A primer on heavy flavor effects in the afterburner

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in collaboration with

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Hirschegg 2024 - “Strong interaction physics of heavy flavors”

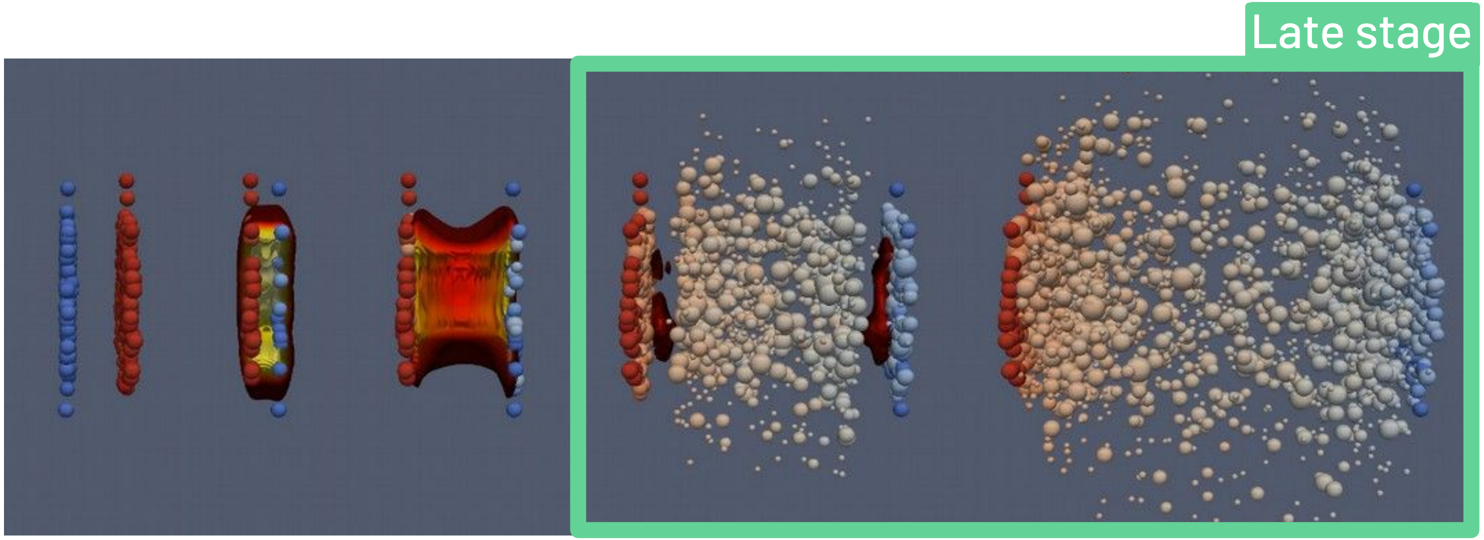
Outline

- A brief review of what we know
- My own attempt in understanding

Introduction

what have we done?

Introduction

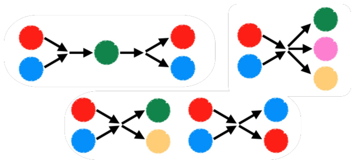


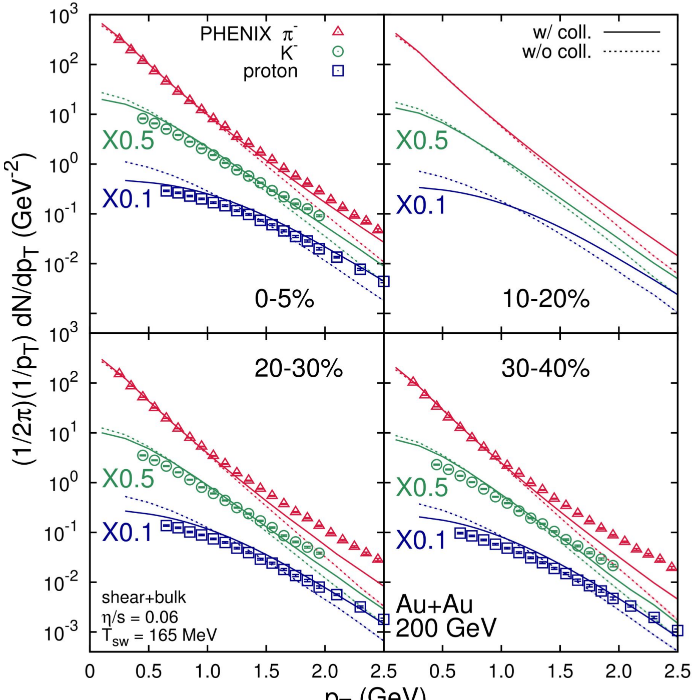
[H. Elfner and J. Bernhard, MADAI collaboration]

Hadronic afterburner

rescattering of hadrons during the non-equilibrium evolution in the late stages of a heavy ion collision

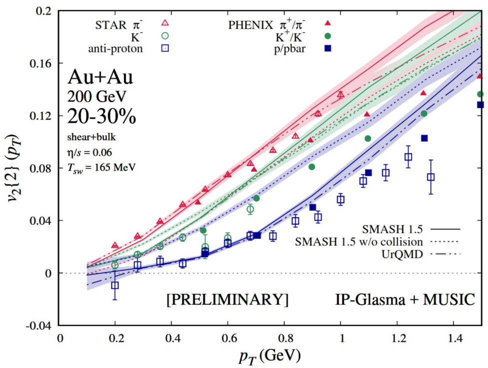
Introduction



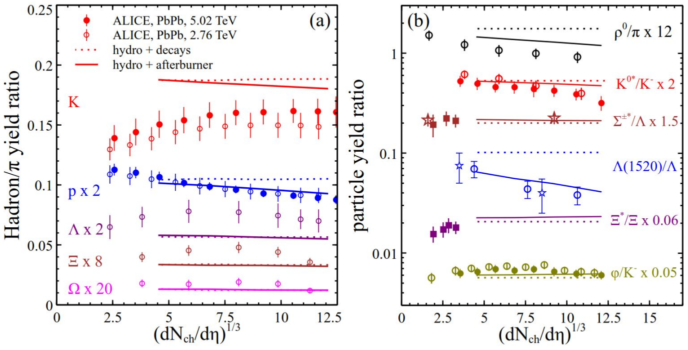


[Ryu S et al. 2015 PRL 115, 132301]

[Elfner and Müller (2023) J. Phys. G 50 103001]



[Oliinychenko and Shen (2021) EPJ 259, 10008]



General behavior (for light hadrons)

- *"Pion wind"* phenomenon: low-momentum protons and kaons are pushed to larger values of p_T.
- Isotropization: elliptic flow decreases for low p_T
- Rebalance of hadron chemistry via inelastic processes.

Angantyr

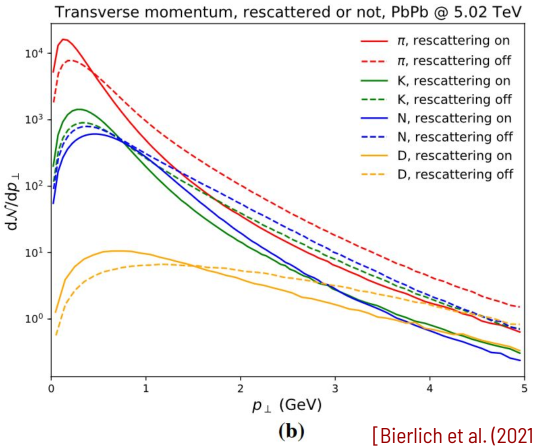
In PYTHIA, charm quarks are only produced in perturbative processes, but not in string fragmentation, so the D mesons start out with a larger momenta than light hadrons, and not blown by the “pion wind”. Instead, the rescattering slows them down.

Included processes

- Elastic
- 2→1 Breit-Wigner resonance
- 2→N diffractive (no color exchange)
- 2→2* non-diffractive

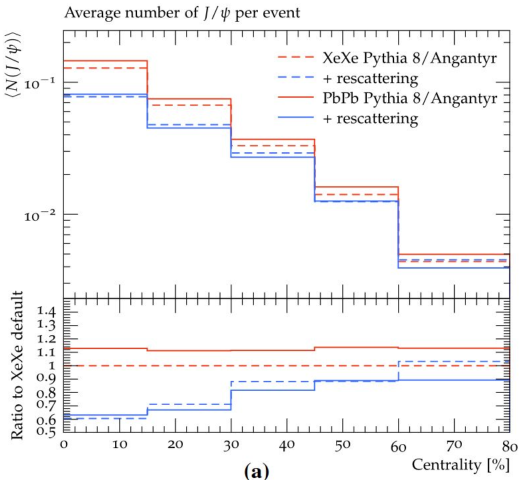
Charmed hadrons: AQM

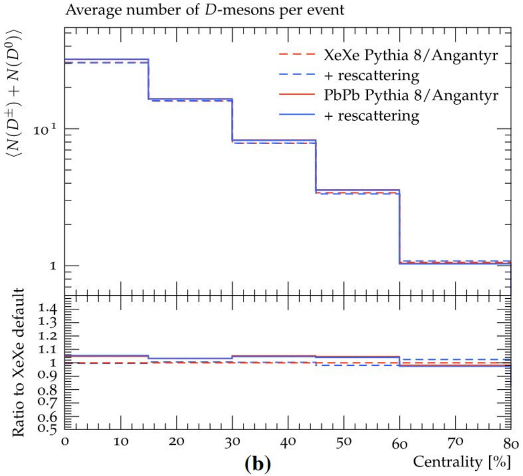
$$n_{\mathrm{q,AQM}} = n_{\mathrm{u}} + n_{\mathrm{d}} + 0.6\, n_{\mathrm{s}} + 0.2\, n_{\mathrm{c}} + 0.07\, n_{\mathrm{b}}.$$



There is no mechanism for charm quarks to vanish in rescattering, so the constituents of J/ψ end up in other charmed hadrons. Since the D mesons are ~100 times more common, their yield is not so affected by this.

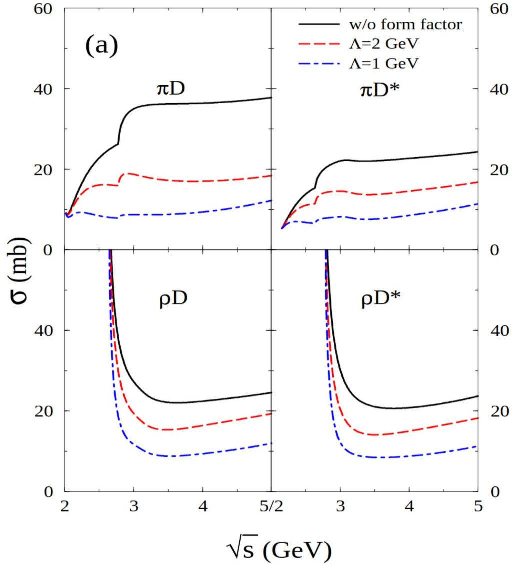
[Bierlich et al. (2021) EPJ A 57, 227]



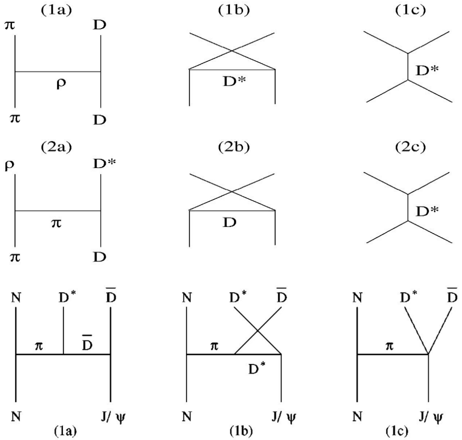


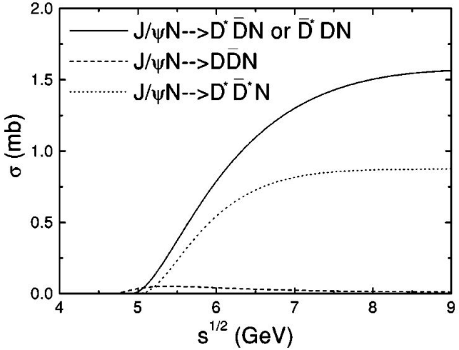
Early cross section calculations

In the early 2000's, some cross sections for hadronic interactions between charmed and light hadrons were computed using a gauge-invariant SU(4), with vector mesons as the gauge bosons.

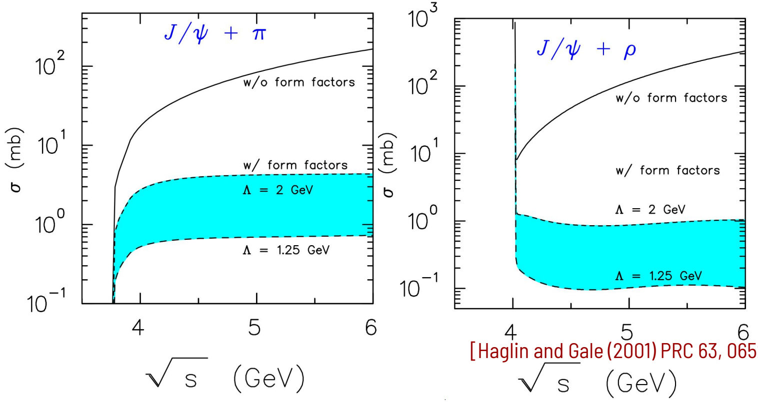


[Z. Lin et al. 2001 NPA 689, 965-979]





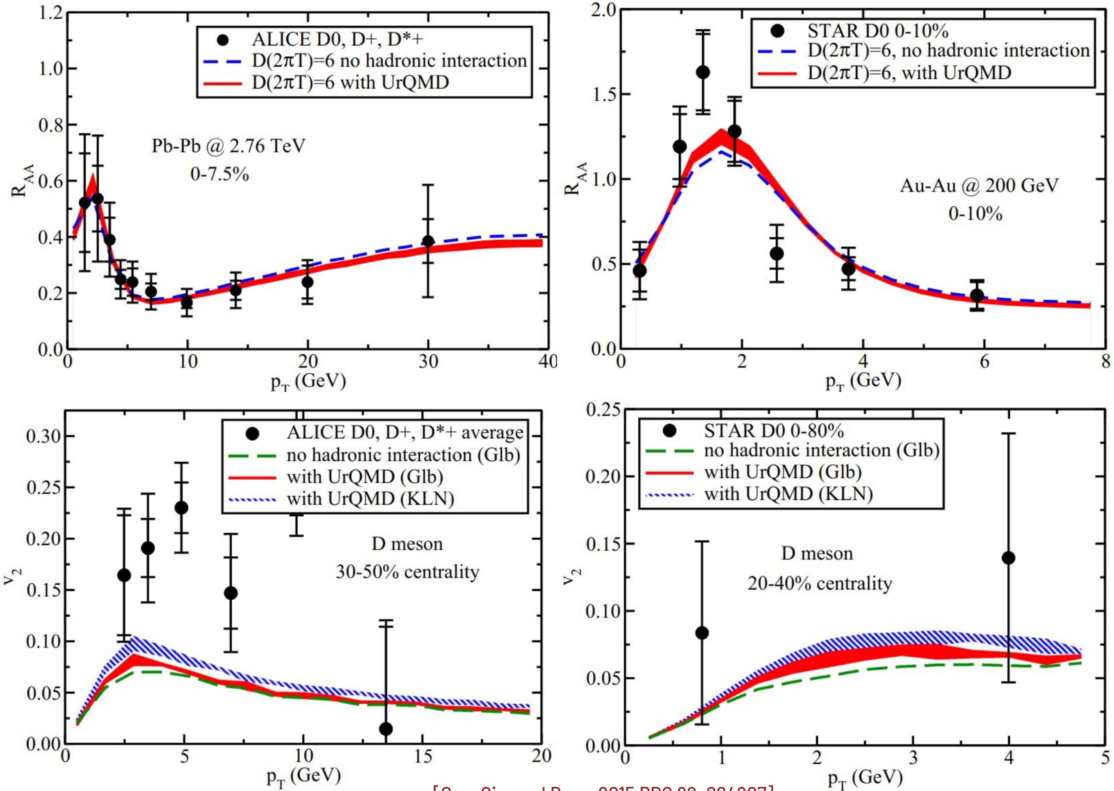
[Liu, Ko, and Lin (2001) PRC 65, 015203]



[Haglin and Gale (2001) PRC 63, 065201]

UrQMD

__U__ltra-__r__elativistic __Q__uantum __M__olecular __D__ynamics



[Cao, Qin, and Bass, 2015 PRC 92, 024907]

Nuclear modification factor

$$R_{AA} = \frac{\mathrm{d}^3 N_{AA}/\mathrm{d}p^3}{\langle N_{\mathrm{coll}} \rangle\, \mathrm{d}^3 N_{pp}/\mathrm{d}p^3}$$

Because D mesons lose momentum in the afterburner, R_{AA} is suppressed at high and enhanced at low p_T.

Elliptic flow coefficient

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

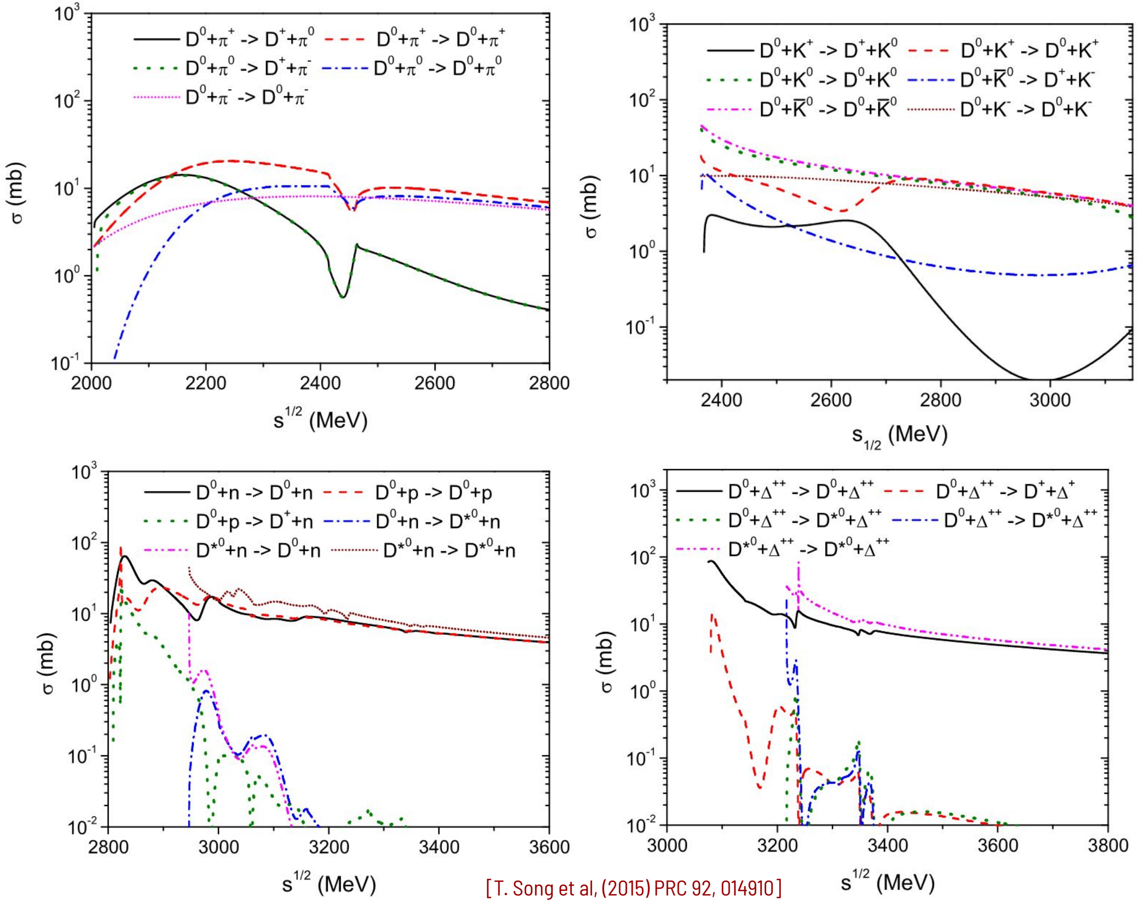
v_2 is enhanced by the hadronic rescattering, bringing it closer to the experimental data, but not enough to reach an agreement.

PHSD

***P**arton-**H**adron **S**tring **D**ynamics*

Cross sections computed with chiral perturbation theory up to NLO for pions, nucleons, kaons and Deltas.

The interactions of D mesons with the remaining hadrons are done with a constant cross section of 10 mb.

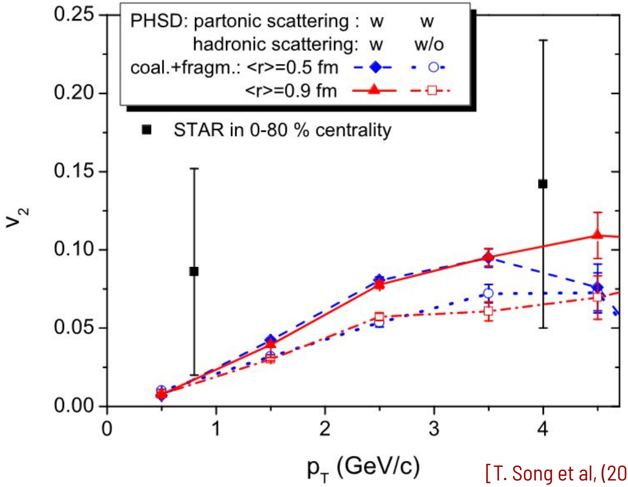


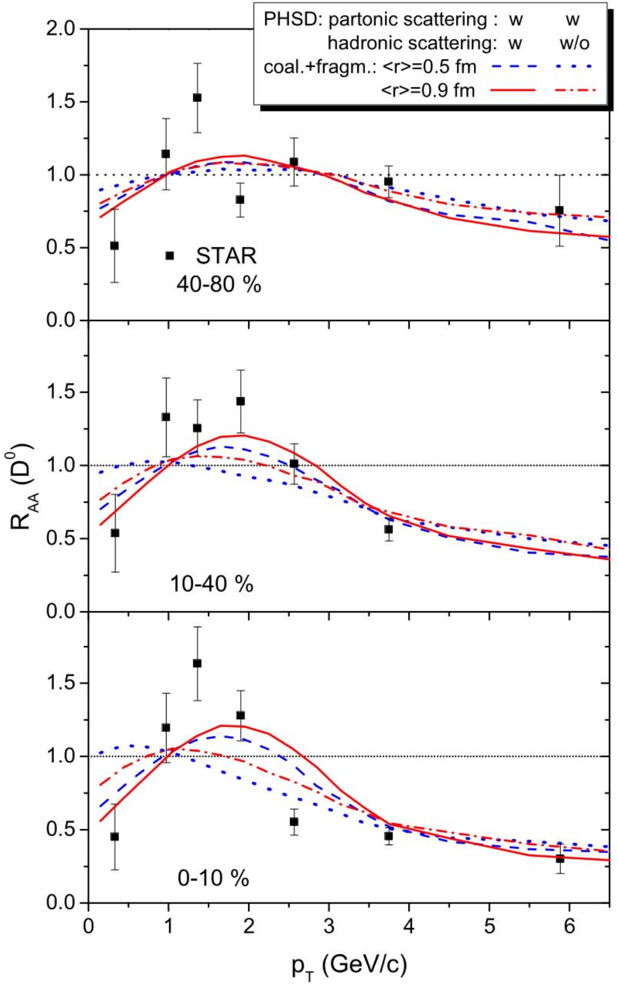
[T. Song et al, (2015) PRC 92, 014910]

PHSD

***P**arton-**H**adron **S**tring **D**ynamics*

With hadronic rescattering, v_2 in PHSD is enhanced by a percentage similar to what is seen in UrQMD. Their R_{AA} also shows some suppression for large p_T, but a significant difference is the shift of the peak to higher momenta, being less compatible with experiment.





[T. Song et al, (2015) PRC 92, 014910]

Motivation

No *systematic* study has been done on how the afterburner affects heavy hadrons!

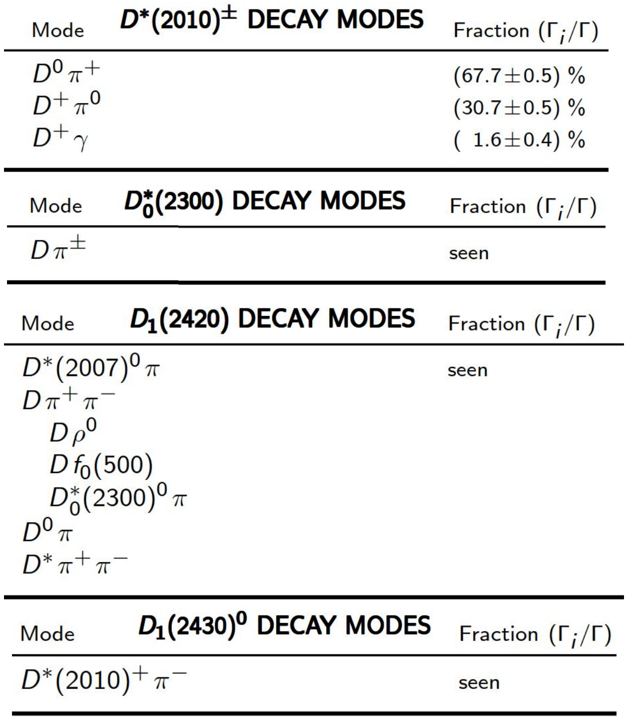
Theory uncertainties

- What are the relevant channels and their corresponding cross sections?
- Can the excited resonances even be treated independently, or is there interference ?

Experimental difficulties

- Interaction cross sections with HF are not directly measurable
- Little data on resonances
- Limited statistics (so far) makes it easy to reach agreement

My approach: try to build knowledge and intuition *systematically* from the ground up



$D^*(2010)^{\pm}$ DECAY MODES

Mode	Fraction (Γ_i/Γ)
$D^0\pi^+$	(67.7±0.5) %
$D^+\pi^0$	(30.7±0.5) %
$D^+\gamma$	(1.6±0.4) %

$D_0^*(2300)$ DECAY MODES

Mode	Fraction (Γ_i/Γ)
$D\pi^{\pm}$	seen

$D_1(2420)$ DECAY MODES

Mode	Fraction (Γ_i/Γ)
$D^*(2007)^0\pi$	seen
$D\pi^+\pi^-$	
$D\rho^0$	
$Df_0(500)$	
$D_0^*(2300)^0\pi$	
$D^0\pi$	
$D^*\pi^+\pi^-$	

$D_1(2430)^0$ DECAY MODES

Mode	Fraction (Γ_i/Γ)
$D^*(2010)^+\pi^-$	seen

[Workman et al. (2022) Prog.Theor.Exp.Phys. 083C01]

Toy-modelling

what is caused by
which mechanisms?

The SMASH approach

__S__imulating __Ma__ny __S__trongly-interacting __H__adrons

https://smash-transport.github.io/

Boltzmann equation

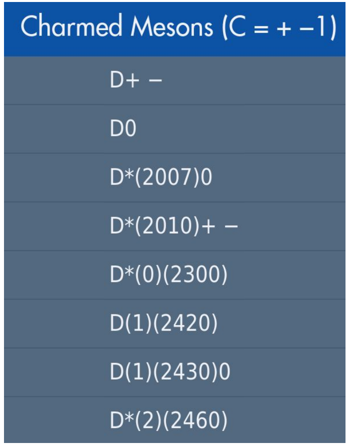
$$p^\mu \partial_\mu f_i(x,p) = C^i_{\text{coll}}[f]$$

- LHS: propagation (“free streaming”)
- RHS: interactions (binary and resonant)

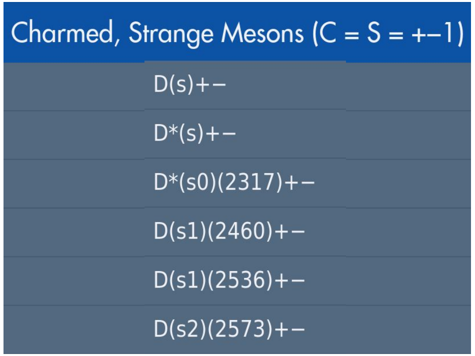
$$C^i_{2\leftrightarrow 2}[f] = \sum_j \int\int |\mathbf{p}'_i - \mathbf{p}'_j| \frac{\mathrm{d}\sigma_{ij}(s)}{\mathrm{d}\Omega} \left[f(\mathbf{p}'_i)f(\mathbf{p}'_j) - f(\mathbf{p}_i)f(\mathbf{p}_j)\right] \mathrm{d}^3\mathbf{p}'\,\mathrm{d}\Omega$$

- Testparticle ansatz: sample the single particle distribution function a number of times, and reduce the cross section by the same amount

- Required (and missing) inputs:
  - Hadron resonance list
  - Decay widths and branching ratios
  - Cross sections



Charmed Mesons (C = + −1)
D+ −
D0
D*(2007)0
D*(2010)+ −
D*(0)(2300)
D(1)(2420)
D(1)(2430)0
D*(2)(2460)



Charmed, Strange Mesons (C = S = +−1)
D(s)+−
D*(s)+−
D*(s0)(2317)+−
D(s1)(2460)+−
D(s1)(2536)+−
D(s2)(2573)+−

The SMASH approach

*Simulating **Ma**ny **S**trongly-interacting **H**adrons*

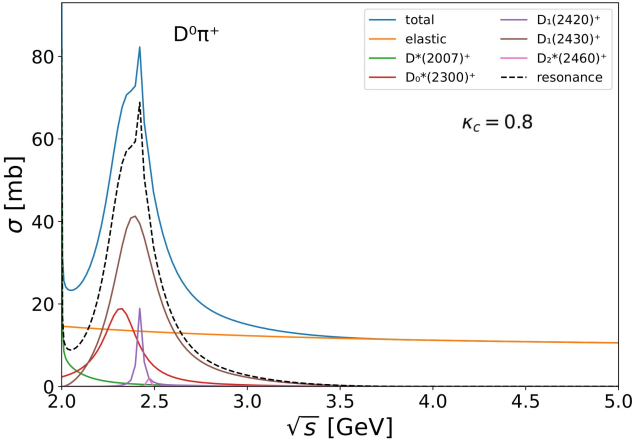
https://smash-transport.github.io/

Detailed balance cross sections for resonance production depend on *modelling* and *data*

$$\sigma_{ab\to R}(s) = \frac{2J_R+1}{(2J_a+1)(2J_b+1)}\mathcal{S}_{ab}\frac{2\pi^2}{p^2_{\mathrm{CM}}(s)}\mathcal{A}_R(s)\Gamma_{R\to ab}(s)\mathcal{F}_{ab}(s)$$

Total cross section from the additive quark model (AQM)

$$\sigma_{AB} = \sigma_{pp}\frac{n_q^A}{3}\frac{n_q^B}{3}\left(1-0.4x_s^A\right)\left(1-0.4x_s^B\right)\left(1-\kappa_c x_c^A\right)\left(1-\kappa_c x_c^B\right)$$



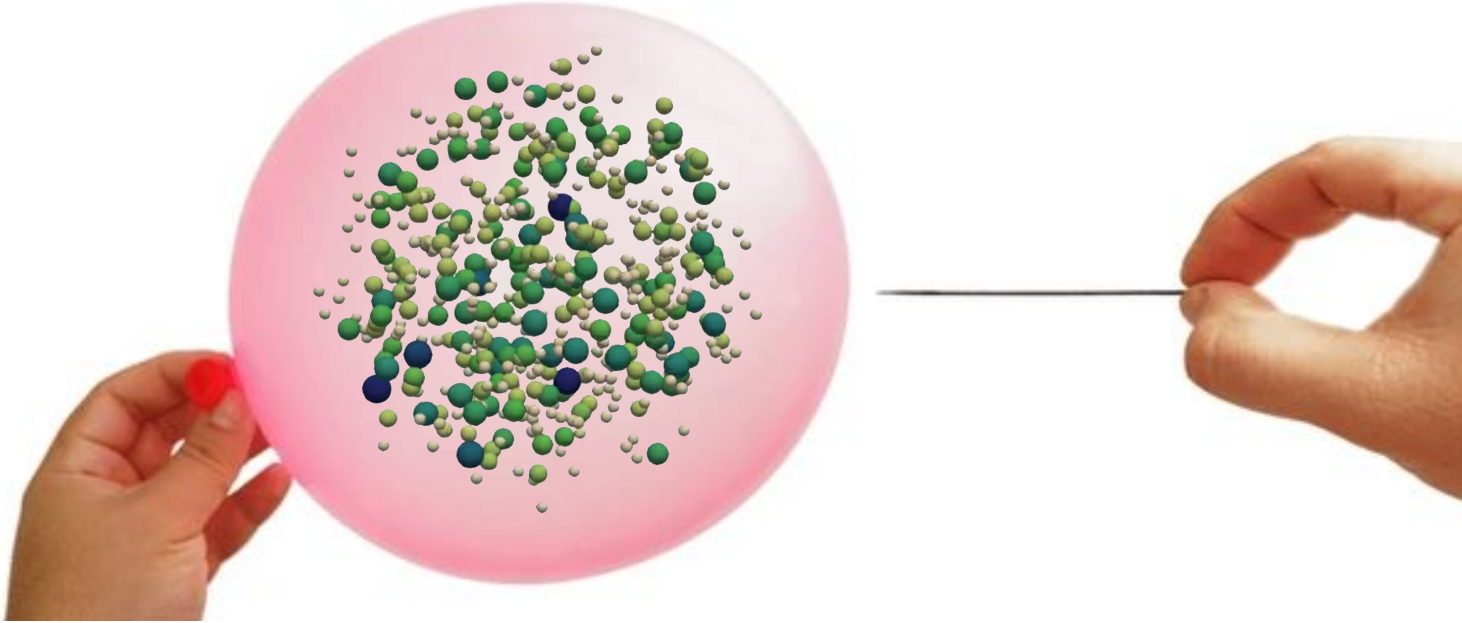
Simplicity and agnosticism

In what follows, I will use the AQM cross section with only elastic processes, unless stated otherwise

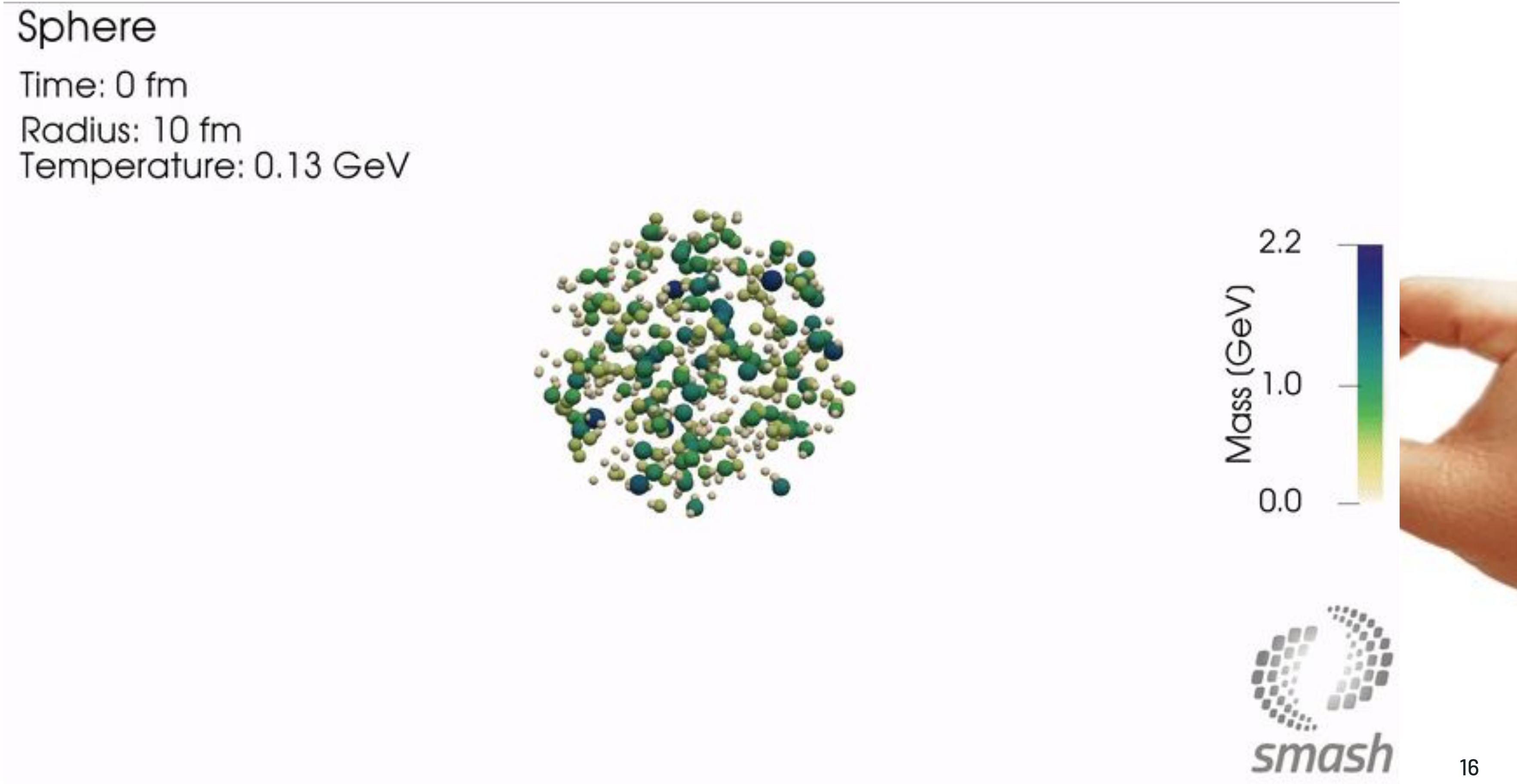
One control parameter!

What about the initial condition?

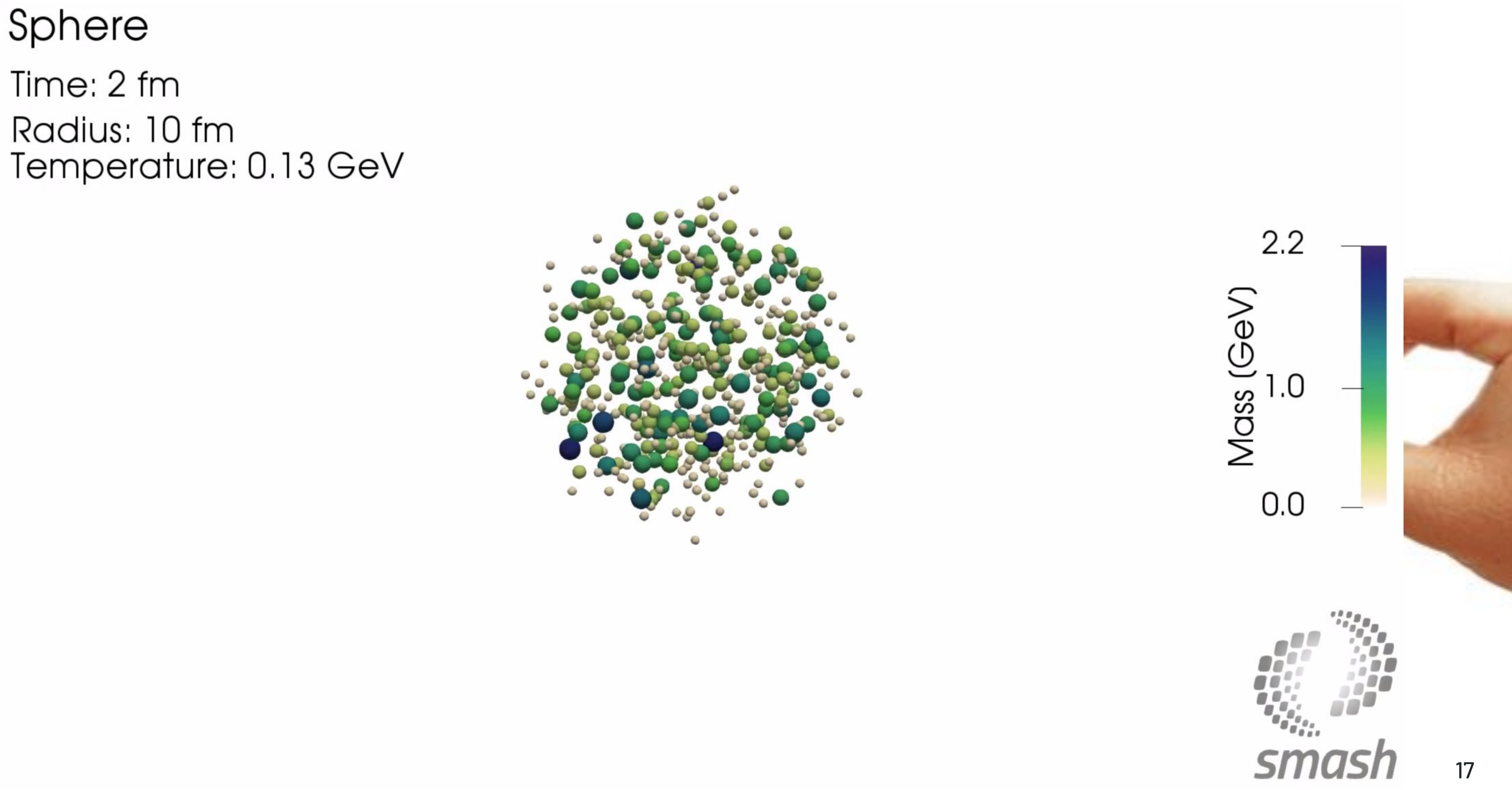
Model: a sphere of hadron gas



Model: a sphere of hadron gas



Model: a sphere of hadron gas



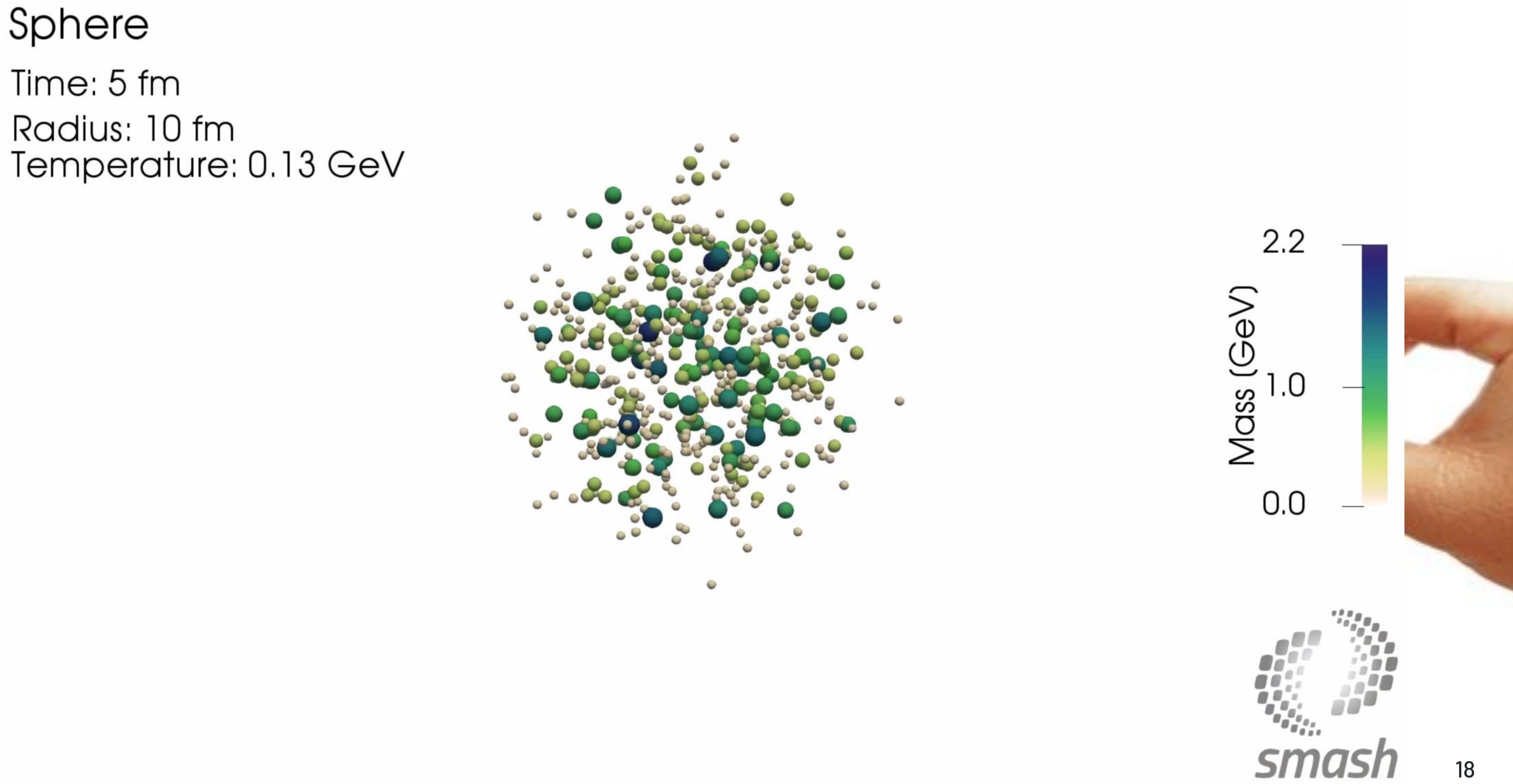
Sphere

Time: 2 fm

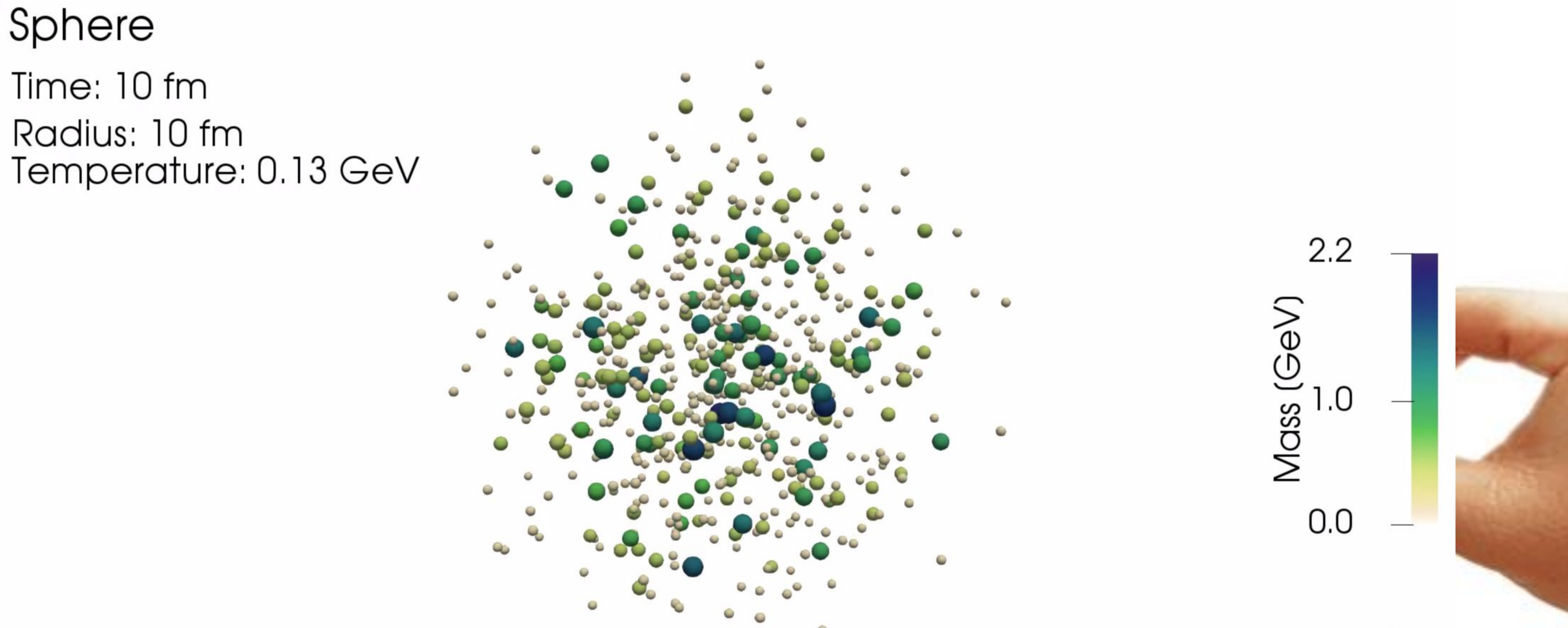
Radius: 10 fm
Temperature: 0.13 GeV

smash

Model: a sphere of hadron gas



Model: a sphere of hadron gas



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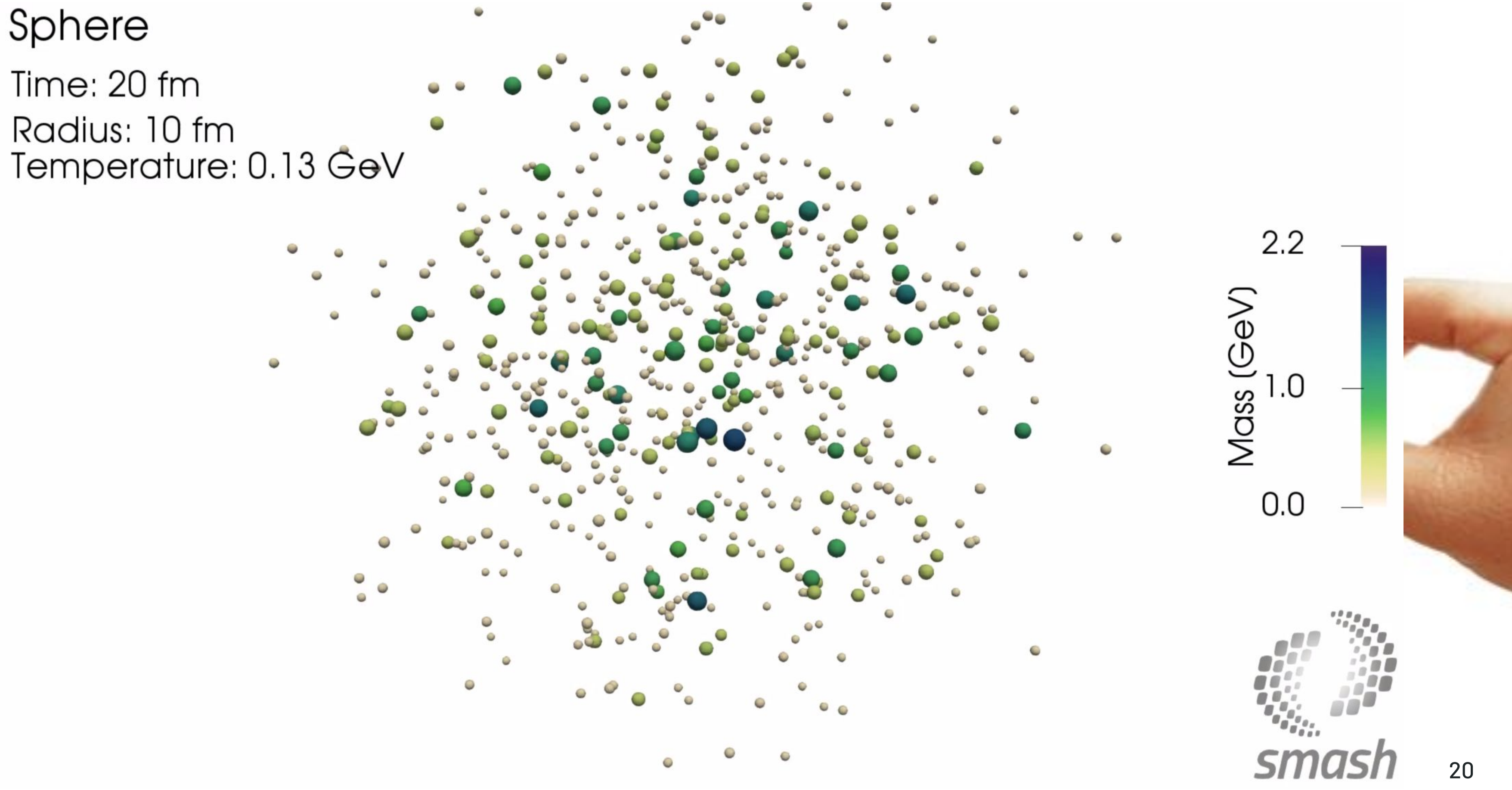
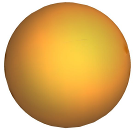


Model: a sphere of hadron gas

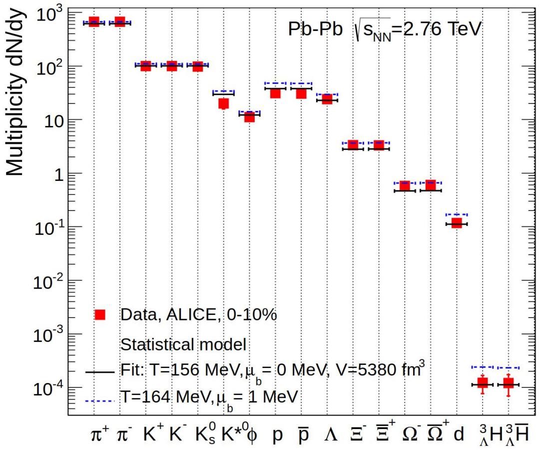


"Thermal sphere" requires input of temperature and size

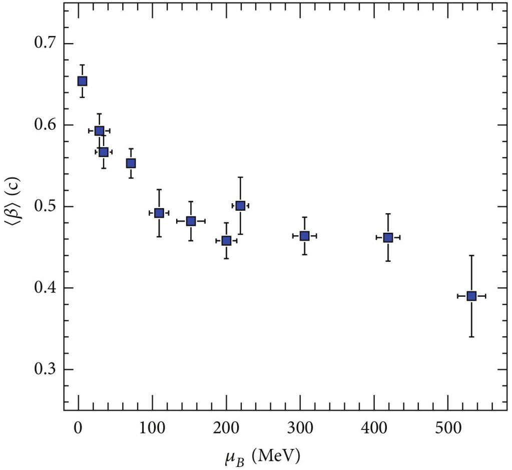
Afterburner: used around chemical freezeout

take (T,V) from Statistical Hadronization Model fits

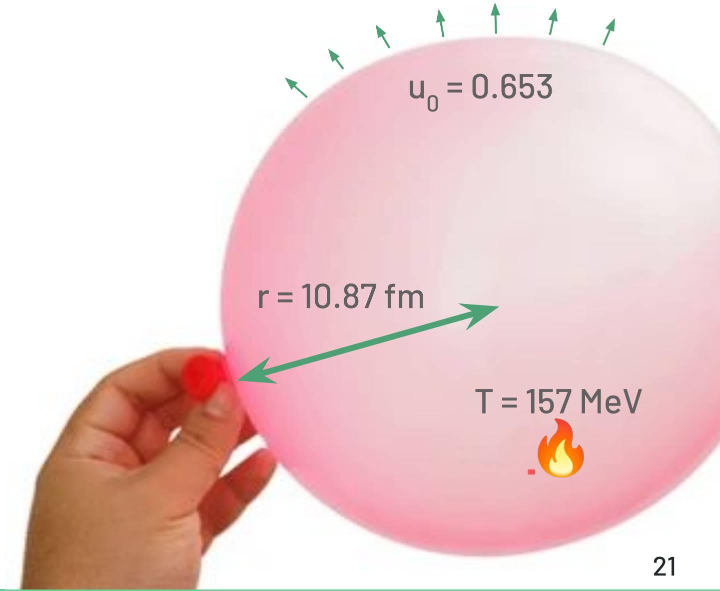
Also *reasonable*: extract radial velocity from blast-wave fits



[Stachel et al. 2014 QM proceedings, 012019]

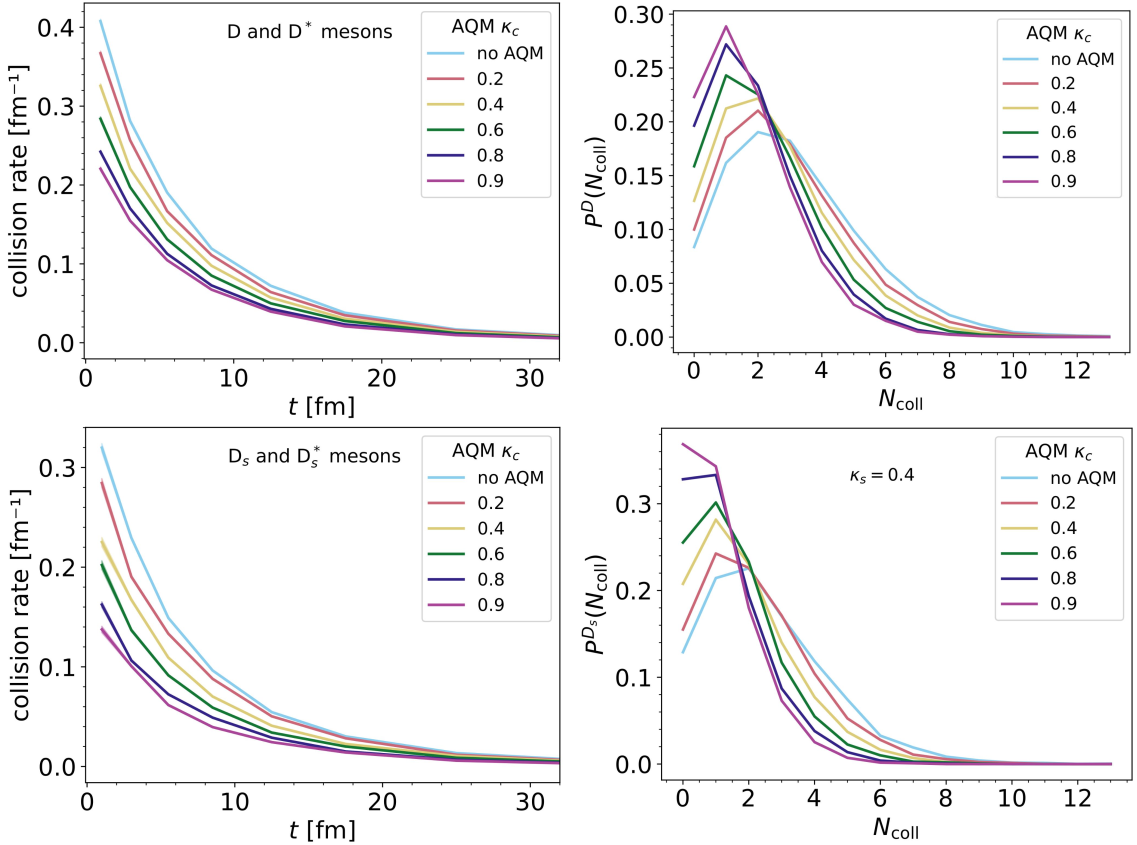


[Chatterjee et al., Adv. HEP review 2015]



Results: a sphere of hadron gas

$P^X(N_{coll})$: probability that X-particles collide N_{coll} times until kinetic freezeout



Global dynamics

Sphere expansion

- collision rate decreases.
- kinetic freezeout at ~30 fm.

D_s also has a strange quark

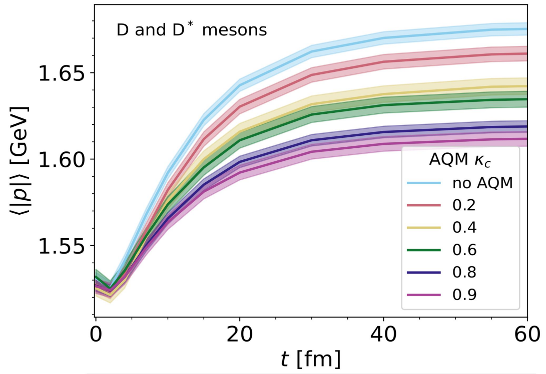
- interactions further suppressed.

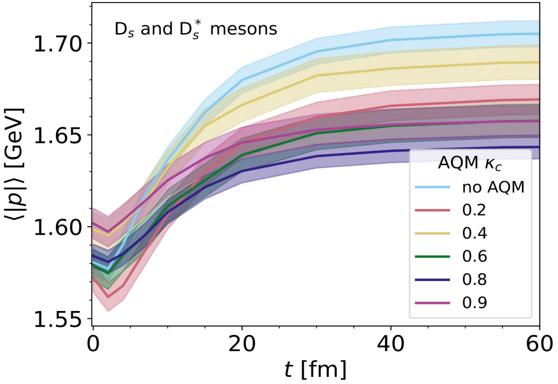
Large cross section *inputs*

Larger collision rate

More interactions before freezeout

Results: a sphere of hadron gas





Momentum shifts

Thermal charmed hadrons are accelerated by ~ 100 MeV

↰stronger with larger cross sections.

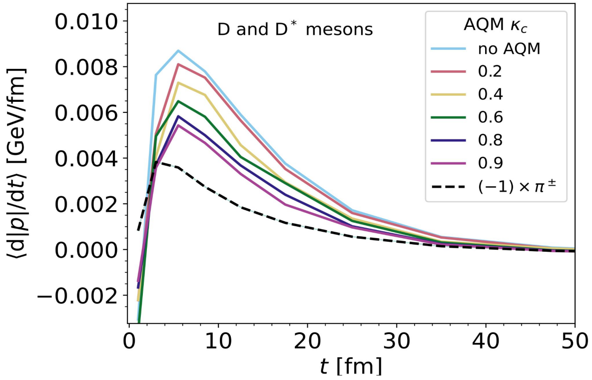
D$_s$ is less frequent

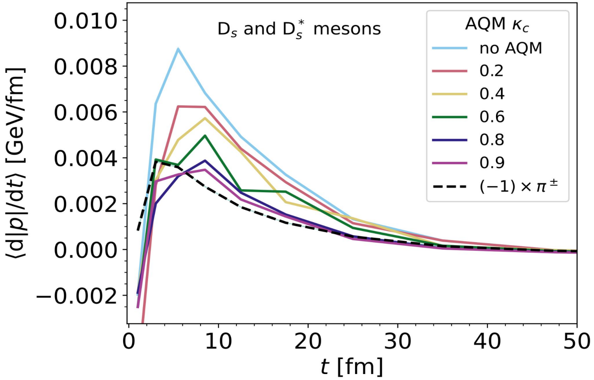
↳initial sampled momentum fluctuates more.

Pions are *slowed down*

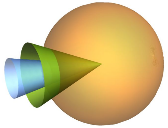
↰ “pion wind” effect.

↳ momentum lost by each pion is not as large.





Model: single jet



Realistically: charmed particles will be faster than light ones post-hadronization → Study what happens to fast-moving particles

“Jet”

A single D meson that does *not* radiate and only scatters elastically, initially fast in the x-direction

Not a real jet!

Results: single jet

Global dynamics

Similar to thermal particles

↳collision rate decreases with sphere expansion.

↳kinetic freezeout at ~30 fm.

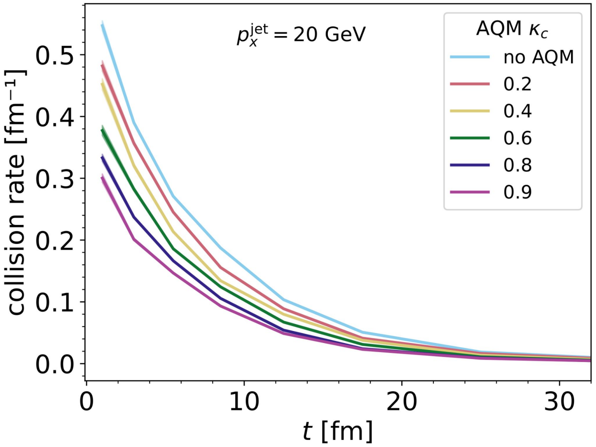
↳larger for lower suppression.

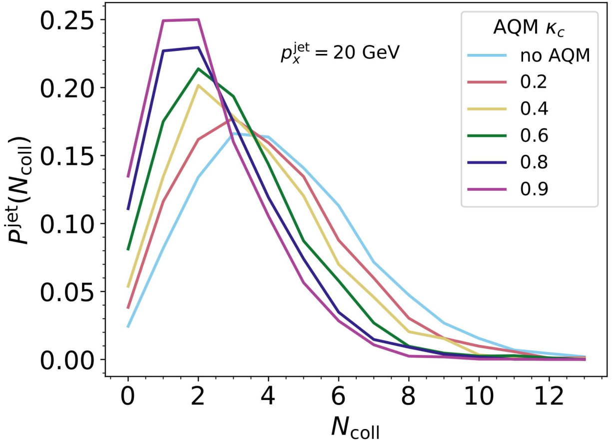
More collisions than thermal D

↑ larger relative momentum in collision integral

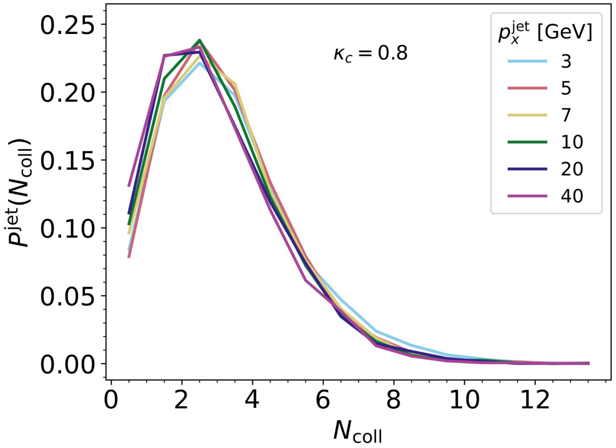
↳ number of interactions correspondingly larger

Some jets escape the medium without interacting, from 3% (κ_c=0) to 14% (κ_c=0.9).

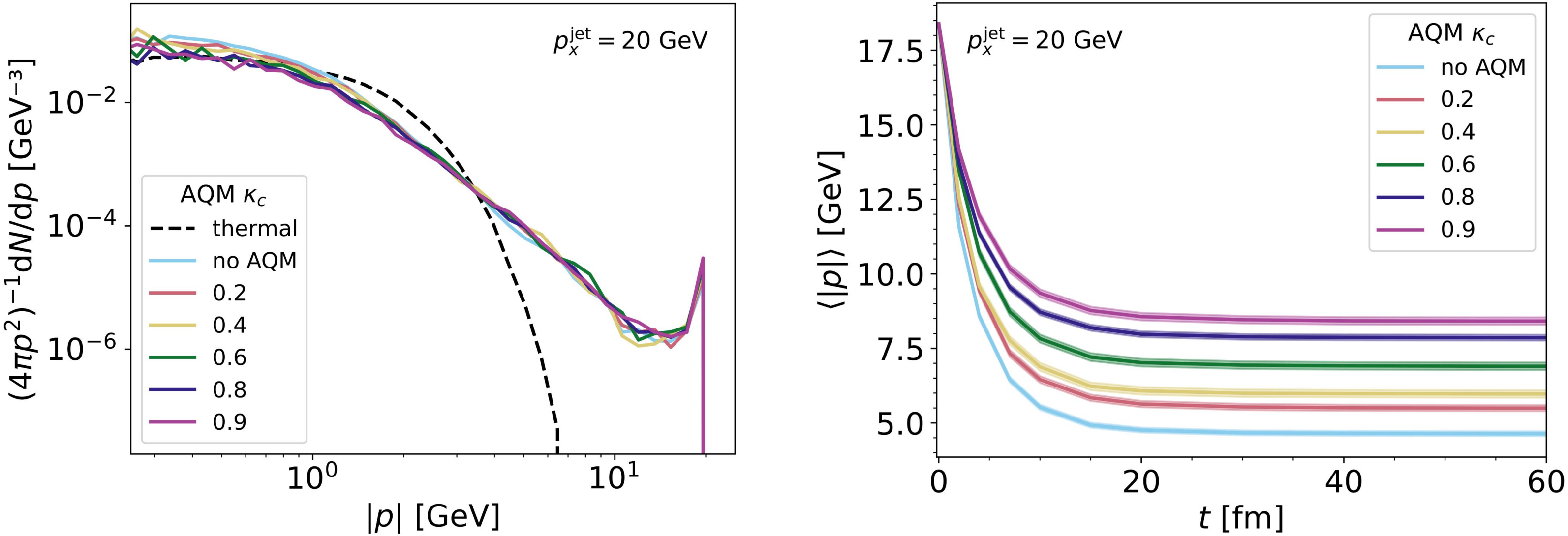




The initial jet momentum is also a control parameter, but the collision probability is not very sensitive to it.



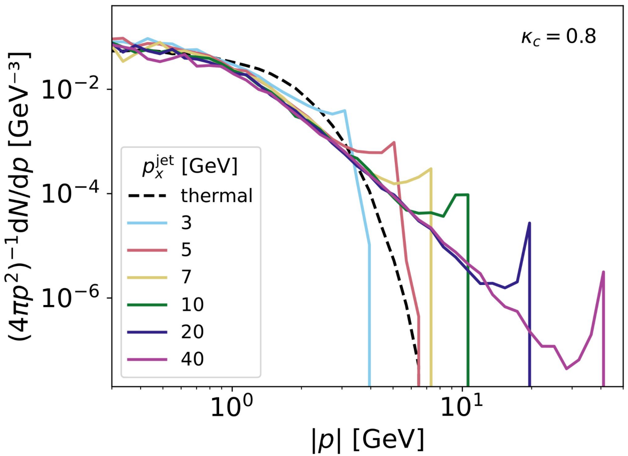
Results: single jet



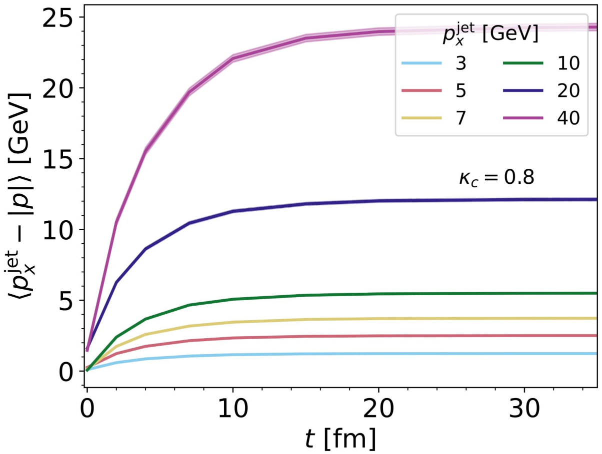
Interaction with the medium *slows down* jet particles

- again stronger with a larger cross section input.
- more interacting jets end up *slower* than if AQM suppressed.

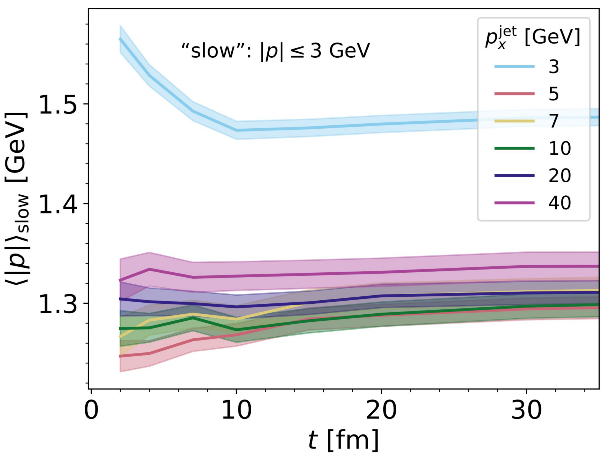
Results: single jet



Rescattered jet particles seem to follow an universal curve, regardless of initial momentum



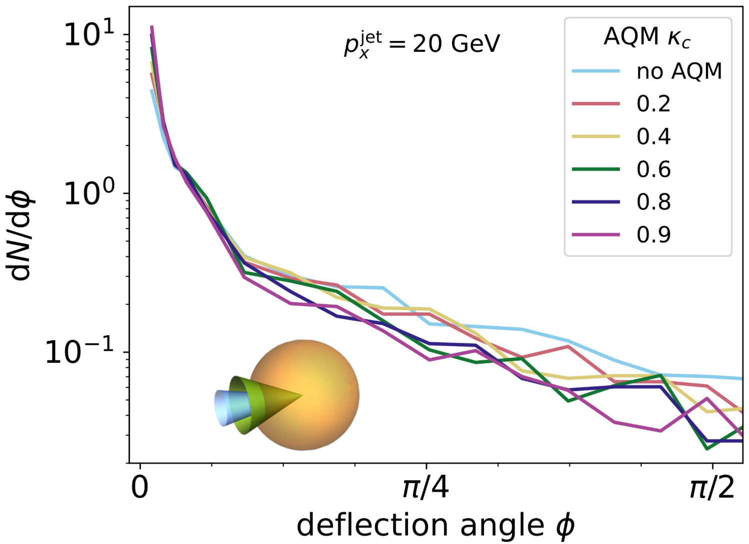
Largest momentum loss from the largest initial momentum, but takes a longer time

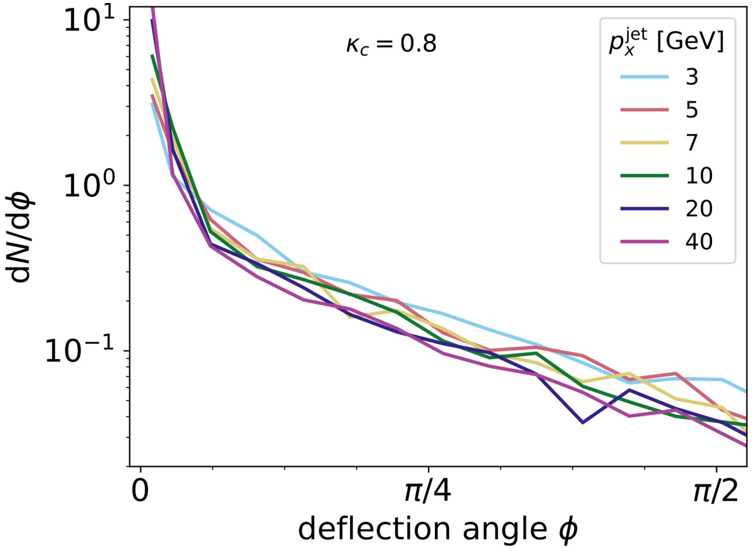


Average momentum of **slow** particles has no sensitivity to the initial condition

no memory + universality ⟶ thermalization?

Results: single jet

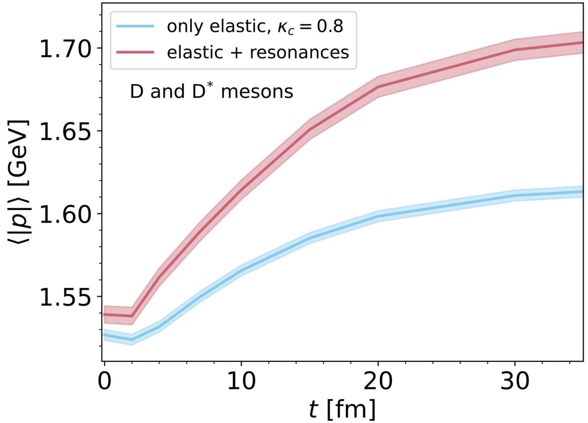




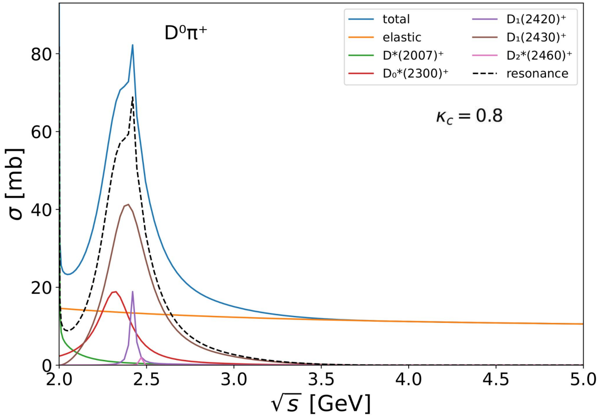
- Even though most momentum is lost, rescattered particles are little deflected
- Small hint of smaller κ_c → larger spread

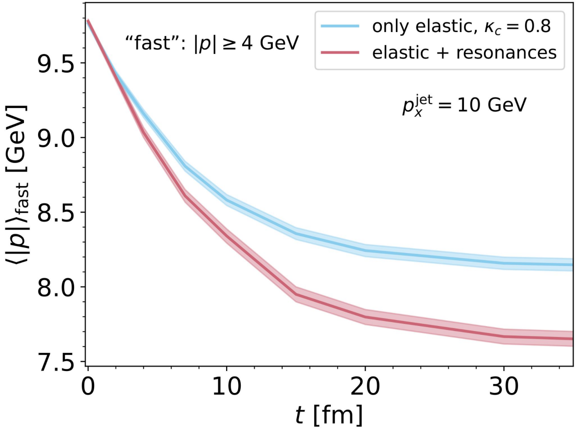
- Slower jets are (slightly) more likely to be deflected to larger angles

Results*: inelastic processes

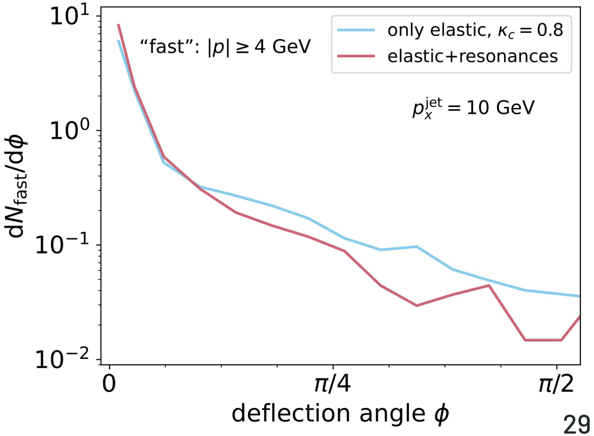


With the inclusion of inelastic processes, the number of interactions increases, and thus the change in average momentum is more pronounced, but so far this is simply because the total cross section is larger.





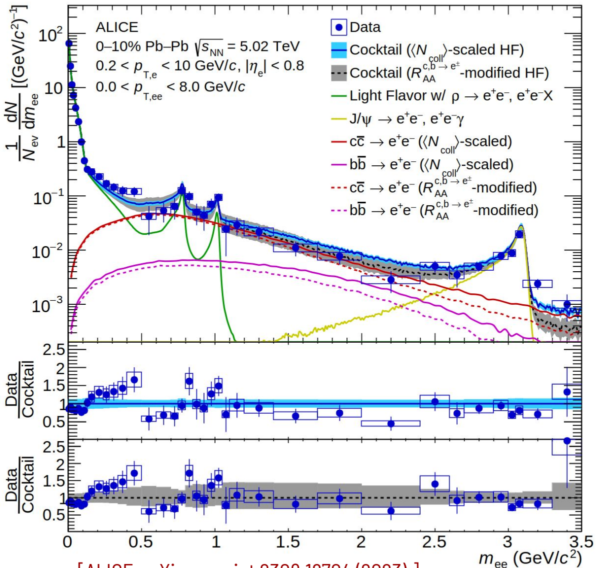
However, the deflection of fast moving particles is *smaller* with inelastic interactions, which may explain why v_2 is enhanced in UrQMD results for STAR and ALICE, but I find it inconclusive.



Model: “dileptons” from heavy “dijets”

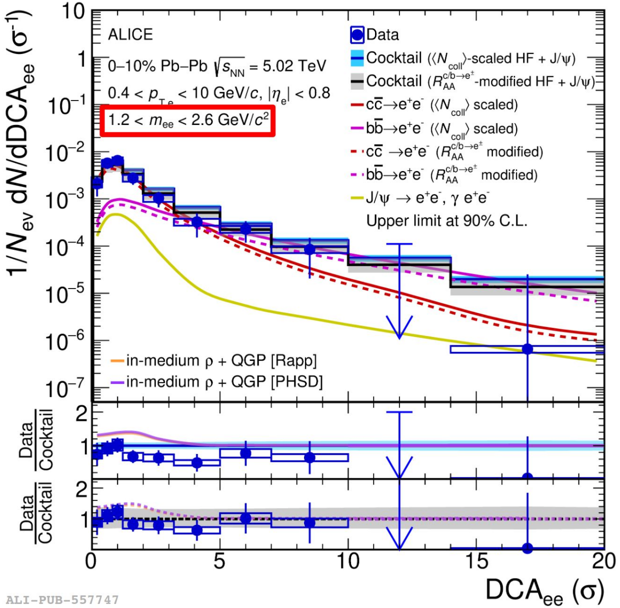
The IMR of dileptons has a large background contribution from (semi-)leptonic decays of correlated heavy flavor.

IMR: intermediate mass range



[ALICE, arXiv preprint 2308.16704 (2023).]

DCA: distance of closest approach



What is the effect of hadronic rescattering on the $c\bar{c}$ pair?

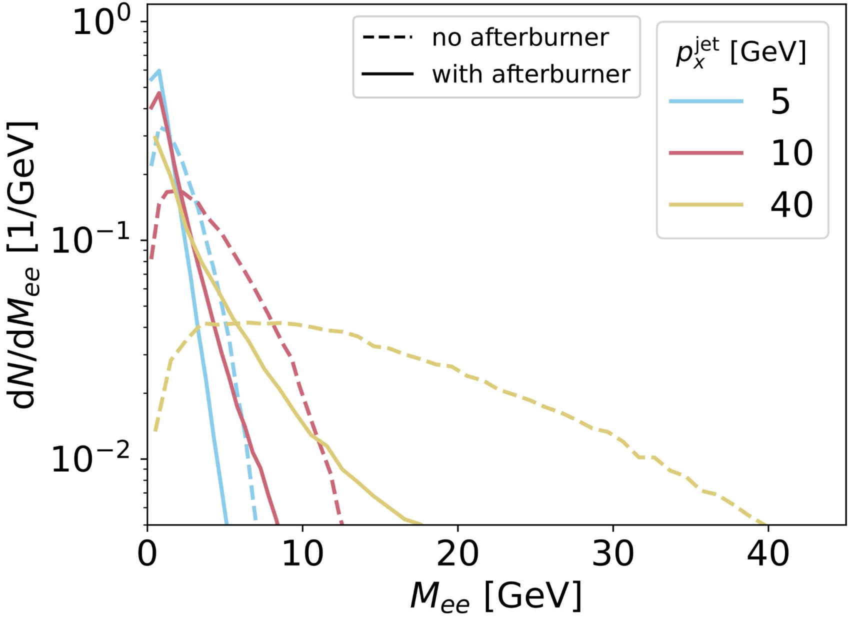
- Back to back D^+ and D^-
- Isotropic decay, no form factor*
- Two most important channels:

Leptonic and semileptonic modes

$D^+ \to \bar{K}^0 e^+ \nu_e$	8.72%
$D^+ \to \bar{K}^*(892)^0 e^+ \nu_e$	5.40%

*results are qualitatively equal with unpolarized FFs

Result: “dileptons” from heavy “dijets”



Without rescattering: indirect dilepton from independent Dalitz decays of D^+ and D^-

↳ large spread in invariant masses

With rescattering: D mesons deposit energy into hadronic medium

↳ available phase space shrinks

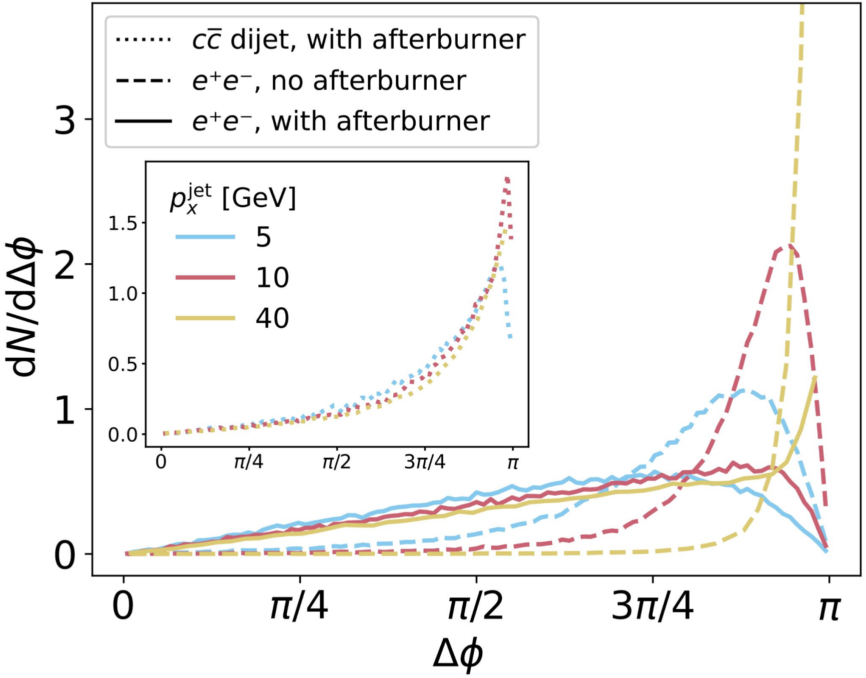
↳ enhancement of lower invariant masses

Result: “dileptons” from heavy “dijets”

Distribution of pair opening angle

- Vacuum (p+p): angle of *detected* lepton pair is very distinct for jets with different momenta
  - ⮡ Lorentz contraction.
- In afterburner: decorrelation of D^+ and D^-
  - ⮡ small dependence on initial momentum.
  - ⮡ only jets that do not scatter much are sensitive.
  - ⮡ resulting “dilepton” is hard to trace back.

L-polarization might enhance the c↔e correlation



Summary

- p_T spectra of heavy hadrons is softened
- Inelastic channels suppress J/ψ but do not affect D mesons
- R_{AA} decreases at high p_T, feeding low p_T region, but in a very small effect
- v_2 increases for all p_T range but still small, may be lacking flow in partonic evolution
- Different theoretical models are used, but limited statistics from experimental data prevents constraints

- I implemented a HF toy model in SMASH, trying to capture basic behaviors that appear in more complex frameworks.
- Thermalized D mesons are pushed forward by pions, much like other light hadrons
- Fast D mesons are slowed down, and fall on a single curve irrespective of initial momentum, which may point to some thermalization effect
- Rescattering decorrelates a back to back $D\bar{D}$ pair, and shifts the invariant mass spectra and opening angle of resulting dileptons
- **Outlook:** add complexity step-by-step