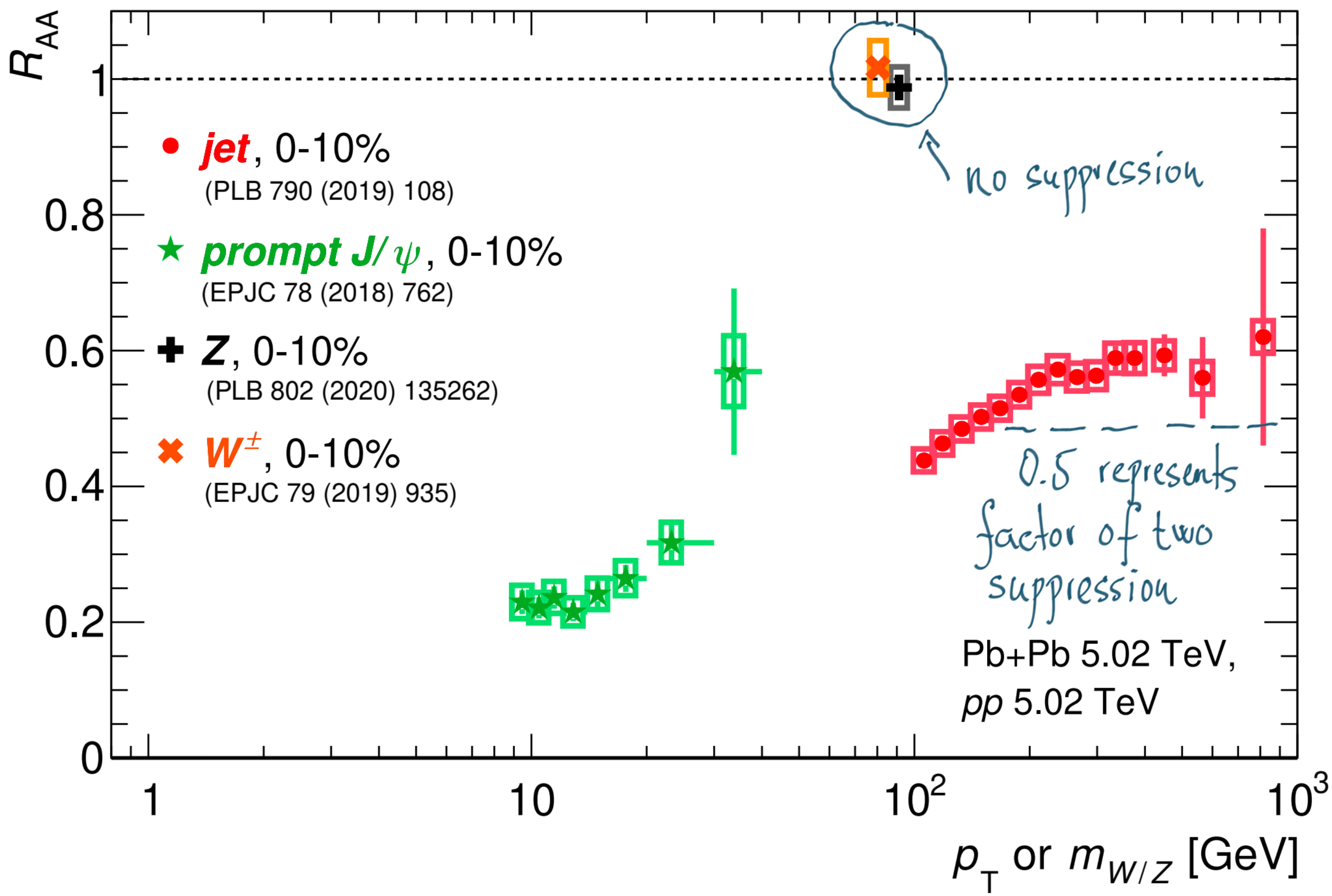
Jet and charmonia suppression in heavy ion collisions

Martin Spousta
with
Martin Rybář, Martin Krivoš, Pavel Váňa

Jet and charmonia suppression

Quantifies level of suppression of yields in heavy-ion collisions with respect to proton-proton collisions. **Unity means no suppression.**

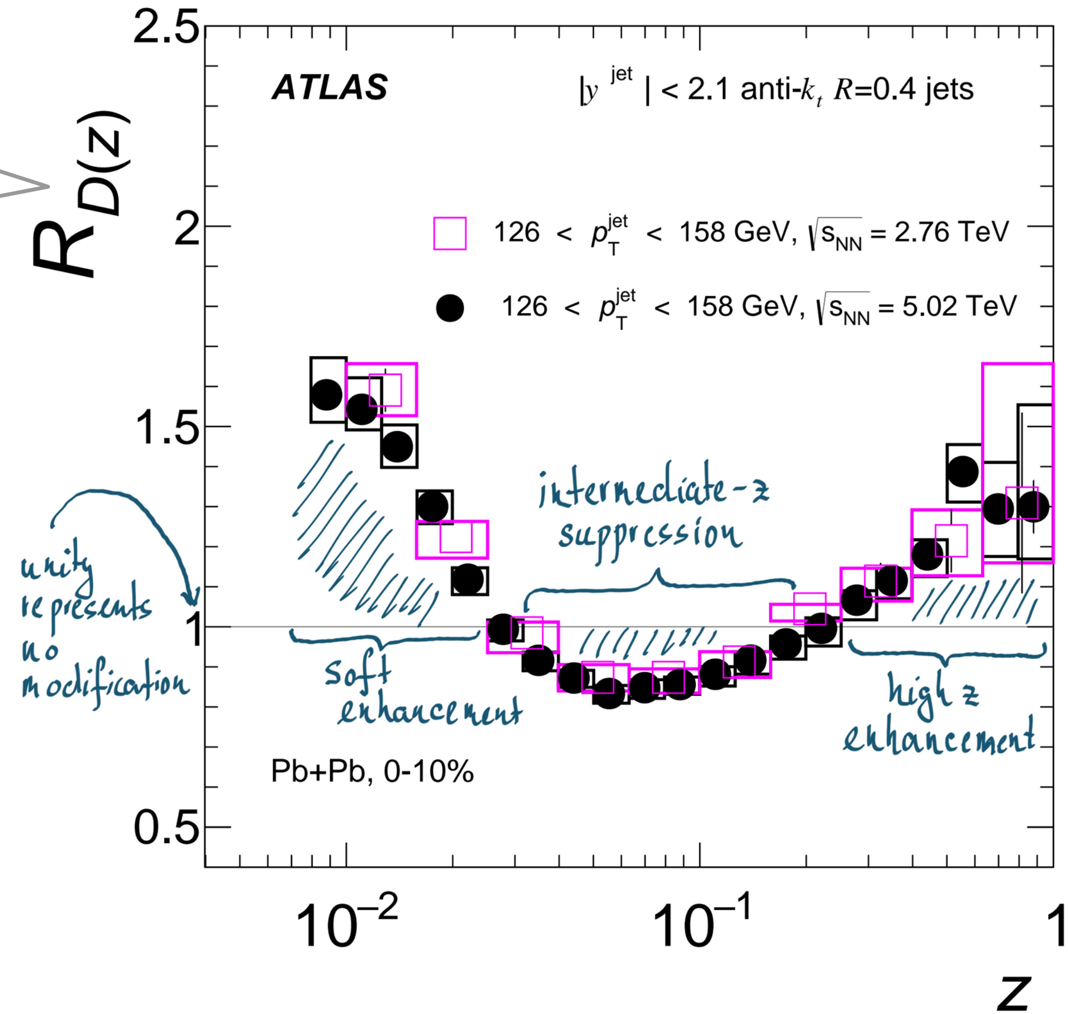


Why are jets and charmonia so much suppressed in heavy-ion collisions?

What is the underlying mechanism?

Jet internal structure

Ratio of fragmentation functions quantifies modification of jet internal structure in heavy ion collisions with respect to proton-proton collisions



Why is the internal structure of jets in heavy-ion collisions modified in such a complex way?

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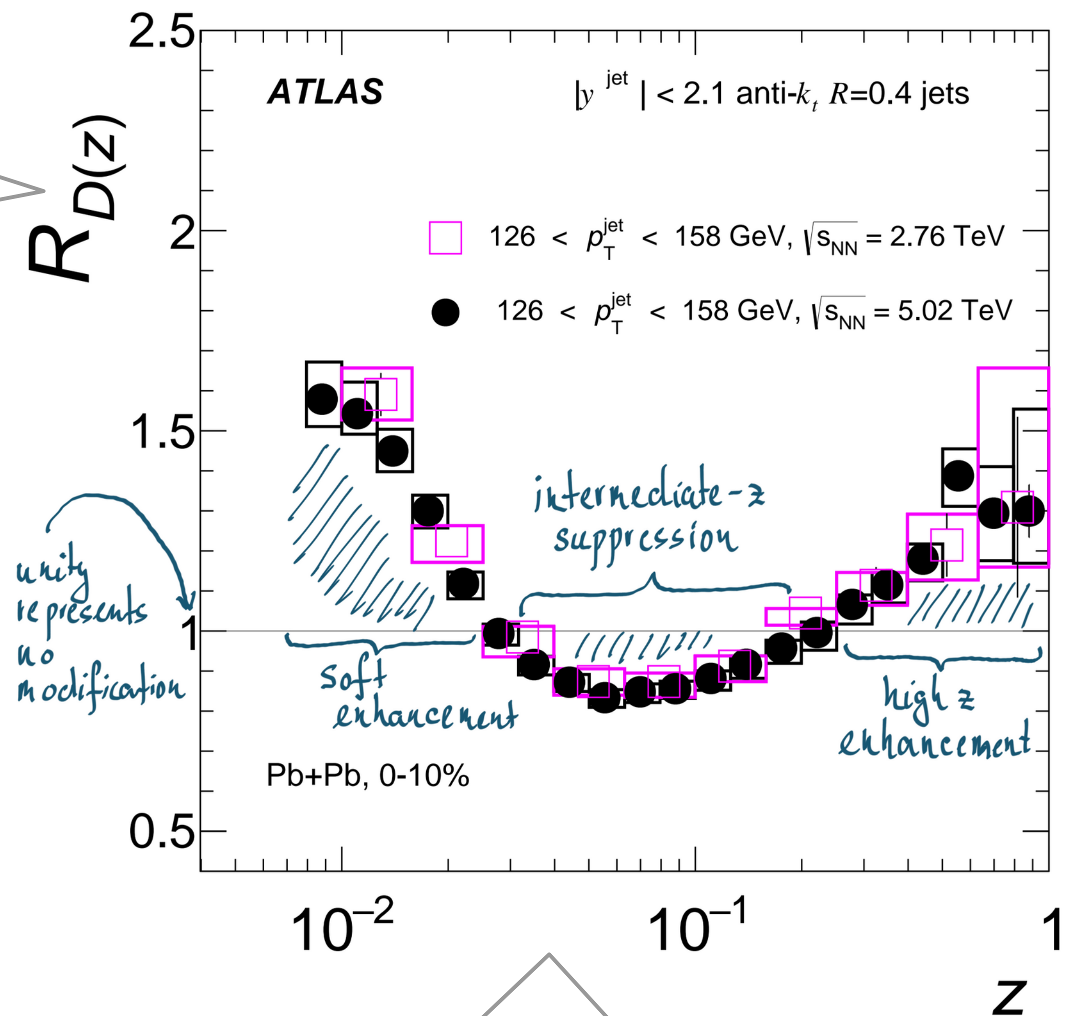

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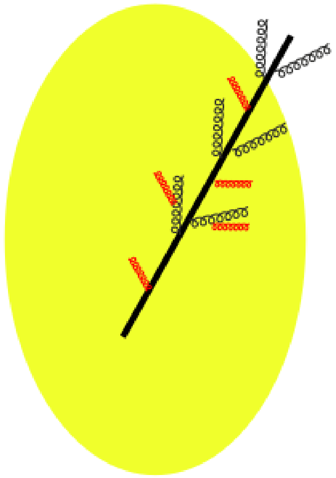
Again, what is the underlying mechanism?

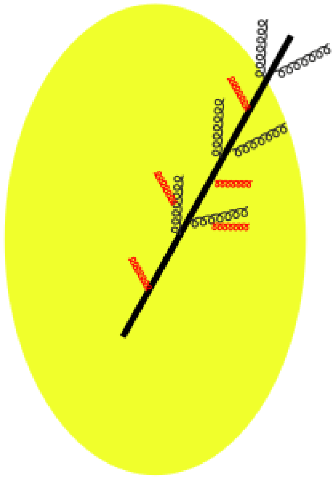
(Majority of results on RD(z) and Raa by people from CU)

Mechanism



- Main mechanism of the jet suppression is the **radiative energy loss** of parton shower propagating trough the strongly interacting medium created in the collision. There are many proofs of that concept, one of them is a dependence of the lost energy on color charge (see M.S., B. Cole, EPCJ 76 (2016) 50).
- Suppression of **charmonia** at low-pt is traditionally explained as result of “melting” (potential between c anti-c is not strong enough). At high-pt the mechanism may however be also the radiative energy loss as suggested e.g. in M.S., PLB 767 (2017) 10-15.
- Understanding the mechanism of energy loss involves understanding:
  - role of color coherence (=important QCD phenomenon which builds jets),
  - the path-length dependence,
  - role of and mechanism of hadronization (esp. for quarkonia),
  - role of mass (e.g. the dead-cone effect),
  - …

Mechanism



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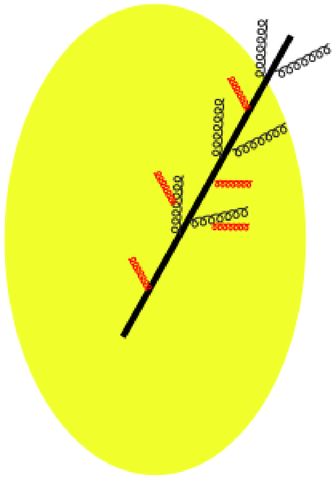
Mechanism



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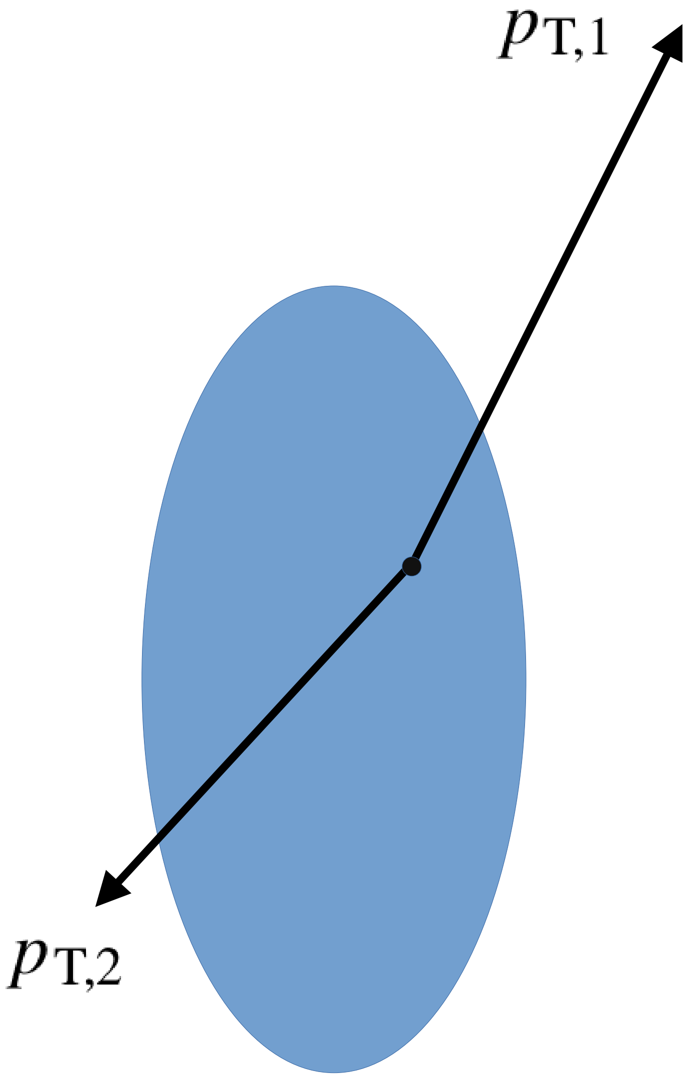
  - … … talk by Martin

In 2021 and 2022 ...

… today

- Tim Rinn, …, M.S. [ATLAS], “**Dijet quenching** in 2018+2015 PbPb & pp”, **arXiv:2205.00682**
- S. Adhya, C. Salgado, M.S., K. Tywoniuk, “Multi-partonic medium induced **cascades in expanding media**”. **EPJC 82 (2022) 20**
- Martin Krivoš, M.S., Martin Rybář [ATLAS] “Dijet quenching in **Xe+Xe** collisions” – to be finalized soon
- Martin Rybář, (M.S., M.K.) [ATLAS], “Suppression in **Large-R**”, to be published soon
- Sebastian Tapia, …, Martin Rybář [ATLAS], “**b-jet** suppression”, **arXiv:2204.13530**
- Pavel Váňa, M.S. – **Radiation of charmonia**

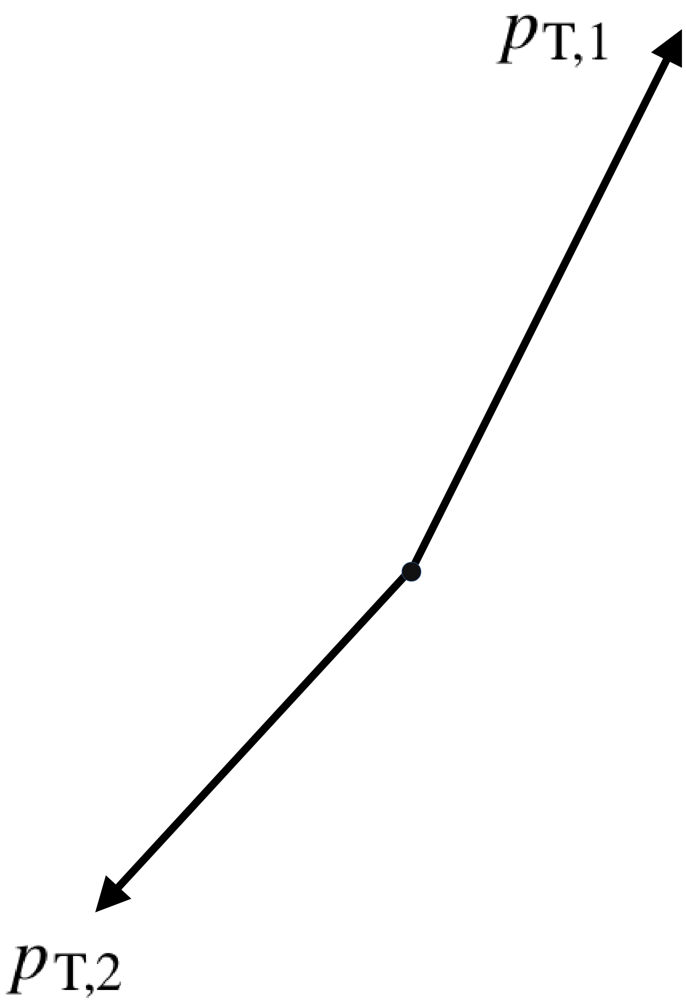
Dijet quenching

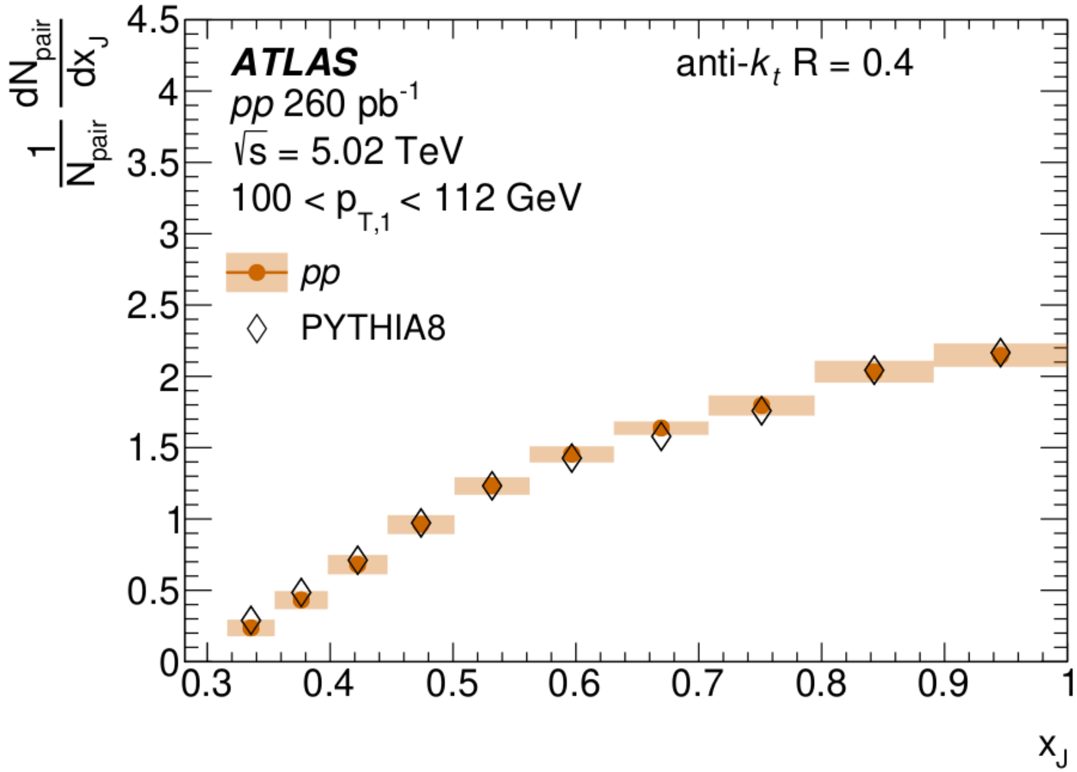


$$x_{\mathrm{J}} \equiv \frac{p_{\mathrm{T},2}}{p_{\mathrm{T},1}}$$

- Sensitive to path-length of partons inside the deconfined matter
- Sensitive to fluctuations in the parton energy loss

Dijets in pp

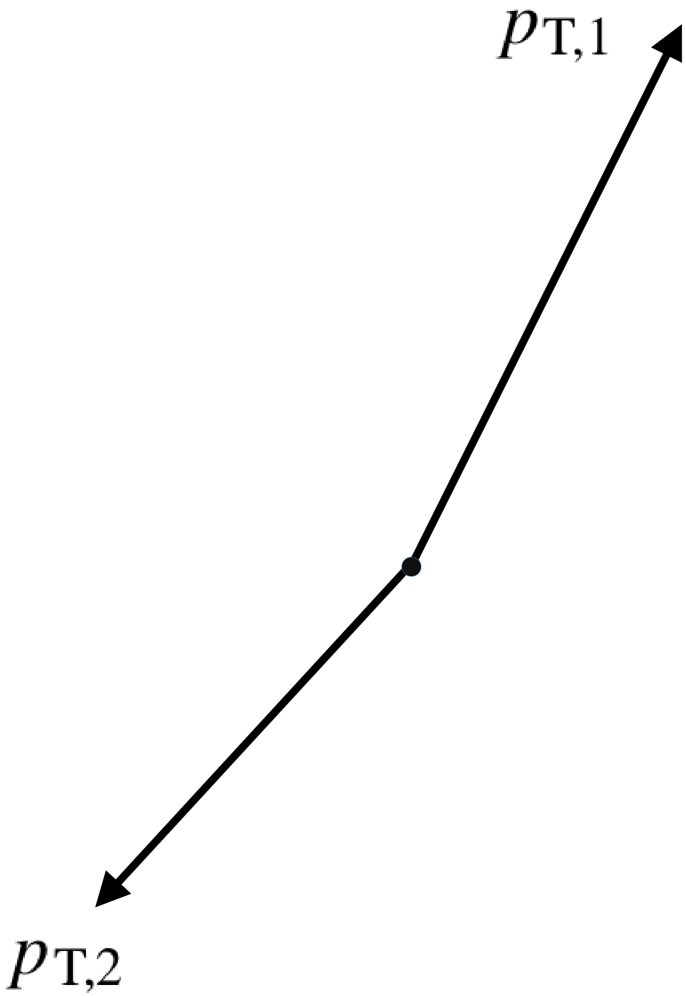




- In pp collisions, the most probable configuration is a balanced dijet

$$x_J \equiv \frac{p_{T,2}}{p_{T,1}}$$

Dijets in pp



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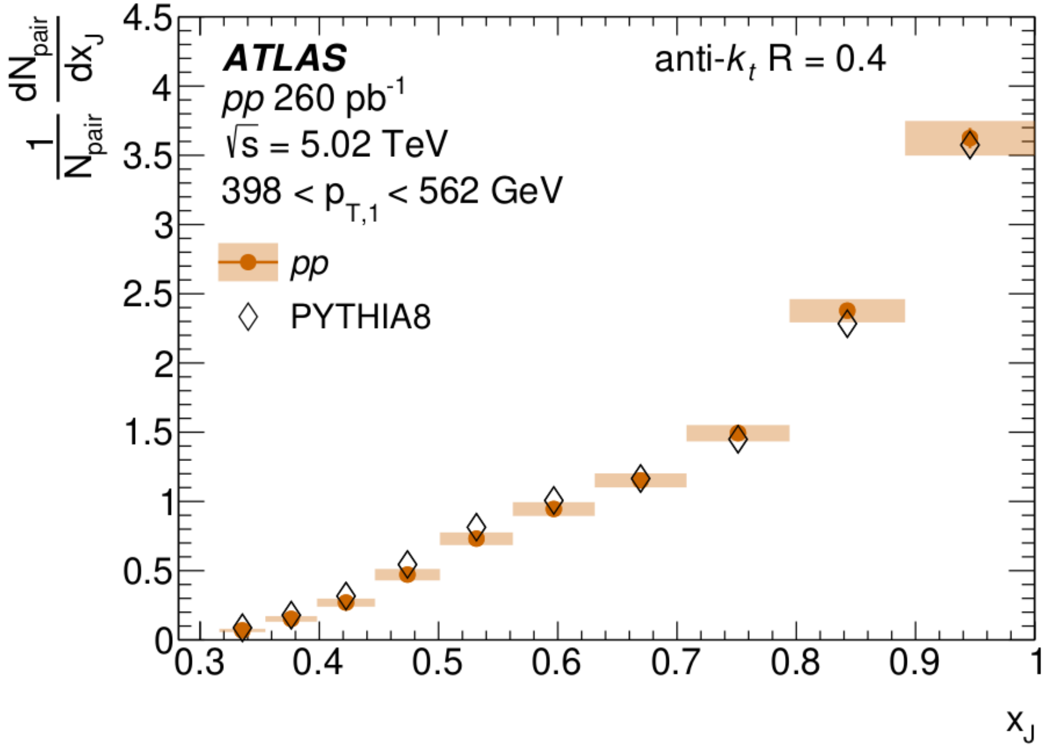
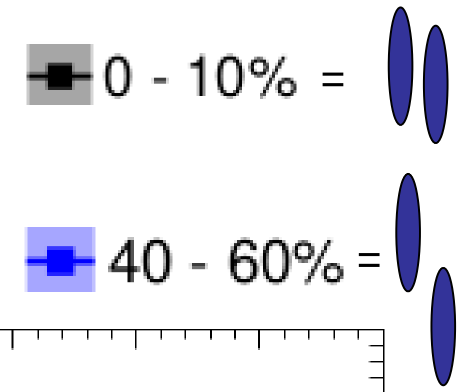
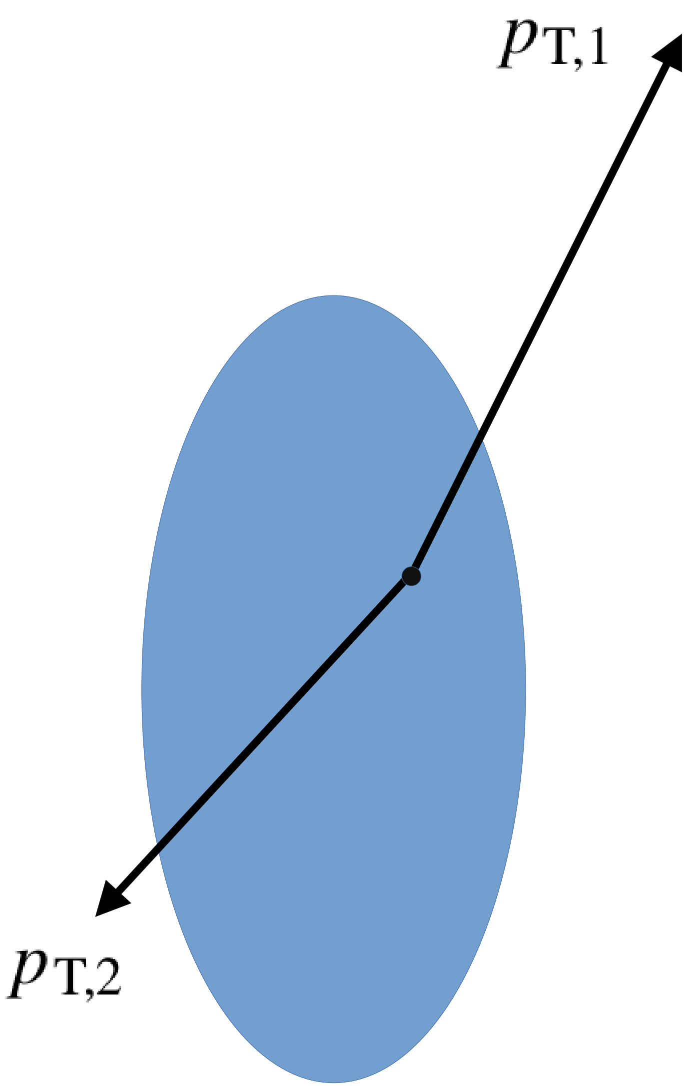


- In pp collisions, the most probable configuration is a balanced dijet
- Higher pt –> better balance
- LO + angular ordered LLA describes the data well

Dijets in Pb+Pb





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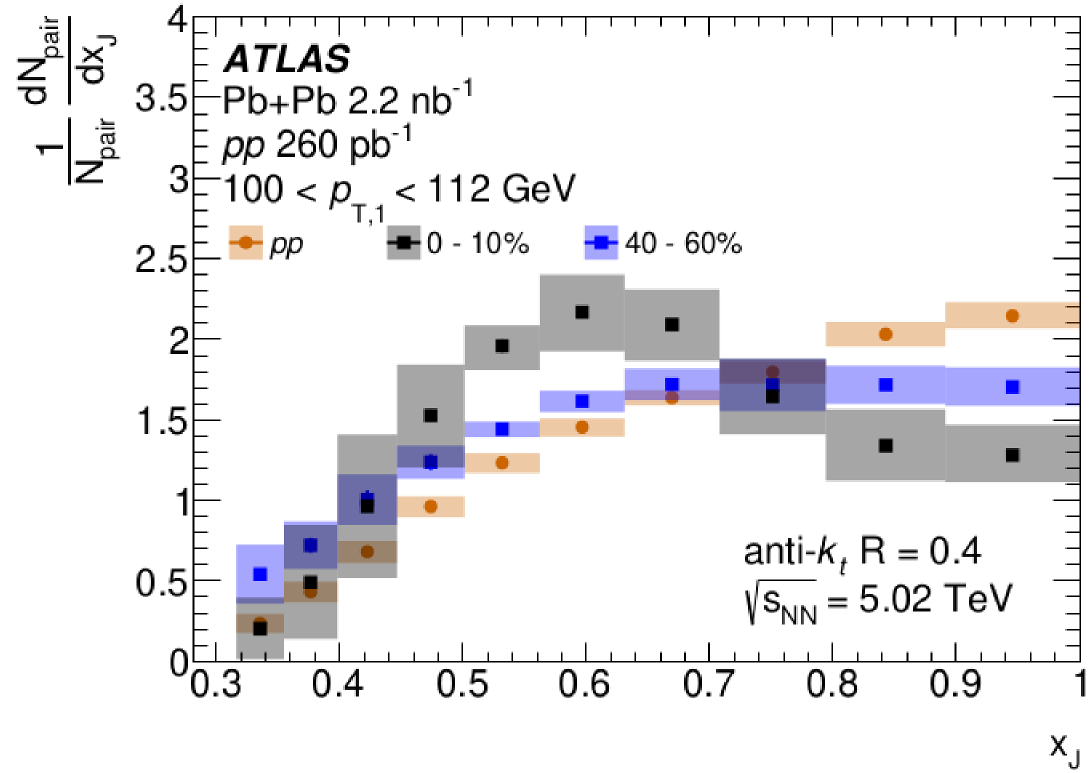
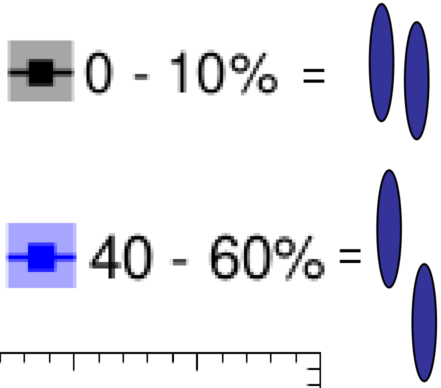
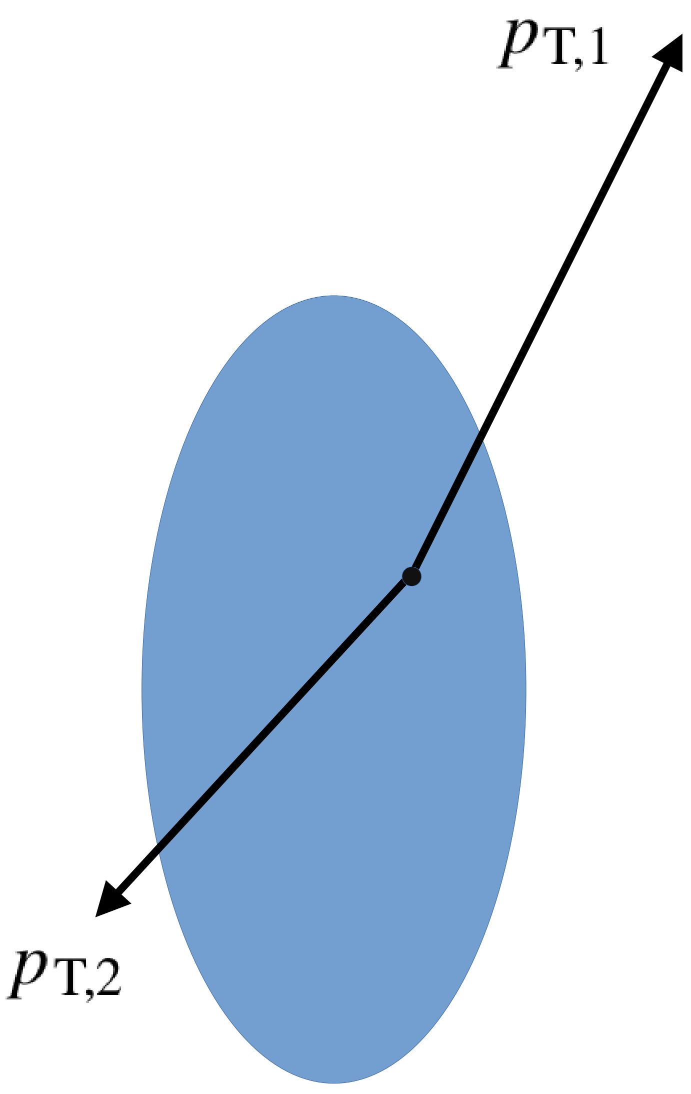


- In central collisions (0-10%) the most probable is significant imbalance
- More peripheral –> the balance is restored

Dijets in Pb+Pb





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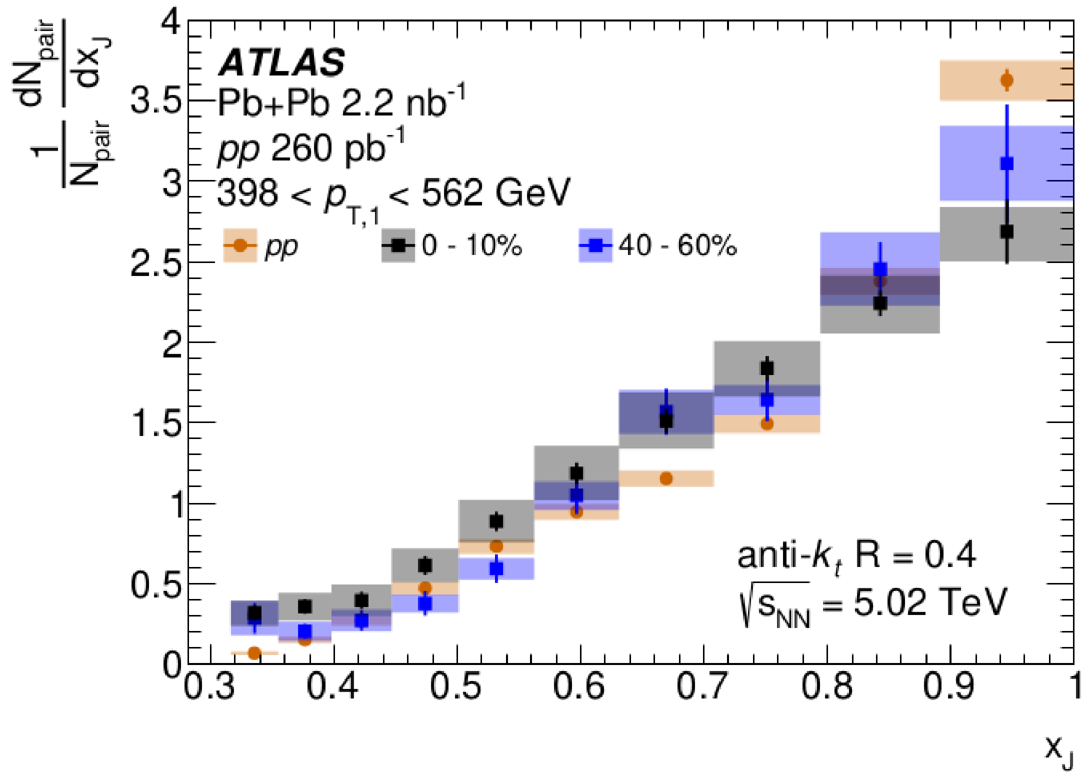

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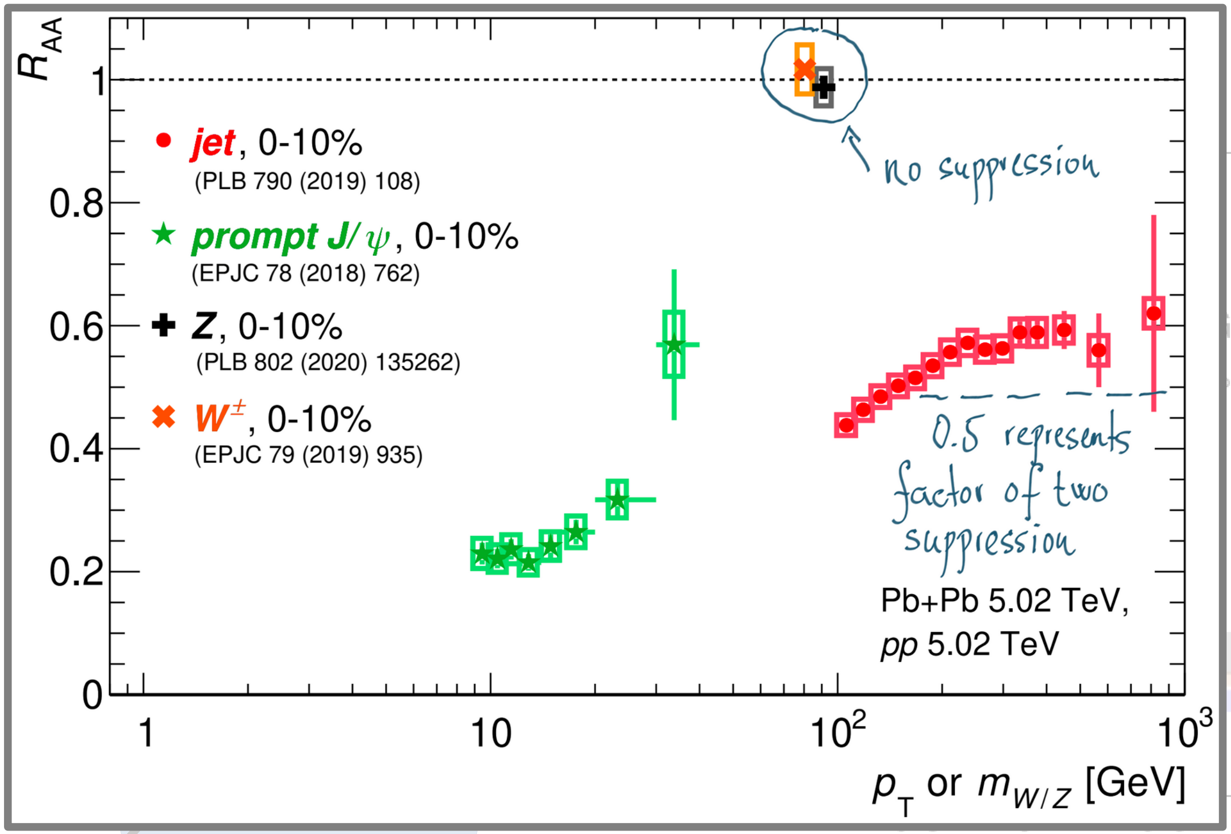
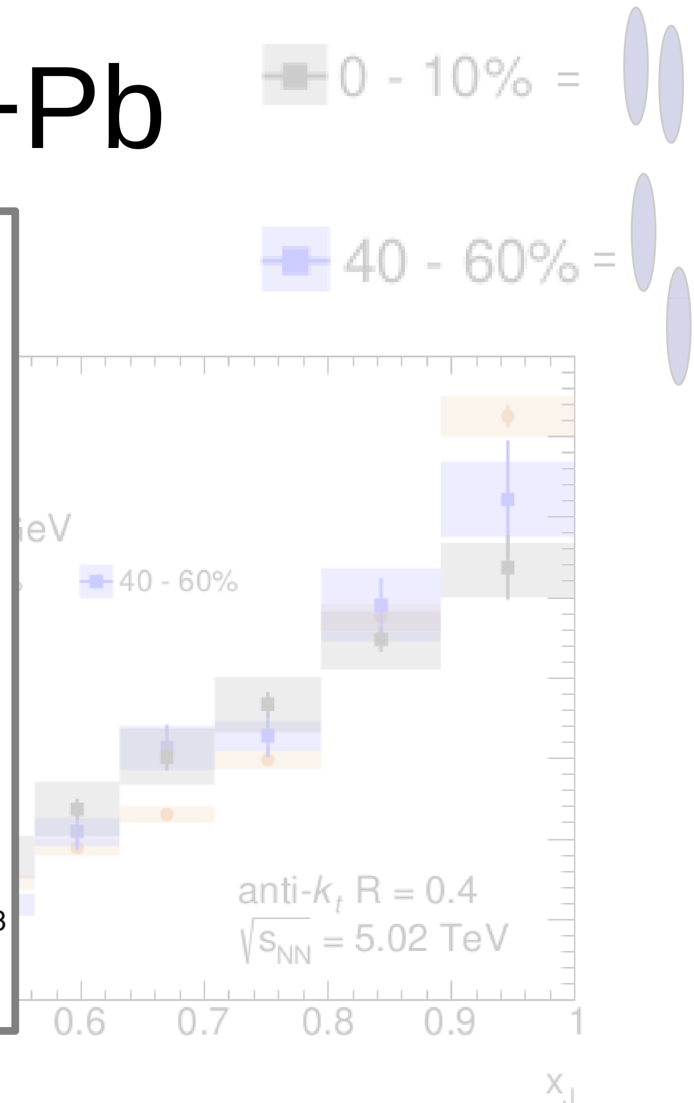
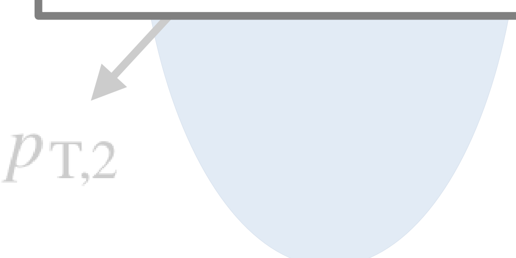


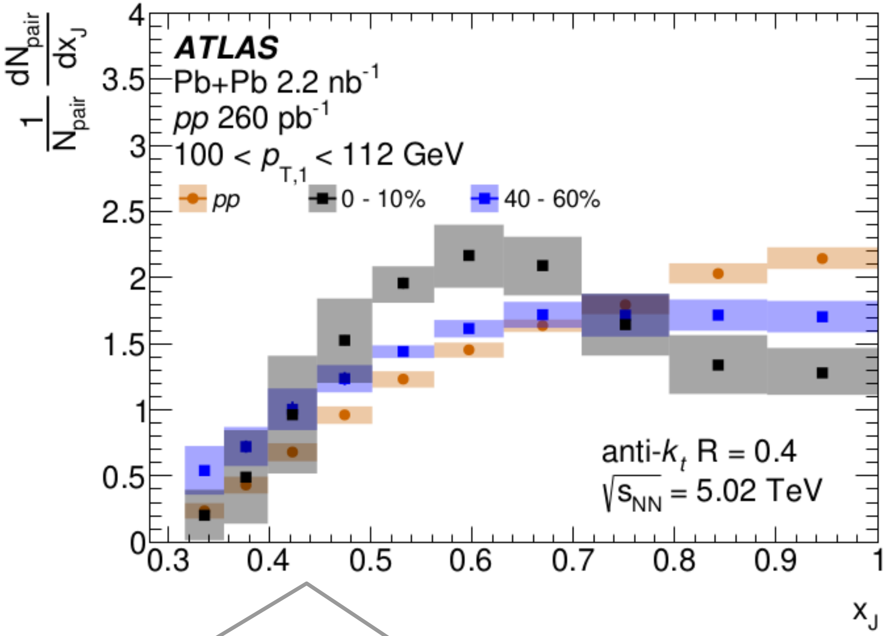




$$x_J \equiv \frac{p_{T,2}}{p_{T,1}}$$

- In central collisions (0-10%) the most probable is significant imbalance
- Higher pt –> the balance is restored
- But remember that the inclusive jet suppression is still large

Different normalization



Per-pair normalized xJ distribution

“Absolutely normalized” xJ distribution

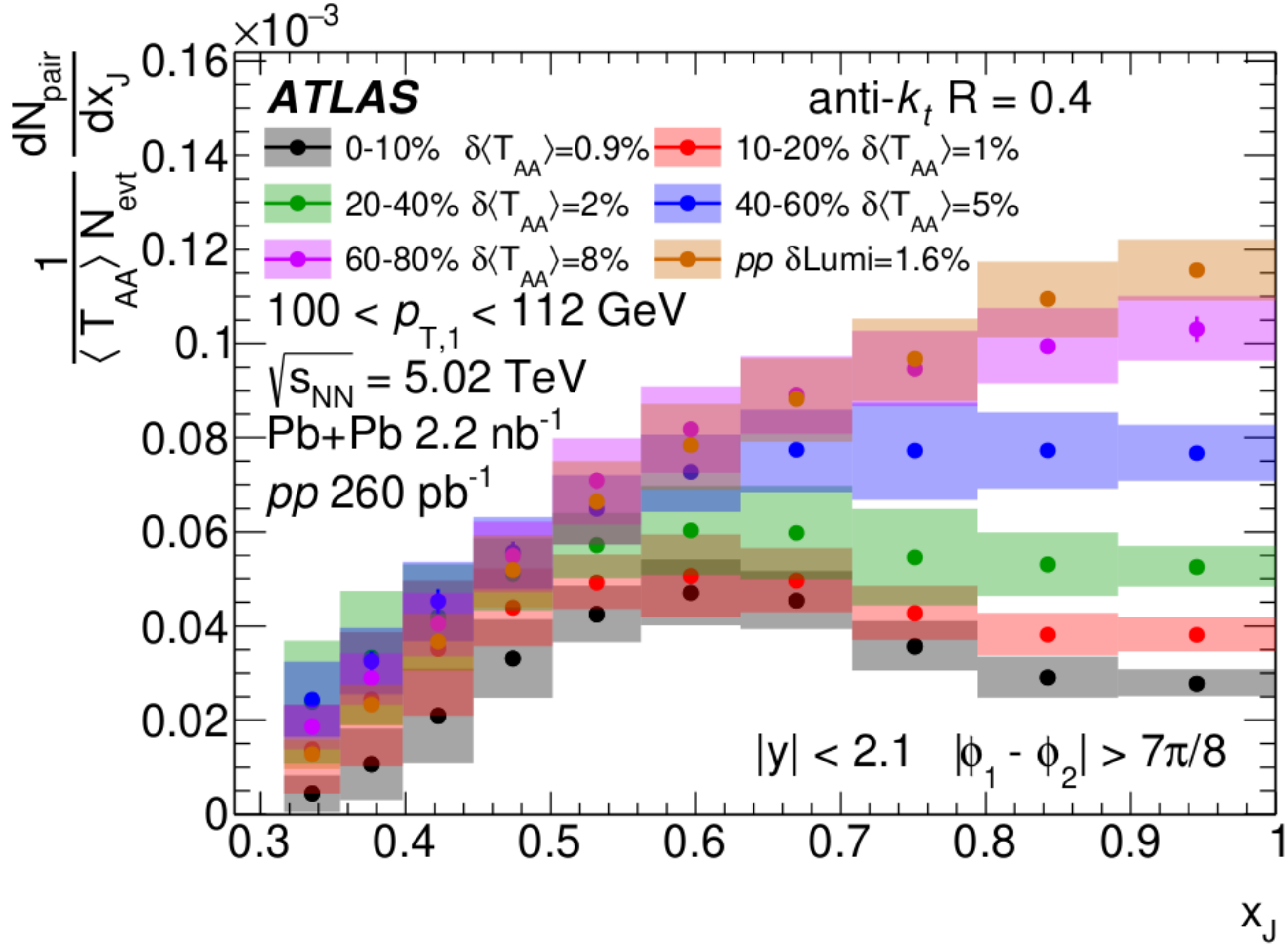
- Look at this using a different normalization
- Borrow the normalization from the Raa:

$$R_{\mathrm{AA}} = \frac{1}{N_{\mathrm{evt}}} \frac{dN_{\mathrm{jet}}}{dp_{\mathrm{T}}} \bigg/ \left(\langle T_{\mathrm{AA}} \rangle \frac{d\sigma_{pp}}{dp_{\mathrm{T}}} \right)$$

- That is evaluate:

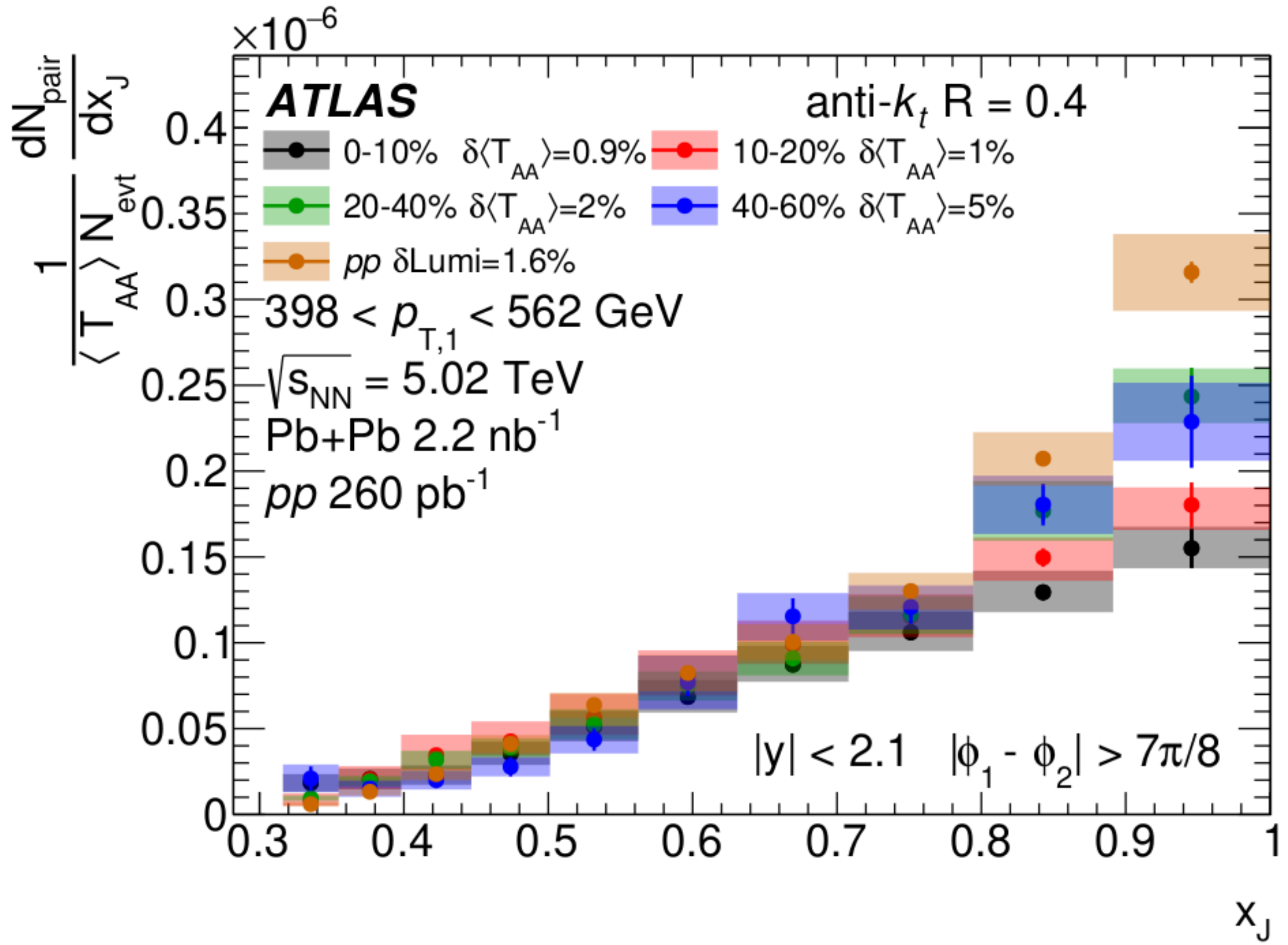
$$\frac{1}{\langle T_{\mathrm{AA}} \rangle N_{\mathrm{evt}}^{\mathrm{AA}}} \frac{dN_{\mathrm{pair}}^{\mathrm{AA}}}{dx_{\mathrm{J}}}$$

Absolutely normalized xJ distribution



- The peak structure observed at intermediate xJ comes from a **suppression of symmetric** dijets
- Production of **asymmetric dijets not enhanced** in Pb+Pb collision compared to pp collisions

Absolutely normalized xJ distribution



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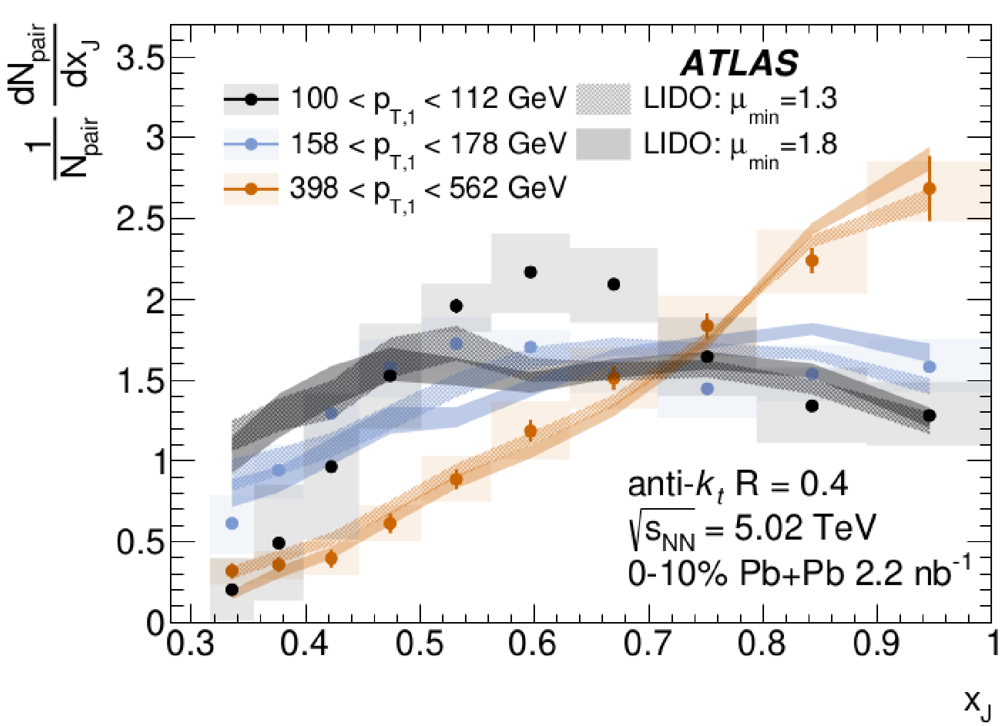
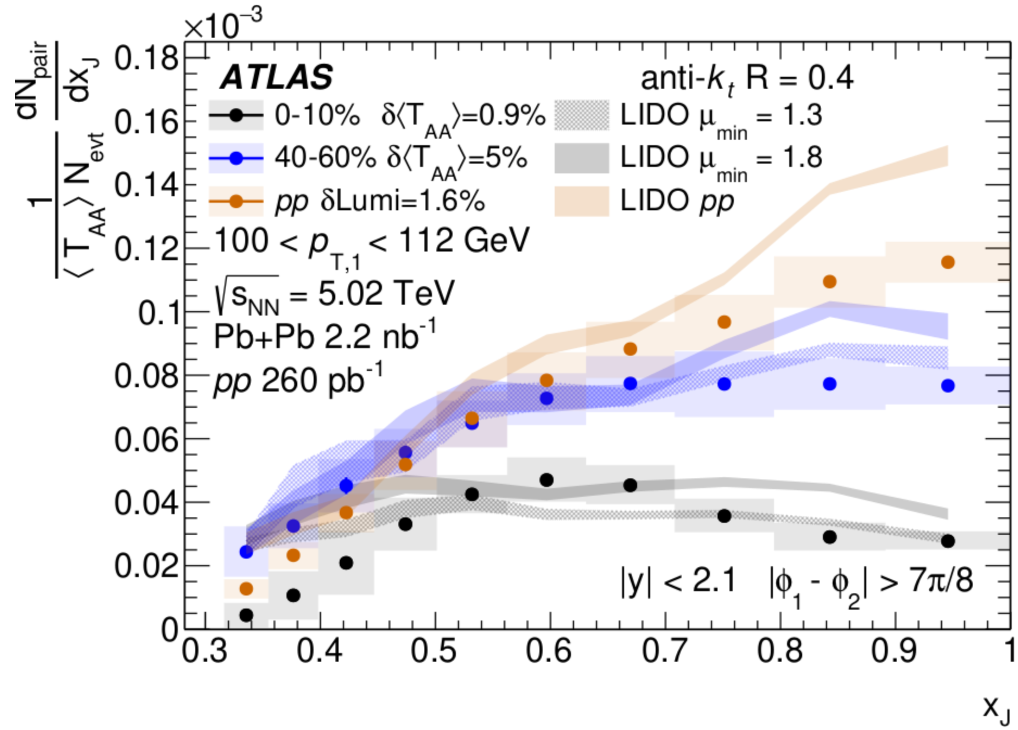
Comparison with theory

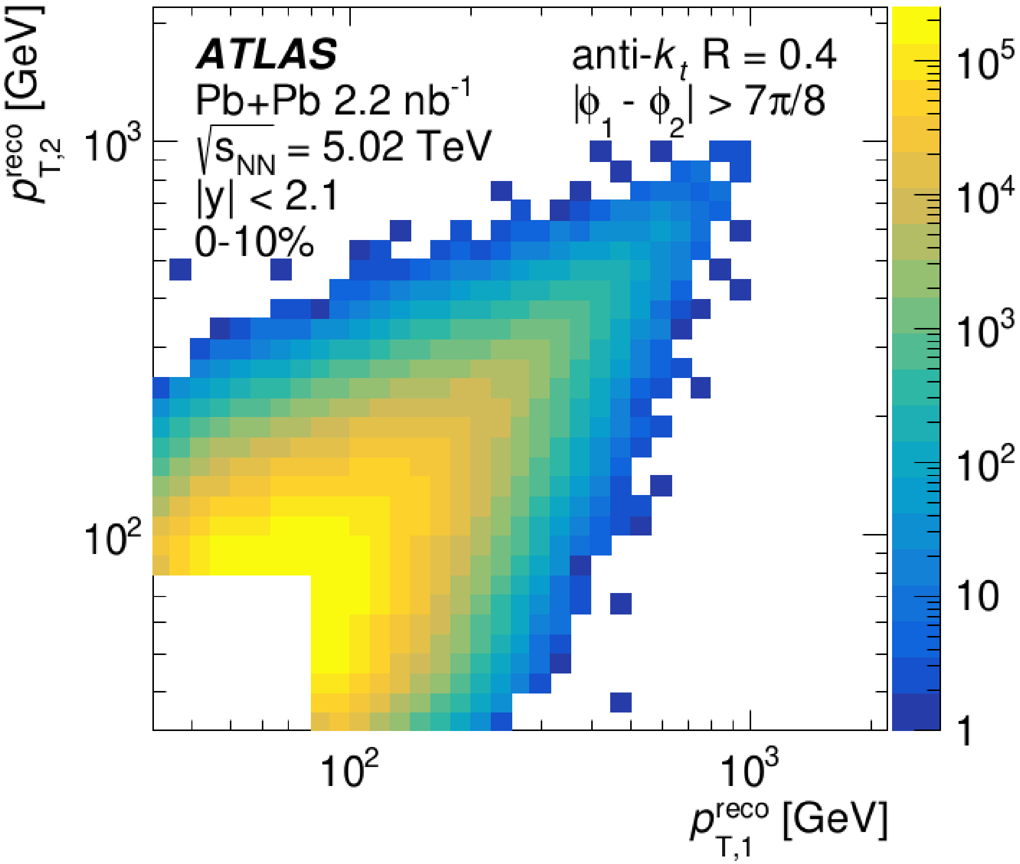




- LIDO is one of models implementing the radiative energy loss + realistic fluctuating nuclear overlap
- Description of data is not perfect => we should learn new things

Technical aspects of analysis

- Quantities calculated here are projections from measured 2D distributions
- This allows for a precise 2D unfolding (using 4D response matrix)
- Analysis also requires several other non-trivial corrections (subtraction of false pairs, correct handling of physics signal in overlay MC, ...)



- The 2D approach also allows to quantify more differentially the inclusive jet suppression

Inclusive suppression more differentially

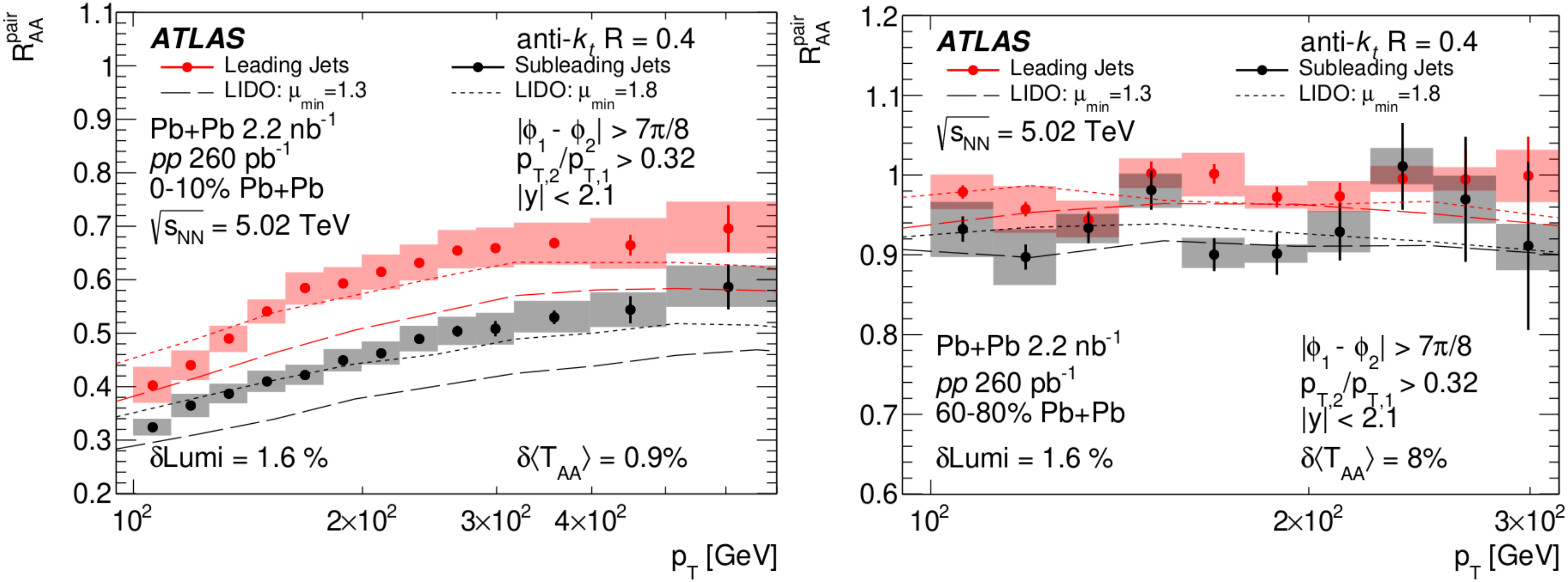
$R_{AA}^{pair}(\boldsymbol{p}_{\mathbf{T},\mathbf{1}})$ quantifies the suppression of the **leading jet** in a dijet

$$R_{\mathrm{AA}}^{\mathrm{pair}}(\boldsymbol{p}_{T,1}) = \frac{\frac{1}{\langle T_{AA}\rangle N_{evt}^{AA}} \int_{0.32\times \boldsymbol{p}_{T,1}}^{\boldsymbol{p}_{T,1}} \frac{d^2 N_{pair}^{AA}}{dp_{T,1}dp_{T,2}} \boldsymbol{dp}_{T,2}}{\frac{1}{L_{pp}} \int_{0.32\times \boldsymbol{p}_{T,1}}^{\boldsymbol{p}_{T,1}} \frac{d^2 N_{pair}^{pp}}{dp_{T,1}dp_{T,2}} \boldsymbol{dp}_{T,2}}$$

$R_{AA}^{pair}(\boldsymbol{p}_{T,2})$ quantifies the suppression of the **subleading jet** in a dijet

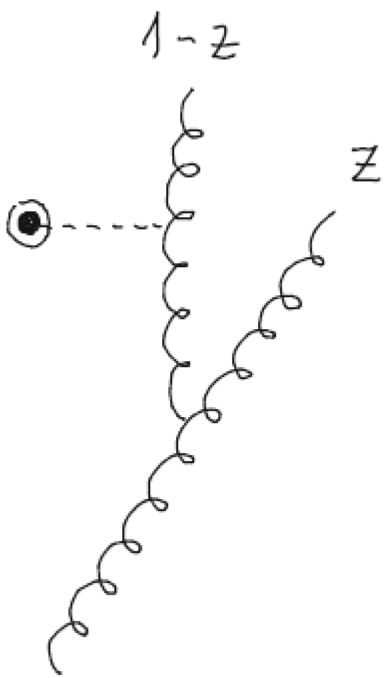
$$R_{\mathrm{AA}}^{\mathrm{pair}}(\boldsymbol{p}_{T,2}) = \frac{\frac{1}{\langle T_{AA}\rangle N_{evt}^{AA}} \int_{\boldsymbol{p}_{T,2}}^{\boldsymbol{p}_{T,2}/0.32} \frac{d^2 N_{pair}^{AA}}{dp_{T,1}dp_{T,2}} \boldsymbol{dp}_{T,1}}{\frac{1}{L_{pp}} \int_{\boldsymbol{p}_{T,2}}^{\boldsymbol{p}_{T,2}/0.32} \frac{d^2 N_{pair}^{pp}}{dp_{T,1}dp_{T,2}} \boldsymbol{dp}_{T,1}}$$

Inclusive suppression more differentially



- Relatively larger suppression of sub-leading jet is observed for all the pt bins.
- In peripheral collisions (right), leading jets almost not suppressed, but subleading jets clearly suppressed... When the quenching dies off? This touches the physics of high-multiplicity *pp* collisions.

Parton cascades in **expanding medium**



$\frac{dI}{dz}$ ... single gluon emission spectra

Example for exponential decaying medium:

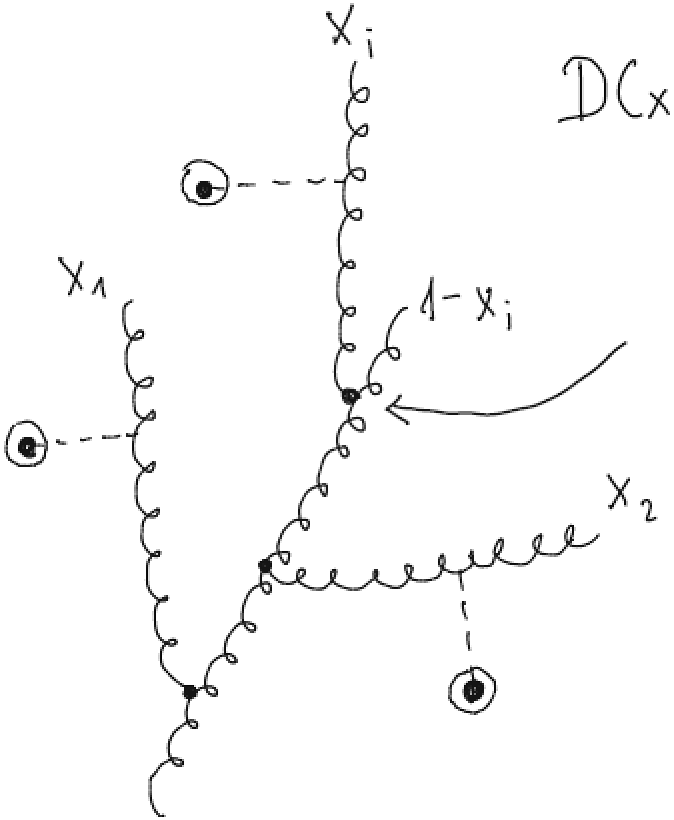
Function of energy transfered

$$\frac{\mathrm{d}I}{\mathrm{d}z} = \frac{\alpha_s}{\pi} P(z)\, \mathrm{Re}\ln J_0(2\Omega_0 L)$$

Splitting function

… calculated in approximation of multiple soft scatterings and leading order in log of number of scattering centers

Parton cascades in expanding medium



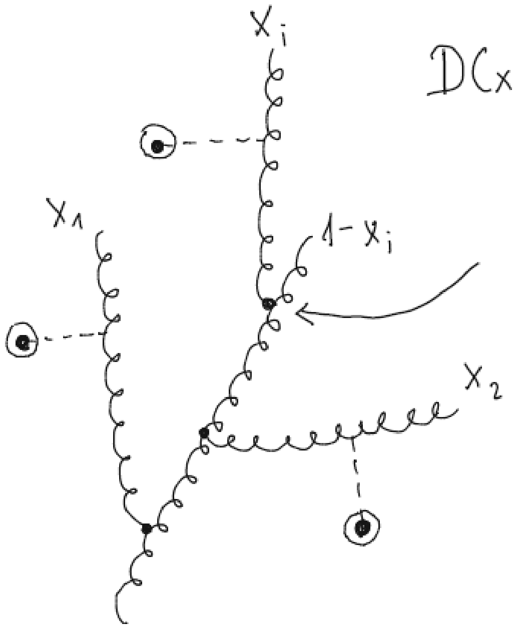
$D(x)$ ... single-inclusive gluon emission spectra

$\frac{dI}{dz d\tau}$ ... splitting rate

"time"

$$\mathcal{K}(z,\tau) \equiv \frac{\mathrm{d}I}{\mathrm{d}z\mathrm{d}\tau} = \frac{\alpha_s}{\pi} P(z)\kappa(z)\,\mathrm{Re}\left[(i-1)\frac{J_1\big((1-i)\kappa(z)\tau\big)}{J_0\big((1-i)\kappa(z)\tau\big)}\right]$$

Parton cascades in expanding medium



$D(x)$ ... single-inclusive gluon emission spectra

$\frac{dI}{dz\,d\tau}$ ... splitting rate

Splitting rate

$$\mathcal{K}(z,\tau) \equiv \frac{\mathrm{d}I}{\mathrm{d}z\,\mathrm{d}\tau}$$

$$\frac{\partial D(x,\tau)}{\partial \tau} = \int_0^1 \mathrm{d}z\, \mathcal{K}(z,\tau) \left[\sqrt{\frac{z}{x}} D\left(\frac{x}{z},\tau\right) \Theta(z-x) - \frac{z}{\sqrt{x}} D(x,\tau) \right]$$

Evolution equation

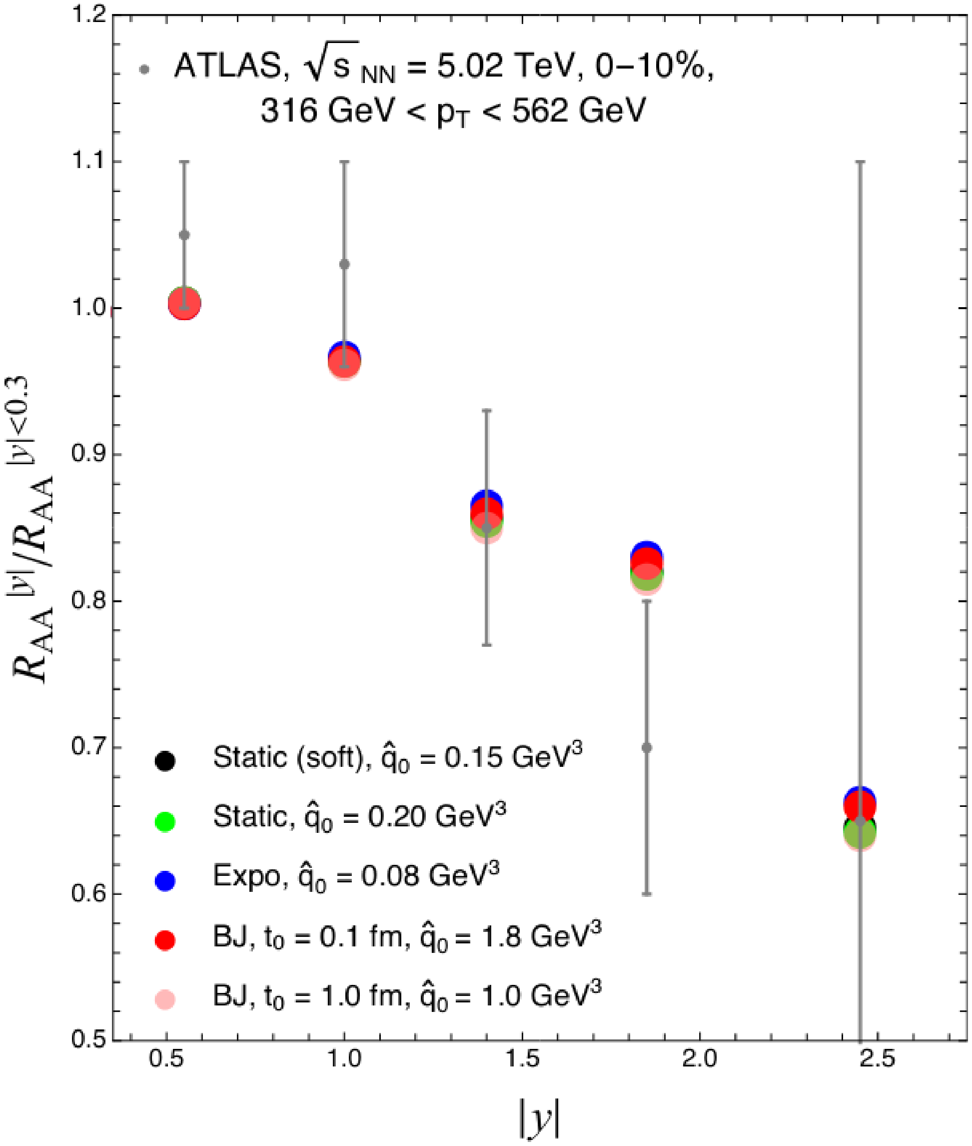
$$\frac{\mathrm{d}\sigma_{\mathrm{AA}}}{\mathrm{d}p_T} = \int_0^\infty \mathrm{d}p'_T \int_0^1 \mathrm{d}x\, \delta(p_T - x p'_T) D\left(x, \tau \equiv \sqrt{\hat{q}_0/p'_T}\, L\right) \frac{\mathrm{d}\sigma_0}{\mathrm{d}p'_T}$$

$$Q_{\mathrm{AA}}(p_T) = \int_0^1 \mathrm{d}x\, x^{n-1} D(x, \sqrt{x}\tau)$$

Suppression factor of jets

Done for quark and gluon jets

S. Adhya, M.S., C.A.Salgado, K. Tywoniuk, EPJC 82 (2022) 20



- Very different types of the expansion of the partonic medium tested
- One particular result: the way how the medium expands has no impact on some of observable quantities

Main message

- In central collisions jet are suppressed by a factor of two and their internal structure is modified in a complex way.
- These effects are predominantly due to radiative energy loss of partons traversing the deconfined medium.
- Dijet measurements will tell us about the path-length dependence.
- In central collisions, a large imbalance is seen which is due to suppression of balanced dijets.
- Phenomenology based on radiative energy loss can describe some of what we see in the data well but there is still much to learn about various phenomena connected with the strong interaction.