Jets and Hadronic Interactions

Hannah Elfner

August 12th 2019, RRTF on „The space-time structure of jet quenching: theory and experiment“ at GSI, Germany

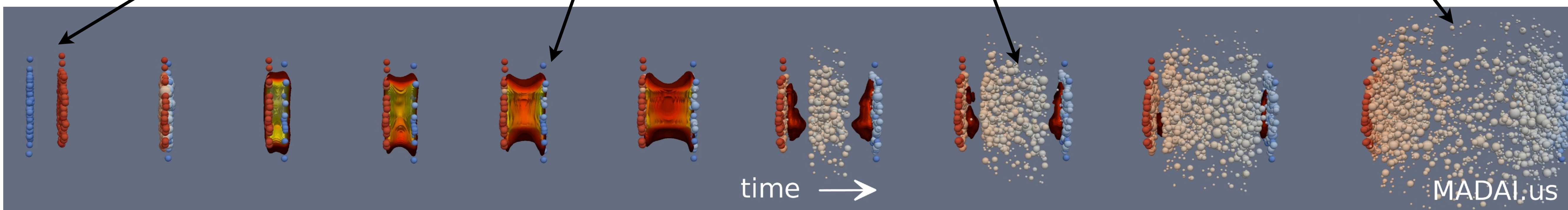
Time Evolution of Heavy Ion Collisions

Nuclei at 99 % speed of light

Quark Gluon Plasma

Hadronic Rescattering

Measurable Fragments in the detector



1x 10^{-23} s

10 x 10^{-23} s

30 x 10^{-23} s

Nonequilibrium initial state dynamics → Relativistic Hydrodynamics → Hadron Transport

- Most jet quenching calculations only care about the partonic phase of the interaction and are based on interactions with the medium in the fluid phase

Dynamic description of heavy ion collisions has to capture all the stages of the reaction

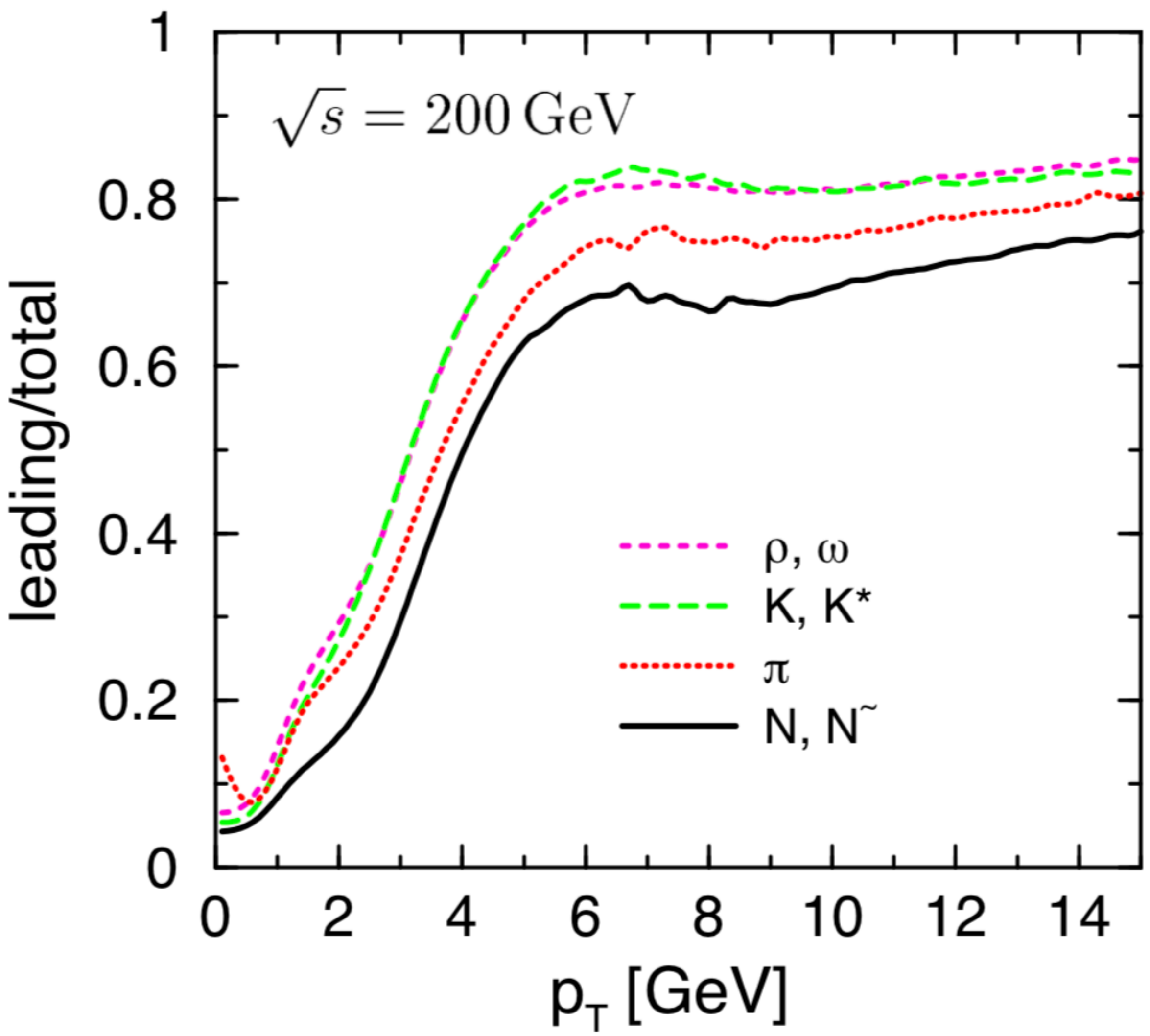
Jets in the Hadronic Stage

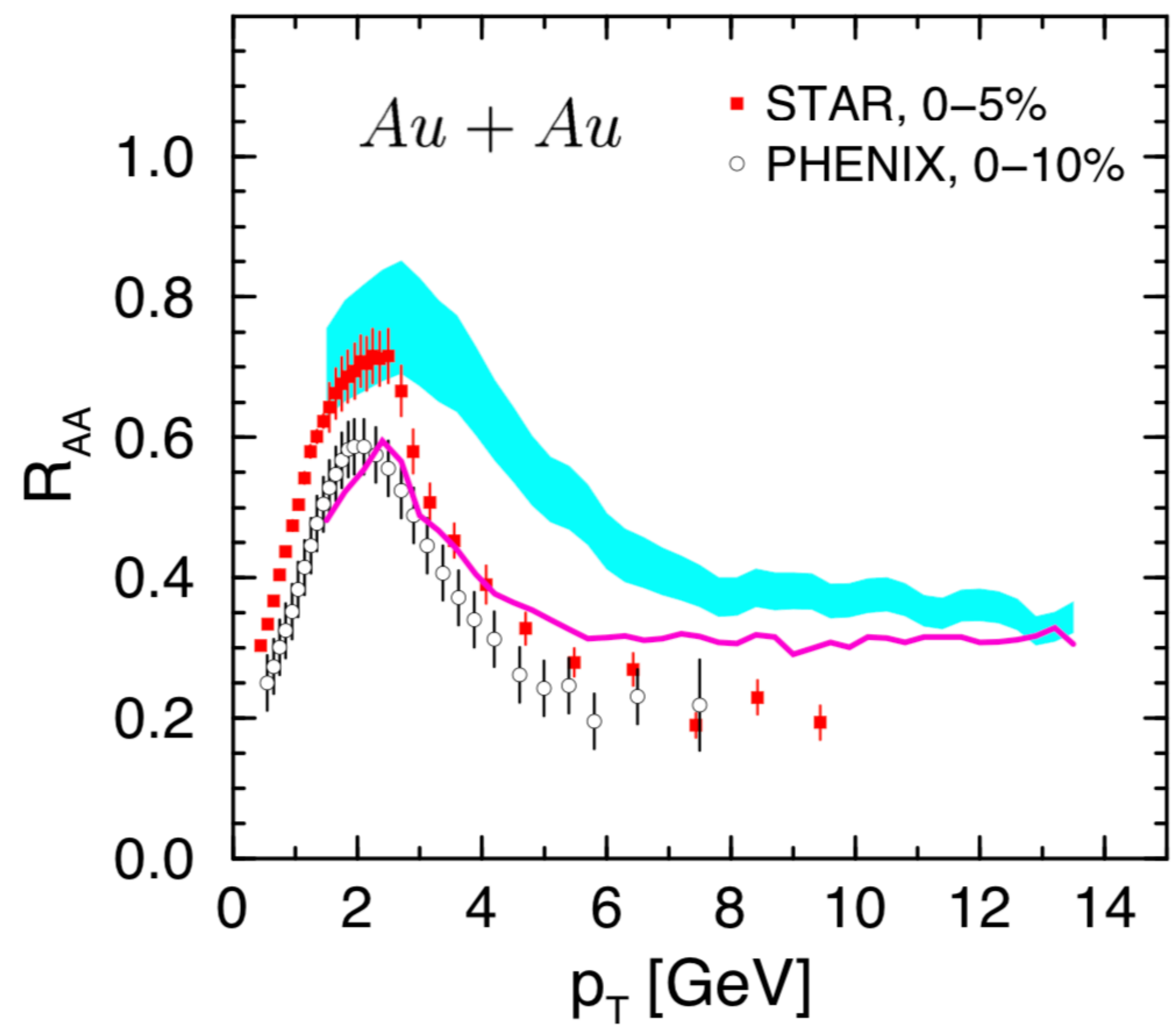
- In principle the particles produced in high p_T processes will also interact with the hadronic medium
- Due to timescales, it is mostly assumed that they have escaped once the medium evolution is in the hadronic stage
- Two approaches:
  - Evolve hadronic medium hydrodynamically and define energy loss probabilities for the hadronic stage
  - Particlization of hydrodynamic evolution is combined with fragmented hadrons from hard processes and fed into hadronic afterburner
- How to take care of backreaction consistently? How does a parton interact with a hadron?

Leading Hadrons

- Suppression factor in HSD transport approach shows significant suppression

W. Cassing, K. Gallmeister, C. Greiner, Nucl.Phys. A735 (2004) 277-299





- Leading particles interact due to reduced hadronic cross-sections

Leading Hadrons

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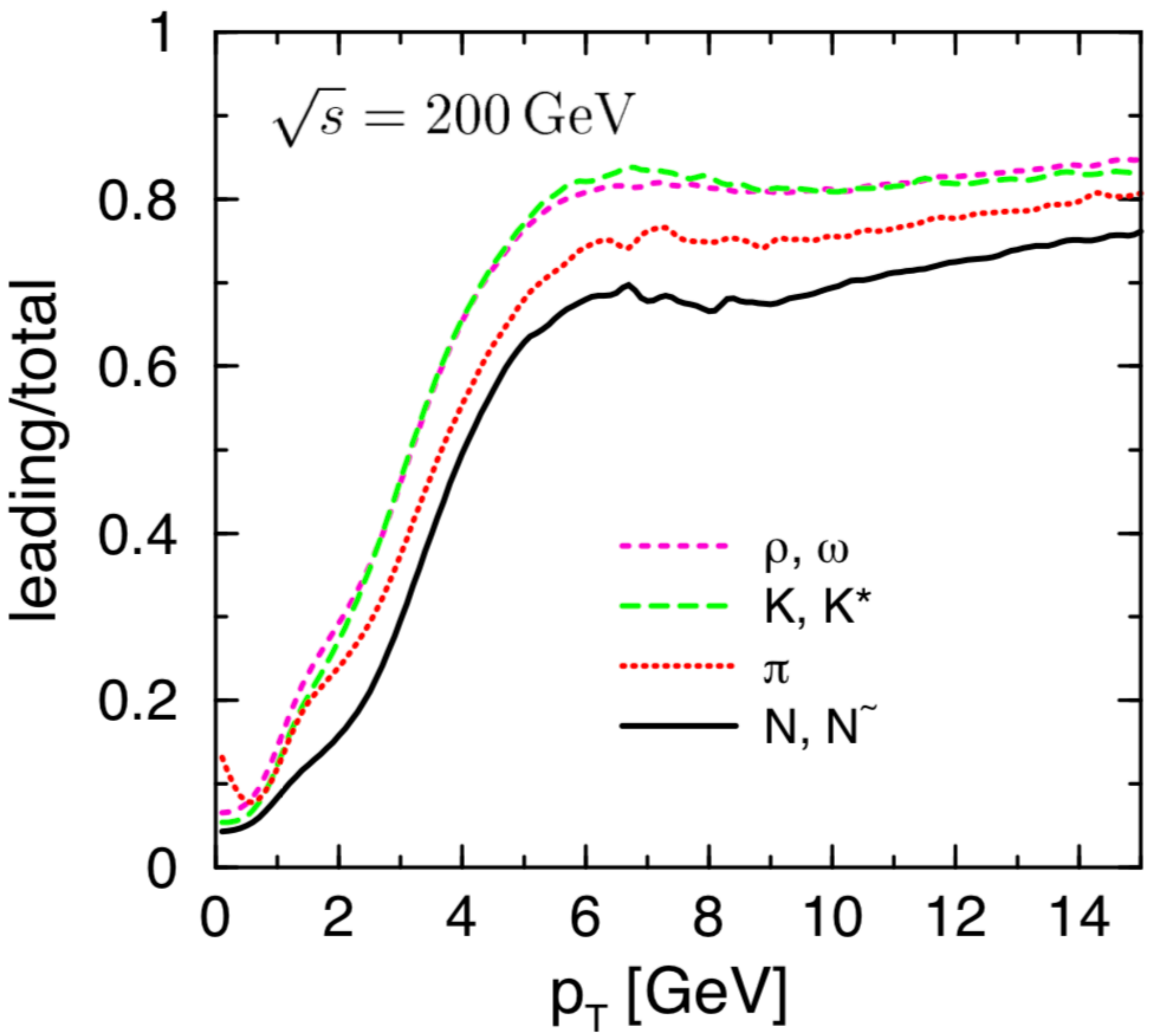
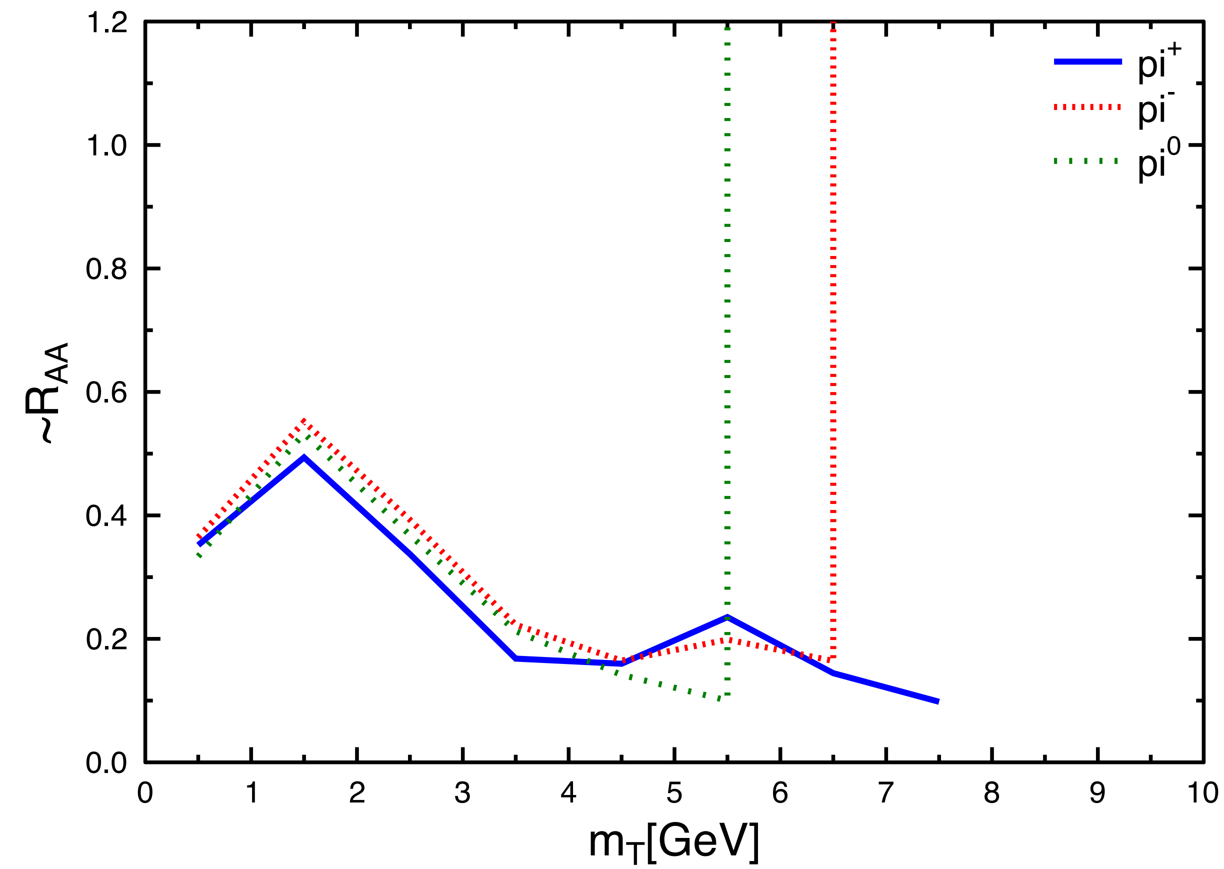




H. Petersen, UrQMD-2.3, private archives

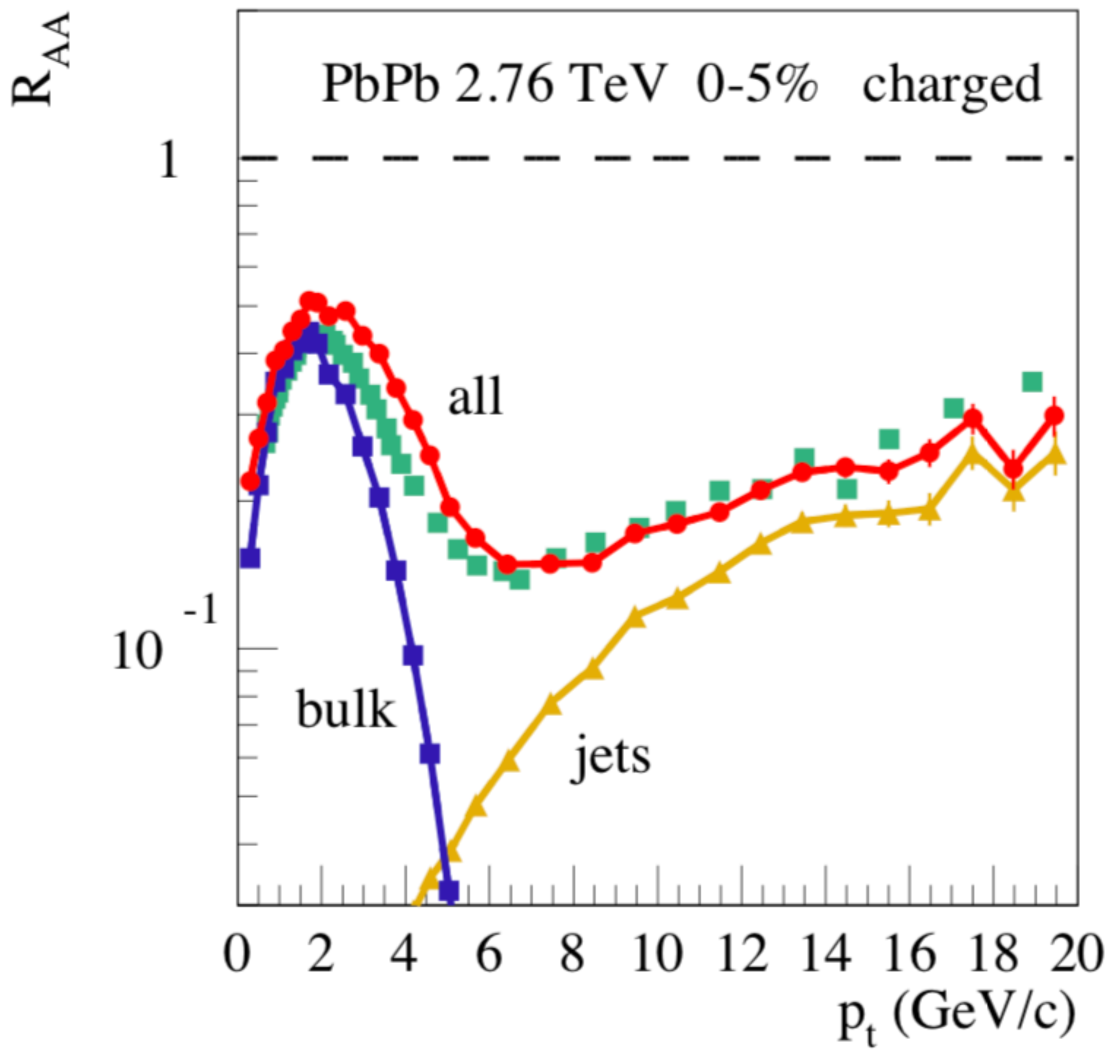
- Leading particles interact due to reduced hadronic cross-sections

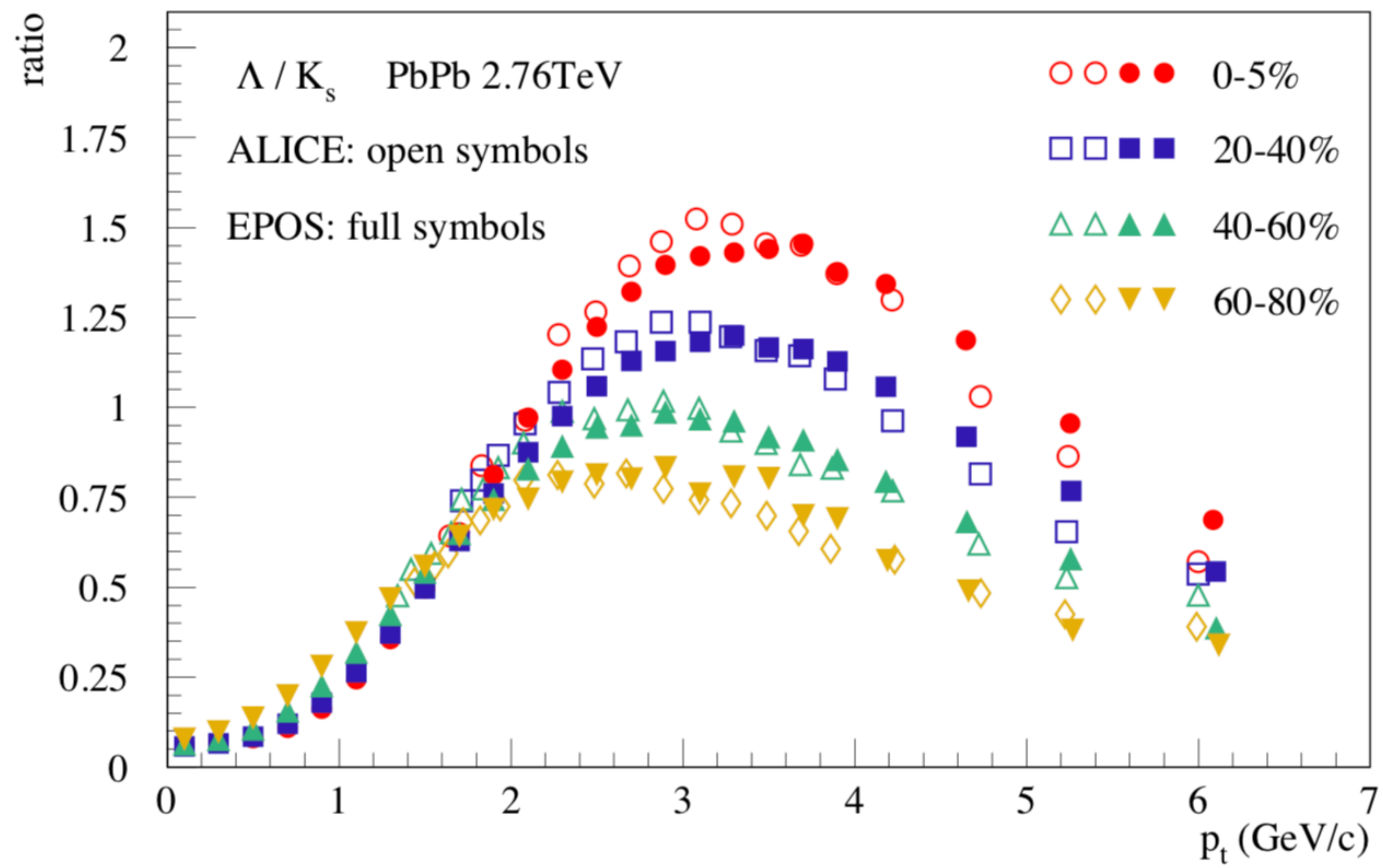
Hybrid Approaches

- EPOS includes viscous hydrodynamics and UrQMD and hard processes

K. Werner et al., Phys.Rev. C85 (2012) 064907

K.Werner, Phys.Rev.Lett. 109 (2012) 102301



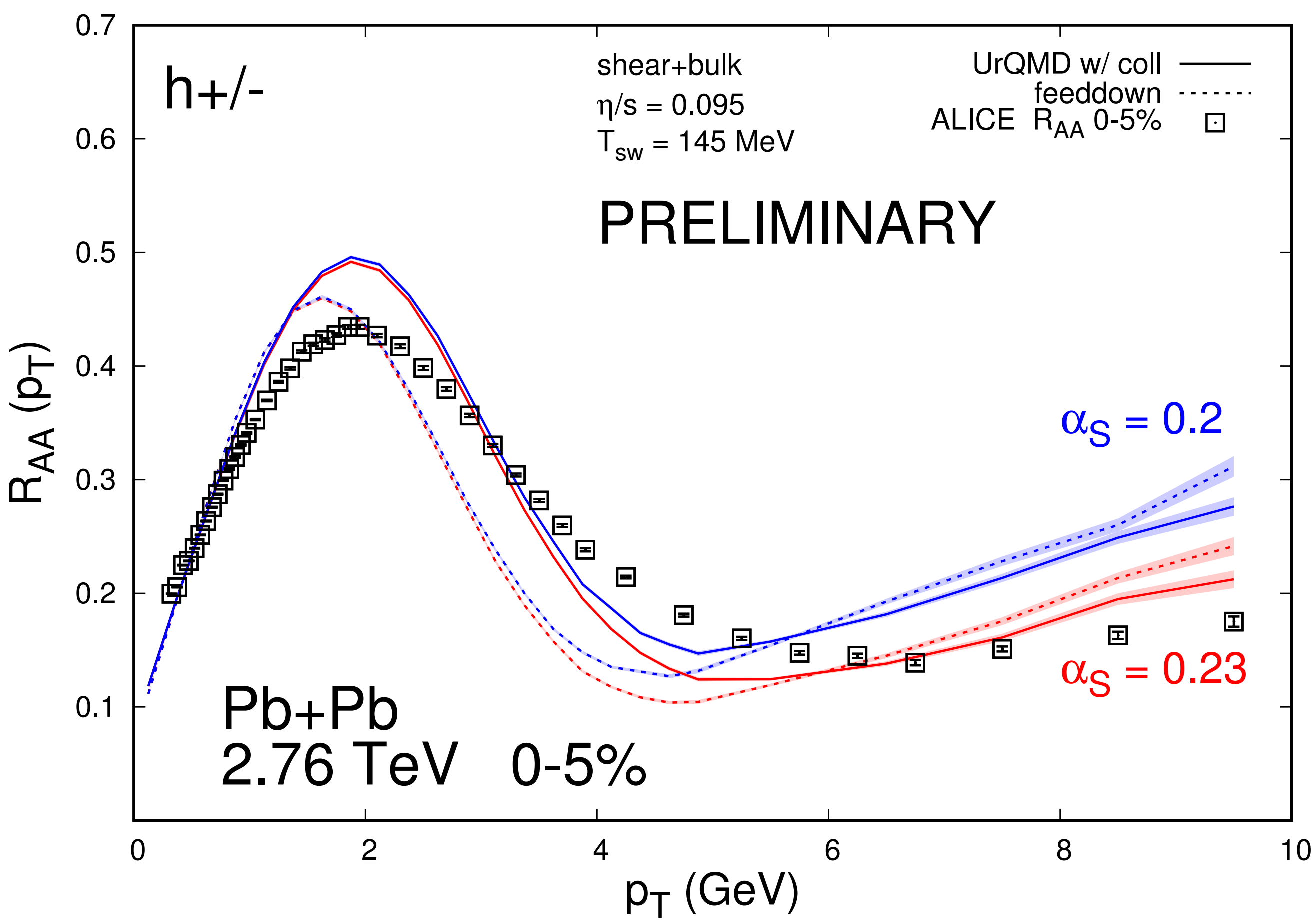


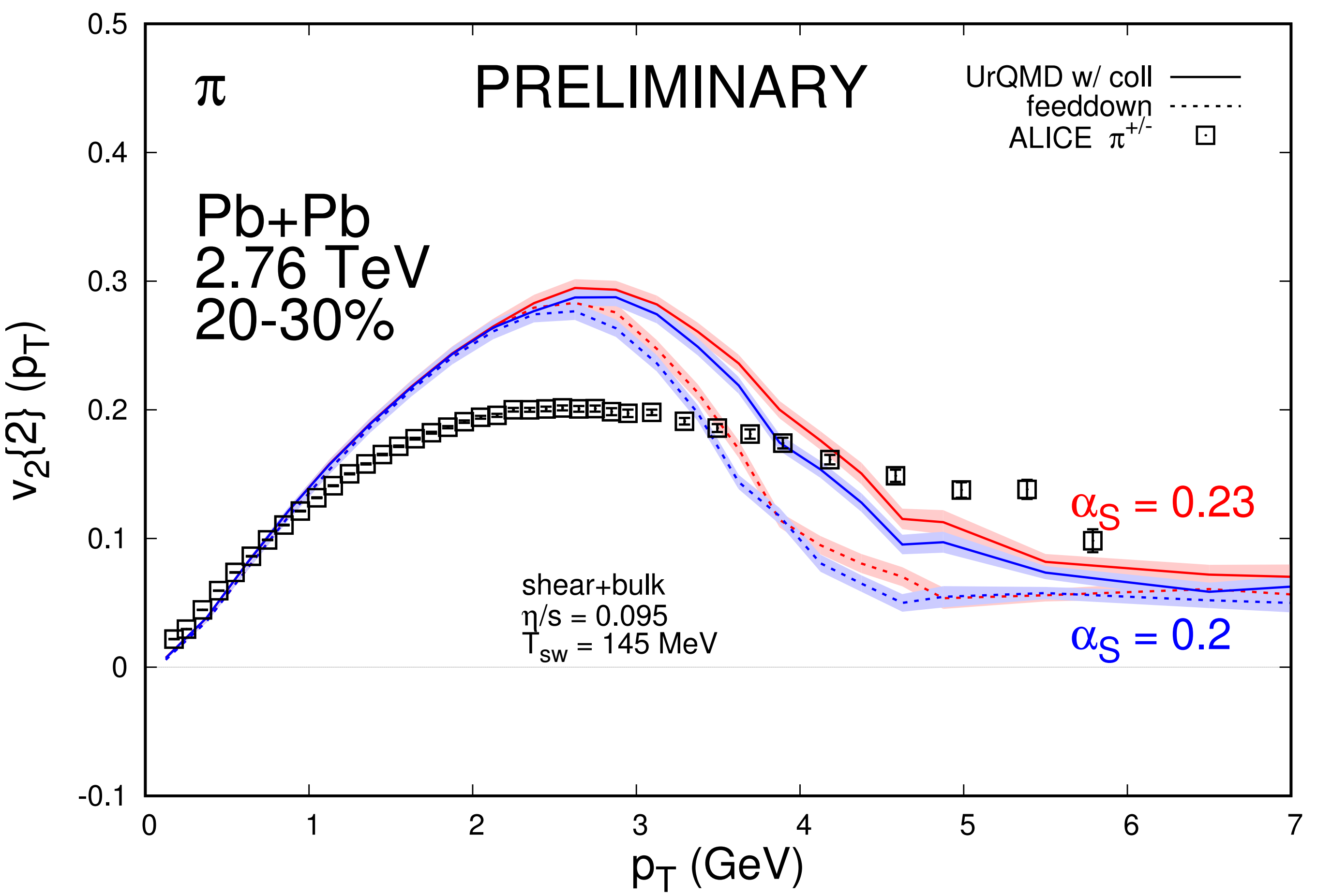
- The interactions between jet and bulk are found to be crucial in the p_T region from 3-6 GeV

MUSIC+UrQMD+MARTINI

- Jets loose energy in the hydrodynamic phase and all (soft+hard) hadrons interact in the hadronic stage

S. Ryu et al, Proceedings of Bergen Workshop 2017



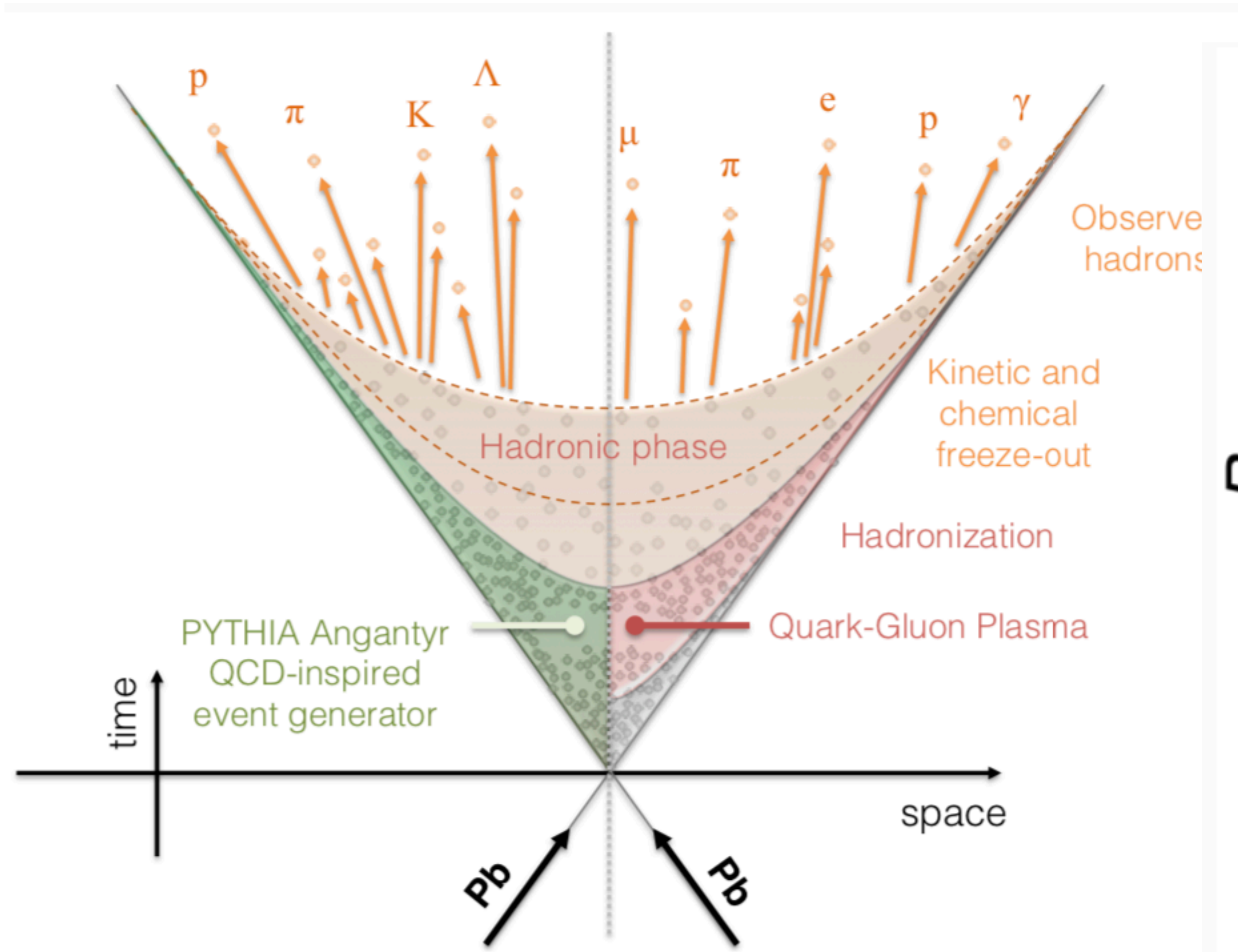


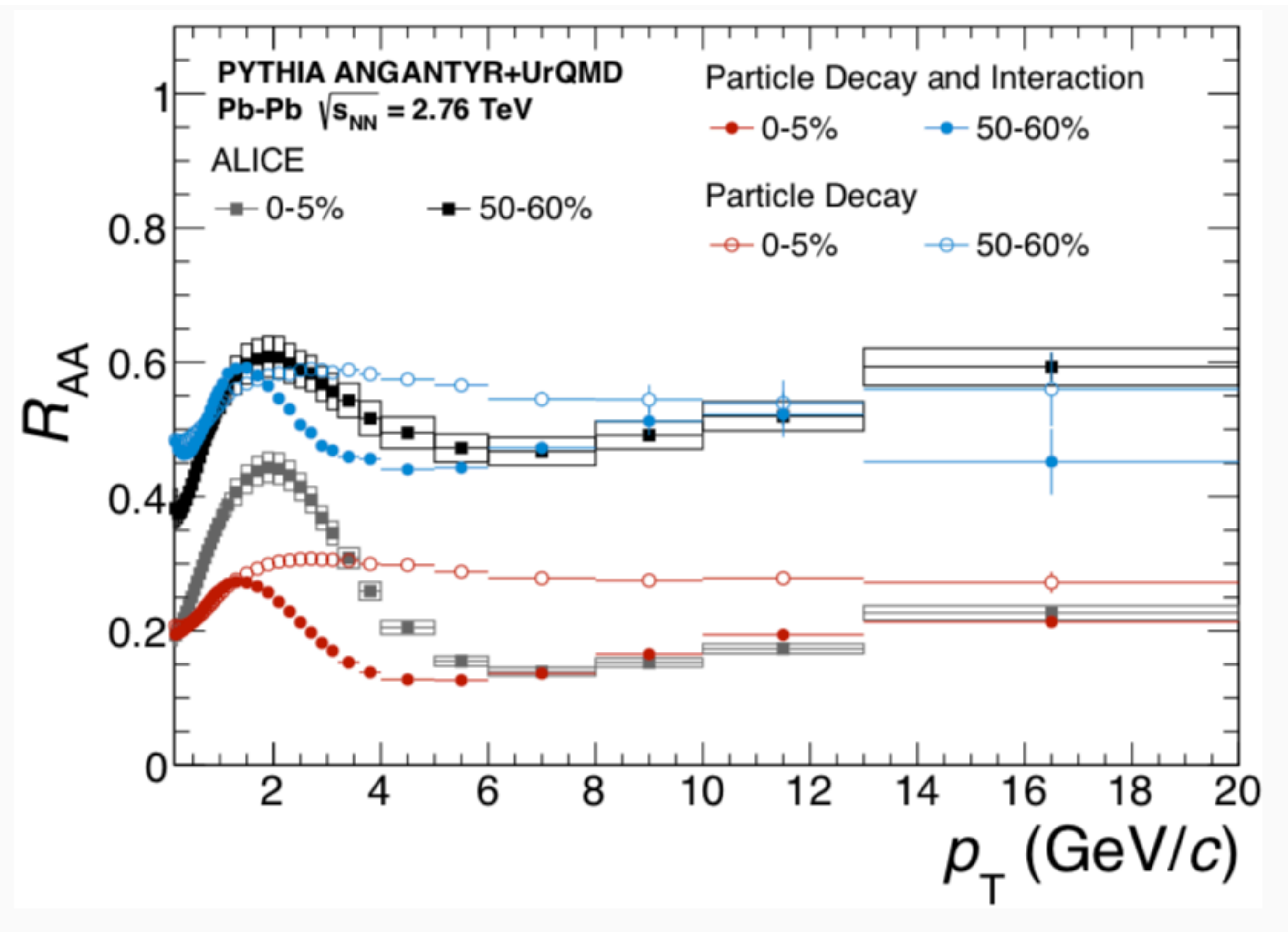
- Hadronic rescattering has distinct effects, that are different from employing a higher coupling in the QGP phase

New Attempts

- Pythia extension to heavy ions connected to UrQMD

C. Bierlich, SQM 2019





- Exploration of ,quenching' just due to hadronic scattering omitting the QGP phase

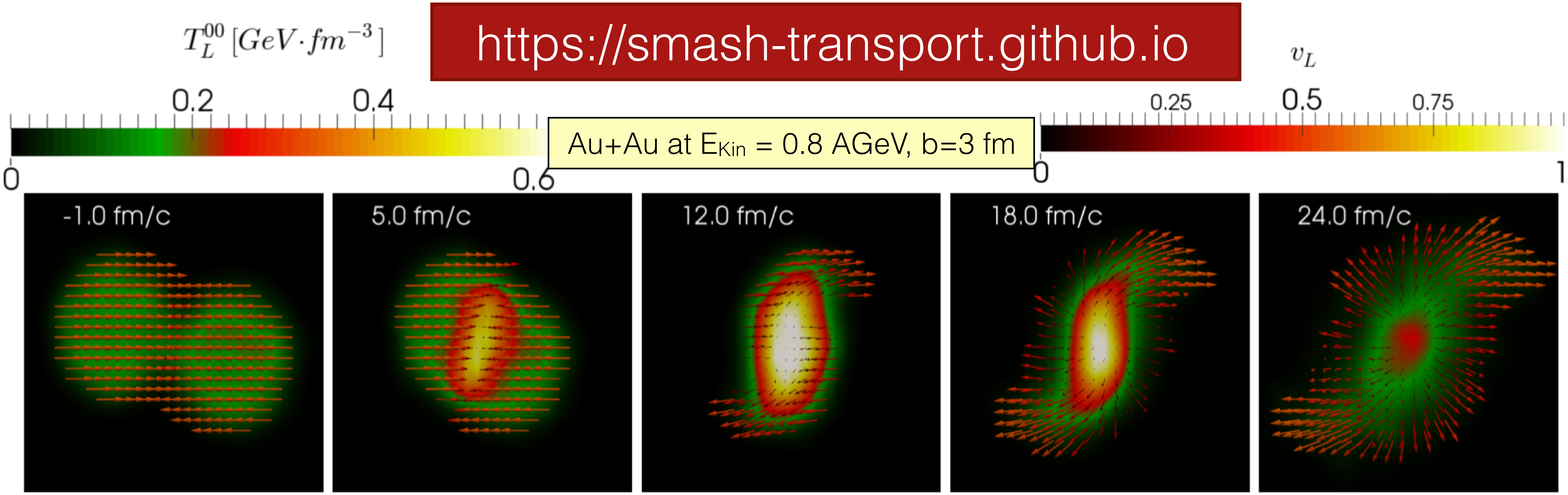
SMASH
A Hadron Transport Approach

SMASH*

J. Weil et al, PRC 94 (2016)

- Hadronic transport approach:
  - Includes all mesons and baryons up to ~2 GeV
  - Geometric collision criterion
  - Binary interactions: Inelastic collisions through resonance/string excitation and decay
  - Infrastructure: C++, Git, Doxygen, (ROOT)

https://smash-transport.github.io



* Simulating Many Accelerated Strongly-Interacting Hadrons

The SMASH Team

- In Frankfurt:
  - Sangwook Ryu
  - Vinzent Steinberg
  - **Jean-Bernard Rose**
  - Jan Staudenmaier
  - Anna Schäfer
  - Justin Mohs
  - Jan Hammelmann
  - Damjan Mitrovic
  - Natey Kübler
  - **Philipp Dorau**
  - Lukas Prinz
- In US/Serbia:
  - Dmytro Oliinychenko
  - LongGang Pang
  - Jussi Auvinen

Subset of the group in November 2016

General Setup

- Transport models provide an effective solution of the relativistic Boltzmann equation

$$p^\mu \partial_\mu f_i(x,p) + m_i F^\alpha \partial^p_\alpha f_i(x,p) = C^i_{\mathrm{coll}}$$

- Particles represented by Gaussian wave packets for density calculations
- Geometric collision criterion

$$d_{\mathrm{trans}} < d_{\mathrm{int}} = \sqrt{\frac{\sigma_{\mathrm{tot}}}{\pi}}$$

$$d^2_{\mathrm{trans}} = (\vec{r_a} - \vec{r_b})^2 - \frac{((\vec{r_a} - \vec{r_b}) \cdot (\vec{p_a} - \vec{p_b}))^2}{(\vec{p_a} - \vec{p_b})^2}$$

As in UrQMD

- Test particle method

$$\sigma \mapsto \sigma \cdot N_{\mathrm{test}}^{-1}$$

$$N \mapsto N \cdot N_{\mathrm{test}}$$

Degrees of Freedom

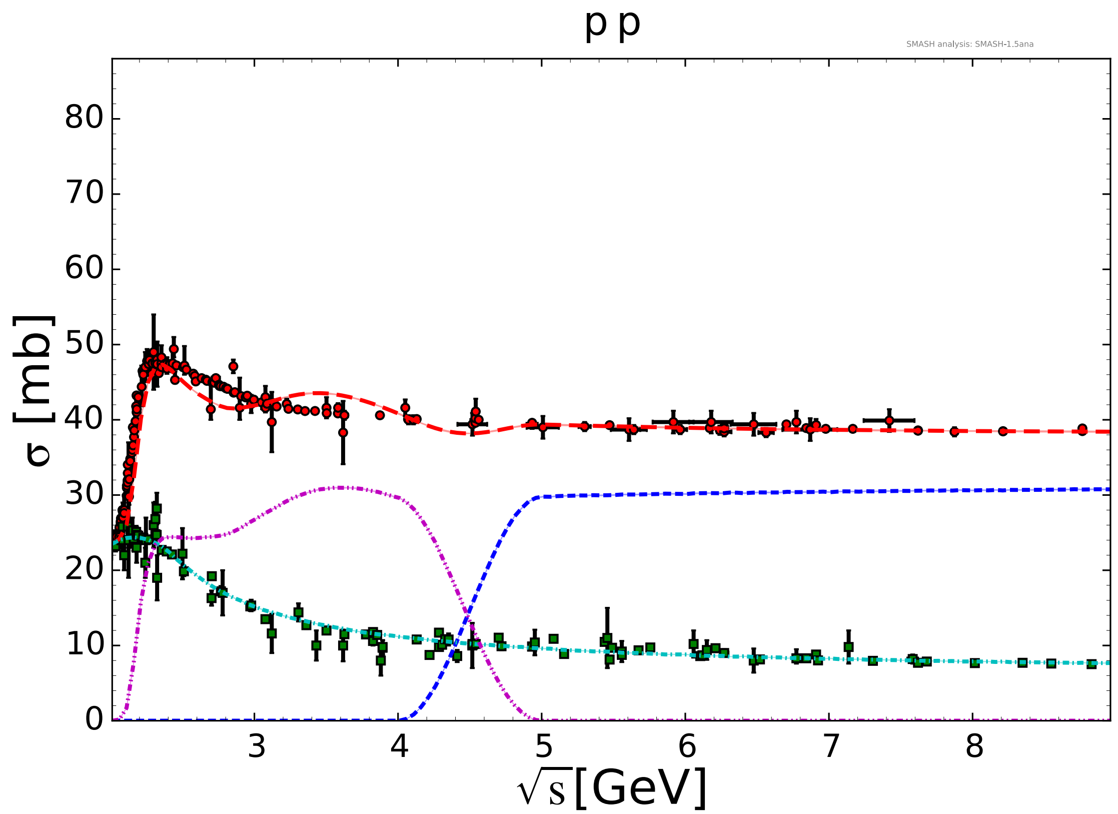
N	Δ	Λ	Σ	Ξ	Ω	Unflavored				Strange
N_{938}	Δ_{1232}	Λ_{1116}	Σ_{1189}	Ξ_{1321}	Ω^-_{1672}	π_{138}	$f_{0\ 980}$	$f_{2\ 1275}$	$\pi_{2\ 1670}$	K_{494}
N_{1440}	Δ_{1620}	Λ_{1405}	Σ_{1385}	Ξ_{1530}	Ω^-_{2250}	π_{1300}	$f_{0\ 1370}$	$f'_{2\ 1525}$		K^*_{892}
N_{1520}	Δ_{1700}	Λ_{1520}	Σ_{1660}	Ξ_{1690}		π_{1800}	$f_{0\ 1500}$	$f_{2\ 1950}$	$\rho_{3\ 1690}$	$K_{1\ 1270}$
N_{1535}	Δ_{1905}	Λ_{1600}	Σ_{1670}	Ξ_{1820}			$f_{0\ 1710}$	$f_{2\ 2010}$		$K_{1\ 1400}$
N_{1650}	Δ_{1910}	Λ_{1670}	Σ_{1750}	Ξ_{1950}		η_{548}		$f_{2\ 2300}$	$\phi_{3\ 1850}$	K^*_{1410}
N_{1675}	Δ_{1920}	Λ_{1690}	Σ_{1775}	Ξ_{2030}		η'_{958}	$a_{0\ 980}$	$f_{2\ 2340}$		$K_0^*{}_{1430}$
N_{1680}	Δ_{1930}	Λ_{1800}	Σ_{1915}			η_{1295}	$a_{0\ 1450}$		$a_{4\ 2040}$	$K_2^*{}_{1430}$
N_{1700}	Δ_{1950}	Λ_{1810}	Σ_{1940}			η_{1405}		$f_{1\ 1285}$		K^*_{1680}
N_{1710}		Λ_{1820}	Σ_{2030}			η_{1475}	ϕ_{1019}	$f_{1\ 1420}$	$f_{4\ 2050}$	$K_{2\ 1770}$
N_{1720}		Λ_{1830}	Σ_{2250}				ϕ_{1680}			$K_3^*{}_{1780}$
N_{1875}		Λ_{1890}				σ_{800}		$a_{2\ 1320}$		$K_{2\ 1820}$
N_{1900}		Λ_{2100}					$h_{1\ 1170}$			$K_4^*{}_{2045}$
N_{1990}		Λ_{2110}				ρ_{776}		$\pi_{1\ 1400}$		
N_{2080}		Λ_{2350}				ρ_{1450}	$b_{1\ 1235}$	$\pi_{1\ 1600}$		
N_{2190}						ρ_{1700}				
N_{2220}							$a_{1\ 1260}$	$\eta_{2\ 1645}$		
N_{2250}						ω_{783}				
						ω_{1420}		$\omega_{3\ 1670}$		
						ω_{1650}				

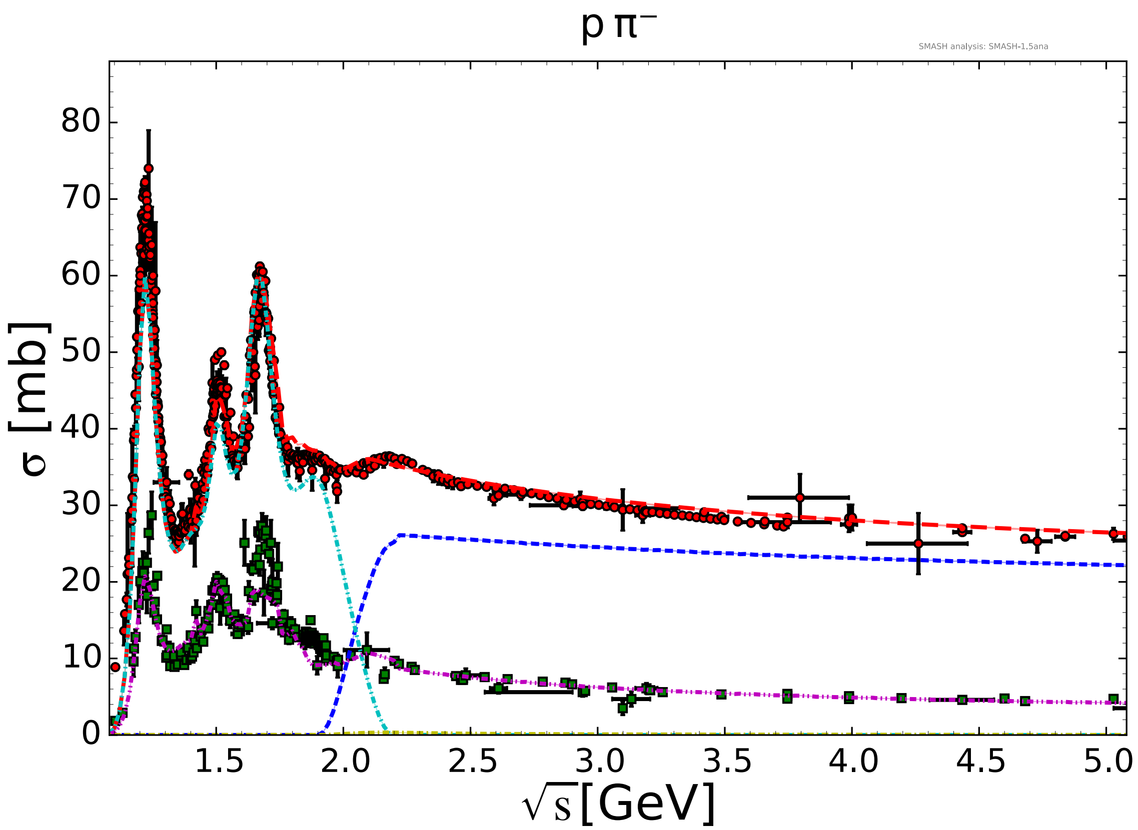
- Isospin symmetry
- Perturbative treatment of non-hadronic particles (photons, dileptons)

- + N(1880), N(1895), N(2060), N(2100), N(2120) and Delta(1900) in SMASH-1.6

Similar to UrQMD,
But many more states

Elementary Cross Sections



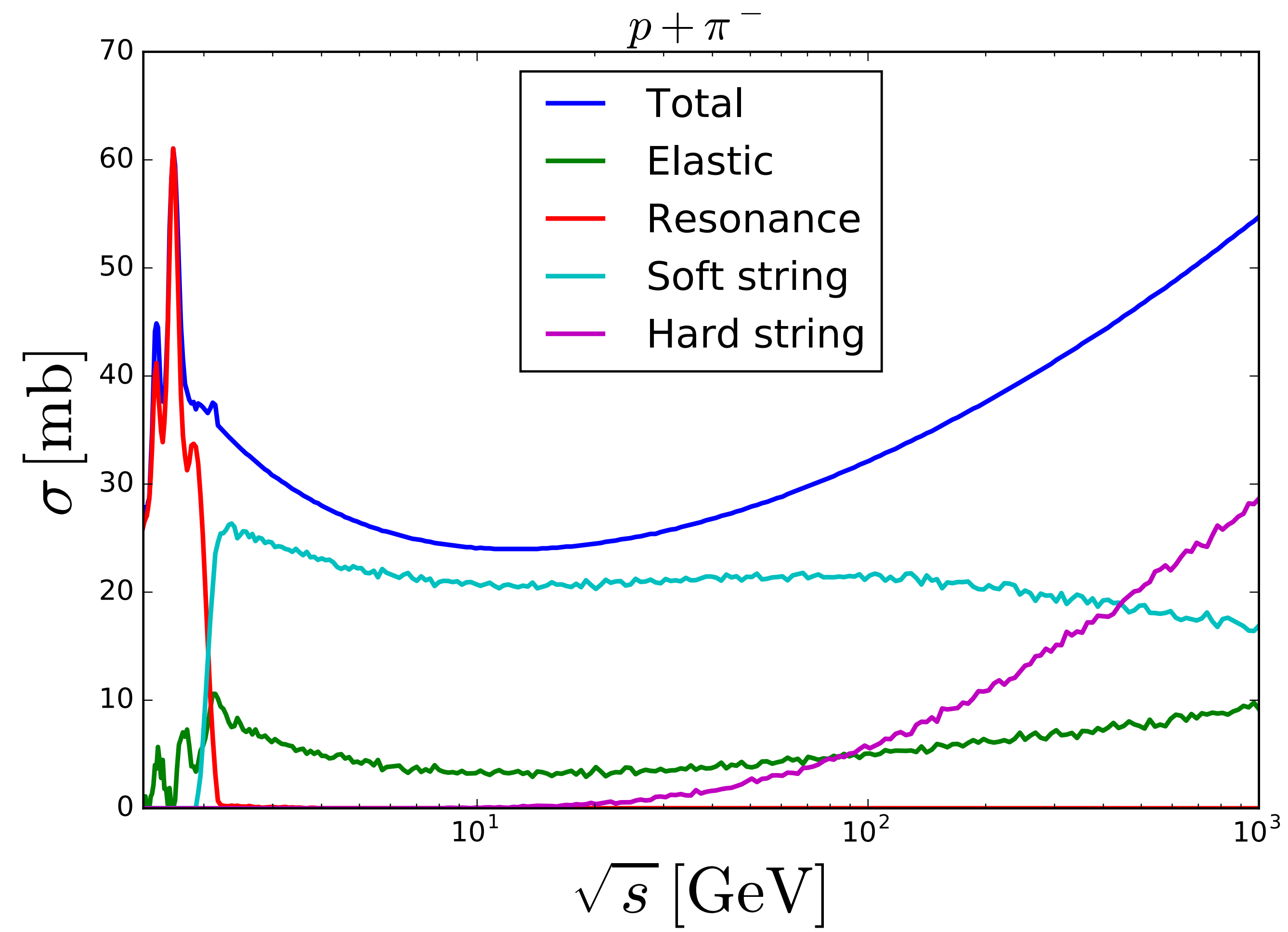


- Total cross section for pp/pπ collisions
- Parametrized elastic cross section
- Many resonance contributions to inelastic cross section
- Reasonable description of experimental data
- Soft strings a la UrQMD and hard strings via Pythia 8

J. Weil et al, PRC 94 (2016), updated SMASH-1.5

High Energy Cross-Sections

- High energy cross-section is dominated by string excitation and fragmentation
- Soft strings
  - Pythia is only employed for fragmentation
  - Single-diffractive, double diffractive and non-diffractive processes
- Hard strings
  - Fully treated by Pythia
  - All species mapped to pions and nucleons



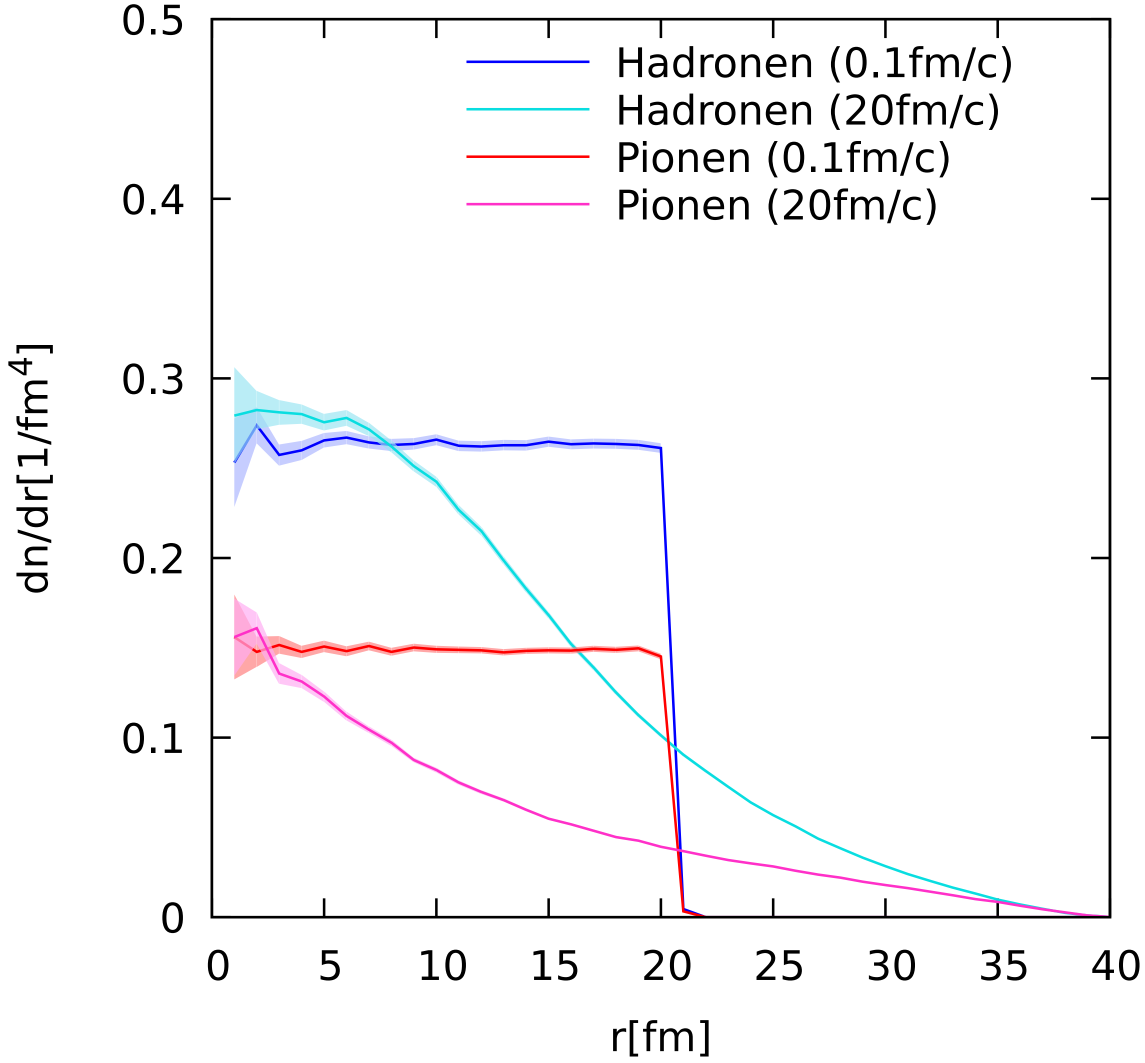
J. Mohs, S. Ryu and HE, in preparation

- All other cross-sections are derived using AQM

Hadronic Jet Quenching

Toy Model - Expanding Sphere

- A full hadron gas (alternatively only pions) are initialised thermally in a uniformly filled sphere of 20 fm radius

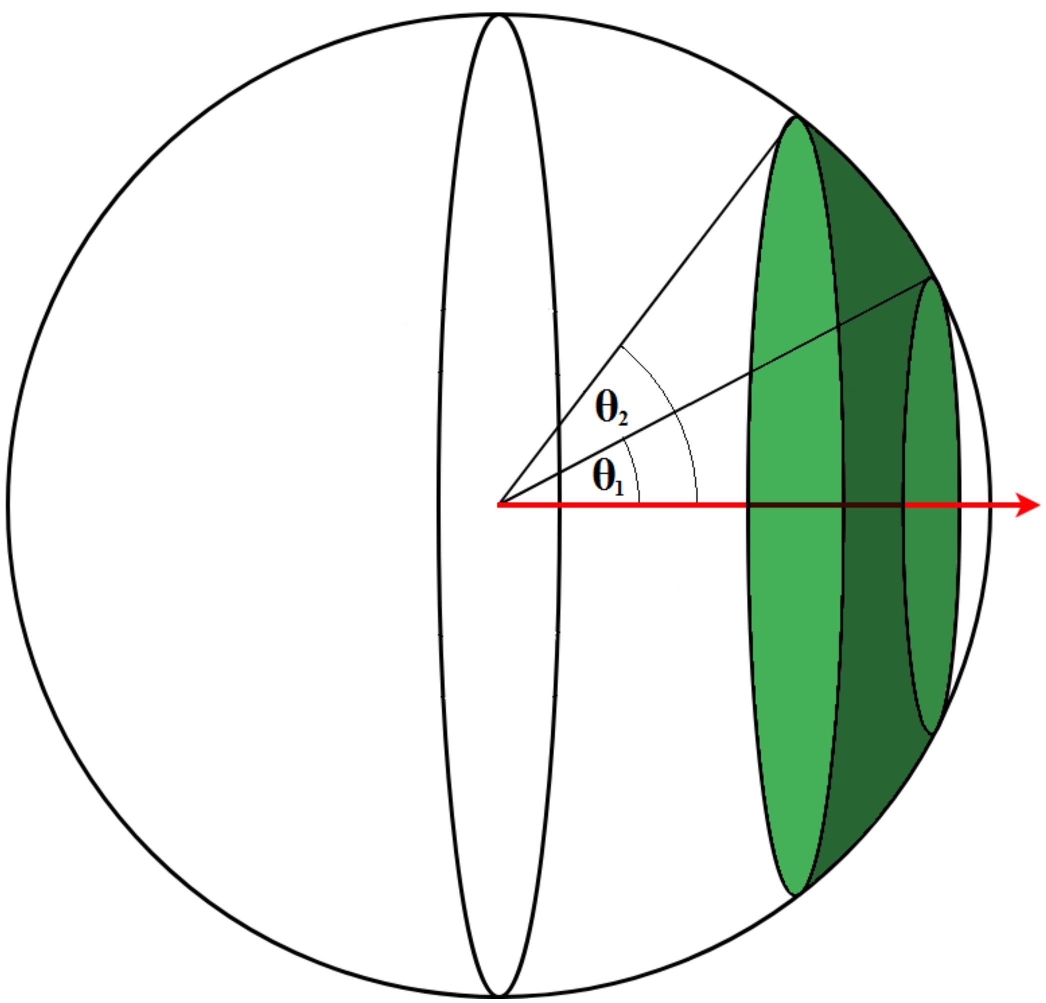


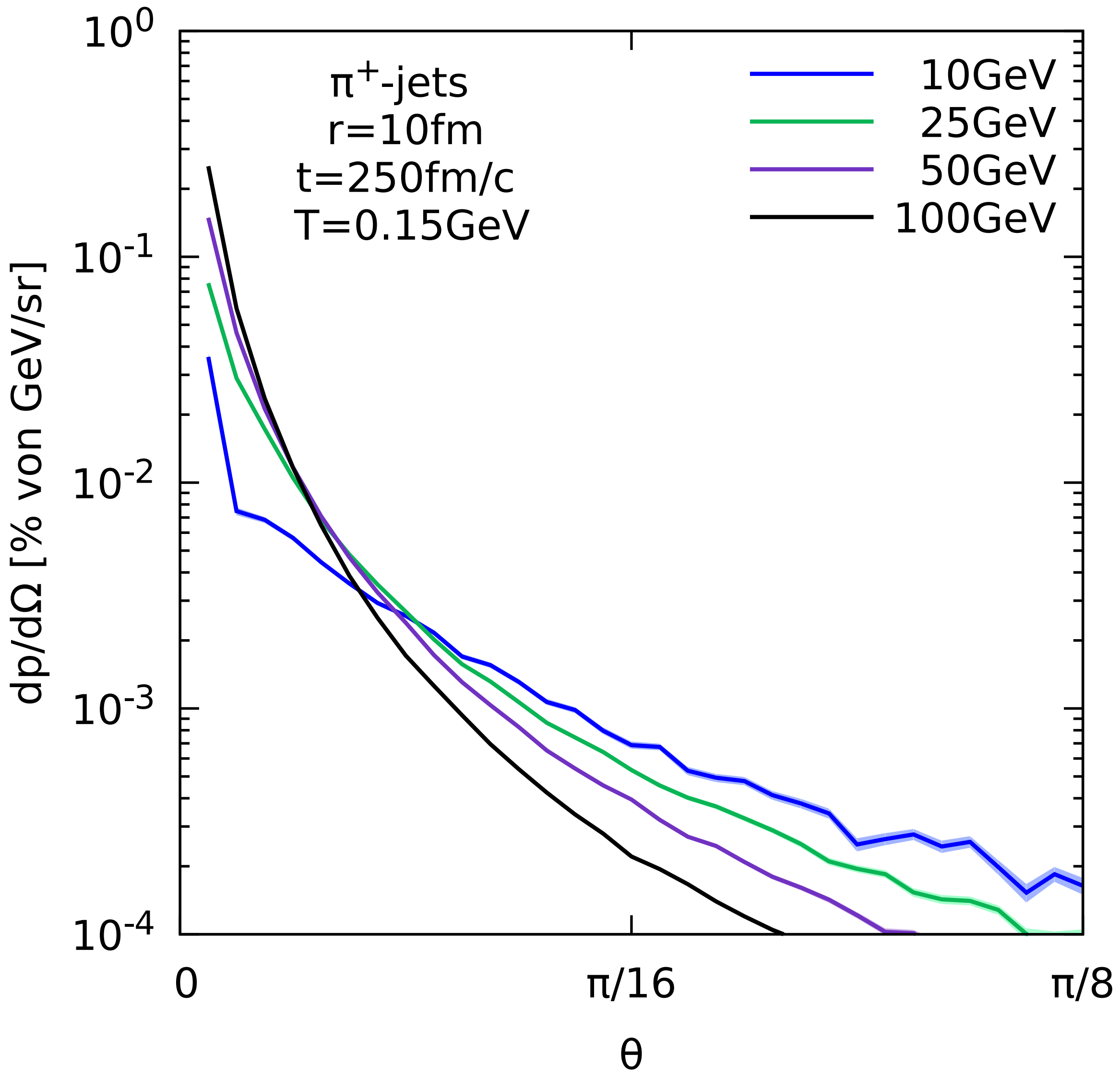
- T = 150 MeV corresponds to a typical switching temperature

- Expansion happens dynamically
- Add high p_T particle in the middle and study the evolution

Extracting Jet Shapes

- Background (= same sphere without the hard particle) has been subtracted

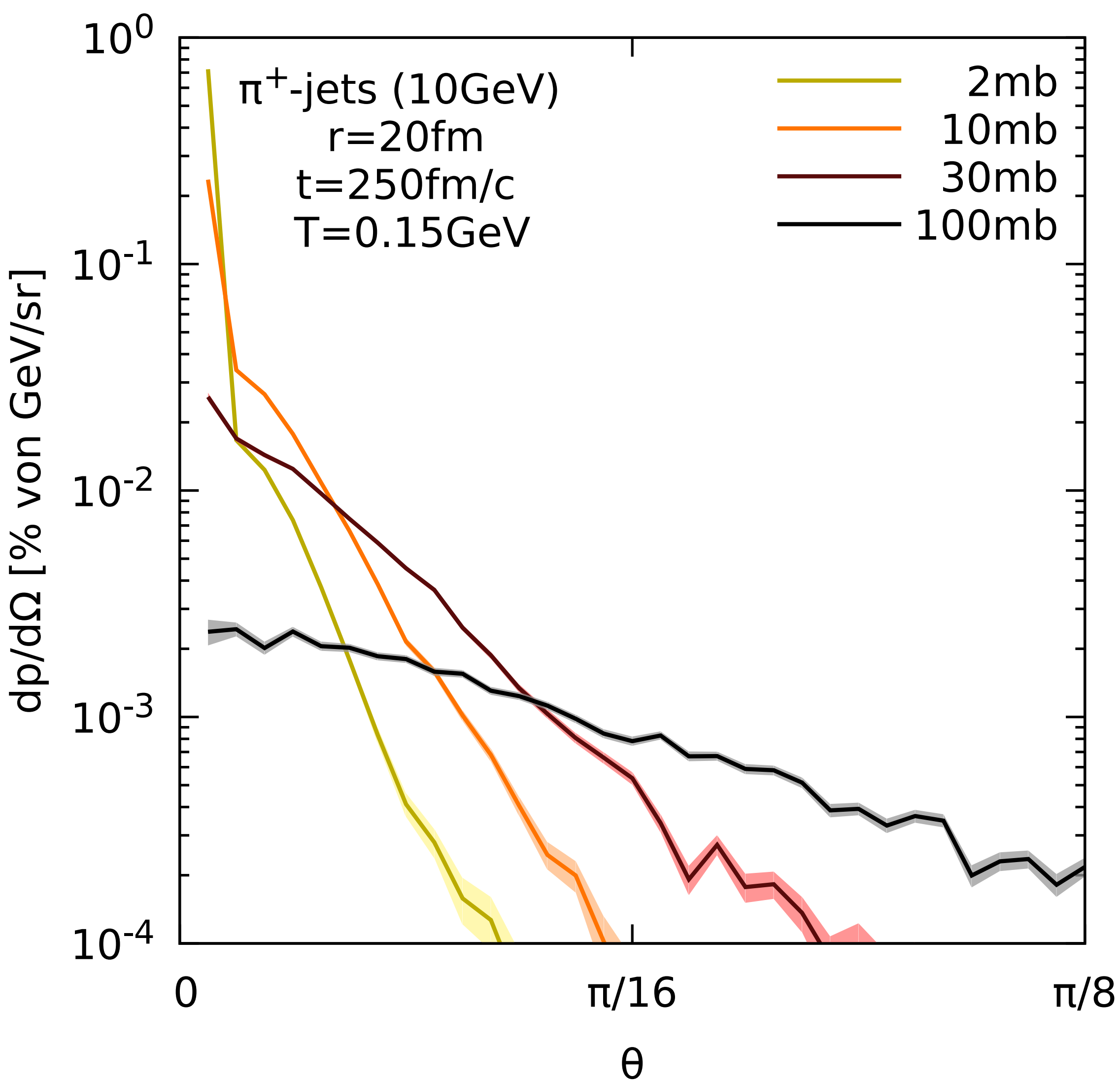


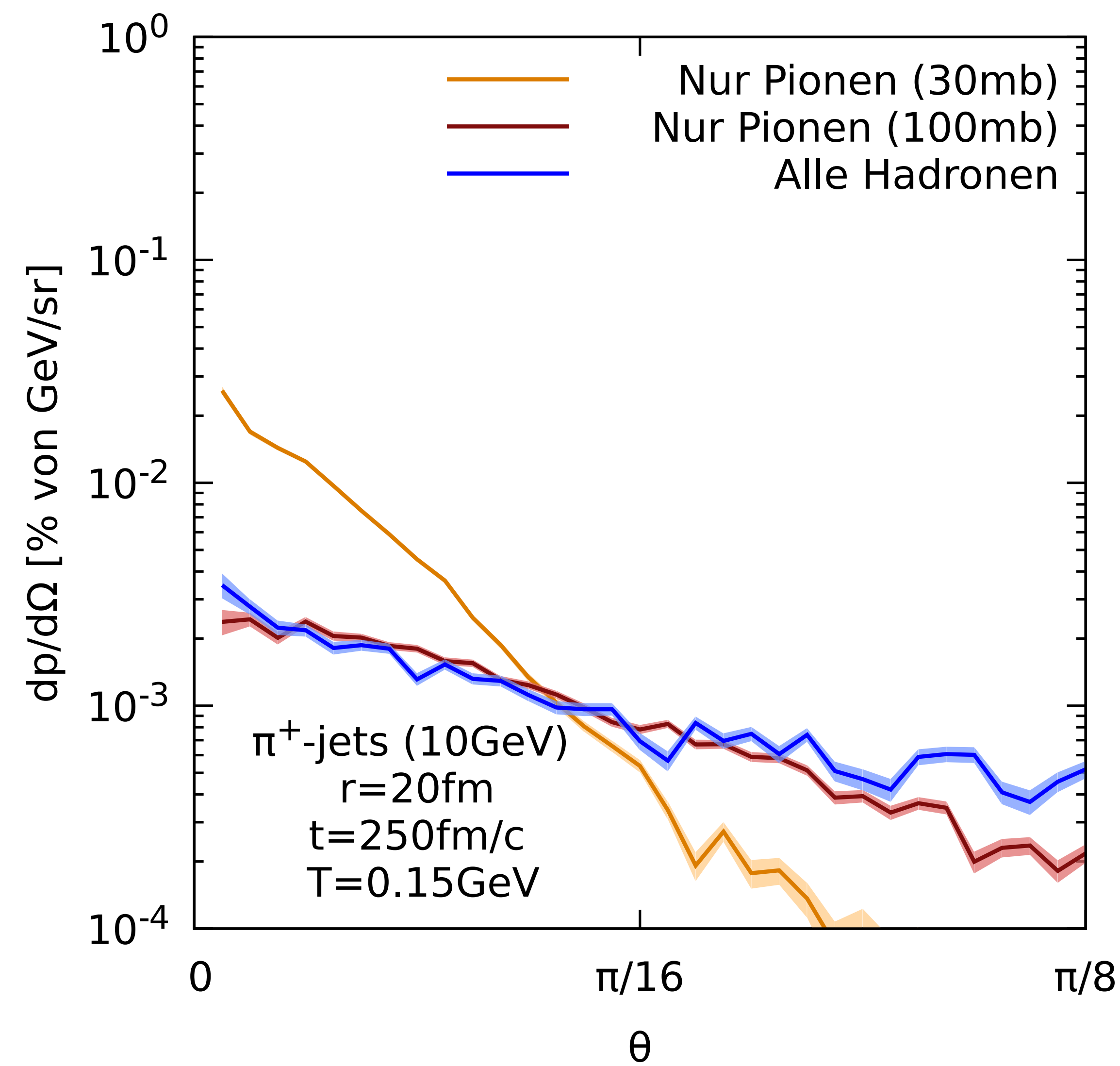


- Results are normalised on the solid angle and the hard particle energy to allow comparison

Dependence on Cross-Section

- Full hadron gas corresponds to pion gas with 100 mb

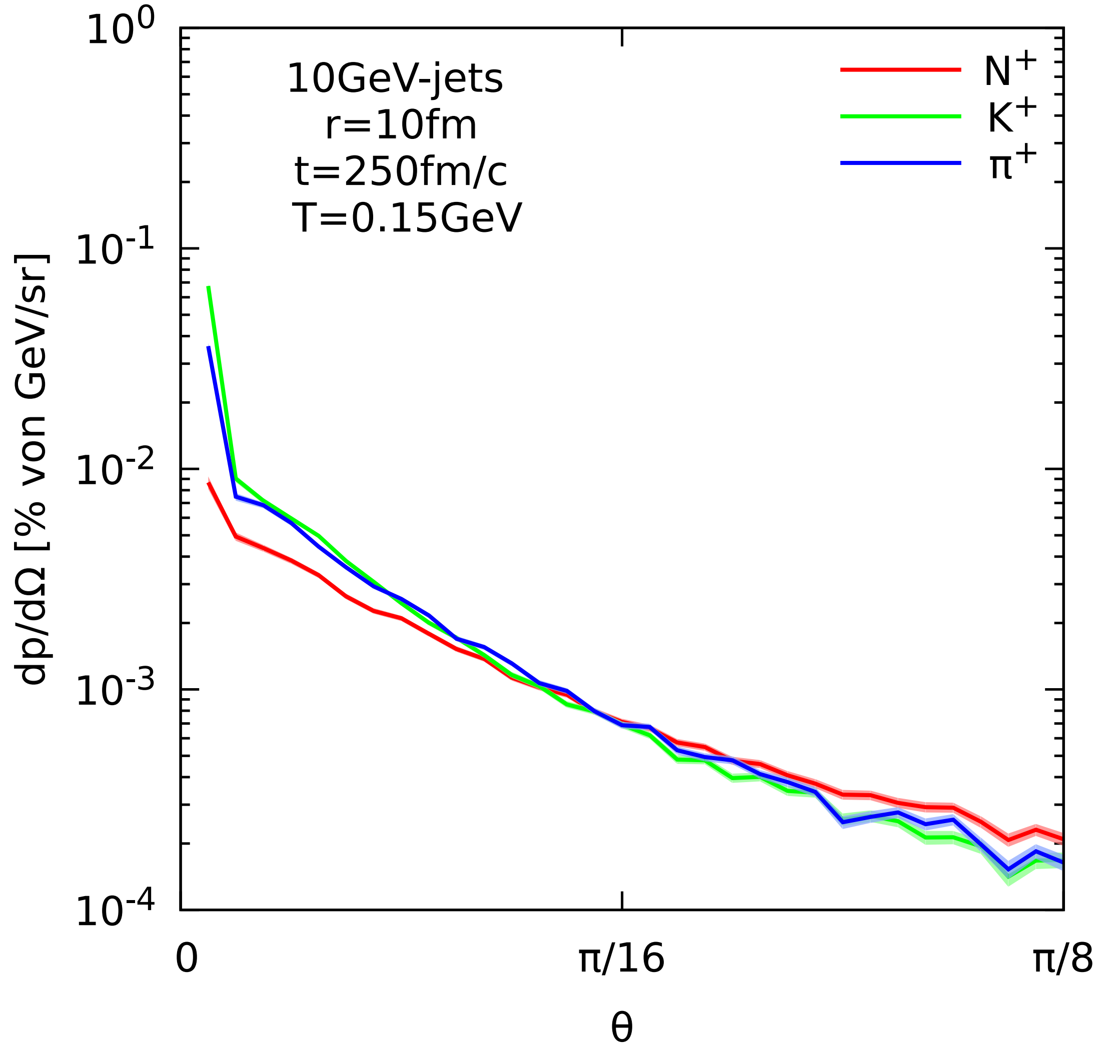


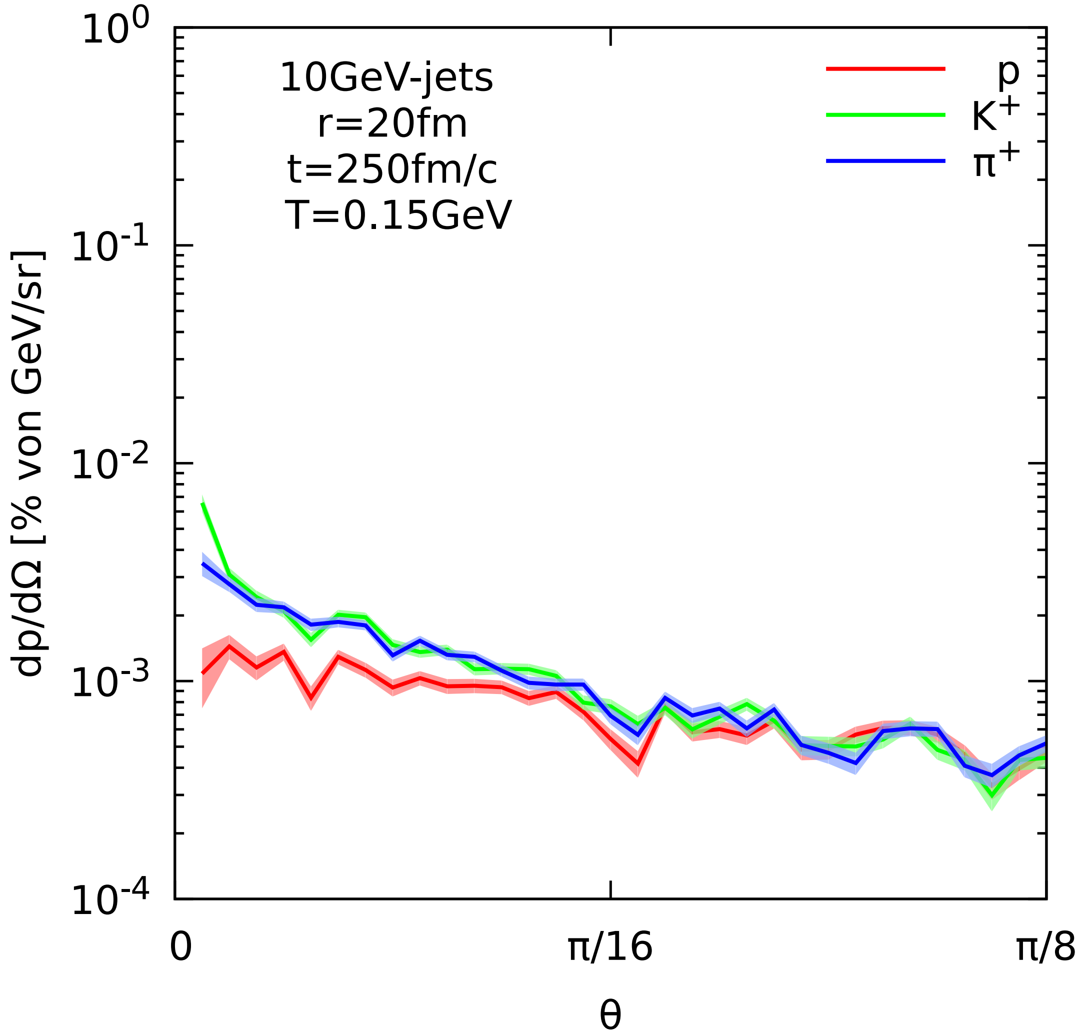


- As expected the shape is more modified with higher cross-sections while for small cross-sections some particles escape undisturbed

Different Particle Species

- Pions, protons and kaons interact differently due to their different cross-sections



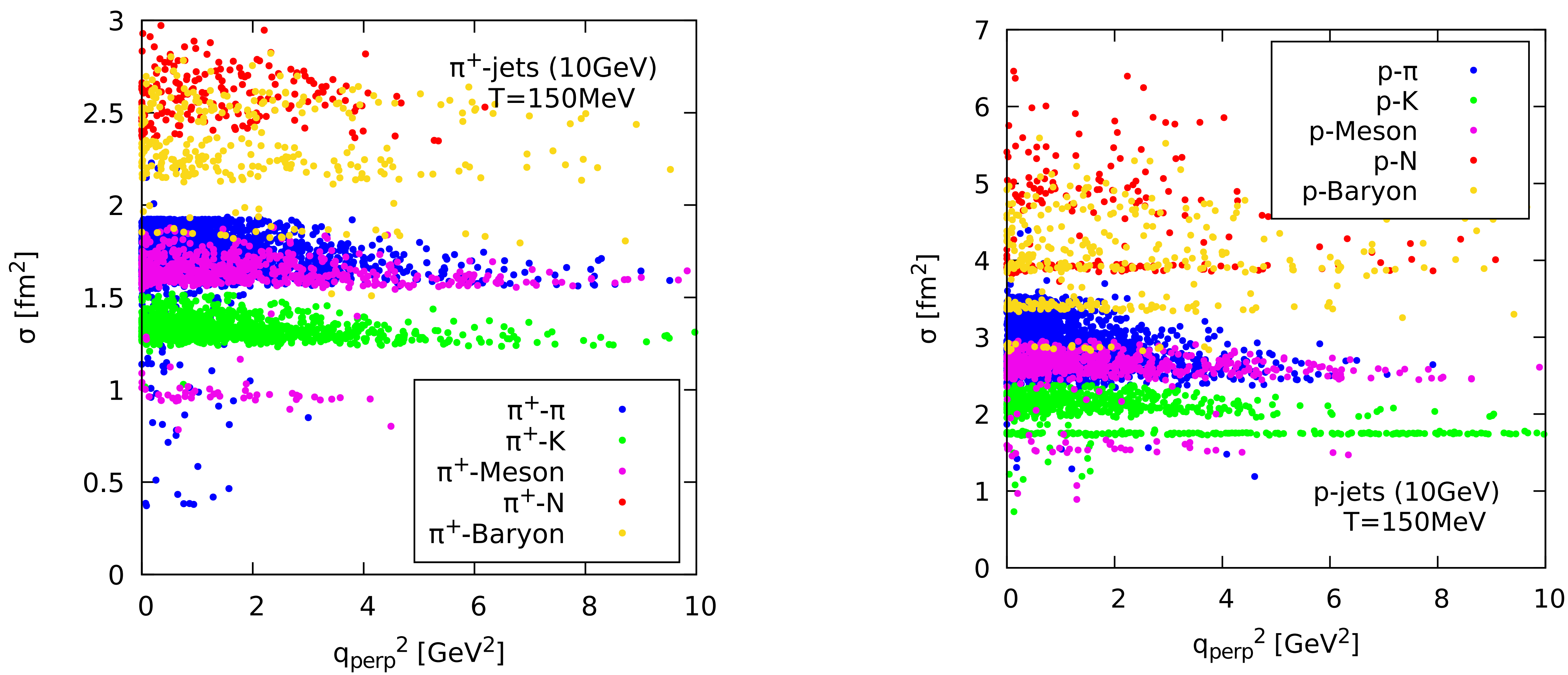


- In a larger medium the distribution gets wider

‚Brick' Studies

- Box with hadronic matter at a certain temperature
- Shoot a high particle in x-direction and analyse the first collision

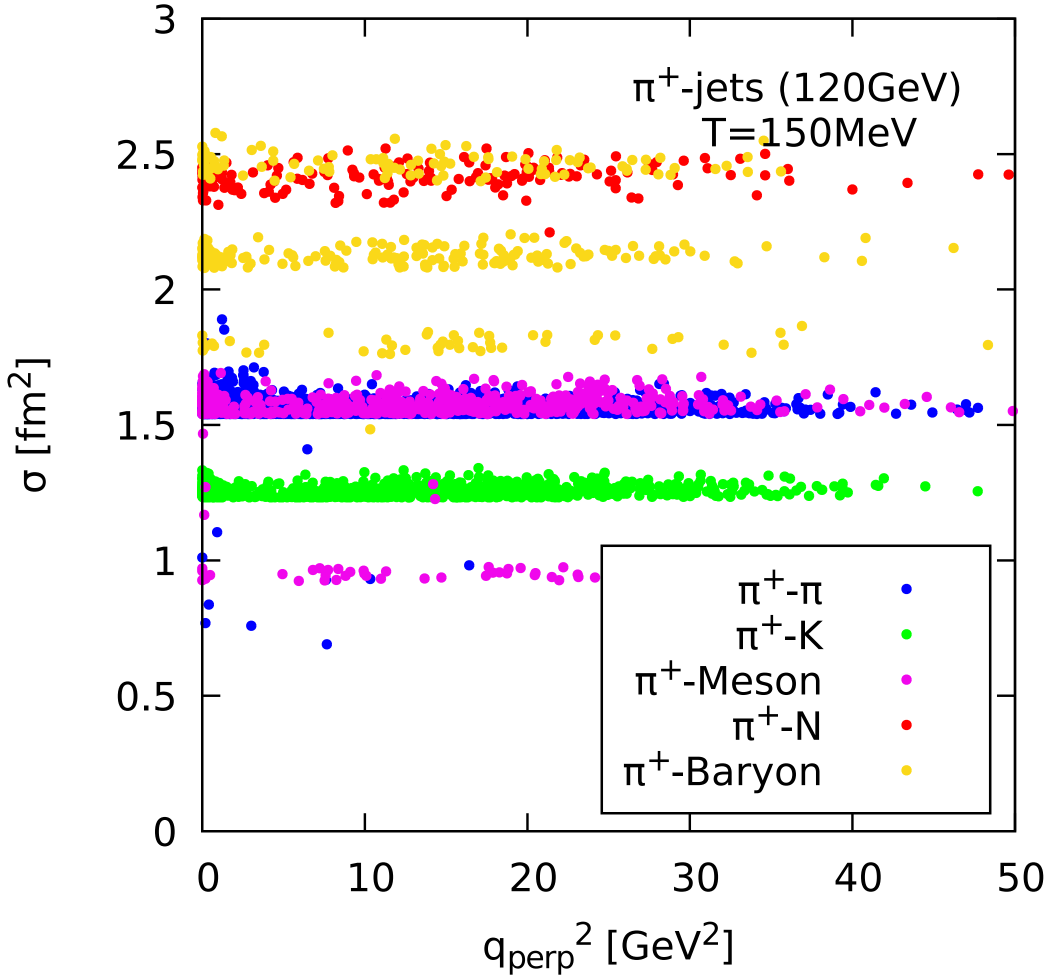
$$q_\perp^2 = q_y^2 + q_z^2 \qquad q_i = \sum_j p'_{ij} - p_i$$

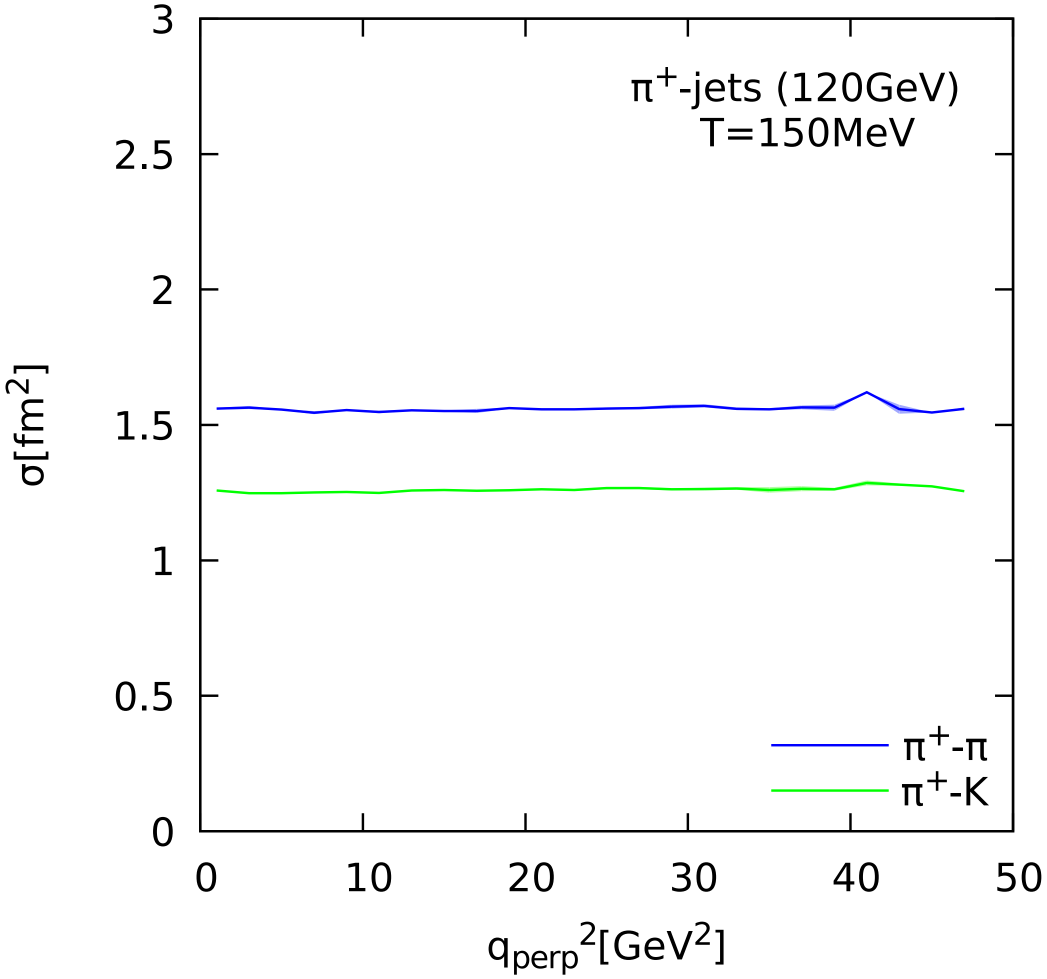


- Cross-sections cluster for different reaction types

Extracting a Hadronic $\hat{q}$

- For higher energies the cross-sections are rather uniform, therefore one can extract averages





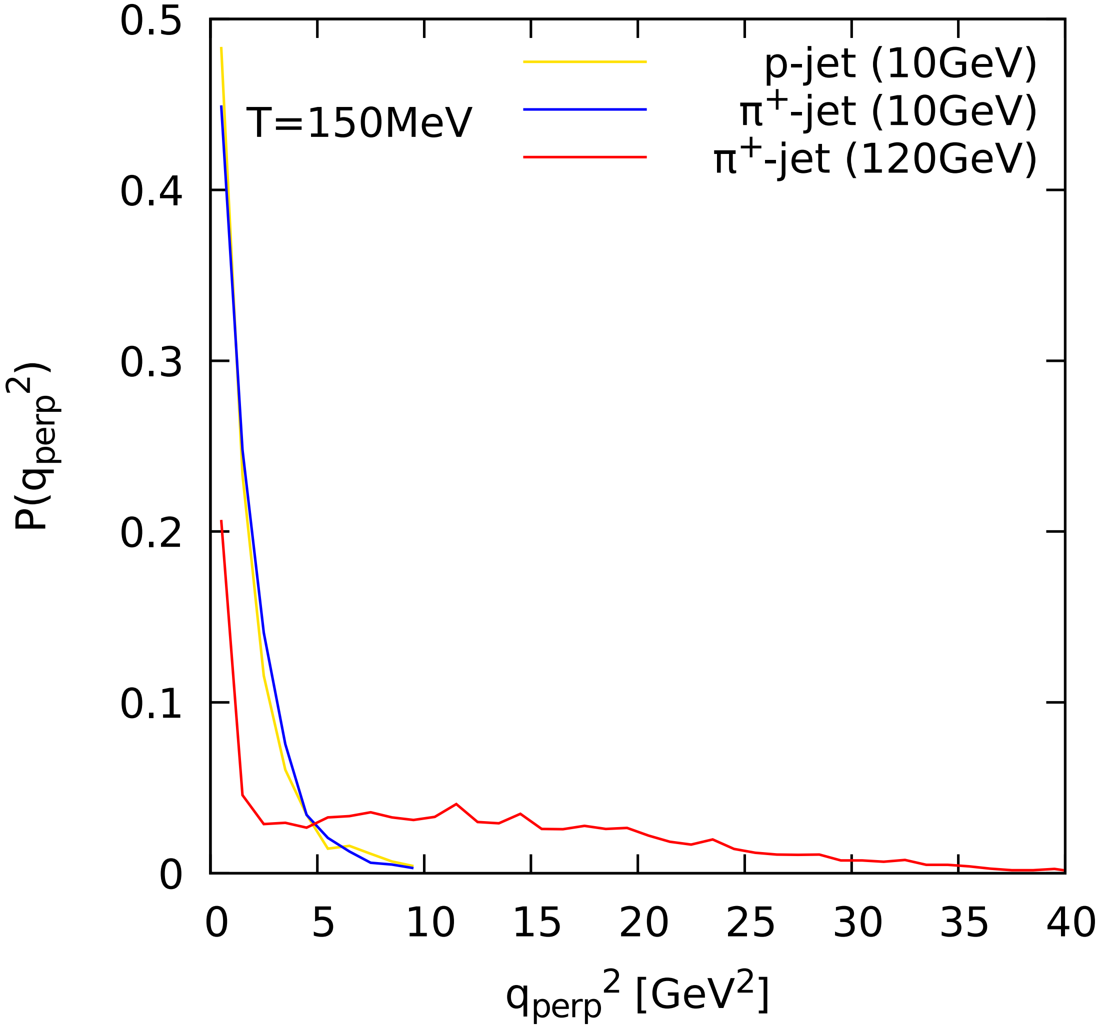
- For radiation of partons $\hat{q}_R = \rho \int dq_\perp^2 q_\perp^2 \frac{d\sigma_R}{dq_\perp^2}$

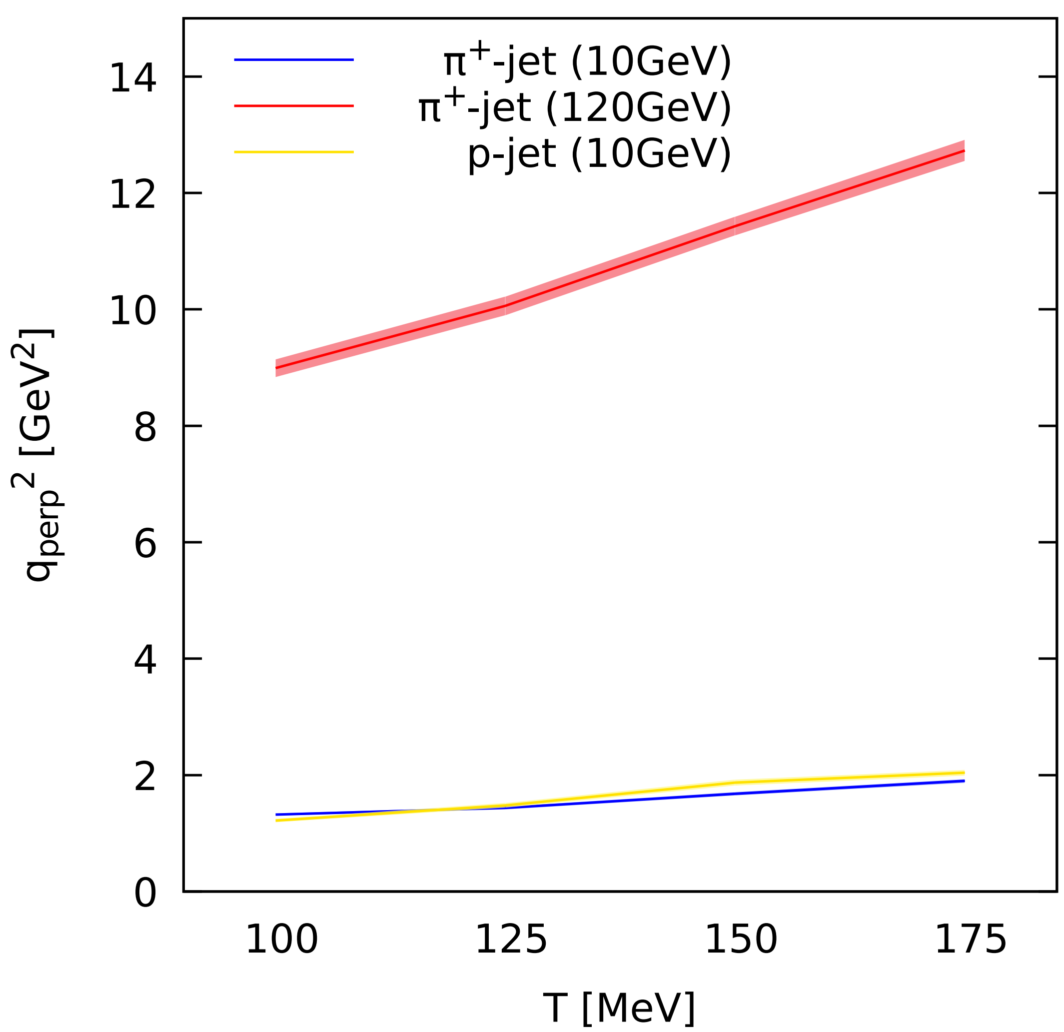
A. Majumder, B. Müller and X.-N. Wang, Phys.Rev.Lett. 99 (2007) 192301

- In our case: the curves are flat or even decrease

Momentum Transfer

- Instead of $\hat{q}$, the probability distribution for certain momentum transfers are extracted

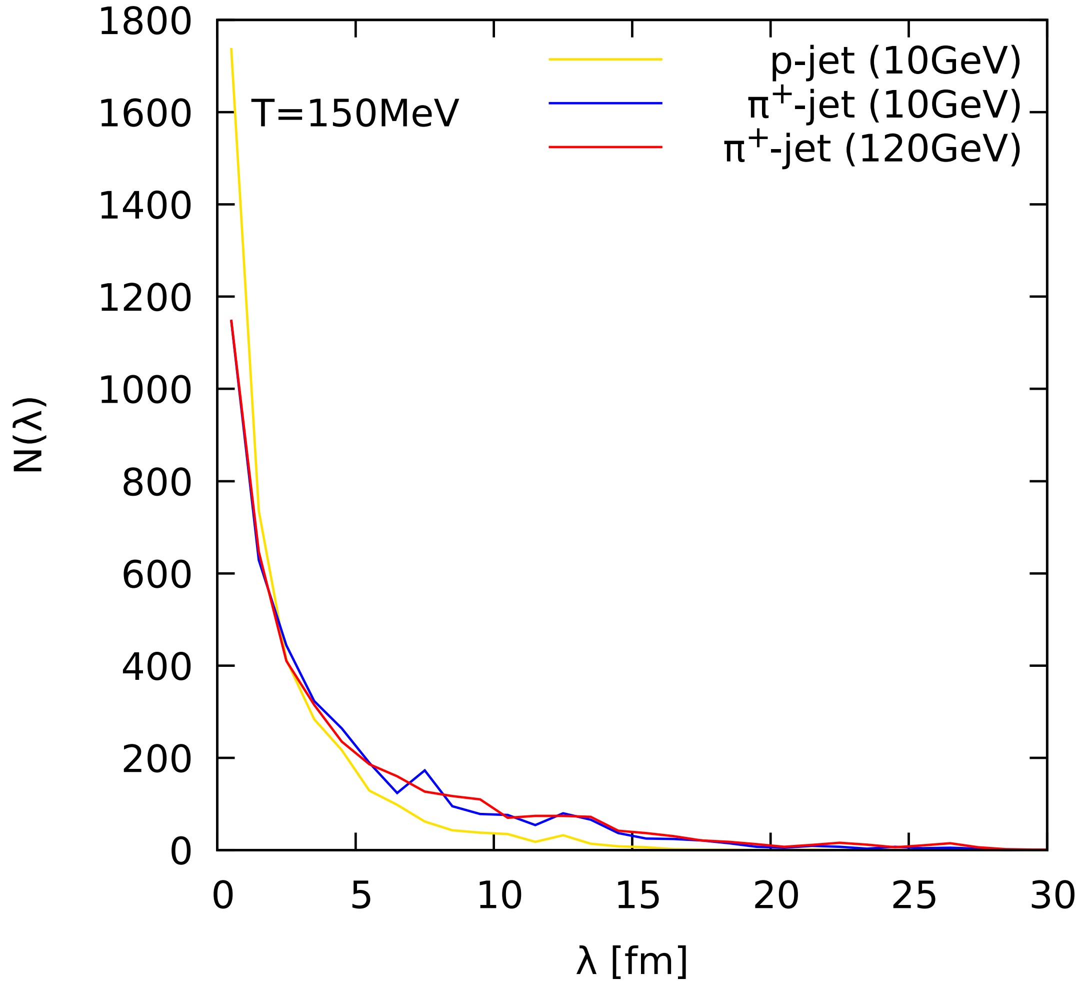


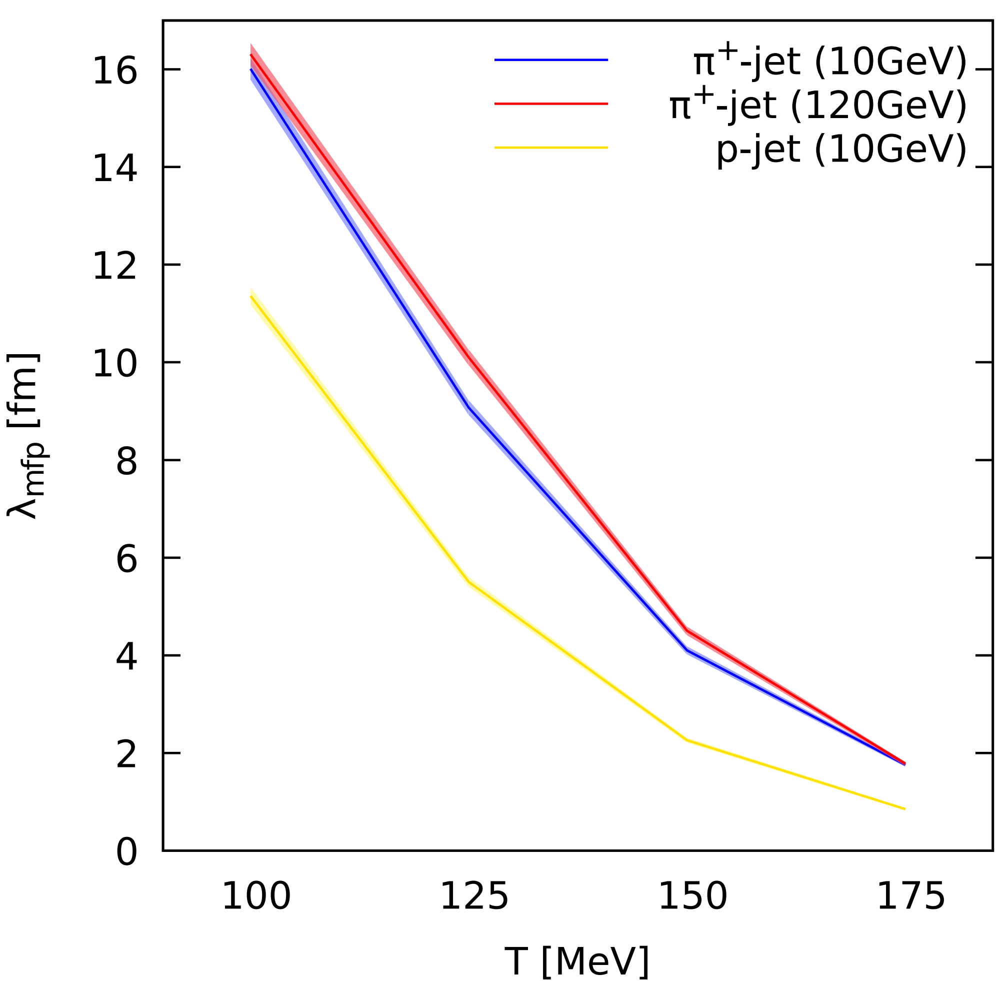


- Average momentum transfer increases as a function of temperature of the hadron gas

Mean Free Path

- The distance to the first interaction can be extracted as well

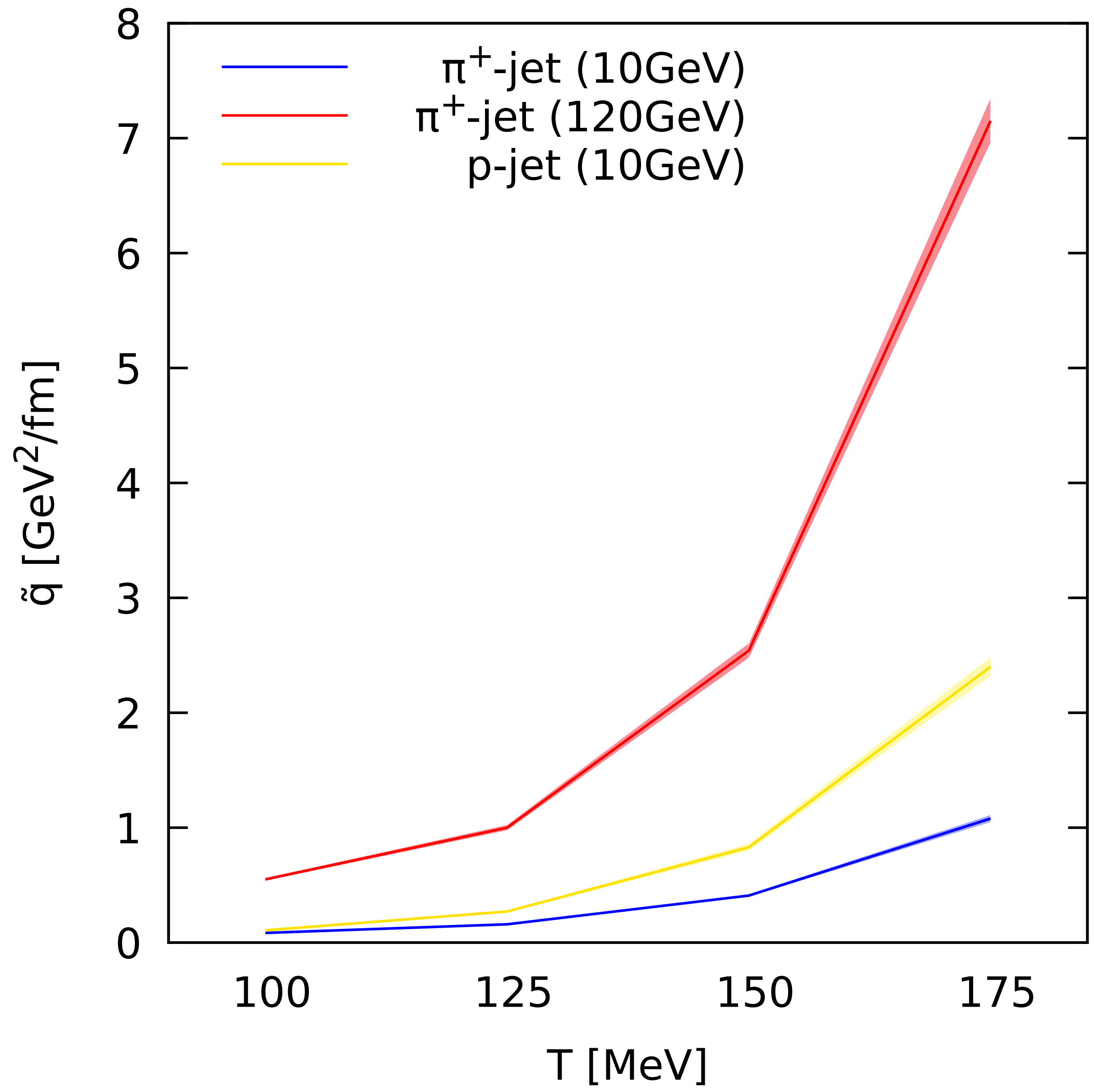




- No energy dependence, but dependence on particle species, opposite behaviour to momentum transfer

Combined Quantity

- Since the traditional $\hat{q}$ does not make sense here, we define a $\tilde{q} = \frac{\langle q_\perp^2 \rangle}{\lambda_{\text{mfp}}}$



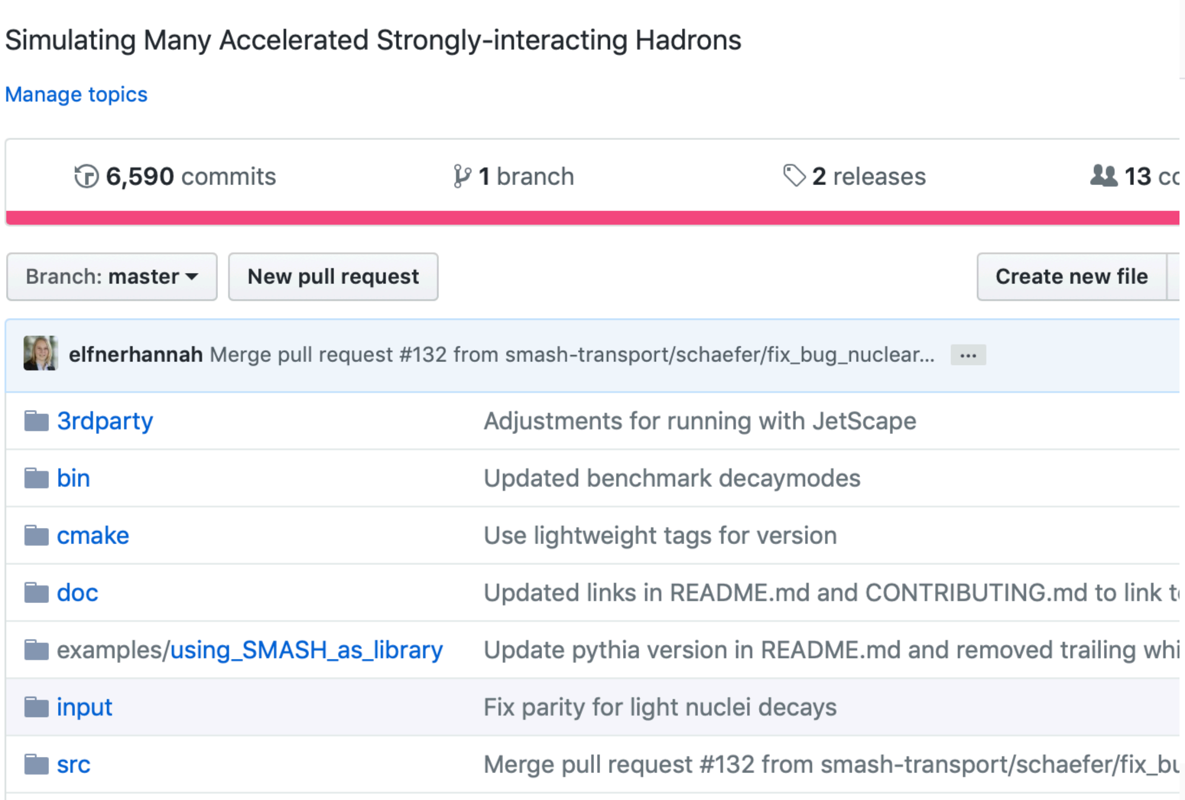
- Depends on properties of medium and probe

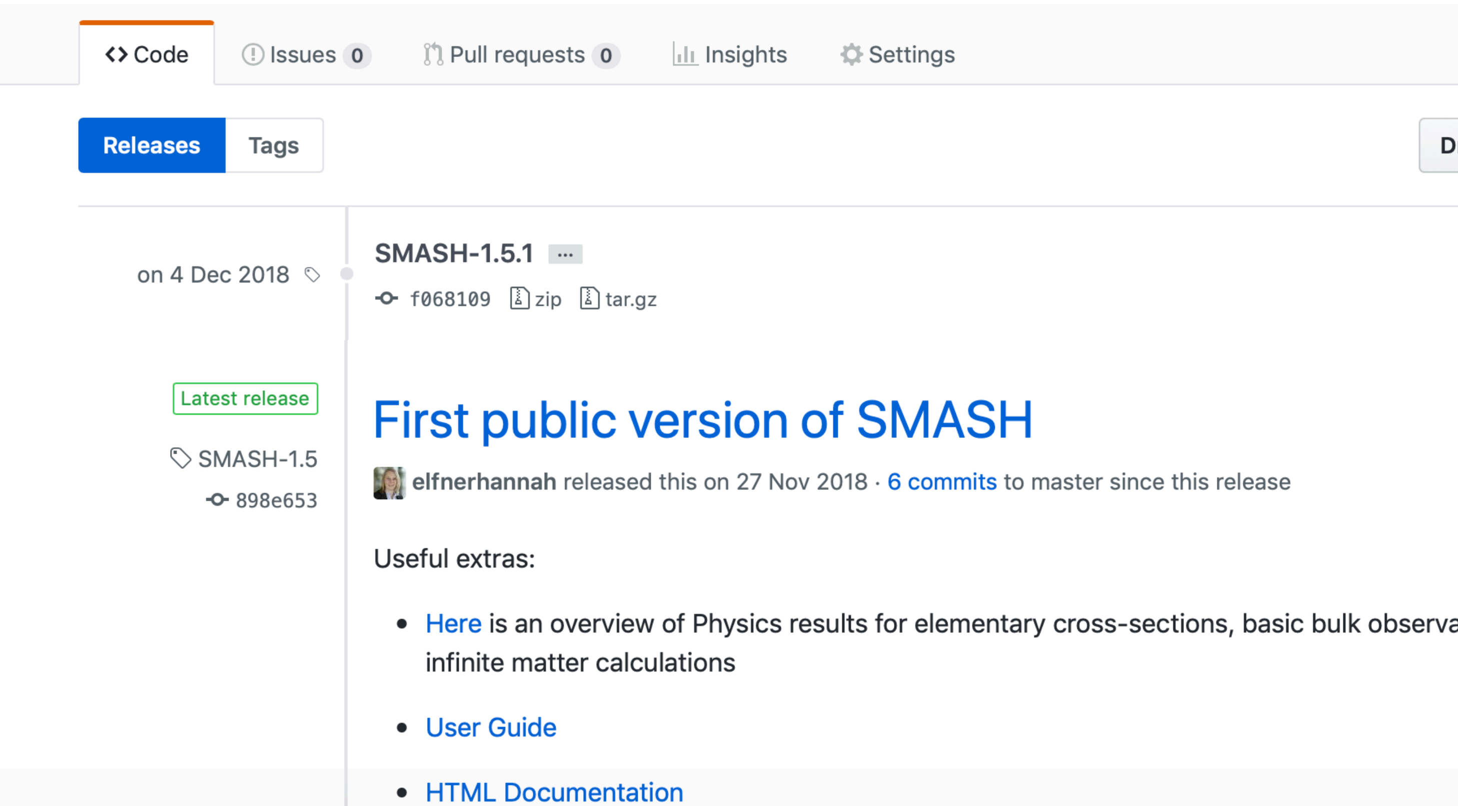
Summary and Outlook

- Jet quenching in the hadronic stage has not been studied very extensively
- For precision comparisons the hadronic stage should be taken into account
- Systematic study with SMASH:
  - Jet shapes in the expanding sphere are modified
  - From box calculations the probability distribution for momentum transfer is extracted
  - $\tilde{q}$ has been defined and depends strongly on the temperature
- Future: full dynamical calculations including the energy loss in the hadronic medium and the backreaction in hybrid approaches

How to Use SMASH?

- Visit the webpage to find publications
  https://smash-transport.github.io
- Download the code at
  https://github.com/smash-transport/smash
- Checkout the Analysis Suite at
  http://theory.gsi.de/~smash/analysis_suite/SMASH-1.6/
- Find user guide and documentation at
  https://github.com/smash-transport/smash/releases

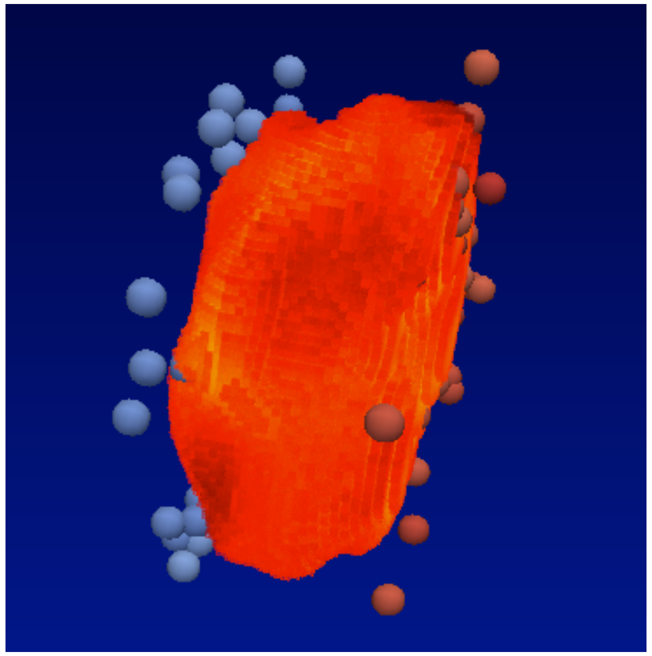




Backup

Why a new Approach?

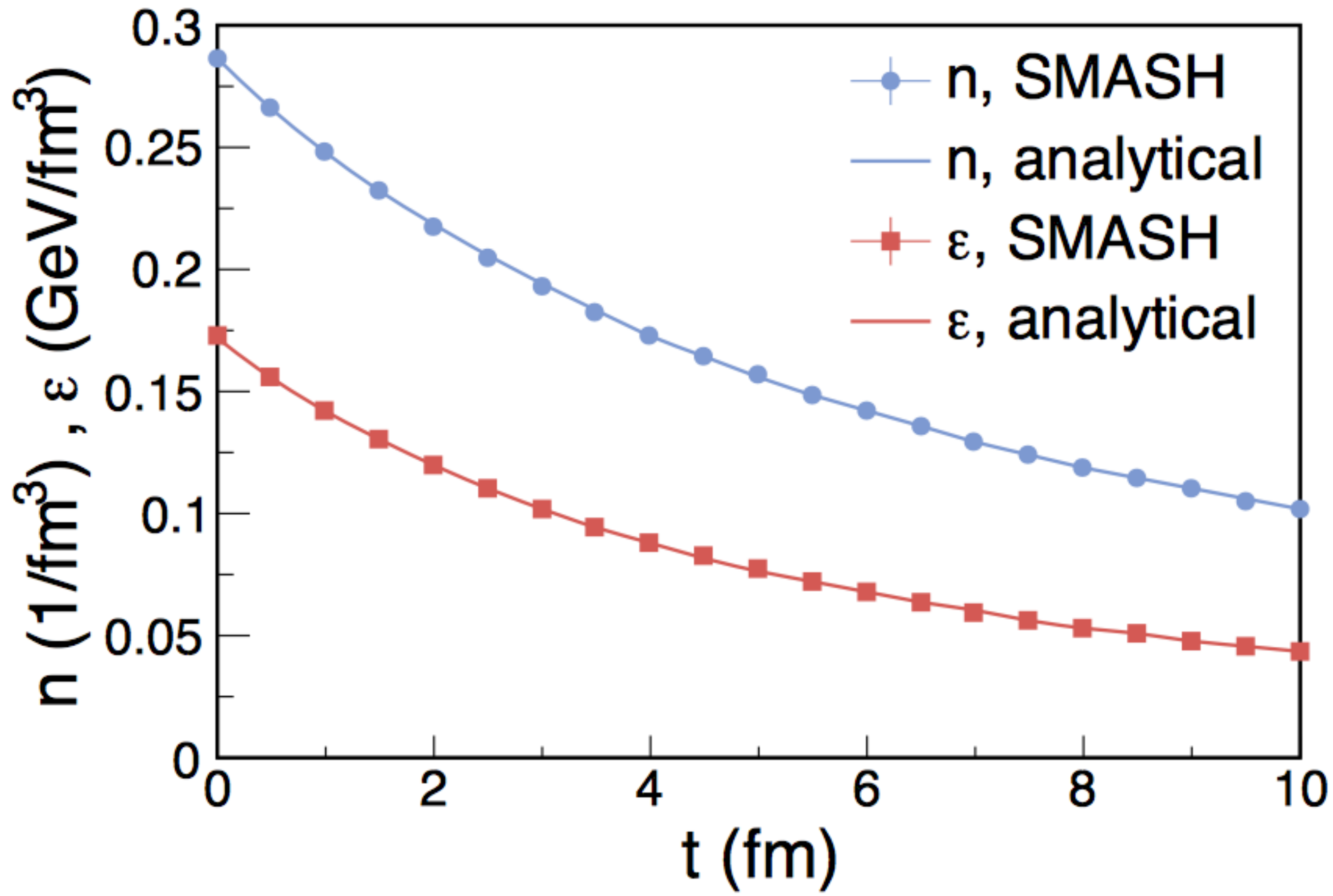
- Hadronic transport approaches are successfully applied for the dynamical evolution of heavy ion collisions
- Hadronic non-equilibrium dynamics is crucial for
  - Full/partial evolution at low/ intermediate beam energies
  - Late stage rescattering at high beam energies (RHIC/LHC)

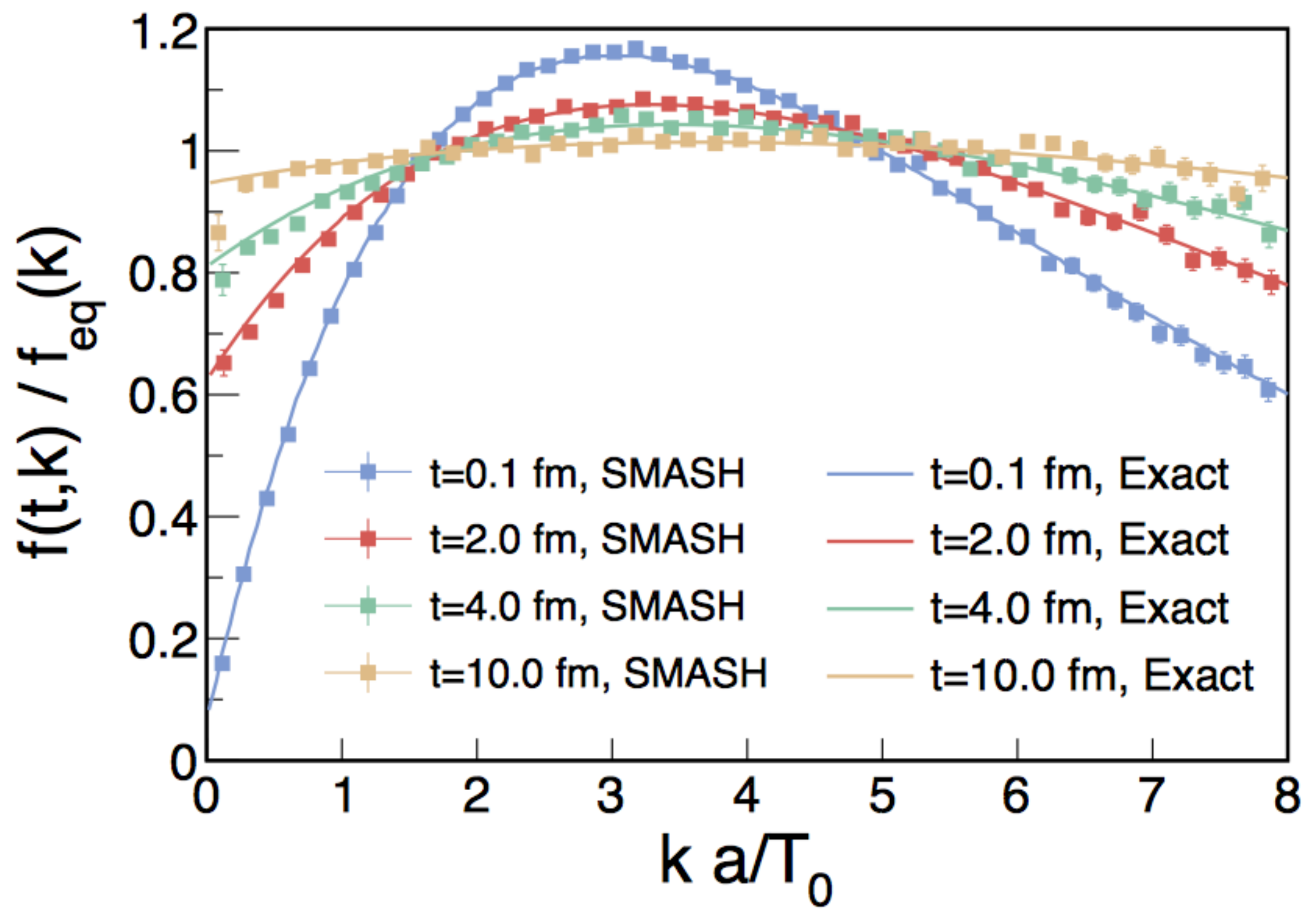


- New experimental data for cross-sections and resonance properties is available (e.g. COSY, GSI-SIS18 pion beam etc)
- Philosophy: Flexible, modular approach condensing knowledge from existing approaches
- Goal: Baseline calculations with hadronic vacuum properties essential to identify phase transition

Analytic Solution

- Comparison to analytic solution of Boltzmann equation within expanding metric





- Perfect agreement proves correct numerical implementation of collision algorithm

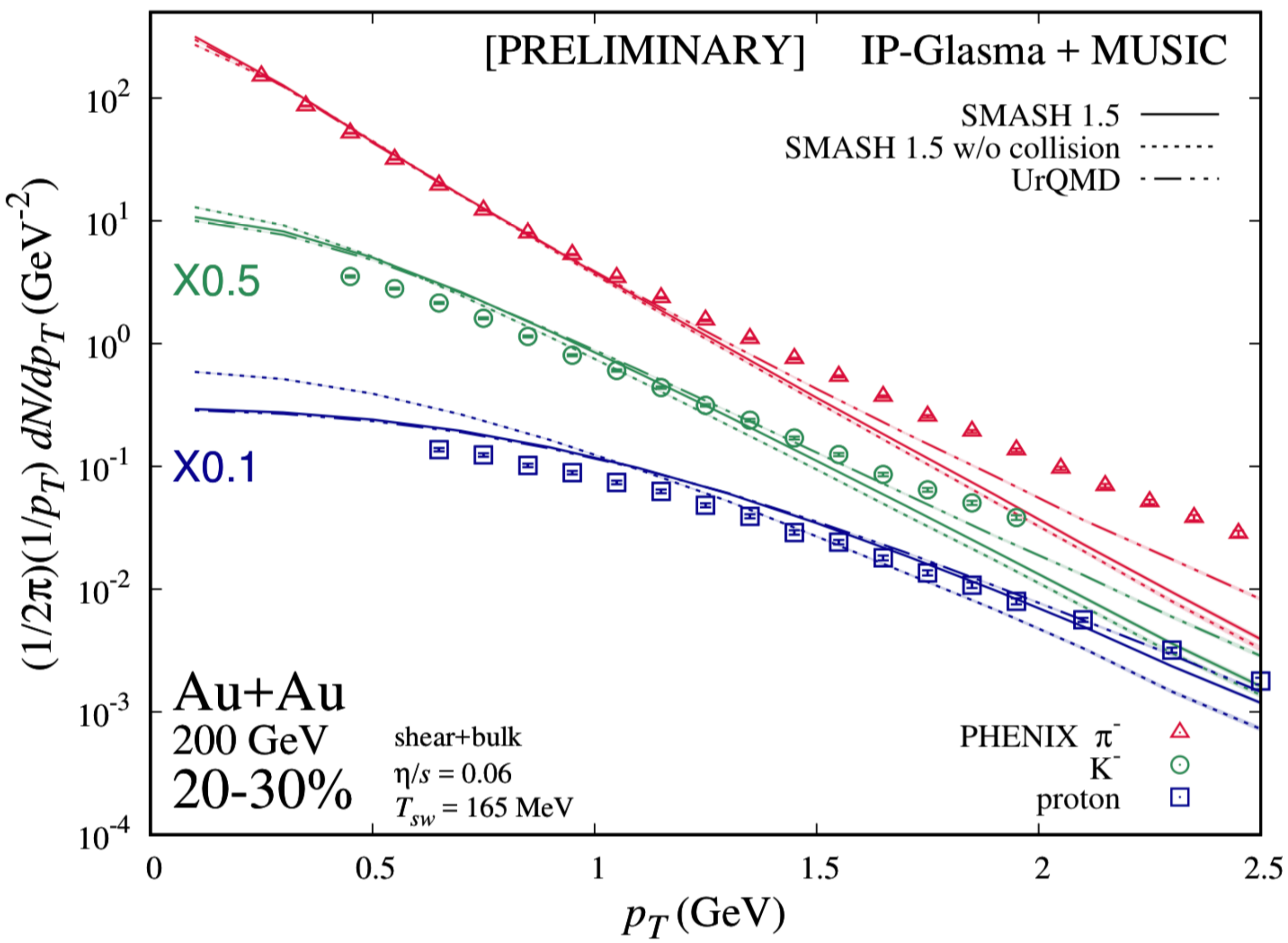
D. Bazow et al., PRL 116 (2016) and PRD 94 (2016)

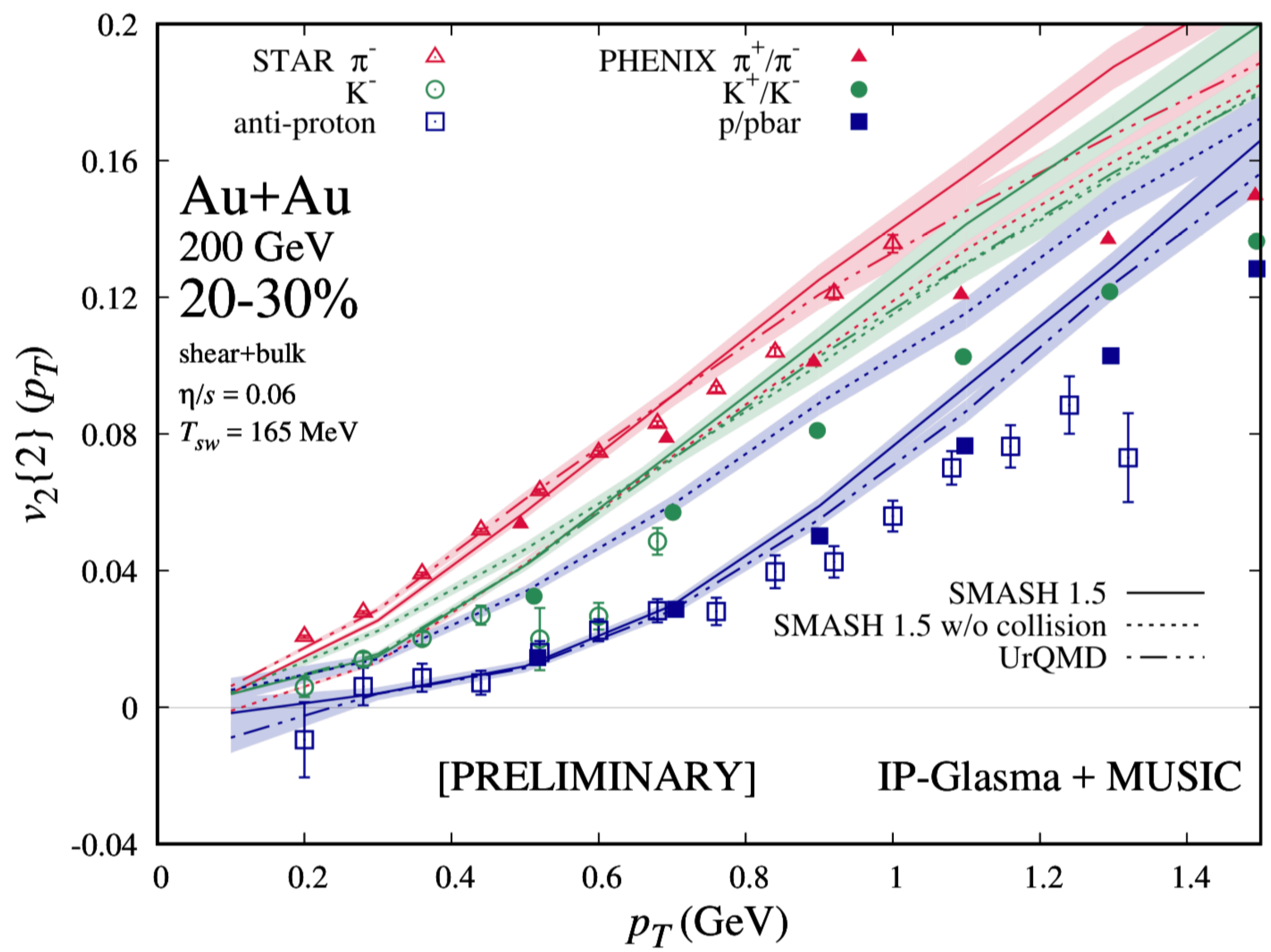
J. Tindall et al., PLB 770 (2017)

SMASH as an Afterburner

- Hadronic rescattering increases mean transverse momentum of protons
- Different behaviour of SMASH versus UrQMD for pions and kaons

S. Ryu HQ proceedings

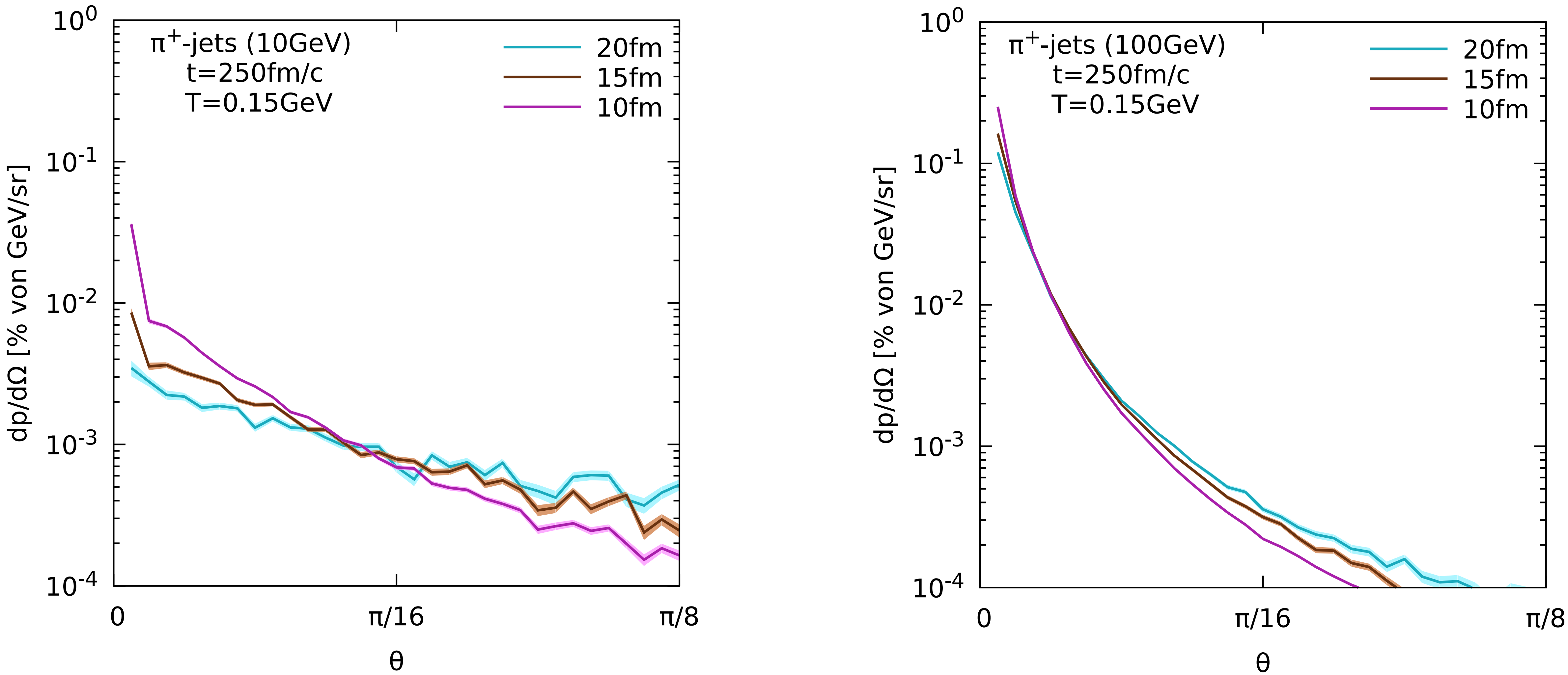




- Global conservation laws and broad resonance mass distributions have no/small effects on single-particle bulk observables

Energies and Lengths

- The medium in a heavy ion reaction at RHIC/LHC has a radius ~10 fm at the transition to the hadronic stage



- Particles with higher energies are less distorted