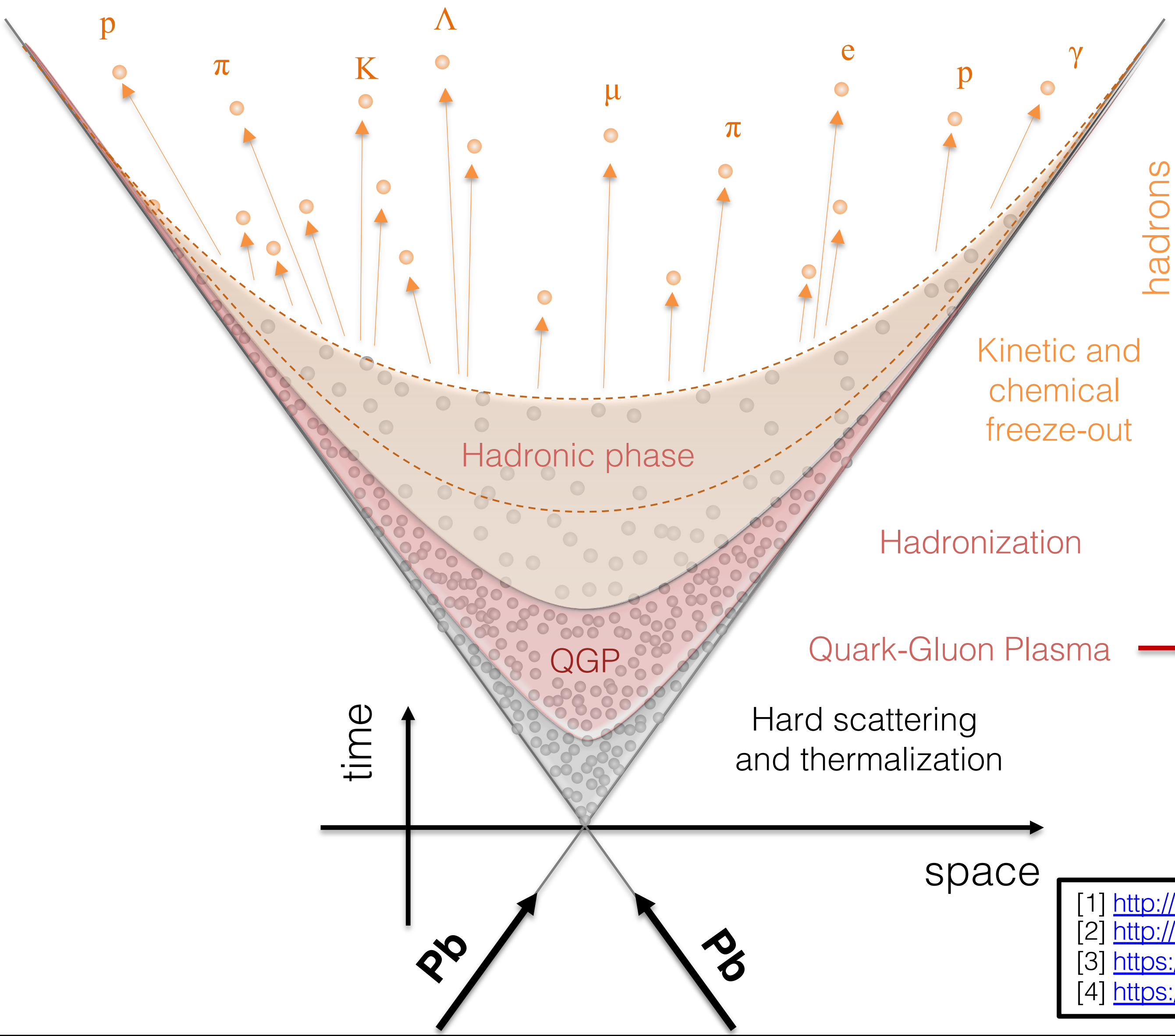
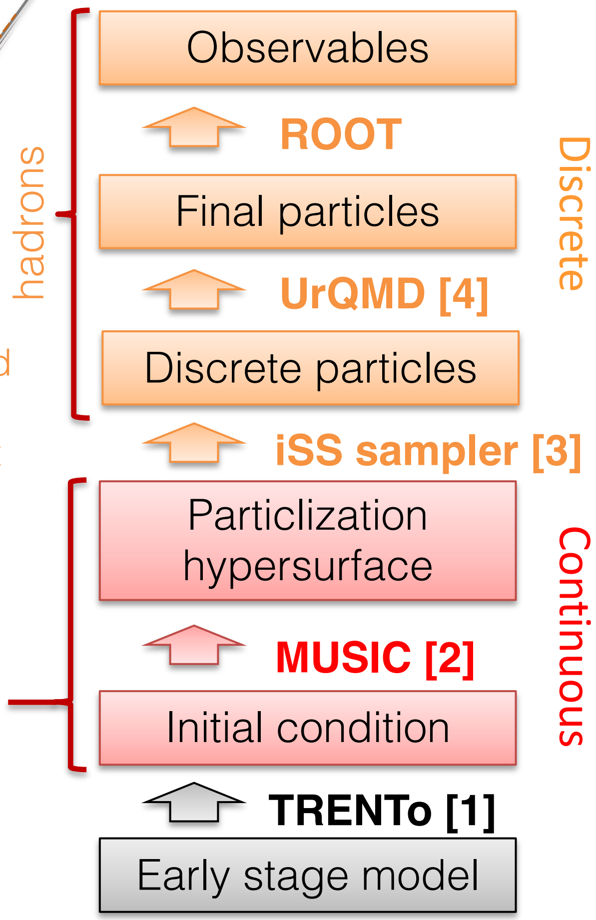
Other hybrid models:
PYTHIA Angantyr + UrQMD

Schematic representation of

A heavy ion collision

(from the MADAI collaboration)

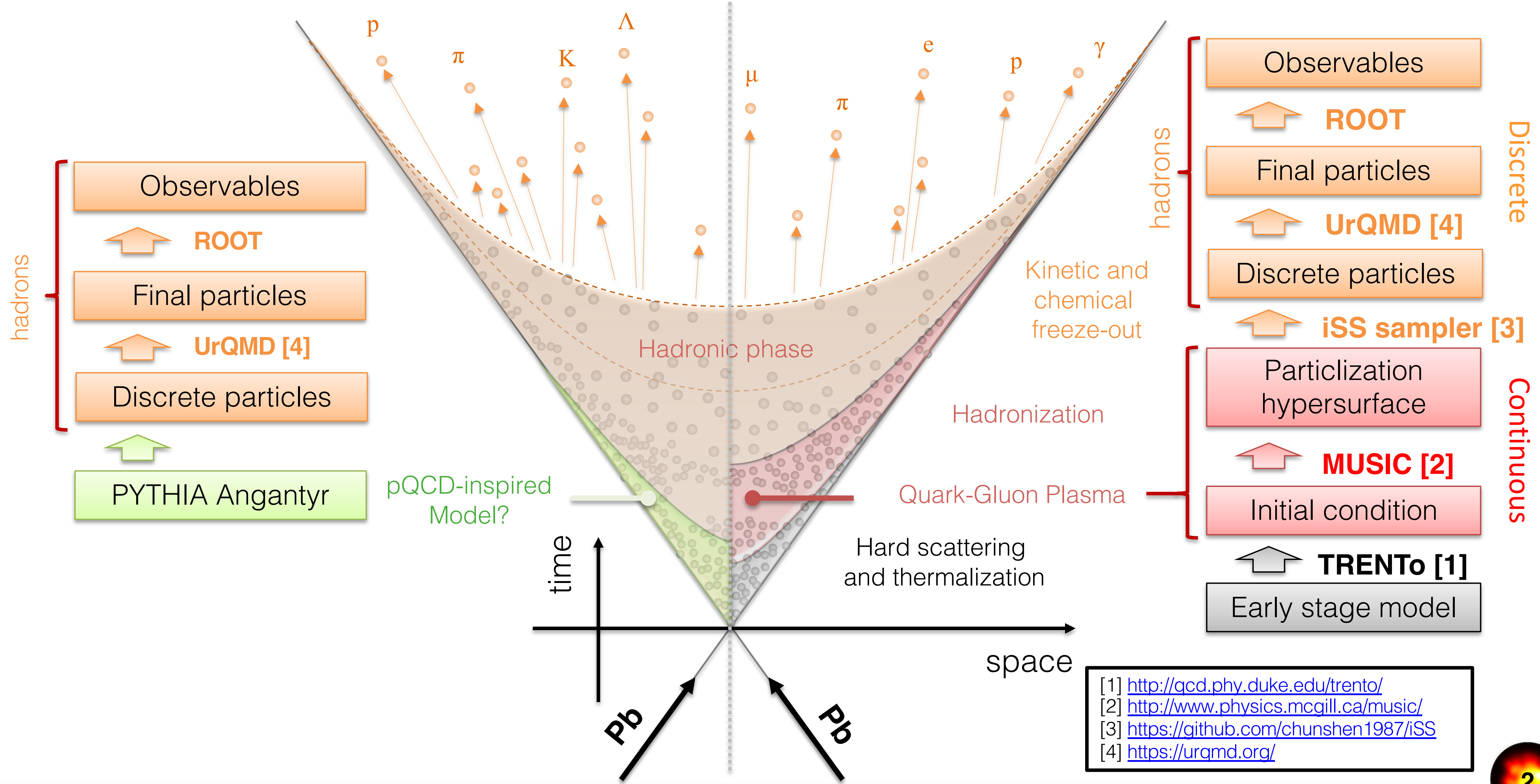




[1] http://qcd.phy.duke.edu/trento/
[2] http://www.physics.mcgill.ca/music/
[3] https://github.com/chunshen1987/iSS
[4] https://urqmd.org/

Schematic representation of

A heavy ion collision



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Schematic representation of

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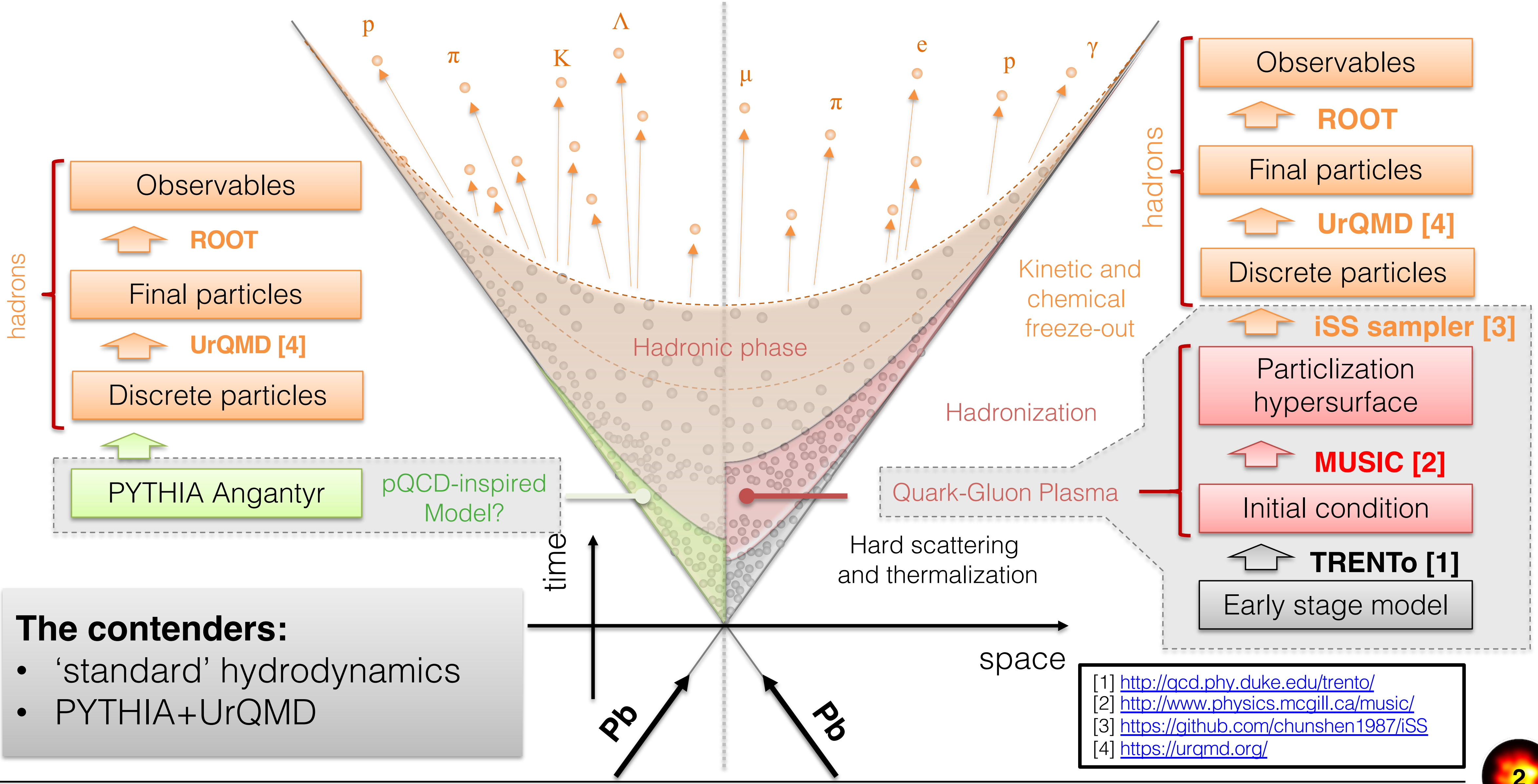

The contenders:

- ‘standard’ hydrodynamics
- PYTHIA+UrQMD

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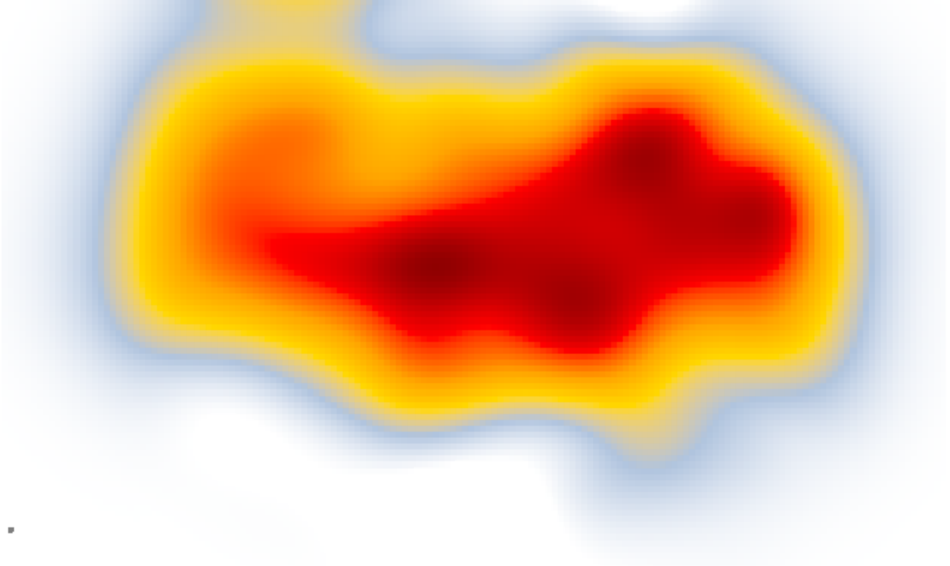
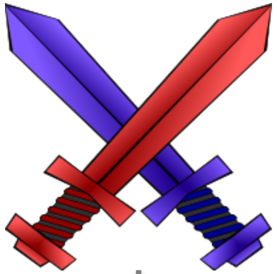
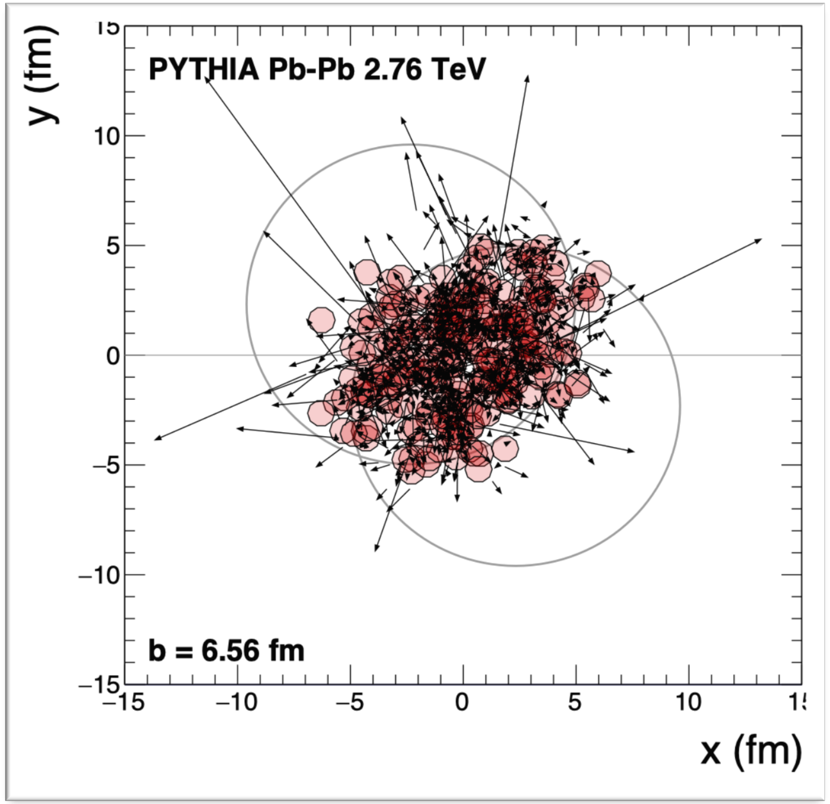






Hydrodynamics

This work: TRENTo + MUSIC + iSS + UrQMD (parametetrs by the Duke group [1])

We utilize these parameters but with a different overall normalization

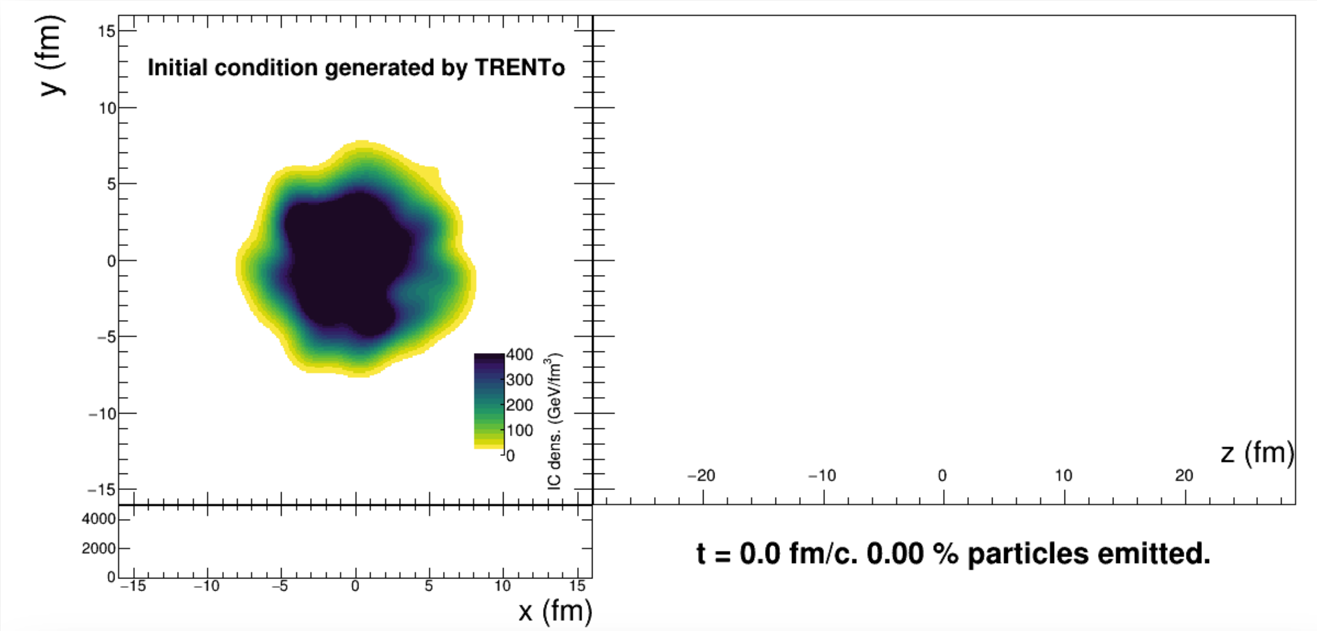
Minor differences in the two approaches under study

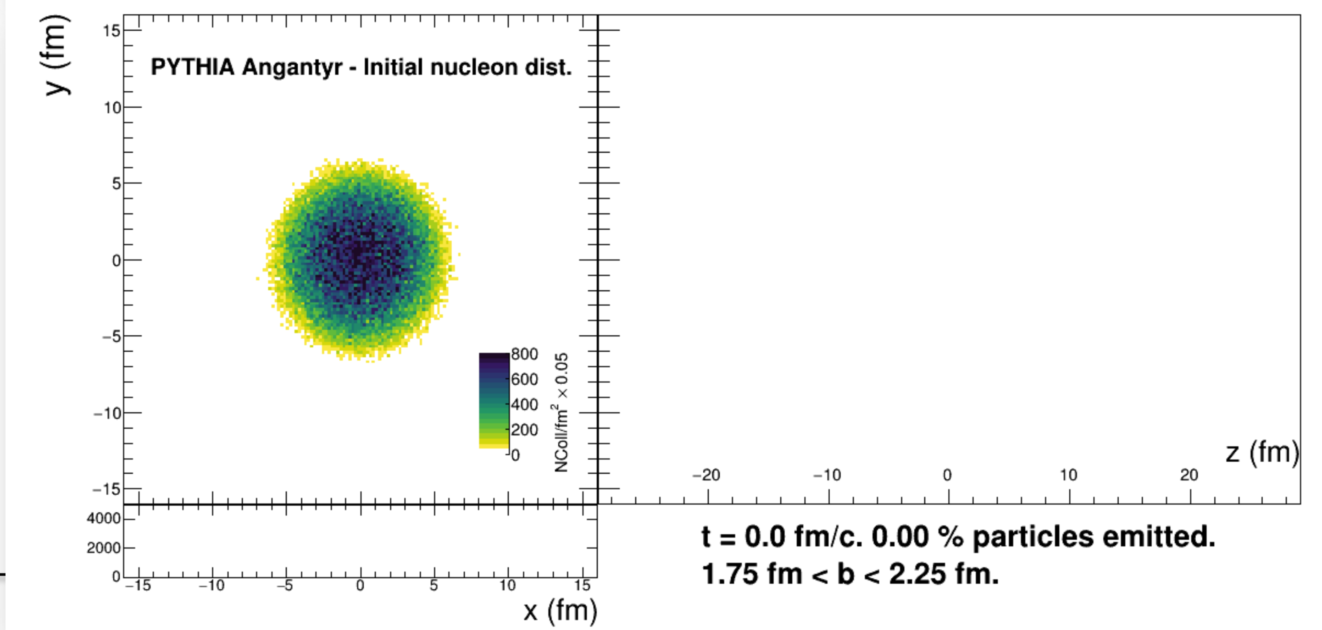
[1] Nuc.Phys.A, 967 (67-73)

PYTHIA+UrQMD

- This work: PYTHIA Angantyr + UrQMD
- Custom PYTHIA Angantyr with hadron vertex model implementation (C. Bierlich) to allow for direct coupling to UrQMD

Hadron production vs time in the two cases





Hydrodynamics
Particlization

- Thin surface
- Emissions lasts longer

PYTHIA Angantyr
Hadron vertex mod.

- Emission over volume
- Shorter emission time

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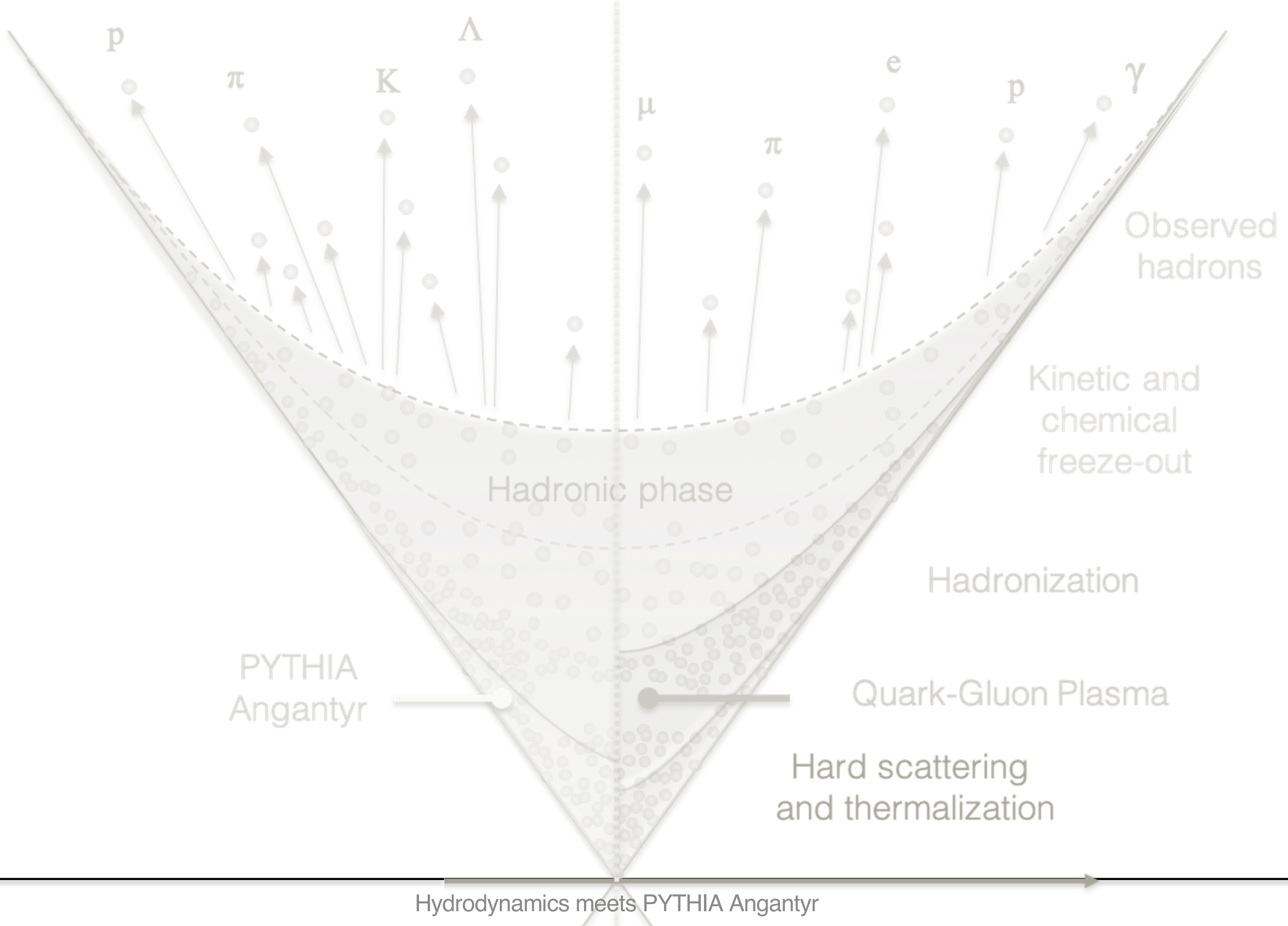
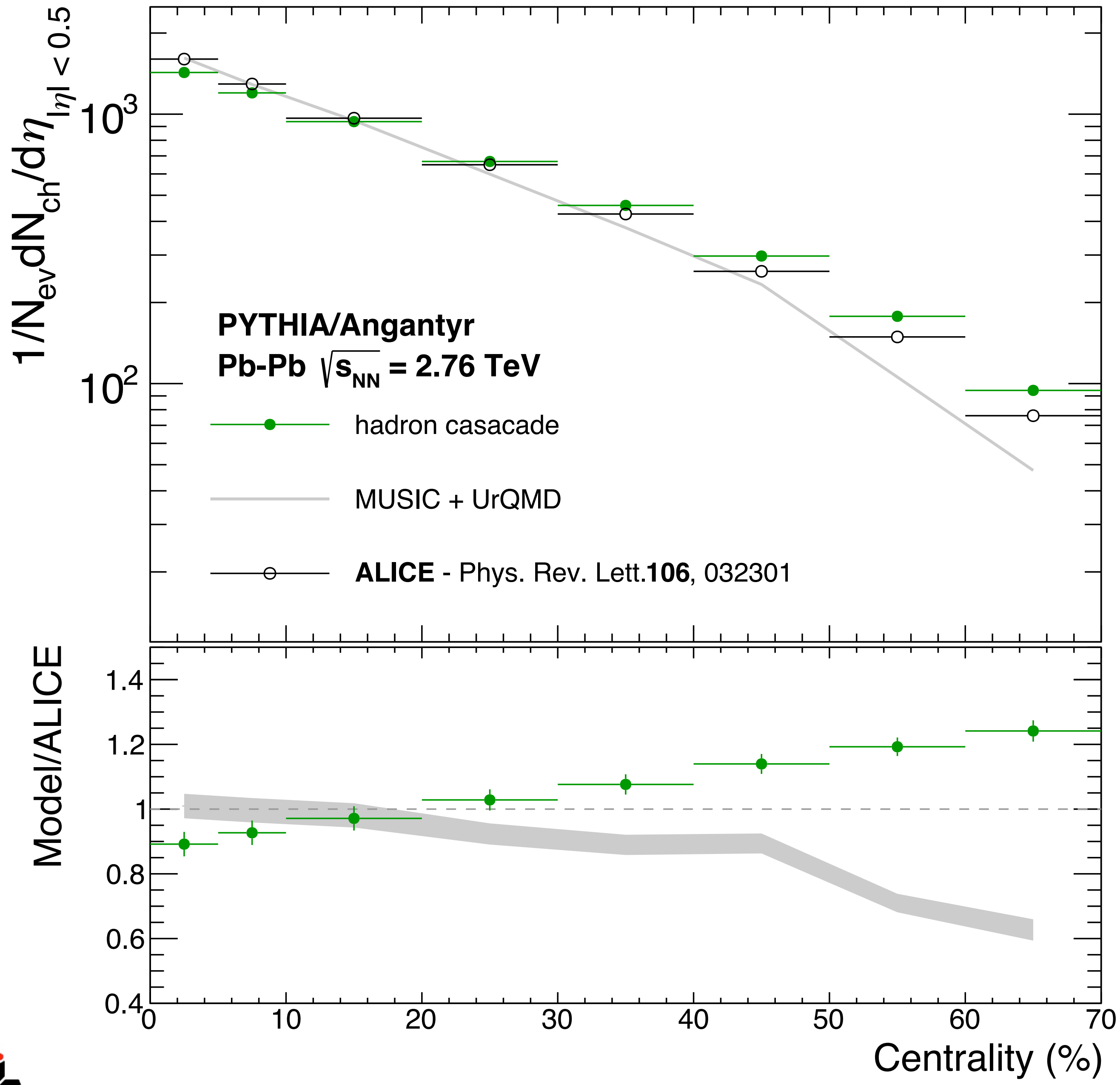
Final-state observables





The basics: multiplicity

PYTHIA: reproduction within ~10% for 0-40%

Hydrodynamics: tuned to reproduce central, good (~10%) in 0-50%

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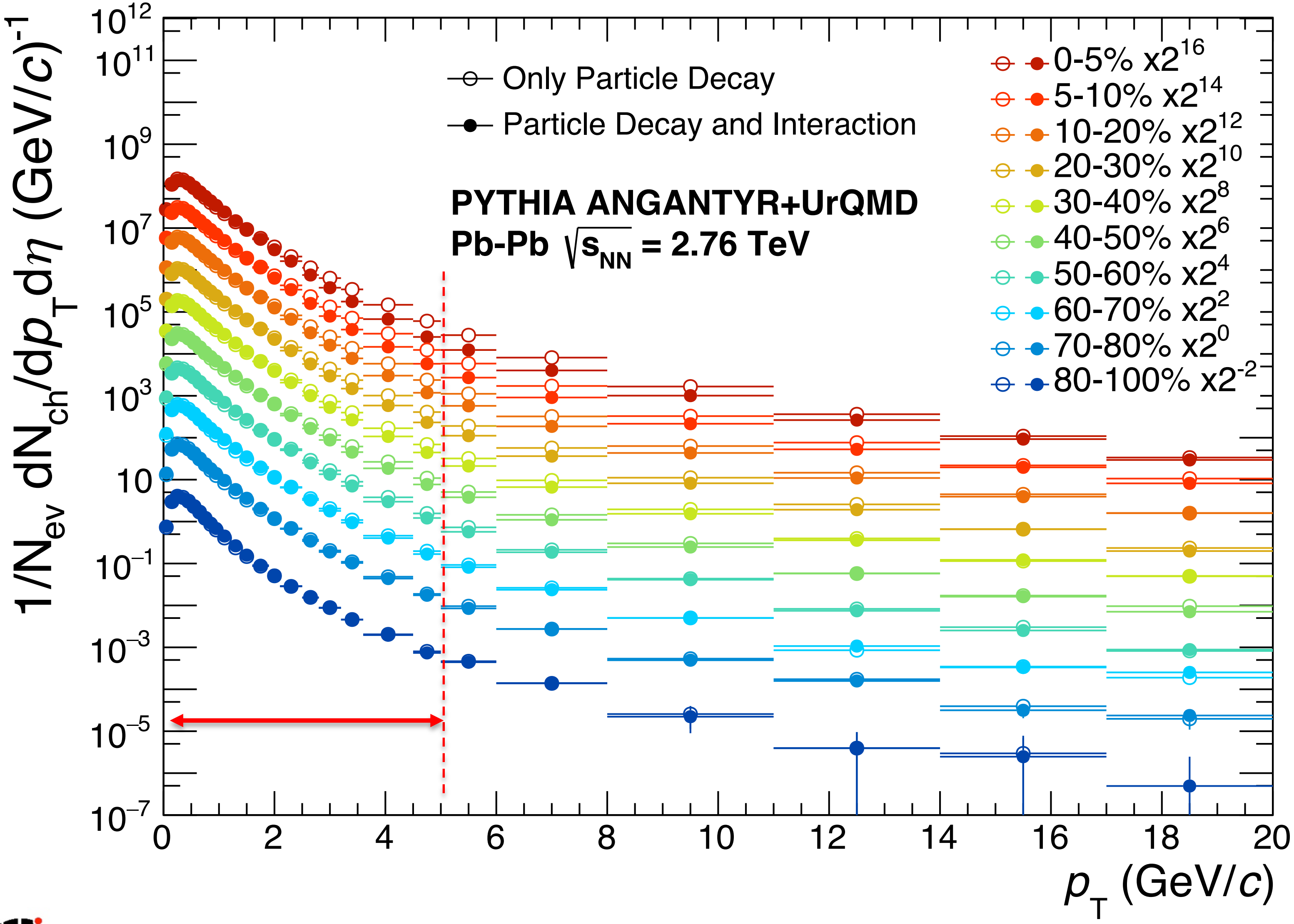
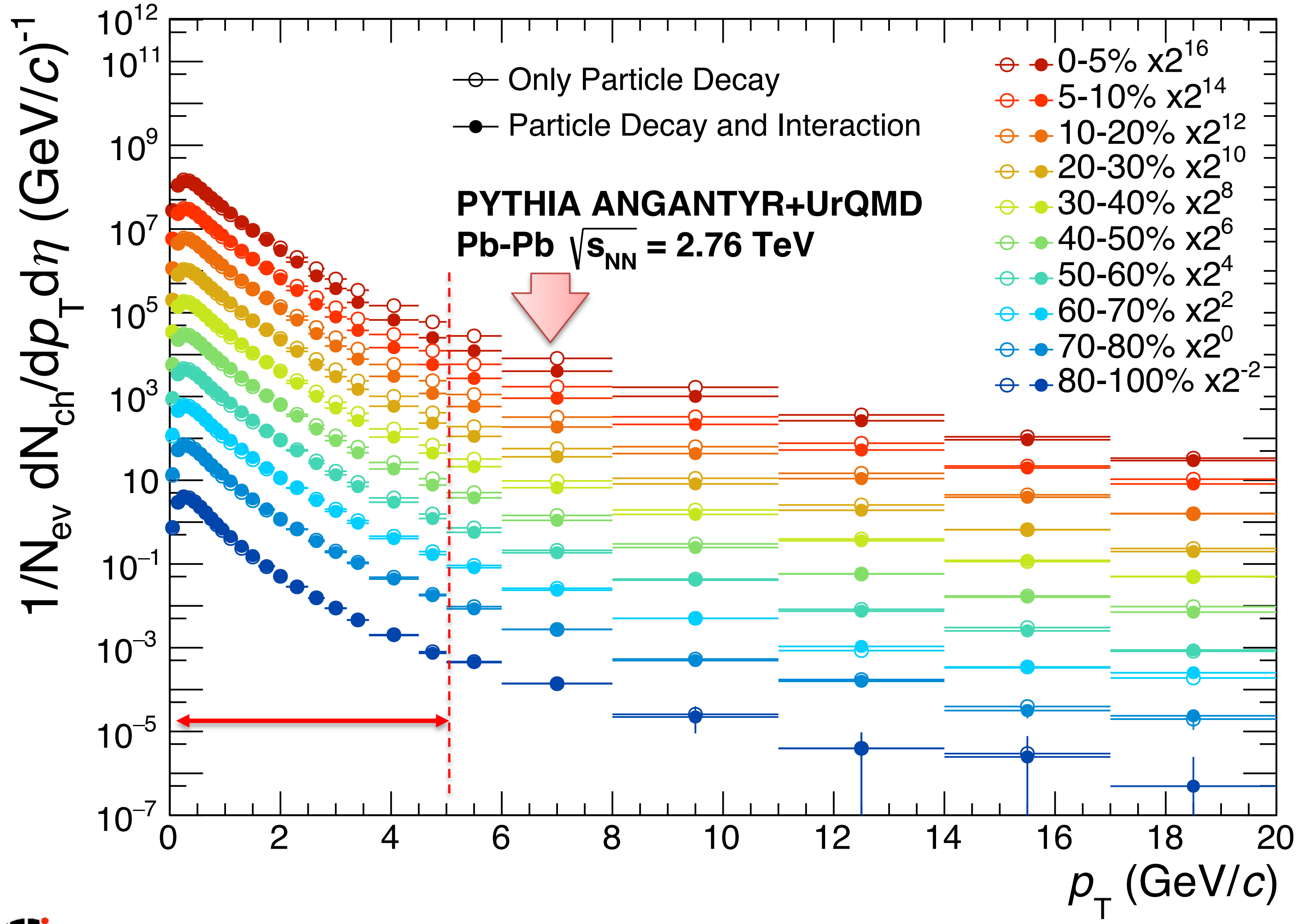
Transverse momentum spectra: PYTHIA+UrQMD



Unique to PYTHIA+UrQMD

- Hydrodynamics sampling usually goes to 3-5 GeV/*c*
- Our simulations: 4.5 GeV/*c*
- PYTHIA: goes far…

Transverse momentum spectra: PYTHIA+UrQMD



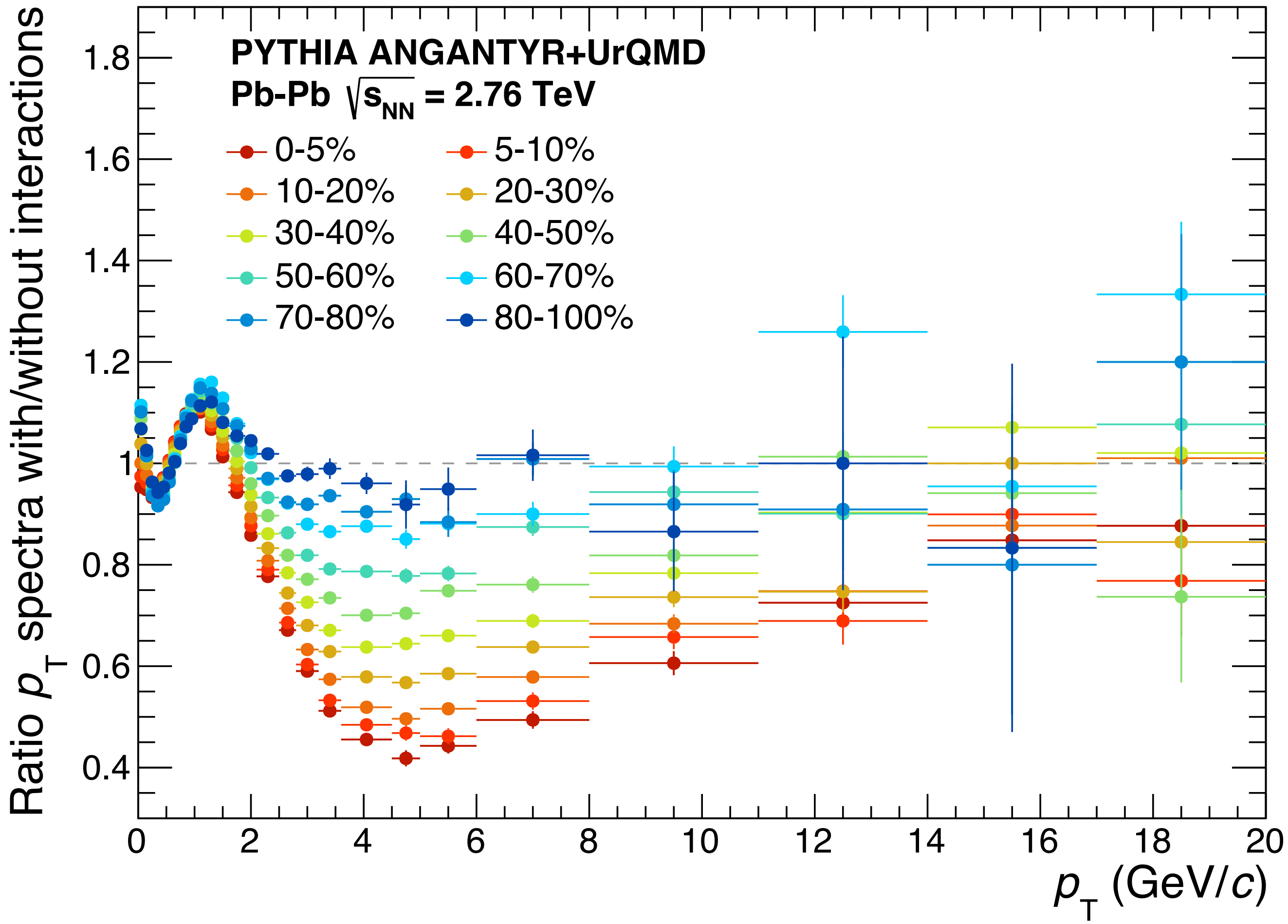
Unique to PYTHIA+UrQMD

- Hydrodynamics sampling usually goes to 3-5 GeV/c
- Our simulations: 4.5 GeV/c
- PYTHIA: goes far…

Enabling hadronic interactions:

- Suppression at high p_T?

Transverse momentum spectra modification



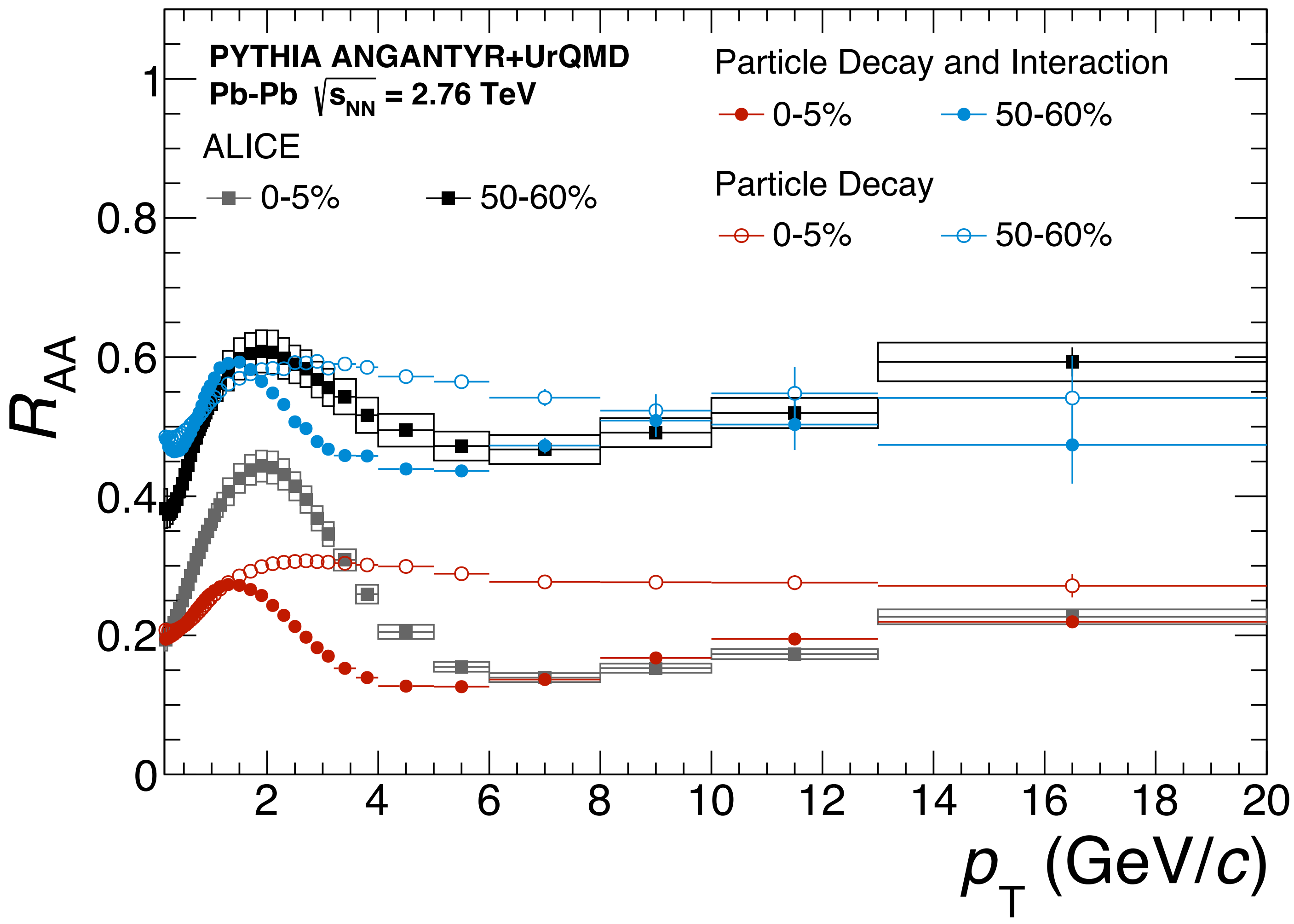
Low p_T:

- Small radial-flow-like boost

Mid- and high p_T:

- Up to 60% suppression at 5 GeV/c
- High-p_T particles stopped by low-p_T
- Effect progressively smaller at high p_T

Nuclear modification factor R_{AA}



$$R_{AA} = \frac{dN^{AA}/dp_T}{N_{coll}\, dN^{pp}/dp_T}$$

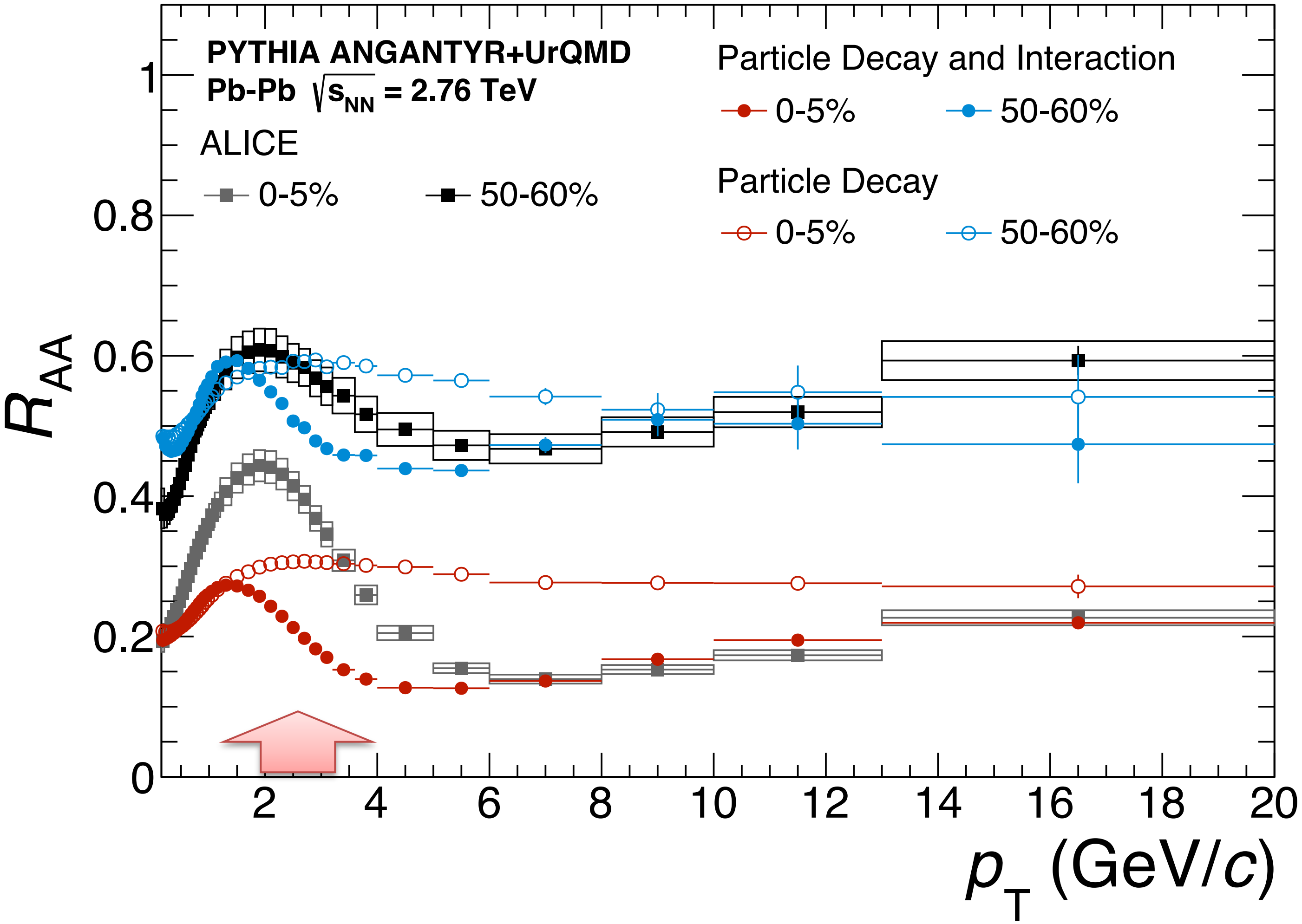
RAA calculation:

- pp reference: PYTHIA Angantyr
- N_{coll}: from ALICE (Glauber Model)

Without hadronic interactions:

- R_{AA} below unity -> PYTHIA Angantyr violates binary scaling

Nuclear modification factor R_{AA}



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Low p_T:

- Data not described: radial flow missing?

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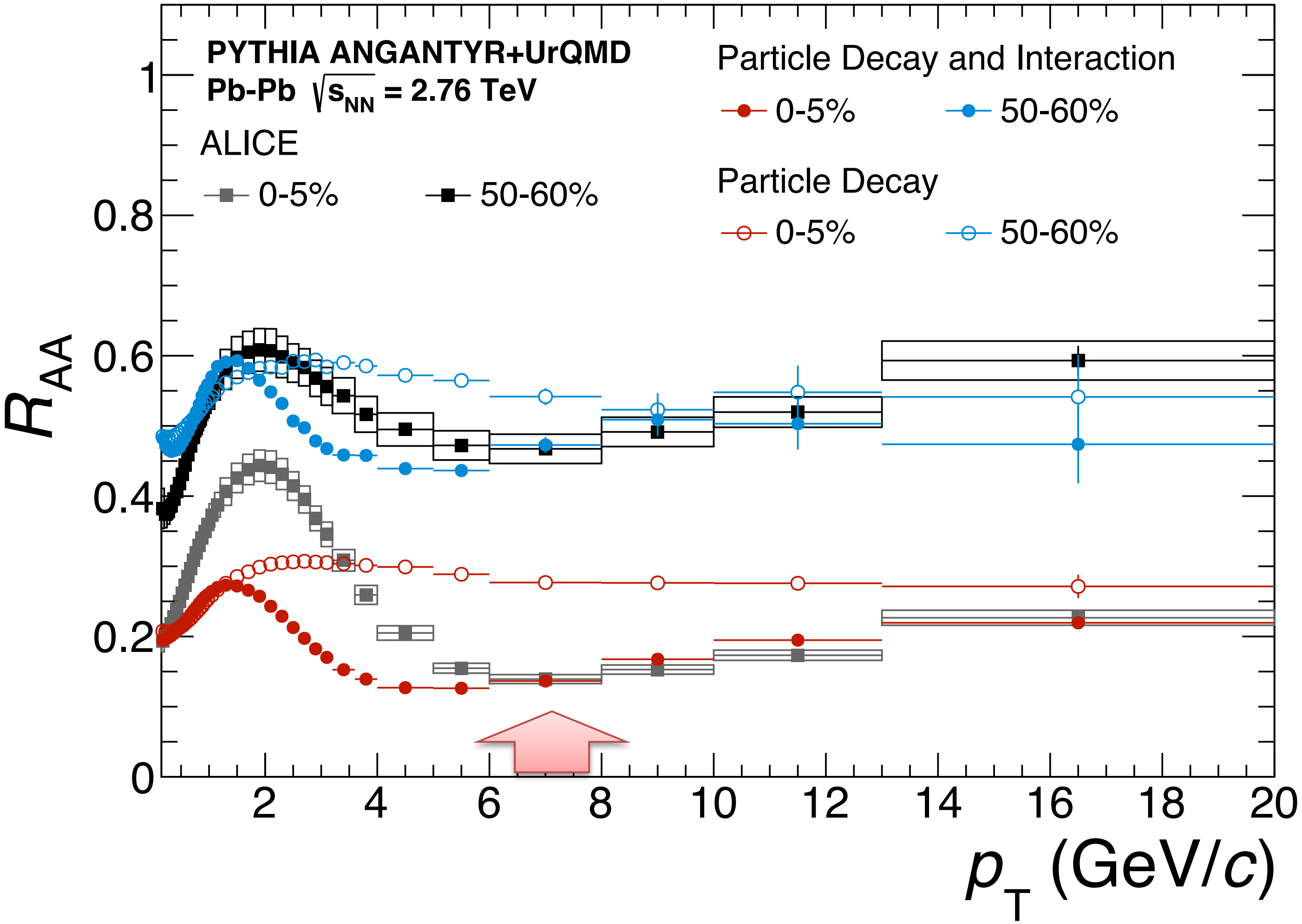

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RAA calculation:

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- N_{coll}: from ALICE (Glauber Model)

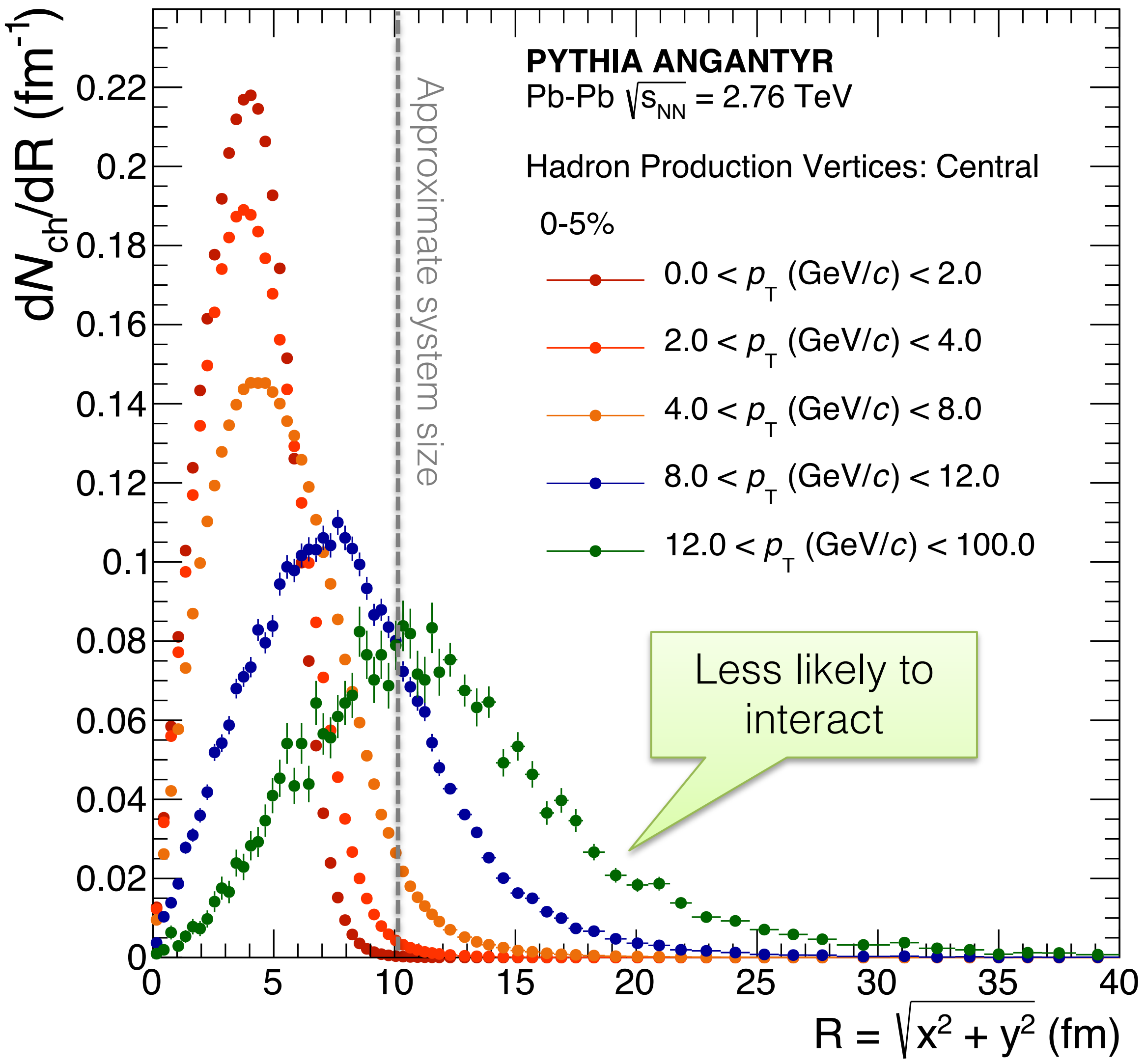
Low p_T:

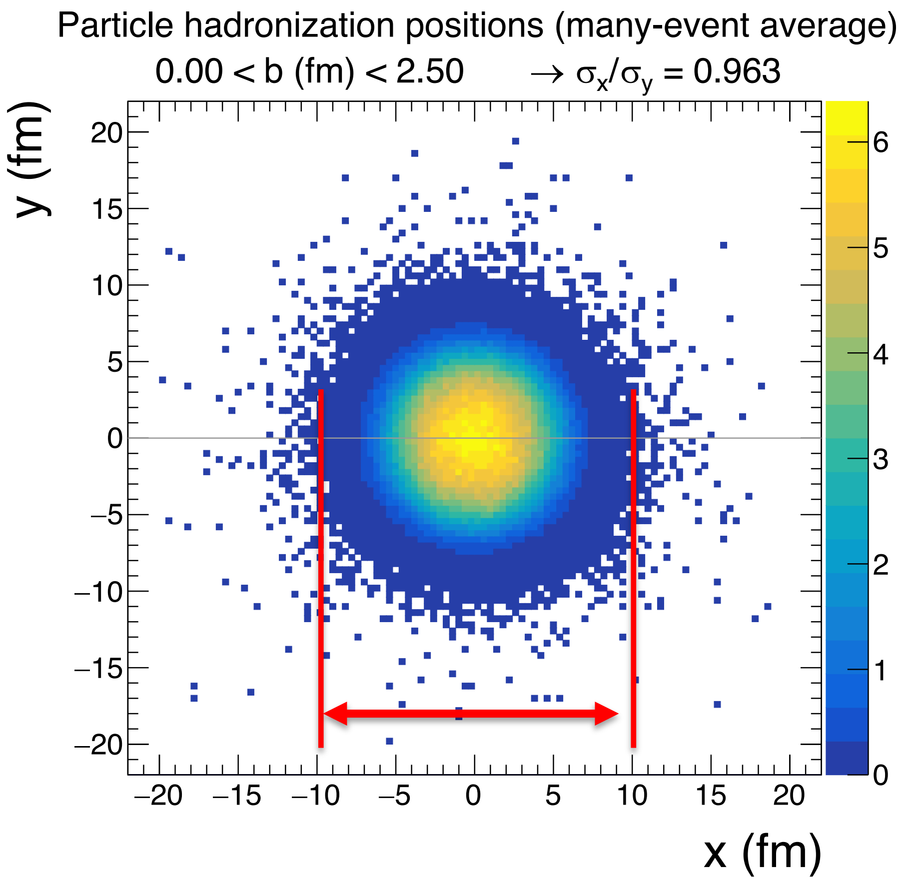
- Data not described: radial flow missing?

Mid- and high p_T:

- Maximum suppression at ~5 GeV/c
- Tends towards no-interactions value at higher momenta

High-p_T particle positions at hadronization





- Position ∝ momentum
- System size (central): x ≅ 10 fm

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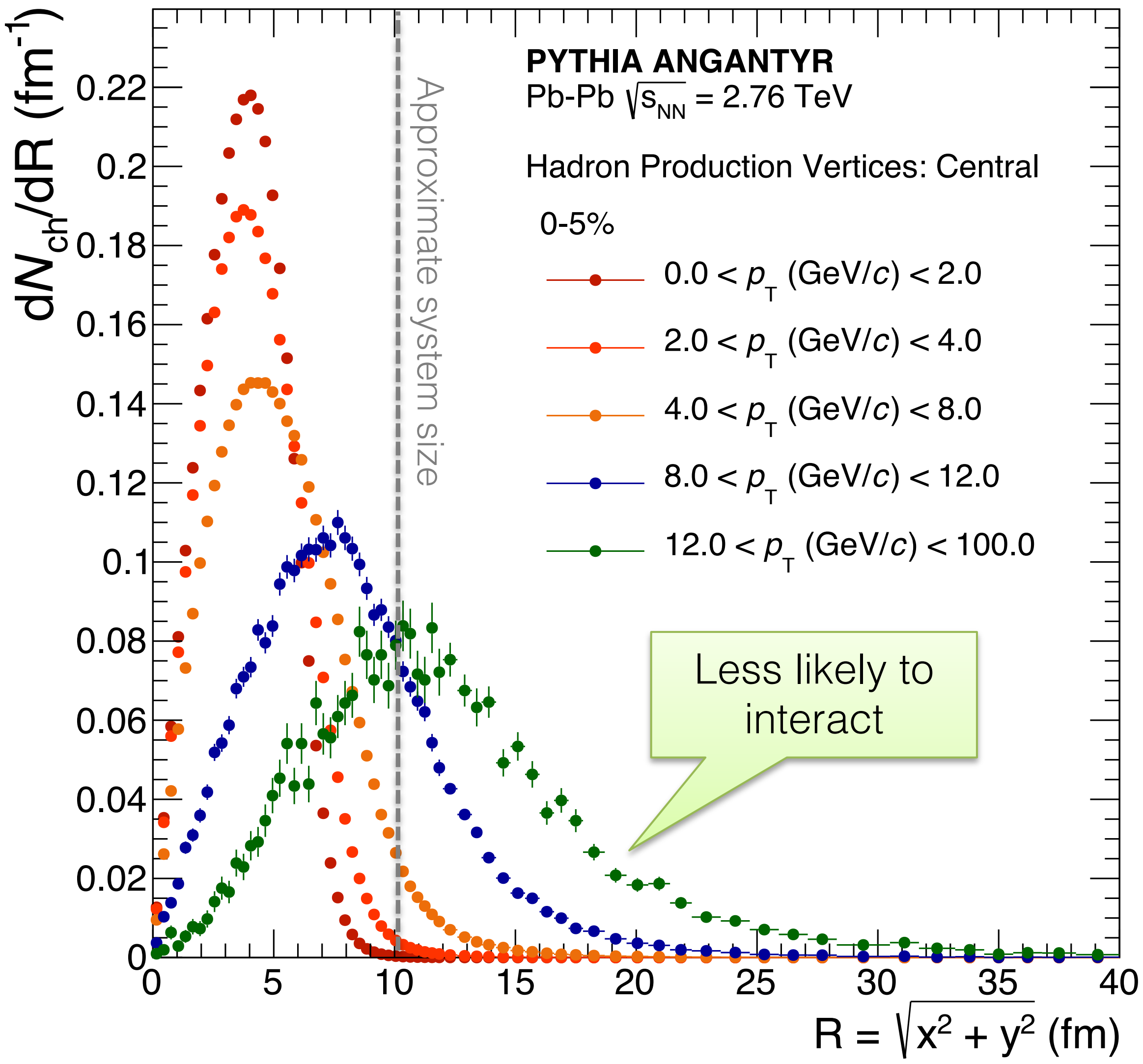
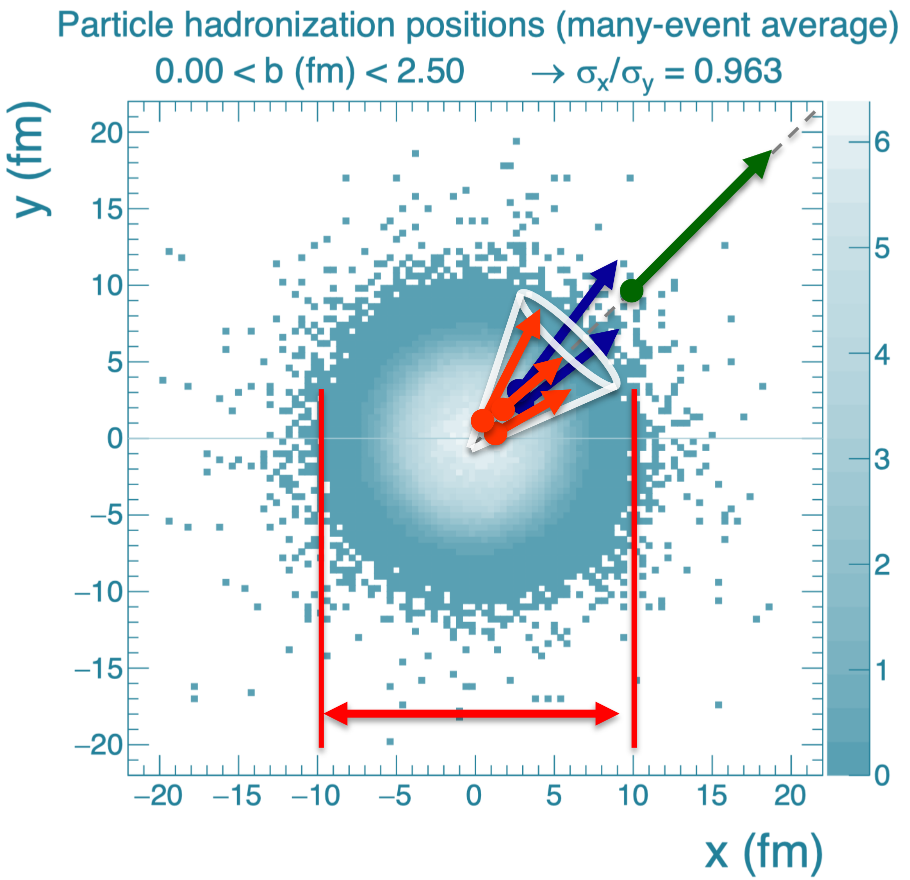
High-p_T particle positions at hadronization





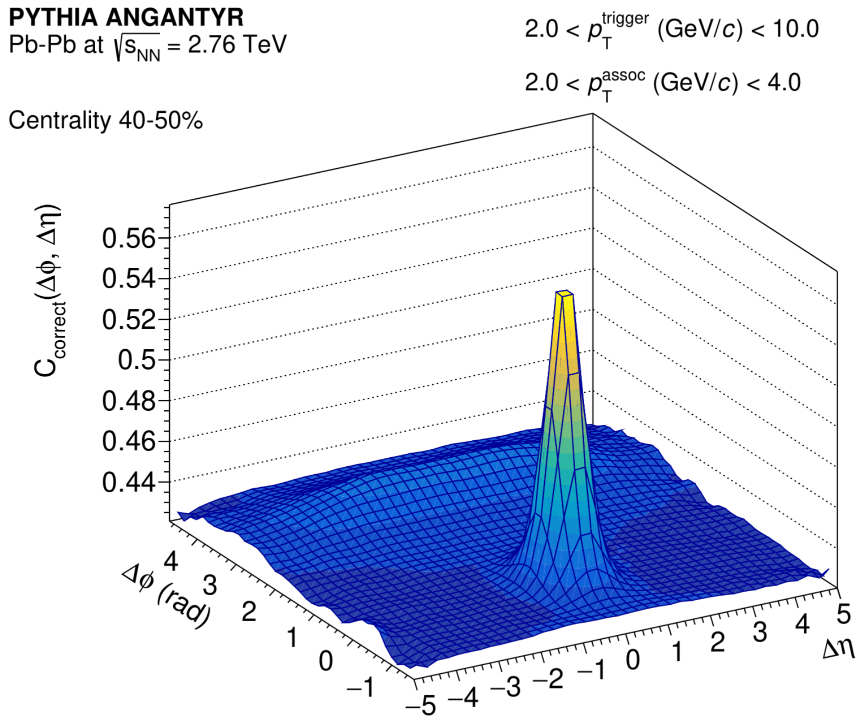
- Position ∝ momentum
- System size (central): x ≅ 10 fm

Two-particle correlation study: homing in on the suppression

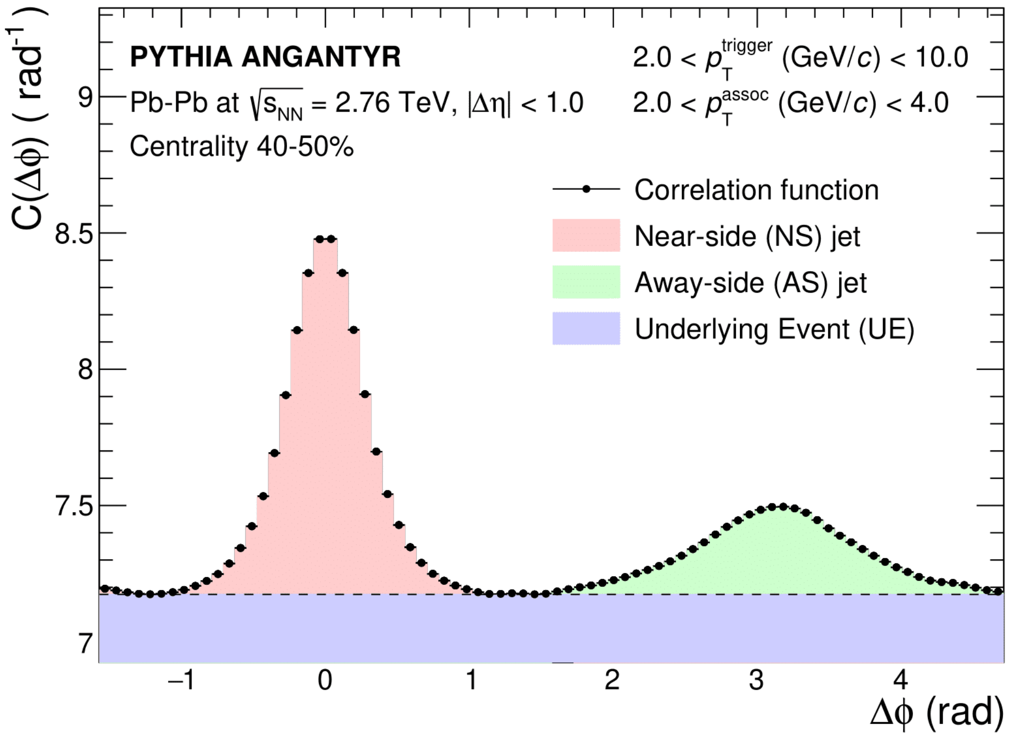
$$C(\Delta\phi, \Delta\eta) = C_{correct}(\Delta\phi, \Delta\eta) - C_{bkg}(\Delta\phi, \Delta\eta)$$

$$C_{correct}(\Delta\phi, \Delta\eta) = \frac{C_{same}(\Delta\phi, \Delta\eta)}{\alpha \times C_{mix}(\Delta\phi, \Delta\eta)}$$

$$C_{bkg}(\Delta\phi, \Delta\eta) = \frac{\beta \times C_{mix}^{aligned\ \ EP}(\Delta\phi, \Delta\eta)}{\alpha \times C_{mix}(\Delta\phi, \Delta\eta)}$$

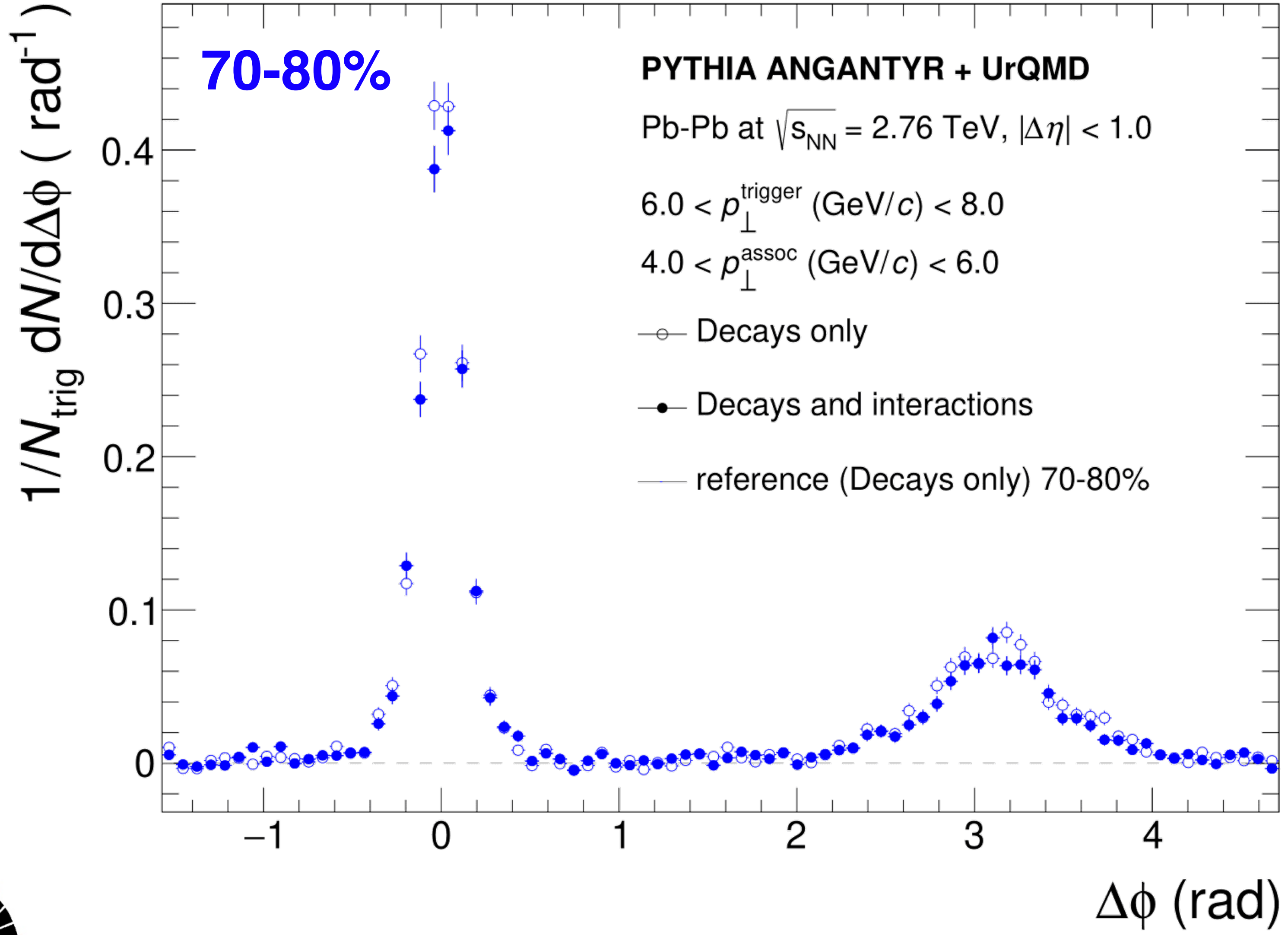


Δφ projection



Two-particle correlations in 70-80%

With and without hadronic interactions

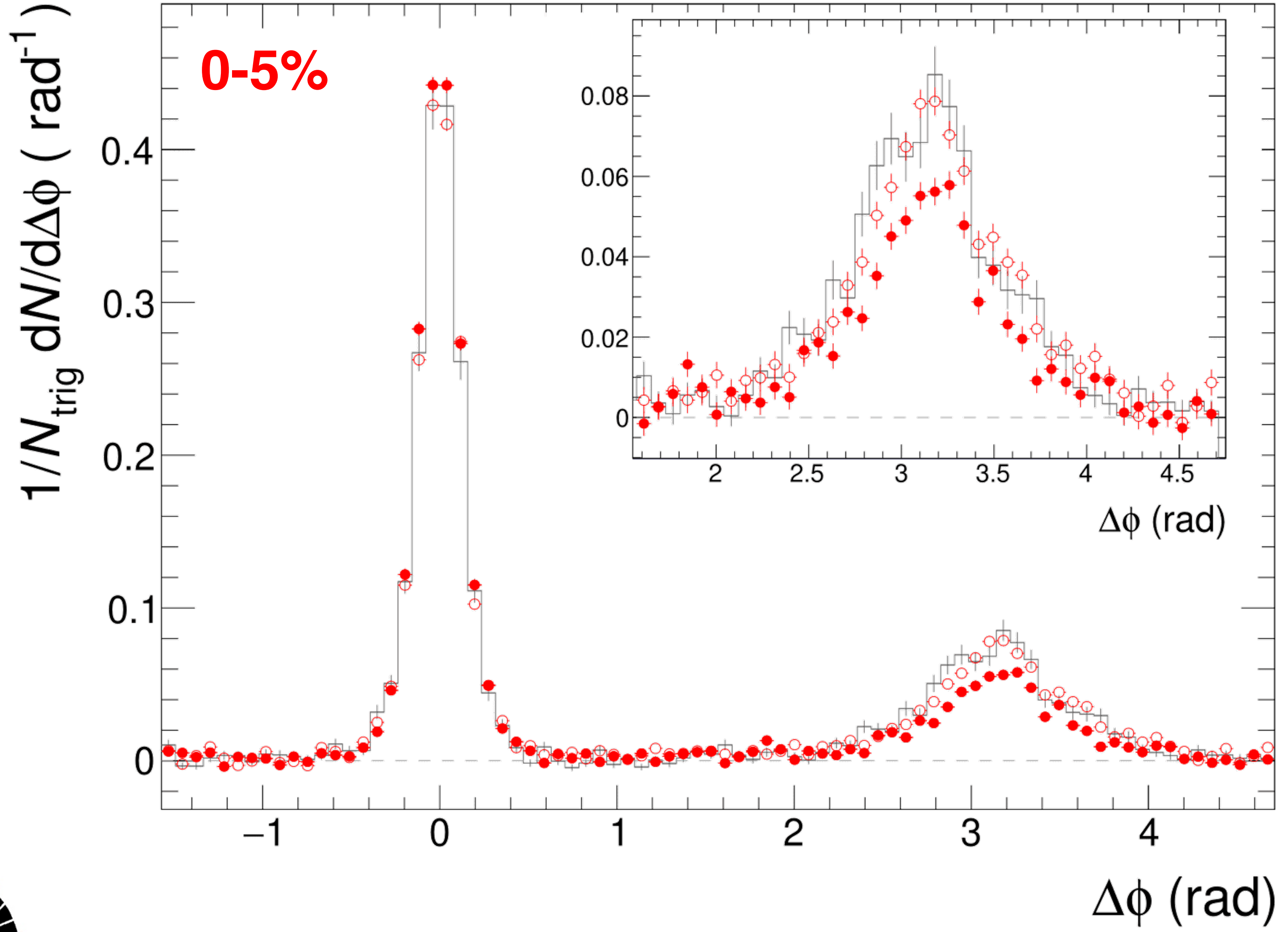


Peripheral collisions: Near-side and away-side not affected by the hadronic interactions in peripheral collisions

Background subtracted

Two-particle correlations in 0-5%

With and without hadronic interactions



Central collisions: visible suppression

Near-side is not affected!

Magnitude of suppression versus centrality?

Background subtracted

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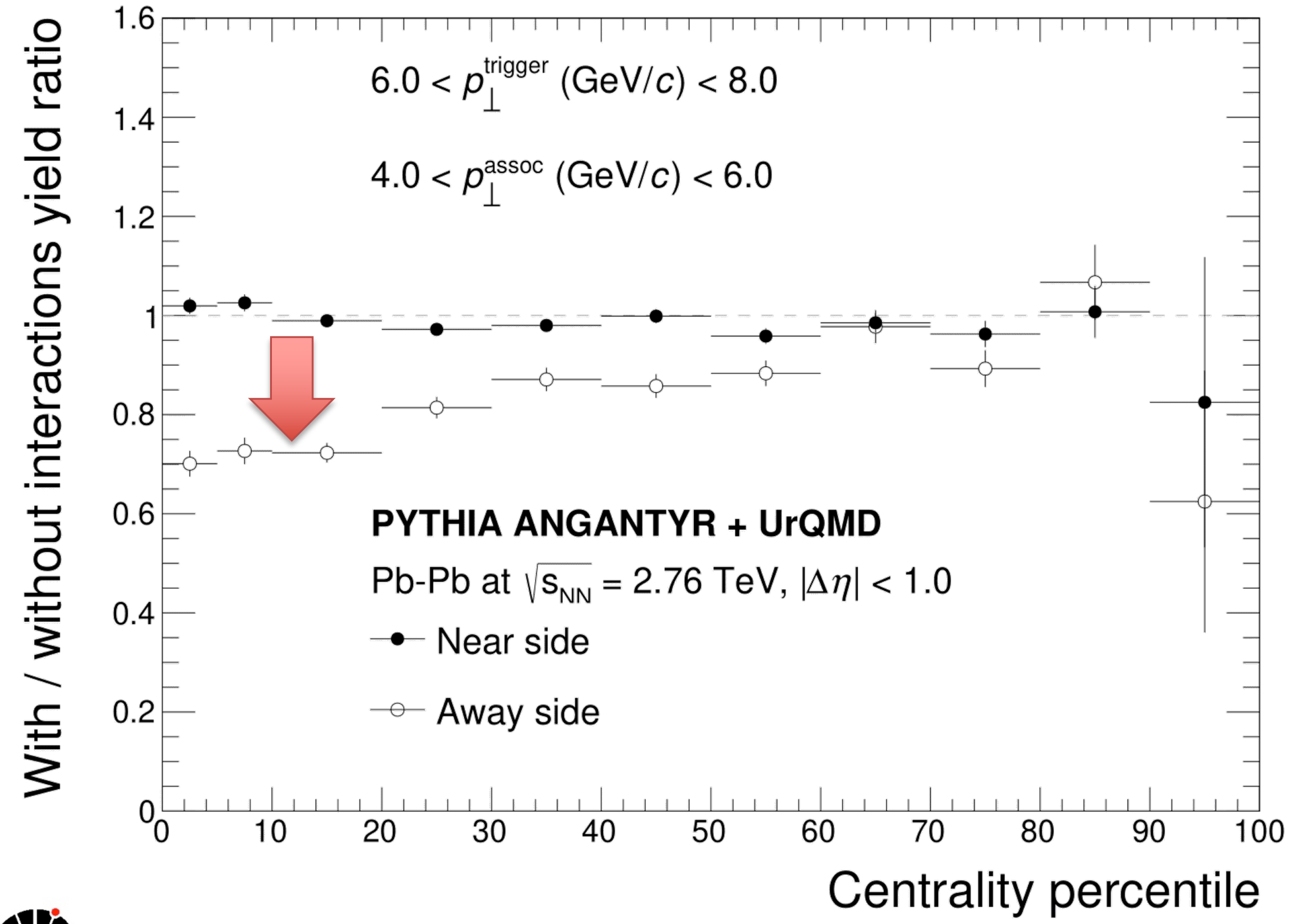
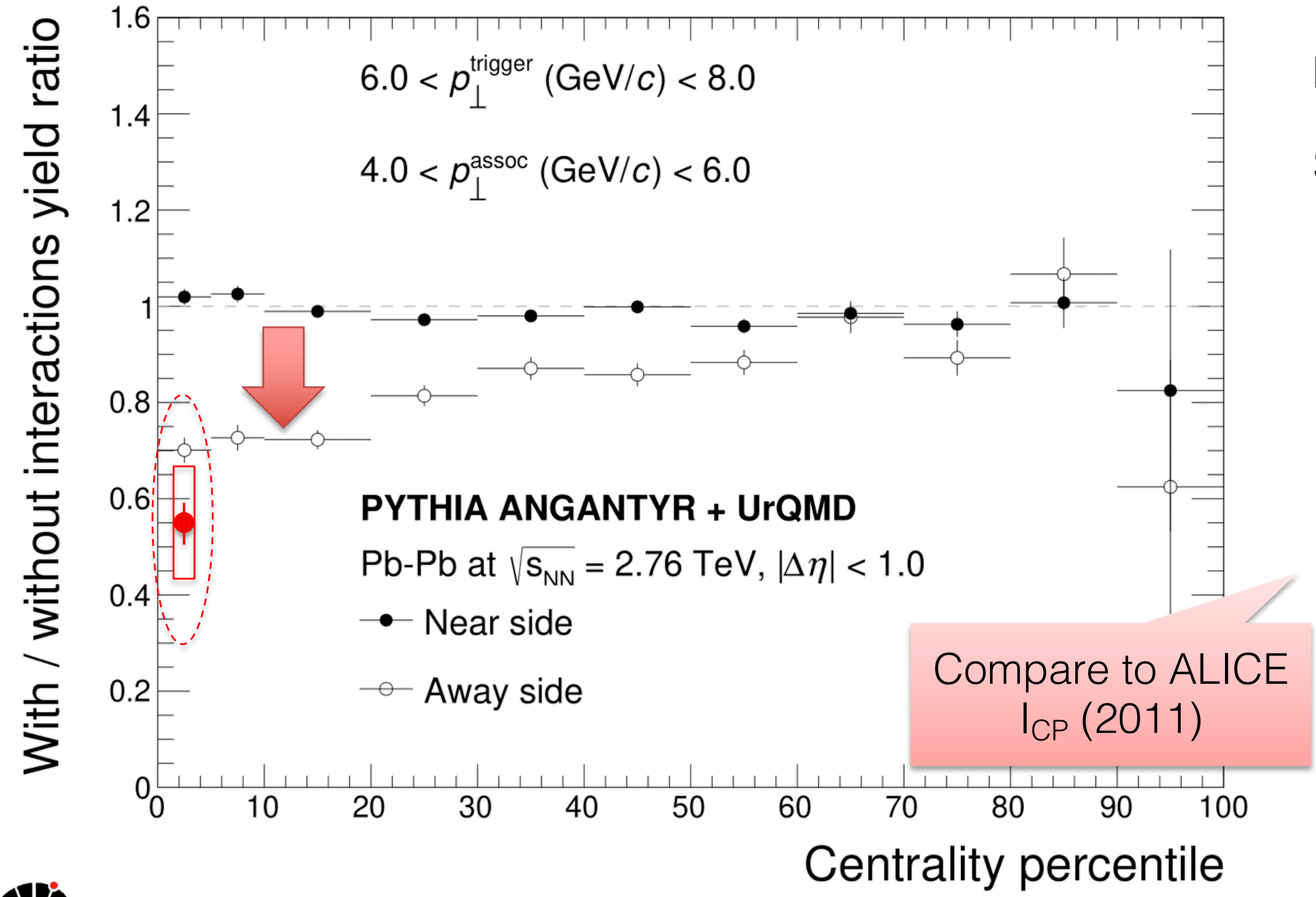
Away-side suppression versus centrality



Effect due to interactions in hadronic phase only!

Suppression of the away-side jet is **~30%** in central collisions (0-5%)

Away-side suppression versus centrality



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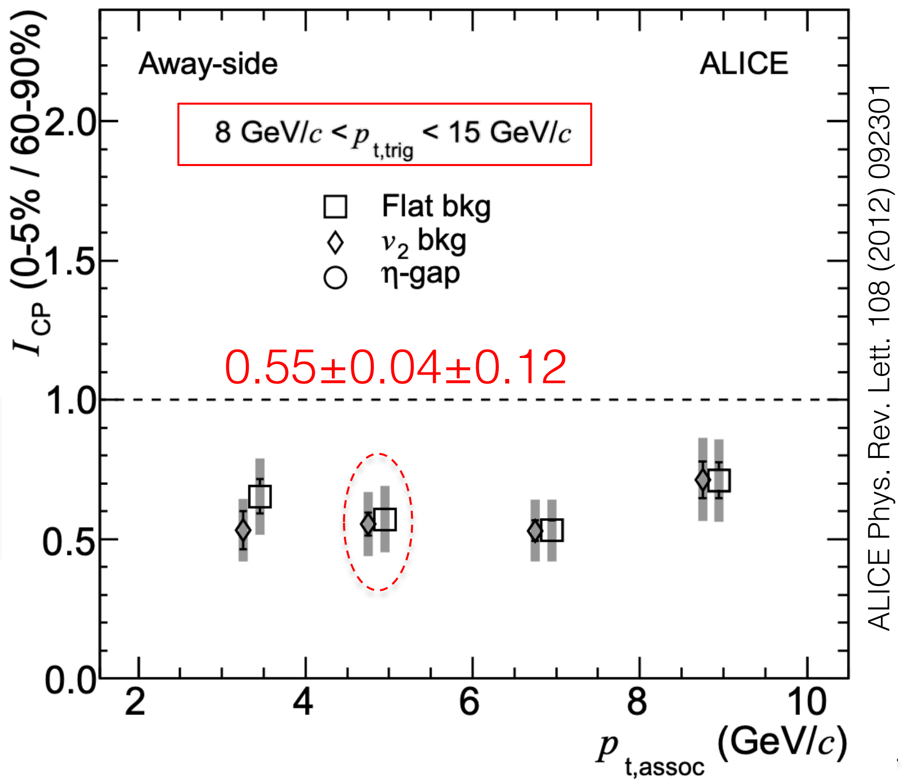


PYTHIA+UrQMD: Flow from the hadronic phase?

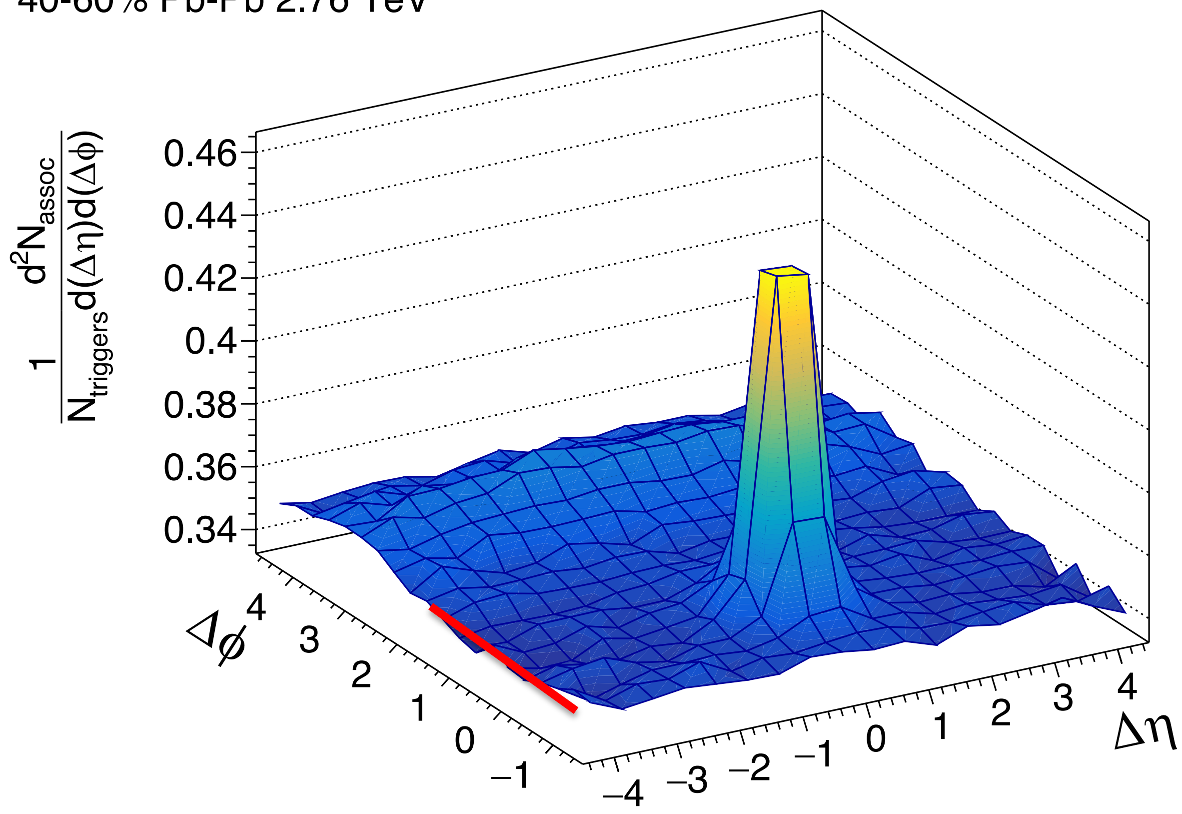
PYTHIA Angantyr + UrQMD

Decays only

40-60% Pb-Pb 2.76 TeV

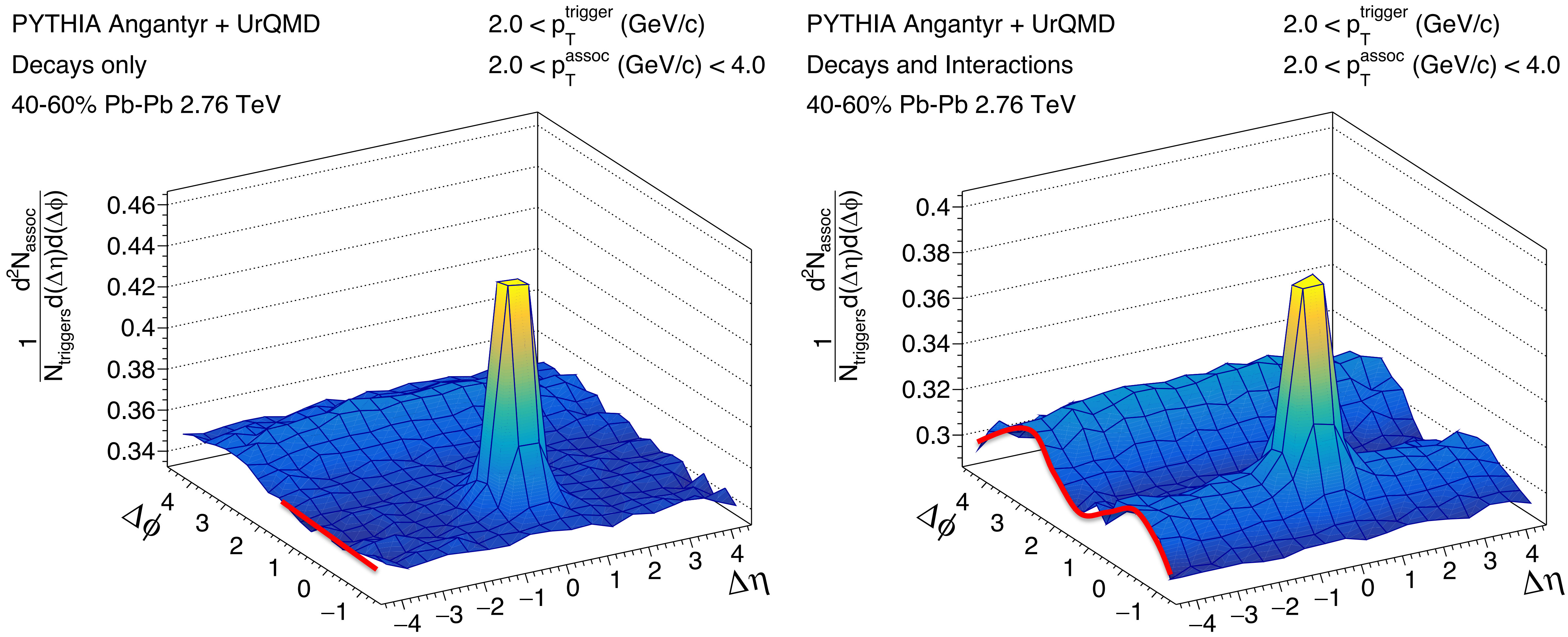
$2.0 < p_T^{trigger}$ (GeV/c)

$2.0 < p_T^{assoc}$ (GeV/c) < 4.0



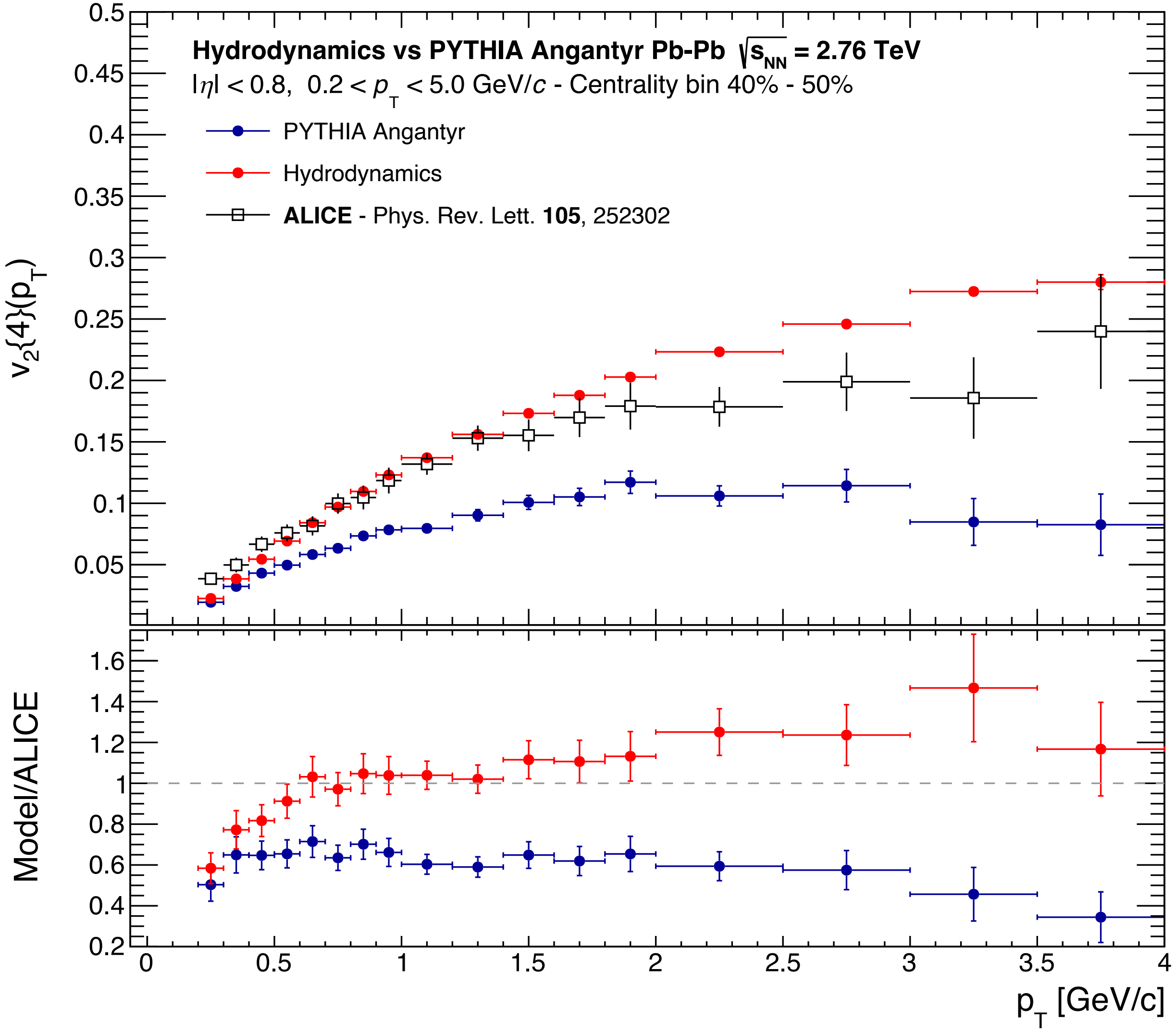
- No hadronic interactions: no near-side Ridge

PYTHIA+UrQMD: Flow from the hadronic phase?



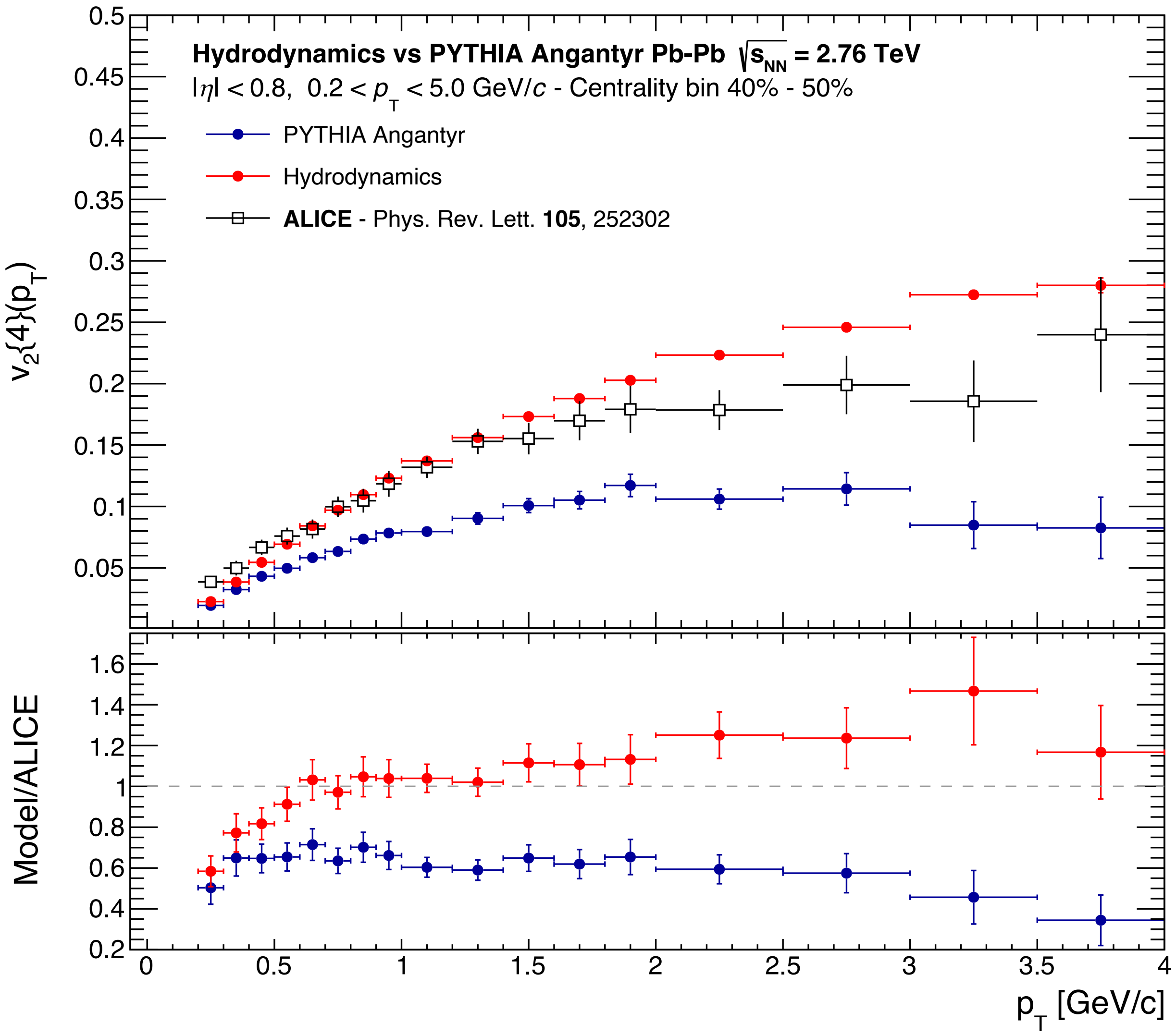
- No hadronic interactions: no near-side Ridge
- With hadronic interactions: long-range near-side Ridge

Elliptic flow coefficient $v_2\{4\}$ vs p_T



- Hydrodynamics:
  - low at low-p_T,
  - high at high-p_T
- PYTHIA+UrQMD:
  - Consistently at 60% of measurement

Elliptic flow coefficient $v_2\{4\}$ vs p_T

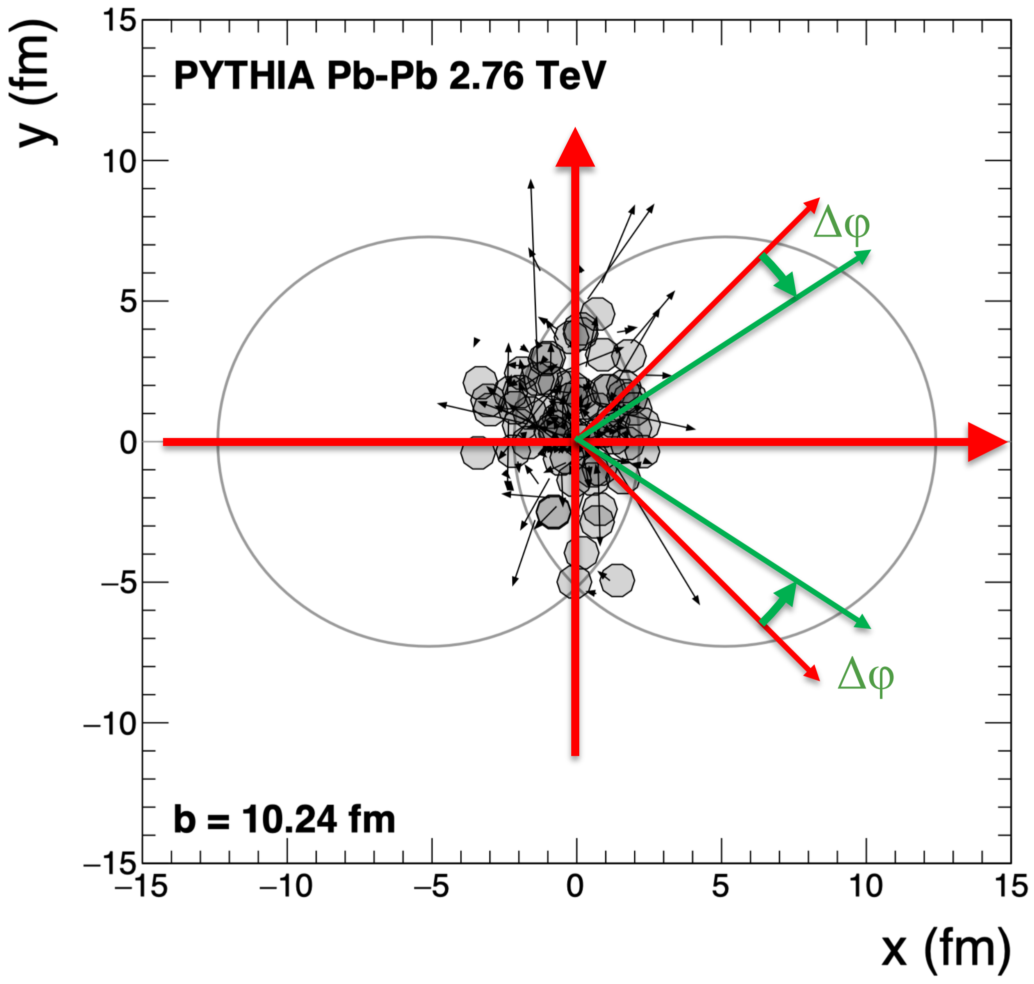


- Hydrodynamics:
  - low at low-p_T,
  - high at high-p_T
- PYTHIA+UrQMD:
  - Consistently at 60% of measurement

What if…

- PYTHIA Angantyr provided already some of the initial flow?
- How does UrQMD response work at PYTHIA densities?

Adding an initial hadronic flow to PYTHIA



- Rotate momenta immediately after hadronization ($\Delta\varphi$ in figure)
- obtain a specific, settable initial $v_2(p_T)$ wrt to event plane

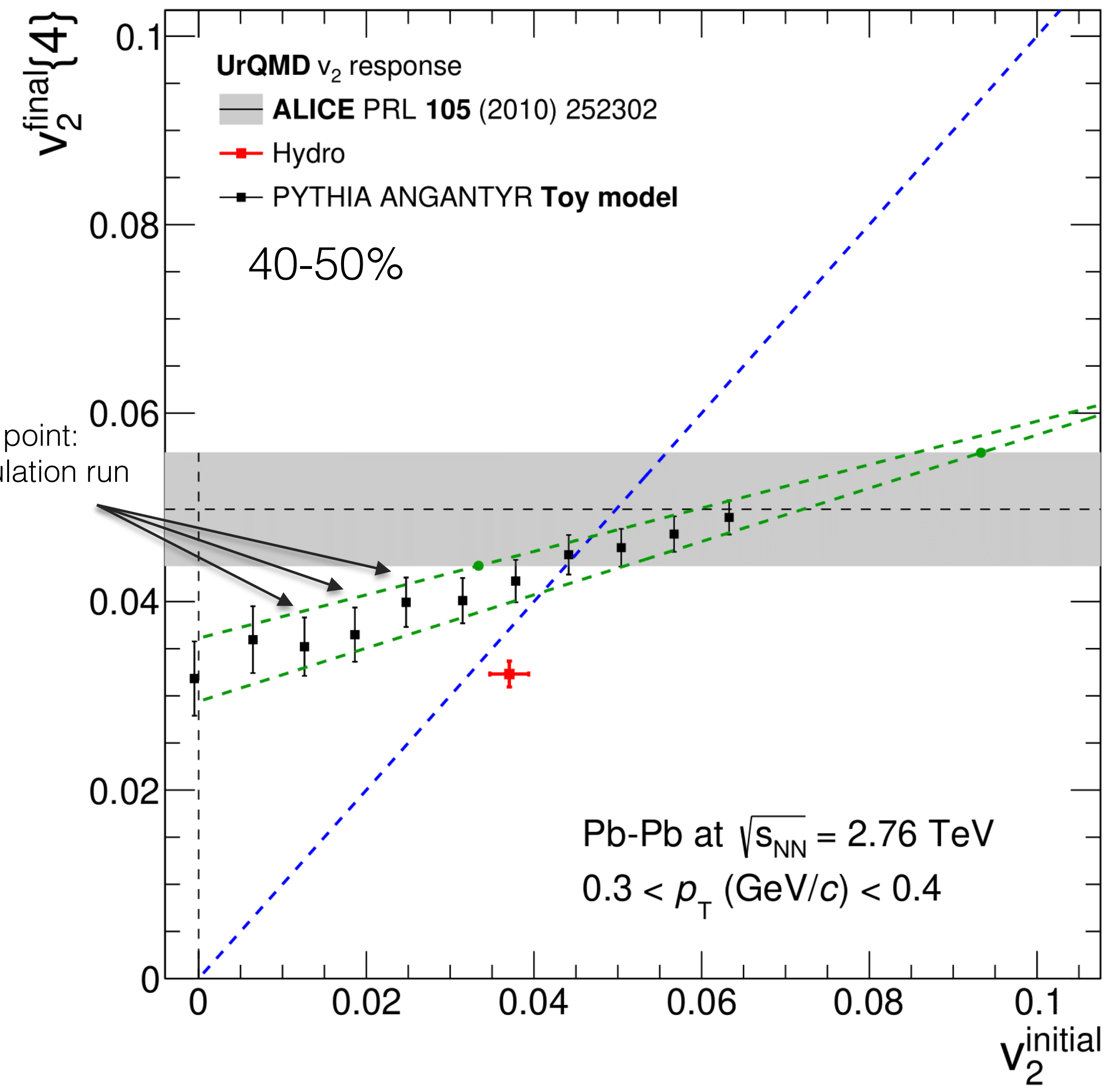
…and then vary the initial v_2 by manually setting it to have the right p_T dependence (~ measured) times a parameter "A" that we change systematically to scale v_2 up.

Goal: check UrQMD hydro-like response in each case.

How to plot? Next slide…

Initial hadronic flow vs final flow, low p_T

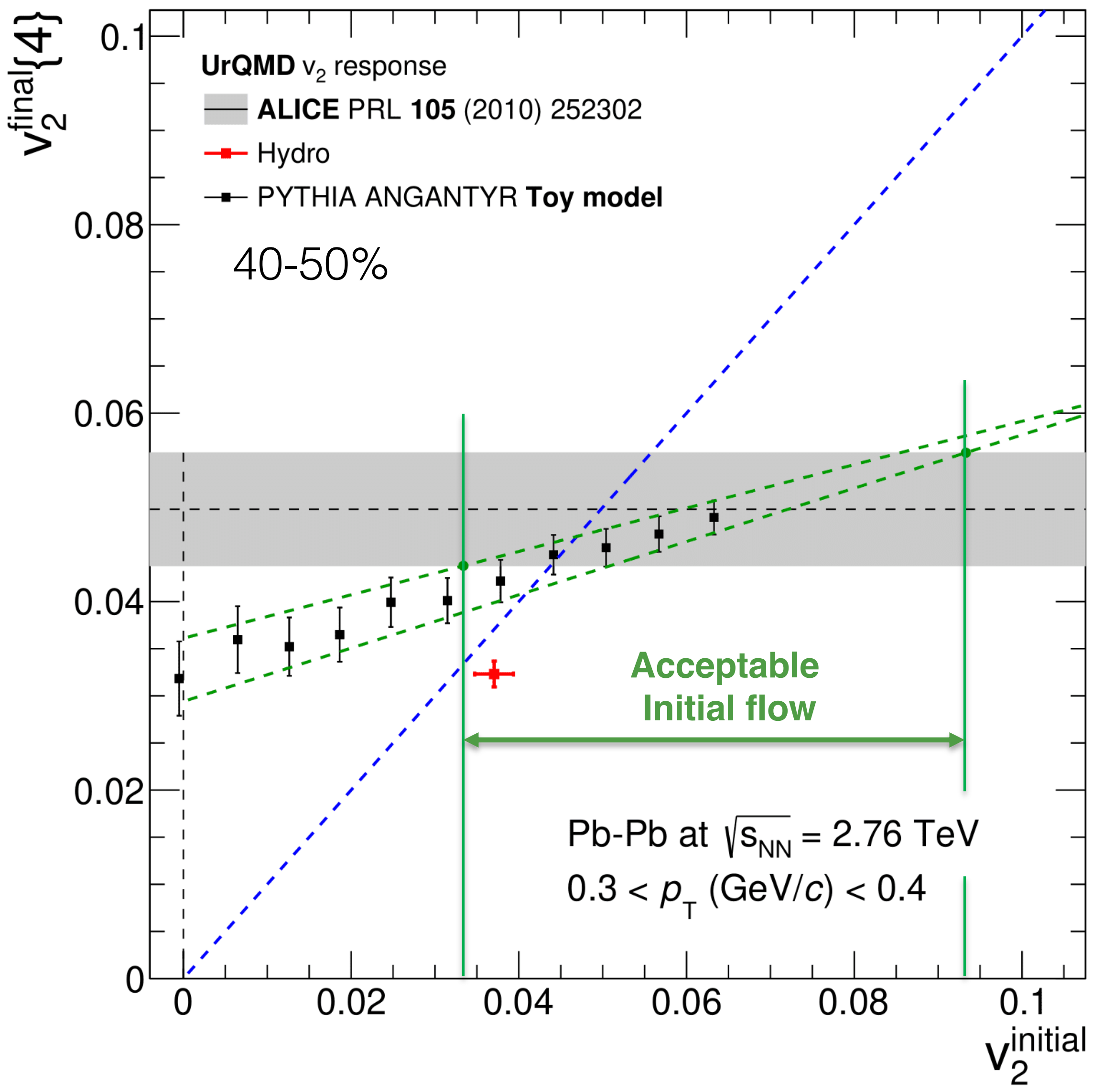
Each point:
One simulation run



At low-p_T:

- UrQMD response diminishes with initial flow
- If very high flow: UrQMD removes some of it (not shown)
- measured value: stable condition

Initial hadronic flow vs final flow, low p_T



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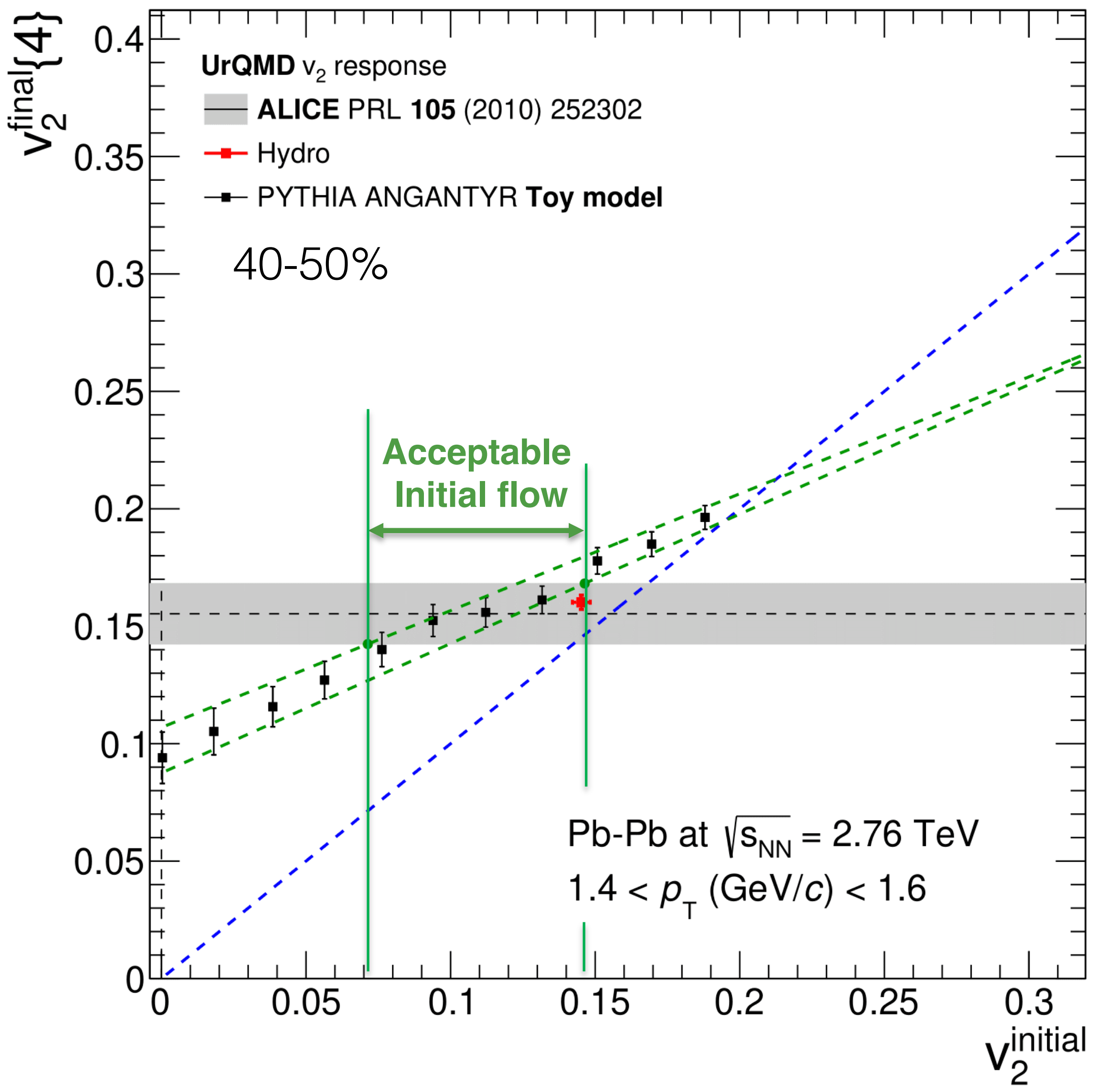


At low-p_T:

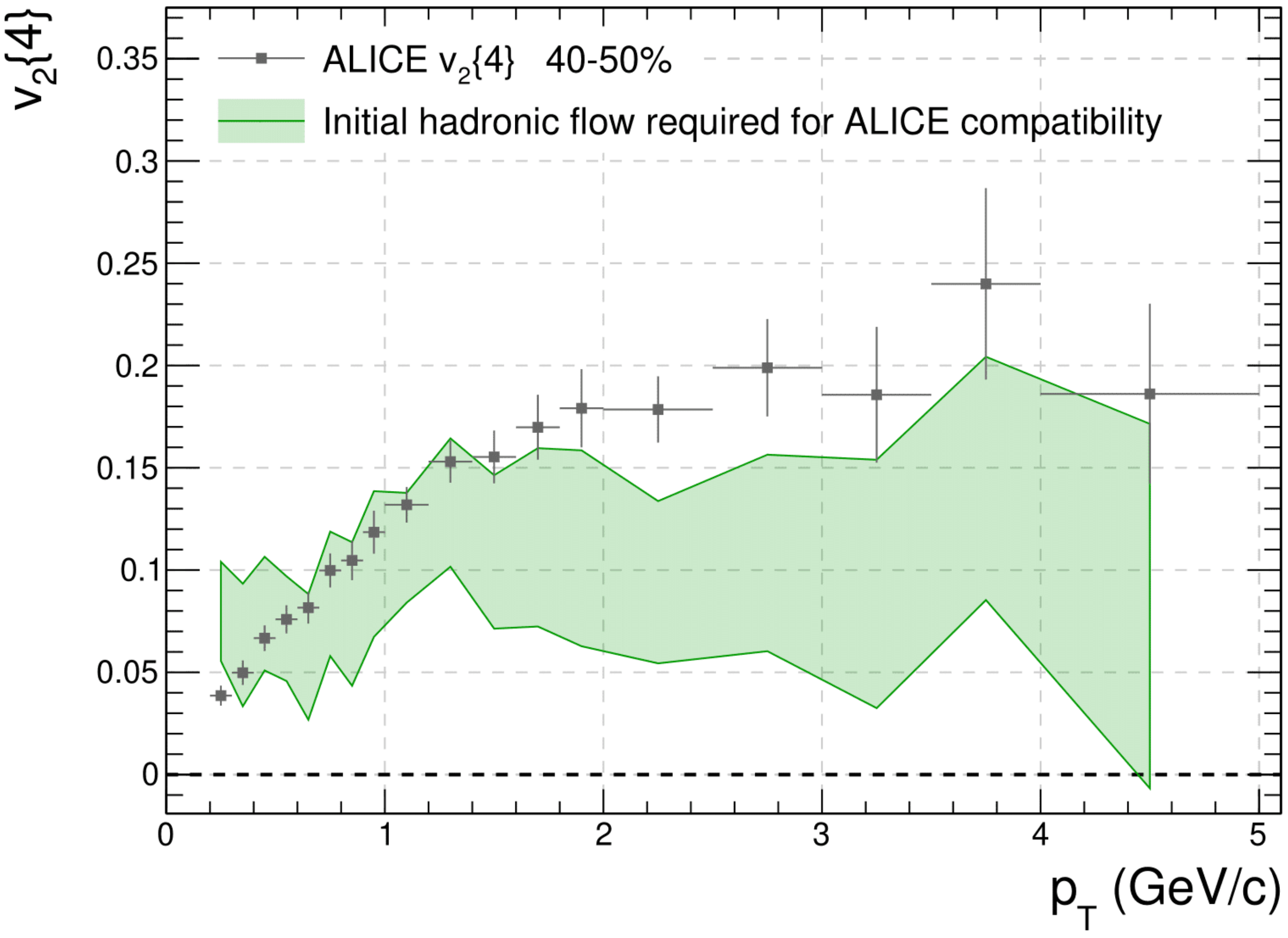
- UrQMD response diminishes with initial flow
- If very high flow: UrQMD removes some of it (not shown)
- measured value: stable condition

At mid-p_T:

- measured value: not necessarily stable condition

How much flow is really needed?

(E.g. via string shoving in Angantyr)



Low-p_T : To recover the ALICE v_2 the $v_2^{initial}$ values need to be similar to the desired final flow

High-p_T: Initial flow can be half of the desired final flow: UrQMD will add more!

Summary

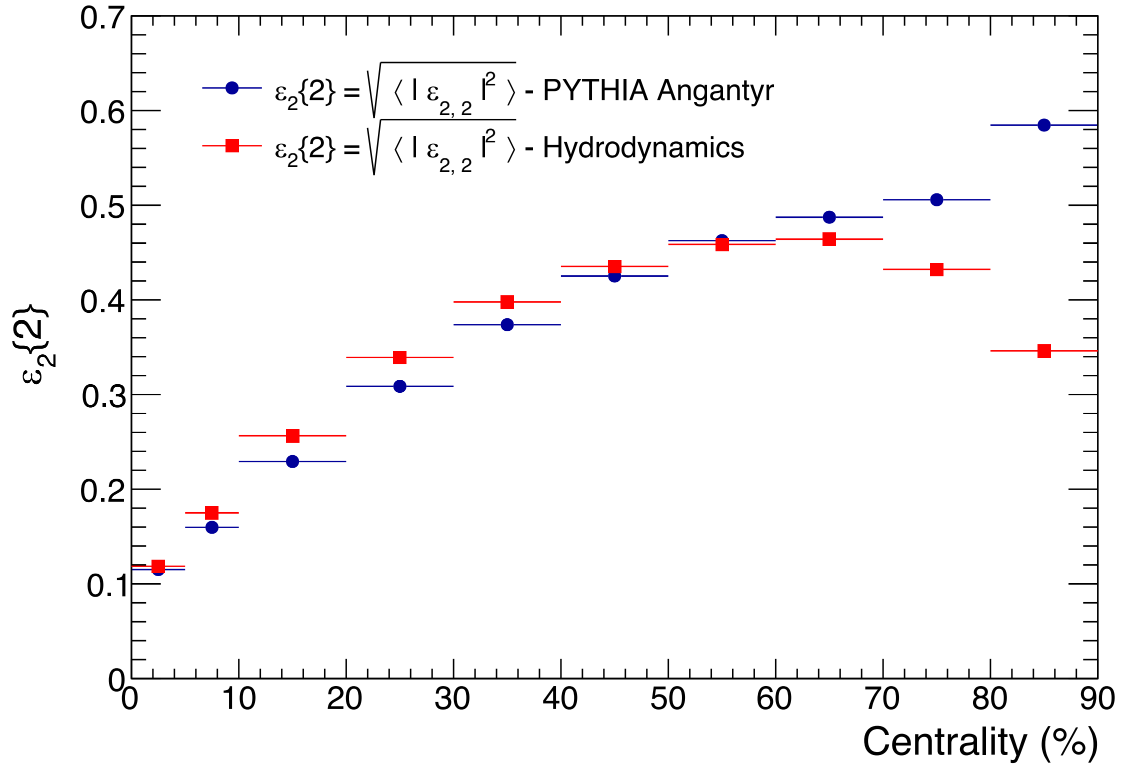
- **PYTHIA Angantyr + UrQMD**: a complete, QGP-free alternative to hydro
- **High-p_T spectra**: suppression of high-p_T yields
  - Jet quenching in the hadronic phase?
  - Hadron vertex model: high-p_T "escapes" without interacting
- **Two-particle correlations**
  - Away-side suppression is there, looks similar to data
- **Elliptic flow / collectivity**: 60% of measured v_2!
  - Less room for QGP effects?...
  - …but UrQMD response is not strictly additive!

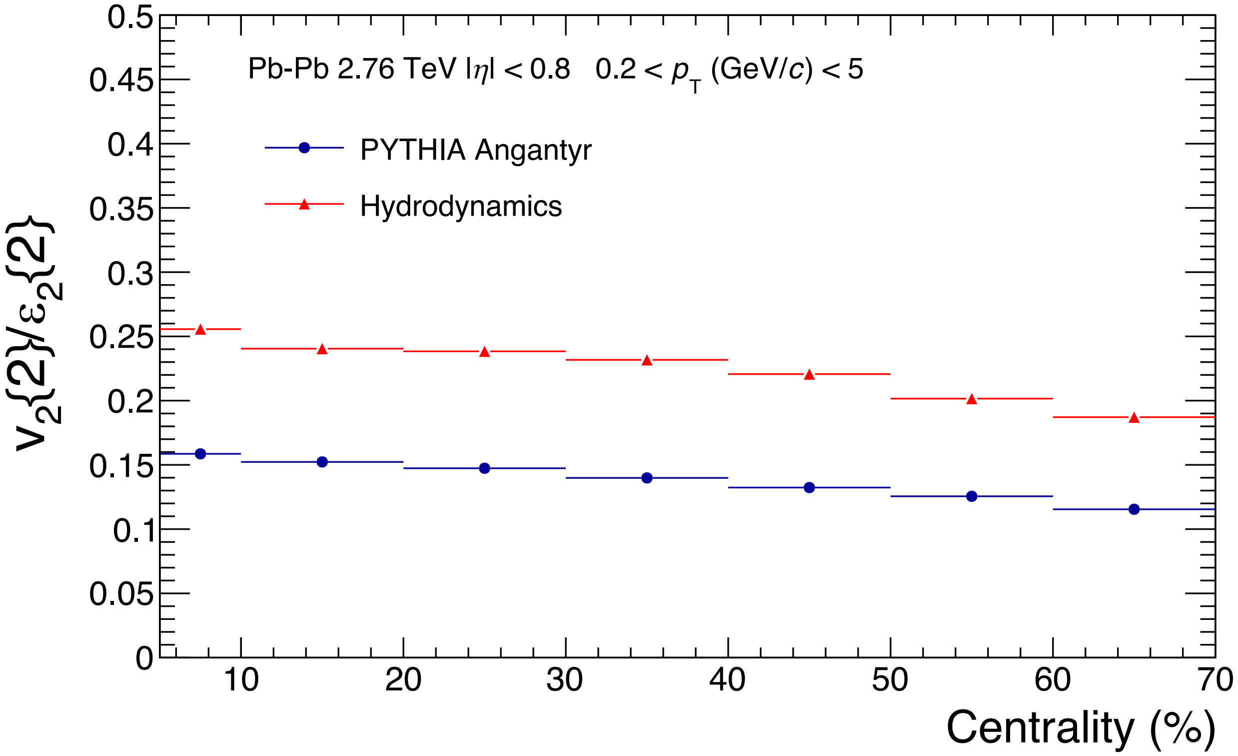
  - Further work will come: string shoving, native PYTHIA hadronic scattering!
  - **Principles over implementation**: a lot of details still being worked out!

Thank you!

Backup

Further studies: relating $v_2\{2\}$, $v_2\{4\}$ to the initial condition





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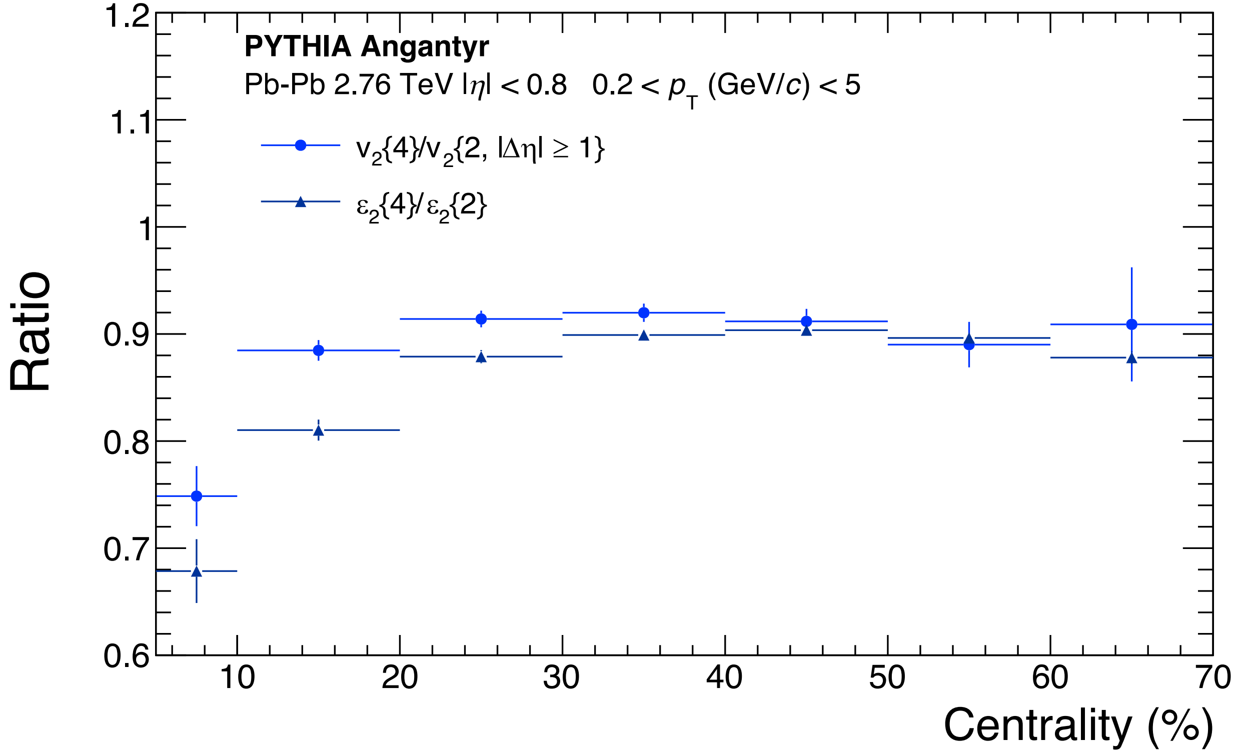
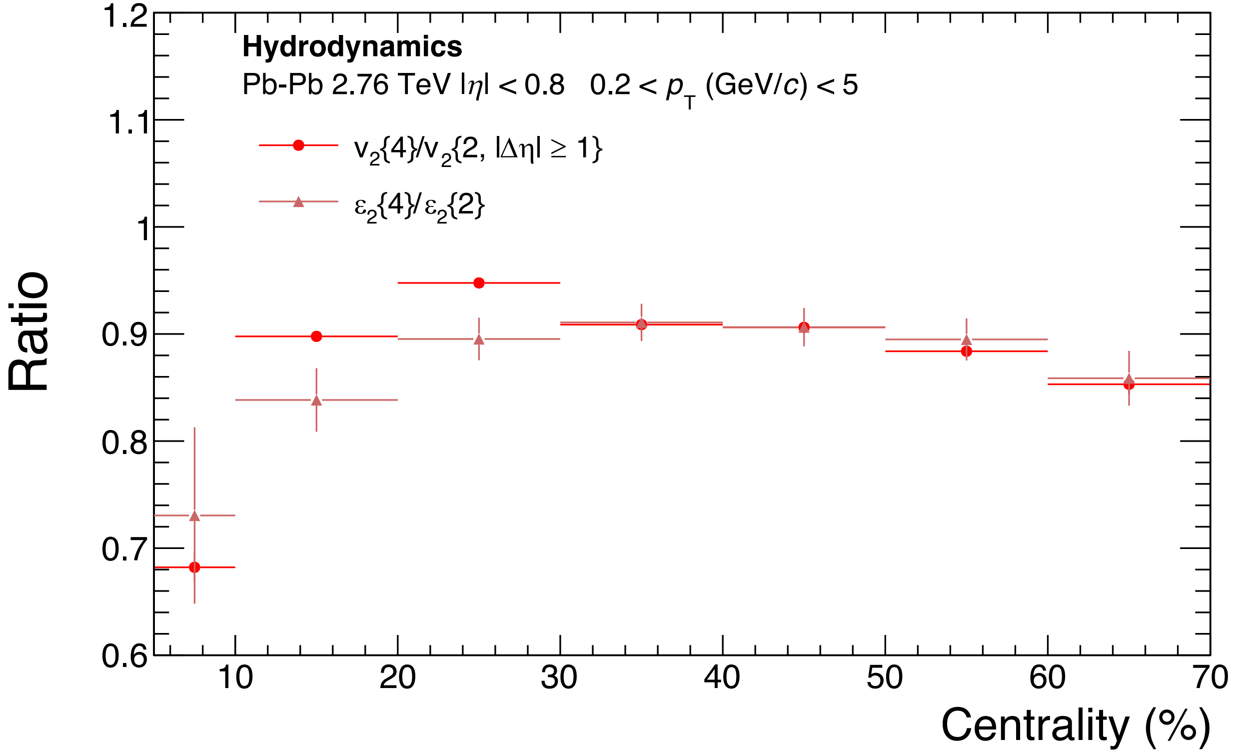
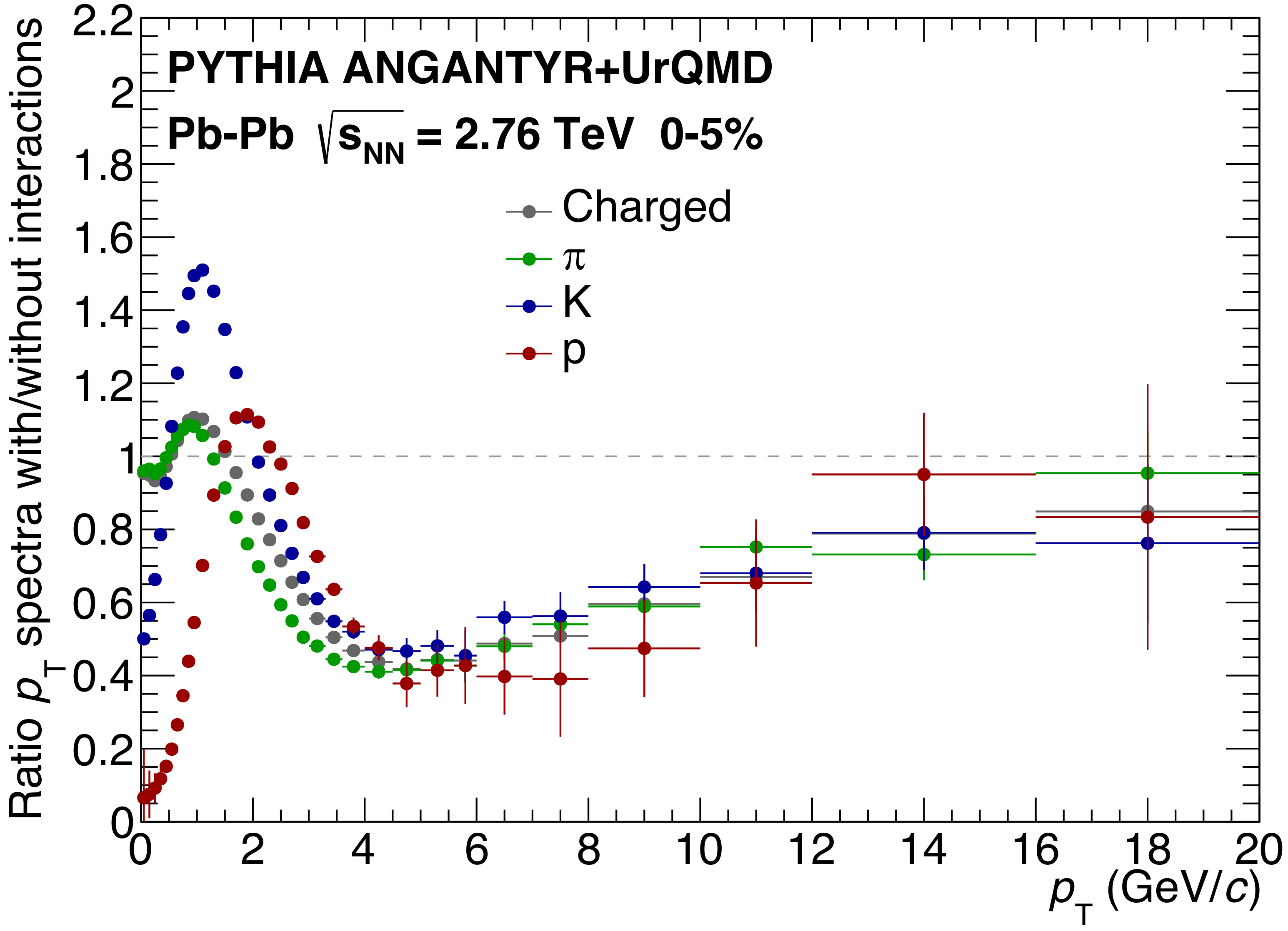




Spectra modification: identified particle species



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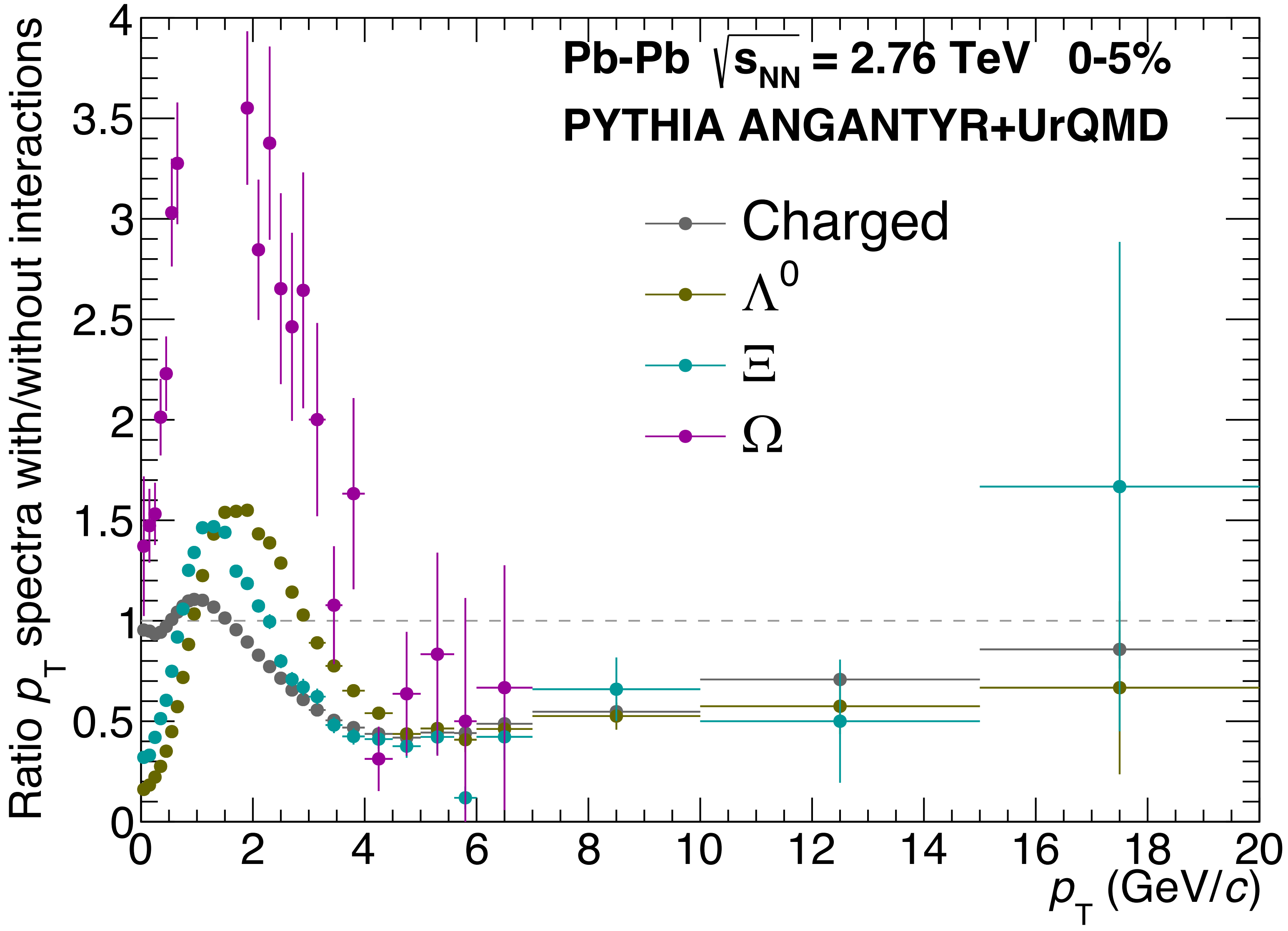

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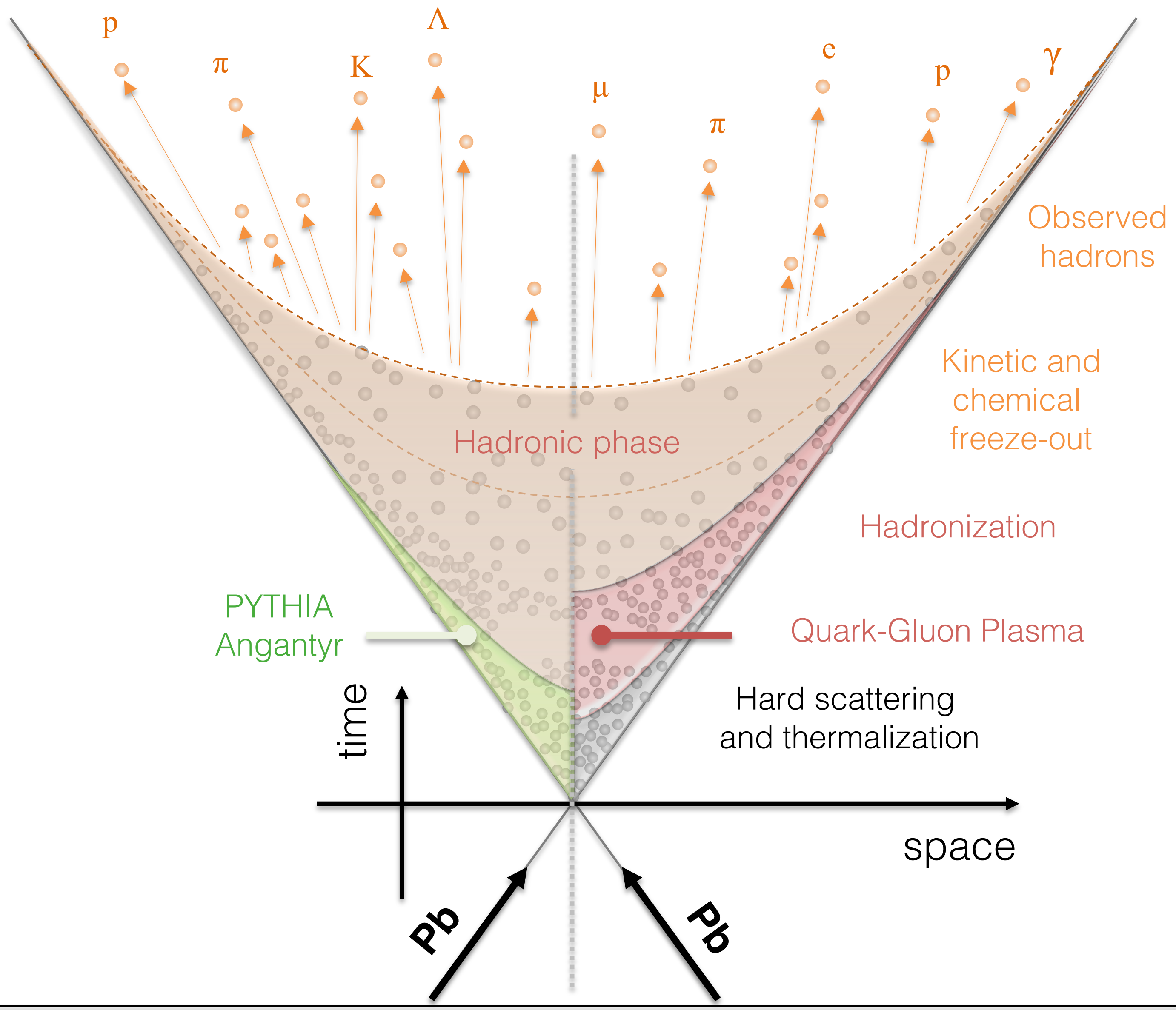
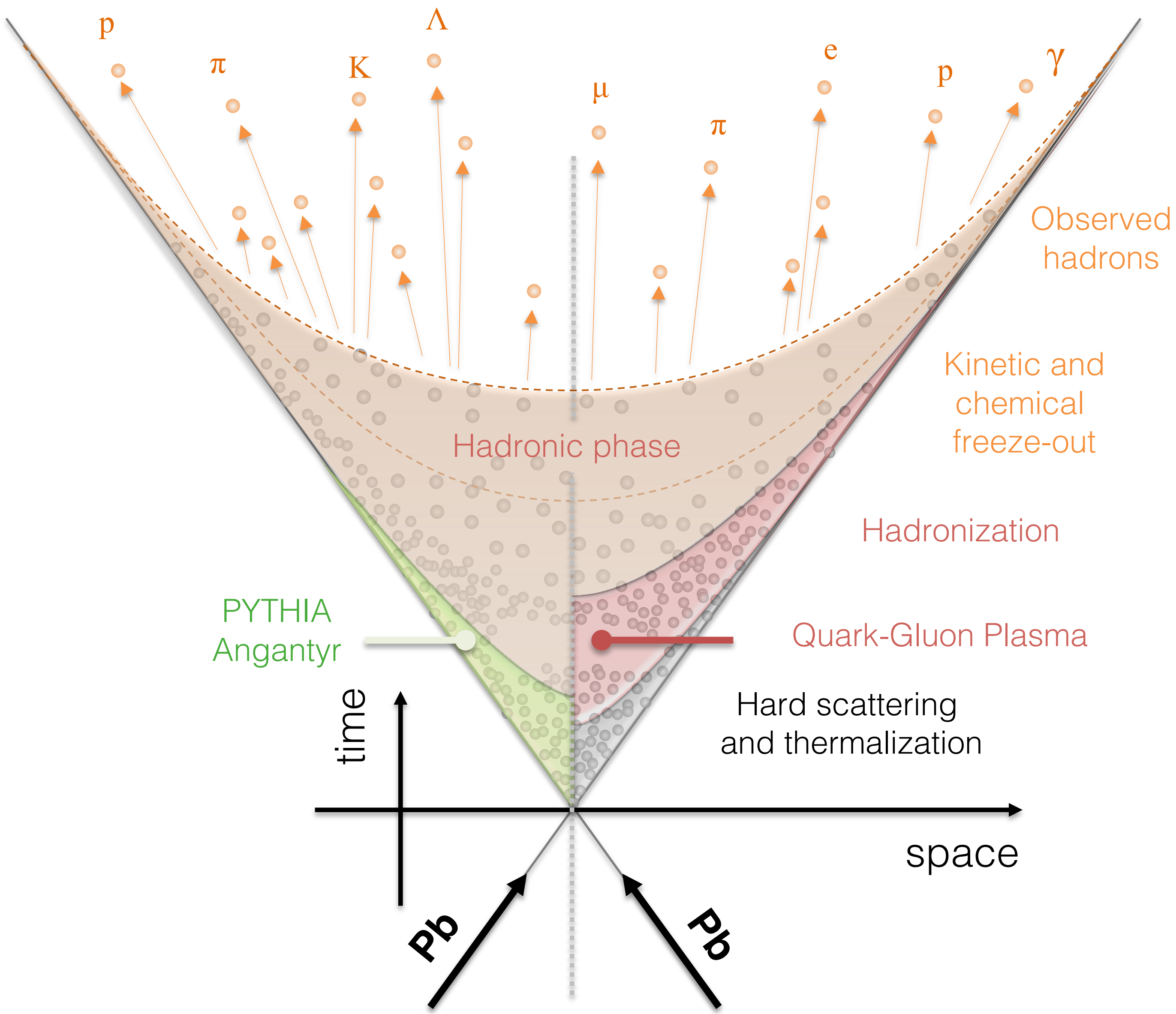

p
π
K
Λ
μ
π
e
p
γ
Observed hadrons
Kinetic and chemical freeze-out
Hadronic phase
Hadronization
Quark-Gluon Plasma
PYTHIA Angantyr
Hard scattering and thermalization
time
space
Pb
Pb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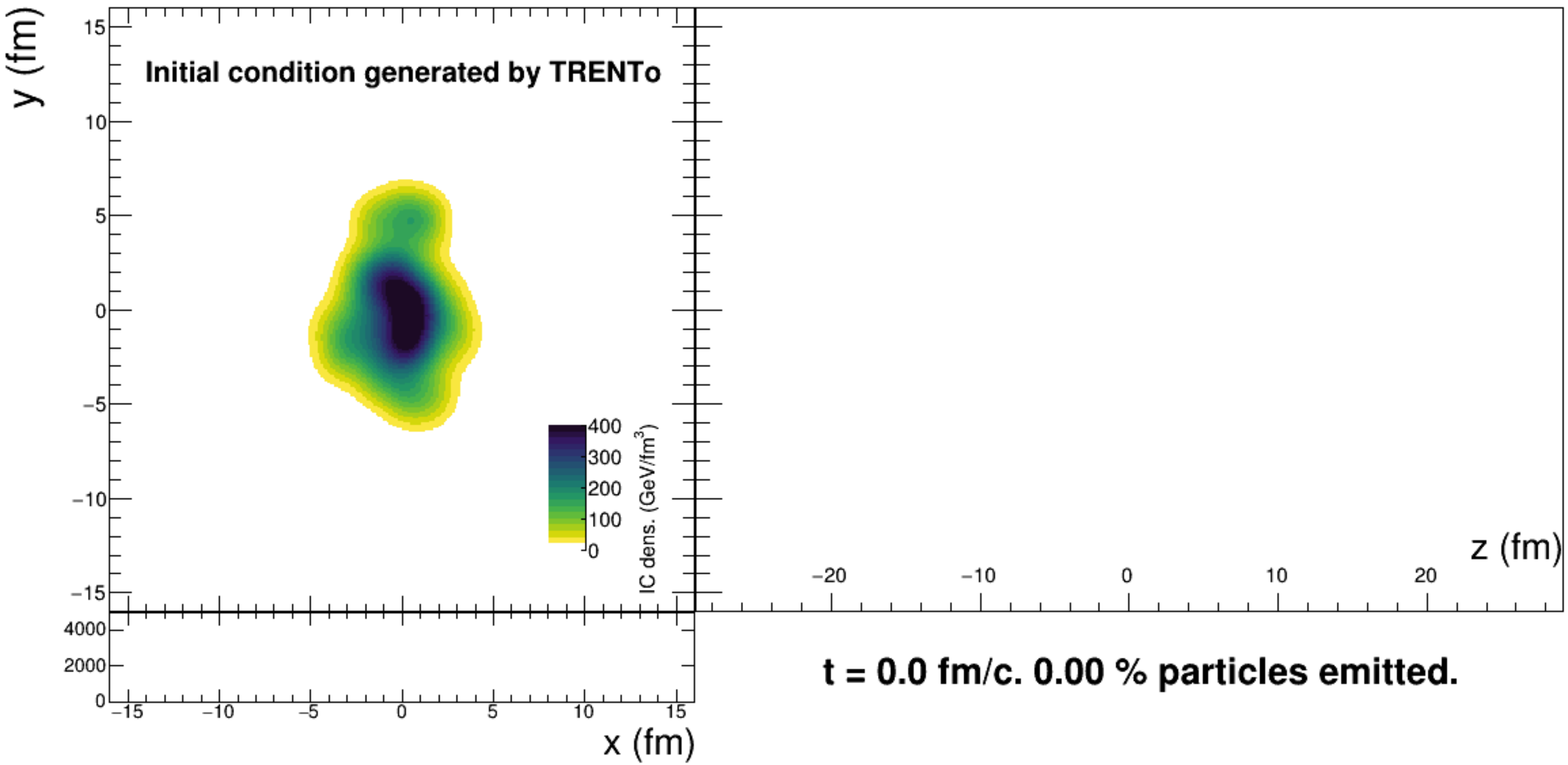
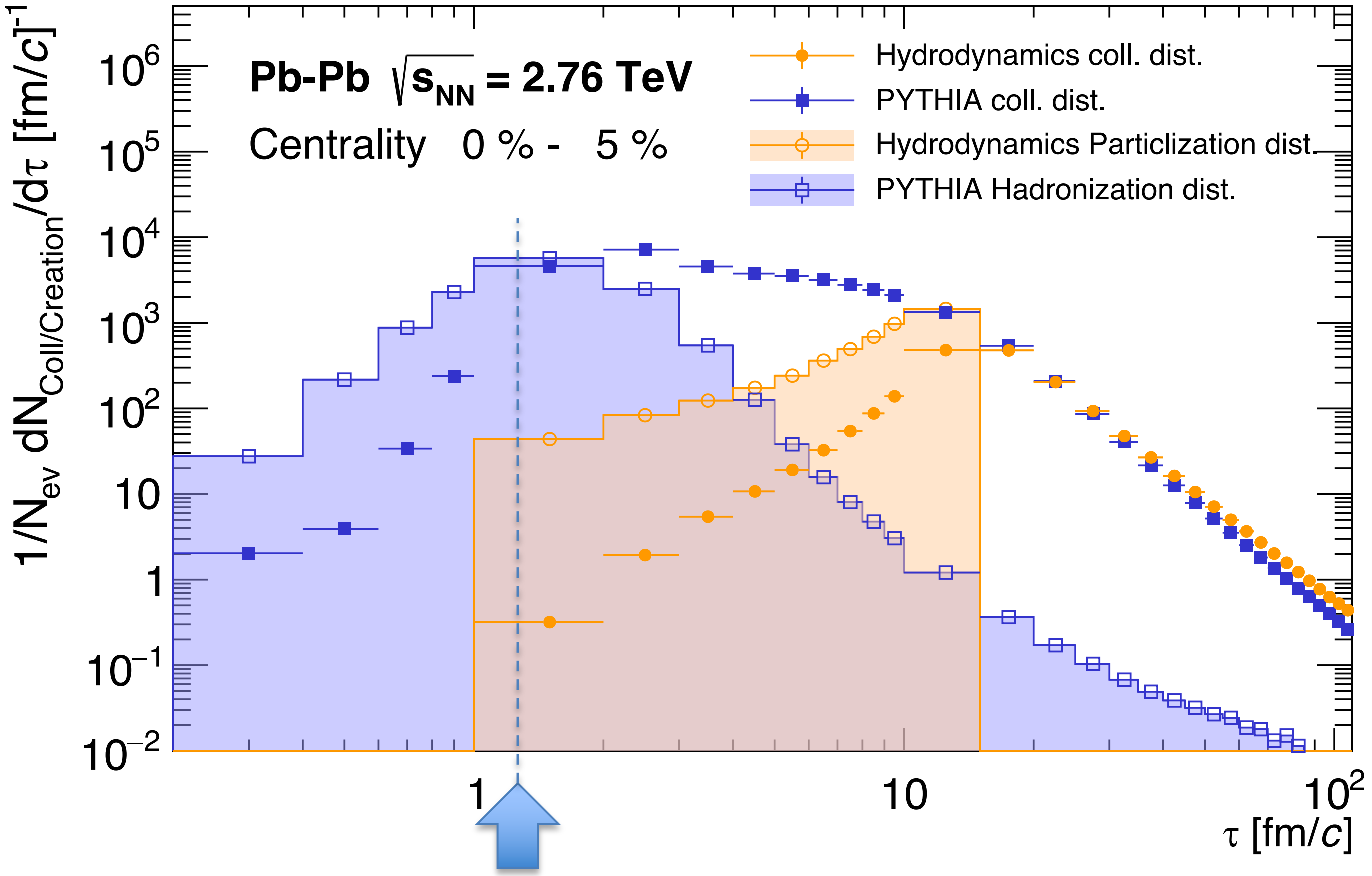


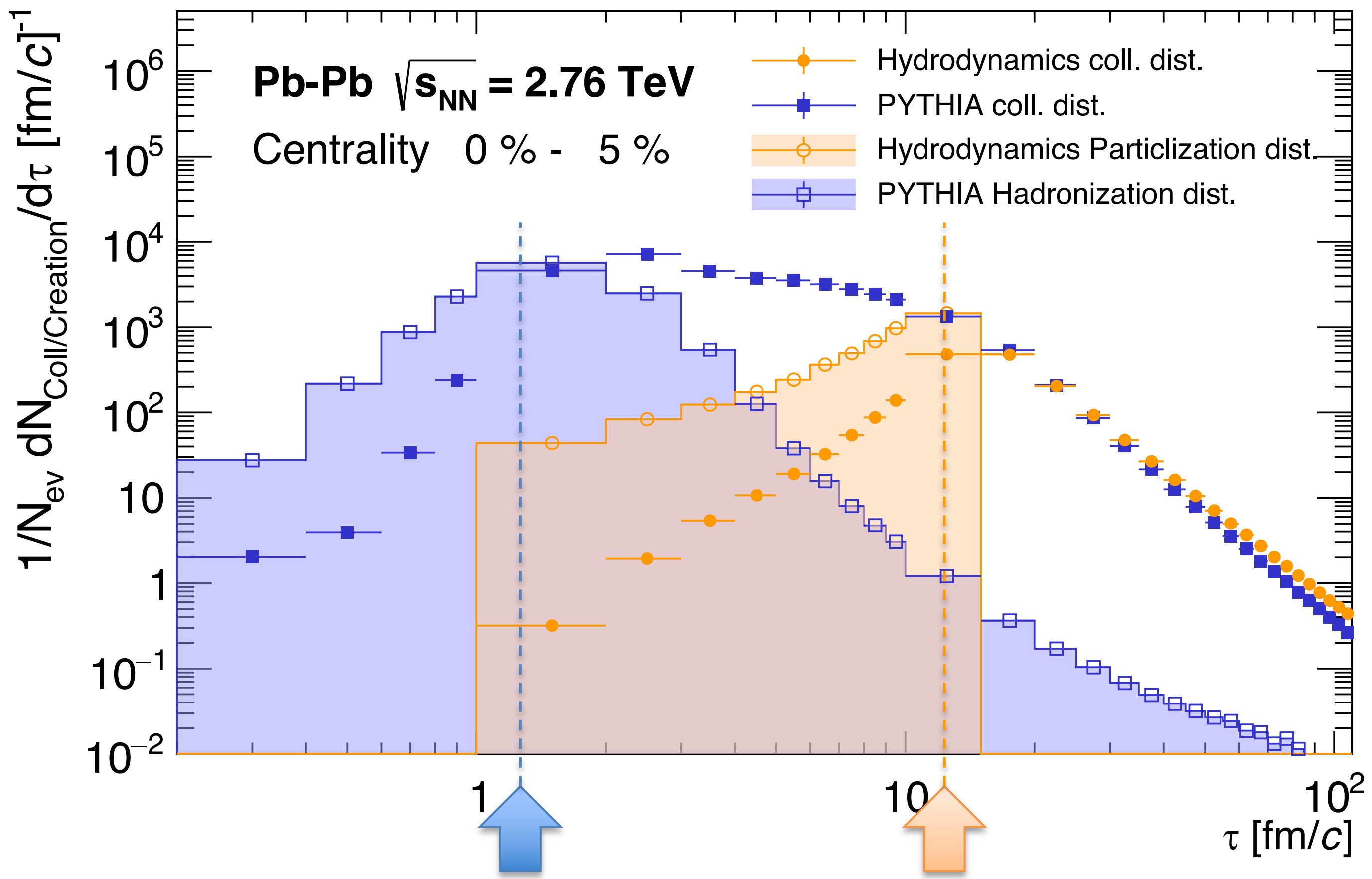
t = 0.0 fm/c. 0.00 % particles emitted.

The hadronic phase in time



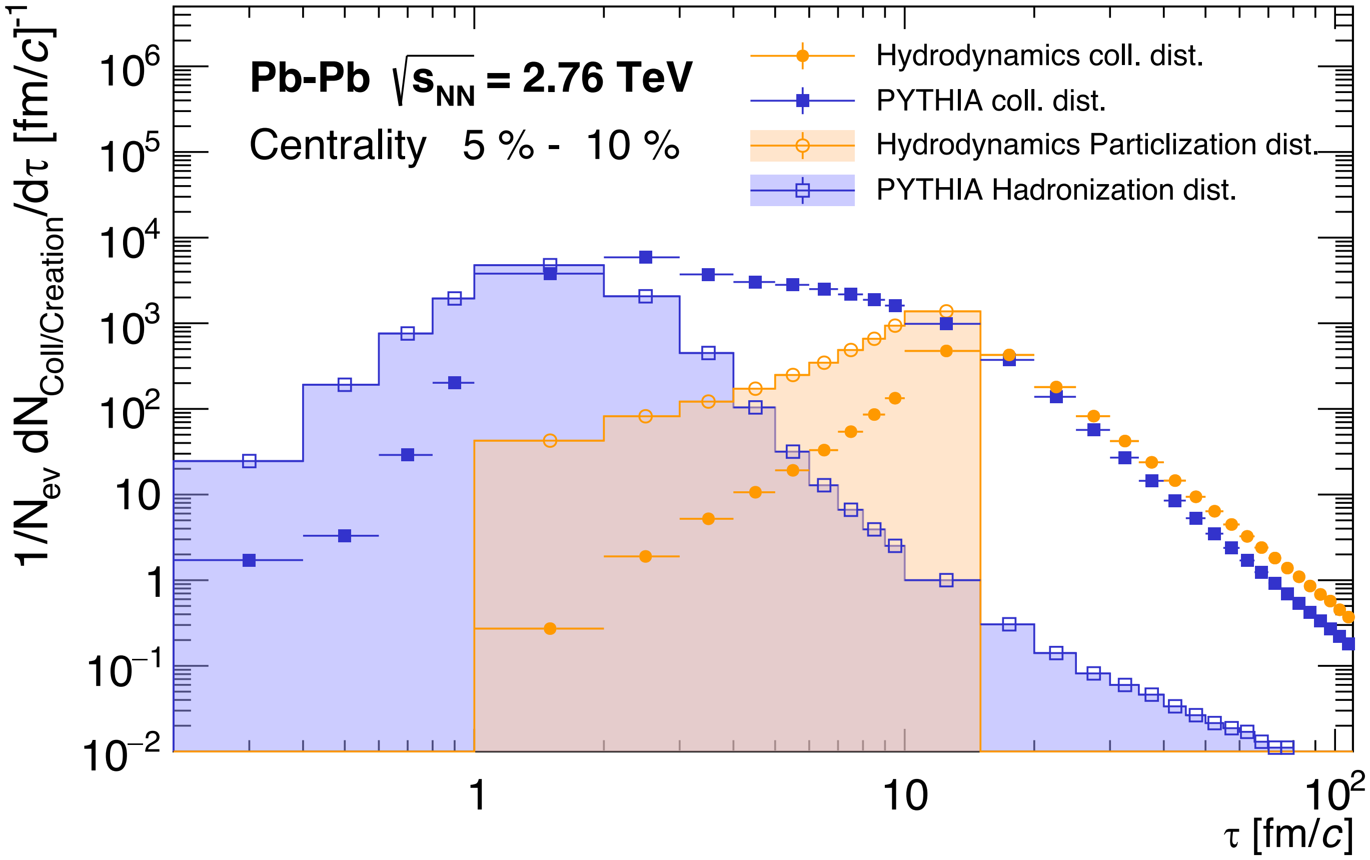
- **PYTHIA** creates particles with a peak at around 1-2 fm/c

The hadronic phase in time



- **PYTHIA** creates particles with a peak at around 1-2 fm/c,
- **Hydro** peaks at higher times: 10 fm/c (0-10%)
- Centrality dependence: hydro phase lasts longer, in PYTHIA: hadronic phase lasts longer

The hadronic phase in time



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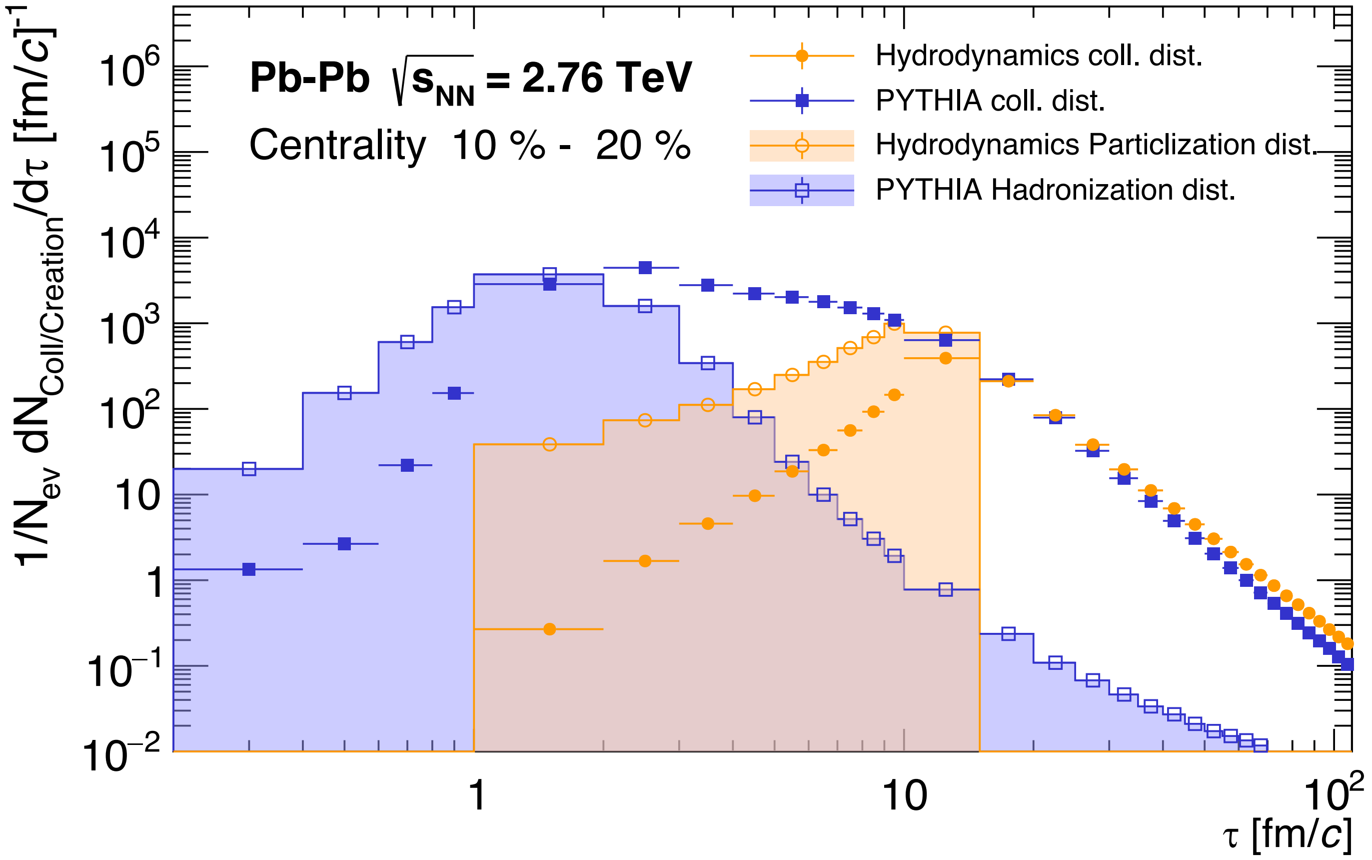

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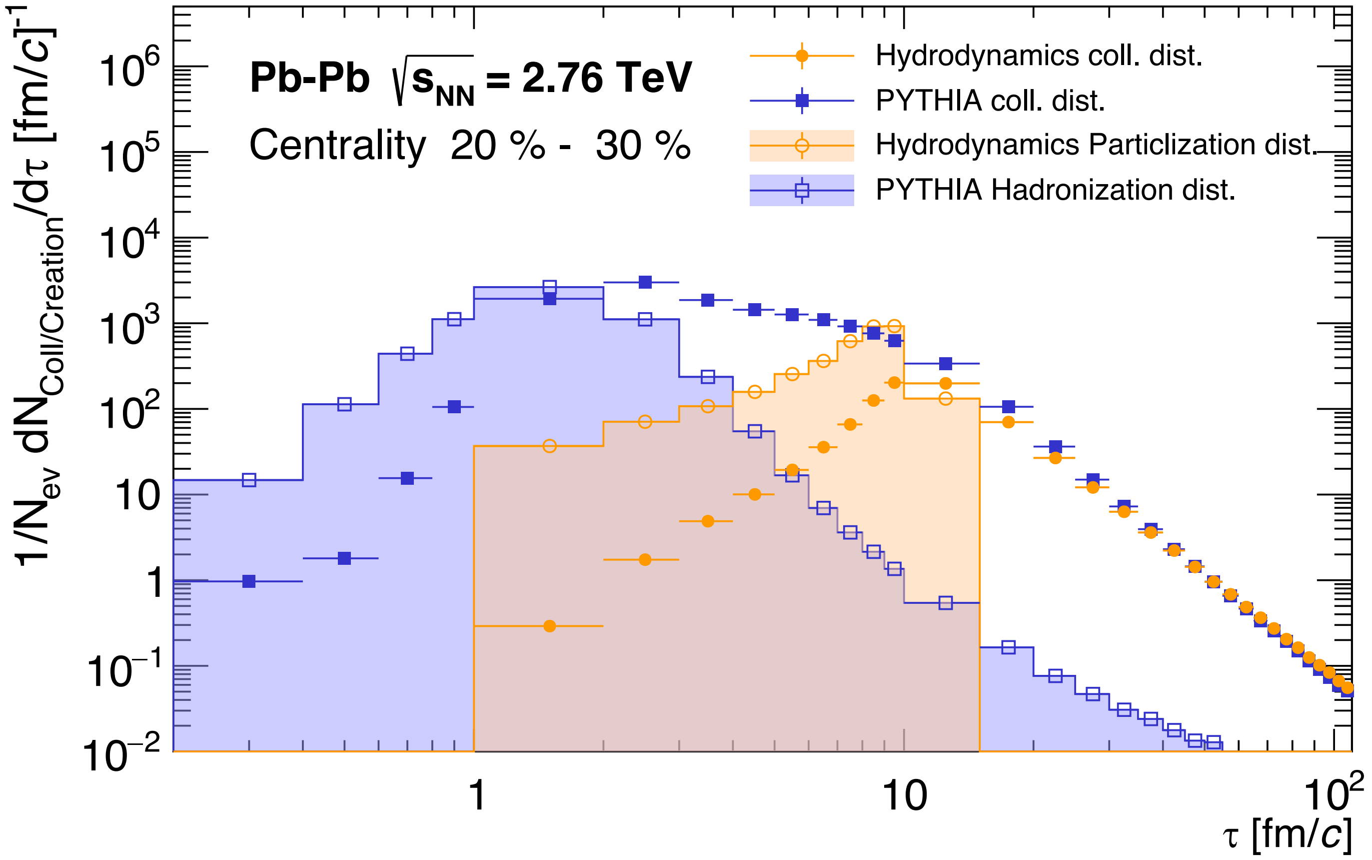
- Centrality dependence: hydro phase lasts longer, in PYTHIA: hadronic phase lasts longer

The hadronic phase in time



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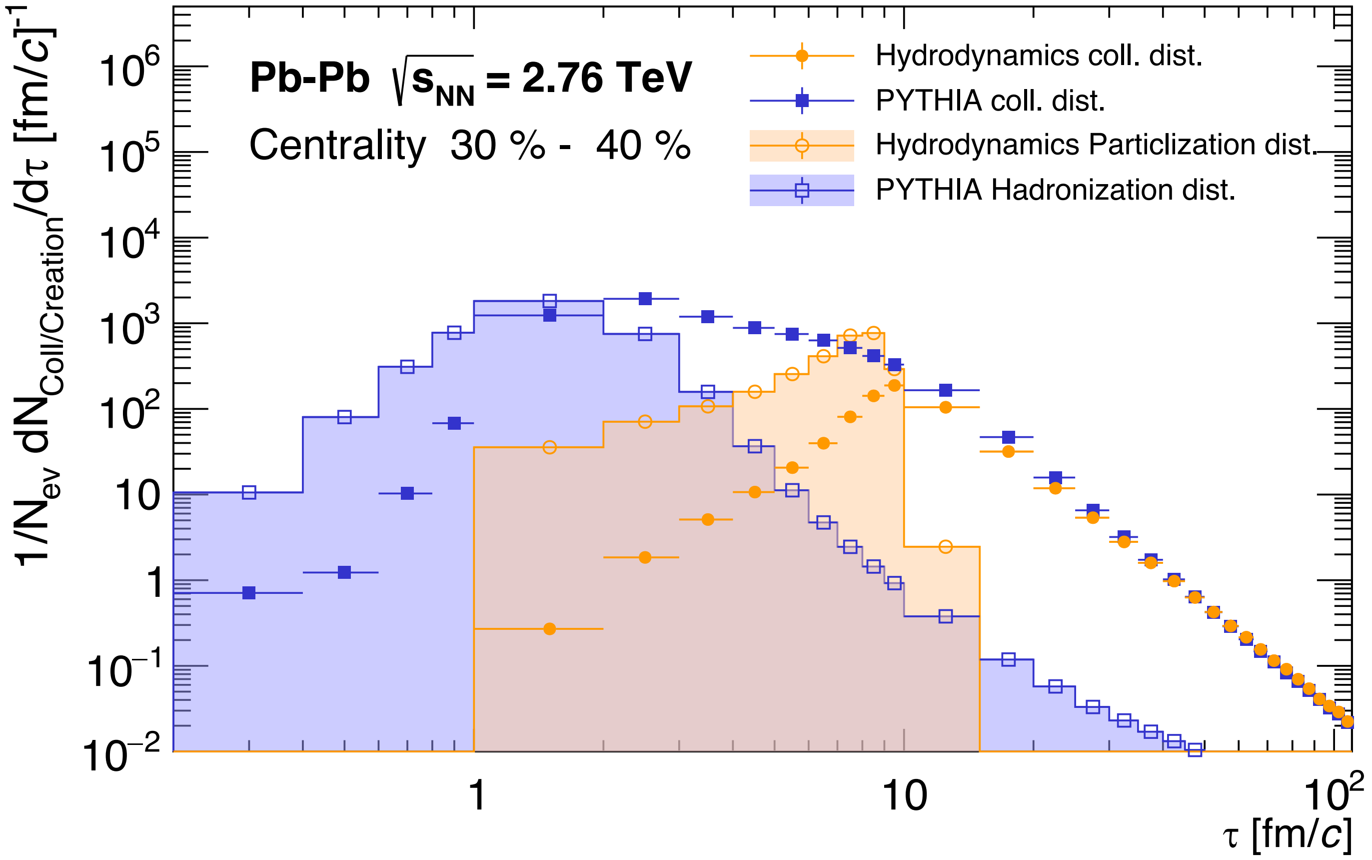

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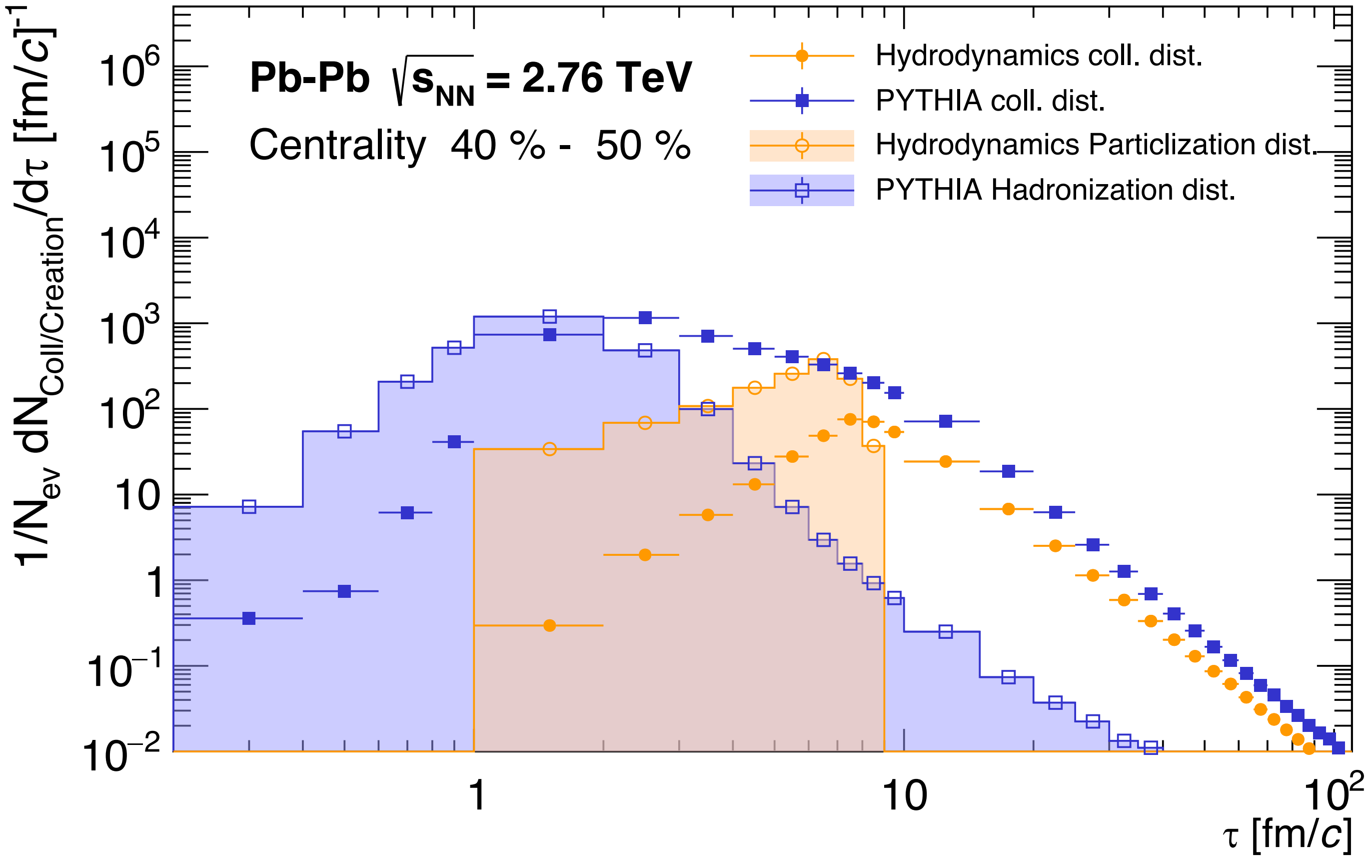

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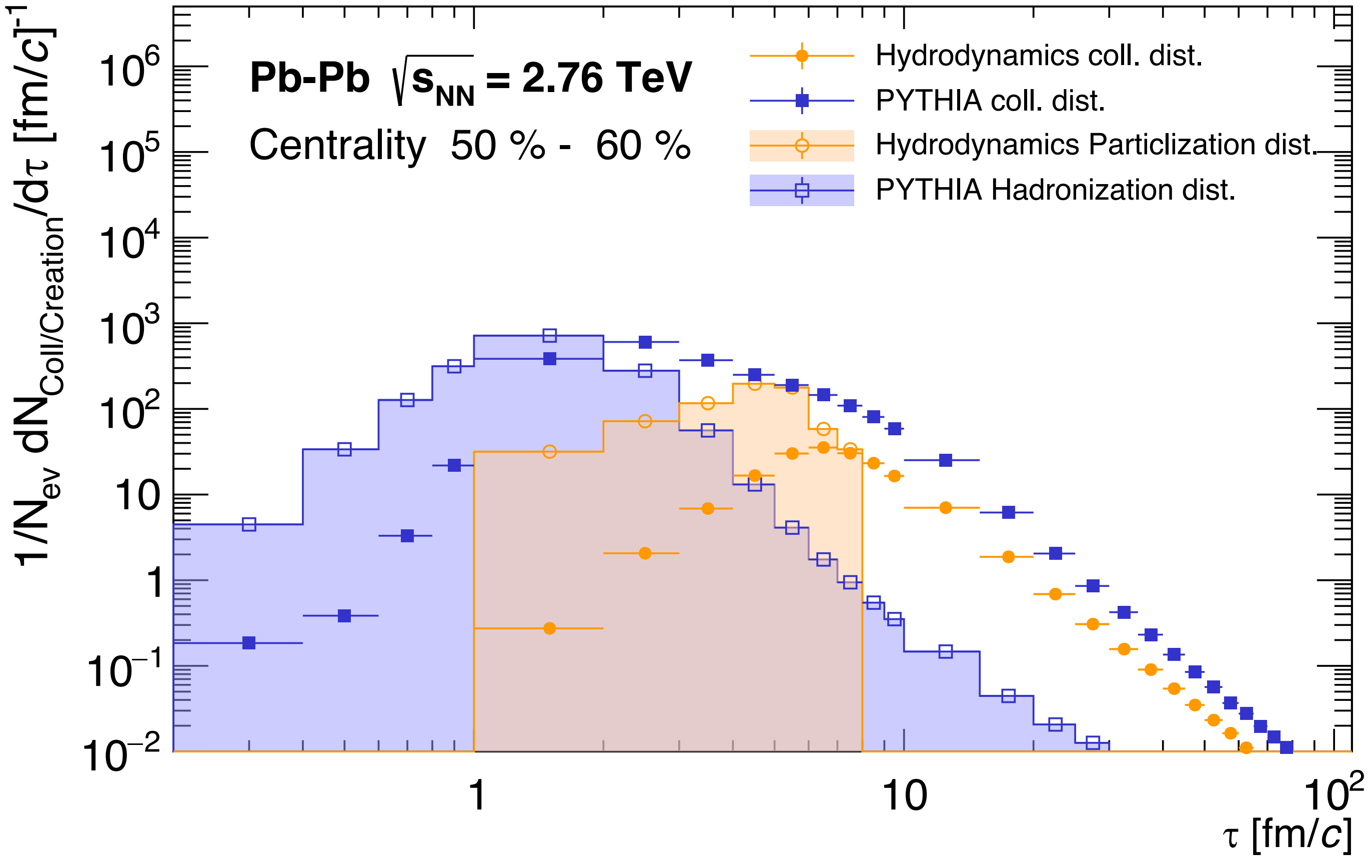

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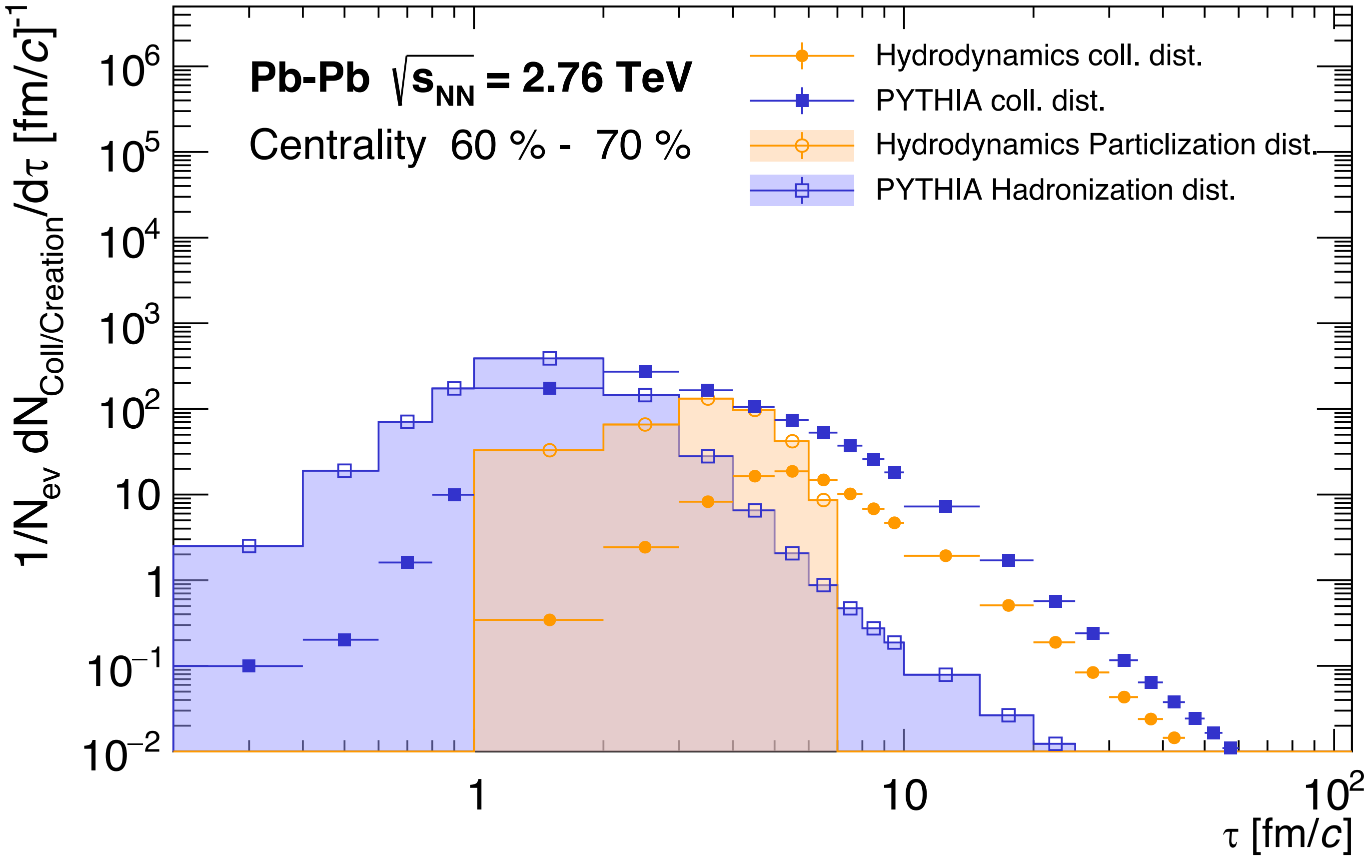

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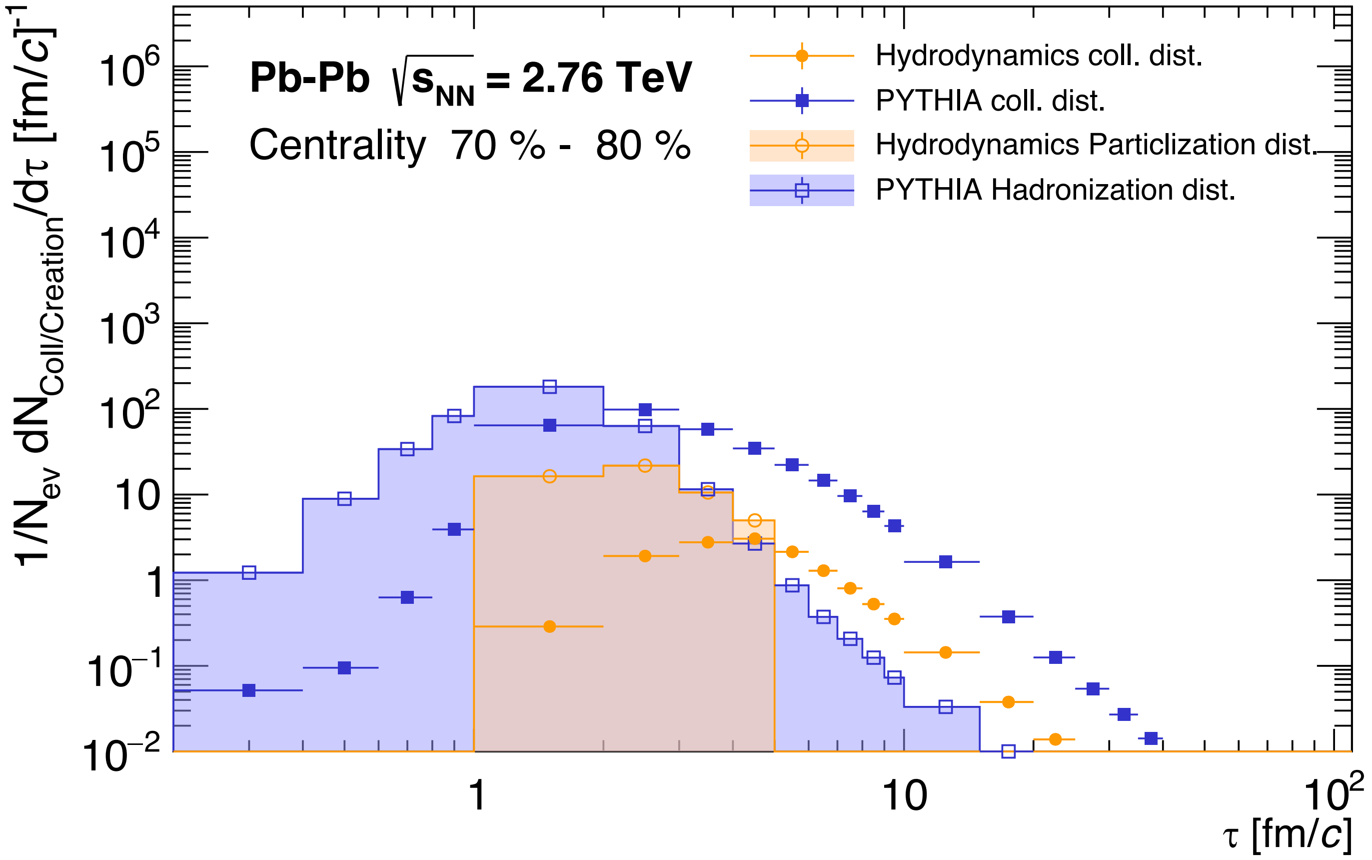

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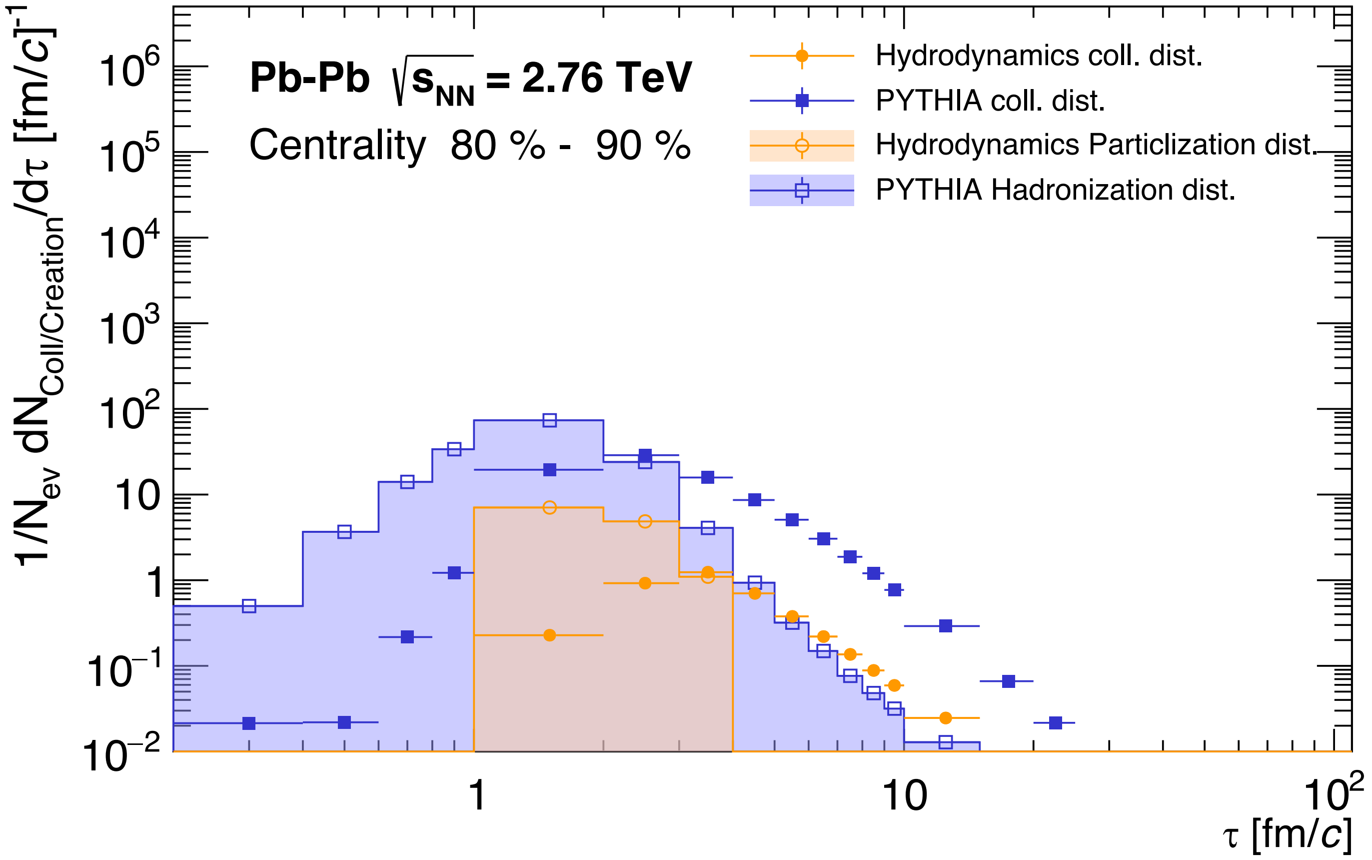

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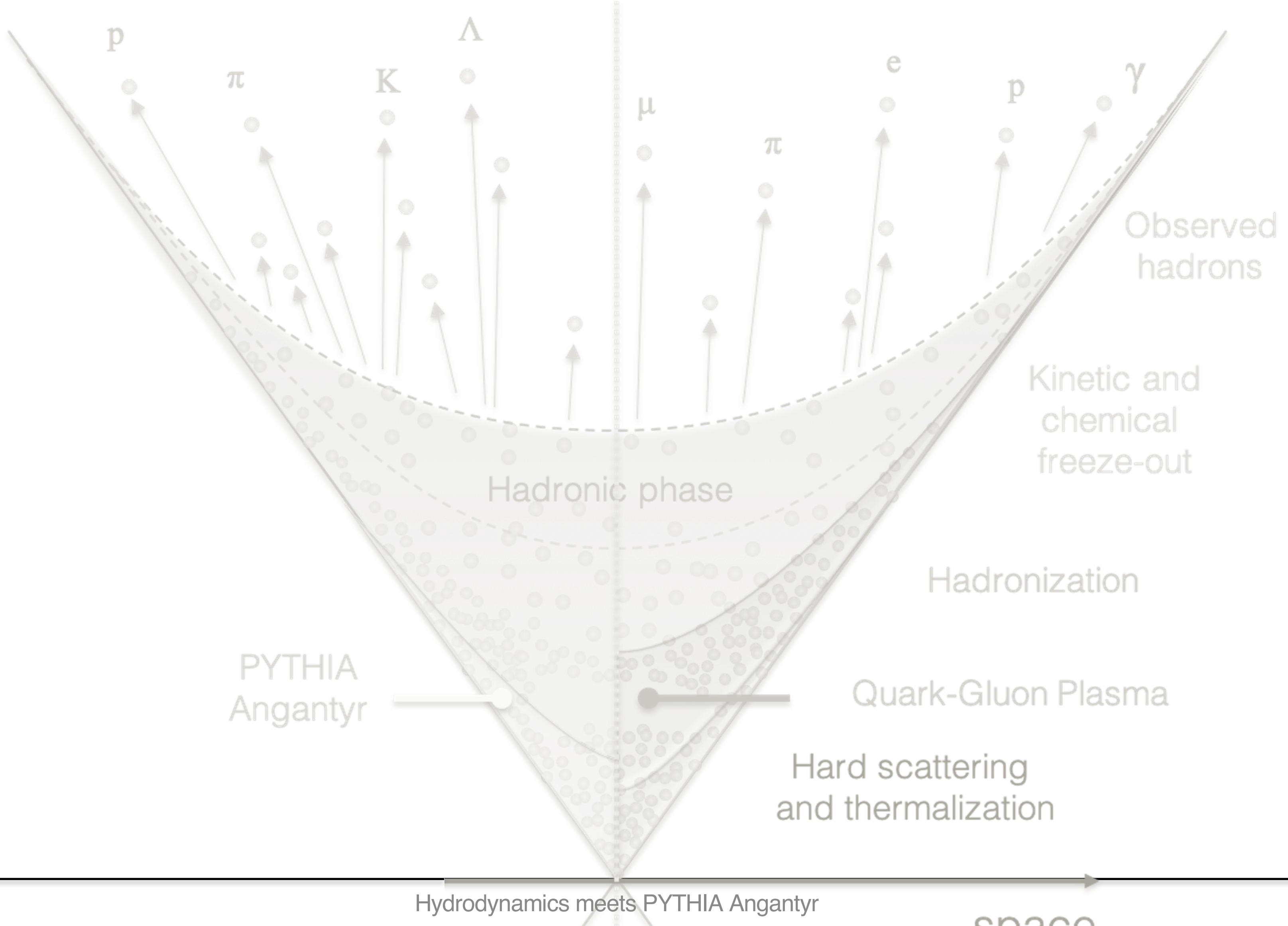
Hadrochemistry



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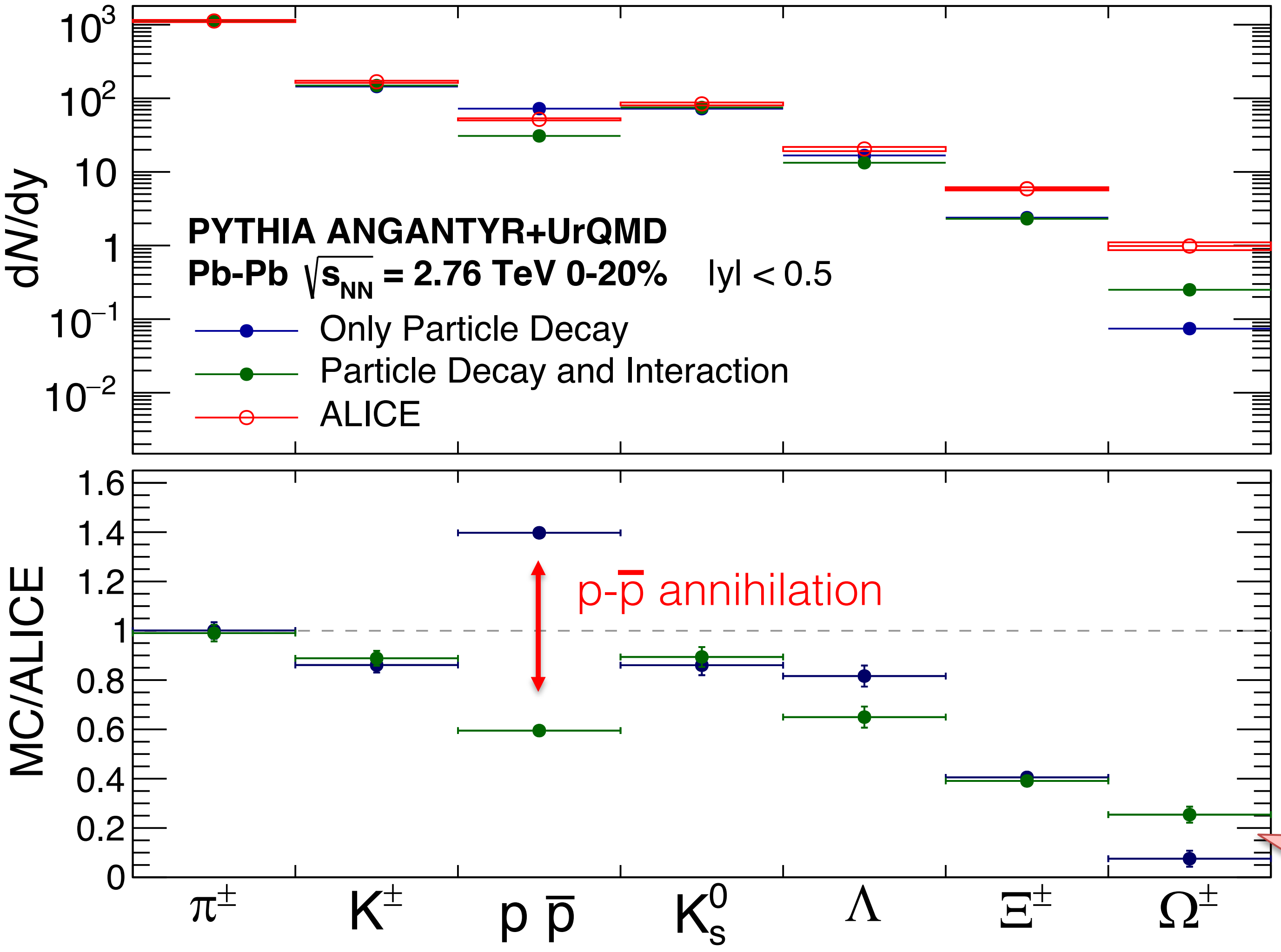

Hadronic interactions

- Strong baryon-antibaryon annihilation: stronger than hydro
- Strangeness exchange re-generates multi-strange baryons?

Strangeness exchange processes?

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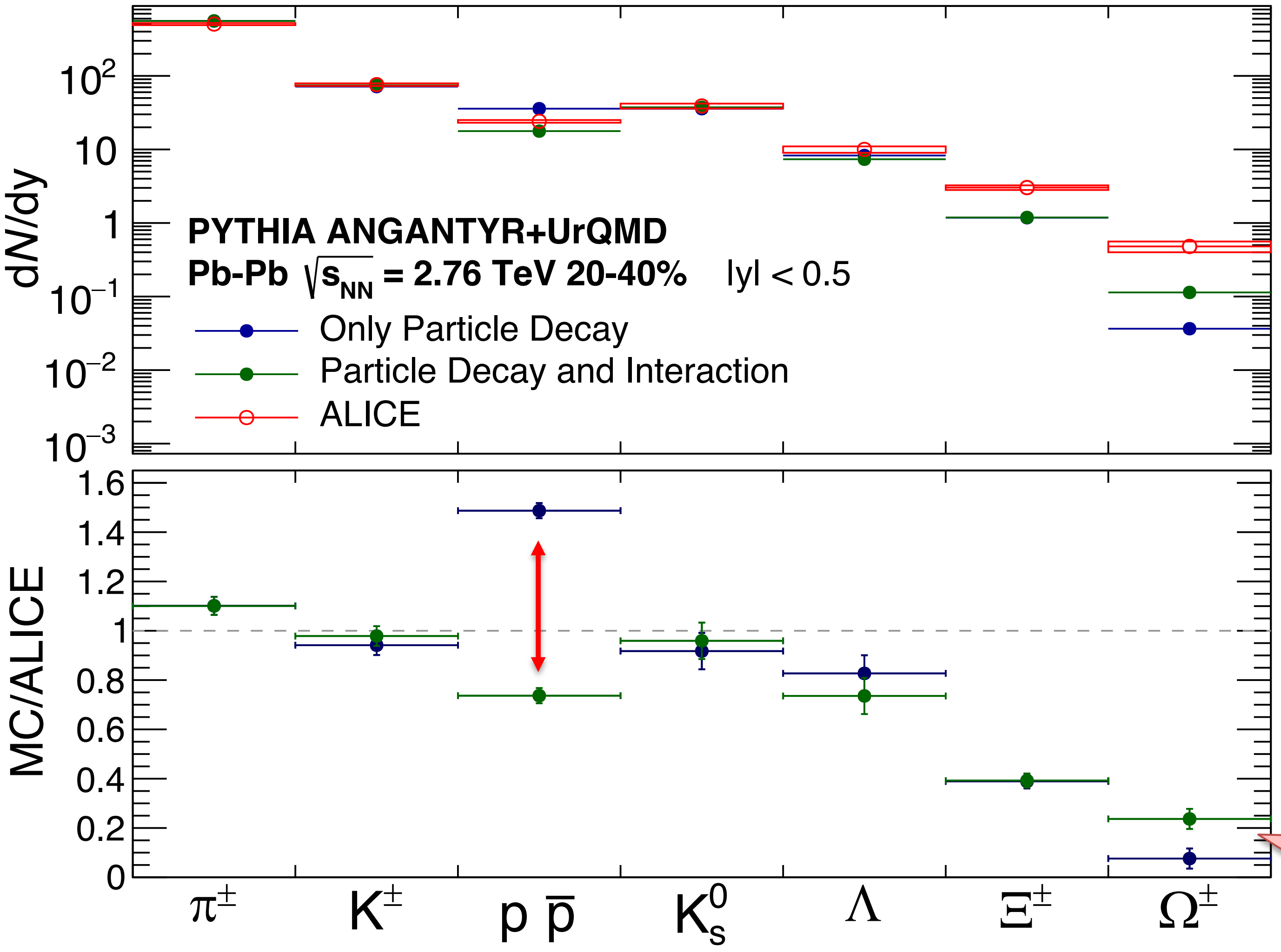
Hadrochemistry



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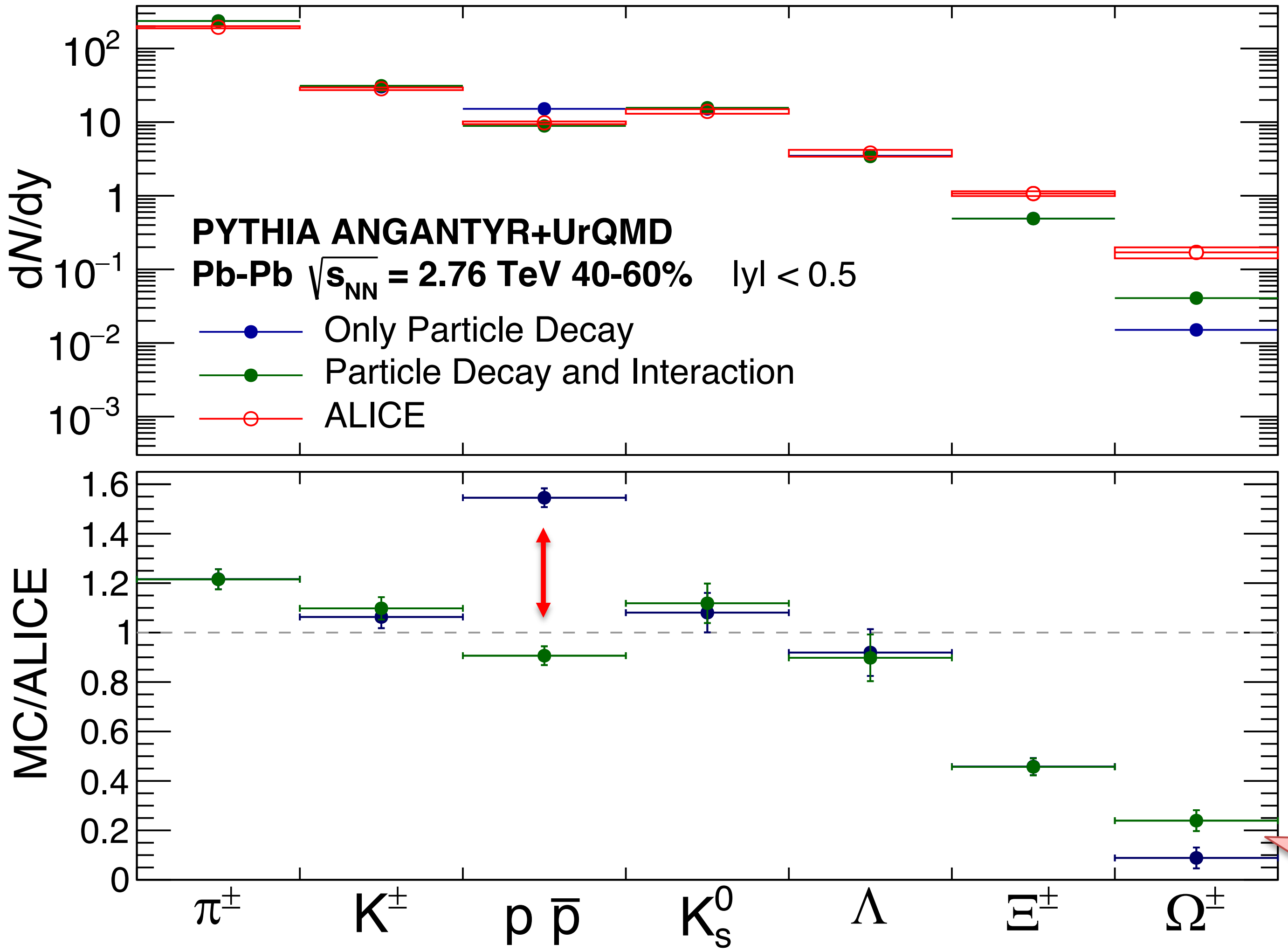

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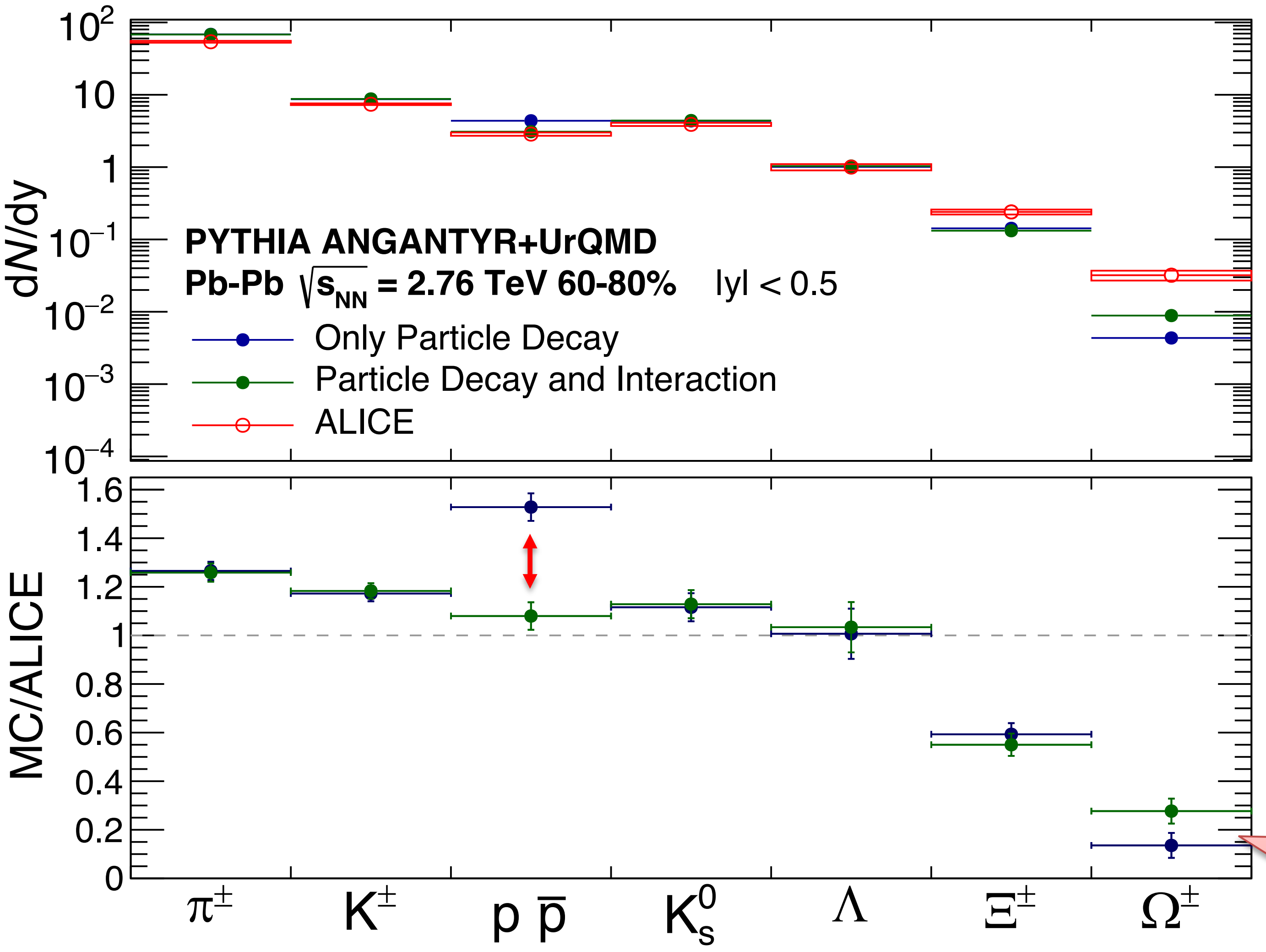

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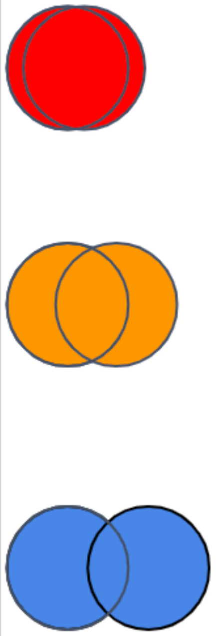
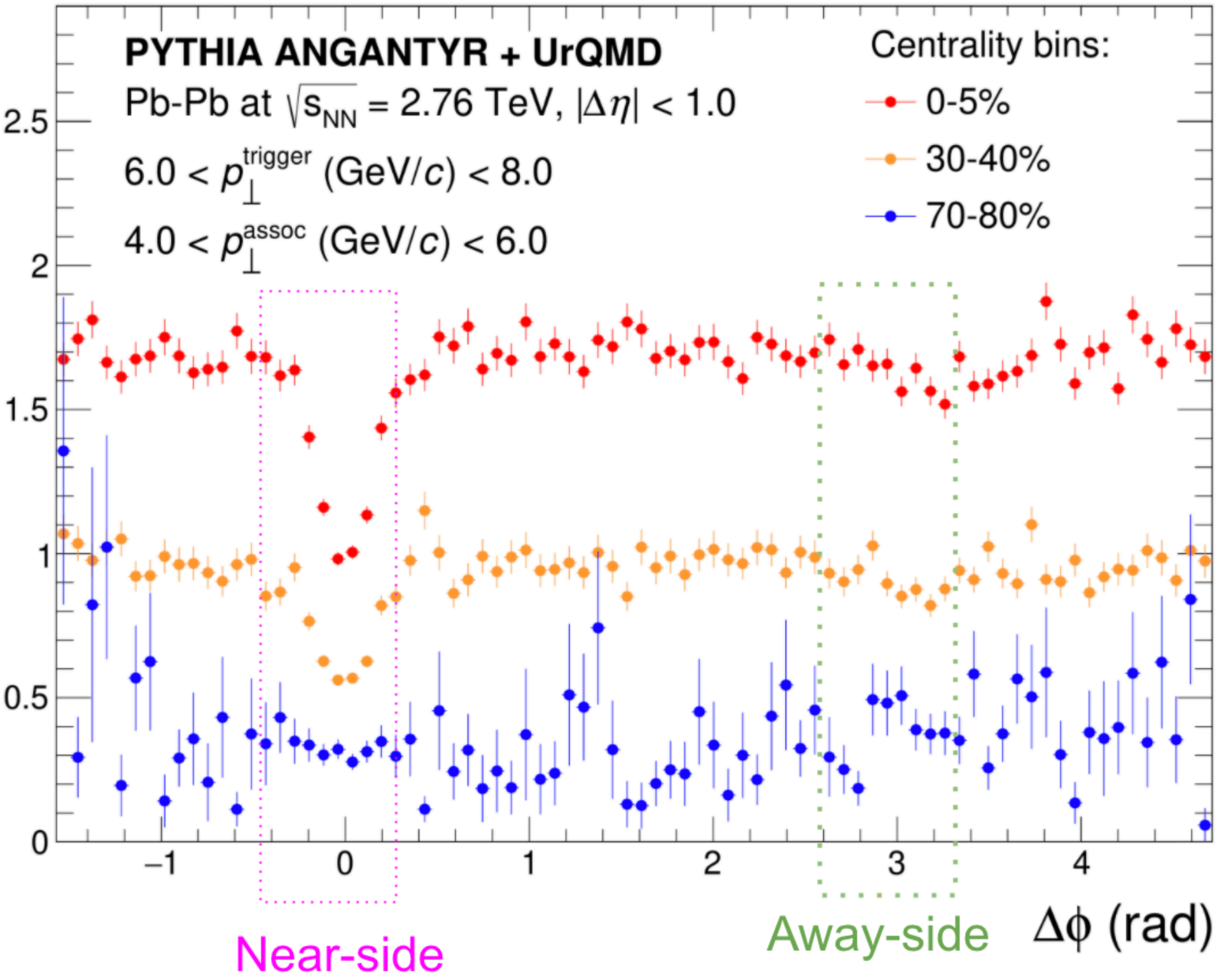
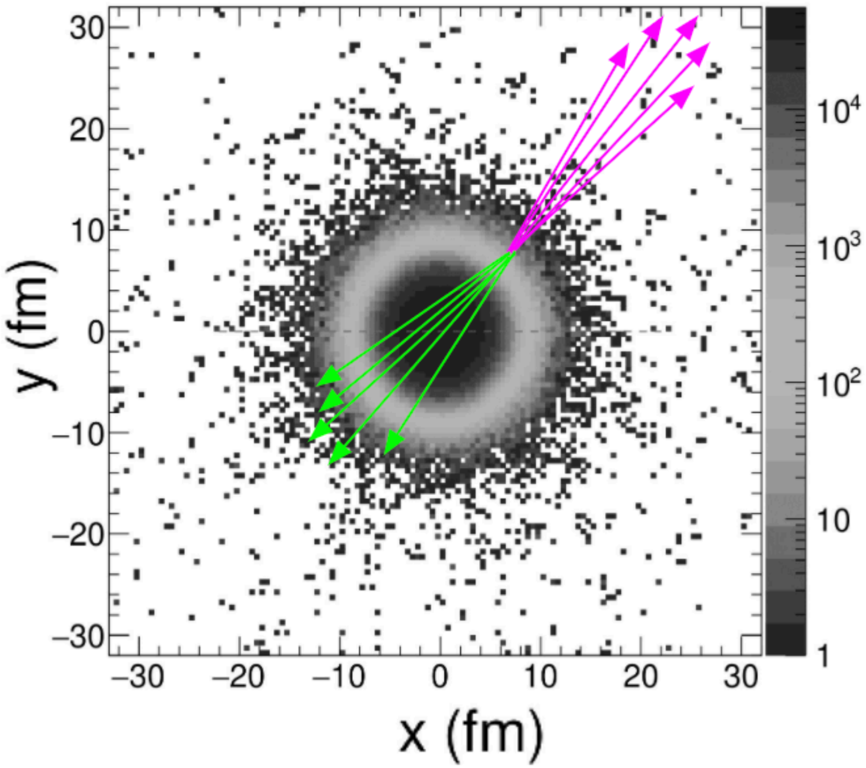
Two-particle correlations: Hadronic collisions

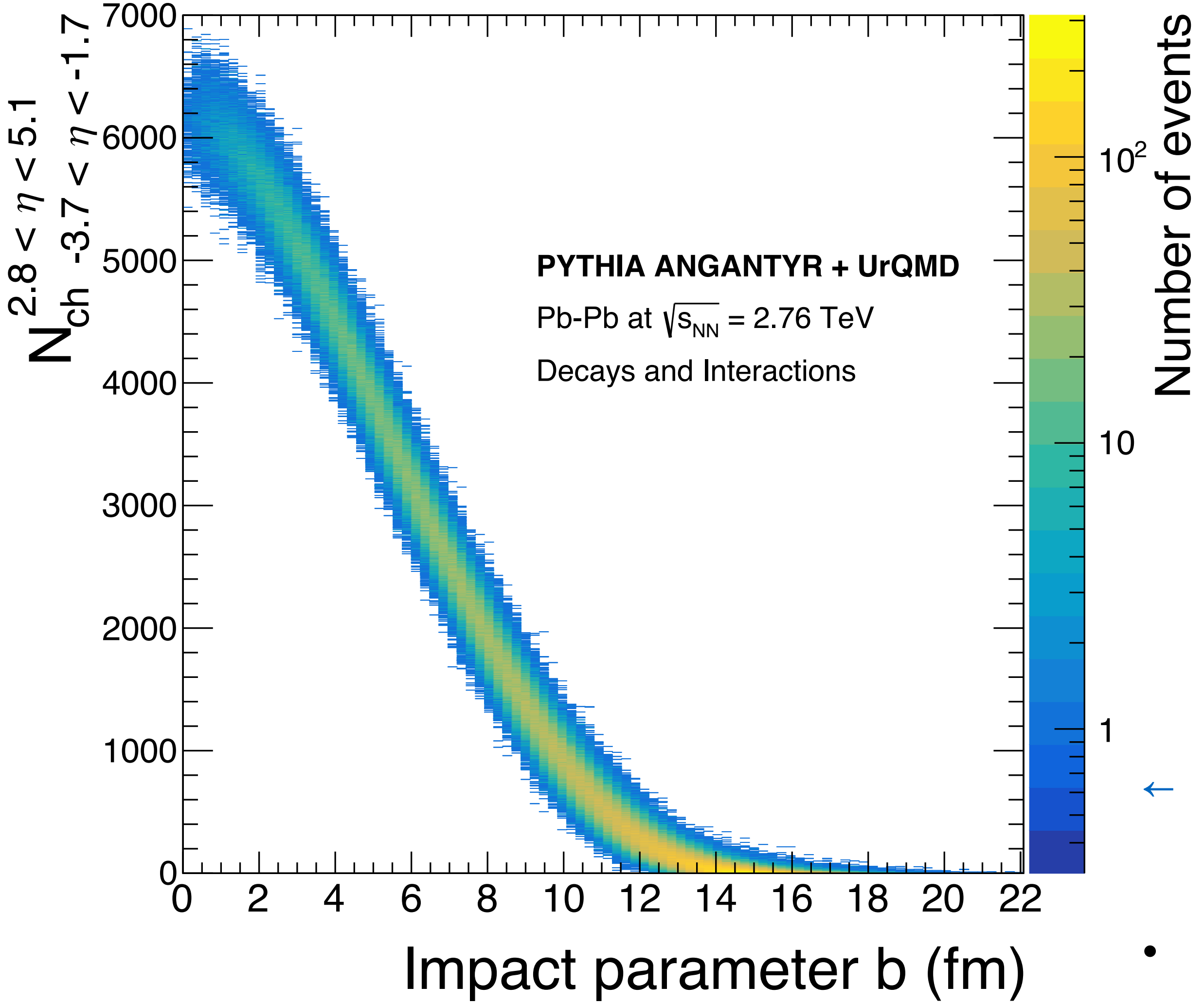


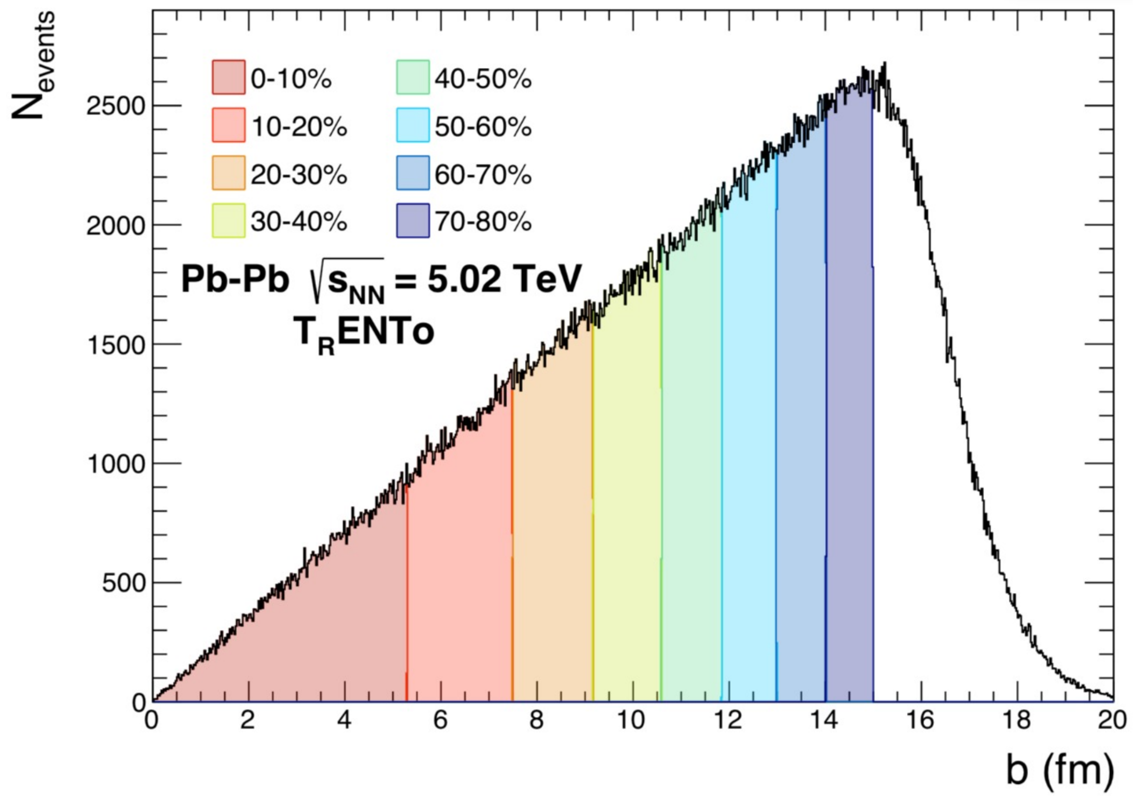


- (Triggered) near-side interacts less than away-side
- Due to hadronic phase!



Determining centrality





← Experimentally done with forward detectors

- Pseudorapidity: $-3.7 < \eta < -1.7$, $2.8 < \eta < 5.1$
- Can't be done with hydro: sampling ends at $\eta = 2.5$

- Correlates with impact parameter b
  - Present in all models
  - Use b for hydro vs PYTHIA: OK within 0-70%

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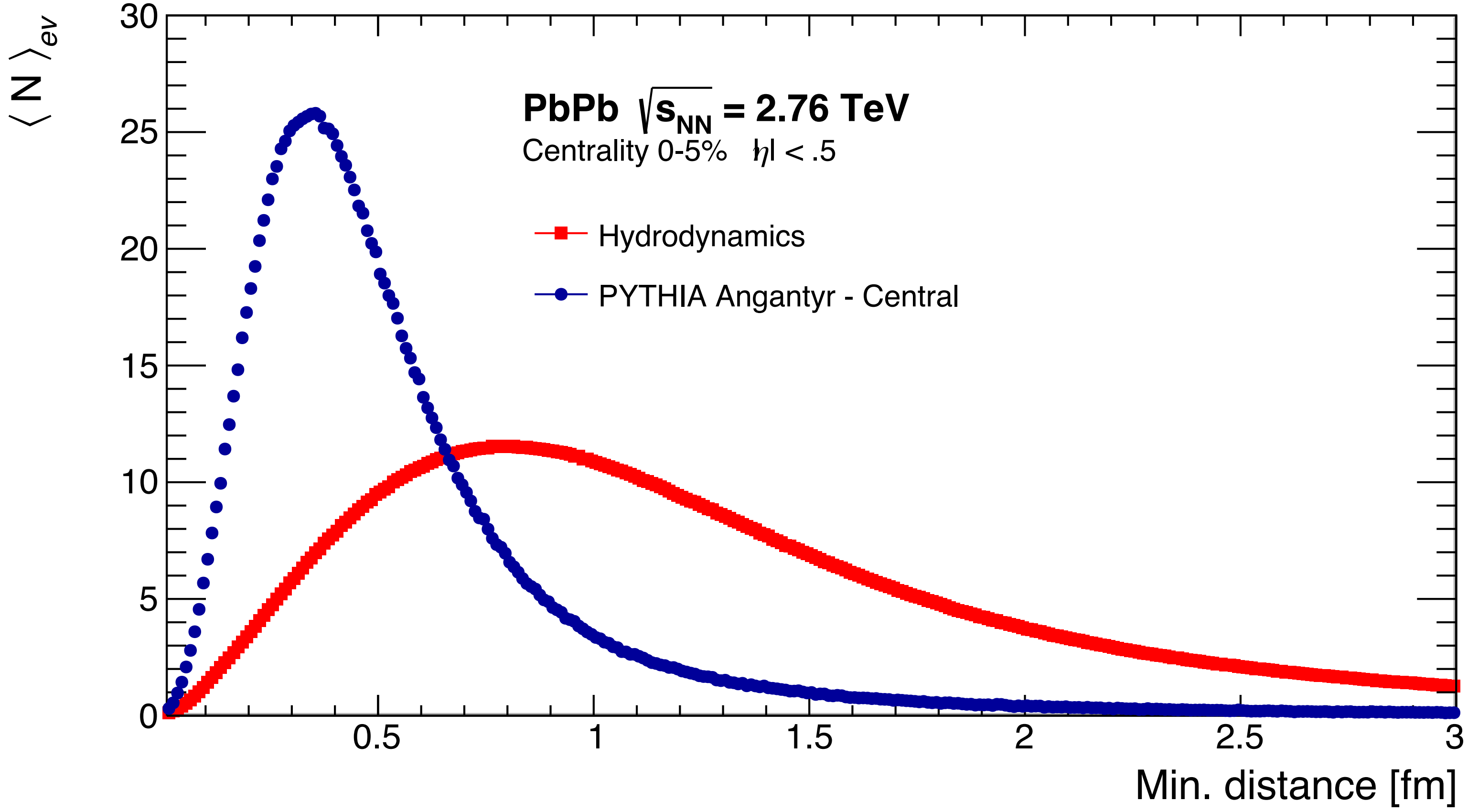
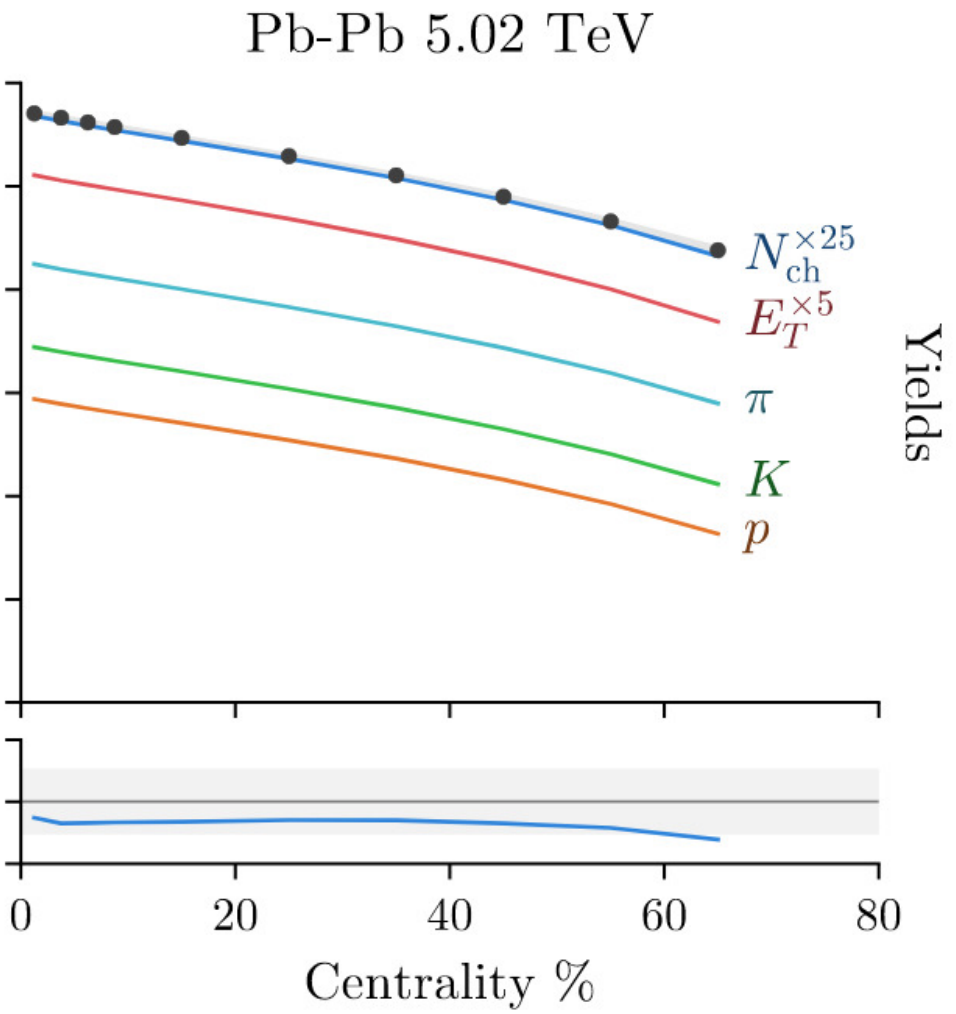
The density problem

- Is the hadronization configuration from PYTHIA **too dense** for UrQMD to handle?
- Approximate factor: density roughly twice on the average
- PYTHIA does not access dramatically different densities compared to hydro…
  - …except for some hotspots with large density: we are testing if these are highly relevant or not



Meet the first contender:

Hybrid model configuration



← TRENTo + Free Streaming + VISH2+1 + FRZOUT + UrQMD (by the Duke group [1]): obtained optimal a posteriori parameters

- We utilize these parameters but with a different overall normalization
- Minor differences in the two approaches under study

[1] Nuc.Phys.A, 967 (67-73)

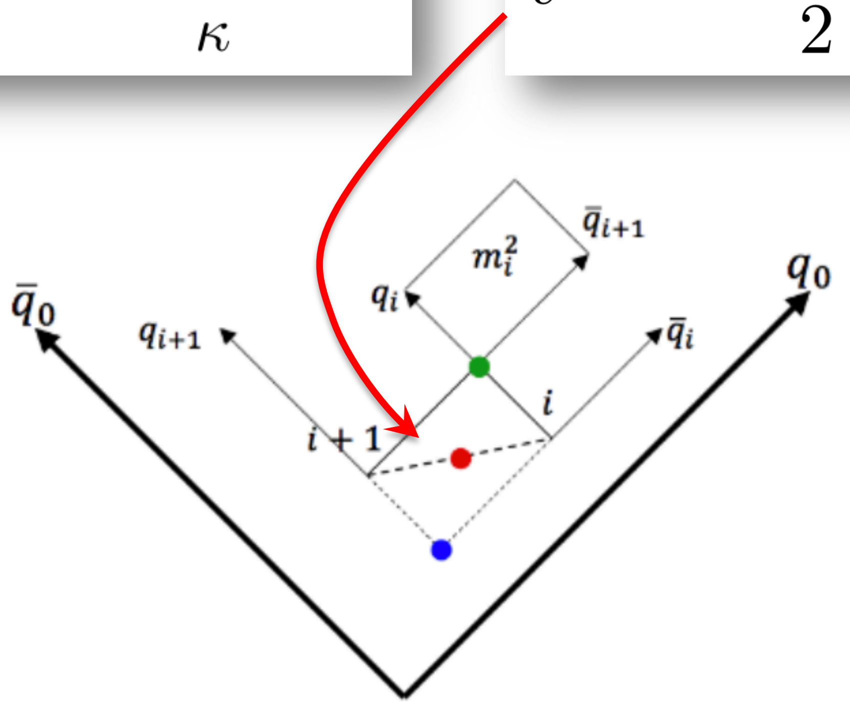
Meet the second contender:

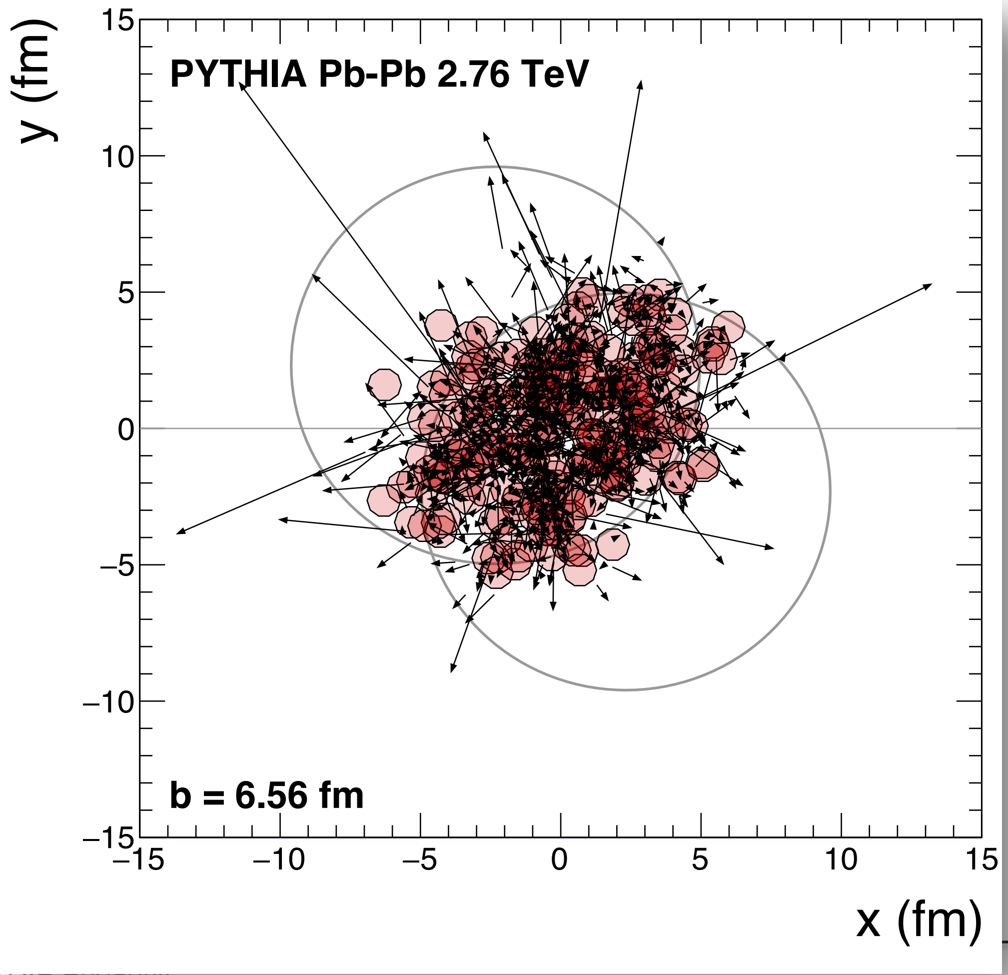
PYTHIA with hadron positions

- Space-time string breakup vertices from 4-momenta p, normalized string breakup positions x
- Hadron position v^h: average between vertices
- Formalism also extended to complex topologies

$$v = \frac{x^+p^+ + x^-p^-}{\kappa}$$

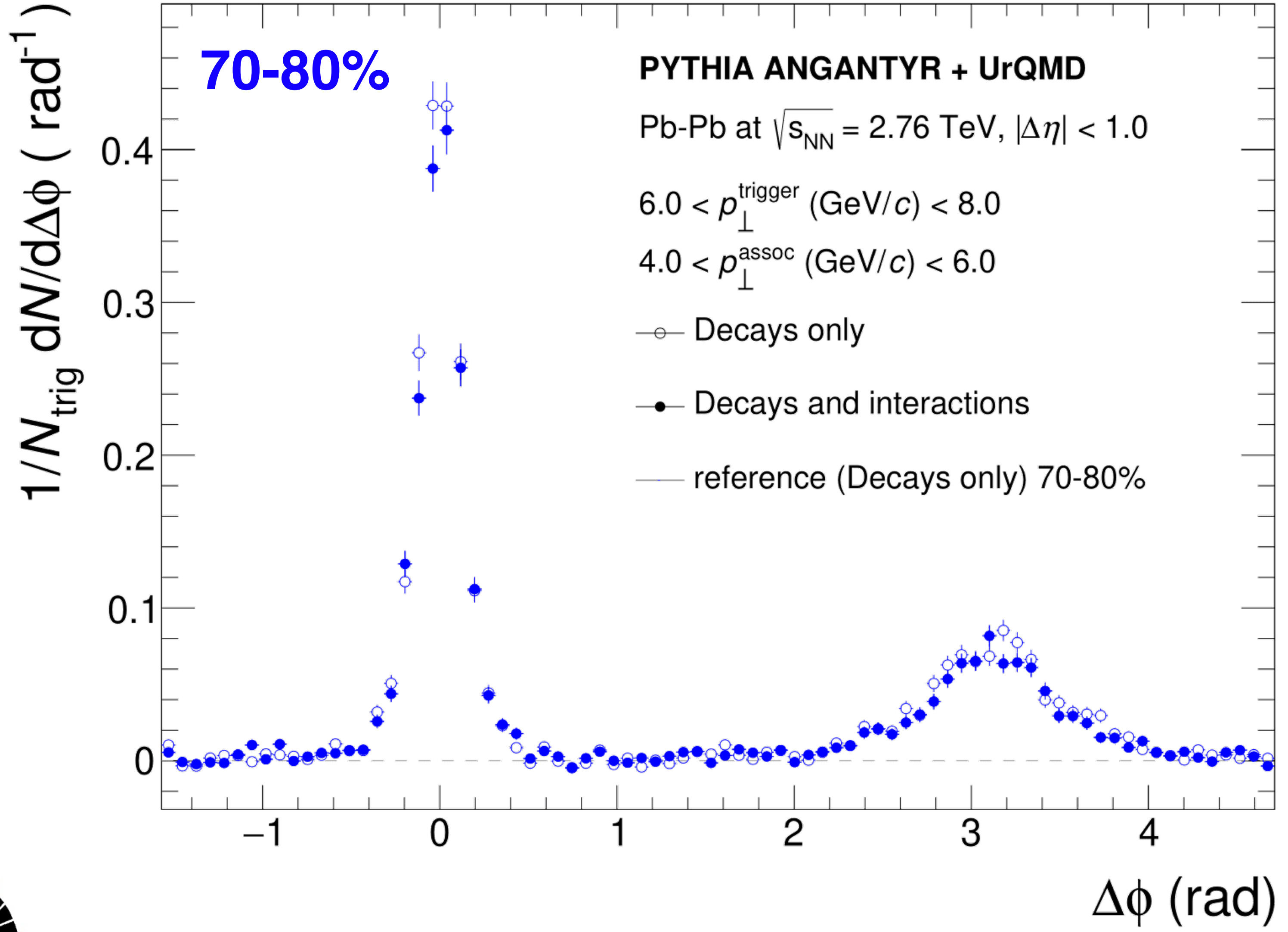
$$v^h = \frac{v_1 + v_2}{2}$$





Two-particle correlations in 70-80%

With and without hadronic interactions

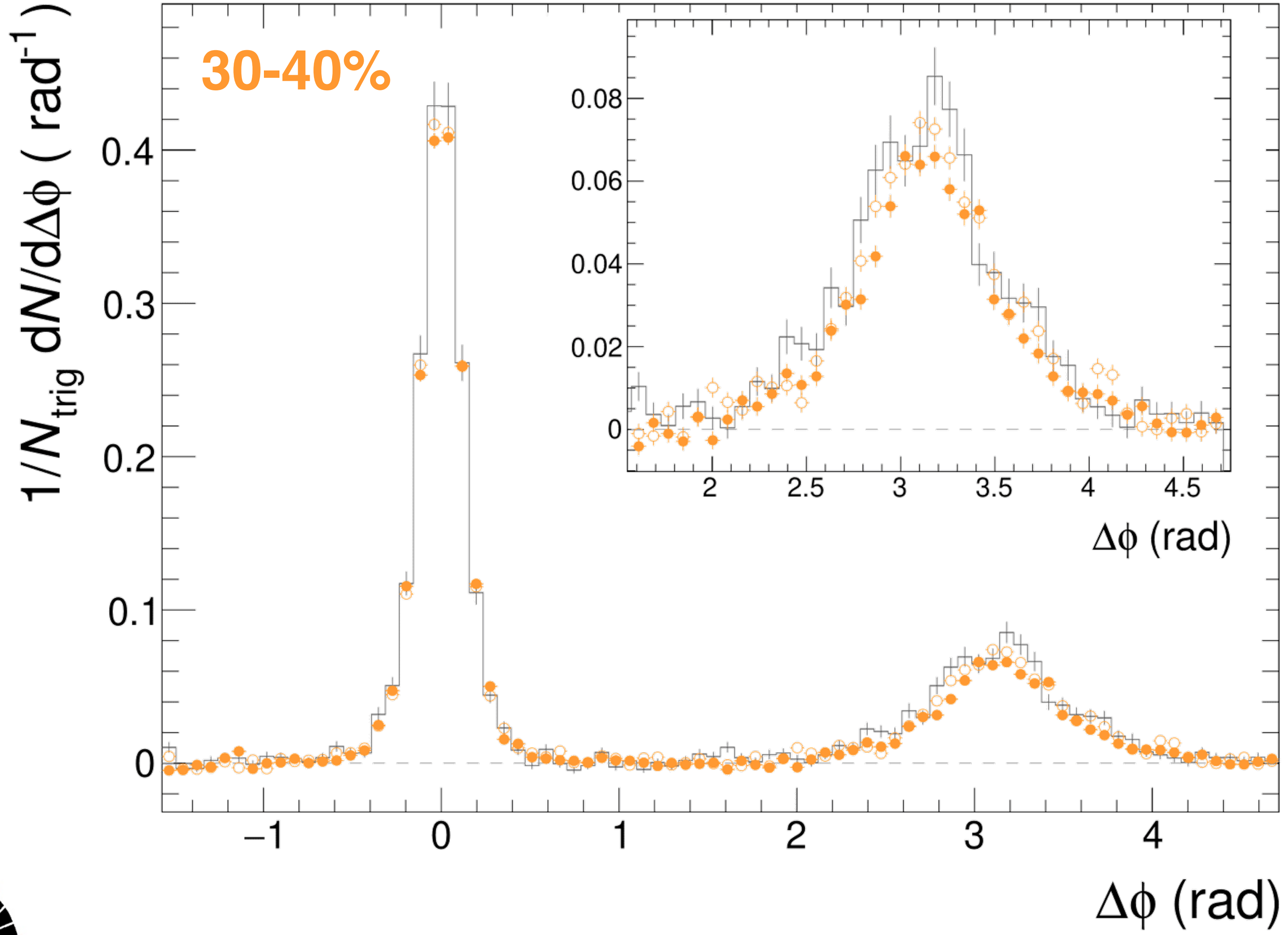


Peripheral collisions: Near-side and away-side not affected by the hadronic interactions in peripheral collisions

Background subtracted

Two-particle correlations in 30-40%

With and without hadronic interactions



Mid-central collisions: small away-side jet suppression due to hadronic interactions

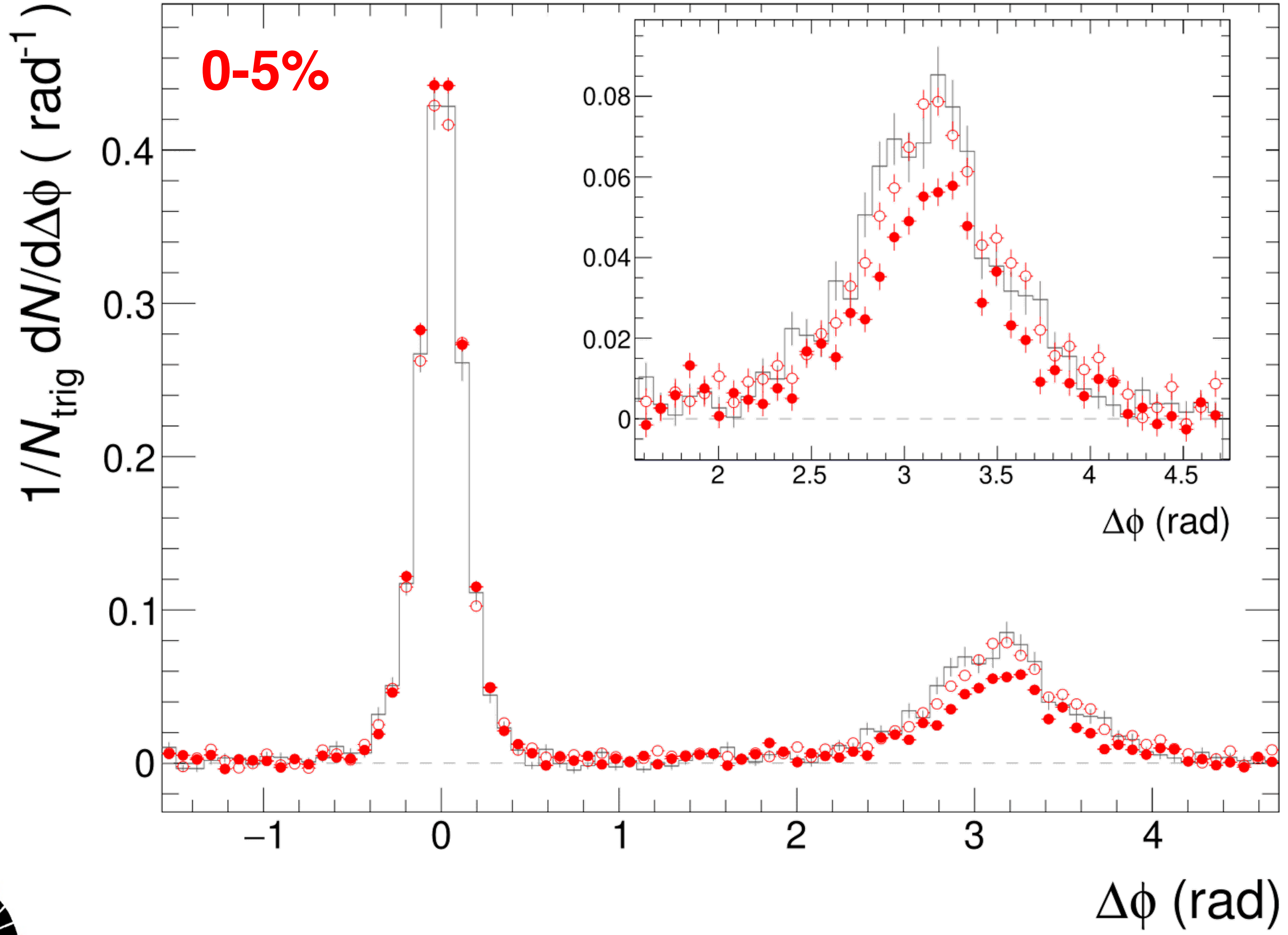
Near-side is not affected!

Due to hadronic phase!

Background subtracted

Two-particle correlations in 0-5%

With and without hadronic interactions



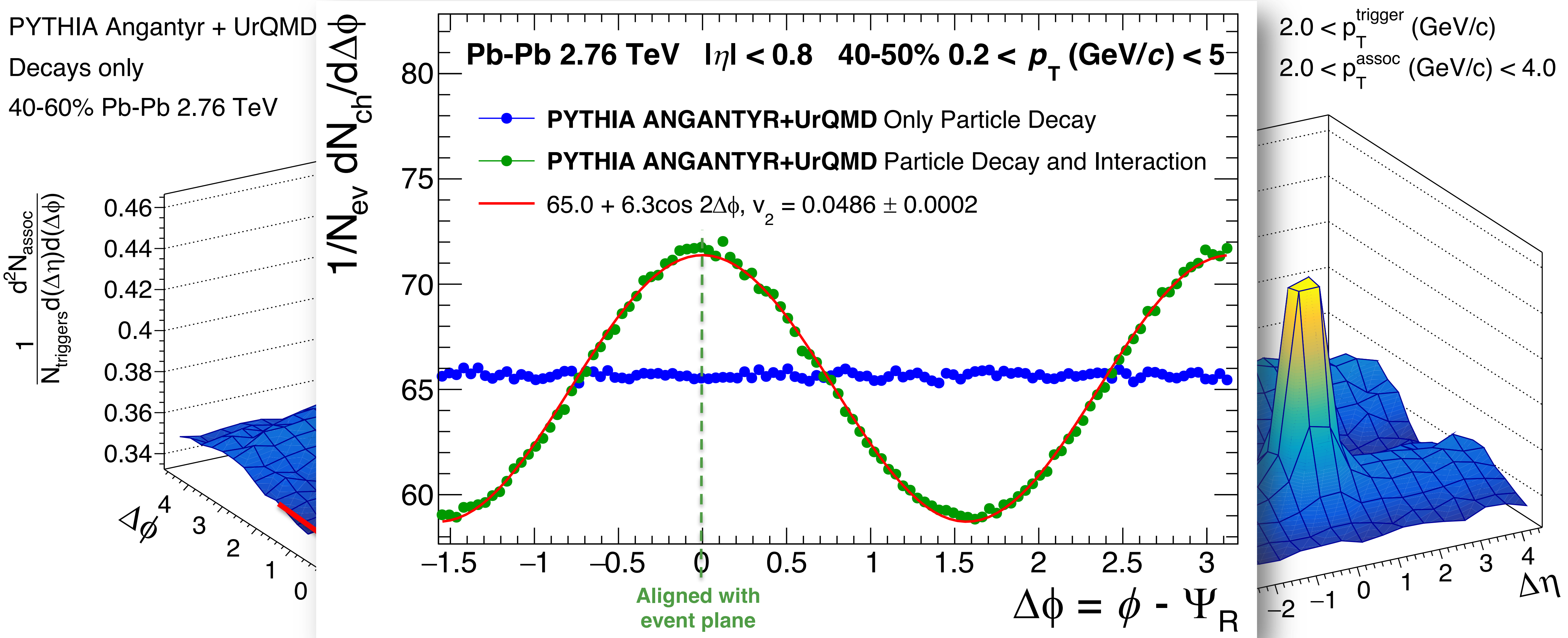
Central collisions: visible suppression

Near-side is not affected!

Magnitude of suppression versus centrality?

Background subtracted

PYTHIA+UrQMD: Flow from the hadronic phase?



- No hadronic interactions: no near-side Ridge
- With hadronic interactions: long-range near-side Ridge

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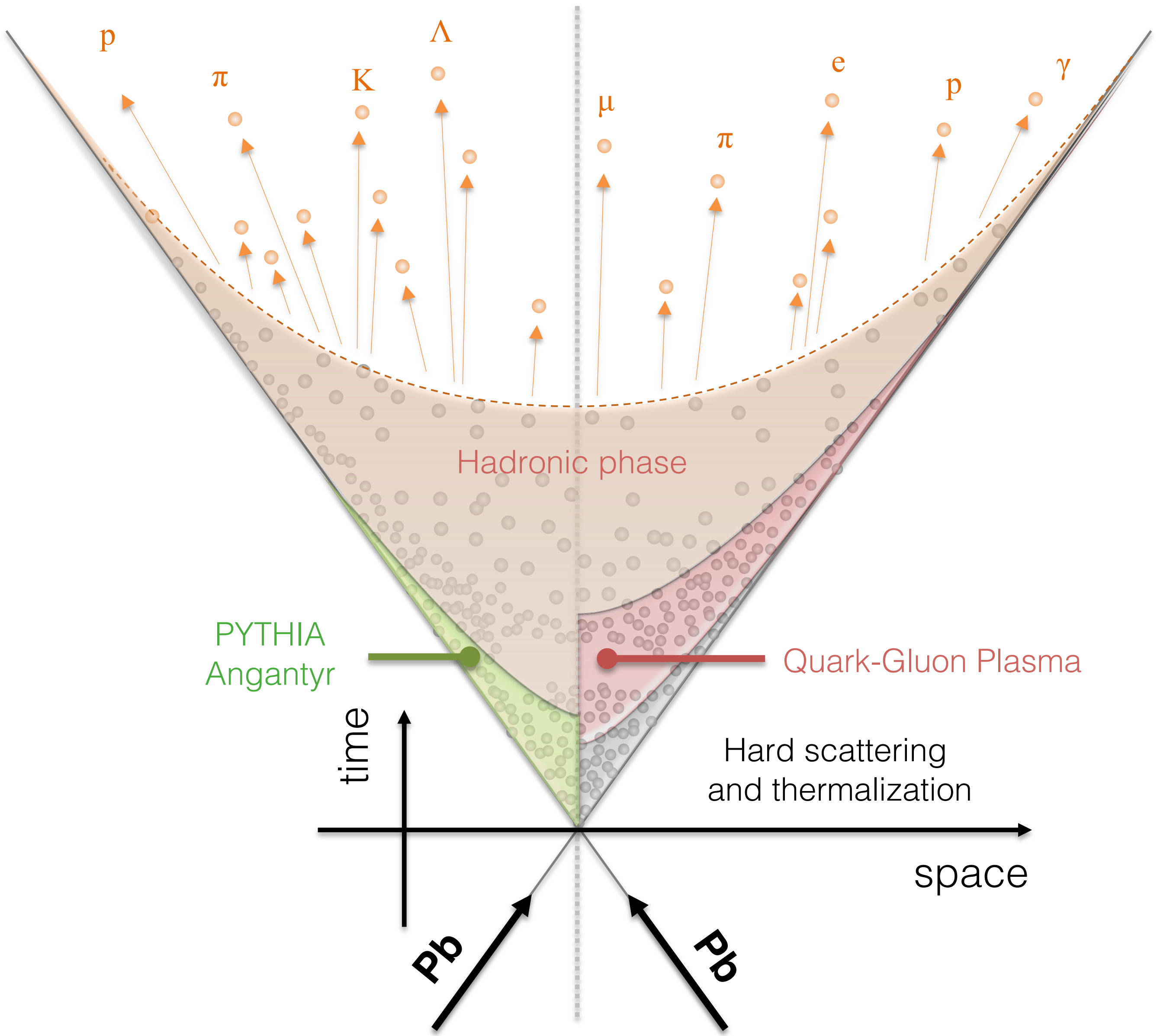
p
π
K
Λ
μ
π
e
p
γ
Hadronic phase
PYTHIA
Angantyr
Quark-Gluon Plasma
time
Hard scattering
and thermalization
space
Pb
Pb