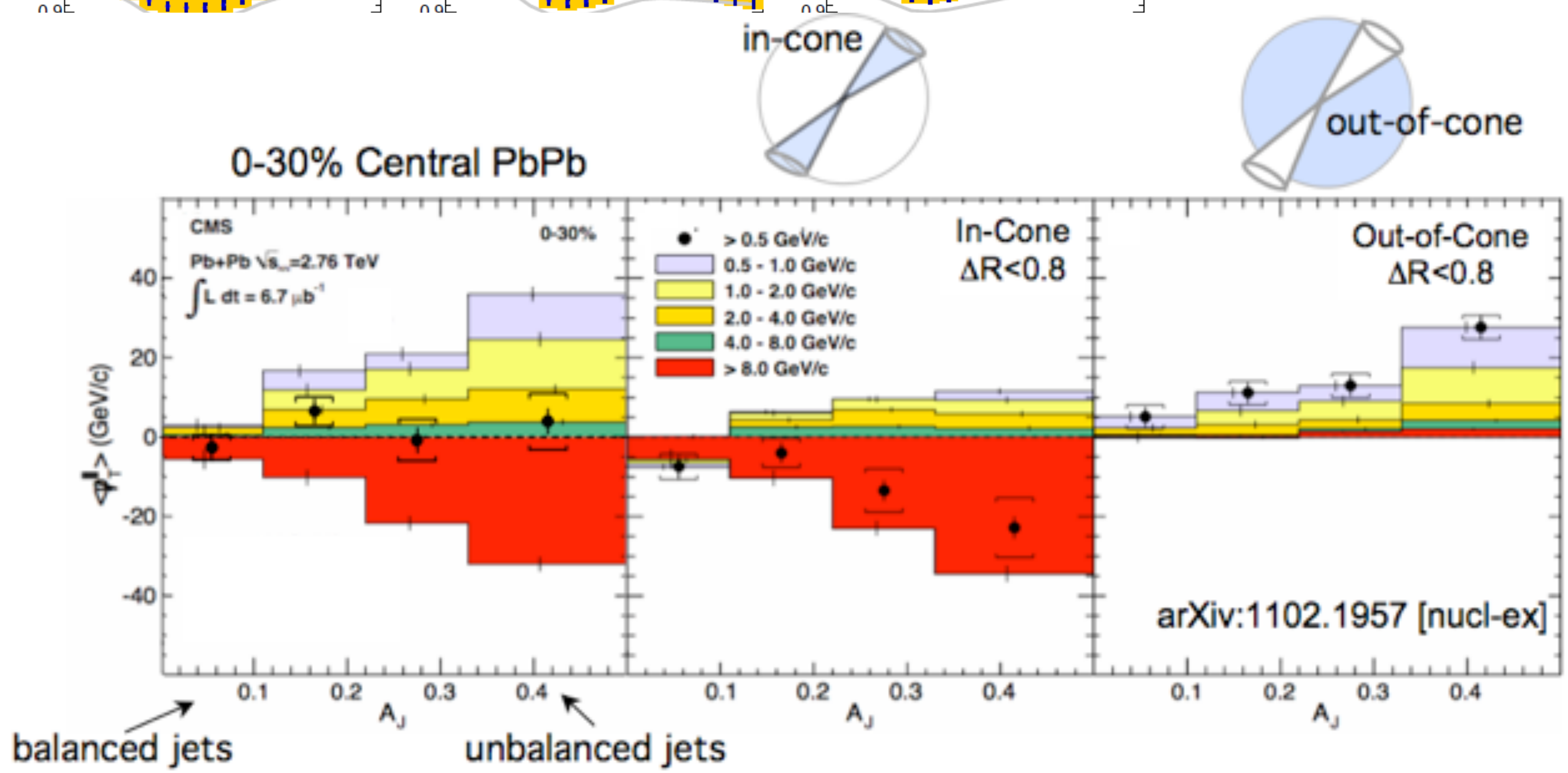

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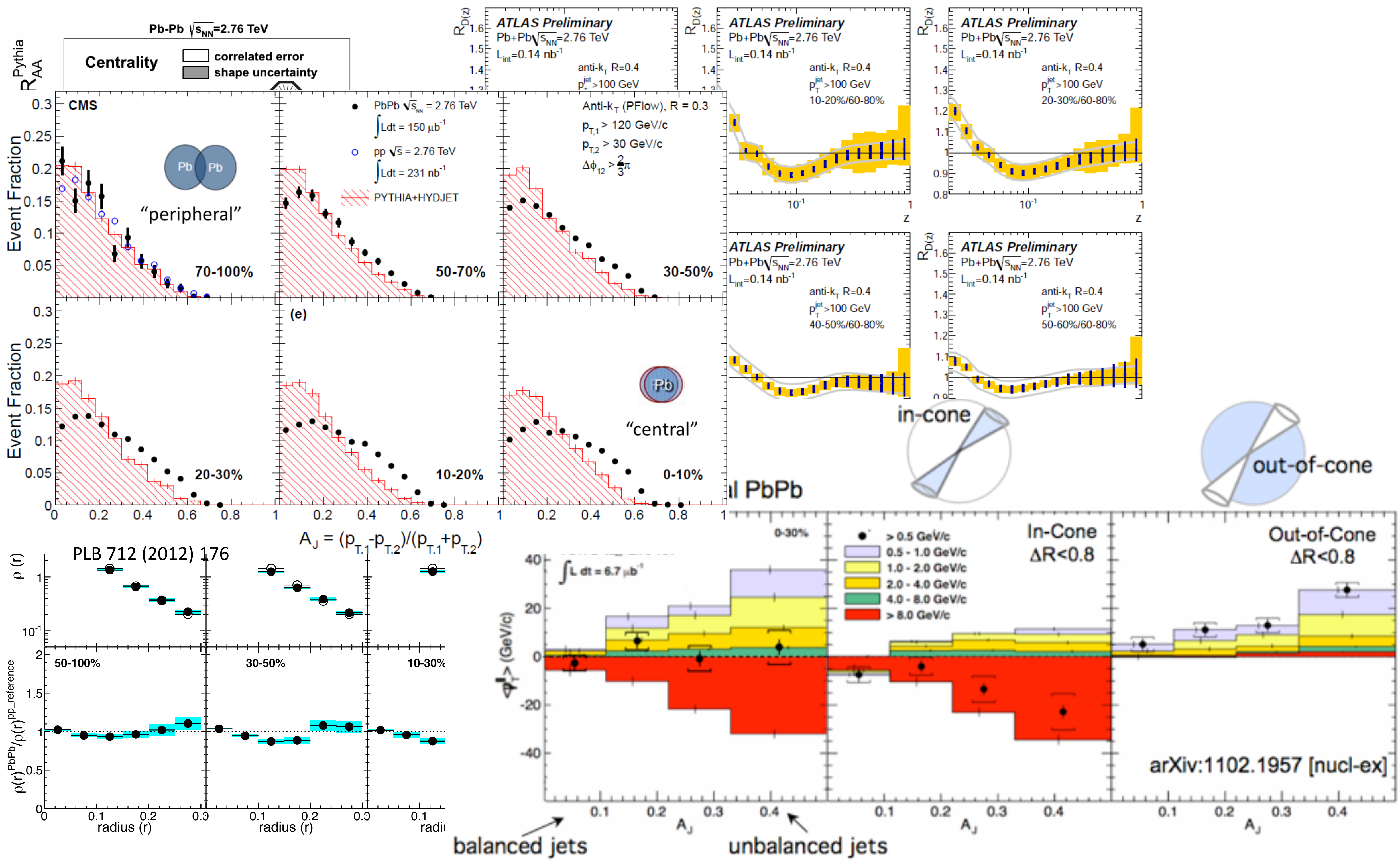
[see talks by A Sidoti; L Cunqueiro and G Bruno]



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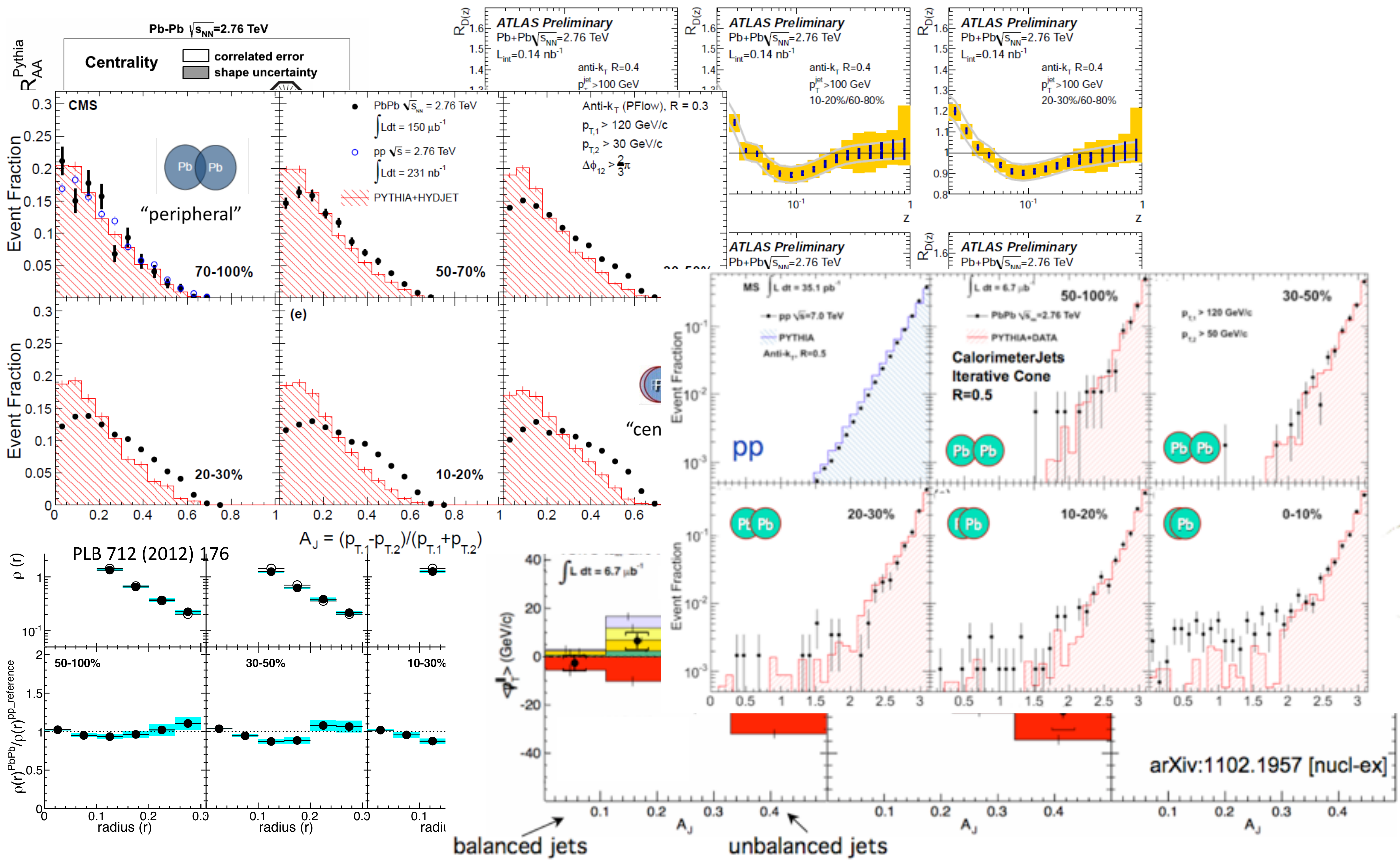
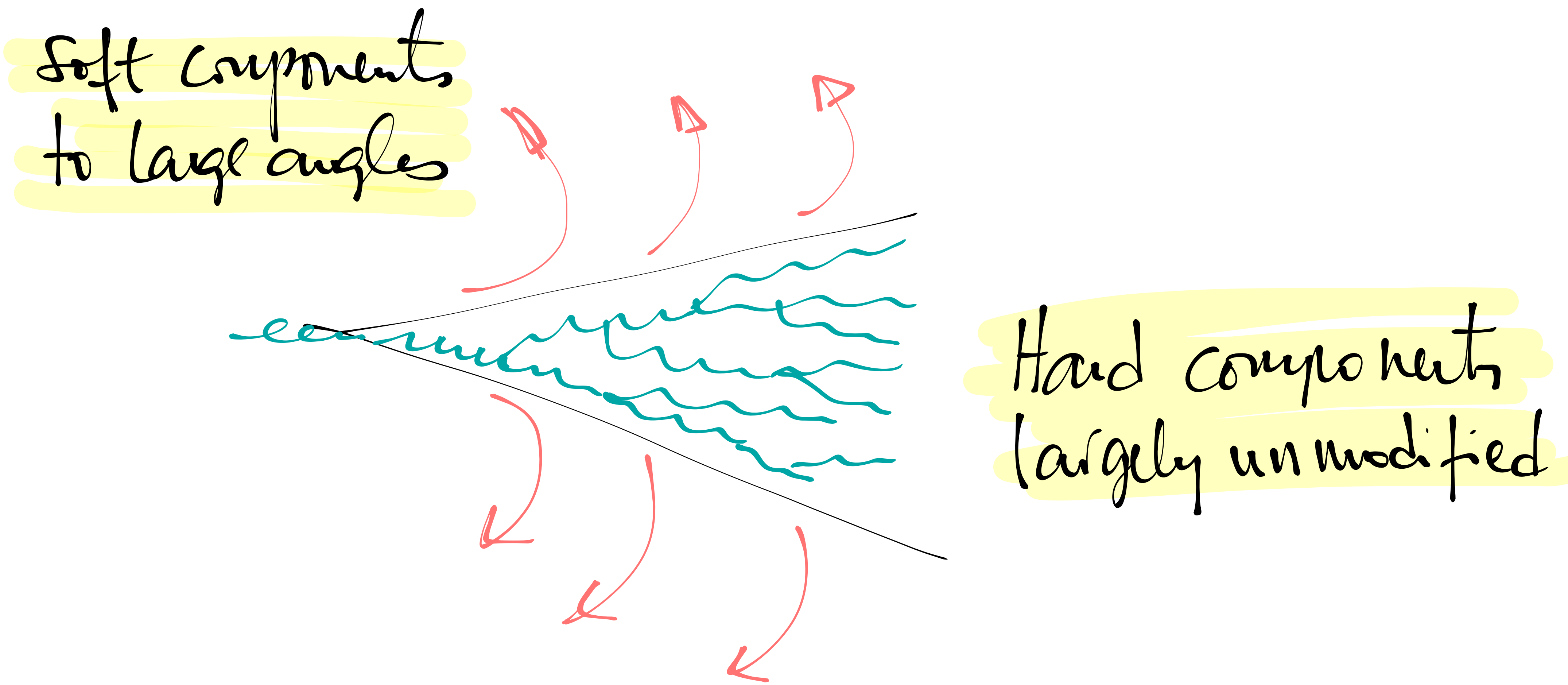


Qualitative description: jet collimation

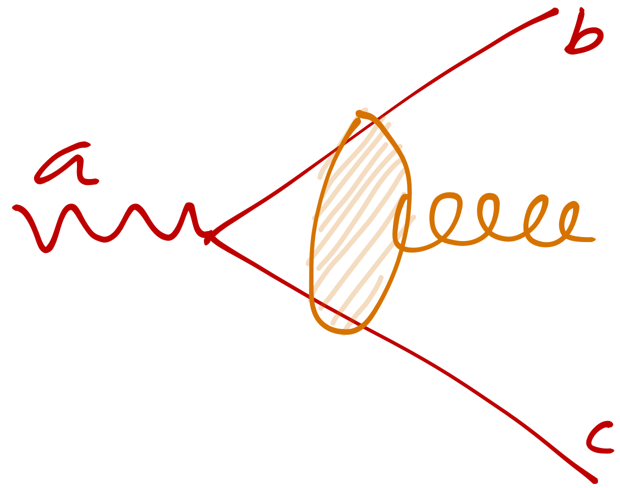
Lessons from experimental data on jet reconstruction

- **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 **almost unmodified**
- Energy taken by **soft particles at large angles**



[Casalderrey-Solana, Milhano, Wiedemann, 2010]

Coherence and decoherence in the antenna



Antenna in the vacuum

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

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

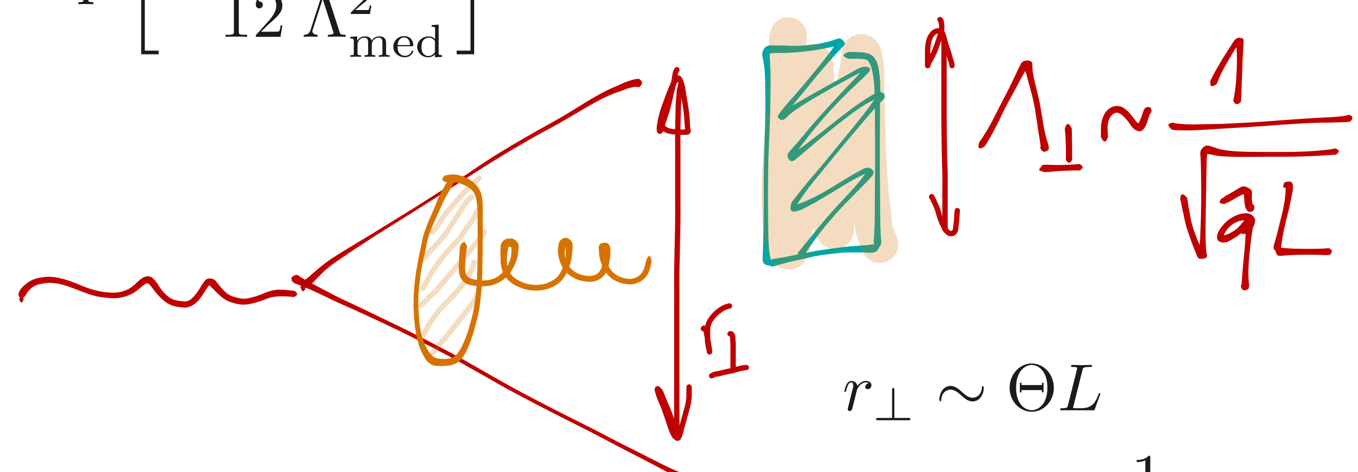
$$r_\perp > \lambda_\perp \iff \Theta > \theta$$

Coherent emission

Antenna in the medium

- Decoherence parameter

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



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

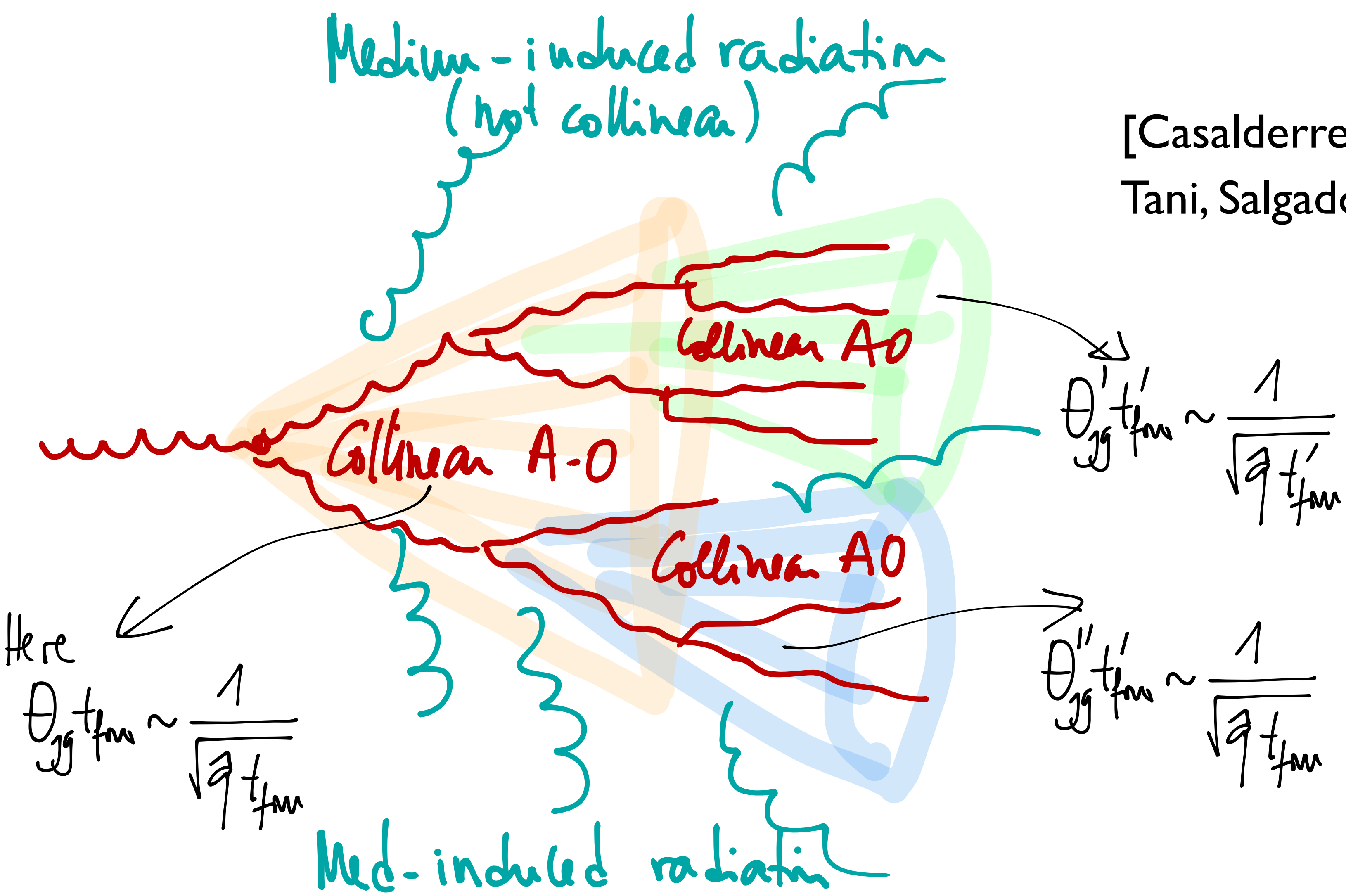
$$\Lambda_{\rm med} \sim \frac{1}{\sqrt{\hat{q} L}}$$

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

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**



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

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

- [Fickinger, Ovanesyan, Vitev 2013; see also Arnold, Iqbal 2015]

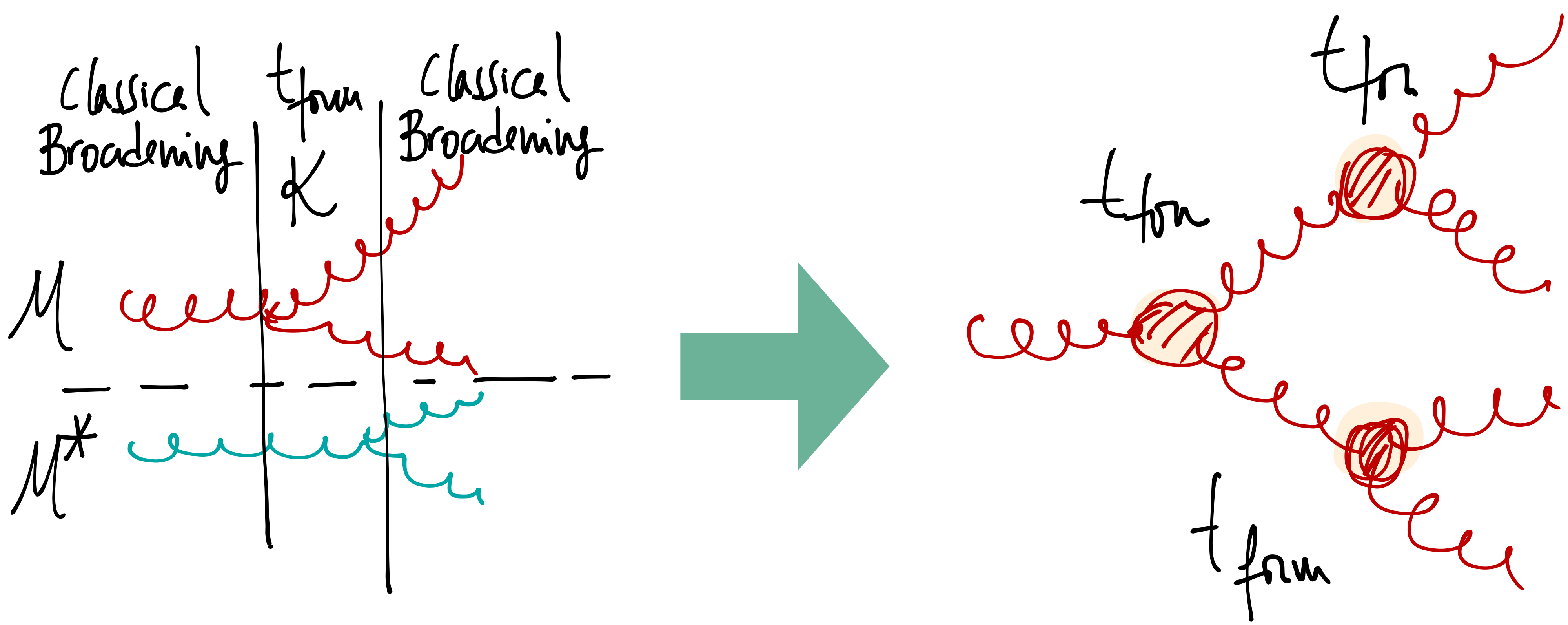
A resummation scheme

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

[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 theory of jet quenching

Remarkable progress in the last years

- Finite-x corrections to the splitting probability
- Role of coherence understood
- New resummation schemes - rigorous parton shower close
- Next orders in alphaS
- Computations of qhat in lattice
- Renormalization of qhat
- Monte Carlo implementations
- ...

A new theory of jets in a medium is being developed

- Several topics need improvements: large angle radiation; jet-medium coupling; role of collisional energy loss; improved Monte Carlo implementations

[Many groups contributing to these theoretical searches - see talk by M Djordjevic]

Summary

Nucleus-nucleus data

- *Good description by hydrodynamical models - extraction of viscosity - role of initial conditions*
- *Remarkable progress on the theory of jet quenching*
- *Improving picture of quarkonia suppression*

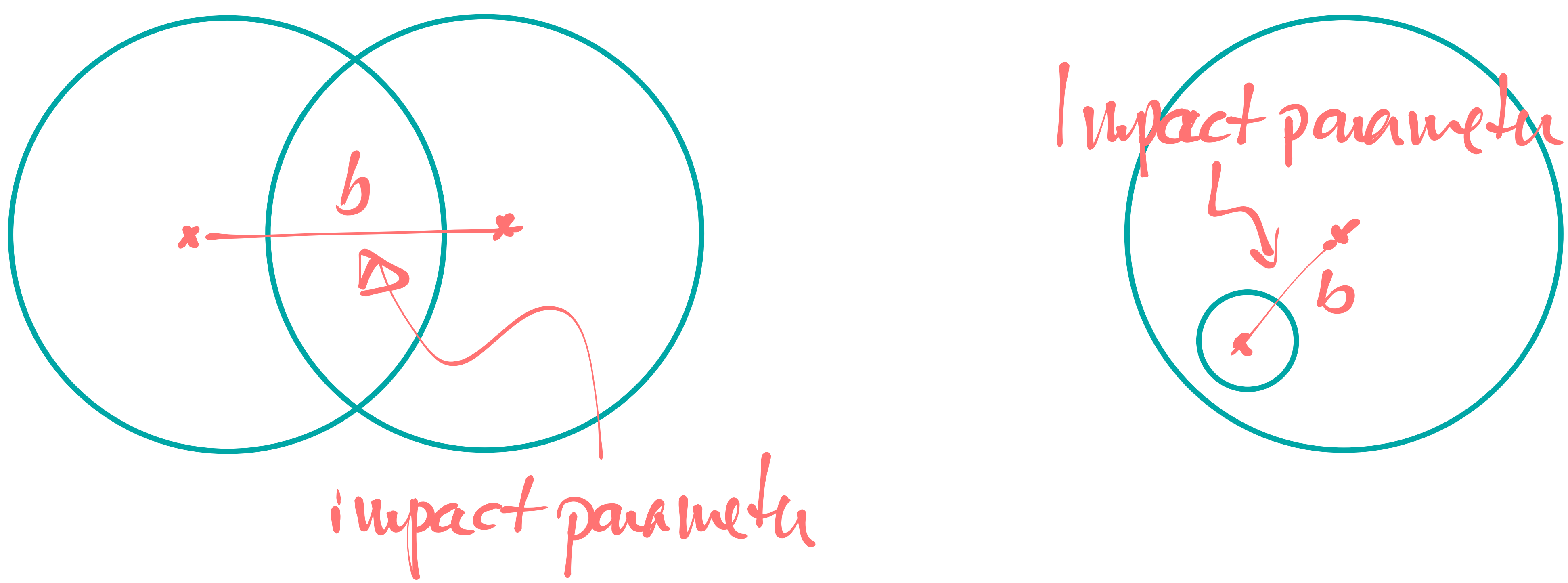
New questions open by the proton-lead run

- *Collective behavior compatible with hydrodynamics*
- *Alternative explanations possible - initial state/CGC*
- *Hard processes in good agreement with nuclear PDFs*
- *Thermalization in small systems?*

Centrality of the collision

Geometry plays a crucial role in heavy-ion collisions

- Access to different geometries (media)
- Experimental control through different global event distributions



Centrality of the collision refers to the amount of overlap

- Central - head-on collisions - maximum overlap
- Peripheral have small overlap

All this very simplified, reality much more complicated than this picture