HEAVY-FLAVOR PROBES OF ISOTROPIZATION IN SMALL SYSTEMS

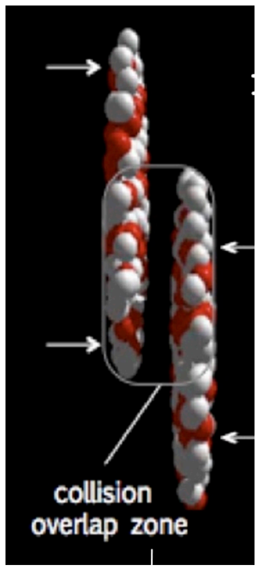
based on Int. J. Mod. Phys. E, 35 (2026) 7, 2641031, arXiv:2509.24316 and arXiv:2609.XXXXX

DARIA PROKHOROVA, SHUZHE SHI, 施舒哲 EVGENY ANDRONOV

Tsinghua University St. Petersburg State University

xQCD, BUSAN
JULY 16, 2026

FROM A+A COLLISIONS



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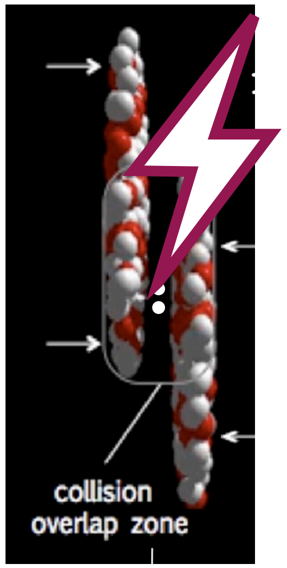

- hard scatterings

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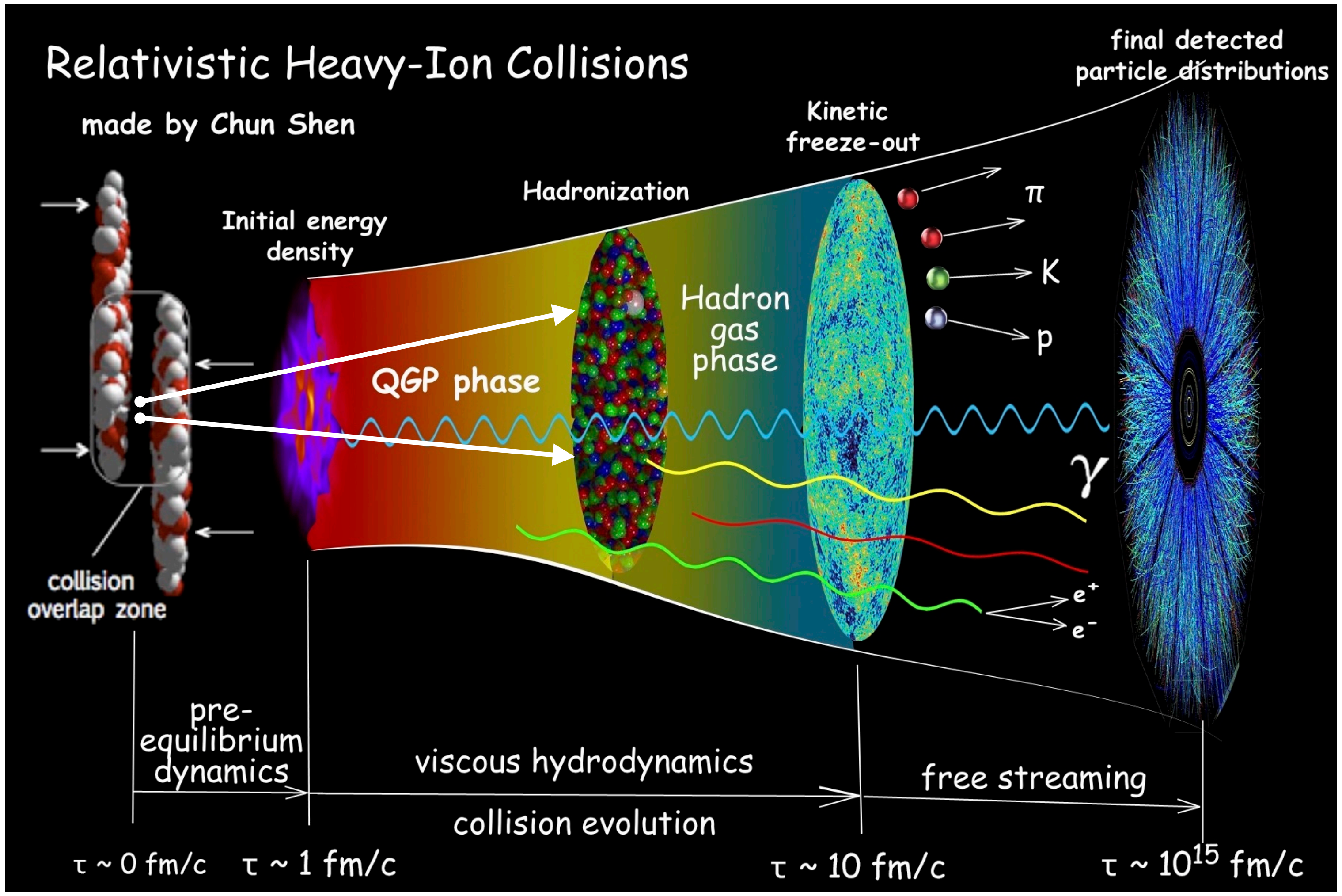

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- **QGP formation**, hadronization

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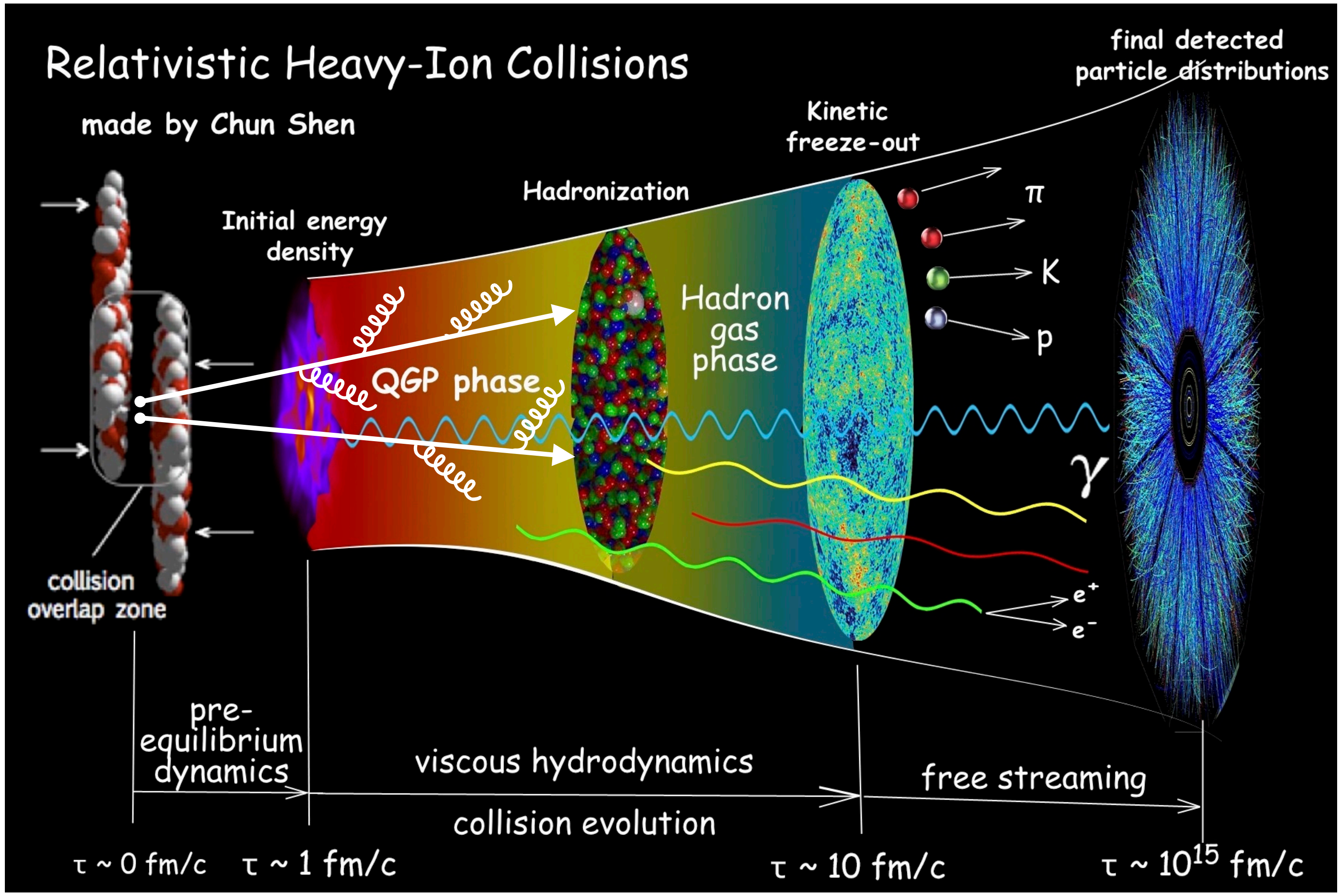

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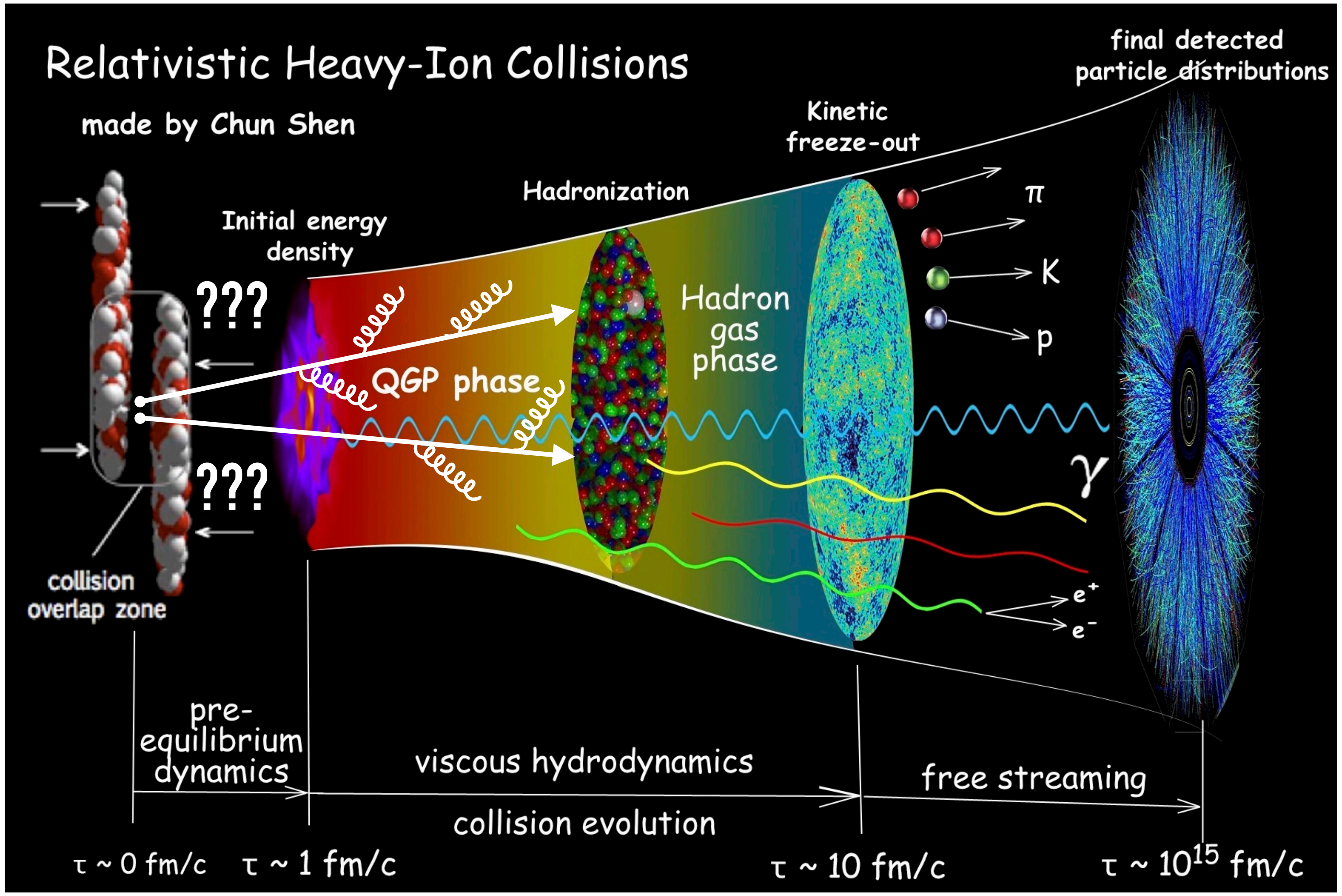

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- initial stages - unclear!

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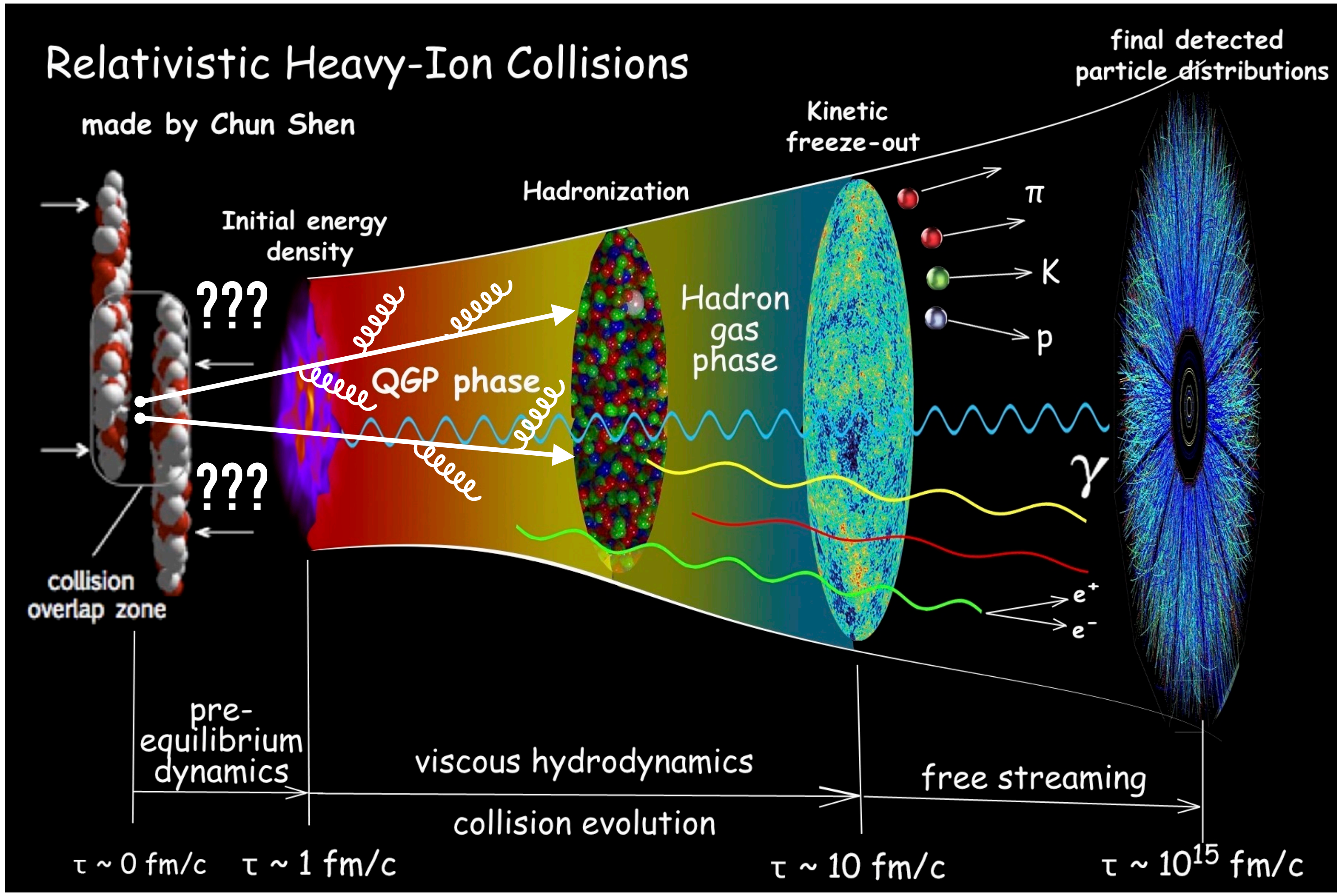

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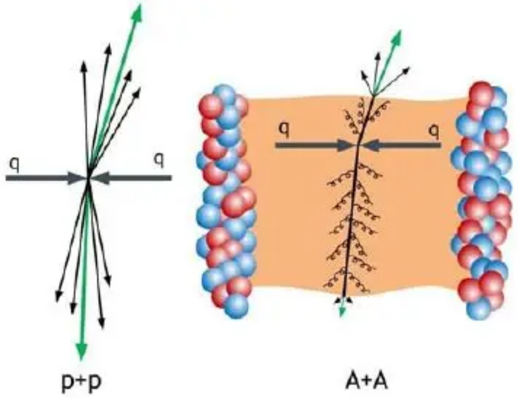
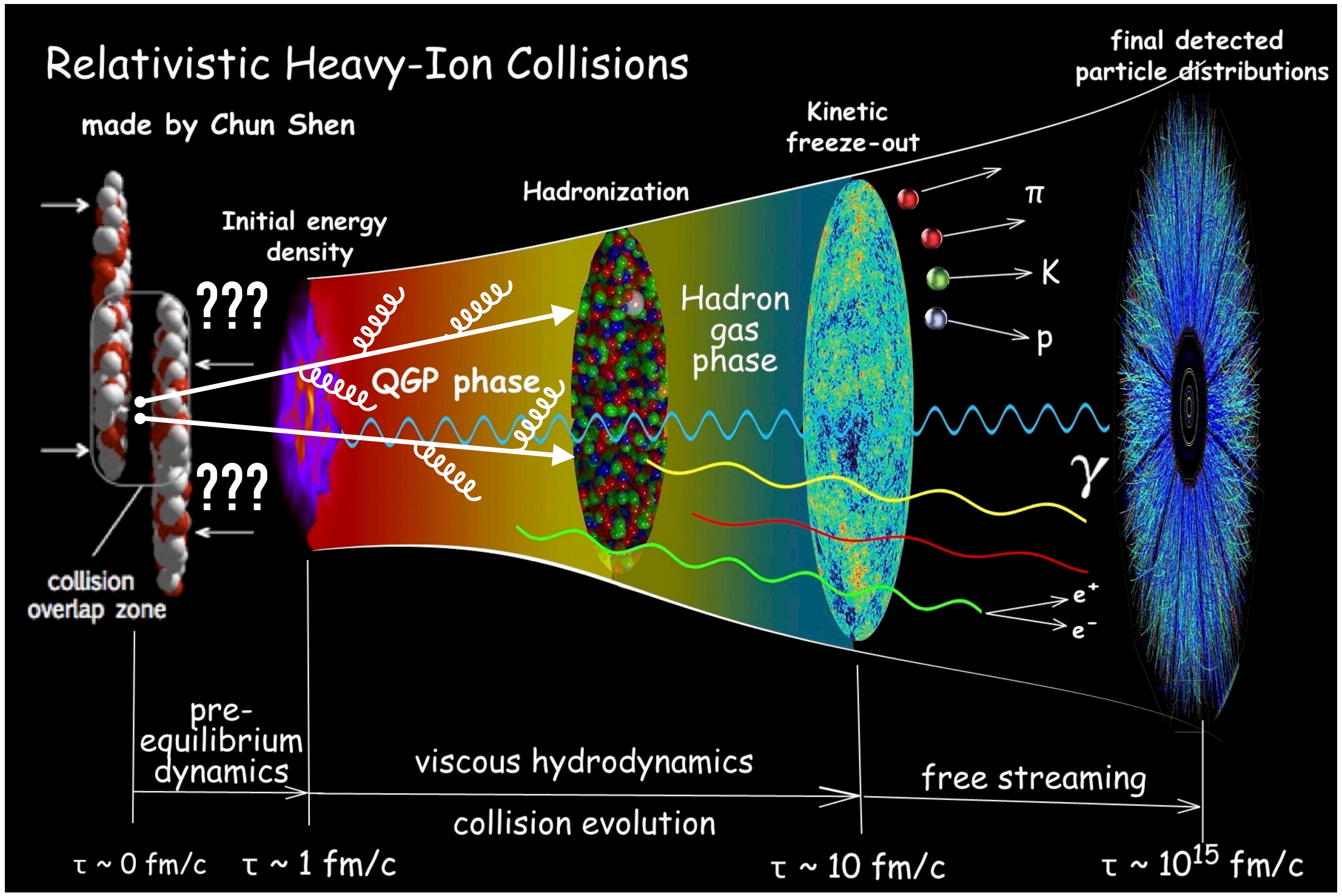
- **p+p data as reference**



FROM A+A COLLISIONS TO P+P INELASTIC INTERACTIONS



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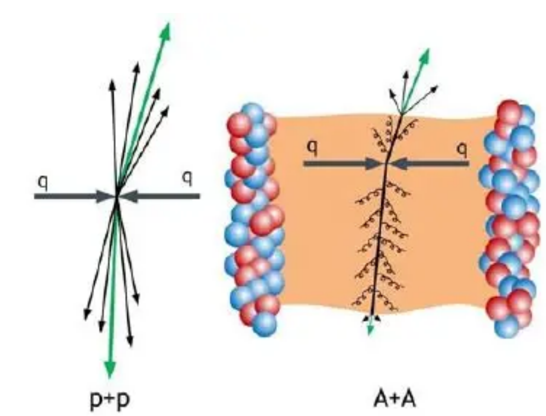
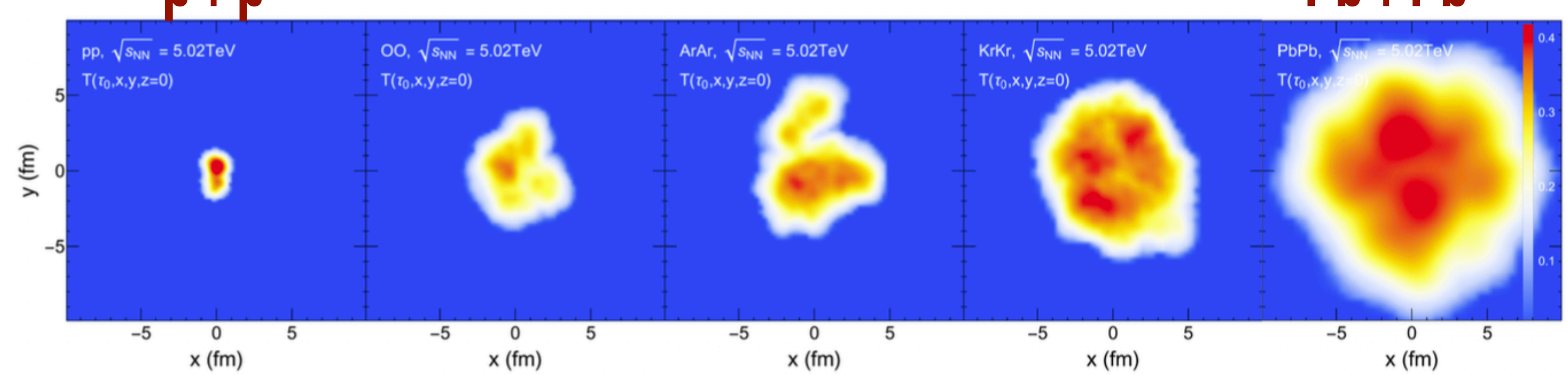


But what **if p+p is not so simple?**



[Zhao et al., Phys. Rev. C 111 (2025) 014907]

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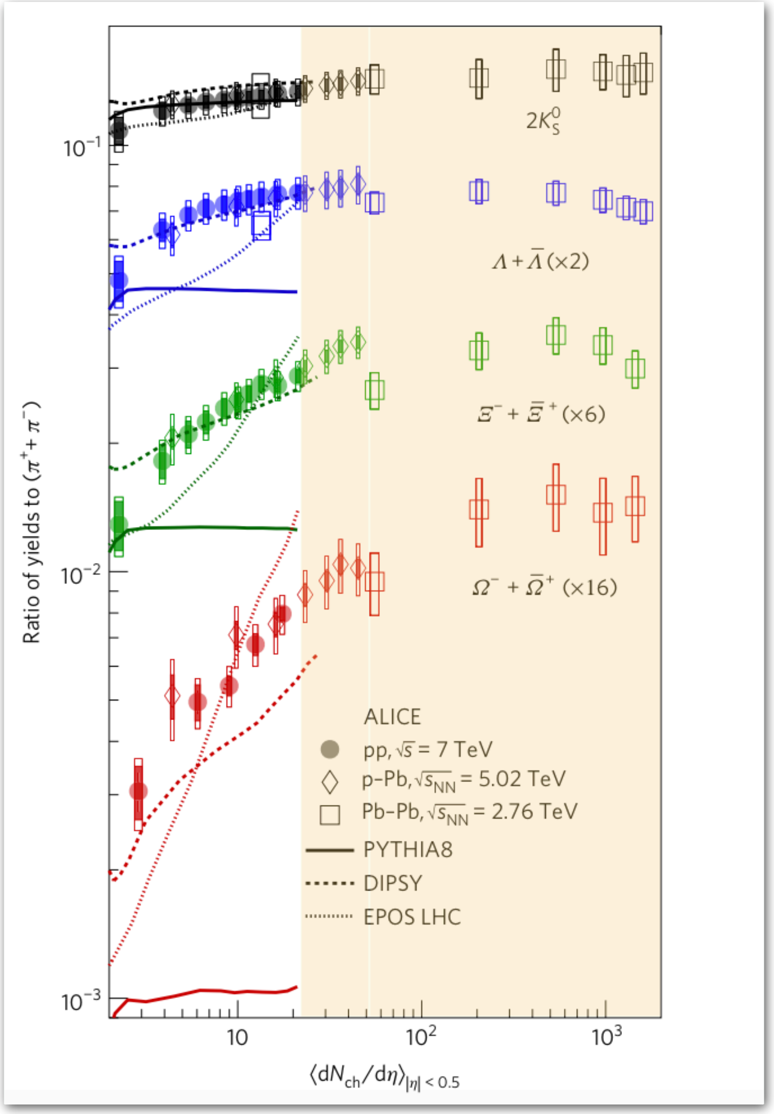
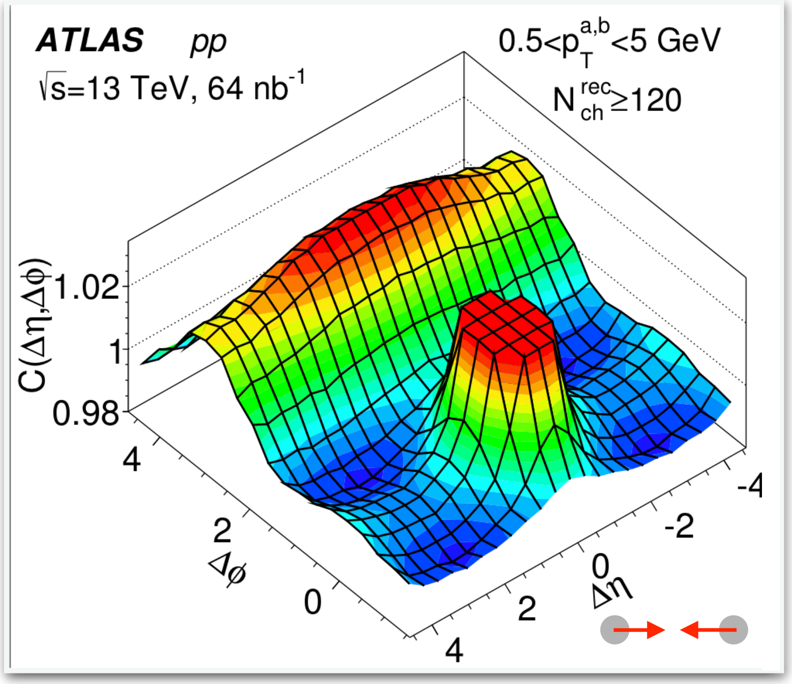


[ALICE, Nature Phys. 13 (2017) 535]

- evidence of collectivity

RIDGE?

[ATLAS, Phys. Rev. C 96 (2017) 024908]



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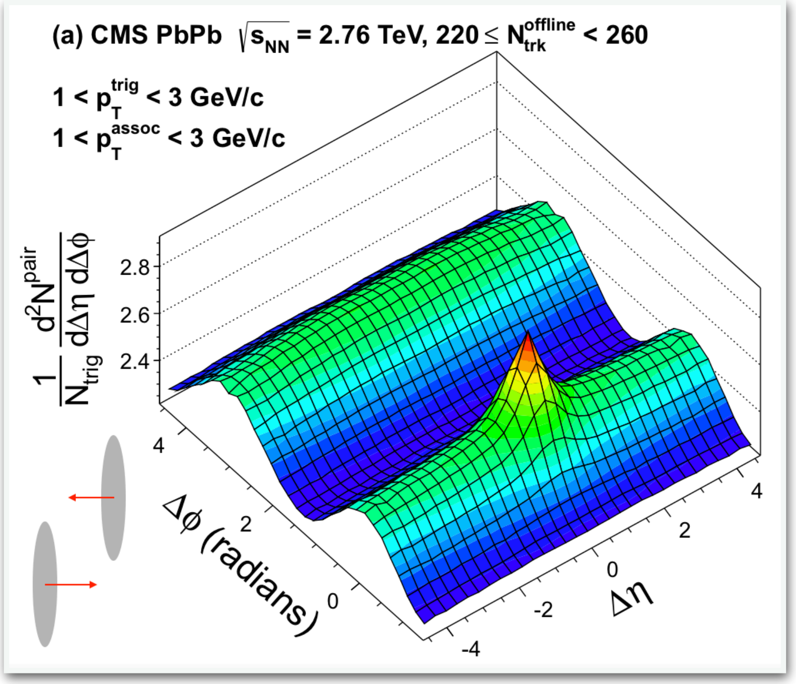
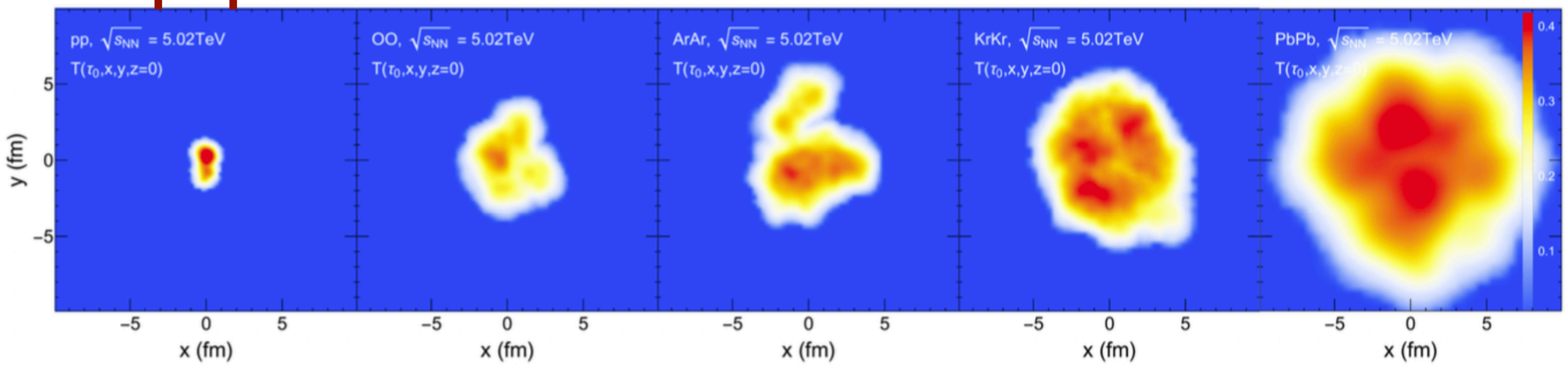
[CMS, Phys. Lett. B 724 (2013) 213]



p+p

Pb+Pb



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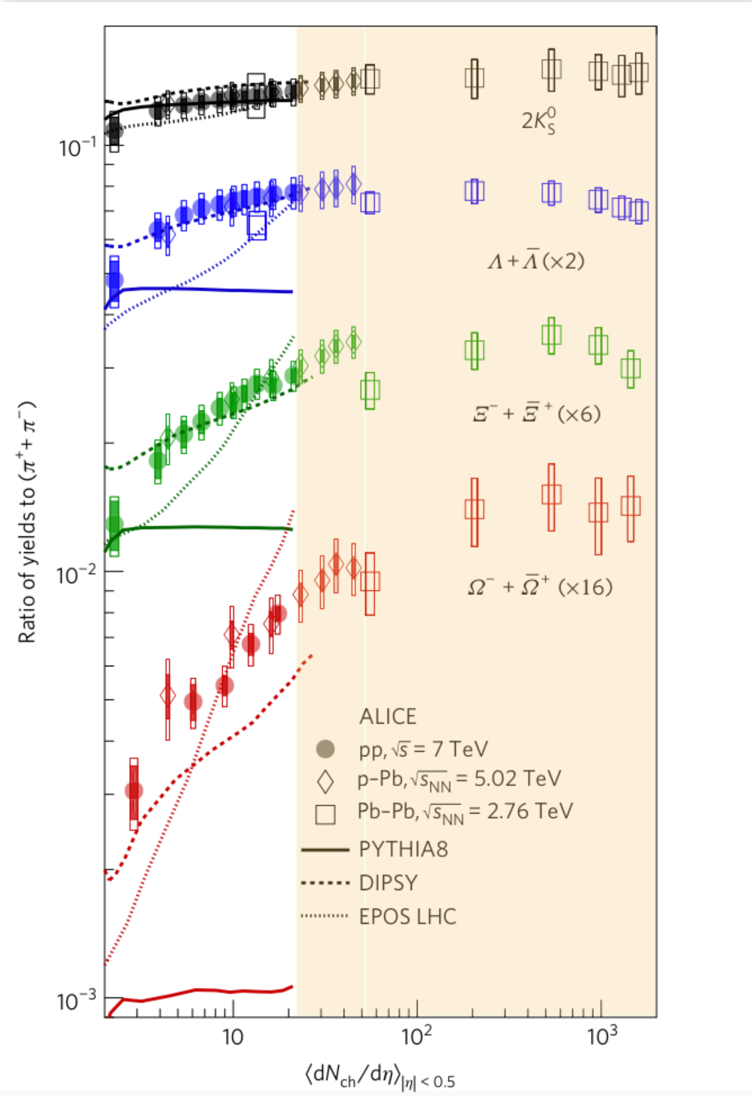

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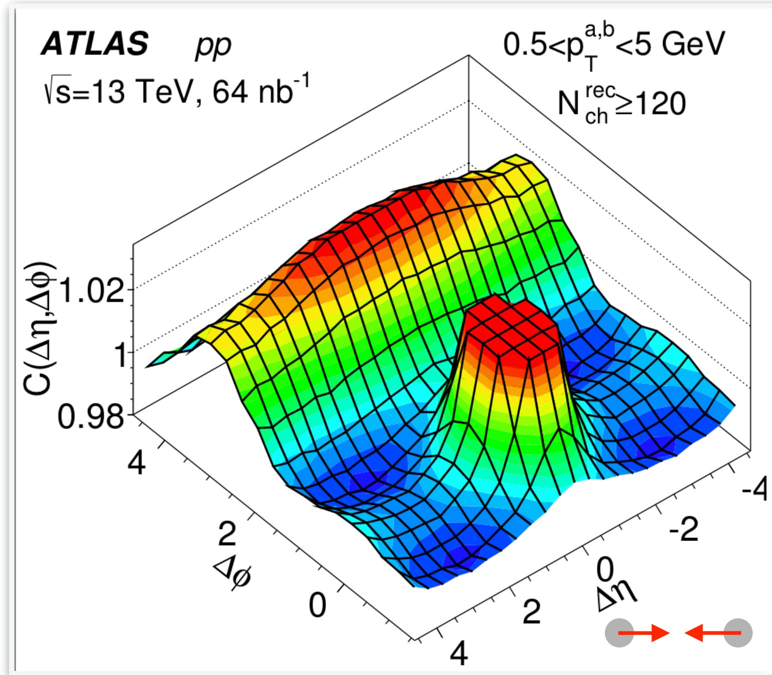

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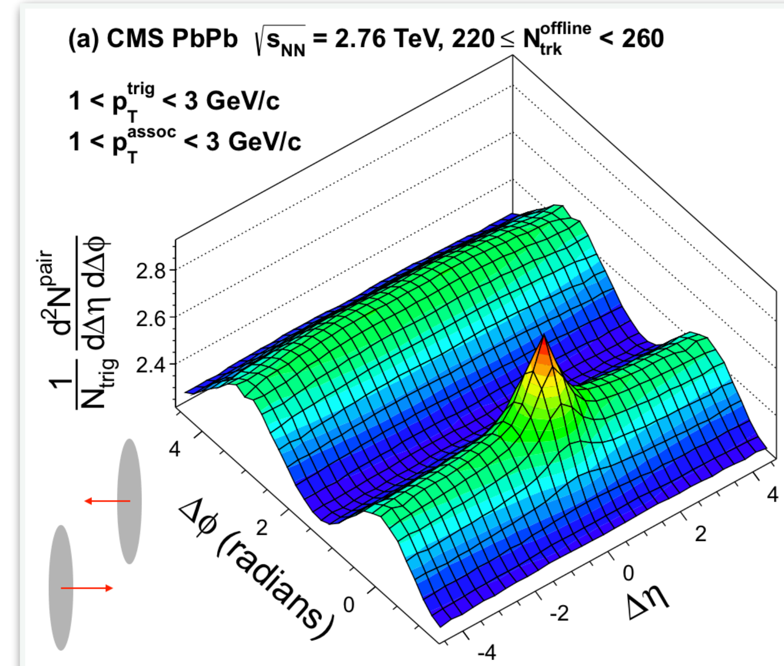
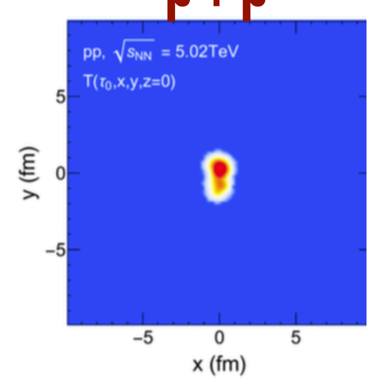
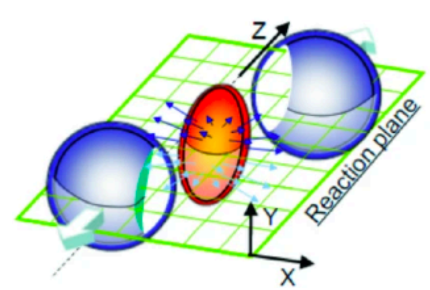
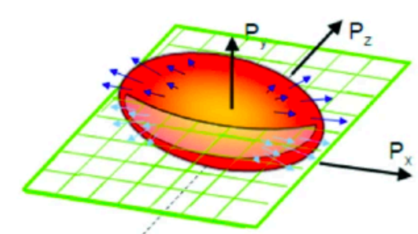


[Aggarwal et al. Adv. Nucl. Phys. 257 (2021) 161]

p+p







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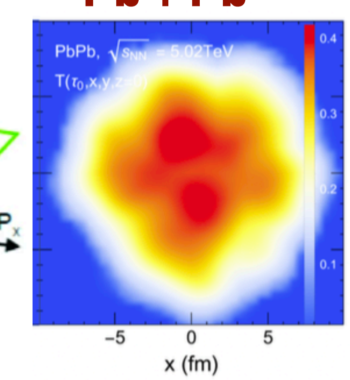

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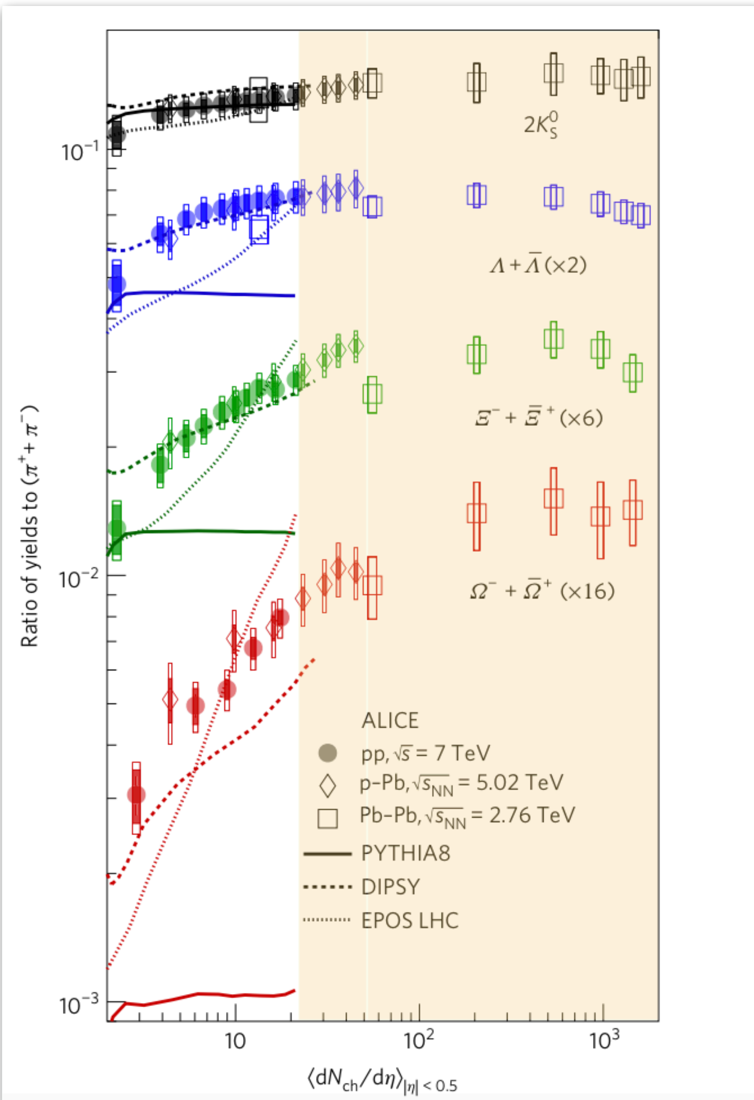

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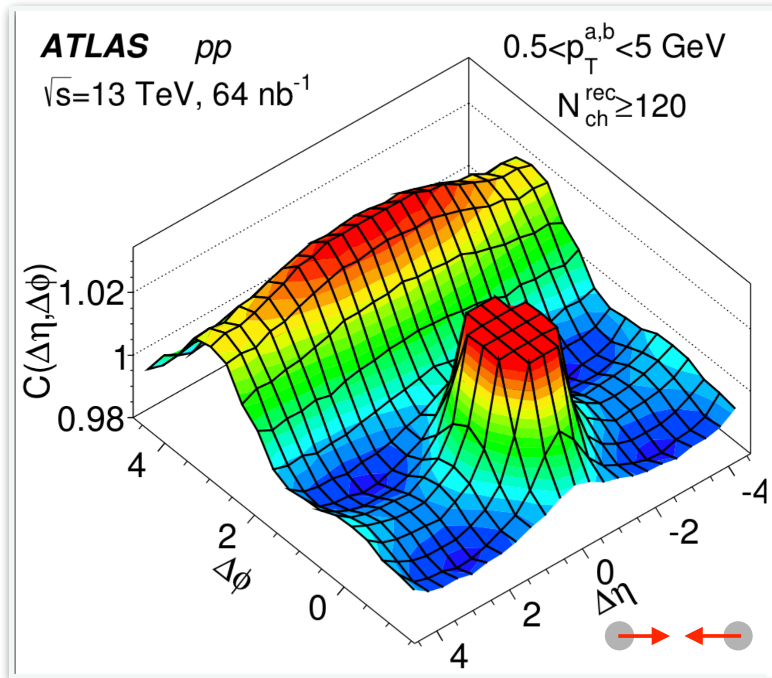

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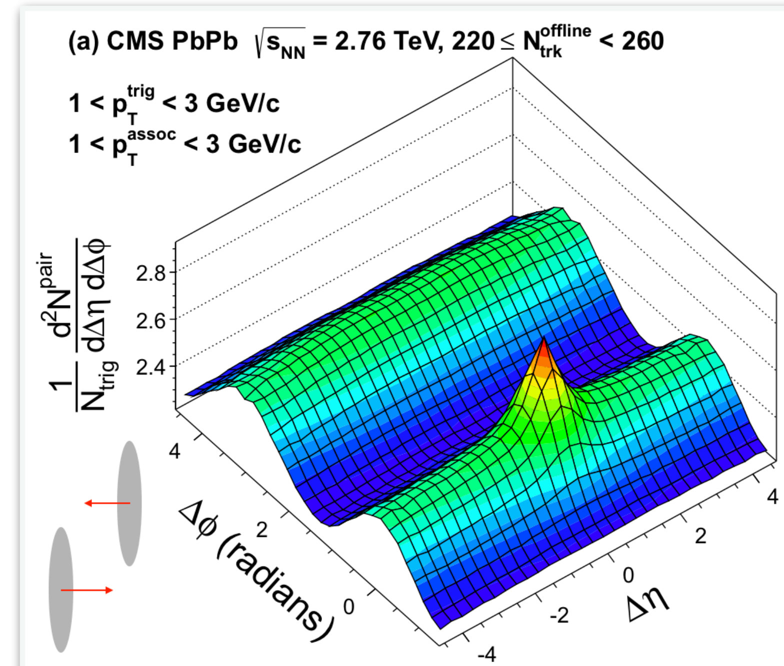

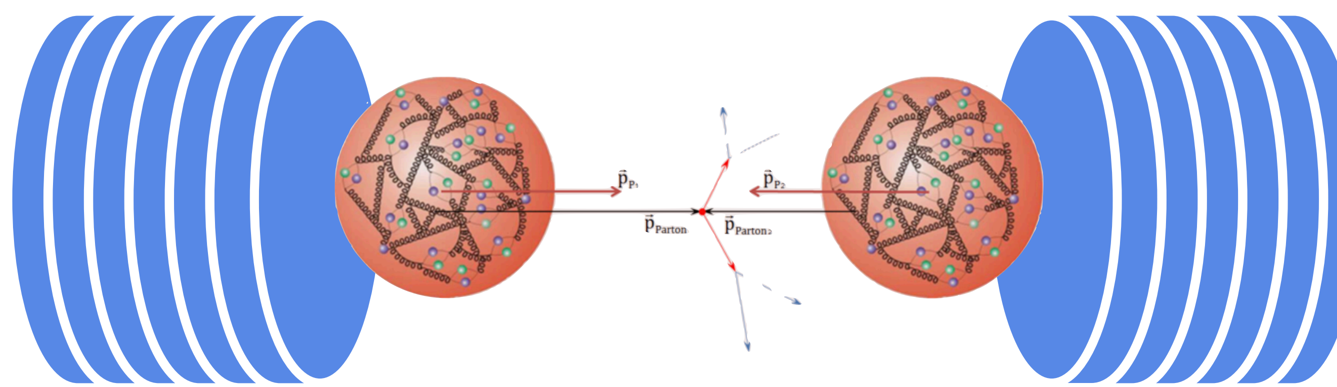

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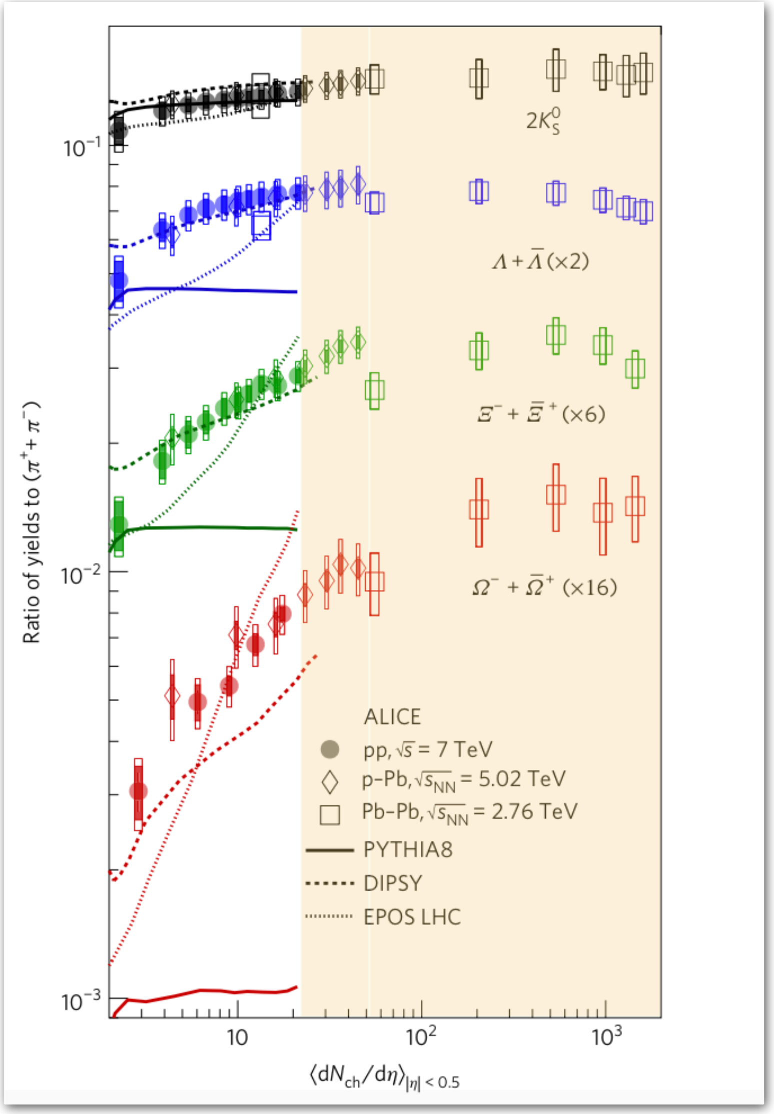

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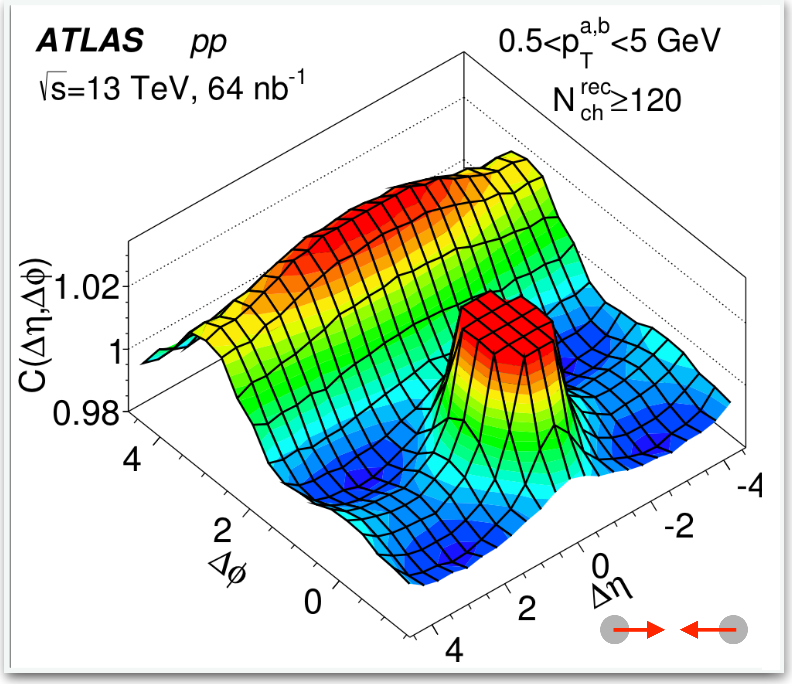

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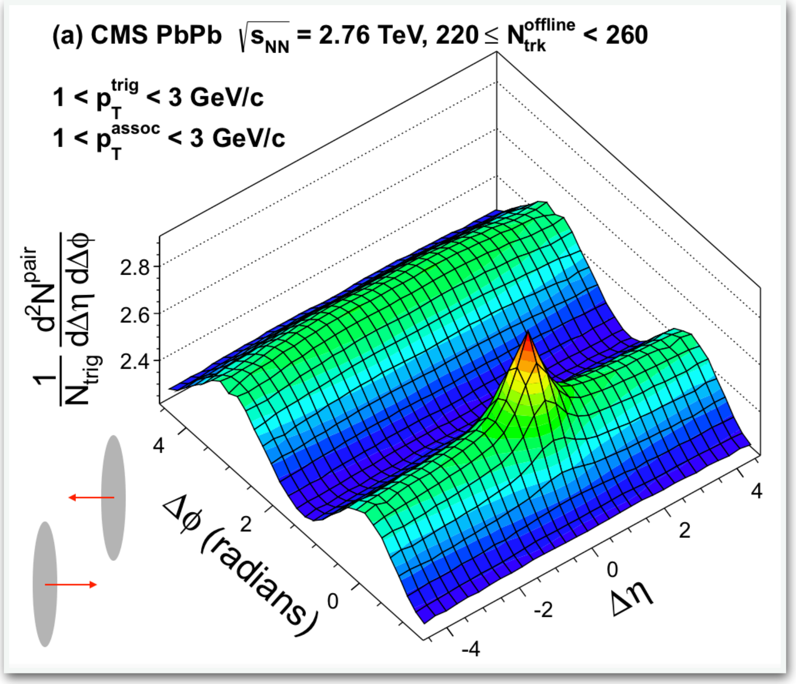

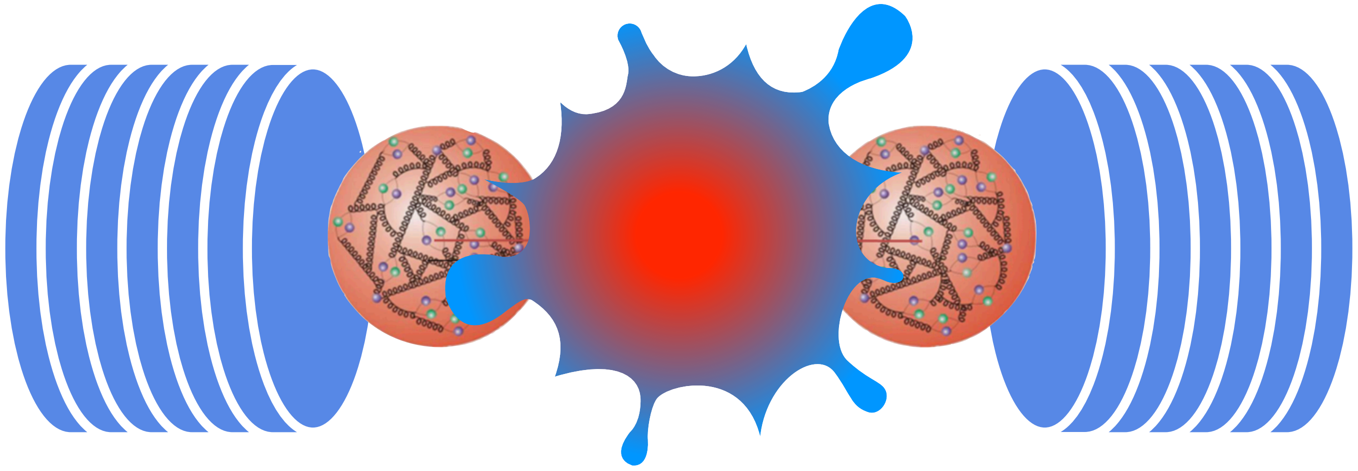

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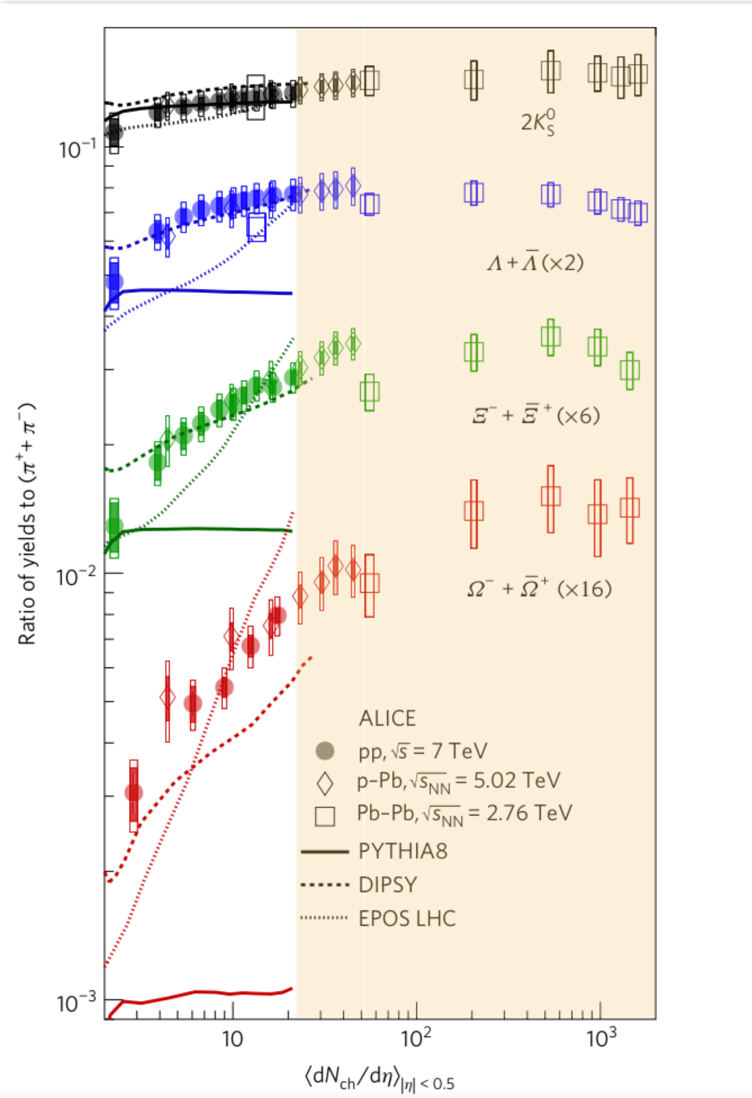

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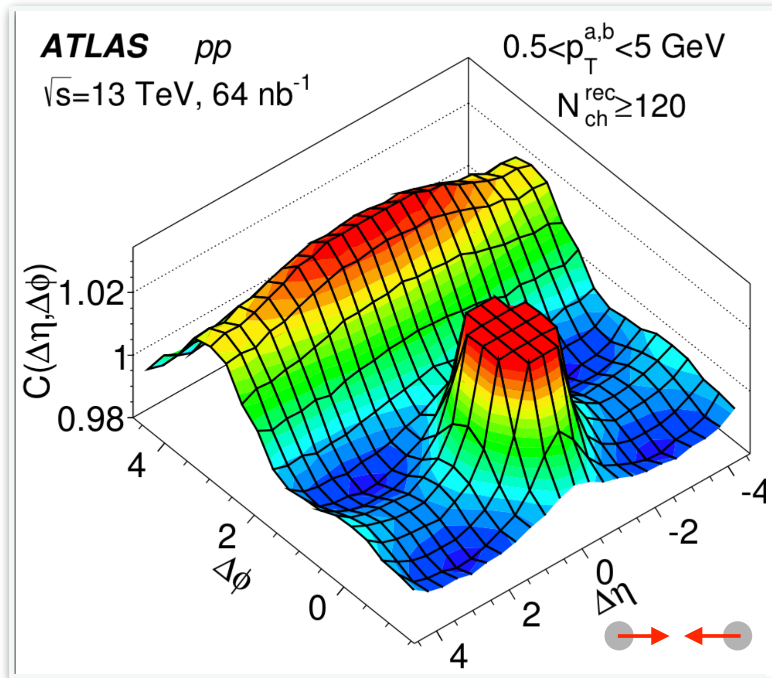

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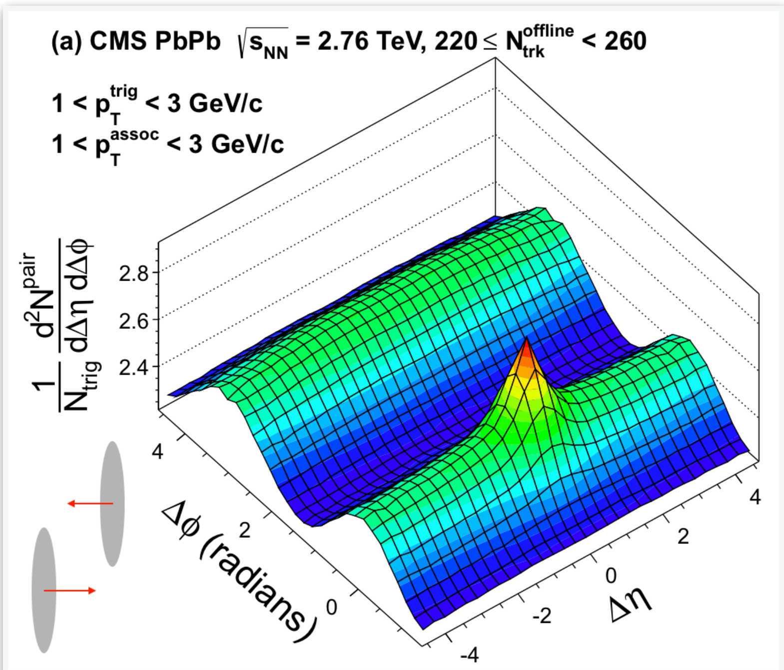

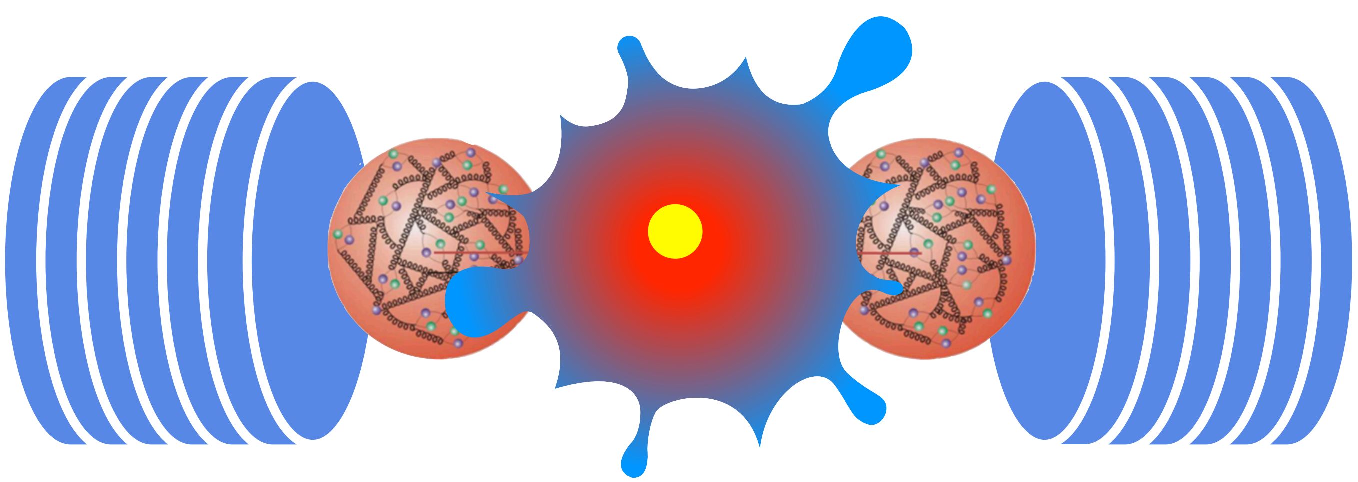

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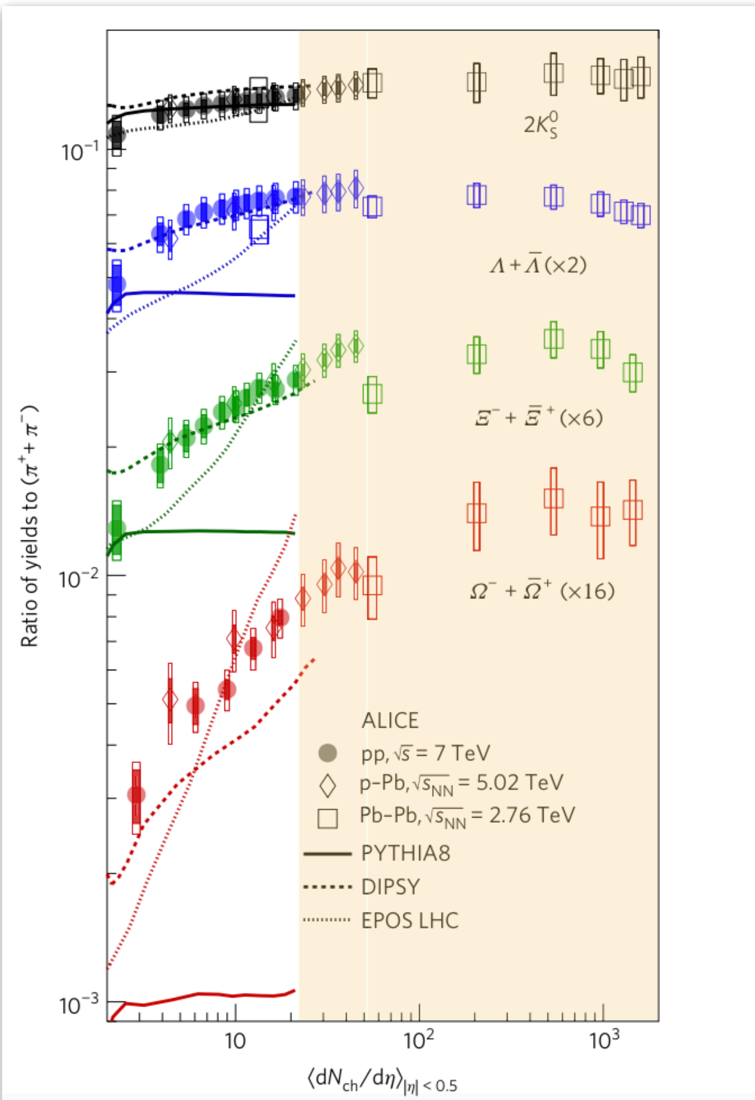

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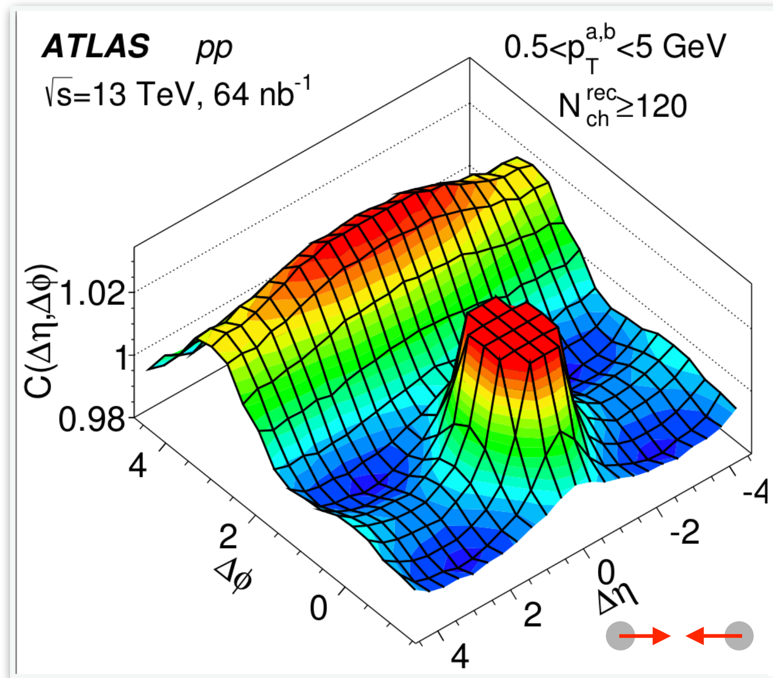

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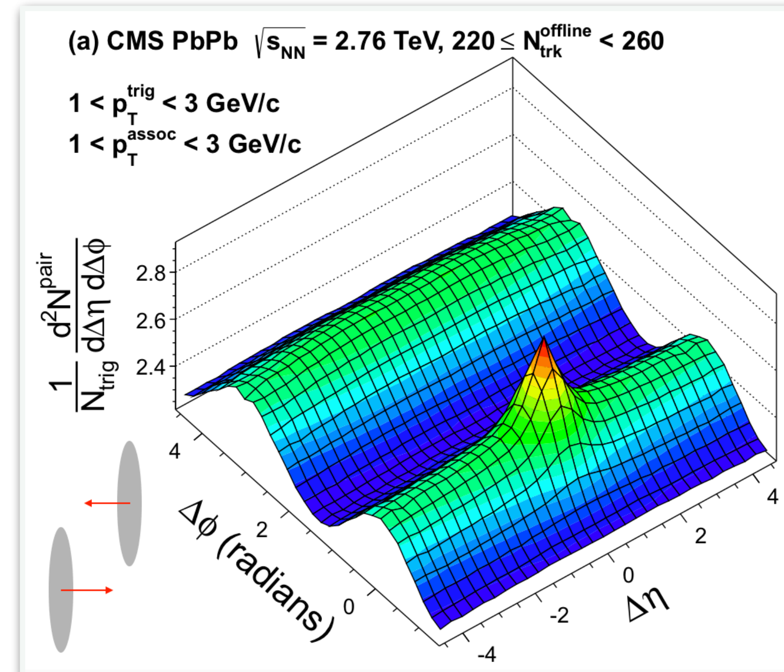

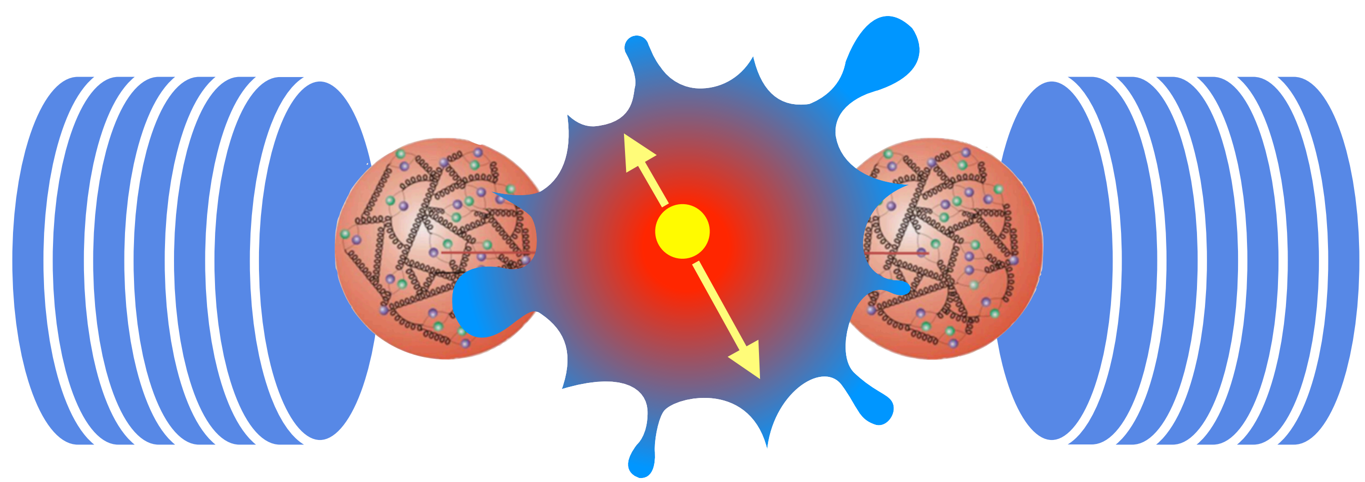

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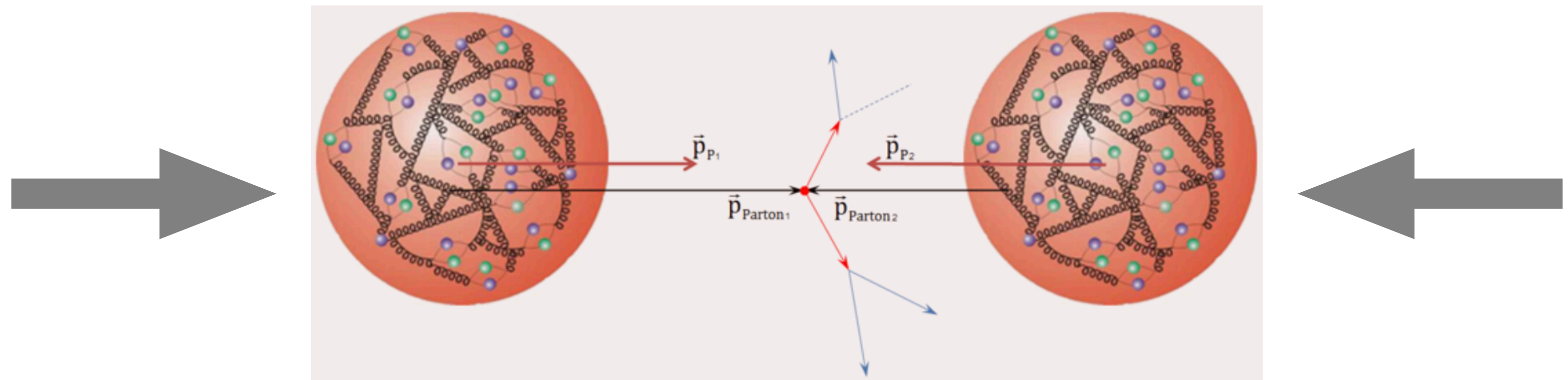
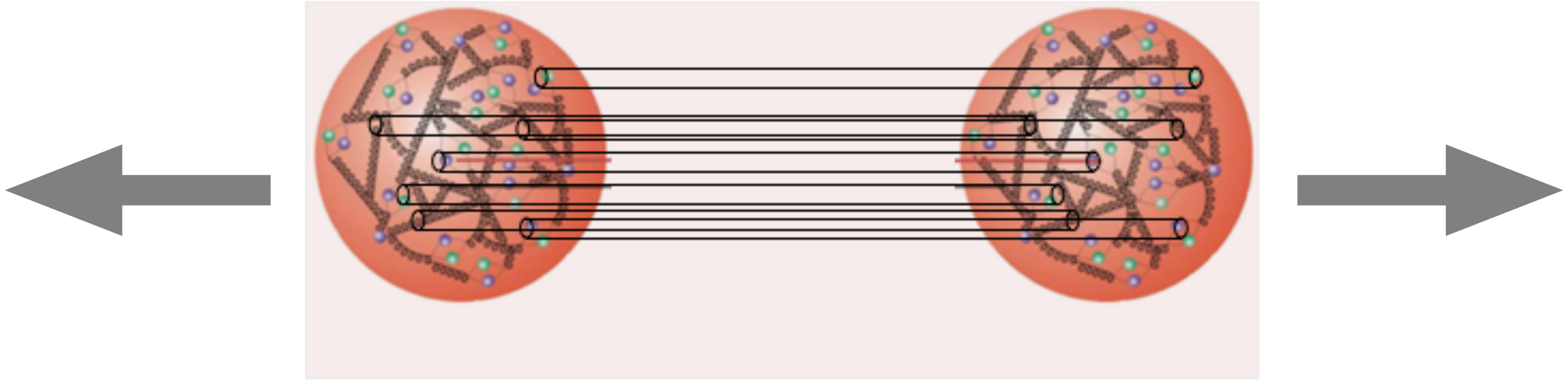
- can we test it with hard probes?
- is jet loss measurable in p+p?

OUR HYBRID MONTE-CARLO APPROACH

INTERACTION



INTERACTION: FLUX TUBES BETWEEN COLOR CHARGES



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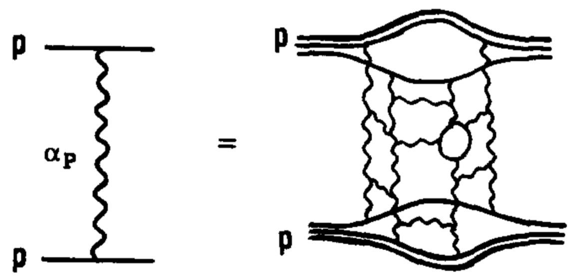
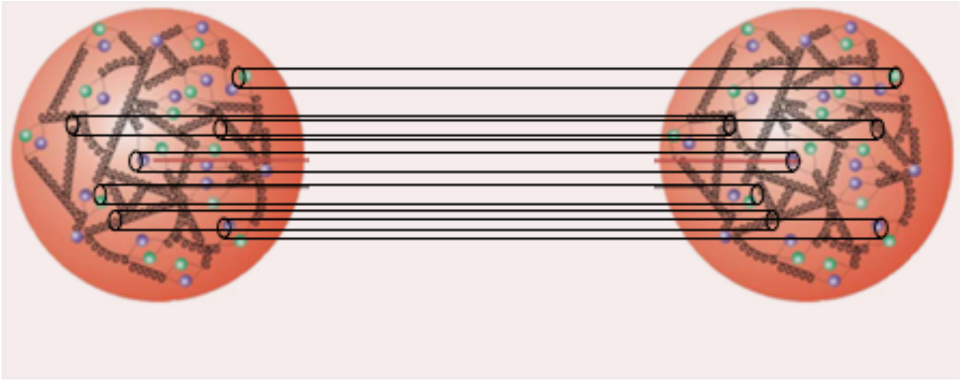
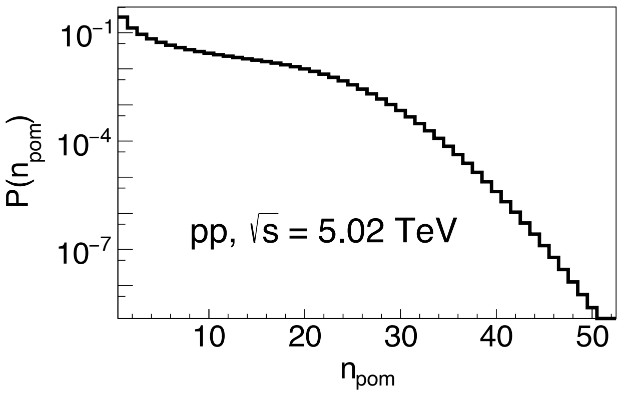
[Capella, Phys. Rep. 236 (1994) 225]







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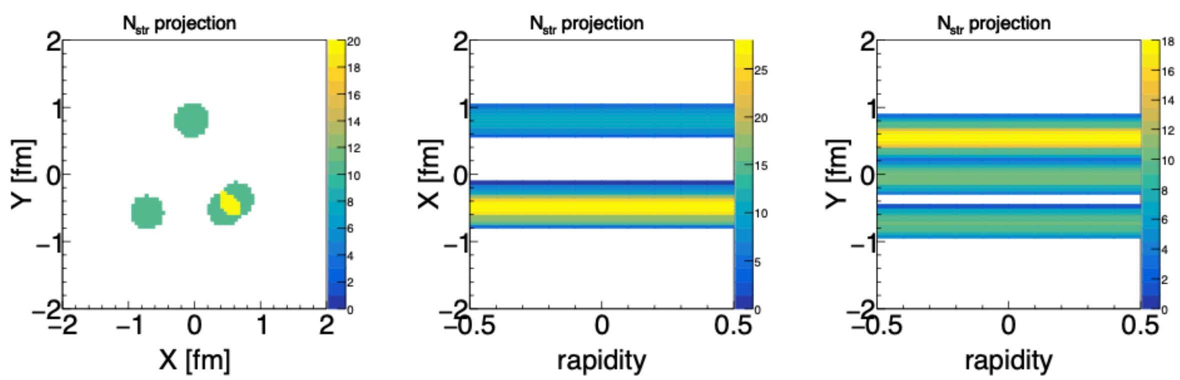

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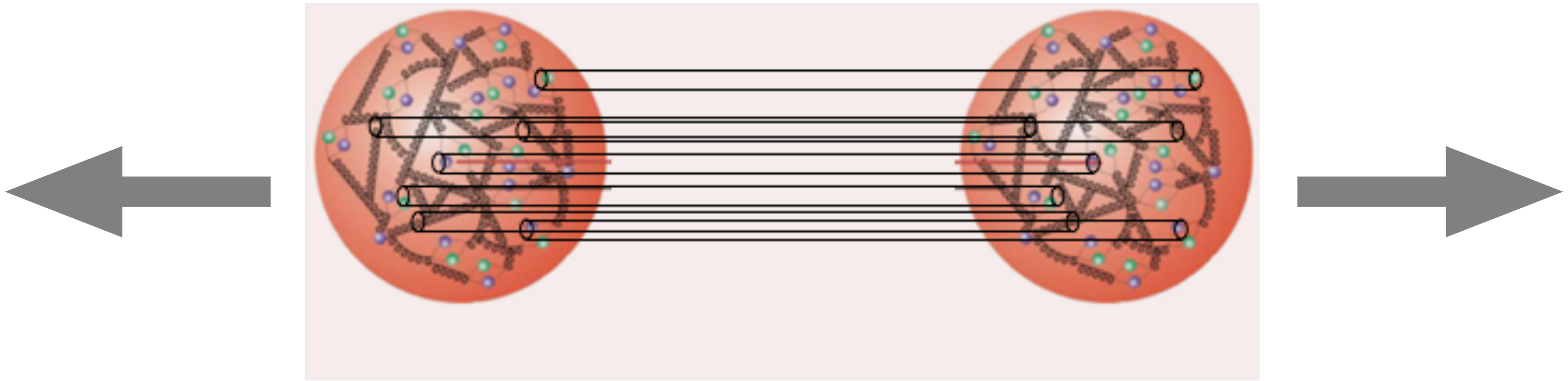

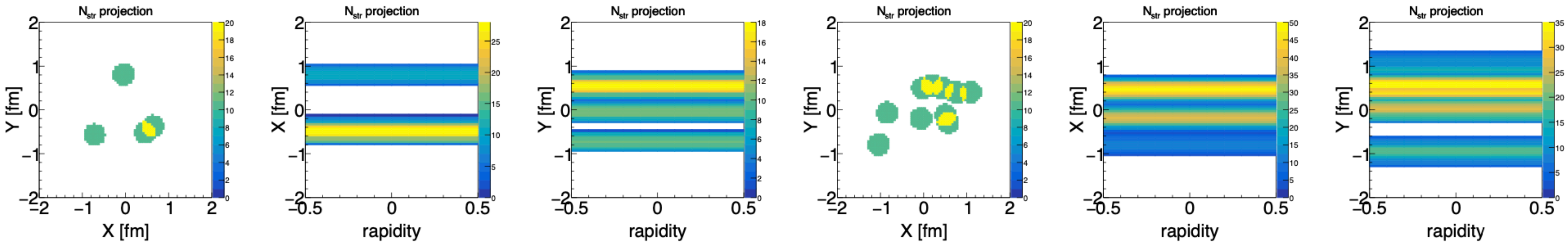

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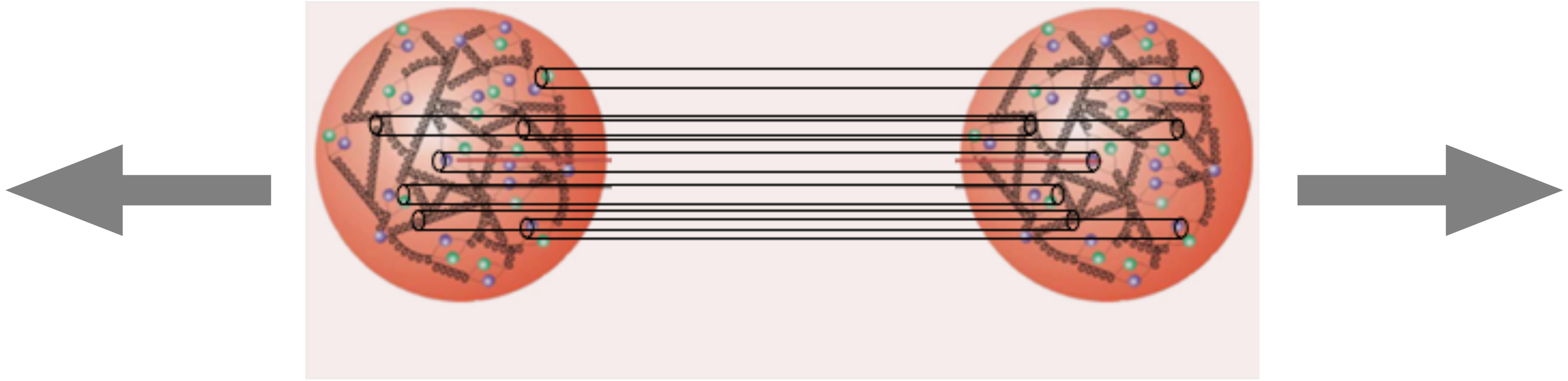

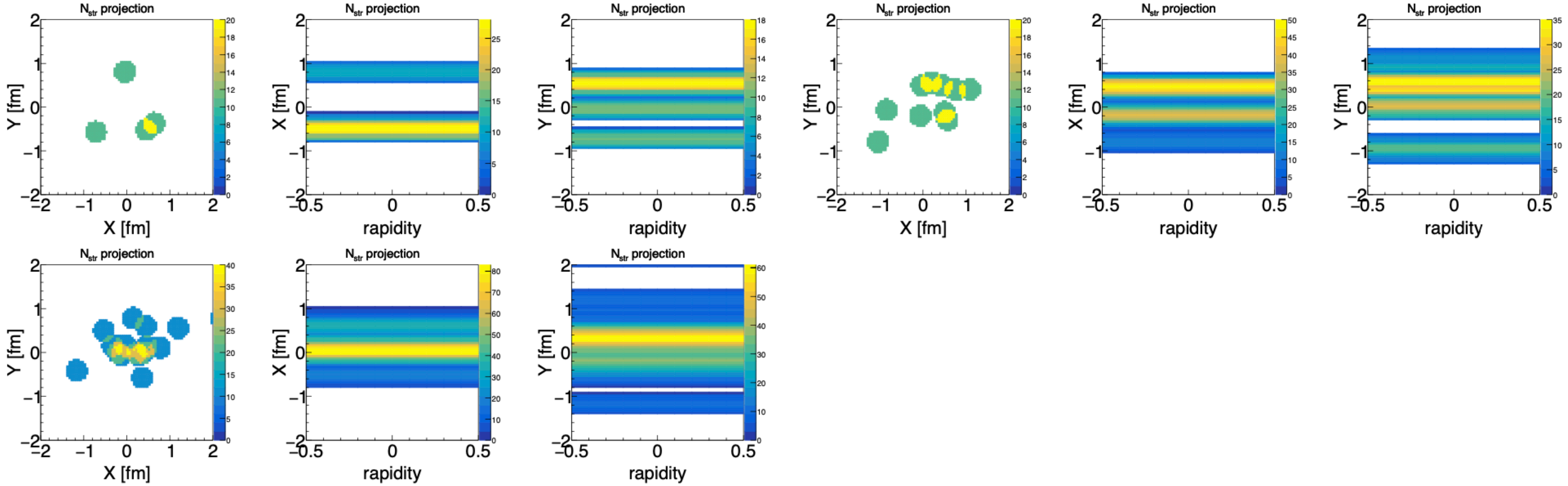

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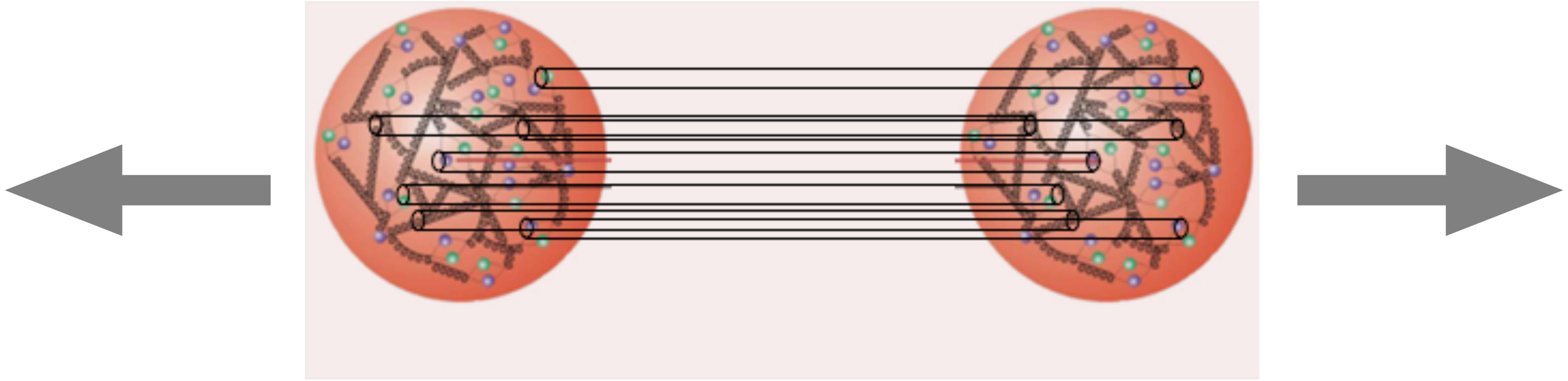

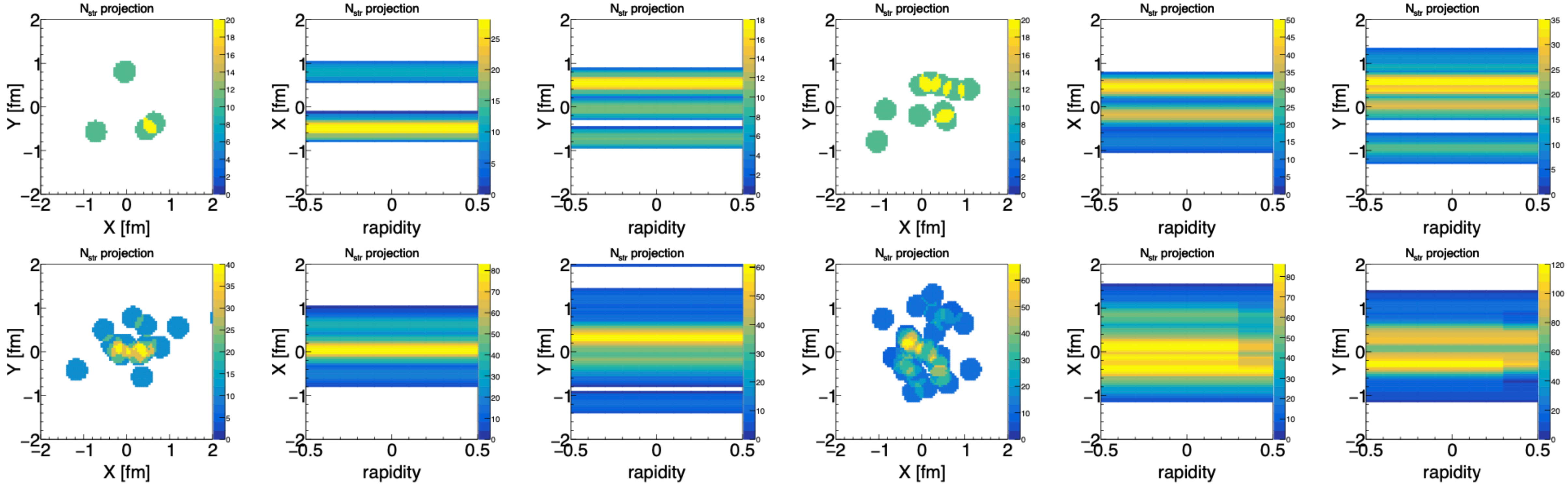

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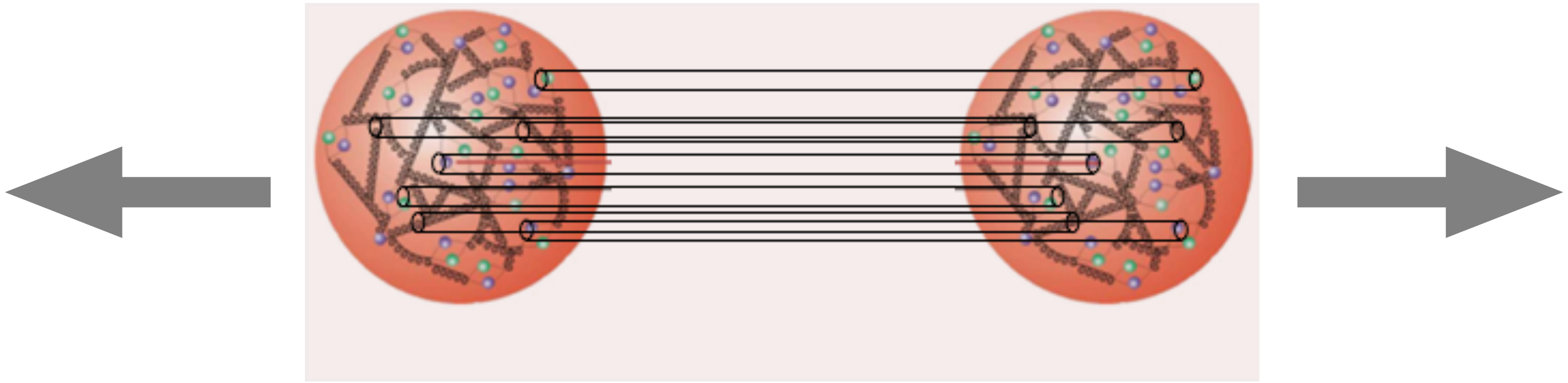

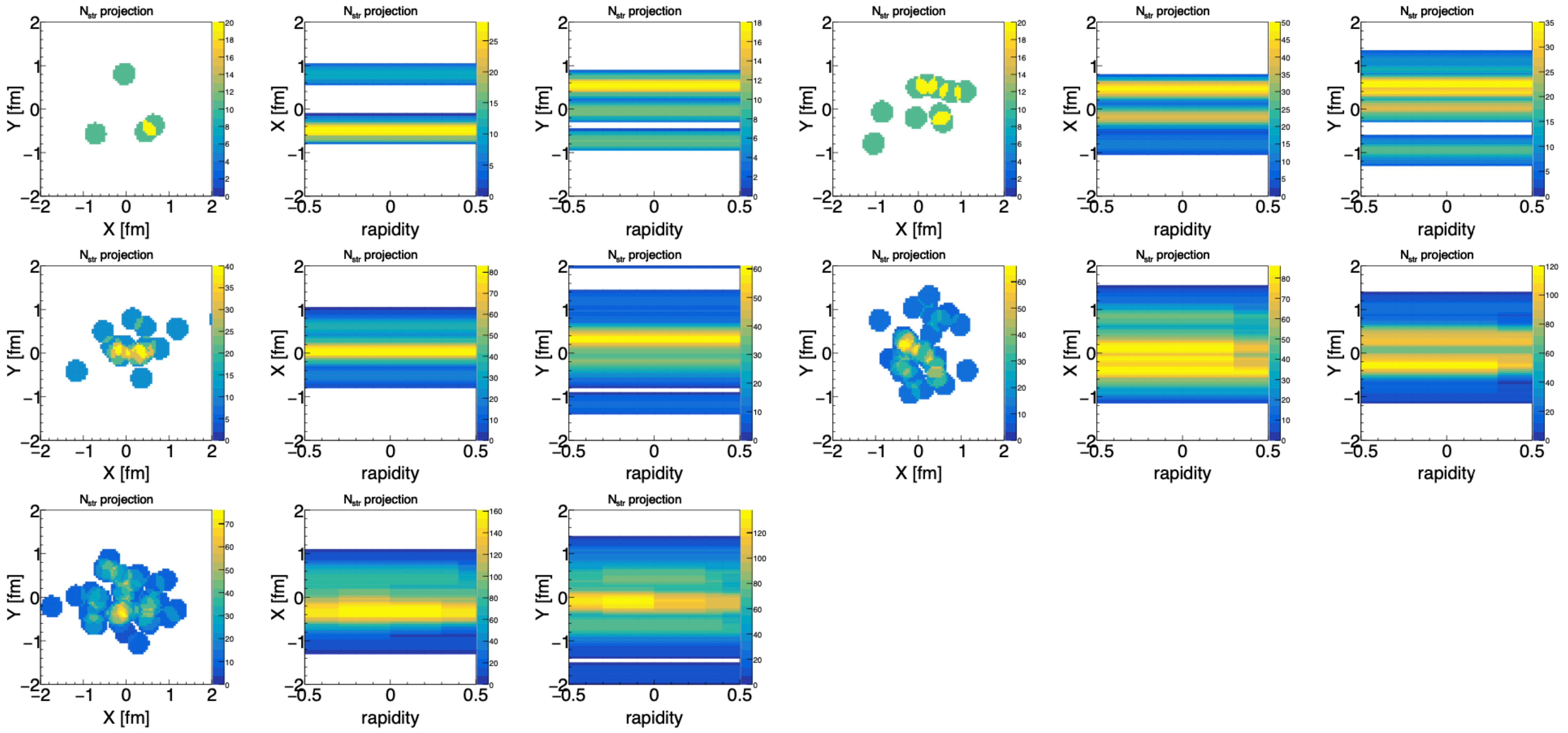

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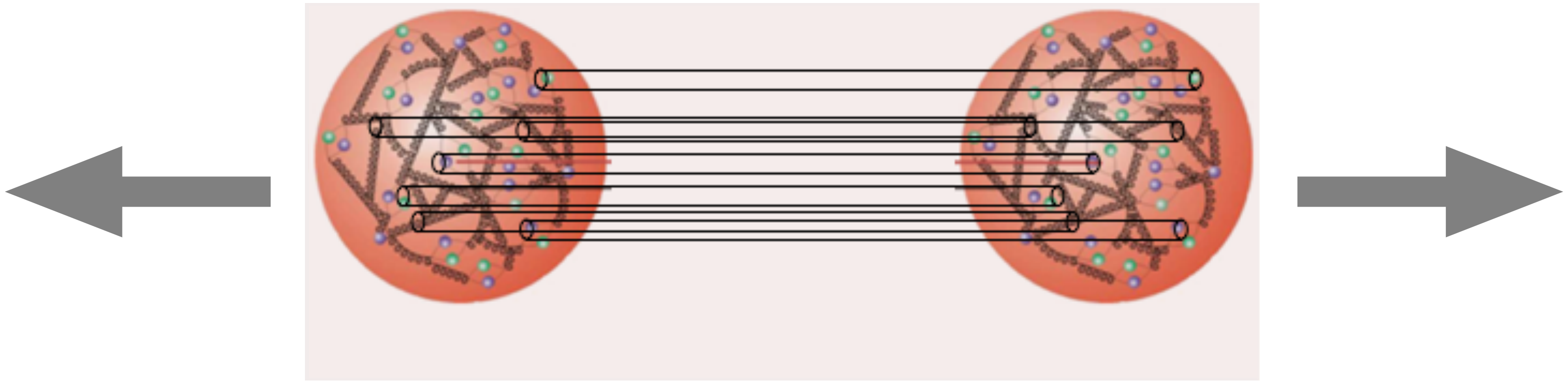

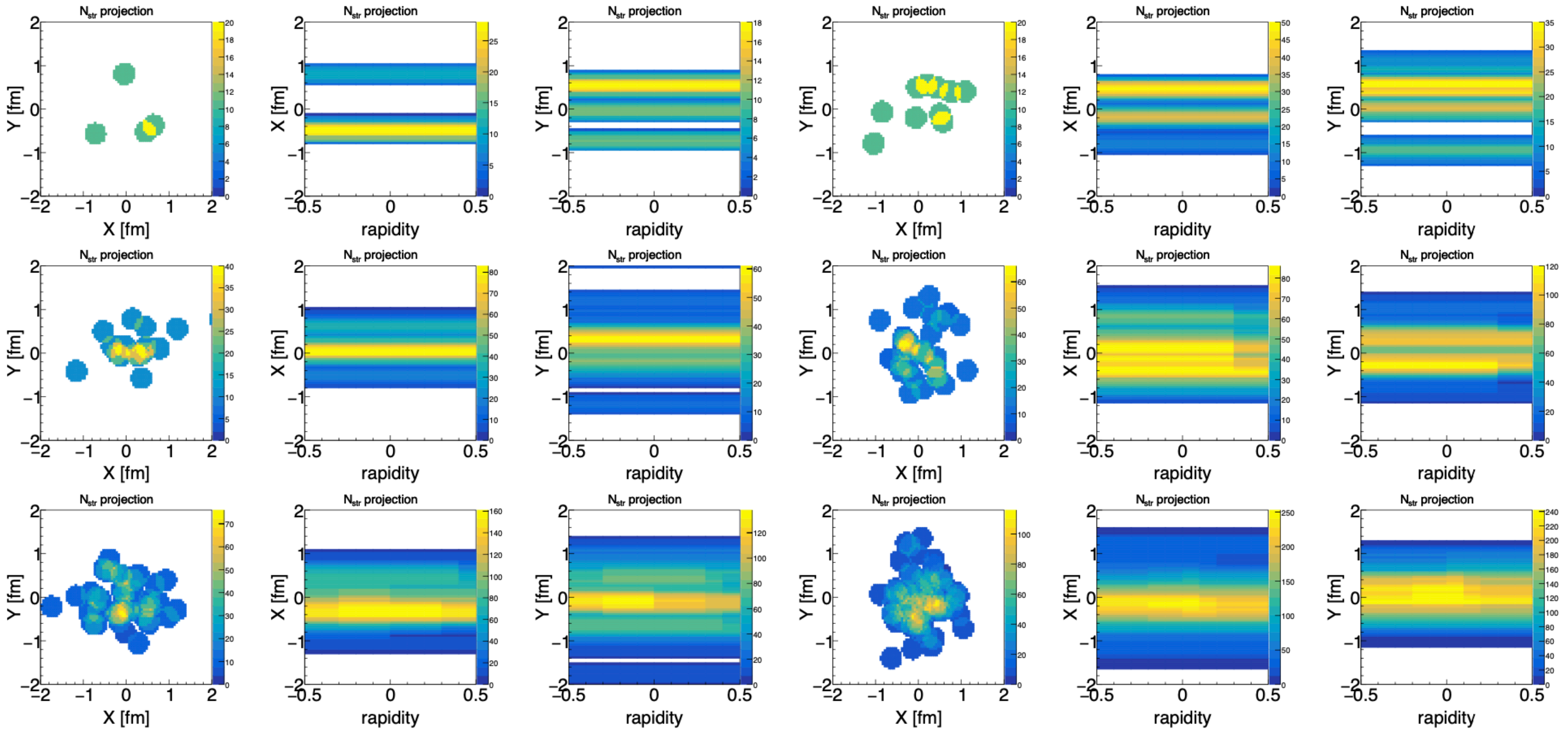

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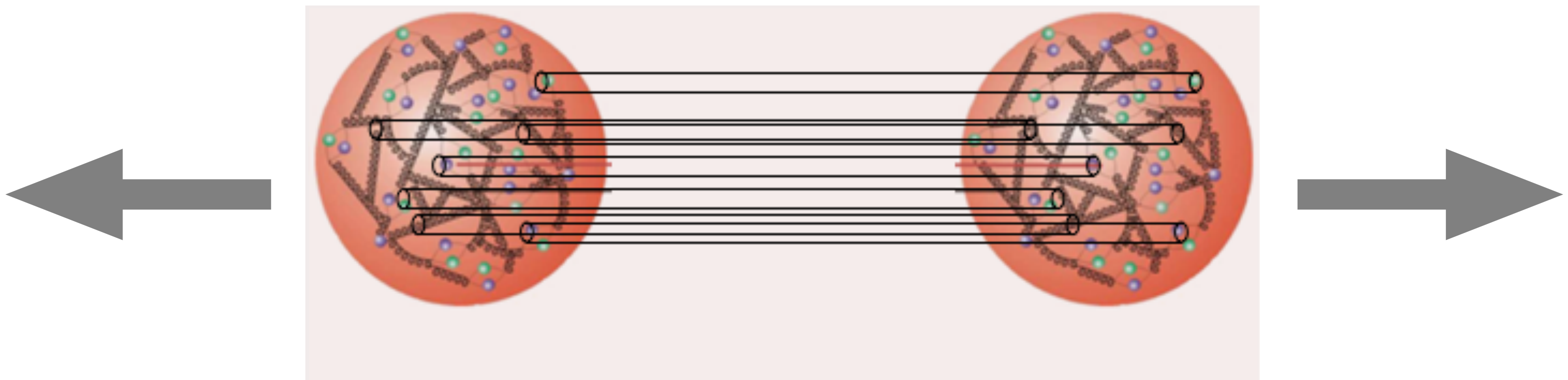

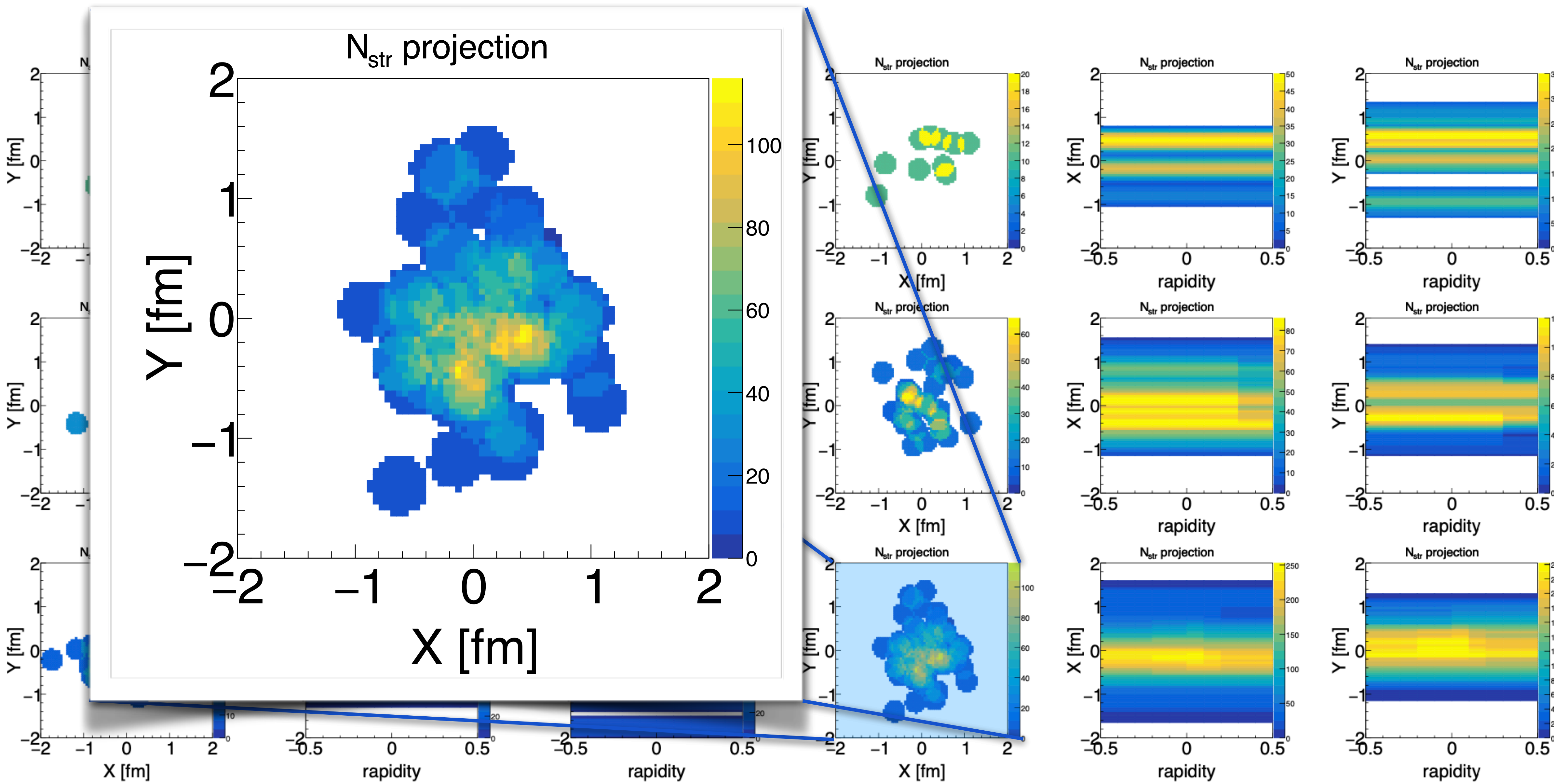

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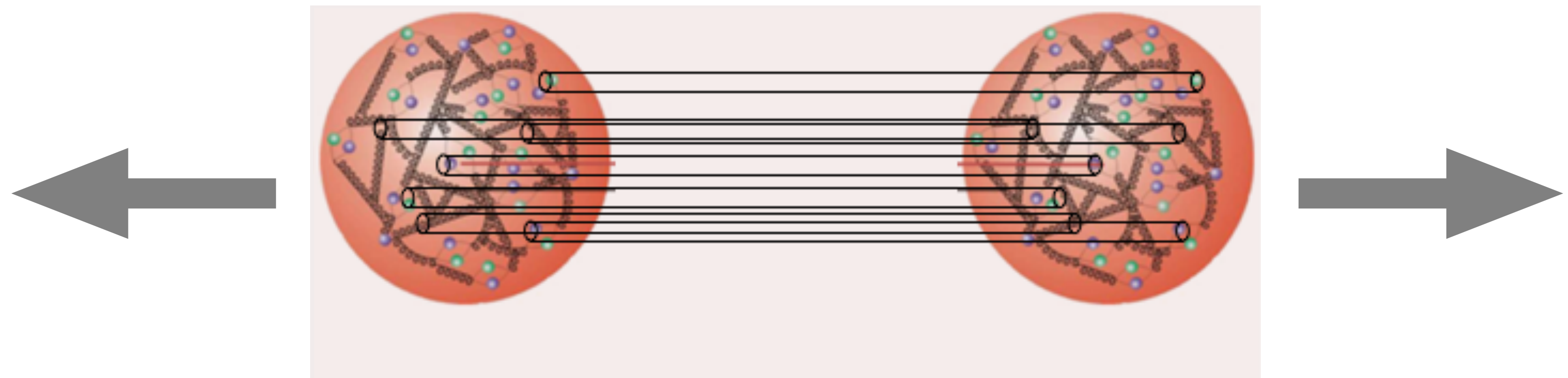

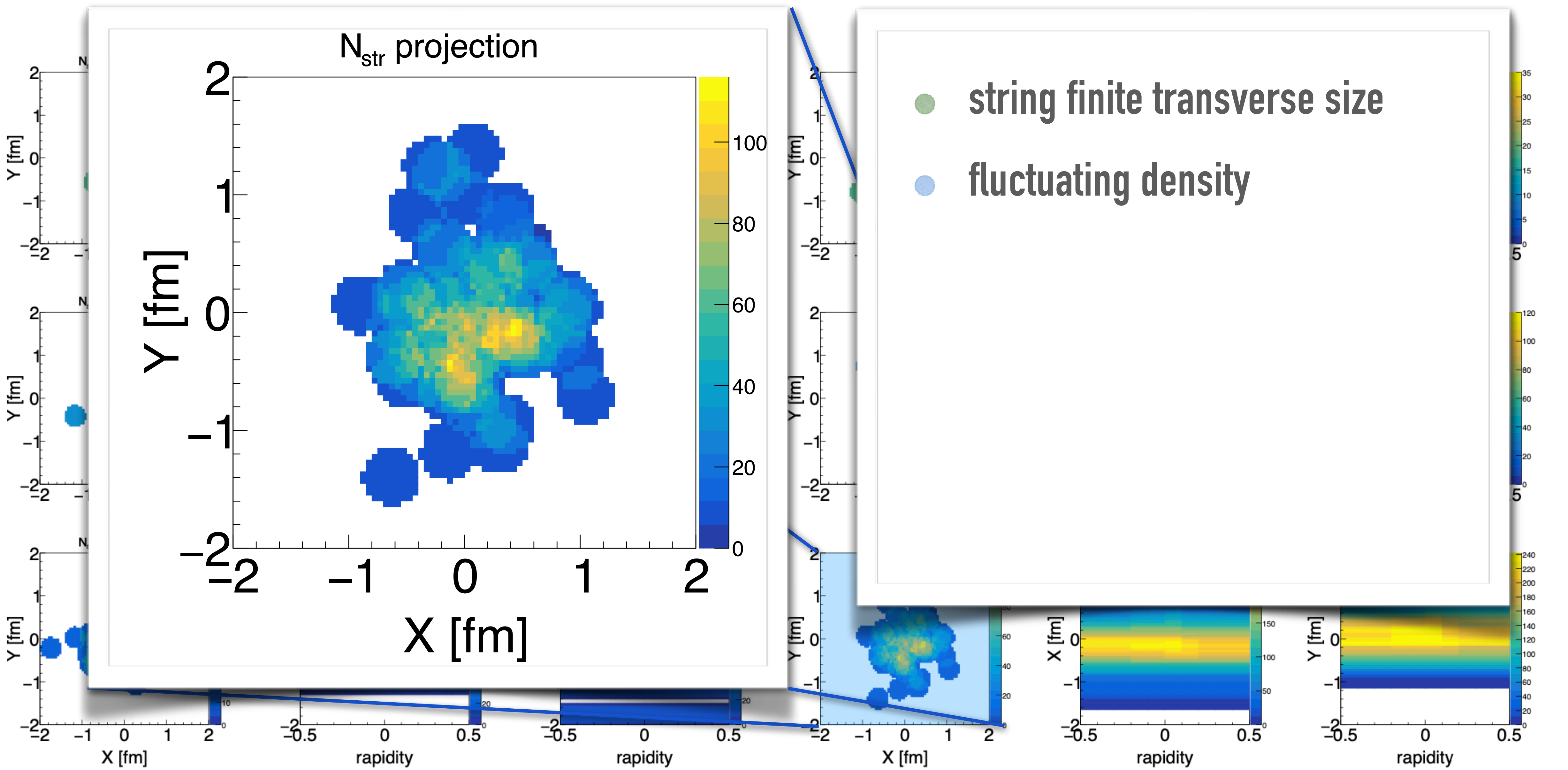

- string finite transverse size
- fluctuating density

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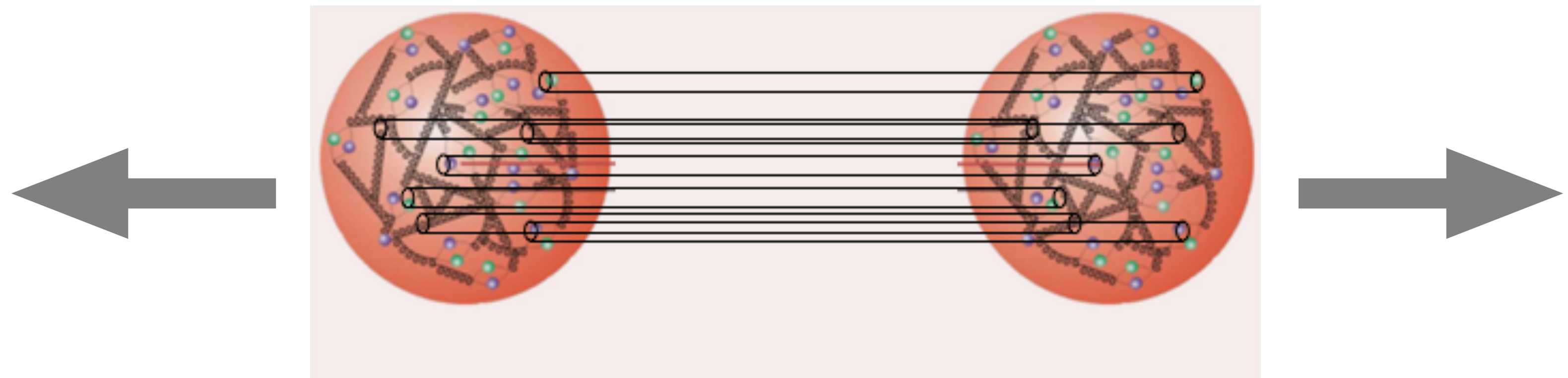
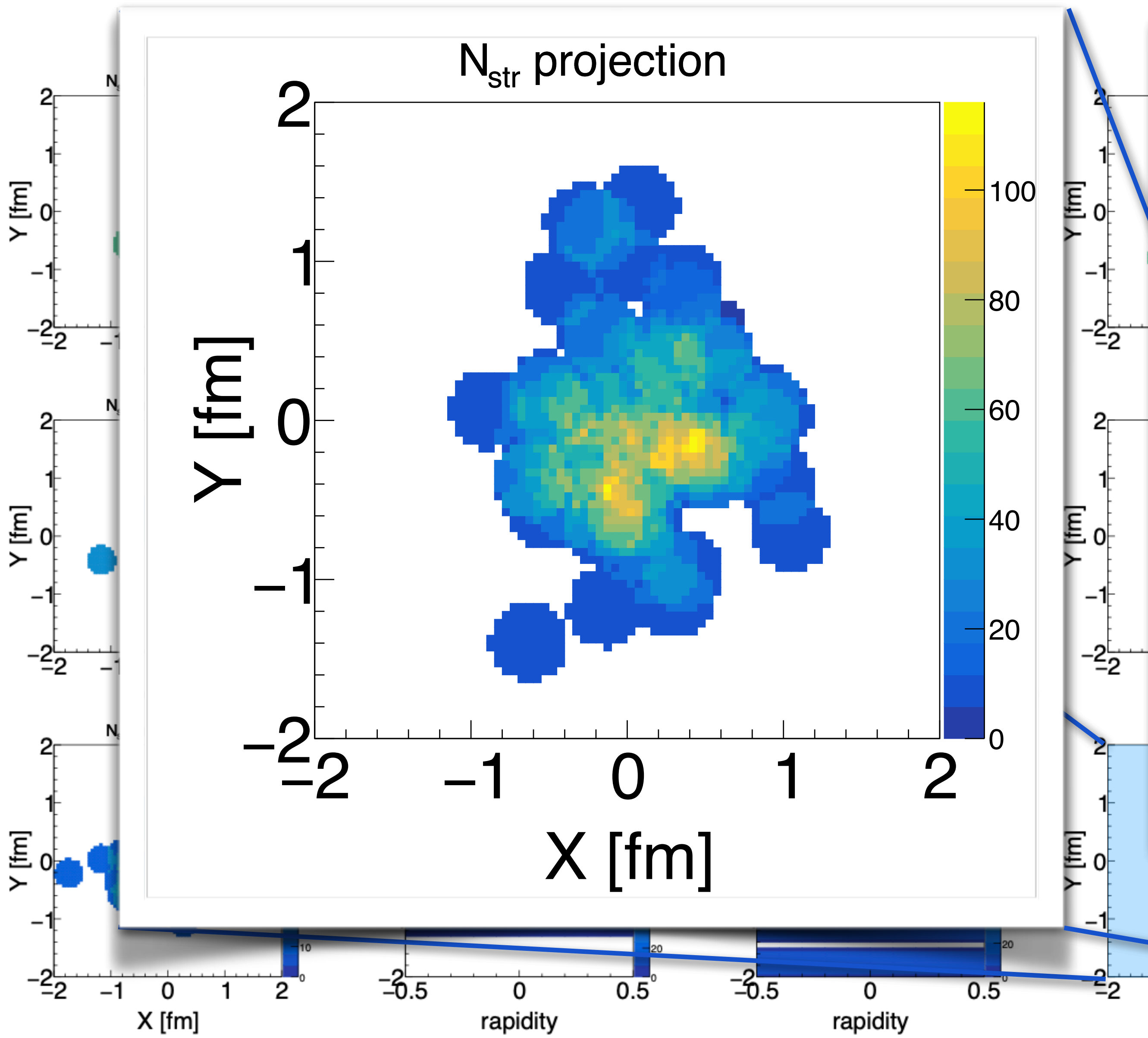
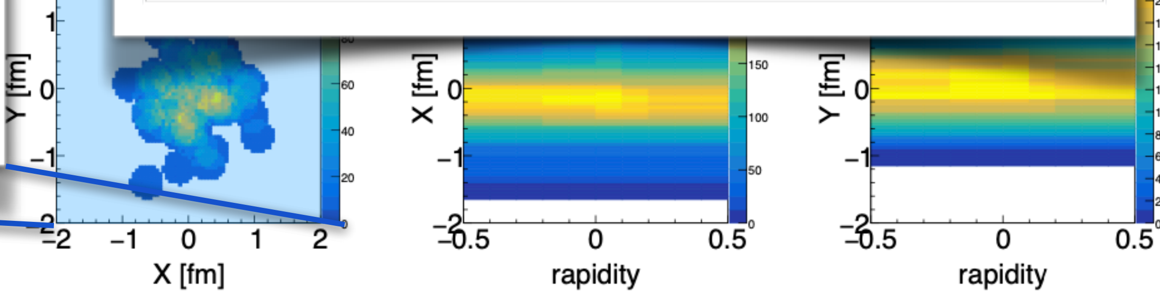




- string finite transverse size
- fluctuating density
- binned energy density (geometry)

$$\varepsilon_{\text{cell}} = \frac{\sigma\sqrt{k_{\text{cell}}}}{\pi r_{\text{str}}^2}$$

[Braun et al. Int.J.Mod.Phys.A 14 (1999) 2689]



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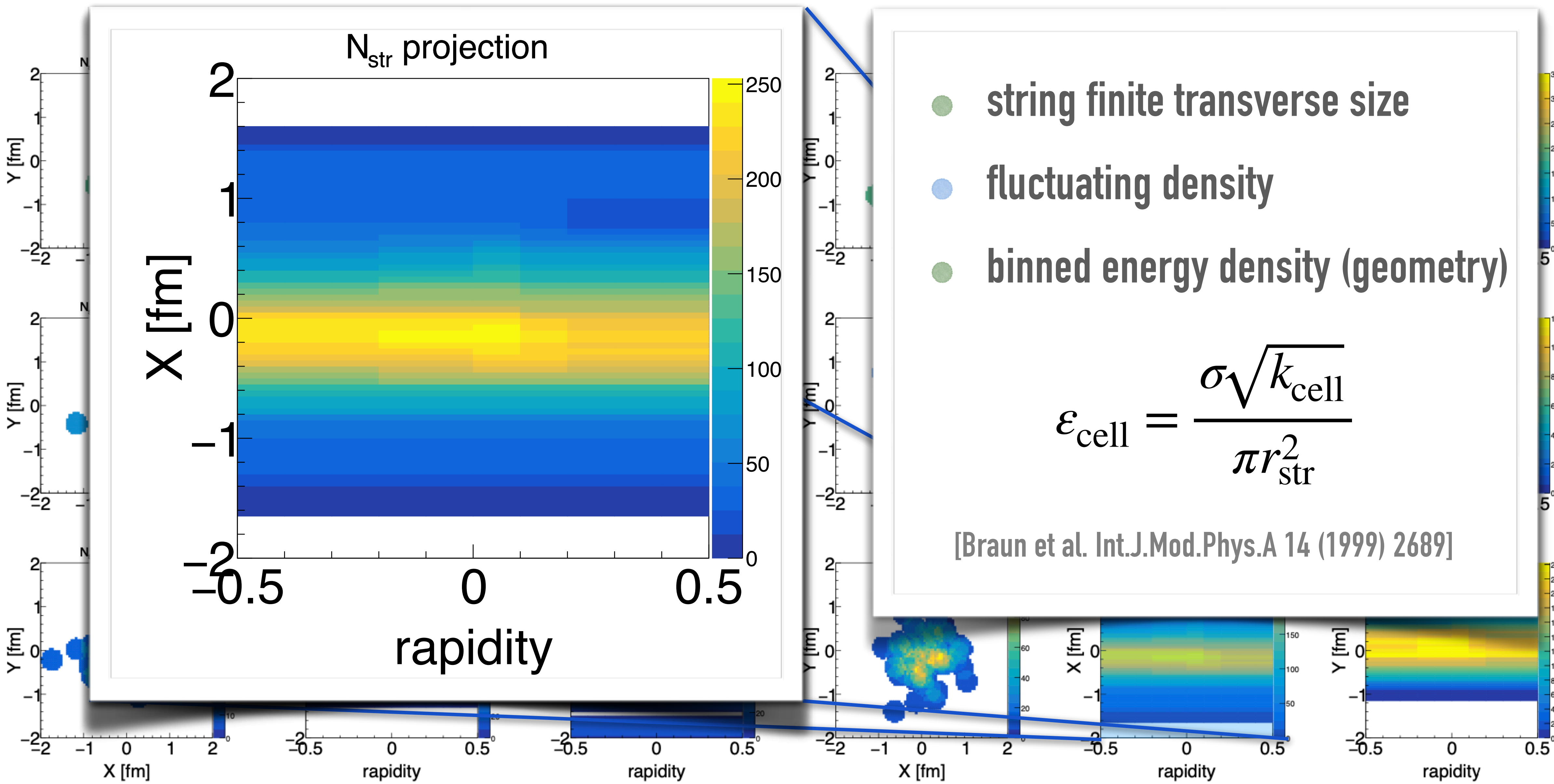

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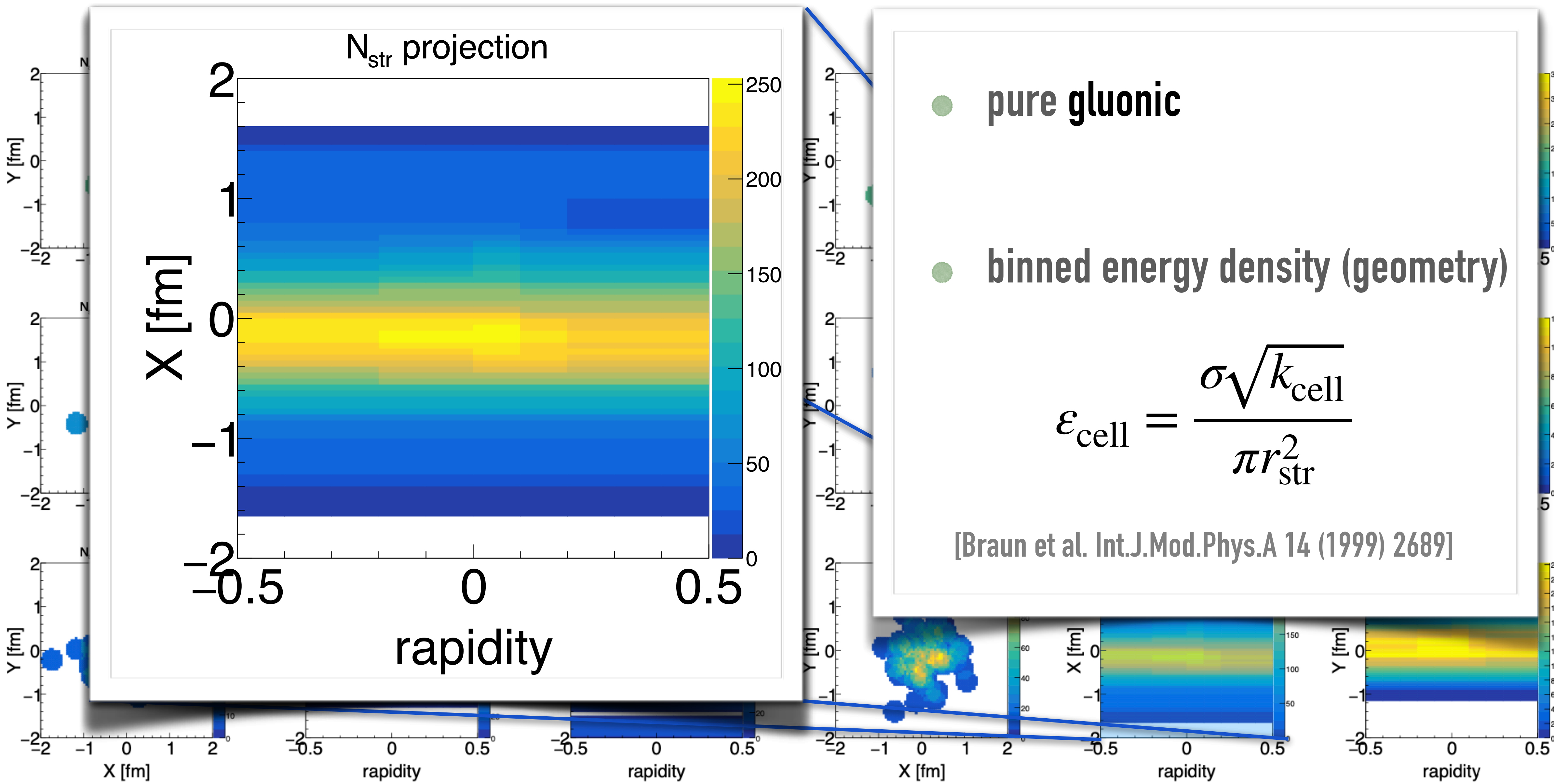
FROM STRINGS TO MEDIUM



- pure **gluonic**
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[Braun et al. Int.J.Mod.Phys.A 14 (1999) 2689]

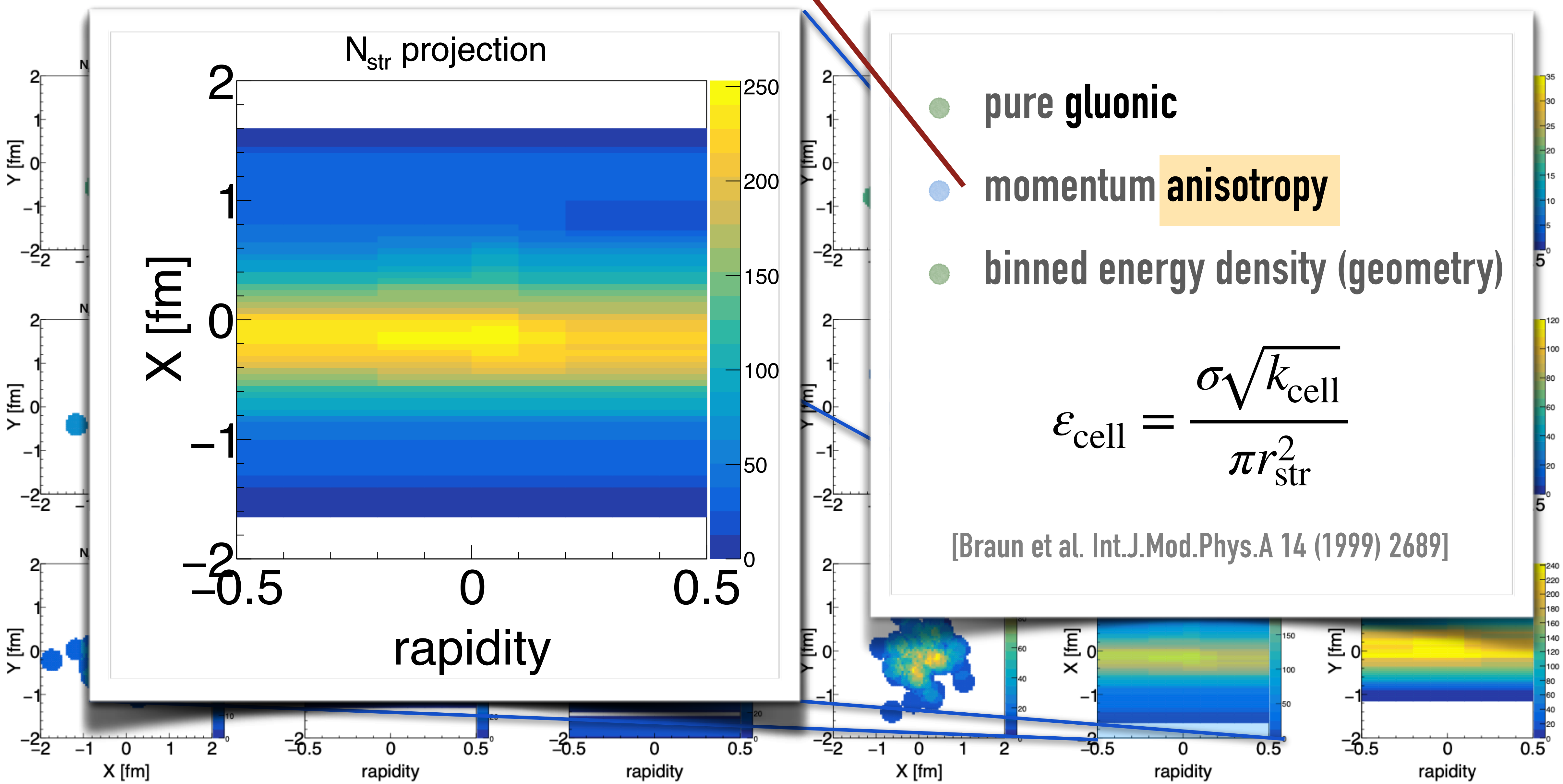
FROM STRINGS TO MEDIUM: ANISOTROPIC

[Romatschke, Strickland, Phys. Rev. D 68 (2003) 036004; Phys. Rev. D 70 (2004) 116006]

$$f_{\text{aniso}}(k) = \frac{1}{e^{\frac{\sqrt{k_T^2+(1+\xi)k_z^2}}{\Lambda}} - 1}$$

Romatschke–Strickland

ξ – degree, global



- pure gluonic
- momentum anisotropy
- binned energy density (geometry)

$$\varepsilon_{\text{cell}} = \frac{\sigma\sqrt{k_{\text{cell}}}}{\pi r_{\text{str}}^2}$$

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$$\Lambda = \left(\frac{\varepsilon}{16\pi^2/60}\right)^{1/4} \cdot \mathcal{F}(\xi)$$

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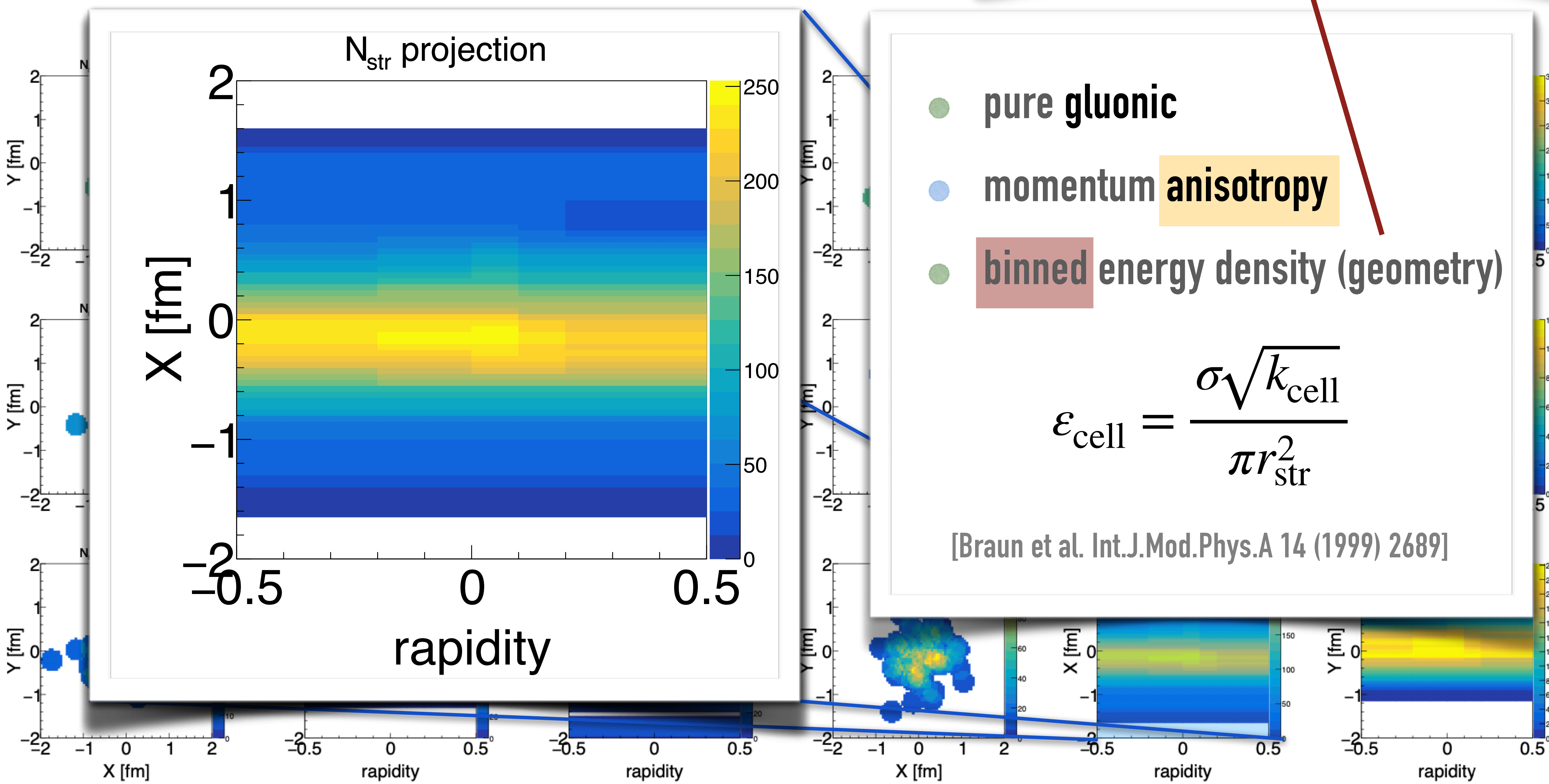

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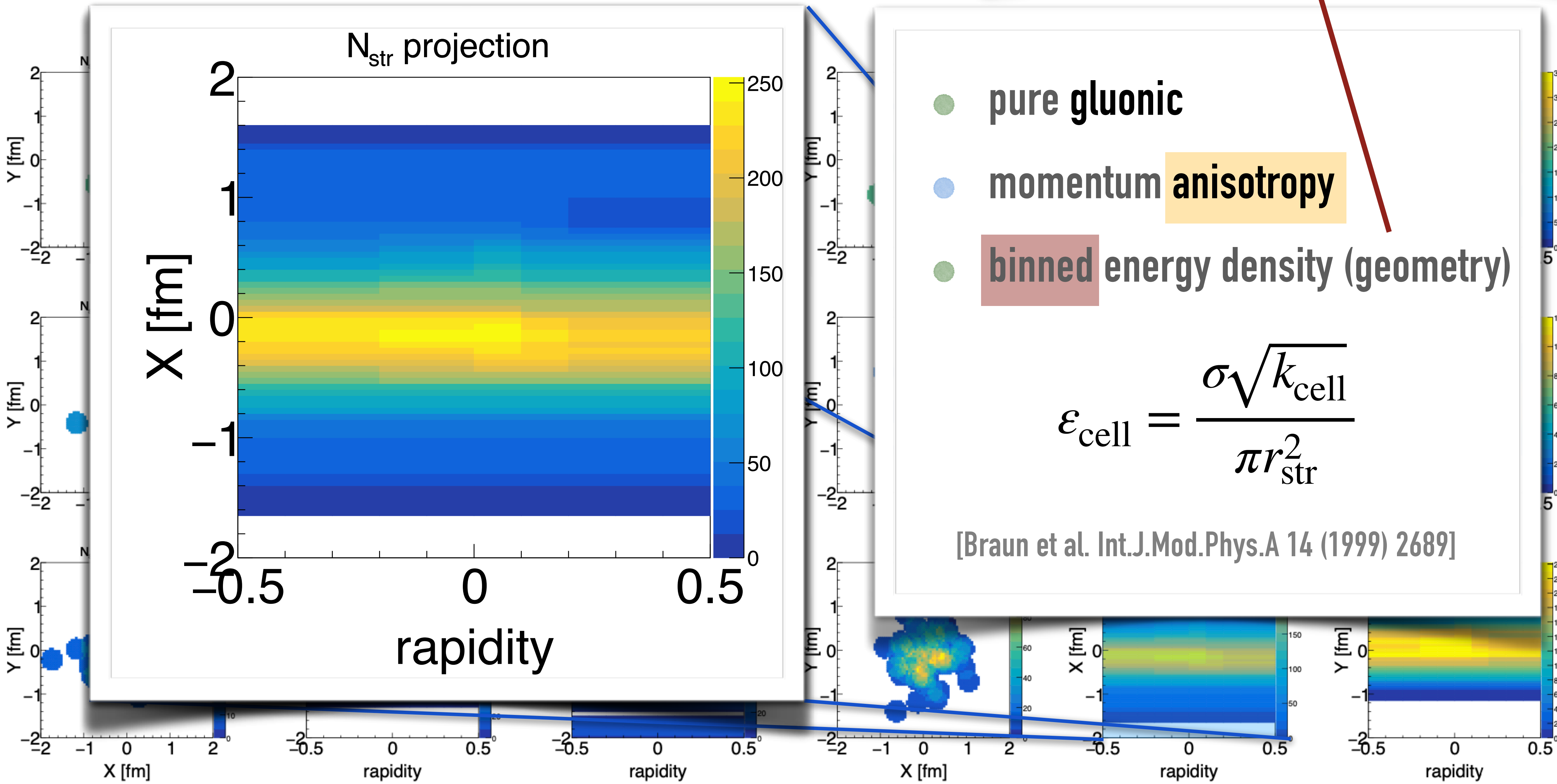

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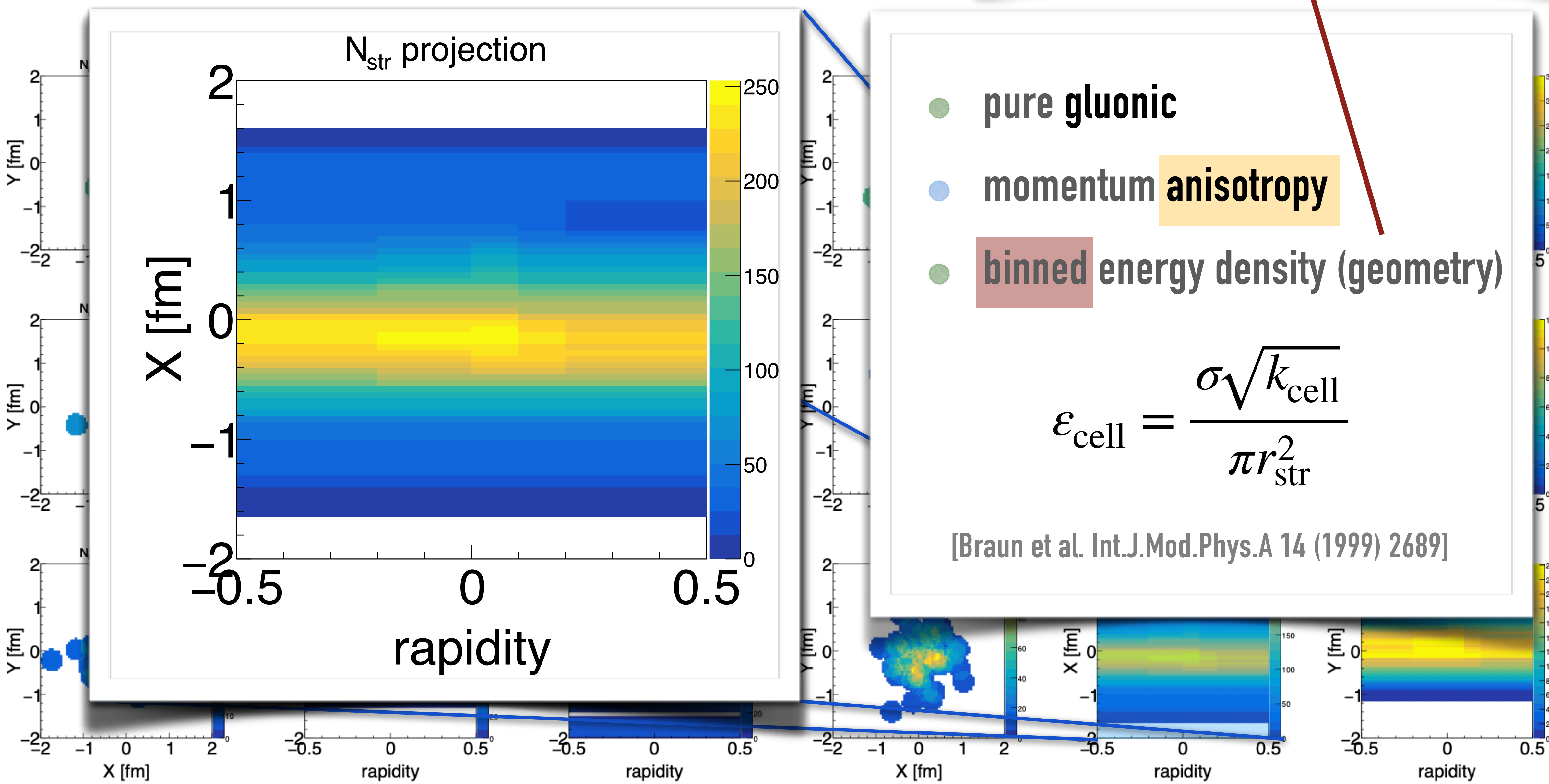

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gluon number density [cell prop.]

characteristic momentum scale

[cell prop.]

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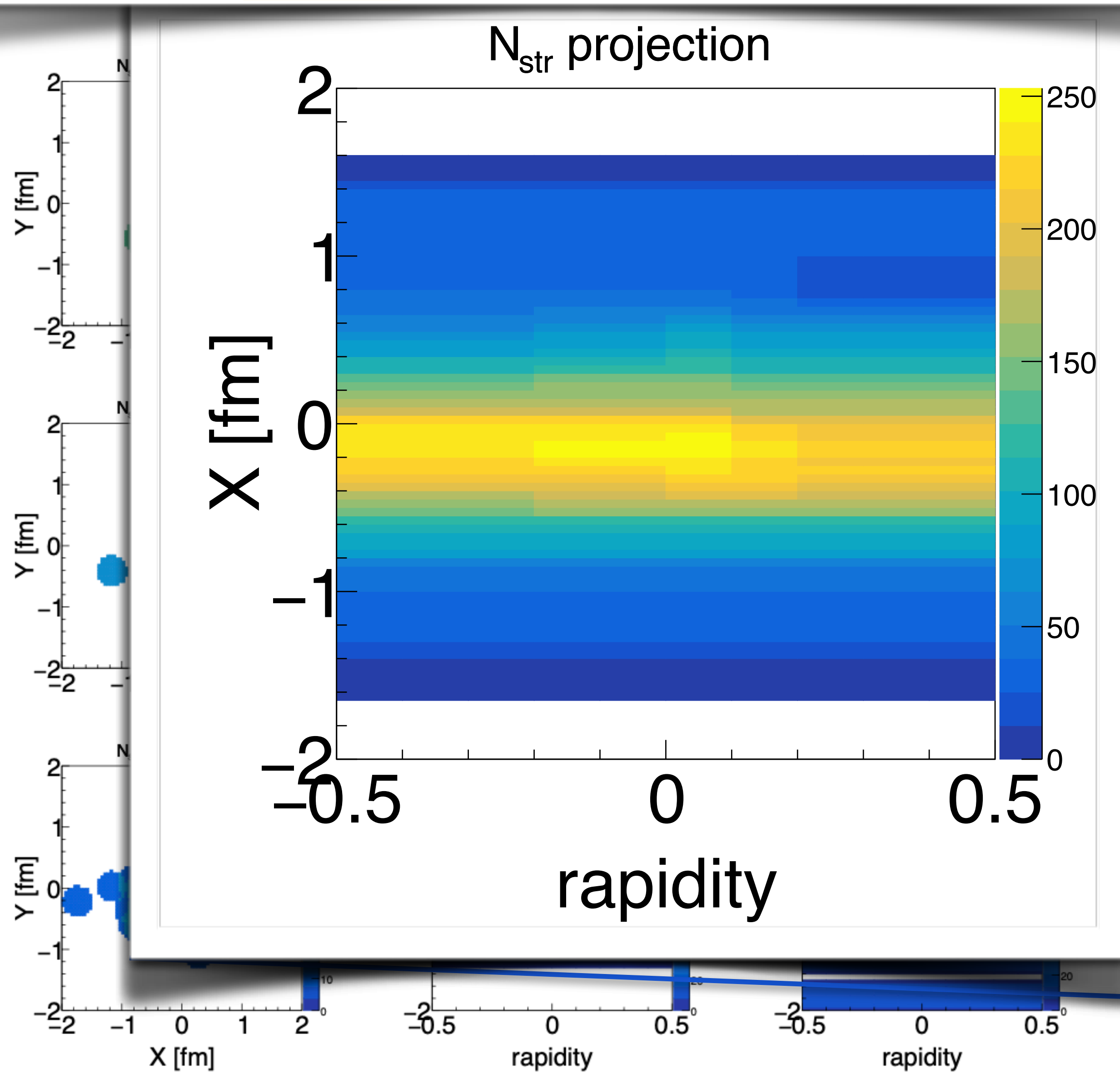
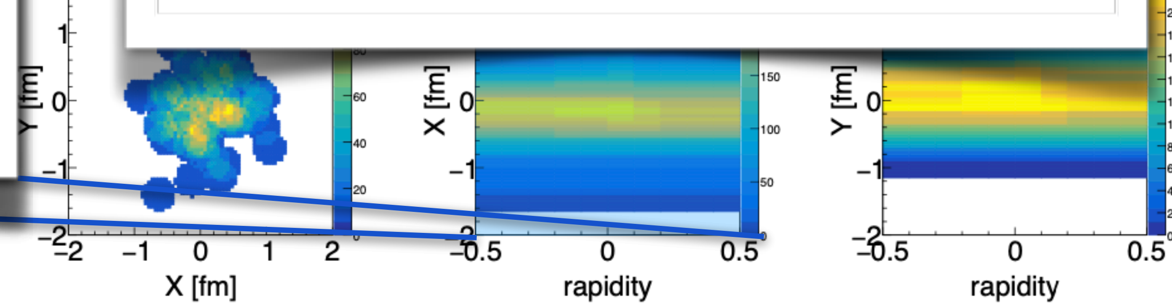
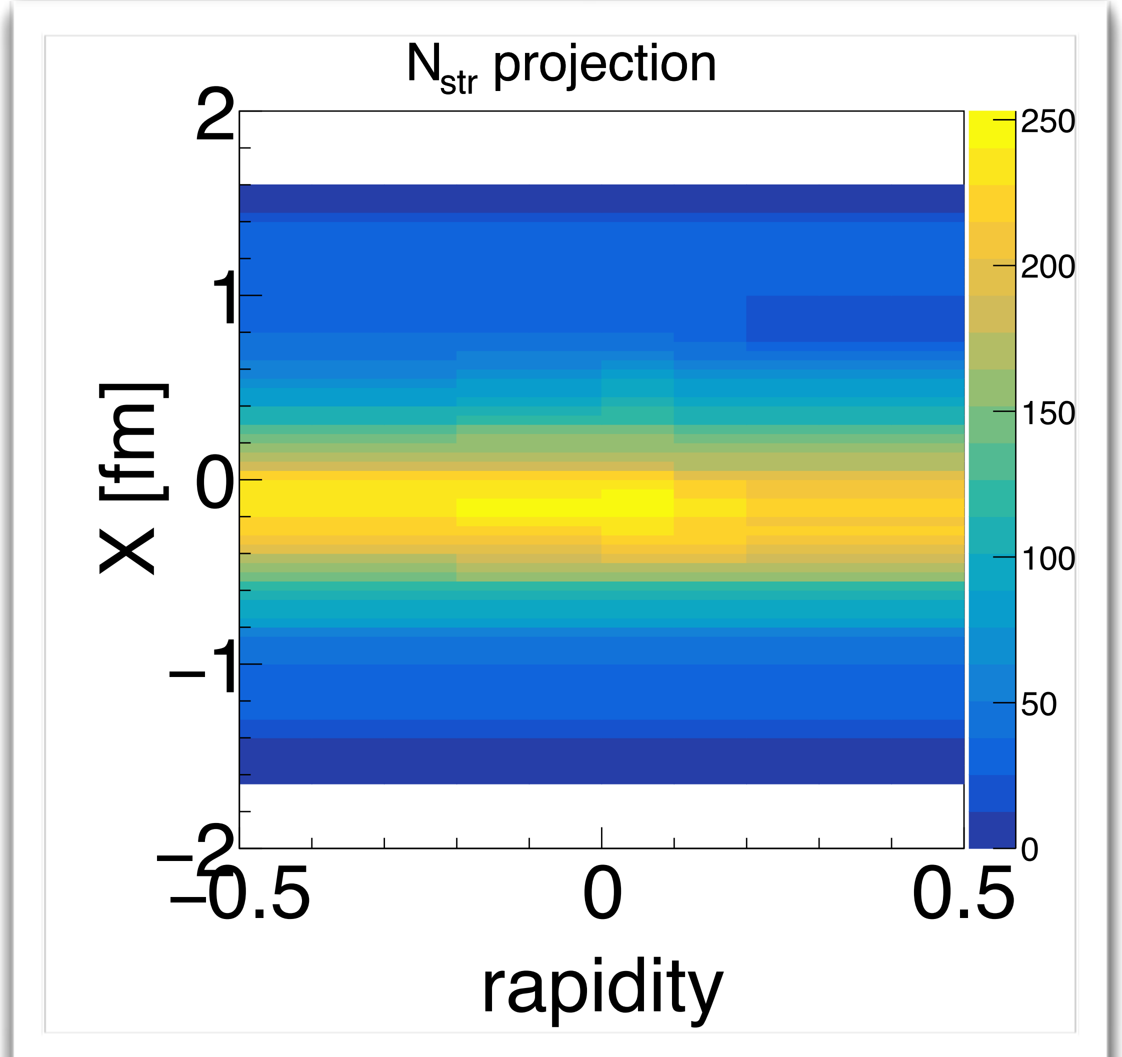




MEDIUM


N_{str} projection
X [fm]
rapidity
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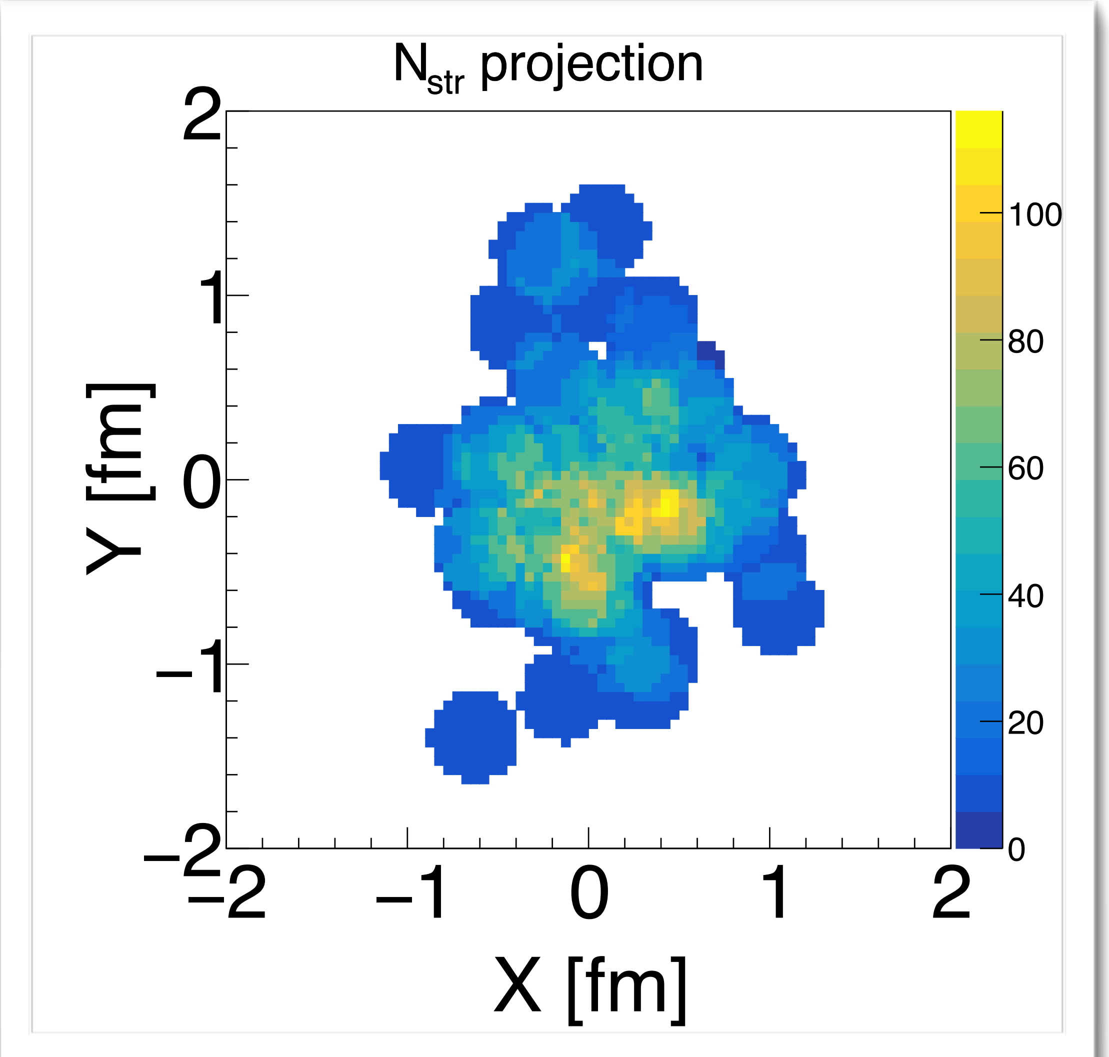
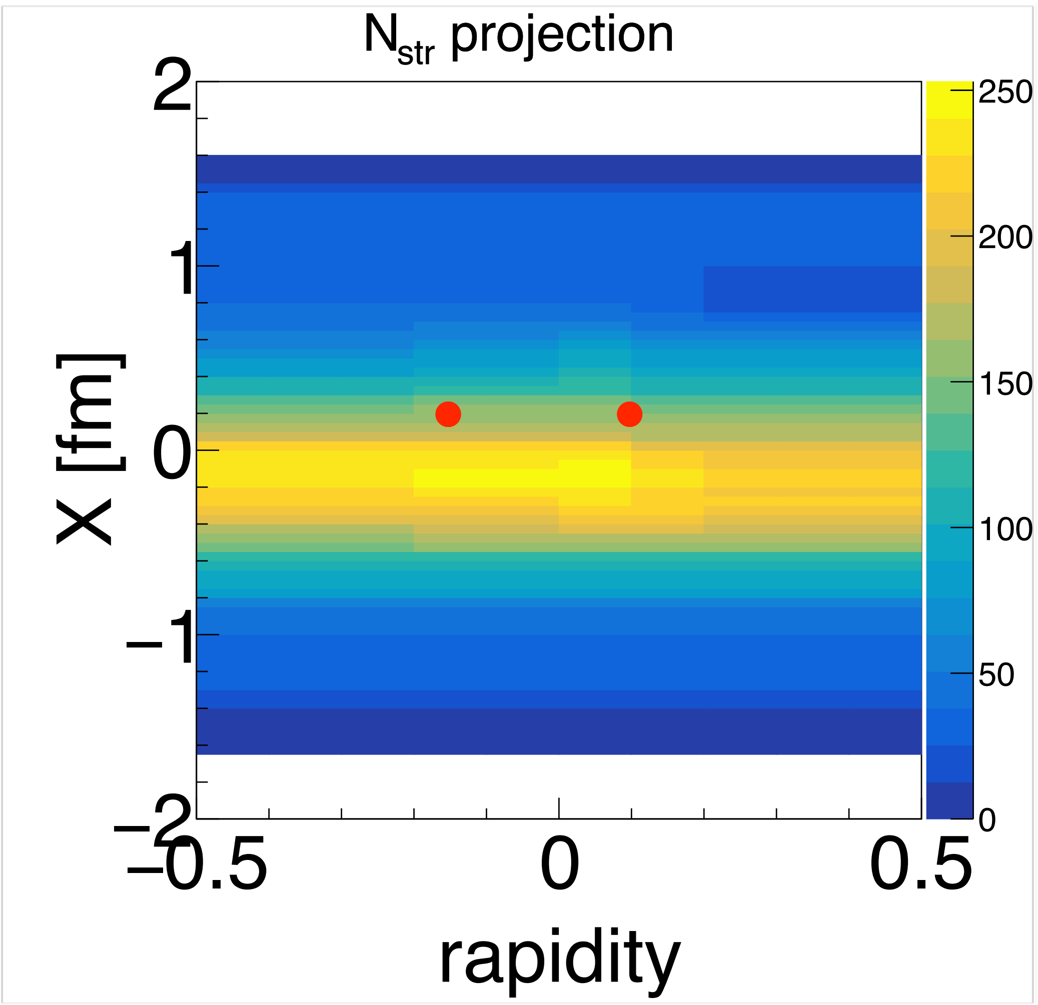
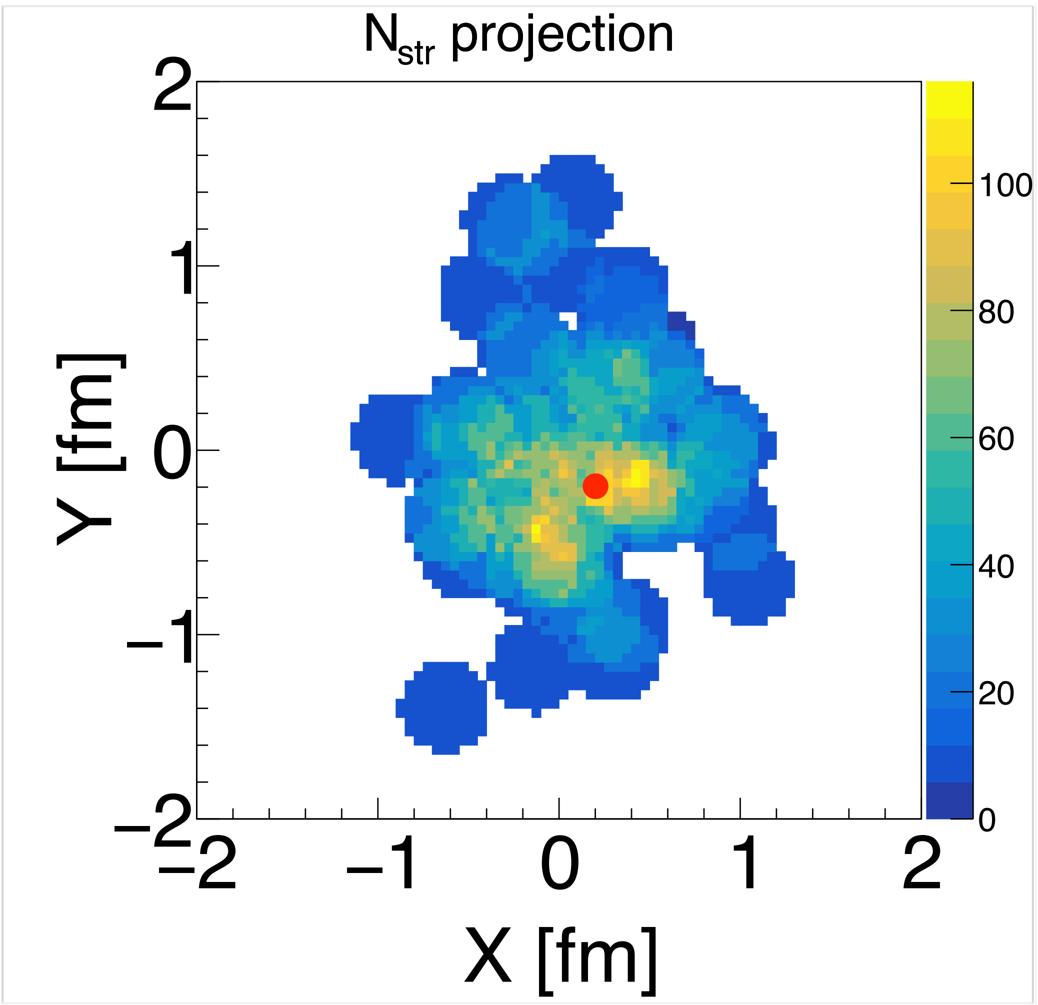
1
0
−1
−2
−0.5
0
0.5
250
200
150
100
50
0


N_{str} projection
Y [fm]
X [fm]
2
1
0
−1
−2
−2
−1
0
1
2
100
80
60
40
20
0

HEAVY QUARKS IN **MEDIUM**





HEAVY QUARKS IN **MEDIUM**

- from PYTHIA

```
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pythia.readString("HardQCD:gg2ccbar = on");
pythia.readString("HardQCD:gg2bbbar = on");
pythia.readString("HardQCD:qqbar2ccbar = on");
pythia.readString("HardQCD:qqbar2bbbar = on");

pythia.readString("HadronLevel:all = off");
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```
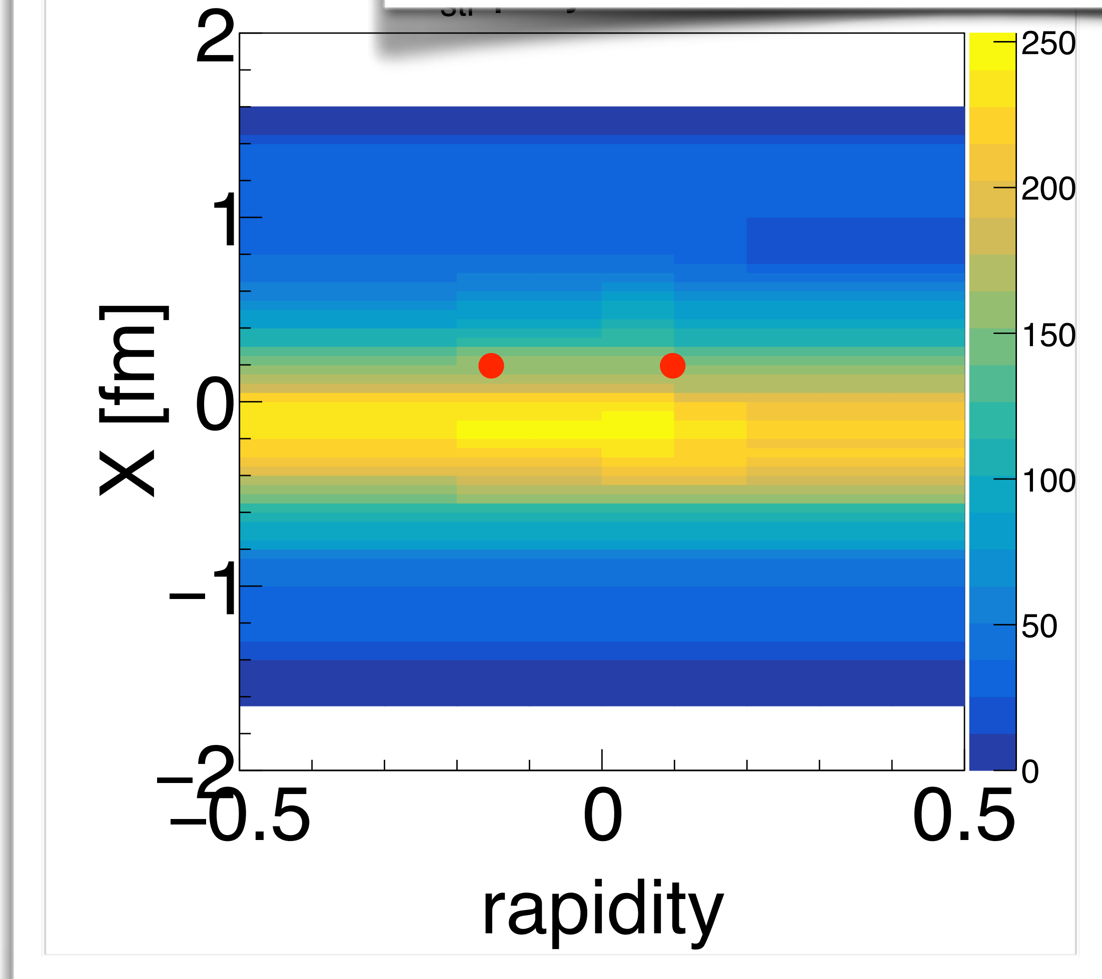
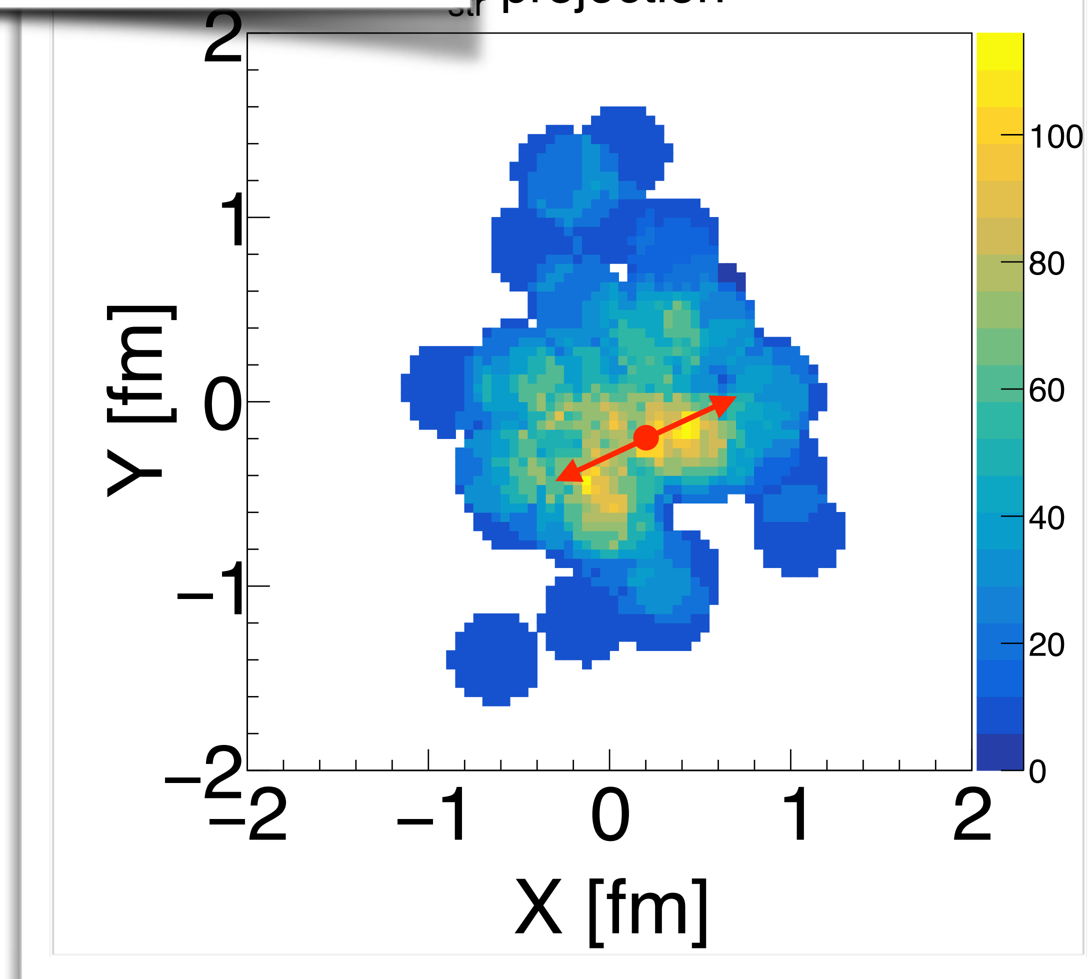
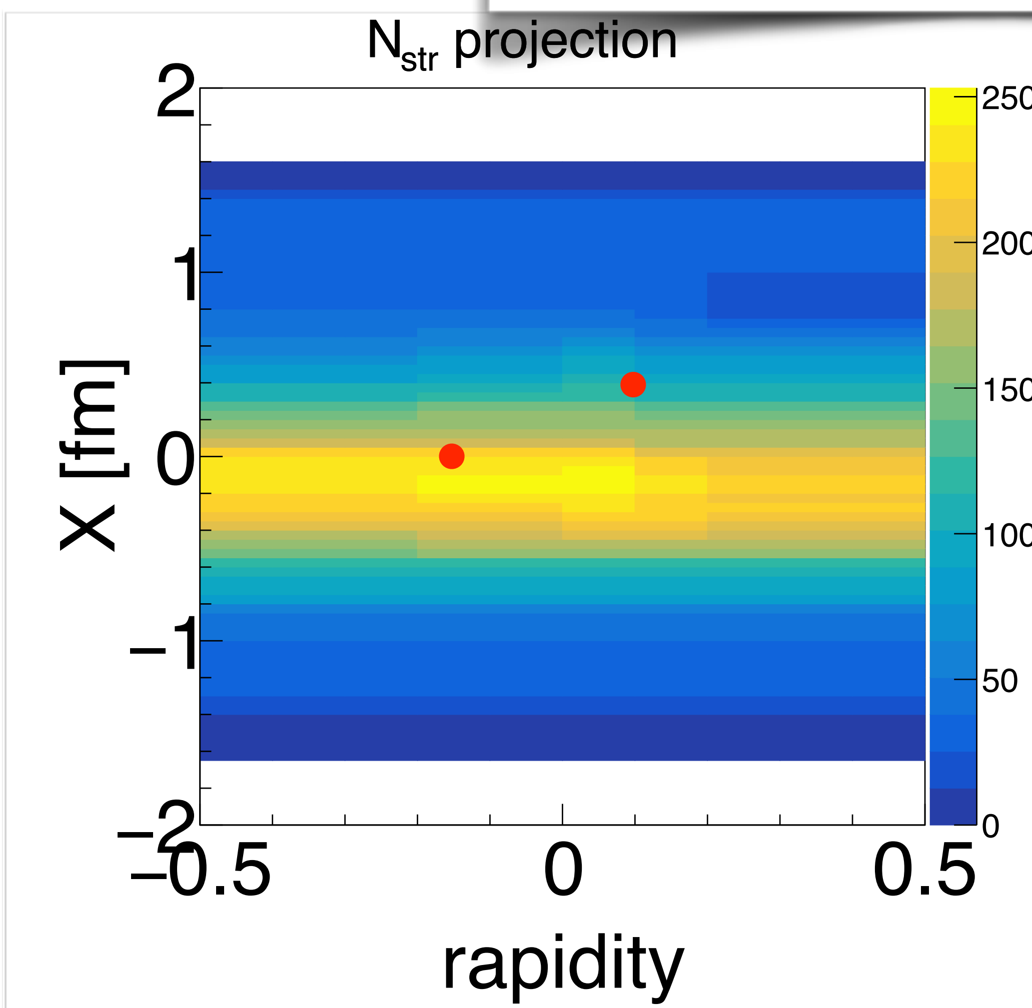



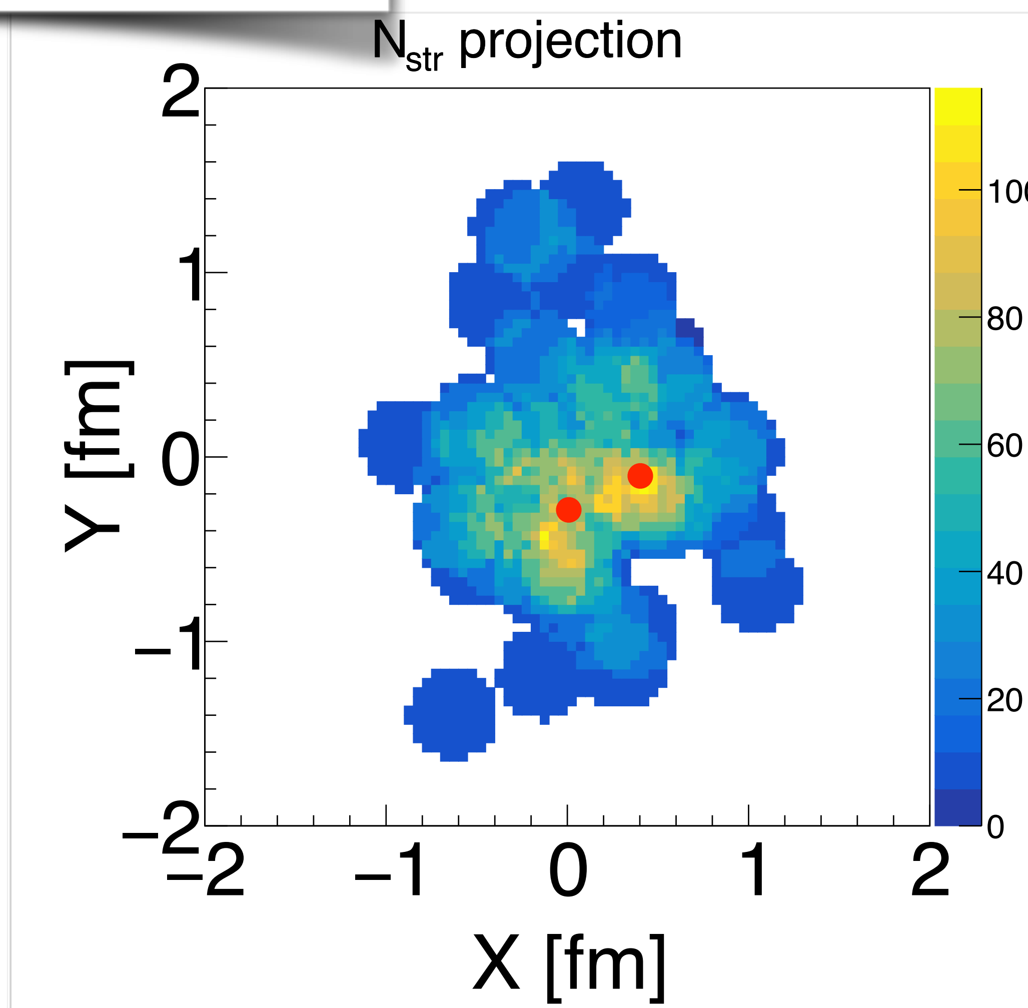


HEAVY QUARKS IN **MEDIUM**

- from PYTHIA
- **eikonal approximation**

- random initial positions in X-Y
- straight line trajectory
- no change of rapidity slice
- propagation in time steps





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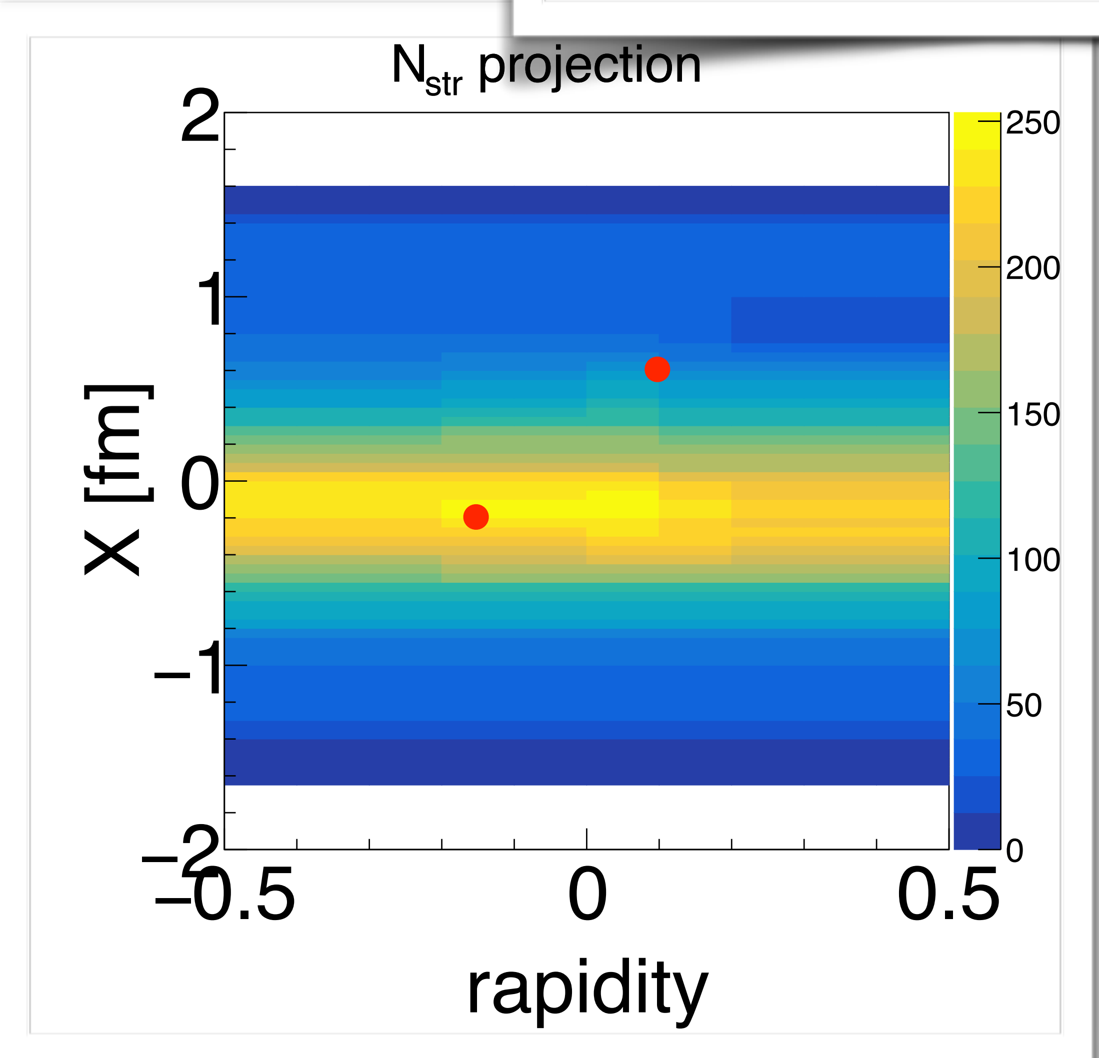

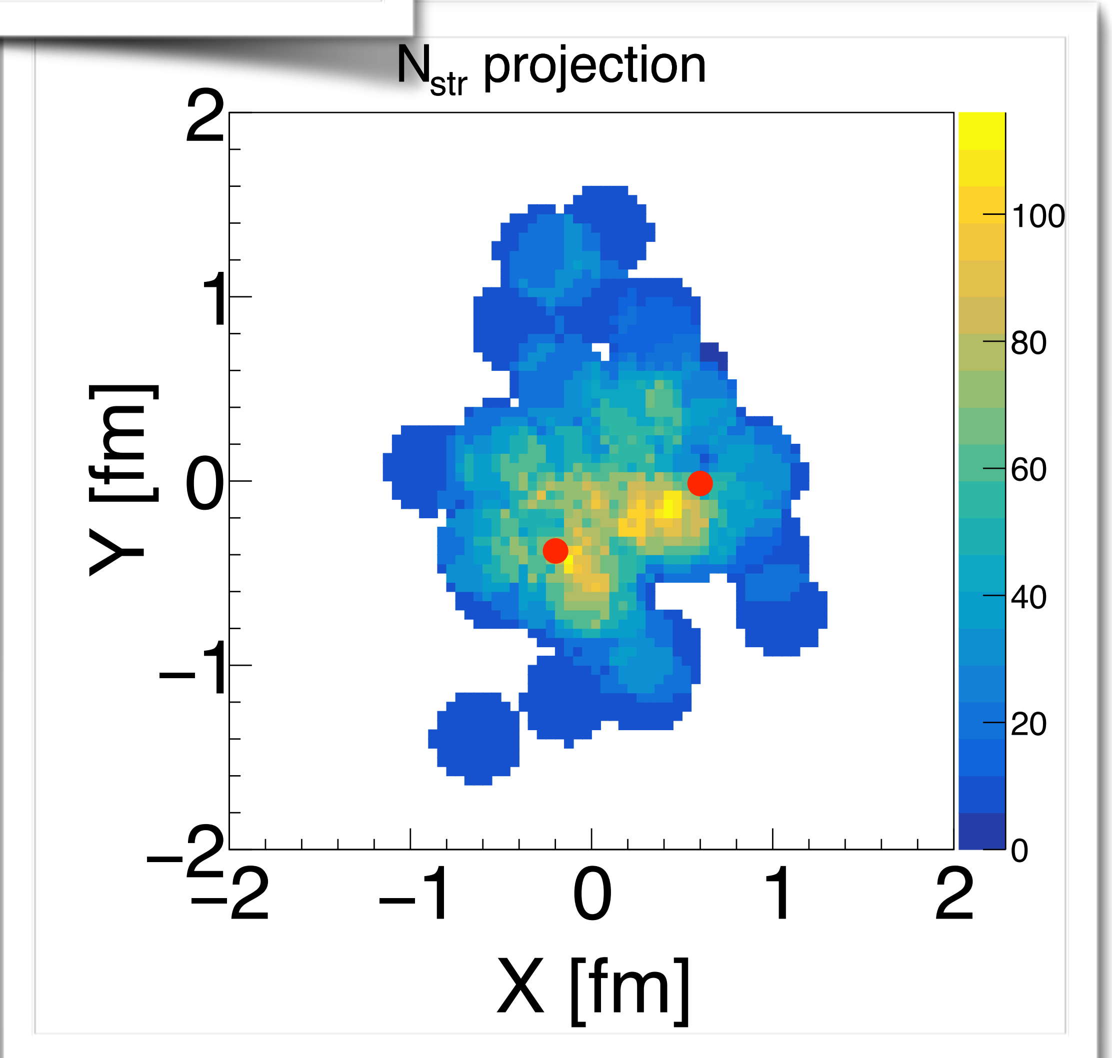

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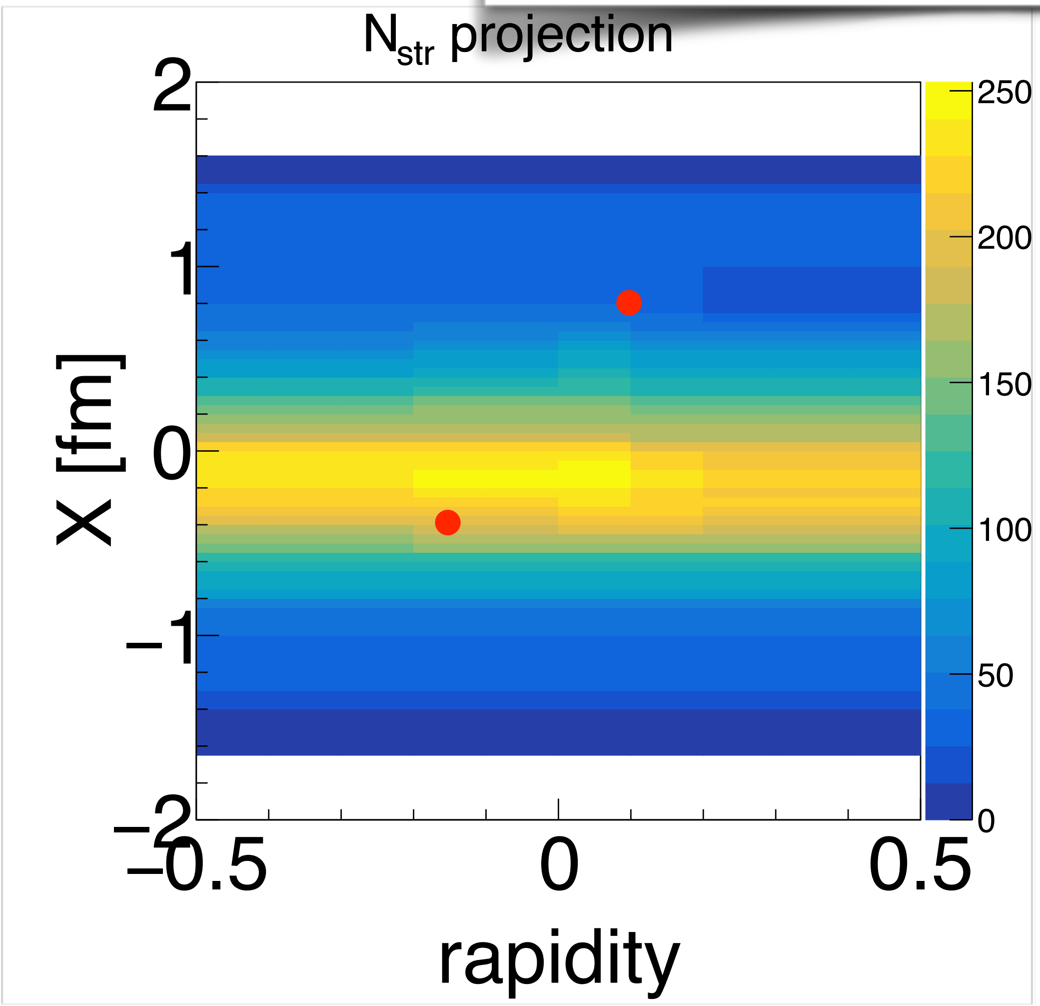
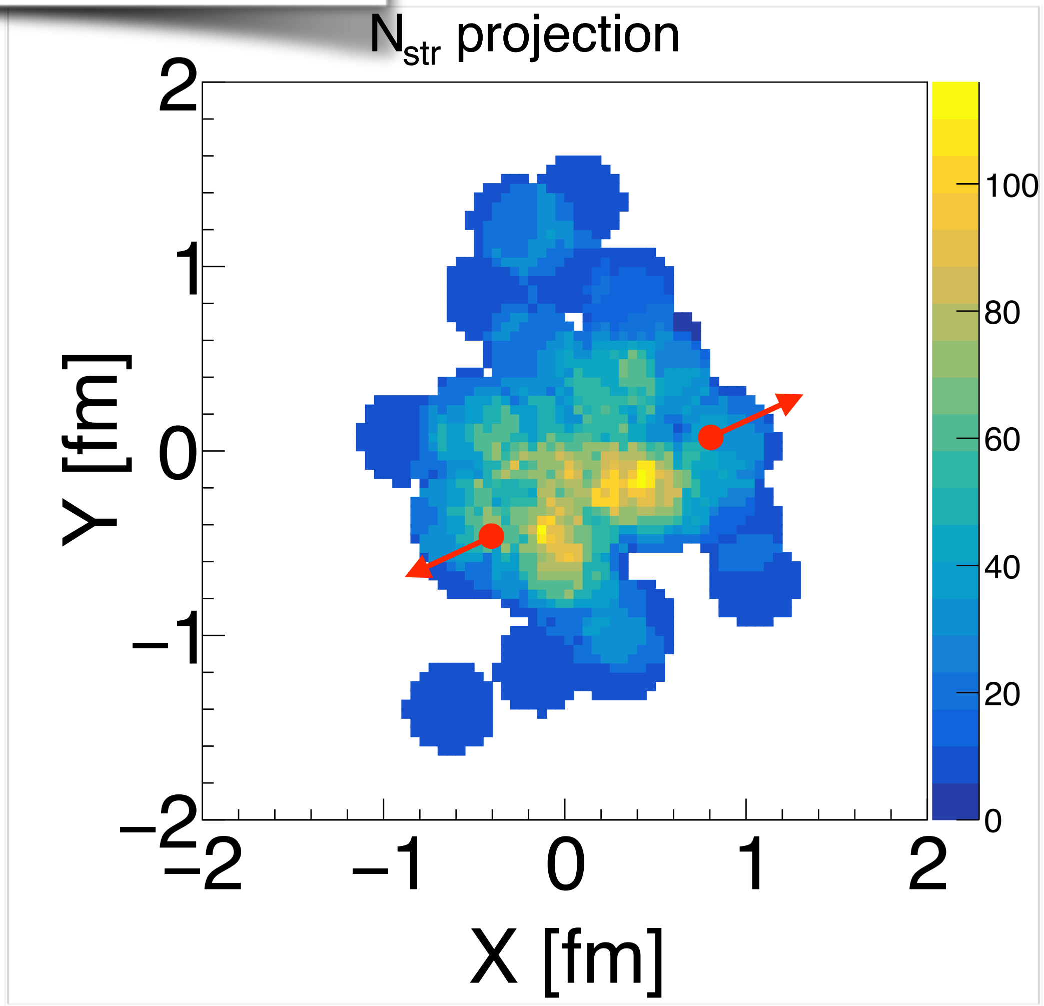
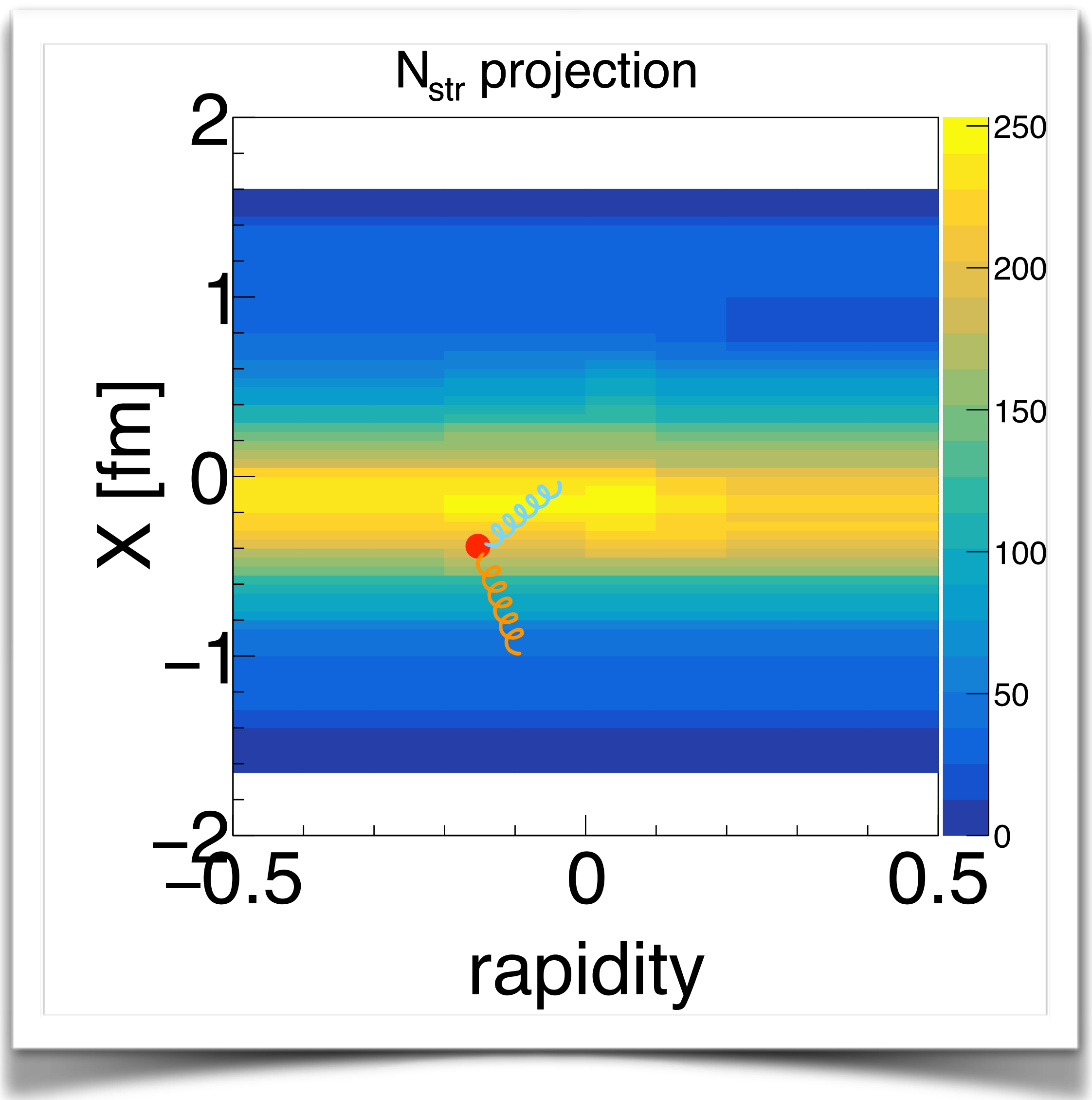
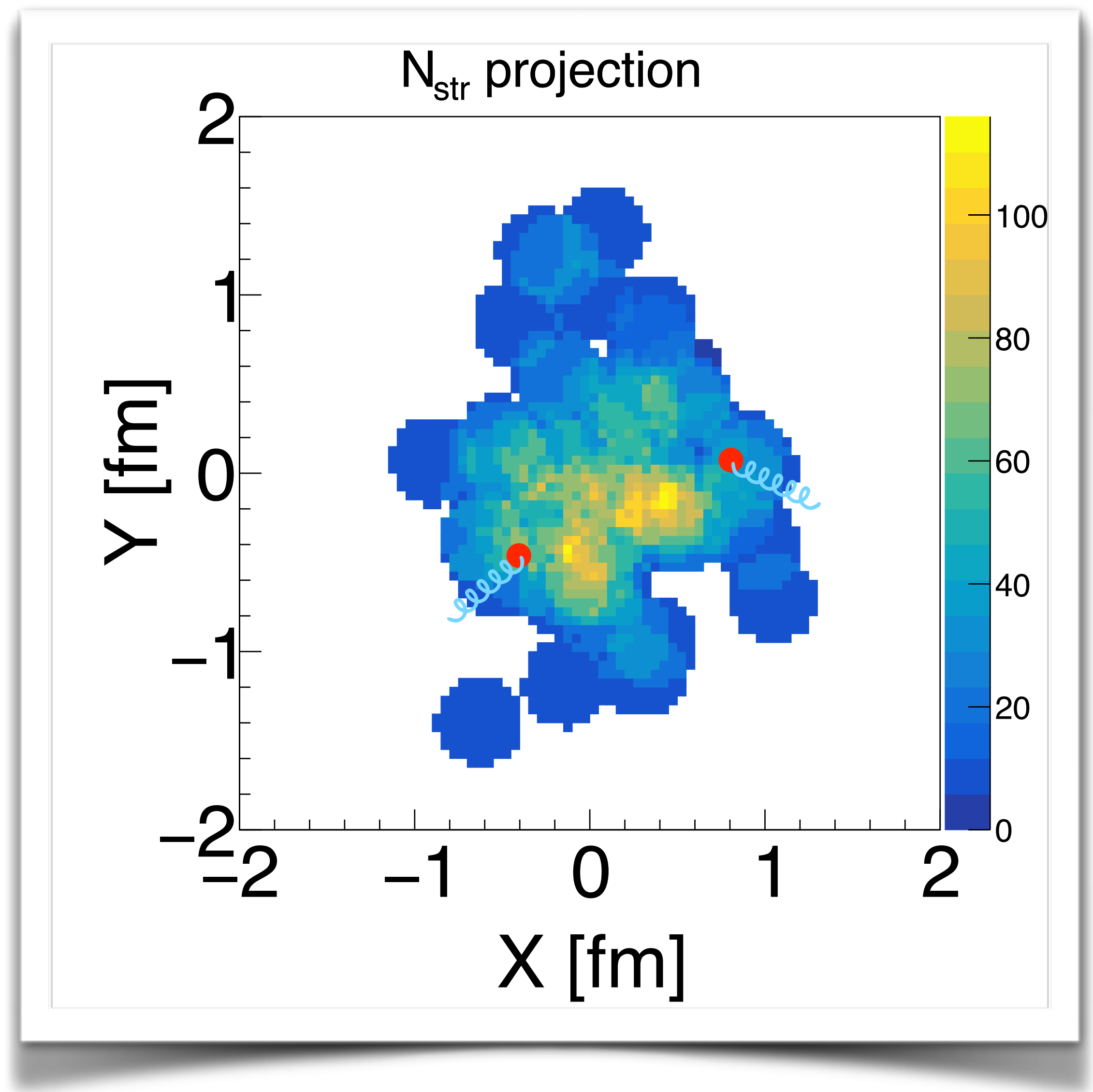




HEAVY QUARKS IN **MEDIUM**

- from PYTHIA
- eikonal approximation
- elastic and inelastic energy loss: each step





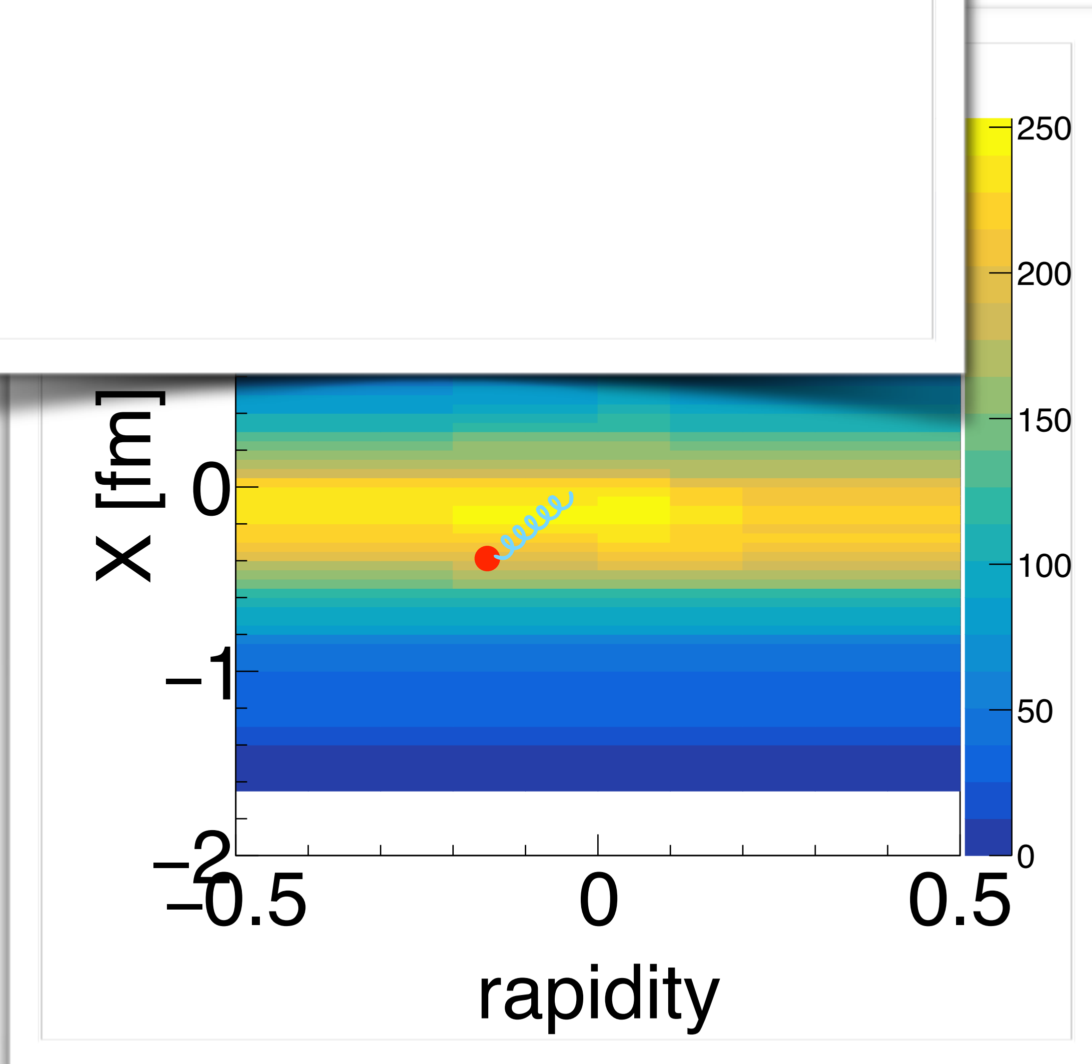
HEAVY QUARKS IN **MEDIUM**

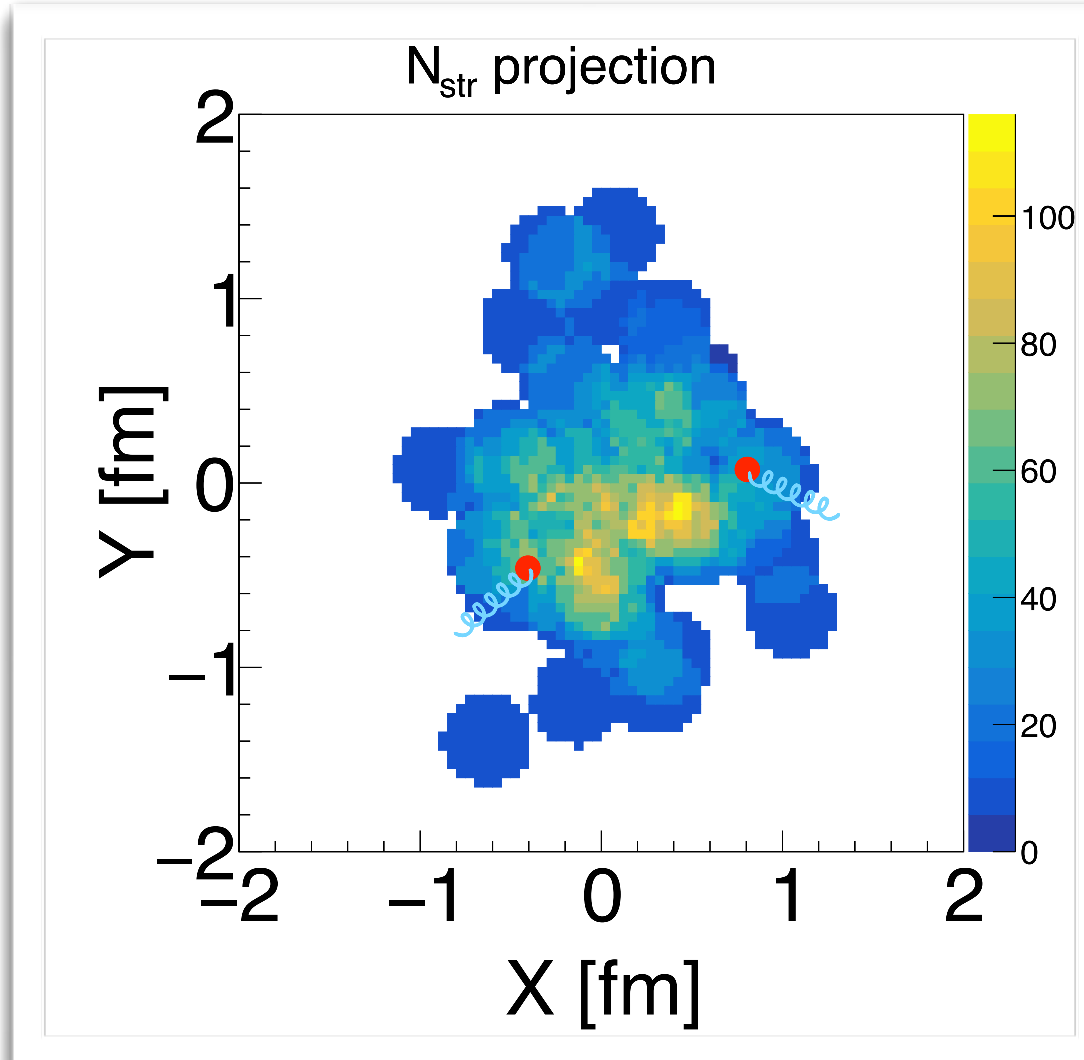
- fr
- ei

Collisional

q + g -> q + g

- elastic and inelastic energy loss: each step





HEAVY QUARKS IN **MEDIUM**

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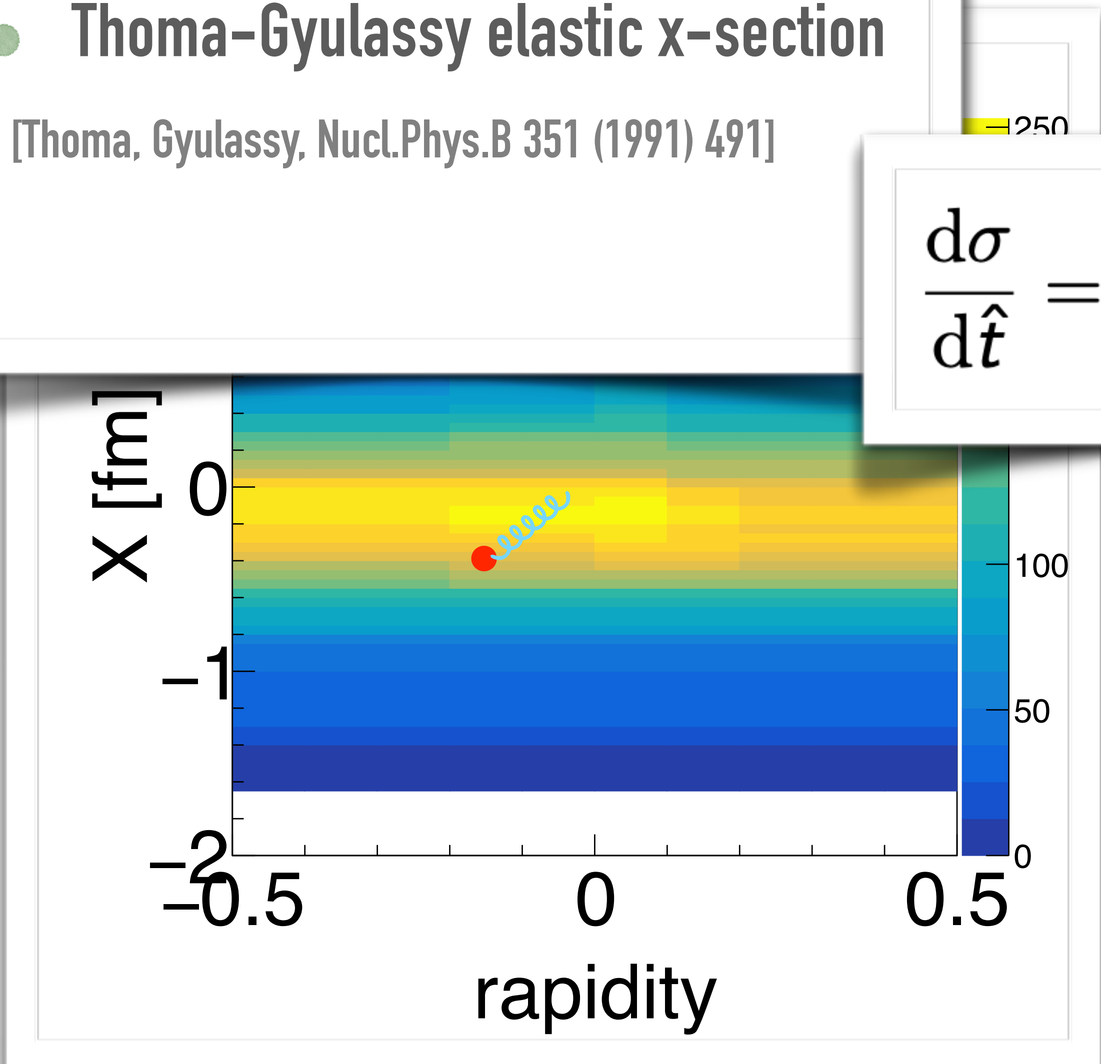
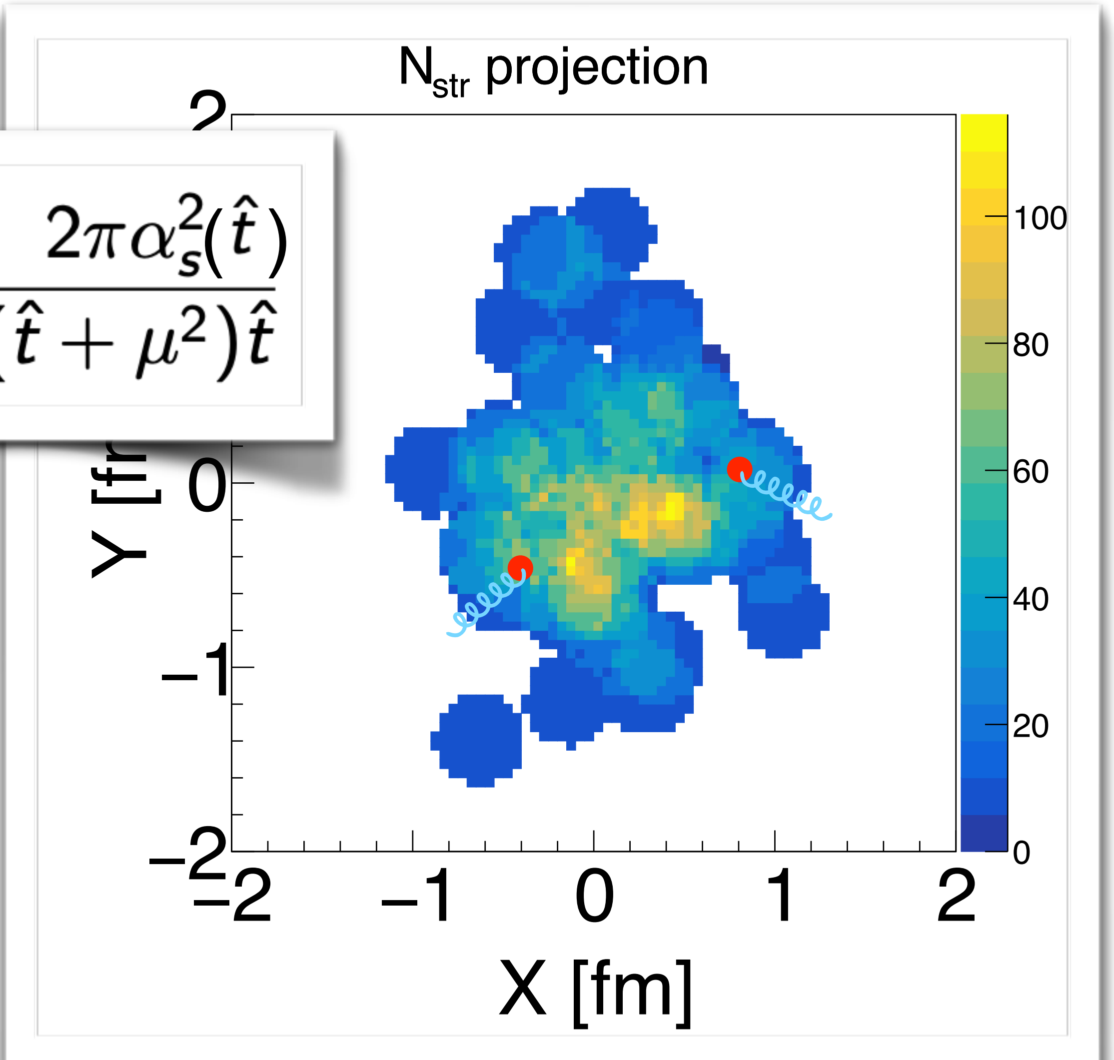
[Thoma, Gyulassy, Nucl.Phys.B 351 (1991) 491]

$$\frac{d\sigma}{d\hat{t}} = \frac{2\pi\alpha_s^2(\hat{t})}{(\hat{t}+\mu^2)\hat{t}}$$





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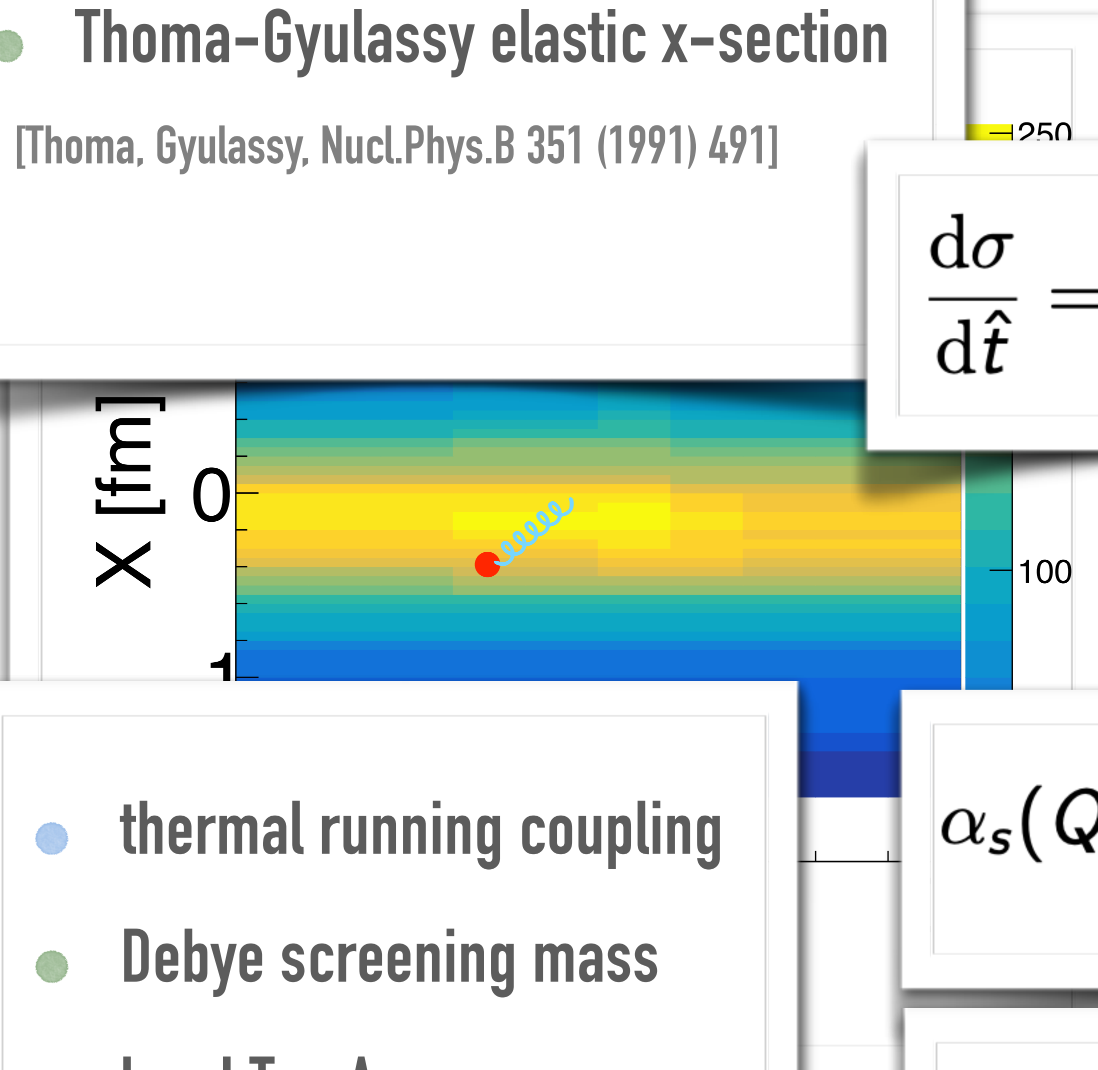

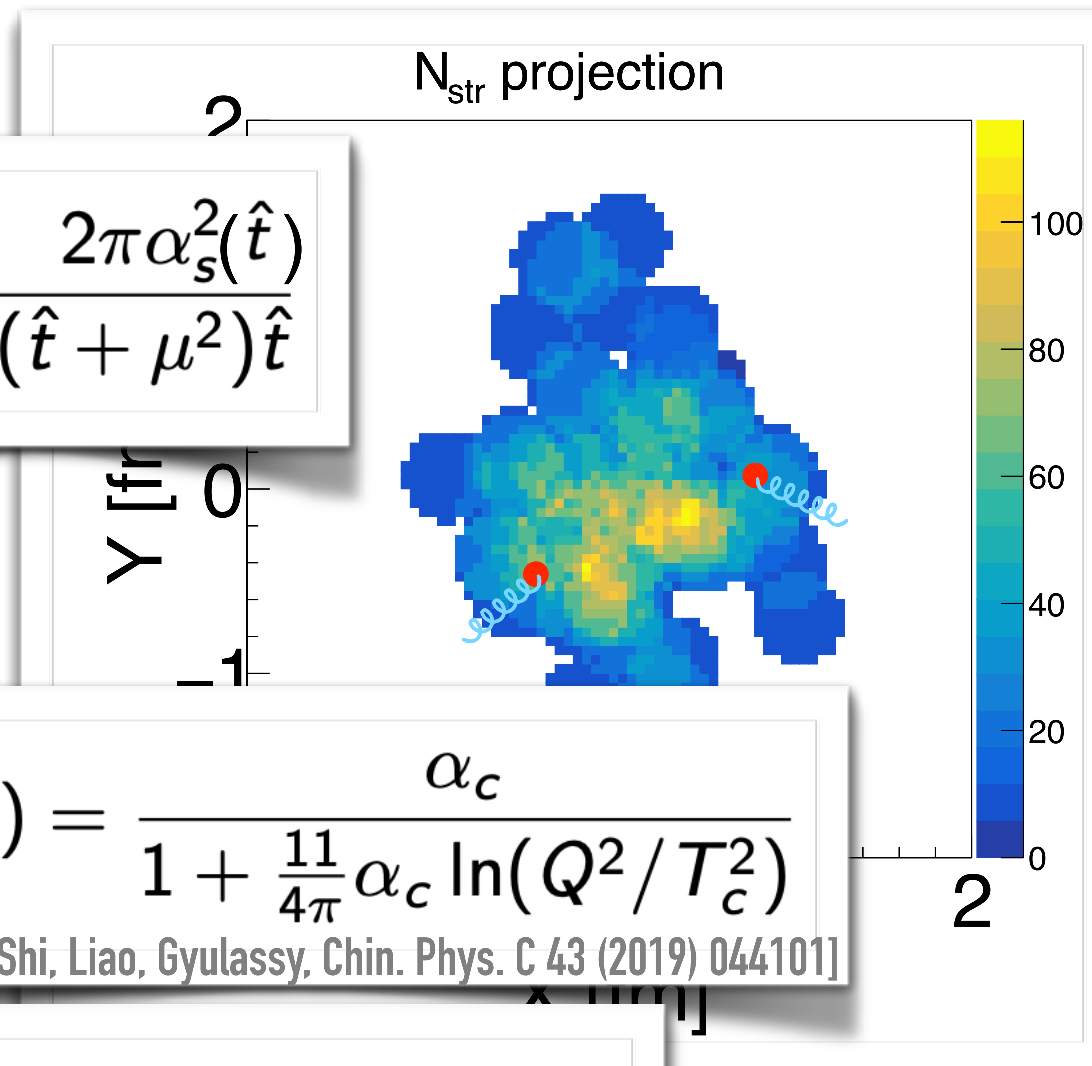

- thermal running coupling
- Debye screening mass
- local T or Λ

$$\alpha_s(Q^2) = \frac{\alpha_c}{1+\frac{11}{4\pi}\alpha_c \ln(Q^2/T_c^2)}$$

[Shi, Liao, Gyulassy, Chin. Phys. C 43 (2019) 044101]

$$\mu(T) = T\sqrt{4\pi\cdot\alpha_s(\mu^2)}$$

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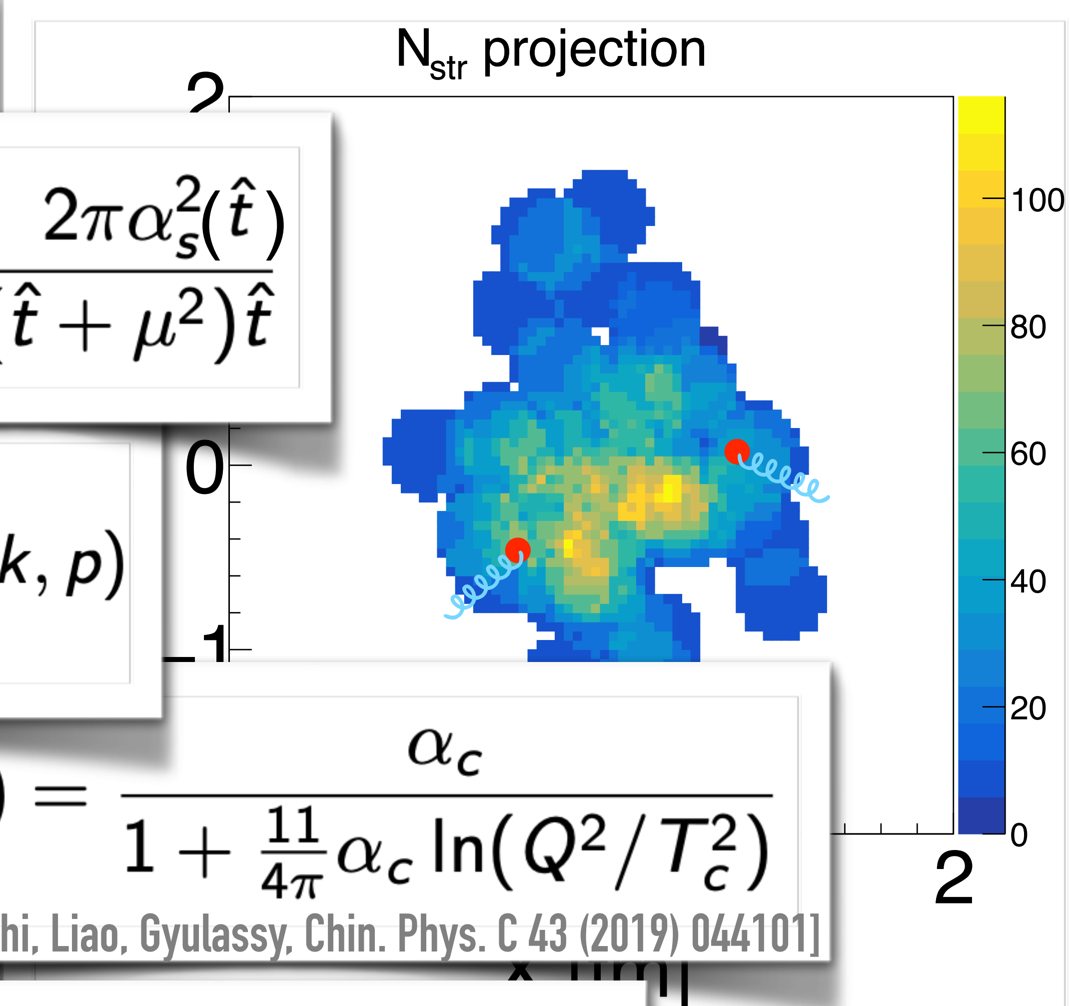

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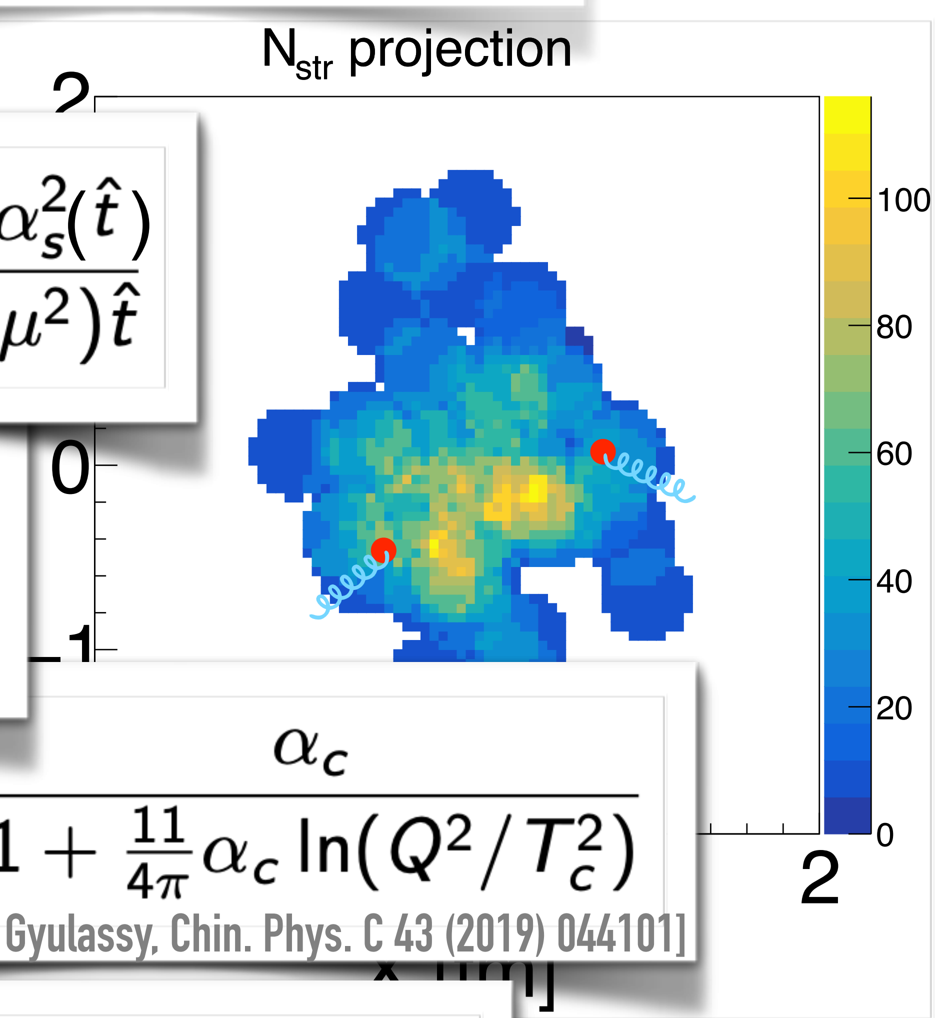

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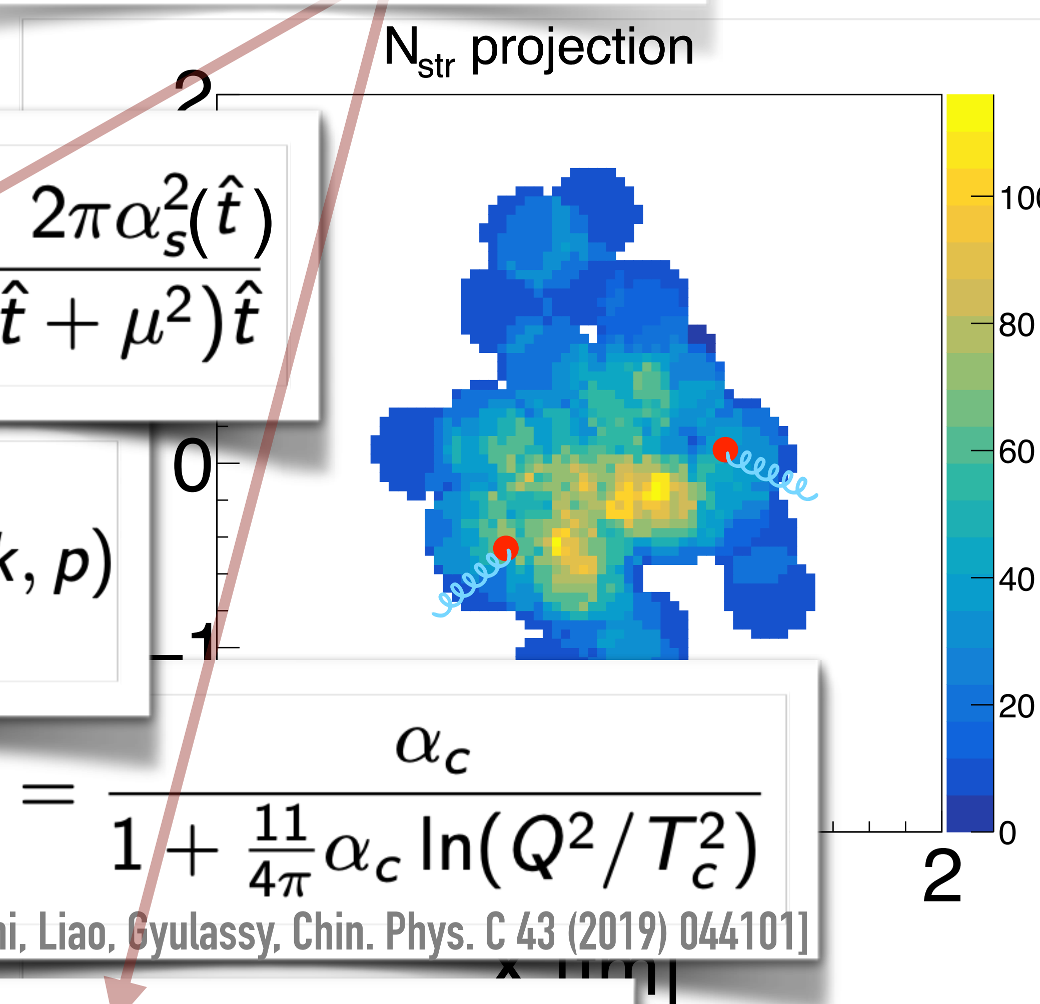

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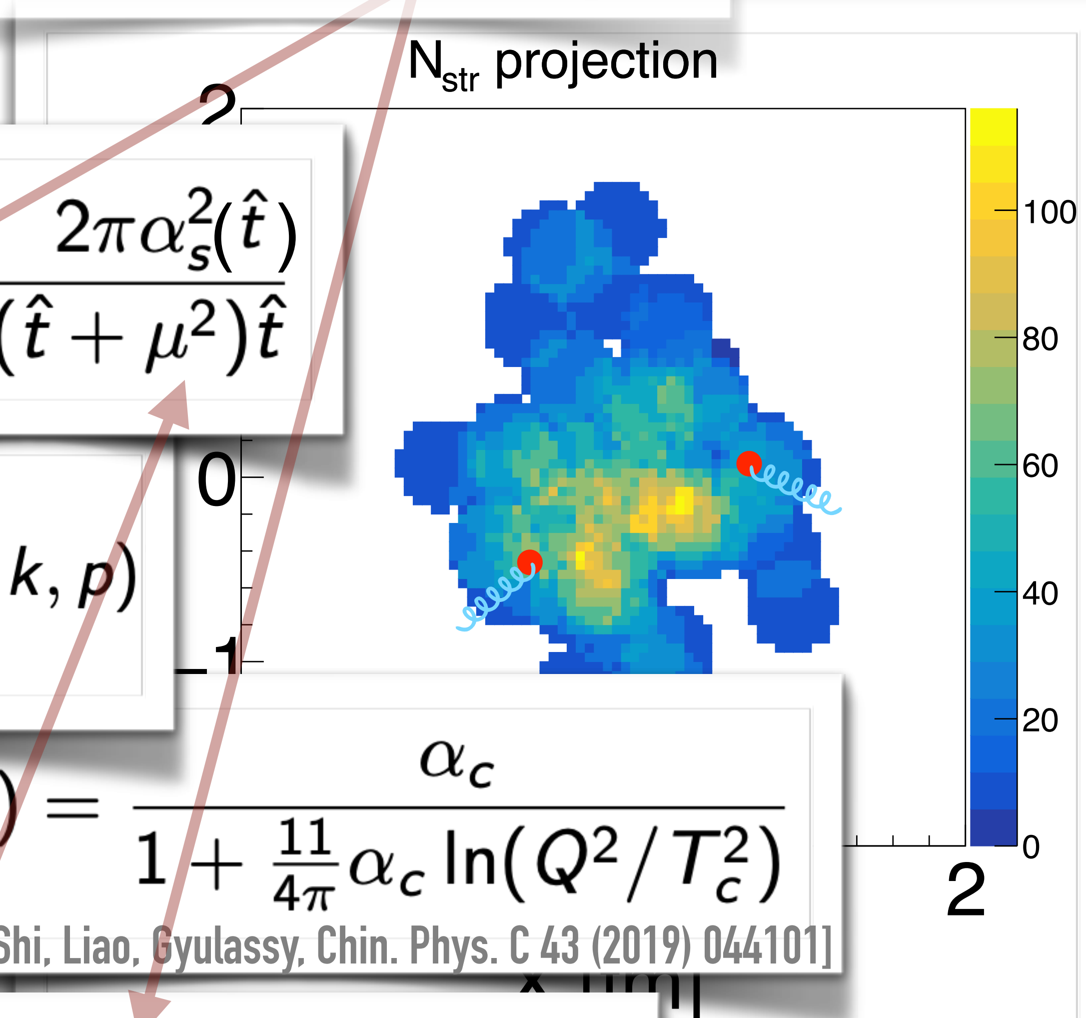

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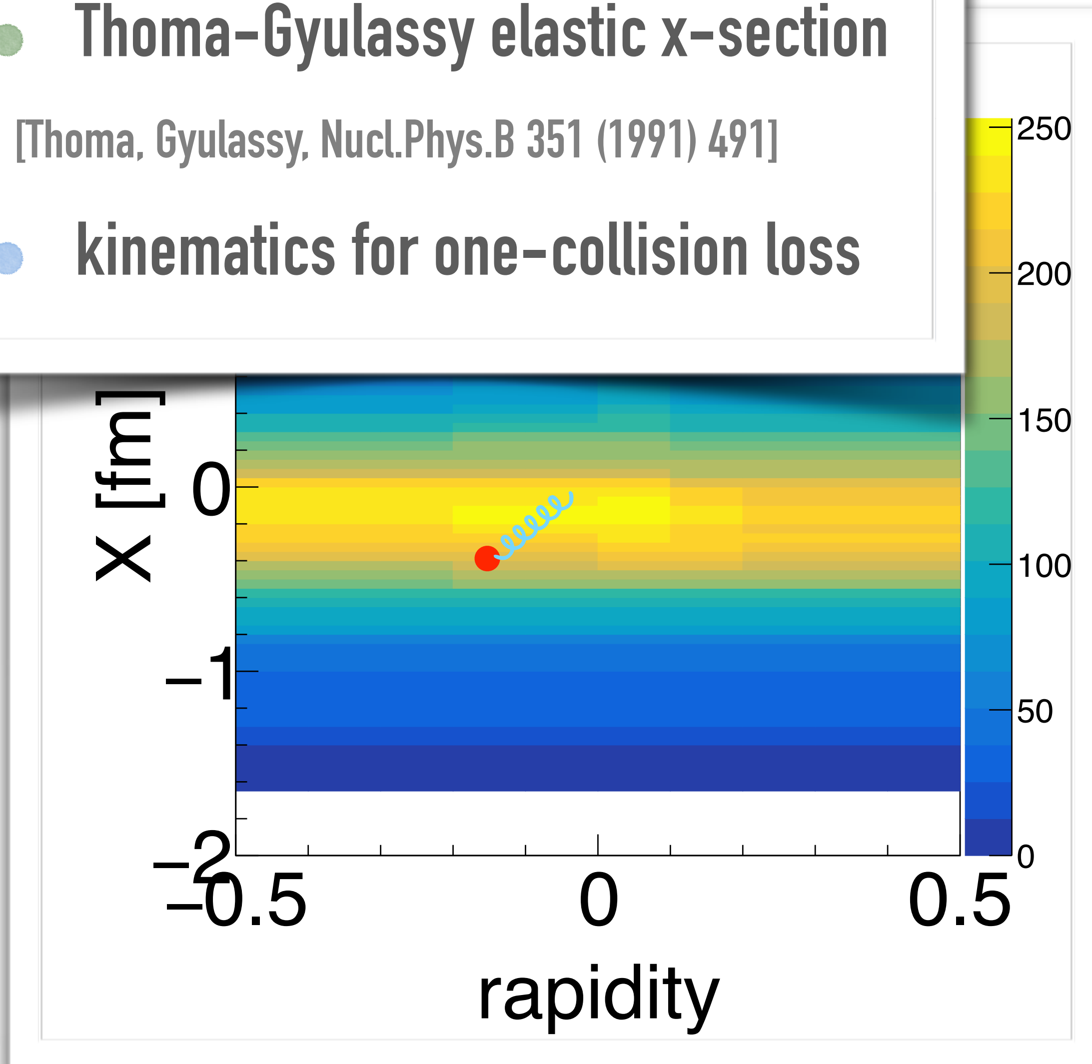

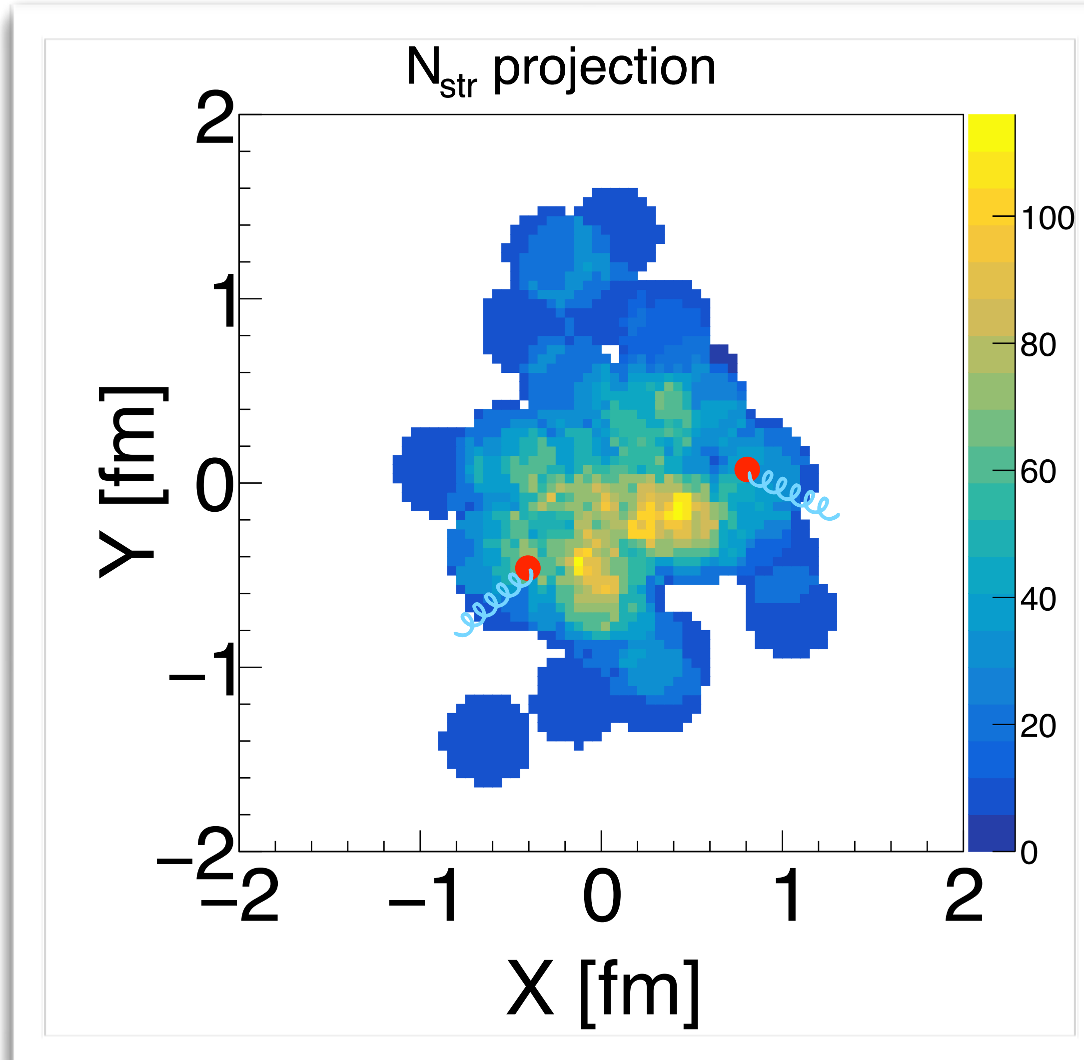

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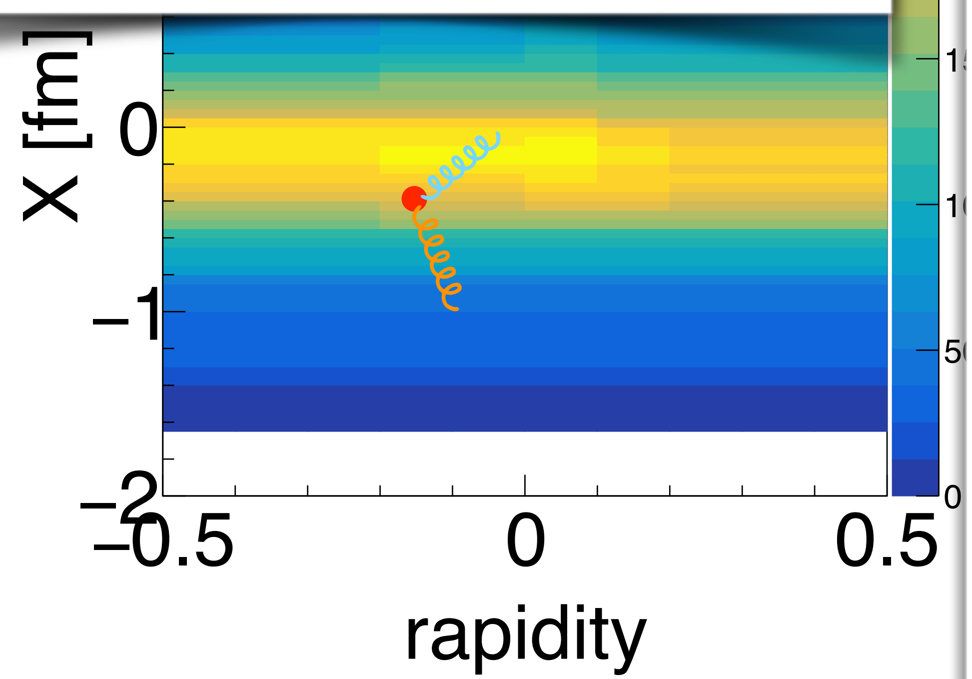

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probabilistic

Radiative

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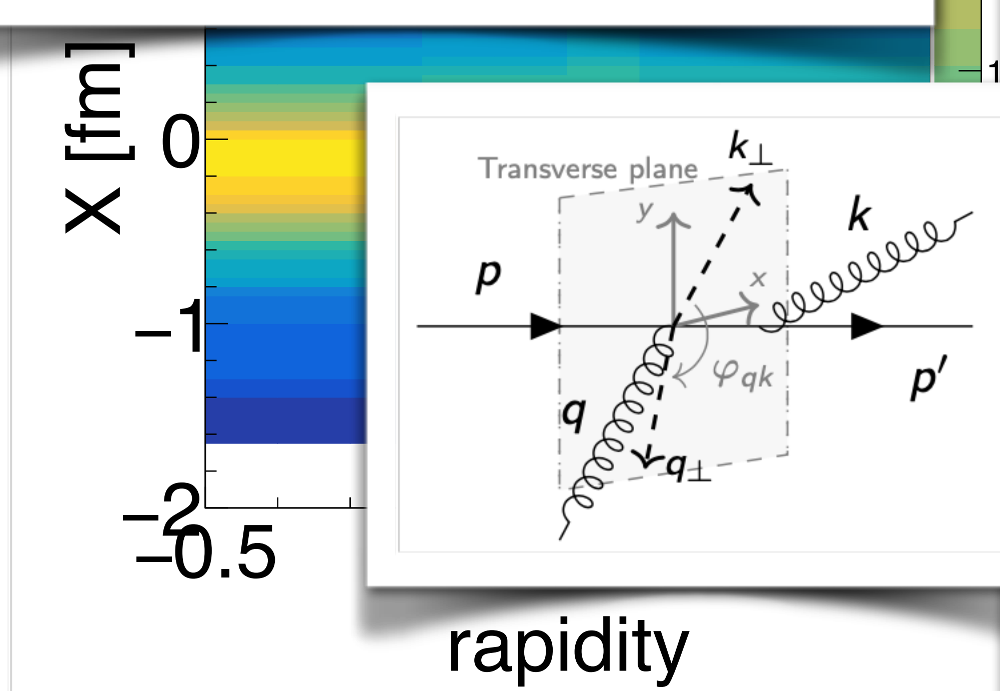

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- DGLV formalism for in-medium gluon radiation

[Gyulassy, Levai, Vitev, Nucl. Phys. B, 571 (2000) 197
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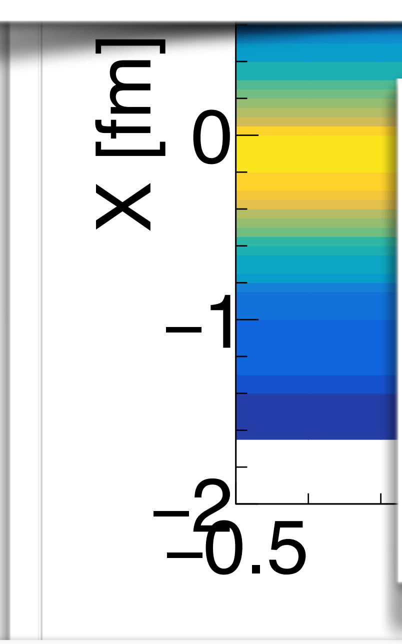

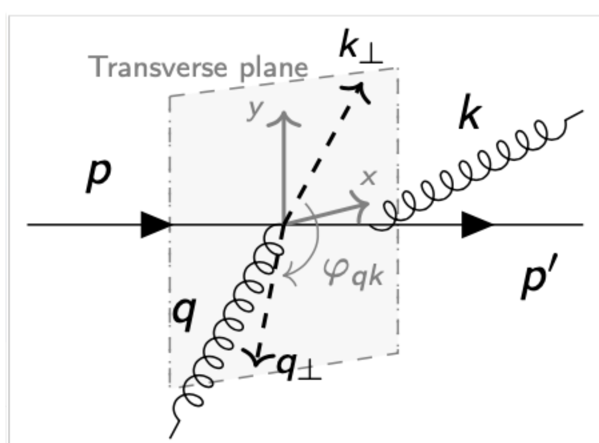

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[Gyulassy, Levai, Vitev, Nucl. Phys. B, 571 (2000) 197
Djordjevic, Gyulassy, Nucl. Phys. A 733 (2004) 265]

- in dynamical finite-size QCD medium

[Djordjevic, Heinz, Phys. Rev. C 77 (2008) 024905,
Phys. Rev. Lett. 101 (2008) 022302]

with LPM destructive interference

$$z\frac{d\Gamma^{\mathrm{n=1}}_{q\to qg}}{dz}(z,p,T,t) \propto \rho(T)\int d^2\mathbf{q}_\perp\, d^2\mathbf{k}_\perp\, \mathcal{K}(\mathbf{k}_\perp,\mathbf{q}_\perp,z,p,T,t)$$

HEAVY QUARKS IN **MEDIUM**

Single gluon emission spectrum at n = 1 DGLV opacity series [Shi, Yazdi, Gale, Jeon, Phys. Rev. C 107 (2023) 3, 034908]

$$z\frac{dN^{\mathrm{n=1}}_{q\to qg}}{dz}(p,T,\tau,z)=\frac{6}{\pi^2}\int_0^{\tau}dt\,\rho(T)\int d^2\mathbf{k}_\perp\,d^2\mathbf{q}_\perp\left\{\frac{\alpha_s^2\,[\mathbf{q}_\perp^2]}{\mathbf{q}_\perp^2(\mathbf{q}_\perp^2+\mu^2)}\longleftarrow \text{elastic}\right.$$

$$\text{gluon emission}\longrightarrow\times\,\alpha_s\left[\frac{\mathbf{k}_\perp^2}{z_+(1-z_+)}\right]\cdot\frac{z}{z_+}\cdot\left|\frac{dz_+}{dz}\right|$$

$$\text{interference}\longrightarrow\times\frac{-2}{(\mathbf{k}_\perp-\mathbf{q}_\perp)^2+\chi^2}\cdot\left(\frac{\mathbf{k}_\perp\cdot(\mathbf{k}_\perp-\mathbf{q}_\perp)}{\mathbf{k}_\perp^2+\chi^2}-\frac{(\mathbf{k}_\perp-\mathbf{q}_\perp)^2}{(\mathbf{k}_\perp-\mathbf{q}_\perp)^2+\chi^2}\right)$$

$$\left.\text{LPM suppression}\longrightarrow\times\left(1-\cos\left[\frac{(\mathbf{k}_\perp-\mathbf{q}_\perp)^2+\chi^2}{2z_+p}\cdot t\right]\right)\right\}$$

dead cone and screening:

$$\chi^2(T)=m^2z_+^2+\frac{\mu^2(T)}{2}(1-z_+)$$

light cone $z+$ vs momentum fraction z:

$$z_+=\frac{1}{2}\left(z+\sqrt{z^2-(\mathbf{k}_\perp/p)^2}\right)$$

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n step

probabilistic

on radiation

m

rapidity

with LPM destructive interference

HEAVY QUARKS IN **MEDIUM**

$$f_{\text{aniso}}(k) = \frac{1}{e^{\frac{\sqrt{k_T^2+(1+\xi)k_z^2}}{\Lambda}} - 1}$$

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HEAVY QUARKS IN MEDIUM

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...on radiation

...m

rapidity

with LPM destructive interference

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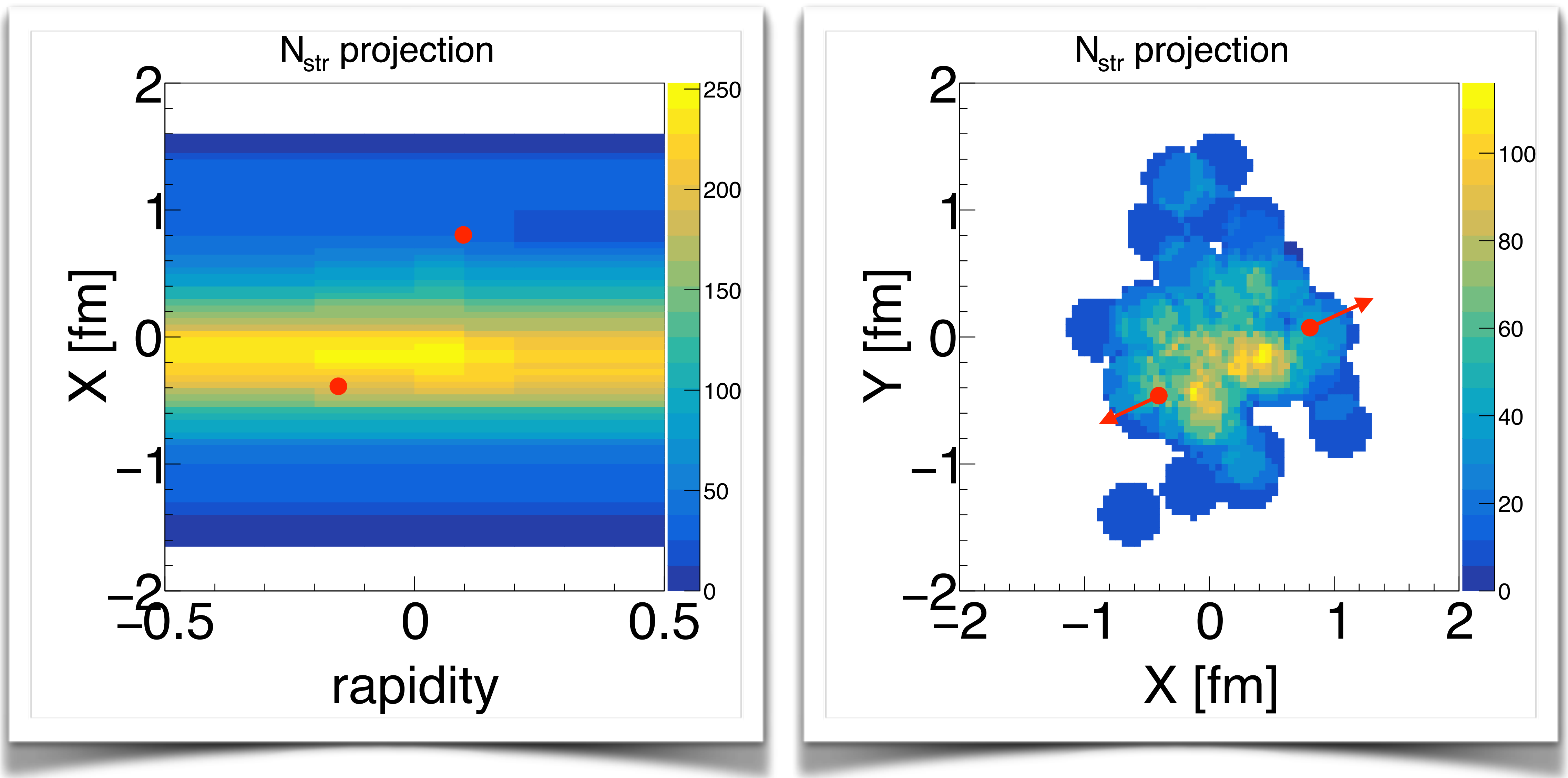
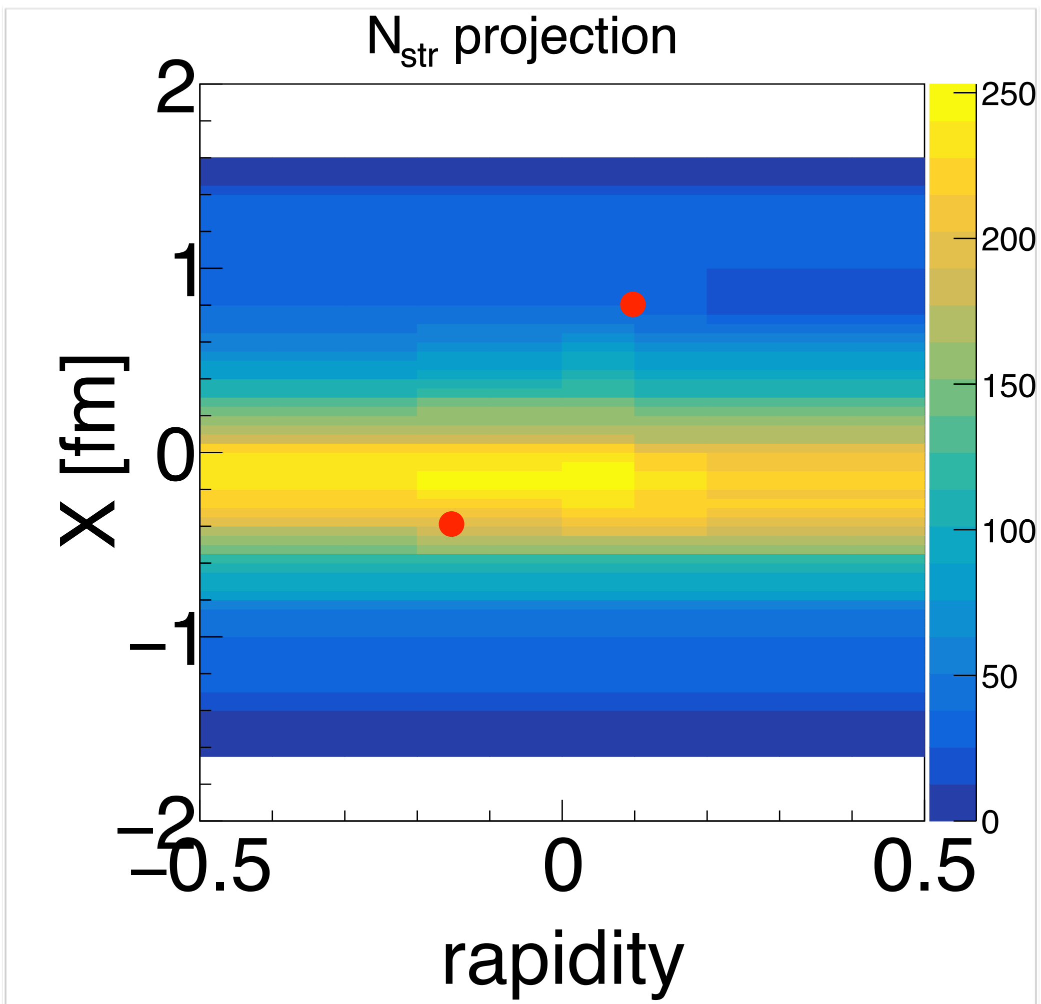
HEAVY QUARKS IN **MEDIUM**

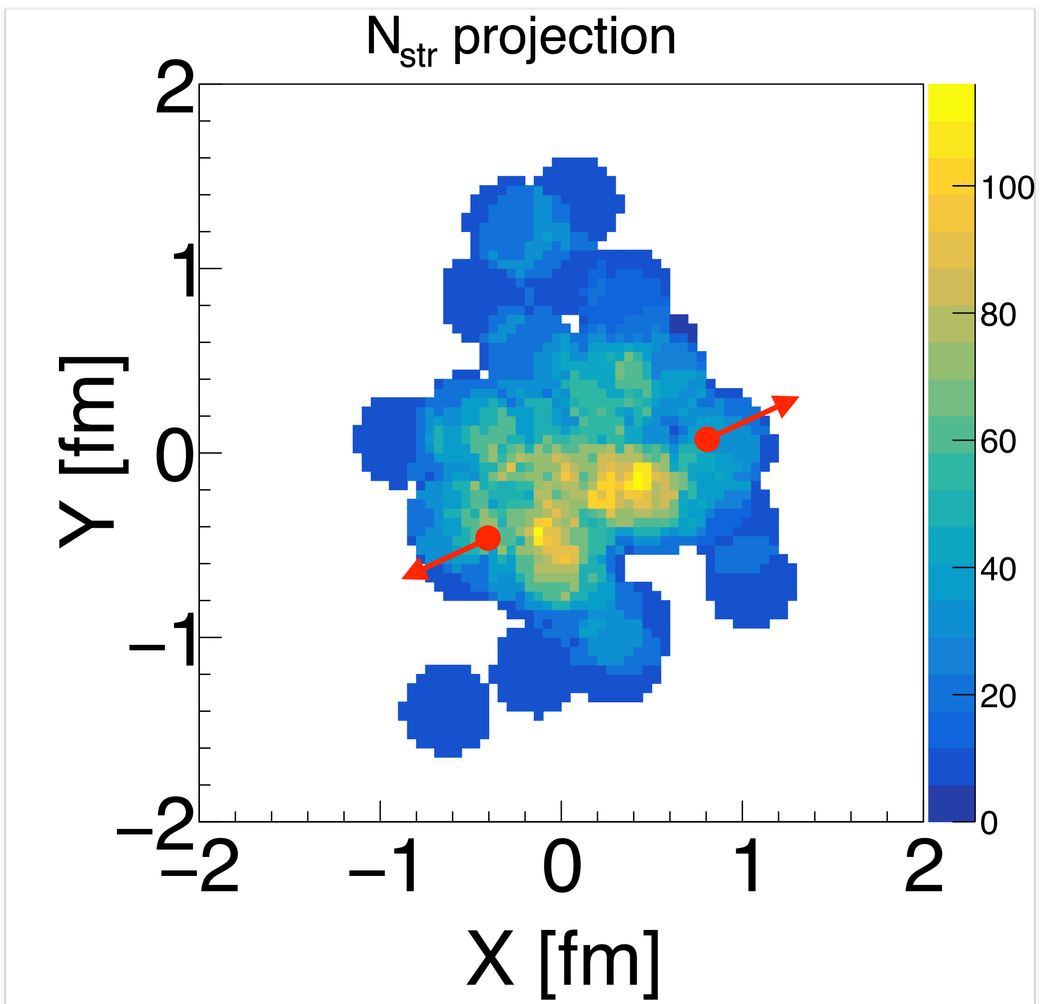
- from PYTHIA
- eikonal approximation
- elastic and inelastic energy loss



HEAVY QUARKS IN **MEDIUM**

- from PYTHIA
- eikonal approximation
- elastic and inelastic energy loss
- **coalescence and fragmentation into HF**



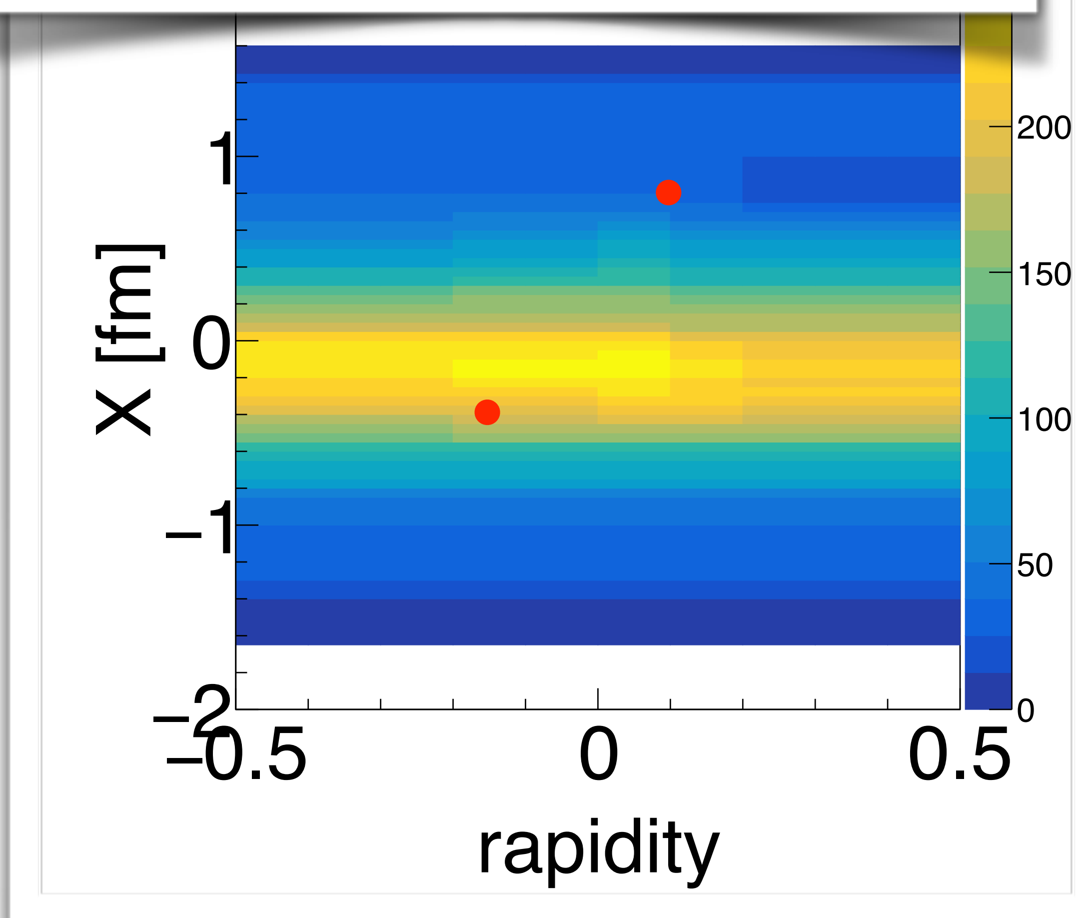


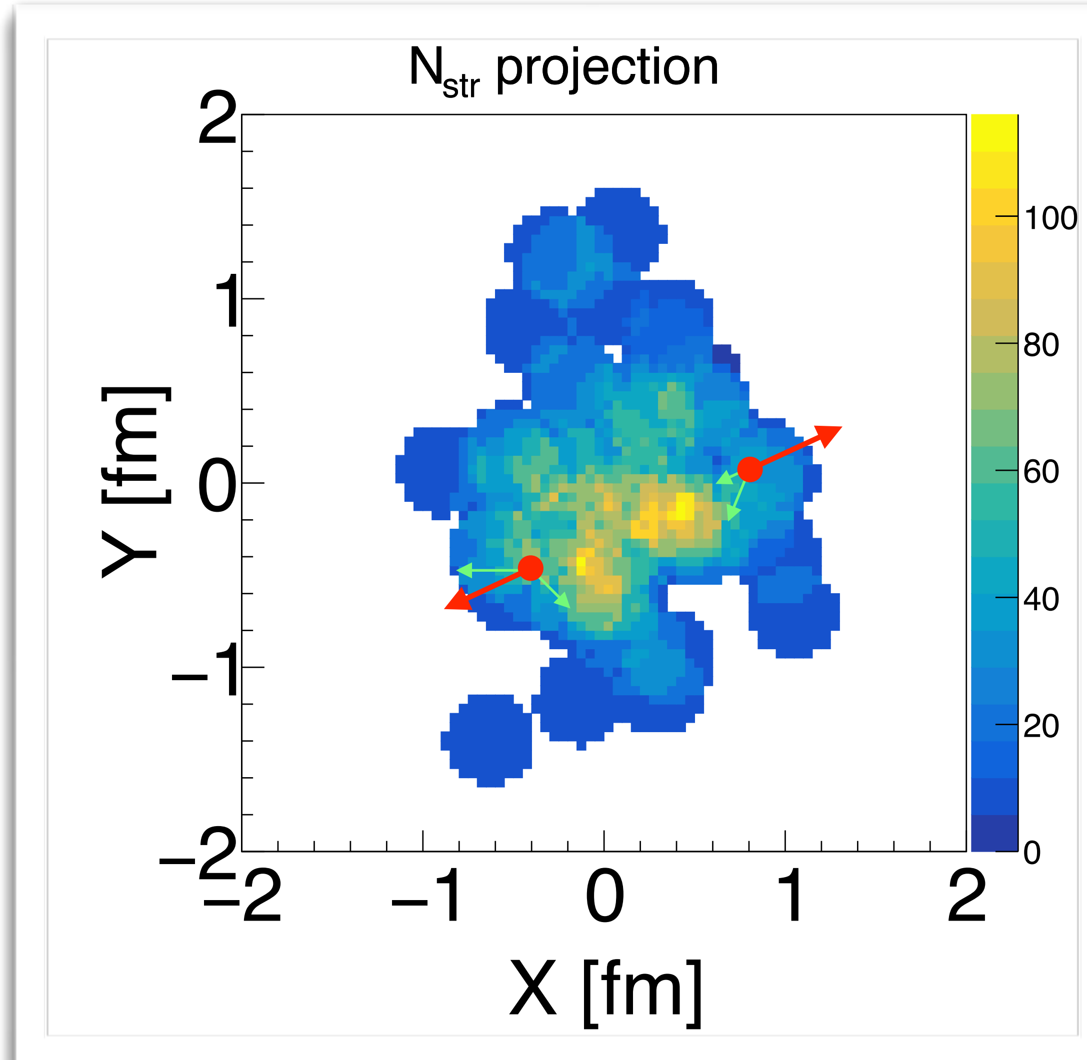
HEAVY QUARKS IN **MEDIUM**

- fron
- eiko

- in-cell **gluons fluctuate** to qqbar pairs
- **coalescence**: cell-proximity, momentum checked

- elastic and inelastic energy loss
- **coalescence and fragmentation into HF**





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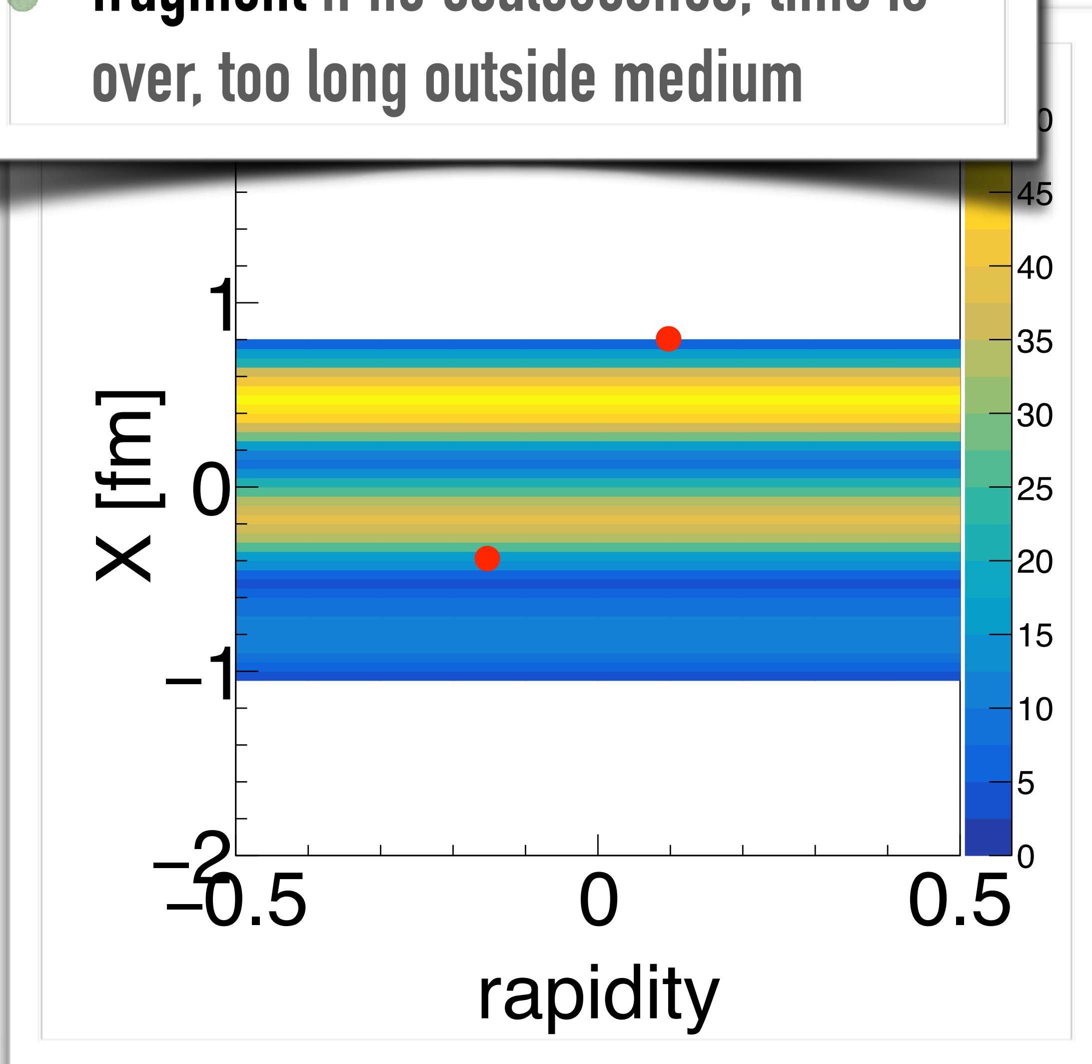

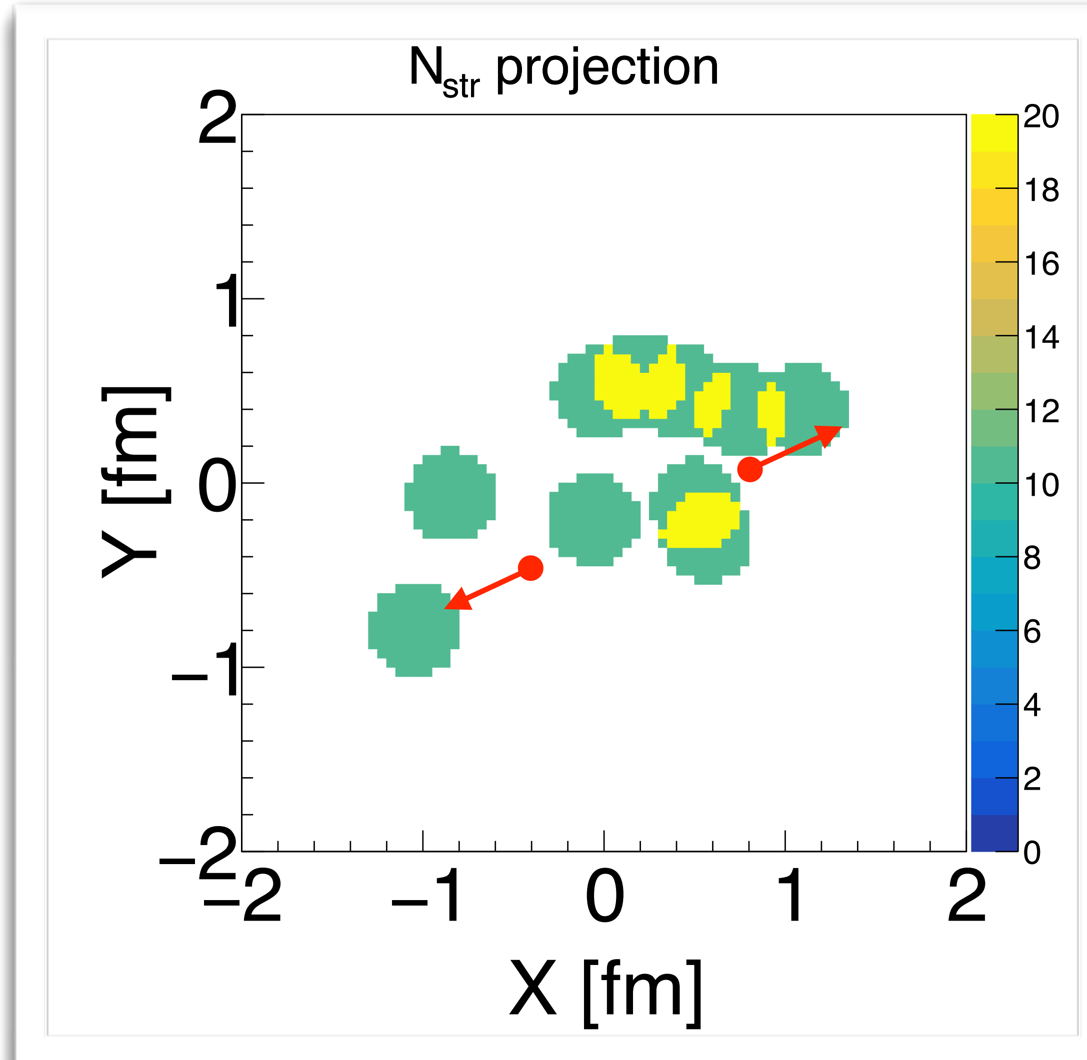

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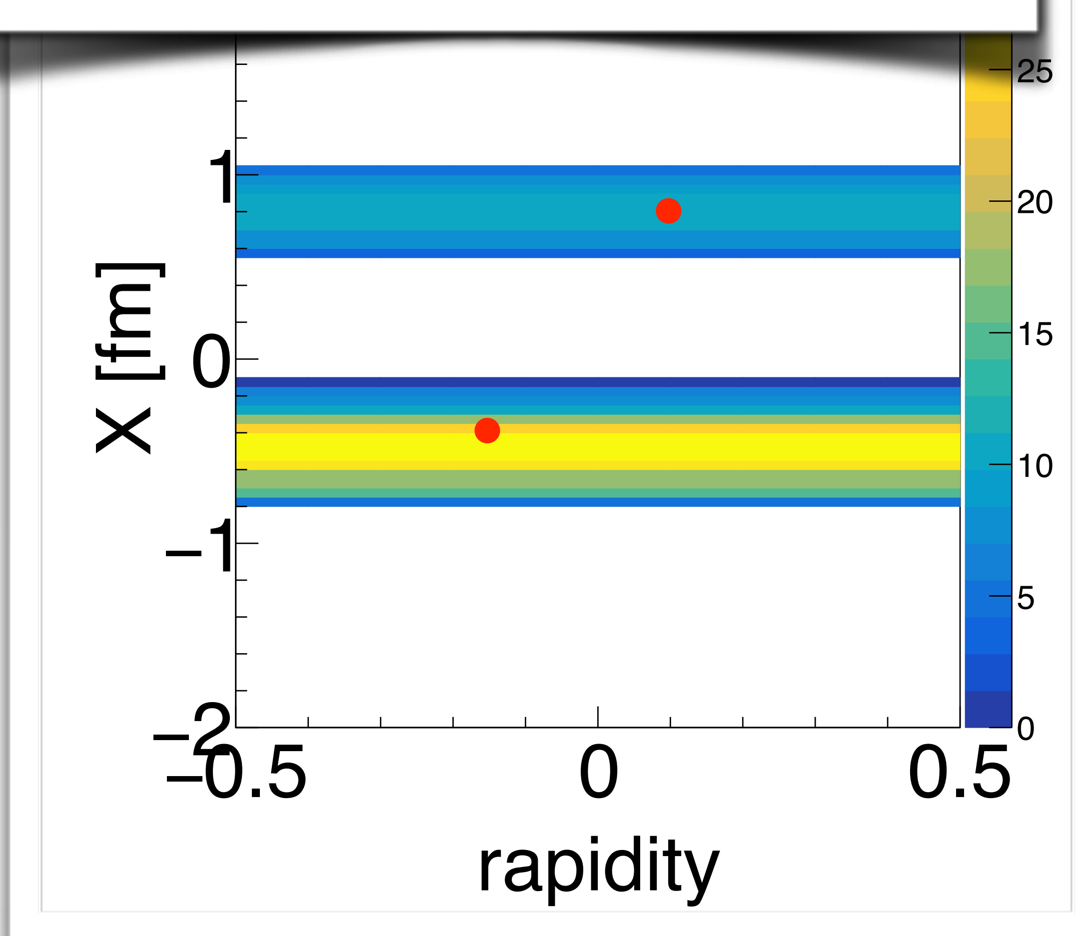
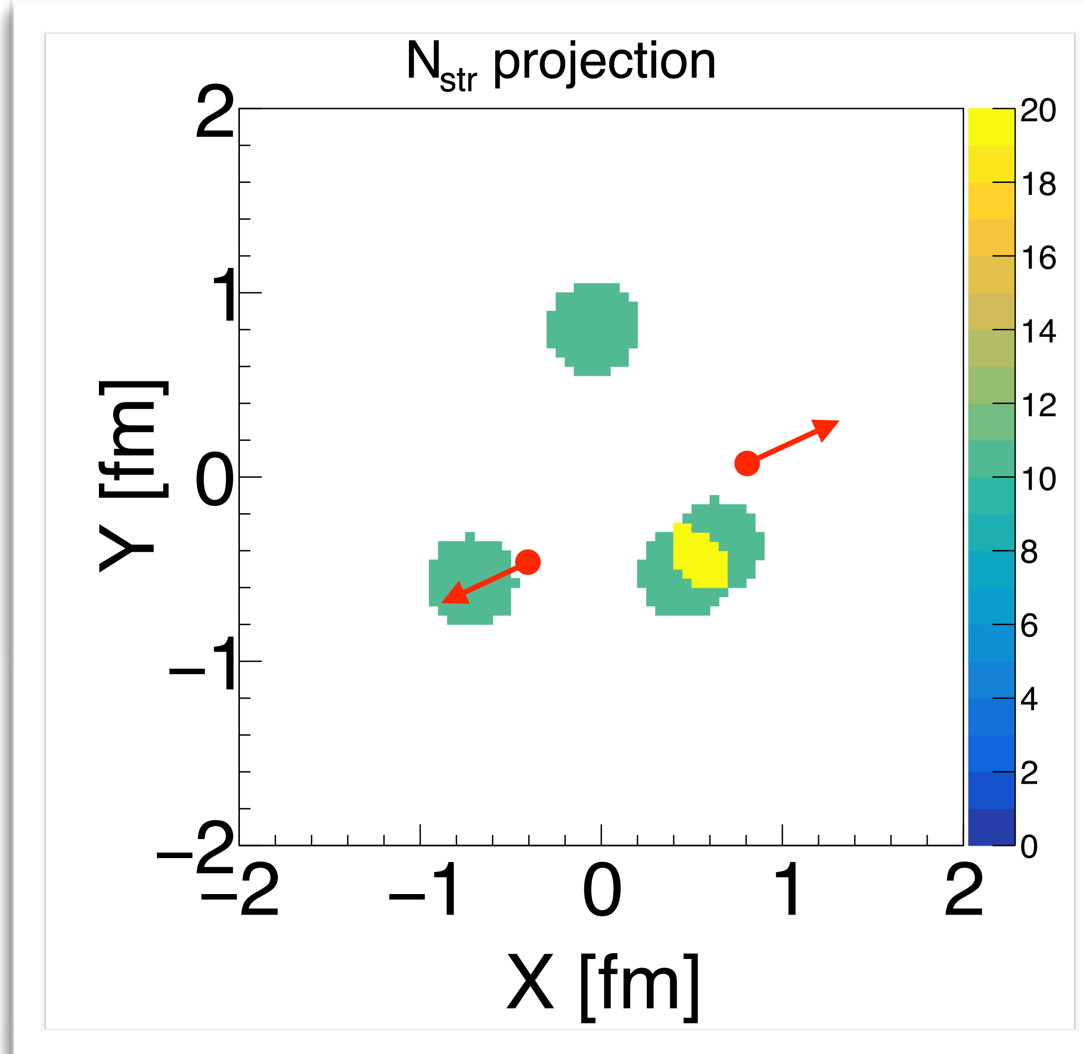
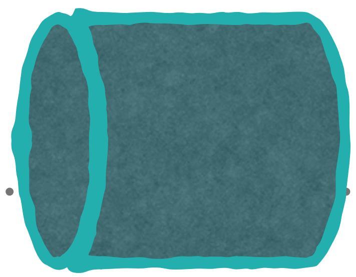


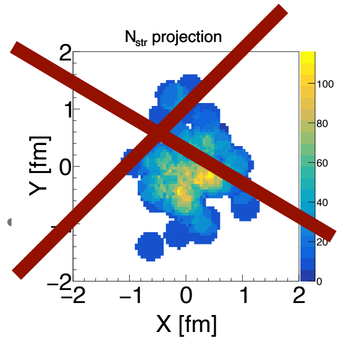


RESULTS

RESULTS

RESULTS: SIMPLIFIED **BRICK MEDIUM**



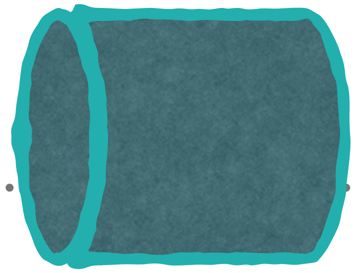


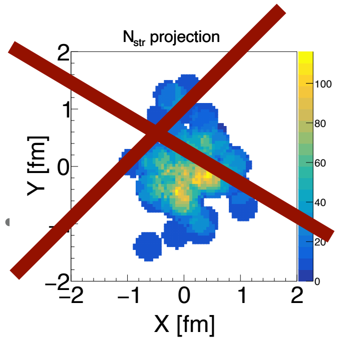
static medium

constant density

no quark escape

RESULTS: SIMPLIFIED BRICK MEDIUM





charm quark

static medium

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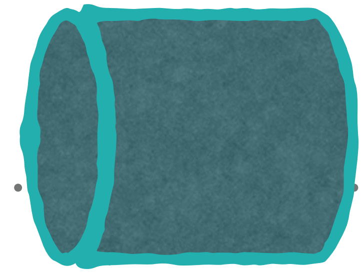
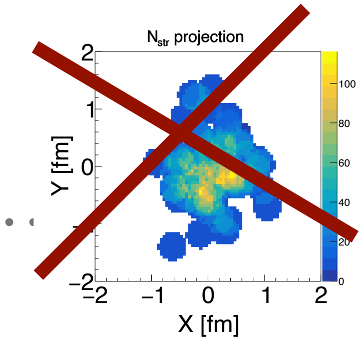
RESULTS: SIMPLIFIED BRICK MEDIUM





collisional loss

charm quark

static medium

constant density

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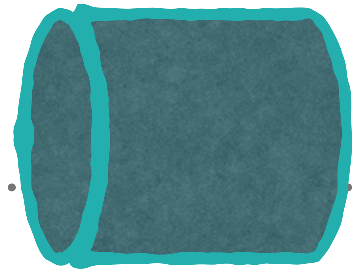
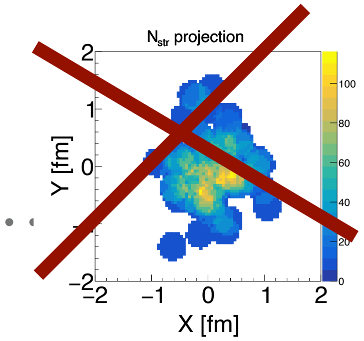
Average loss as a function of initial momentum for

RESULTS: SIMPLIFIED BRICK MEDIUM





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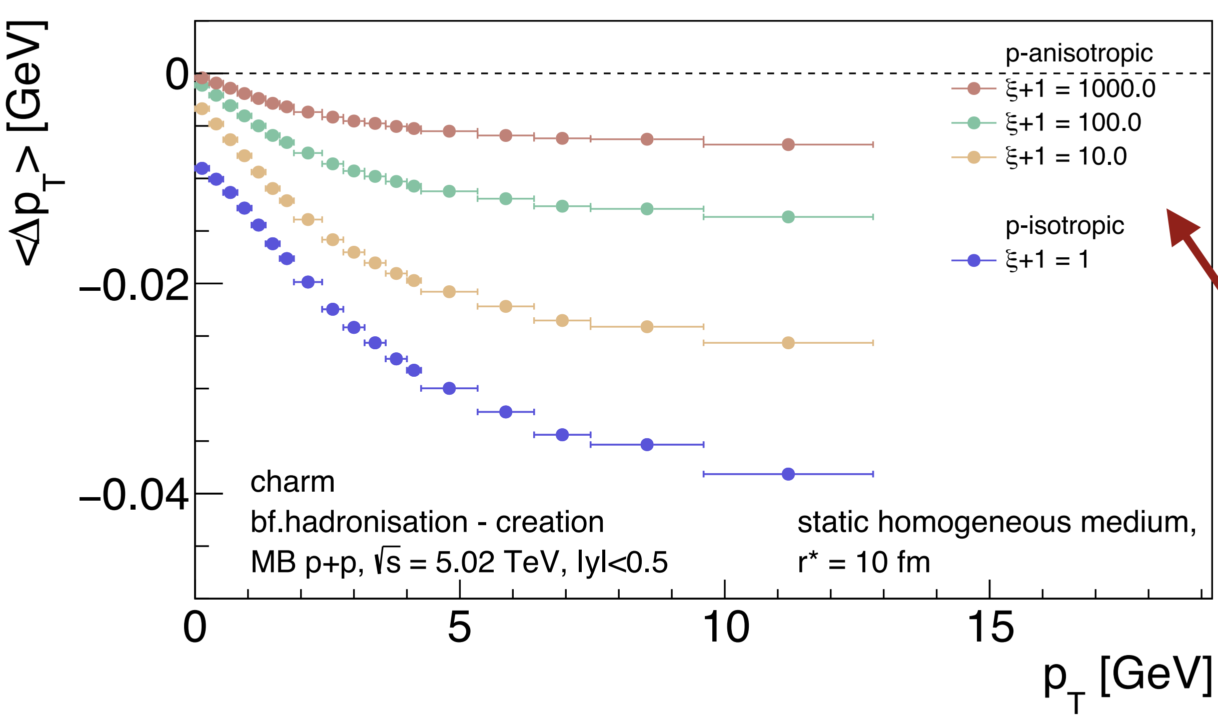
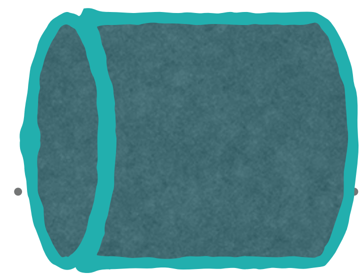


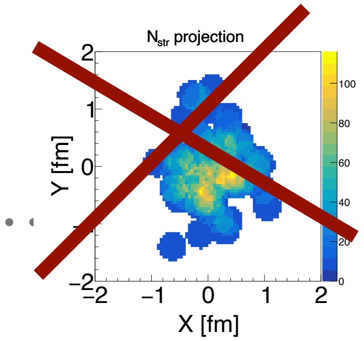
Average loss as a function of initial momentum for

- anisotropy parameter

$$f_{\mathrm{aniso}}(k) = \frac{1}{e^{\frac{\sqrt{k_T^2+(1+\xi)k_z^2}}{\Lambda}} - 1}$$

RESULTS: SIMPLIFIED BRICK MEDIUM





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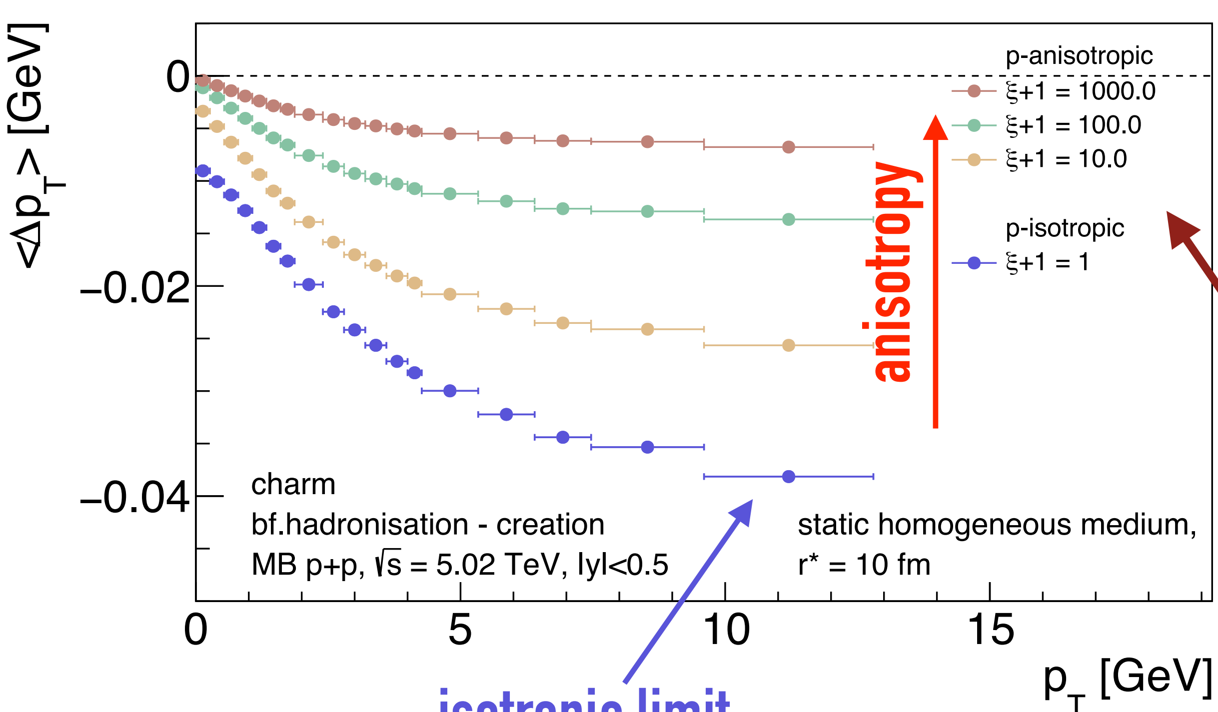

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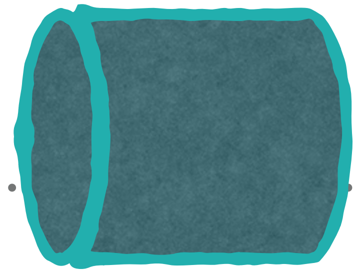

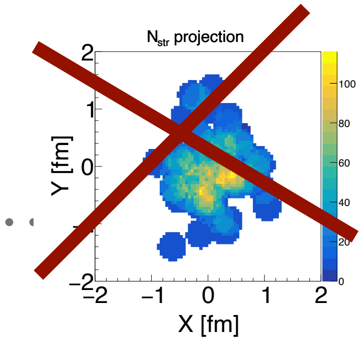

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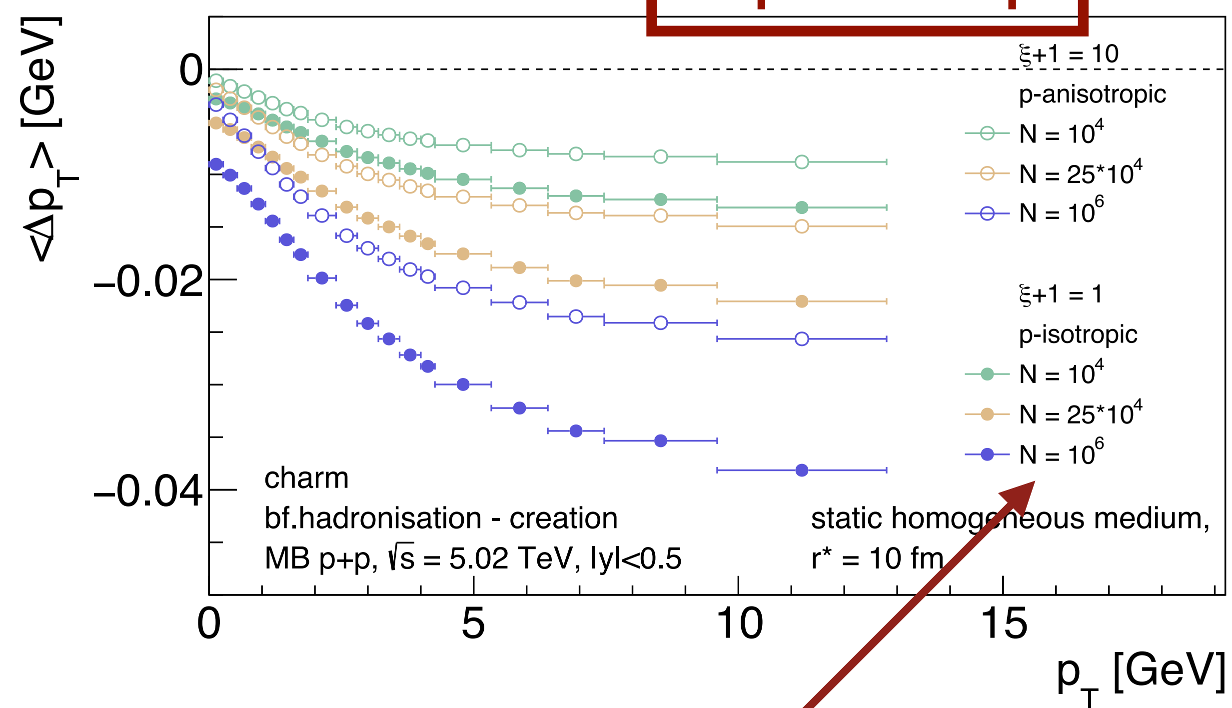

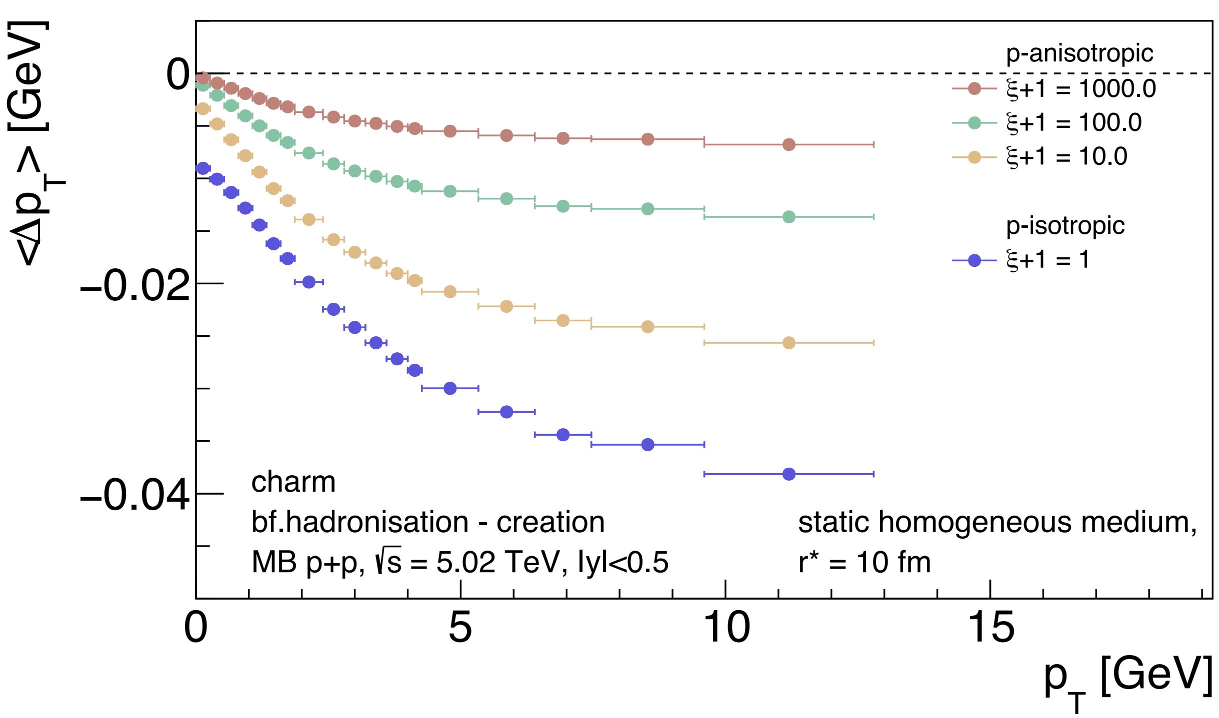

Average loss as a function of initial momentum for

- string density (a-la event activity)
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RESULTS: SIMPLIFIED BRICK MEDIUM

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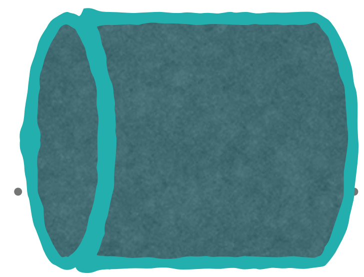
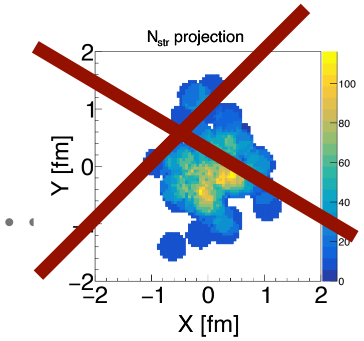
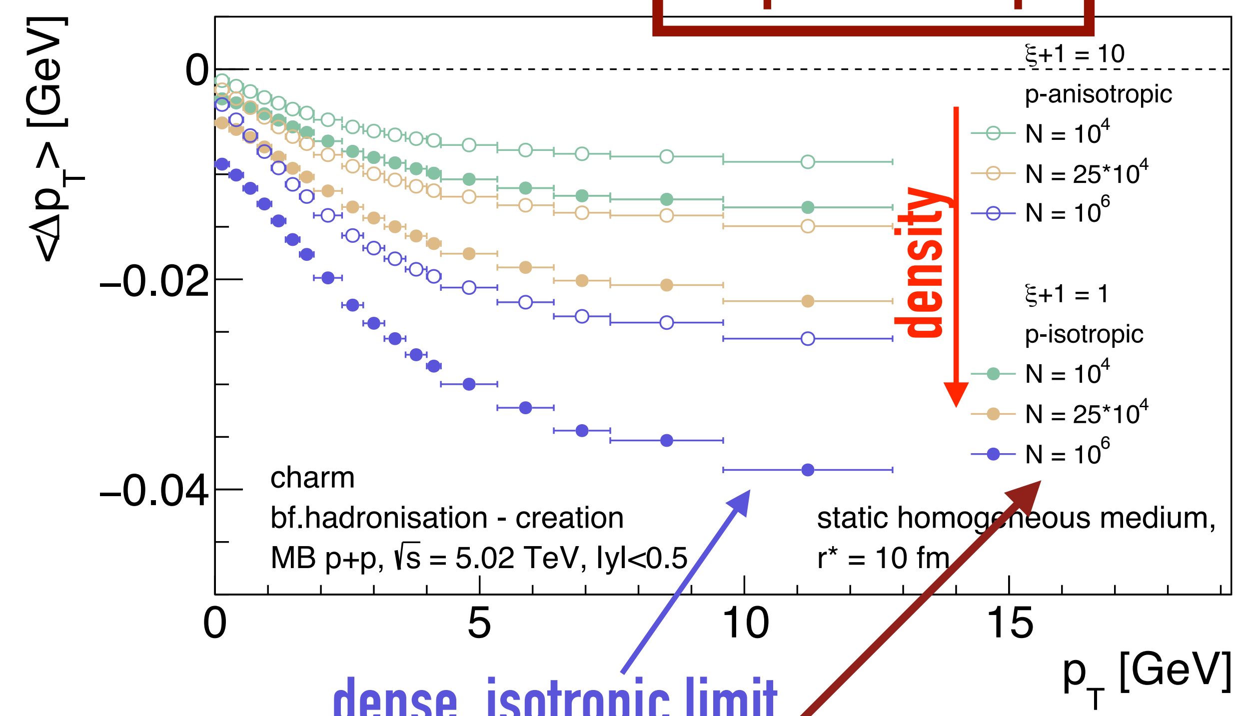
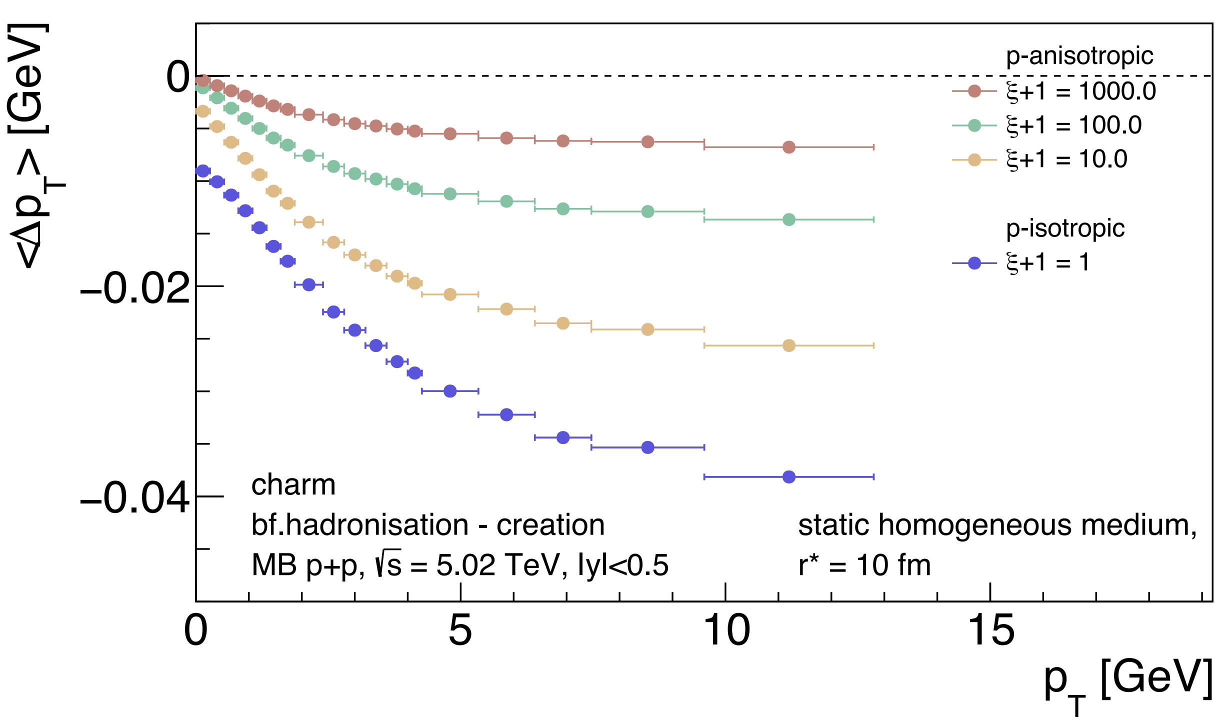




no quark escape





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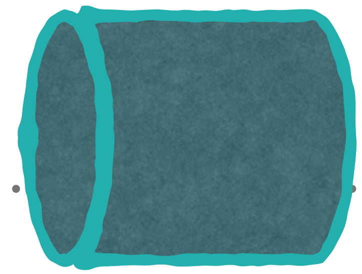

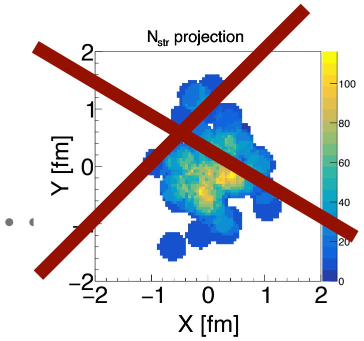

collisional loss

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static medium

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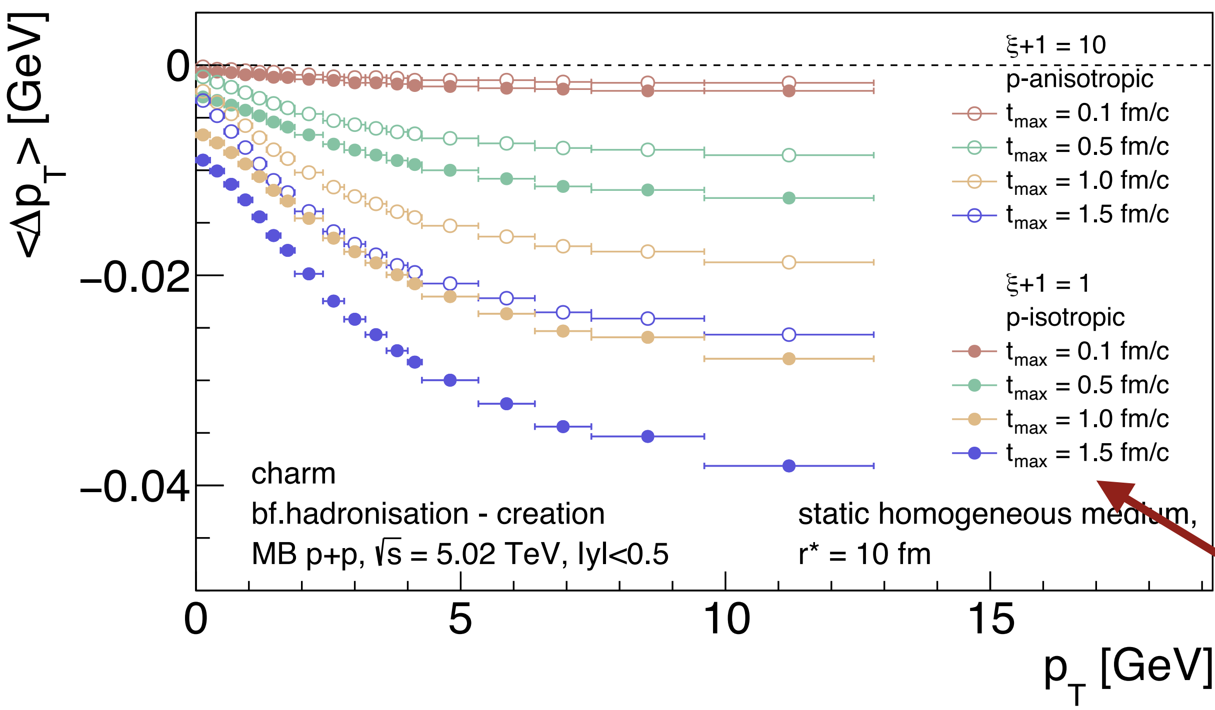
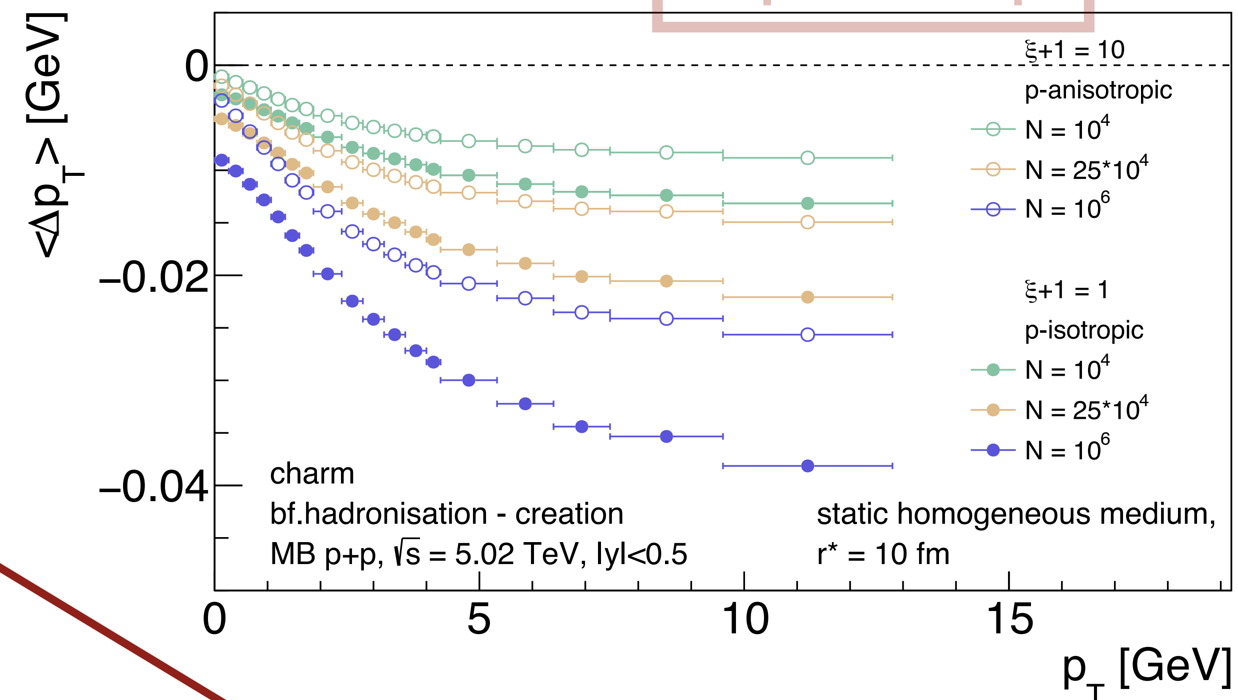
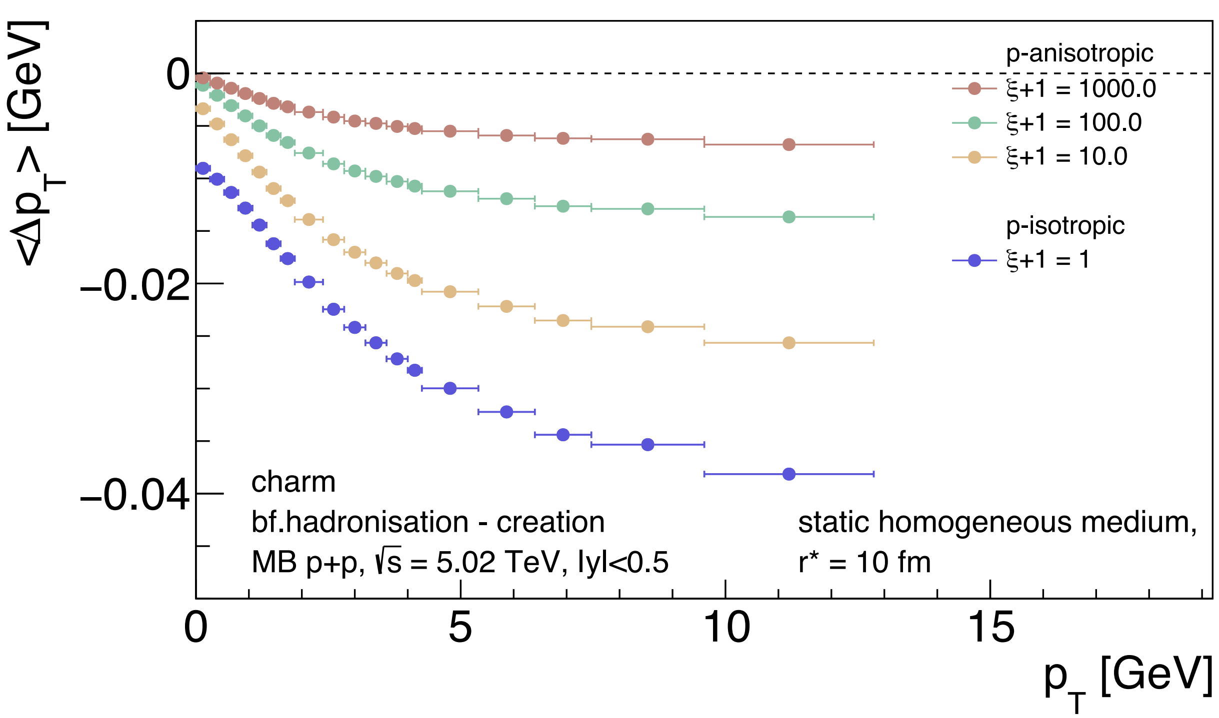




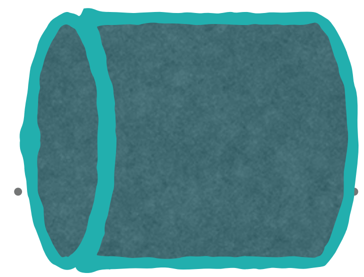


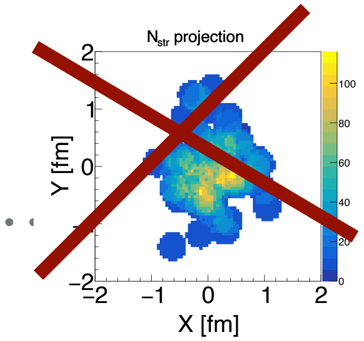
Average loss as a function of initial momentum for

- max quark propagation time
- string density (a-la event activity)
- anisotropy parameter

$$f_{\text{aniso}}(k) = \frac{1}{e^{\frac{\sqrt{k_T^2+(1+\xi)k_z^2}}{\Lambda}} - 1}$$

RESULTS: SIMPLIFIED BRICK MEDIUM





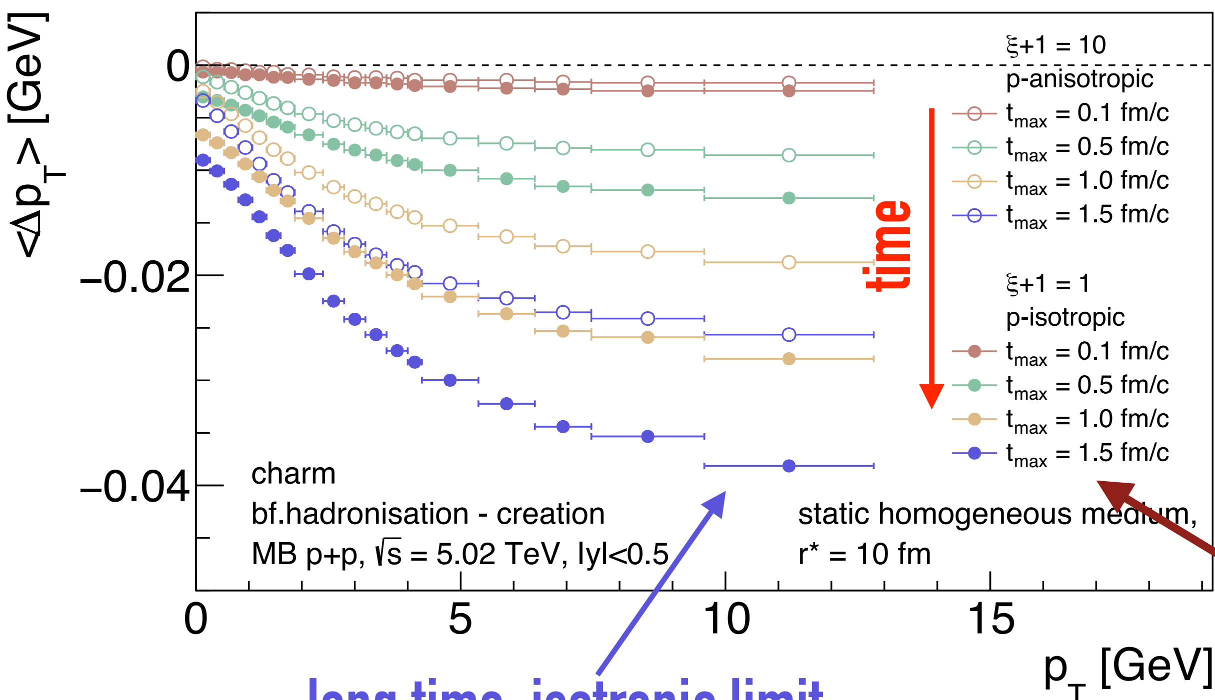
collisional loss

charm quark

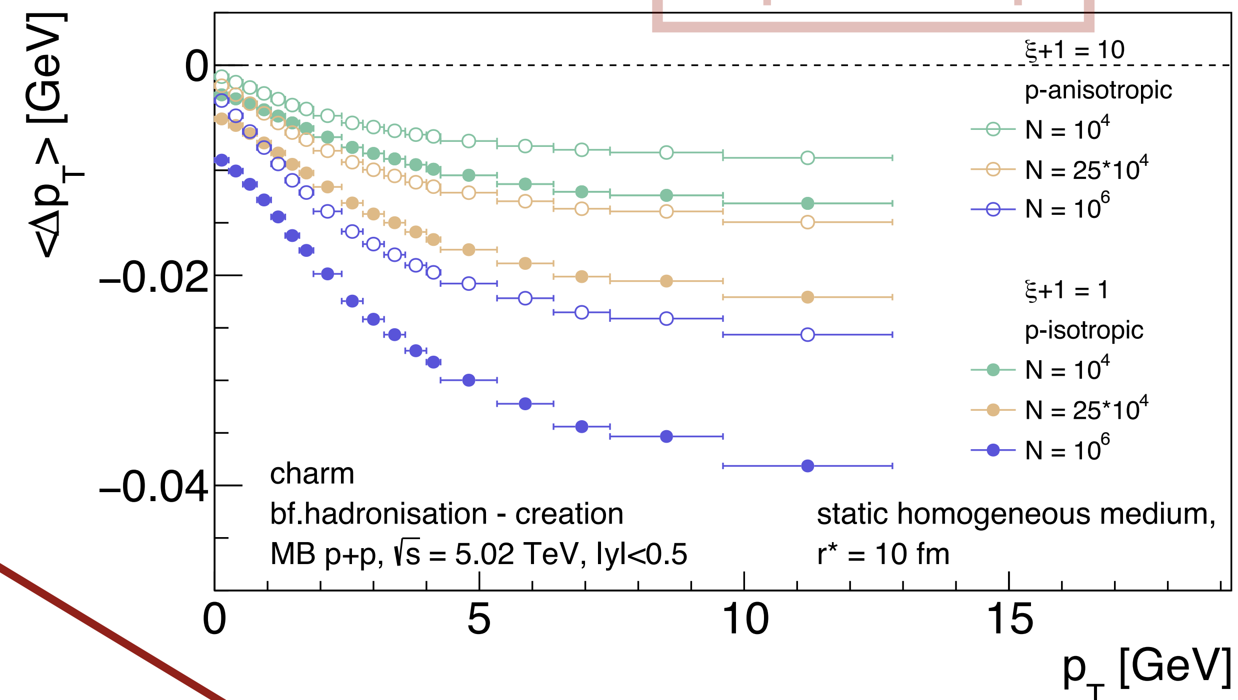
static medium

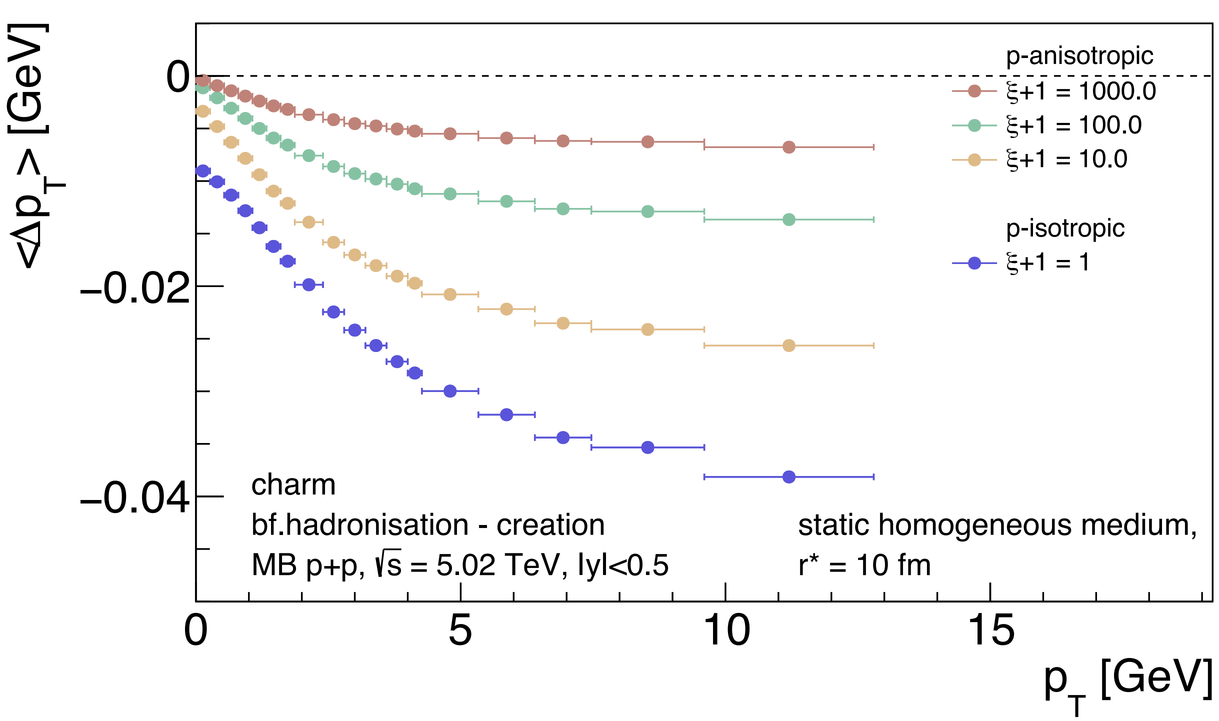
constant density

no quark escape



long time, isotropic limit





Average loss as a function of initial momentum for

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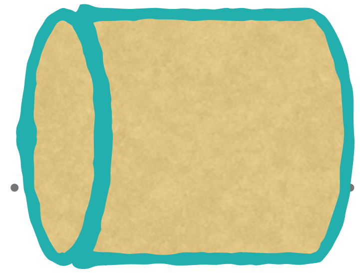
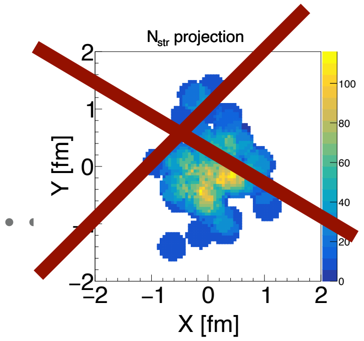
- string density (a-la event activity)
- anisotropy parameter

$$f_{\text{aniso}}(k) = \frac{1}{e^{\frac{\sqrt{k_T^2+(1+\xi)k_z^2}}{\Lambda}} - 1}$$

RESULTS: SIMPLIFIED BRICK MEDIUM





collisional loss

charm quark

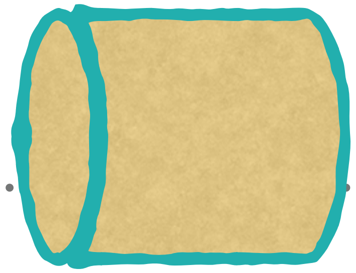
static medium

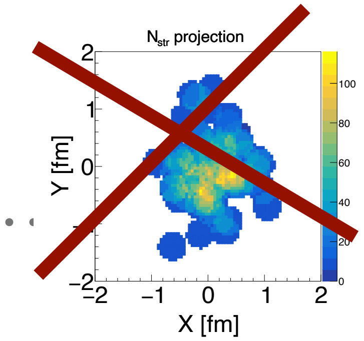
constant density

no quark escape

- extremely high string density

RESULTS: SIMPLIFIED BRICK MEDIUM





collisional loss

charm quark

bottom quark

static medium

constant density

no quark escape

- extremely high string density
- mass dependence:

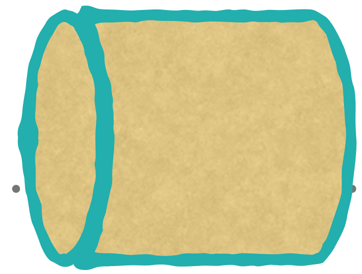
$m_c = 1.5$ GeV

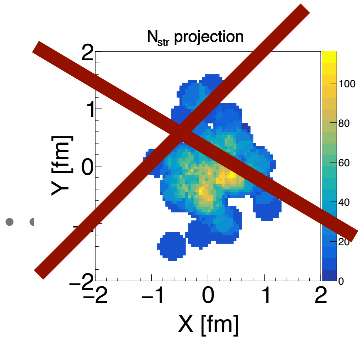
$m_b = 4.8$ GeV

- ξ dependence

$$f_{\text{aniso}}(k) = \frac{1}{e^{\frac{\sqrt{k_T^2+(1+\xi)k_z^2}}{\Lambda}} - 1}$$

RESULTS: SIMPLIFIED BRICK MEDIUM





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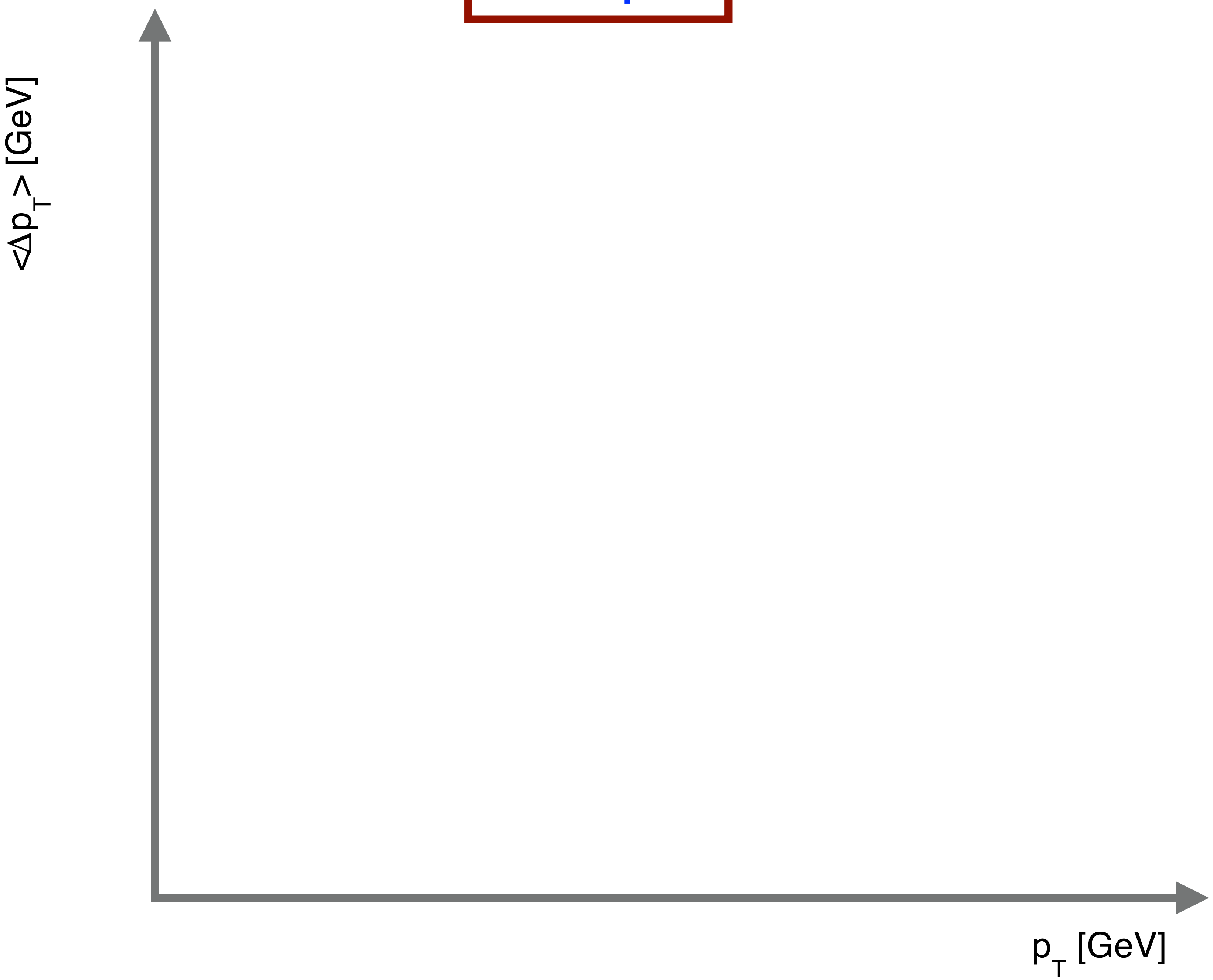

- extremely high string density
- mass dependence:

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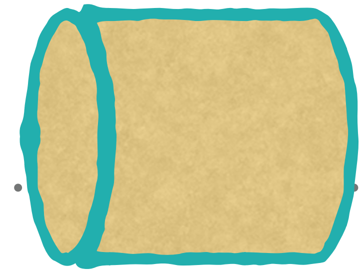

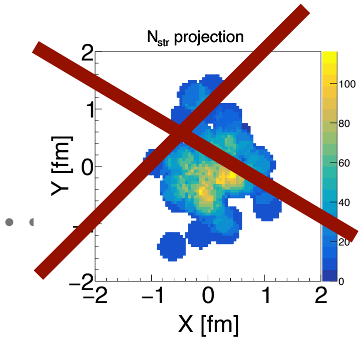

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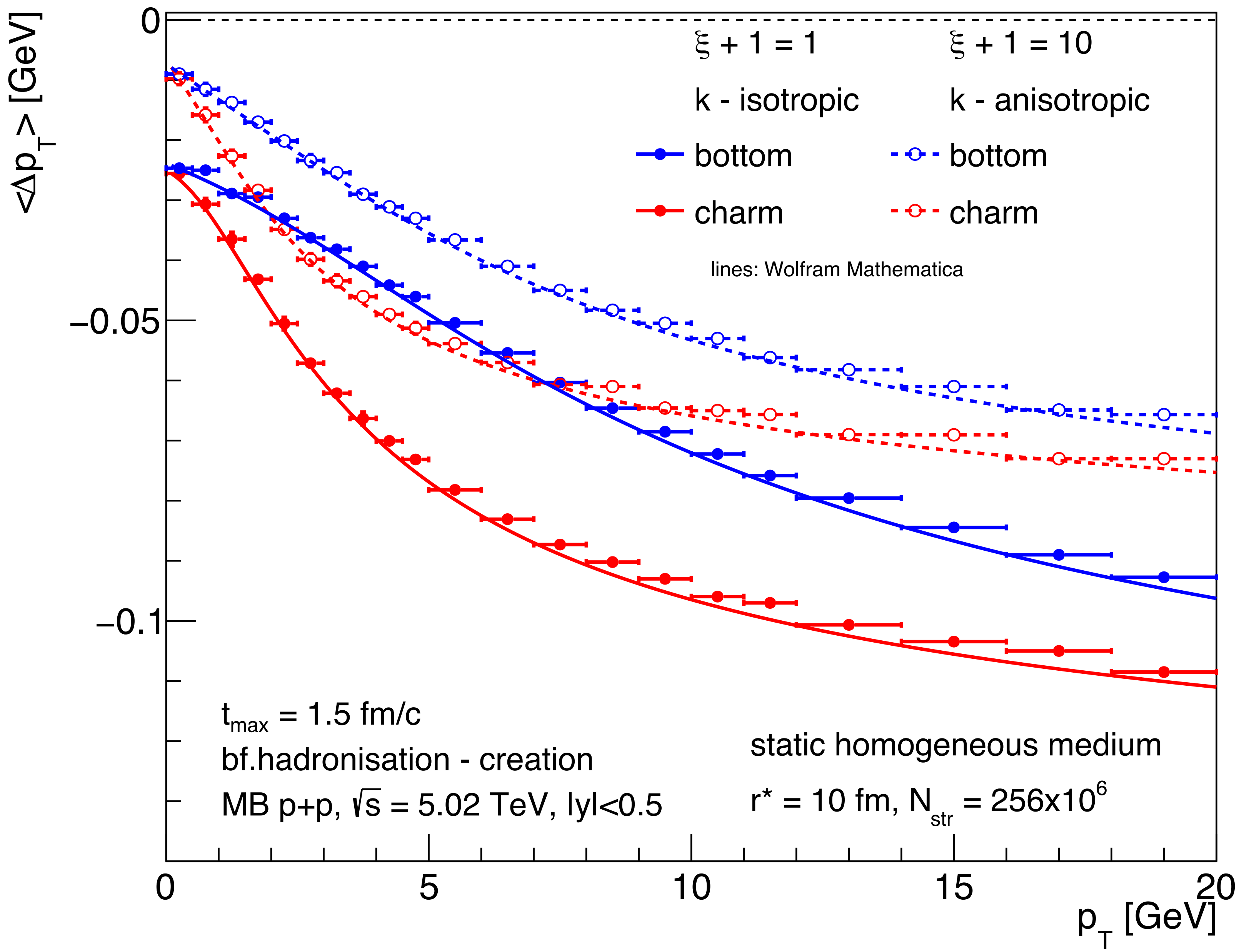

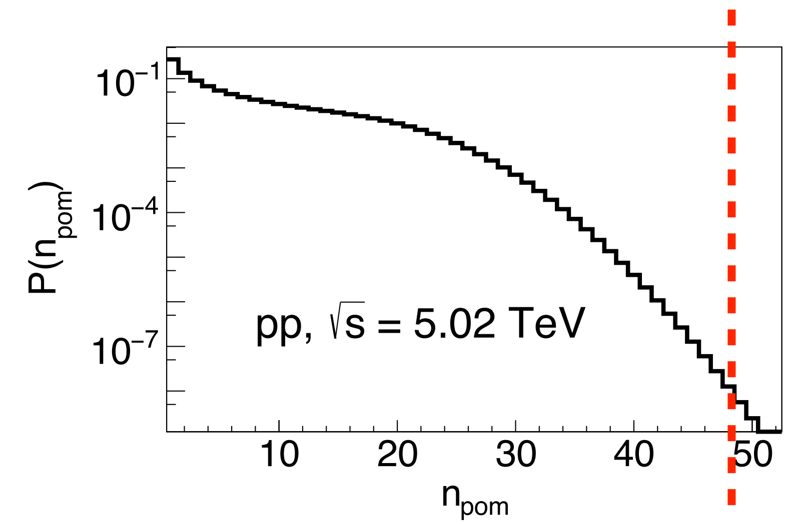

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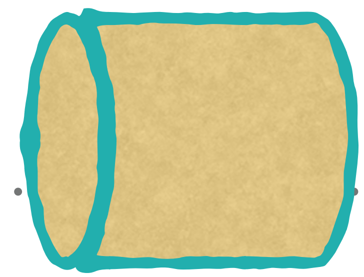

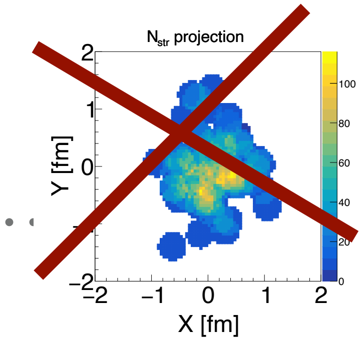

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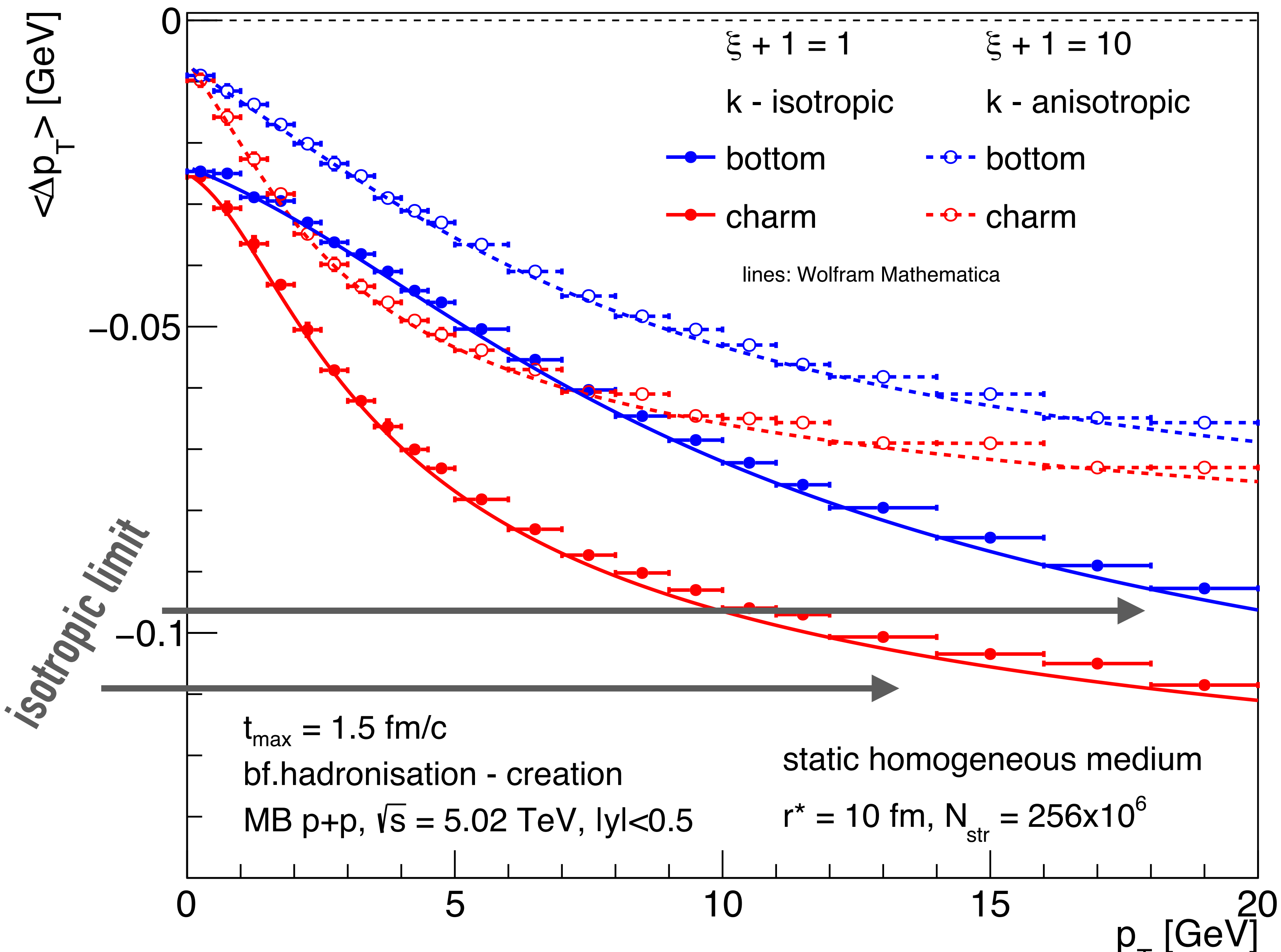

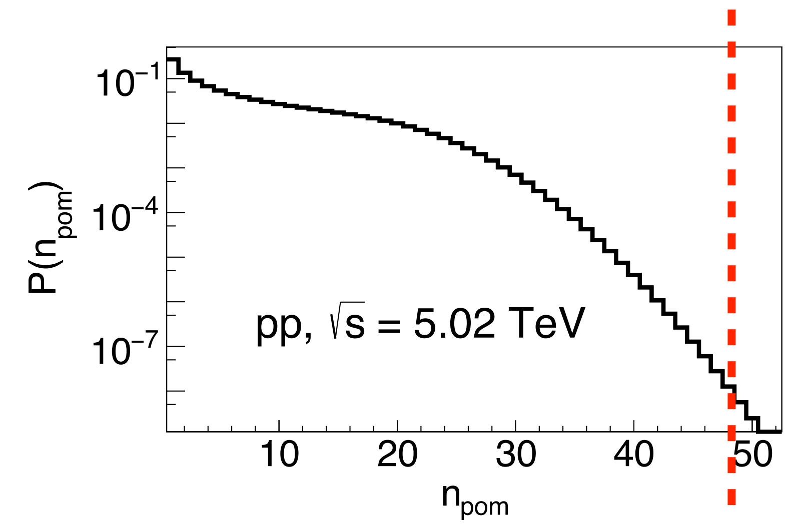

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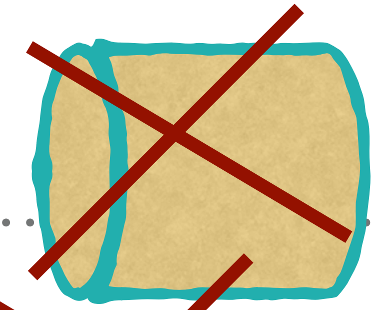
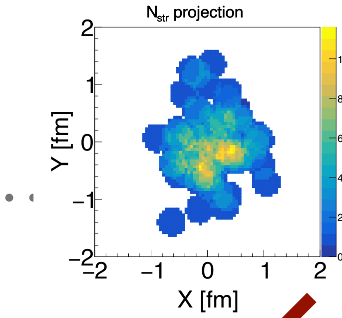
RESULTS: FLUCTUATING MEDIUM





collisional loss

charm quark

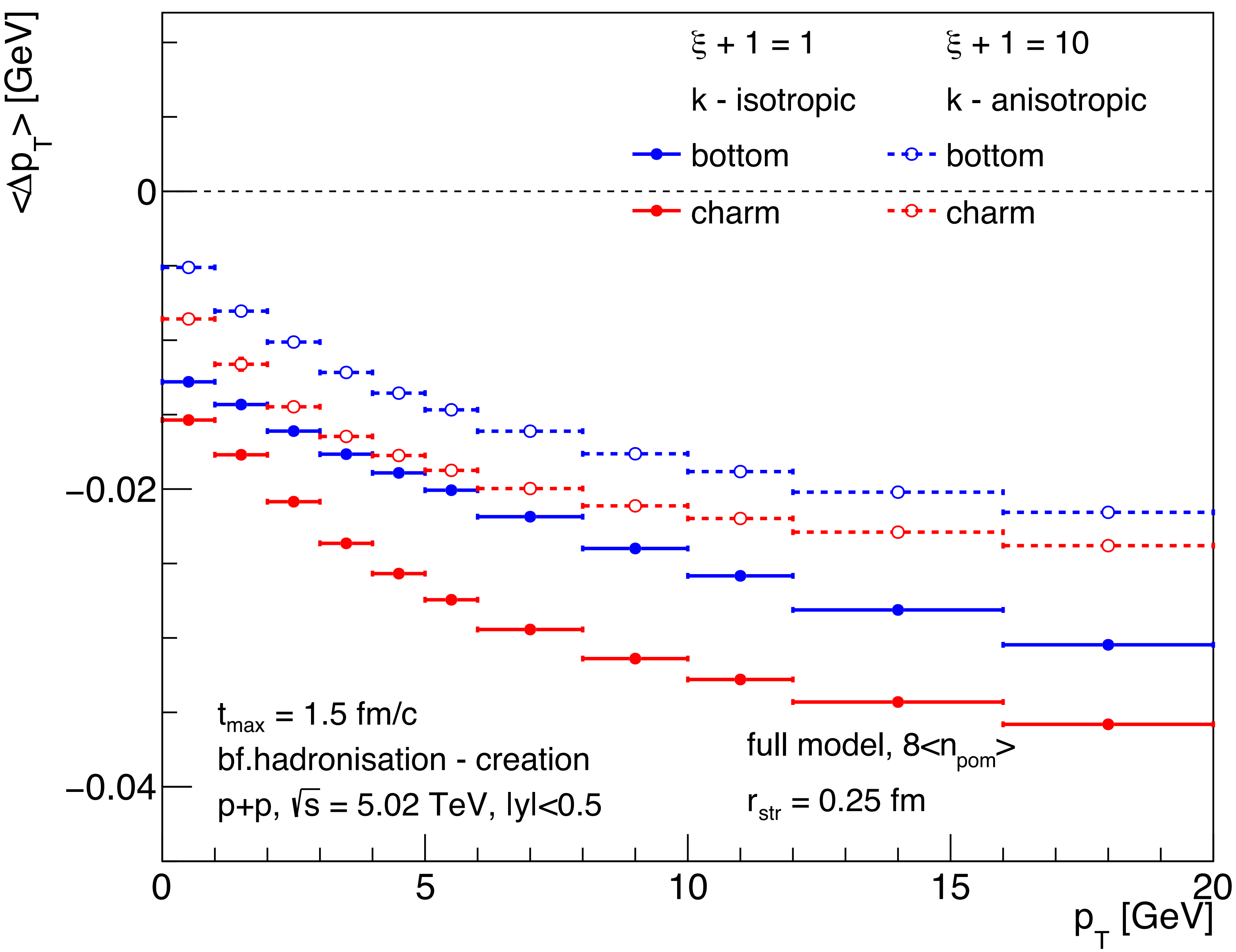
bottom quark

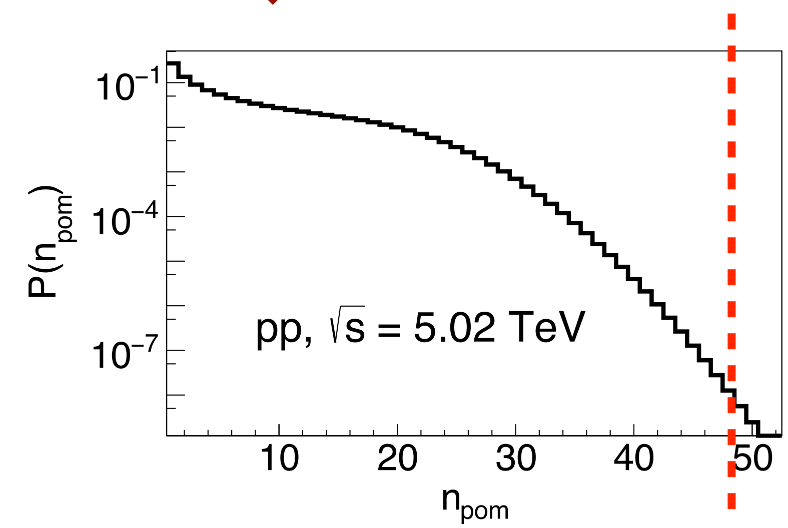
~~static medium~~

~~constant density~~

~~no quark escape~~

$8\langle n_{pom}\rangle$





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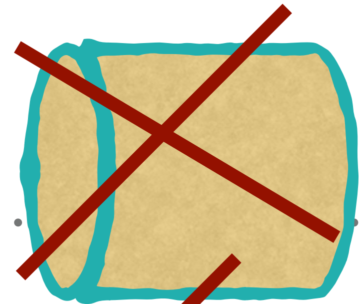
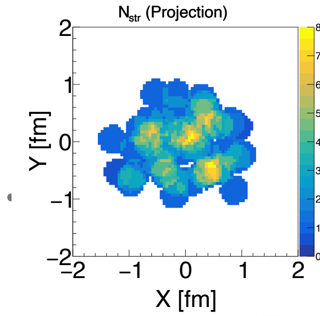
RESULTS: FLUCTUATING MEDIUM





collisional loss

charm quark

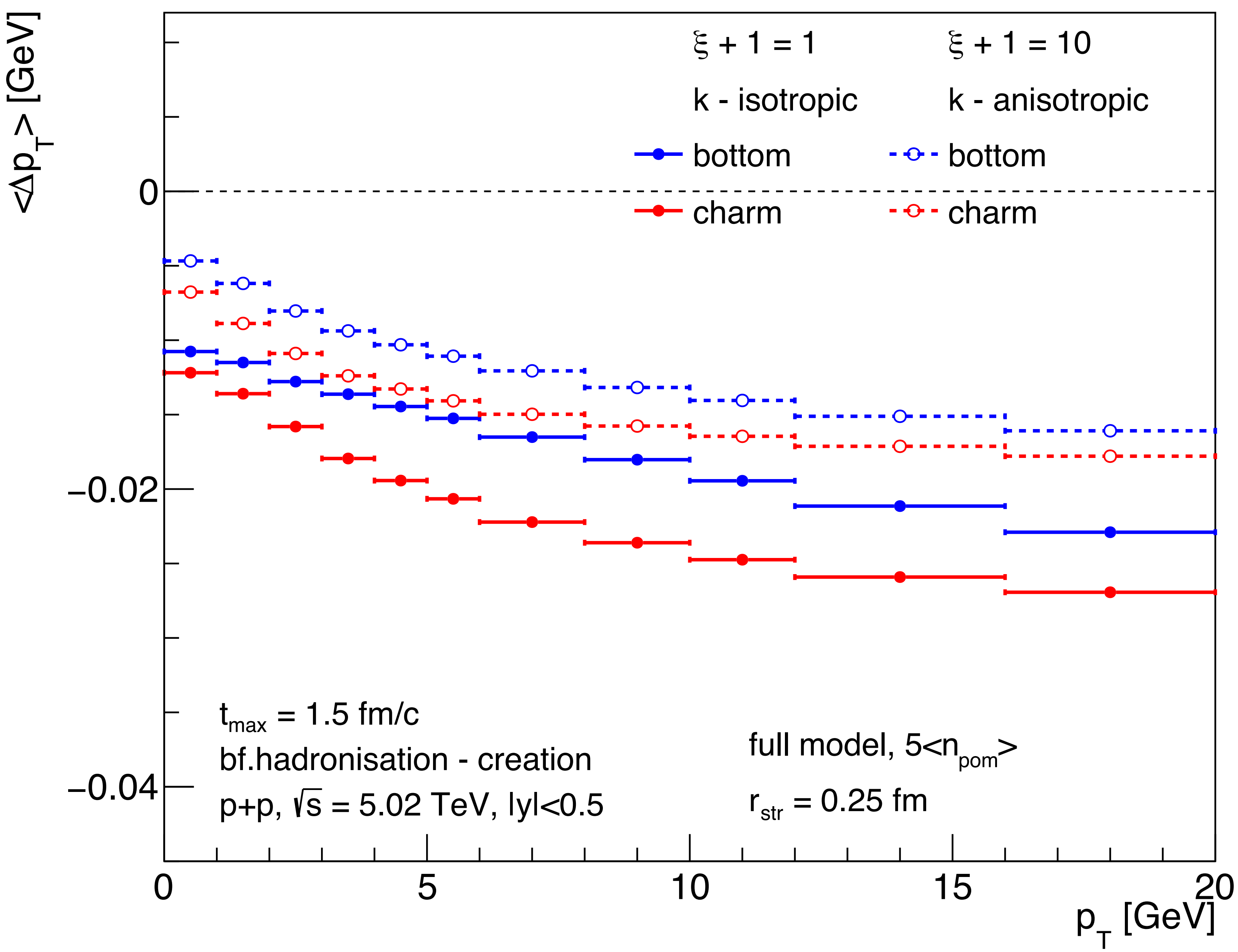
~~static medium~~

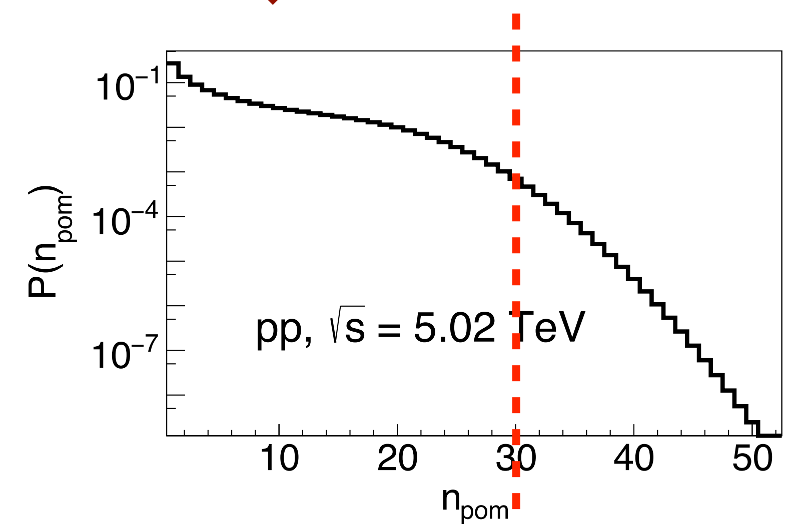
~~constant density~~

~~no quark escape~~

5<npom>

bottom quark





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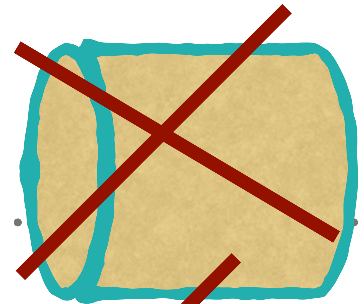
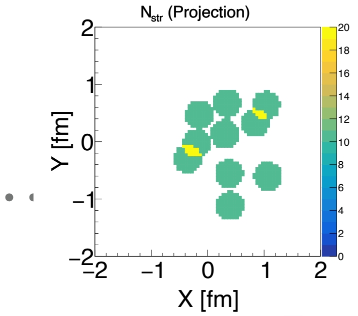
RESULTS: FLUCTUATING MEDIUM





collisional loss

charm quark

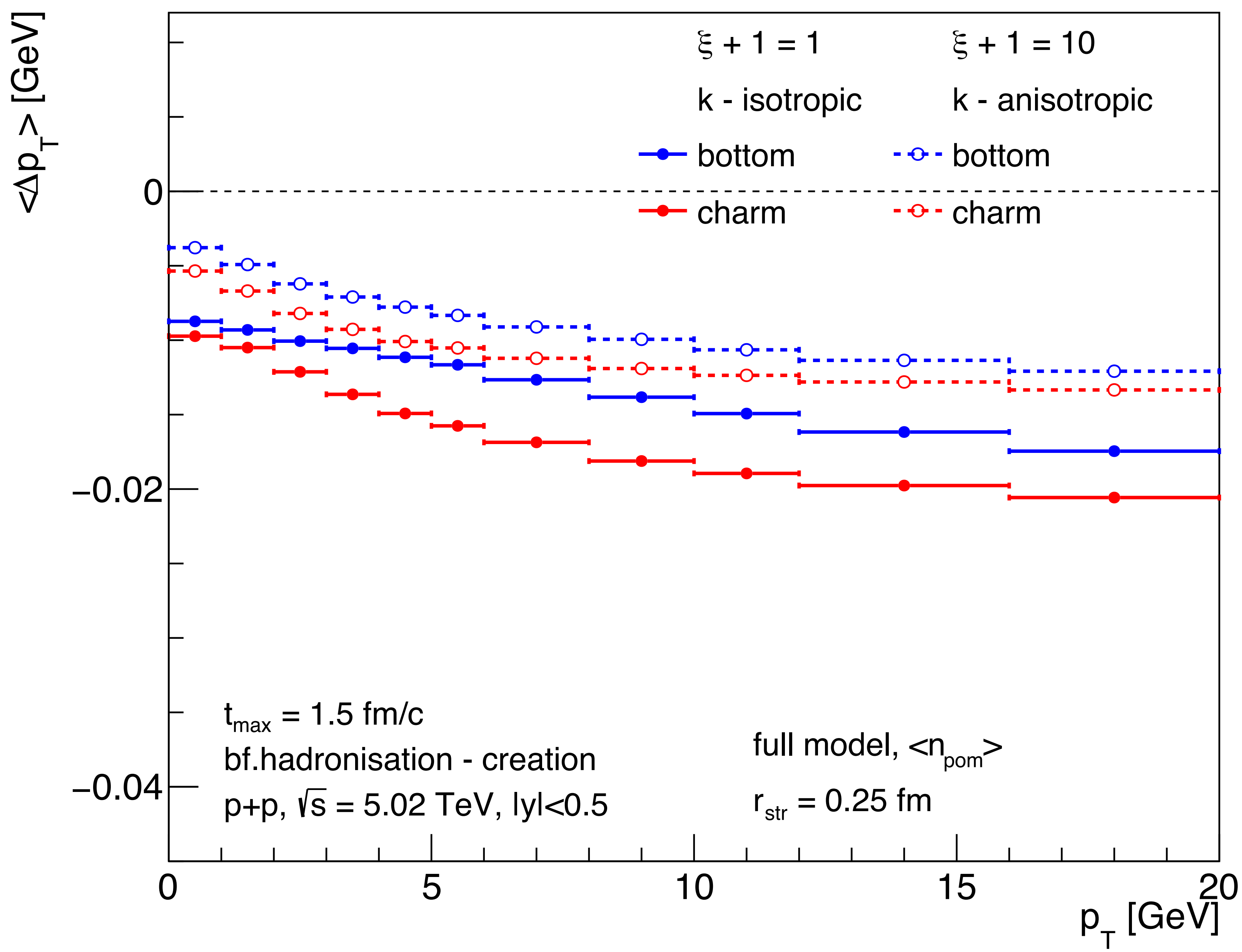
~~static medium~~

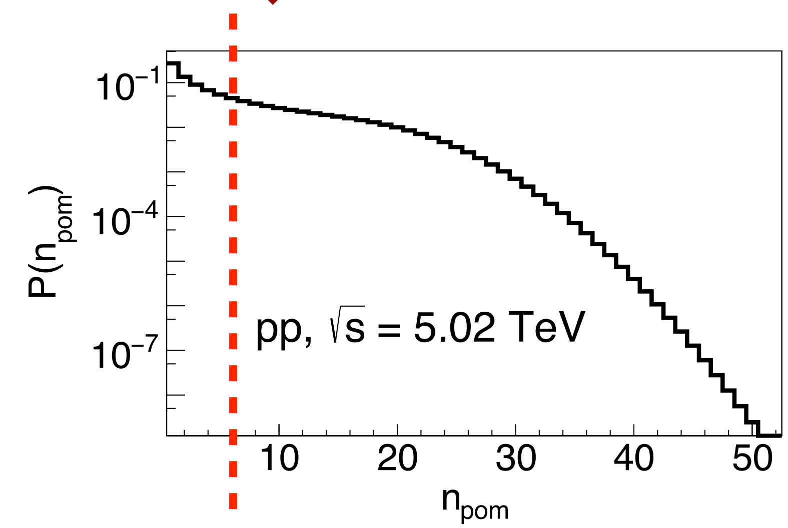
~~constant density~~

~~no quark escape~~

<npom>

bottom quark





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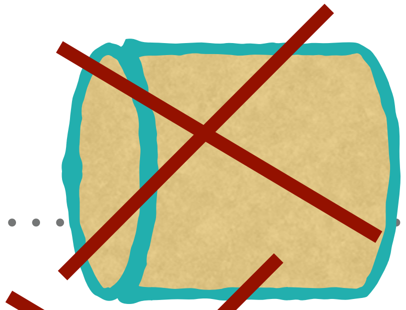
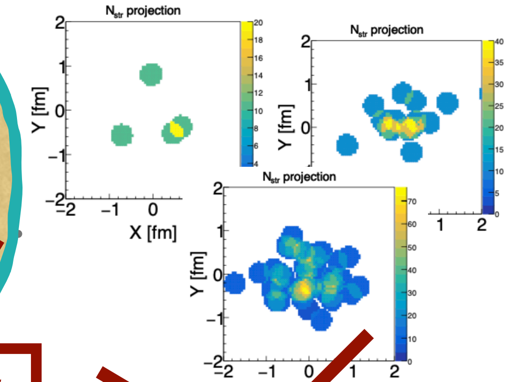




collisional loss

charm quark

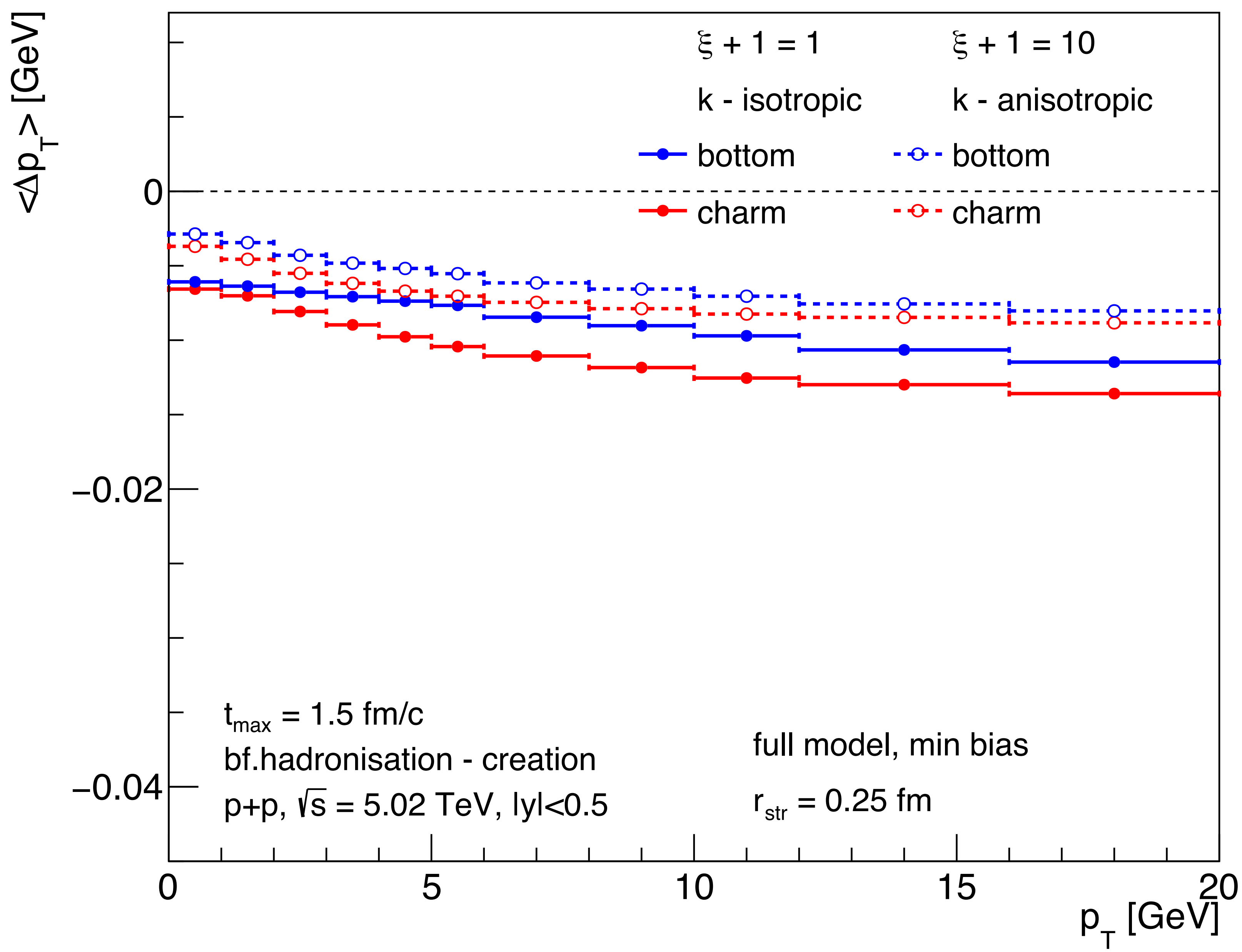
~~static medium~~

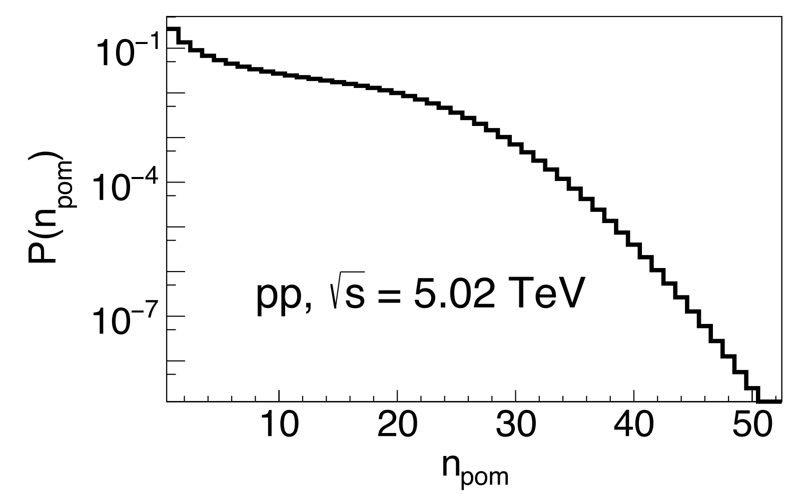
~~constant density~~

~~no quark escape~~

min bias

bottom quark





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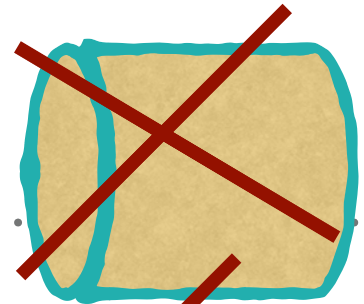

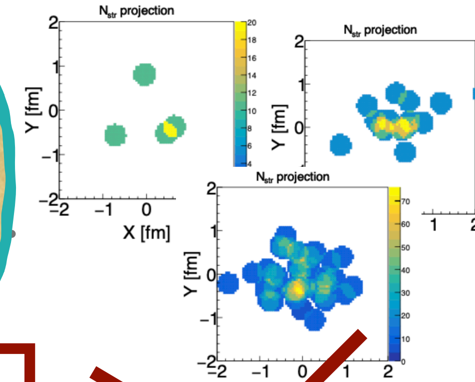

collisional loss

charm quark

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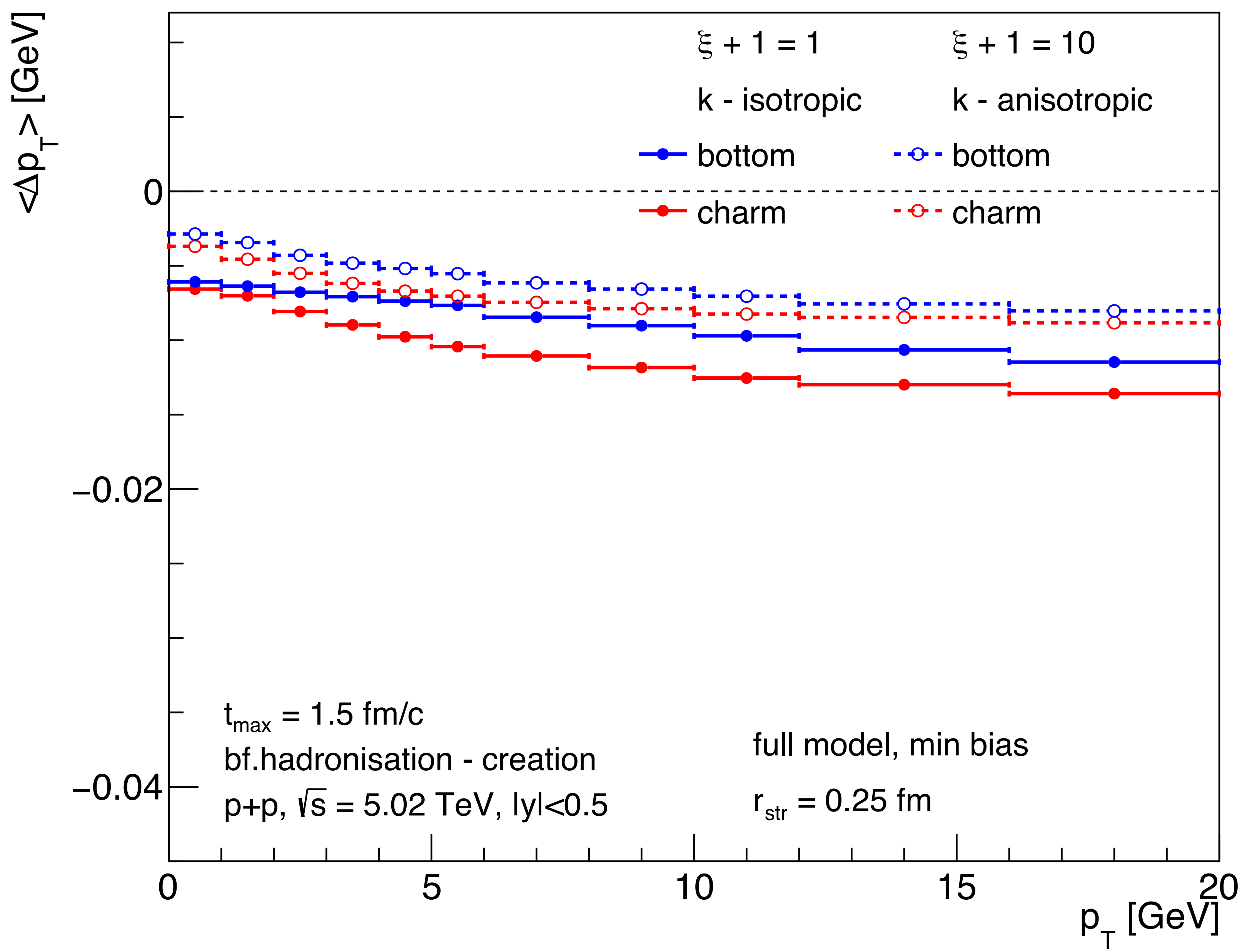
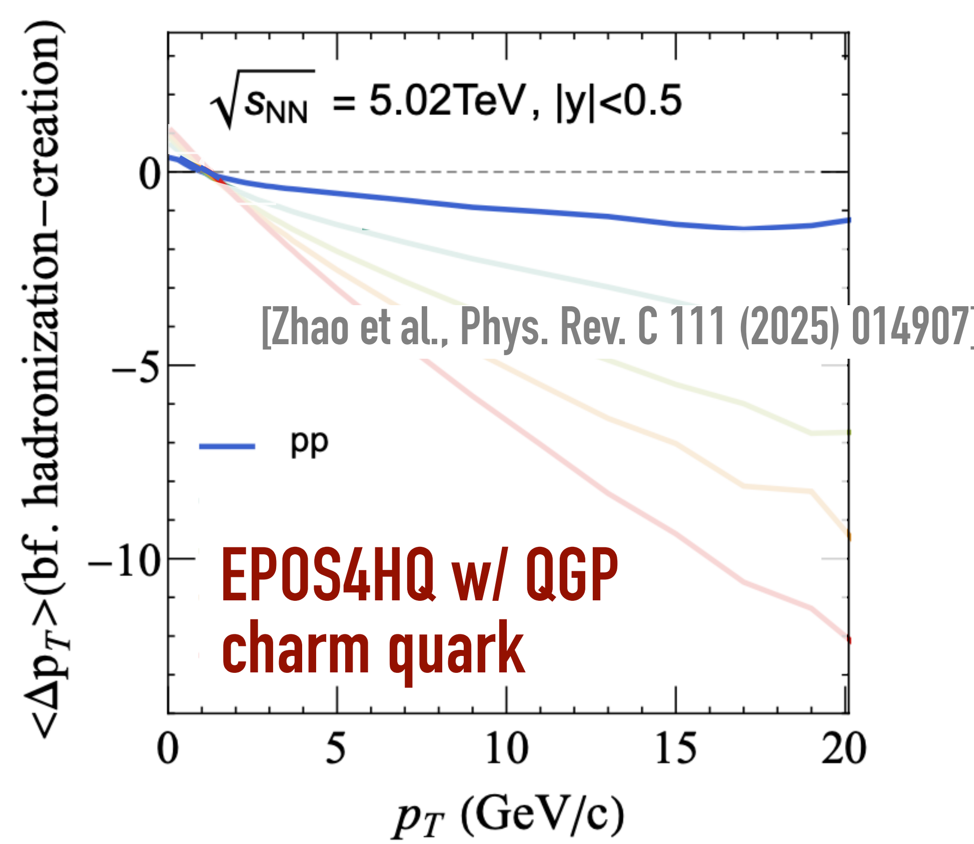
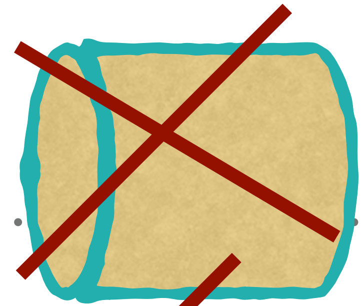
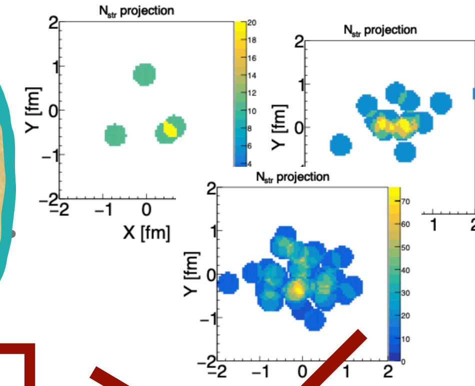
bottom quark





RESULTS: FLUCTUATING MEDIUM





collisional loss

charm quark

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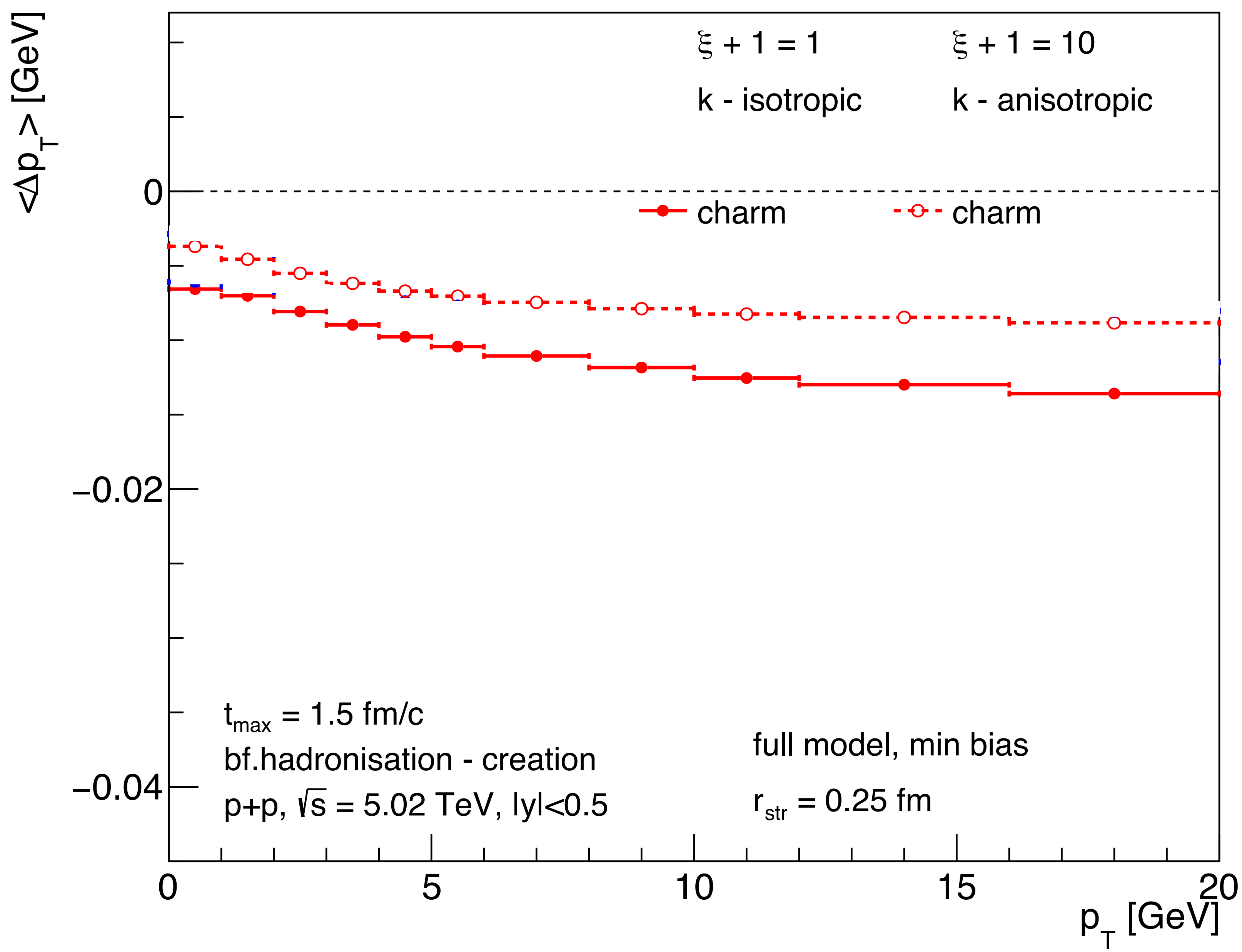
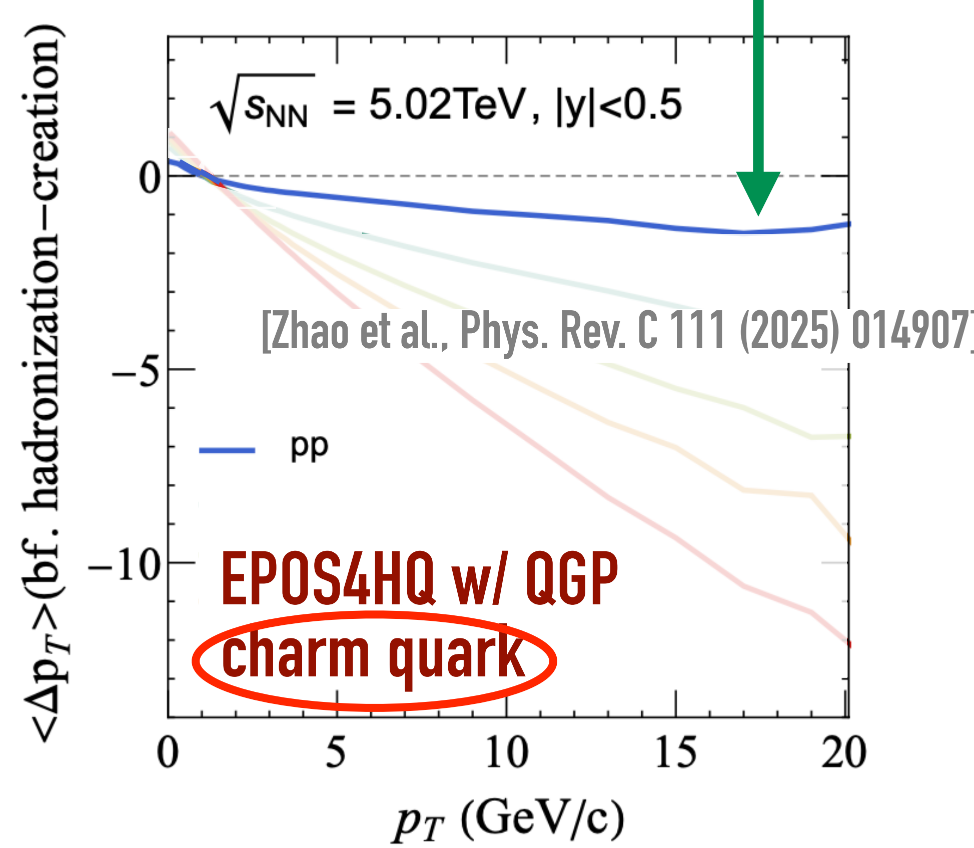
min bias

bottom quark



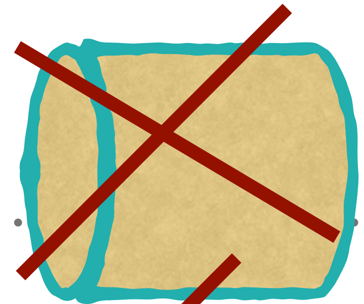
[Werner, Phys.Rev.C 109 (2024) 1, 014910]

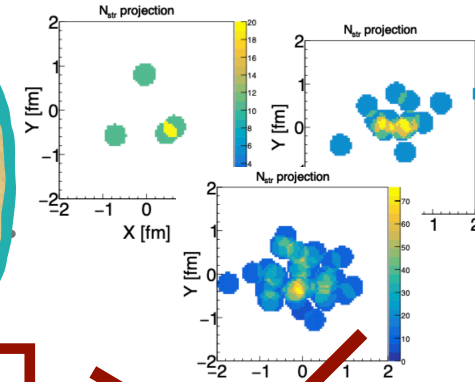
core (QGP, loss) +
corona (strings, no loss)



[Zhao et al., Phys. Rev. C 111 (2025) 014907]

RESULTS: FLUCTUATING MEDIUM





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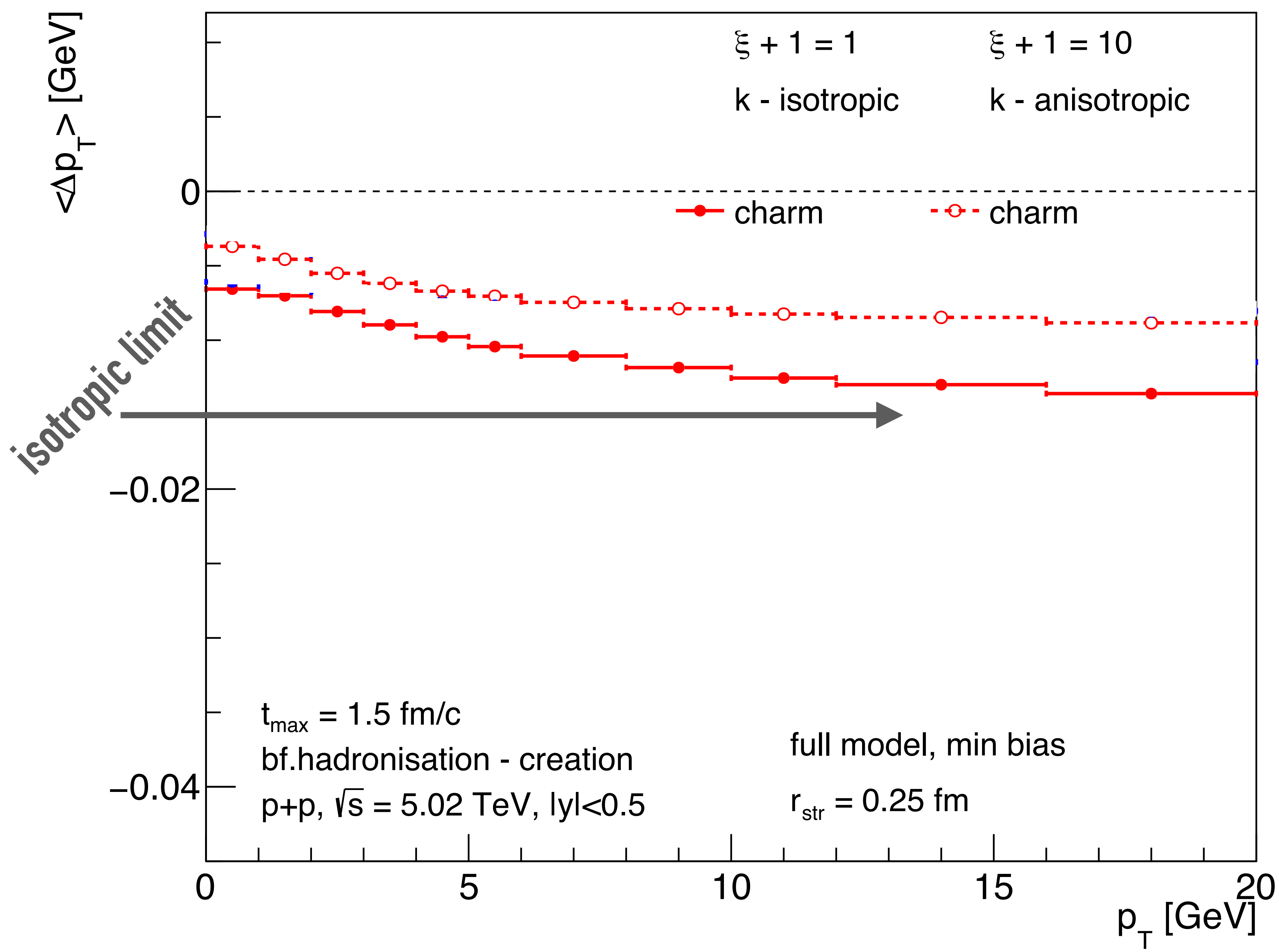

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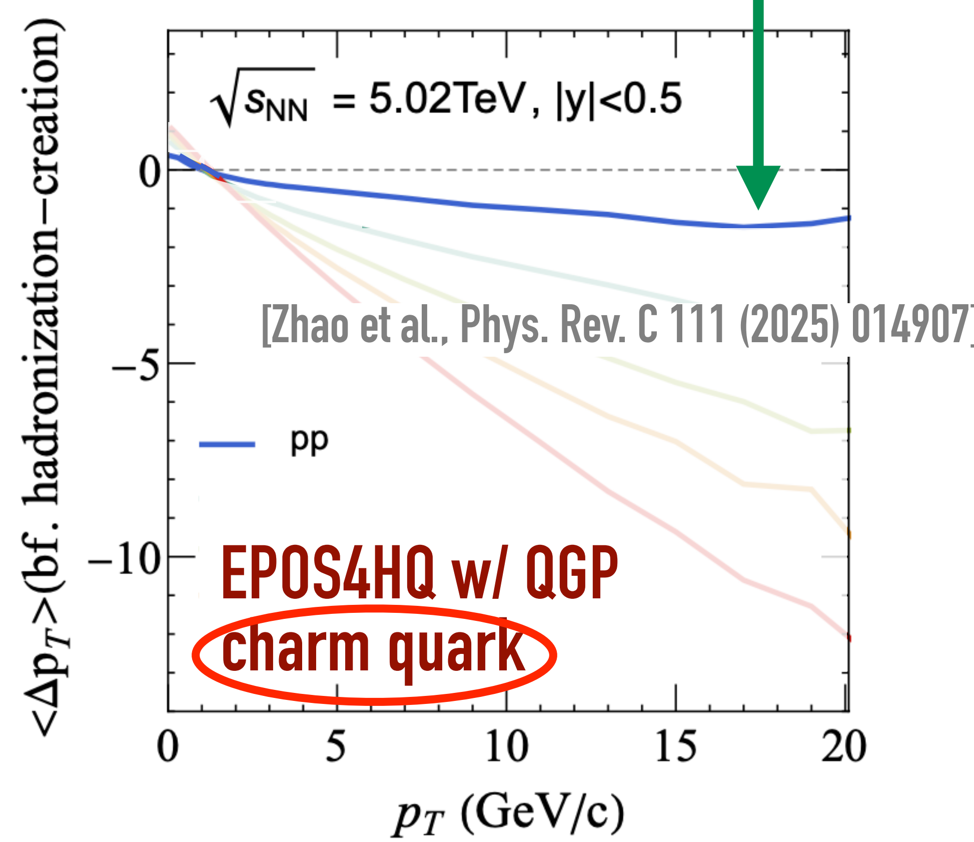


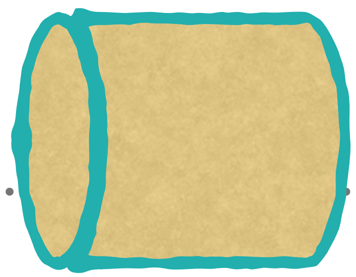
[Zhao et al., Phys. Rev. C 111 (2025) 014907]

RESULTS: SIMPLIFIED BRICK MEDIUM

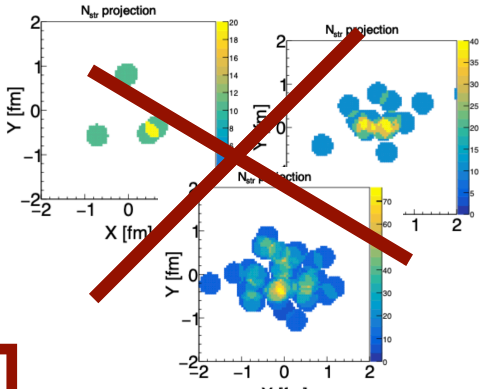
radiative loss

charm quark

static medium



constant density



no quark escape

[Werner, Phys.Rev.C 109 (2024) 1, 014910]

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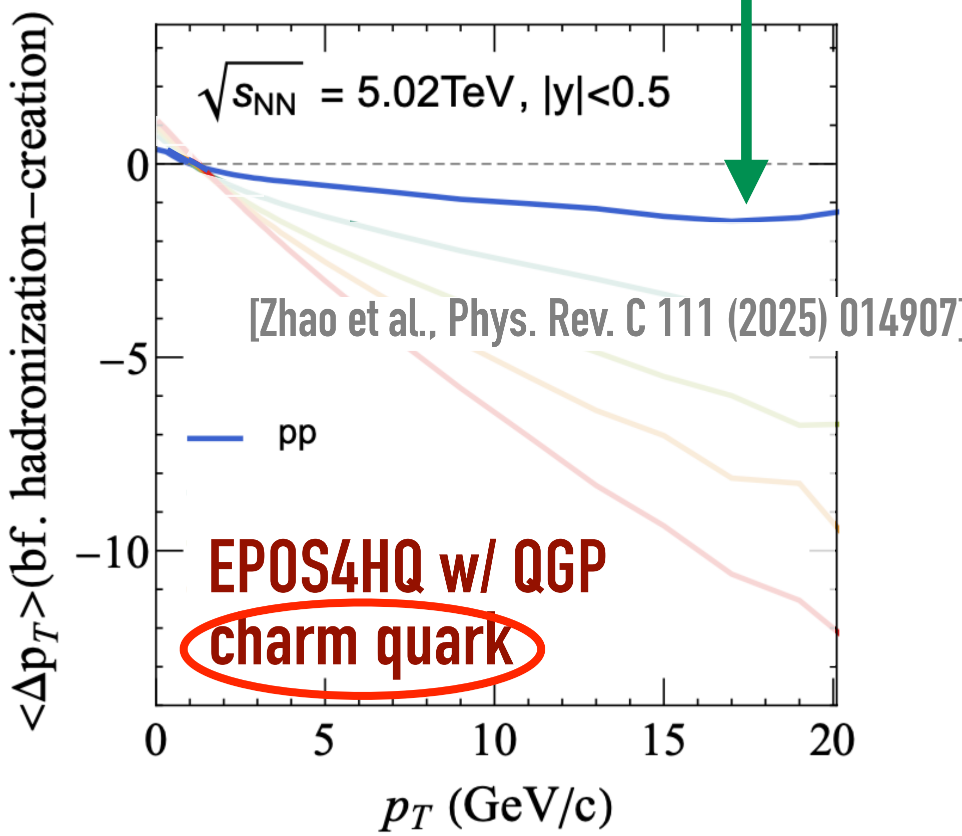

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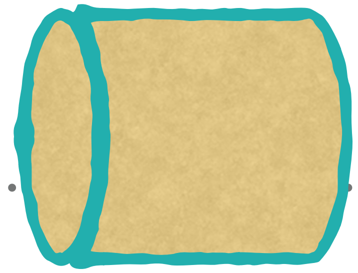

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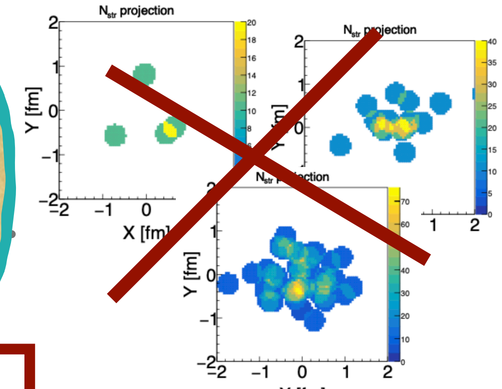

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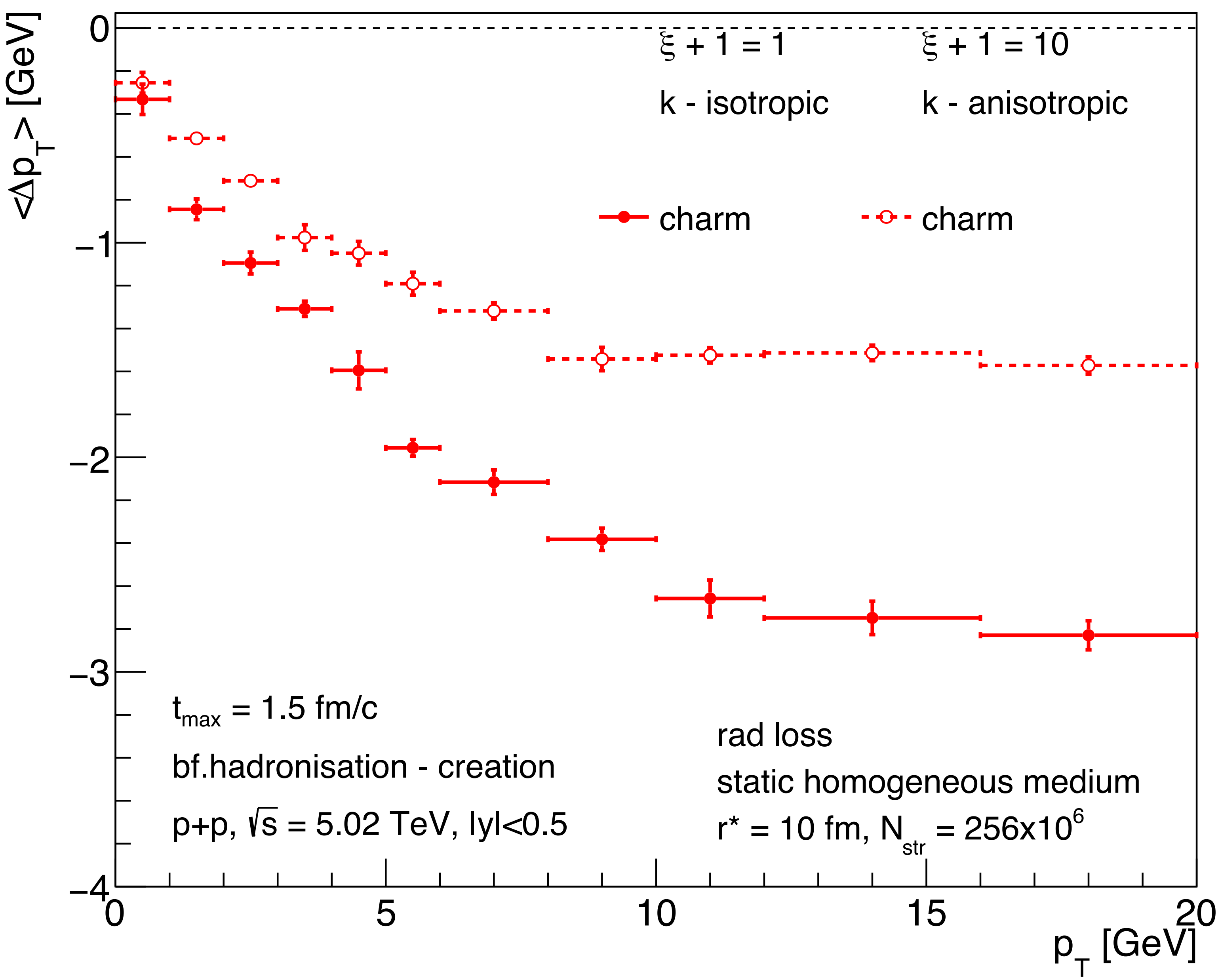
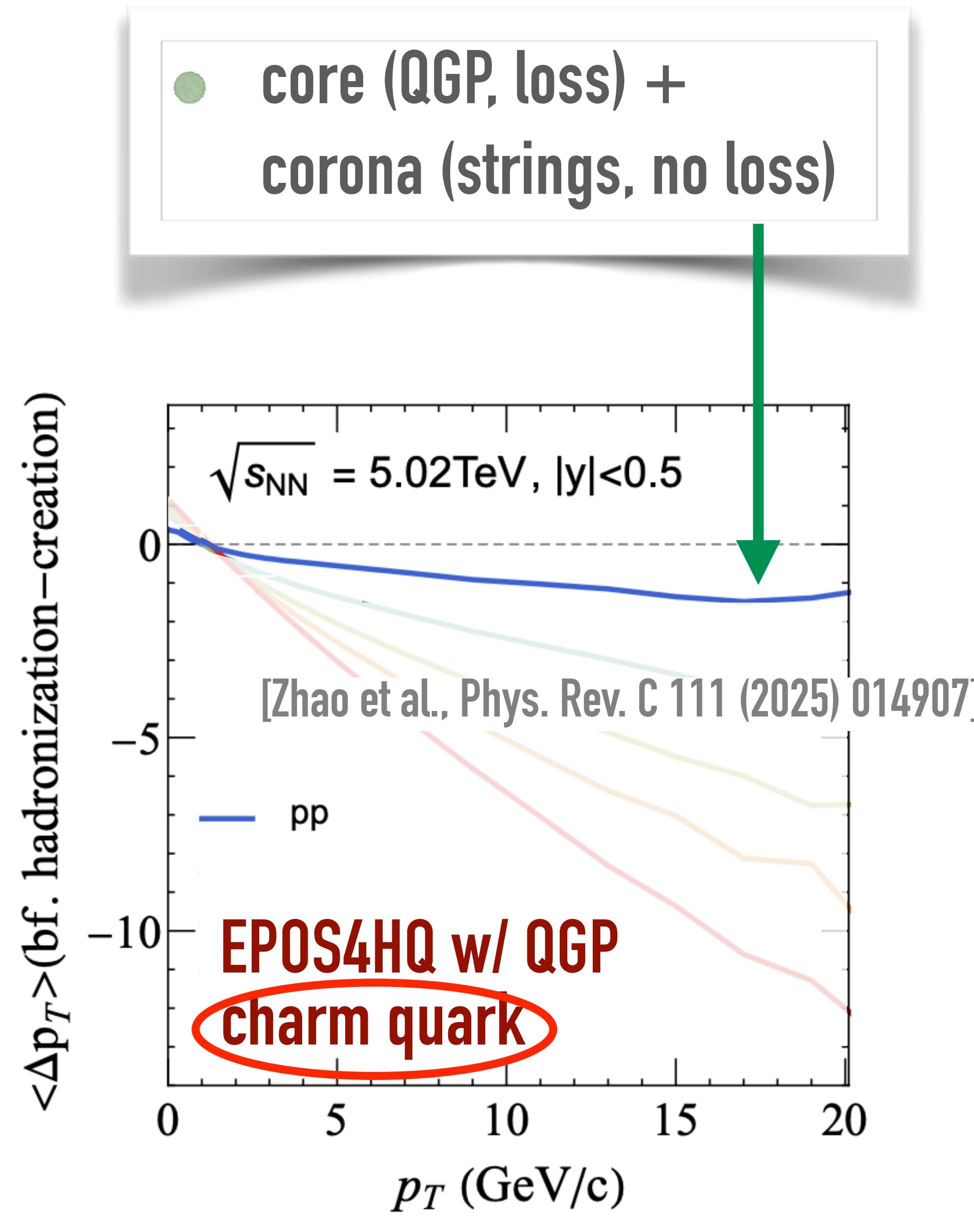


[Werner, Phys.Rev.C 109 (2024) 1, 014910]



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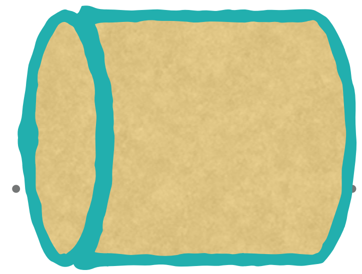

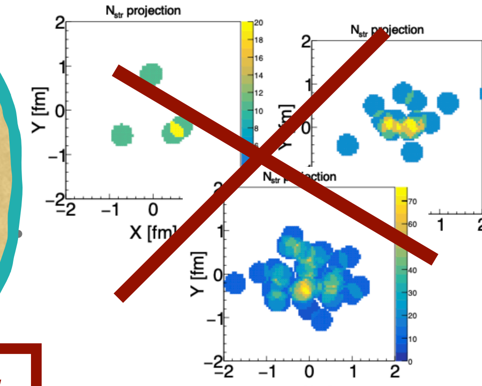

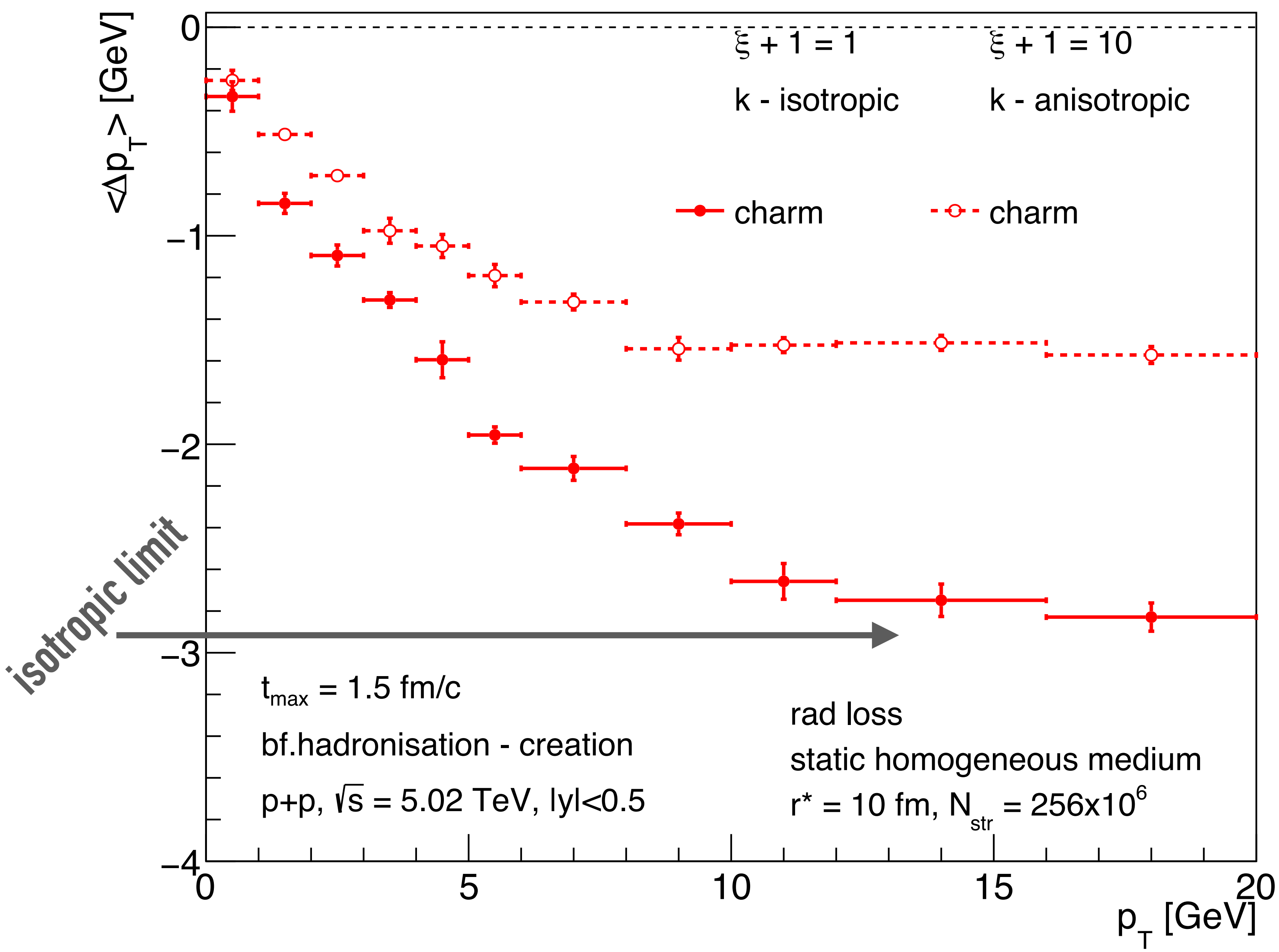

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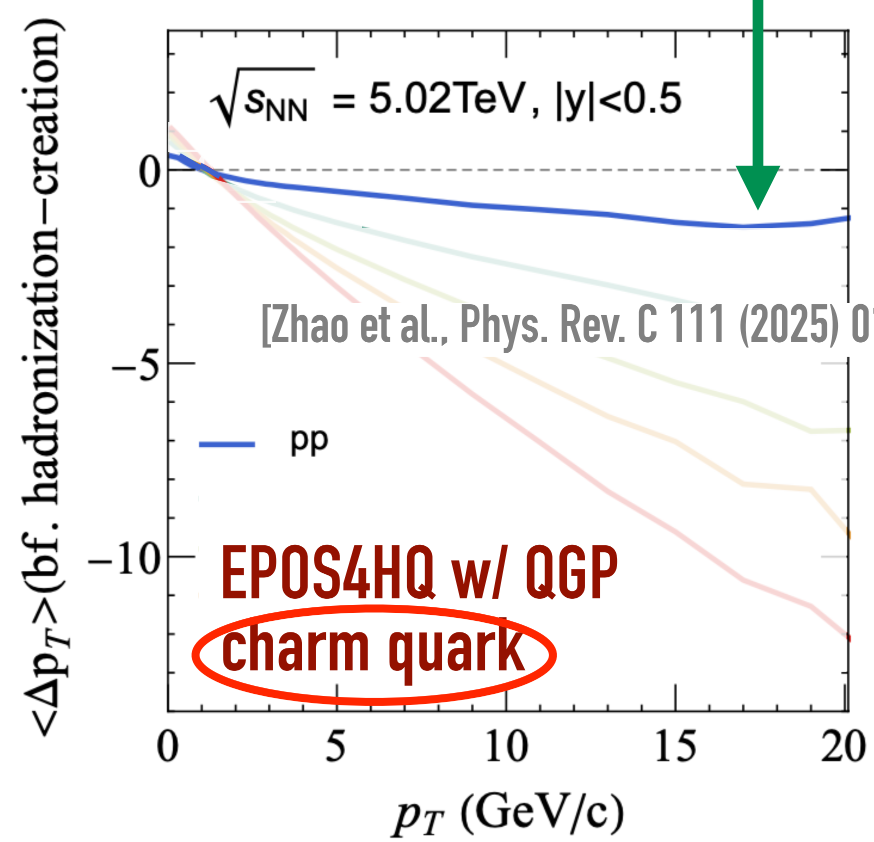

[Zhao et al., Phys. Rev. C 111 (2025) 014907]

RESULTS: FLUCTUATING MEDIUM

radiative loss

charm quark

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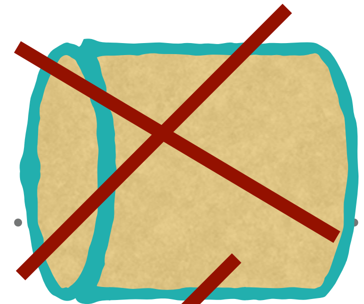
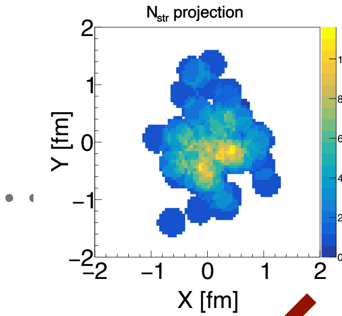
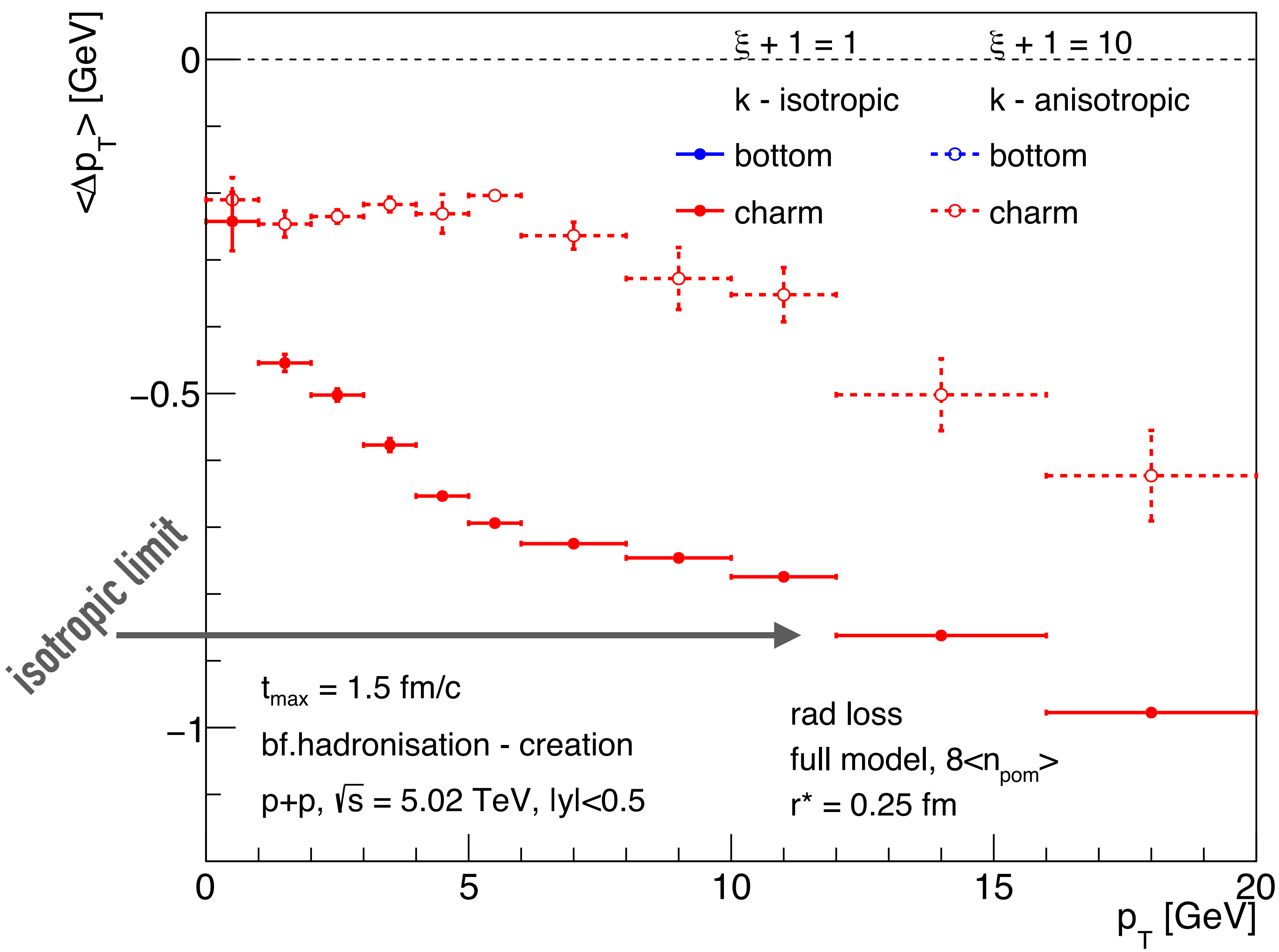
$8\langle n_{pom}\rangle$

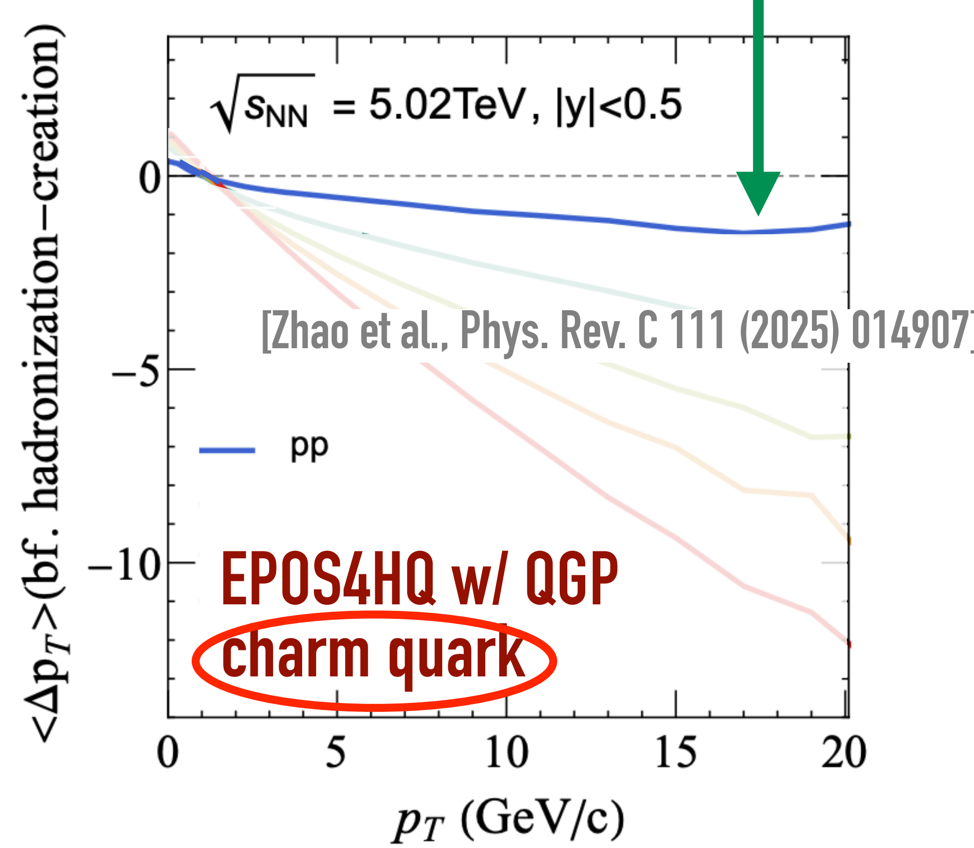






[Werner, Phys.Rev.C 109 (2024) 1, 014910]

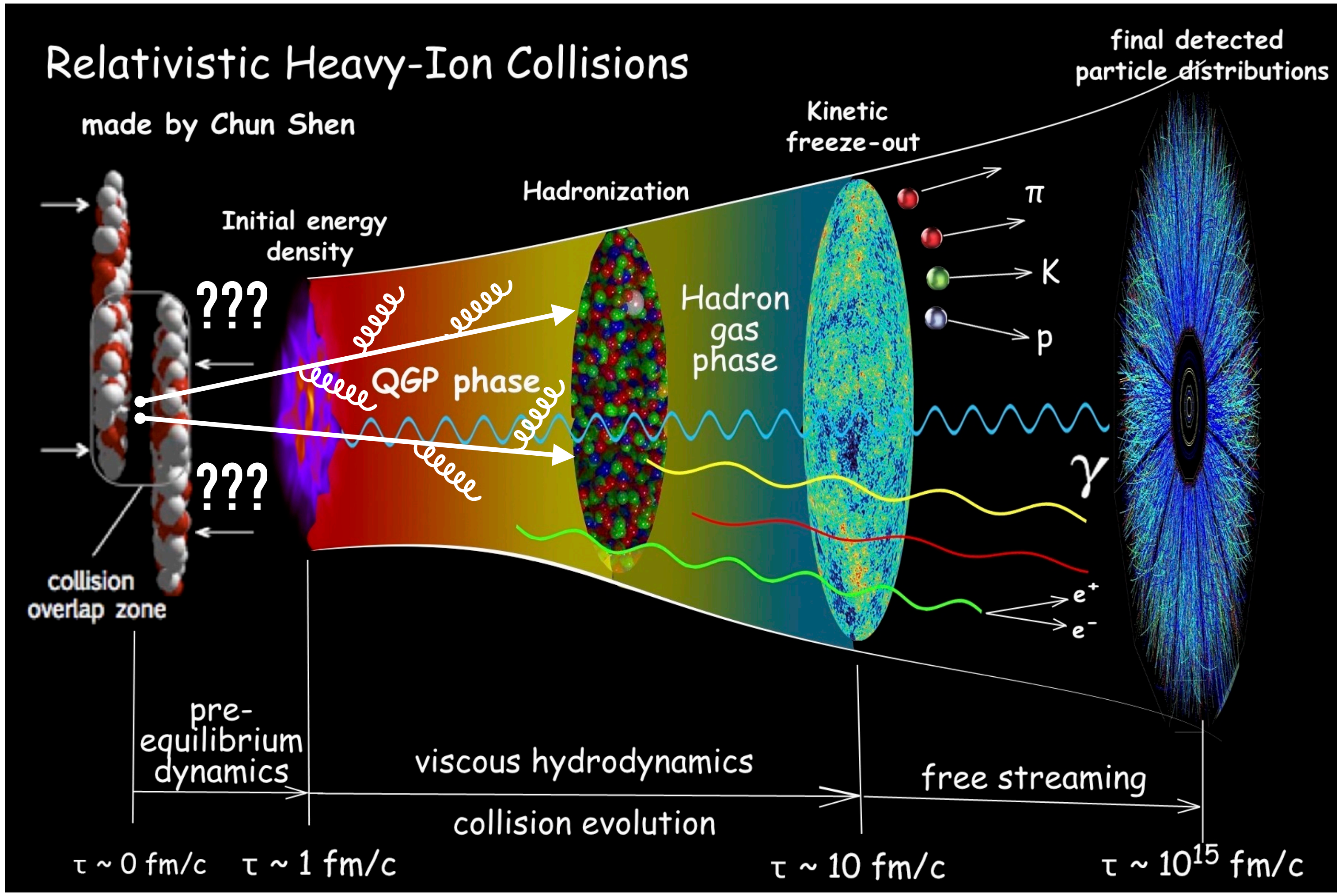
core (QGP, loss) +
corona (strings, no loss)



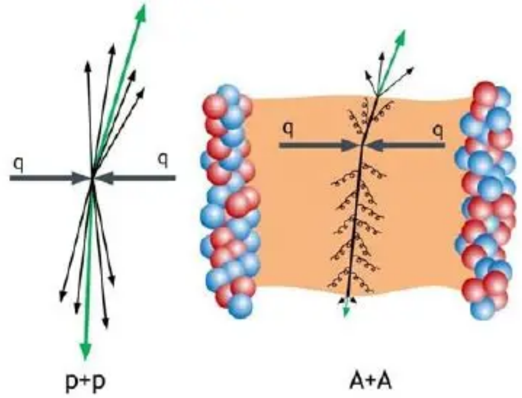
[Zhao et al., Phys. Rev. C 111 (2025) 014907]

SUMMARY AND OUTLOOK

HOW WE STARTED



- hard scatterings
- **QGP formation**, hadronization
- in-medium jet energy loss
- initial stages - unclear!
- p+p data as reference

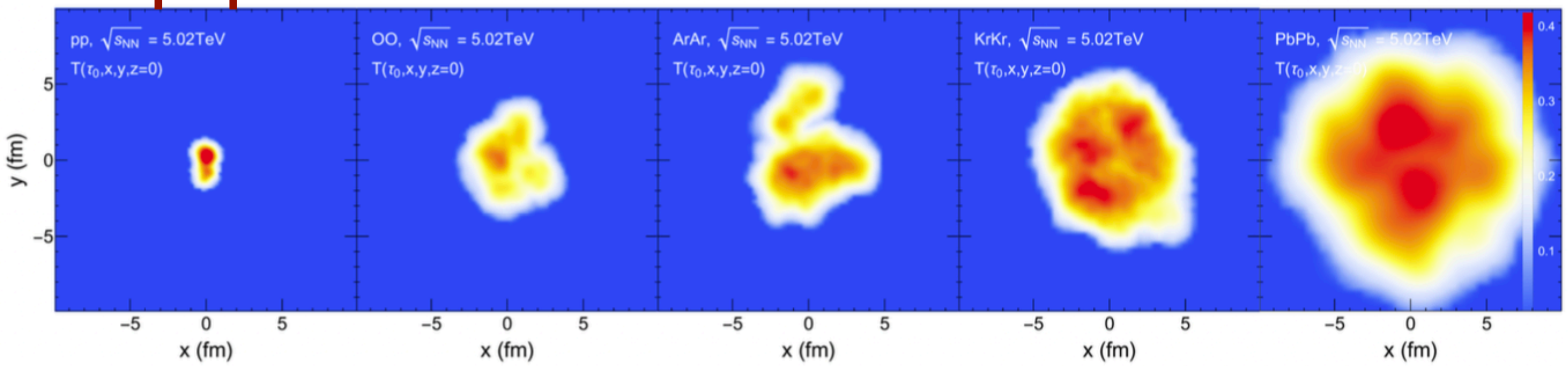


But what if **p+p is not so simple?**

- evidence of collectivity
- what is the kind of medium formed?
- can we test it with hard probes?
- is jet loss measurable in p+p?

p+p

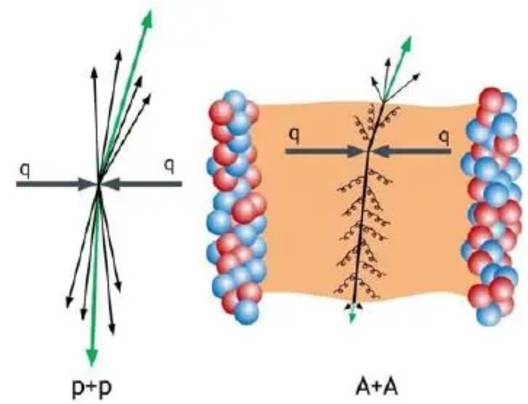
Pb+Pb



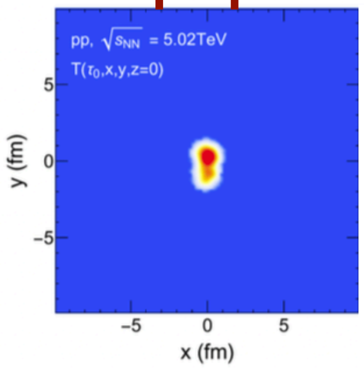
[Zhao et al., Phys. Rev. C 111 (2025) 014907]

CONCLUSIONS

- p+p data as reference

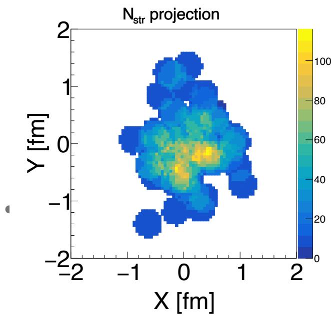


p+p

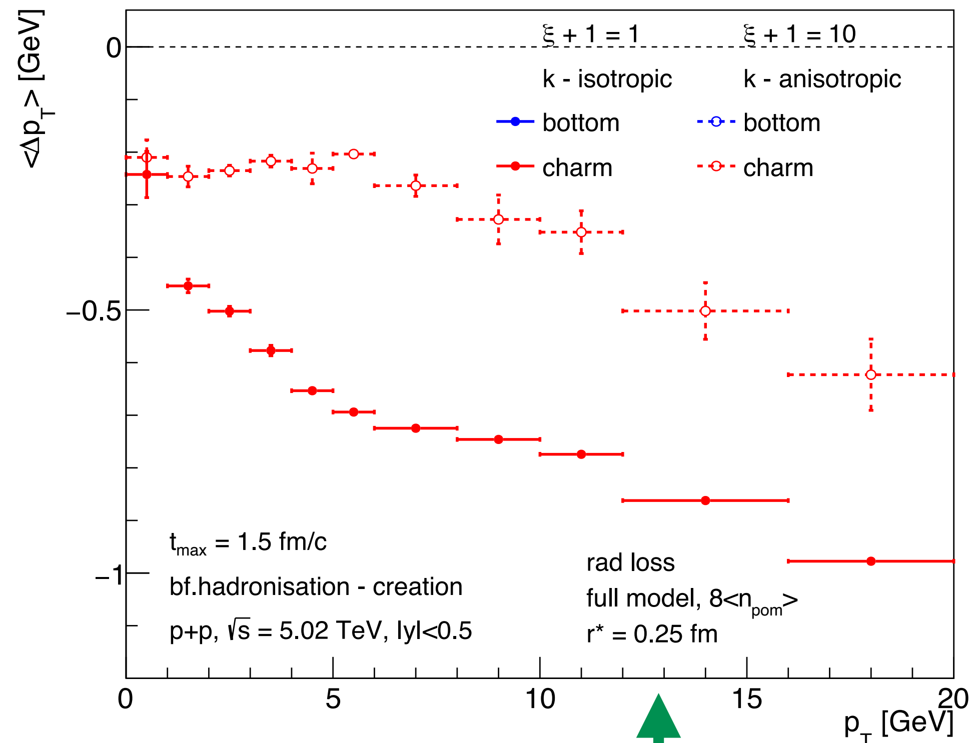


- what is the kind of medium formed?
- can we test it with hard probes?
- is jet loss measurable in p+p?

CONCLUSIONS

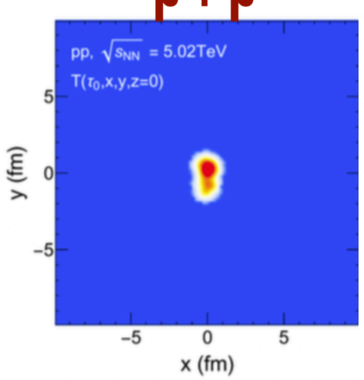


[this work]



- no QGP, no flow, pre-equilibrium

p+p



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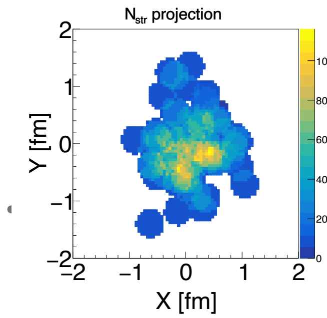
CONCLUSIONS



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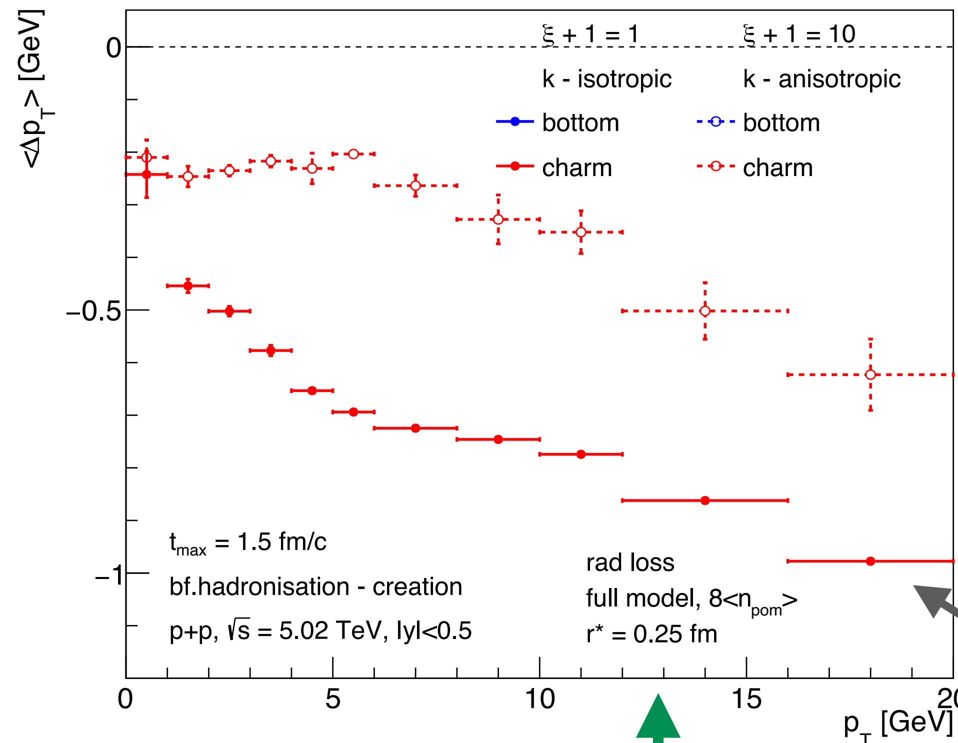
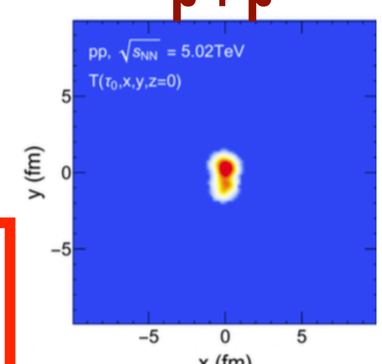


anisotropy

isotropic limit

- no QGP, no flow, pre-equilibrium

p+p



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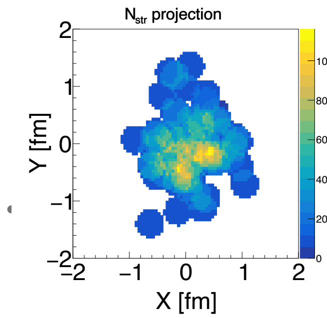
CONCLUSIONS



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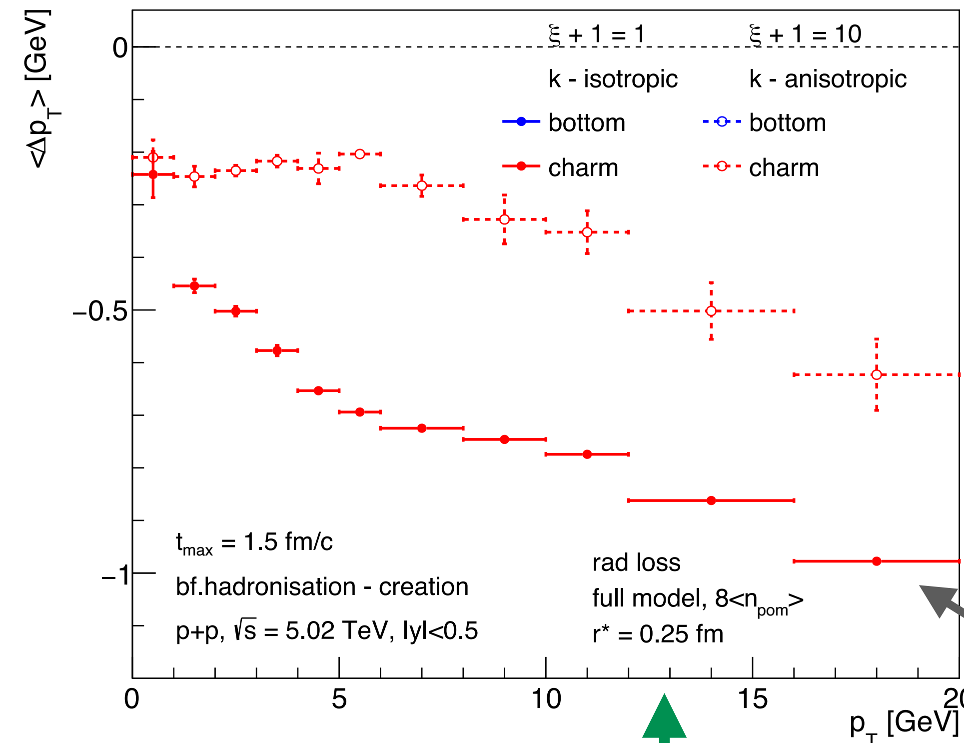

anisotropy

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[Werner, Phys.Rev.C 109 (2024) 1, 014910]
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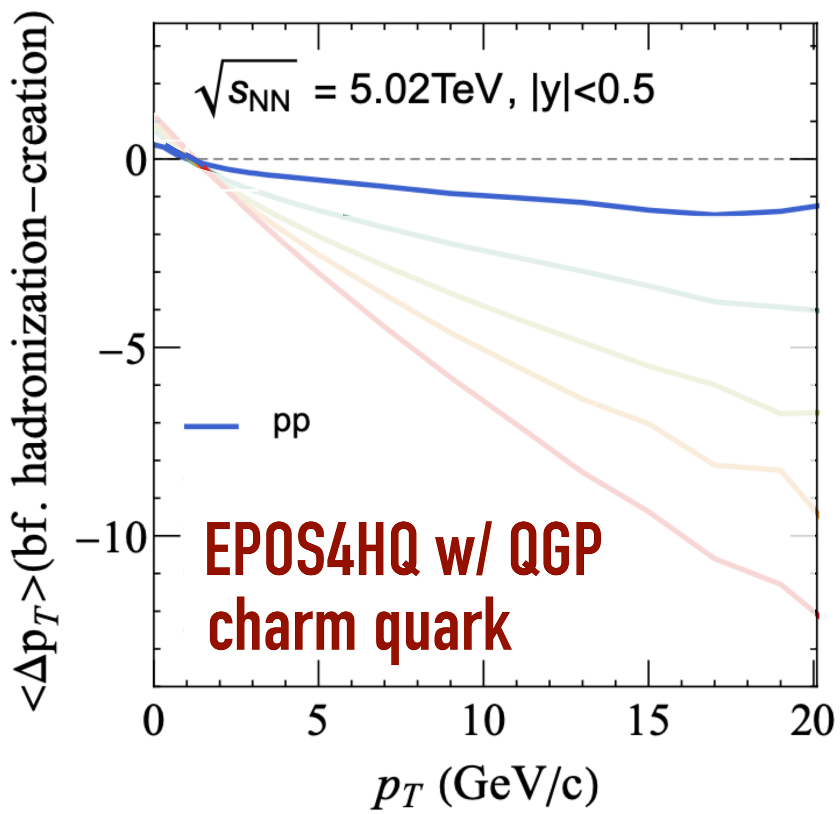
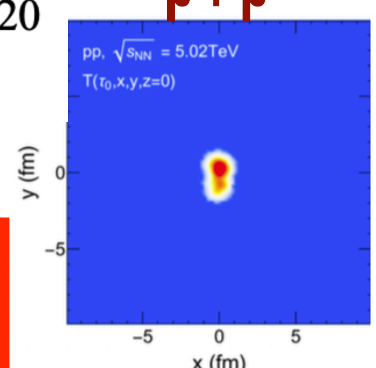


p+p



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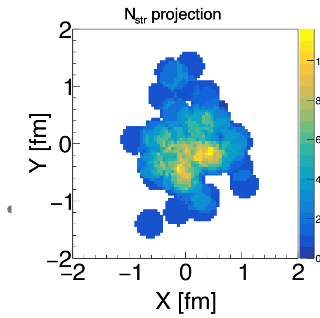
CONCLUSIONS



[this work]

- corona (strings, no loss) + core (QGP, loss)

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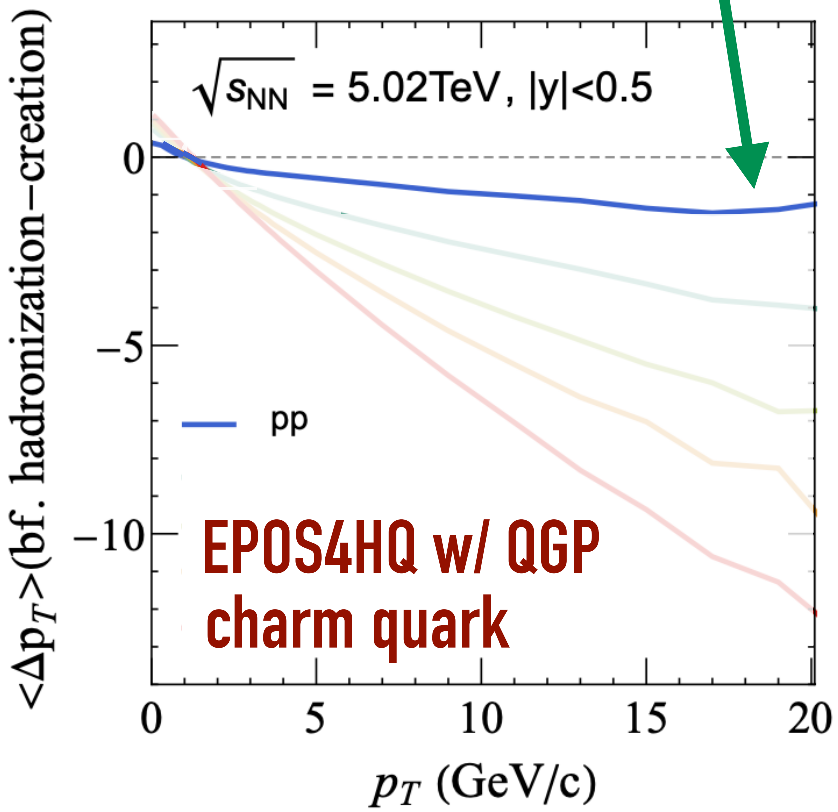
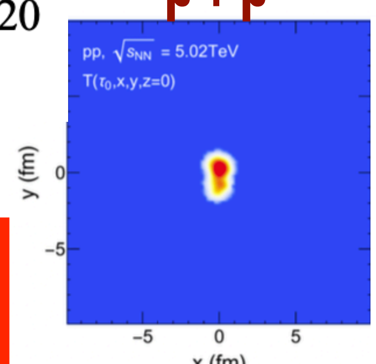
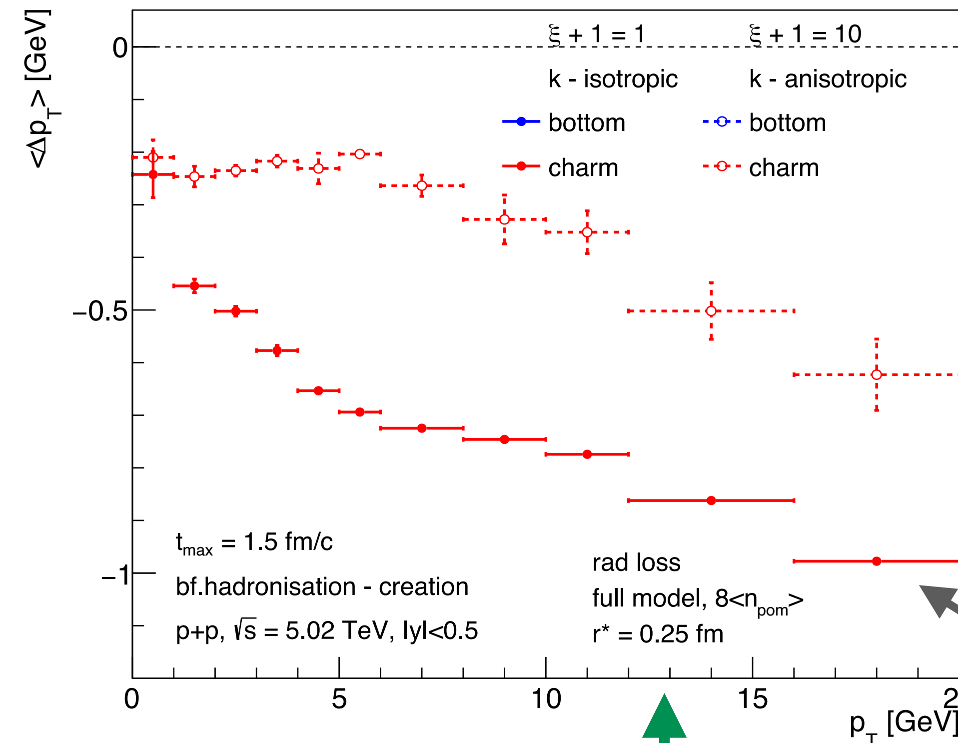
[Zhao et al., Phys. Rev. C 111 (2025) 014907]



p+p





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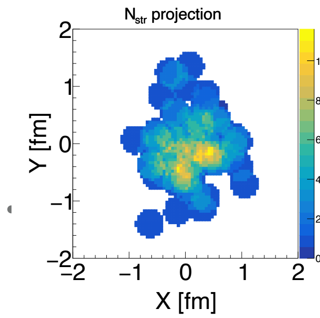

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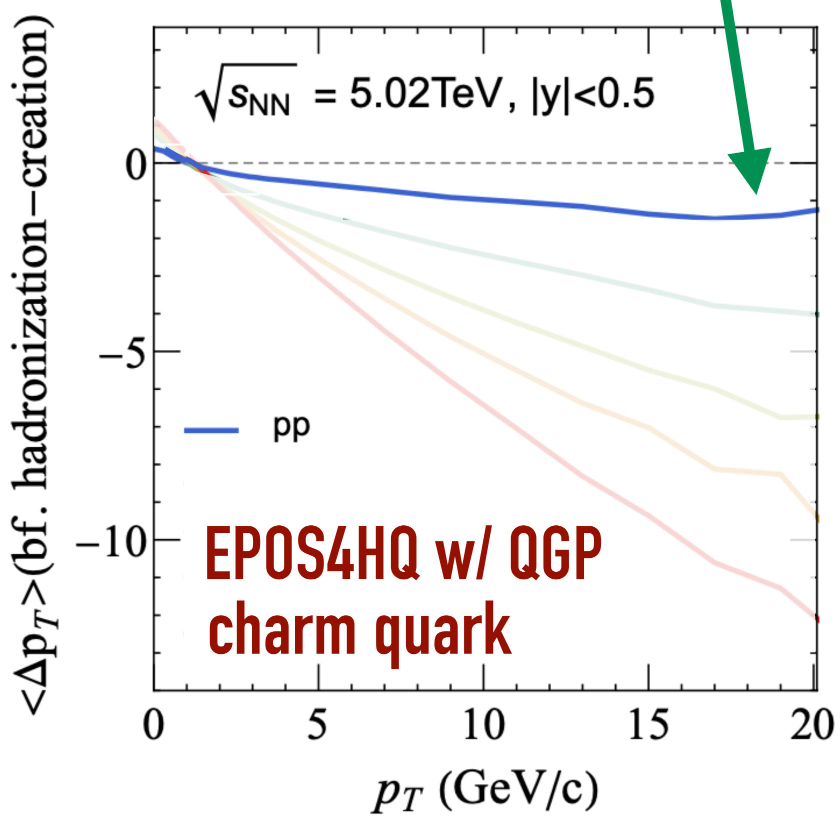
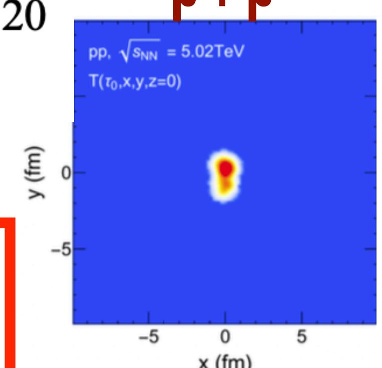


p+p



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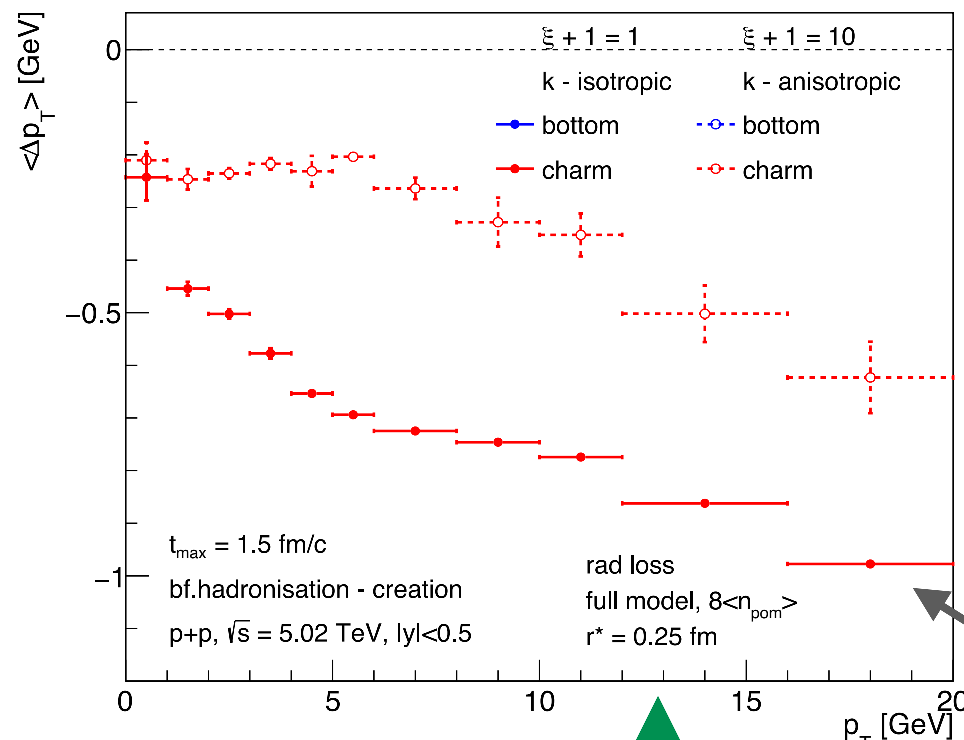

- no QGP, no flow, pre-equilibrium
- can be added to model total loss

- what is the kind of medium formed?
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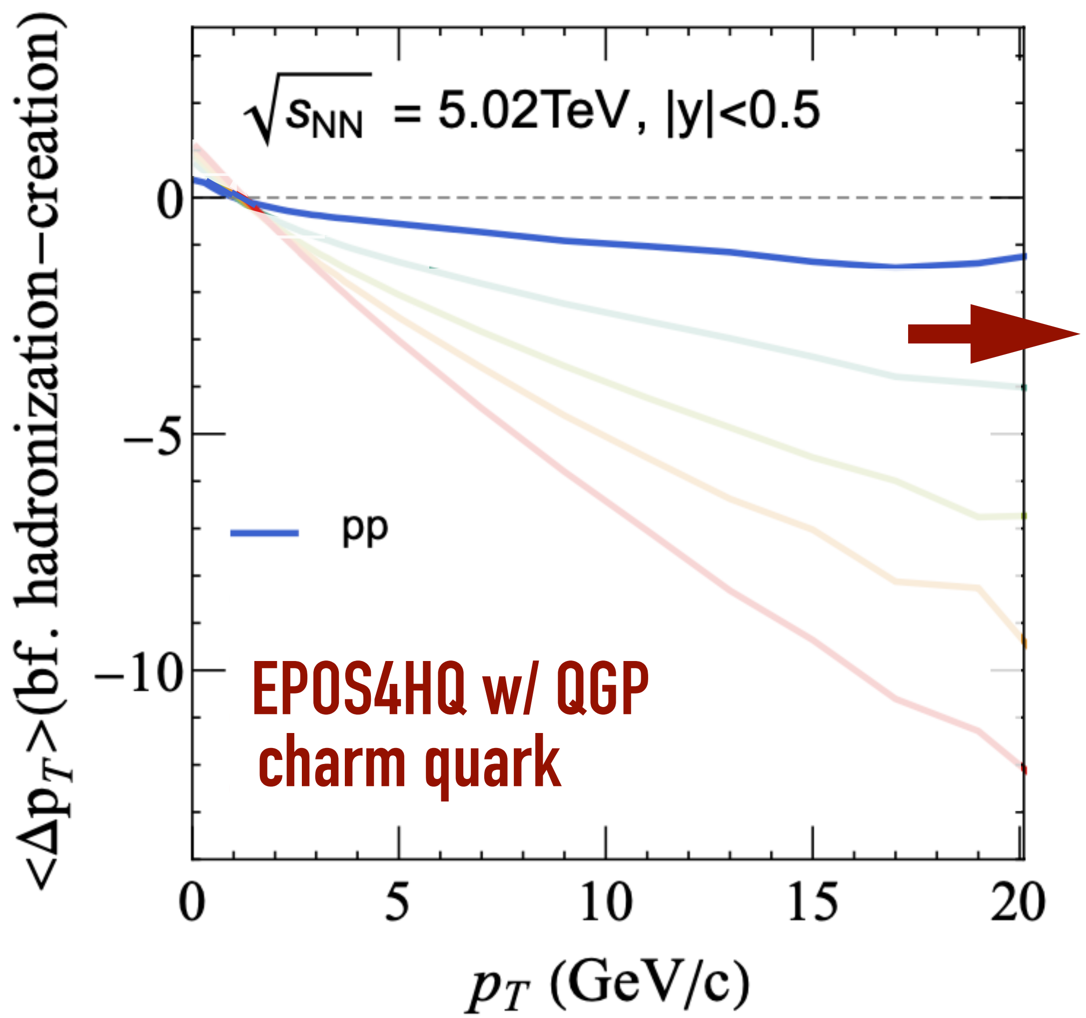
- is jet loss measurable in p+p?

- we test anisotropic gluon medium
- HF energy loss is sensitive to the degree of medium momentum anisotropy
- harder at HF hadron level…

PLANS: FROM HF QUARKS TO HF HADRONS

EPOS results:

[Zhao et al., Phys. Rev. C 111 (2025) 014907]



PLANS: FROM HF QUARKS TO HF HADRONS

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[Zhao et al., Phys.Rev.D 109 (2024) 5, 054011]

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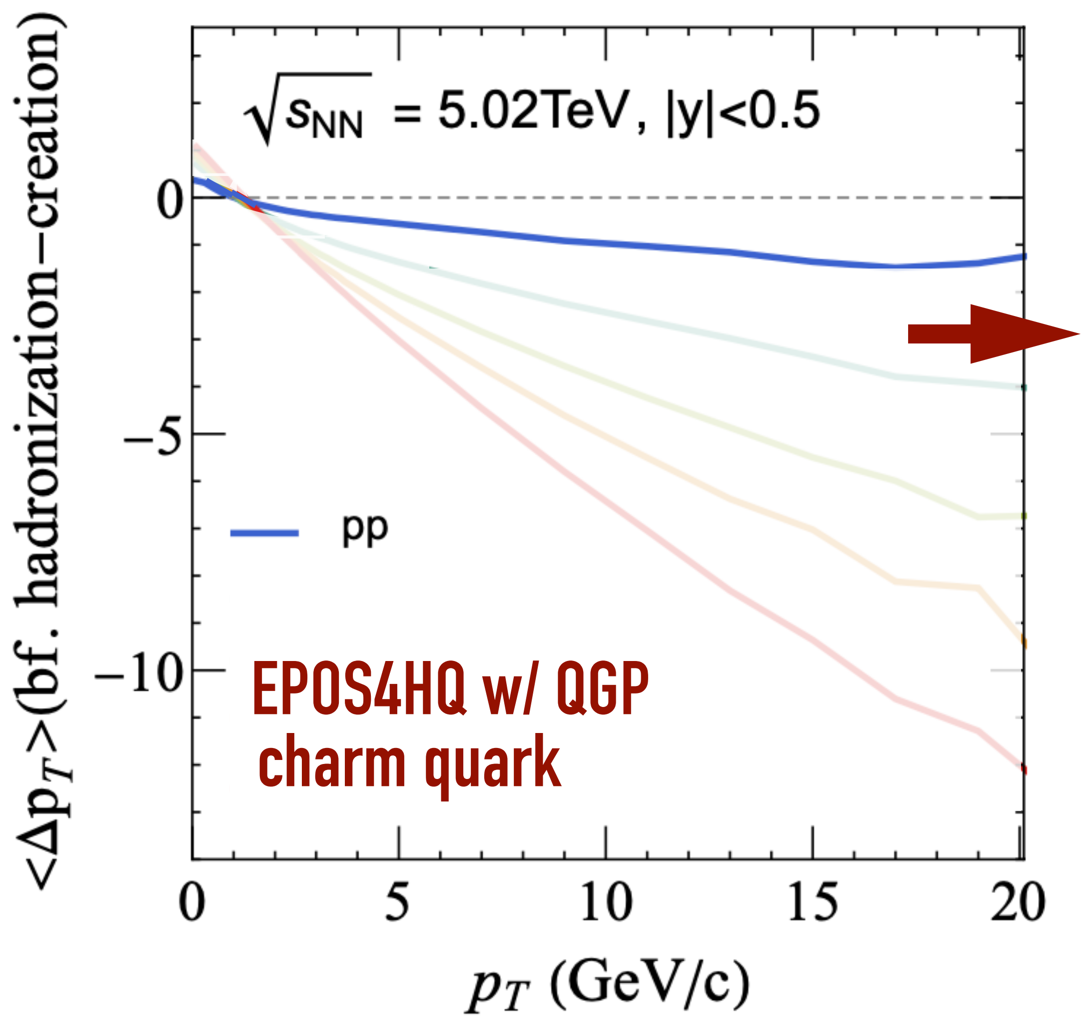
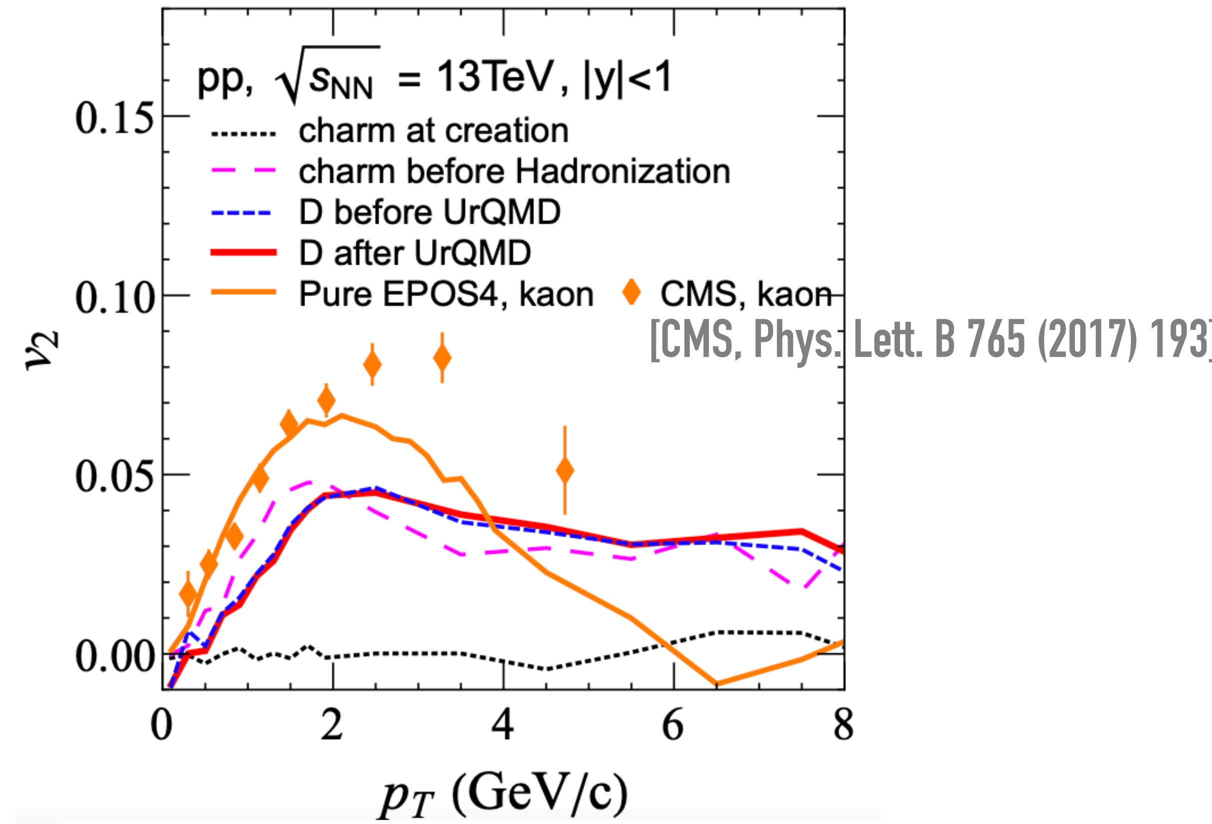
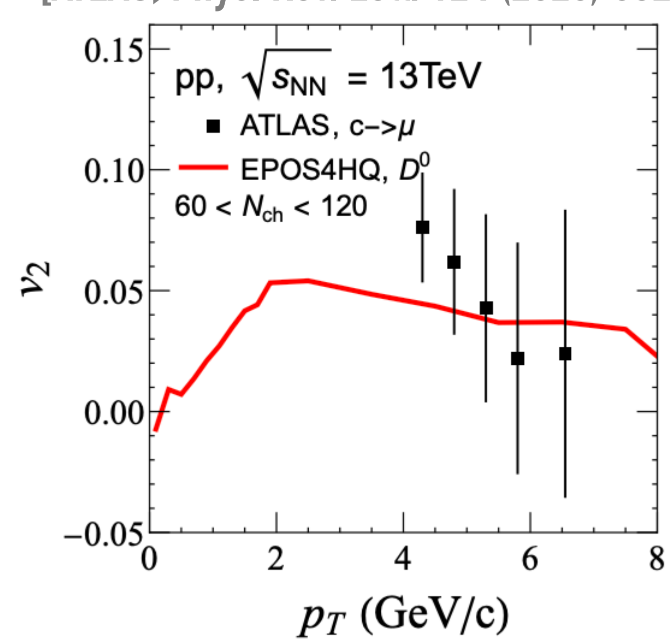
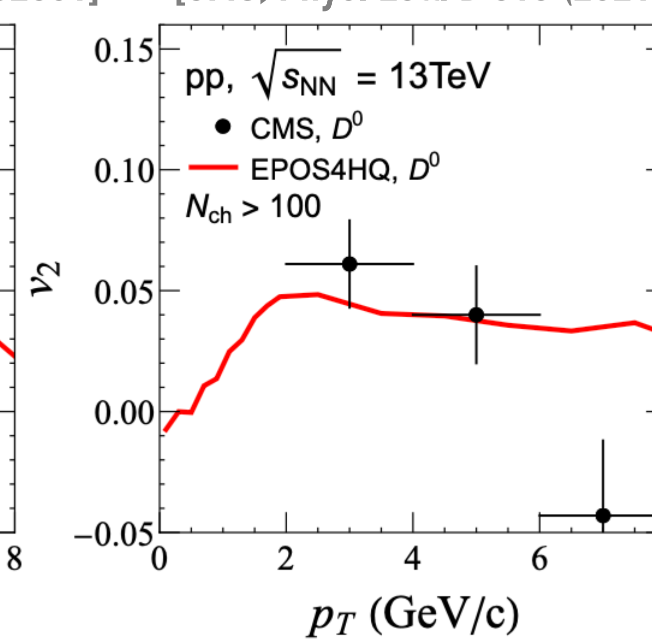




[ATLAS, Phys. Rev. Lett. 124 (2020) 082301]



[CMS, Phys. Lett. B 813 (2021) 136036]



- azimuthal flow (v2)

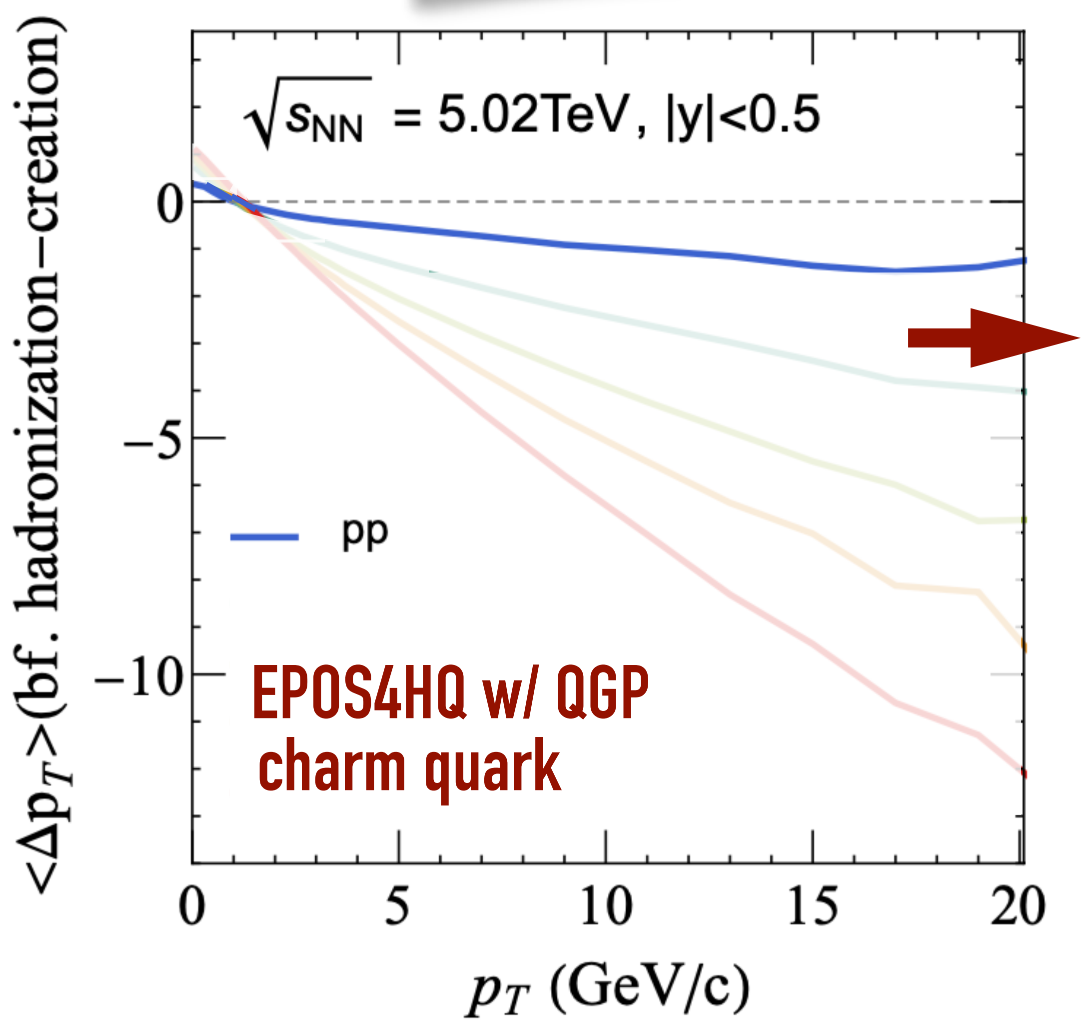
PLANS: FROM HF QUARKS TO HF HADRONS

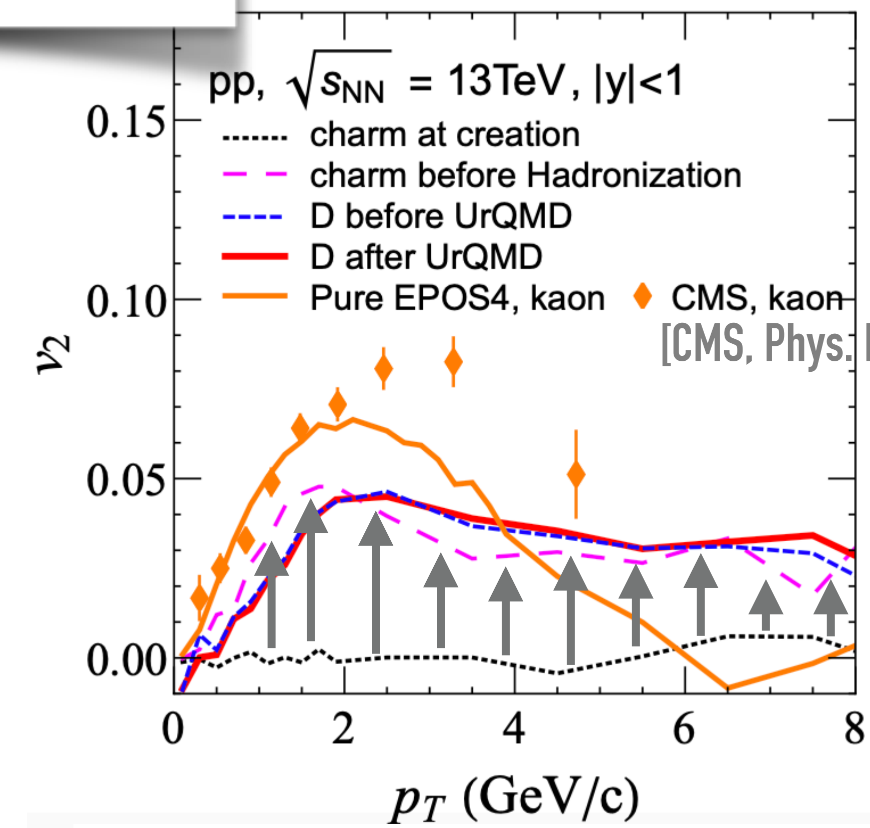
EPOS results:

no v2 expected for HF from hard scattering, but **interactions with QGP** create it!

o et al., Phys.Rev.D 109 (2024) 5, 054011]

[Zhao et al., Phys. Rev. C 111 (2025) 014907]

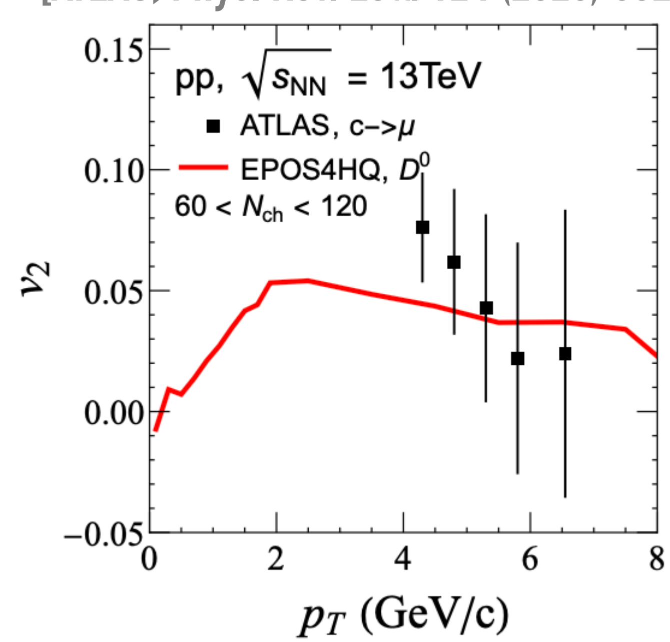




[CMS, Phys. Lett. B 765 (2017) 193]

- azimuthal flow (v2)

[ATLAS, Phys. Rev. Lett. 124 (2020) 082301]



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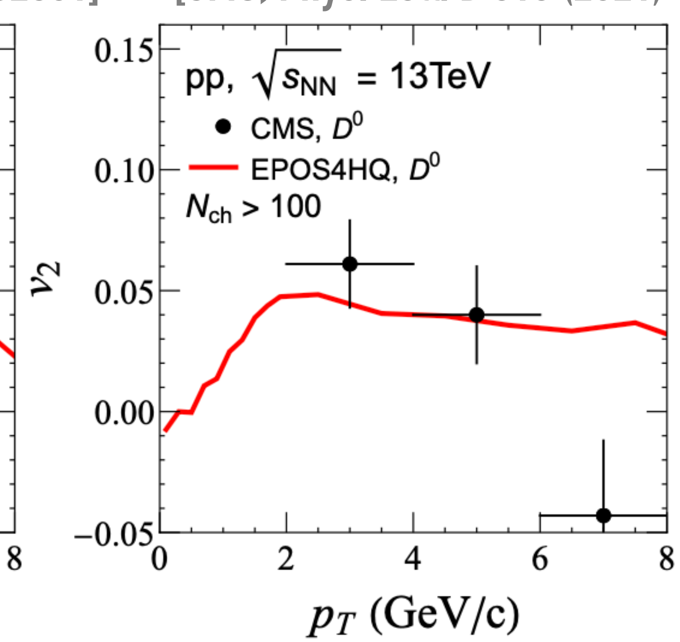

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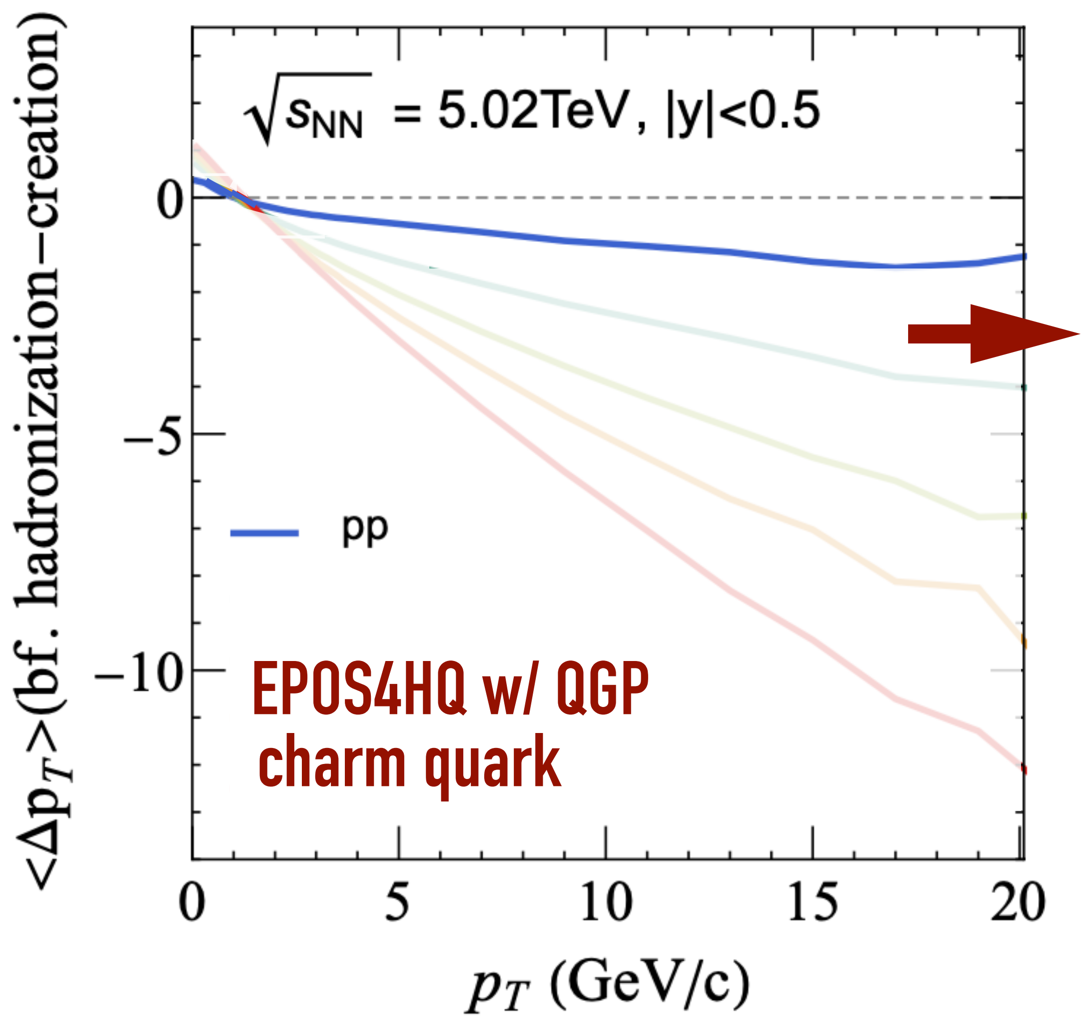
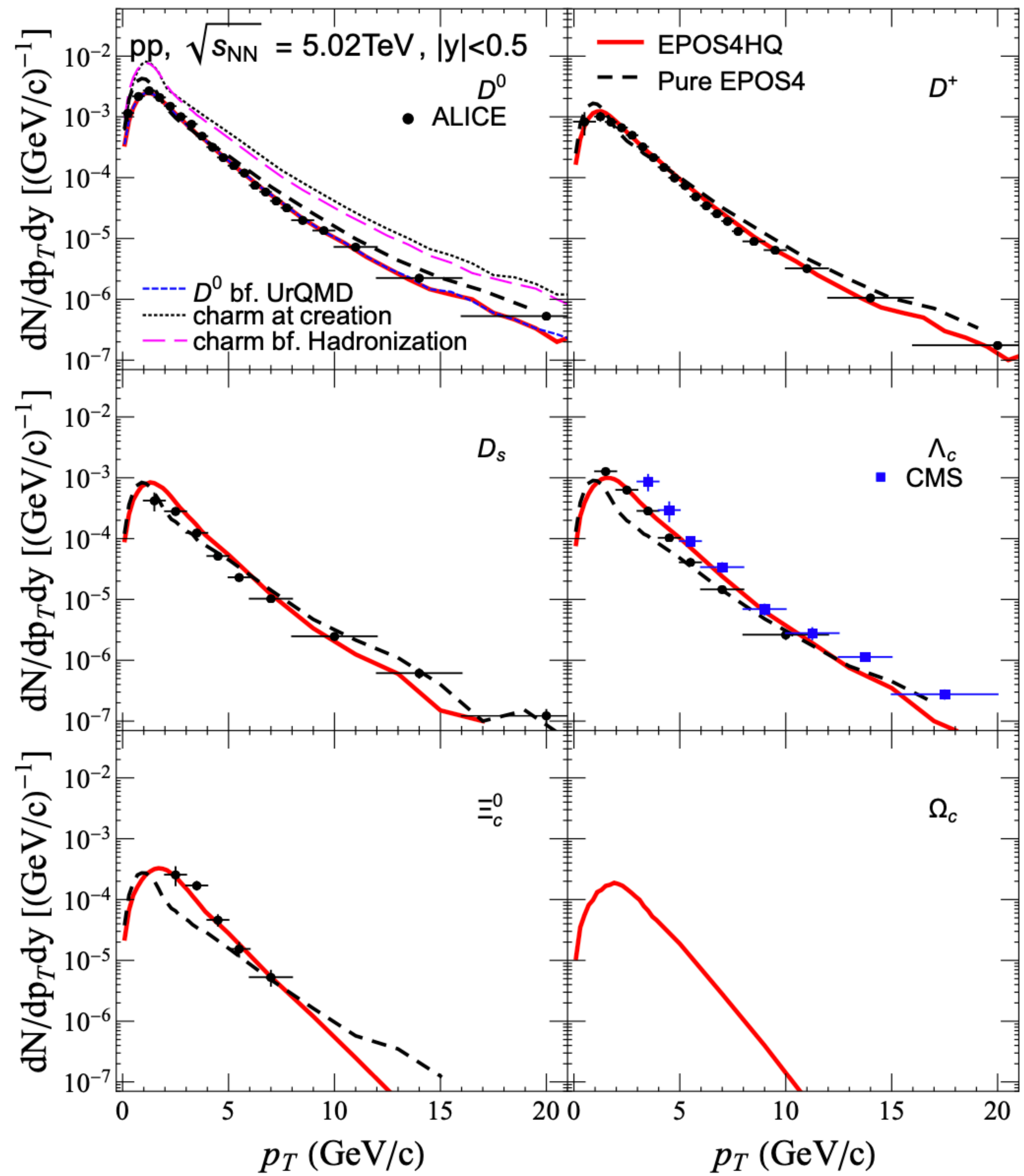




- azimuthal flow (v2)
- spectra

Data from: [ALICE, Phys. Rev. Lett. 127 (2021) 202301]

[ALICE, JHEP 10, (2021) 159] [CMS, JHEP 01 (2024) 128]

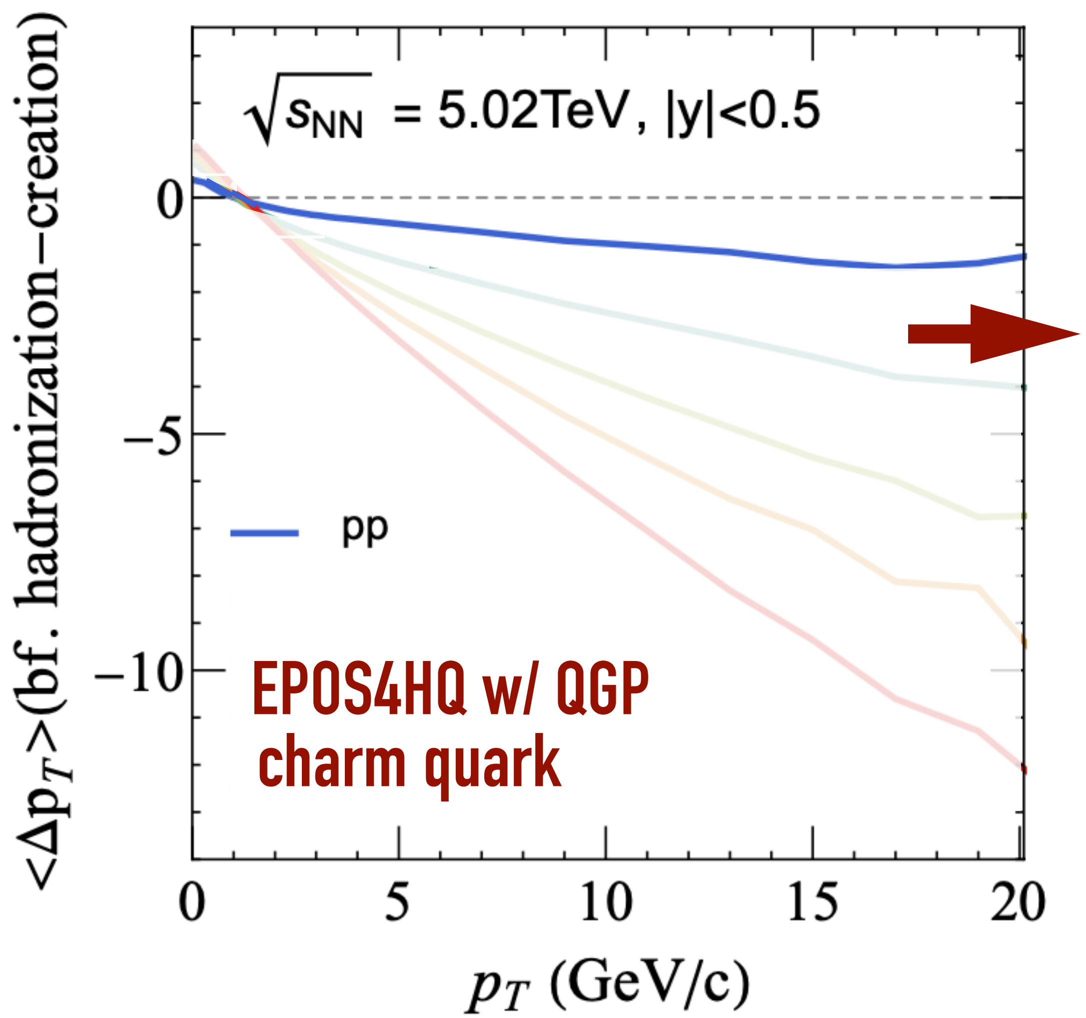
PLANS: FROM HF QUARKS TO HF HADRONS

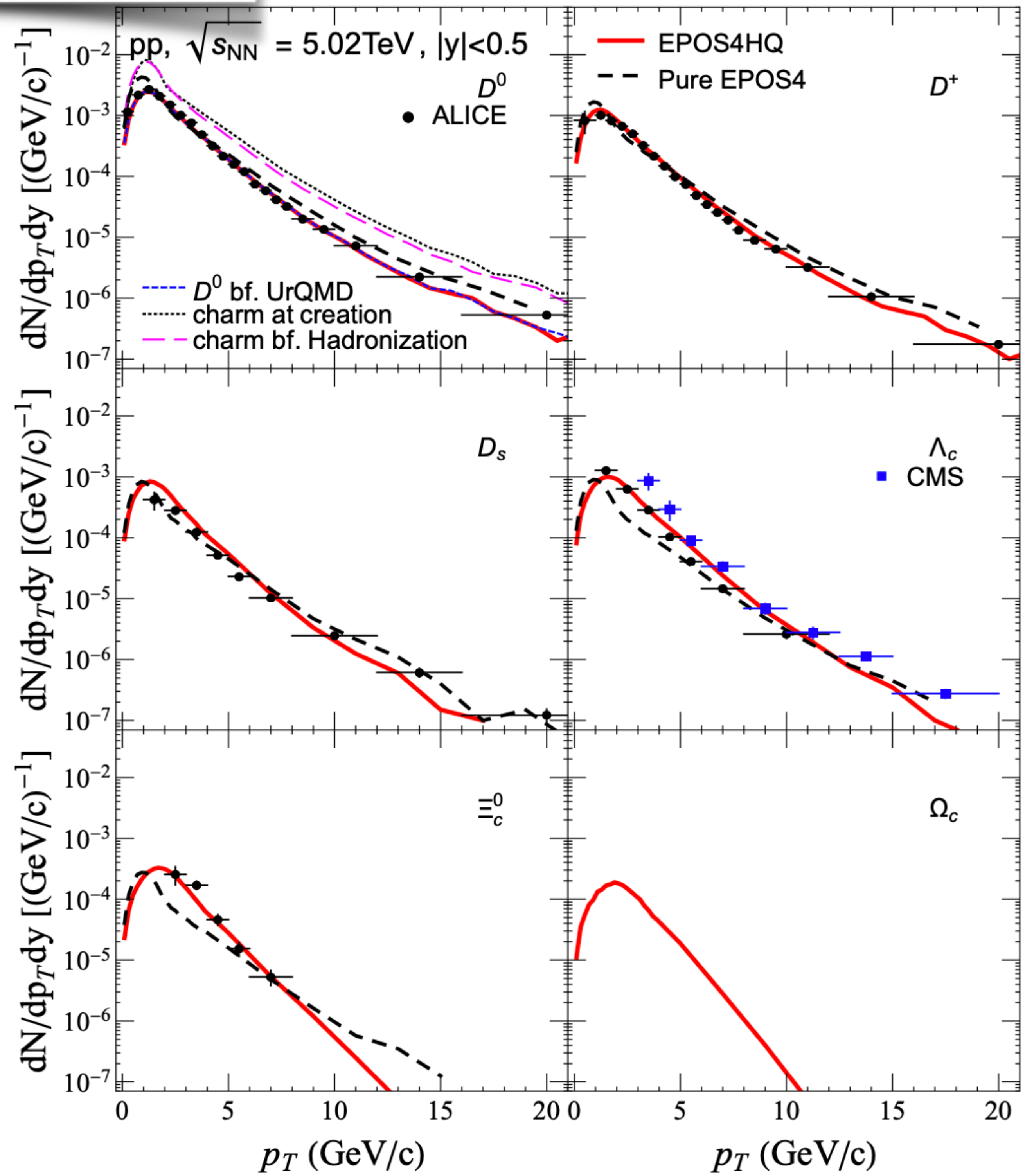
EPOS results:

max shift of spectra at HADRONIZATION !

[Zhao et al., Phys.Rev.D 109 (2024) 5, 054011]

[Zhao et al., Phys. Rev. C 111 (2025) 014907]





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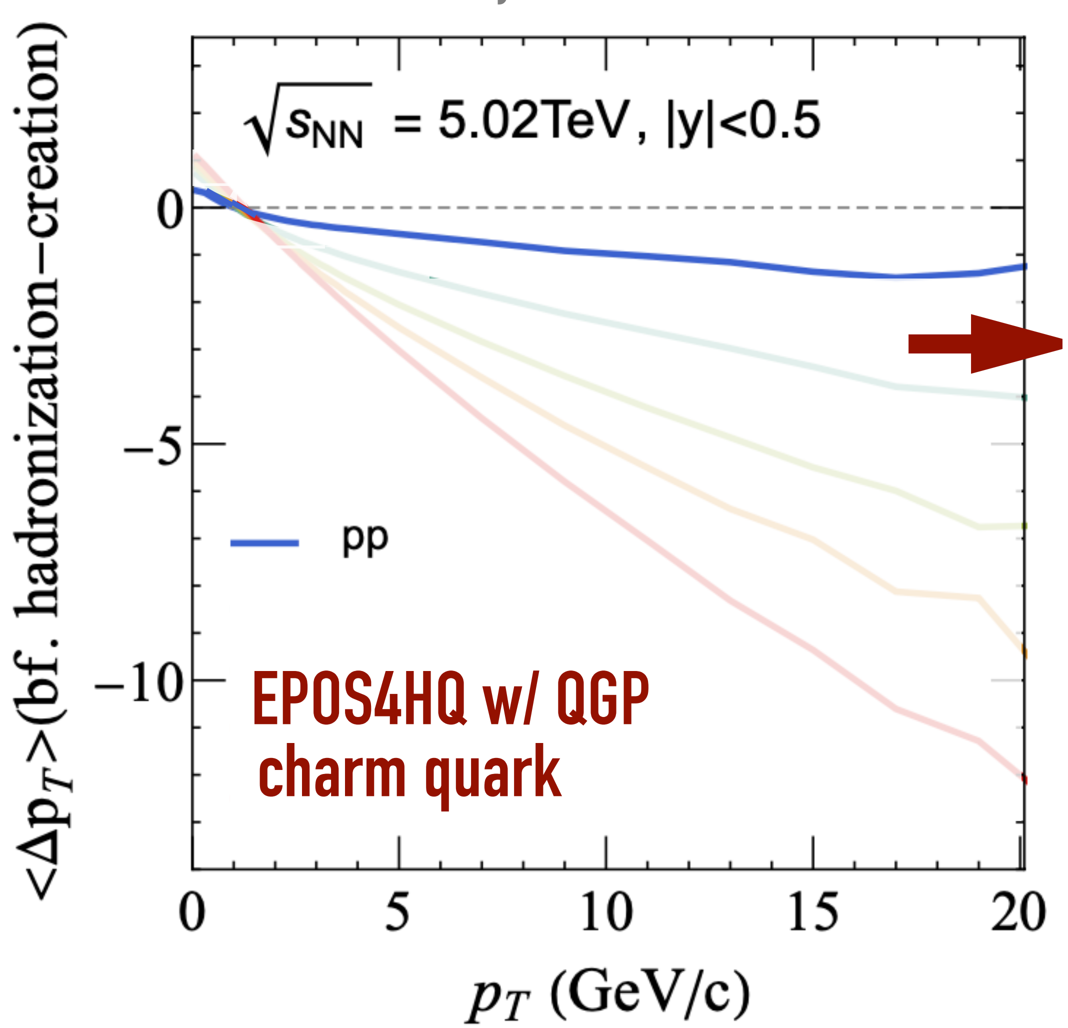
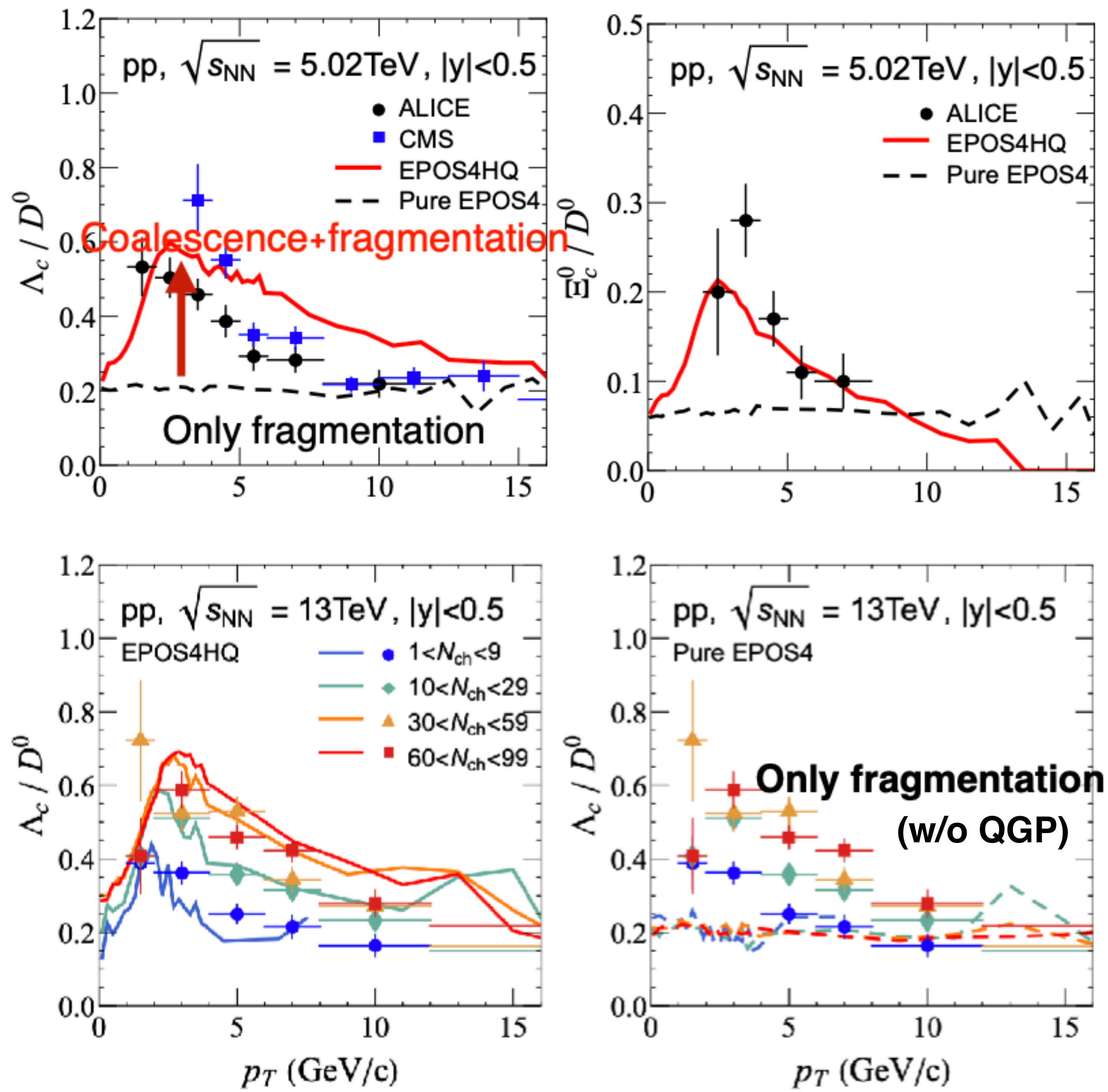




- azimuthal flow (v2)
- spectra
- baryon to meson ratio

Data from: [ALICE, Phys. Rev. Lett. 127 (2021) 202301]
[ALICE, JHEP 10, (2021) 159] [CMS, JHEP 01 (2024) 128]

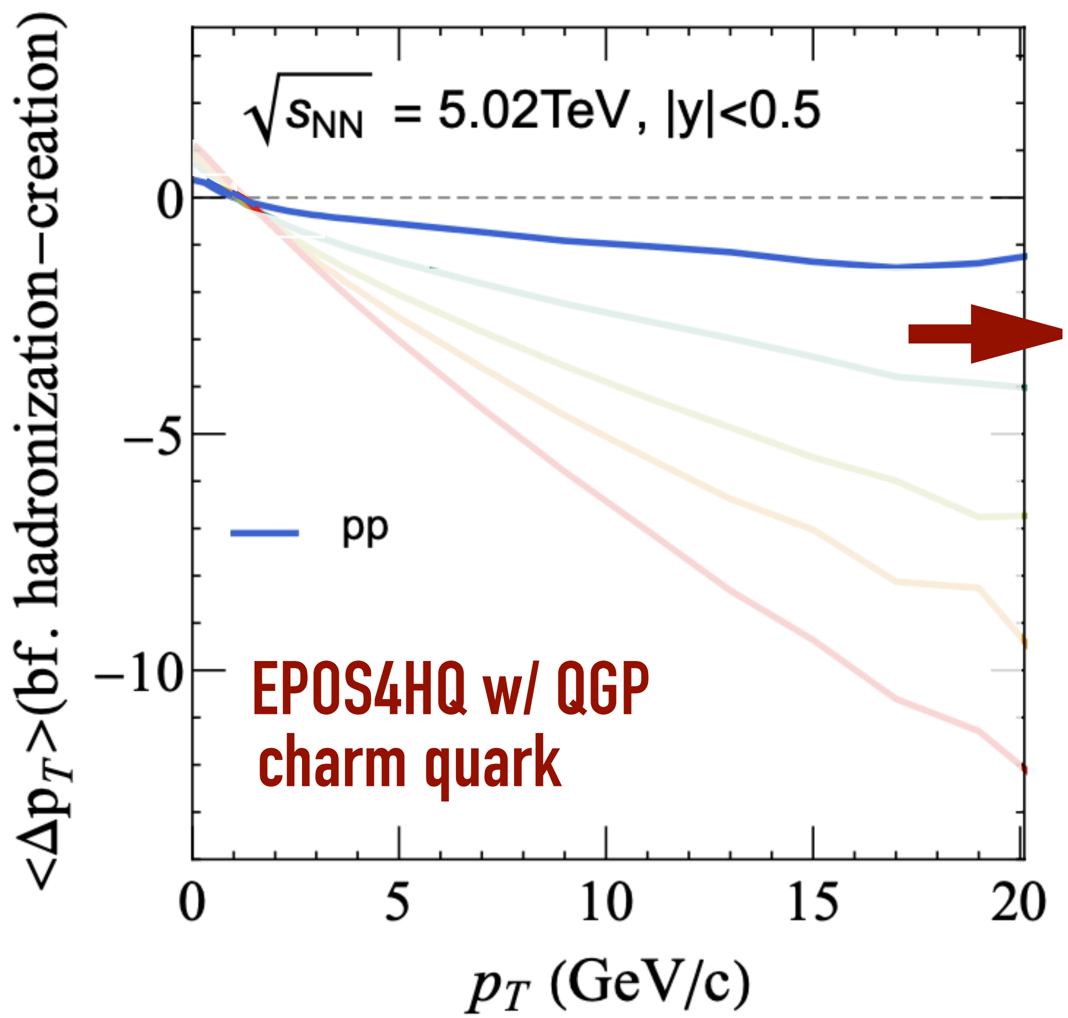
PLANS: FROM HF QUARKS TO HF HADRONS

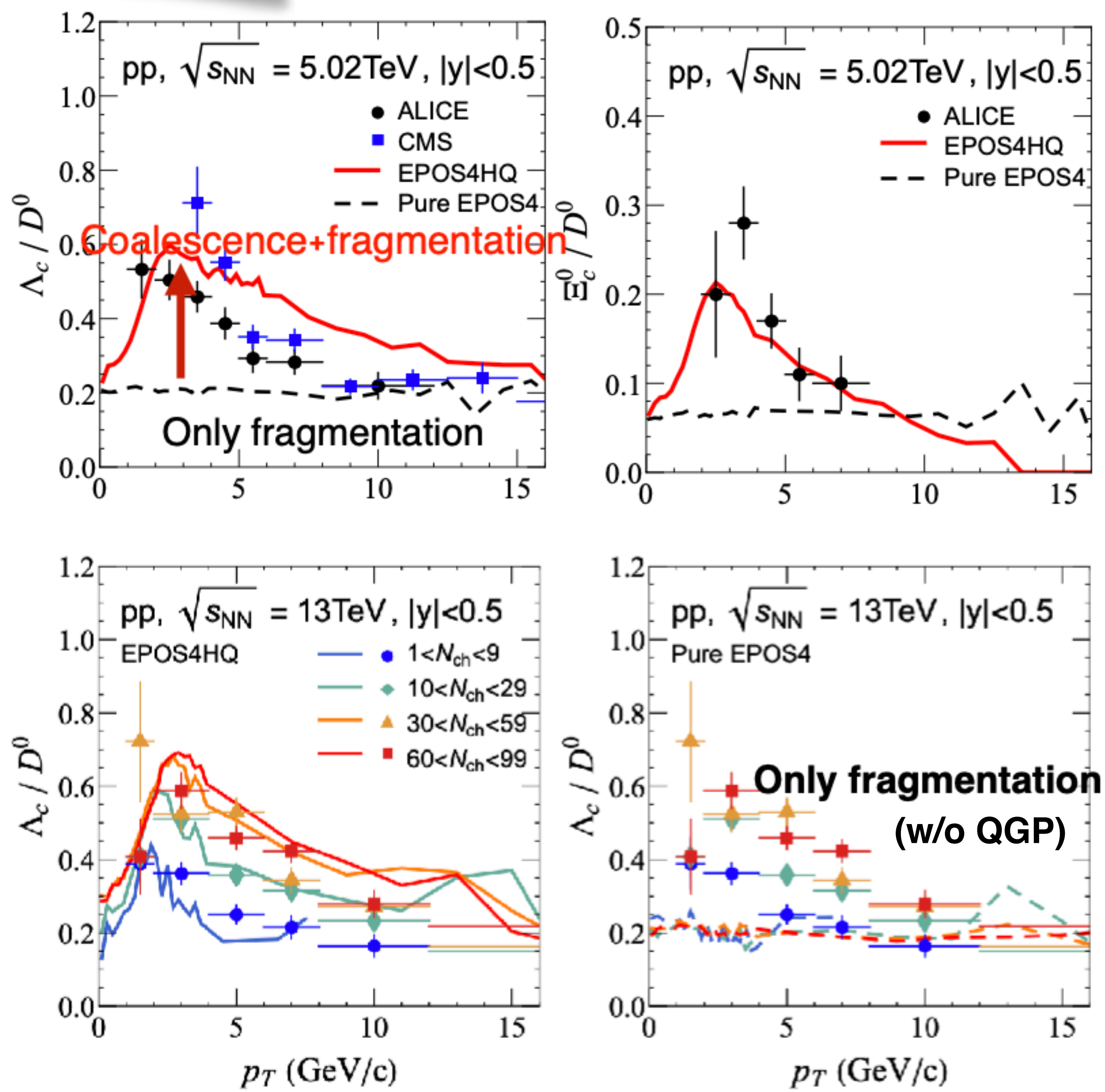
EPOS results:

coalescence + fragmentation is better!

[Zhao et al., Phys.Rev.D 109 (2024) 5, 054011]

[Zhao et al., Phys. Rev. C 111 (2025) 014907]





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Data from: [ALICE, Phys. Rev. Lett. 127 (2021) 202301]
[ALICE, JHEP 10, (2021) 159] [CMS, JHEP 01 (2024) 128]

THANK YOU FOR YOUR ATTENTION

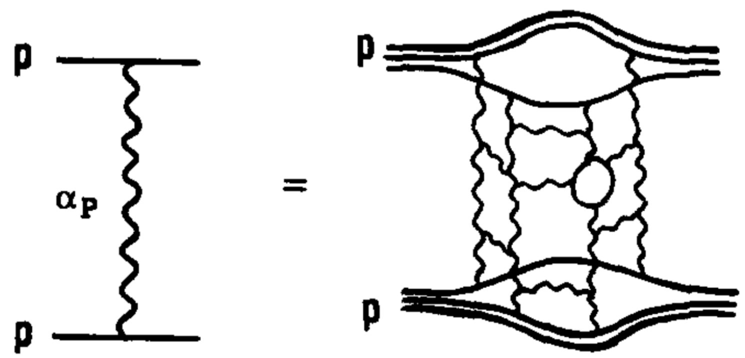
DARIA-PROKHOROVA@MAIL.TSINGHUA.EDU.CN

BACKUP

PROTON-PROTON INELASTIC INTERACTIONS

pomeron exchange

[Capella, Phys. Rep. 236 (1994) 225]



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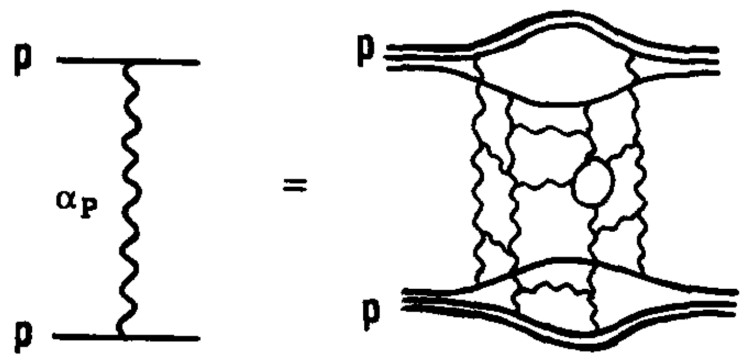

QCD topological expansion in large Nc and Nf limits

[Veneziano, Phys. Lett. B 52 (1974) 220; Nucl. Phys. B 117 (1976) 519]

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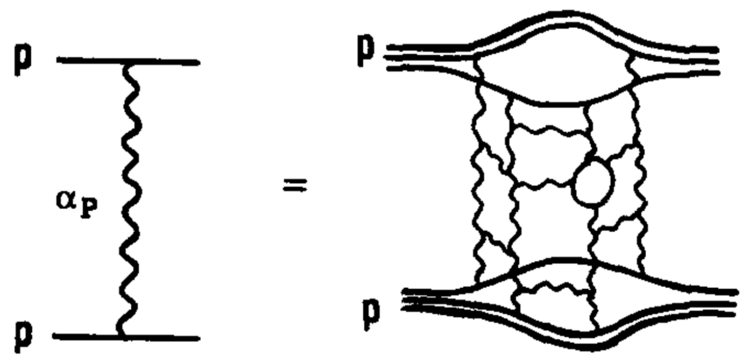

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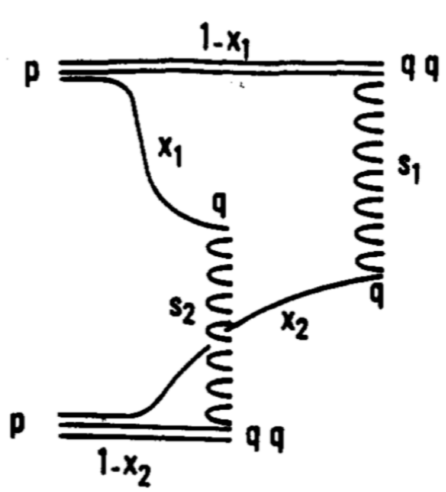
unitarity cut of cylindrical diagram



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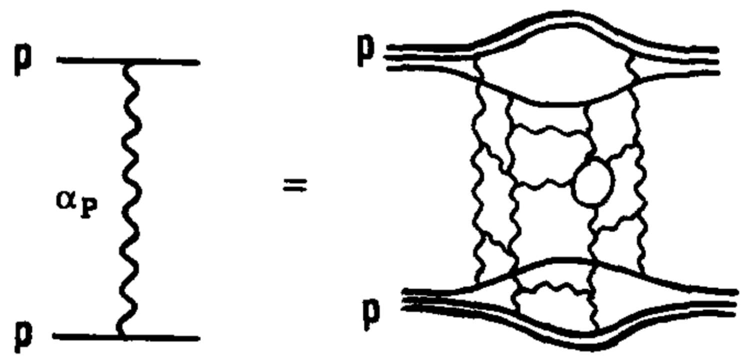

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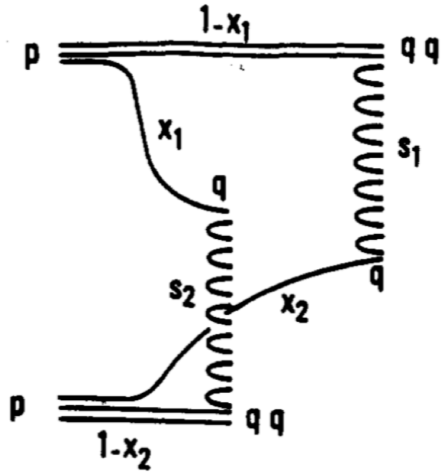

two-rapidity-chains

fragmenting into soft particles

[Kaidalov, Phys. Lett. B 116 (1982) 459
Artru, Phys. Rep. 97 (1983) 147
Werner, Phys. Rep. 232 (1993) 87]

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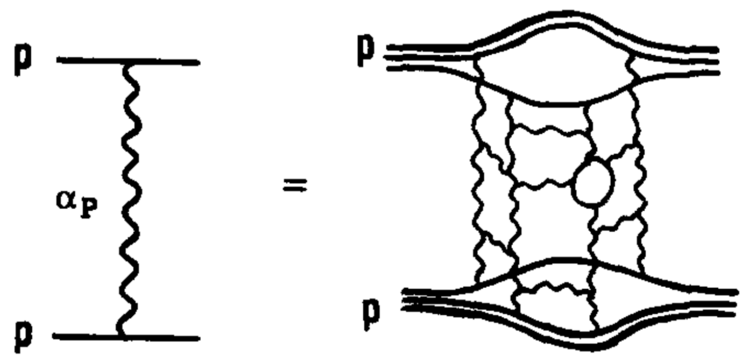
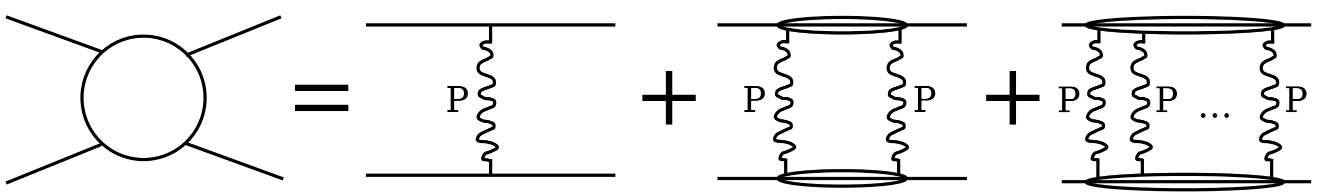


number of exchanged pomerons grows with energy!



[Gribov, JETP 53 (1967) 654]

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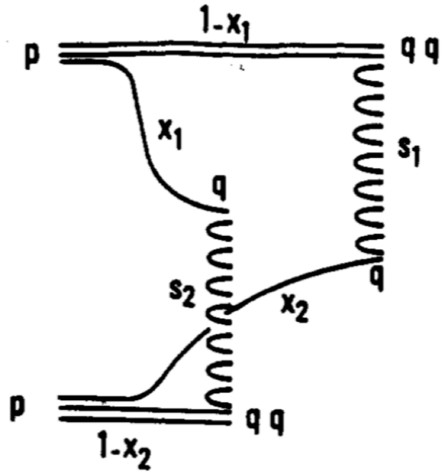

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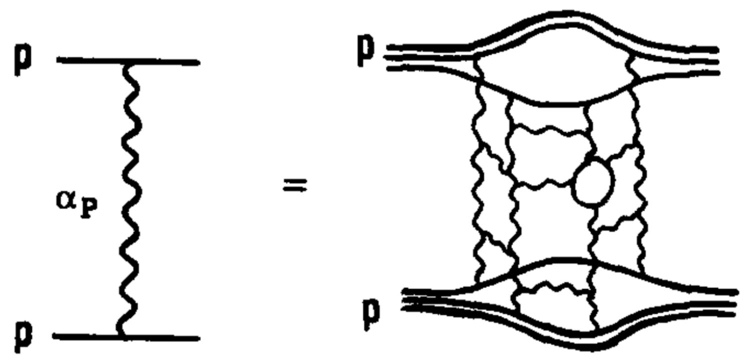

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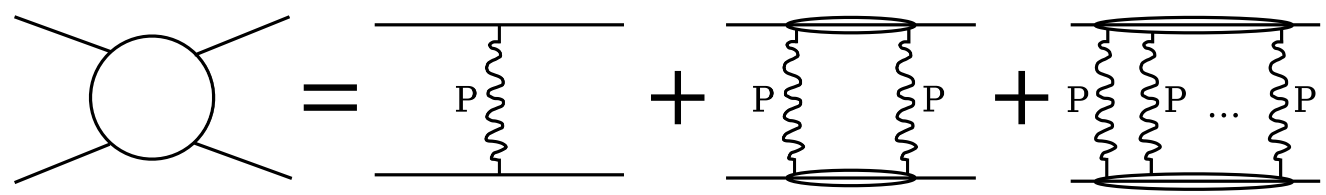
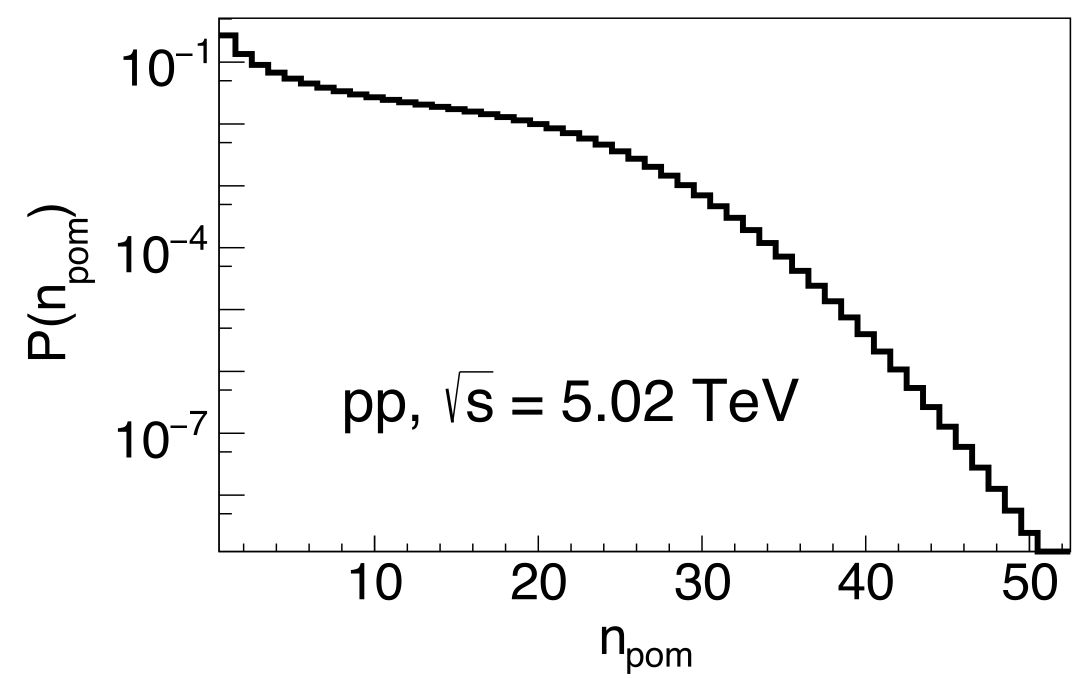
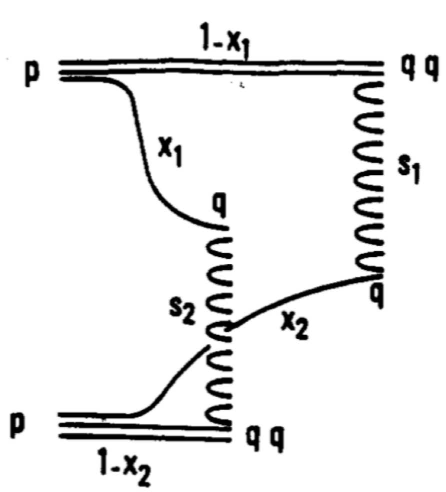


[Gribov, JETP 53 (1967) 654]

broad distribution in n_{pom}



unitarity cut of cylindrical diagram



two-rapidity-chains

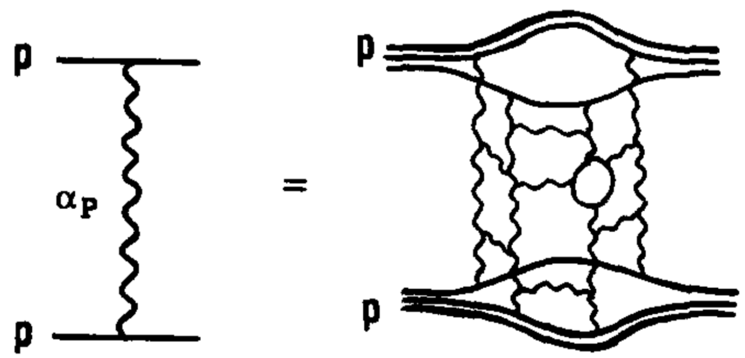
fragmenting into soft particles

[Kaidalov, Phys. Lett. B 116 (1982) 459
Artru, Phys. Rep. 97 (1983) 147
Werner, Phys. Rep. 232 (1993) 87]

PROTON-PROTON INELASTIC INTERACTIONS

pomeron exchange

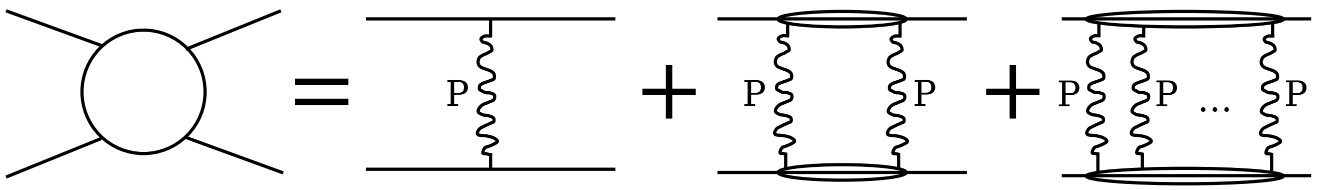
[Capella, Phys. Rep. 236 (1994) 225]



QCD topological expansion in large Nc and Nf limits

[Veneziano, Phys. Lett. B 52 (1974) 220; Nucl. Phys. B 117 (1976) 519]

number of exchanged pomerons grows with energy!



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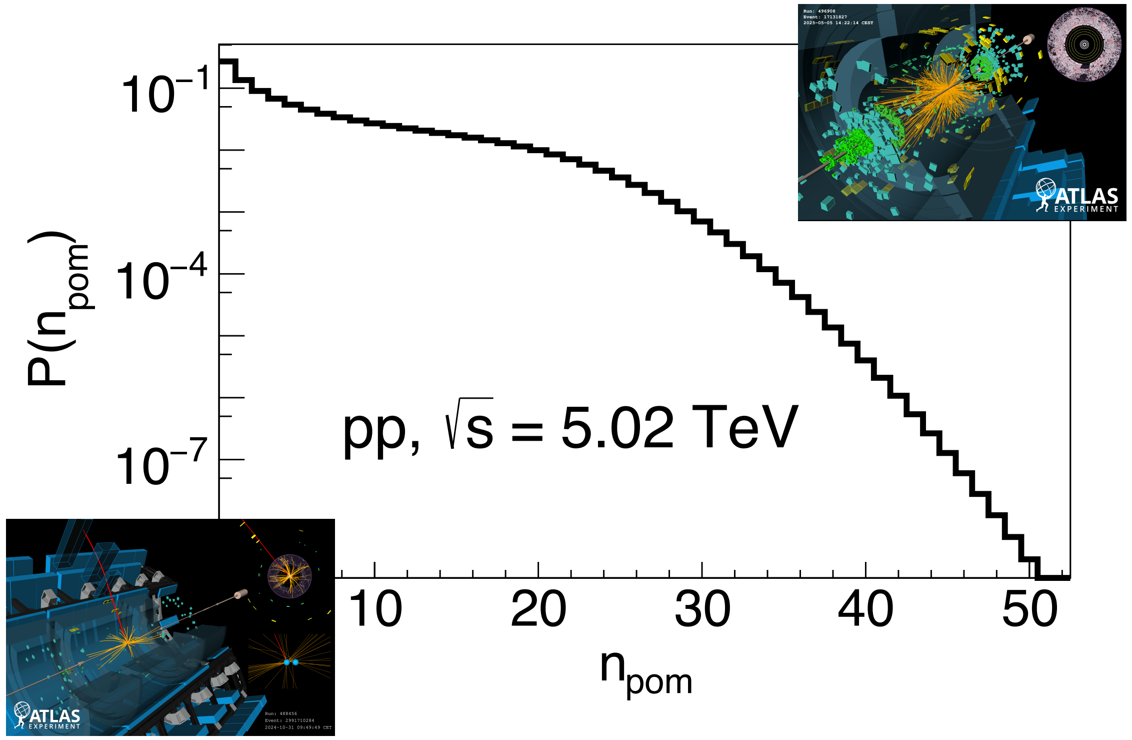

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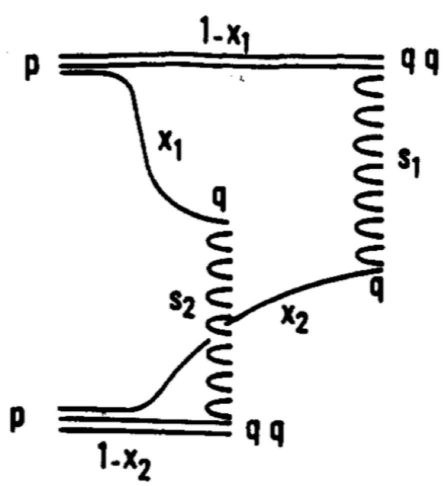

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PROTON–PROTON INELASTIC INTERACTIONS

[Kaidalov, Ter-Martirosian. Phys. Lett. B. 117 (1982) 247]

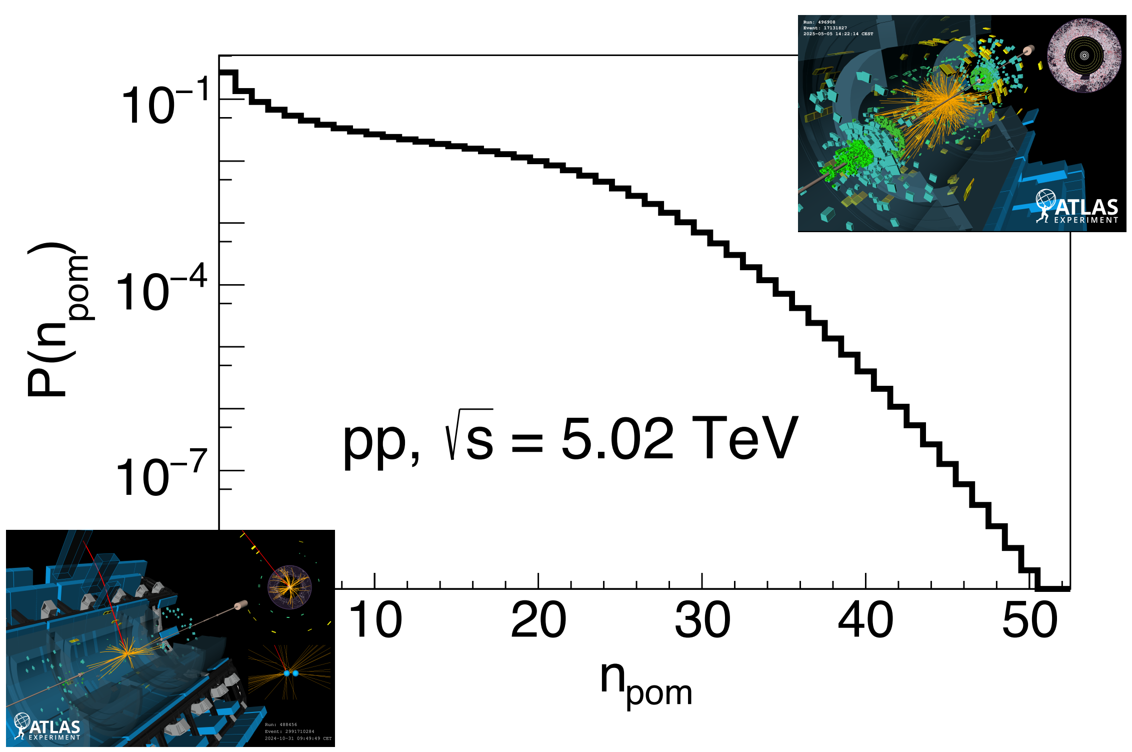
Regge-theory parametrized distribution

$$P\left(n_{\mathrm{pom}}\right) = C\left(z\right) \frac{1}{z n_{\mathrm{pom}}} \left(1 - \exp\left(-z\right) \sum_{l=0}^{n_{\mathrm{pom}}-1} \frac{z^l}{l!}\right), \quad z = \frac{2 w \gamma s^{\Delta}}{R^2 + \alpha' \ln s}$$

$$w = 1.5,\ \Delta = \alpha(0) - 1 = 0.2,\ \gamma = 1.035\ \text{GeV}^{-2},\ R^2 = 3.3\ \text{GeV}^{-2},\ \alpha' = 0.05\ \text{GeV}^{-2}$$

[Vechernin, Belokurova, J. Phys. Conf. Ser. 1690 (2020) 012088]

broad distribution in n_{pom}



PROTON-PROTON INELASTIC INTERACTIONS

[Kaidalov, Ter-Martirosian. Phys. Lett. B. 117 (1982) 247]

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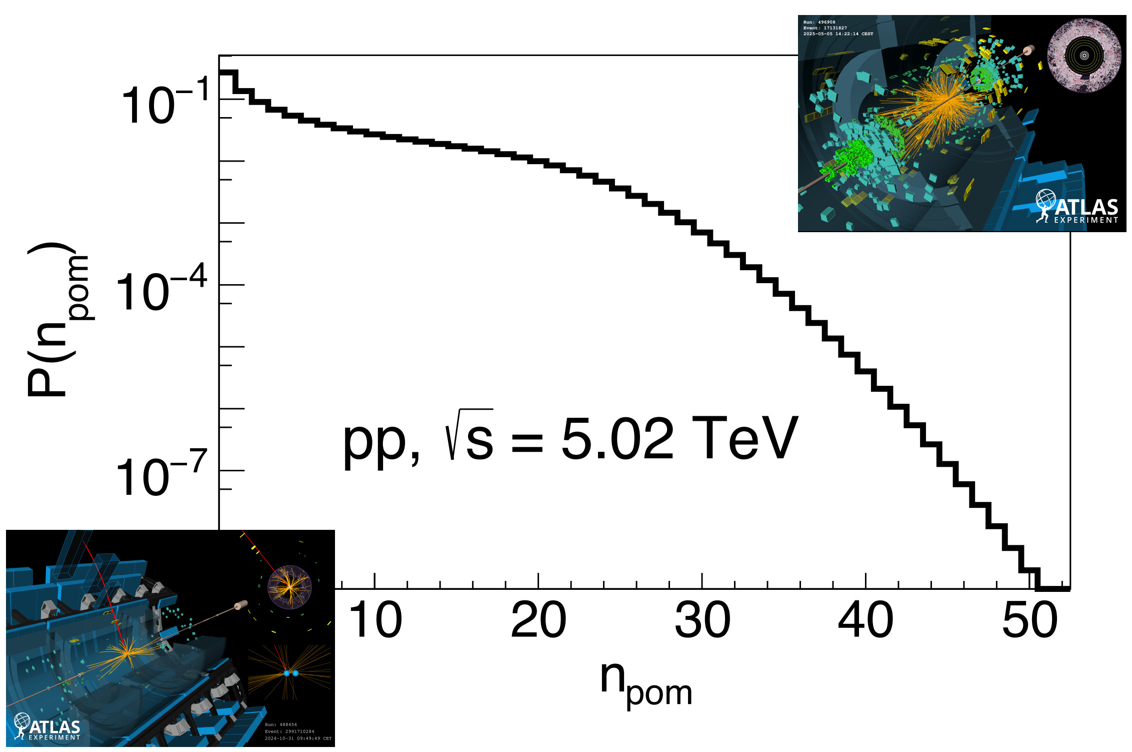
[Vechernin, Belokurova, J. Phys. Conf. Ser. 1690 (2020) 012088]

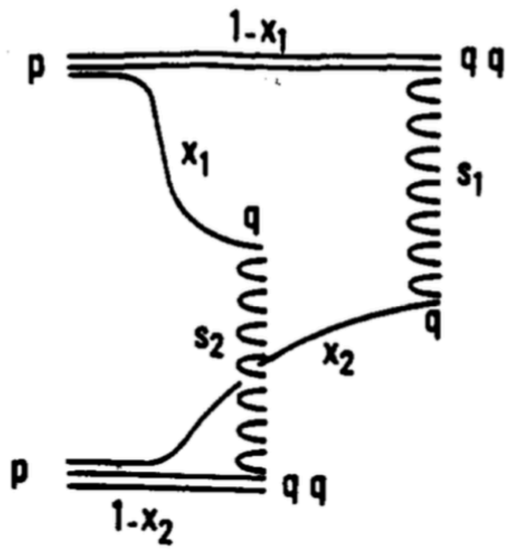
can also be obtained from parton-parton interaction probability

[Vechernin, Lakomov, PoS, Baldin-ISHEPP-XXI (2012) 072]

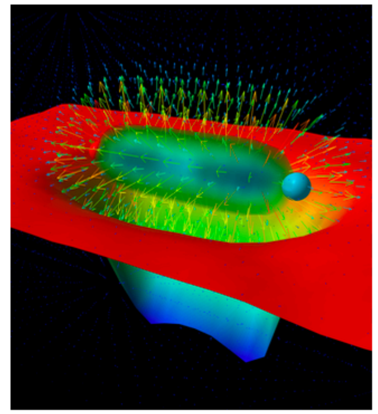
broad distribution in n_{pom}



PROTON-PROTON INELASTIC INTERACTIONS

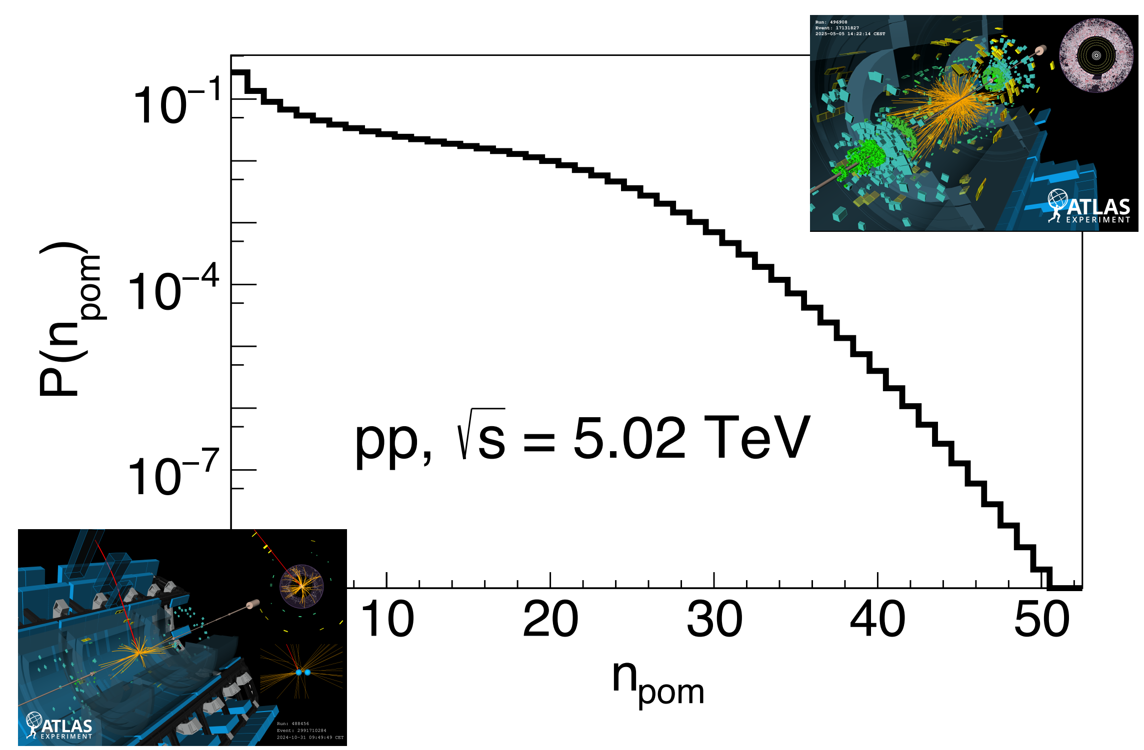


[Capella, Phys. Rep. 236 (1994) 225]



[Varilly, Thesis (2006) MIT]

broad distribution in n_{pom}



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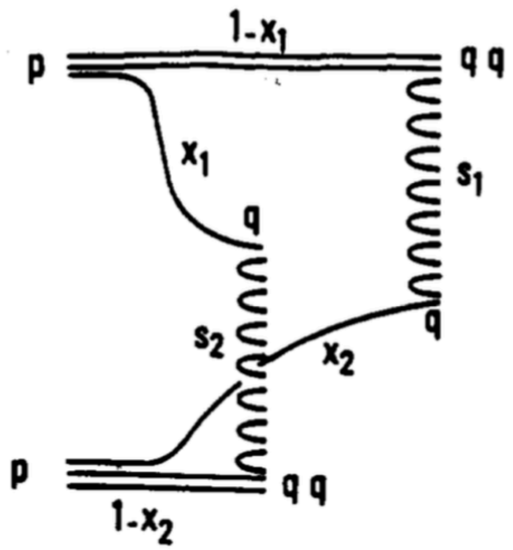

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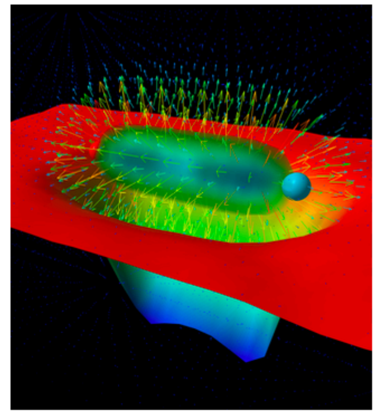
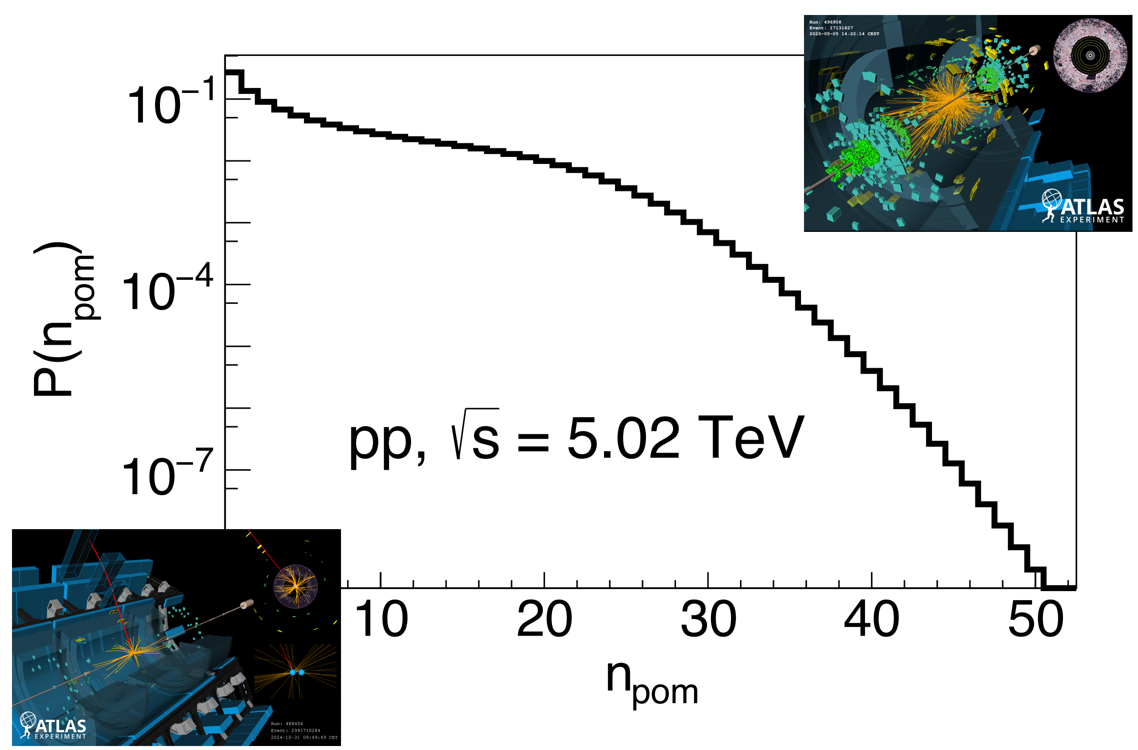


[Varilly, Thesis (2006) MIT]

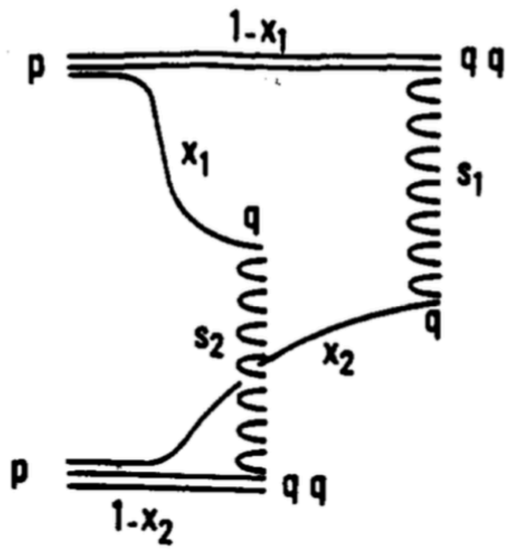
Cornell potential between confined color charges

$$V(r) = -\frac{4}{3} \cdot \frac{\alpha_s}{r} + \sigma_T \cdot r$$

broad distribution in n_{pom}



PROTON-PROTON INELASTIC INTERACTIONS



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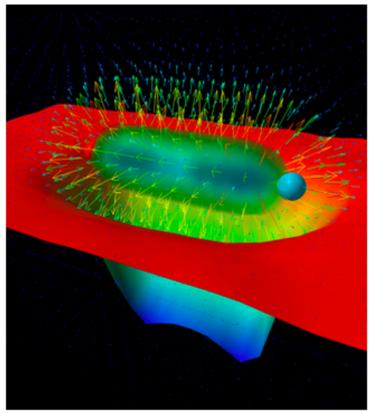

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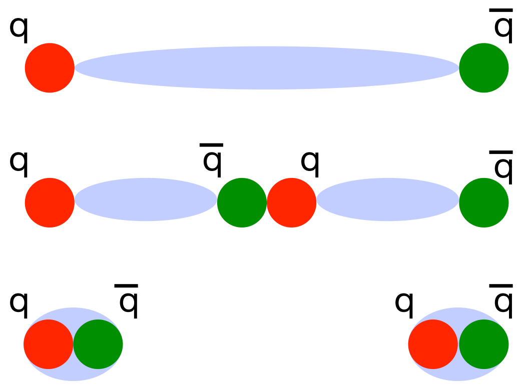
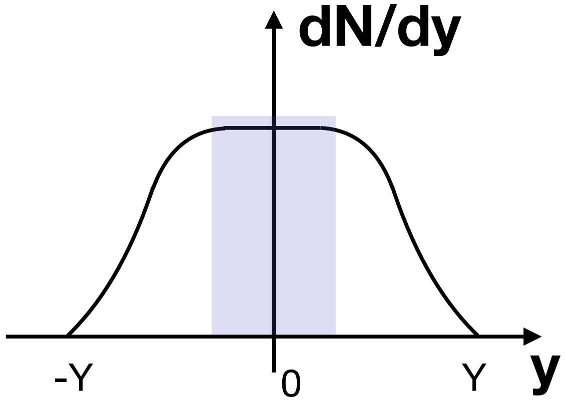
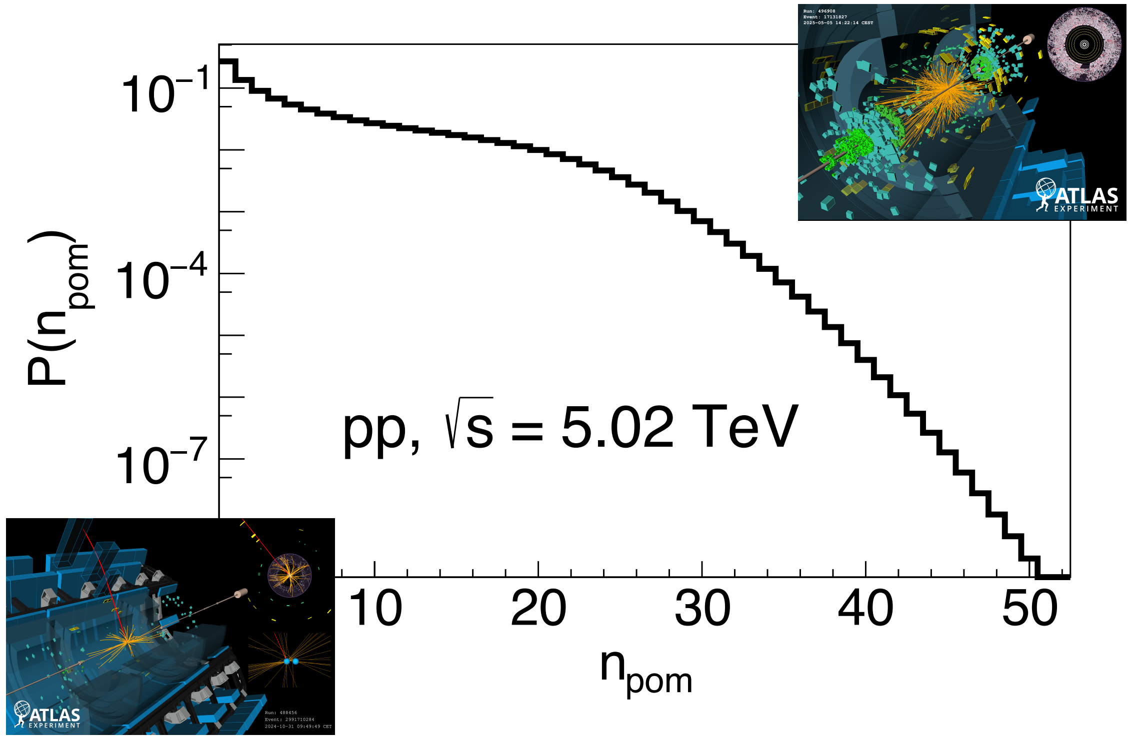
string breaking (qqbar production)

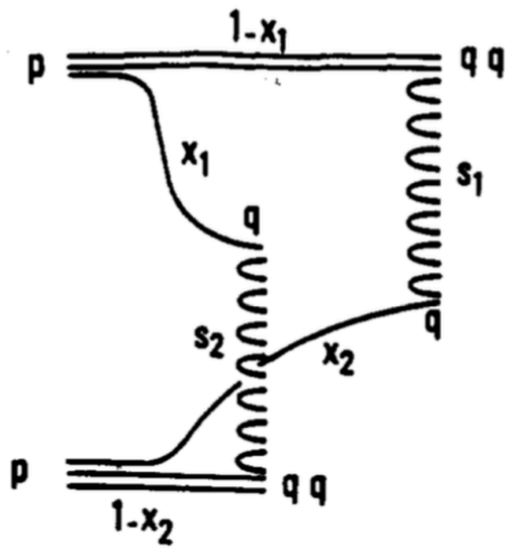




broad distribution in n_{pom}



PROTON-PROTON INELASTIC INTERACTIONS



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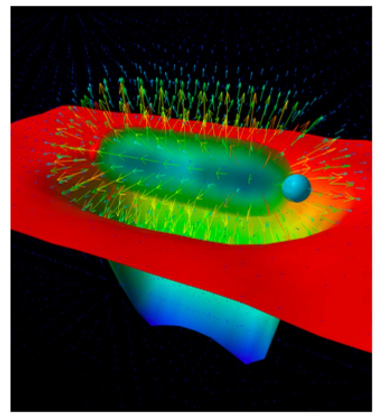
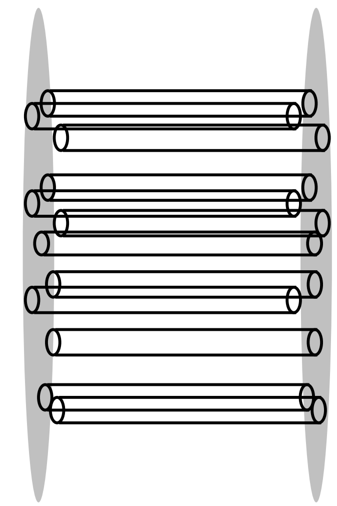


[Varilly, Thesis (2006) MIT]

initial energy deposition in color flux tubes



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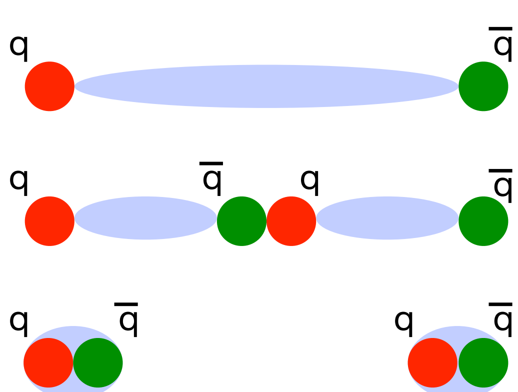
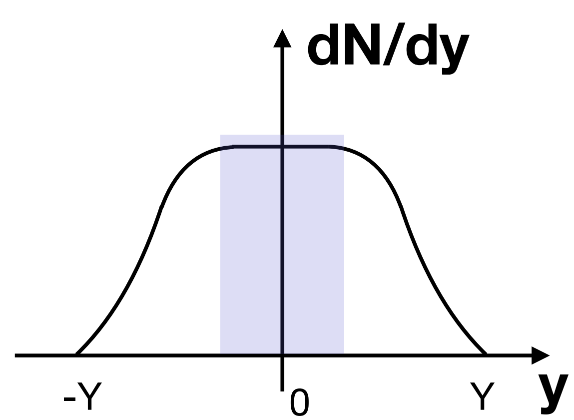
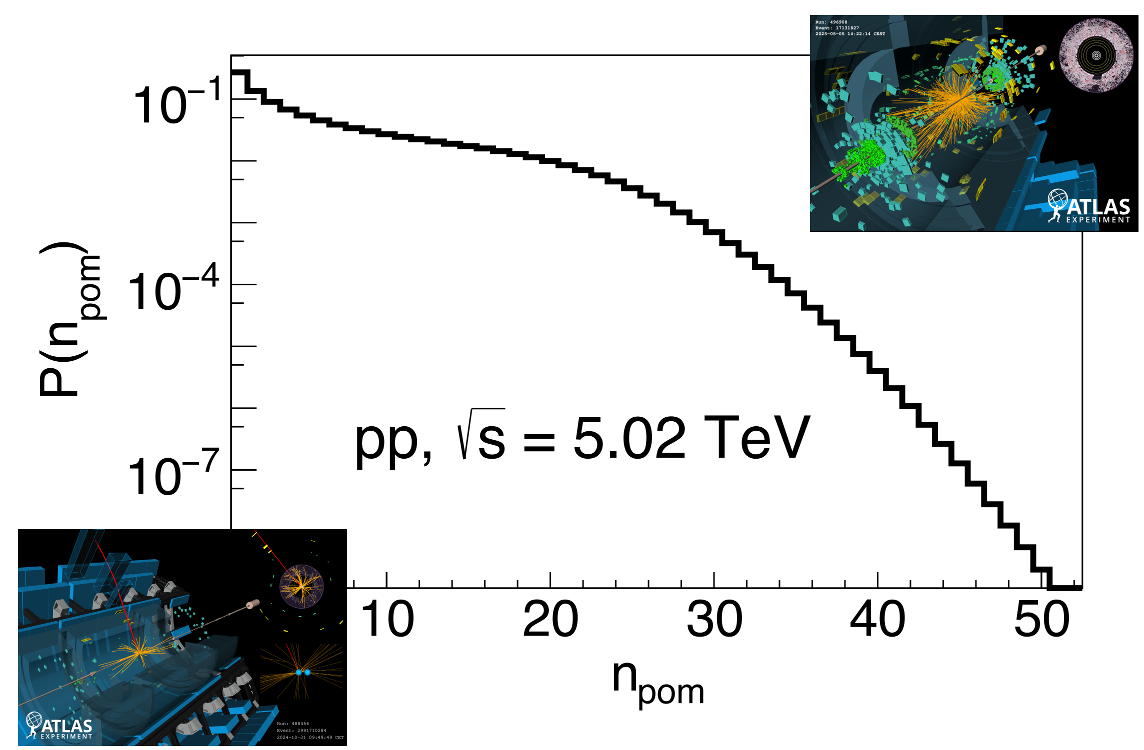
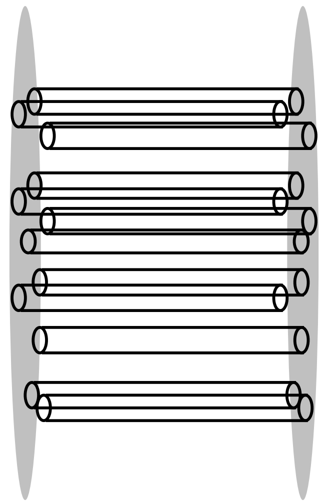


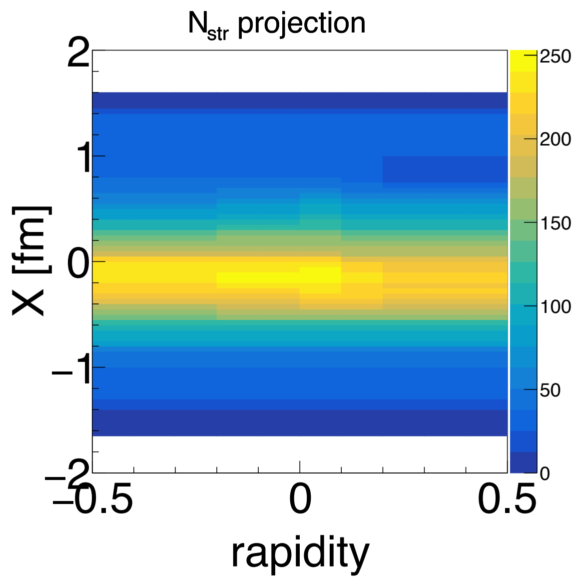


broad distribution in n_{pom}



FROM STRINGS TO MEDIUM





string overlaps → interplay of color fields

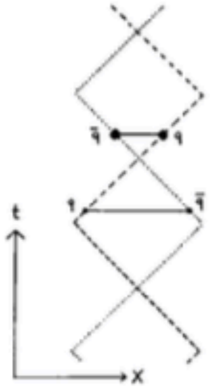
string evolution in rapidity → dynamical update of the energy density

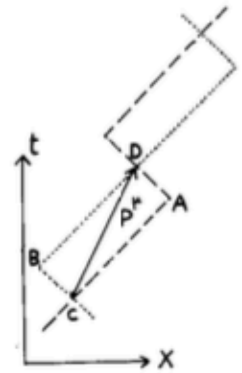
$$y_{\mathrm{init}} = \sinh^{-1}\left(\frac{p_z}{m}\right)$$

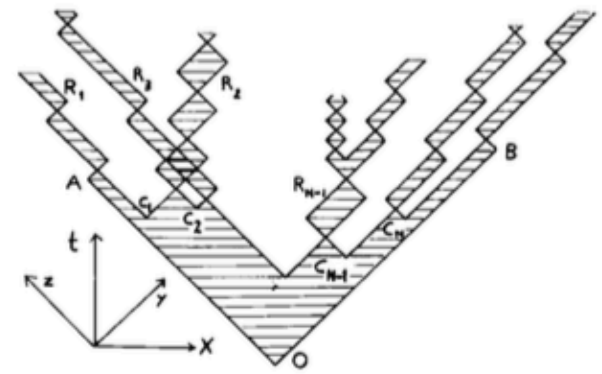
[Shen, Schenke, Phys. Rev. C 97 (2018) 024907]

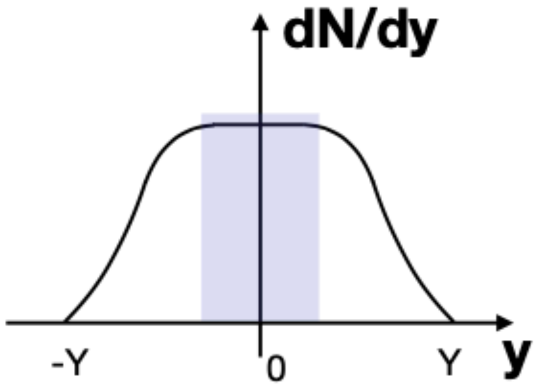
$$y_q^{\mathrm{fin}} = \sinh^{-1}\left(\frac{x_q \cdot p_{\mathrm{beam}}}{m_q}\right) \pm \cosh^{-1}\left(\frac{\tau^2\sigma^2}{2m_q^2} + 1\right)$$

STRING EVOLUTION



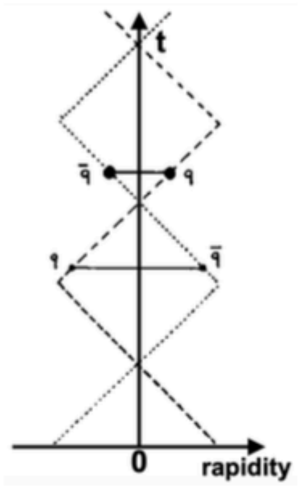






❹ Strings evolution [C. Shen, B. Schenke, Phys. Rev. C **97** (2018) 024907]

For a **parton at string end** with m and $p_z = xp_{\mathrm{beam}}$:



- ◇ initial rapidity: $y_{\mathrm{init}} = \sinh^{-1}\left(\frac{p_z}{m}\right)$
- ◇ equations of motion: $\frac{dp_z}{dt} = -\sigma, \quad \frac{dE}{dz} = -\sigma$
- ◇ proper time before flip ($\tilde{y}$ in string rest frame):
  $\Delta\tau_{\mathrm{max}} = \frac{m}{\sigma}\sqrt{2\left(\cosh(\tilde{y}_{\mathrm{init}} - 1)\right)}$ – **periodicity!**

- relation between proper time $\Delta\tau$ and lab time Δt intervals:

$$\Delta t = \Delta\tau\left(\pm\frac{\sigma\Delta\tau}{2m}\sinh(y_{\mathrm{init}}) + \cosh(y_{\mathrm{init}})\sqrt{\frac{\sigma^2\Delta\tau^2}{4m^2} + 1}\right)$$

- change of rapidity: $y_{\mathrm{loss}} = \cosh^{-1}\left(\frac{\sigma^2\Delta\tau^2}{2m^2} + 1\right)$
- final rapidity after proper time $\Delta\tau$: $y_{\mathrm{fin}} = y_{\mathrm{init}} \pm y_{\mathrm{loss}}$

IN-MEDIUM ENERGY LOSS: ELASTIC

Momentum loss rate of HF quark in elastic scattering: $q+g \to q+g$

$$\frac{\mathrm{d}p}{\mathrm{d}t} = 16 \int \frac{\mathrm{d}^3 k}{(2\pi)^3} \, f(k) \, \Phi \int_{\hat{t}_{\min}}^{\hat{t}_{\max}} \mathrm{d}\hat{t} \frac{\mathrm{d}\sigma}{\mathrm{d}\hat{t}} \, \Delta p(\hat{t}, k, p),$$

$\Delta p(\hat{t}, k, p)$ - one-collision momentum loss, Φ - flux of HF quarks

elastic x-section [Thoma, Gyulassy, Nucl.Phys.B 351 (1991) 491]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\hat{t}} = \frac{2\pi\alpha_s^2}{(\hat{t}+\mu^2)\hat{t}}$$

CUJET3 **thermal running coupling** [Xu, Liao, Gyulassy, Chin.Phys.Lett. 32 (2015) 092501]

$$\alpha_s(Q^2) = \frac{\alpha_c}{1 + \frac{11}{4\pi}\alpha_c \ln(Q^2/T_c^2)}$$

critical parameters [Shi, Liao, Gyulassy, Chin.Phys. C 43 (2019) 4, 044101]

$$\alpha_c = 0.9, \;\; T_c = 0.16 \,\mathrm{GeV}$$

gluon **Debye screening** mass [Gossiaux, Aichelin, Phys.Rev. C 78 (2008) 014904]

$$\mu(T) = T\sqrt{4\pi \cdot \alpha_s(\mu^2)}$$

IN-MEDIUM ENERGY LOSS: ELASTIC

Momentum loss rate of HF quark in elastic scattering: $q+g \to q+g$

$$\int_{\hat{t}_{\min}}^{\hat{t}_{\max}} \mathrm{d}\hat{t}\, \frac{\mathrm{d}\sigma_{i,j}}{\mathrm{d}\hat{t}}(p - p'\cos\theta_{pp'}) = -\frac{\pi c_{i,j}\alpha_s^{\mathrm{th}}(\hat{t}_{\max})\alpha_s^{\mathrm{th}}(\hat{t}_{\min})}{k} \ln\left(\frac{\hat{t}_{\max}}{\hat{t}_{\min}}\right) \times \left(\frac{E(p - E\cos\theta)}{(E - p\cos\theta)^2} - \frac{k\cos\theta}{E - p\cos\theta}\right). \tag{14}$$

Here, the momentum transferred is limited from below by μ^2 and from above by

$$\begin{aligned} \hat{t}_{\max} &= \frac{4(k\cdot p)^2}{2k\cdot p + m^2} \approx 2Ek - m^2 + \frac{m^4}{4kp}\ln\frac{m^2 + 2k(E+p)}{m^2 + 2k(E-p)} \\ &\approx 6ET - m^2 + \frac{m^4}{12Tp}\ln\frac{m^2 + 6T(E+p)}{m^2 + 6T(E-p)} \end{aligned} \tag{15}$$

IN-MEDIUM ENERGY LOSS: ELASTIC

Anisotropic medium: $k_T - k_z$ anisotropy parameter $\xi > 0$, Λ - scale

$$\frac{\mathrm{d}p}{\mathrm{d}t} = \frac{2}{3}\pi \cdot \alpha_s\left[\mu^2\right] \cdot \alpha_s\left[6E\Lambda\right] \cdot \ln\left[\frac{6E\Lambda - E^2(1-\varepsilon^2) + \frac{E^3(1-\varepsilon^2)^2}{12\varepsilon\Lambda} \cdot \ln\left[\frac{E(1-\varepsilon^2)+6\Lambda(1+\varepsilon)}{E(1-\varepsilon^2)+6\Lambda(1-\varepsilon)}\right]}{\mu^2}\right]$$

$$\times (1-\varepsilon) \cdot \left(\frac{\Lambda^2}{\xi+\varepsilon^2} \cdot \left\{\frac{\arctan\sqrt{\xi}}{\sqrt{\xi}} \cdot \left(\xi + \frac{1+\xi}{1-\varepsilon} - \frac{2\xi}{\gamma}\right) + 1 + \ln\left[\frac{1-\varepsilon}{1+\varepsilon}\right] \cdot \left(\frac{\varepsilon}{\gamma} + \frac{1}{2}\right)\right\}\right.$$

$$\left. + \frac{12\zeta(3)}{\pi^2} \cdot \frac{\Lambda^3}{E} \cdot \frac{1}{(\xi+1)^{\frac{3}{2}}} \cdot \left\{\frac{\operatorname{arctanh}\sqrt{\gamma}}{\gamma^{\frac{3}{2}}} - \frac{1}{\gamma}\right\}\right), \text{ where } \boxed{\varepsilon = \frac{p}{E}, \quad \gamma = \frac{\xi+\varepsilon^2}{\xi+1}}$$

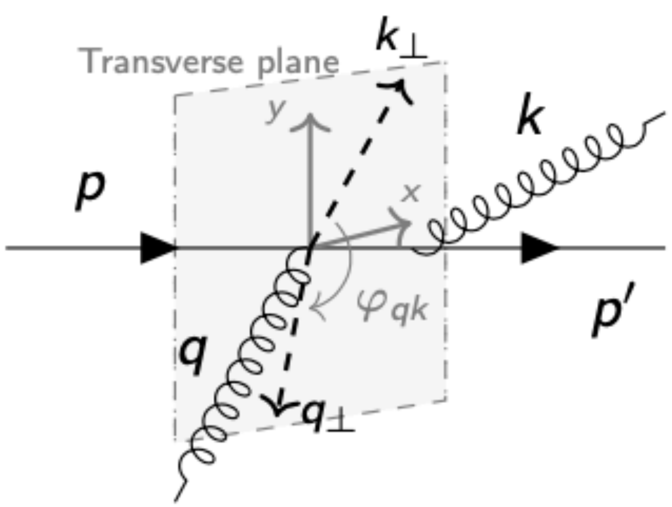
Isotropic medium: $\xi = 0$, T - temperature

$$\frac{dp}{dt} = \frac{2}{3}\pi \cdot \alpha_s\left[\mu^2\right] \cdot \alpha_s\left[6ET\right] \cdot \ln\left[\frac{6ET - E^2(1-\varepsilon^2) + \frac{E^3(1-\varepsilon^2)^2}{12\varepsilon T} \cdot \ln\left[\frac{E(1-\varepsilon^2)+6T(1+\varepsilon)}{E(1-\varepsilon^2)+6T(1-\varepsilon)}\right]}{\mu^2}\right]$$

$$\times \left(\frac{T^2}{\varepsilon^3} \cdot \left\{(2-\varepsilon)\varepsilon - (2-\varepsilon-\varepsilon^2)\operatorname{arctanh}[\varepsilon]\right\} + \frac{12\zeta(3)}{\pi^2} \cdot \frac{T^3}{E} \cdot \frac{1-\varepsilon}{\varepsilon^3} \cdot \left(\operatorname{arctanh}[\varepsilon] - \varepsilon\right)\right)$$

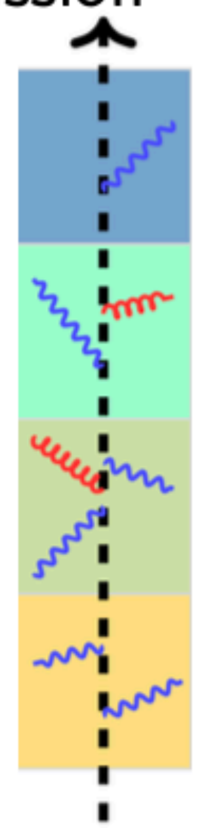
IN-MEDIUM ENERGY LOSS: INELASTIC

q + g -> q + g + g



Djordjevic-Gyulassy-Levai-Vitev (**DGLV**) opacity expansion [Gyulassy, Levai, Vitev, Nucl. Phys. B, 571 (2000) 197; Djordjevic, Gyulassy, Nucl. Phys. A 733 (2004) 265]

- $n = 1$: single scattering $\rightarrow$ single gluon emission
- finite size medium



$$z\frac{d\Gamma^{\mathrm{n=1}}_{q\rightarrow qg}}{dz}(z,p,T,t) \propto \rho(T)\int d^2\mathbf{q}_\perp\, d^2\mathbf{k}_\perp\, \mathcal{K}(\mathbf{k}_\perp,\mathbf{q}_\perp,z,p,T,t)$$

- emission probability $P_{\mathrm{rad}} = \int dz \int dt\, \frac{d\Gamma}{dz}$, $z = \frac{k}{p}$
- if occurs in a cell, sample z, reduce quark momentum by zp
- reset time since last splitting