Hard probes of the hot plasma

HIC for FAIR
Helmholtz International Center

Redmer Alexander Bertens - Utrecht University

Kernphysikalisches Kolloquium

Outline

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Hard probes of the hot Quark Gluon Plasma

1. **Understand** interactions between the hard partons (quarks, gluons) and the QGP ('microscopic')
2. **Use this** to deduce properties of the QGP (degrees of freedom, viscosity, density, temperature, etc, 'macroscopic')

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A few questions for this afternoon

- How-to: constrain QGP properties?
- Which **process** is dominant? (radiative, elastic)
- Where does radiated energy **go** ?
- What **drives** e-loss? Geometry or fluctuations?

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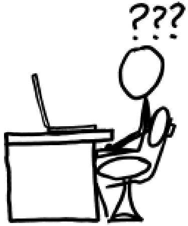
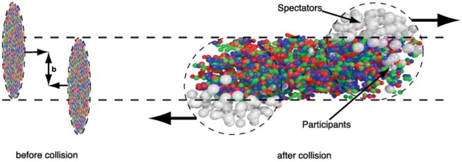


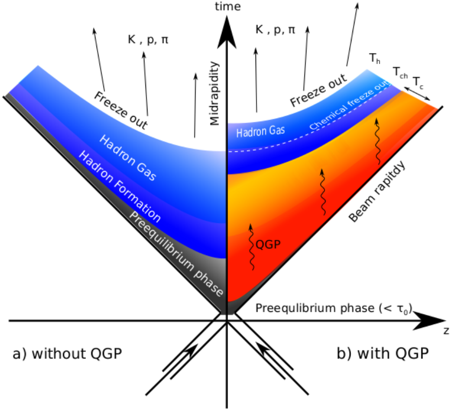
Disclaimer: ... far from complete discussion ... Disclaimer2: ... I'm not a theorist ... Disclaimer3: ... possible slight bias towards ALICE ...

Hard probes
what and why

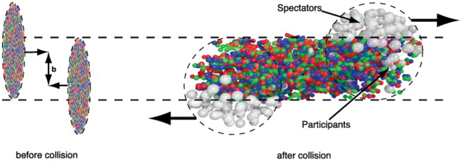


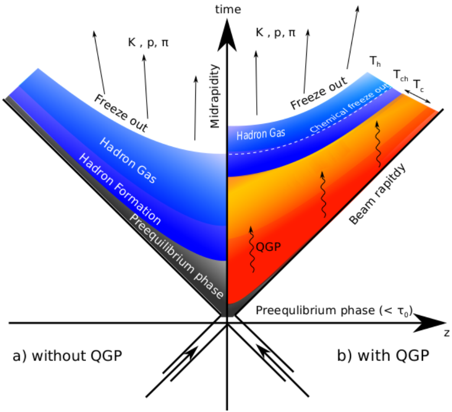
The usual diagram ...

1. Collision, formation of dense system
2. **Deconfined** quarks and gluons interact as fundamental degrees of freedom (**QGP**)
3. Collective expansion
4. Chemical freeze-out to hadrons and finally kinetic freeze-out



Pb–Pb collisions in a nutshell





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General problem in **determining** QGP properties:

- Medium dynamics as well as hadronization **non-perturbative**

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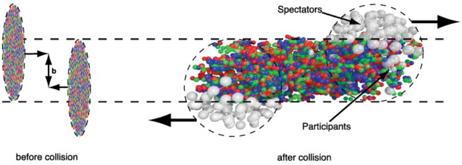

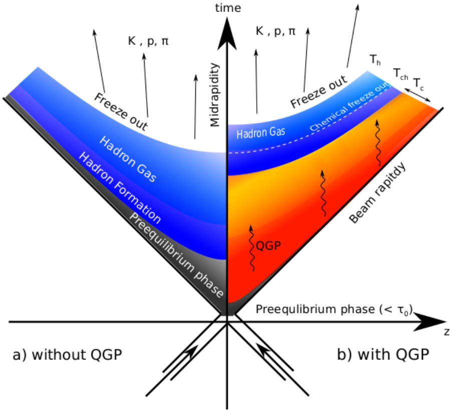

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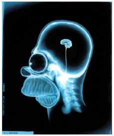
General problem in **determining** QGP properties:

- Medium dynamics as well as hadronization **non-perturbative**
- *How do you look inside a 'patient' if you cannot open him up ?*

⟶ *Tomography: imaging through* **modification** *of penetrating wave*



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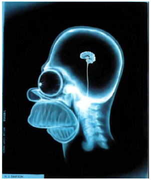
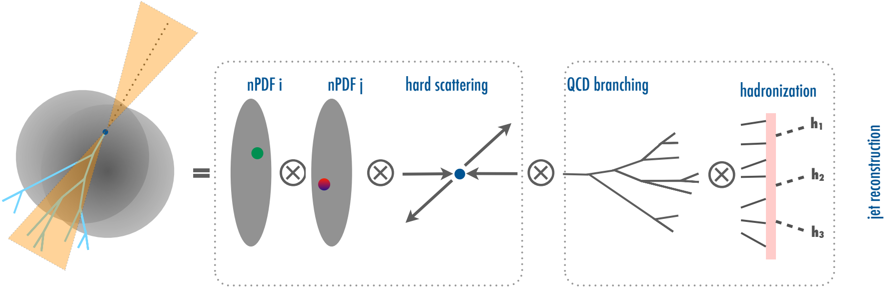


Tomography

'imaging through **modification** *of penetrating wave'*

'**Motivation**' for hard probes similar:

- Use **well-known** (perturbative) **probe** (i.e. large Q^2 process)
- Deduce medium properties from **modification** in medium vs. vacuum



Chapter 1) R_{AA}

‘nuclear modification factor’

single tracks

Nuclear modification factor R_{AA}

'Simplest' probe: (high-p_T) particle production in **vacuum** vs. in **medium**

$$R_{AA} = \frac{d^2 N^{AA}/dp_T d\eta}{\langle T_{AA}\rangle \cdot d^2\sigma_{pp}/dp_T d\eta} \approx \frac{\text{QCD medium}}{\text{QCD vacuum}}$$

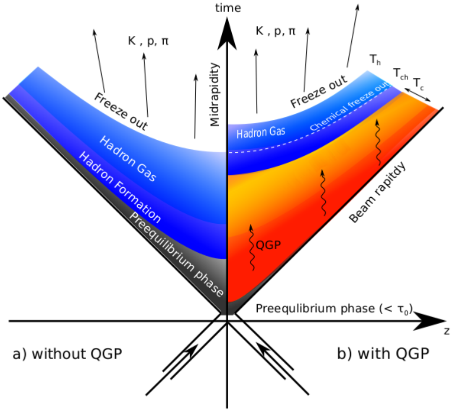
$\langle T_{AA}\rangle \propto \langle N_{coll}\rangle$ = no. of binary nucleon-nucleon collisions

Possible scenarios

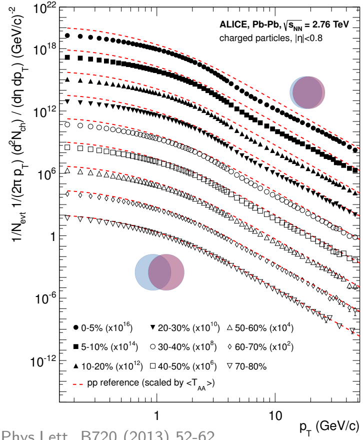
- $R_{AA} > 1$ (enhancement)
- $R_{AA} = 1$ (no medium effect)
- $R_{AA} < 1$ (**suppression**)

Assumption

- partons **lose** energy in the medium
- $R_{AA} < 1$

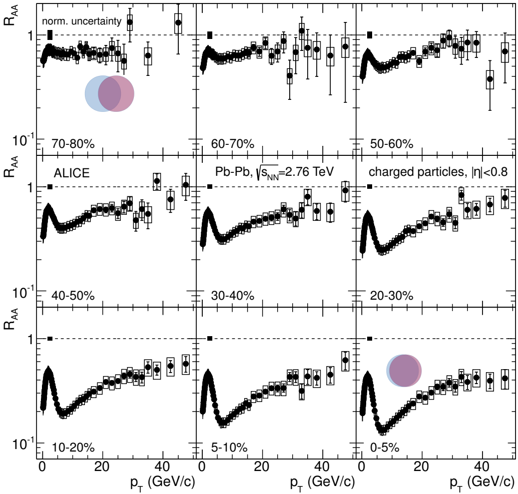


‘Convenient’ to measure ...



Phys.Lett. B720 (2013) 52-62

... from spectra to R_{AA} ...



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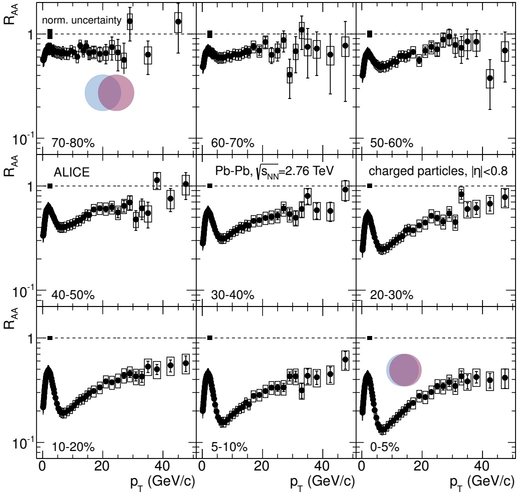
... and qualitatively understand

Suppression depends on **centrality**: stronger for more central collisions

- Strongest suppression around 7 GeV/c for all centralities
- Suppression non-zero up to high transverse momenta



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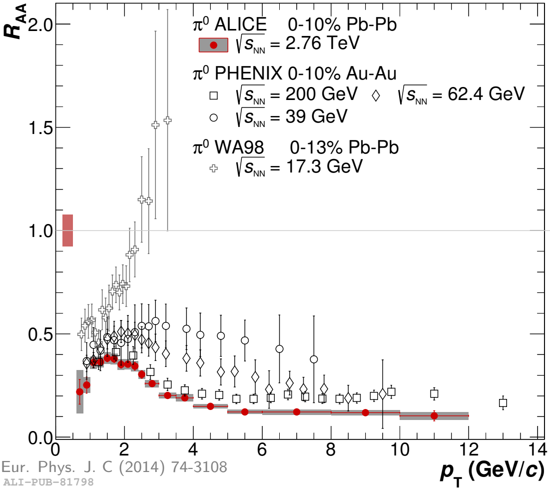
More **central** collisions

- longer average path length
- **denser medium**

⟶ stronger suppression

R_{AA} - from RHIC to LHC



Eur. Phys. J. C (2014) 74-3108
ALI-PUB-81798

Results from LHC and RHIC are qualitatively similar

- Shape of R_{AA} and maximum agrees, offset however is different

High p_T R_{AA} is lower for LHC

- Decrease of R_{AA} with increasing $\sqrt{s_{NN}}$ observed at RHIC
- **Indicative of higher medium density at the LHC compared to RHIC**

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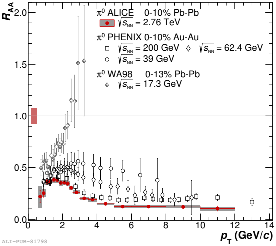
Statements up till now are very **generic**: '*partons lose energy in QGP, $\sqrt{s_{NN}}$ and density dependent*'

- Comparison of R_{AA} to theory necessary



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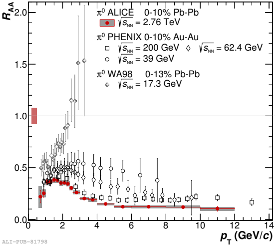

Modeling R_{AA} is not trivial

- **Initial state** of HI collisions not fully understood (Glauber / CGC)
- Medium **geometry** (density profile, path-length or parton through medium)
- Energy loss is a **distribution**, not single valued
- Energy loss is **partonic**, not hadronic
  - Understanding of medium modified shower / hadronization
  - Quark/gluon fragmentation differences

... and there's a very large variety of models on the market ...

A common ansatz

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Simplest (and most often used in analytical of MC calculations) ansatz is

$$\underbrace{\left.\frac{dN}{dp_{\mathrm{T}}}\right|_{\mathrm{hadrons}}}_{\text{final state}} = \underbrace{\left.\frac{dN}{dE}\right|_{\mathrm{jets}}}_{\text{pQCD, nPDF's}} \otimes \underbrace{P(\Delta E)}_{\text{energy loss distribution}} \otimes \underbrace{D(p_{\mathrm{T}}/E)}_{\text{fragmentation function}}$$

- **Medium** information is in $P(\Delta E)$

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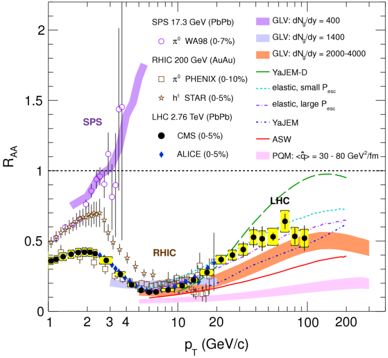
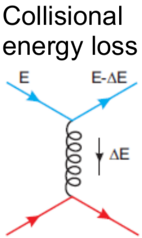
- **Medium** information is in $P(\Delta E)$

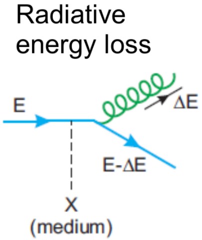
Wealth of models available from low to high (200 GeV/c!) p_T

- Qualitatively similar outcome: **relative e-loss** decreases with **increasing** p_T
- *let's look at this in a more systematic way*



Not too fast: **processes** contributing to e-loss





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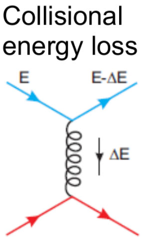

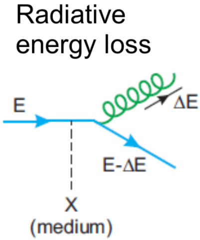

- $\hat{q}$: transverse momentum **diffusion** (radiative energy loss)

$$\hat{q} = \rho \int dq_\perp^2 q_\perp^2 \frac{d\sigma}{dq_\perp^2} = \frac{\langle q_\perp^2 \rangle}{\lambda}$$

- $\hat{e}$: longitudinal drag (collisional energy loss)

Ansatz: express model 'predictions' in a **common parameter**: transport coefficient $\hat{q}$

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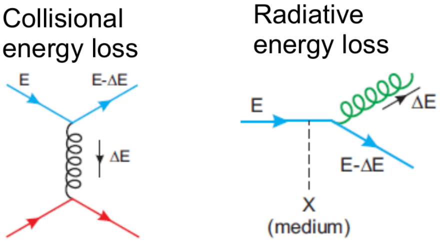

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Sidenote: **relative** importance of radiative vs. elastic e-loss can be disentangeled by heavy-flavor e-loss (**dead cone**: radiative energy loss is suppressed)

systematic approach

(see Phys. Rev. C 90, 014909 (2014))

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tune parameters of model to best fit data

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(MARTINI,HT-BW, HT-M, AMY, CUJET)

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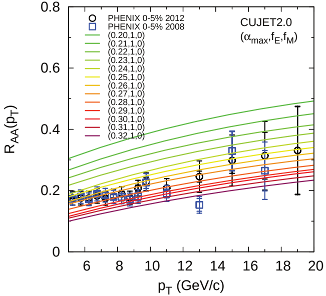
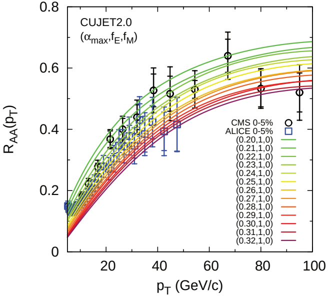
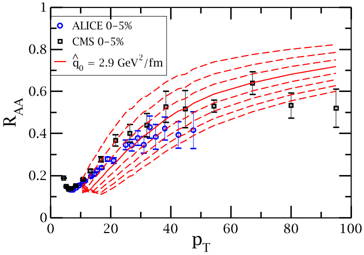
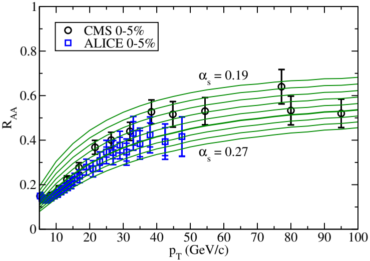
repeat for many models
(MARTINI,HT-BW, HT-M, AMY, CUJET)
extract most probable $\hat{q}$

The tuning process



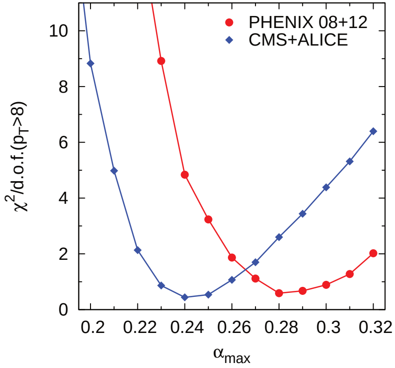






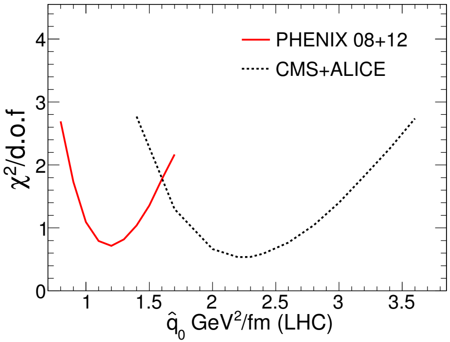
The tuning process cont.

CUJET 2.0

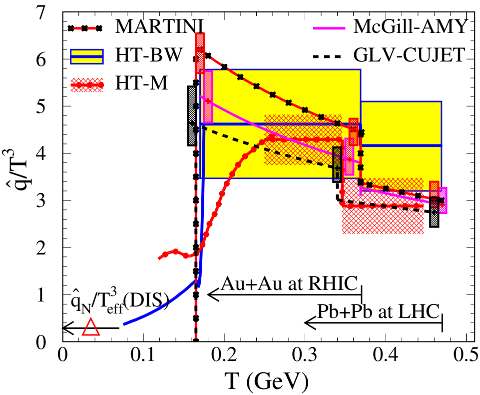


CUJET: α_s is medium parameter
Lower at LHC

HT-BW



HT: $\hat{q}$ is direct parameter
Higher at LHC



$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 \text{ (RHIC)} \\ 3.7 \pm 1.4 \text{ (LHC)} \end{cases}$$

AdS/CFT correspondence **compatible** using CUJET α_s:

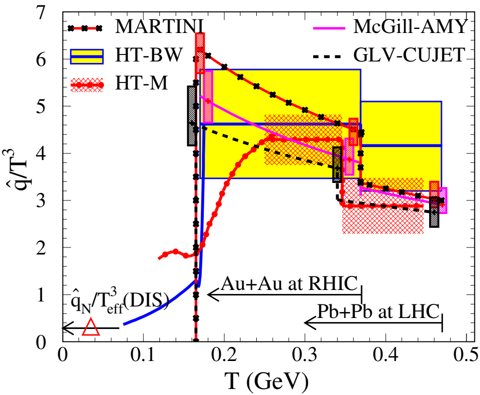
$$\frac{\hat{q}}{T^3} = 2.27 - 3.64$$

For a 10 GeV/c quark jet

$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \frac{\text{GeV}^2}{\text{fm}} \text{at T=370 MeV} \\ 1.9 \pm 0.7 \frac{\text{GeV}^2}{\text{fm}} \text{at T=470 MeV} \end{cases}$$

- **$\hat{q}$ determined with $\approx$ 35% certainty**
- $\hat{e}$ needs input from heavy-flavor jet measurements (stay tuned for the next hard probes seminar)

... to arrive at a common $\hat{q}$



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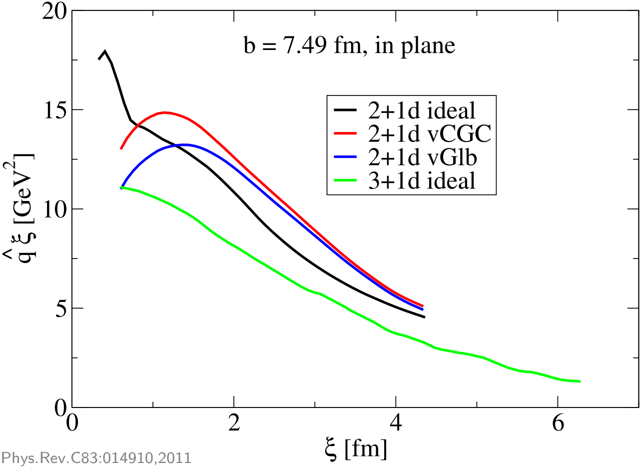
And then there is the bulk

What about the **medium** evolution?



Phys.Rev.C83:014910,2011

when does e-loss **start** ? when does e-loss **stop**?

what is the medium **density** profile ? **initial** conditions?

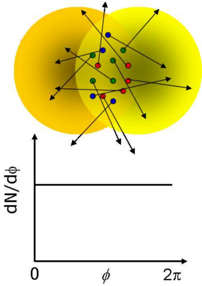
... so ... hard probes constrain $\hat{q}$

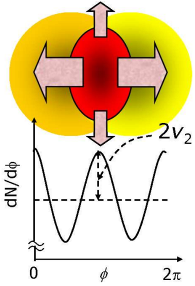
connection to soft observables ?

Short intermezzo: 'hydrodynamic' flow

In a nutshell ...

- **Almond-shaped** overlap region
- **Collective** expansion of **thermalized** medium in vacuum
- **Geometric** anisotropy is converted to **momentum** anisotropy





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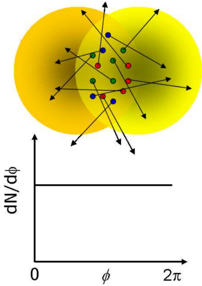
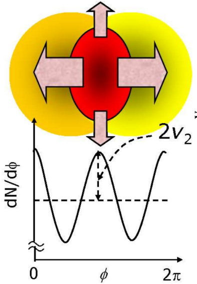
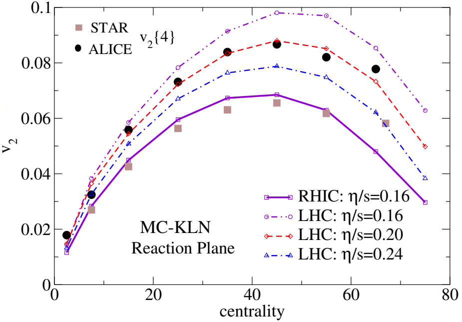






Result: low p_{T} **azimuthal** modulation of tracks $v_n = \langle \cos n[\varphi - \Psi_n] \rangle$

Connecting $\hat{q}$ to viscosity

Shear viscosity $\eta(/s)$

$$\eta \propto \rho \langle p \rangle \lambda$$

can be related to $\hat{q}$

see Phys.Rev.Lett.99:192301,2007

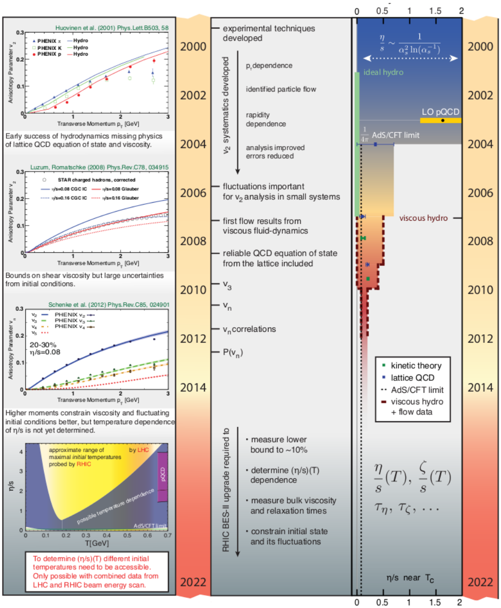
$$\frac{\hat{q}}{T^3} \propto \left(\frac{\eta}{s}\right)^{-1}$$

for a QCD medium

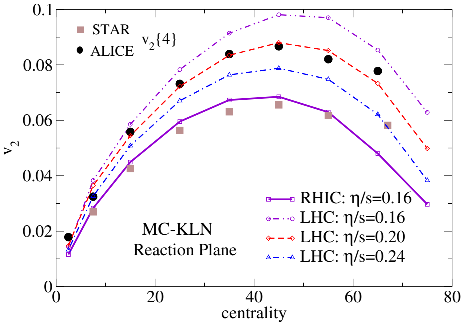
$$\frac{\eta}{s} \approx 1.25 \frac{T^3}{\hat{q}}$$

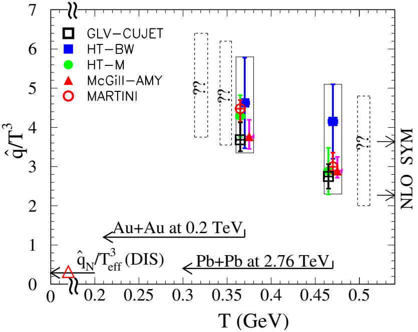
depending on coupling

I realize the font is too small, *but take away: a lot of progress has been made for η/s via flow measurements* $\longrightarrow$



Agreement from the hard and the soft side?





Reasonable agreement with QGP expectation of $\frac{\eta}{s} \approx 1.25 \frac{T^3}{\hat{q}}$

- η/s slightly **larger** at LHC vs. RHIC
- $\hat{q}/T^3$ slightly **lower** at LHC vs. RHIC

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R_{AA} is a **valuable** probe ($\hat{q}$)

$$\underbrace{\left.\frac{dN}{dp_{T}}\right|_{\text{hadrons}}}_{\text{final state}} = \underbrace{\left.\frac{dN}{dE}\right|_{\text{jets}}}_{\text{pQCD, nPDF's}} \otimes \underbrace{P(\Delta E)}_{\text{e-loss}} \otimes \underbrace{D(p_{T}/E)}_{\text{fragmentation function}}$$

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... bus has its limitations

- 'hadronic observable' (not **parton** spectrum)
- sensitive to ill-understood **hadronization** physics
- ... and **where** does the lost energy go ?

'Solutions'

- Jets as a partonic probe

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Chapter 2) Jets

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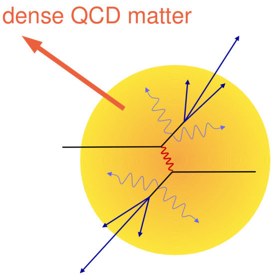

Hard scattering ($Q^2 > 1$ (GeV/c)^2)

- (induced) **radiation** of quarks and gluons
- Hadronization into colorless spray: *'jets'*
- Reconstructed jet: as close as one can experimentally get to **original parton**

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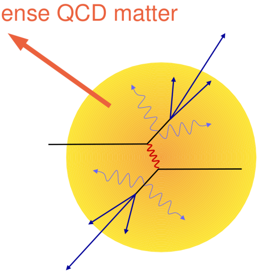

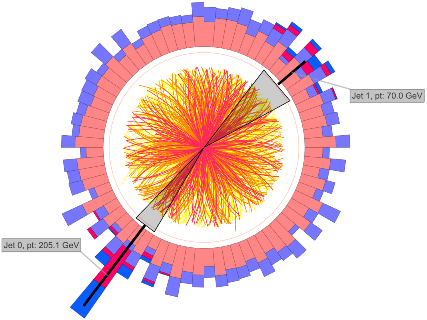

Let's try to answer

- Are jets suppressed?
- Where does the energy go ?
- What determines e-loss? (geometry or fluctuations?)

but before going into results ...

... a small experimental detour

Experimentally, jets are tricky

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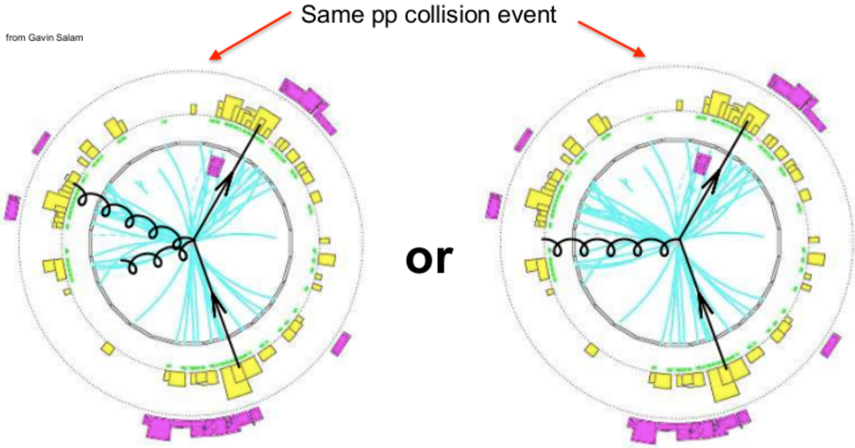

Need to ***define*** jet in experiment ***and*** theory

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For a rainy afternoon: **(anti)-k_T jet finding**:
define for all **protojets** (tracks)

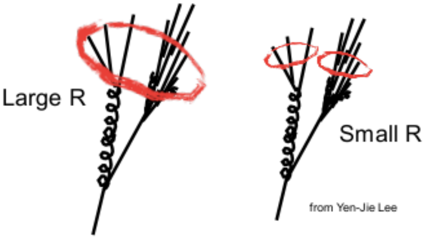
$$d_i = {p_\mathrm{T}}_{,i}^{2p}$$

$$d_{i,j} = \min\left({p_\mathrm{T}}_{,i}^{2p}, {p_\mathrm{T}}_{,j}^{2p}\right) \frac{\Delta_{i,}^2}{R^2}$$

$$\Delta_{i,j}^2 = (y_i - y_j)^2 + (\varphi_i - \varphi_j)^2$$

- smallest $d_x = d_{i,j} \longrightarrow$ merge tracks
- smallest $d_x = d_i \longrightarrow d_i$ is a jet

... go back to the beginning



R: **resolution parameter** (maximum angular separation of tracks in η, φ)

Fast, infrared / collinear safe
... **but all tracks get clustered**

Jet reconstruction in Pb–Pb collisions

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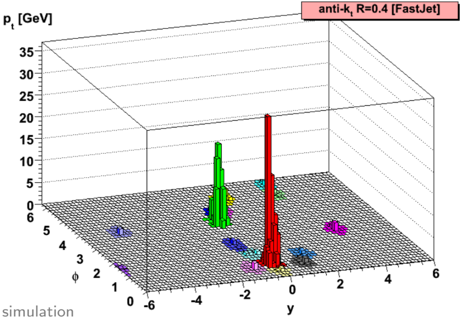
' ... **all** tracks get clustered '

- Generally **not** so problematic in pp collisions ...
- ... but in Pb–Pb this means including **overwhelming** energy from **uncorrelated emissions**



simulation

Jet reconstruction in Pb–Pb collisions

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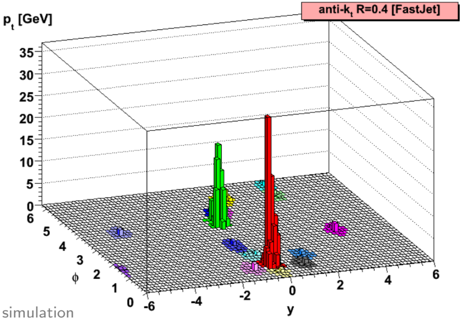
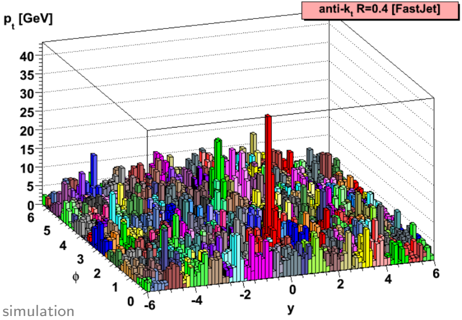
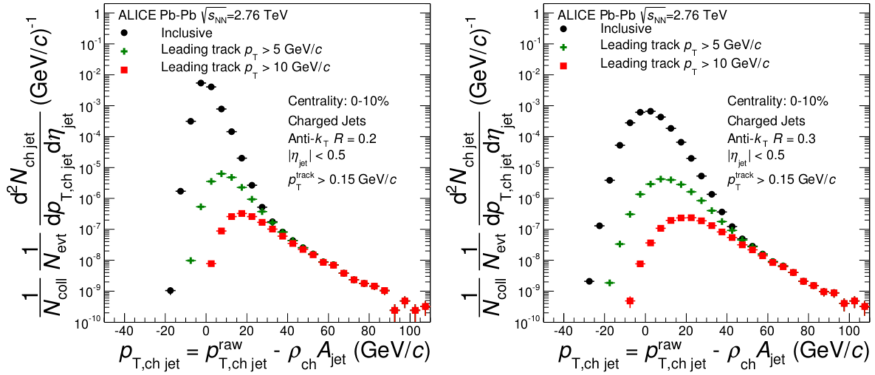




Challenge: inclusive measurement of jets while **removing** UE

- ‘Background’ (*Underlying Event*) **large** [1] compared to jet energy
- UE is **not uniform** (e.g. flow [2]) and has large **statistical** fluctuations [3])

To get a feeling



Leading hadron cut removes **fake** jets

At low p_T contribution from fake clusters is **overwhelming**

[1] UE energy $\langle \rho_{ch} \rangle$

Event-by-event estimate of **energy density** of UE

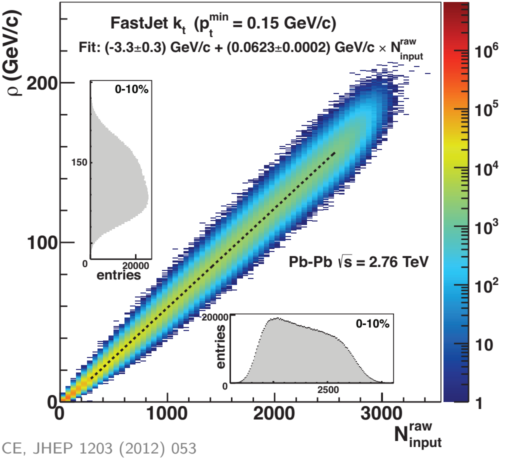
$$\langle \rho_{ch} \rangle = \text{median}\left(\frac{p_{T,\,ch}^{jet}}{A^{jet}}\right)$$

Linear dependence of $\langle \rho_{ch} \rangle$ on multiplicity

Quick example: 0–10% centrality

- $\langle \rho_{ch} \rangle \approx 140$ GeV/c A^{-1}
- $A \propto \pi R^2$

$\propto$ **70 GeV/c charged background for $R = 0.4$**



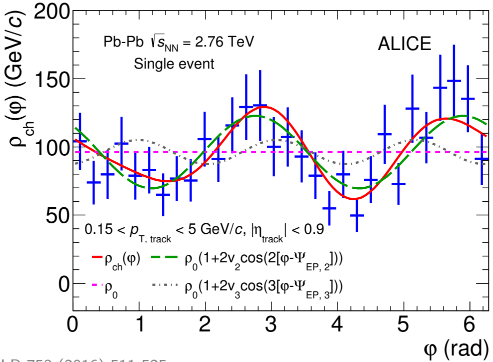
ALICE, JHEP 1203 (2012) 053

[2] Jet-by-jet UE subtraction

Adjust **jet-by-jet** for **UE** energy

$$p_{T,\,ch}^{jet} = p_{T,\,ch}^{raw} - \rho_{ch\ local} A$$

using jet **area A** and UE energy **density** $\rho_{ch\ local}$



PLB 753 (2016) 511-525

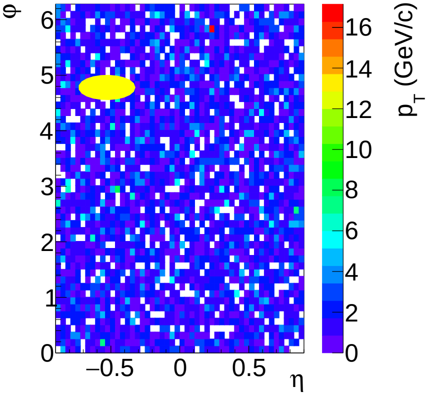
UE **flow** (v_2 and v_3 and ...) can be **accounted for** in $\rho_{ch\ local}$ **event-by-event**

$$\rho_{ch}(\varphi) = \rho_0\left(1 + 2\{v_2\cos[2(\varphi - \Psi^{V0}_{EP,\,2})] + v_3\cos[3(\varphi - \Psi^{V0}_{EP,\,3})] + \ldots\}\right)$$

[3] Fluctuations of UE

UE fluctuations in φ, η around $\langle \rho_{ch} \rangle$

- A jet of $p_T = x$ sitting on an upward fluctuation of magnitude a will be reconstructed at $p_T = x + a$ ...
- ... likewise a jet of $p_T = x$ sitting on a downward fluctuation of magnitude a will be reconstructed at $p_T = x - a$



Use e.g. **random cone** procedure to determine magnitude of fluctuations

$$\delta p_T = \underbrace{\sum p_T^{track}}_{\text{cone } p_T} - \underbrace{\rho \pi R^2}_{\text{expectation}}$$

δp_T distribution used to **unfold** jet spectra:

$$f_{meas}(x) = \int R(x|y) f_{true}(y) dy$$

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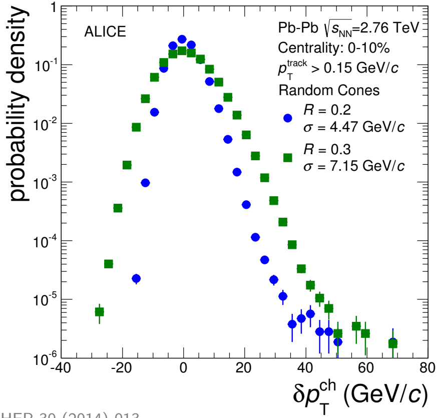

JHEP 30 (2014) 013

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δp_T distribution used to **unfold** jet spectra:

$$f_{meas}(x) = \int R(x|y) f_{true}(y) dy$$

... and no jet talk without unfolding ...

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$$f_{\text{meas}}(x) = \int R(x|y) f_{\text{true}}(y) dy$$

- $f_{\text{true}}(y)$: 'true' jet p_{T}
- $f_{\text{meas}}(x)$: 'measured' jet p_{T}
- $R(x|y)$: response function

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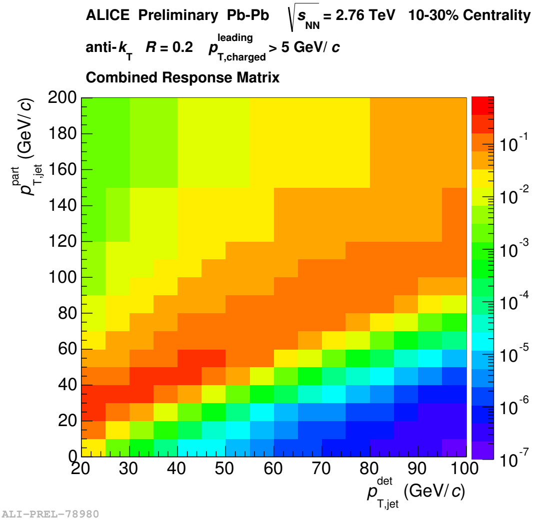
- $f_{true}(y)$: 'true' jet p_T
- $f_{meas}(x)$: 'measured' jet p_T
- $R(x|y)$: response function

A particle level jet at 200 GeV ....

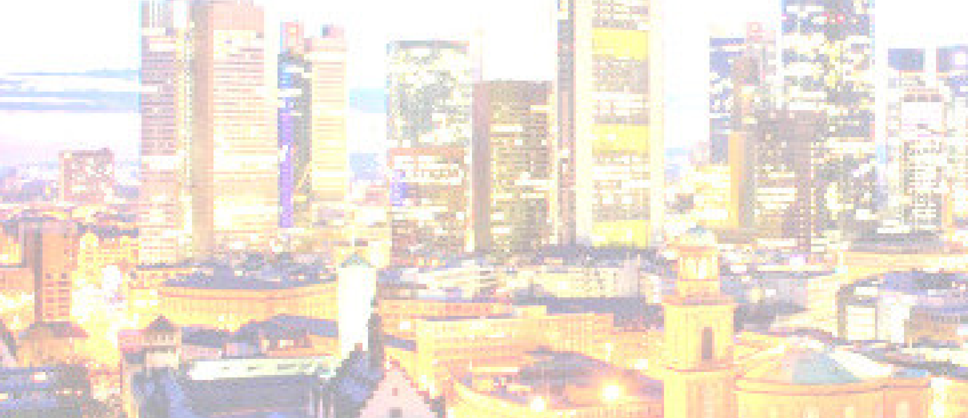
- ... can end up between 20 and 100 GeV in the detector ... !

Unfolding spectra introduces a **systematic uncertainty**

- Unavoidable for meaningful comparison to **theory** and between **experiments**



Jet analysis is tricky



Jet analysis is tricky
needs large statics data sample

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UE is well-understood, but this comes at the price of (large) systematic uncertainties

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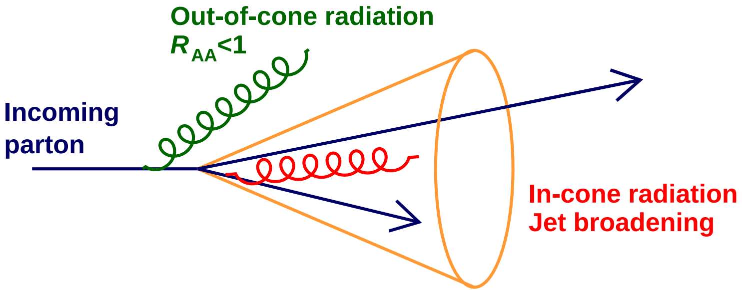
unfolding !!!

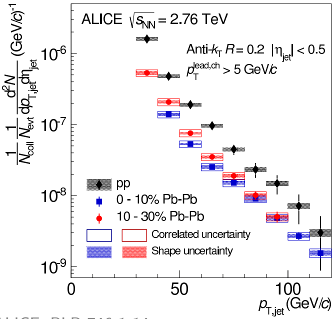
Chapter 2 cont.)
Jets and physics

Are jets suppressed &
Where does the energy go?

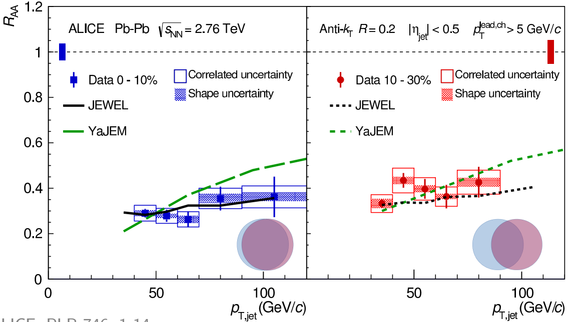


Two **qualitative** scenarios
1) **Out-of-cone** radiation: $R_{\mathrm{AA}} < 1$
2) **In-cone** radiation: $R_{\mathrm{AA}} = 1$, fragmentation function changes
Of course, these are **not exclusive ...**

Out-of-cone radiation: R_{AA} of jets



ALICE, PLB 746 1-14



ALICE, PLB 746, 1-14

$$R_{AA} = \frac{d^2 N^{AA}/dp_T d\eta}{\langle T_{AA}\rangle \cdot d^2\sigma_{pp}/dp_T d\eta} \approx \frac{\text{QCD in medium}}{\text{QCD in vacuum}}$$

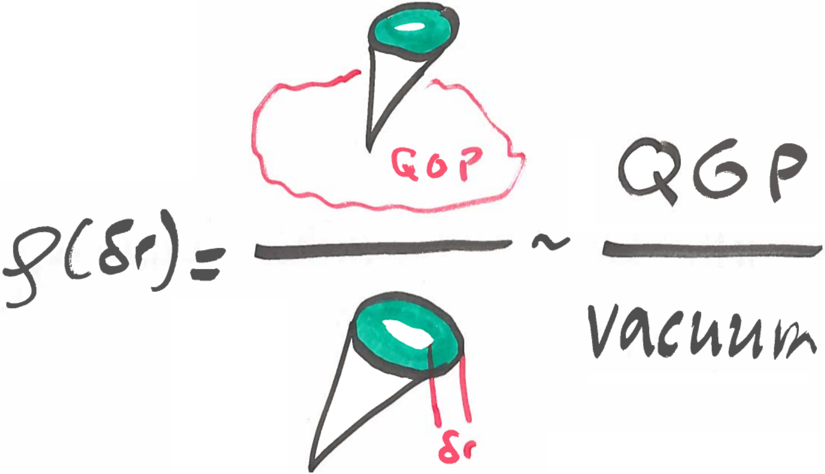
- **Strong** suppression in central and semi-central colisions
- Resonable model agreement (JEWEL[1], YaJEM[2])

Indication of **out-of-cone** radiation

[1] K.C.Zapp *et al.* JHEP 1303 080

[2] T.Renk, PRC 78 034908

… and what about inside the jet?



Where does the energy go?

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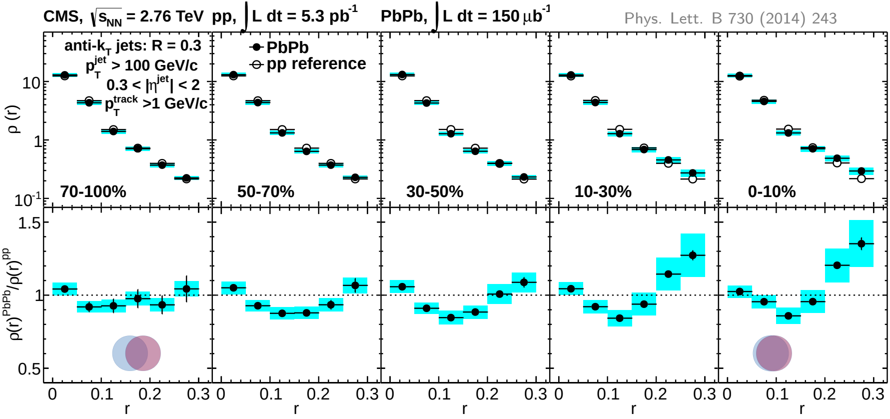
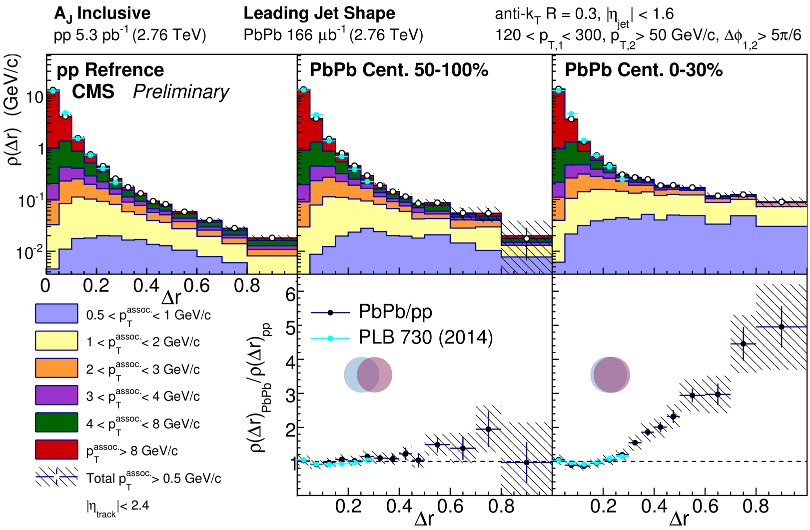


$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\text{jets}}}\frac{\sum_{\text{tracks}\in[r_a,r_b)} p_{\text{T}}}{p_{\text{T}}^{\text{jet}}} \longrightarrow$$ fractional **radial** intrajet p_{T} distribution

- **Ratio** Pb–Pb to pp: distribution close to the jet axis approximately **unmodifed**
- p_{T} **excess** at large R for Pb–Pb jets: jet **broadening**



Lower panels: energy recovered at **very** large angles and **low** p_T?

e-loss: strong out-of-cone radiation
moderate change in jet shape

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moderate change in jet shape
What is driving e-loss:
fluctuations or **geometry**?

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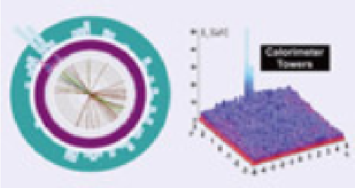
CERN COURIER

Jan 25, 2011

ATLAS observes striking imbalance of jet energies in heavy ion collisions



Highly asymmetric dijet event

The ATLAS experiment has made the first observation of an unexpectedly large imbalance of energy in pairs of jets created in lead-ion collisions at the LHC (G Aad *et al.* 2010). This striking effect, which is not seen in proton–proton collisions, may be a sign of strong interactions between jets and a hot, dense medium

Path-length dependence: di-jet systems

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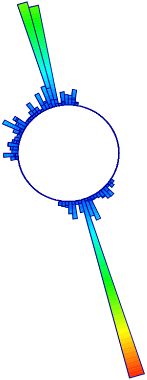
$$\underbrace{\left.\frac{dN}{dp_T}\right|_{\text{hadrons}}}_{\text{final state}} = \underbrace{\left.\frac{dN}{dE}\right|_{\text{jets}}}_{\text{pQCD, nPDF's}} \otimes \underbrace{P(\Delta E)}_{\text{energy loss distribution}} \otimes \underbrace{D(p_T/E)}_{\text{fragmentation function}}$$

$P(\Delta E)$ combines **geometry** and **energy loss**



Di-jet system: $2 \longrightarrow 2$ process

- Jets traveling in **opposite** direction with **equal** transverse momentum
- $L_1 < L_2$

Path-length dependence: di-jet systems

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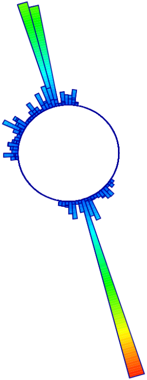

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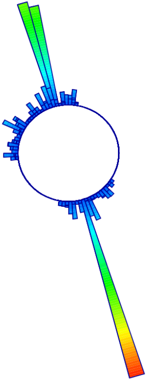

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- Jets traveling in **opposite** direction with **equal** transverse momentum
- $L_1 < L_2$ **(... ?)**

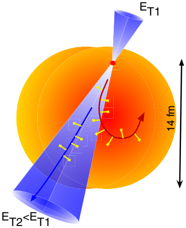
In the lab, $p_{T1} \neq p_{T2}$

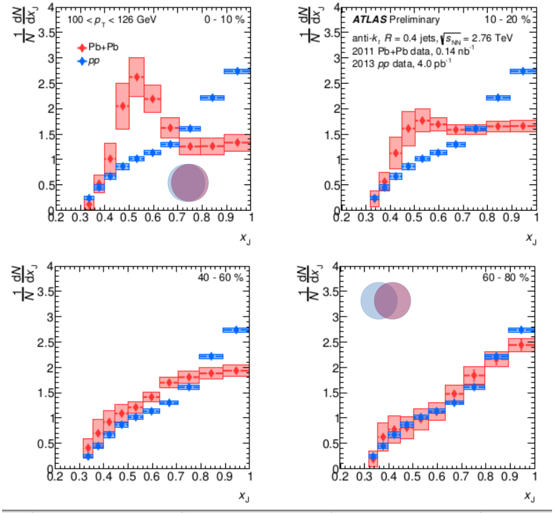
- pp: recoil, out-of-cone radiation
- AA: energy loss fluctuations, different path-lengths

Difference probes medium

$$A_J = \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}}$$

$$x_j = p_{T1}/p_{T2}$$





Asymmetry quantified as

$$x_j = p_{T1}/p_{T2}$$

Fully **unfolded**

- Direct comparison to **theory**
- ... and (eventually) other experiments

In **pp**

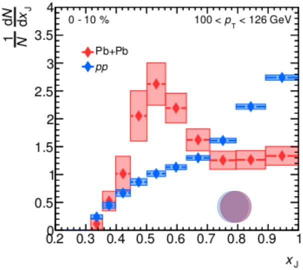
- most probable dijet configuration: $x_j \approx 1$

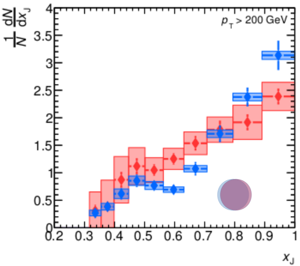
In **Pb–Pb**

- most probable configuration: subleading jet has **half** as much energy as leading jet

Strong **centrality** dependence

New observable $x_j = p_{T1}/p_{T2}$





Asymmetry: $x_j = p_{T1}/p_{T2}$

- With **increasing** $p_T \longrightarrow x_j$ goes **towards 1**

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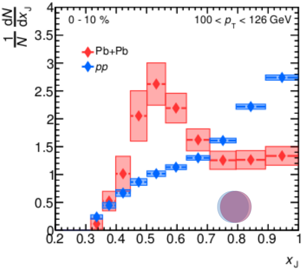

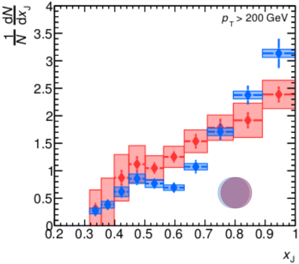

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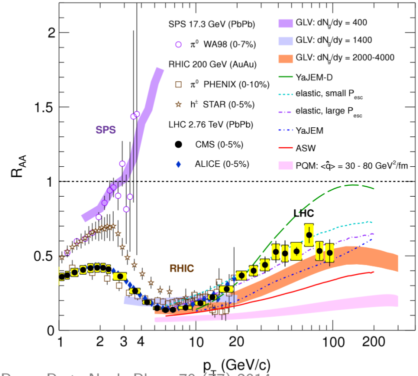
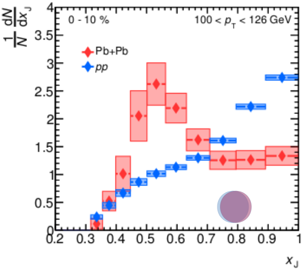
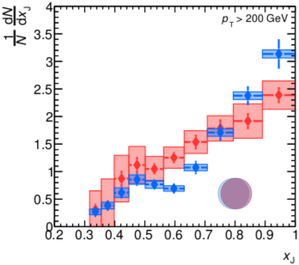


Prog. Part. Nucl. Phys. 70 (77) 2014

confirms sl. 16 'Relative loss decreases with p_T'

New observable $x_j = p_{T1}/p_{T2}$

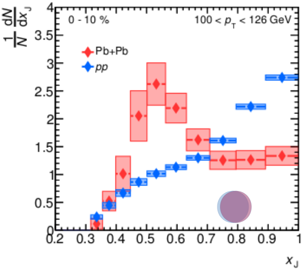




Let's back up a bit …

- … doesn't this raise more questions than it answers ? (at least, for me it does)

New observable $x_j = p_{T1}/p_{T2}$



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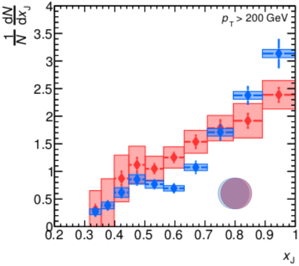
We have

- R_{AA}: moderate **average** energy loss
- di-jets: **wide variation** in possible energy loss

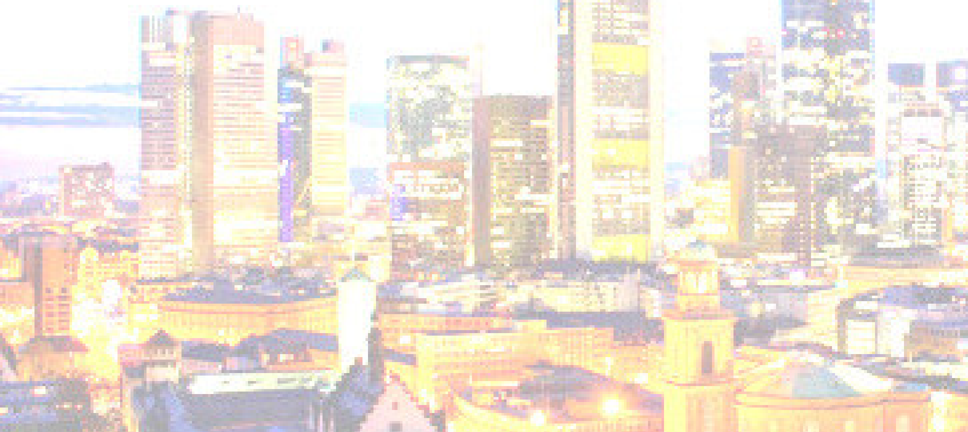


What is the **balance** between

- **per-jet** energy loss **fluctuations**? (analogous to fluctuations in vacuum radiation)
- **average** energy loss from **kinematics**, **medium compisition** and **geometry**?

Remember that e-by-e fluctuations turn out to be **crucial** *in explaining hydro flow phenomena*

How can we **disentangle** geometry and fluctuations?



How can we **disentangle** geometry and fluctuations?

Theory: fix path-lengths

How can we **disentangle** geometry and fluctuations?

Theory: fix path-lengths

Experiment: try **also** fixing path-lengths

Theory: fix path-lengths

Briefly introducing the model: JEWEL

JEWEL (Jet Evolution With Energy Loss)

- **Radiative** energy loss and elastic **scatterings** (plus momentum exchange [recoil] with medium)
- Radiation: **LPM** interference (matches multiple soft scattering)
- Longitudinally expanding Glauber overlap
- Very succesful in describing RHIC and LHC data

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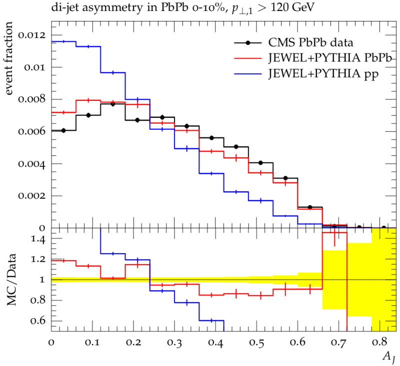
In earlier slides (42) we saw that JEWEL gives good description of R_{AA} of jets

Also reasonable agreement with CMS di-jet imbalance (slide 47)

- $p_{T1} > 120$ GeV/c
- $p_{T2} > 30$ GeV/c
- $\Delta\varphi_{1,2} > 2\pi/3$

Folded with detector resolution



Fixing path-lengths

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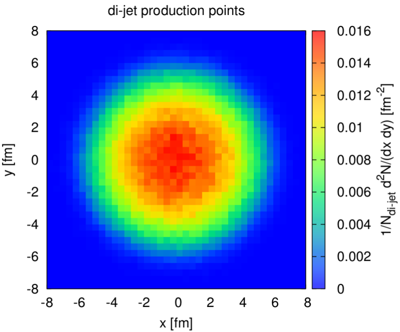
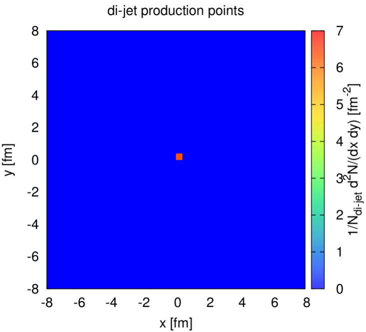
'**Origins of the di-jet asymmetry in heavy ion collisions**'
(26/12/2015, arXiv:1512.08107)

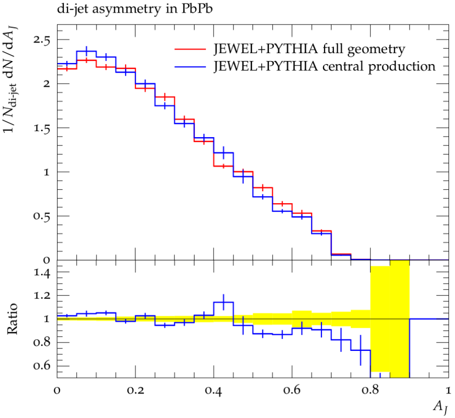


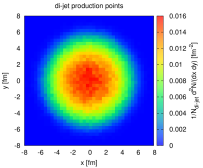


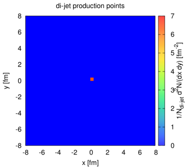
Study original of imbalance by using random (**left**) or fixed (**right**) di-jet production points

- Fixed points: both jets **'see' same** medium distance L

‘Origins of the di-jet asymmetry in heavy ion collisions’
(26/12/2015, arXiv:1512.08107)







(≈ verbatim) from the paper

- Path-length difference plays **no significant role** in generating di-jet asymmetry
- **Increase** w.r.t. pp due to fluctuations in **vacuum-like fragmentation** and medium related **fluctuations**
- Amount of energy lost is determined strongly by ratio of m/p_T of original parton

'Origins of the di-jet asymmetry in heavy ion collisions'
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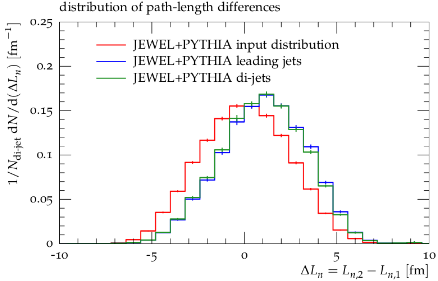
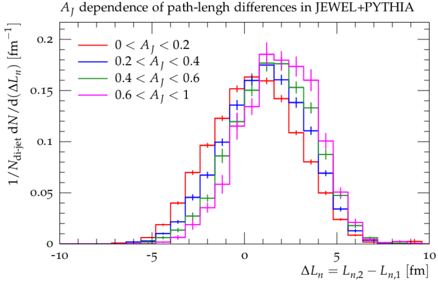
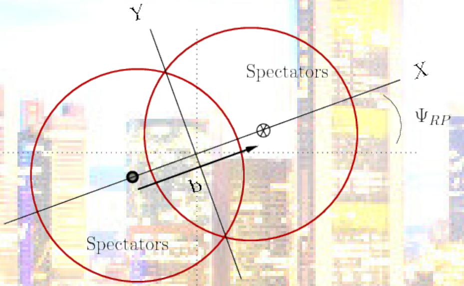




$\approx$ 35% of cases $L_1 > L_2$ (**density** weighted path-length)
Dependence of A_j on ΔL_n **small** compared to **width** (strong fluctuations)

experimental answers ?

Experiment: try **also** fixing path-length



event-plane dependence

Event-plane dependence of di-jets

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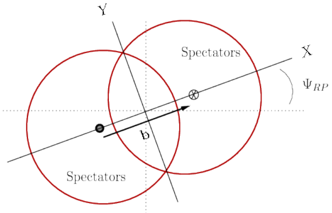
Distance traveled by di-jet depends on orientation w.r.t. $\Psi_{\text{EP, 2}}$



- $\langle A_j \rangle$ **smaller** for dij-ets in direction of $\Psi_{\text{EP, 2}}$

Event-plane dependence of di-jets

Universiteit Utrecht

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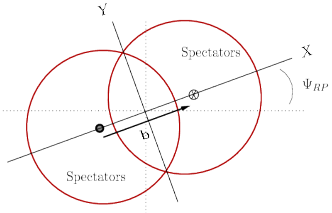

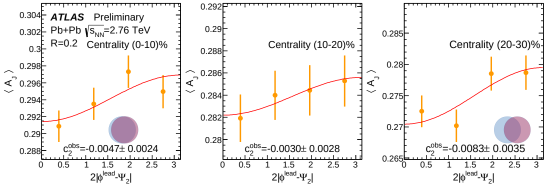

$$\langle A_j \rangle = A_J^0 \left(1 + 2c_2 \cos(2(\varphi^{\text{lead}} - \Psi_{\text{EP, }2}))\right)$$

- $\langle A_j \rangle$ **smaller** for dij-ets in direction of $\Psi_{\text{EP, }2}$
- Reasonably described by cosine modulation
- Anti-correlation is **signficant**

Event-plane dependence of di-jets

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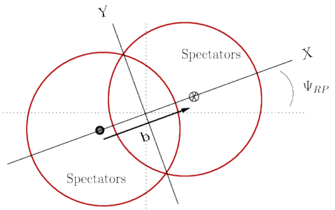

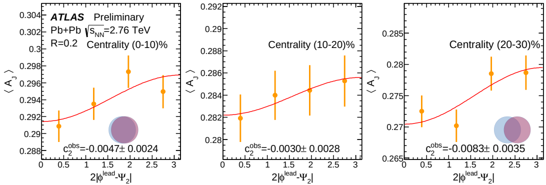

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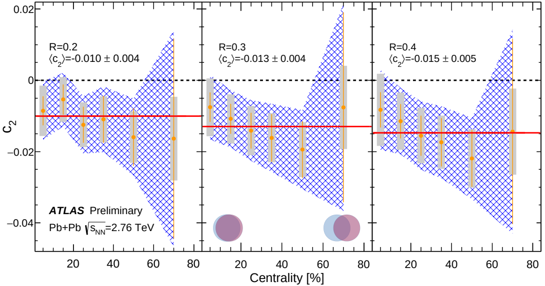


- $\langle A_j \rangle$ **smaller** for dij-ets in direction of $\Psi_{\text{EP, 2}}$
- Reasonably described by cosine modulation
- Anti-correlation is **signficant**

Points at small but **significant**(?) contribution to asymmetry from **geometry**

$v_2^{\text{ch jet}}$: 'fixing' the medium geometry

Different theoretical predictions on path-length (L) dependence of parton energy loss (ΔE)[3,4,5]

$$\underbrace{\Delta E \propto L}_{\text{collisional}} \leftrightarrow \underbrace{\Delta E \propto L^2}_{\text{radiative}} \leftrightarrow \underbrace{\Delta E \propto L^3}_{\text{AdS/CFT}}?$$

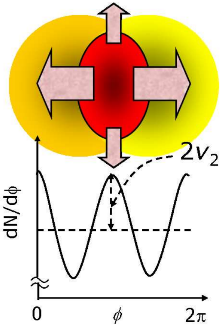
$v_2^{\text{ch jet}}$: comparing short to long L at fixed medium density

$\langle L_{\text{in}} \rangle \approx \langle L_{\text{out}} \rangle$

$v_2^{\text{ch jet}} \approx 0$?

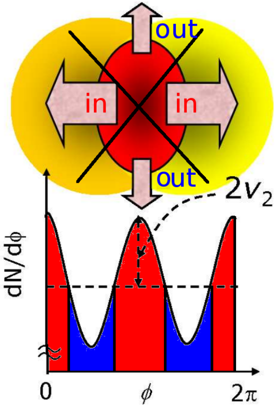
$\langle L_{\text{in}} \rangle < \langle L_{\text{out}} \rangle$

$v_2^{\text{ch jet}} > 0$?



[3] R.Baier *et al.* NPB484 265-282 ($\propto L$)
[4] R.Baier *et al.* NPB483 291-320 ($\propto L^2$)
[5] C. Marquet, T. Renk, PLB685 270-276 ($\propto L^3$)

$v_2^{\text{ch jet}}$ is measured using the 'in-plane' and 'out-of-plane' p_{T}-differential jet yields N_{in}, N_{out}



$$v_2^{\text{ch jet}} = \frac{\pi}{4}\frac{1}{R}\frac{N_{\text{in}} - N_{\text{out}}}{N_{\text{in}} + N_{\text{out}}}$$

resolution R corrects for the finite precision of symmetry plane estimate $\Psi_{\text{EP, 2}}$

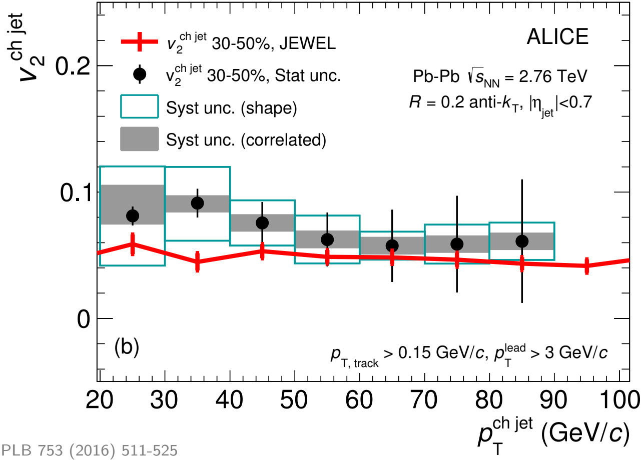
$v_2^{\text{ch jet}}$ is the second coefficient of a Fourier series

$$\frac{dN_{\text{jet}}}{d(\varphi_{\text{jet}} - \Psi_n)} \propto 1 + \sum_{n=1}^{\infty} 2v_n^{\text{ch jet}} \cos[n(\varphi_{\text{jet}} - \Psi_n)]$$

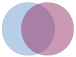
$$N_{\text{in}} = \int_{in} \frac{dN_{\text{jet}}}{d(\varphi_{\text{jet}} - \Psi_{\text{EP, 2}}^{\text{V0}})} = a\left(\pi + 4v_2^{\text{ch jet}}\right)$$

$$N_{\text{out}} = \int_{out} \frac{dN_{\text{jet}}}{d(\varphi_{\text{jet}} - \Psi_{\text{EP, 2}}^{\text{V0}})} = a\left(\pi - 4v_2^{\text{ch jet}}\right)$$

$v_2^{\text{ch jet}}$ in 30–50% and JEWEL



PLB 753 (2016) 511-525



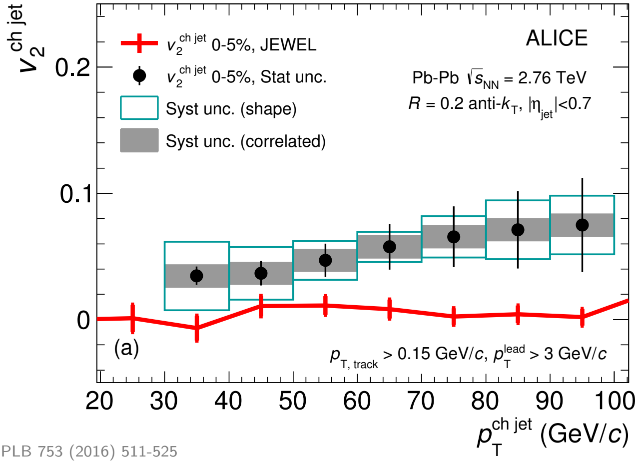
$\langle L_{in} \rangle < \langle L_{out} \rangle$

$v_2^{\text{ch jet}} >?$

Non-zero $v_2^{\text{ch jet}}$ over full p_T range

Good agreement with JEWEL

What about central collisions ?



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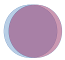

$\langle L_{in} \rangle \approx \langle L_{out} \rangle$

$v_2^{\text{ch jet}} \approx 0?$

Strong effect of fluctuations in the **participant** distribution ?

... but beware the **large** and **correlated** systematic uncertainties

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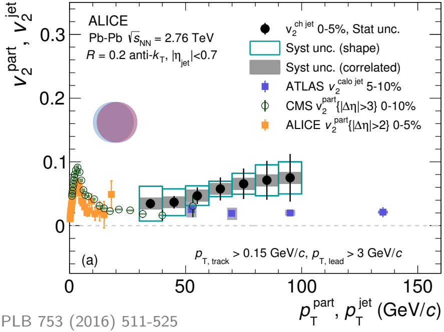
Different energy scales for v_2^{part}, $v_2^{\text{ch jet}}$ and $v_2^{\text{ch+emjet}}$, qualitative comparison only



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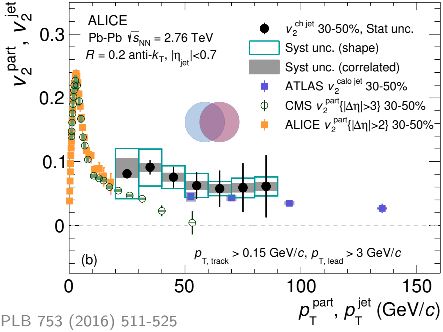

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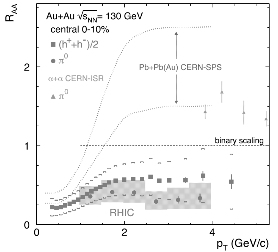
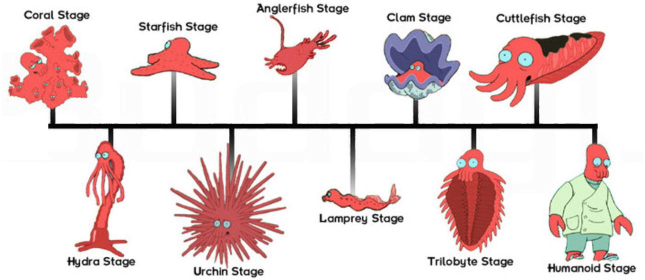
Non-zero $v_2^{(\dots)}$ indicative of dependence on (effective) **path-length**

Needs **high-precision** follow-up



first 'hard probe' measurement 15 years ago

but the field has evolved quite a bit



How-to: constrain QGP properties ?

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Which **processes** is dominant?
(radiative, elastic)

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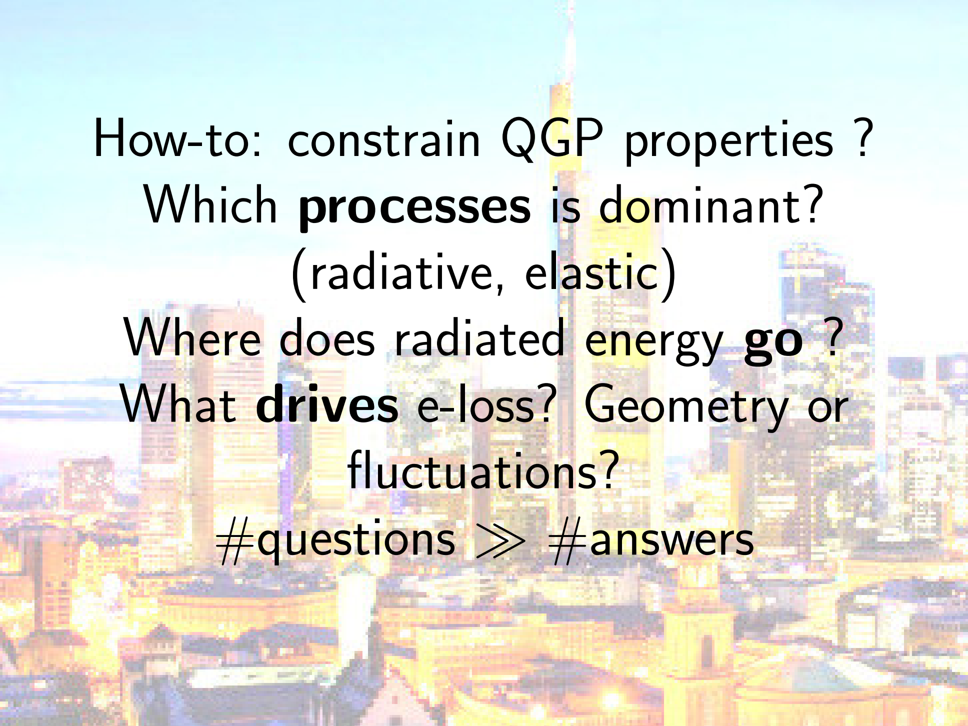
Where does radiated energy **go** ?
What **drives** e-loss? Geometry or fluctuations?



How-to: constrain QGP properties ?
Which **processes** is dominant?
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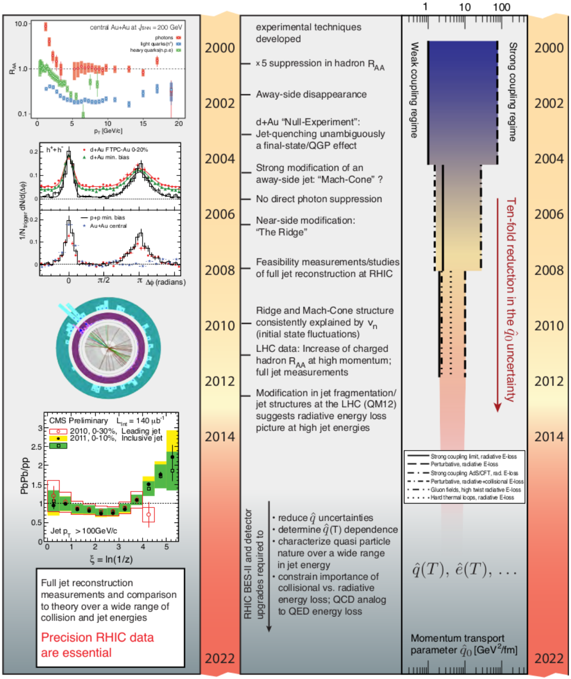
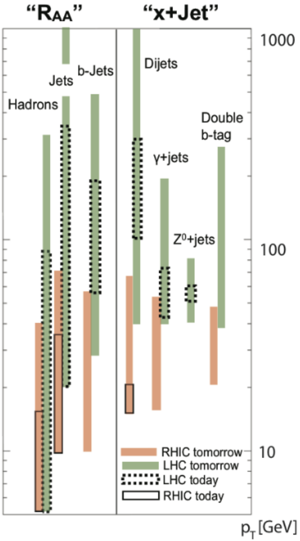
$\#\text{questions} \gg \#\text{answers}$





'Hot and Dense QCD matter, Unraveling the Mysteries of the Strongly Interacting QGP' & 'The Hot QCD White Paper'

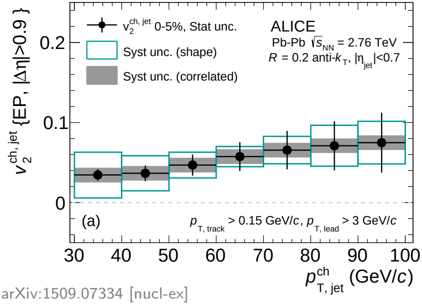
fin

thanks for your attention / patience

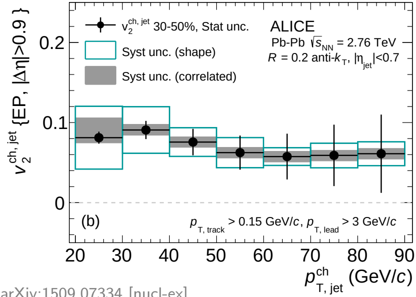
BACKUP

$v_2^{\text{ch jet}}$ is measured in 0-5% (left) and 30-50% (right) collision centrality

- [0-5%] $\approx 2\ \sigma$ deviation from 0
- [30-50%] ≈ 3 - $4\ \sigma$ deviation from 0



arXiv:1509.07334 [nucl-ex]



arXiv:1509.07334 [nucl-ex]

p-value is derived from minimizing a modified[6] χ^2-function w.r.t. $\epsilon_{corr}, \epsilon_{shape}$

$$\tilde{\chi}^2(\epsilon_{corr}, \epsilon_{shape}) = \left[\left(\sum_{i=1}^{n} \frac{(v_{2\,i} + \epsilon_{corr}\sigma_{corr,i} + \epsilon_{shape})^2}{\sigma_i^2} \right) + \epsilon_{corr}^2 + \frac{1}{n} \sum_{i=1}^{n} \frac{\epsilon_{shape}^2}{\sigma_{shape,i}^2} \right]$$

[6] Phys.Rev. C77, 064907 (2008), 0801.1665

UE flow under control?

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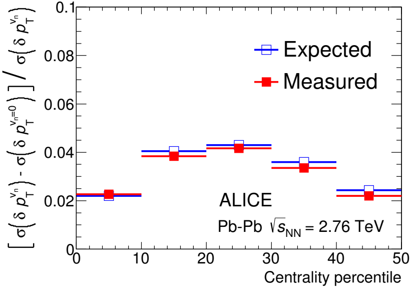
Expected δp_{T} width without flow from charged particles from N_A (multiplicity in a cone) $\langle p_{\mathrm{T}} \rangle$ (mean p_{T} of particle spectrum) $\sigma(p_{\mathrm{T}})$ (width of particle spectrum)

$$\sigma(\delta p_{\mathrm{T}}^{v_n=0}) = \sqrt{N_A \sigma^2(p_{\mathrm{T}}) + N_A \langle p_{\mathrm{T}} \rangle^2}$$

Adding v_n by introducing non-Poissonian fluctuations $\sigma^2_{NP}(N_A) = 2N_A^2(v_2^2 + v_3^2)$

$$\sigma(\delta p_{\mathrm{T}}^{v_n}) = \sqrt{N_A \sigma^2(p_{\mathrm{T}}) + (N_A + \sigma^2_{NP}(N_A)) \langle p_{\mathrm{T}} \rangle^2}$$

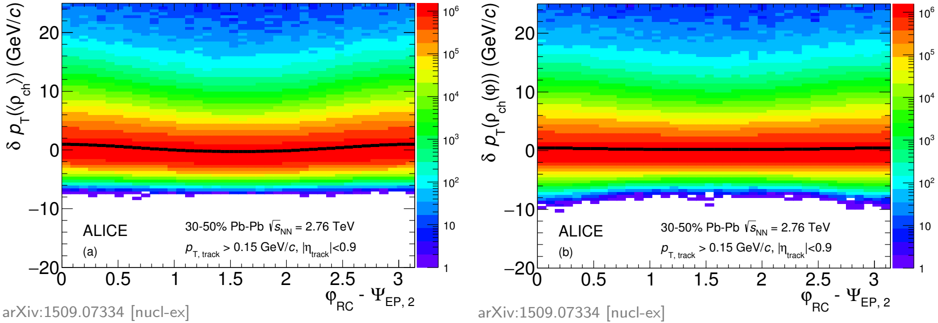


arXiv:1509.07334 [nucl-ex]

- 'expected' as above: from N_A and $\langle p_{\mathrm{T}} \rangle$, etc.
- 'measured': from δp_{T} distributions
  - $\sigma(\delta p_t^{v_n})$ from $\langle \rho_{\mathrm{ch}} \rangle$
  - $\sigma(\delta p_t^{v_n=0})$ from $\rho_{\mathrm{ch\ local}}$

$\rho_{ch\ local}$ gives expected reduction of flow contribution to the δp_T width

Fluctuations quantified by δp_T



δp_T distribution built using $\langle\rho_{ch}\rangle$ δp_T distribution built using $\rho_{ch\ local}$

UE subtraction technique succesfully removes flow bias from UE

- Modulation of mean δp_T decreases strongly
- Width of δp_T in-plane is larger than out-of-plane
- In-plane and out-of-plane jet spectra need to be unfolded independently to properly treat UE fluctuations

Q_{pPb} and centrality in p–Pb collisions

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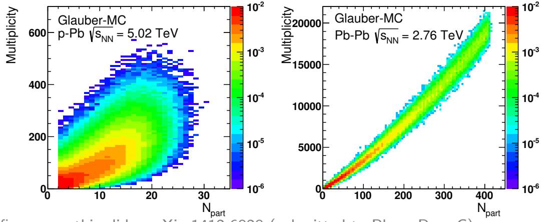
$\langle N_{coll} \rangle$ not easy to determine in p–Pb collisions

$$Q_{pPb}(p_T, \text{cent}) = \frac{dN^{pPb}_{\text{cent}}/dp_T}{\langle N^{\text{coll}}_{\text{cent}} \rangle \cdot dN^{pp}/dp_T}$$

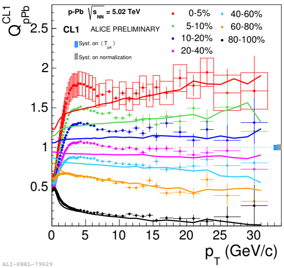
'Pb–Pb approach'(a) is biased

Hybrid centrality method (b):

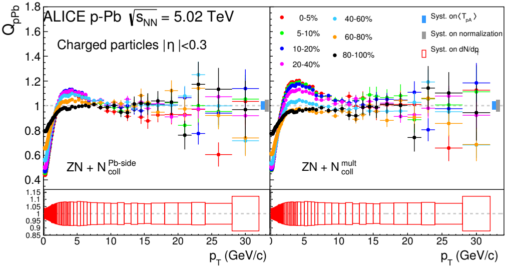
- Estimate centrality from Zero Degree Calorimeter
- $\langle N^{\text{coll}}_{\text{cent}} \rangle$ scales with charged particle multiplicity in mid-rapidity or Pb-going side



figures on this slide: arXiv 1412.6828 (submitted to Phys. Rev. C)



a



b

R_{AA}, R_{pPb} of identified particles and jets

R_{AA} of identified particles gives deeper insight into energy loss mechanisms in the plasma and hadron production

Light flavor hadrons

- Medium modification of hadronization process

Jets

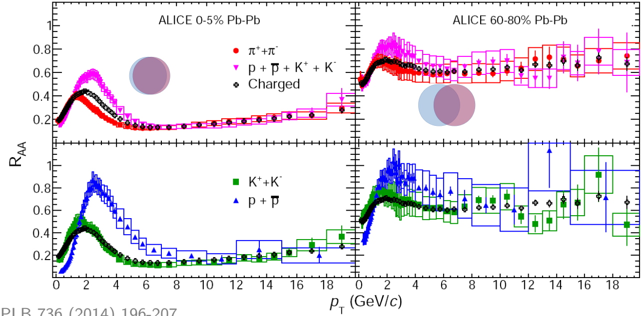
- Energy loss of hard partons
- High Q^2 process: perturbative probes of the QGP

Open charm mesons (D^0, D^+, D^{*+}) R_{AA} and quarkonium

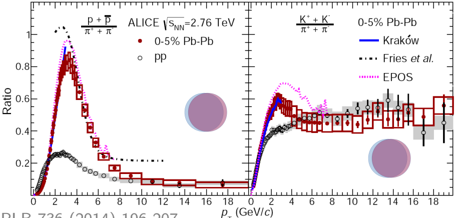
- Heavy quarks probe the full evolution of the medium
- Quark vs gluon energy loss, dead cone effect

Light flavor hadron R_{AA}

- Mass ordering at intermediate p_T: less suppression of protons
- At large p_T no difference between species



PLB 736 (2014) 196-207

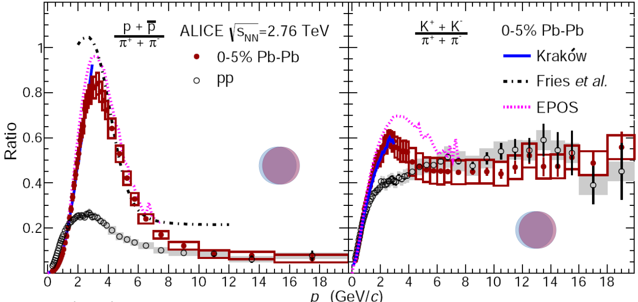


PLB 736 (2014) 196-207

Peak at 3 GeV/c for p/π and K/π ratios

- More pronounced for p/π ratio
- Indicative of radial flow? What about e.g. the ϕ-meson (next slide)?
- High p_T suggests hadronization through fragmentation

- Mass ordering at intermediate p_T: less suppression of protons
- At large p_T no difference between species



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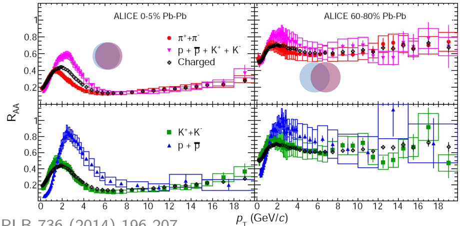

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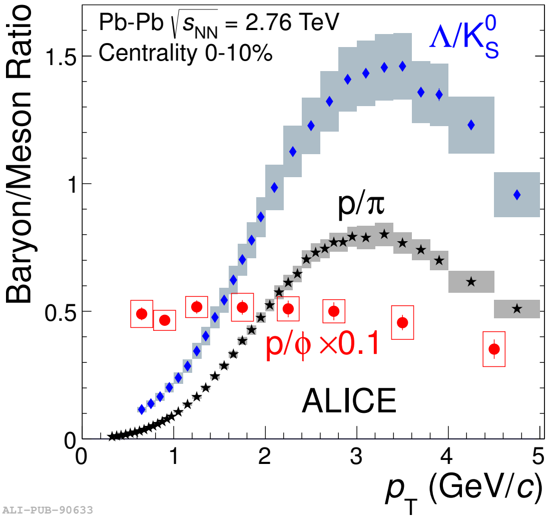

ϕ-meson and p have similar mass

- Ratio ϕ/p flat for central collisions

Shape of p_T distributions determined by particle mass, not recombination

Phys. Rev. Lett. 111 222301 (2013)
Phys. Lett. B 736 196-207 (2014)
Phys. Rev. C 91 (2015) 024609

R_{pPb} model comparison

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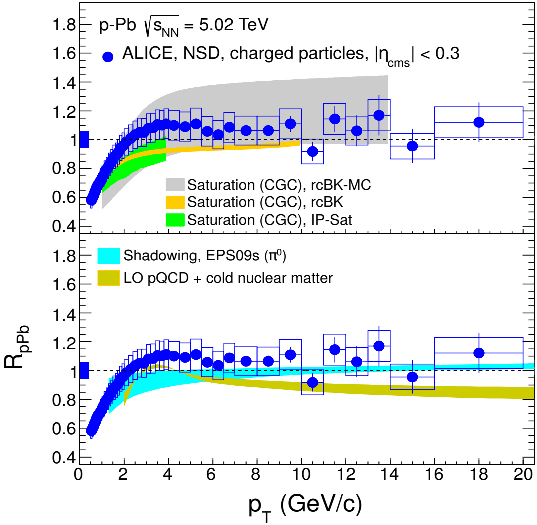

Several models describe R_{pPb}

- Gluon saturation models (color glass condensate) agree with the data, however only small effects are expected
- NLO pQCD with EPS09s agrees with data for transverse momenta > 6 GeV/c
- LO pQCD + cold nuclear matter under-predicts data at high p_T

Known potential nuclear effects (CGC/saturation and nPDF) are small at mid-rapidity/high p_T: consistent with measurement

PRL 110, 082302 (2013)

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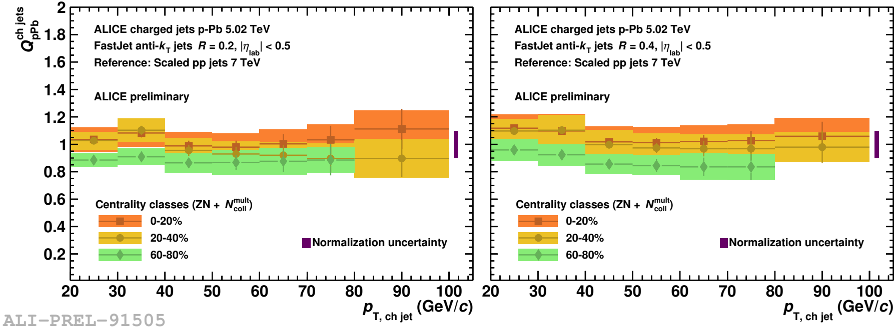


$R = 0.2$ (left) and $R = 0.4$ (right) charged jets, anti-k_T

- Q_{pPb} following hybrid centrality estimation
- Results compatible with no final state effect on jet spectra

See also arXiv:1503.00681

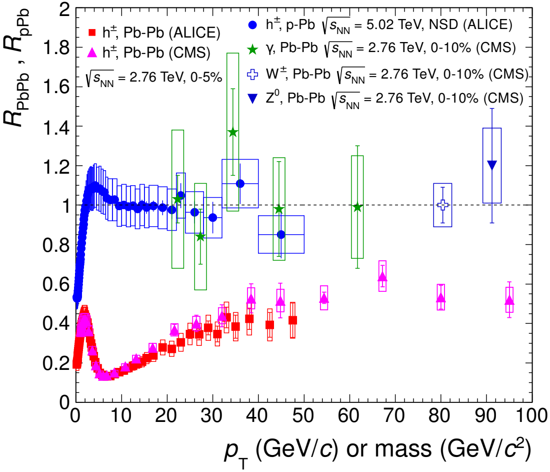
R_{pPb} in p–Pb collisions

- Compound system (p–nucleus)
- expected to be sensitive to initial state, but not final state (QGP) effects

R_{pPb} is consistent with unity for $p_T > 2$ GeV/c

- Small Cronin-like enhancement visible at low p_T
- Consistent with R_{AA} of particles which are not sensitive to QGP dynamics ($\gamma, W^{\pm}, Z^0$)

Suppression of hadron production in Pb–Pb collisions is **final** state effect



PRL 110, 082302 (2013)

R_{AA} vs EP

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