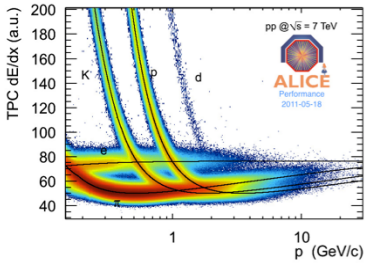
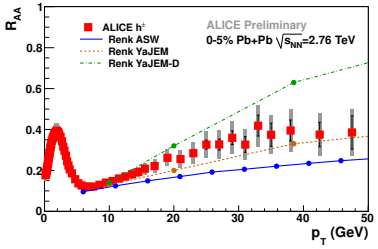
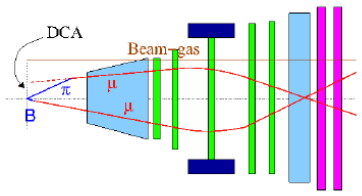
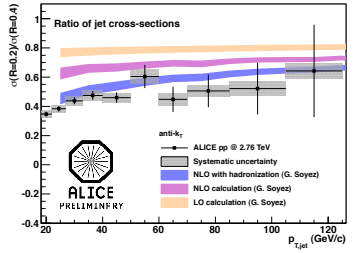
# Characterizing energy loss with ALICE

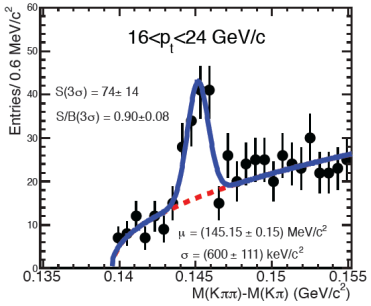
Peter Jacobs, LBNL/CERN
*for the ALICE Collaboration*

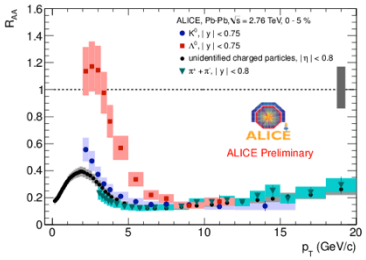


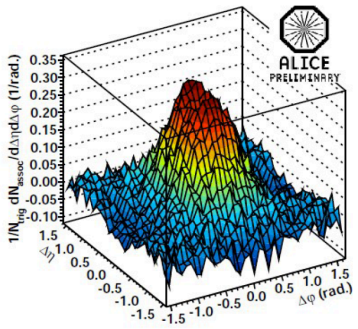



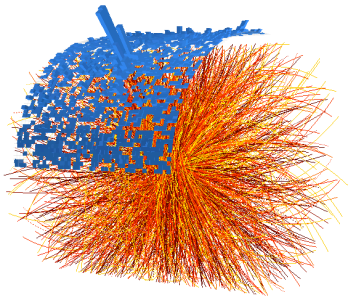



# Outline

Goal: bring together a wide array of ALICE results to obtain a global view of what we know about partonic energy loss

- compare and contrast data
- compare to theory

Observables:

- Inclusive charged hadrons
- Identified light hadrons
- Heavy flavor
- Hadron correlations
- Jets in p+p
- Jets in Pb+Pb

# Energy loss scorecard

| | **Observables** | **Score** |
|---|---|---|
| Radiative++ E-loss | | |
| In-medium high $p_T$ fragmentation | | |
| Color charge dependence | | |
| Induced large-angle radiation | | |
| Jet/bulk medium Coalescence | | |
| Dead cone effect | | |
| AdS/CFT | | |

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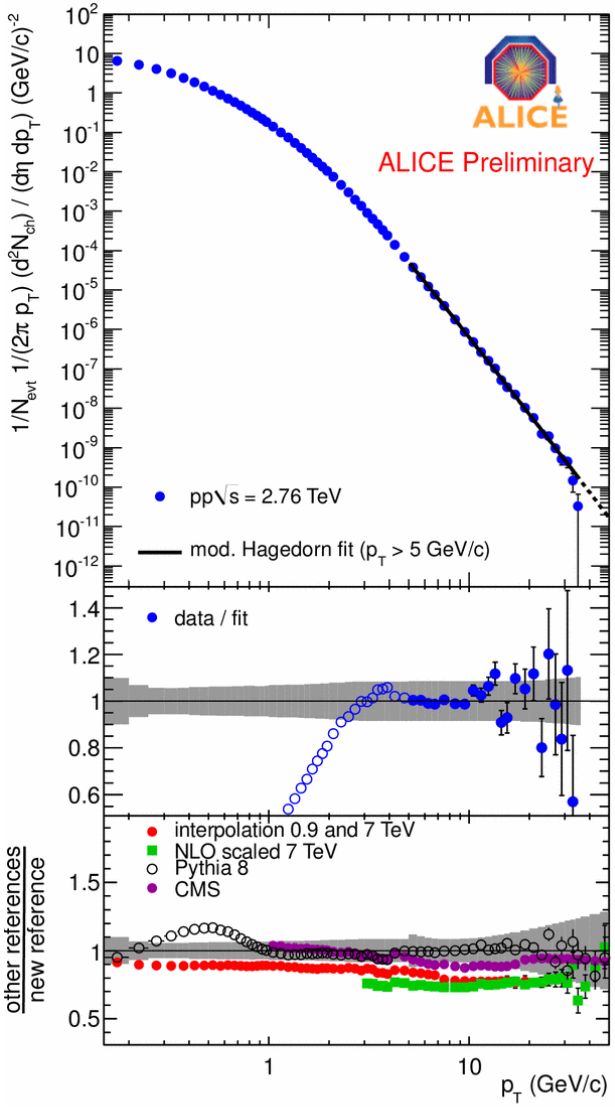
We take this approach in the spirit of a workshop discussion

Any such scorecard is by its nature a simplification

But it can focus discussion about what is really established, what is not, and what is needed to resolve key issues

# The reference: inclusive charged hadron spectrum

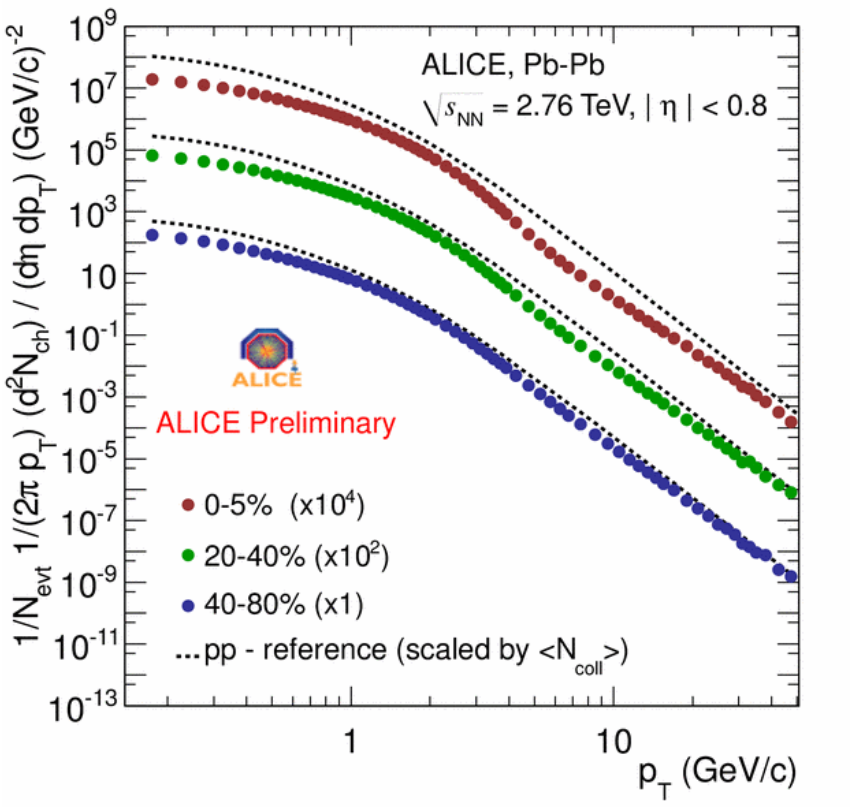
*Talk: M. Floris*

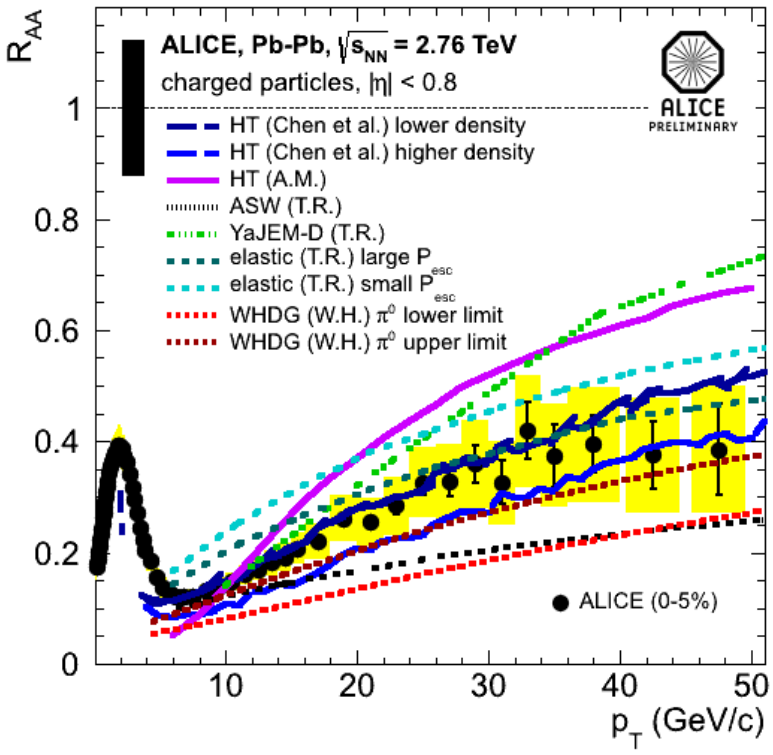



Charged particle tracking under good control

# Charged hadron $R_{AA}$: Comparison to theory

*Talk: M. Floris*

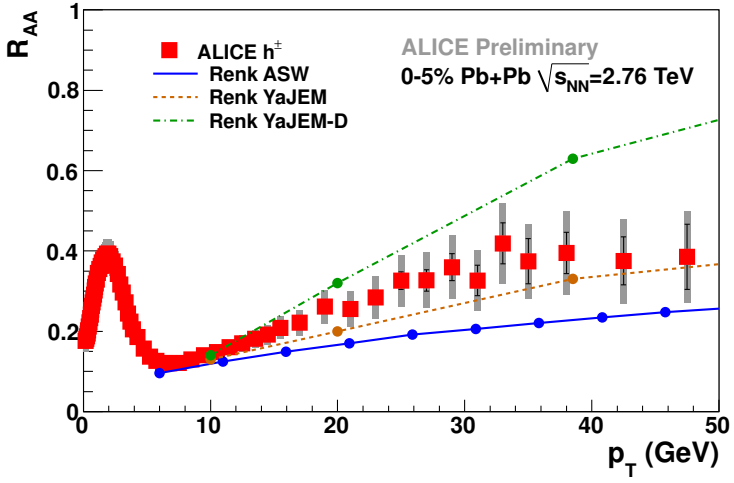


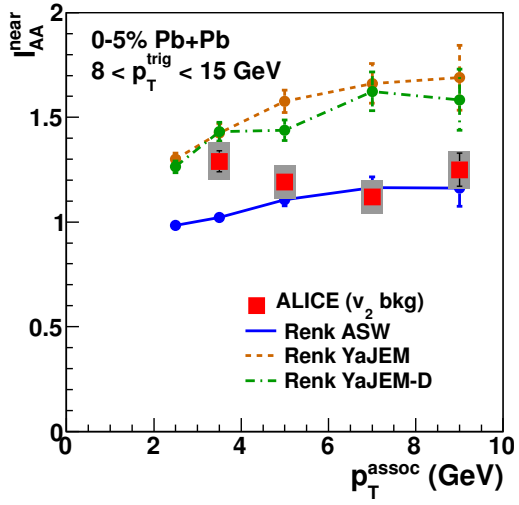



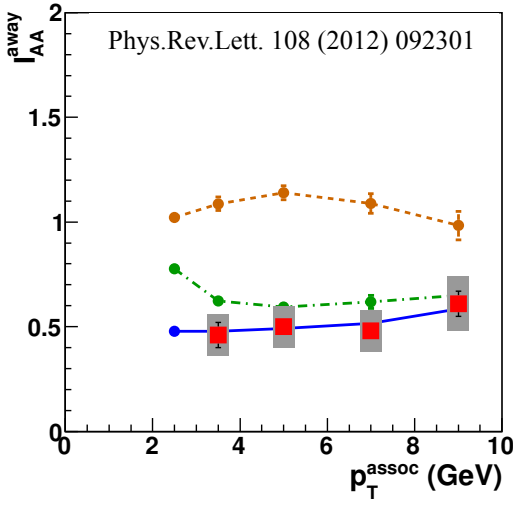

$R_{AA}$ alone is not highly discriminating

# Charged hadron $R_{AA}$ and $I_{AA}$

*See talk by T. Renk*




Multiple observables provide significant discrimination

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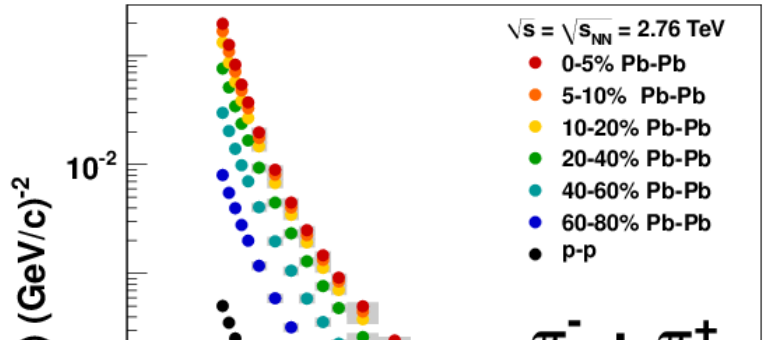
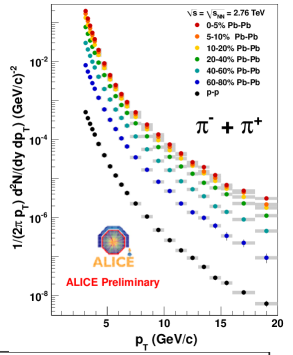
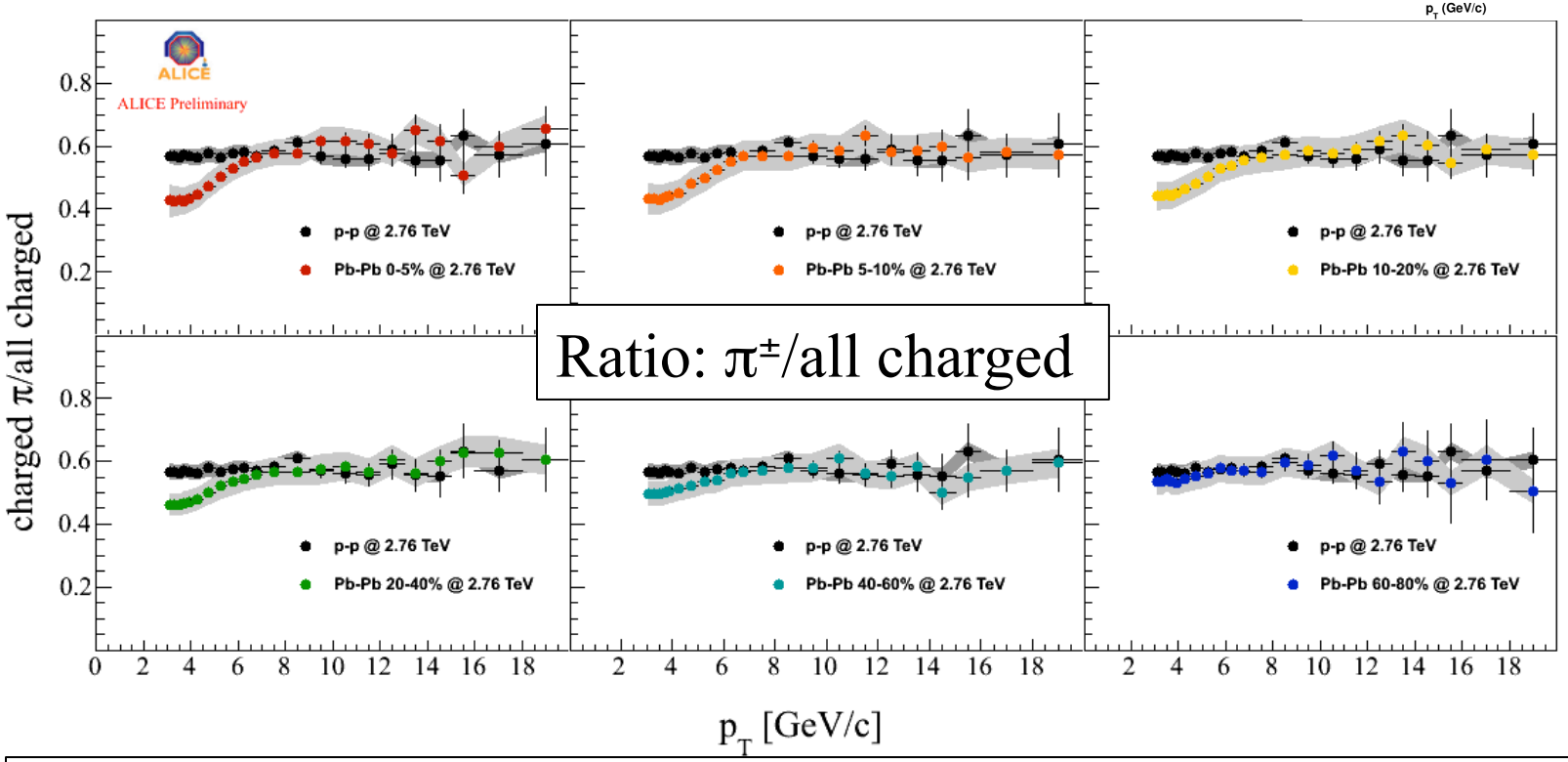
# High $p_T$ fragmentation

# Charged pion inclusive spectrum

*Talk: P. Christiansen*



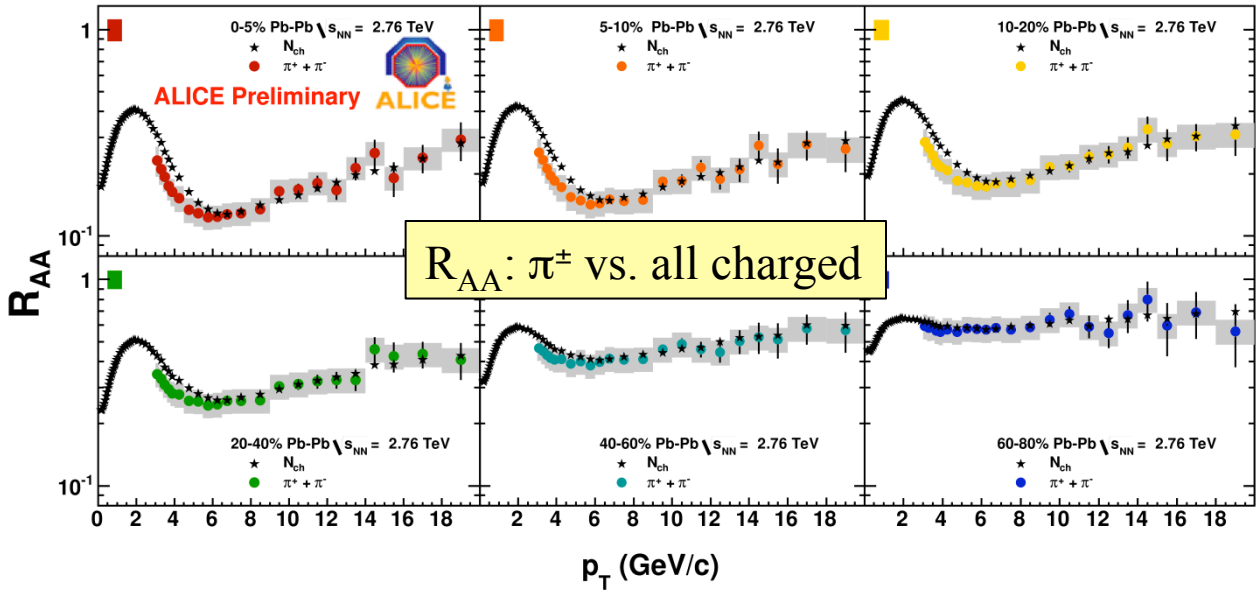




Ratio: $\pi^{\pm}$/all charged

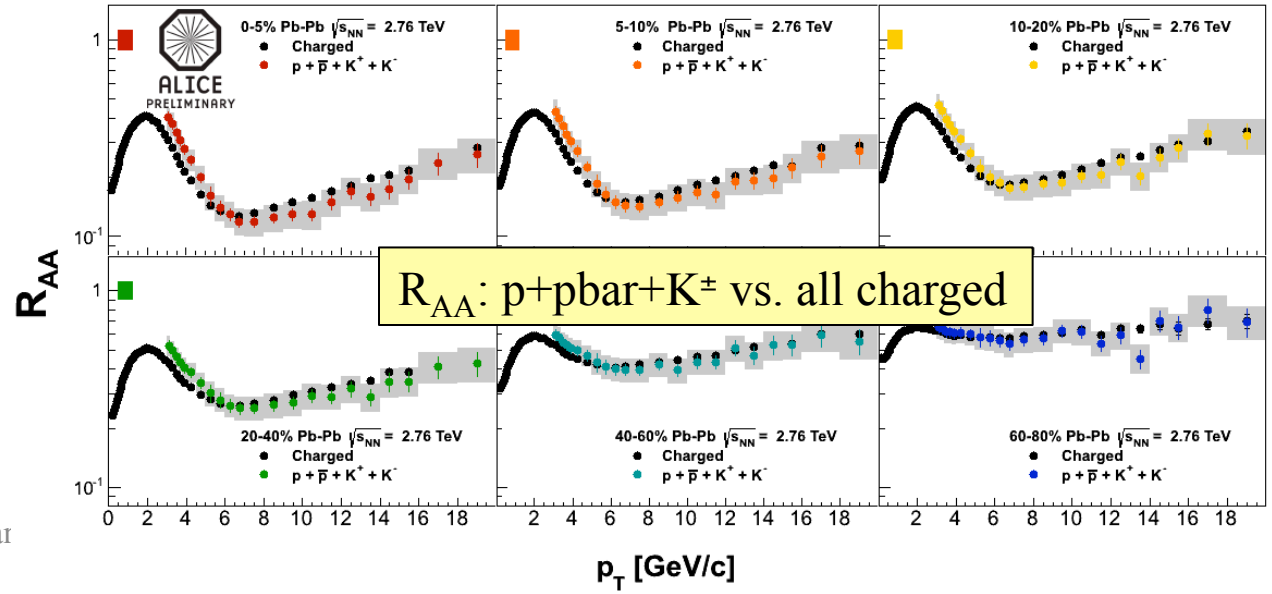
high $p_T$ ratios in central Pb+Pb similar to vacuum fragmentation

# $R_{AA}$: Separate π, p+K vs. all charged

*Talk: P. Christiansen*



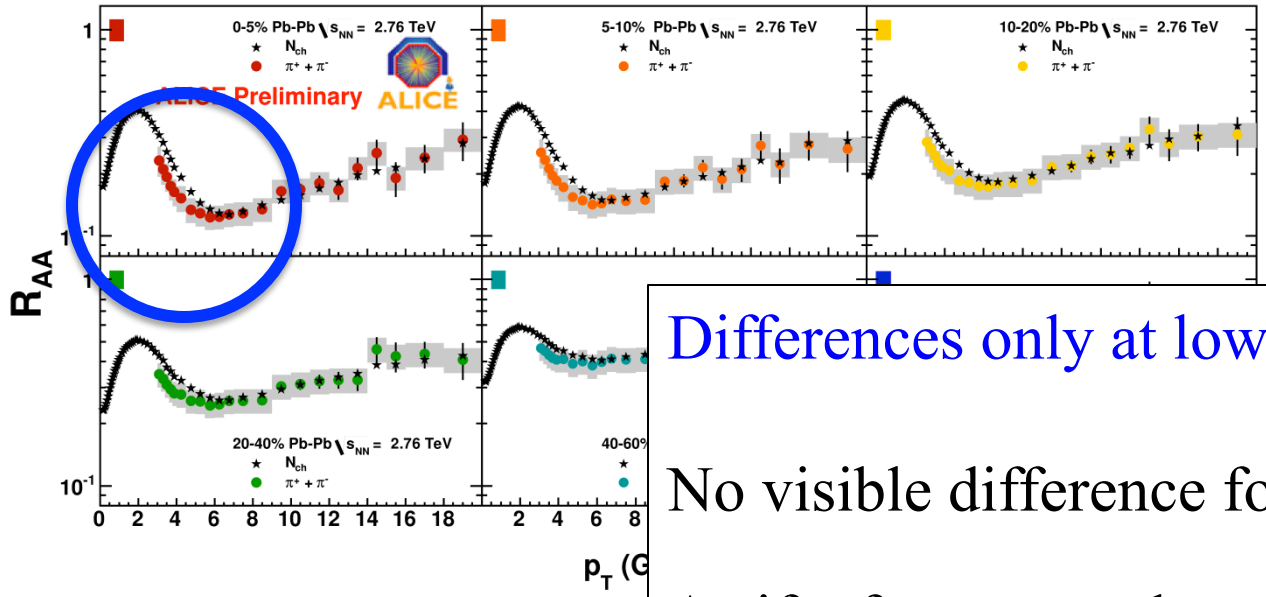

$R_{AA}$: π± vs. all charged




$R_{AA}$: p+pbar+K± vs. all charged

# $R_{AA}$: Separate p, p+K vs. all charged

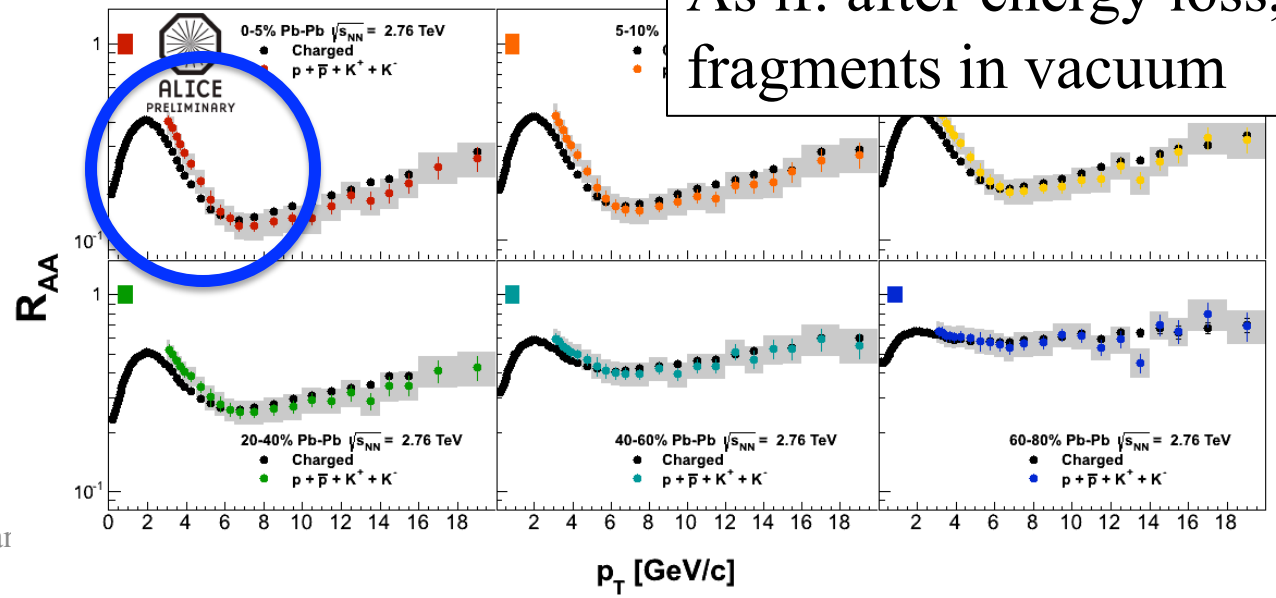
*Talk: P. Christiansen*




Differences only at low $p_T$

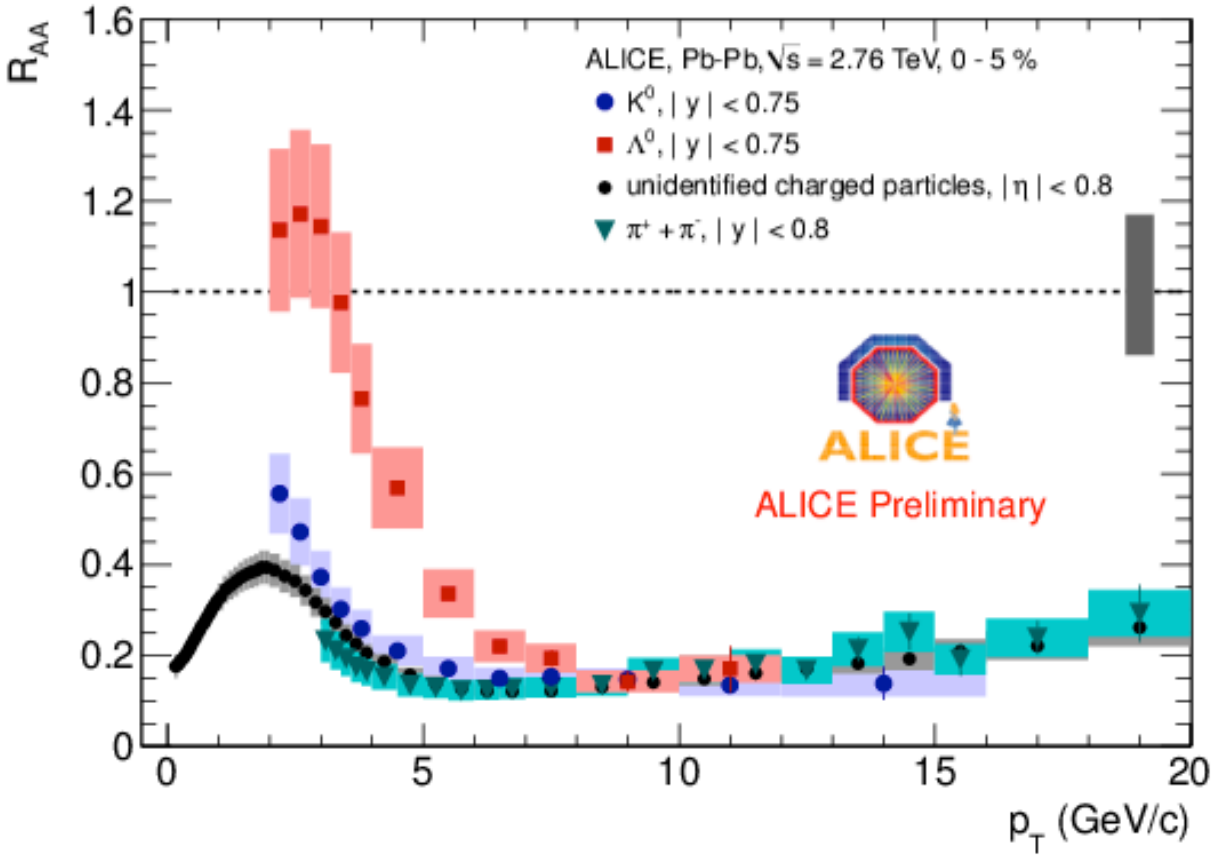
No visible difference for $p_T$>~8 GeV

As if: after energy loss, leading parton fragments in vacuum



# $R_{AA}$: $\Lambda$, $K^{0,}$ $\pi^0$, all charged

*Talk: P. Christiansen*




Similar picture: energy loss followed by fragmentation in vacuum?

Leading hadron bias ➔ measure within reconstructed jets

# Energy loss scorecard

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| Induced large-angle radiation | | |
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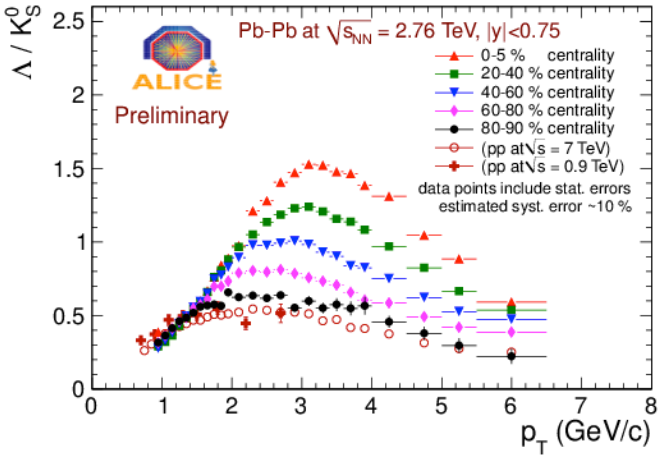
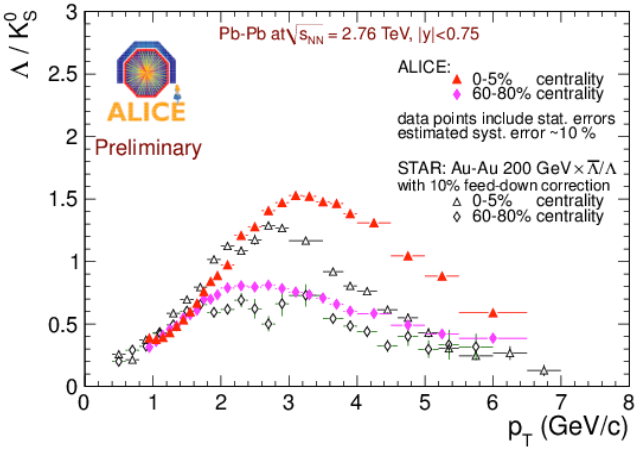
| Dead cone effect | | |
| AdS/CFT | | |

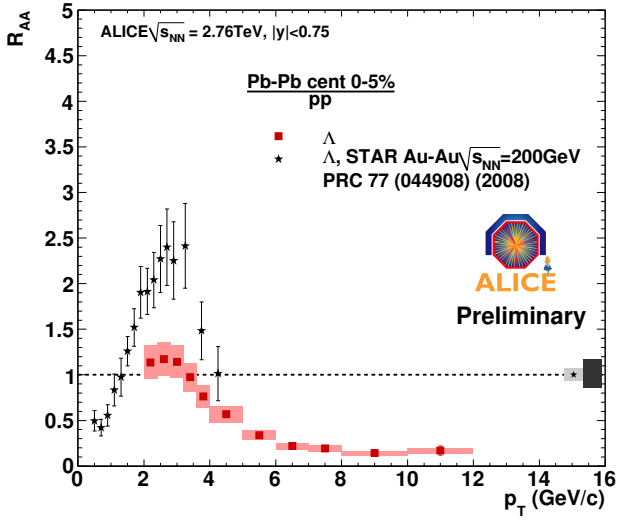
# Intermediate $p_T$ : Jet-medium coalescence?

# $\Lambda/K^0$ ratio, $\Lambda$ $R_{AA}$; Comparison with RHIC

*Talk: P. Christiansen*



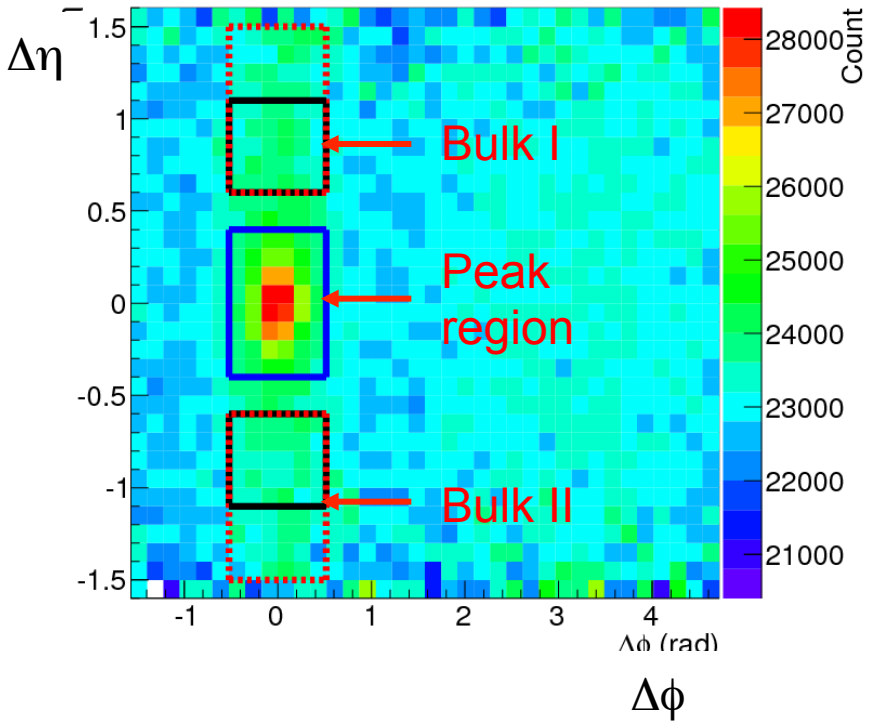

LHC vs RHIC: quantitatively different but qualitatively similar

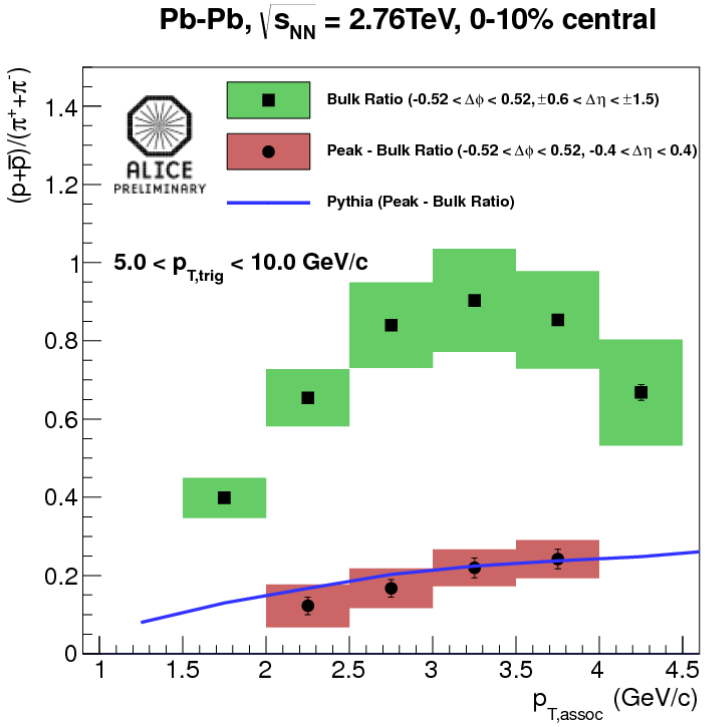
Enhancement has similar $p_T$ range and magnitude despite large increase in relative jet rate at LHC vs RHIC

➔ No evidence that jet production plays a dominant role

# Near-side di-hadron correlations: p/π ratio

*Talks: M. Veldhoen, J F Grosse-Oetringhaus*




p/π in jet peak consistent with PYTHIA

- No evidence of medium-induced modification of fragmentation
- Caution: physics evolves rapidly with $p_T$ in this region

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| Dead cone effect | | |
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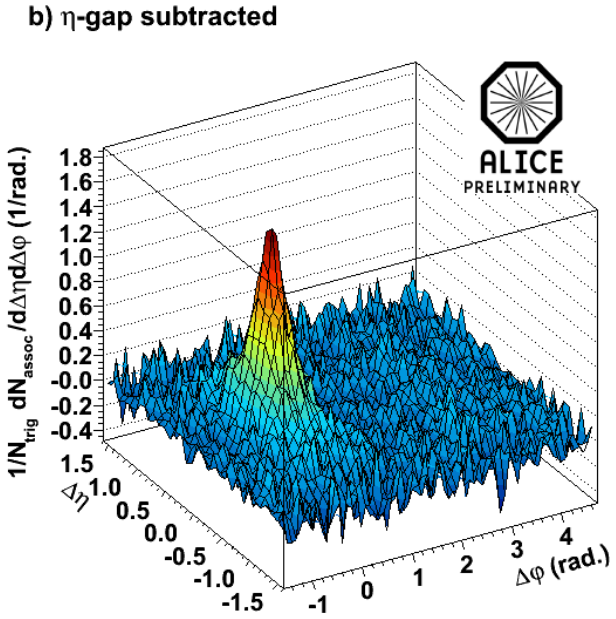
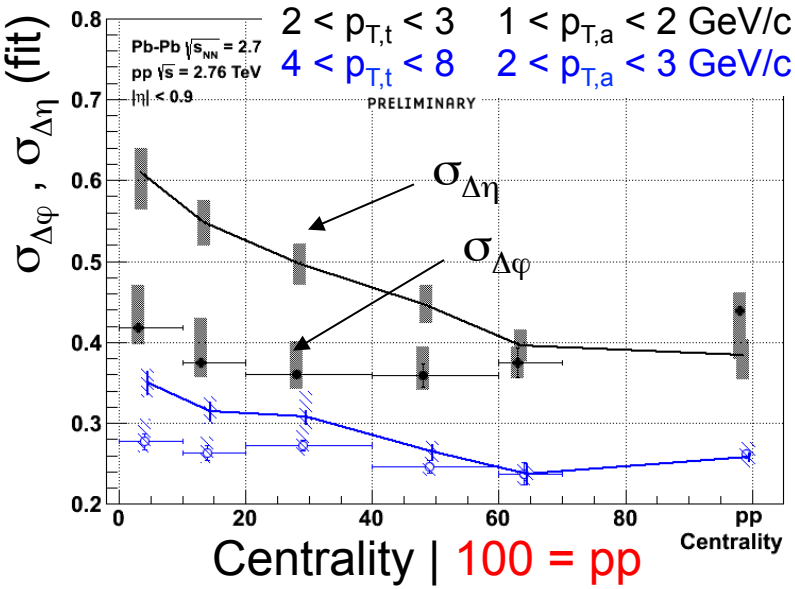
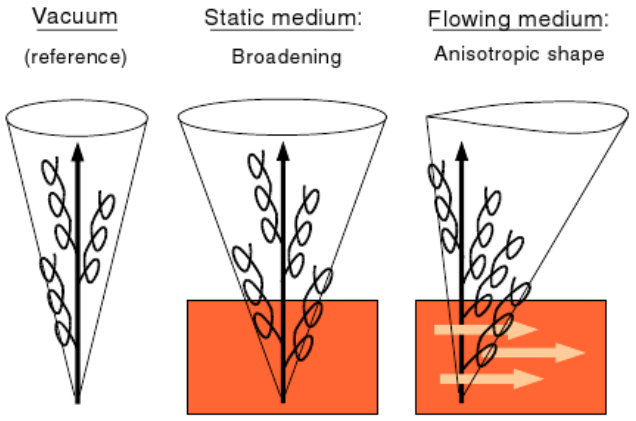
# Charged hadron correlations

*Talks: A. Morsch, J F Grosse-Oetringhaus*




- Greater longitudinal than azimuthal broadening
- Suggestive of "medium drag" of radiation
- Caution: physics evolves rapidly with $p_T$ in this region



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| Dead cone effect | | |
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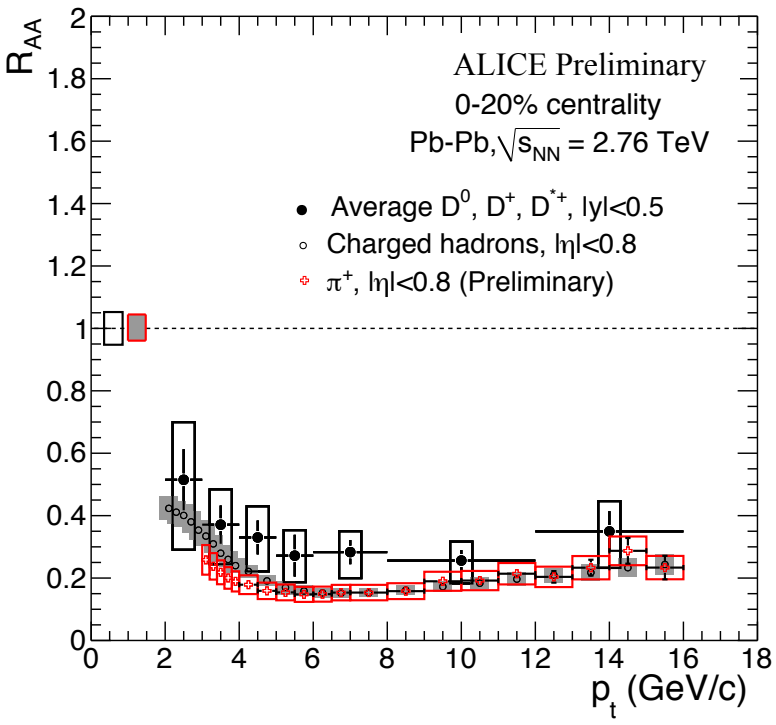
# Charm

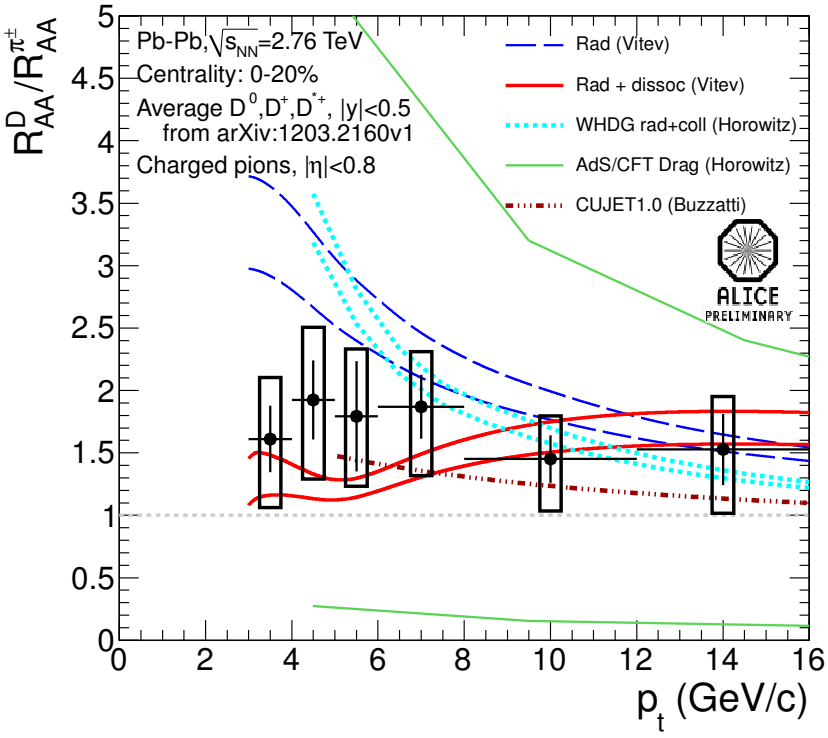
*Plenary talk: S. Masciocchi*
*Parallel talks: Z. Conesa de Valle, M. Kweon, G. Ortona, D. Stocco*

# D meson $R_{AA}$

$R_{AA}$



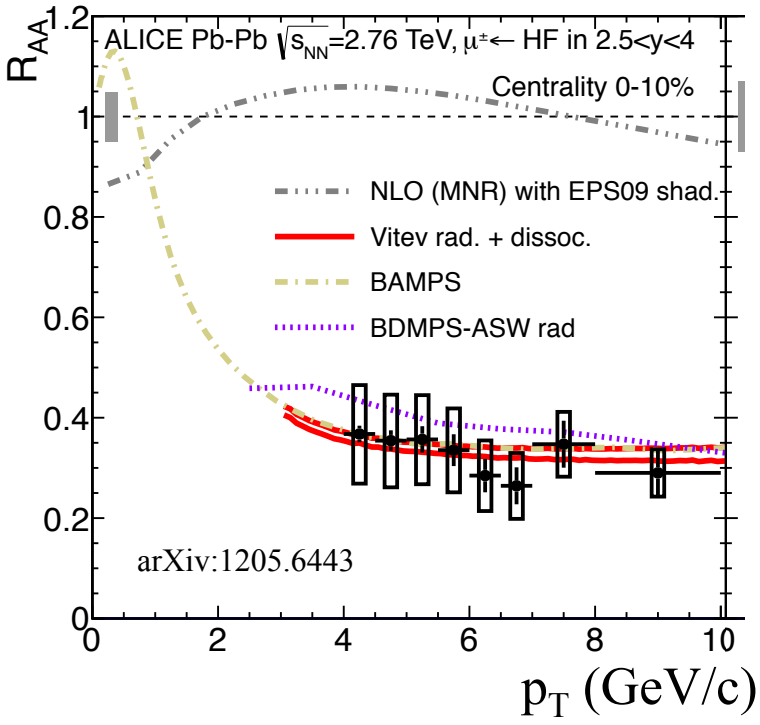

$R_{AA}$ Ratio D/π

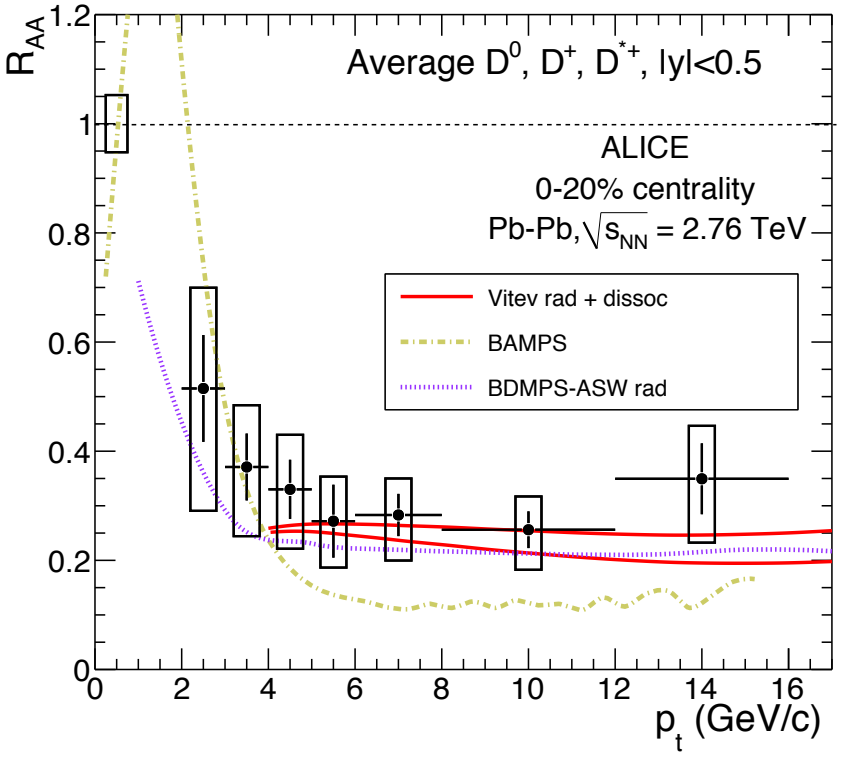



Hint of larger $R_{AA}$ for D than π

- Color-charge effect?
- No evidence for dead cone effect ($p_T$ dependence)
- Higher precision in progress

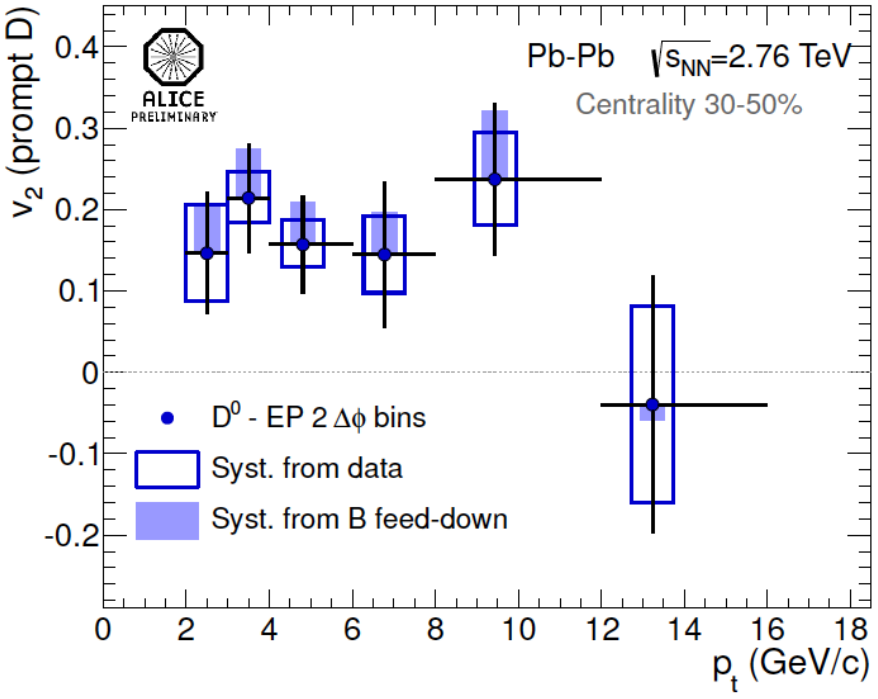
# Heavy flavor $R_{AA}$: simultaneous modeling of forward HF muons and central D-mesons

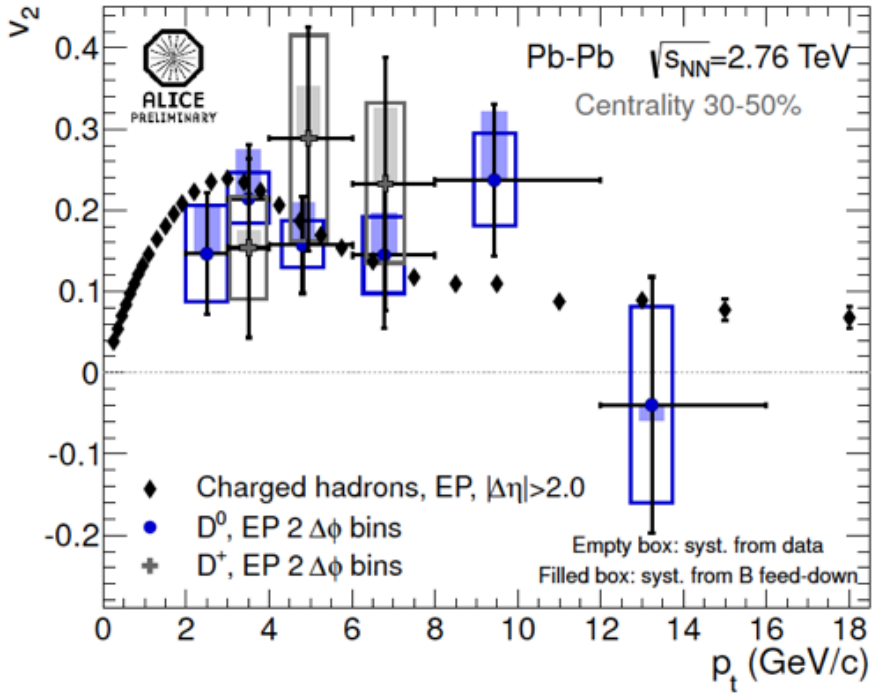



Variants of radiative++ energy loss agree with data

# D meson $v_2$

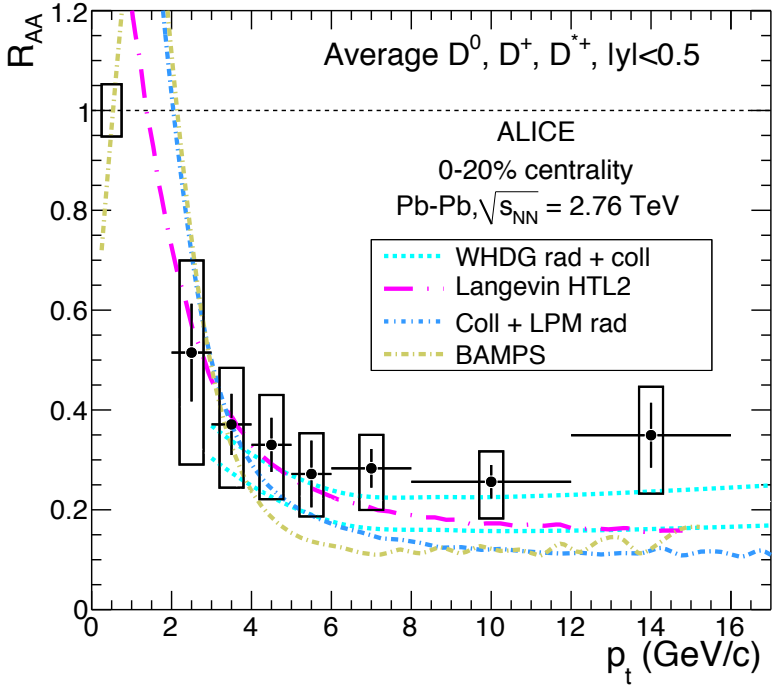


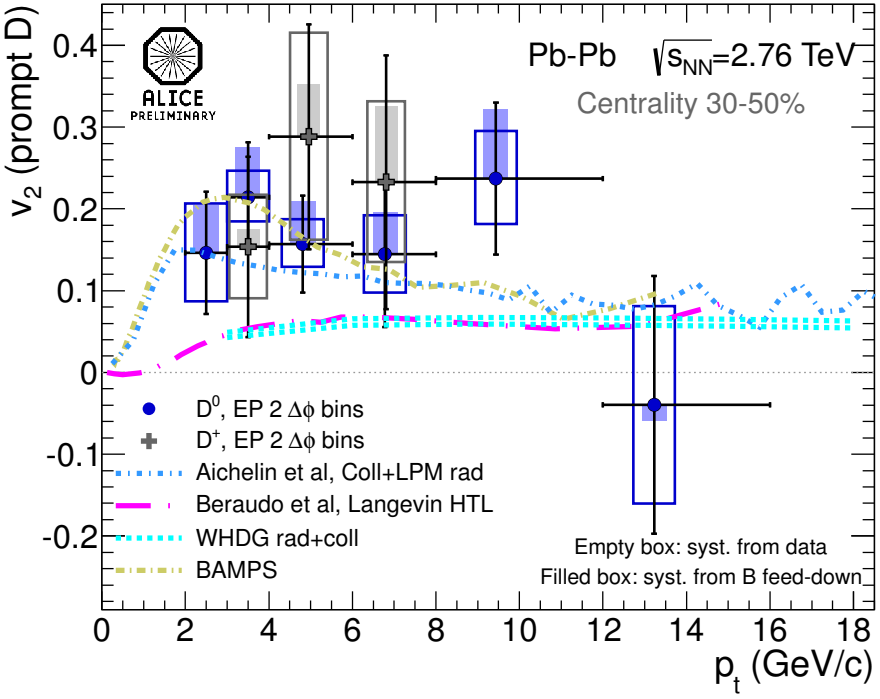




Highly anticipated measurement…

D-mesons flow like charged hadrons

# D-meson $R_{AA}$ and $v_2$: compare to models




Charm is conserved: significant constraints on models
Higher precision in progress ➔ yet stronger constraints

# Energy loss scorecard

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| Color charge dependence | $R_{AA}$ ratio D/π | Maybe |
| Induced large-angle radiation | Di-hadron correlations: longitudinal but not azimuthal broadening | Maybe |
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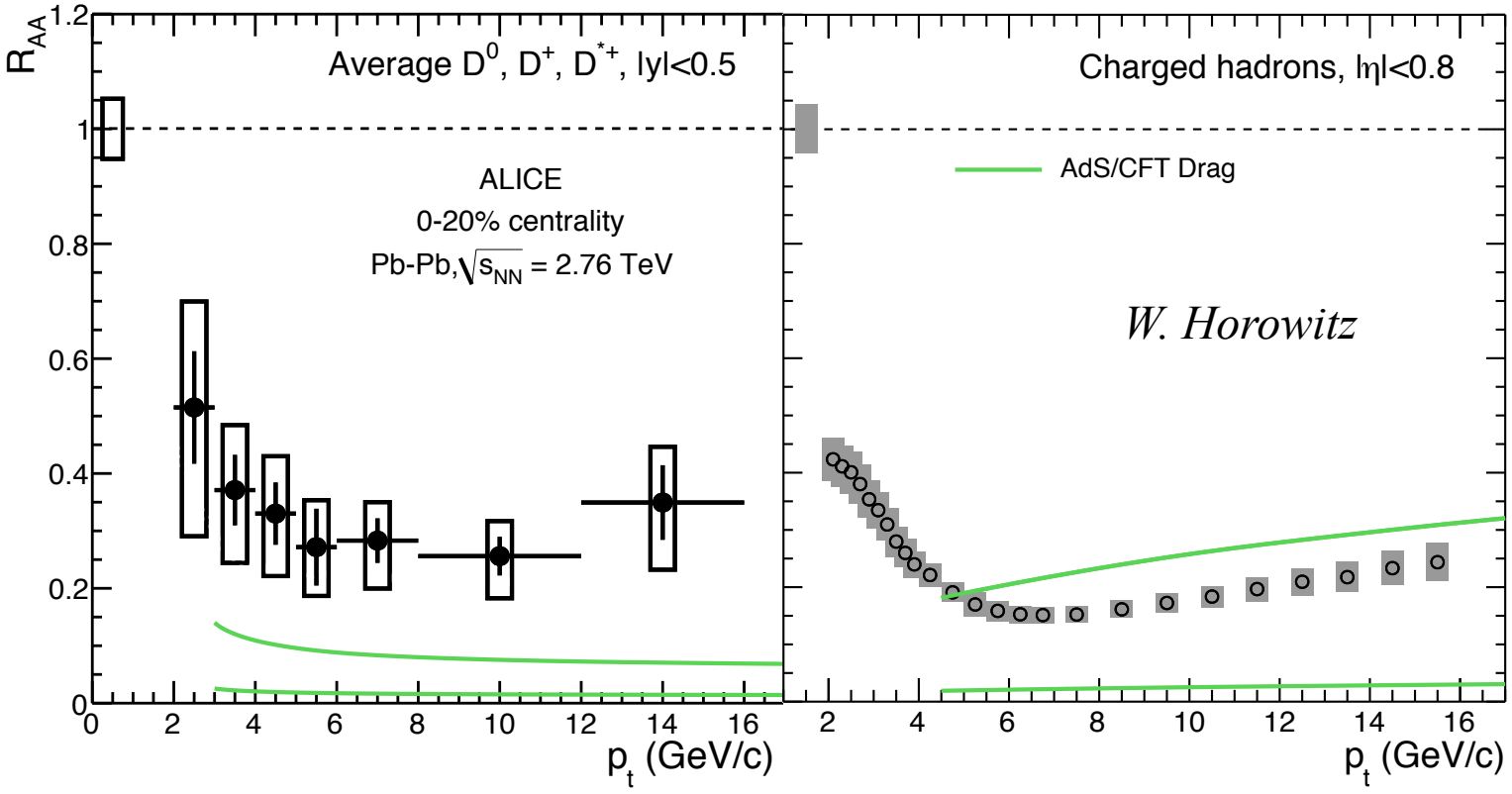
| Dead cone effect | $R_{AA}$ ratio D/π | No evidence |
| AdS/CFT | | |

# AdS/CFT vs charm and charged hadron $R_{AA}$




Consistent with NPE data at RHIC

Describes LHC charged and displaced J/ψ $R_{AA}$ (CMS)

Does not describe open charm $R_{AA}$

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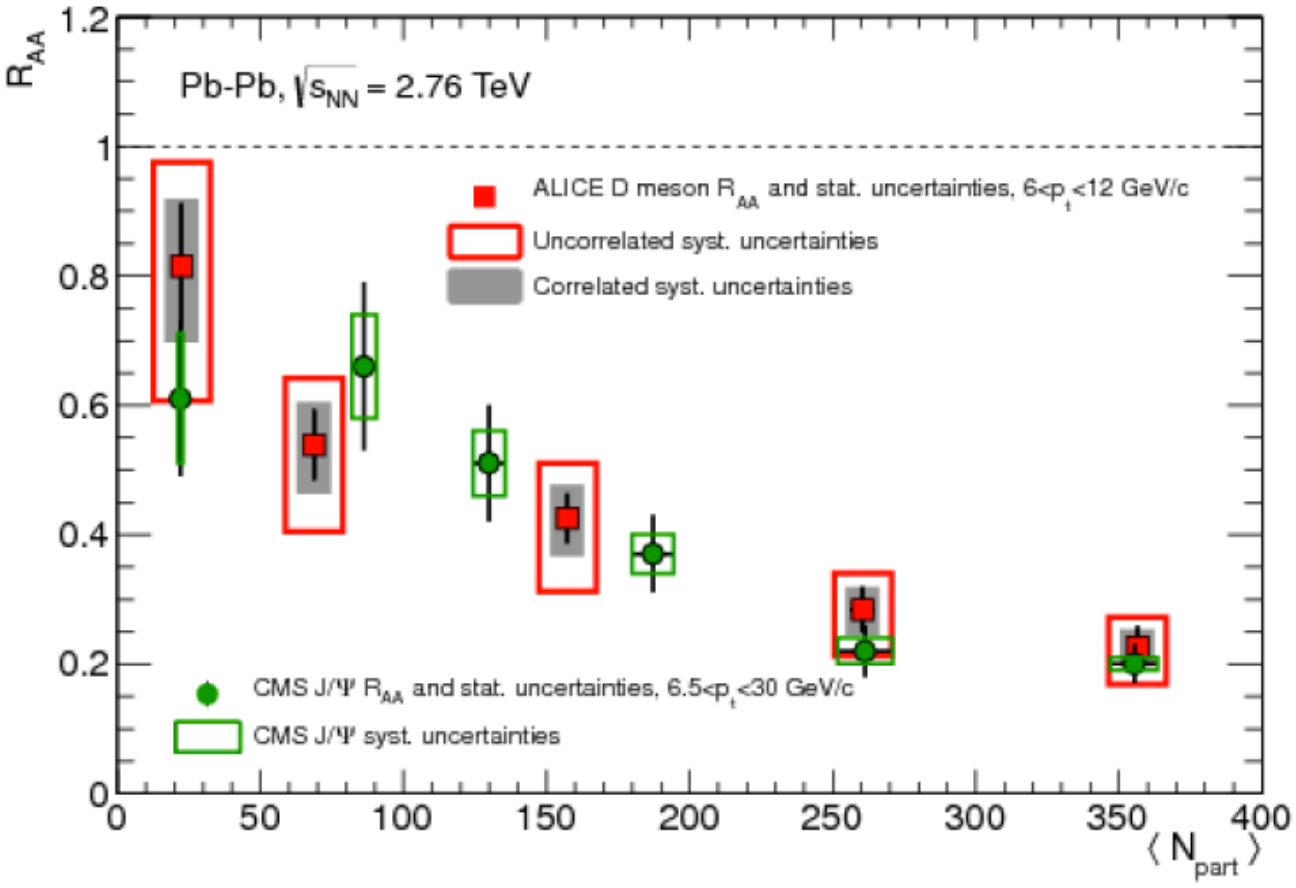
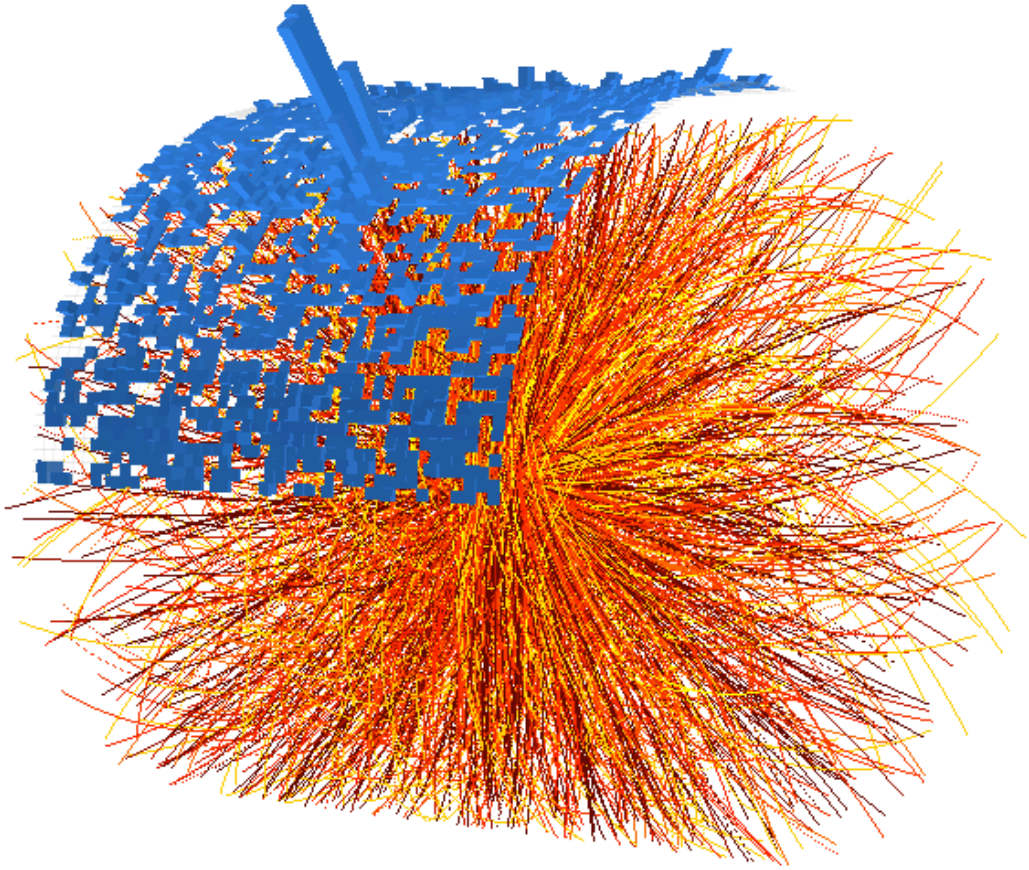
| Jet/bulk medium Coalescence | p/π ratio in jet-like peak; weak evolution of baryon/meson ratio vs RHIC | No evidence |
| Dead cone effect | $R_{AA}$ ratio D/π | No evidence for large effect |
| AdS/CFT | $R_{AA}$ ratio D/π | Unlikely? |

# Centrality dependence of $R_{AA}$: Compare D meson with prompt J/ψ (CMS)

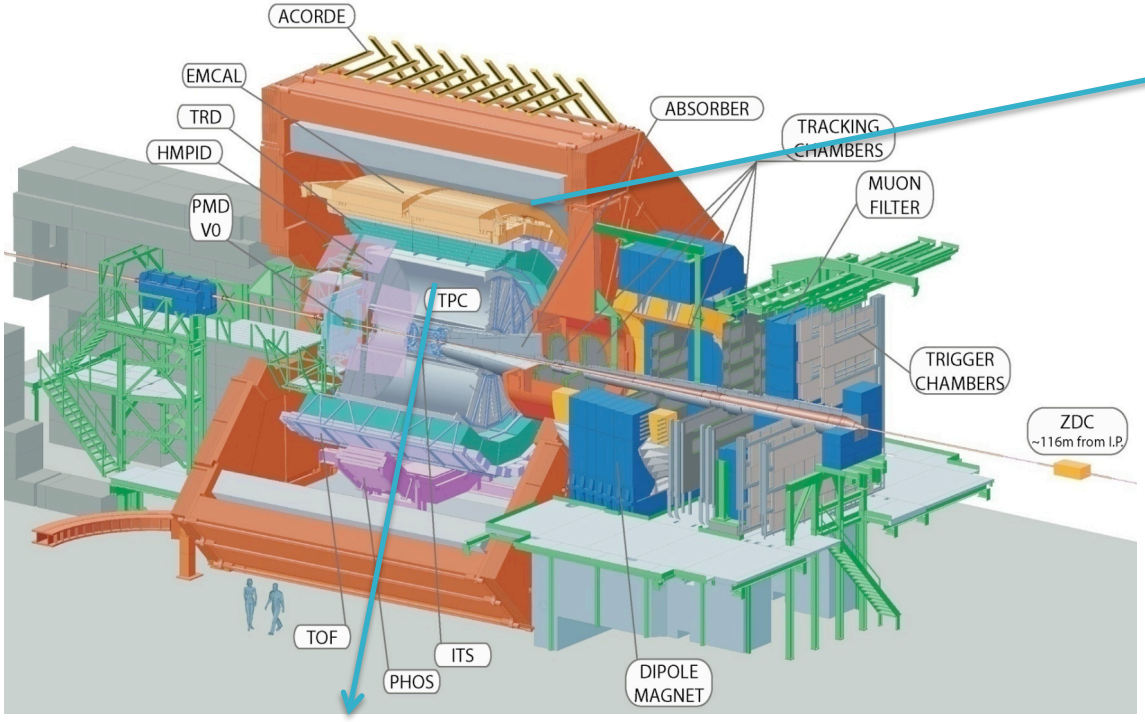


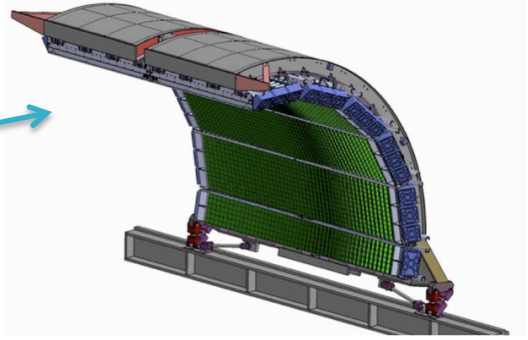

Coincidence?

# Jets



# ALICE jet measurements



- EMCal: Pb-scintillator sampling calorimeter which covers:
  $|\eta|<0.7,\ 80°<\varphi<180°$
- 11520 towers with each covers
  $\Delta\eta \times \Delta\phi \sim 0.014 \times 0.014$

Tracking: $|\eta|<0.9,\ 0<\varphi<360°$
TPC: gas detector
ITS: silicon detector

→ ***Charged constituents*** → **JET** ← ***Neutral constituents***

# ALICE jet measurement strategy

Measure almost all jet constituents explicitly

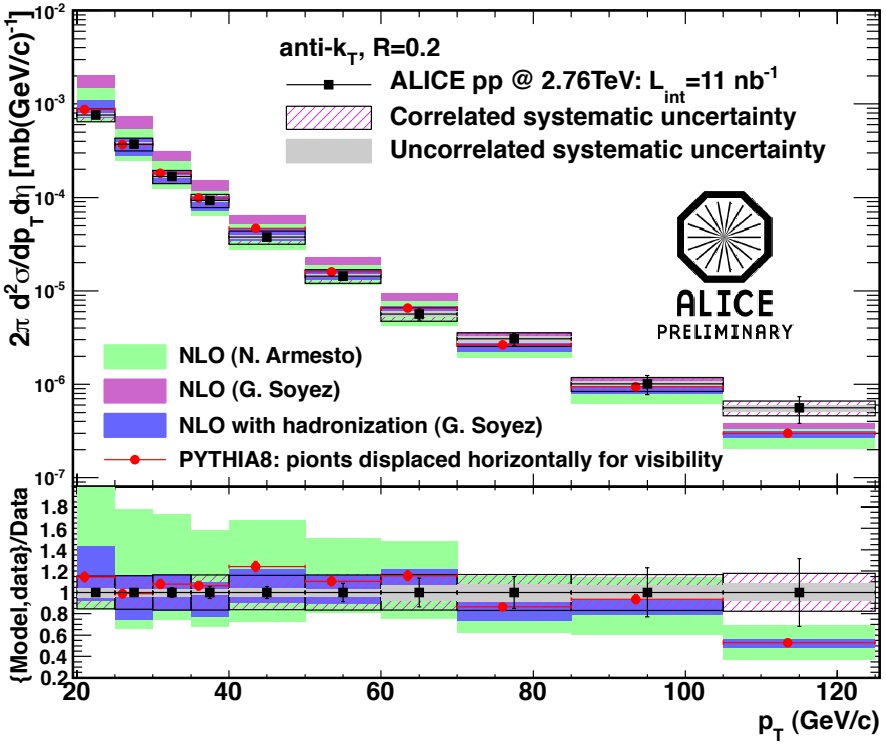
- Efficient charged particle tracking over wide $p_T$ range
- Highly granular EM calorimetry

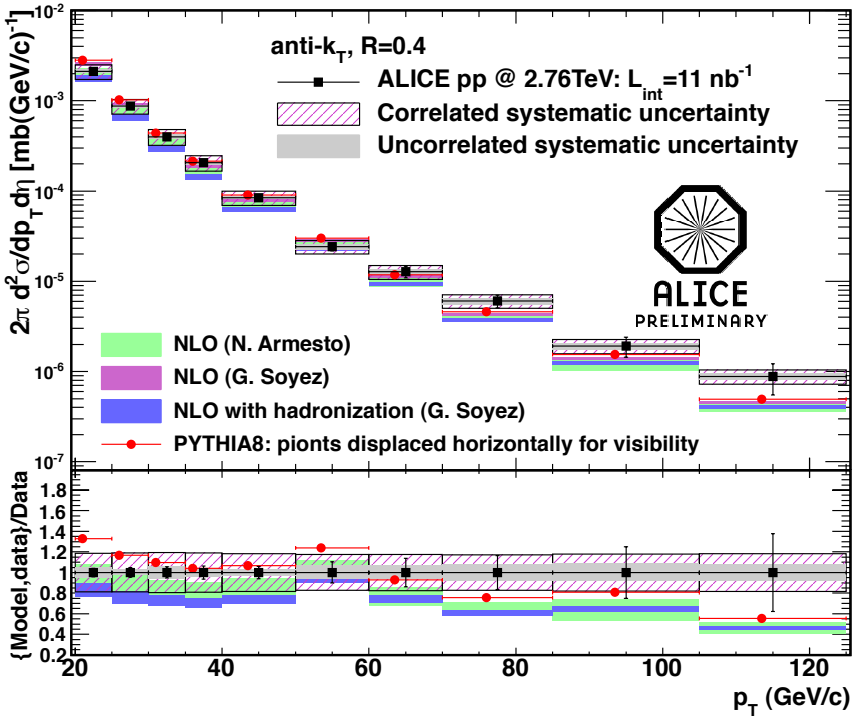
pp collisions: well controlled systematics

- Jet Energy Scale uncertainty ~4% at $p_T$=100 GeV/c
  ➔ ~20% cross section uncertainty

# pp at $\sqrt{s} = 2.76$ TeV: inclusive jet cross section

*Talk: R. Ma*



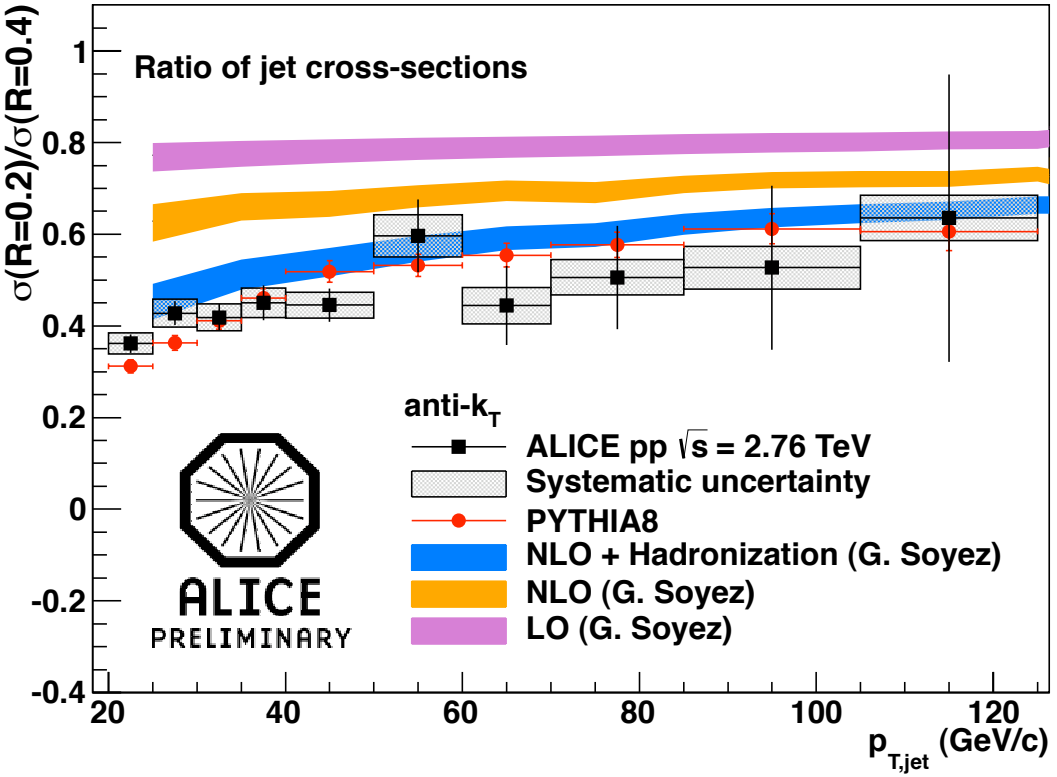




Agreement within uncertainties with NLO pQCD, PYTHIA8

# pp at $\sqrt{s}$ = 2.76 TeV: ratio of jet cross-sections R=0.2/R=0.4

*Talk: R. Ma*

## Probe of jet structure

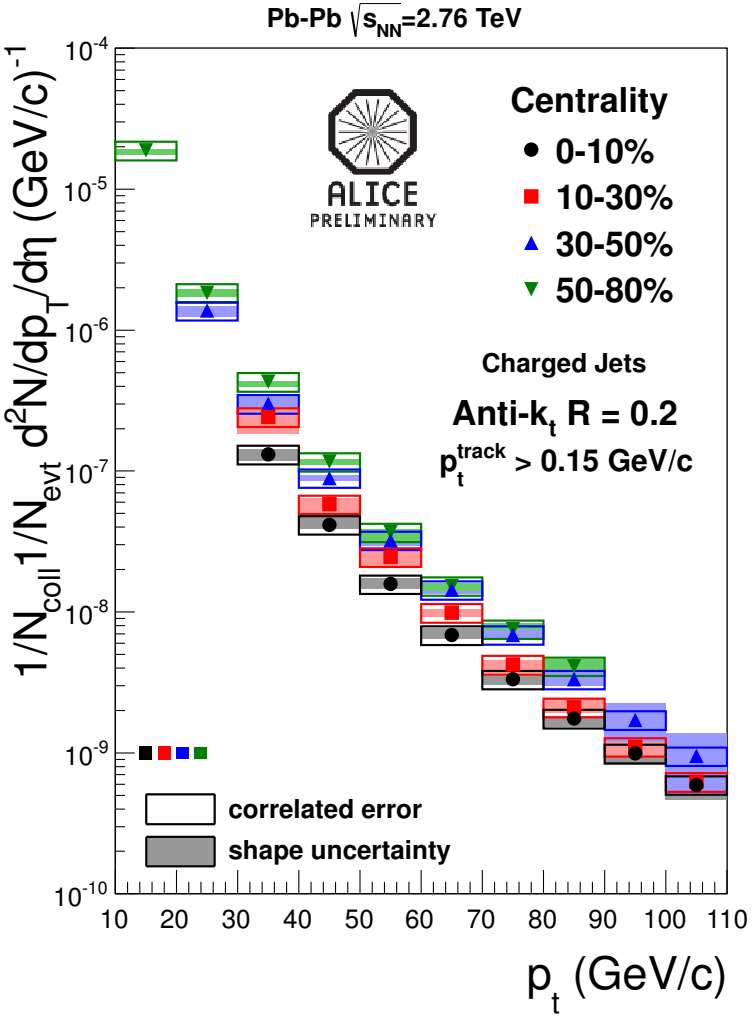


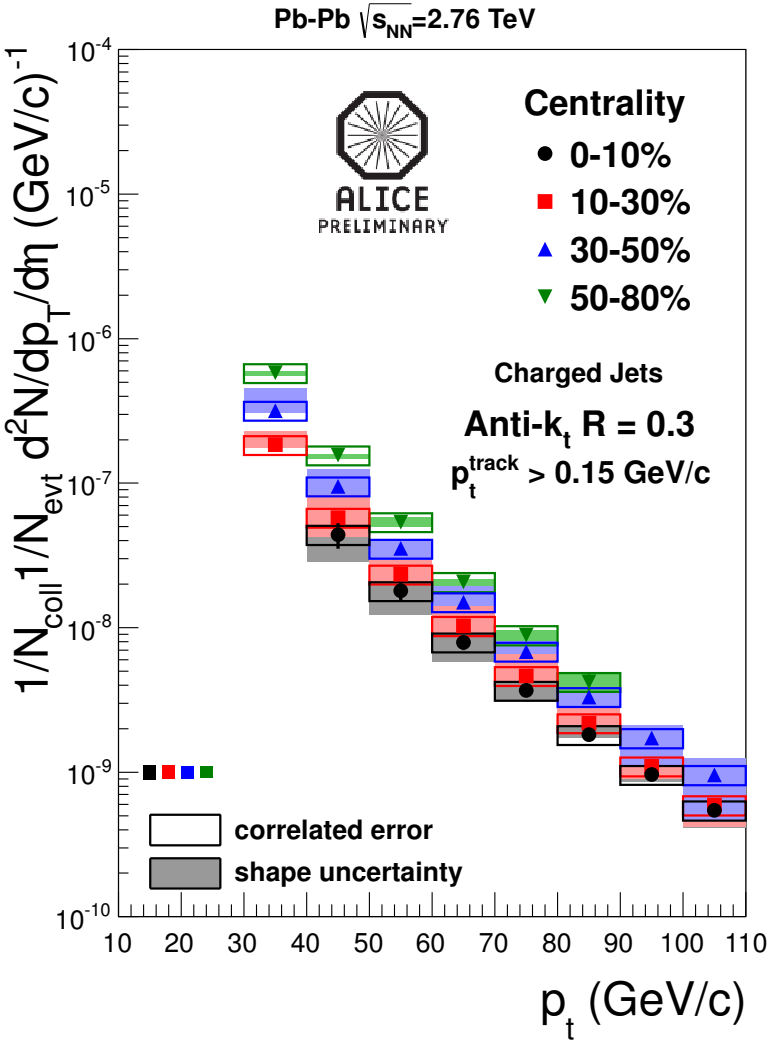

Soyez '12: direct calculation of ratio is effectively NNLO

Reasonable agreement with NLO+hadronization

# Charged Particle Jets in Pb+Pb

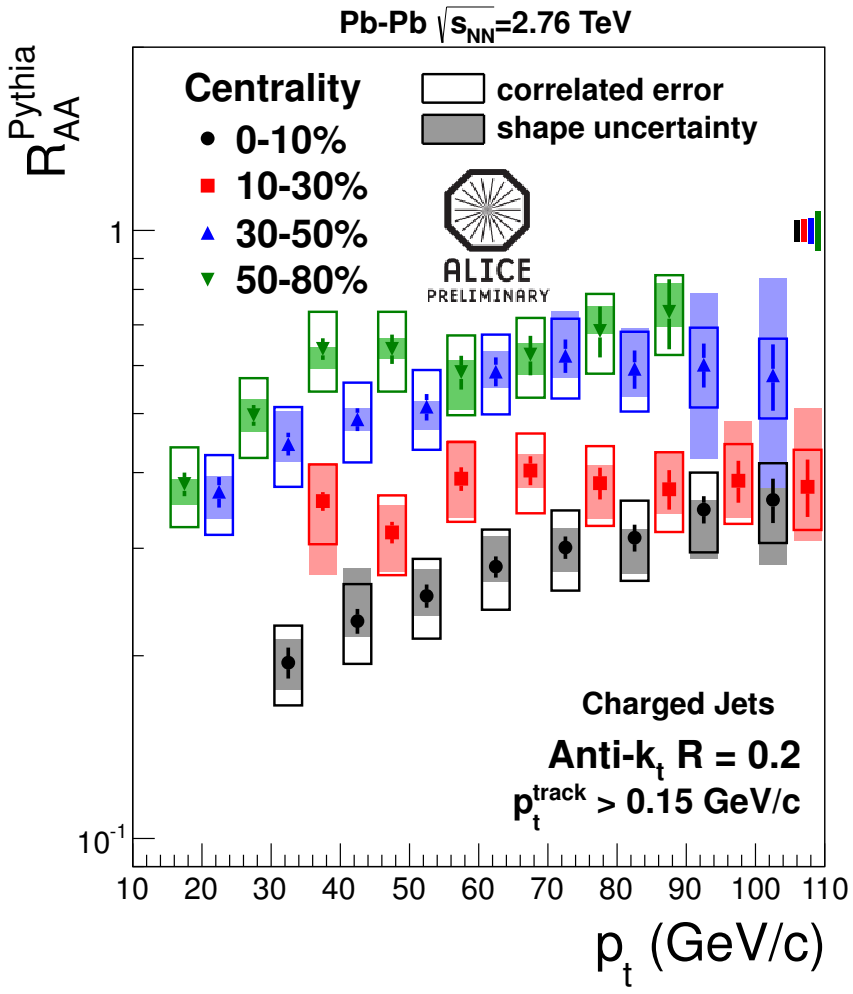
*Talk: M. Verweij*

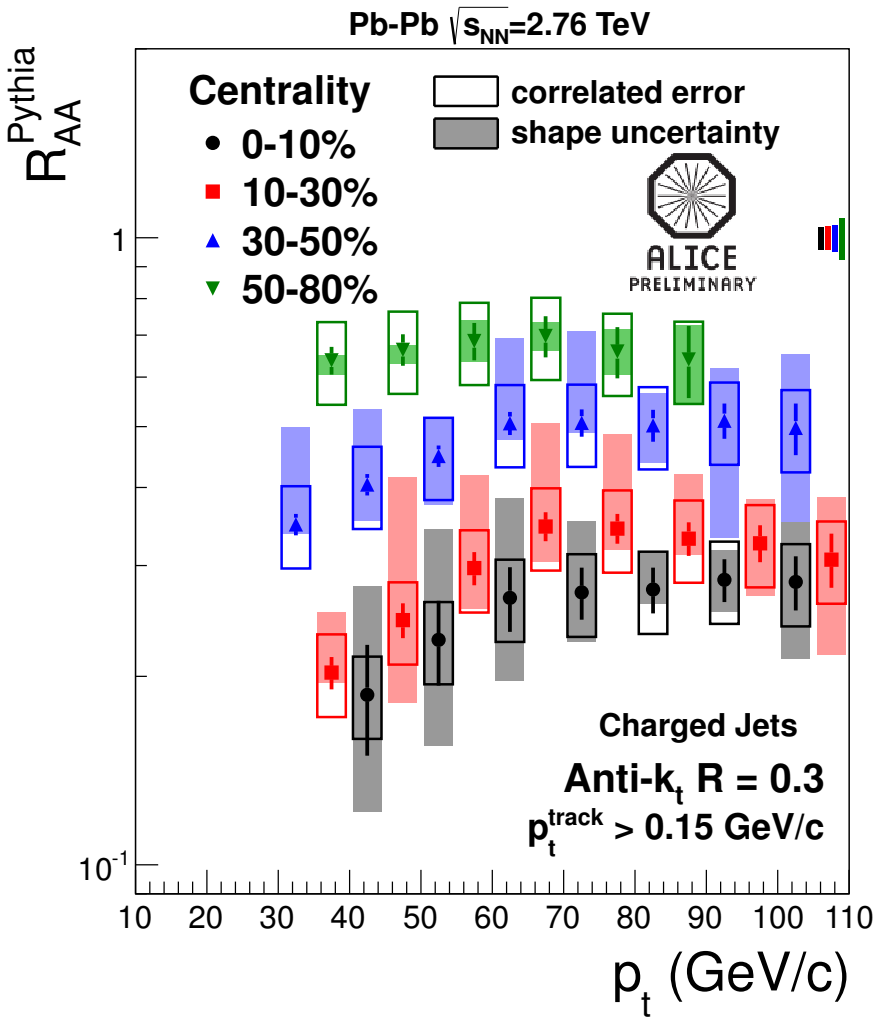


# Charged jet $R_{AA}$ (vs PYTHIA)

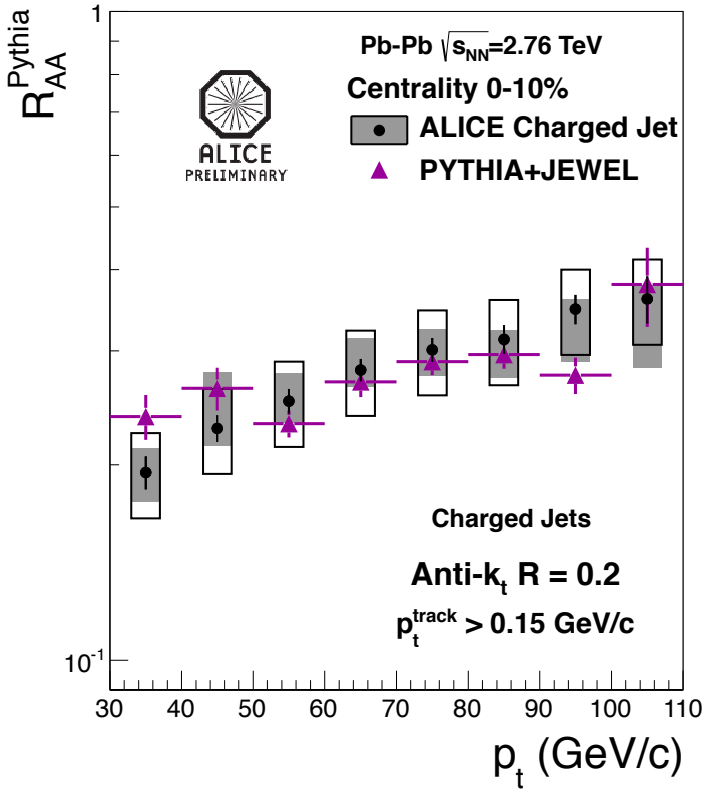
*Talk: M. Verweij*

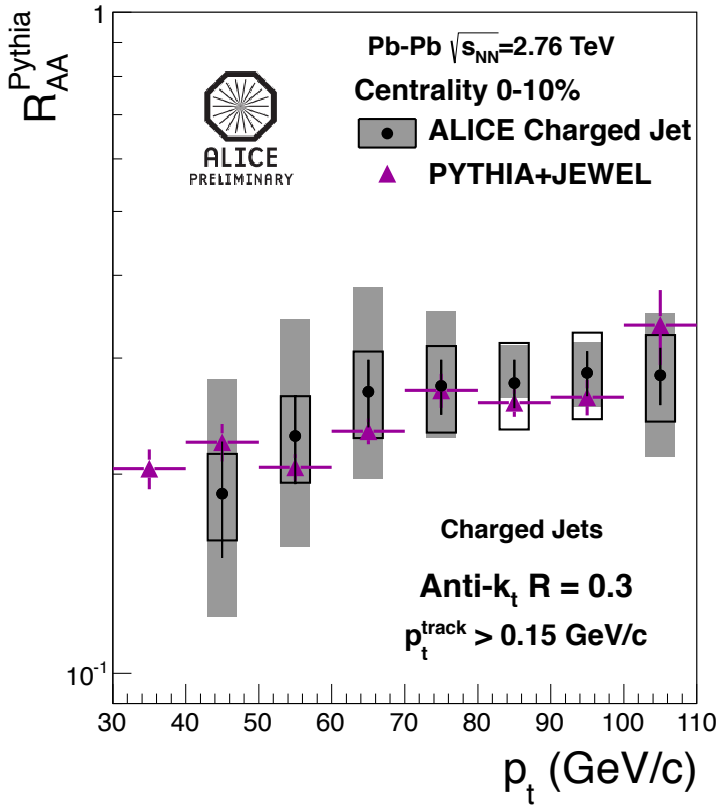


# Charged jet $R_{AA}$: compare to Jewel MC

*Talk: M. Verweij*




JEWELtuned on hadron $R_{AA}$
➔reproduces jet $R_{AA}$

# Energy loss scorecard

| | **Observables** | **Score** |
|---|---|---|
| Radiative++ E-loss | Charged hadron $R_{AA}$+$I_{AA}$ ; Charm $R_{AA}$+$v_2$; charged jet $R_{AA}$ | Compatible |
| In-medium high $p_T$ fragmentation | Identified particle ratios, $R_{AA}$ | No evidence |
| Color charge dependence | $R_{AA}$ ratio D/π | Maybe |
| Induced large-angle radiation | Di-hadron correlations: longitudinal but not azimuthal broadening | Maybe |
| Jet/bulk medium Coalescence | p/π ratio in jet-like peak; weak evolution of baryon/meson ratio vs RHIC | No evidence |
| Dead cone effect | $R_{AA}$ ratio D/π | No evidence for large effect |
| AdS/CFT | $R_{AA}$ ratio D/π | Unlikely? |

# Summary and Outlook

ALICE measures a wide array of observables to probe the mechanisms underlying partonic energy loss

- Unique capabilities for particle identification and low $p_T$ charm measurements
- We can begin to exclude models or concepts based on current results

Consistent picture thus far: radiative+elastic energy loss followed by fragmentation in vacuum

More discriminating measurements to come, especially:

- Correlations
- Charm
- Jets