Investigating Heavy Ion Phenomenology with Monte Carlo Event Generators

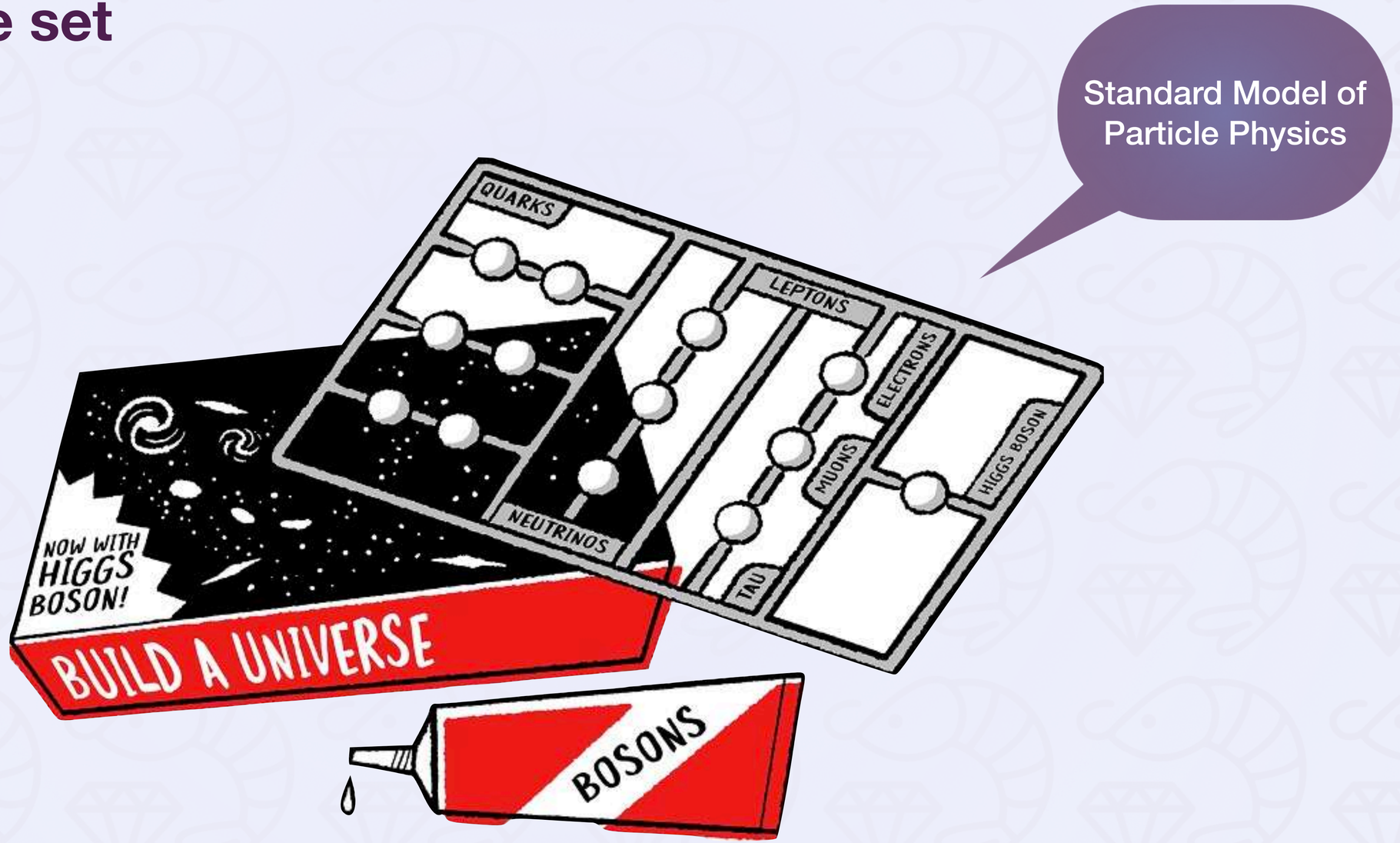
Chiara Le Roux
Supervisor: Korinna Zapp

December 13th 2023 - PhD Day
Division of Particle and Nuclear Physics

The Standard Model of Particle Physics

Particle Physics in a nutshell

Or in a game set



https://www.iop.org/explore-physics/big-ideas-physics/standard-model#gref

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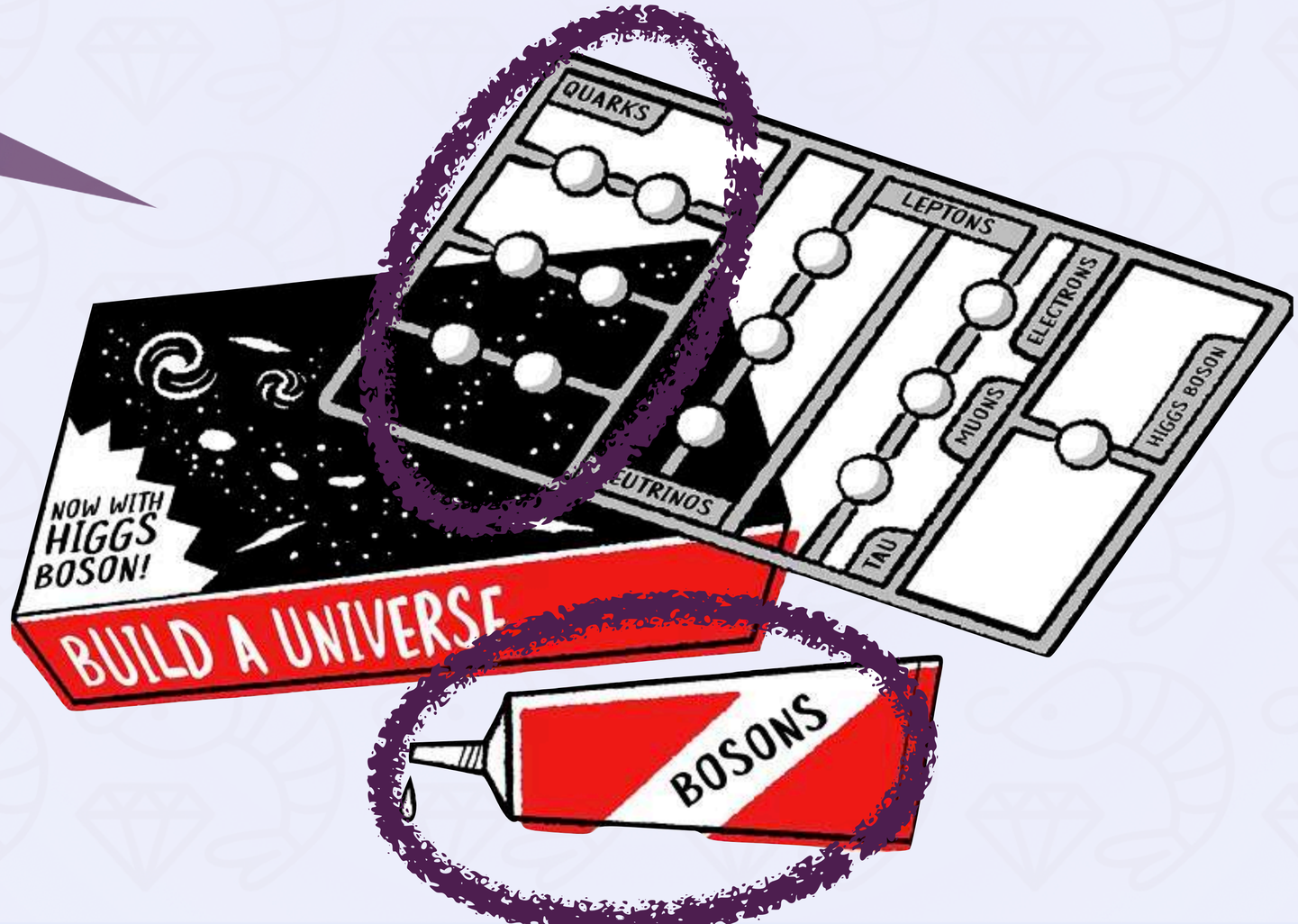
Let’s pick just the quarks and the gluons



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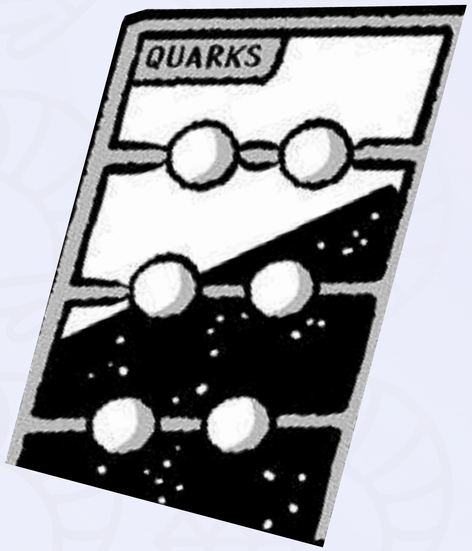

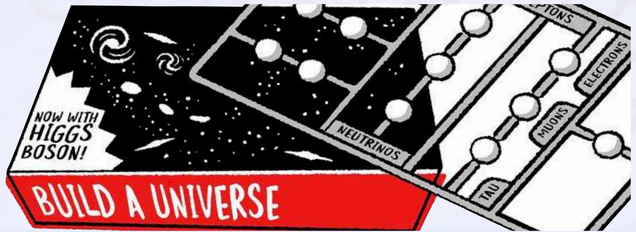

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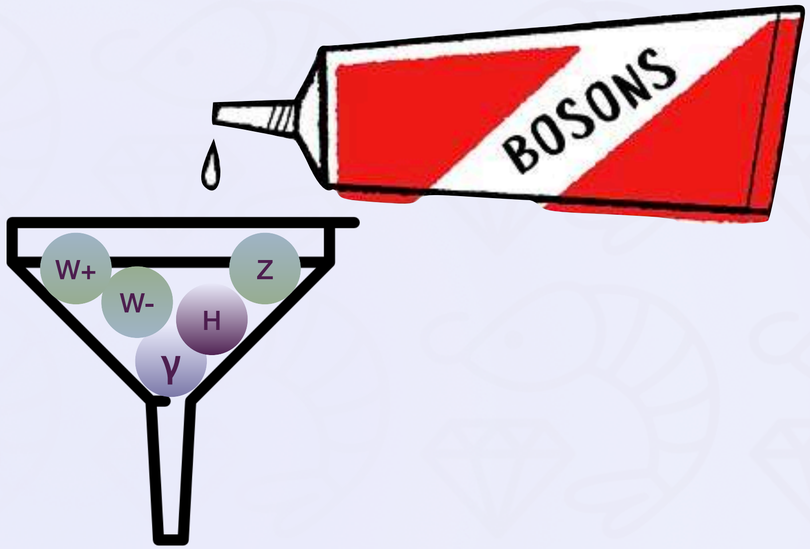

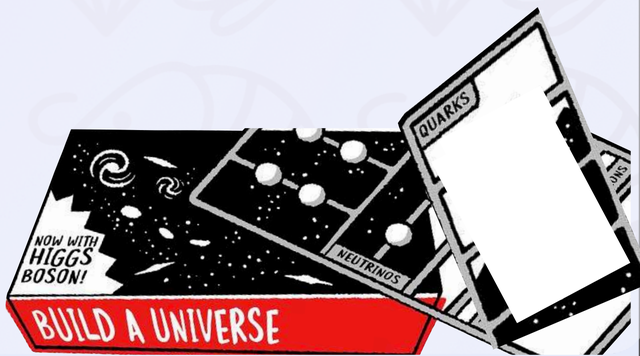

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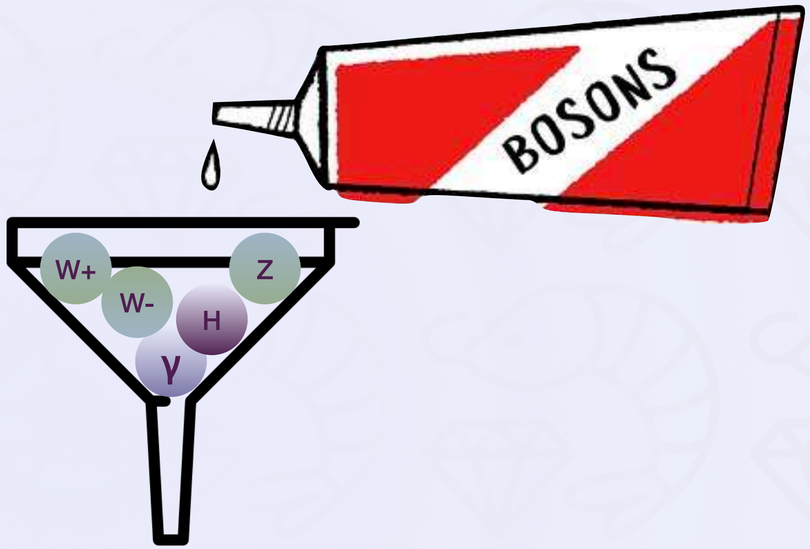
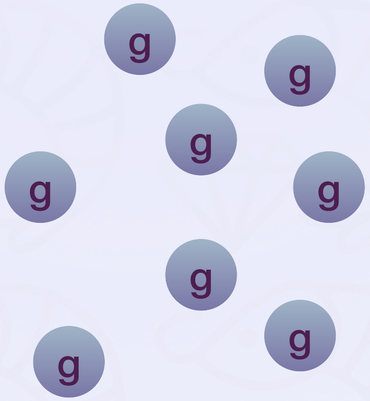
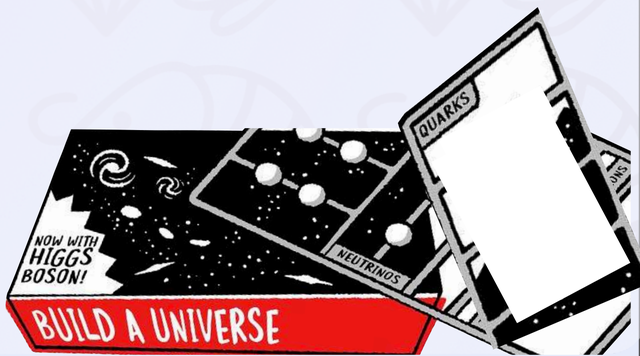
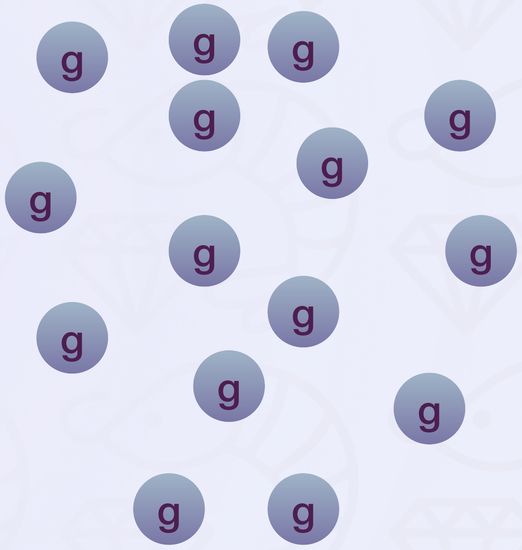




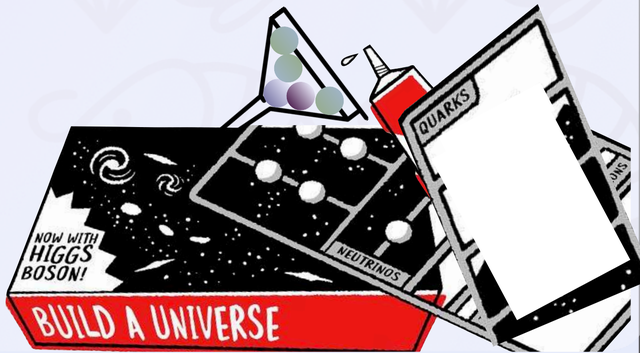


Strong Interaction

The fun part of the Standard Model



(I might refer to these as partons!)



Strong Interaction

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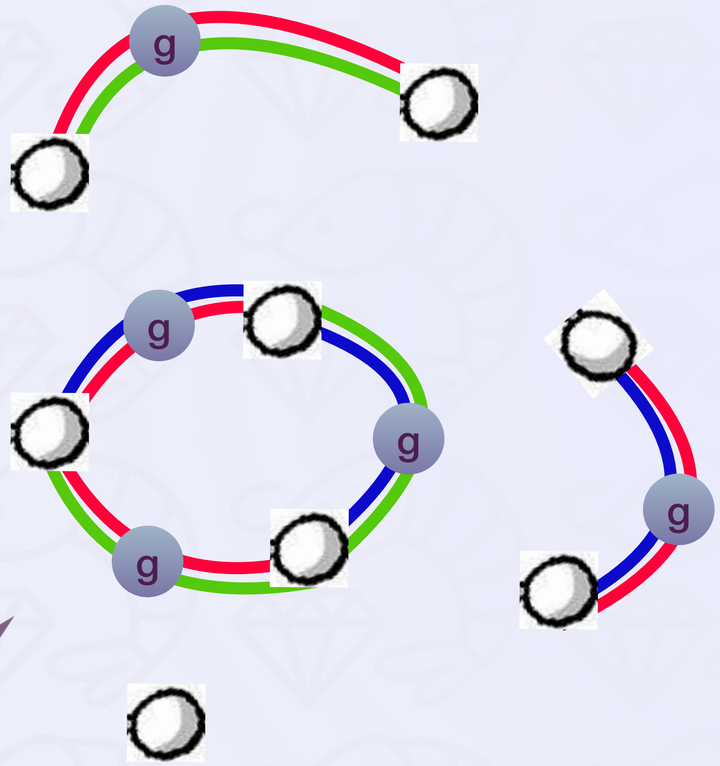
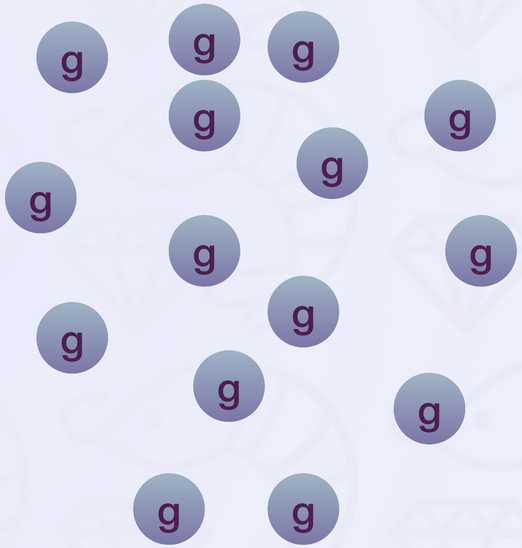
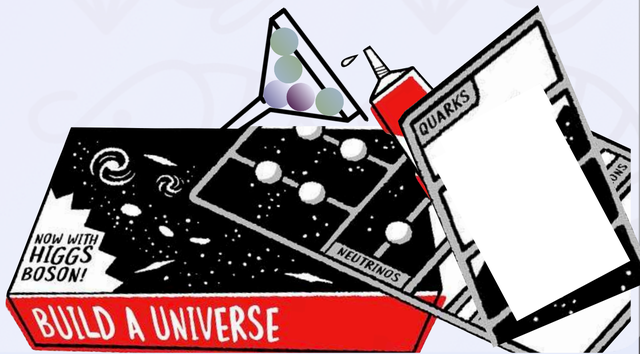
Quarks interact via exchange of gluons





And form 3 quark (baryons) or 2 quarks (mesons) structures



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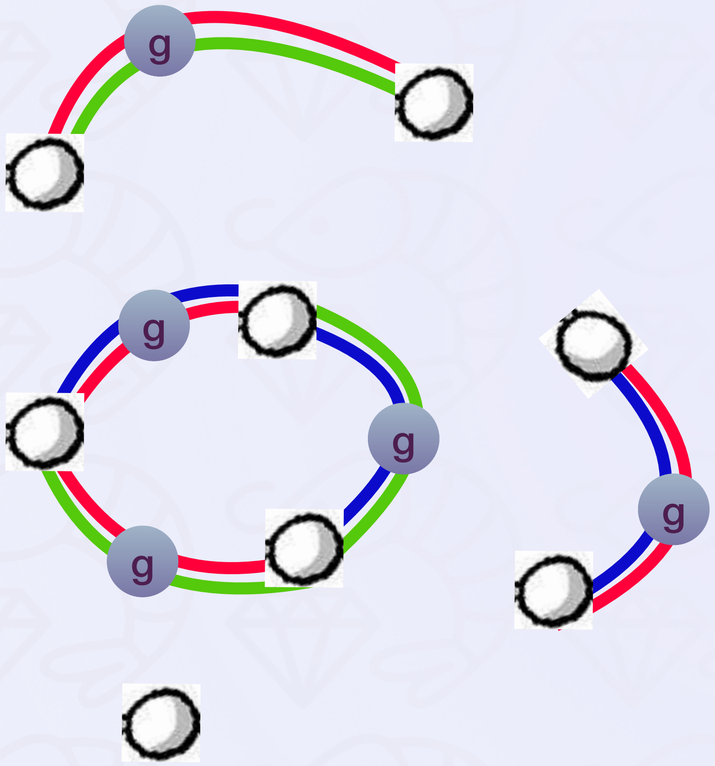
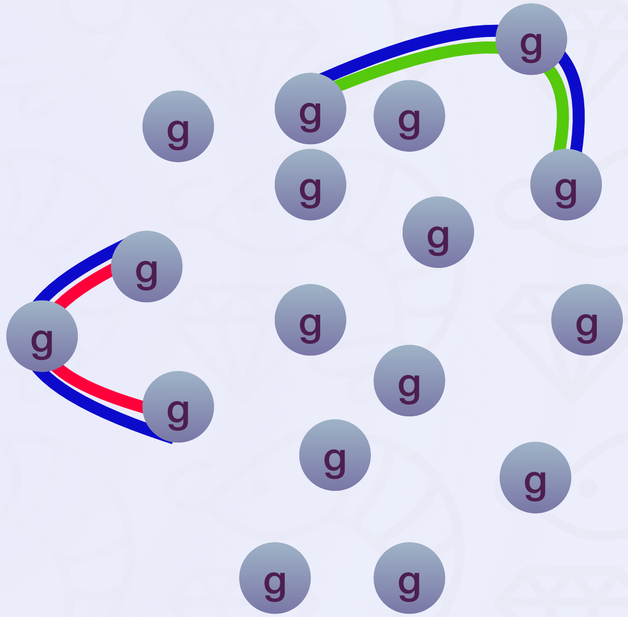
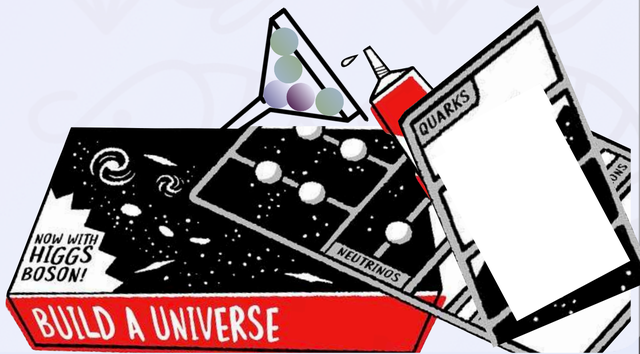
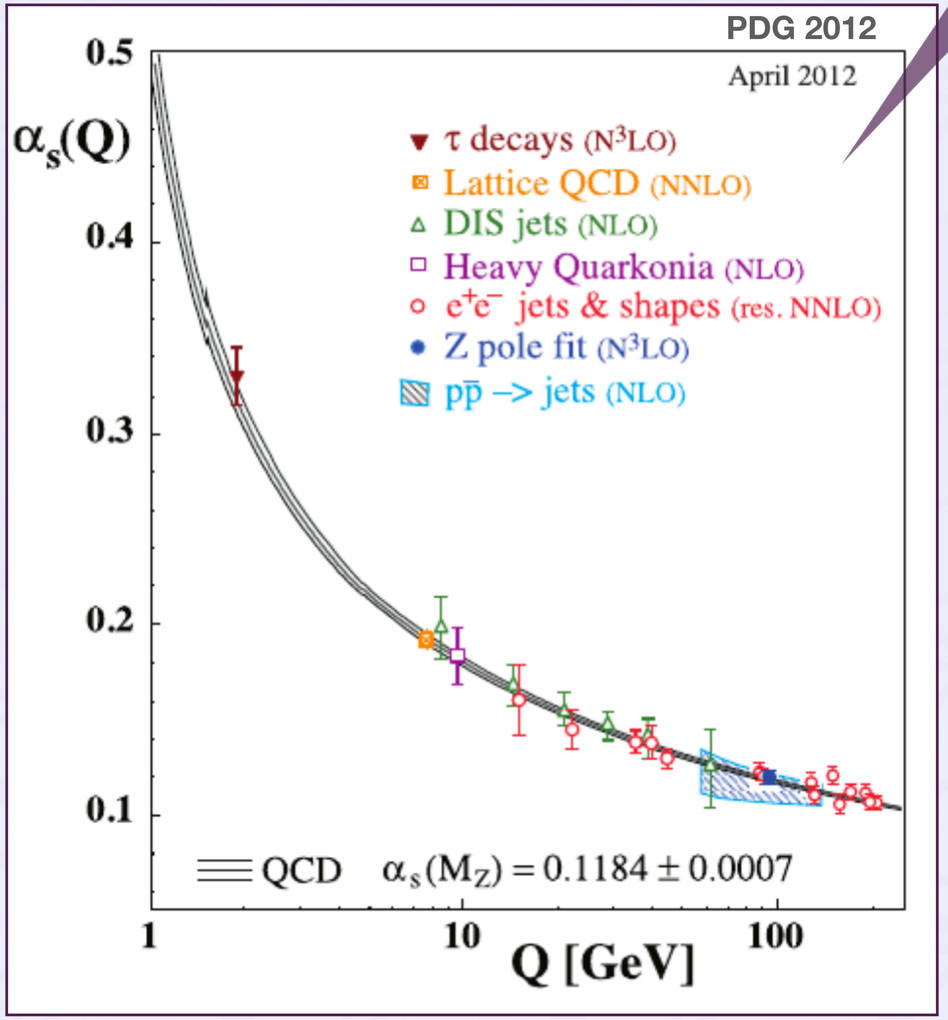






Strong Interaction

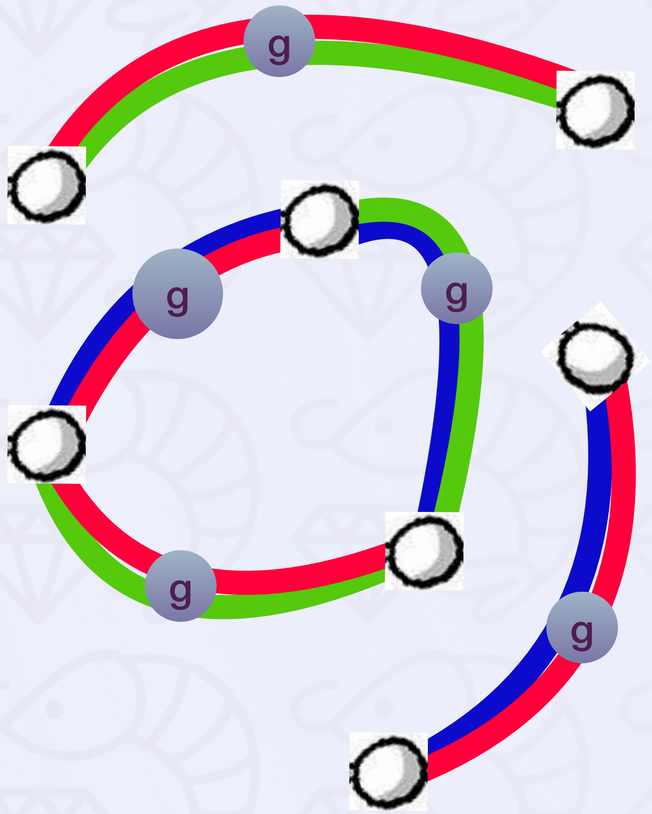
How strong is the strong interaction?!

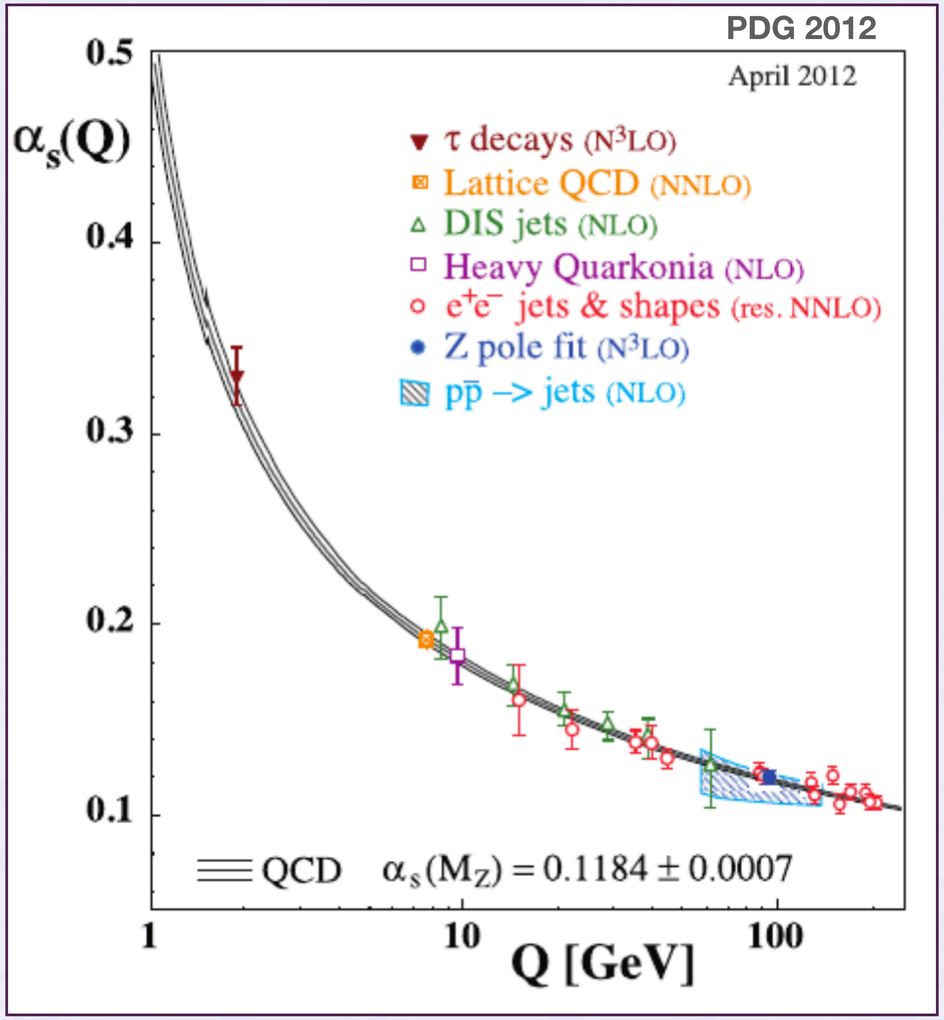


Decreases with the scale (distance)

Strong Interaction

How strong is the strong interaction?!





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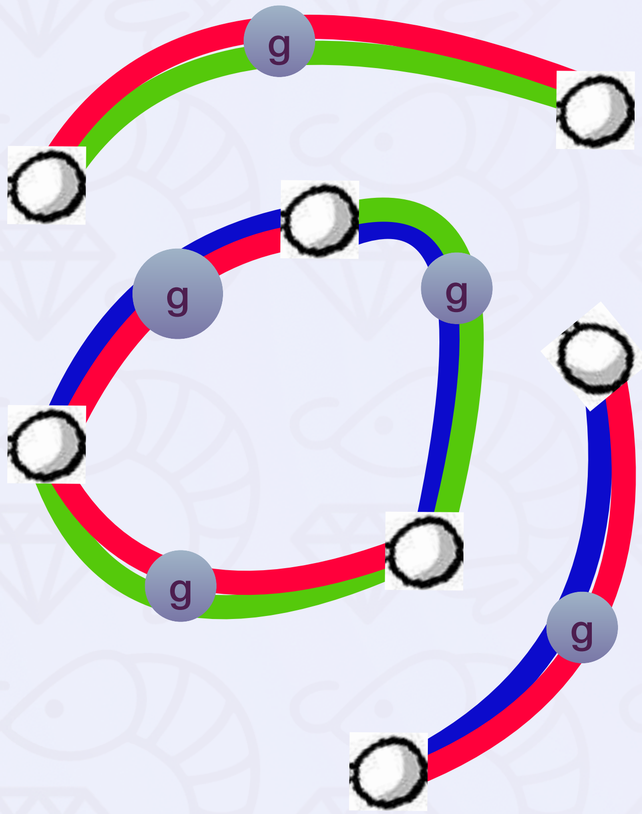

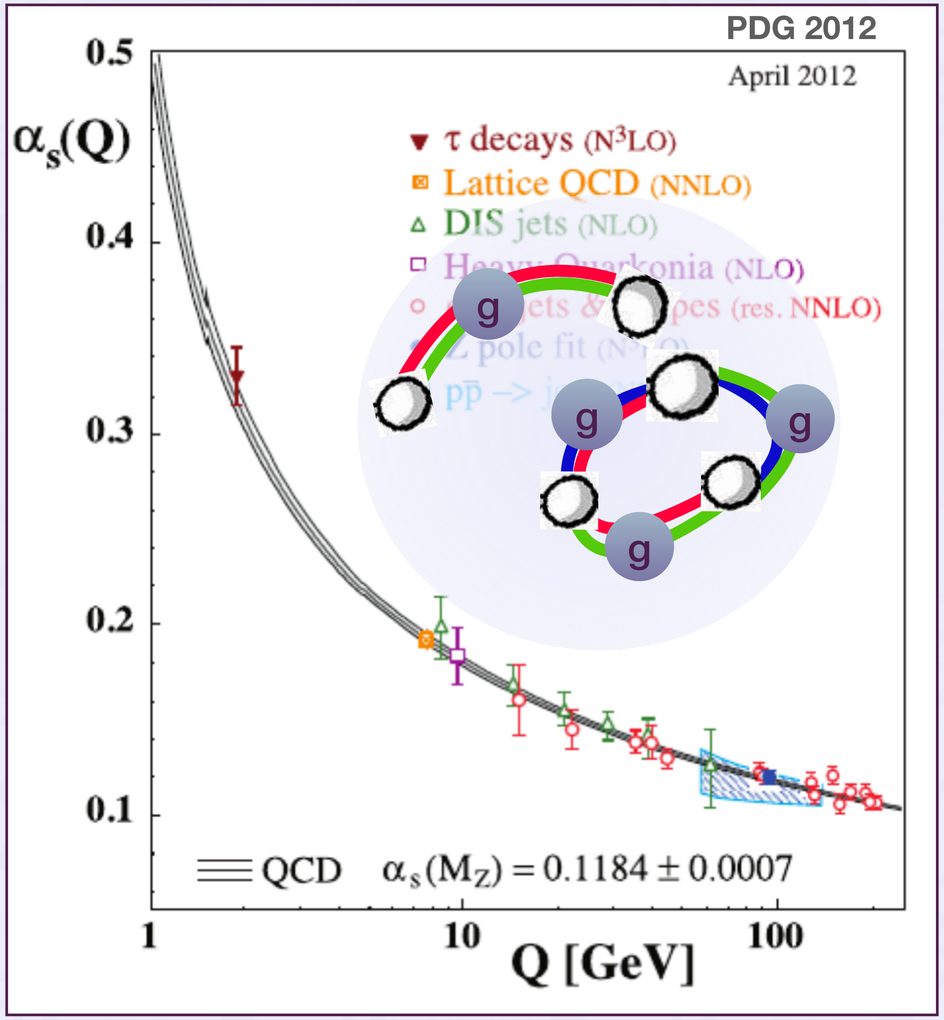

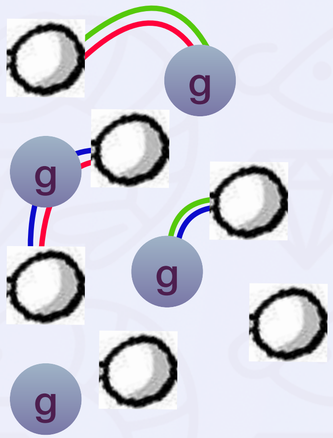

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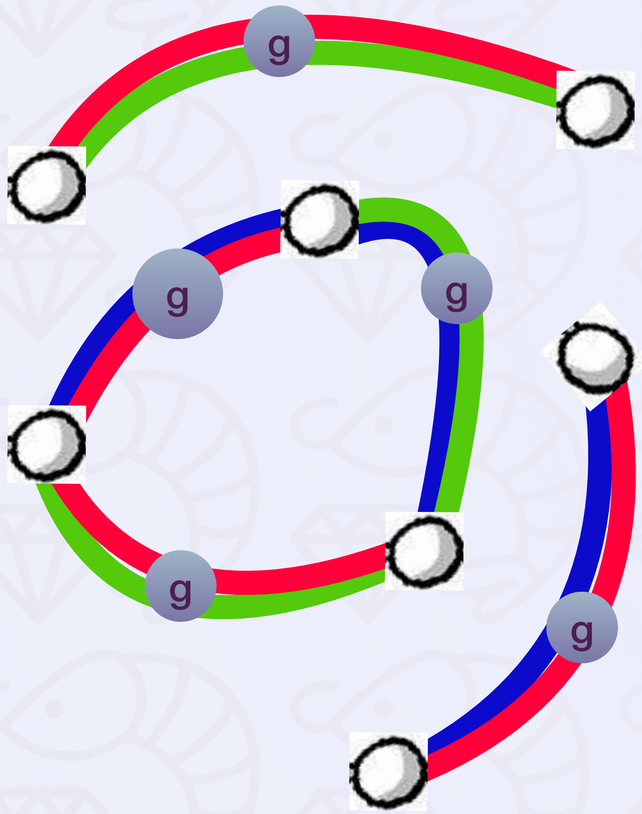
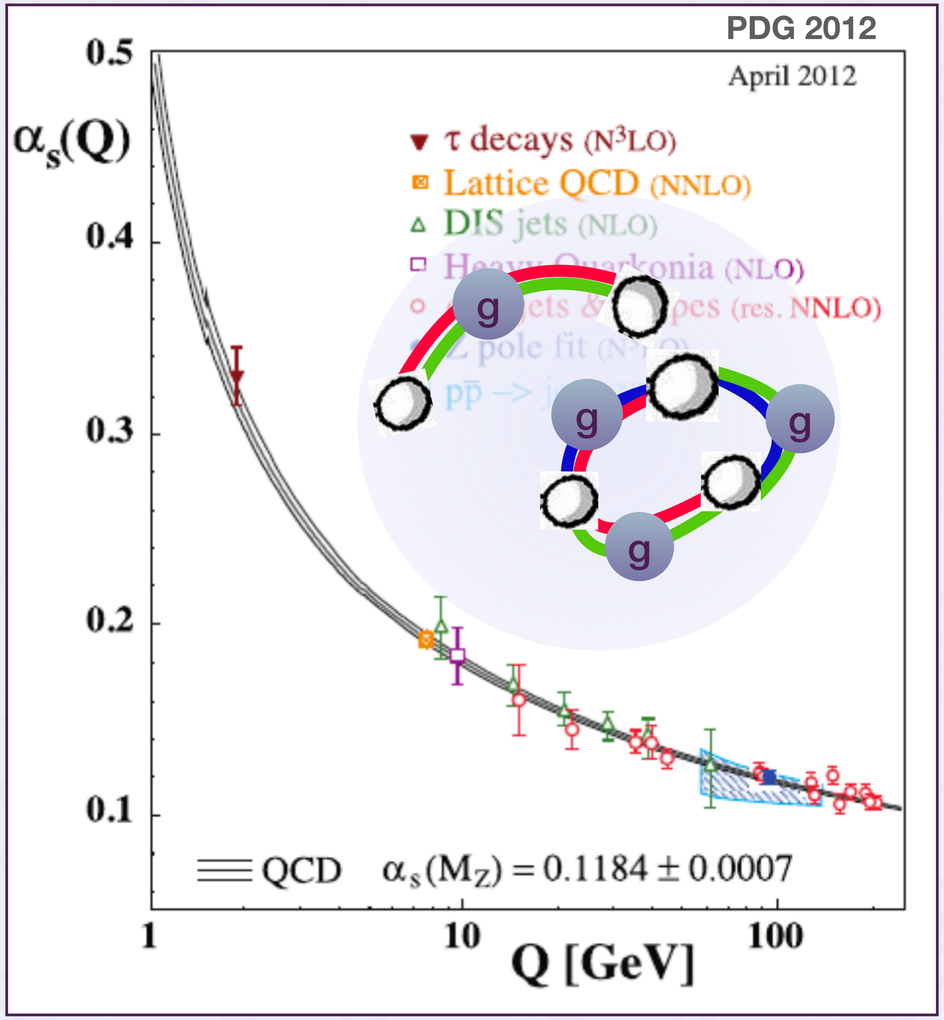
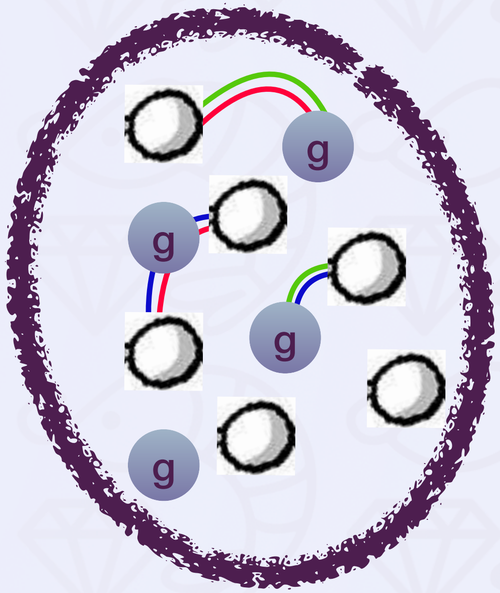




How can we probe this regime?!



Relativistic Heavy Ion Collisions

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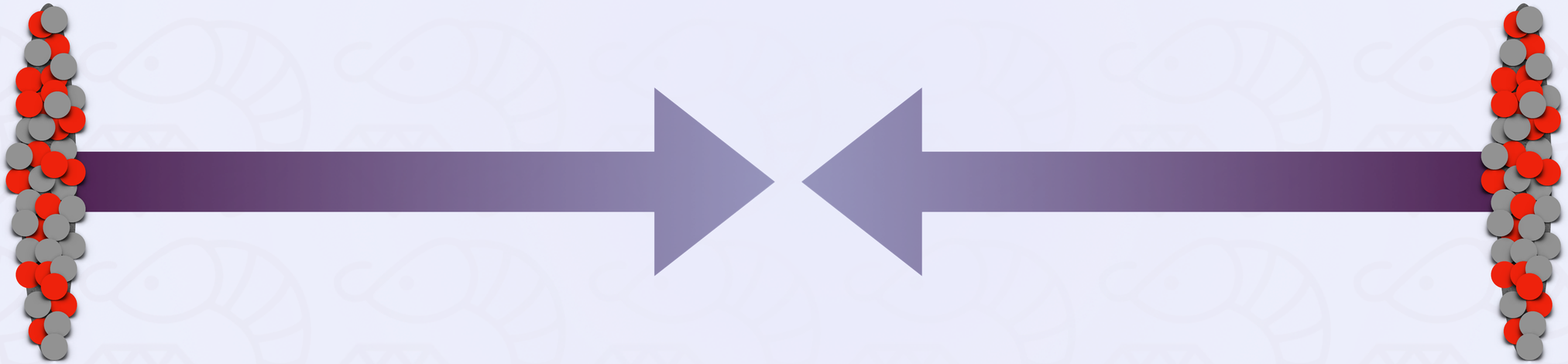
If you want to make QGP you need to break some heavy ions



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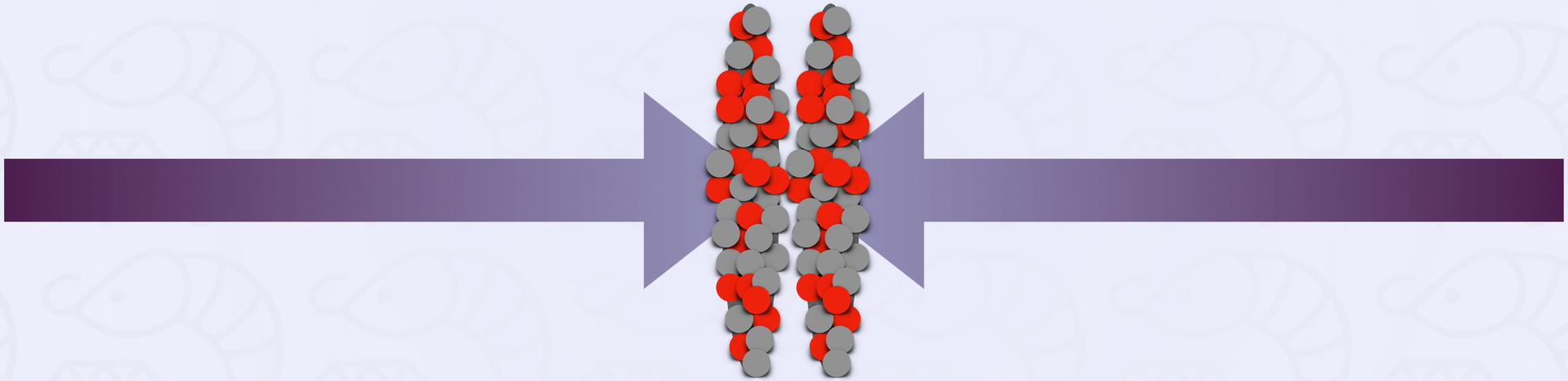

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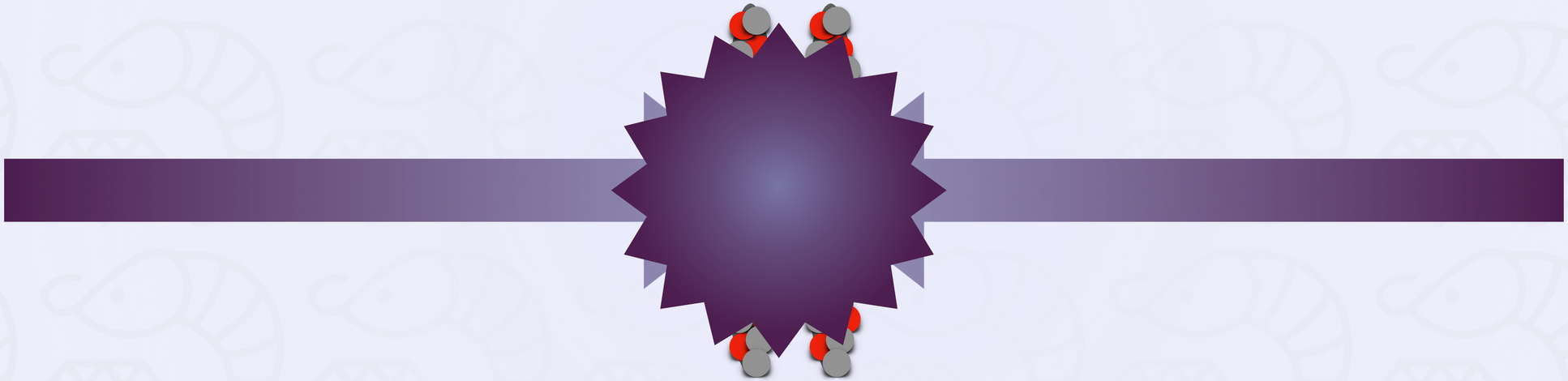

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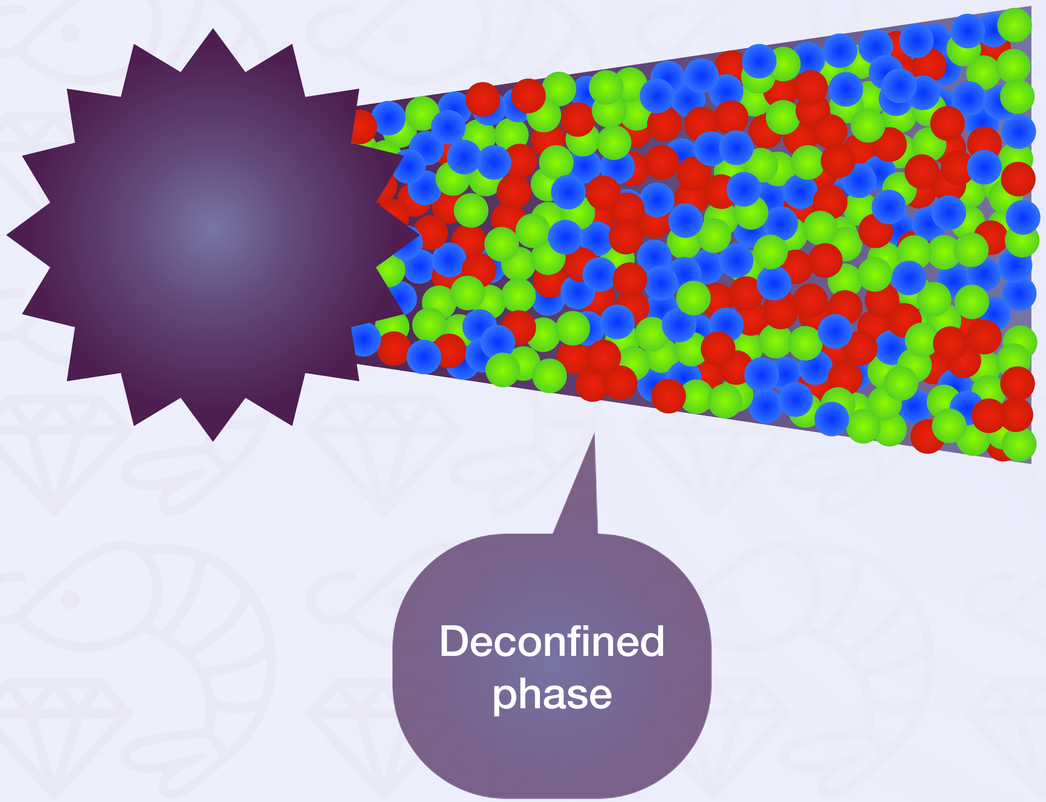

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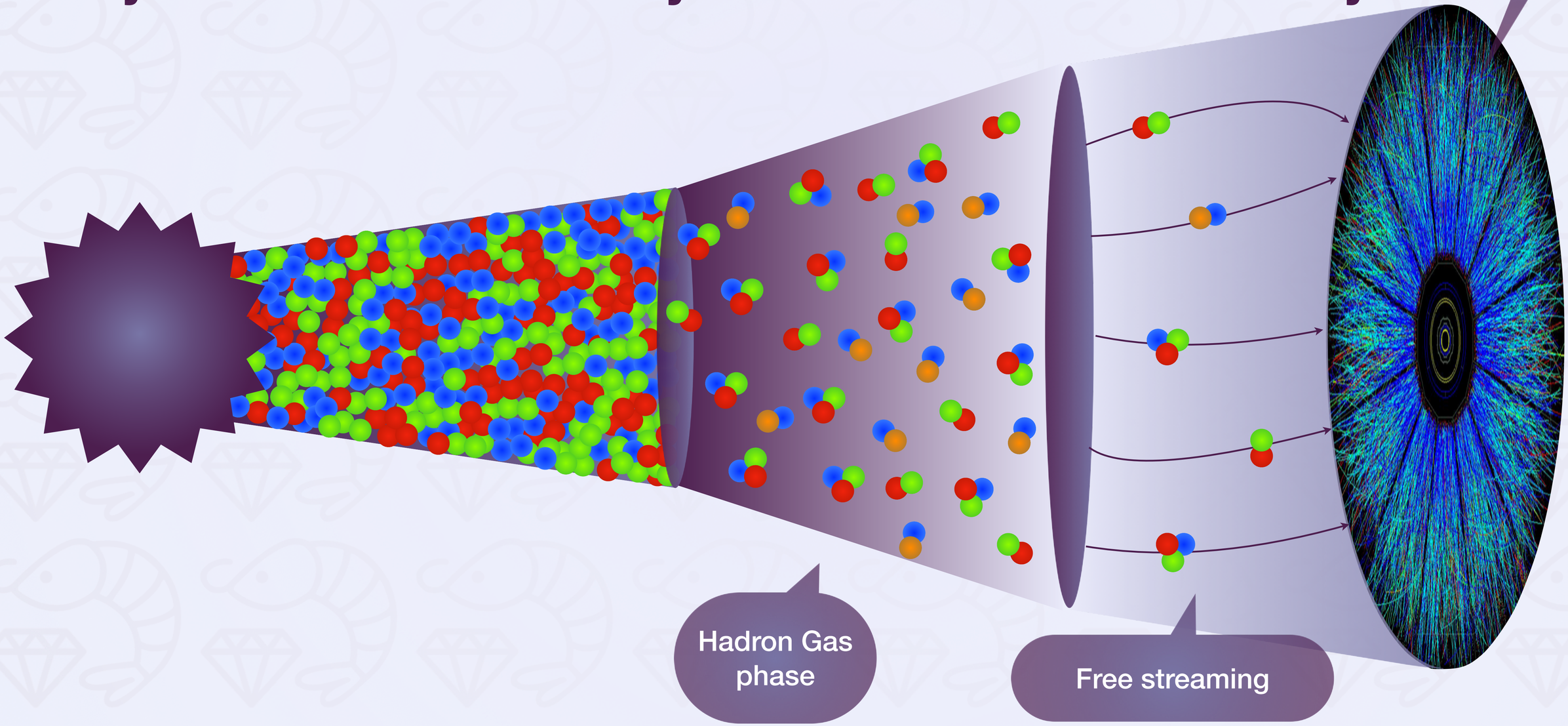

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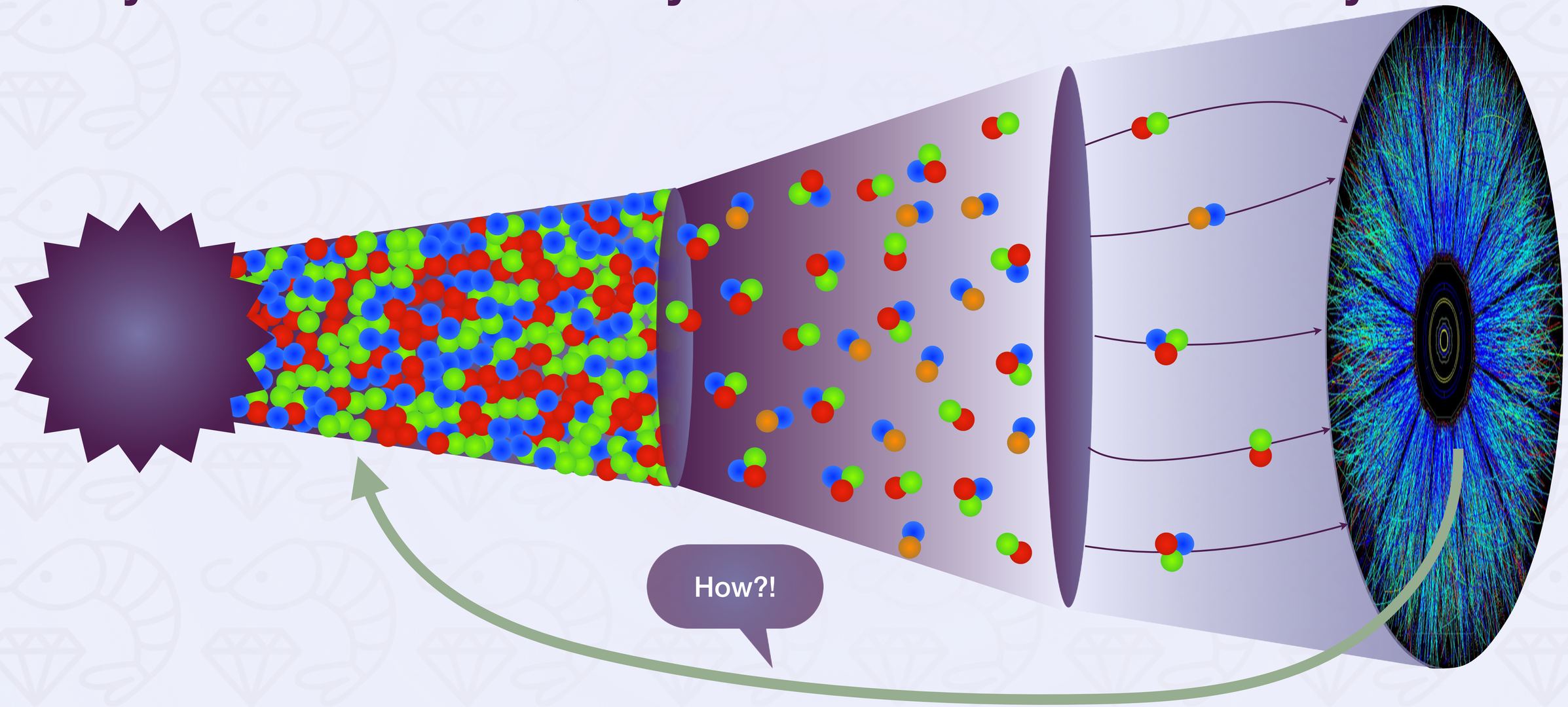

Signatures of a Quark Gluon Plasma

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Collective Flow

Jet Quenching

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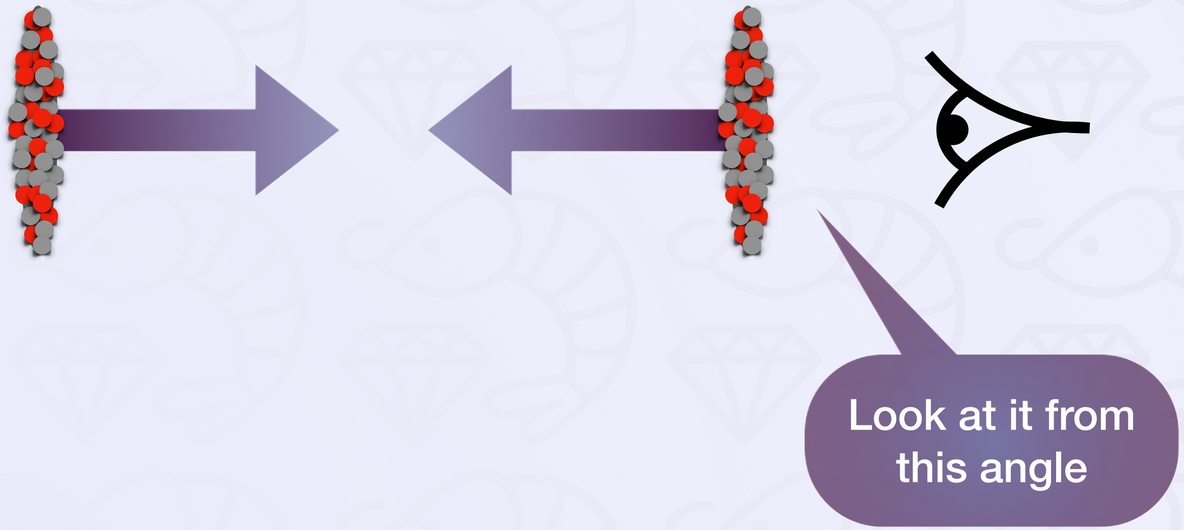
QGP signatures

Collective flow



QGP signatures

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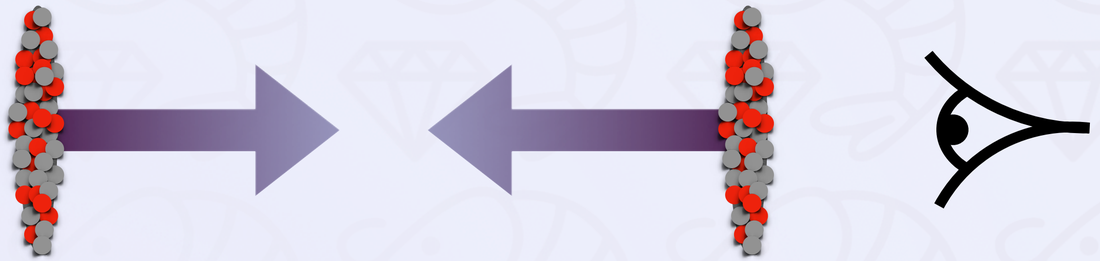
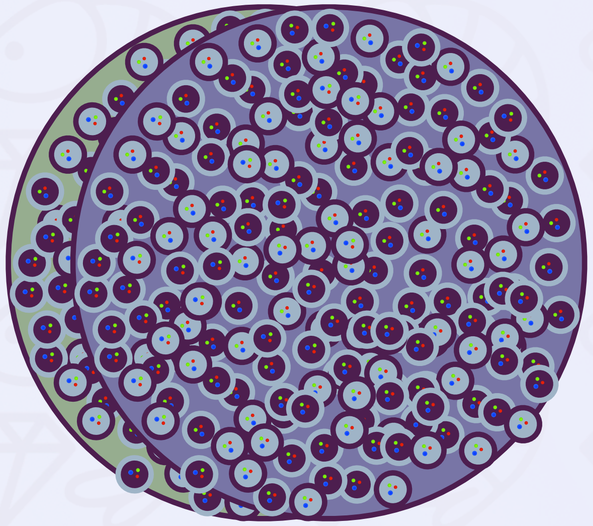
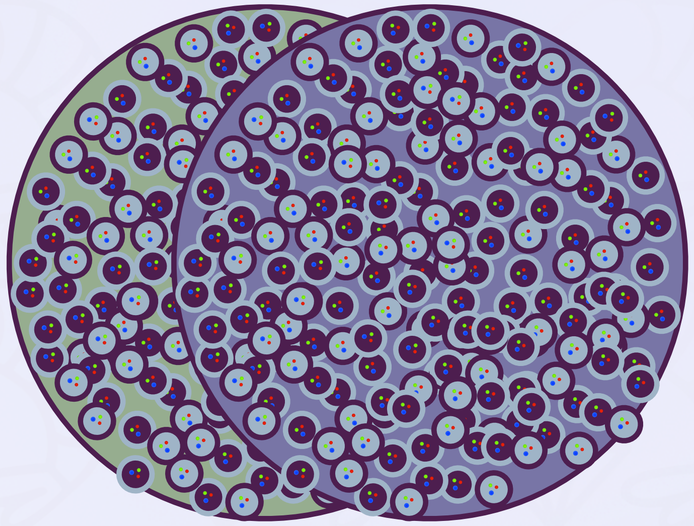
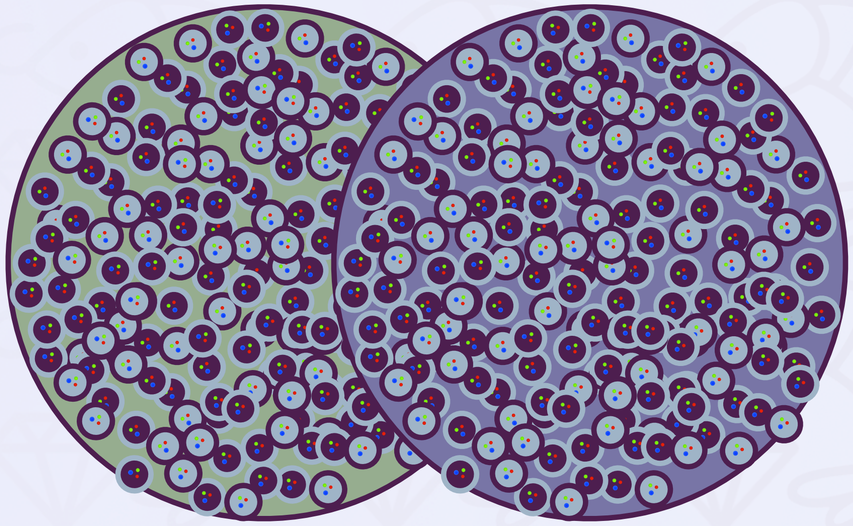


Ions overlap with some impact parameter

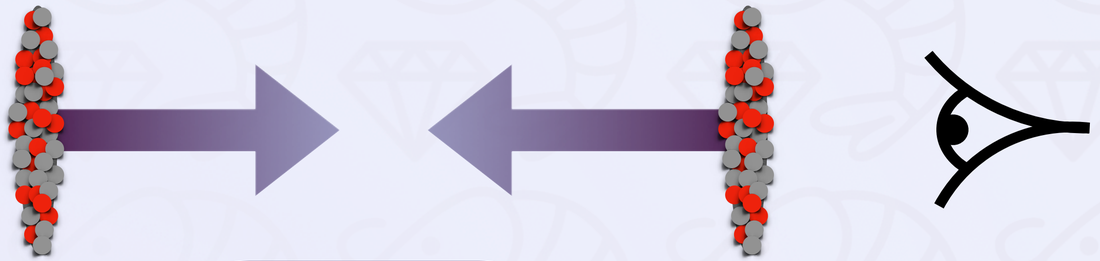






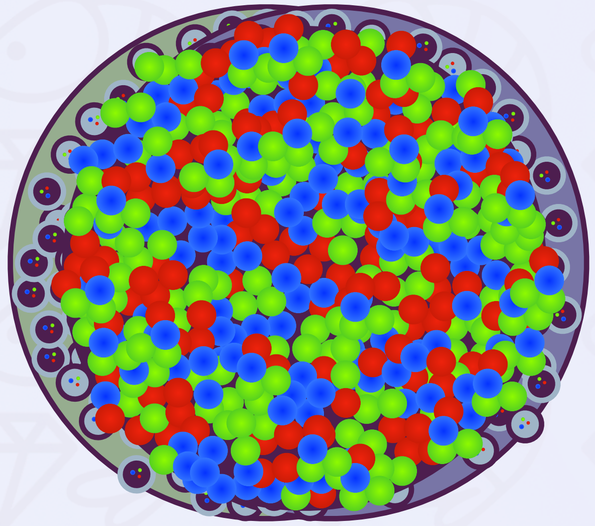
QGP signatures

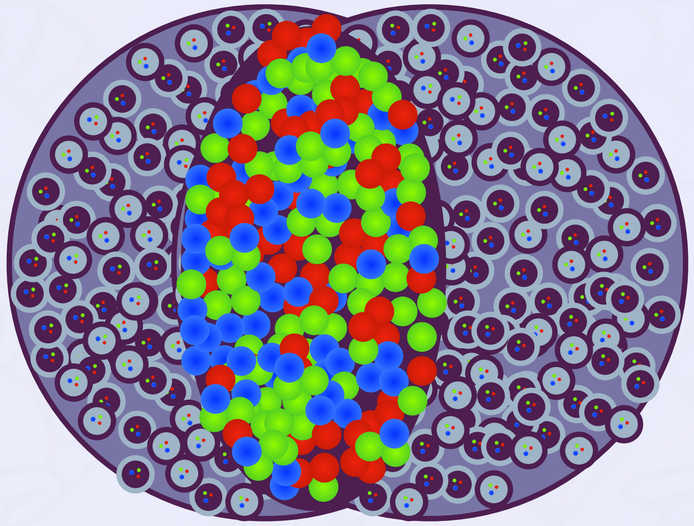
Collective flow

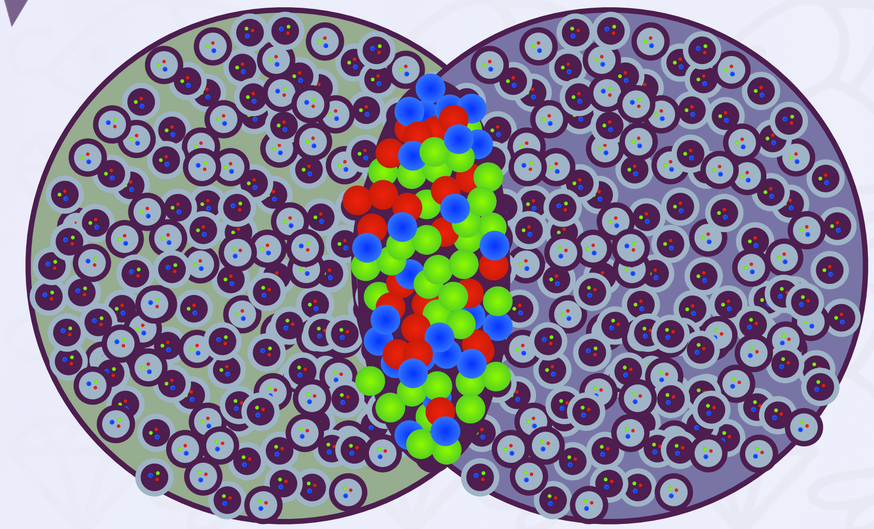


Ions overlap with some impact parameter

Medium shape reflects that

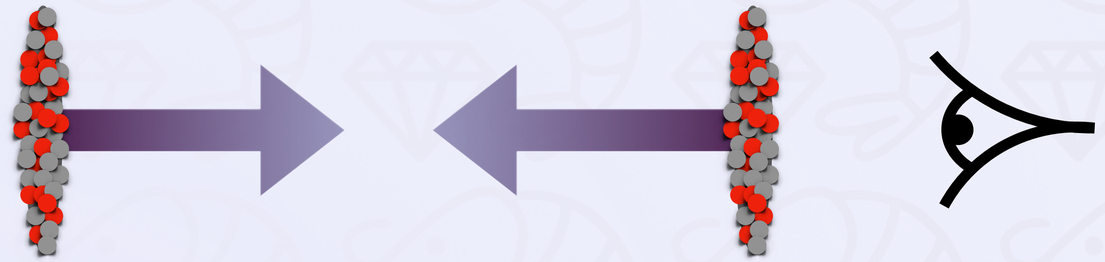


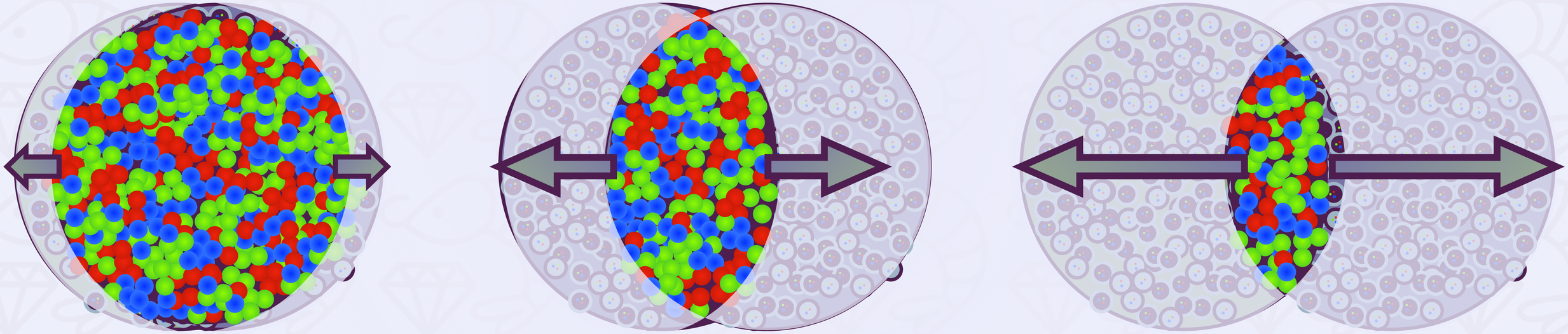




QGP signatures

Collective flow

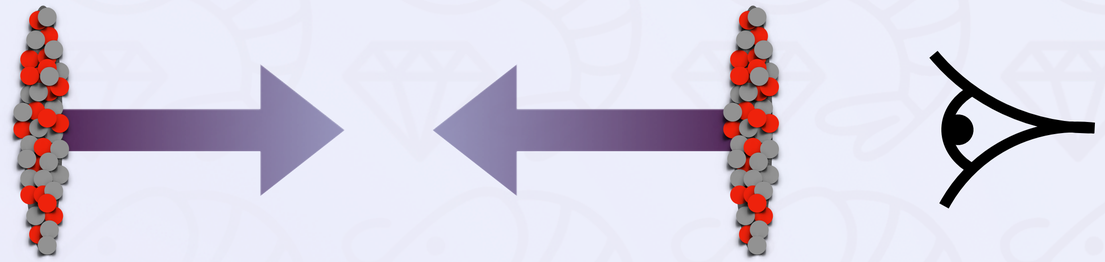


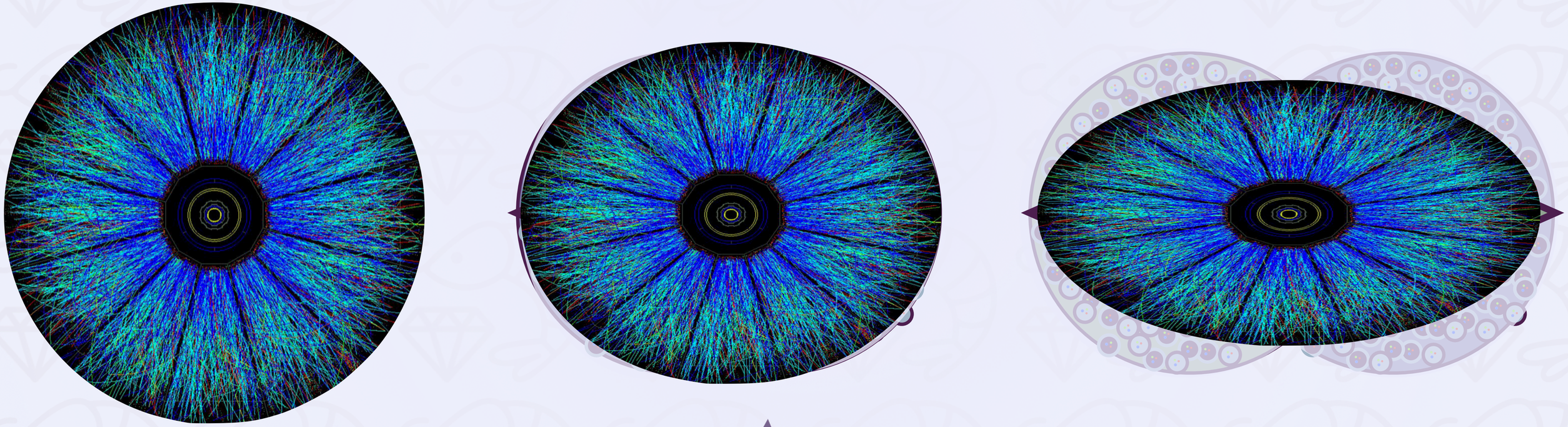


Different pressure gradients

QGP signatures

Collective flow



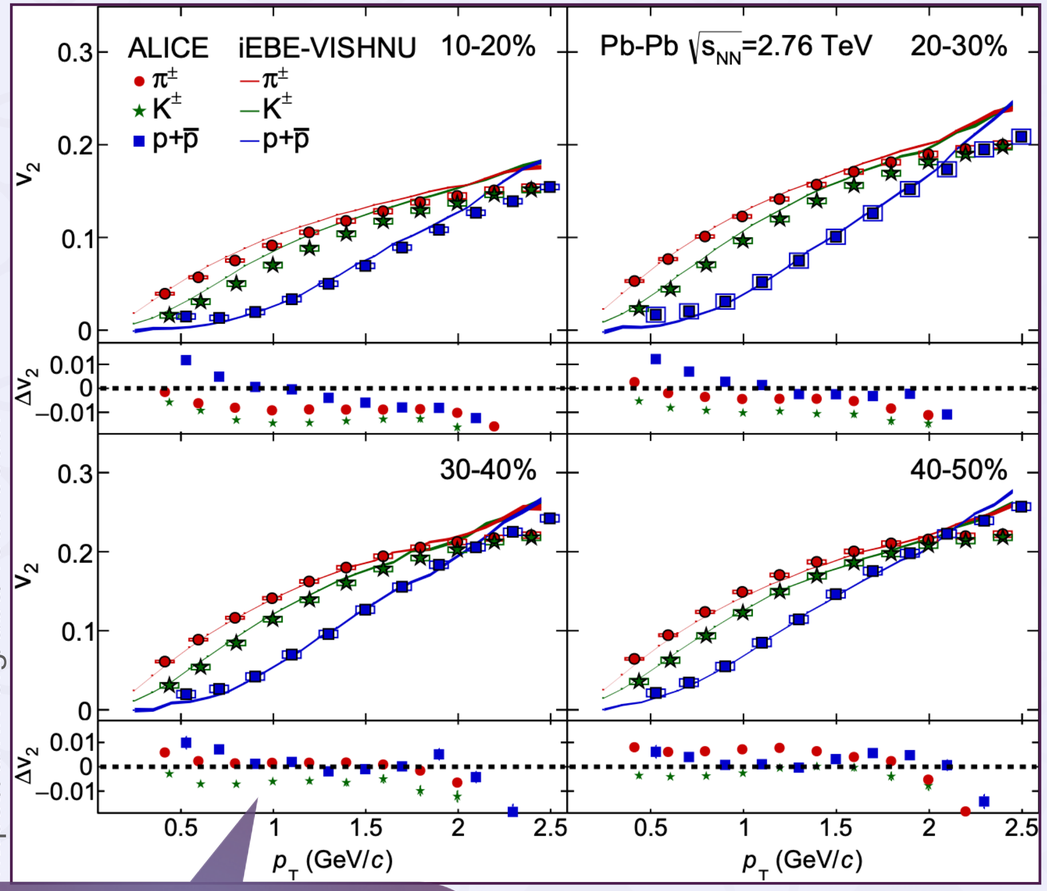


Reflected on the final state particle distribution

QGP signatures

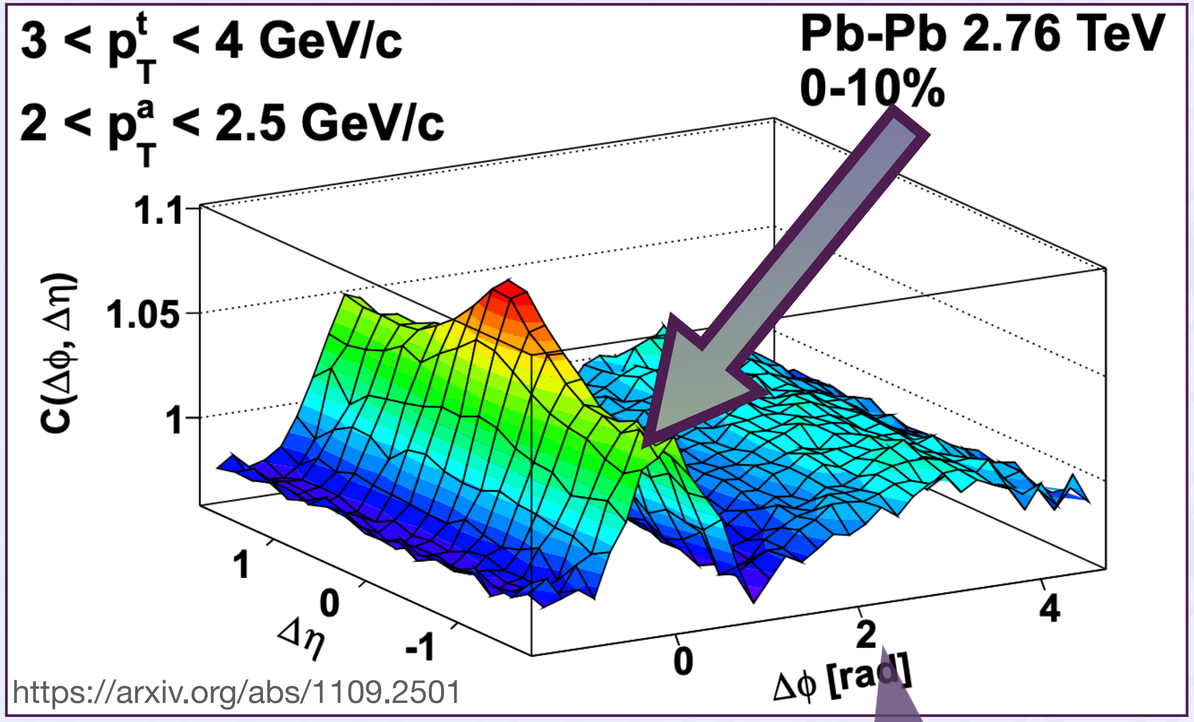
End of story!

QGP in large systems! (PbPb)



https://arxiv.org/abs/1606.06057

Jaha! Non zero flow coefficients in PbPb

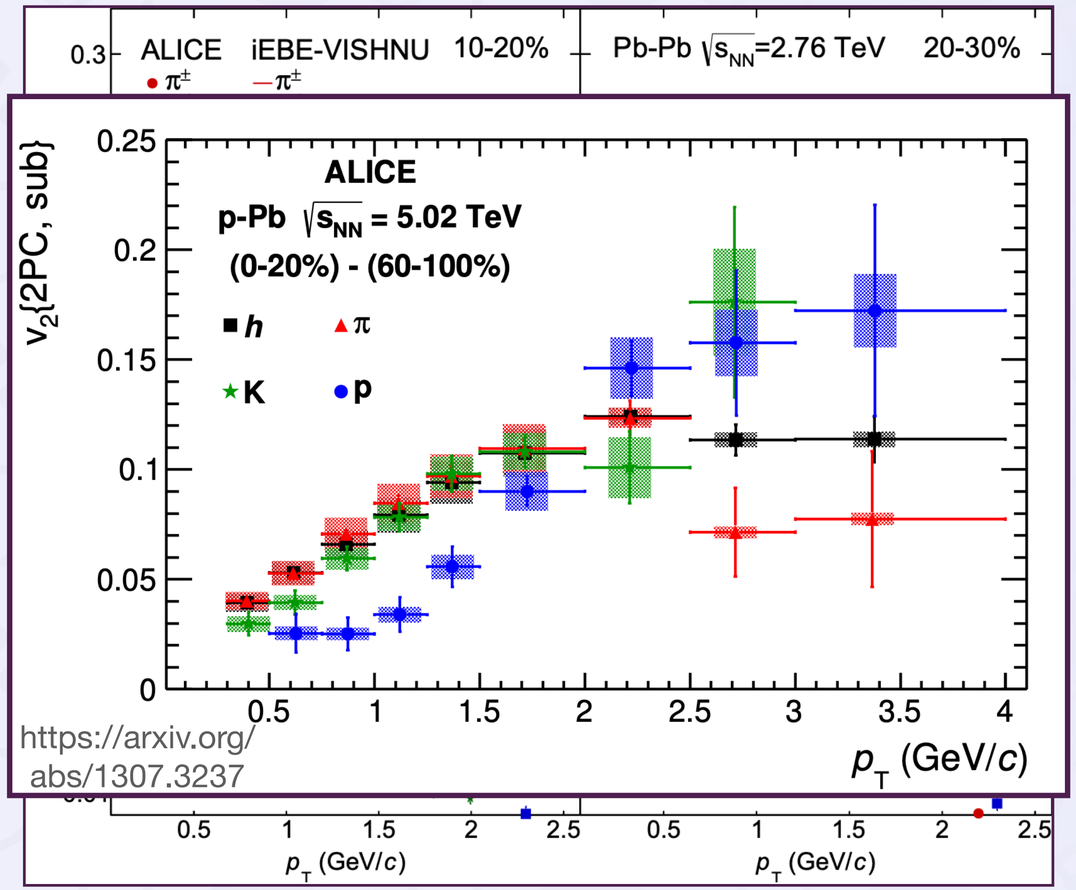


https://arxiv.org/abs/1109.2501

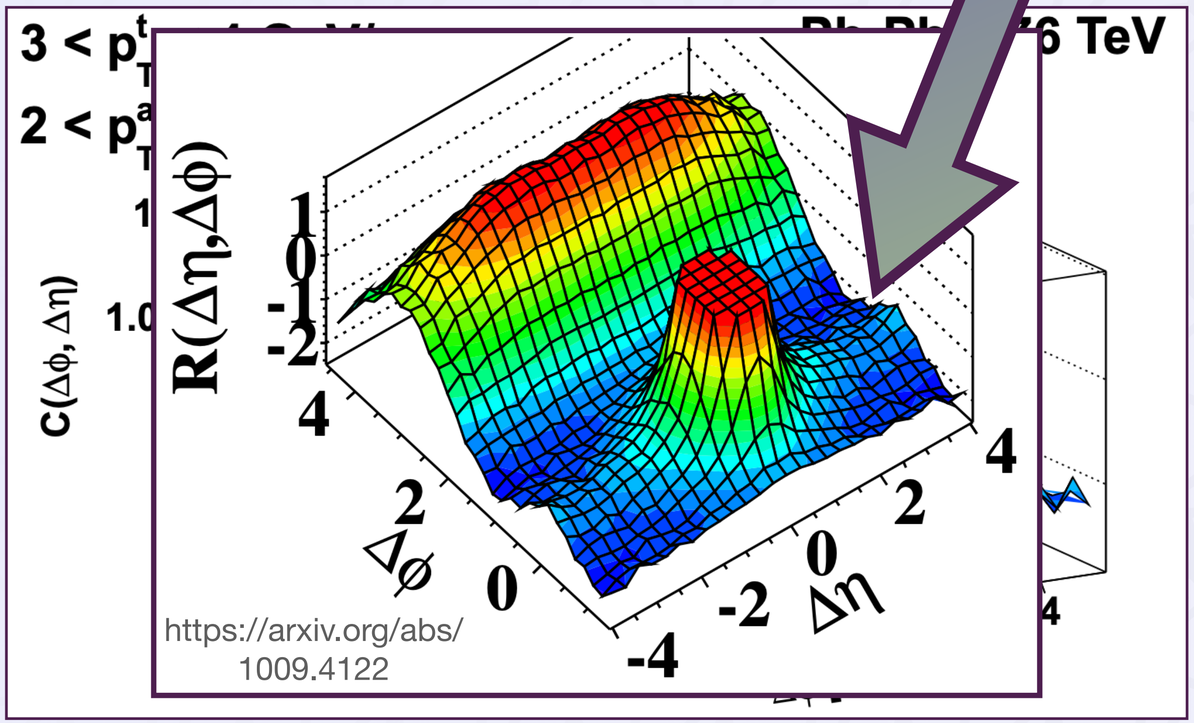
And also signs of long range correlations

QGP signatures

Ops…



But also in small systems! (pPb and pp)



QGP signatures

Ops…

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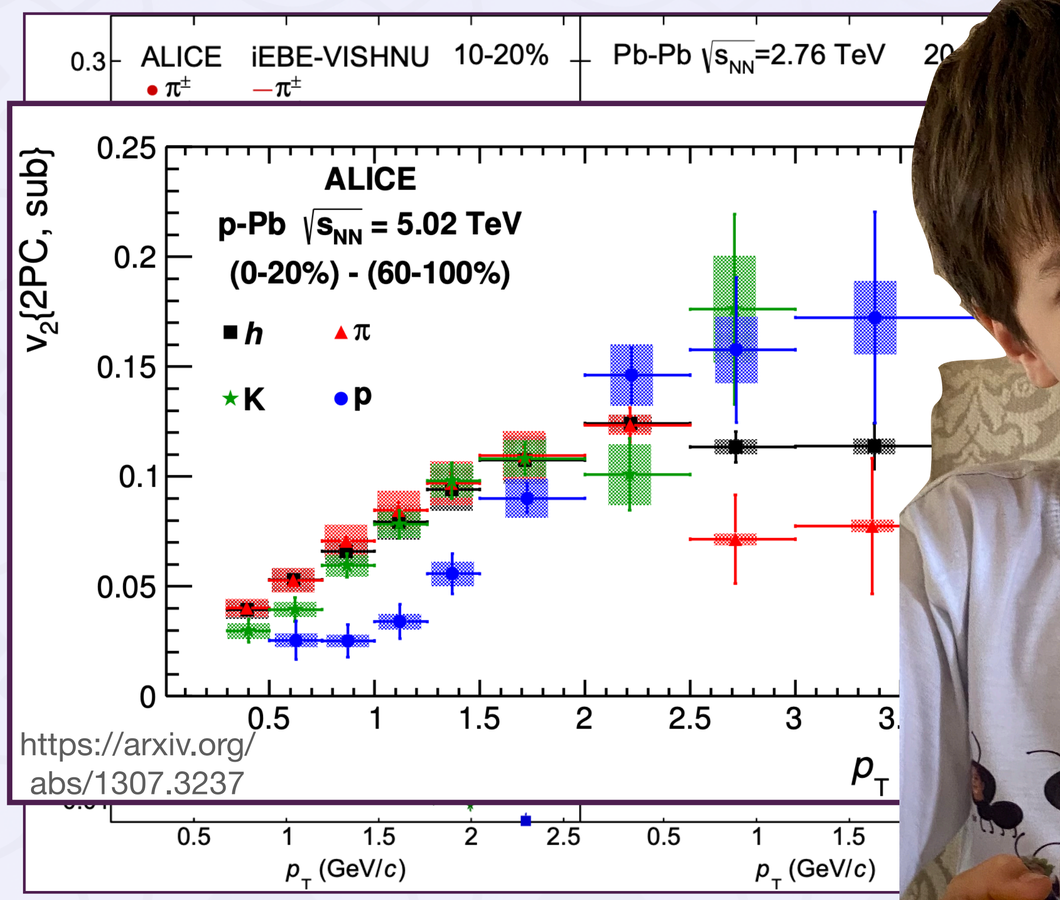
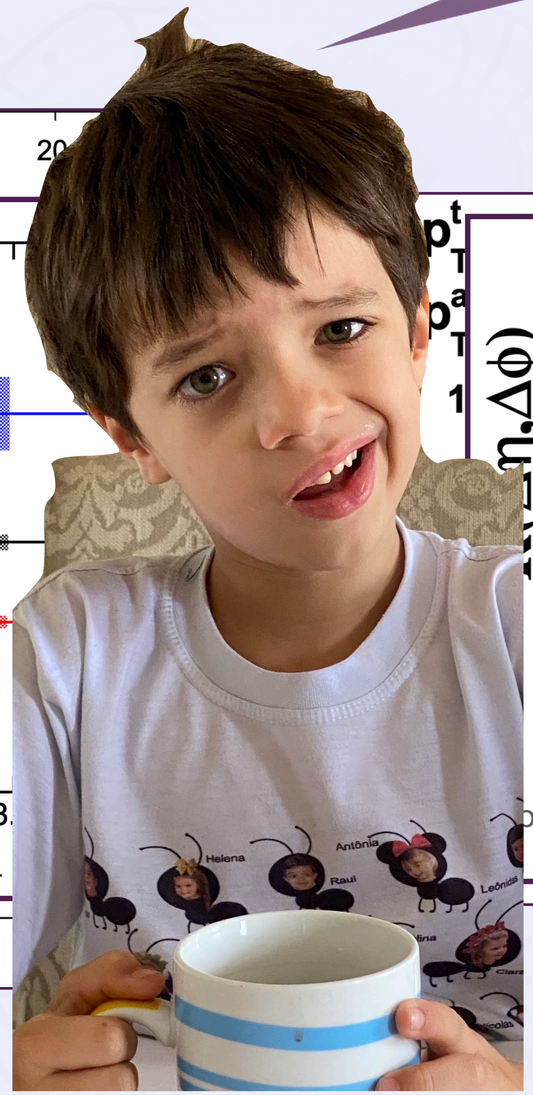
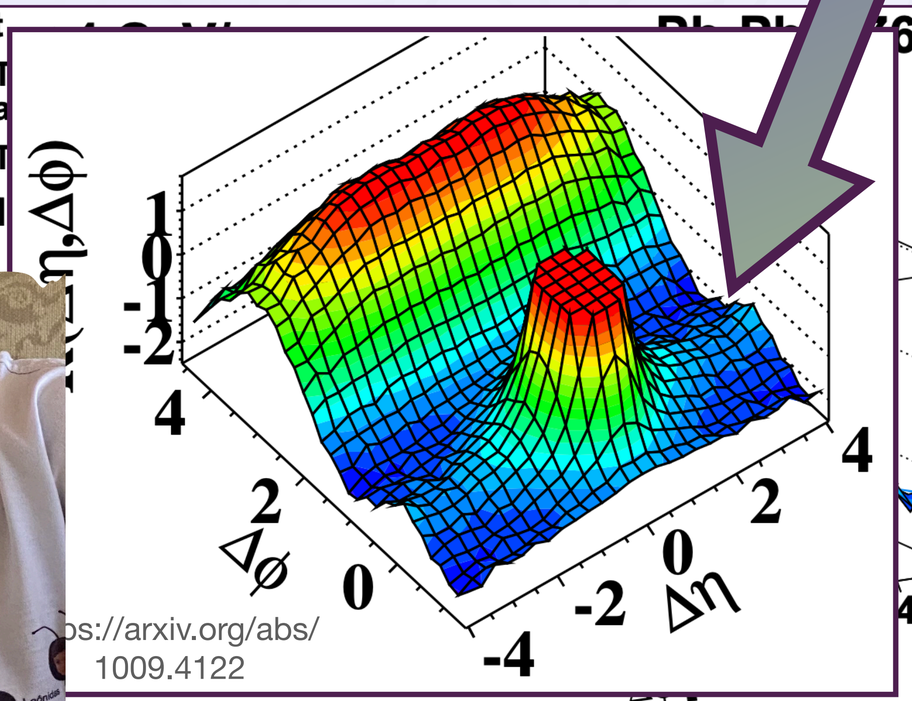


https://arxiv.org/abs/1307.3237





https://arxiv.org/abs/1009.4122

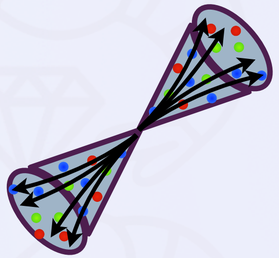
Signatures of a Quark Gluon Plasma

Collective Flow

Jet Quenching

QGP signatures

Jet quenching



Collimated spray of particles

Created in pairs with opposite momentum

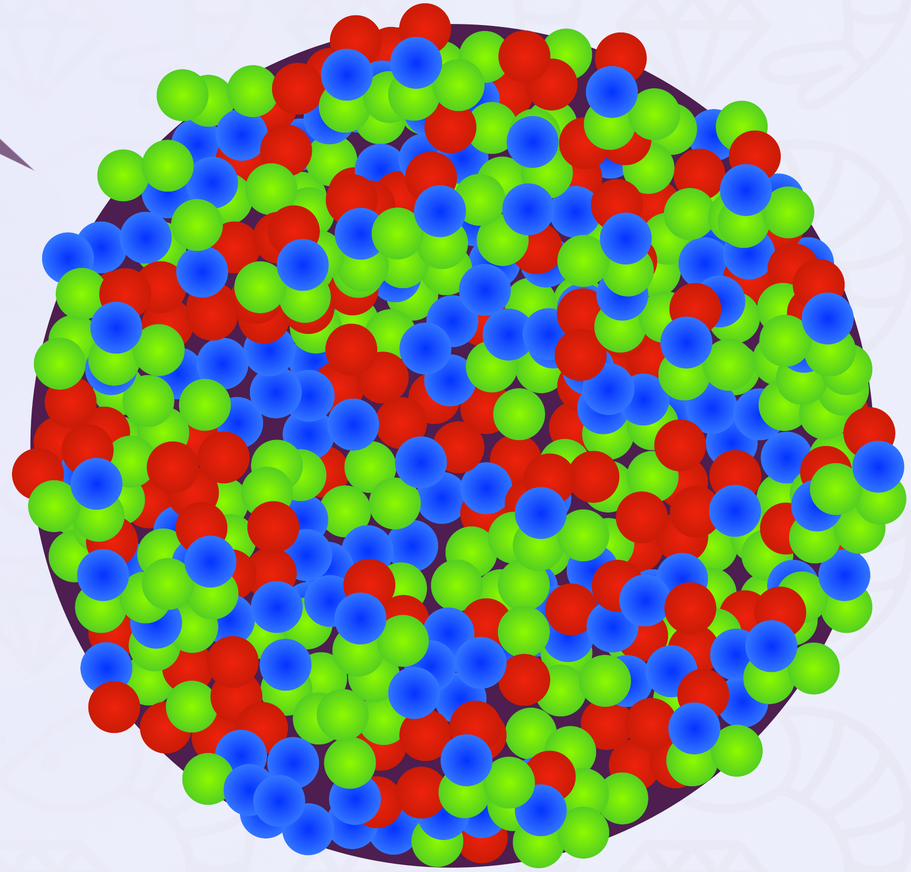
QGP signatures

Jet quenching

QGP signatures

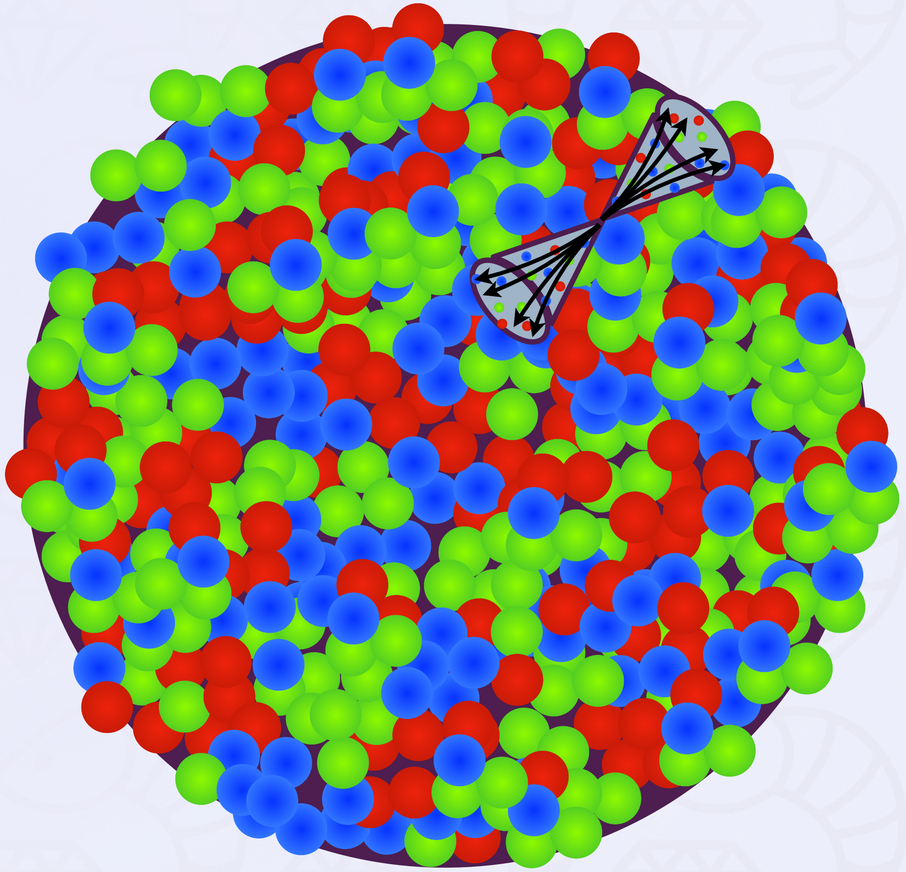
Jet quenching

But in a medium…



QGP signatures

Jet quenching

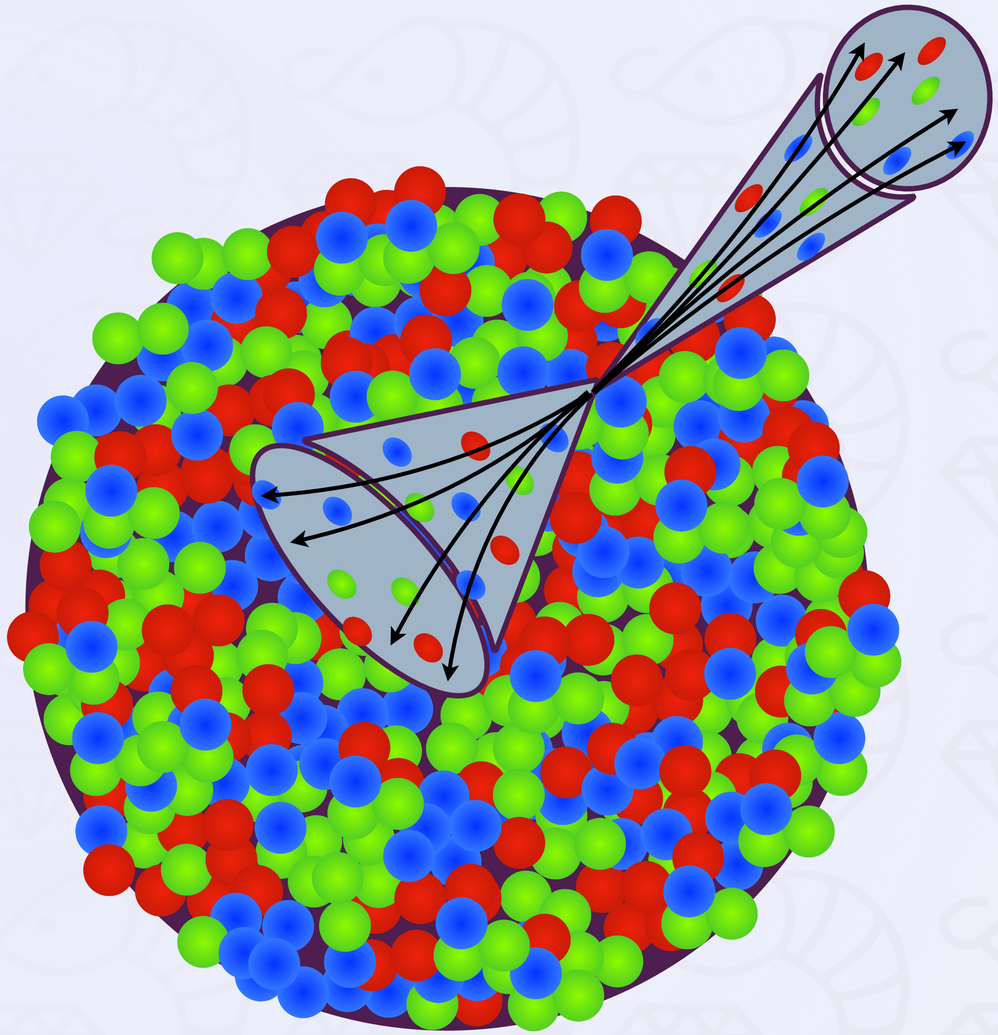


…jet particles interact with medium…

QGP signatures

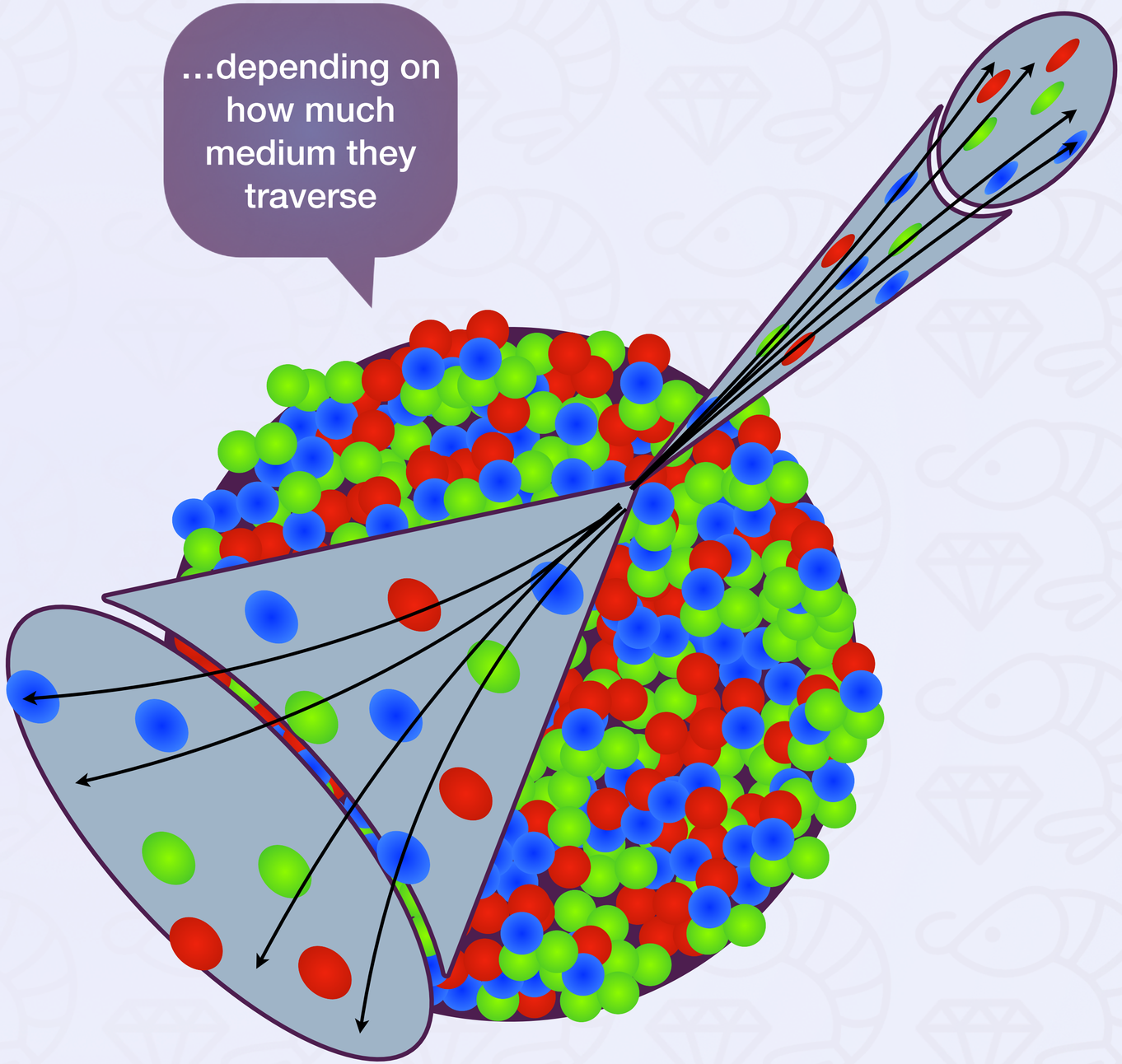
Jet quenching

…jets get quenched…



QGP signatures

Jet quenching

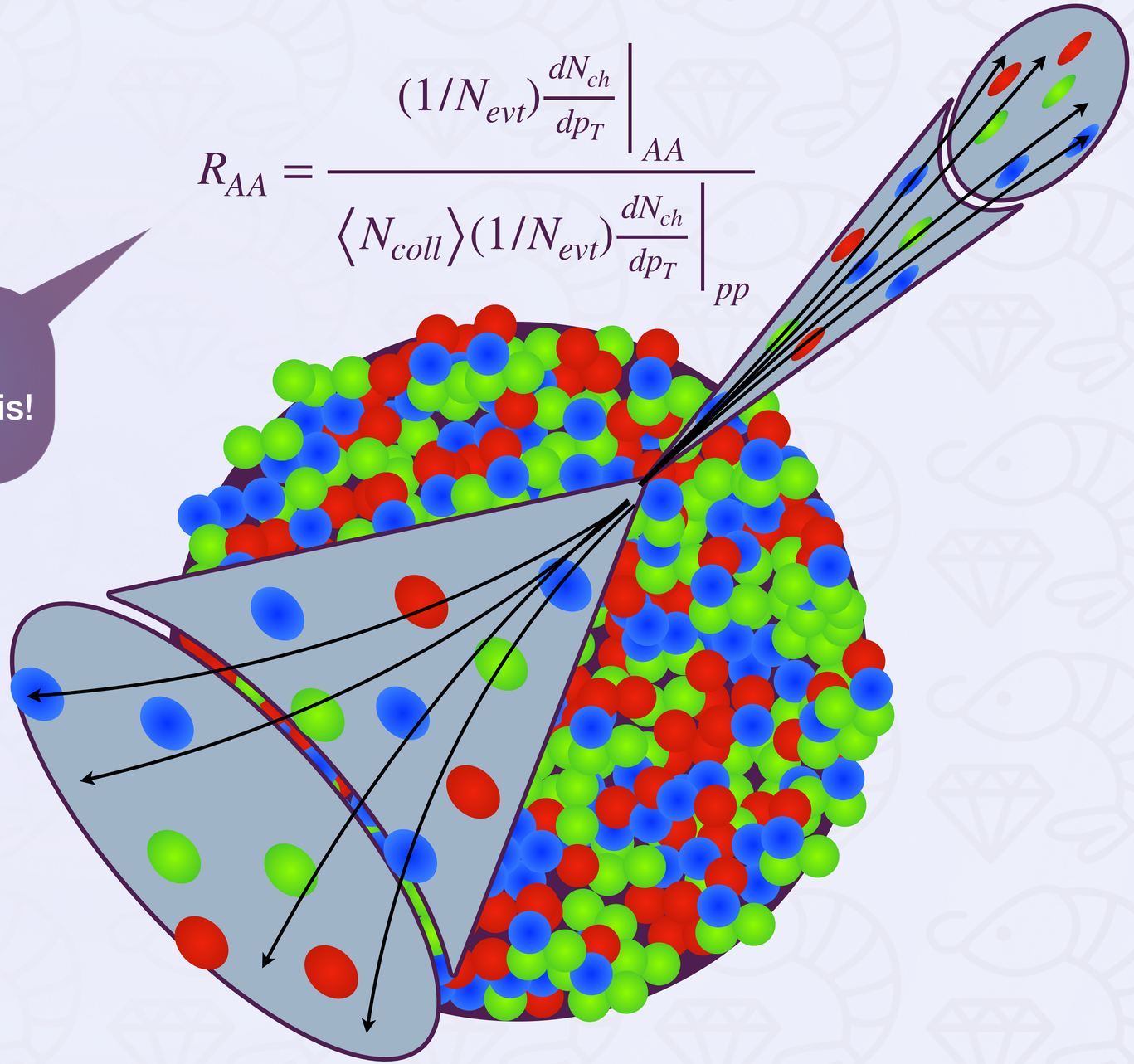


QGP signatures

Jet quenching

$$R_{AA} = \frac{(1/N_{evt})\left.\frac{dN_{ch}}{dp_T}\right|_{AA}}{\langle N_{coll}\rangle (1/N_{evt})\left.\frac{dN_{ch}}{dp_T}\right|_{pp}}$$

We can quantify this!



QGP signatures

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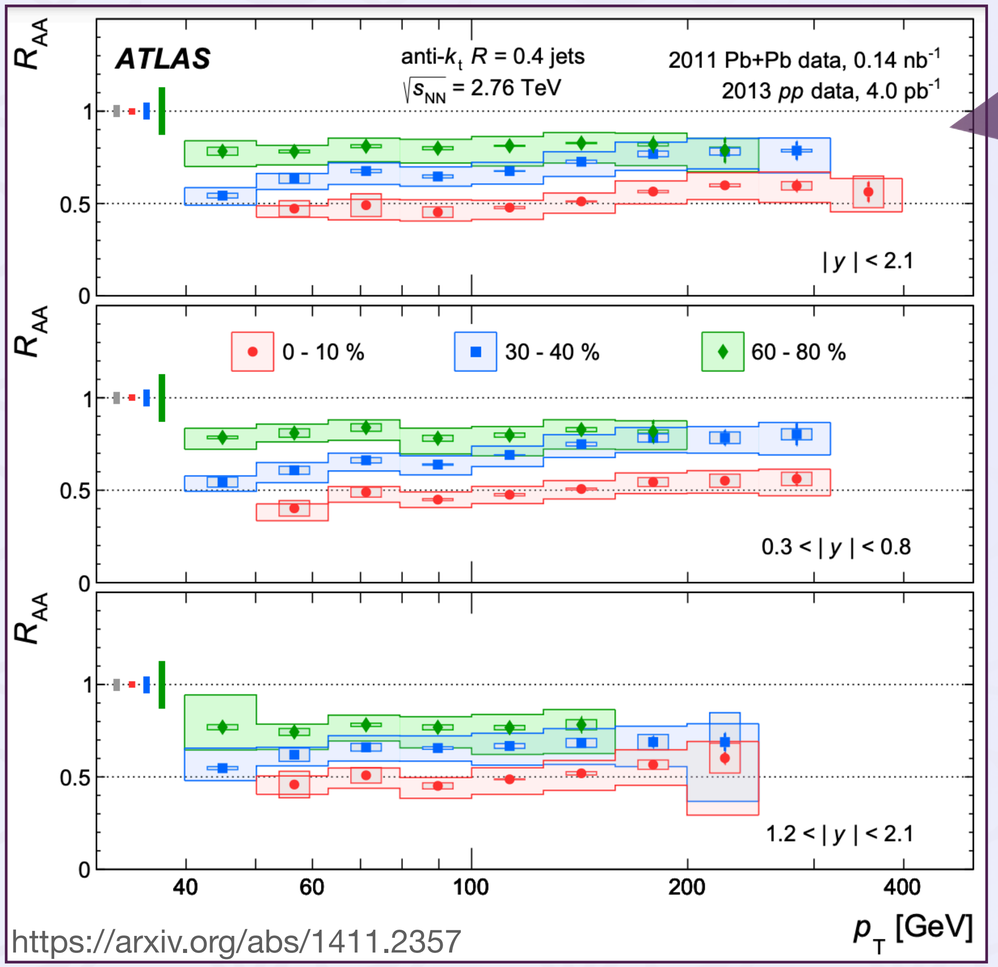
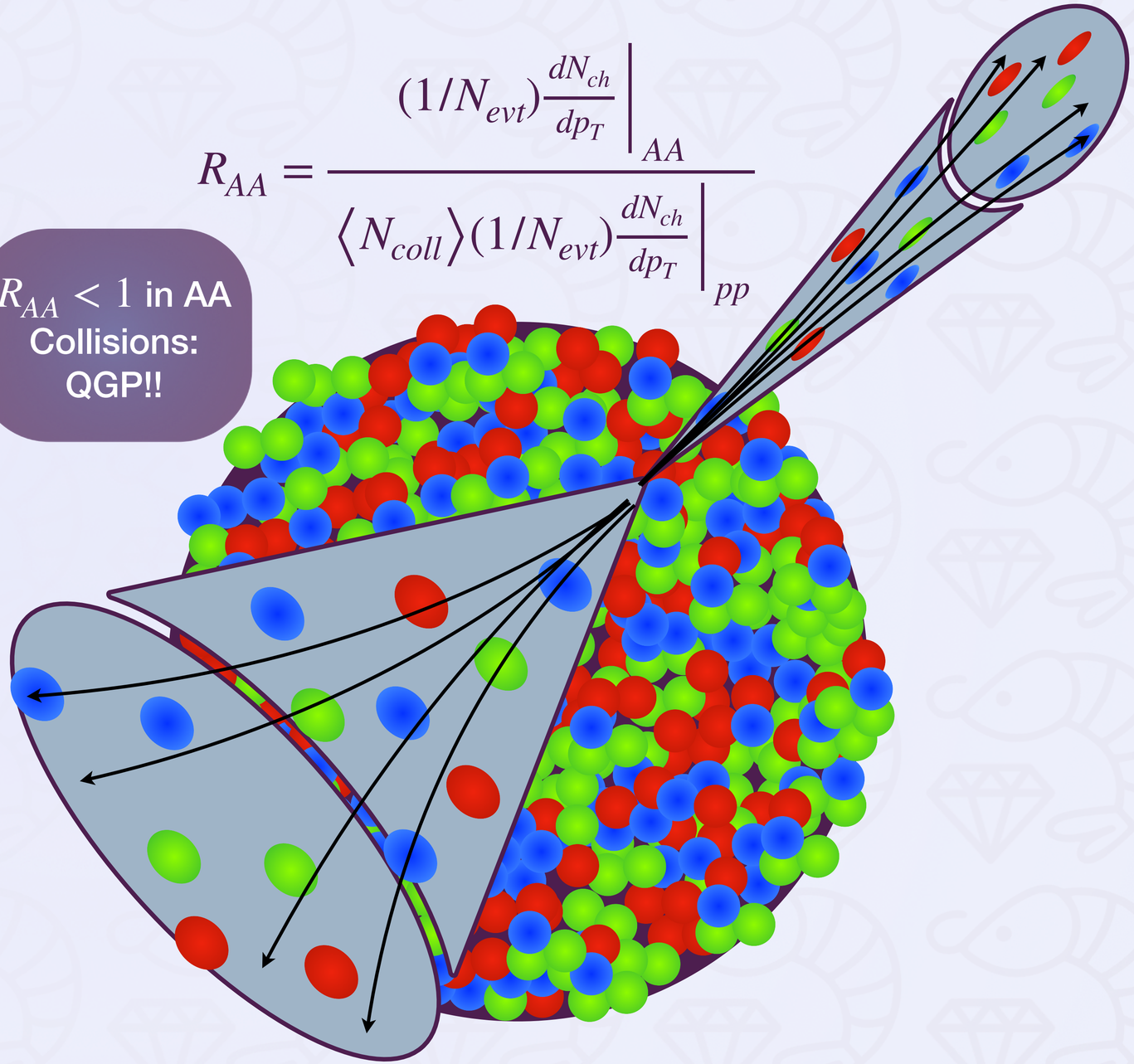
$R_{AA} < 1$ in AA Collisions: QGP!!





QGP signatures

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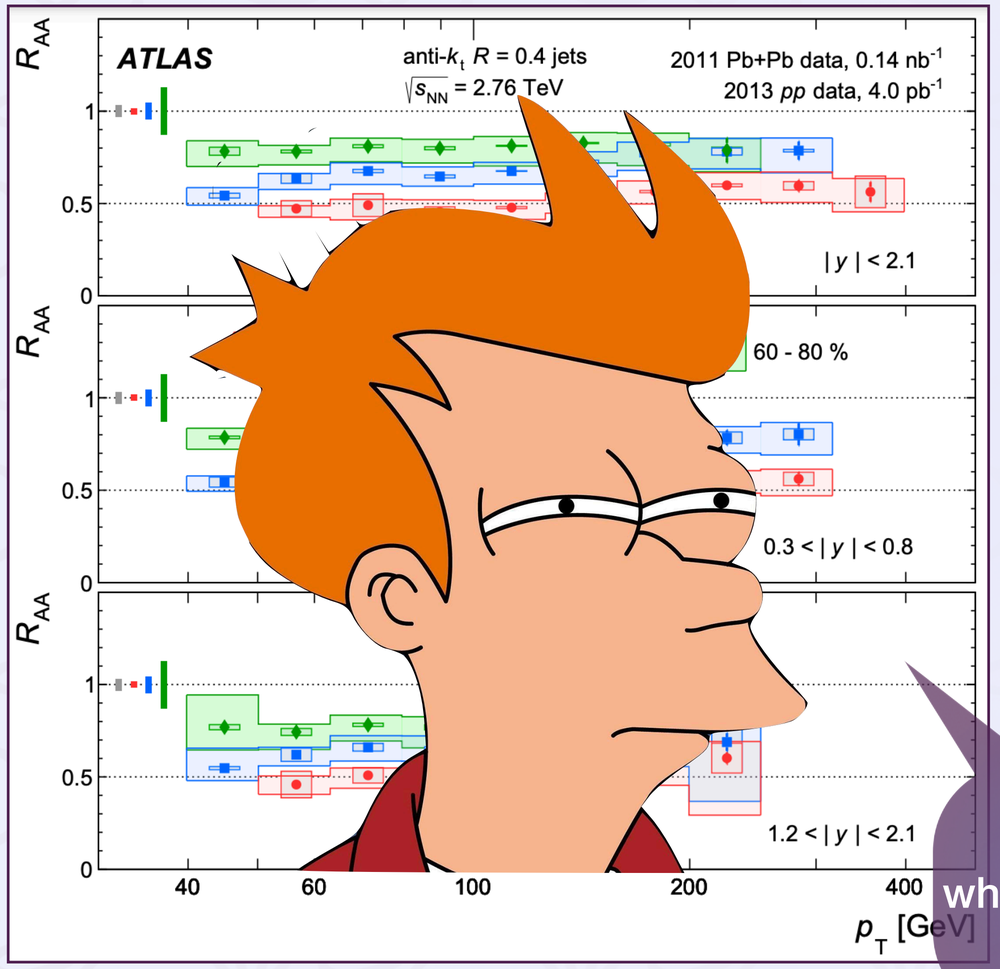
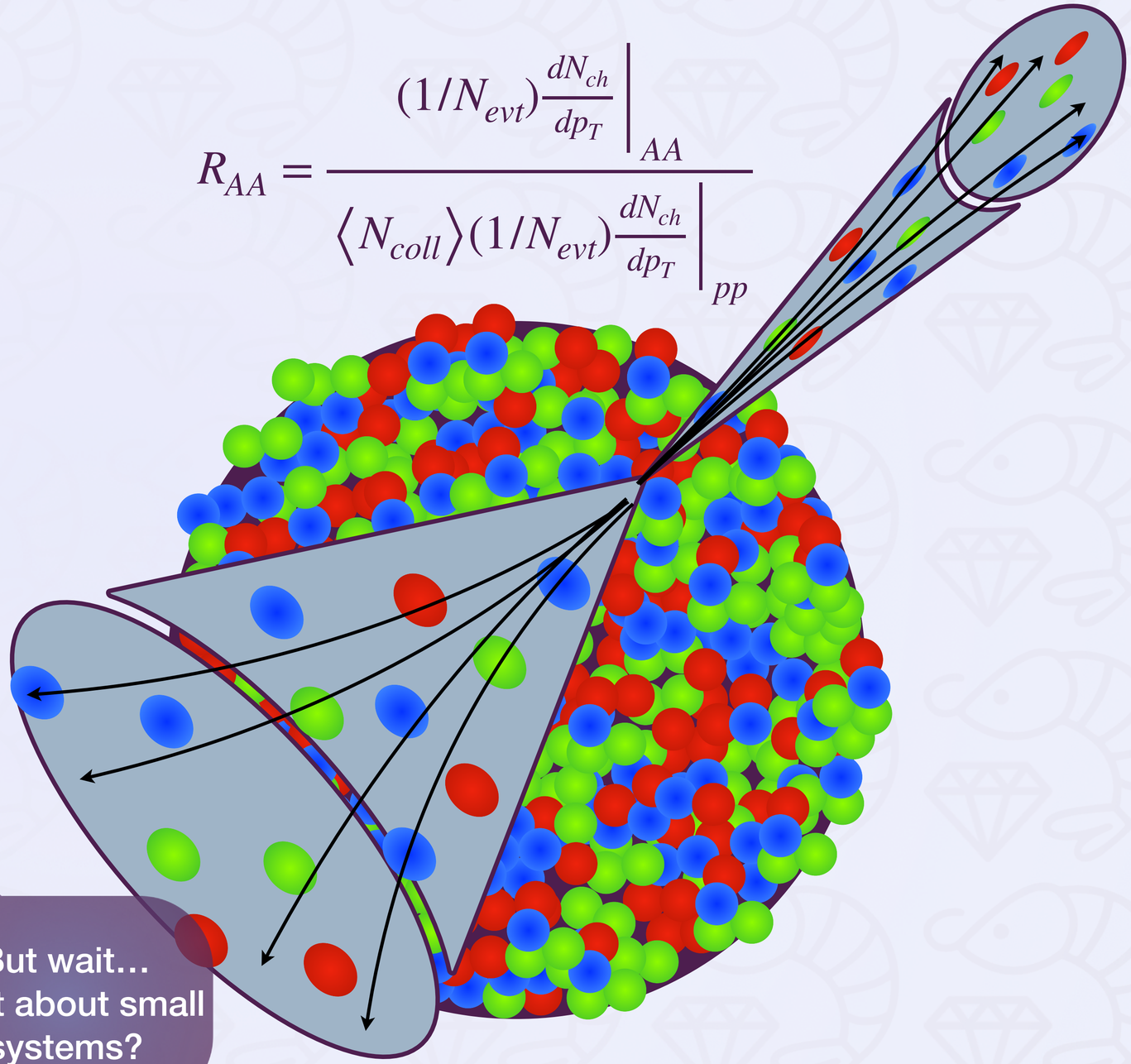


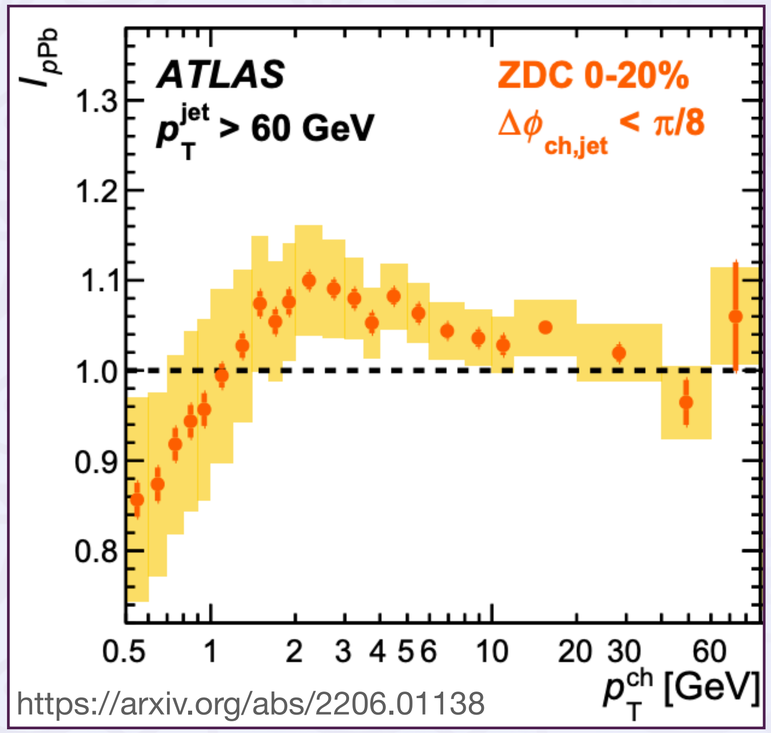


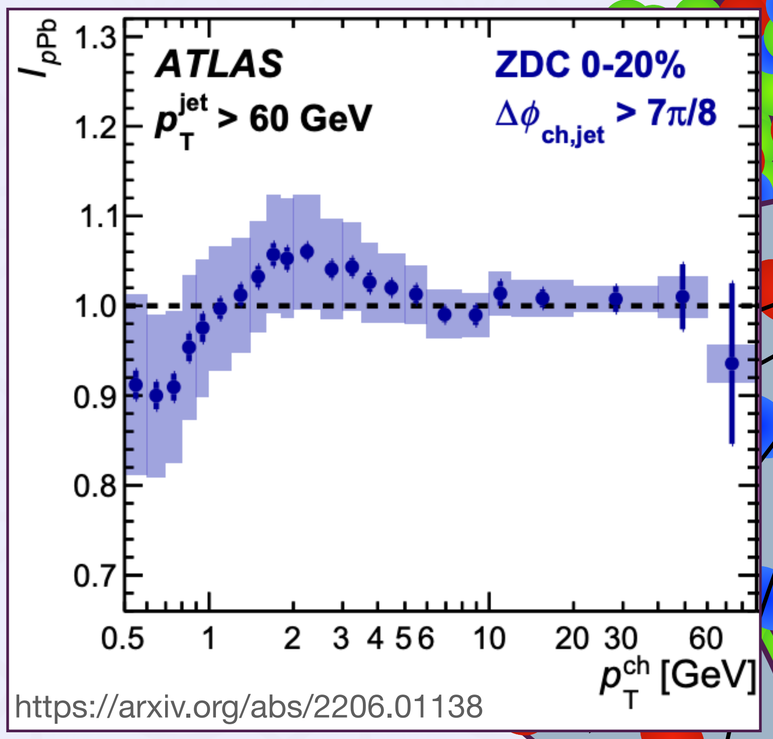
But wait… what about small systems?

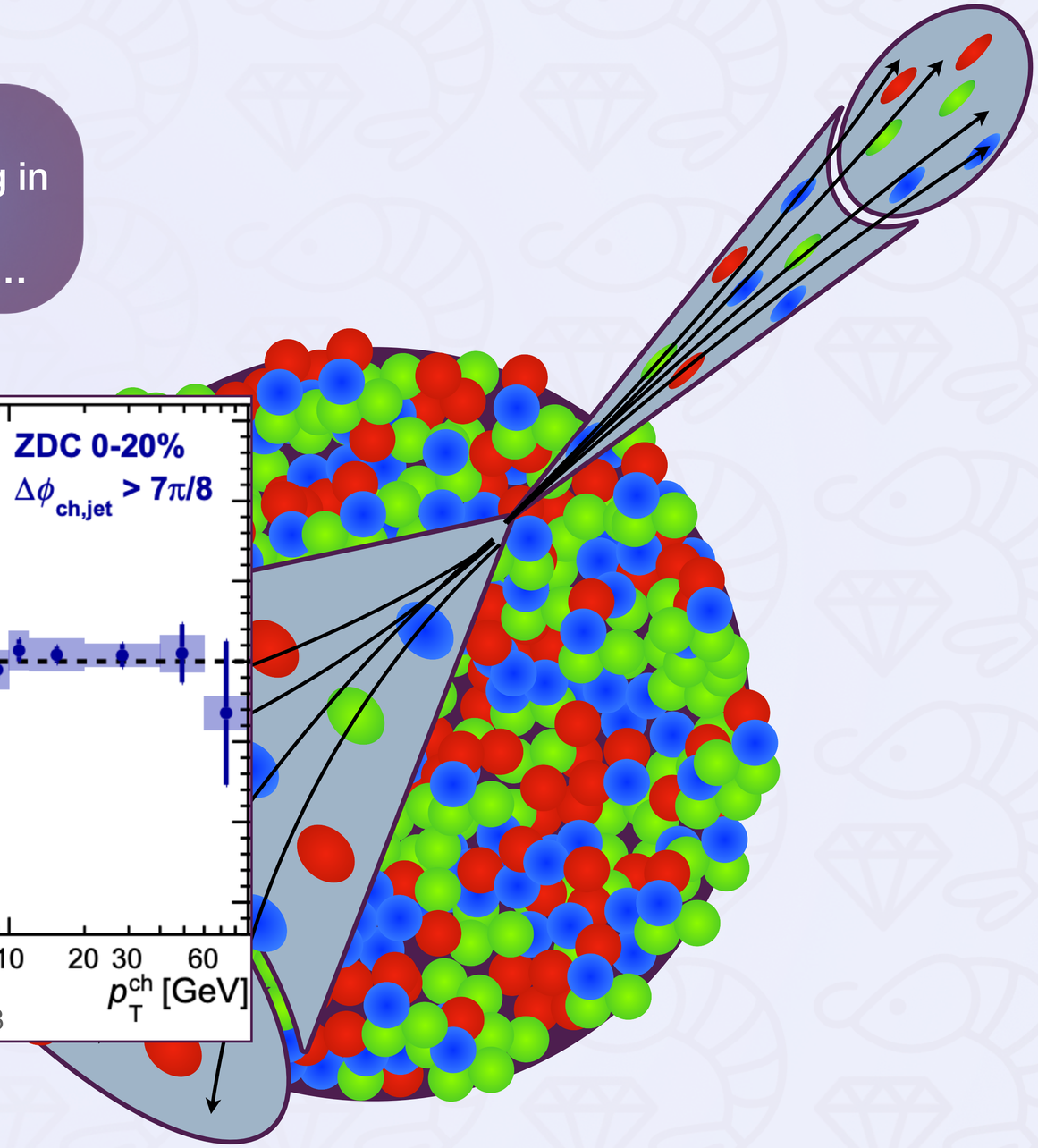
QGP signatures

Jet quenching

No quenching in small systems…

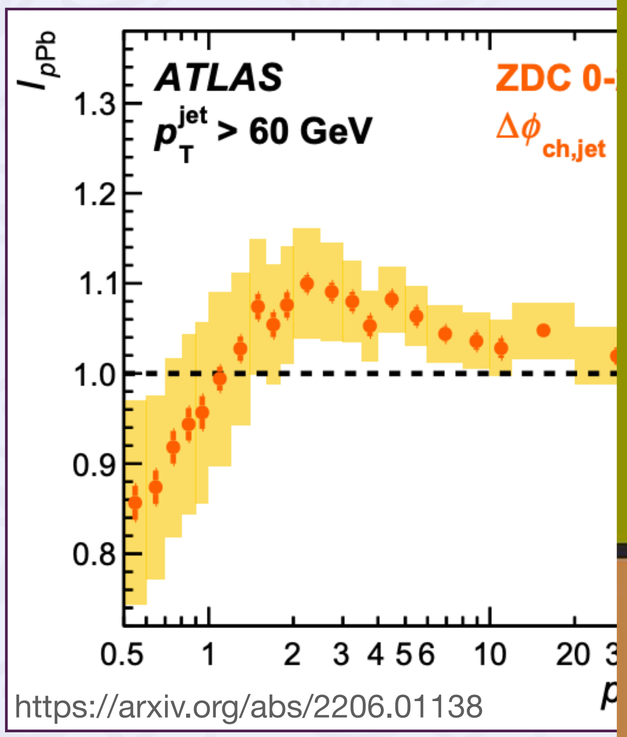




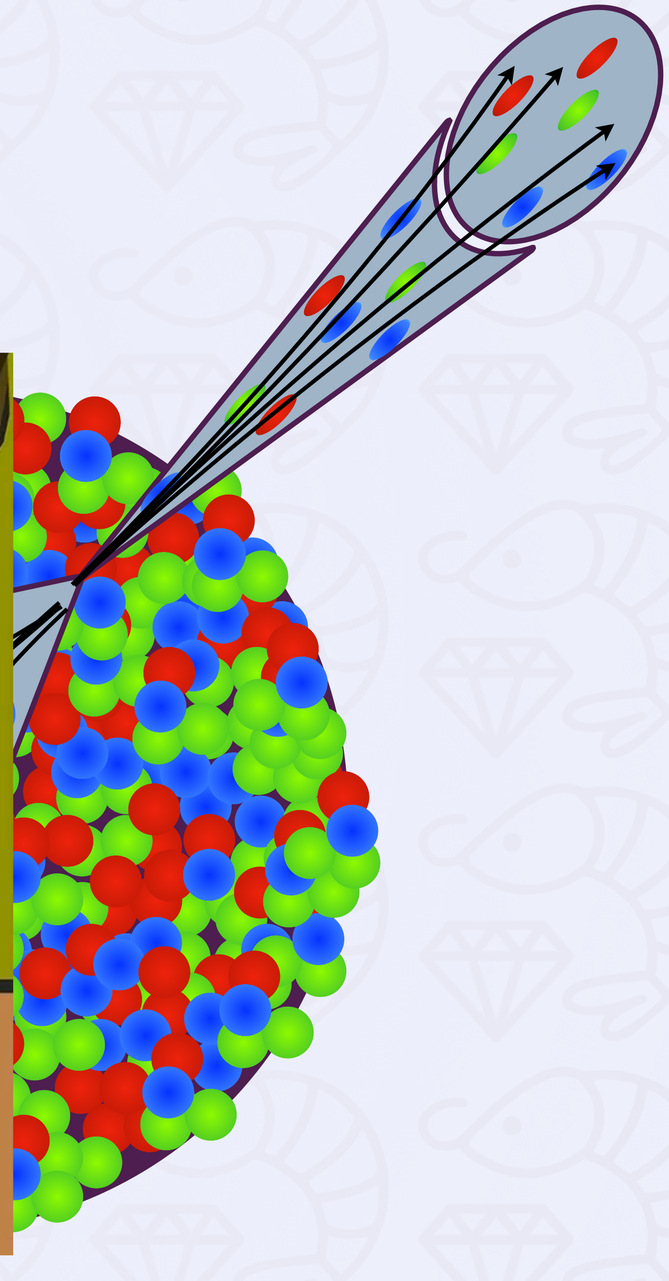


QGP signatures

Jet quenching



https://arxiv.org/abs/2206.01138



Monte Carlo Simulations

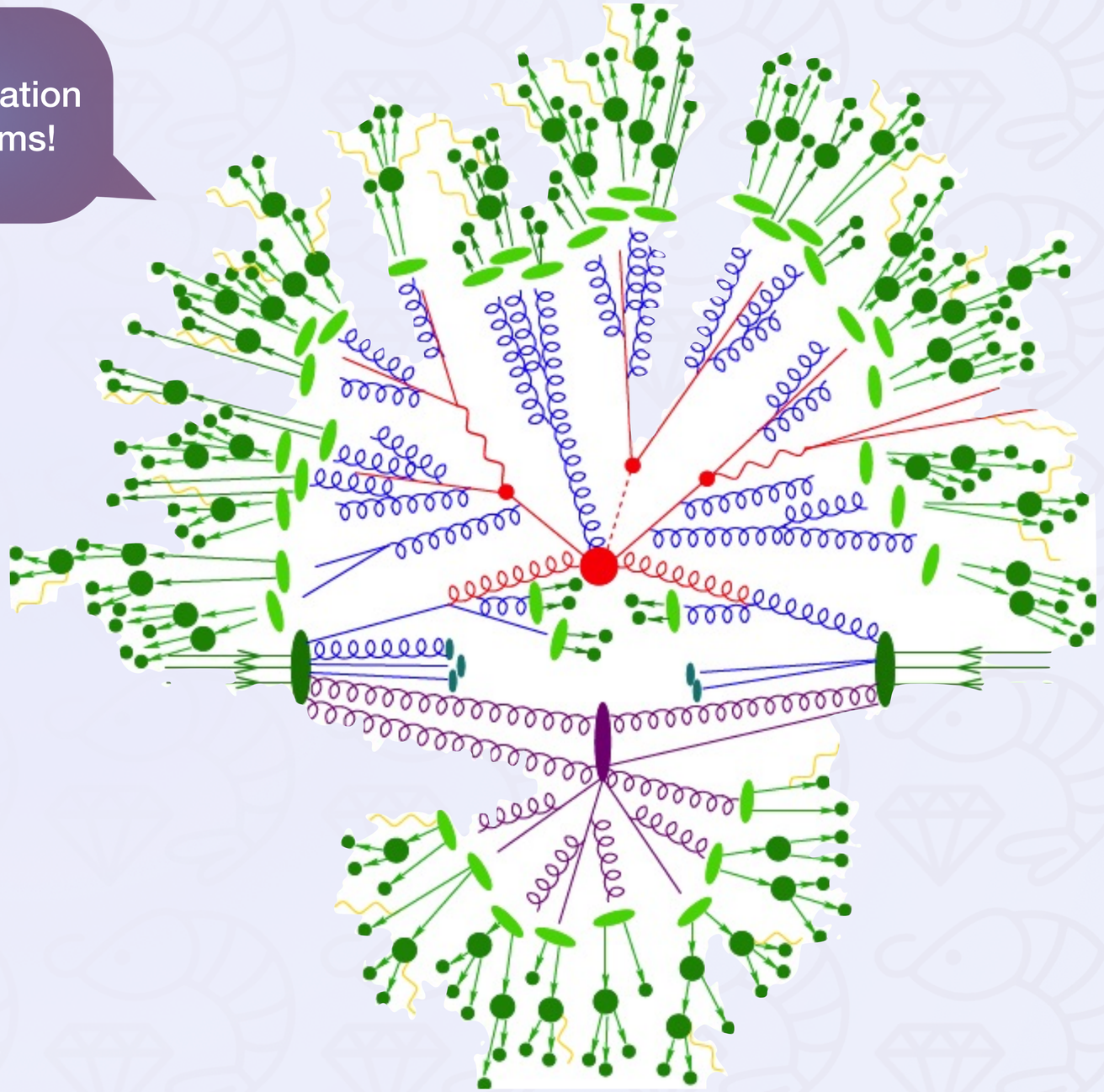
Monte Carlo Simulations

PP Collisions

PP collisions

The Monte Carlo Way

Factorization theorems!



- Hard scattering
- Parton shower
- Hadronization
- Decays
- Possibility of multi parton interaction
- Photon Emission
- Beam remnants

Monte Carlo Simulations

Heavy Ion Collisions

Heavy Ion Collisions

The Monte Carlo… Maze?

- Overlapping pp collisions is not enough

Heavy Ion Collisions

The Monte Carlo… Maze?

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- A few attempts so far: Angantyr, EPOS (mixes hydro simulation and pythia), etc.

Heavy Ion Collisions

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- Still lacking a unique framework that can go naturally from pp to pA and AA in a coherent way:

Heavy Ion Collisions

The Monte Carlo… Maze?

- Overlapping pp collisions is not enough
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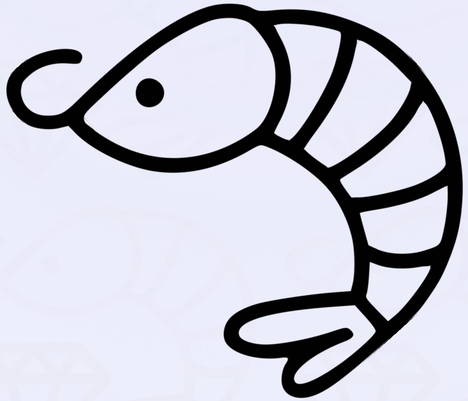
- Still lacking a unique framework that can go naturally from pp to pA and AA in a coherent way:



SHRiMPS for pp
(in a nutshell!)

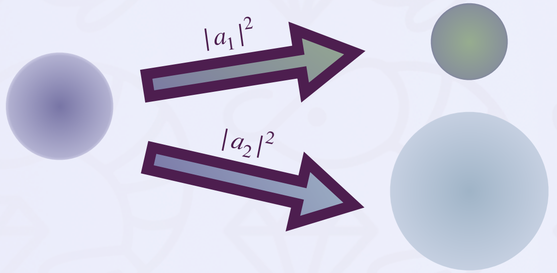
Soft and Hard Reactions Involving Multi Pomeron Scattering

SHRiMPS

Soft and Hard Reactions Involving Multi Pomeron Scattering

- Protons are described as a superposition of Good-Walker states:

$$|p> = \sum_{i=1}^{N_{GW}} a_i |\phi_i>$$



- Using optical theorem we can get differential cross sections in S-matrix formalism:

$$\frac{d\sigma_{tot}(Y)}{d\vec{B}_\perp}$$

Total

$$\frac{d\sigma^{pp}_{\text{inel}}(Y)}{d\vec{B}_\perp}$$

protons break up

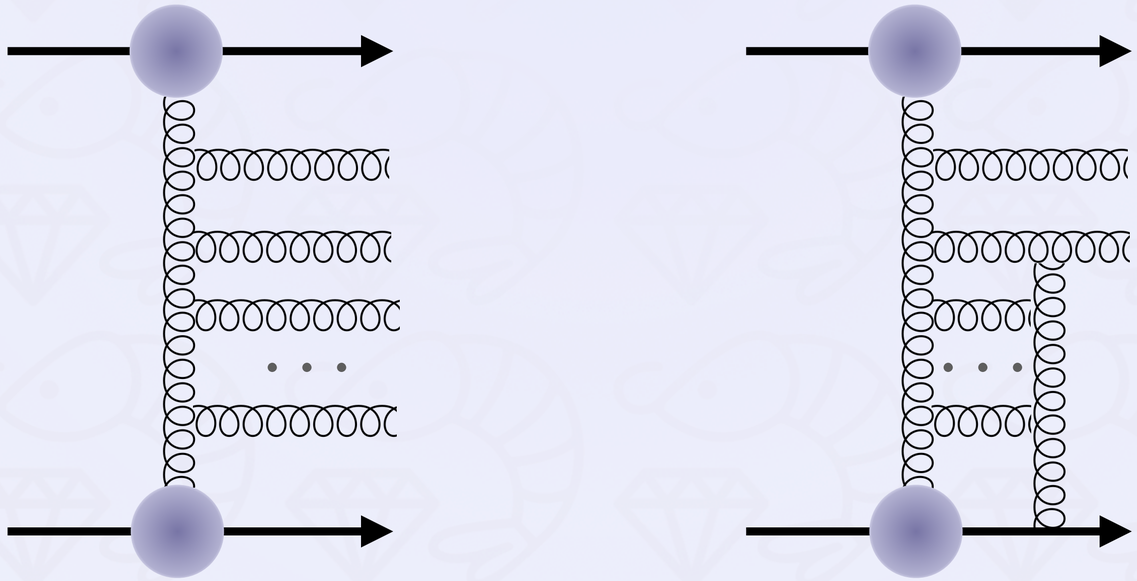
$$\frac{d\sigma^{pp}_{\text{QE}}(Y)}{d\vec{B}_\perp}$$

protons just bounce off of each other or get excited

SHRiMPS

Soft and Hard Reactions Involving Multi Pomeron Scattering

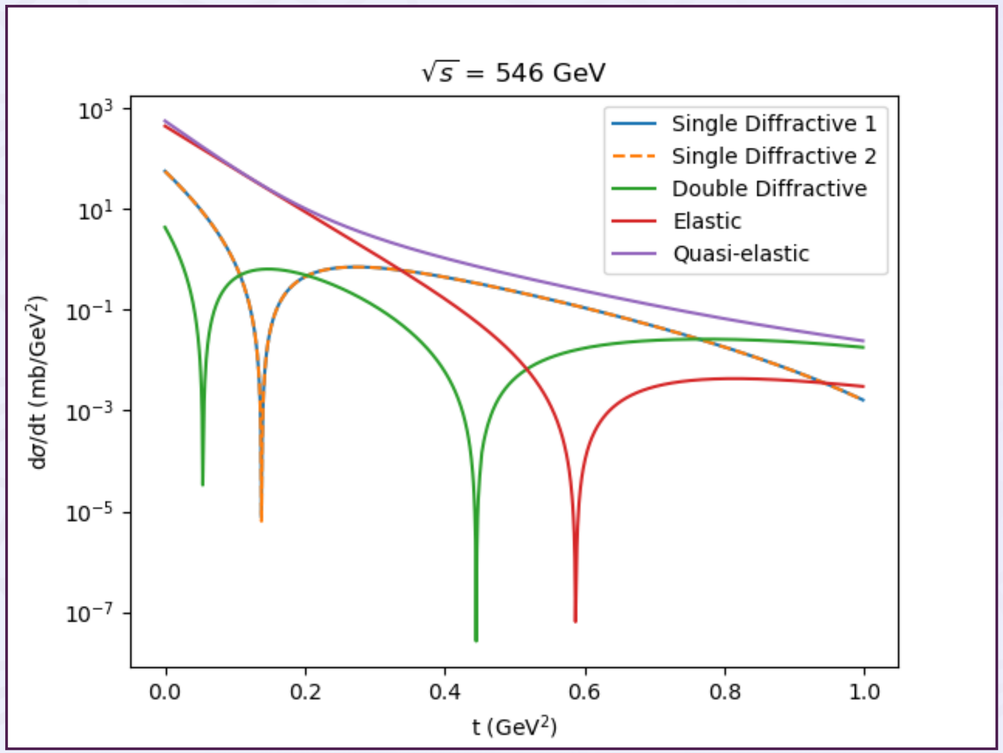
- How to describe inelastic non-diffractive interactions in a nutshell:
- Protons exchange gluons that can emit or absorb other partons according to certain probabilities, e.g.:

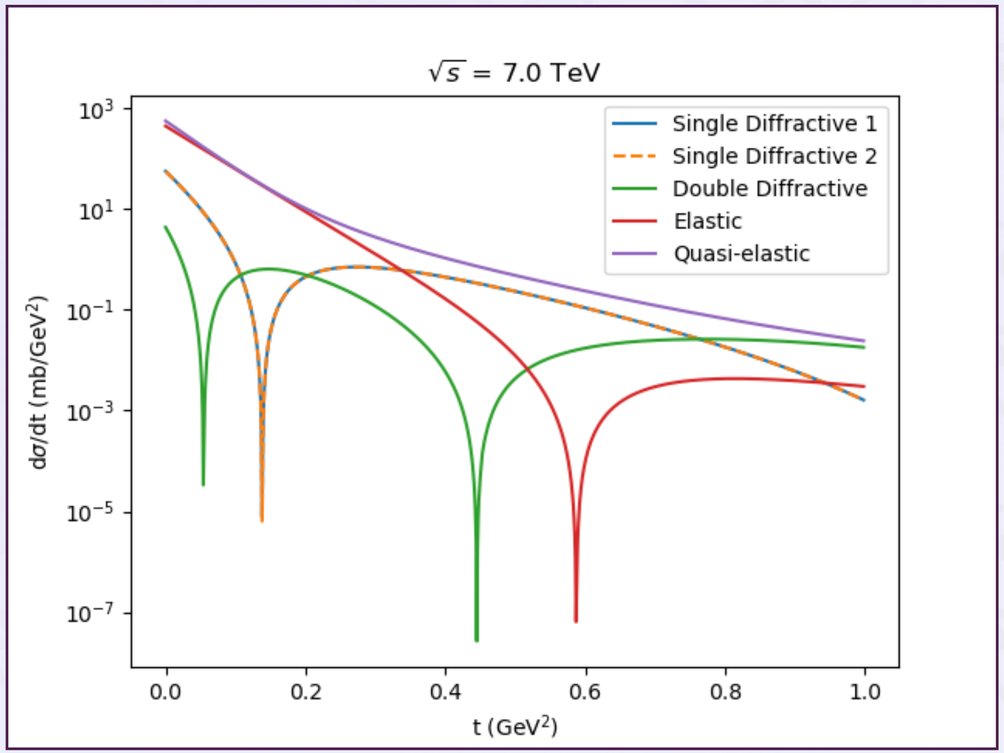


SHRiMPS

Soft and Hard Reactions Involving Multi Pomeron Scattering

As for quasi elastic interactions, we can plot the cross sections for the different types as a function of $|t| = Q_\perp^2$:





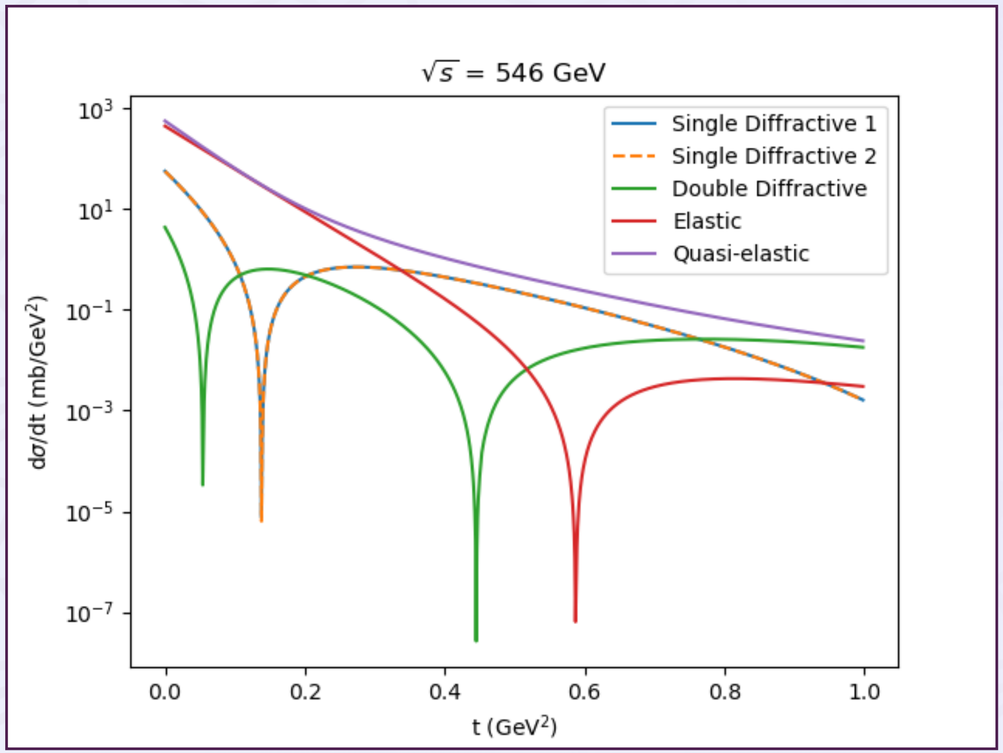
SHRiMPS

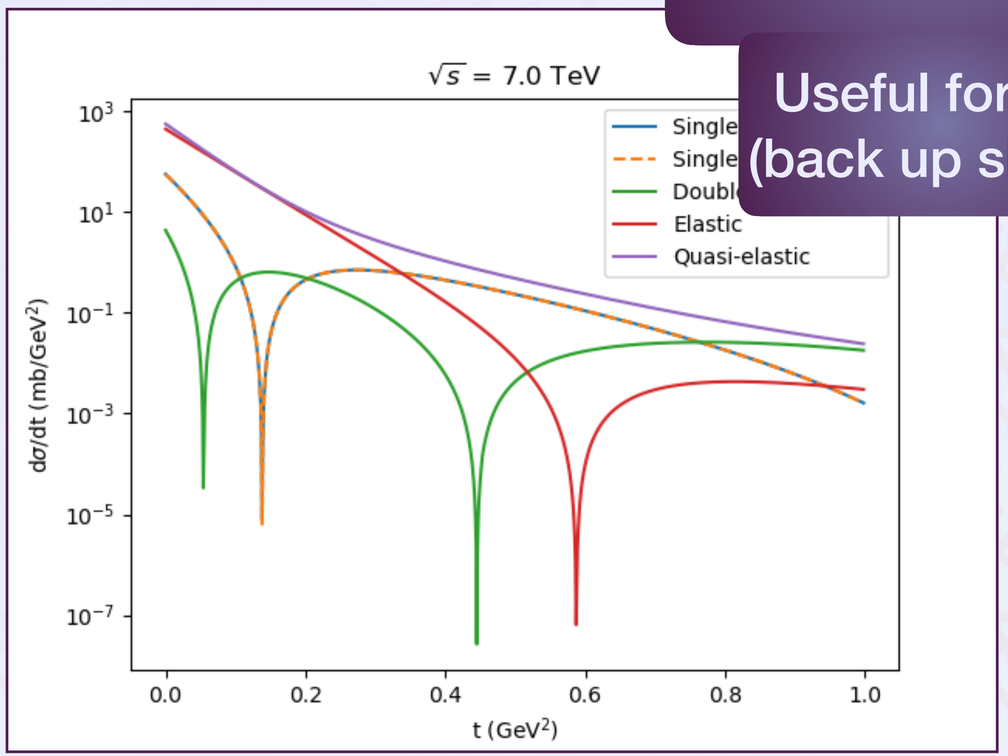
Soft and Hard Reactions Involving Multi Pomeron Scattering

As for quasi elastic interactions, we can plot the cross sections for the c
a function of $|t| = Q_\perp^2$:

Can also get QE cross section for fixed GW states!

Useful for pA! (back up slides)



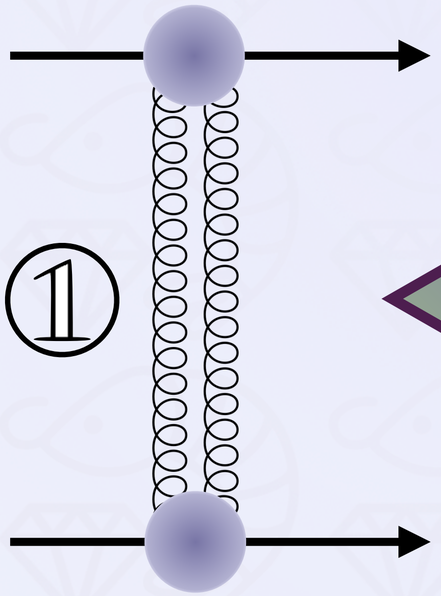


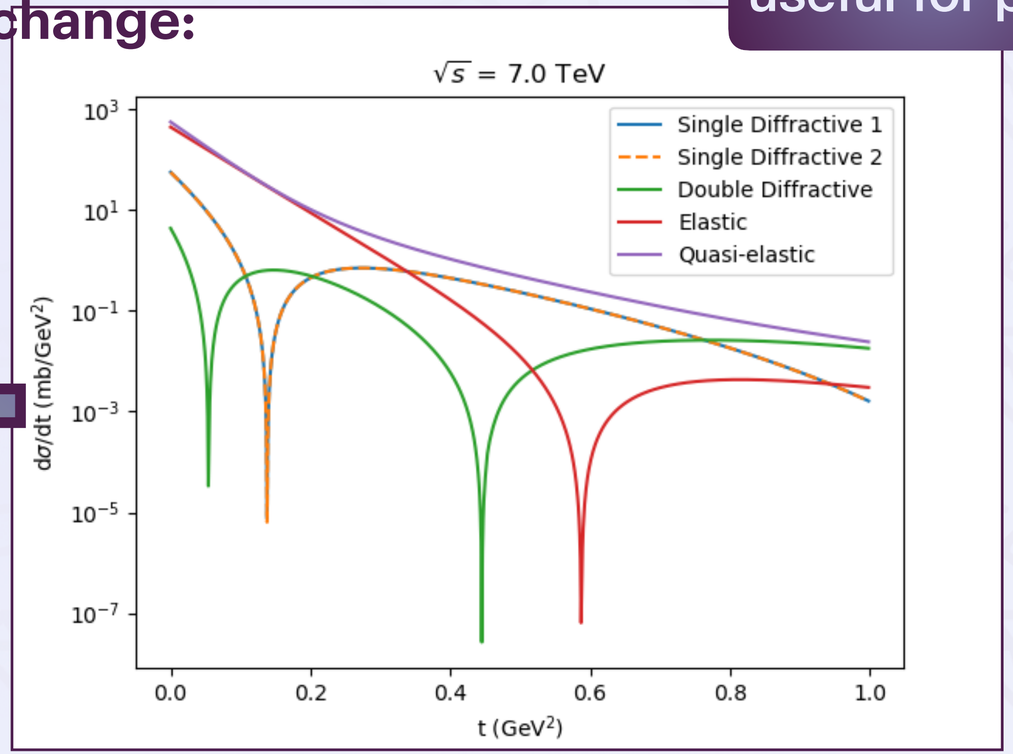
SHRiMPS

Soft and Hard Reactions Involving Multi Pomeron Scattering

- As for quasi elastic interactions, we can plot the cross sections for the different types as a function of $|t| = Q_\perp^2$;
- Can also be described as a “gluon ladder” exchange:

Will also be useful for pA…





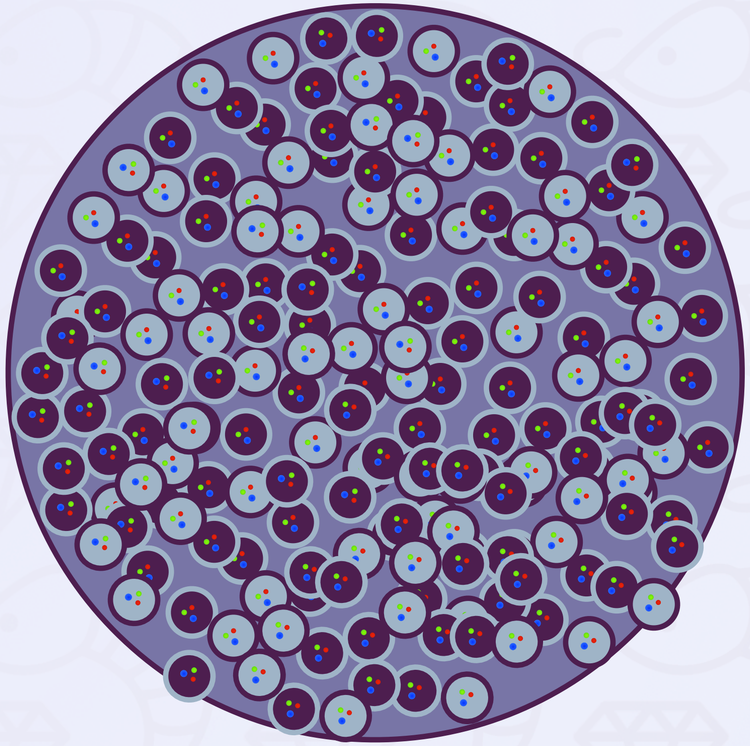
SHRiMPS for pA

Glauber Model

SHRiMPS for pA collisions

Glauber Model

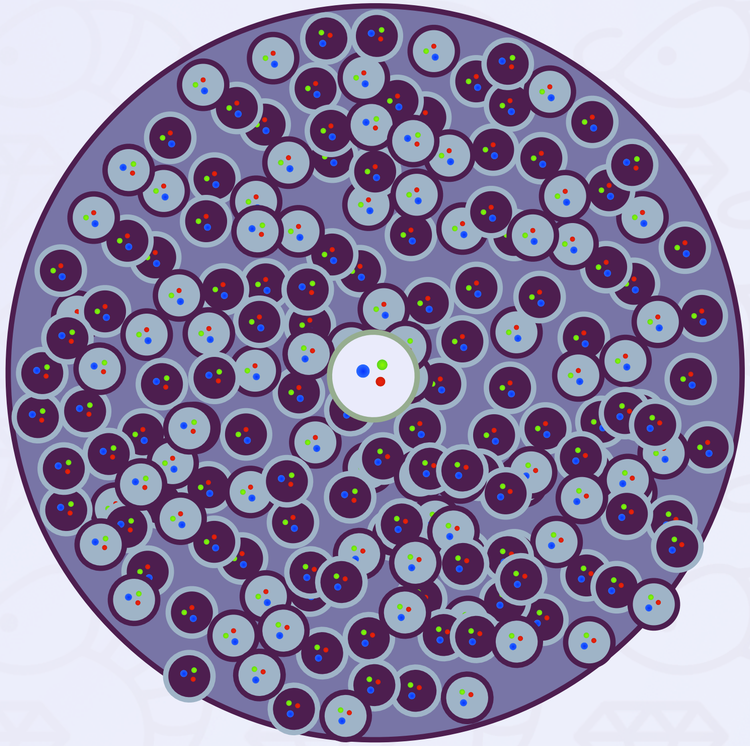
- Now we can take a nucleus and distribute nucleons inside it



SHRiMPS for pA collisions

Glauber Model

- Now we can take a nucleus and distribute nucleons inside it
- Shoot a proton on it

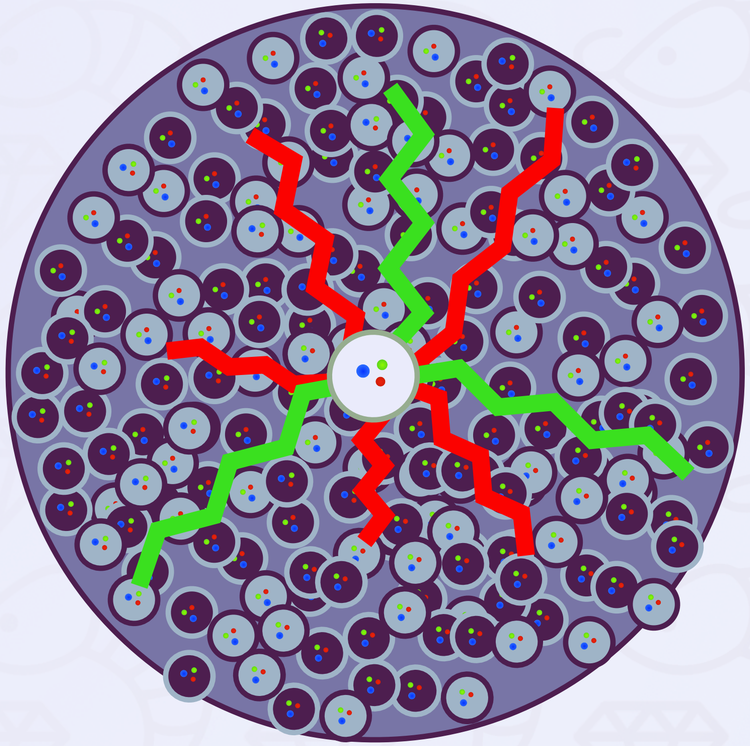


SHRiMPS for pA collisions

Glauber Model

- Now we can take a nucleus and distribute nucleons inside it
- Shoot a proton on it
- And ask our impact parameter dependent cross sections

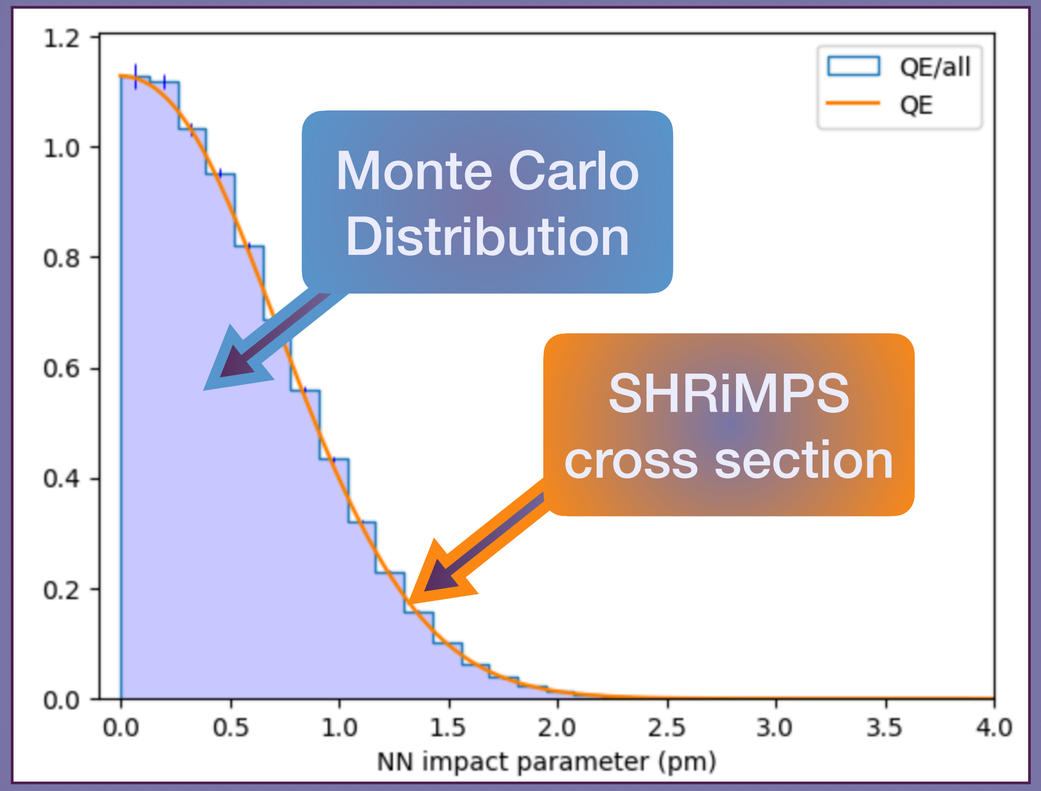
what kinds of ladders we should exchange with each of the nucleons

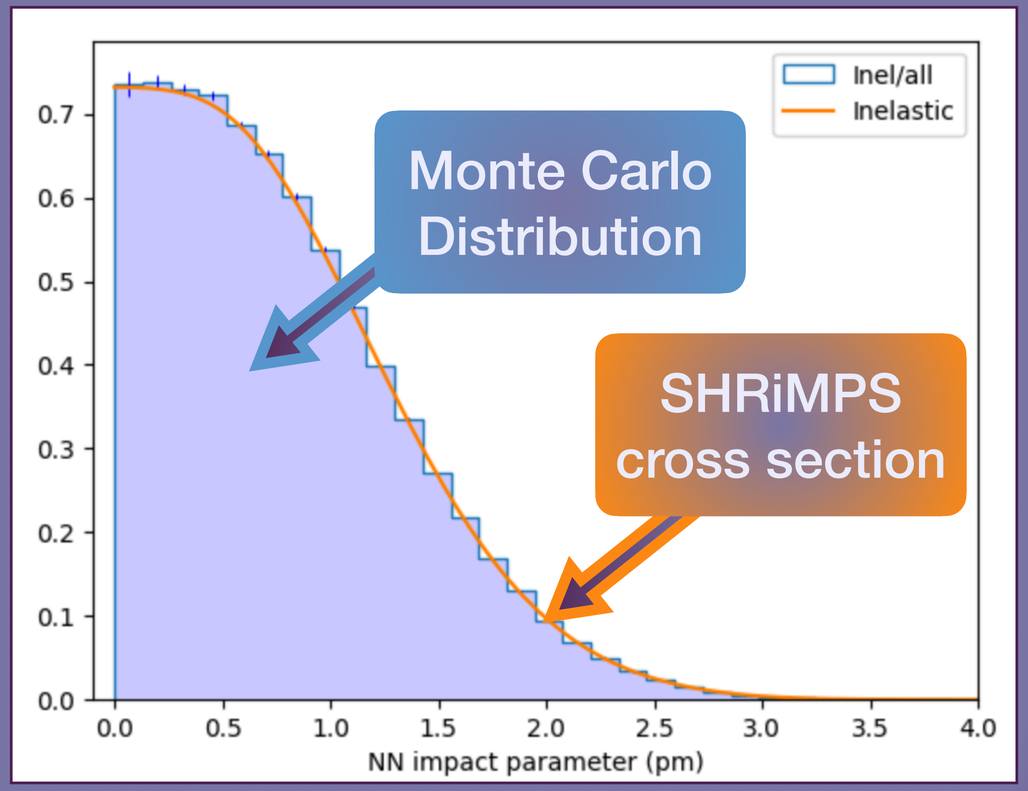


SHRiMPS for pA collisions

Glauber Model

So far, we can obtain the correct distributions of quasi-elastic and inelastic events:

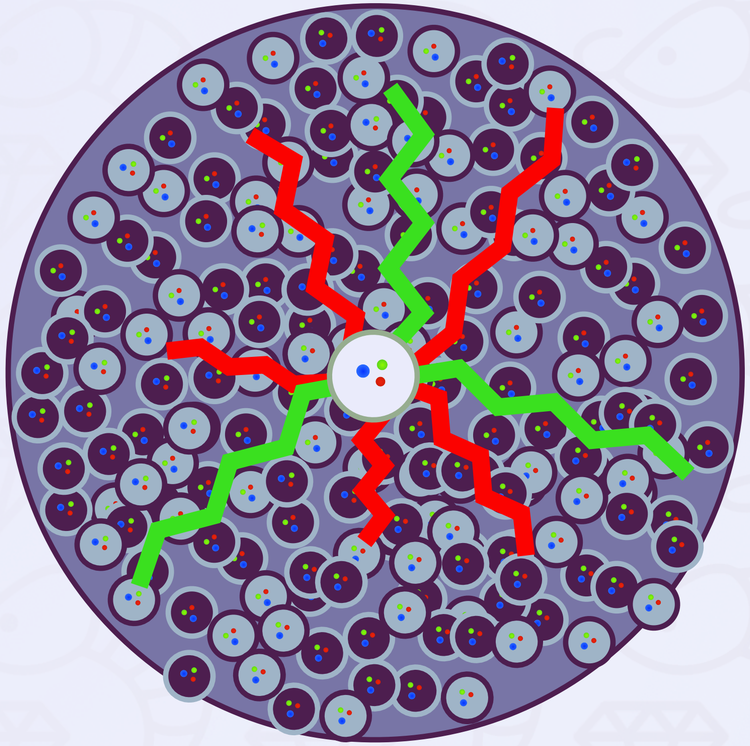




SHRiMPS for pA collisions 🦐

Glauber Model

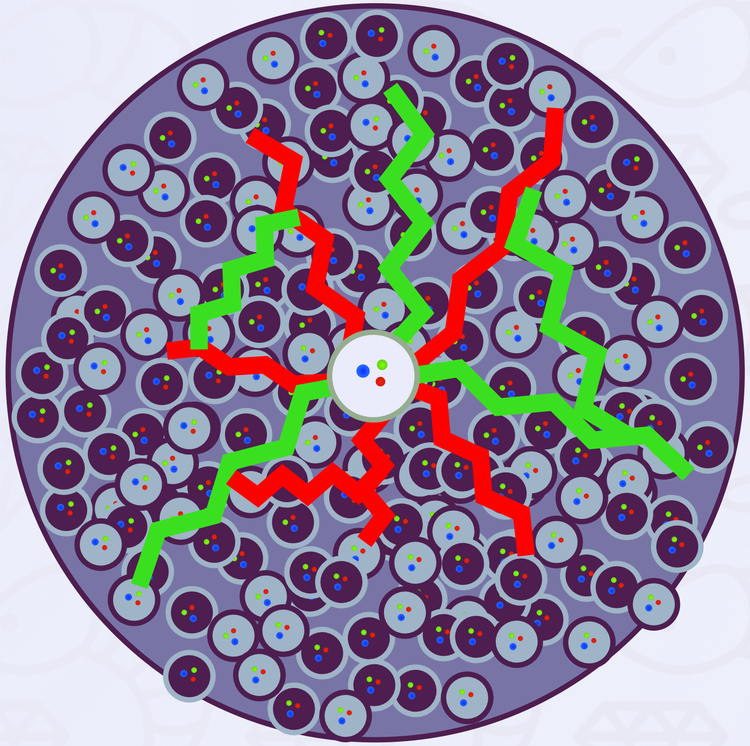
- Now we can take a nucleus and distribute nucleons inside it
- Shoot a proton on it
- And ask our impact parameter dependent cross sections what kinds of ladders we should exchange with each of the nucleons
- Glauber: done! ✅



SHRiMPS for pA collisions 🦐

Heavy Ion Events

- Now we can take a nucleus and distribute nucleons inside it
- Shoot a proton on it
- And ask our impact parameter dependent cross sections what kinds of ladders we should exchange with each of the nucleons
- Glauber: done! ✅
- We also want to allow for those ladders to rescatter and hopefully we can see collectivity effects!

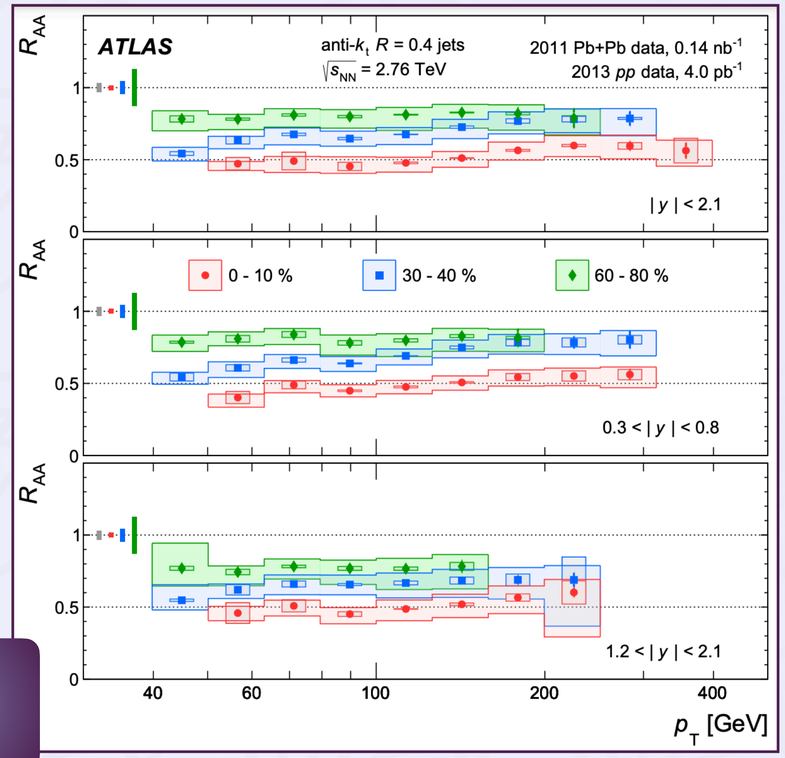


Tackling the puzzle of small systems from a different angle

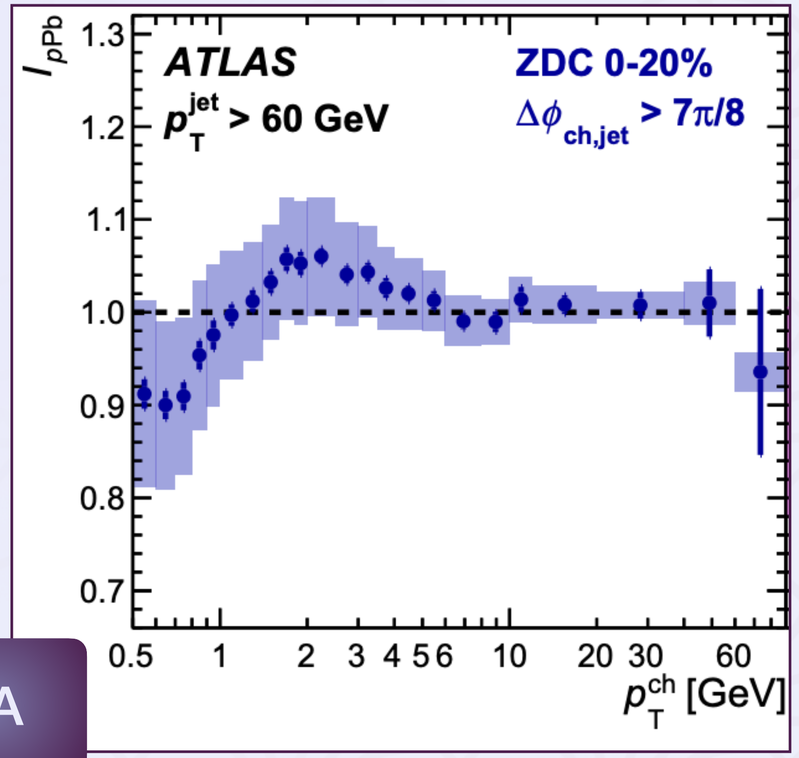
JEWEL

Jet quenching in small and large systems

Remember this intriguing issue?!



AA

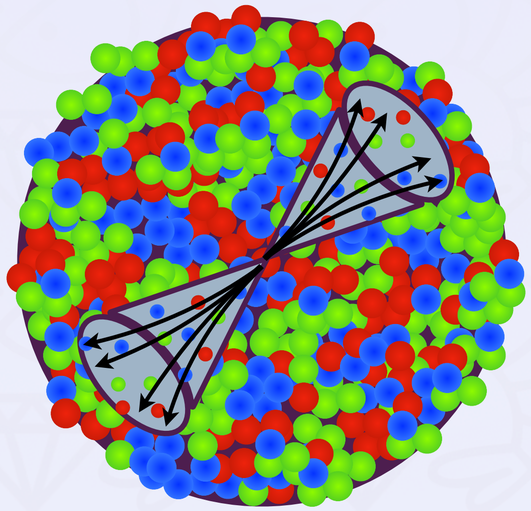


pA

JEWEL

In a nutshell

- Another Monte Carlo event generator
- Virtuality ordered parton shower (simulates jet evolution)
- The medium is formed by a collection of partons
- Medium interaction described with $2 \rightarrow 2$ matrix elements in pQCD

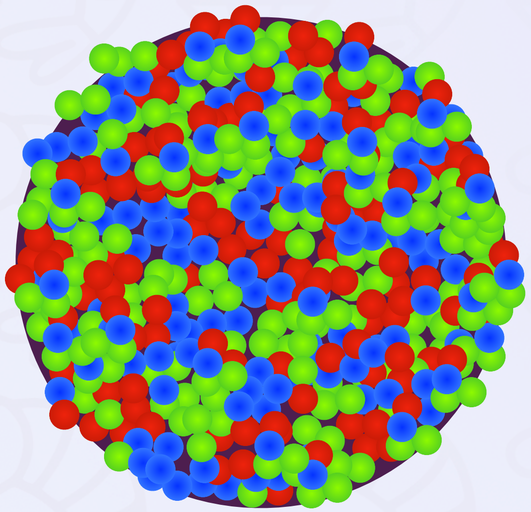


JEWEL

Opacity Expansion

- Let’s investigate it with a very simplified model for a medium:

Gluon brick



With a fixed temperature…

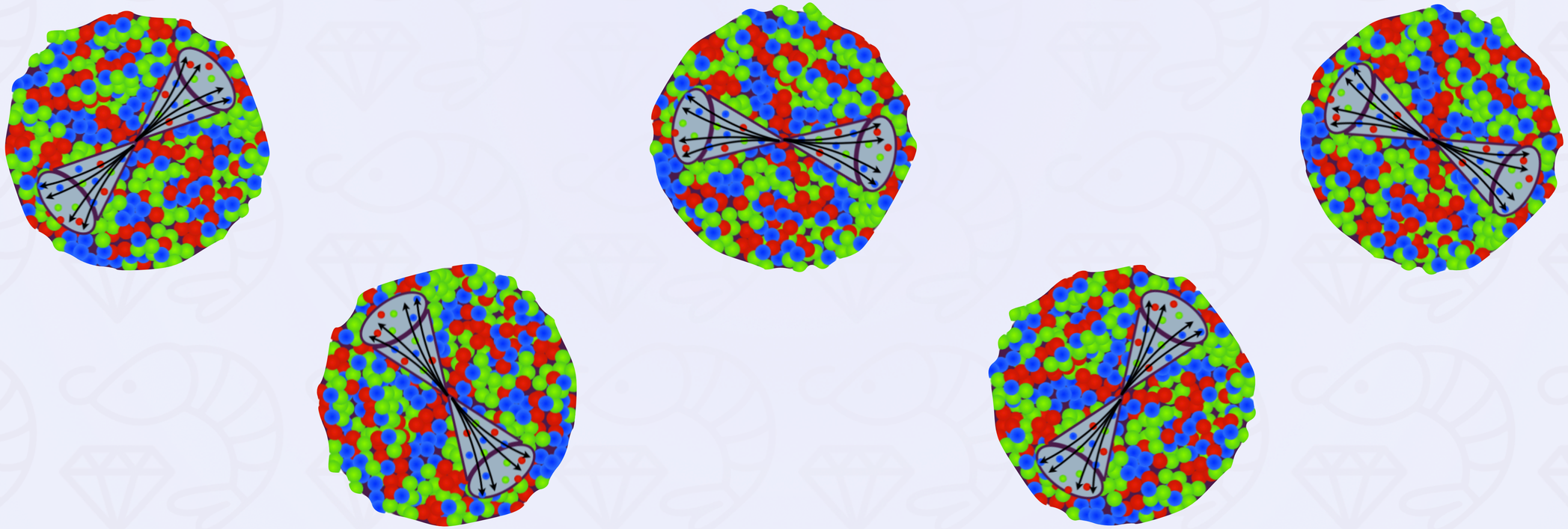
… a fixed density…

…and a fixed radius!

JEWEL

Opacity Expansion

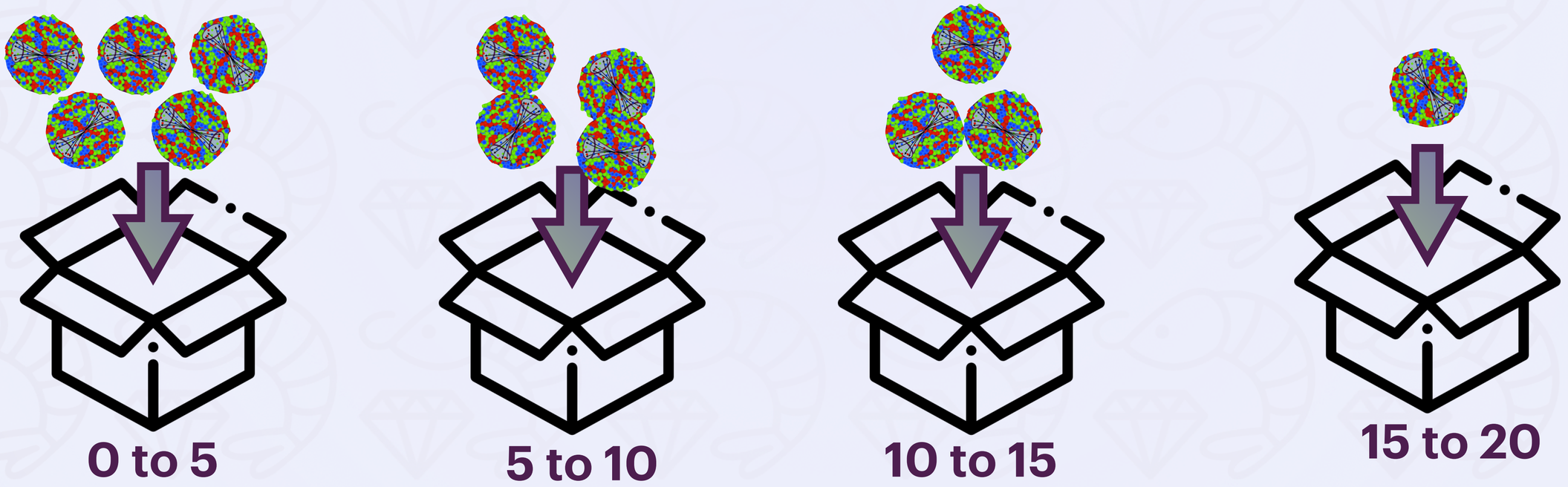
- Let’s investigate it with a very simplified model for a medium;
- Then we look at different jets evolving inside this medium:



JEWEL

Opacity Expansion

- Let’s investigate it with a very simplified model for a medium;
- Then we look at different jets evolving inside this medium;
- And then we bin them in number of jet-medium interactions:



JEWEL

Opacity Expansion

- Let’s investigate it with a very simplified model for a medium;
- Then we look at different jets evolving inside this medium;
- And then we bin them in number of jet-medium interactions;
- Finally, we look at different observables and how they vary in the different bins!

JEWEL

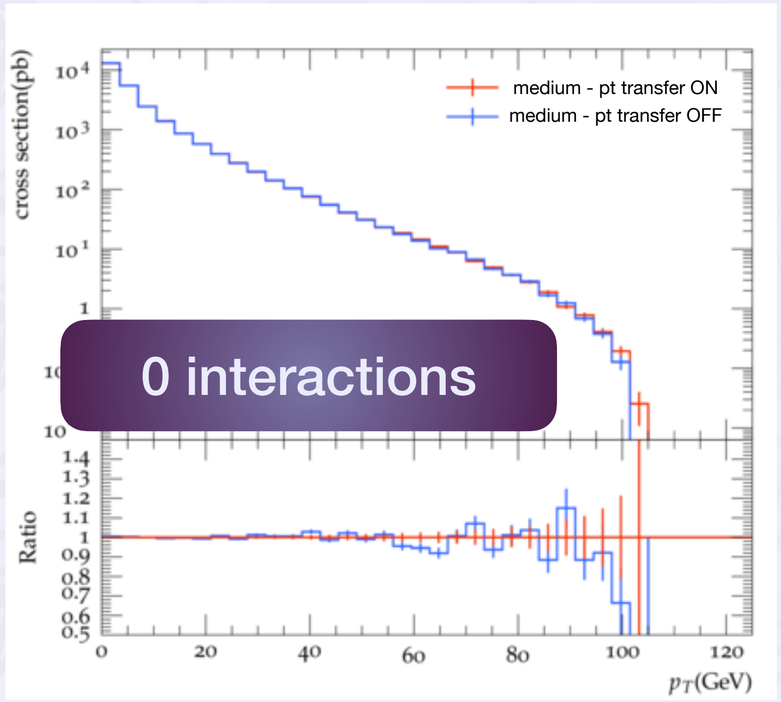
Jet RAA

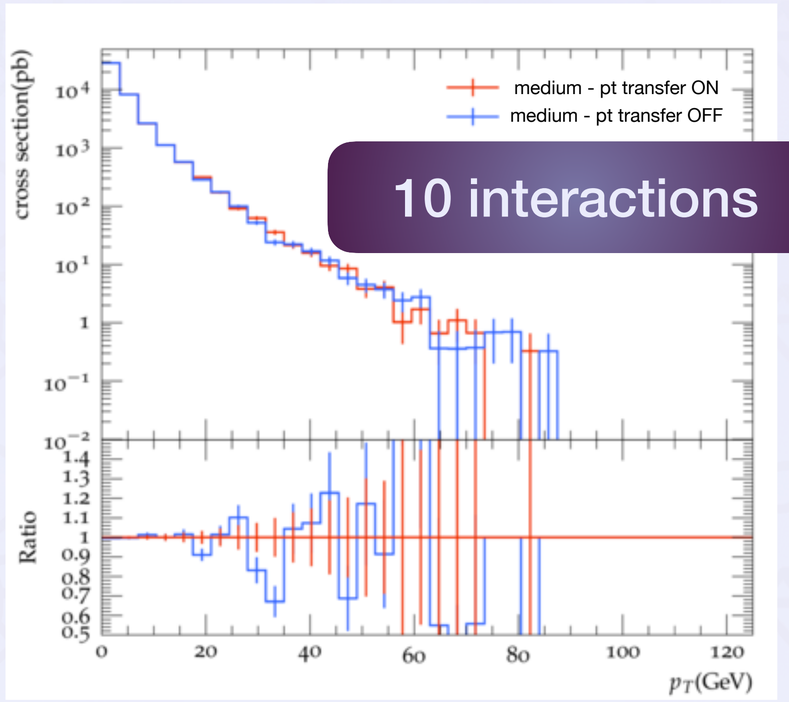
(There are a few caveats so ask me during the questions if you wish, but...)

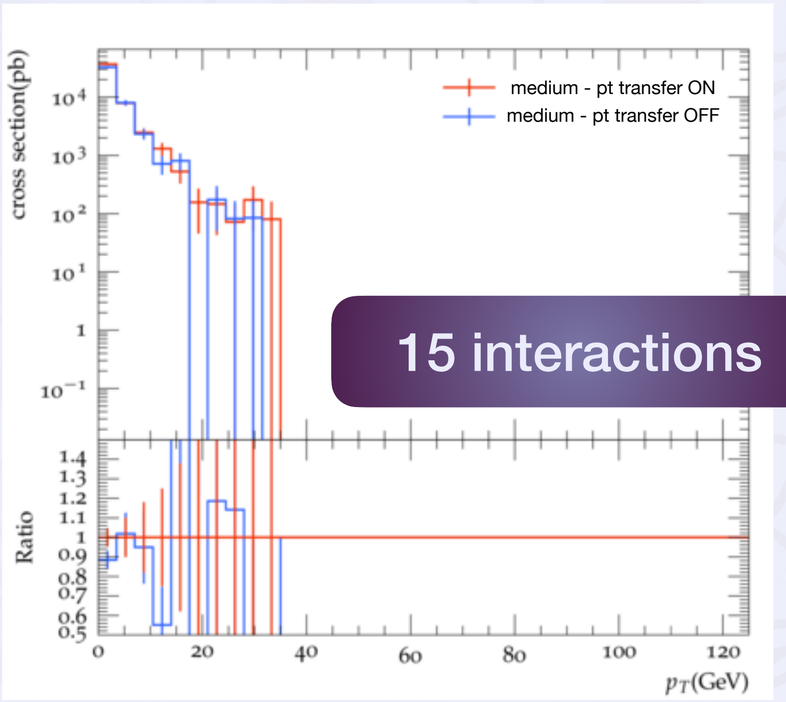
JEWEL

Jet RAA

- (There are a few caveats so ask me during the questions if you wish, but...)
- So far, results show that it takes more than ~15 jet-medium interactions to see signs of jet quenching







Conclusions and outlook

- SHRiMPS for pA (and AA 🤞) is under construction!
- It will contain effect that can hopefully described experimental observations of collectivity and other effects in a unique and coherent framework from pp to AA
- 💎 Opacity expansion studies will shine light on how much jet-medium interaction is necessary for observables to be affected
- 💎 We will look into RAA as well as collective flow observables (v_2)

Thank you!

Back up slides

SHRiMPS

Soft and Hard Reactions Involving Multi Pomeron Scattering

Average over GW states!

Using that and the optical theorem, the differential pp cross sections are obtained:

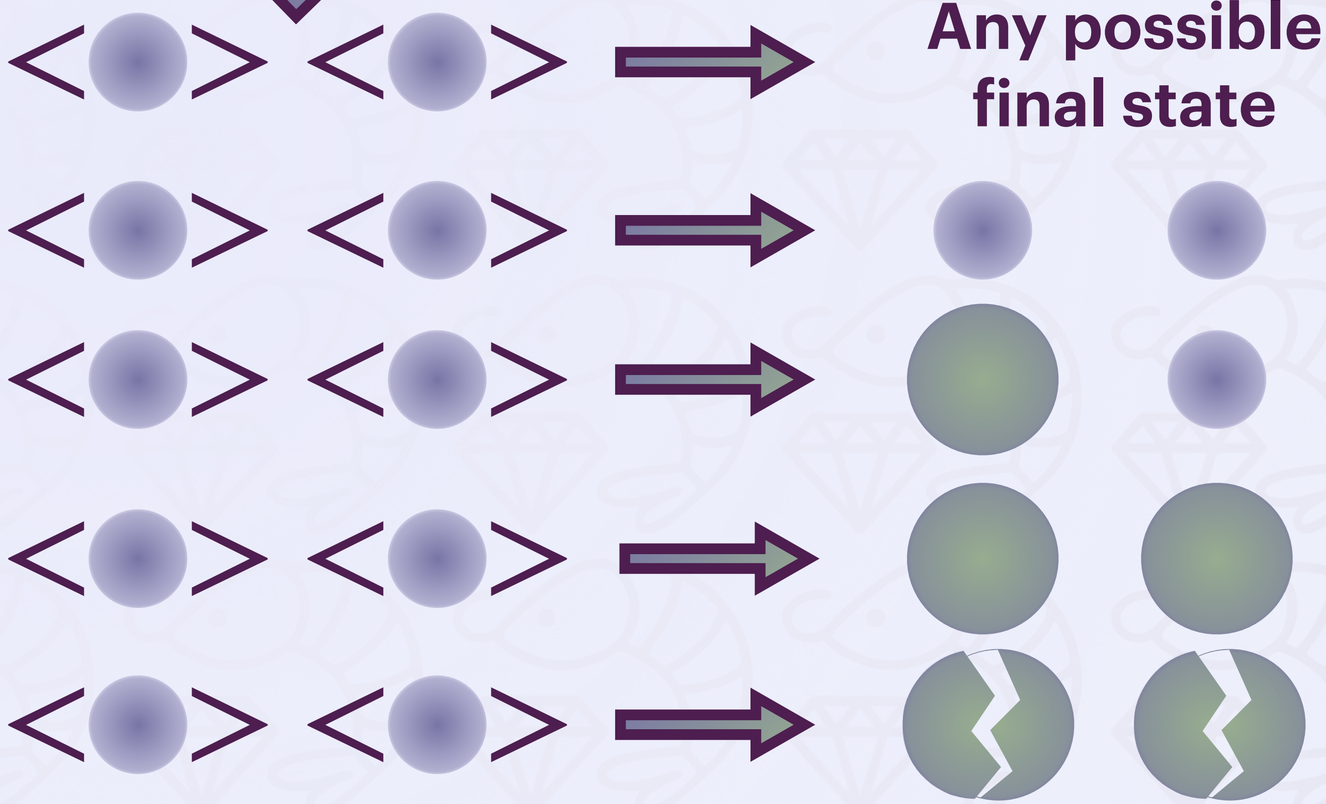
$$\frac{d\sigma_{tot}}{d\vec{B}_\perp} = 2\sum_{i,k=1}^{N_{GW}} |a_i|^2 |a_k|^2 (1 - e^{-\Omega_{ik}(s,b)/2})$$

$$\frac{d\sigma_{el}}{d\vec{B}_\perp} = \left[\sum_{i,k=1}^{N_{GW}} |a_i|^2 |a_k|^2 (1 - e^{-\Omega_{ik}(s,B_\perp)/2})\right]^2$$

Similar for Low Mass Single Diffraction

And for Low Mass Double Diffraction

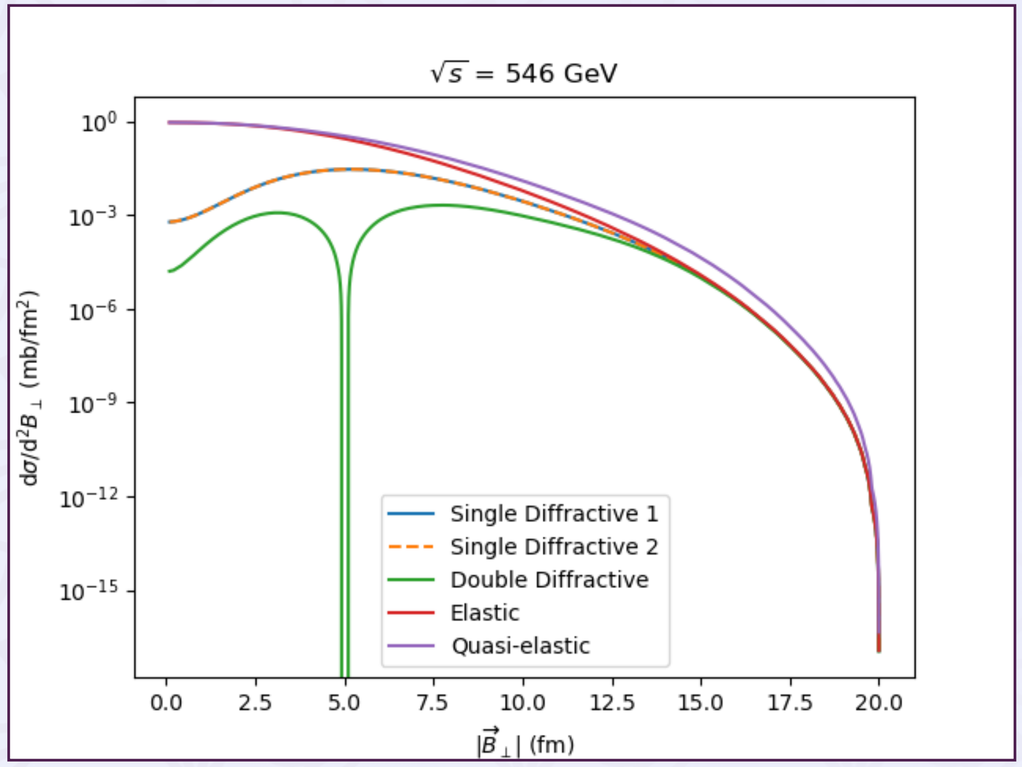
And for Inelastic Non-Diffractive

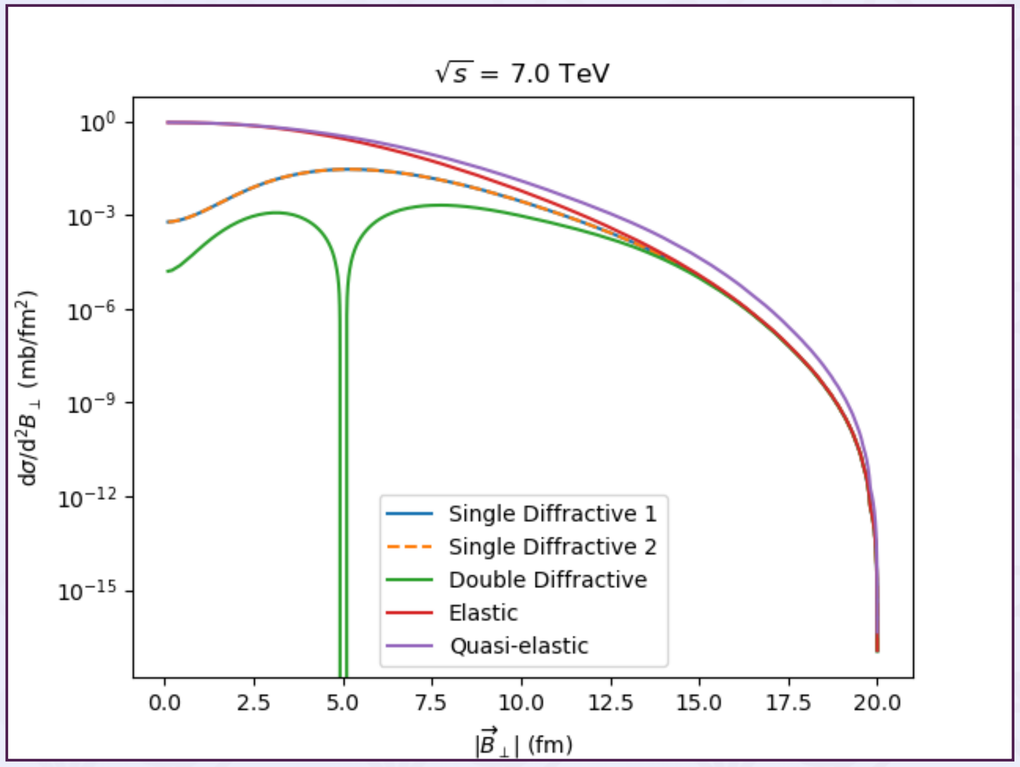


SHRiMPS

Soft and Hard Reactions Involving Multi Pomeron Scattering

The quasi elastic (elastic or low mass diffractive) cross sections as functions of impact parameter are:

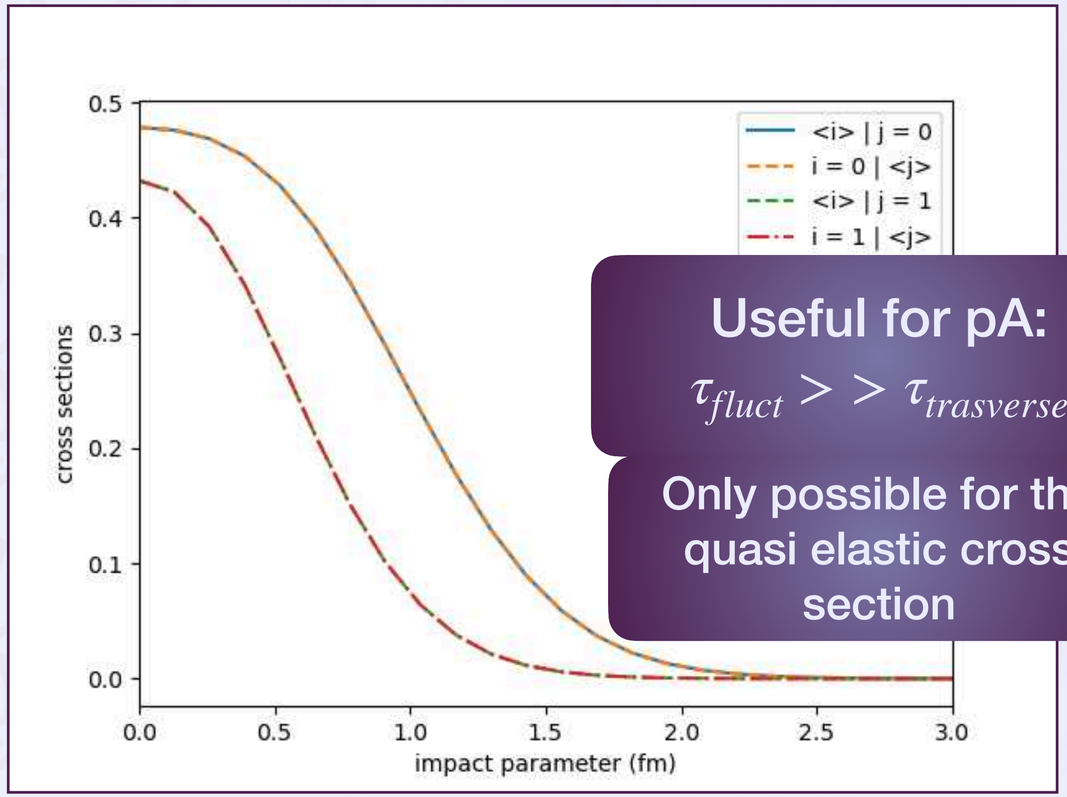




SHRiMPS

Soft and Hard Reactions Involving Multi Pomeron Scattering

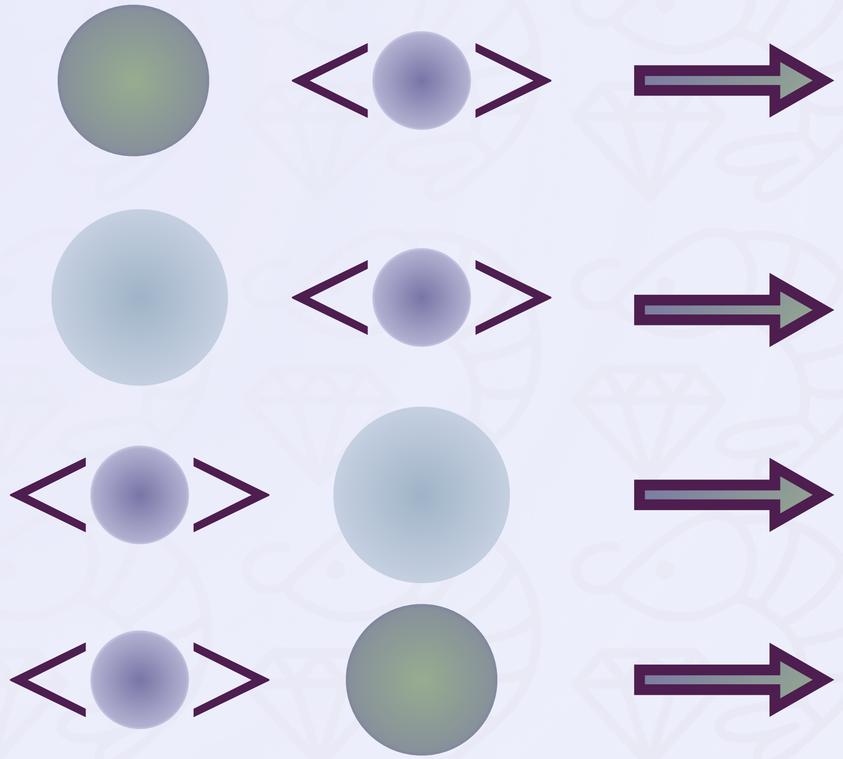
We can also obtain the quasi elastic cross section when one of the incoming protons is in a fixed Good Walker state!!



Useful for pA:

$\tau_{fluct} >> \tau_{trasverse}$

Only possible for the quasi elastic cross section



Quasi-elastic

Quasi-elastic

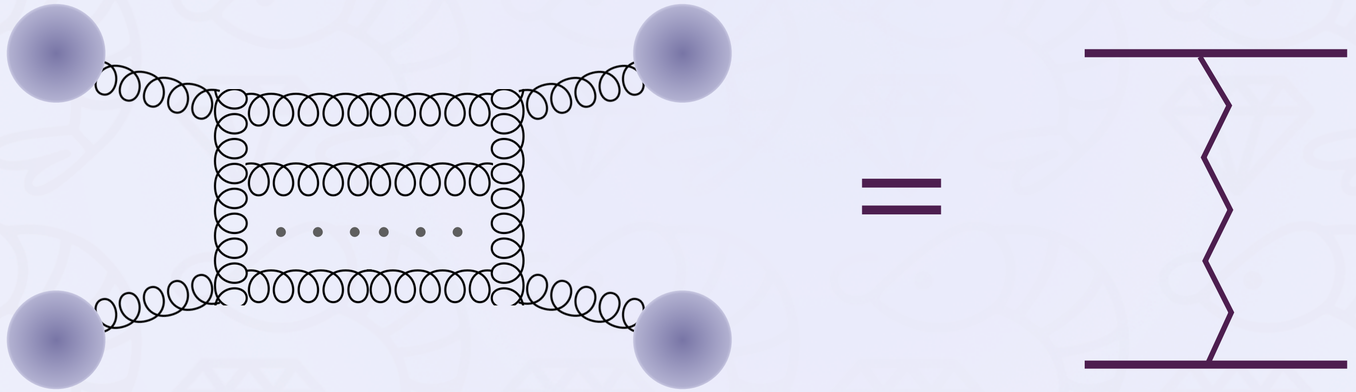
Quasi-elastic

Quasi-elastic

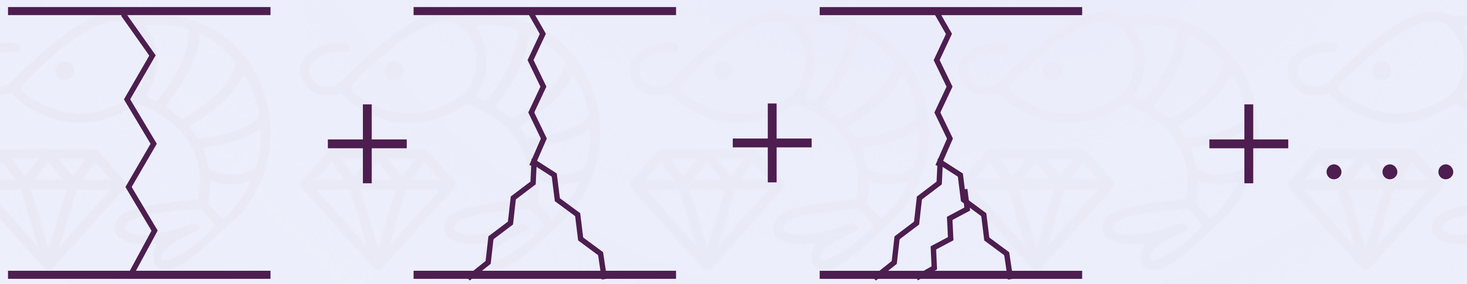
SHRiMPS

Soft and Hard Reactions Involving Multi Pomeron Scattering

- As for inelastic non-diffractive interactions...
- One can write probabilities for gluon emission per unit rapidity...



- ... and absorption, such that one can obtain diagrams as:



OBS: in SHRiMPS we generate the cut diagrams directly

Can obtain high mass diffraction or rescattering depending on how to cut the diagram