To equilibrate or not to equilibrate: Hydrodynamics meets PYTHIA Angantyr

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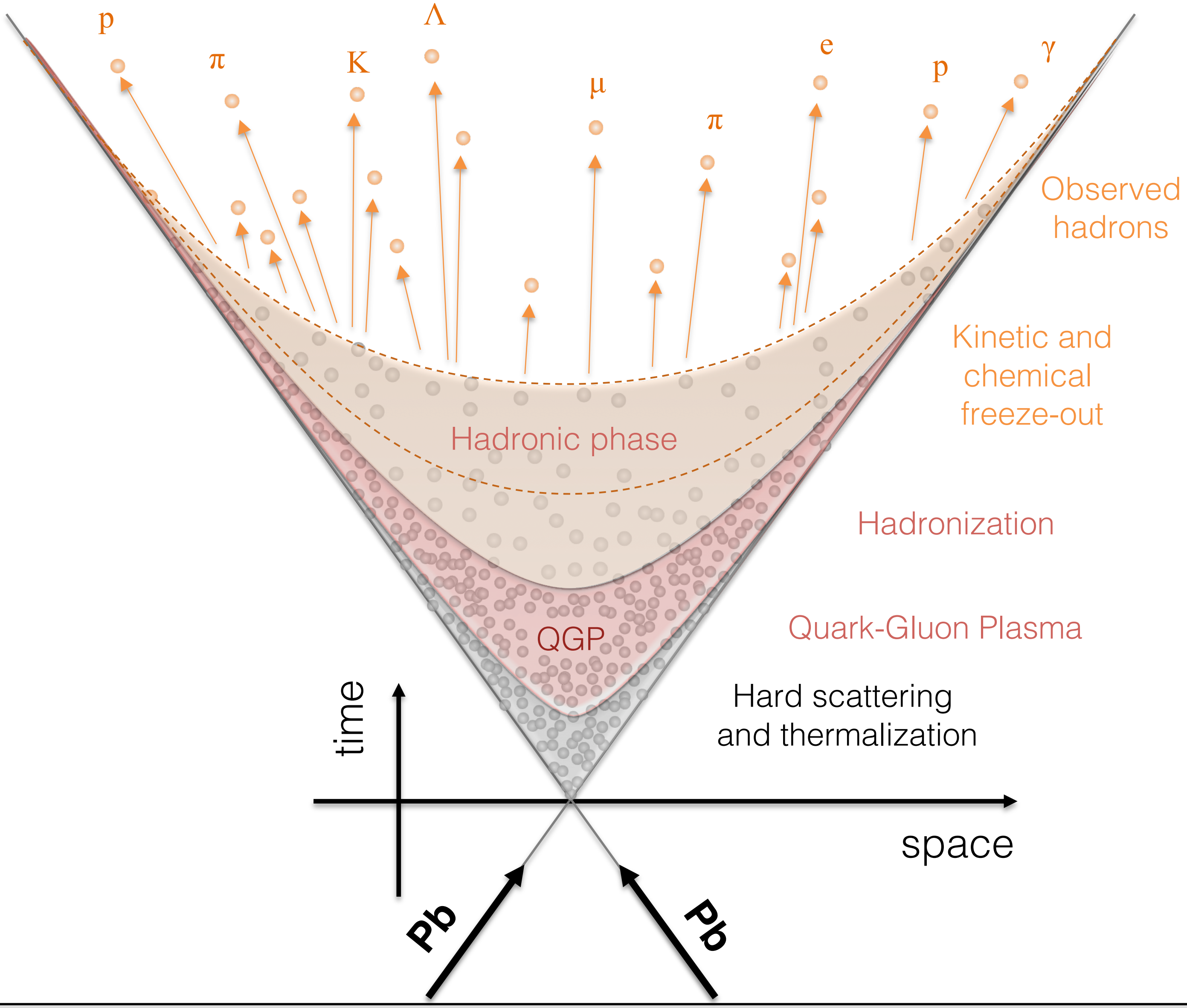
Schematic representation of

A heavy ion collision

(from the MADAI collaboration)



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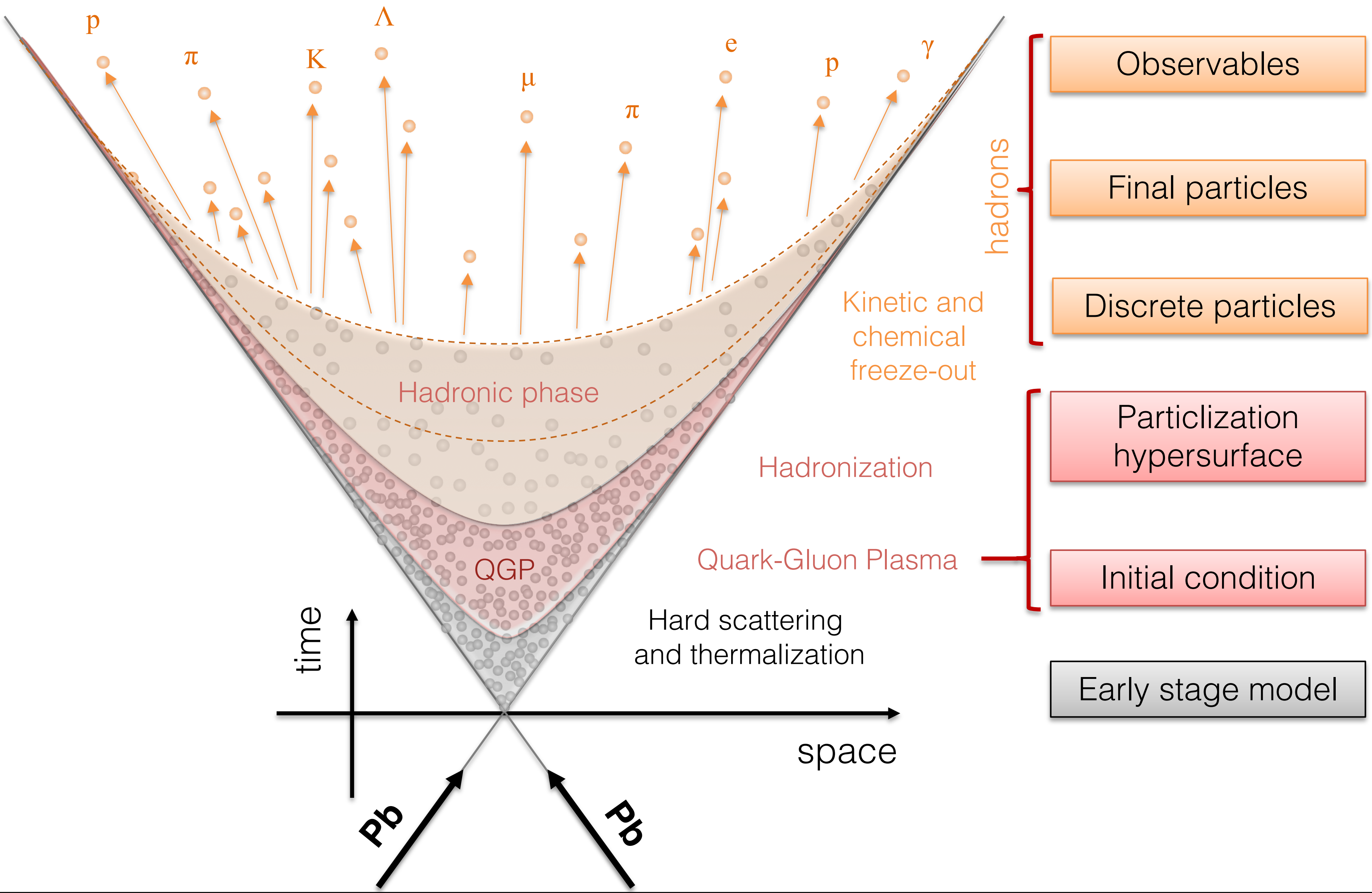

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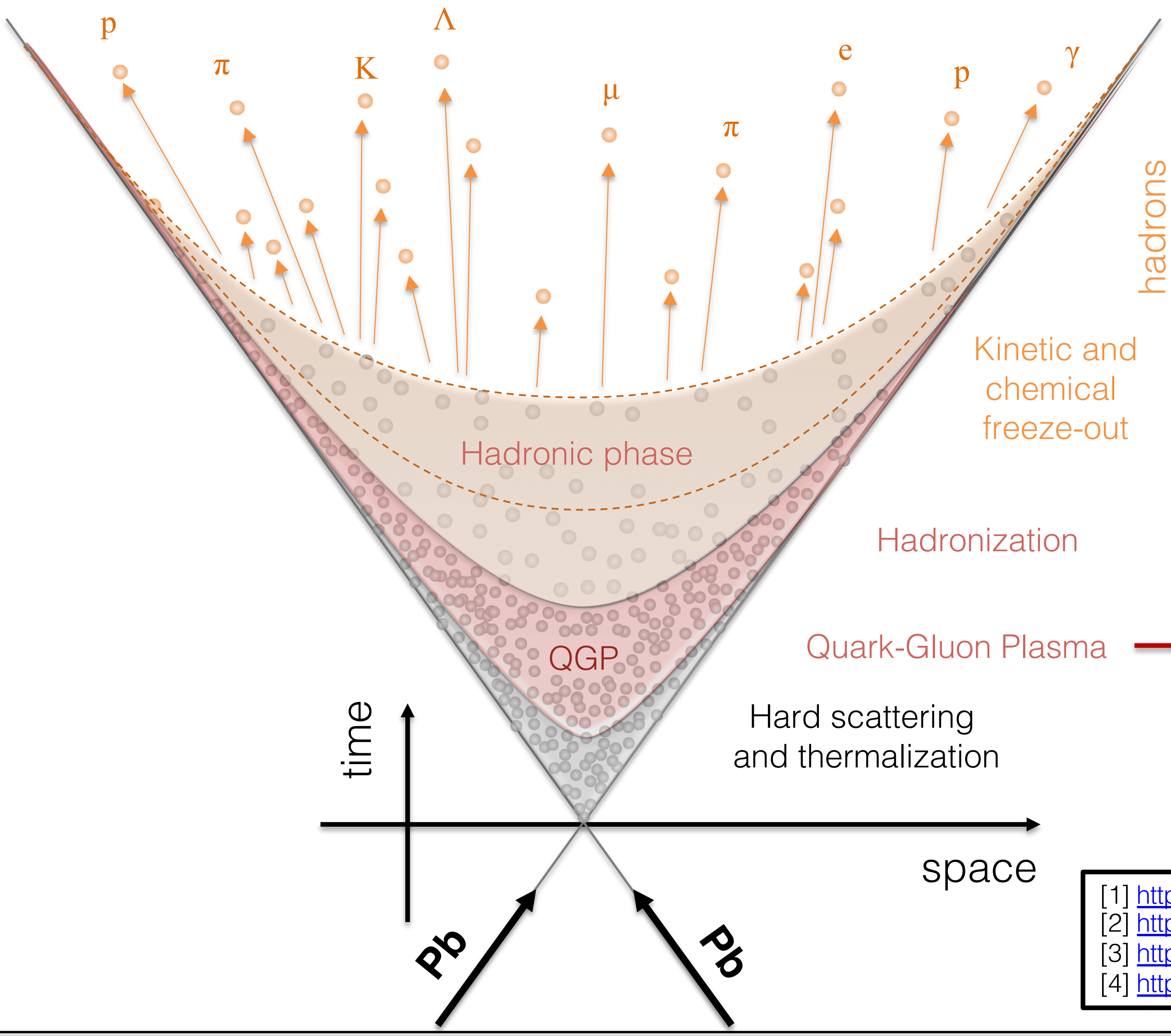

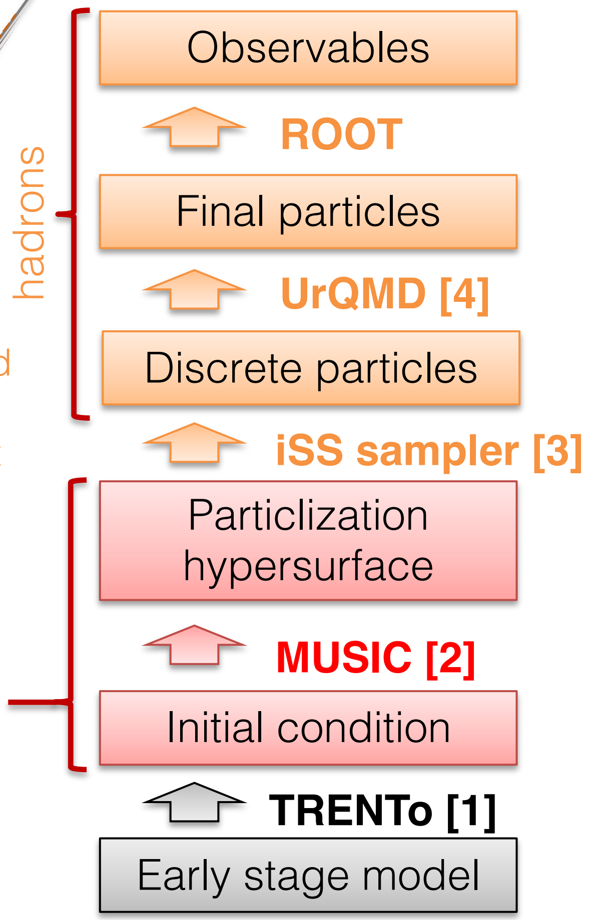

[1] http://qcd.phy.duke.edu/trento/
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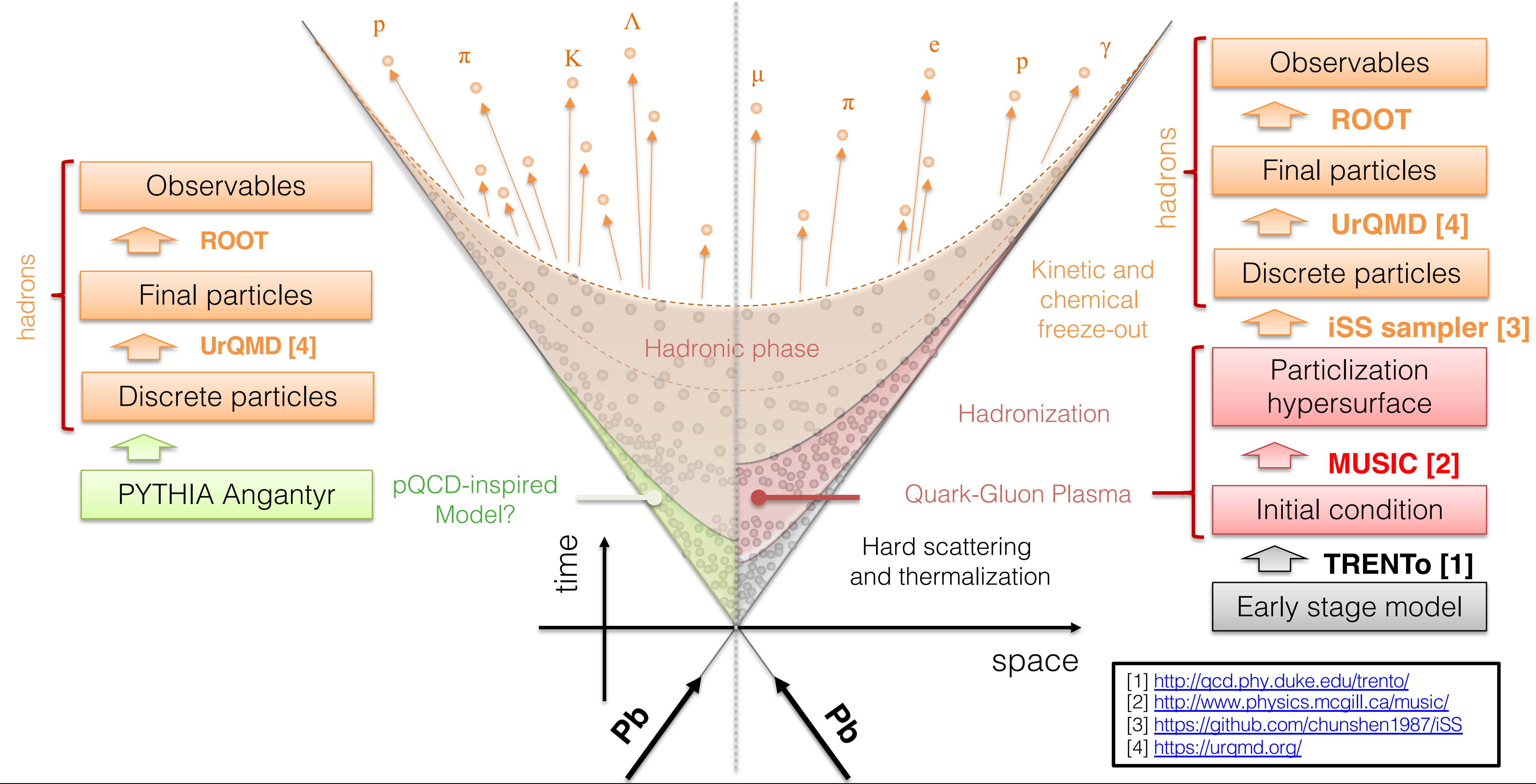

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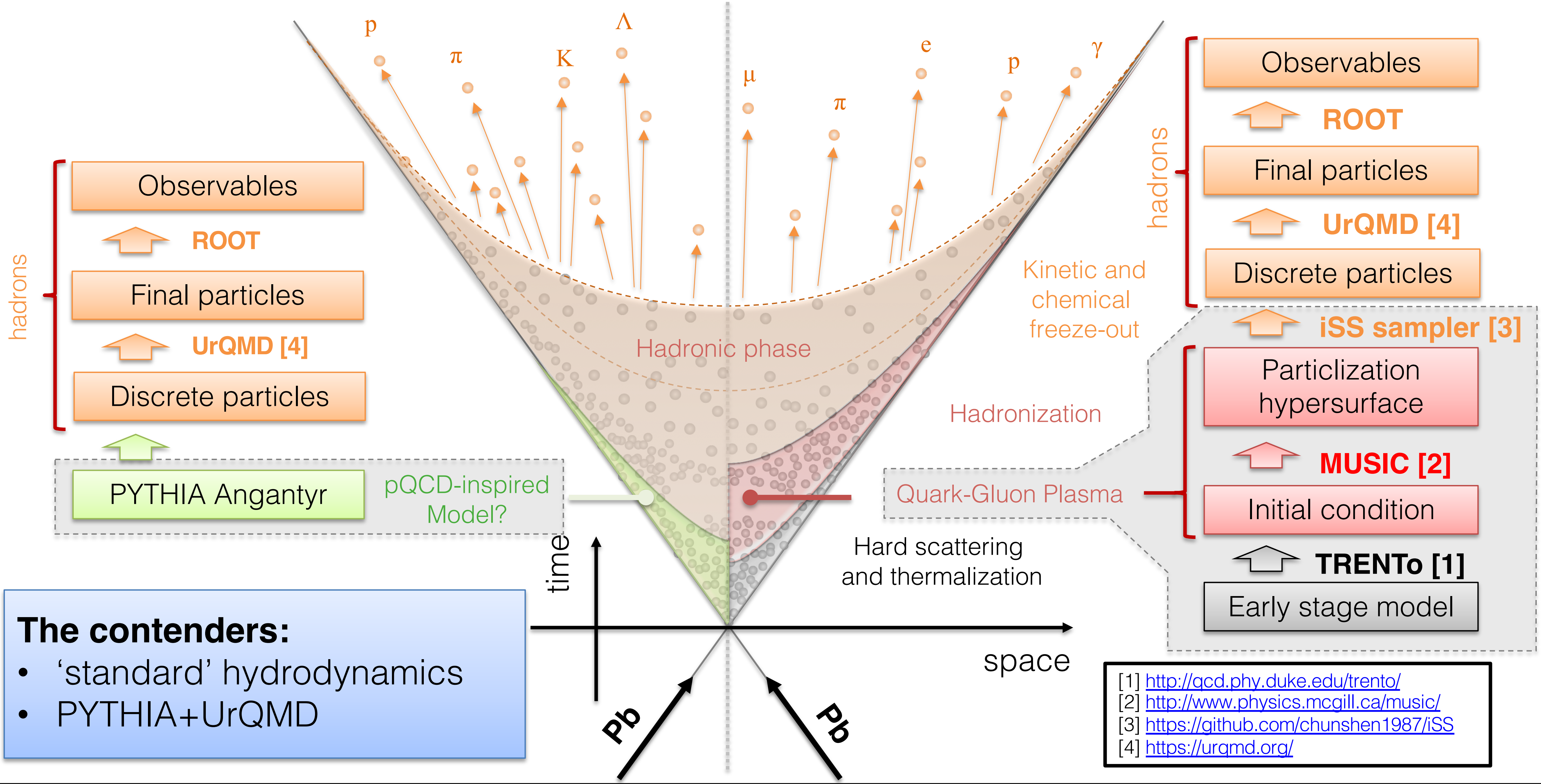

The contenders:

- ‘standard’ hydrodynamics
- PYTHIA+UrQMD

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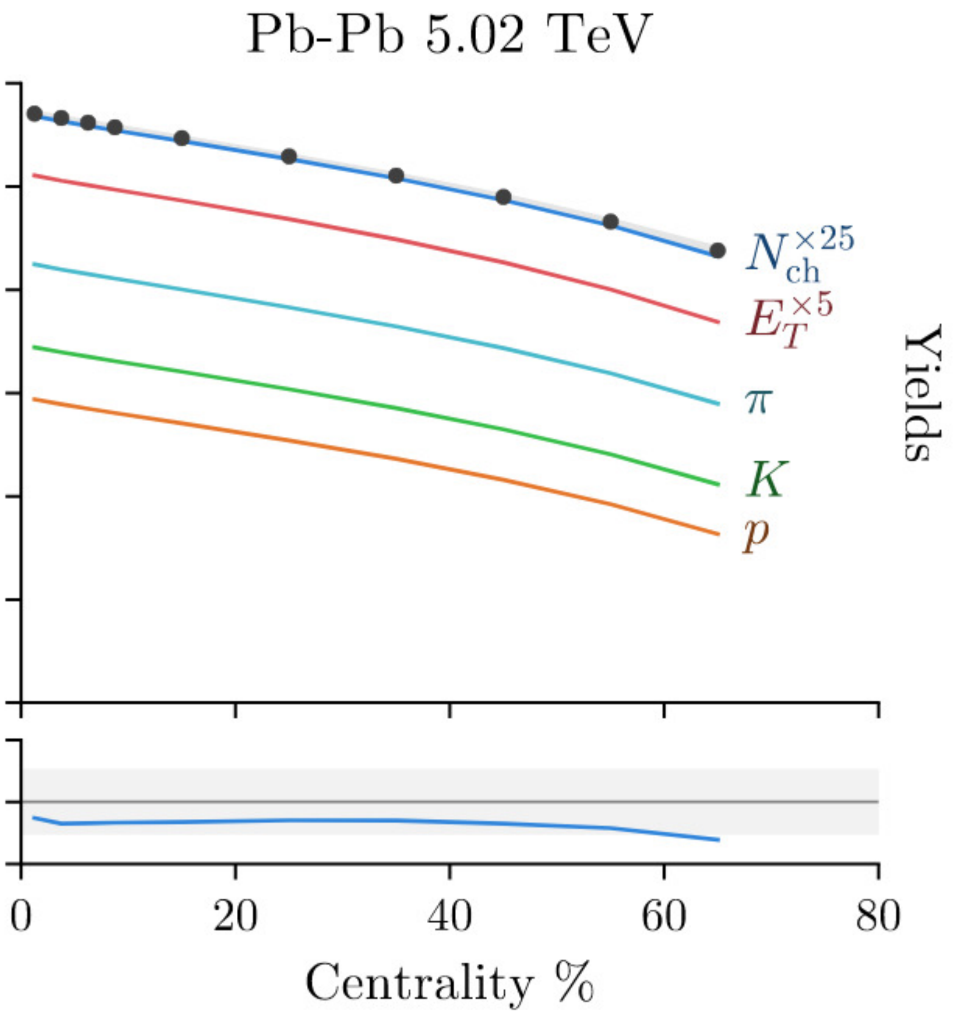
Meet the first contender:

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)

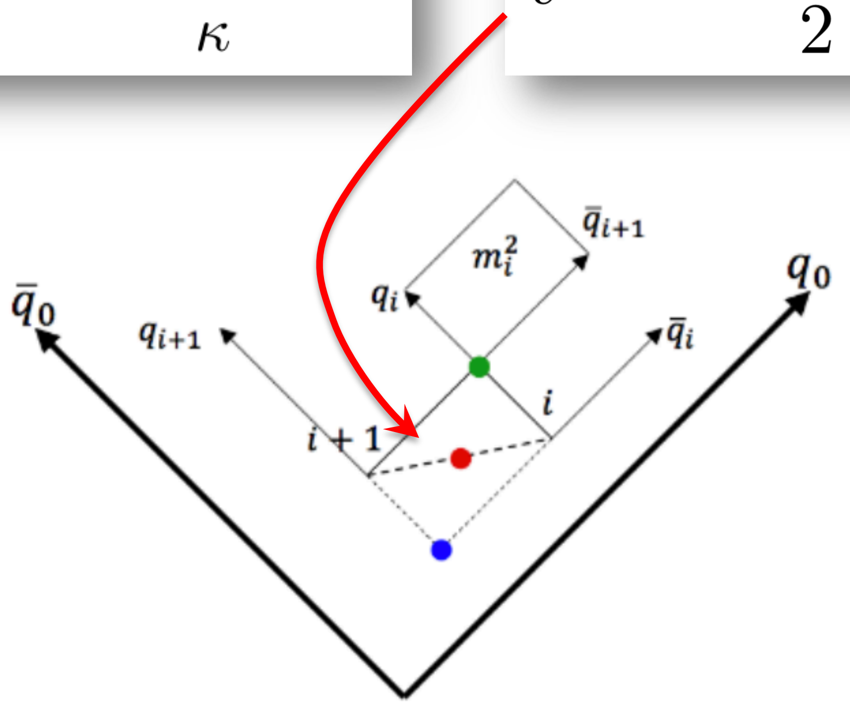
Meet the second contender:

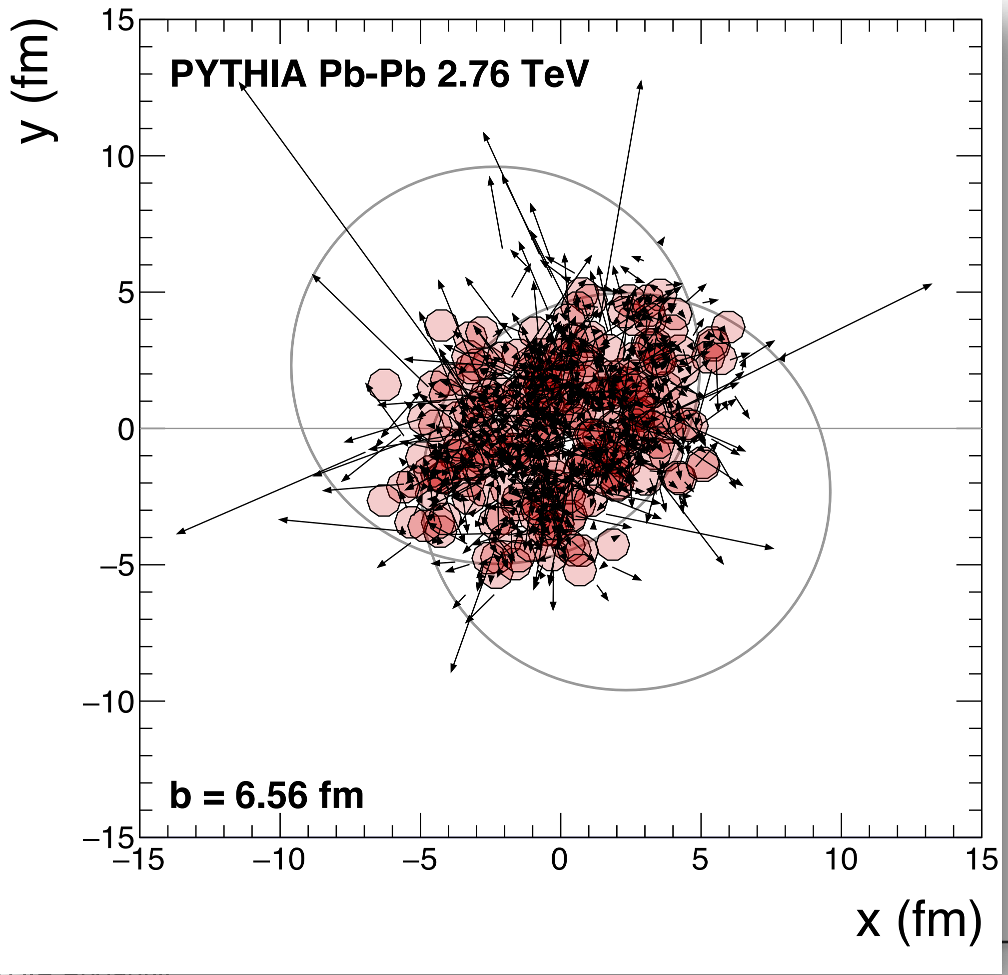
PYTHIA with hadron positions

- 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

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

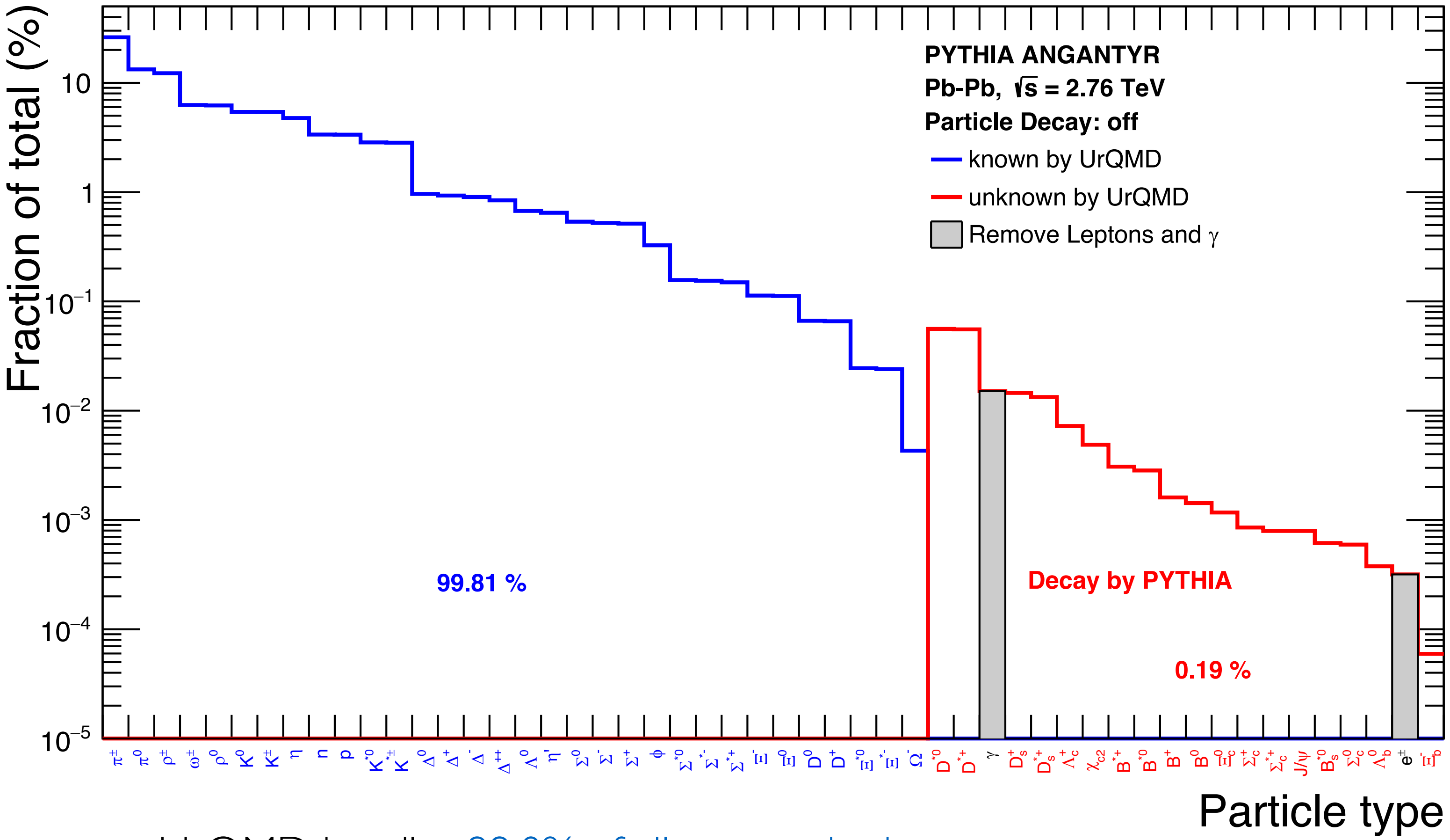
$$v^h = \frac{v_1 + v_2}{2}$$





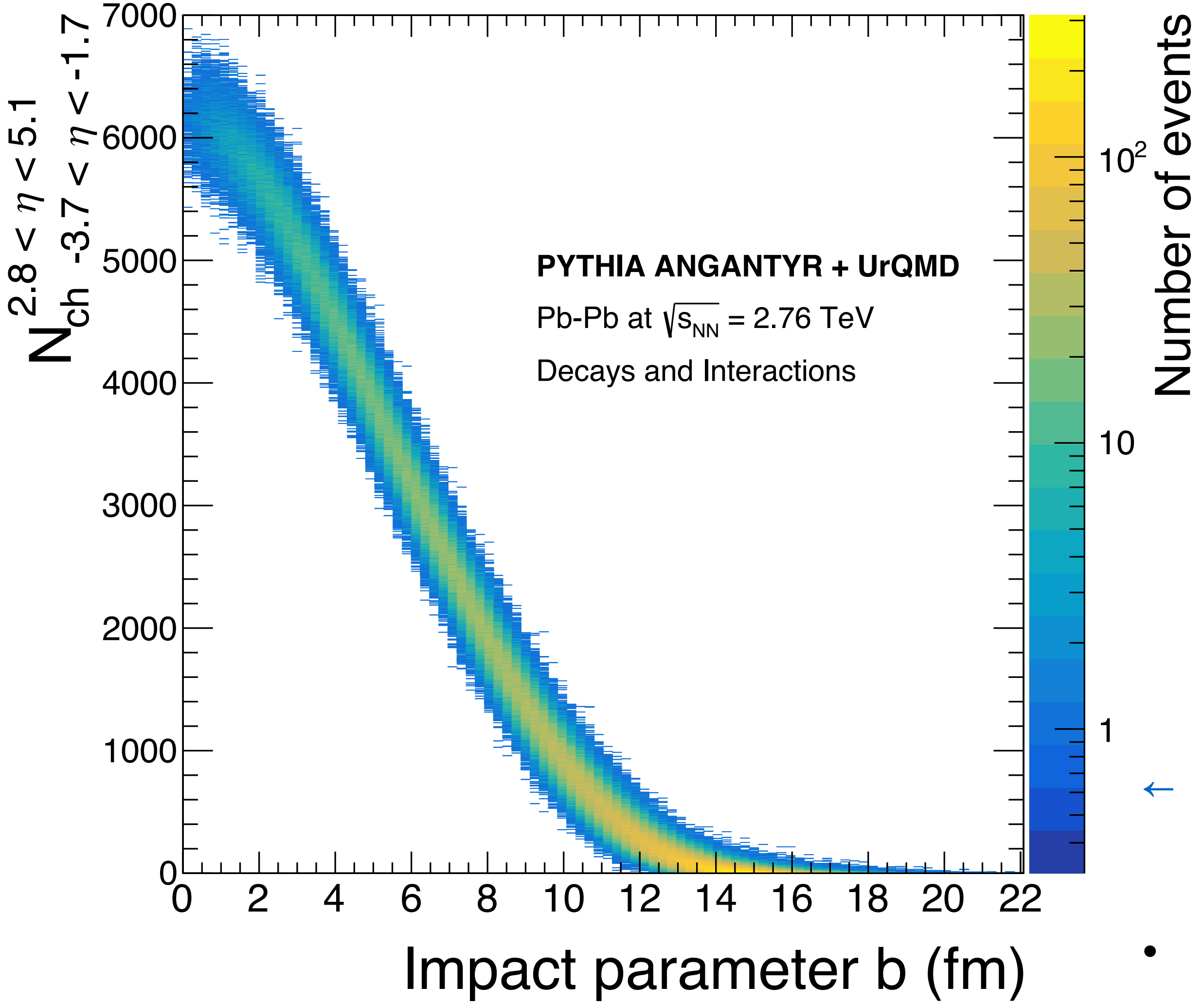
Meet the second contender:

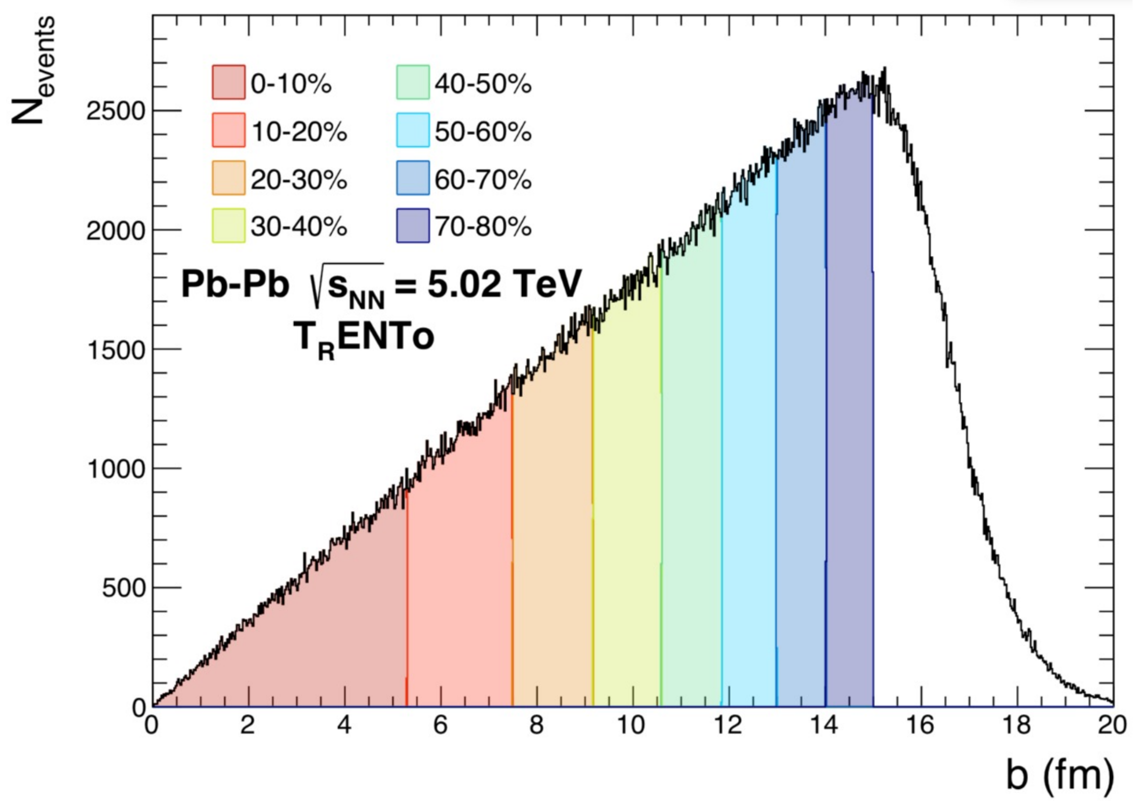
Coupling PYTHIA to Angantyr



- UrQMD handles 99.8% of all prompt hadrons
- Remaining 0.2%: heavy flavor, leptons, photons not treated by UrQMD
- Heavy flavor (~0.2%): decayed by PYTHIA;
- Leptons+photons (~0.01%): removed for now

Determining centrality



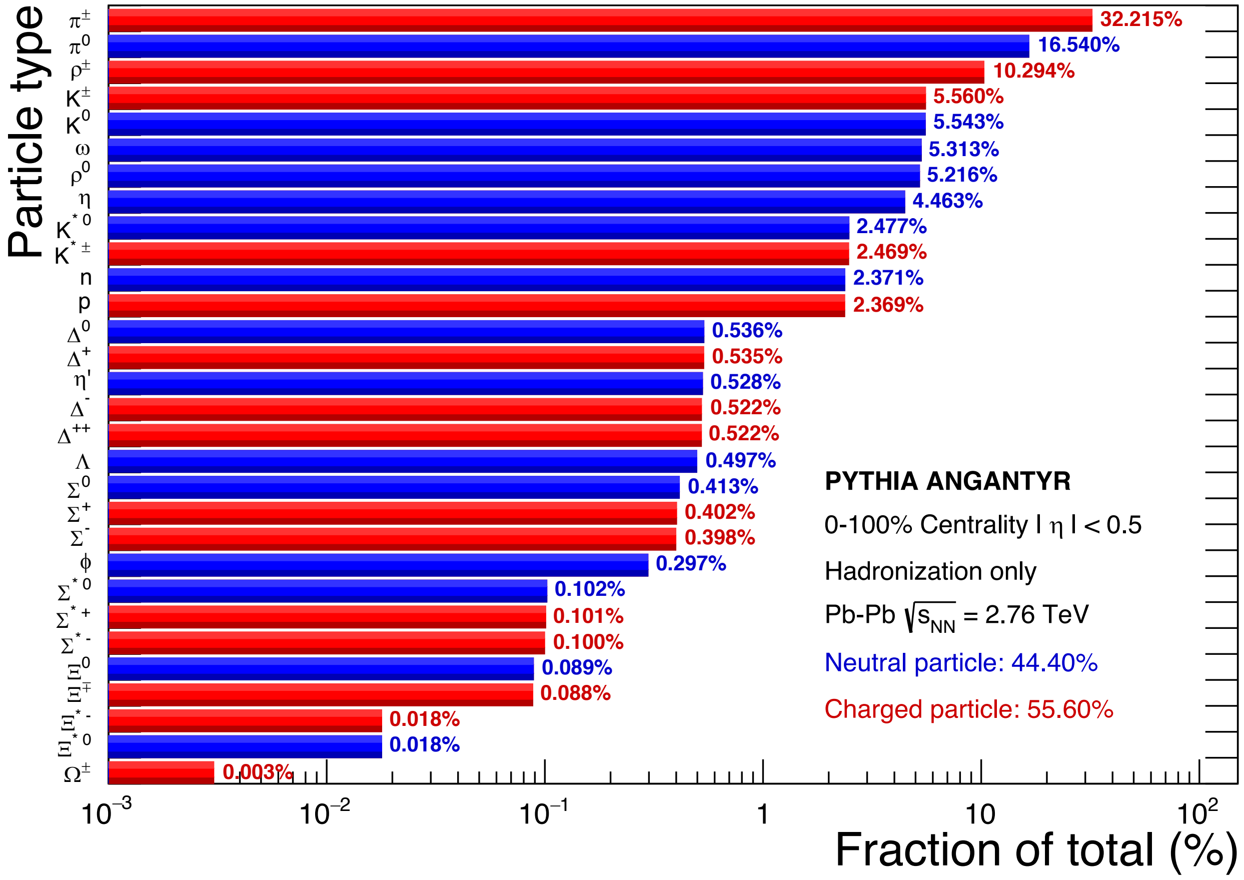


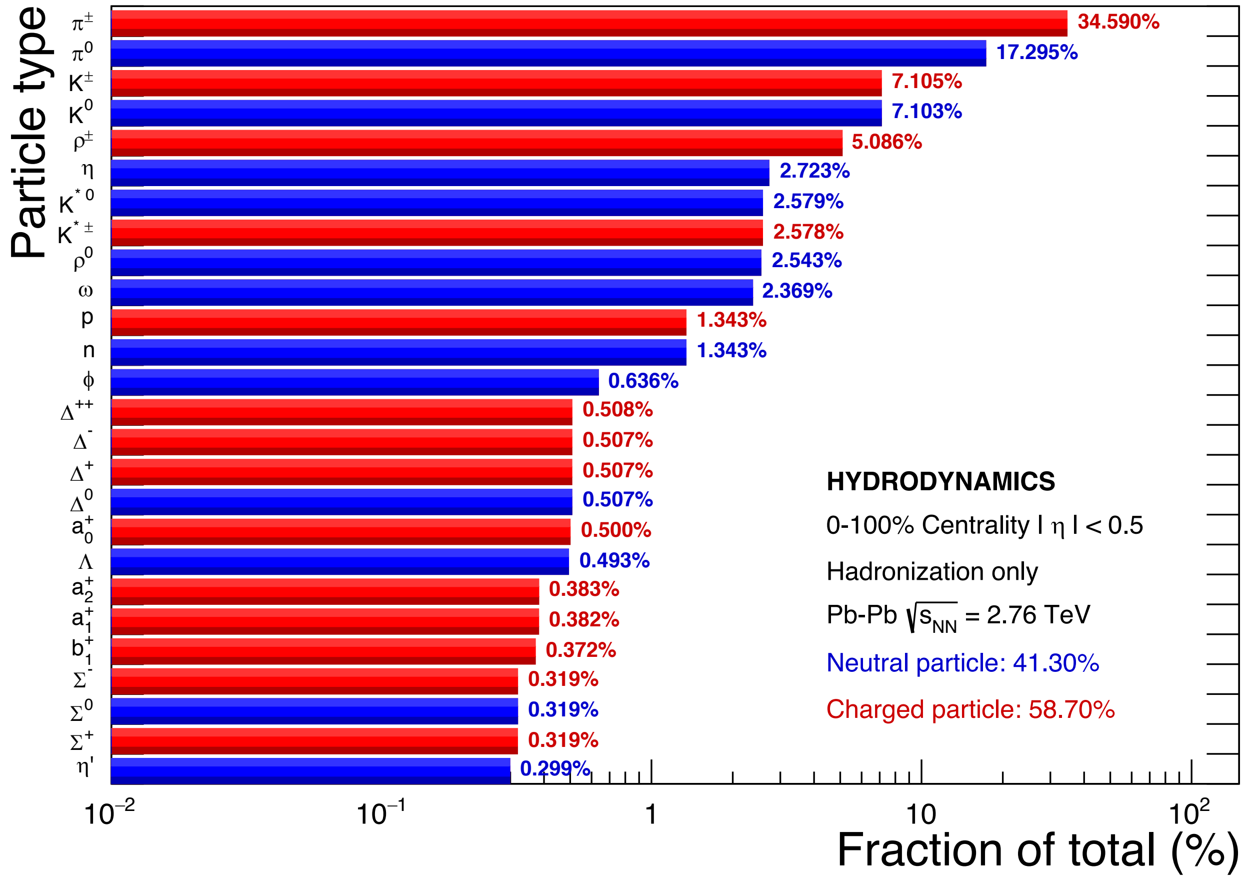
← Experimentally done with forward detectors

- 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%

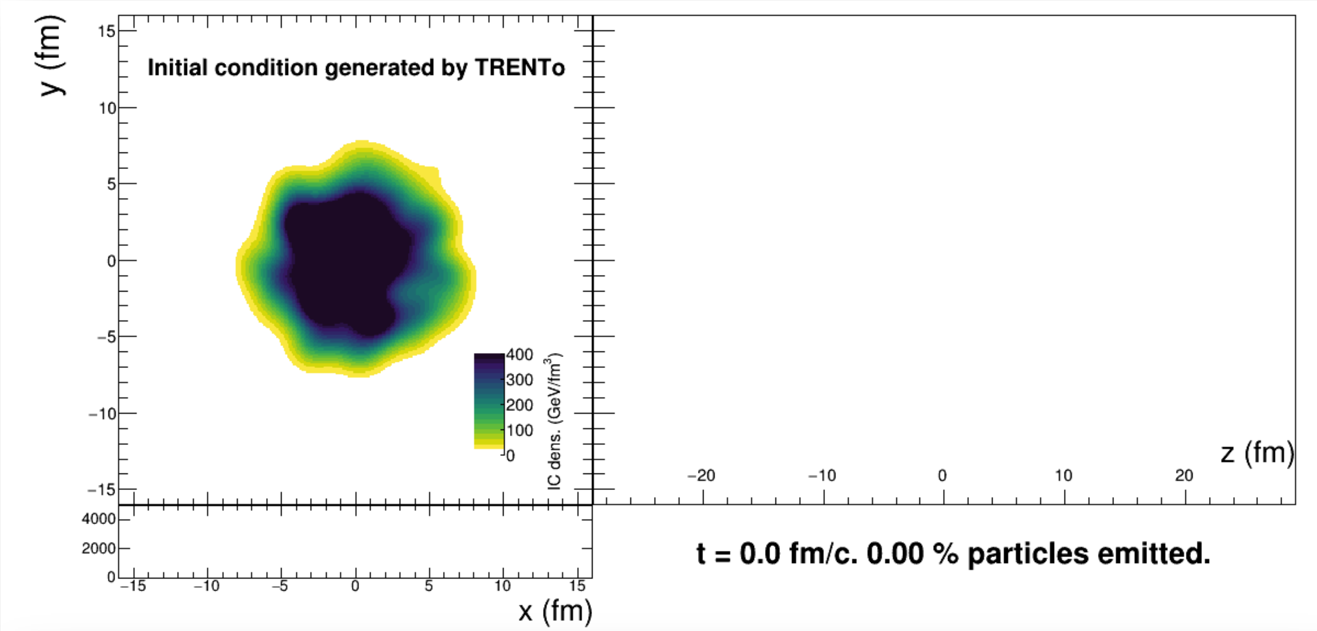
Particle abundances at beginning of UrQMD





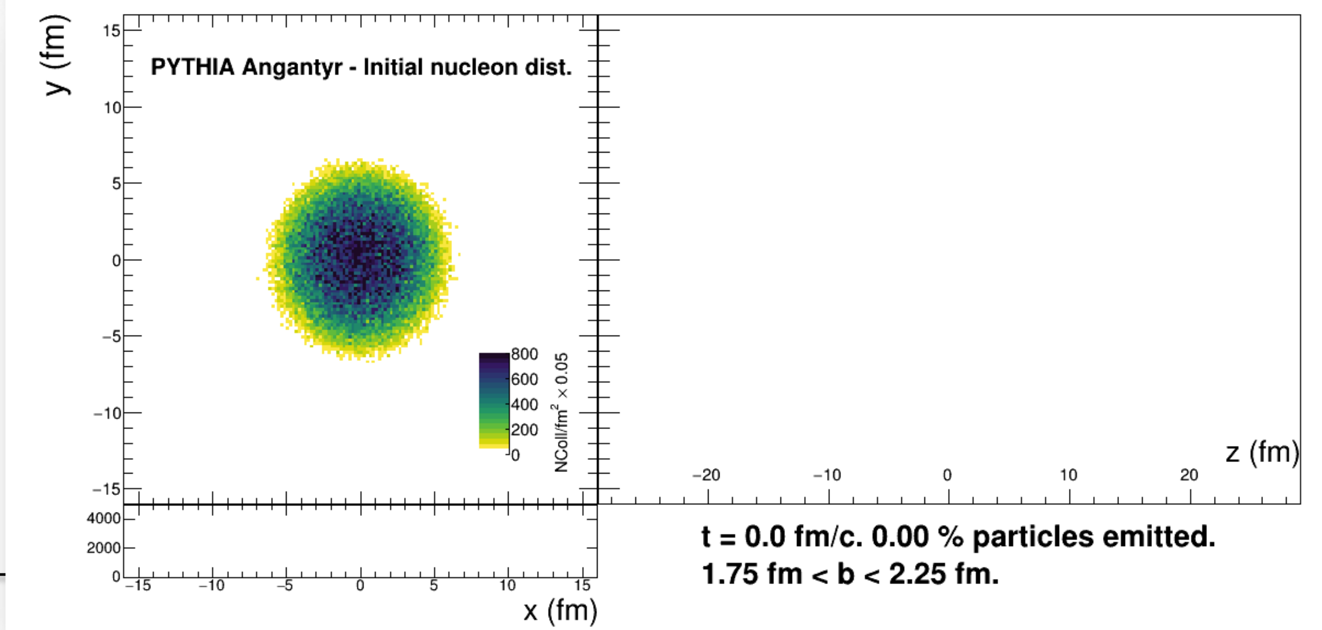
- Hadrochemistry similar, but details differ:
  - PYTHIA produces more neutral particles, especially resonances
  - Hydro produces large variety of excited states

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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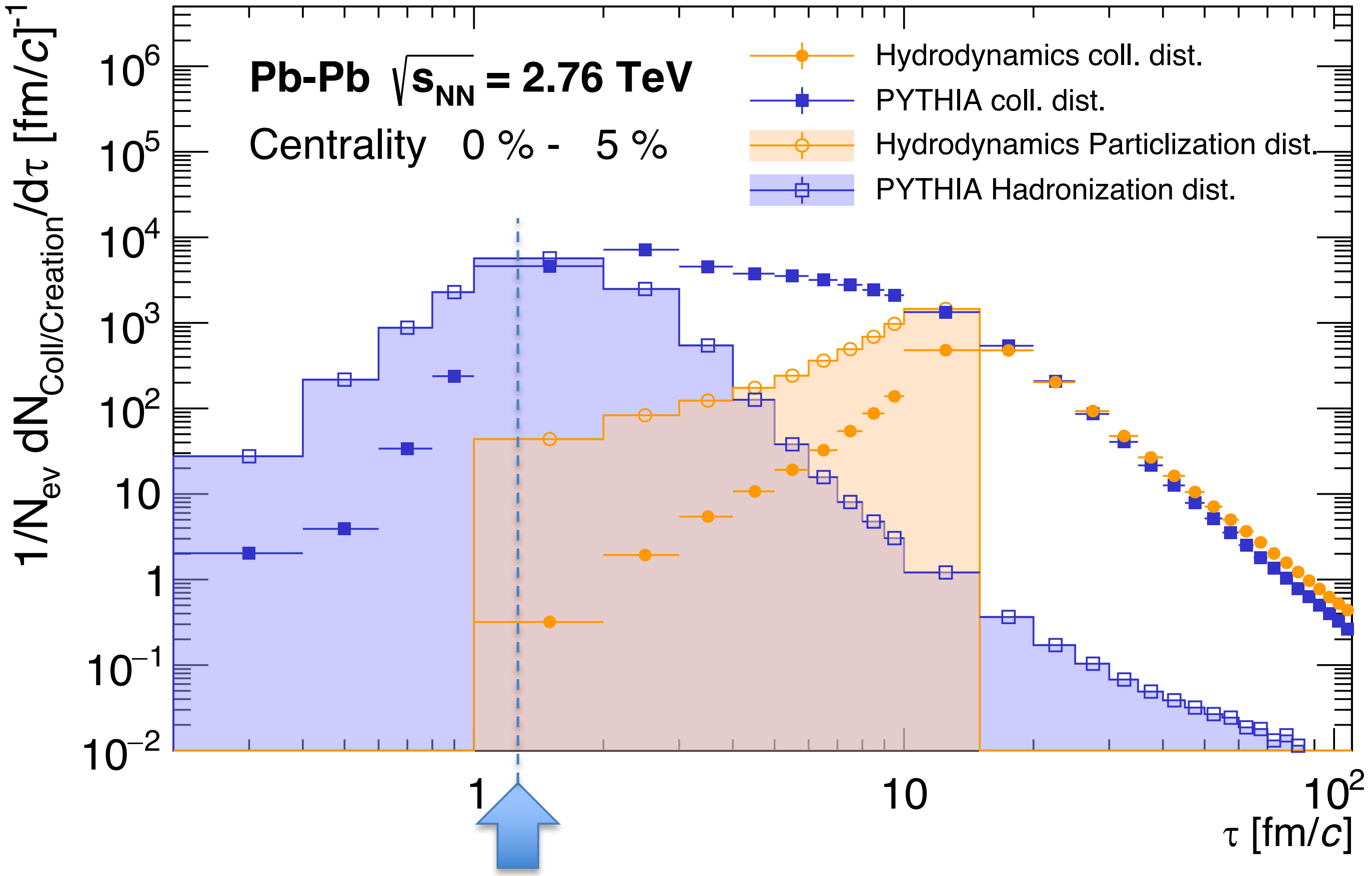
The hadronic phase in time



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

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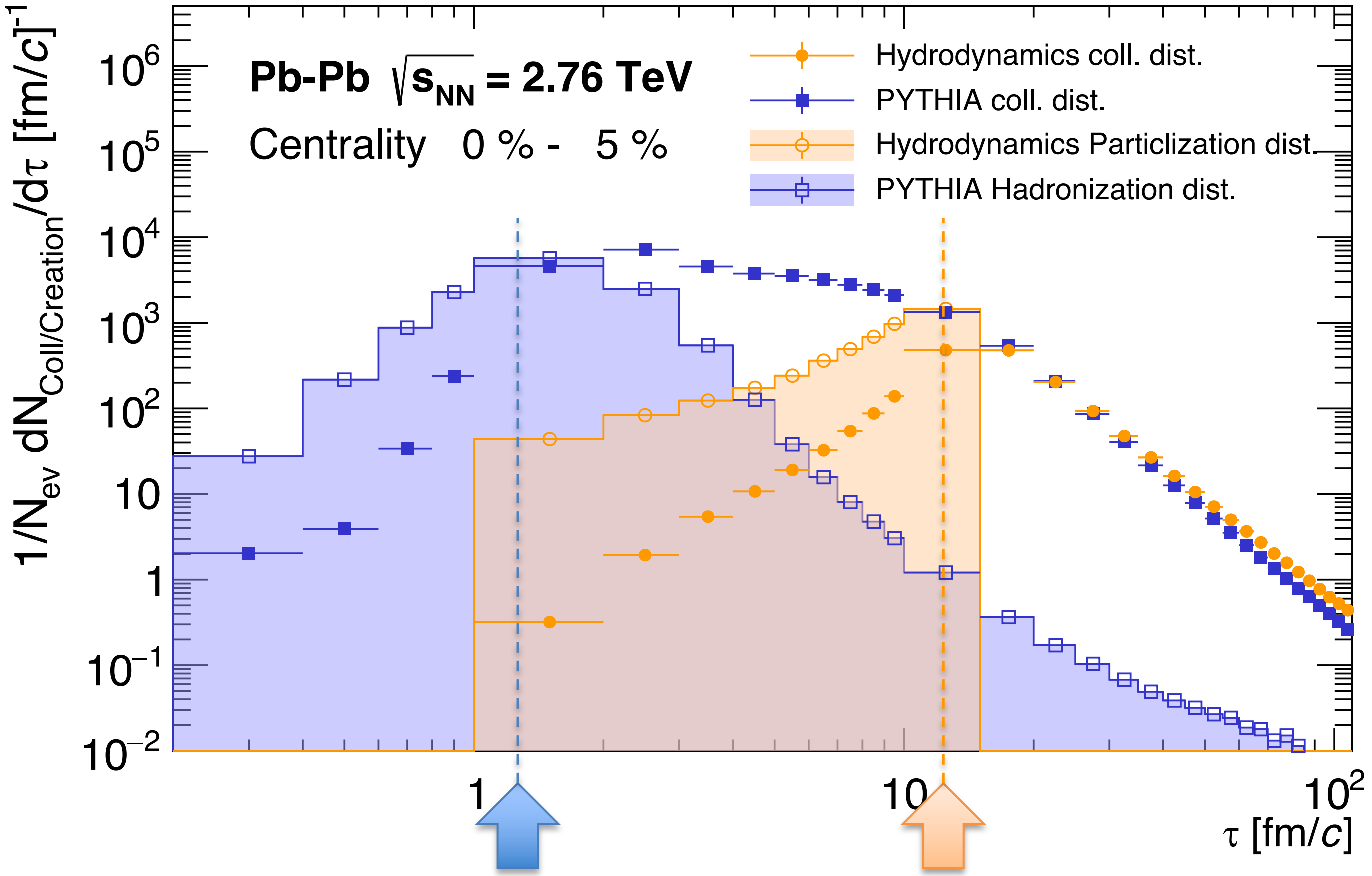

- **PYTHIA** creates particles with a peak at around 1-2 fm/c,
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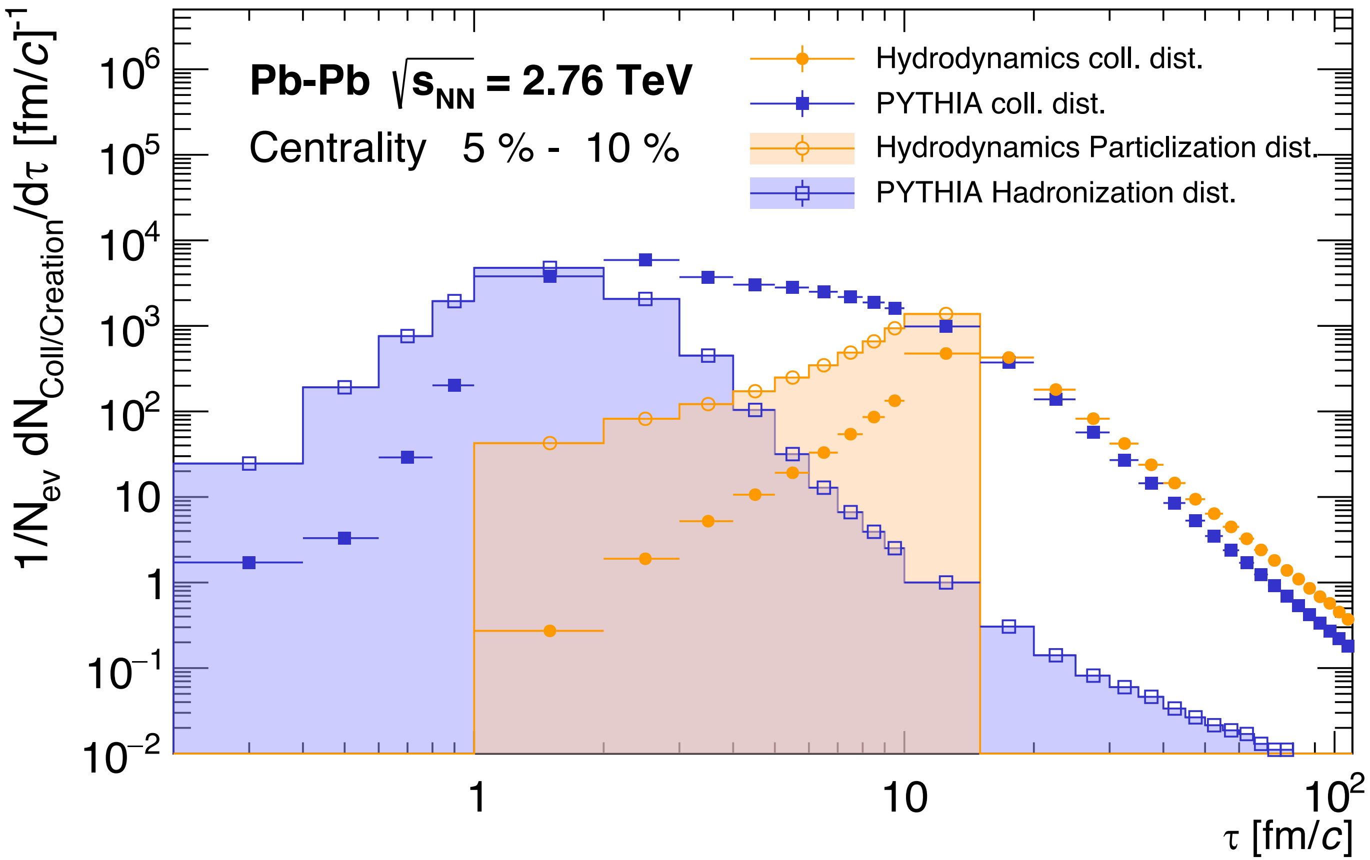

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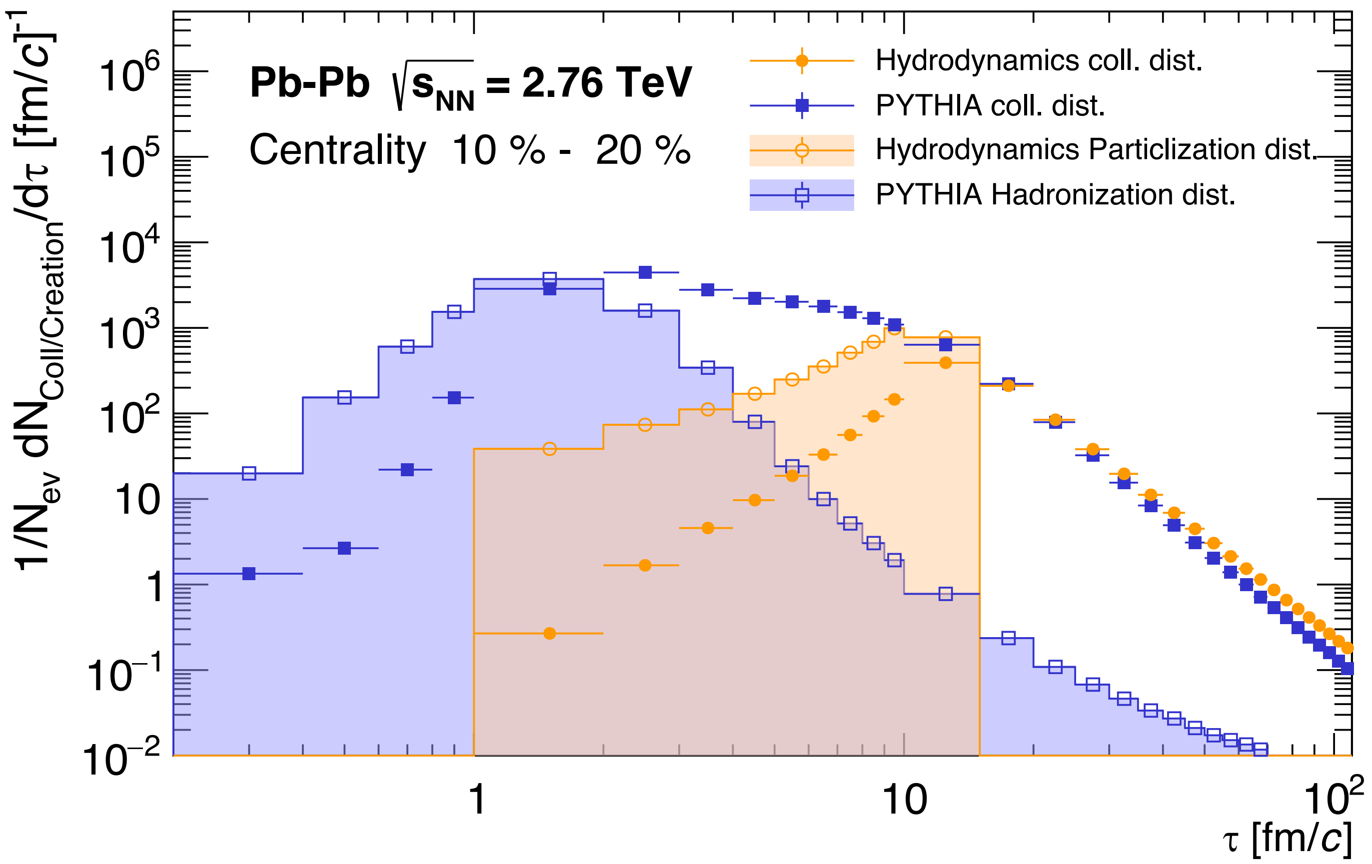

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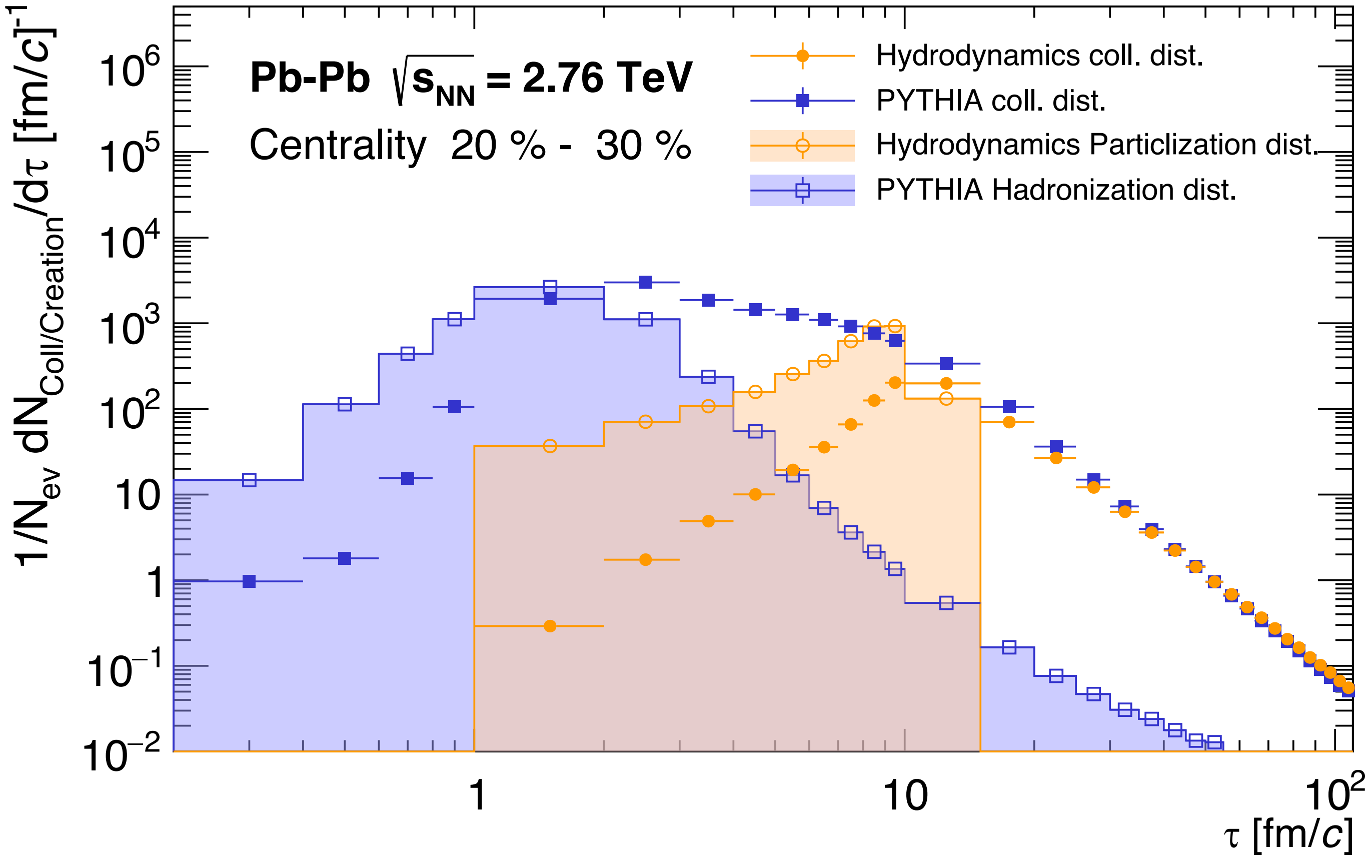

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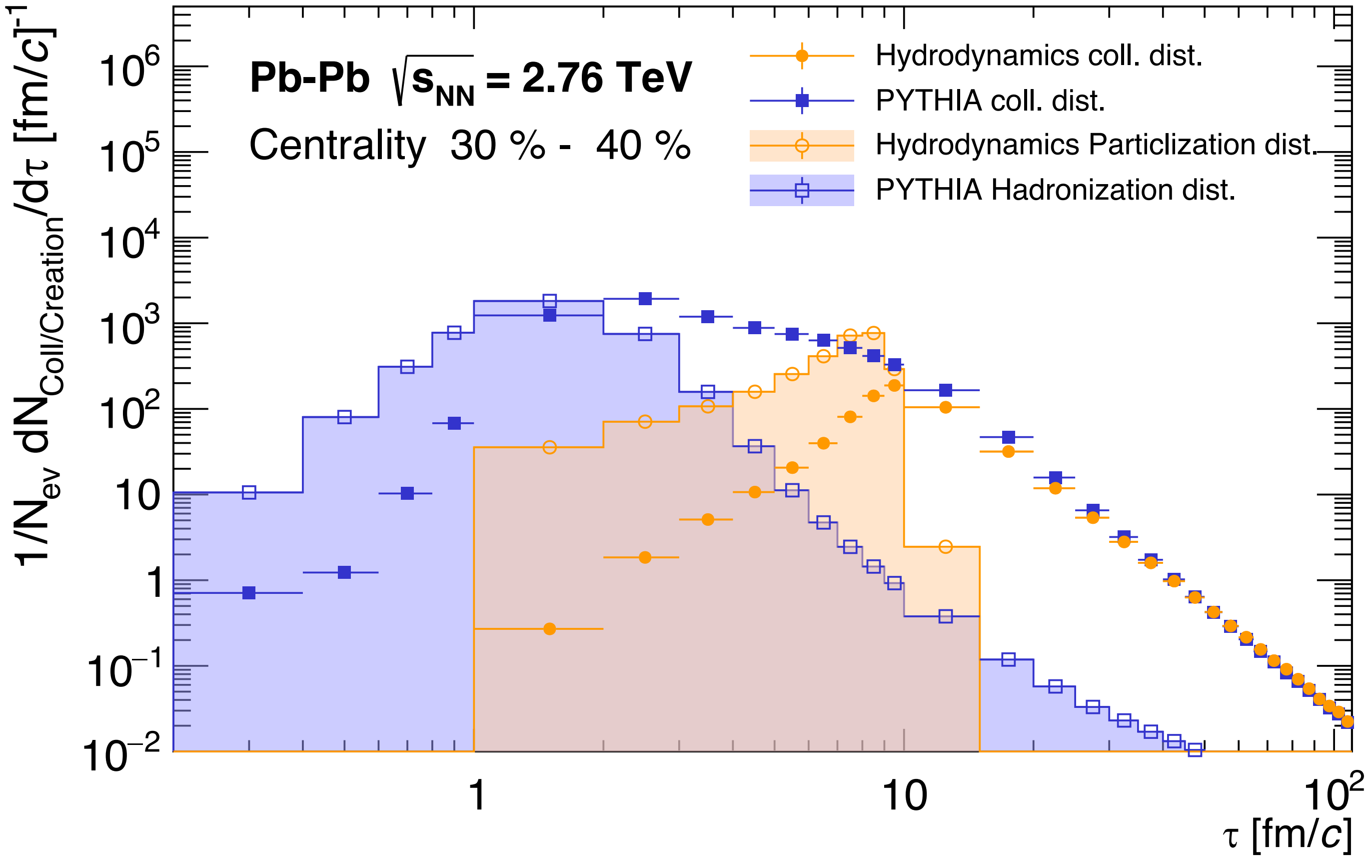

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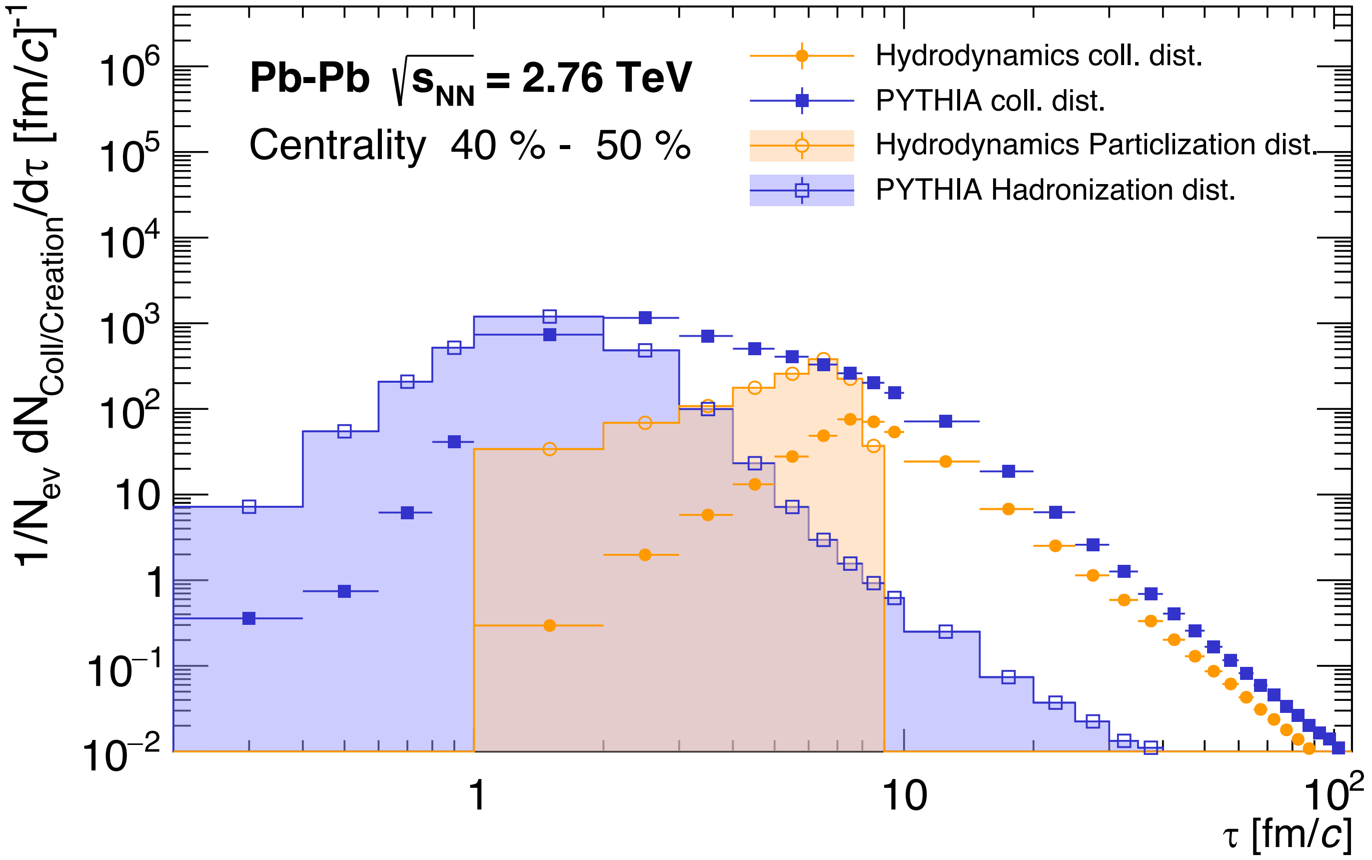

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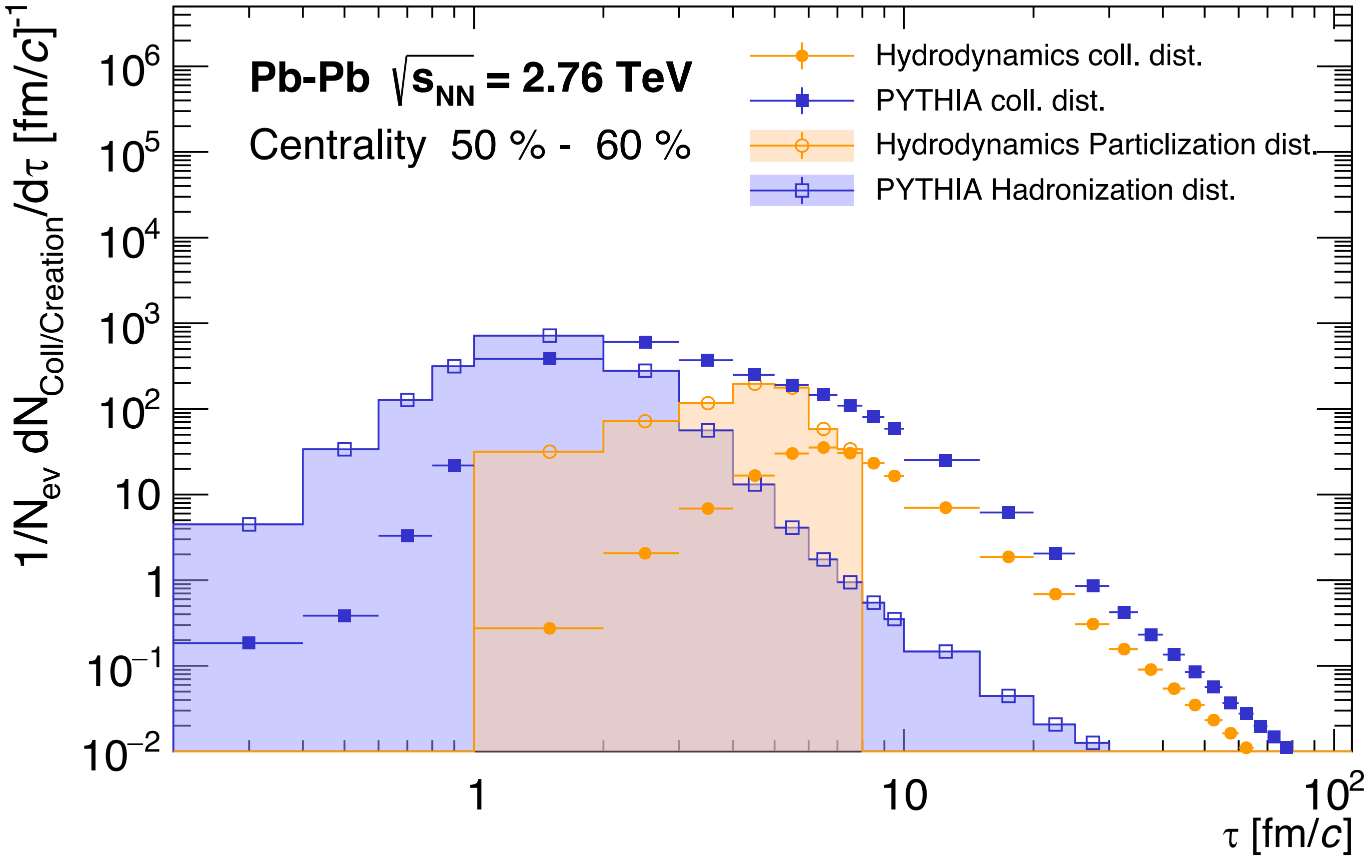

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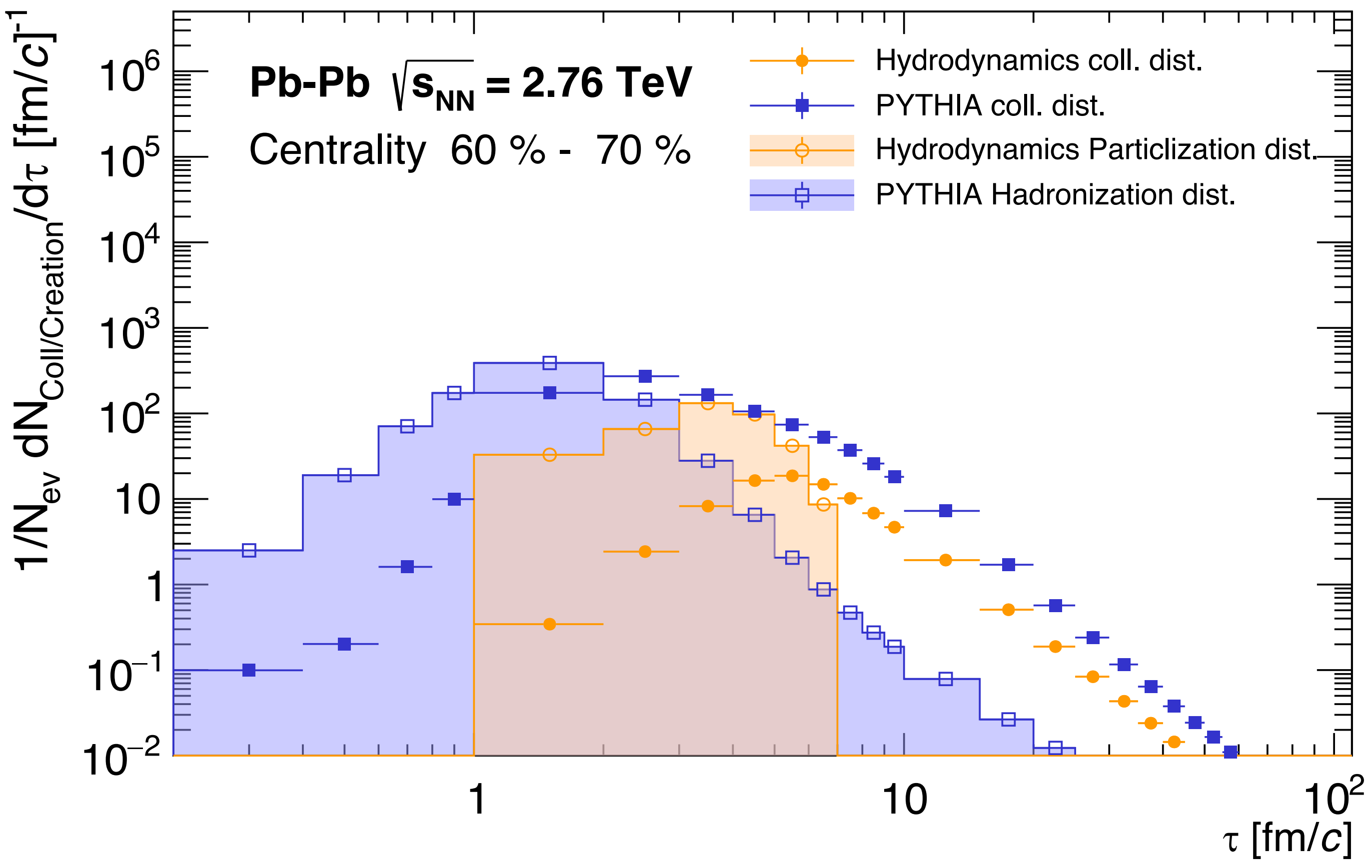

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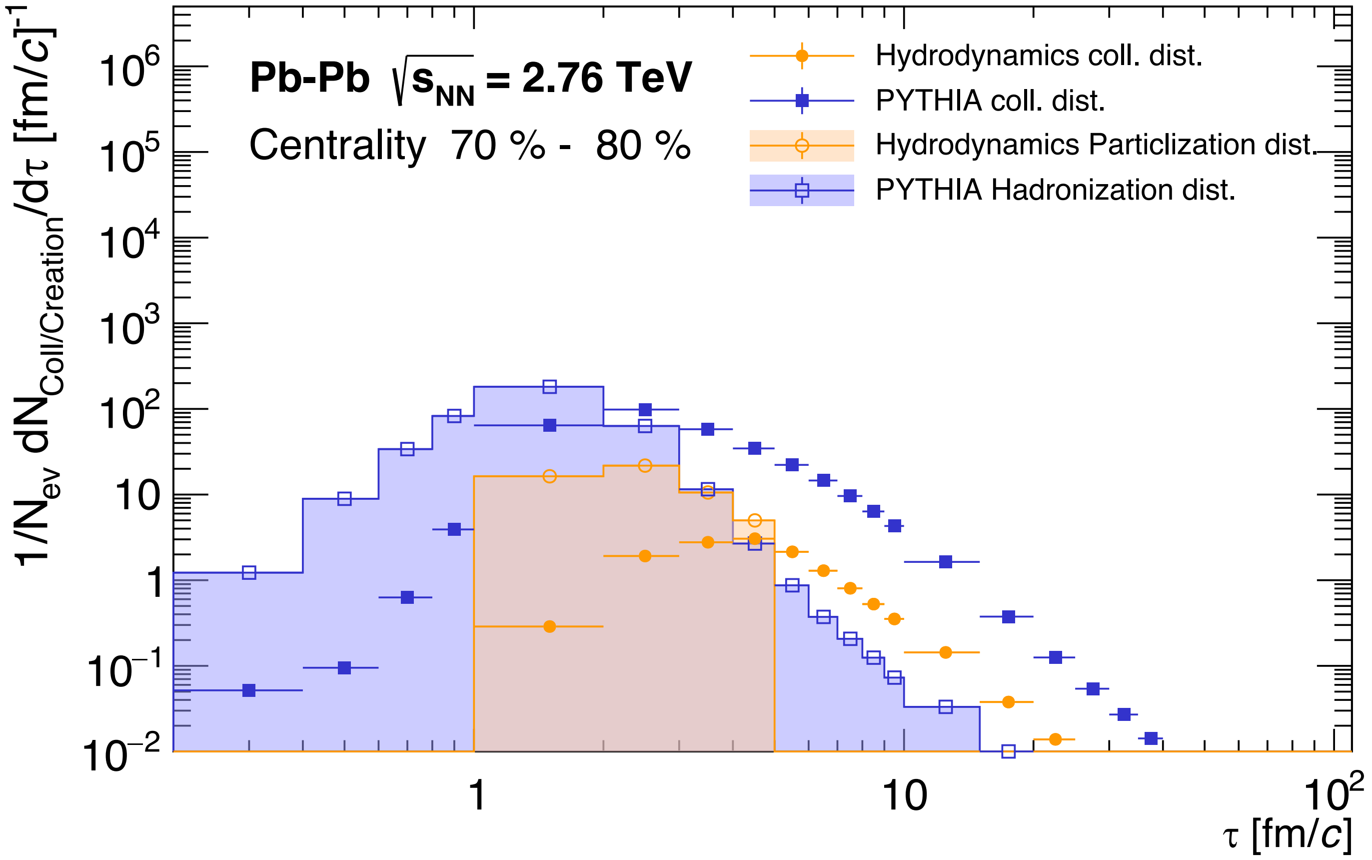

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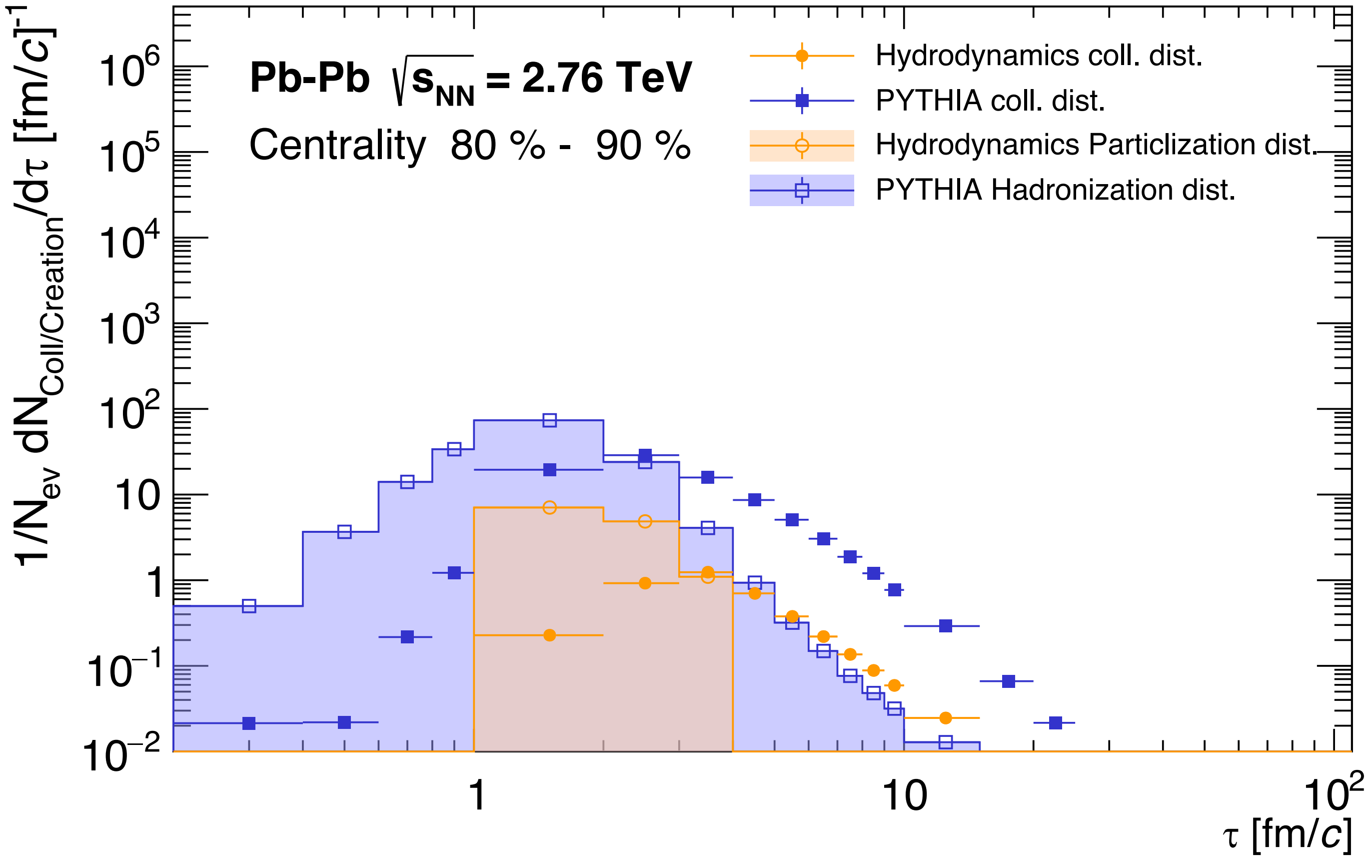

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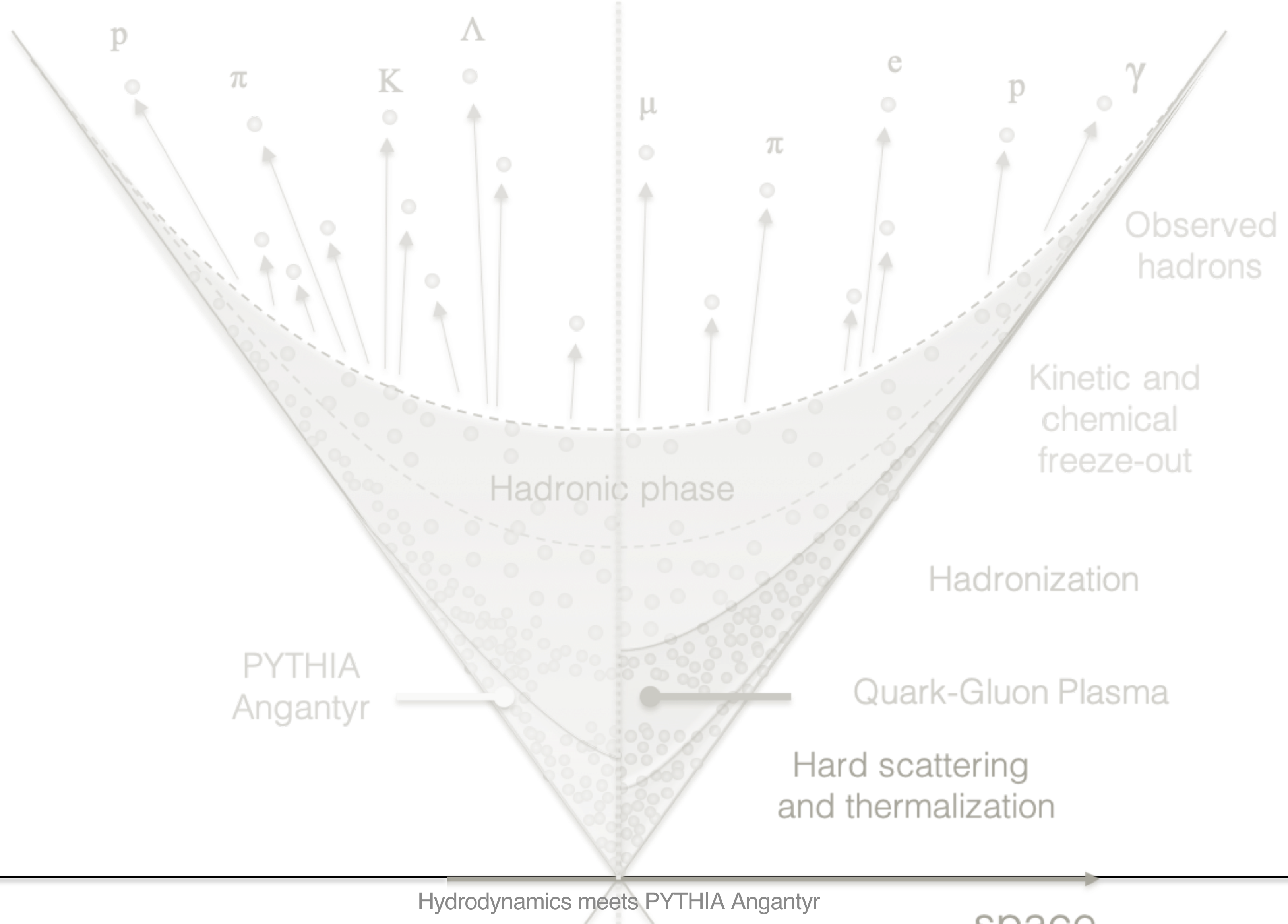
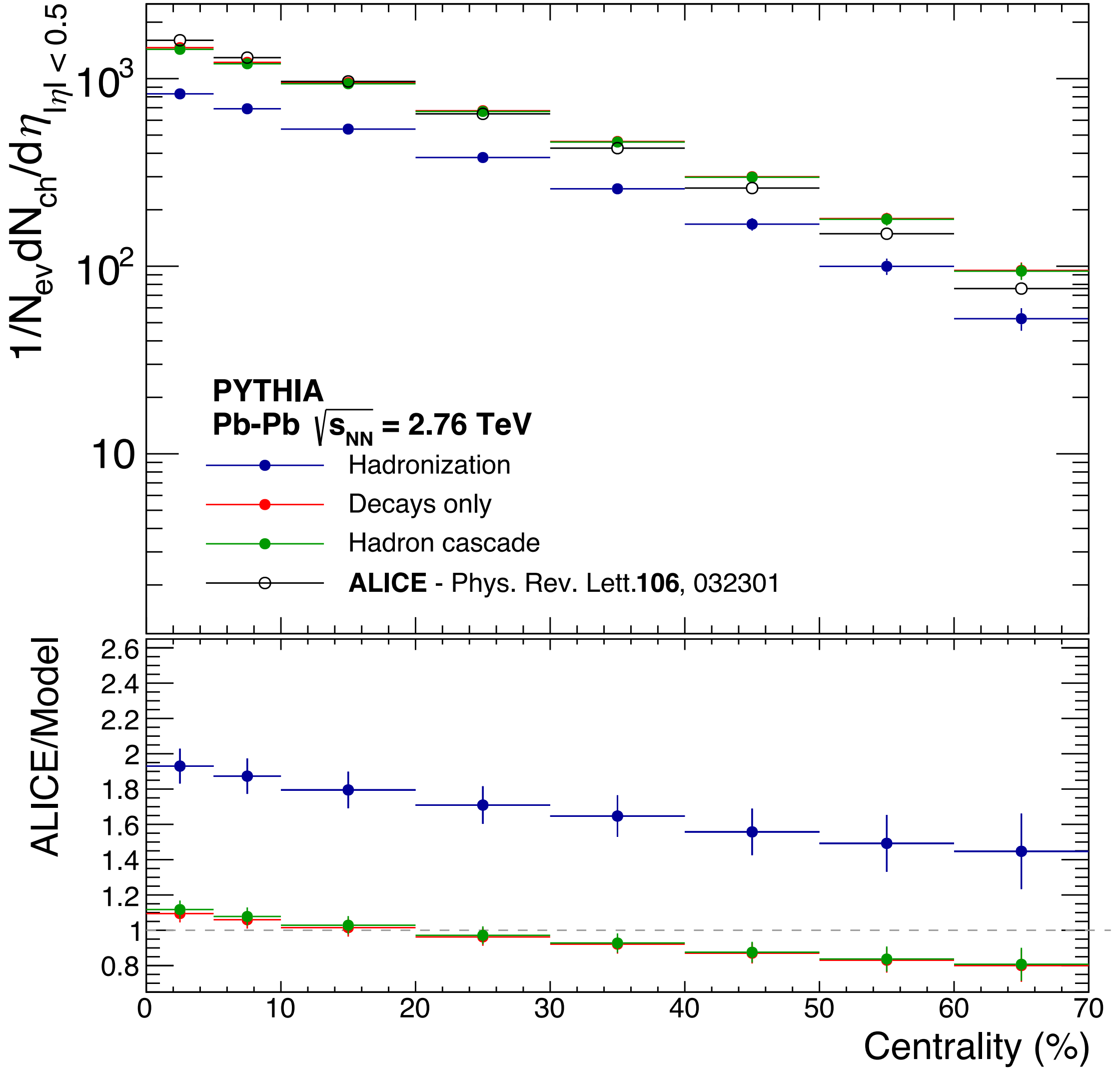
Final-state observables



The basics: multiplicity



- Particle decays responsible for 35-50% of charged particles (both models)
- Hadronic interactions: no significant change in N_{ch}

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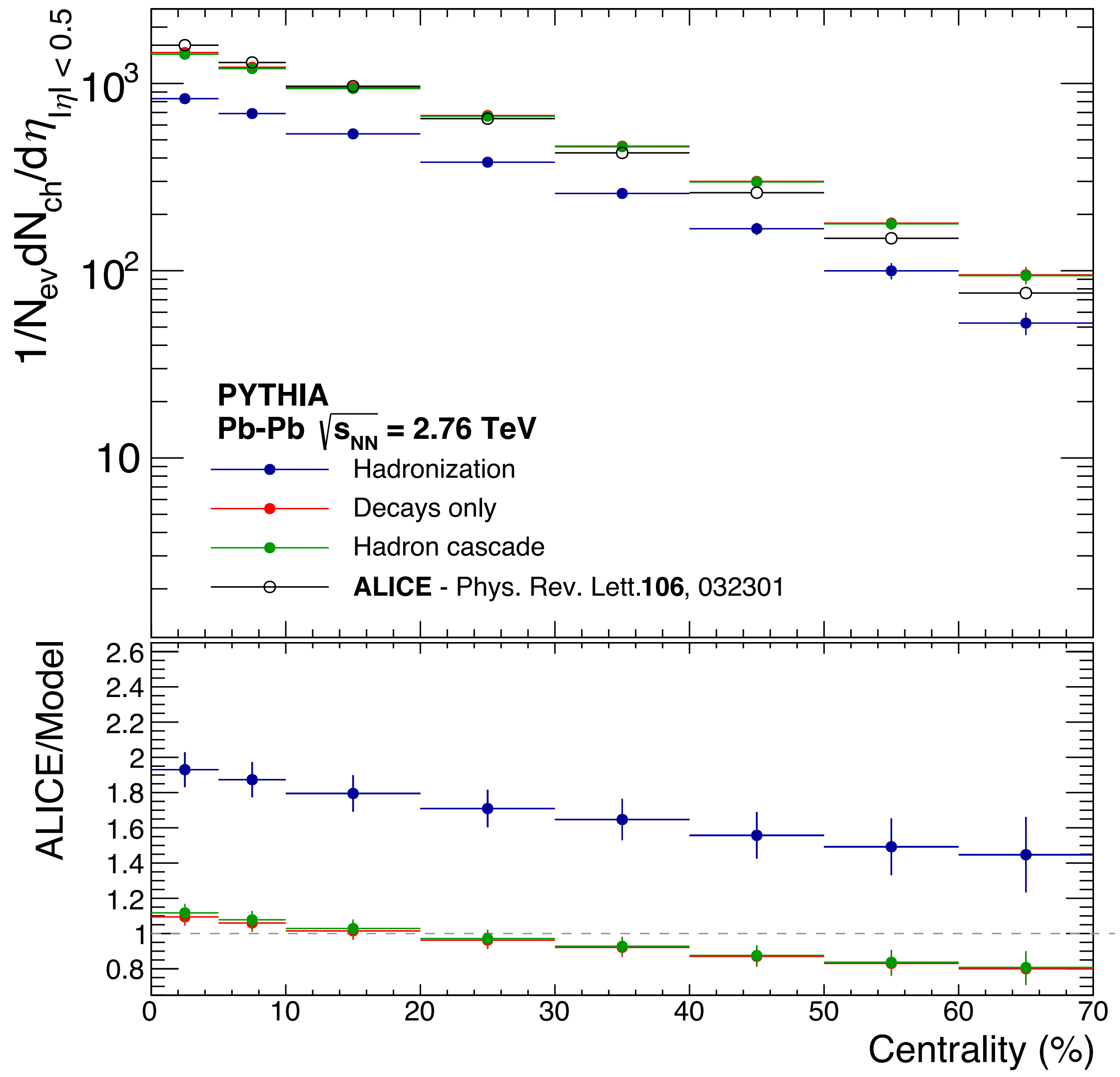

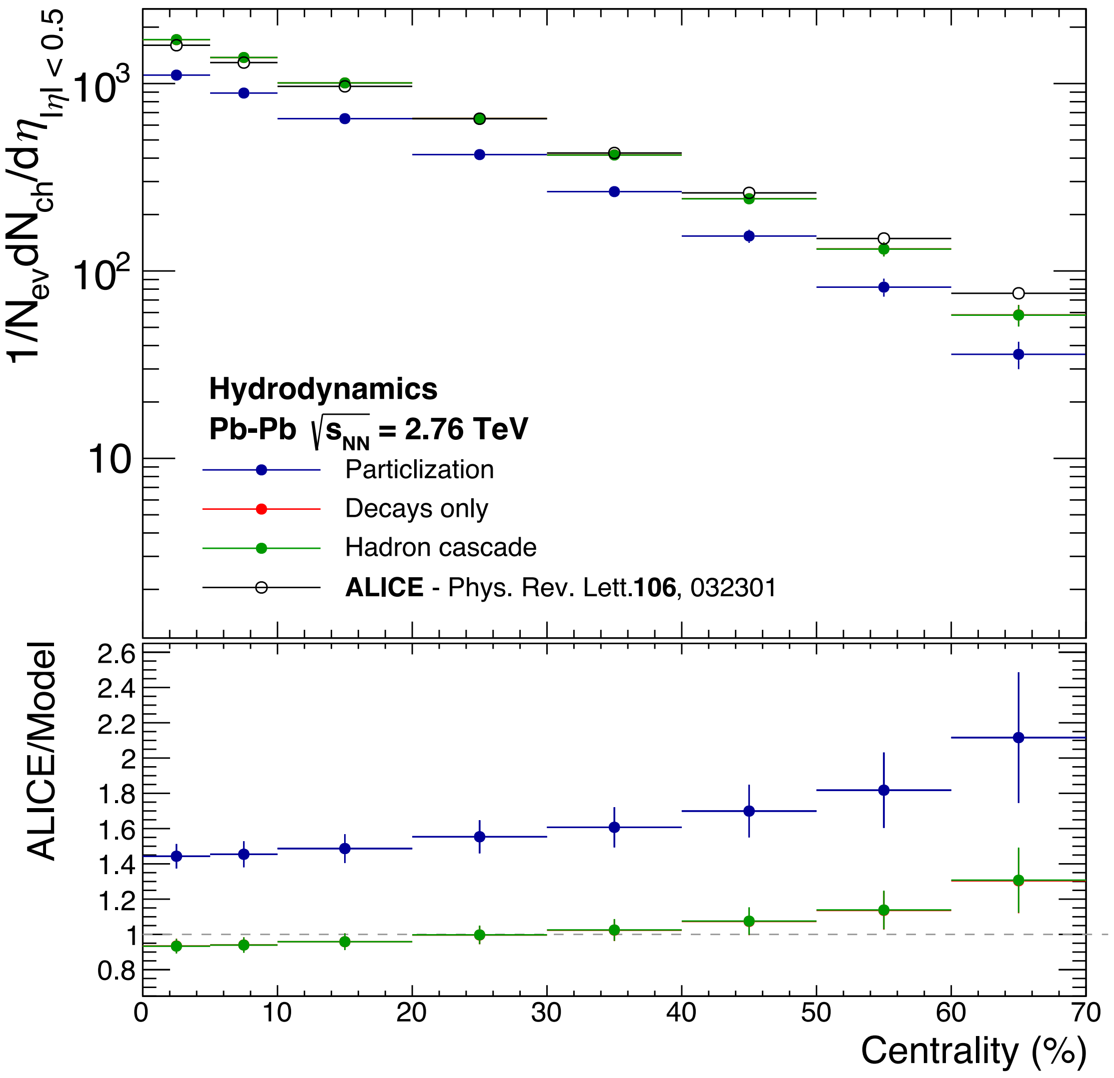

- Particle decays responsible for 35-50% of charged particles (both models)
- Hadronic interactions: no significant change in N_{ch}
- Both models fine within 10% for 0-50% collisions

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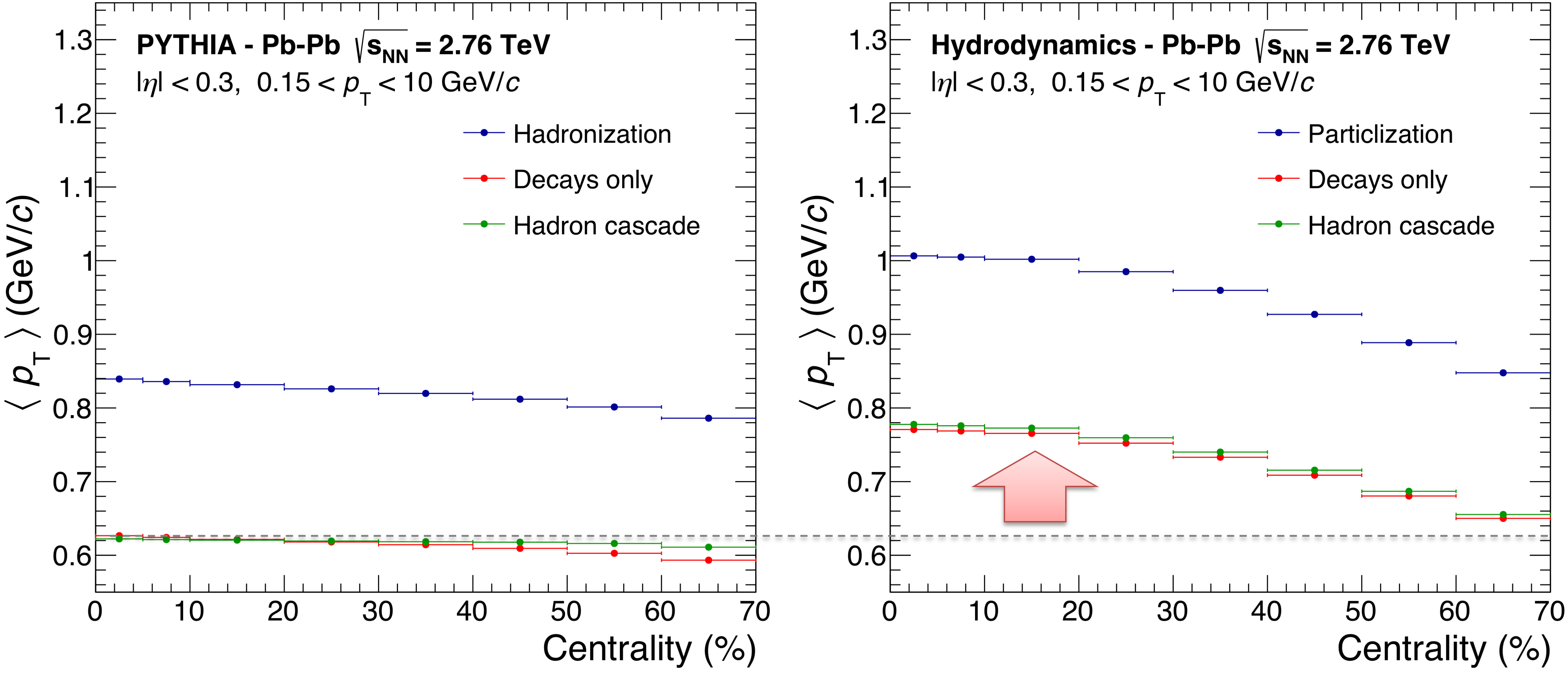
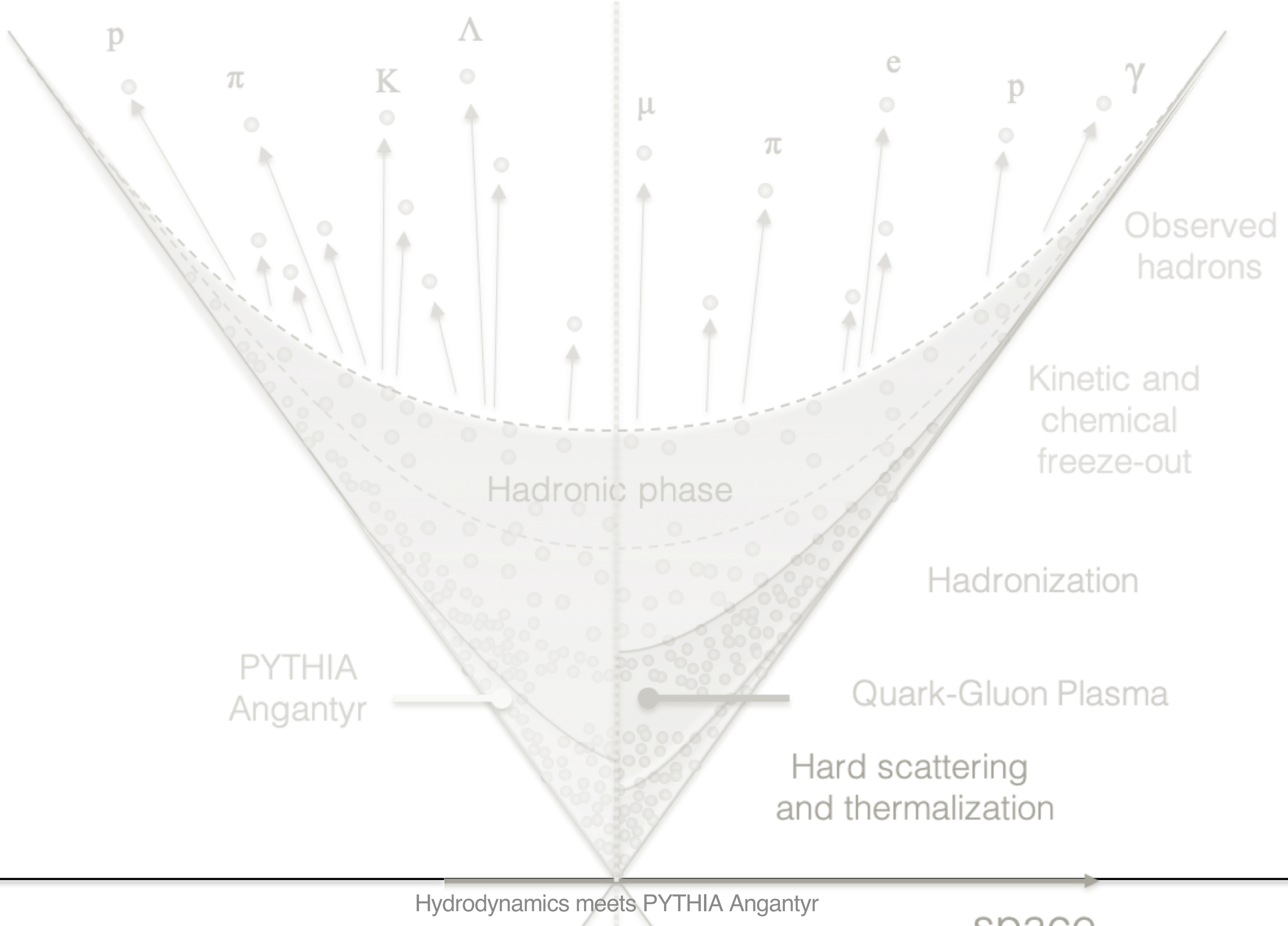
The basics: mean p_T



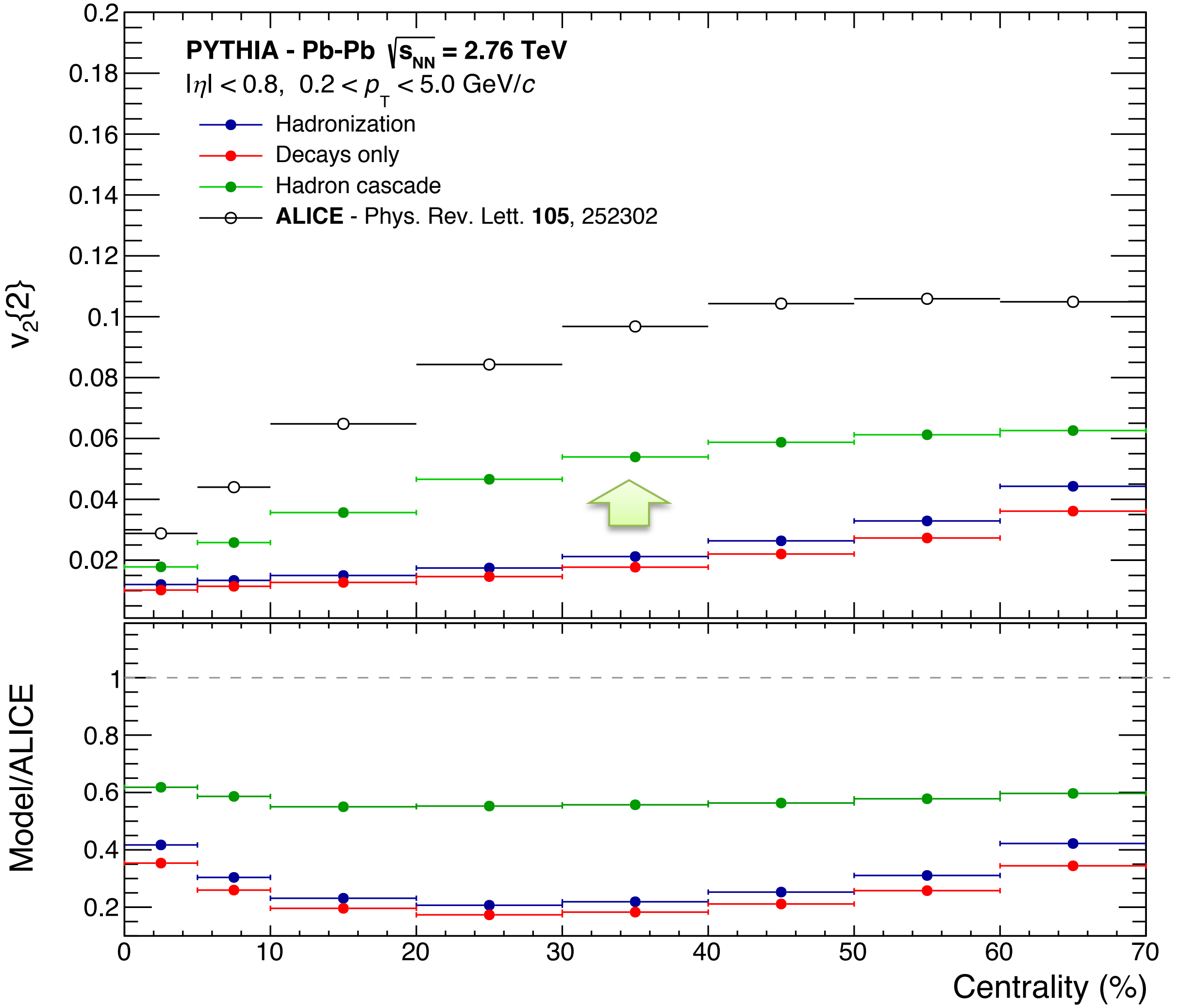
- Both models: decays push towards smaller average p_T
- Hadronic interactions: still no major effect
- PYTHIA: no significant changes vs centrality
- Hydrodynamics: radial flow buildup visible

Collective behavior and flow



Elliptic flow coefficient $v_2\{2\}$ (2-particle cumulants)

(warning: no eta gap)



- PYTHIA: elliptic flow buildup in the hadronic phase? 60% of measured

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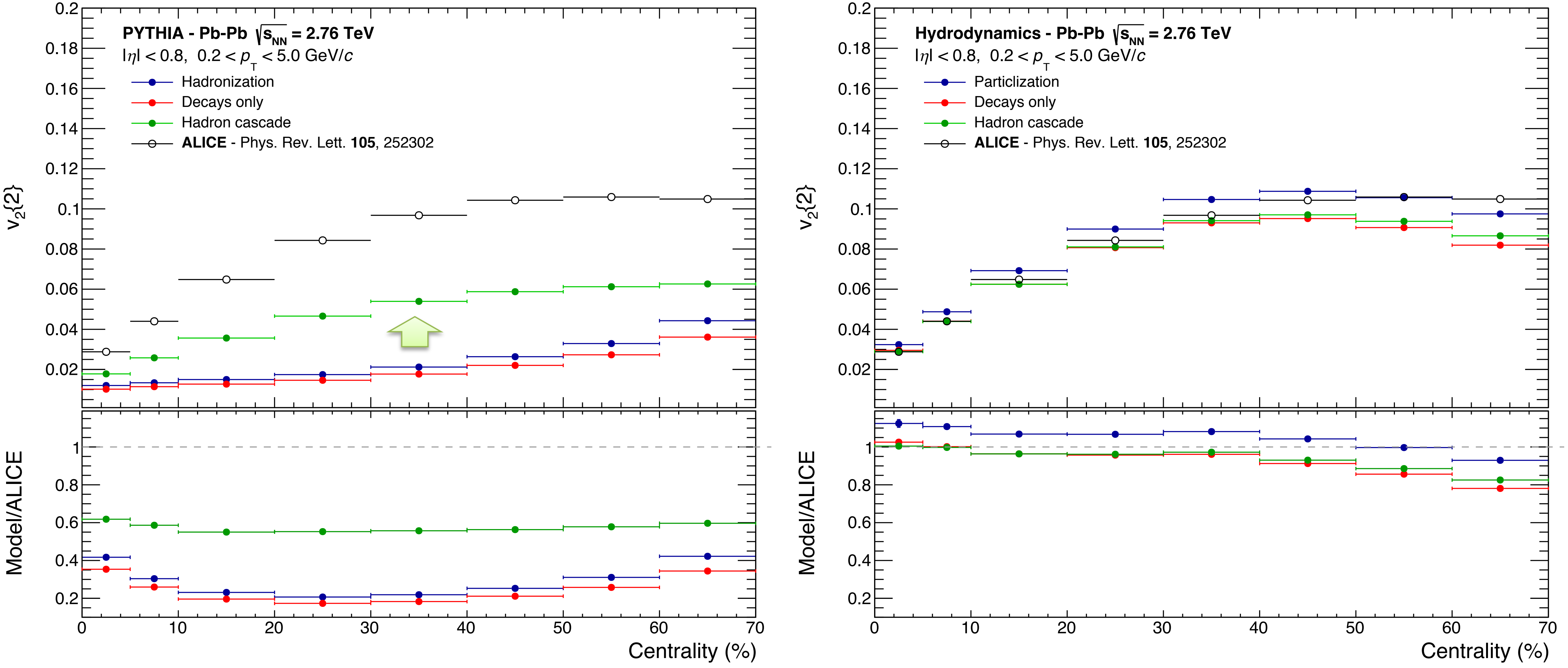

- PYTHIA: elliptic flow buildup in the hadronic phase? 60% of measured
- Hydro: elliptic flow already ~matches data before hadronic interactions

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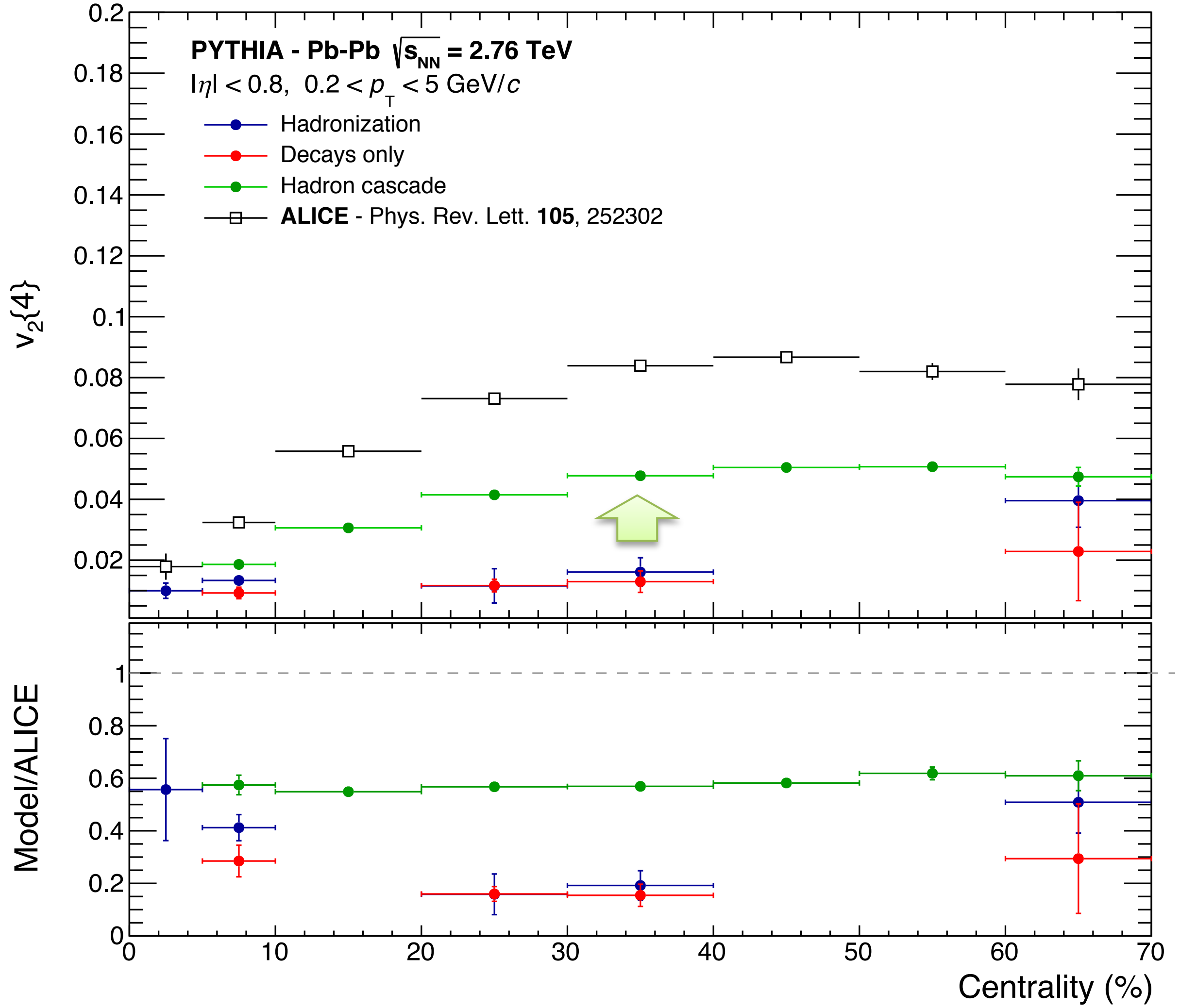
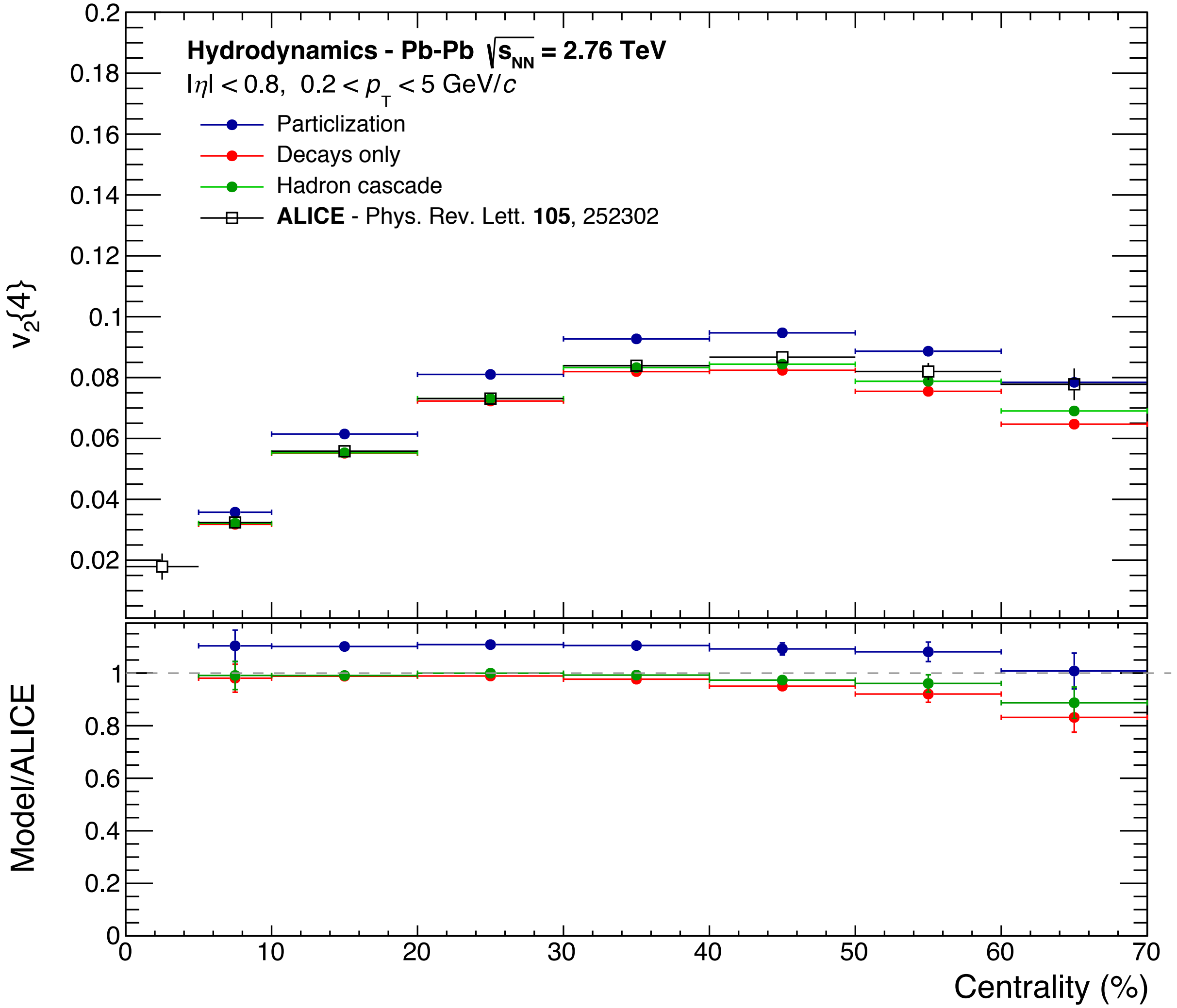
Elliptic flow coefficient $v_2\{4\}$ (4-particle cumulants)





- PYTHIA: elliptic flow survives in 4-particle correlations!
- Hydro: elliptic flow already ~matches data before hadronic interactions

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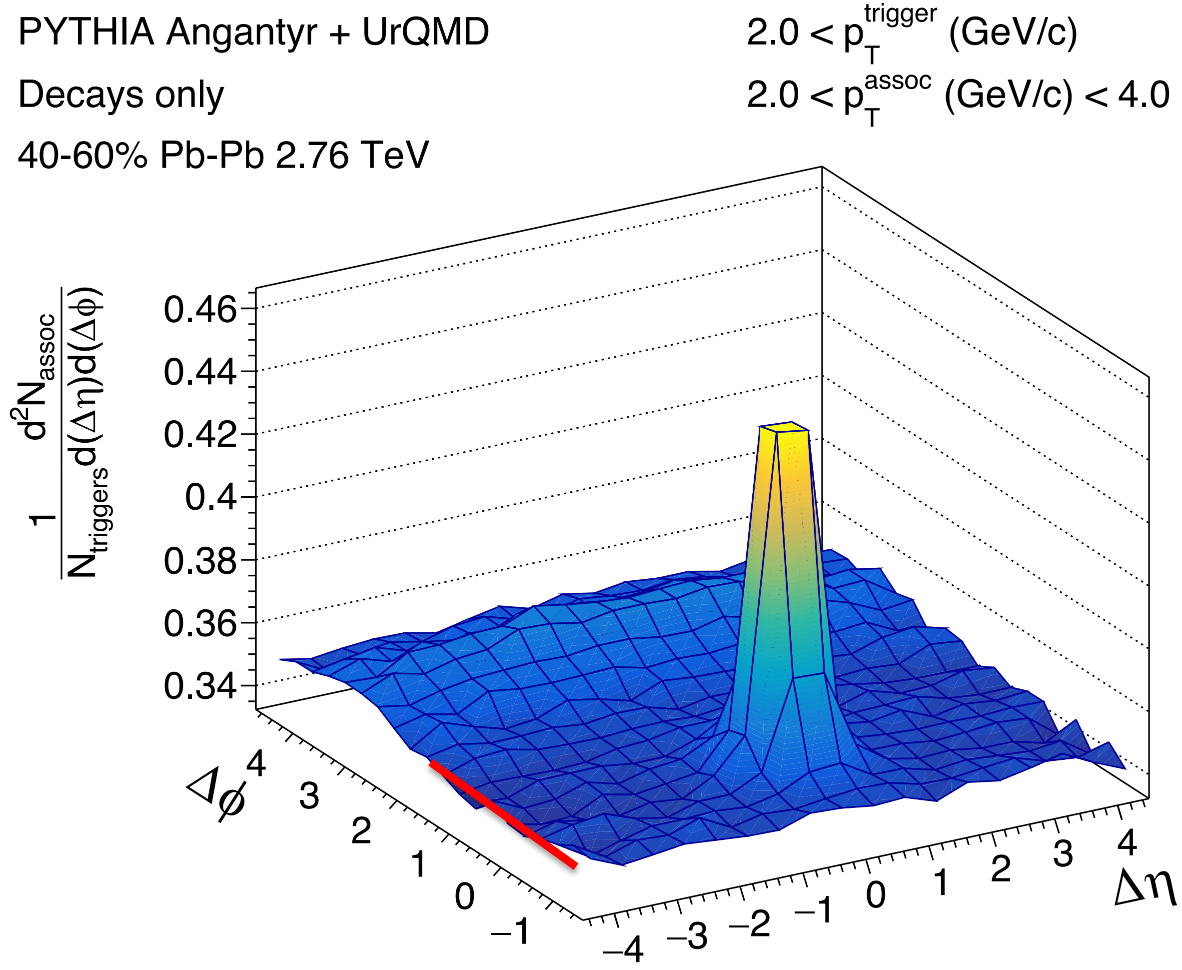
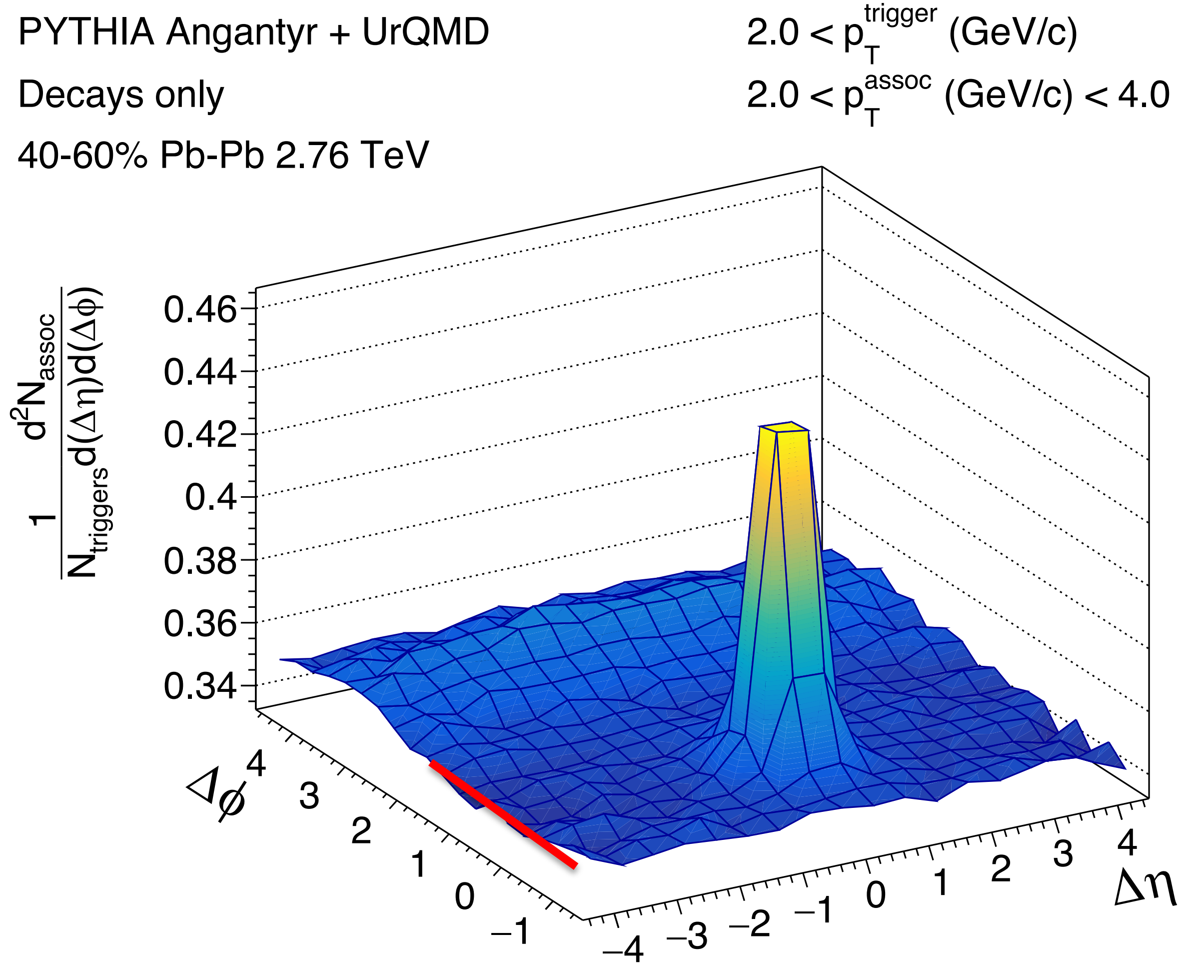
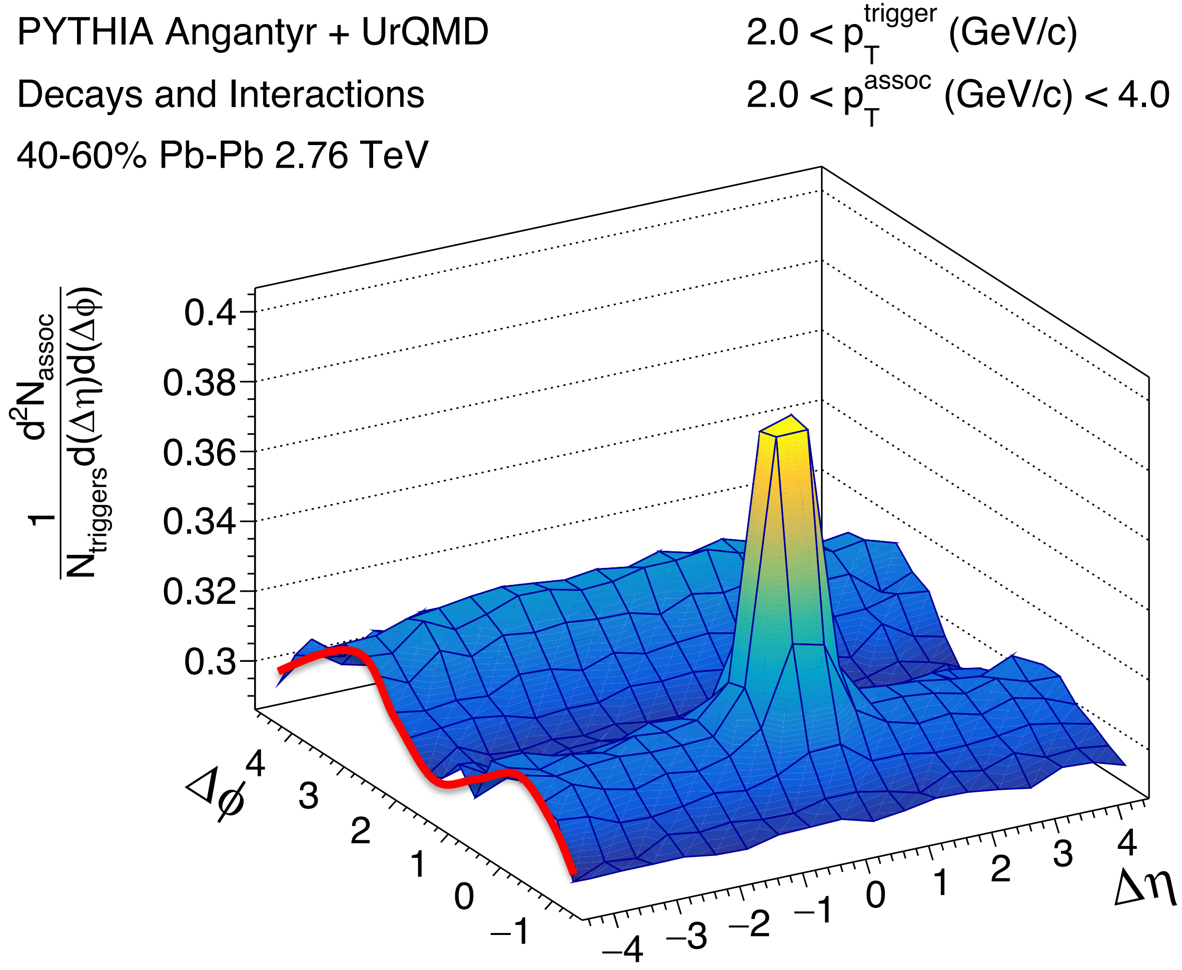
PYTHIA+UrQMD: Flow from the hadronic phase?



- 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

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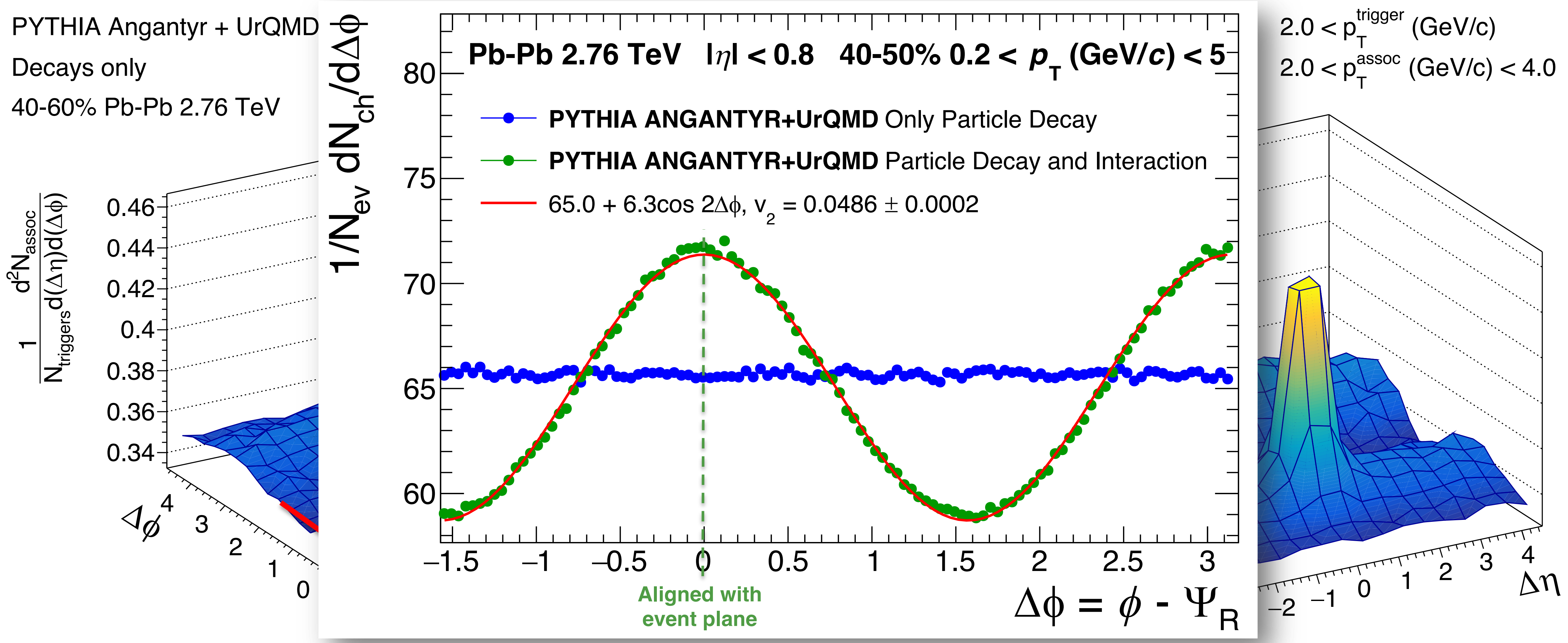

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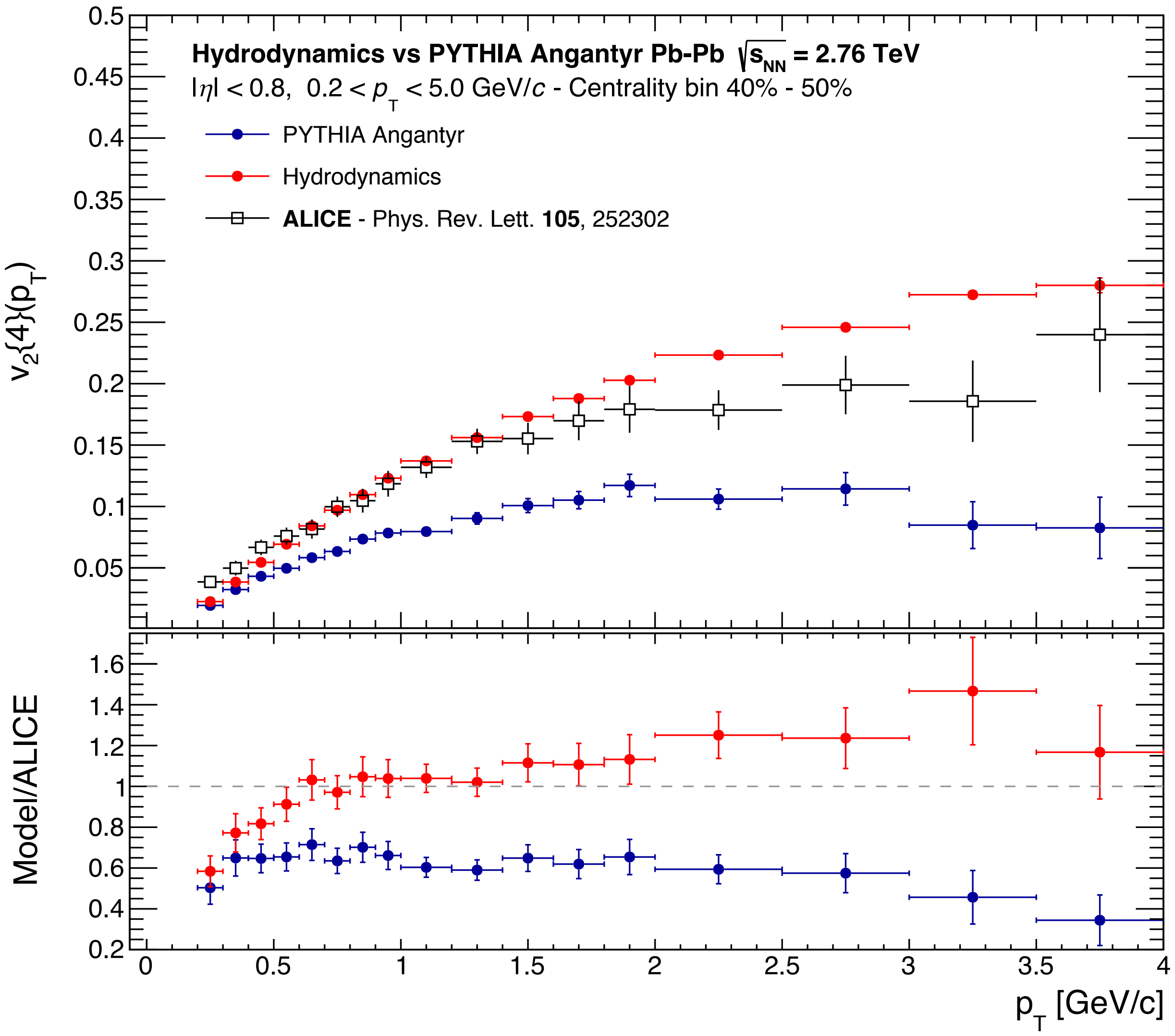
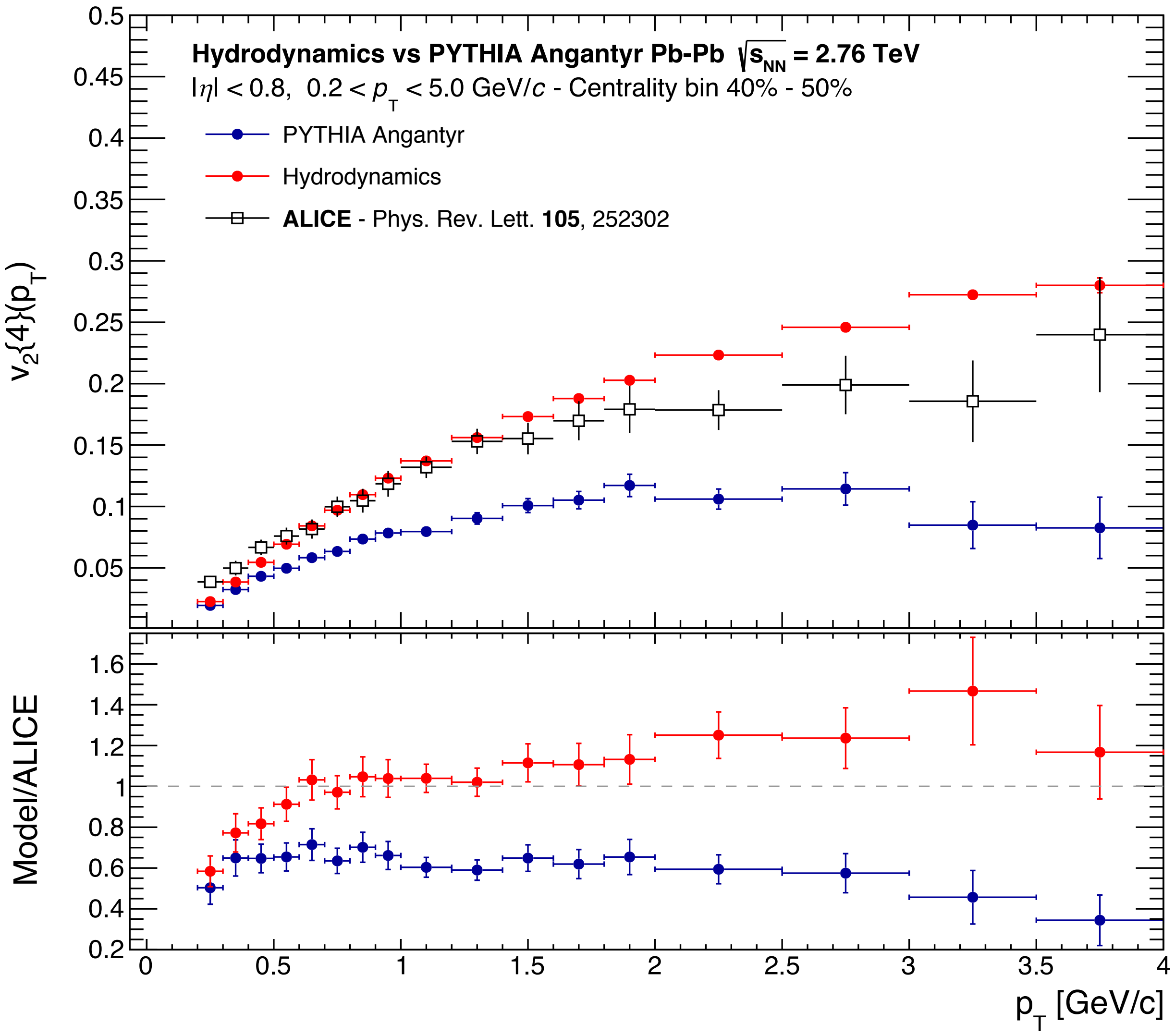
Elliptic flow coefficient $v_2\{4\}$ vs p_T



- 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



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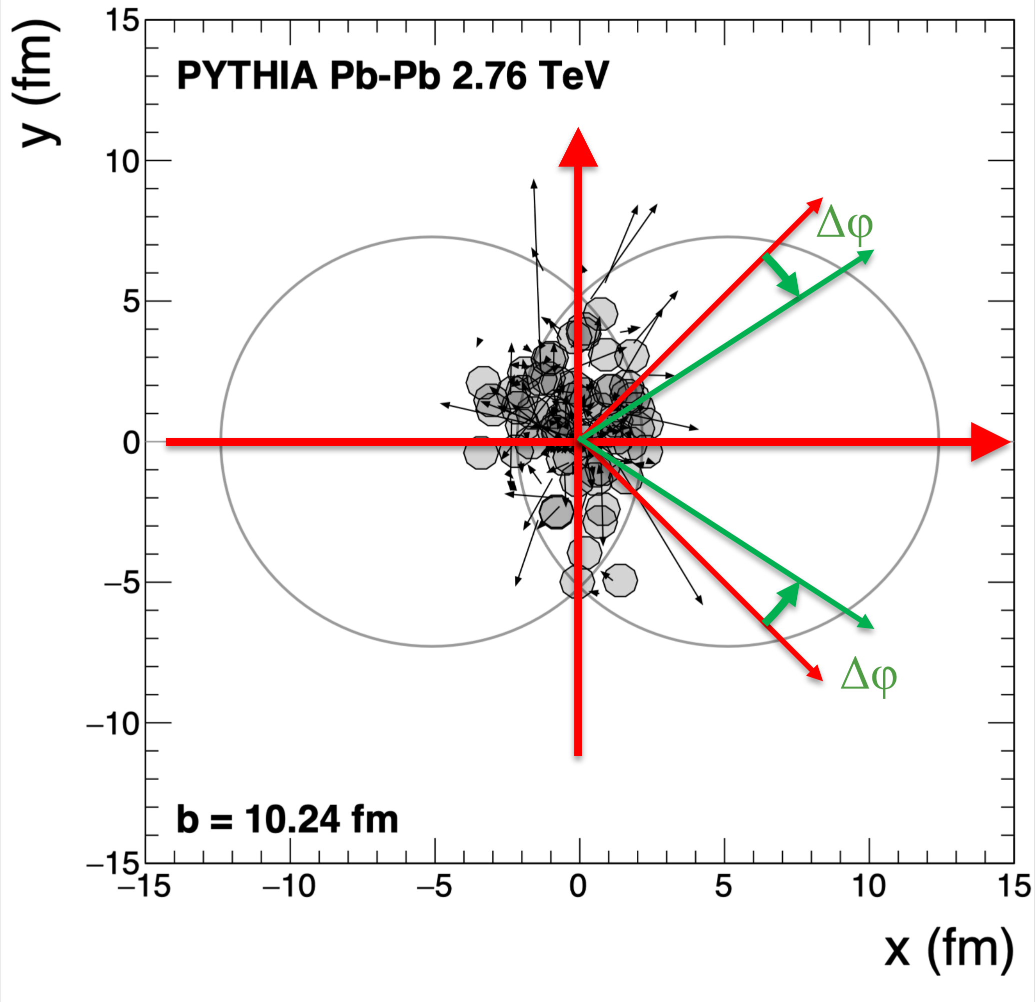
What if…

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

Adding an initial hadronic flow to PYTHIA



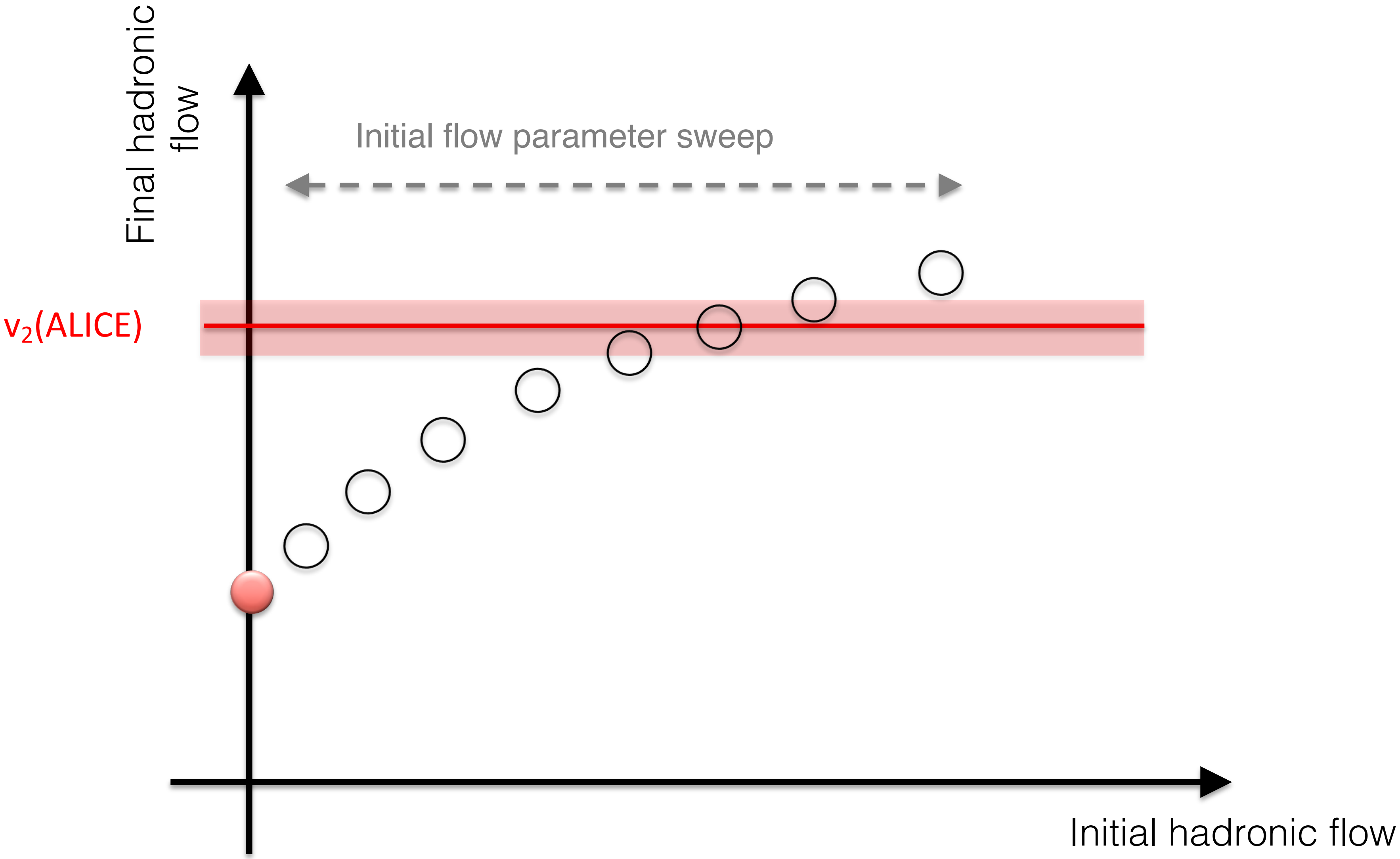
- Rotate momenta immediately after hadronization ($\Delta\varphi$ in figure)
- obtain a specific, settable initial $v_2(p_T)$ wrt to event plane

…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.

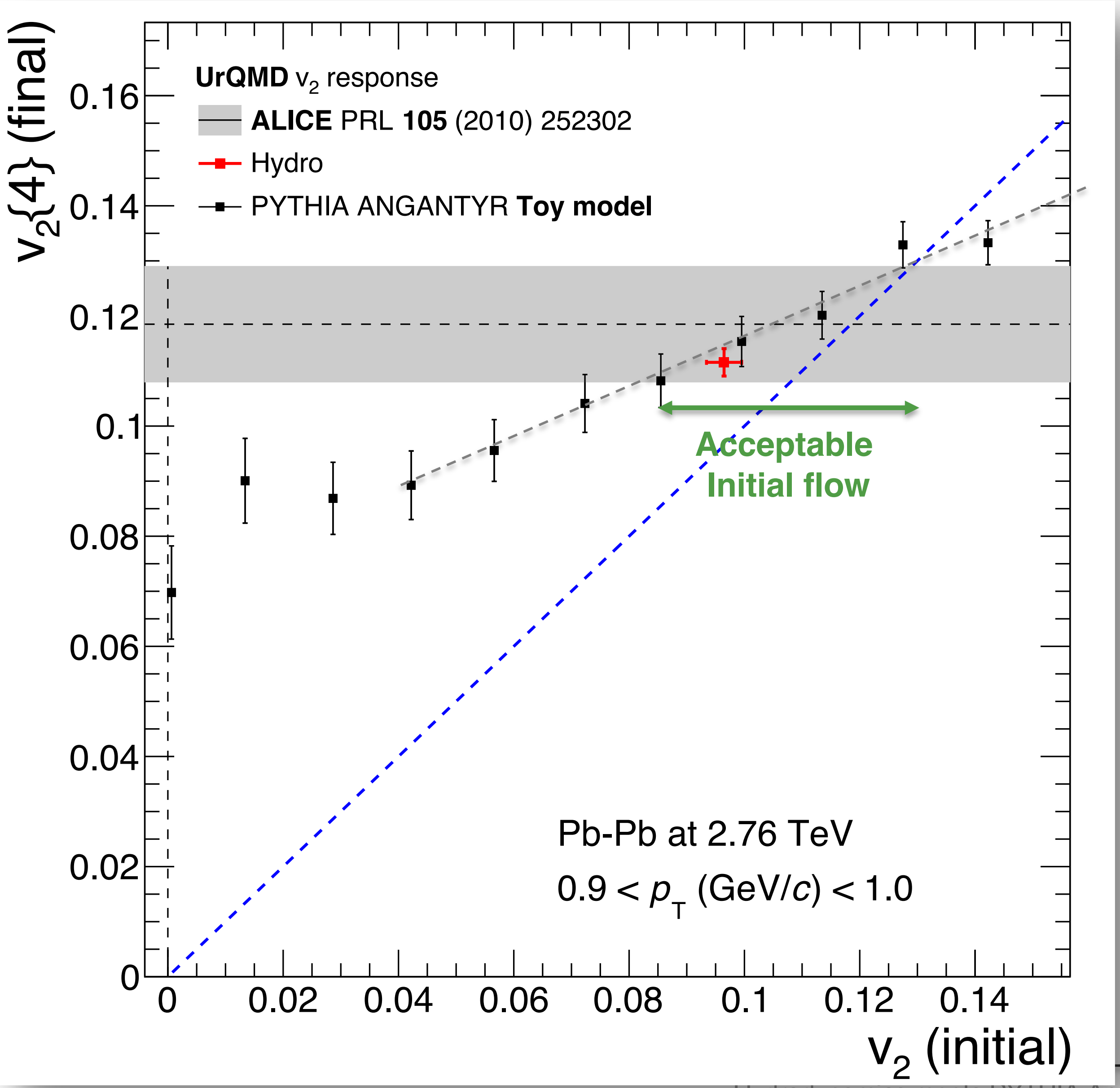
Goal: check UrQMD hydro-like response in each case.

How to plot? Next slide…

Initial hadronic flow vs final flow



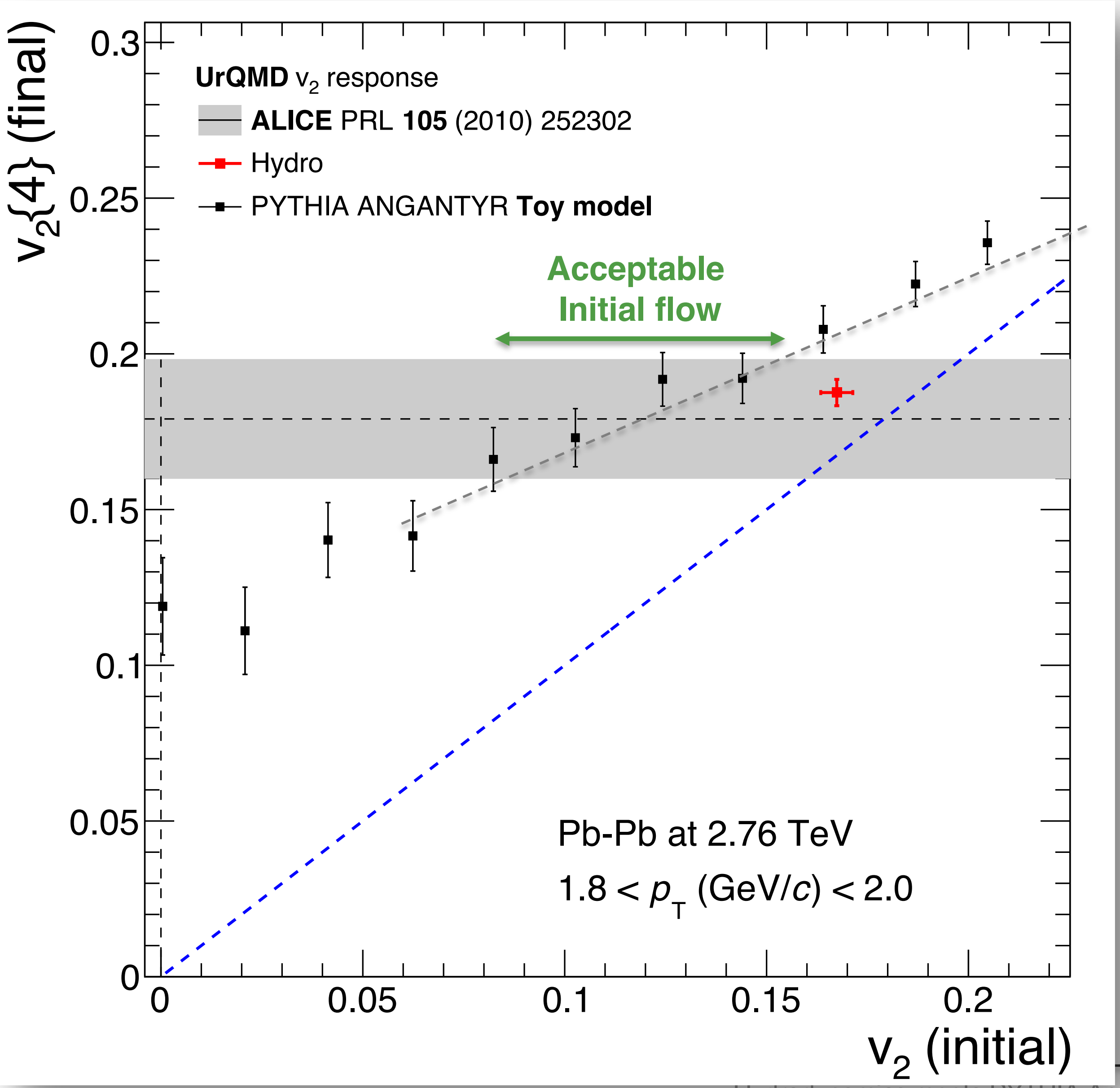
Initial hadronic flow vs final flow, low p_T



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



At low-p_T:

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At mid-p_T:

- measured value: not necessarily stable condition

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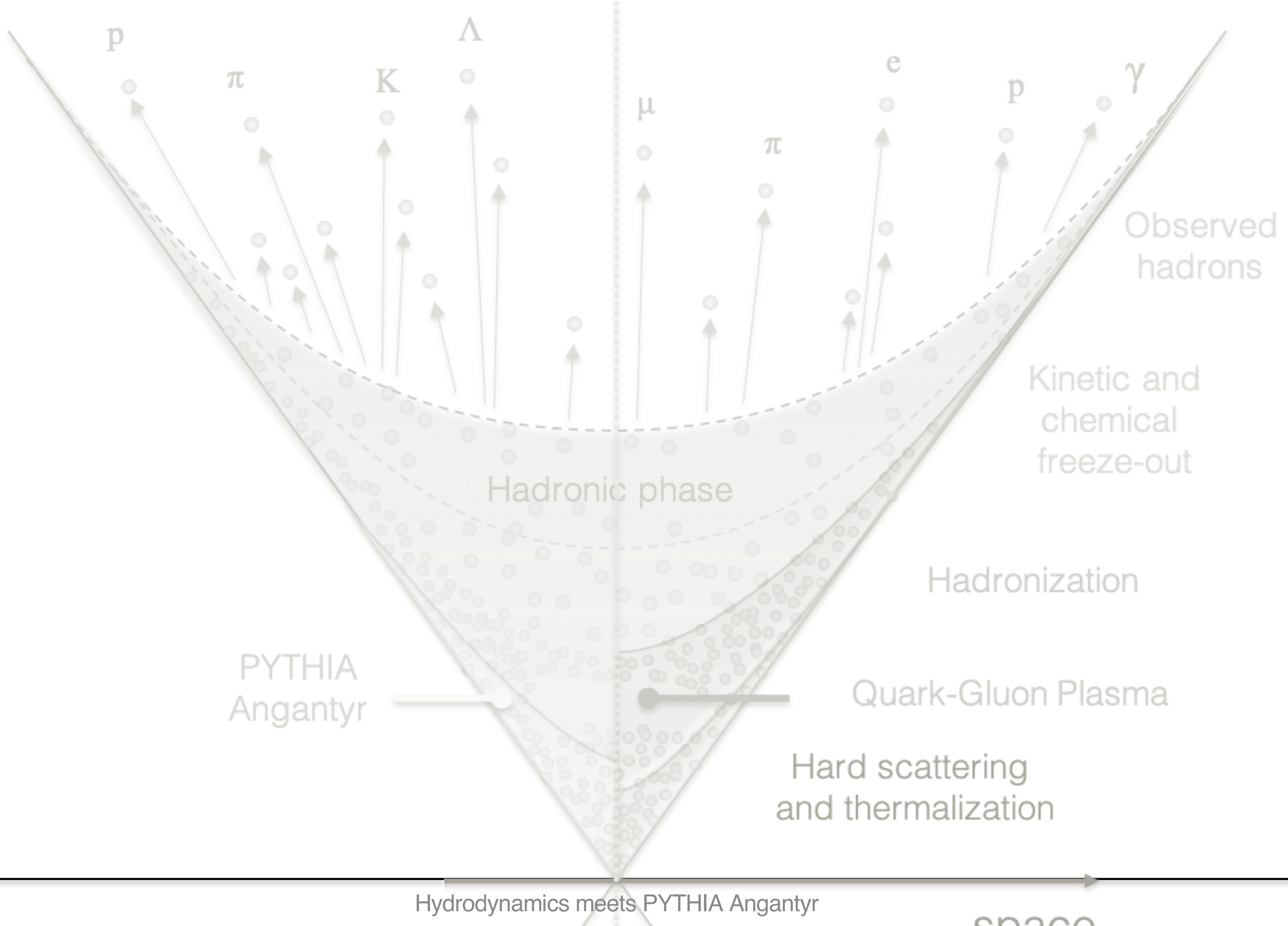
Hadrochemistry



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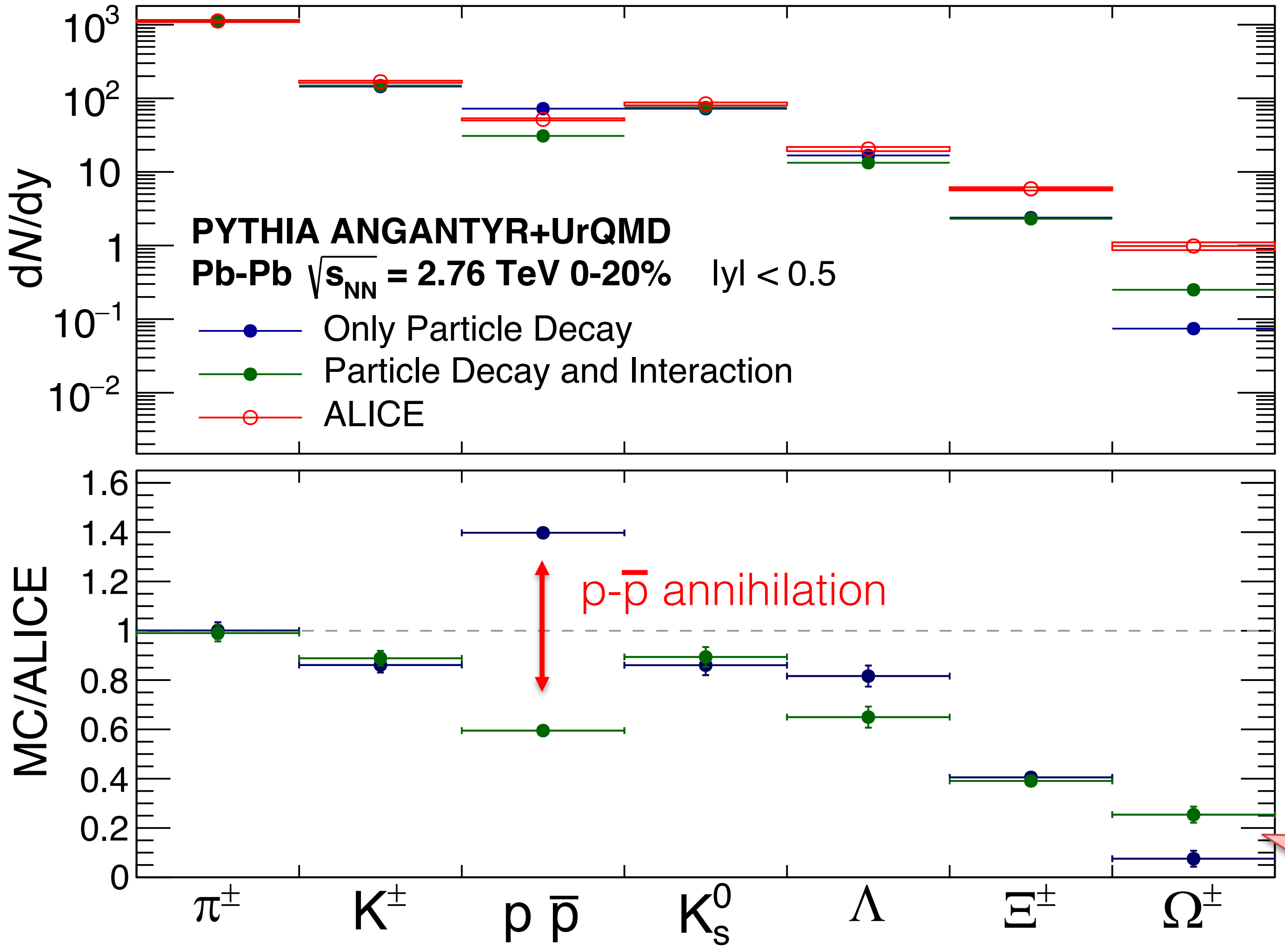

Hadronic interactions

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

Strangeness exchange processes?

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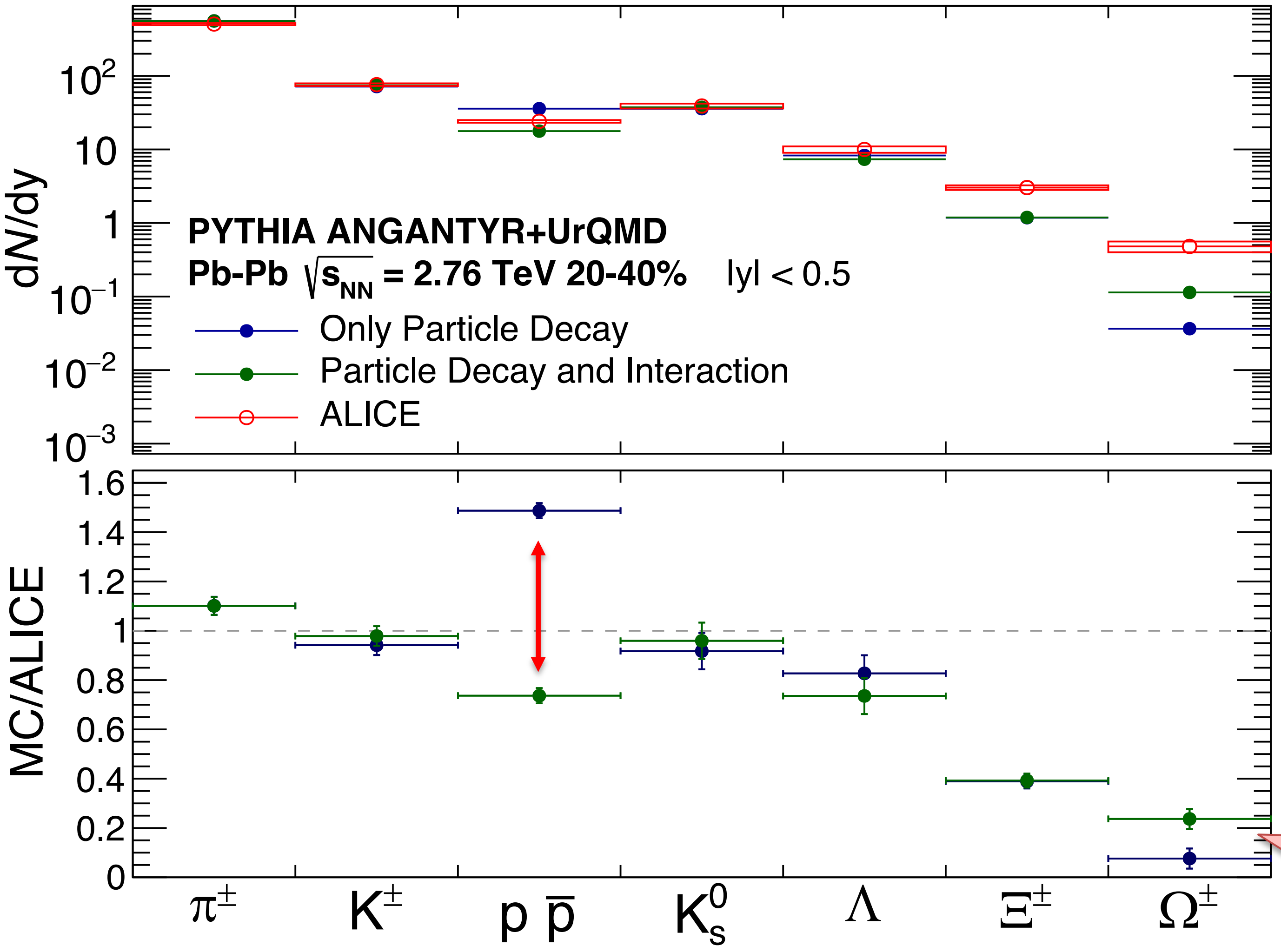

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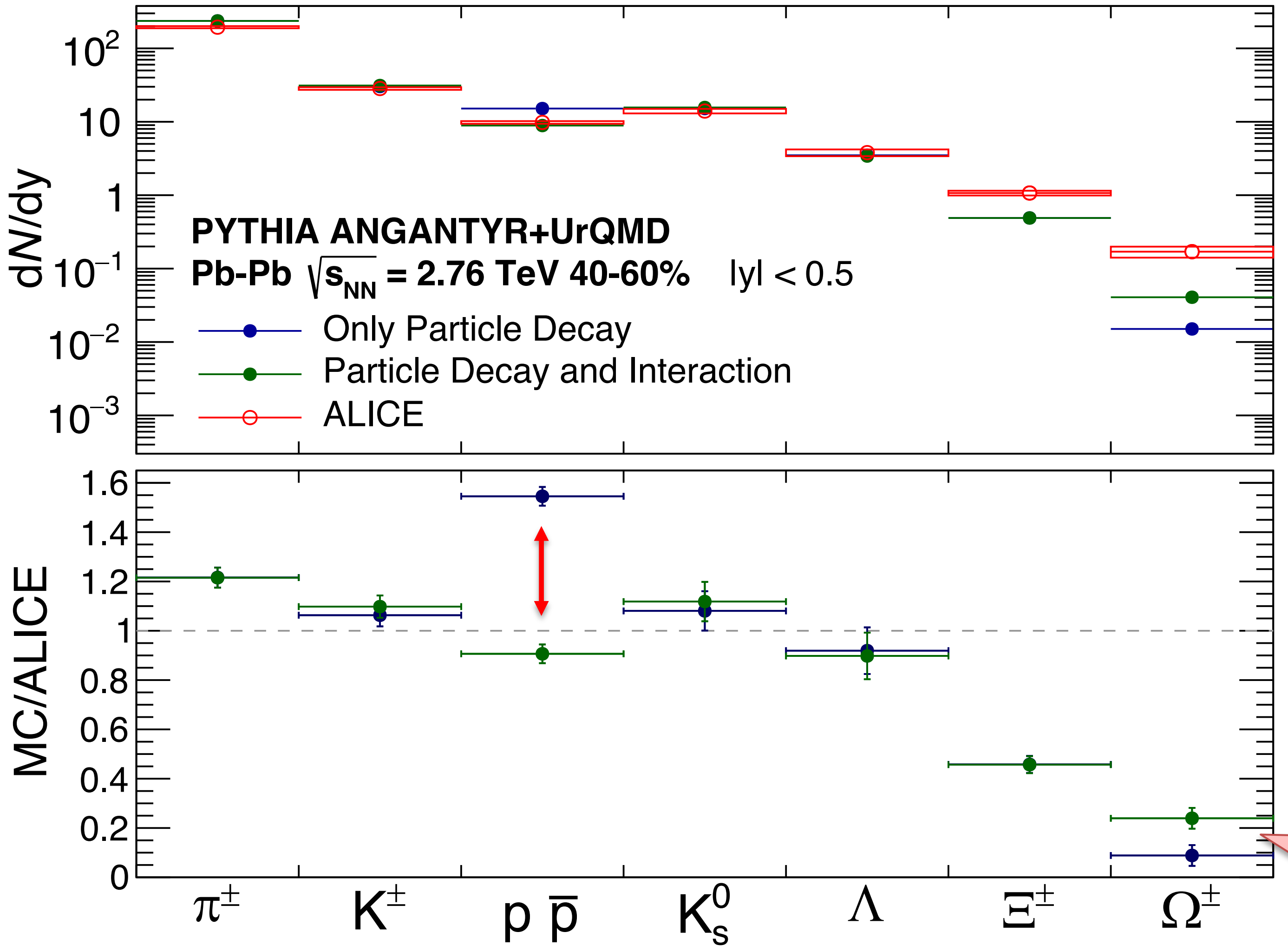

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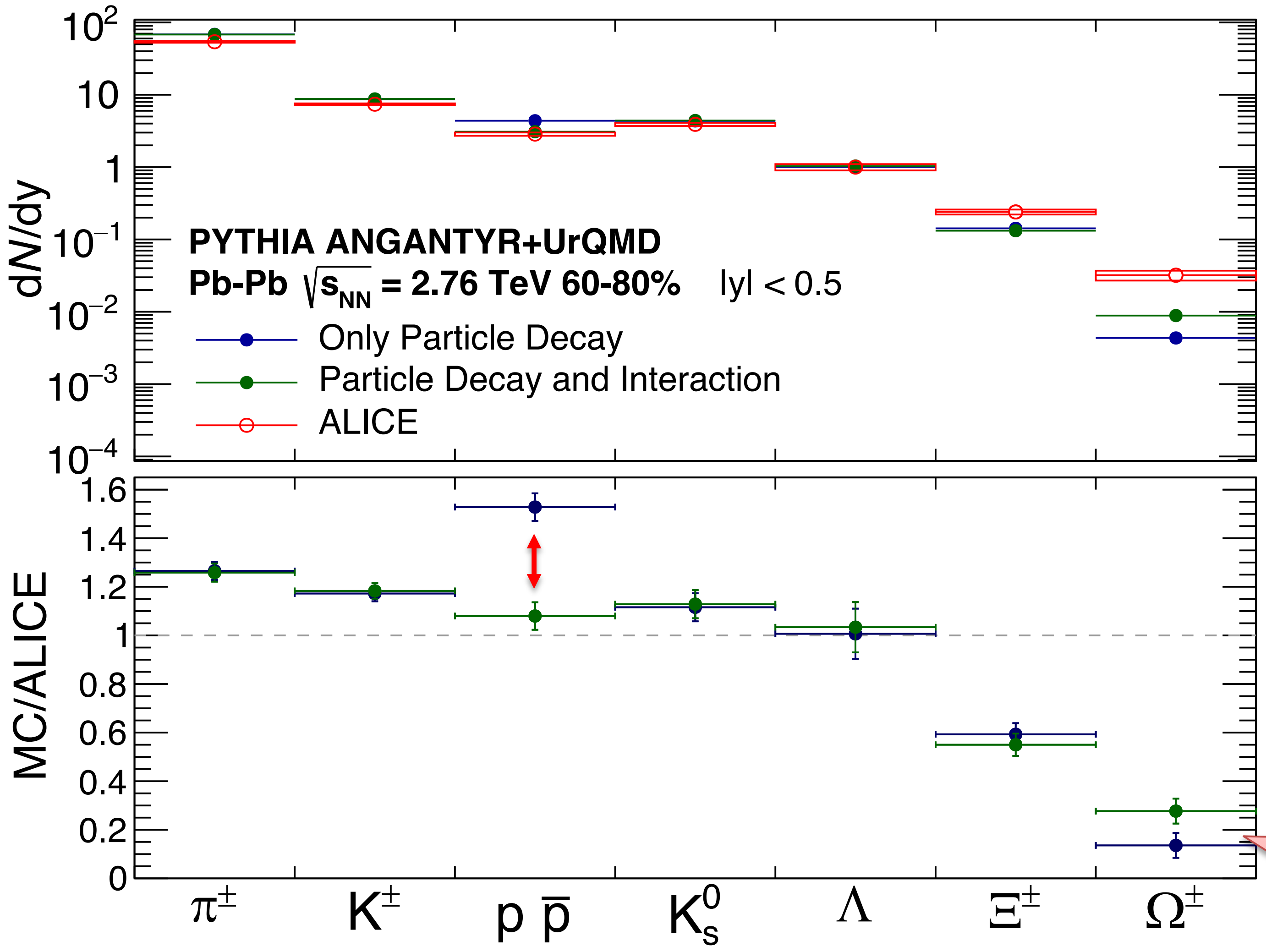
Hadrochemistry

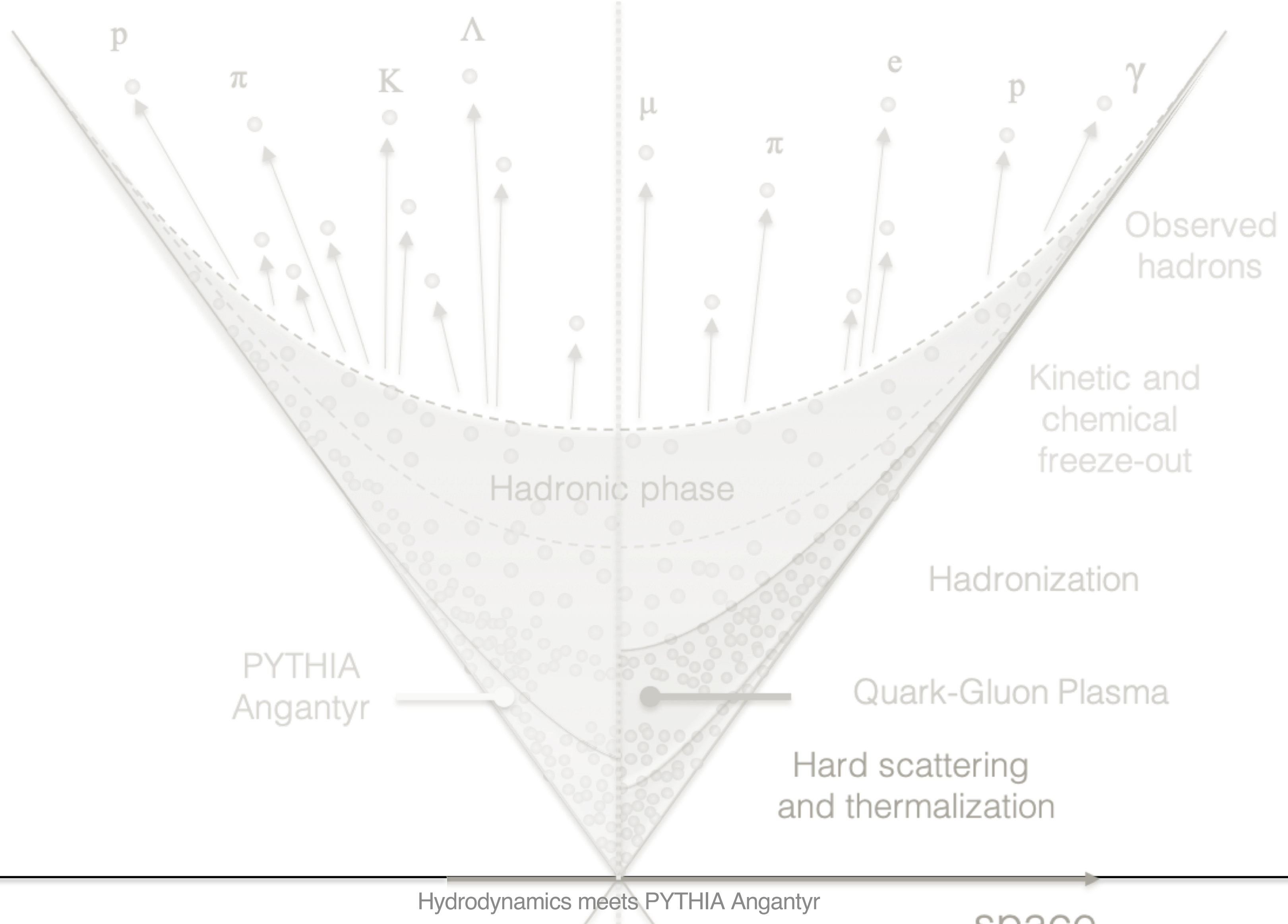


Hadronic interactions

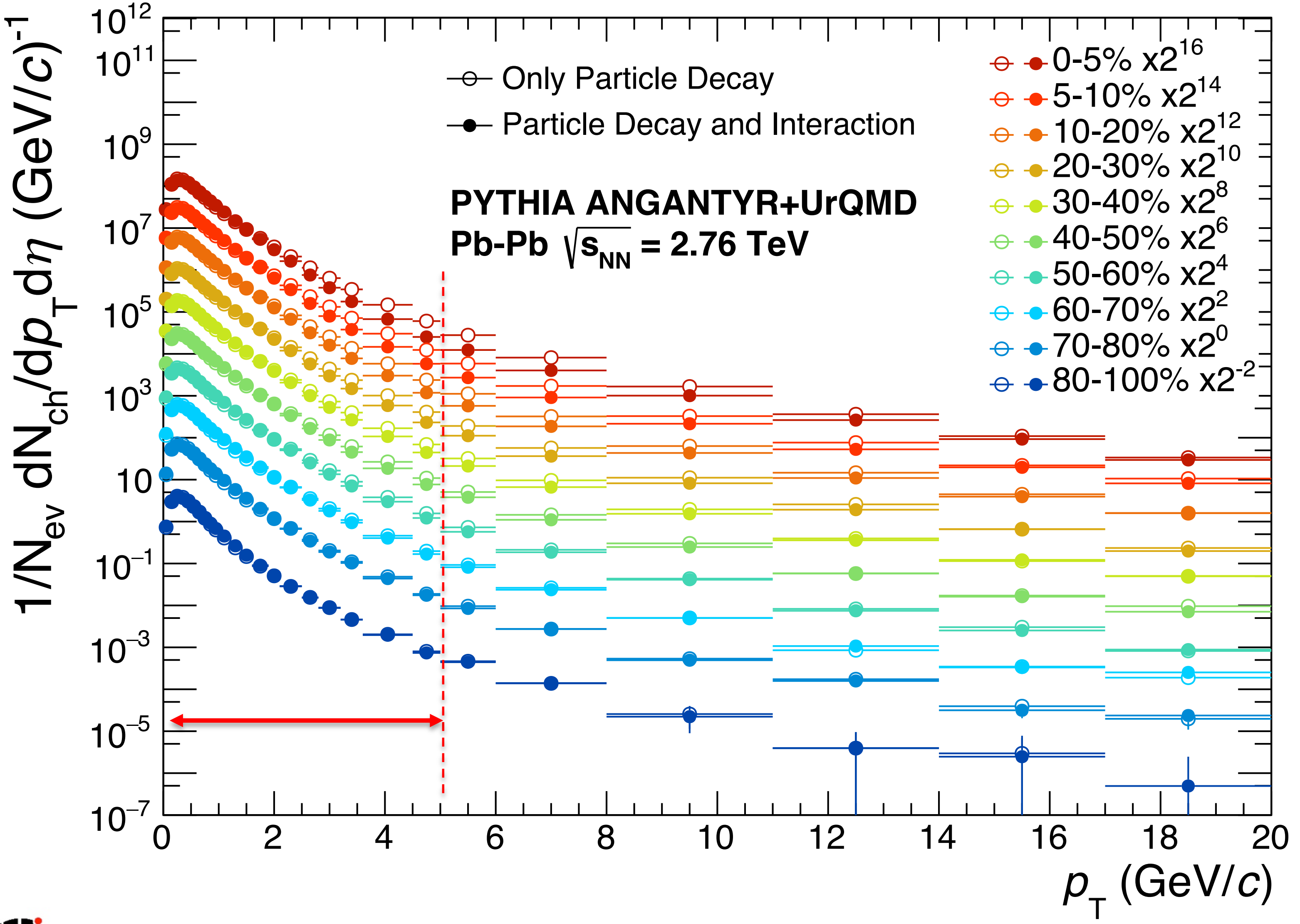
- Strong baryon-antibaryon annihilation: stronger than hydro
- Strangeness exchange re-generates multi-strange baryons?

Strangeness exchange processes?

High-transverse momentum physics



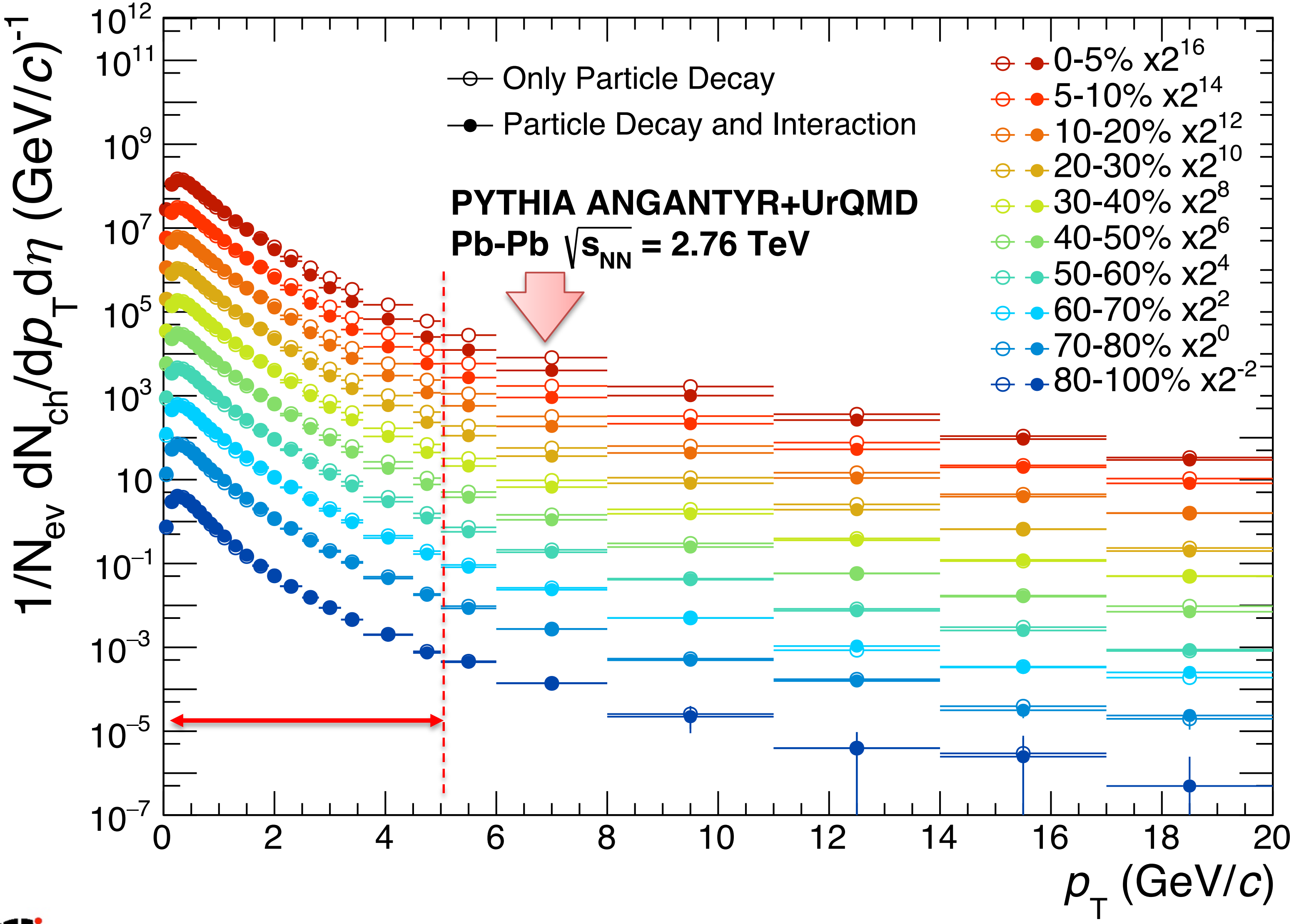
Transverse momentum spectra: PYTHIA+UrQMD



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?

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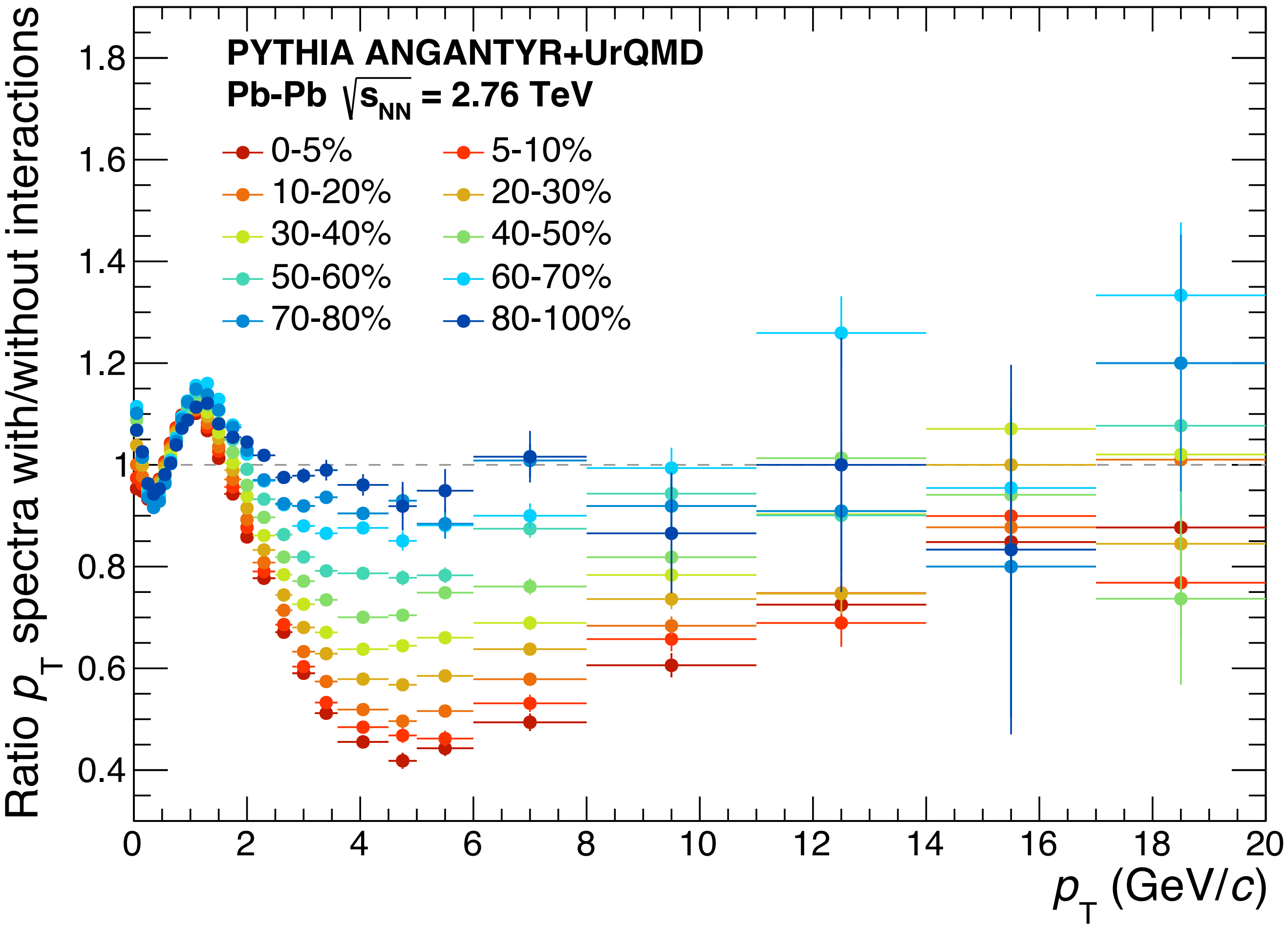
Transverse momentum spectra modification



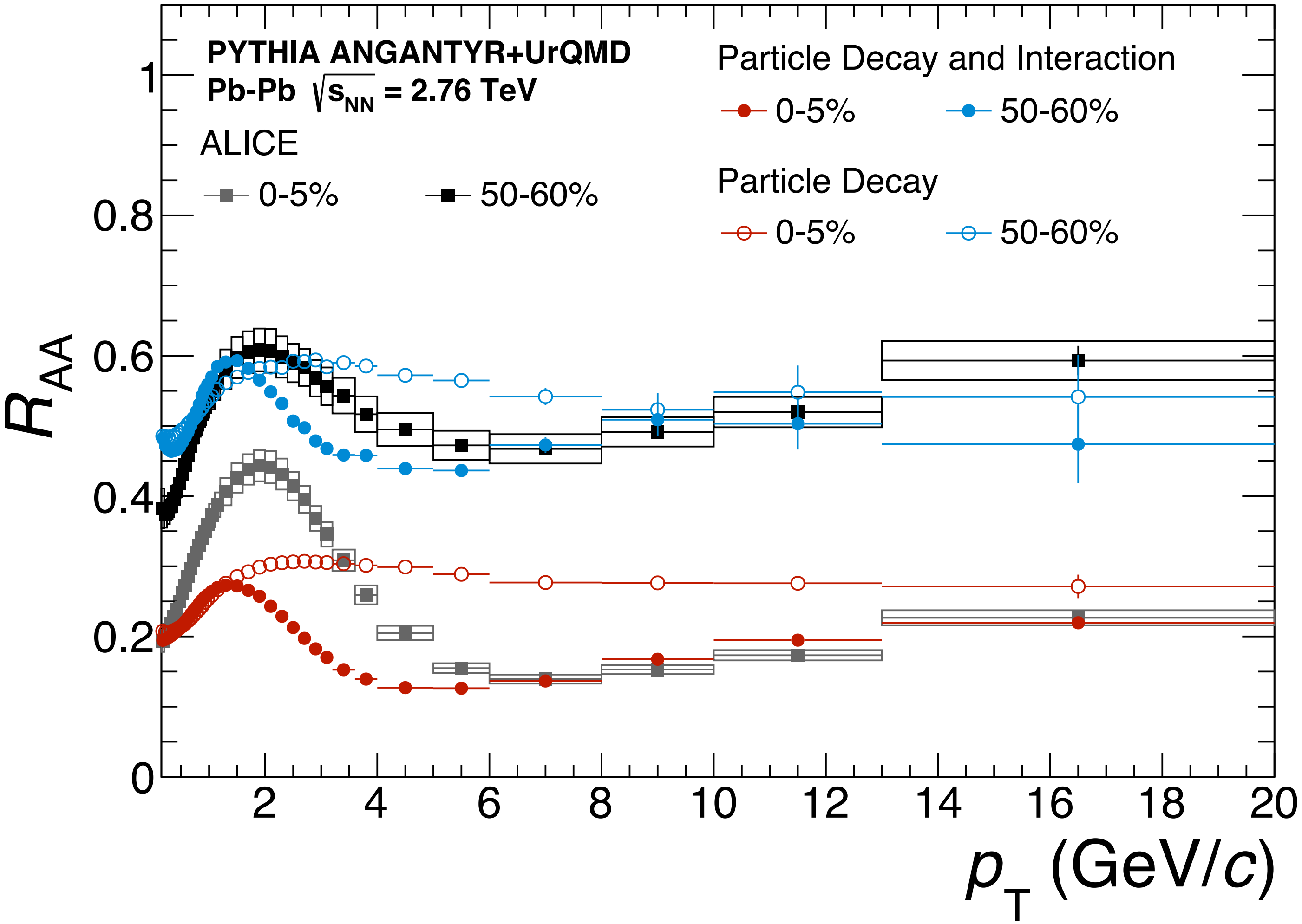
Low p_T:

- 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}

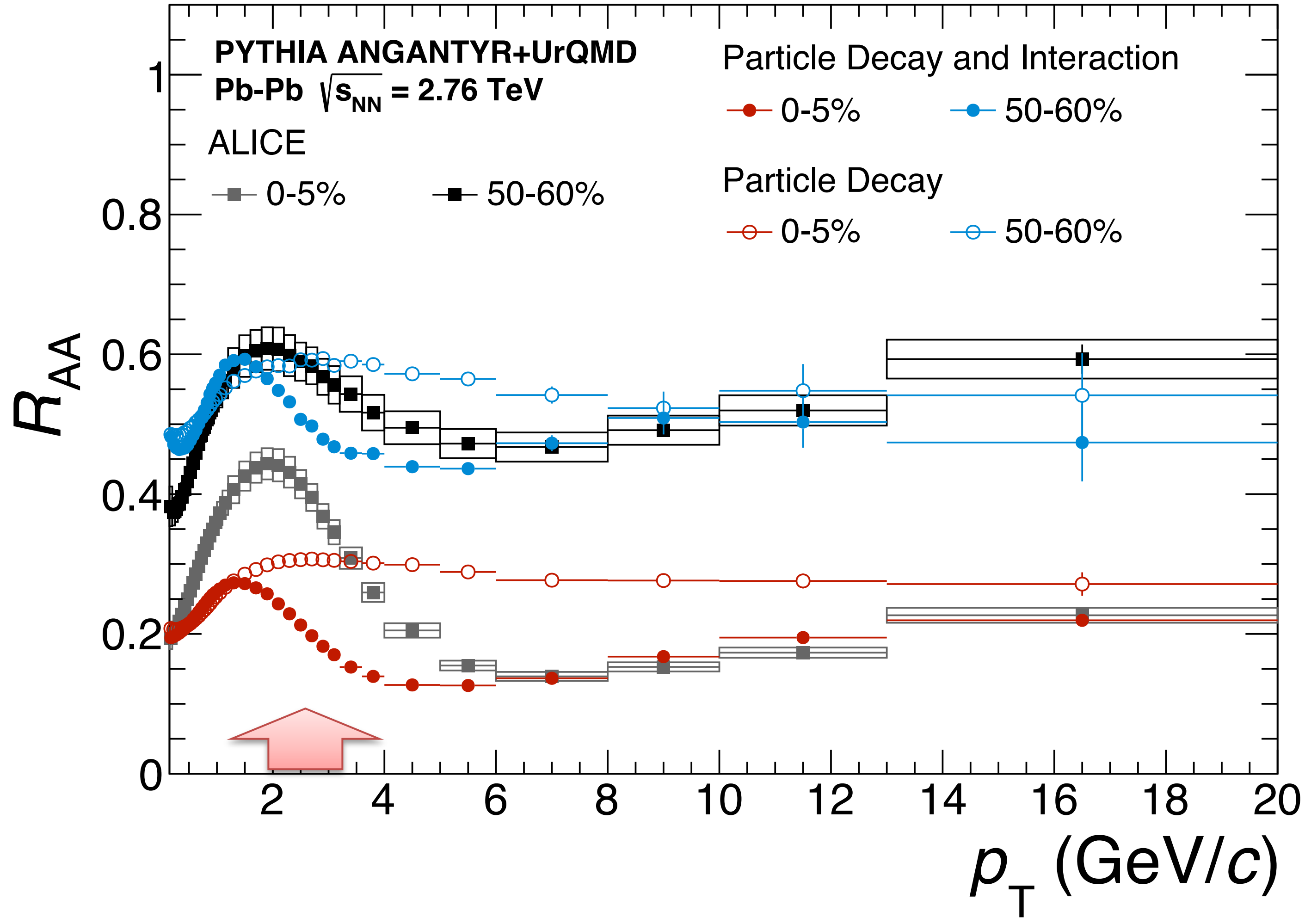


$$R_{AA} = \frac{dN^{AA}/dp_T}{N_{coll}\, dN^{pp}/dp_T}$$

RAA calculation:

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

Nuclear modification factor R_{AA}



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RAA calculation:

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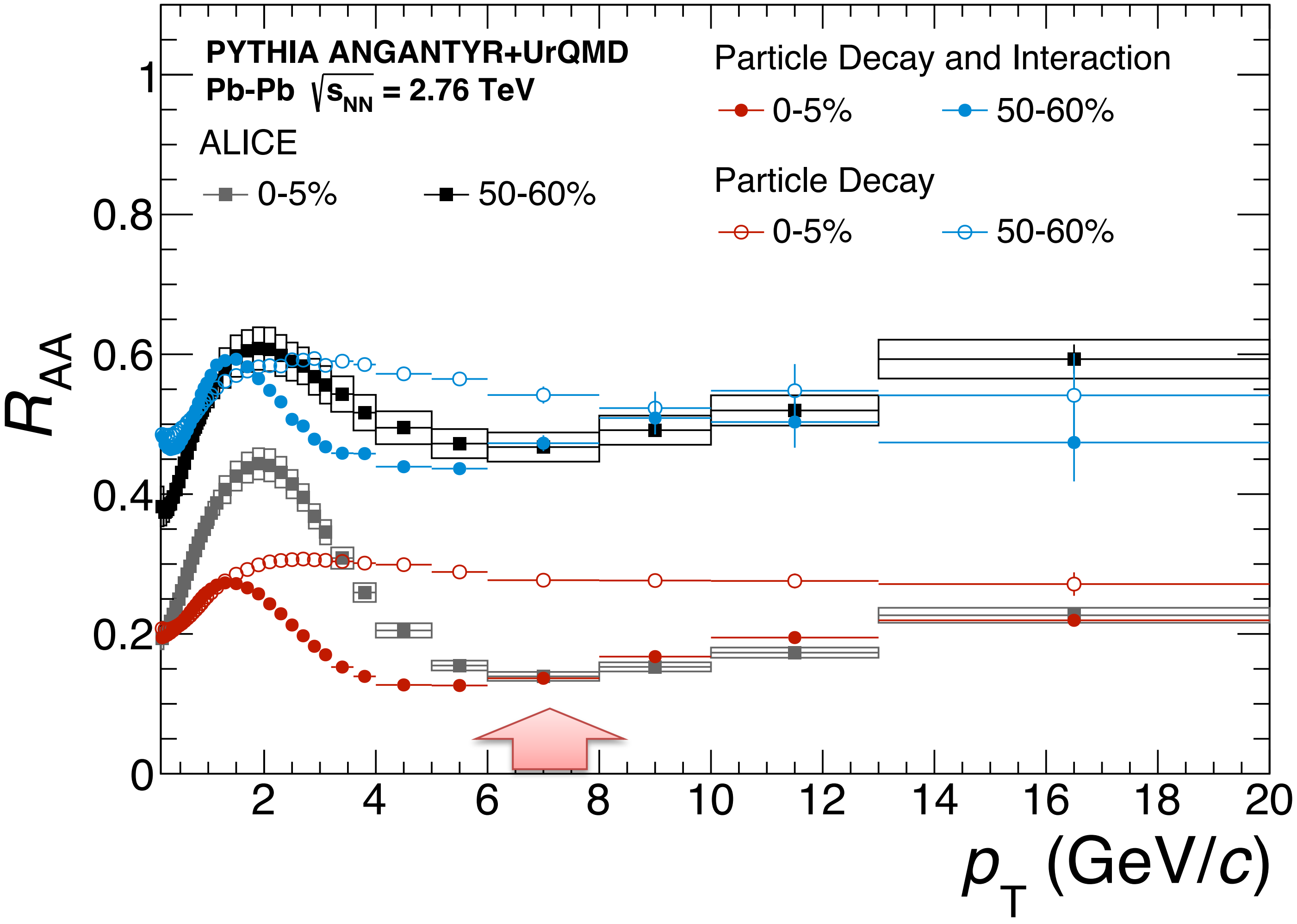
Low p_T:

- Data not described: radial flow missing?

Nuclear modification factor R_{AA}



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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

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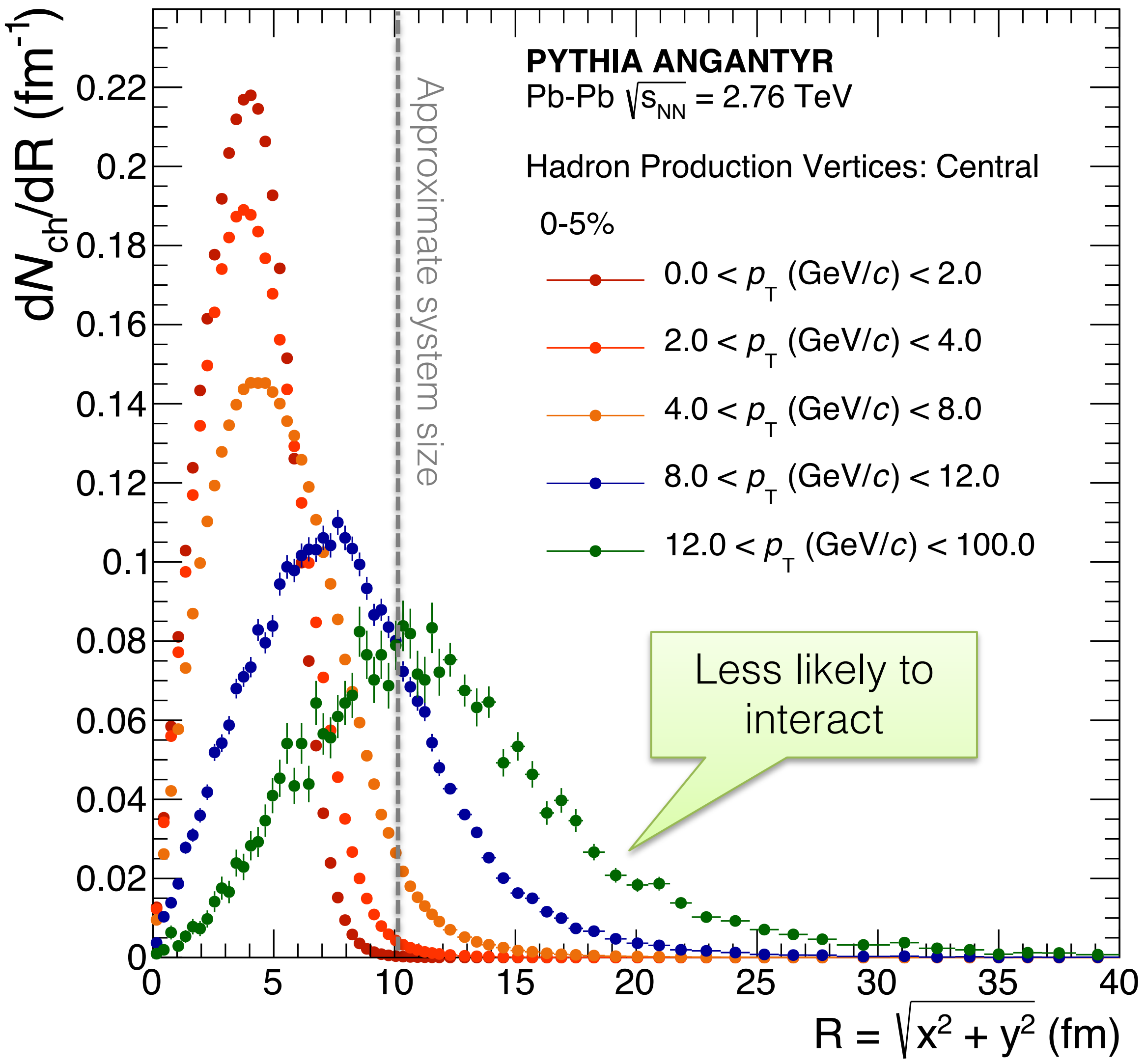
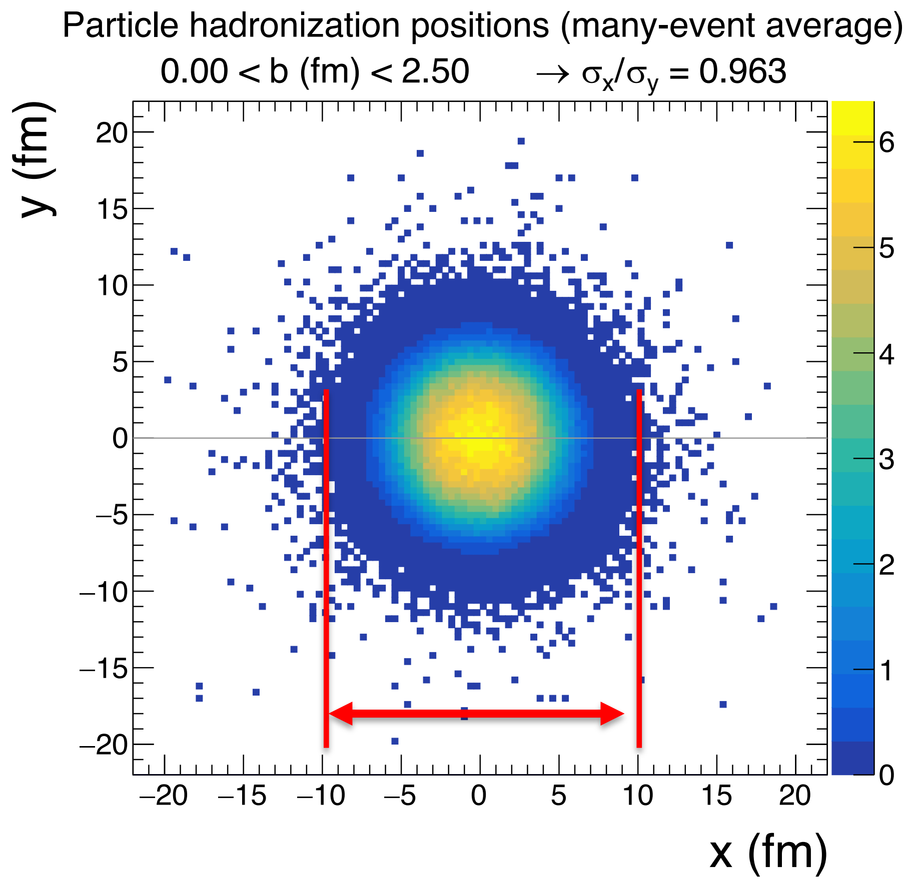
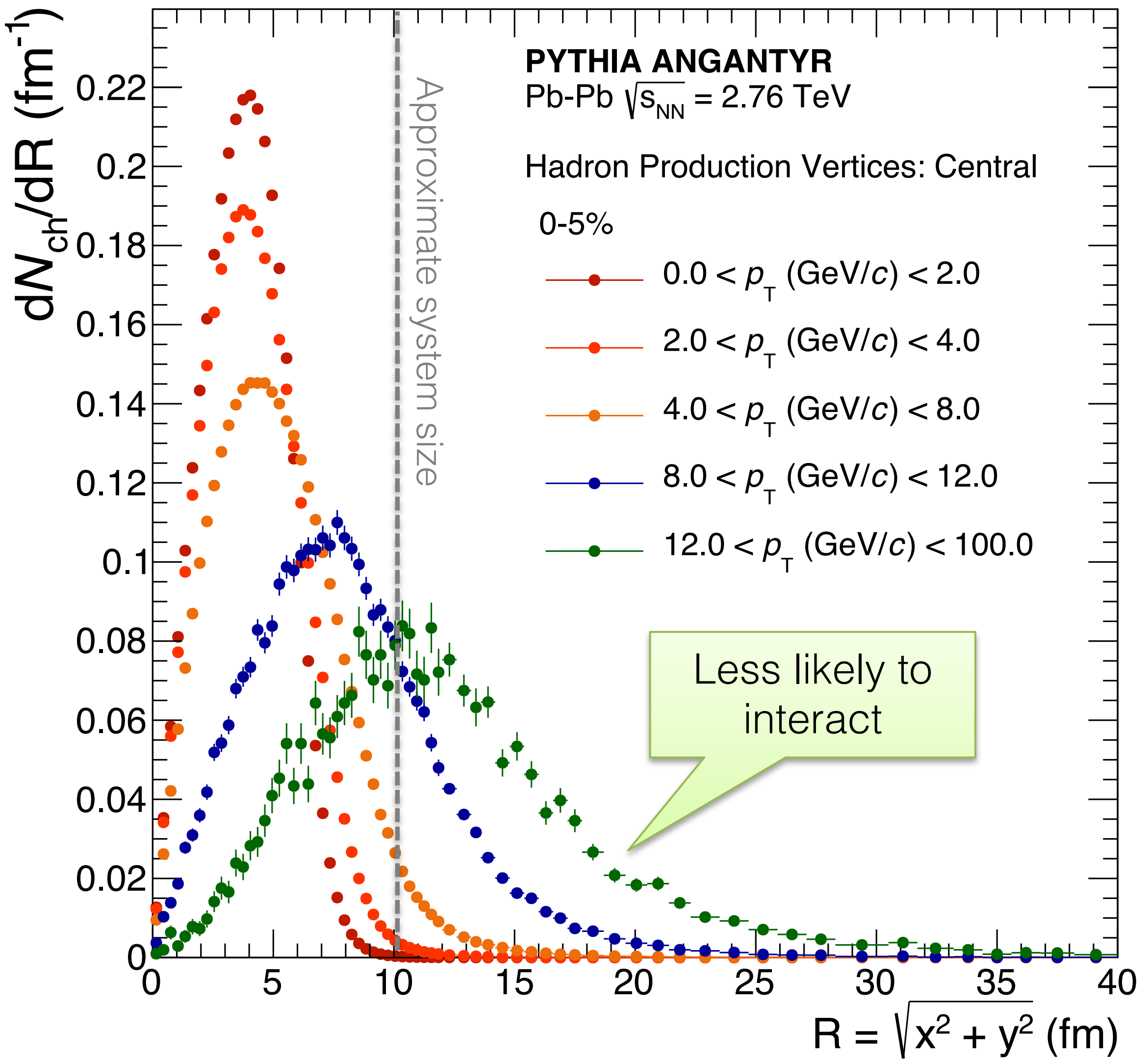
High-p_T particle positions at hadronization

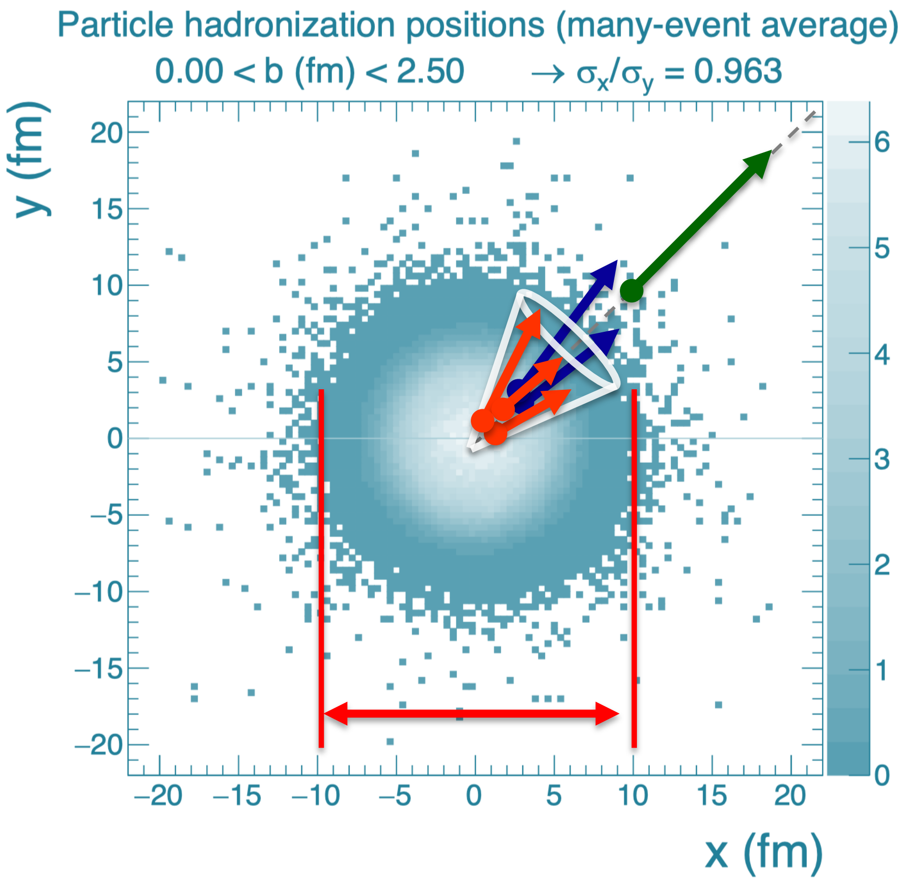




- Position ∝ momentum
- System size (central): x ≅ 10 fm

High-p_T particle positions at hadronization





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

Summary

- **PYTHIA Angantyr + UrQMD**: a complete, QGP-free alternative to hydro

- **Multiplicity**: reproduced within ~10% (similar to hydro)
- **Average p_T**: too low, missing radial flow / (string shoving?)

- **Elliptic flow / collectivity**: 60% of measured v_2!
  - Less room for QGP effects?...
  - …but UrQMD response is not strictly additive!

- **Hadrochemistry**: significant effect for baryons, strangeness

- **High-pT spectra**: suppression of high-p_T yields
  - Jet quenching in the hadronic phase?
  - Hadron vertex model: high-p_T "escapes" without interacting

Thank you!

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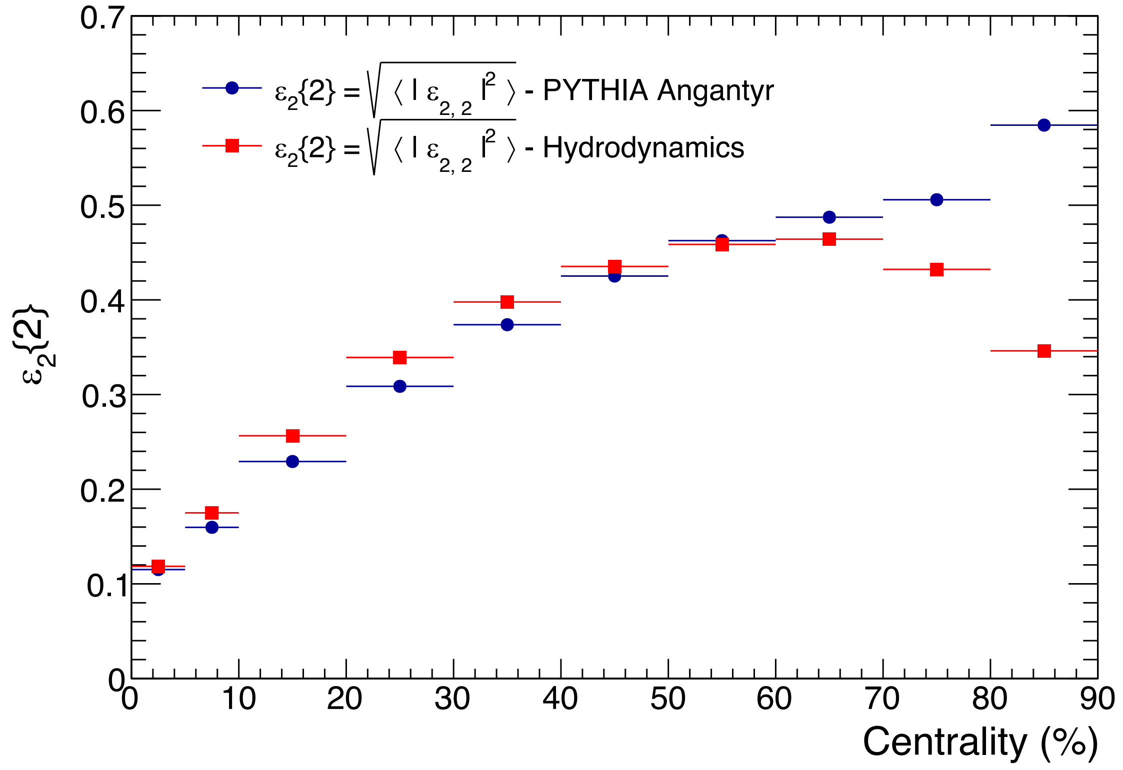
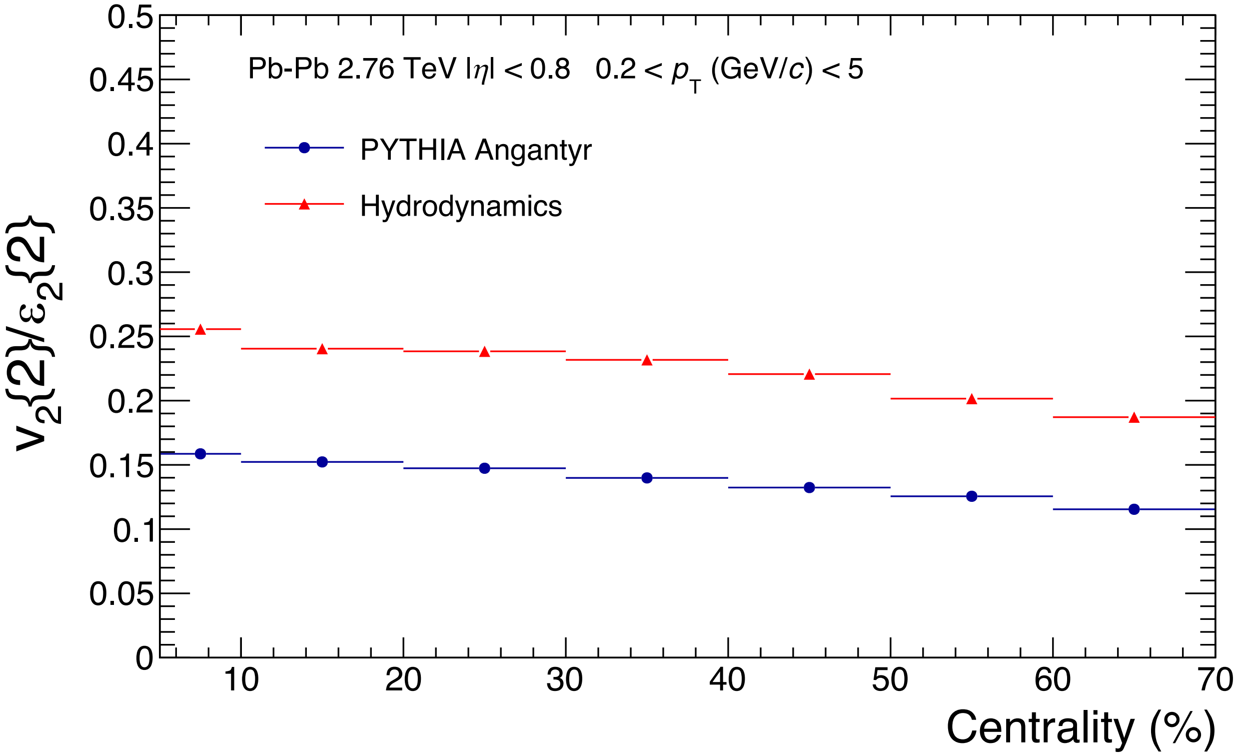
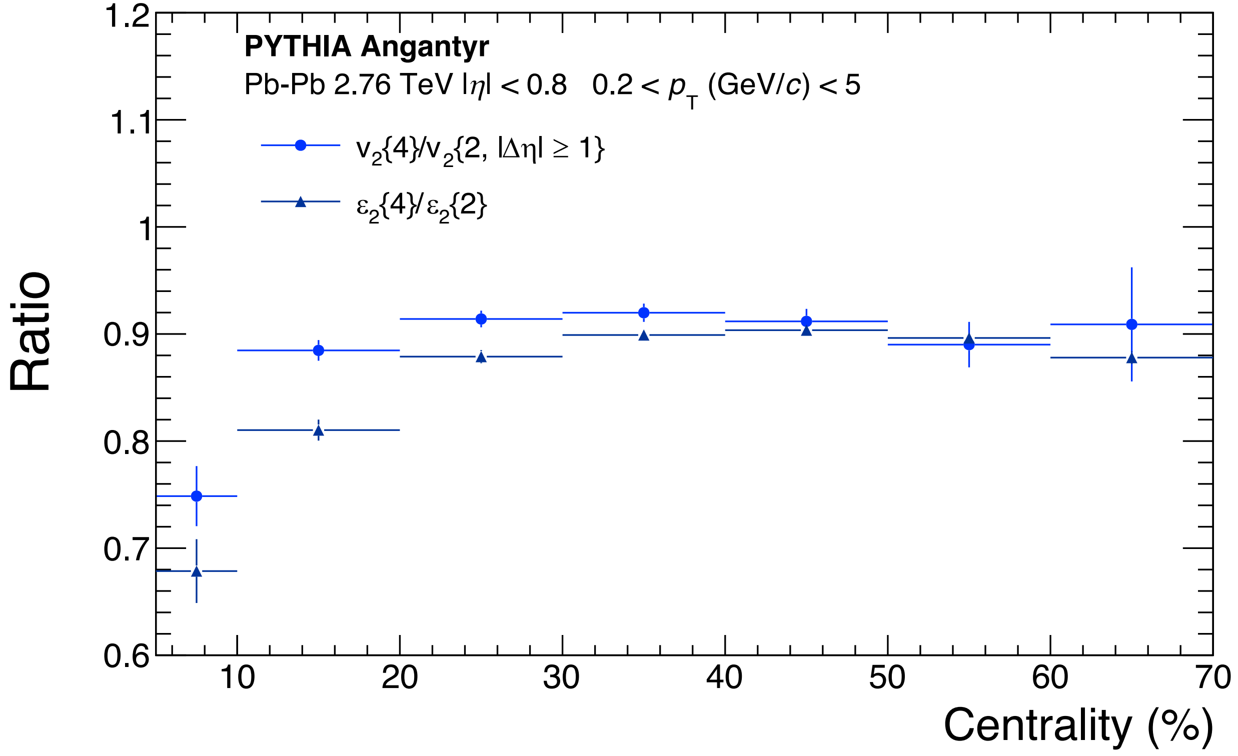
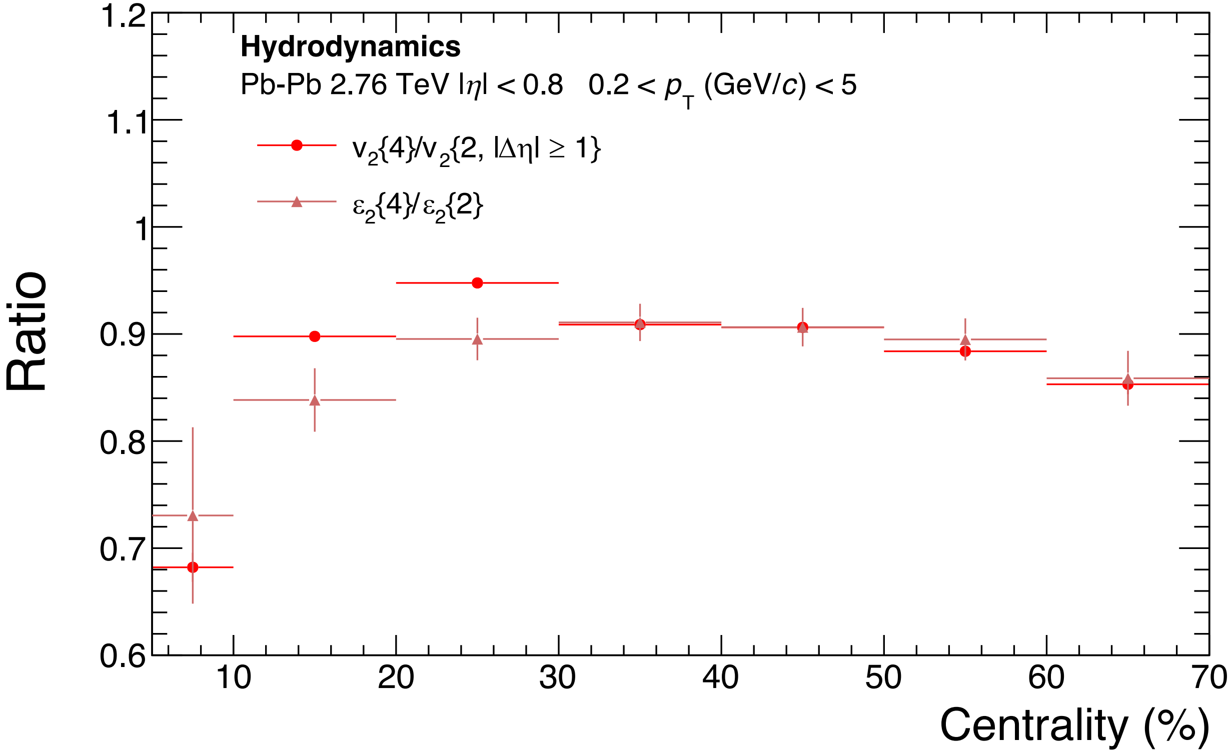
Further studies: relating $v_2\{2\}$, $v_2\{4\}$ to the initial condition



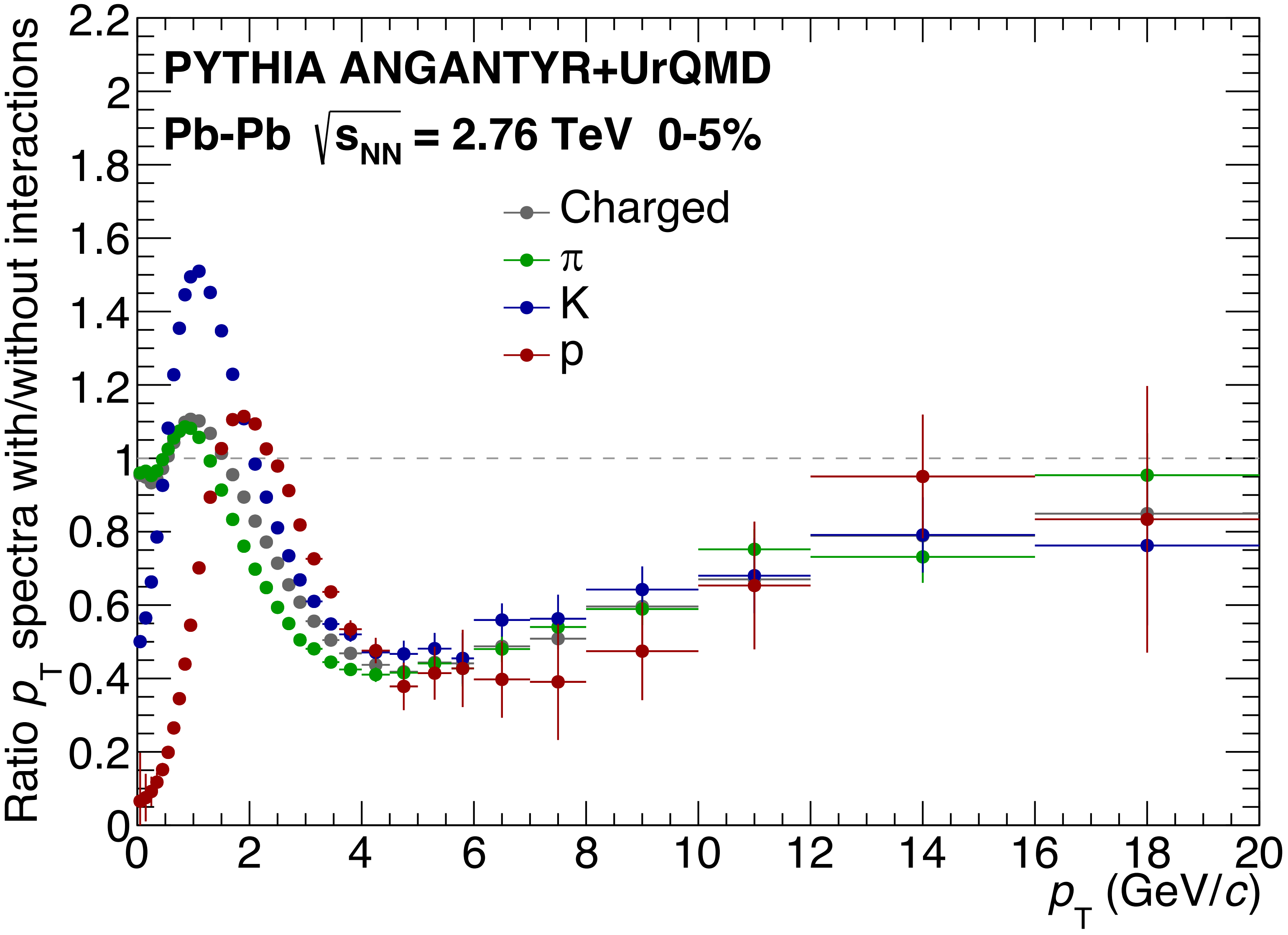


Further studies: relating $v_2\{2\}$, $v_2\{4\}$ to the initial condition





Spectra modification: identified particle species



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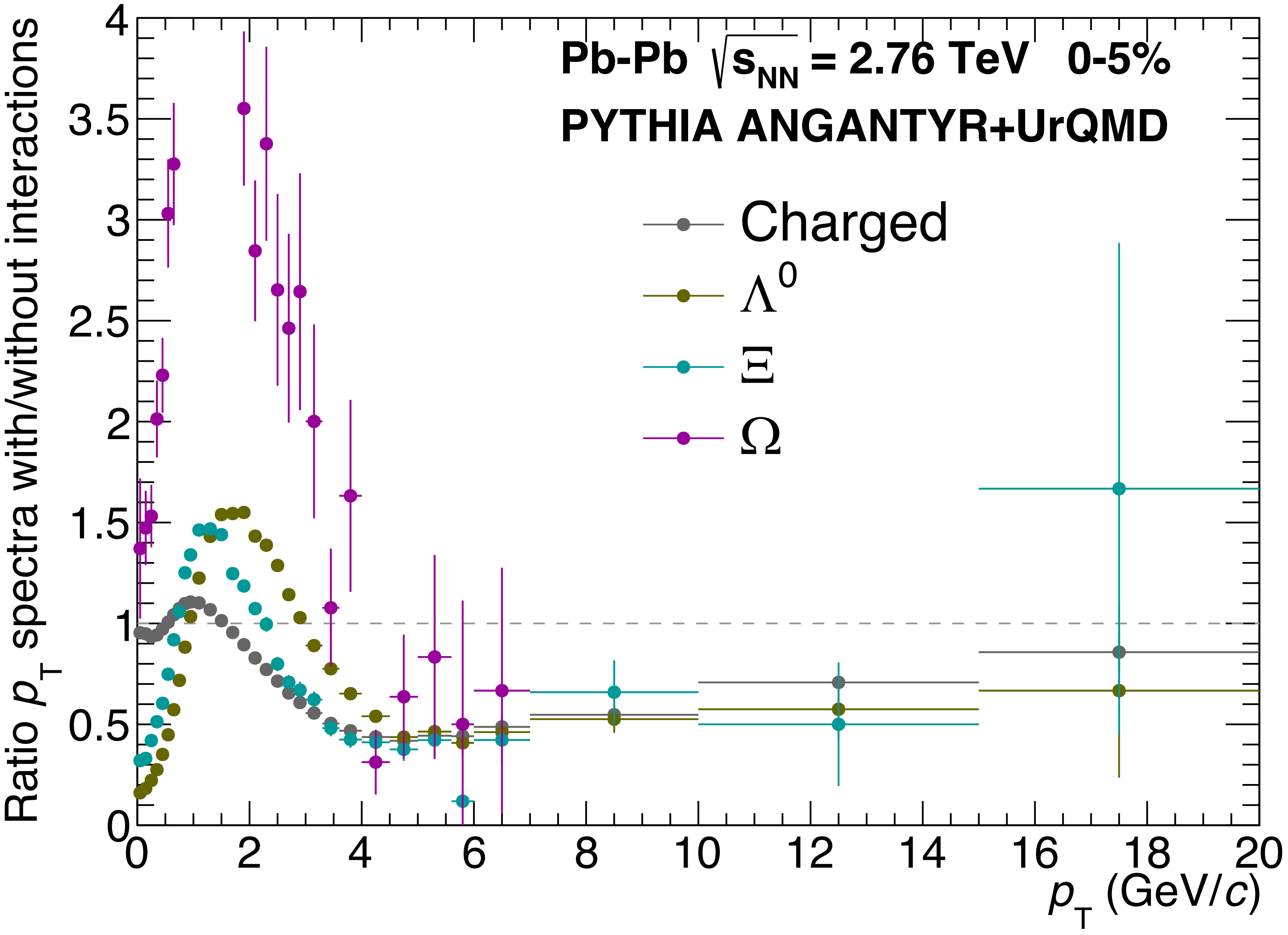

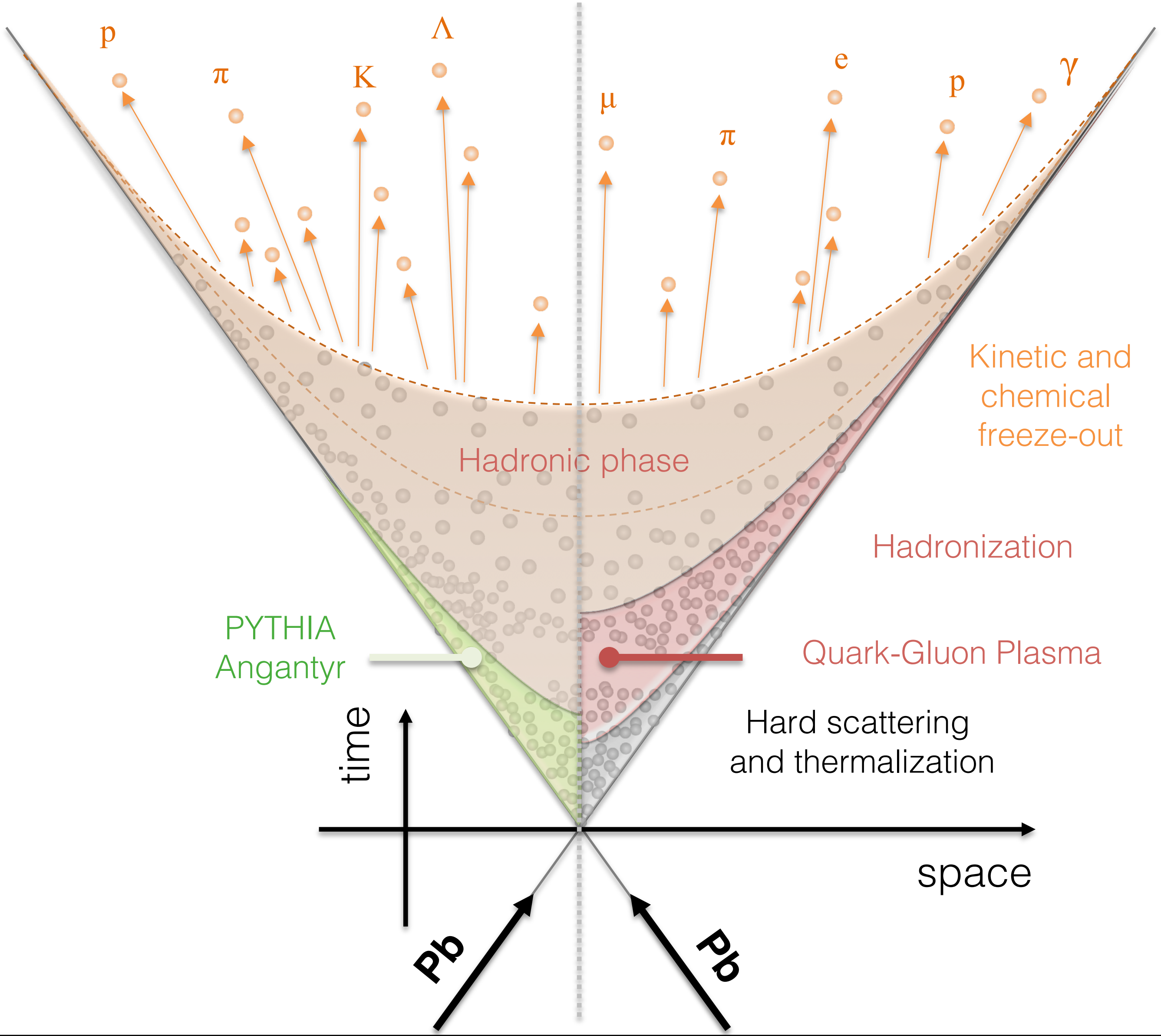
p
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Kinetic and
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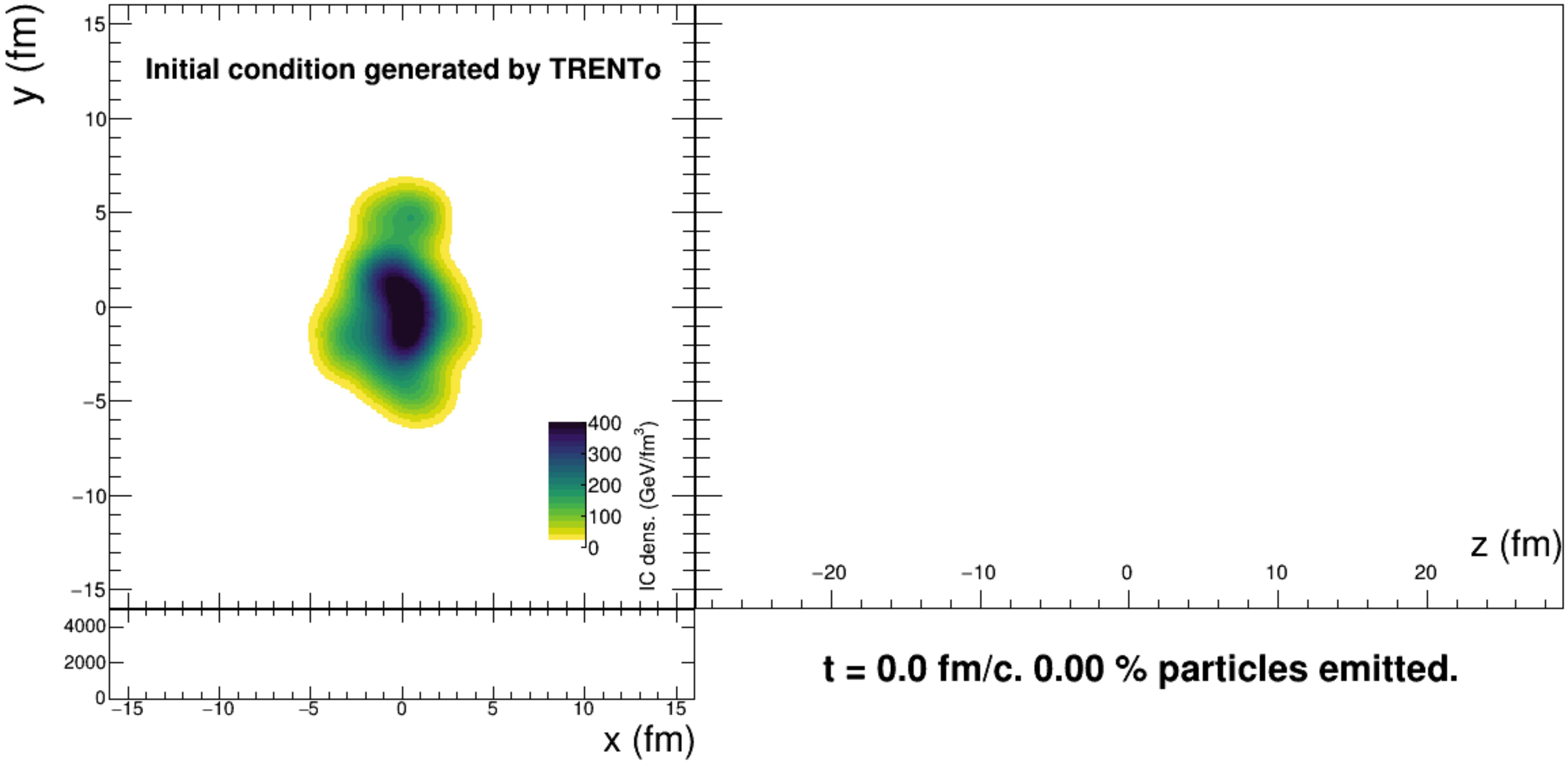
Hadronization
PYTHIA
Angantyr
Quark-Gluon Plasma
Hard scattering
and thermalization
time
space
Pb
Pb



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