Warsaw University of Technology
Subatech - IMT Atlantique

ZIMÁNYI SCHOOL
WINTER WORKSHOP
2020

EQUATION OF STATE @ EPOS

Maria Stefaniak

Budapest
but online...

08/12/2020

MOTIVATION

How to study Equation of State of QCD?

MOTIVATION

EPOS model

!Separate process!

Initial Conditions	Core / corona division	Viscous hydro	Hadronization	Hadronic Cascades
Parton-based Gribov-Regge theory	Core -> hydro Corona -> jets	Based on EoS	Microcanonical	UrQMD

MOTIVATION

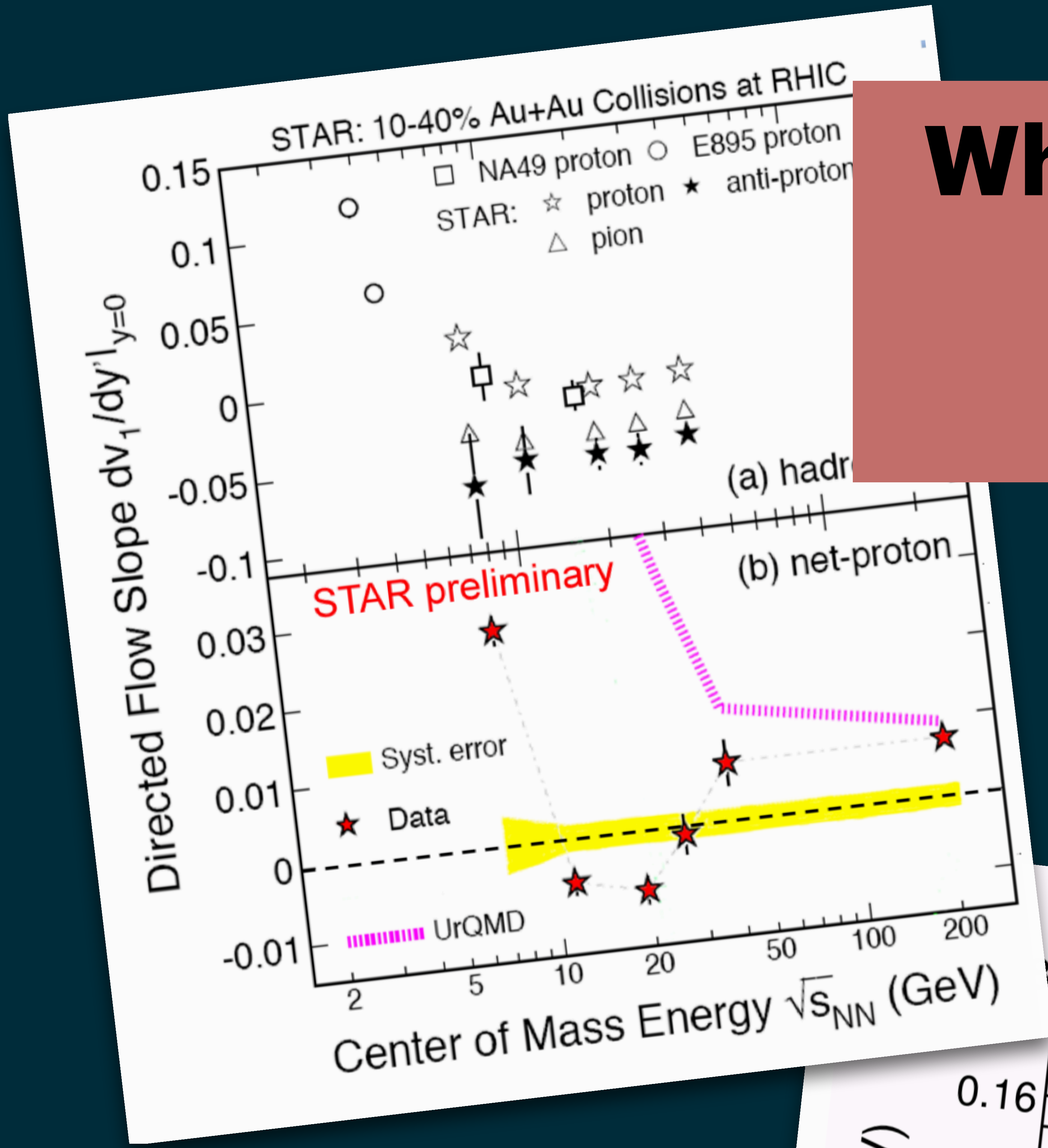
EPOS model

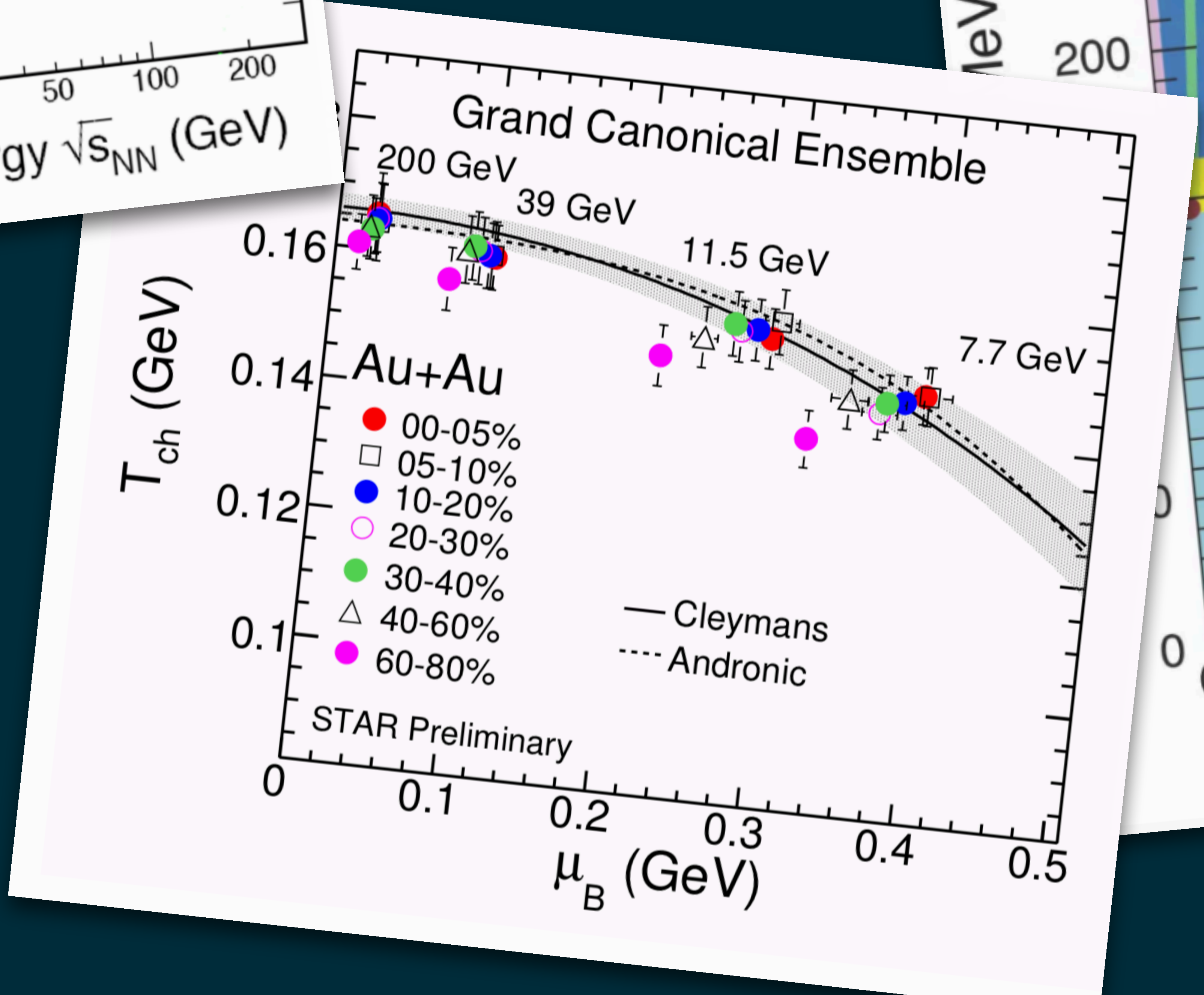
Viscous hydro based on:

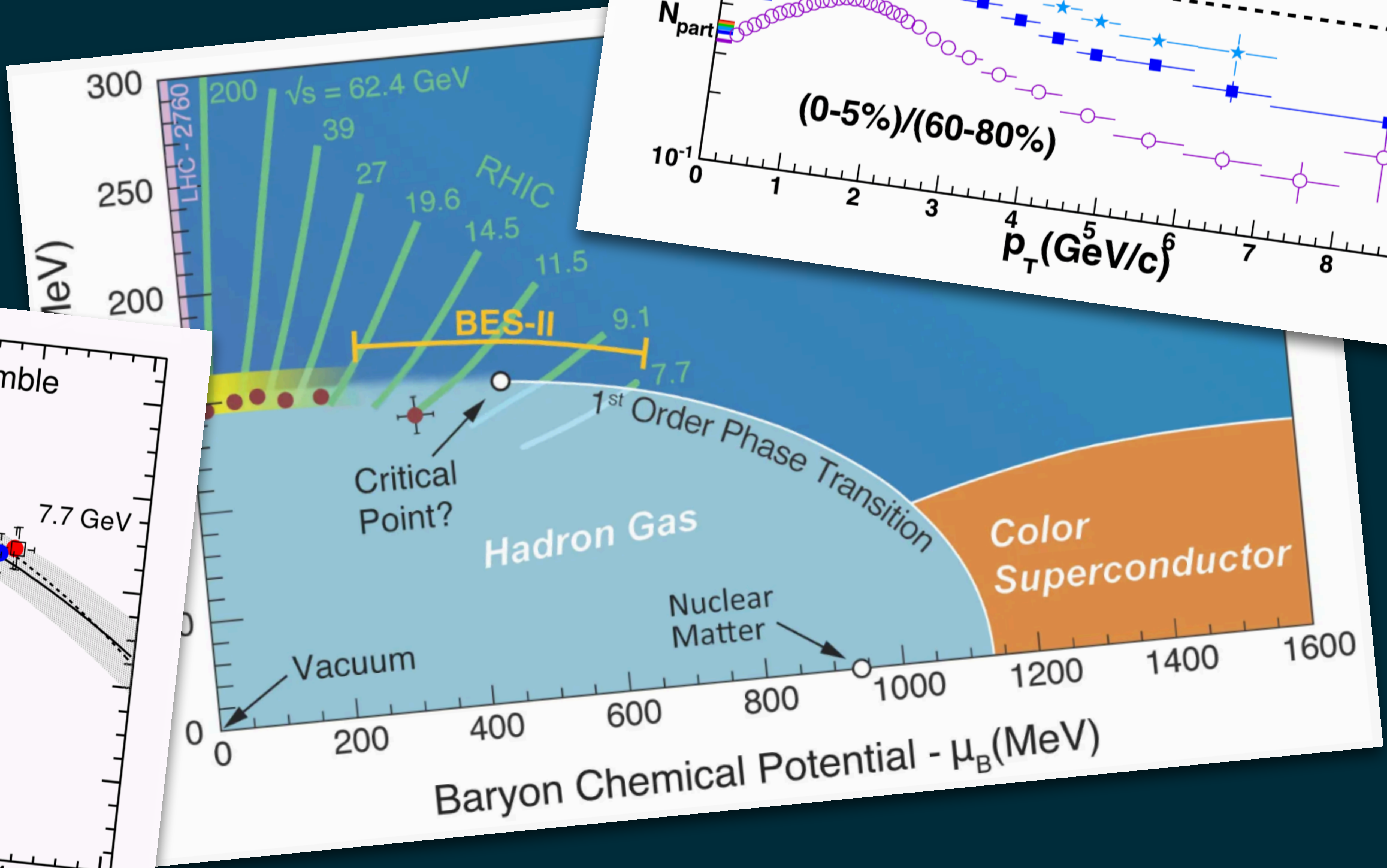
Initial Conditions	Core / corona division	3D+1 cross-over BEST EoS: par 1 BEST EoS: par 2 BEST EoS: par 3 ...	Hadronization	Hadronic Cascades
Parton-based Gribov-Regge theory	Core -> hydro Corona -> jets		Microcanonical	UrQMD

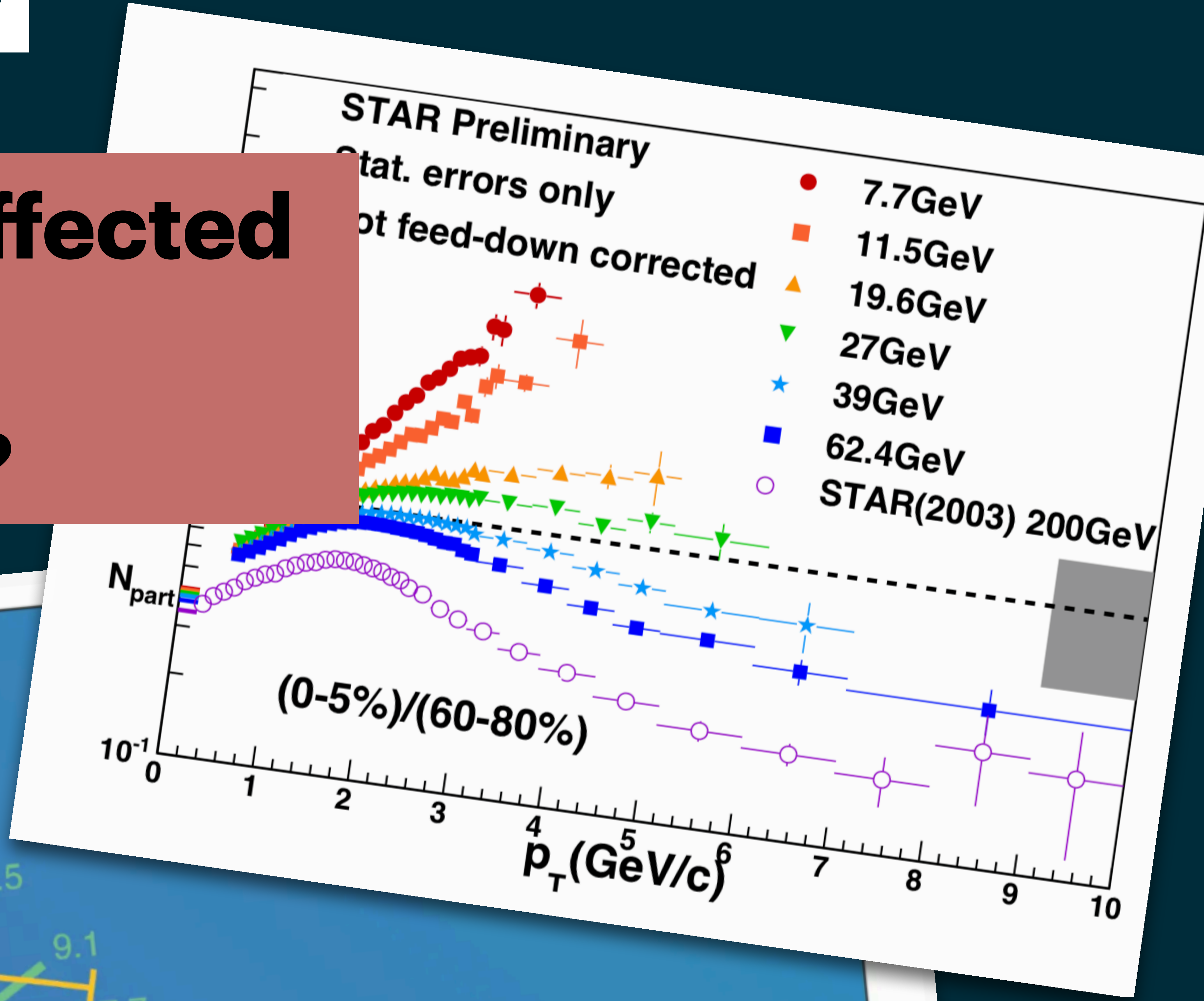
MOTIVATION

Which final observables are affected by changes of EoS within the same model?







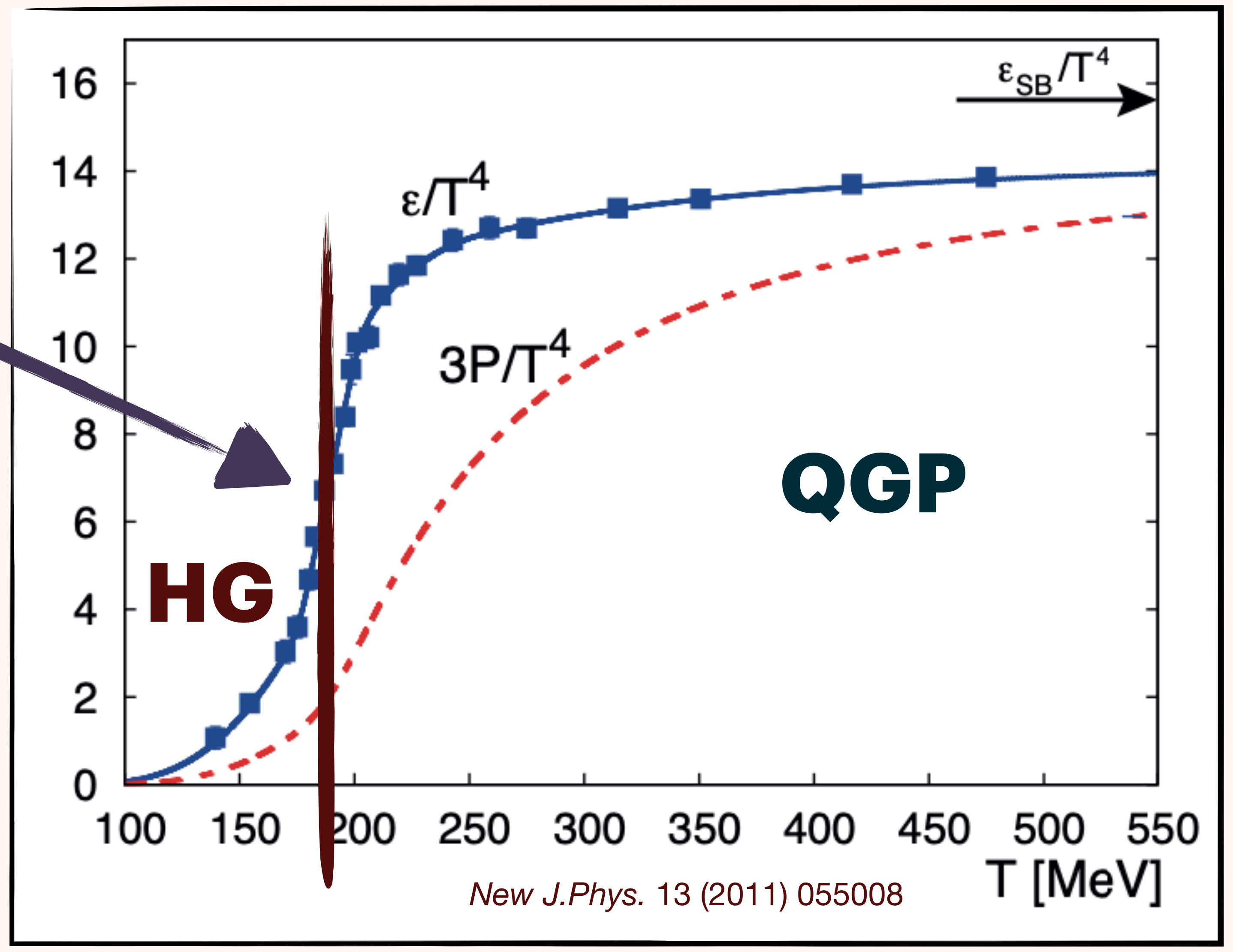


EQUATION OF STATE

The **Equation of State (EoS)** completely describes the equilibrium properties of QCD matter.

Lattice QCD EoS

increase of the degrees of freedom
➜ **phase transition**



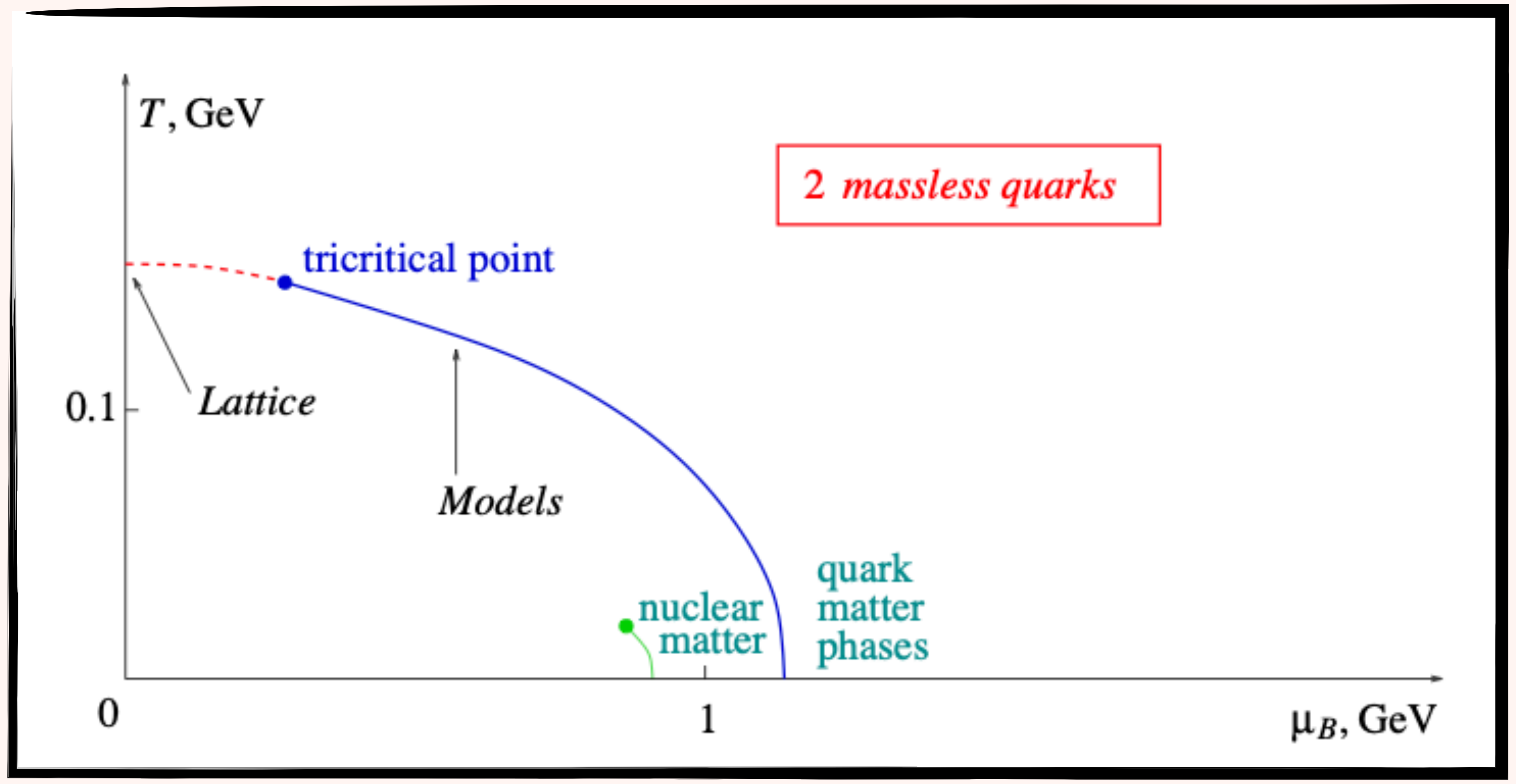
New J.Phys. 13 (2011) 055008

Stefan-Boltzmann limit
(ideal massless gas)

Highly recommend to read:
M. Stephanov: PoS LAT2006 (2006) 024

LATTICE QCD

- **From the first principles with Lattice calculations possible to obtain the EoS for $\mu_B = 0$**
- **EoS Lattice ➜ *cross-over***
- **What with the finite μ_B ?**



Highly recommend to read:
M. Stephanov: PoS LAT2006 (2006) 024

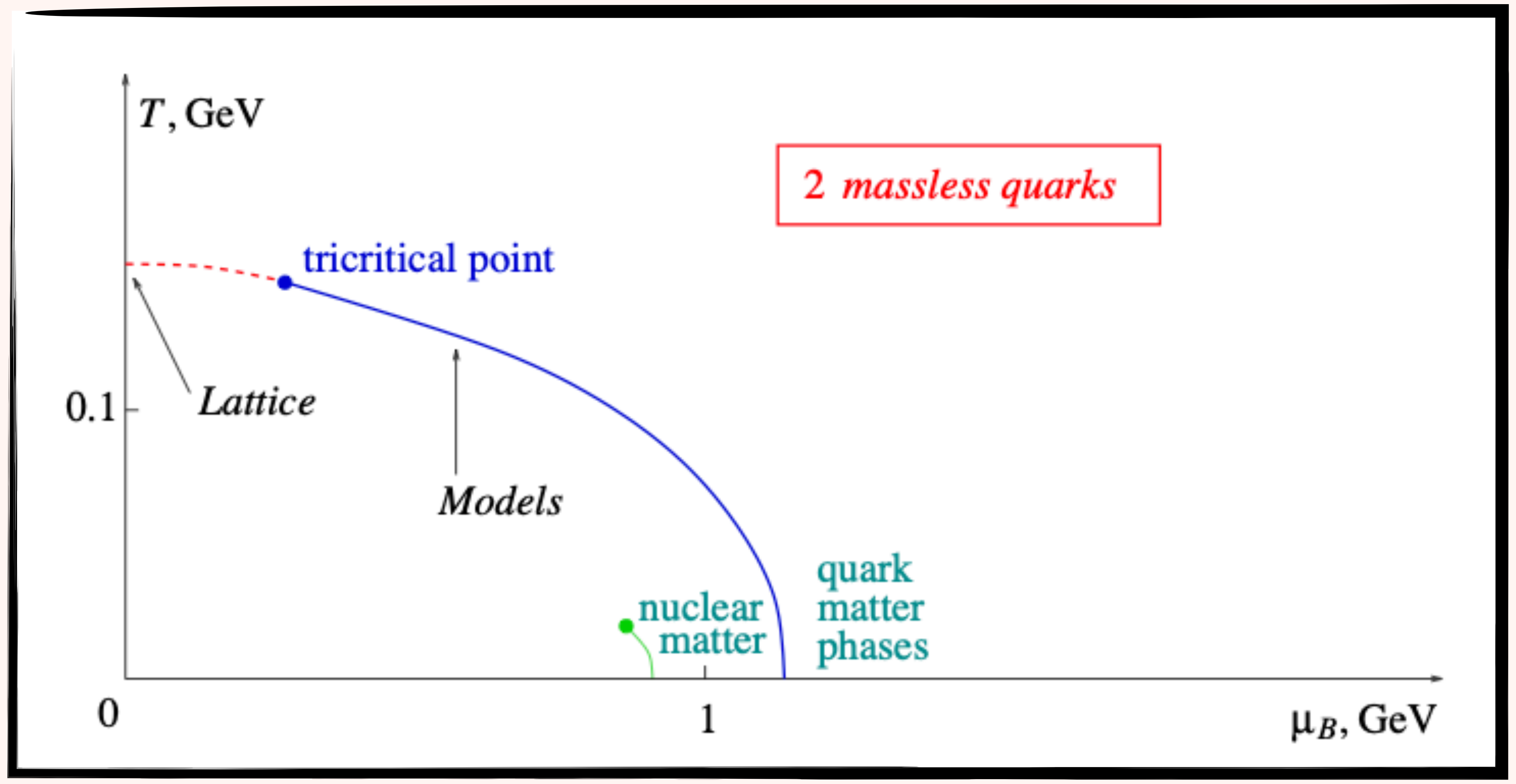
LATTICE QCD

- **From the first principles with Lattice calculations possible to obtain the EoS for $\mu_B = 0$**
- **EoS Lattice ➜ *cross-over***
- **What with the finite μ_B ?**

Taylor expansion…

$$\frac{P(T,\mu_B)}{T^4} = \Sigma_n c_{2n}(T)(\frac{\mu_B}{T})^{2n}$$

still in the limit of *cross-over*



M. Stephanov: PoS LAT2006 (2006) 024

BEST EOS WITH CP

- Choose a **CP location** in the (μ_B,T) plane,
- Map the 3D Ising model phase diagram onto the one of QCD,
- Use the thermodynamics of the Ising model EoS to estimate the critical contribution to the expansion coefficients,
- Reconstruct the **full pressure**, matching lattice QCD at μ_B = 0 and including the critical behaviour.

From the pressure, one can calculate thermodynamic observables:

- Entropy density, baryon density, energy density, speed of sound, specific heat
- Baryon susceptibilities (i.e., fluctuations)

* **Phys. Rev. C 101, 034901 (2020)**
* **Nucl. Phys. A 982 (2019)**

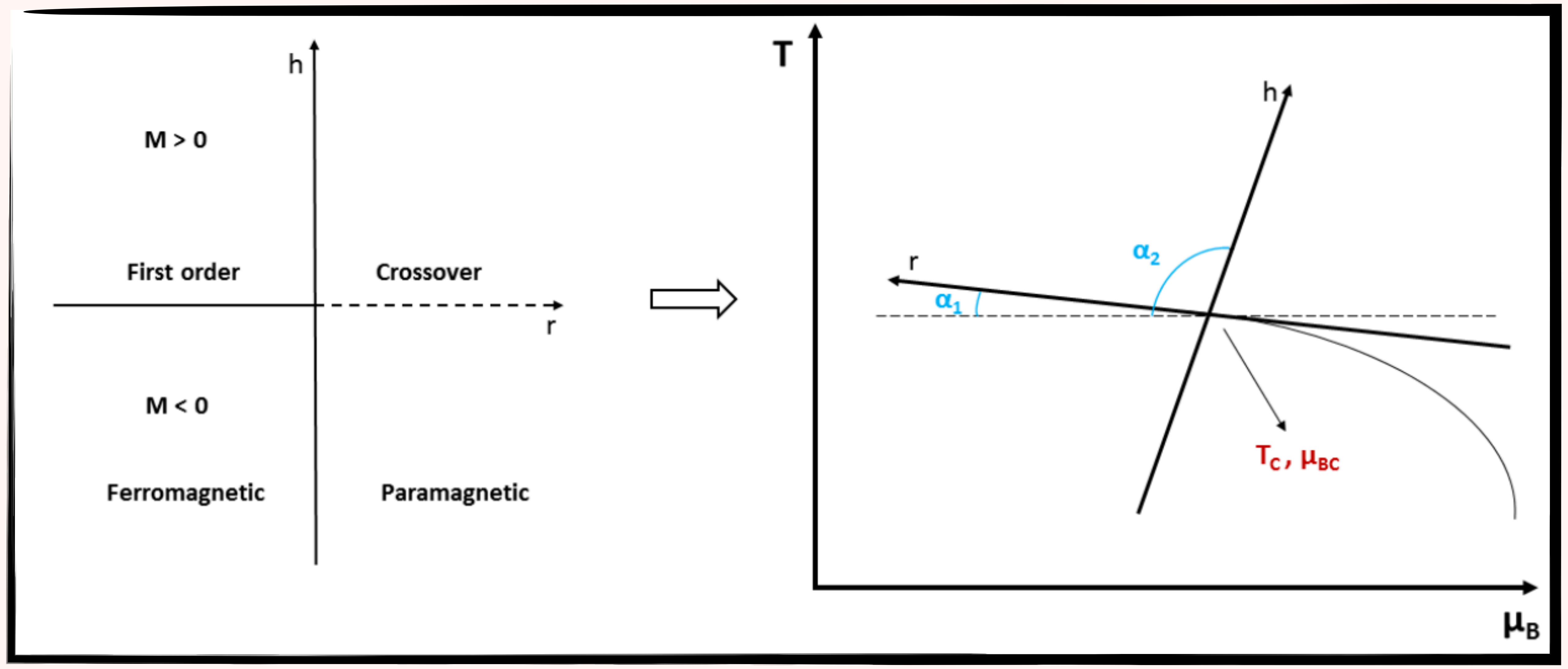
* Phys. Rev. C 101, 034901 (2020)
* Nucl. Phys. A 982 (2019)

BEST EOS WITH CP

PAR	155	-0.0149	350	90	4	1
Parabola	T	curvature	μ_{BC}	$\alpha_1 - \alpha_2$	ω	ρ

Play with coefficients to increase the critical contribution

- smaller **ω**
- put CP closer from „your location"
- smaller $\alpha_1 - \alpha_2$

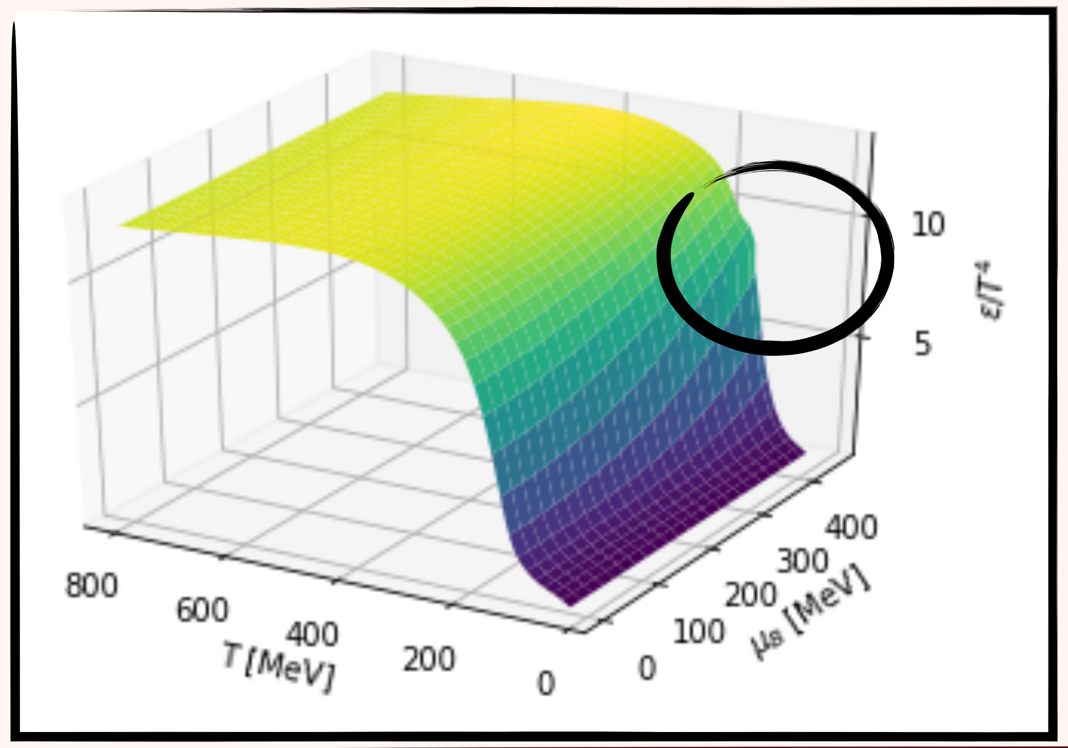


ρ - the relative scaling in the mapping

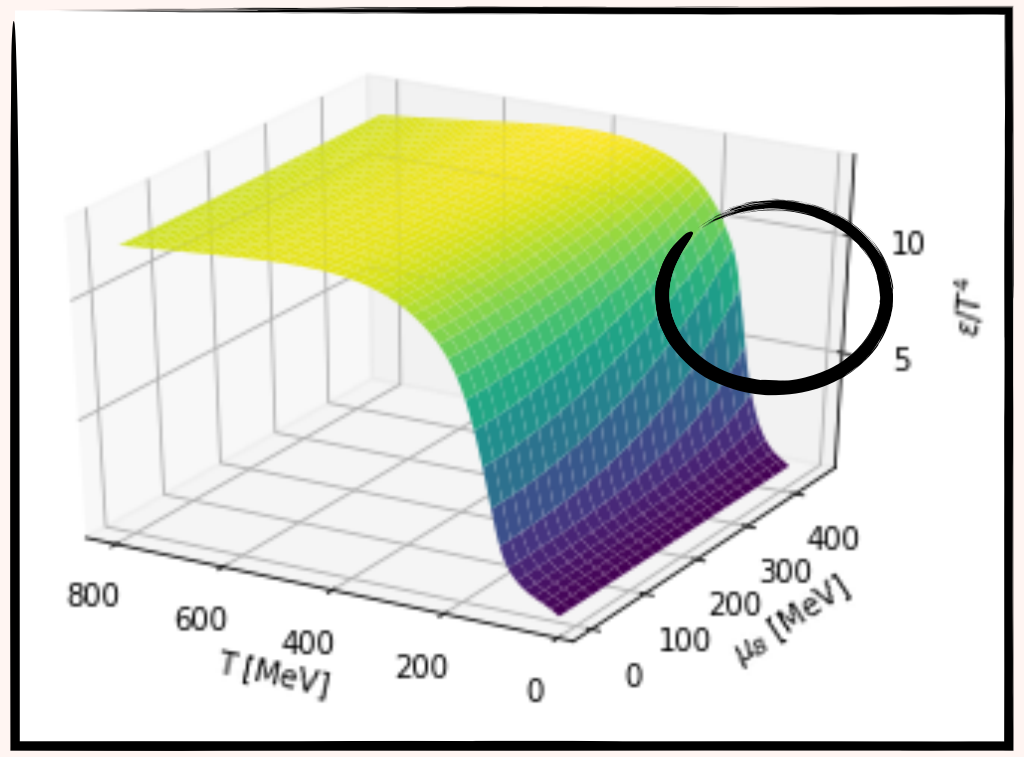
ω - the global scaling parameter in the mapping

ϵ/T^4

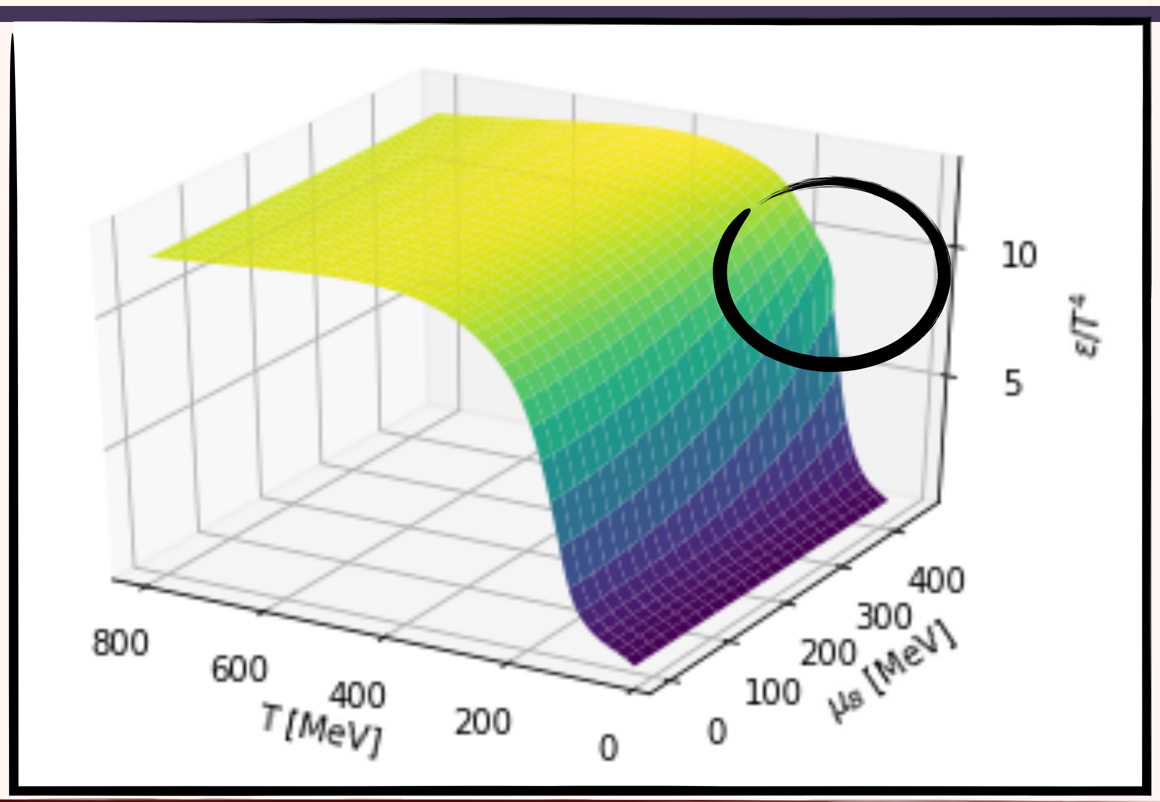
BEST 1: PAR 155 -0.0149 350 90 1 2



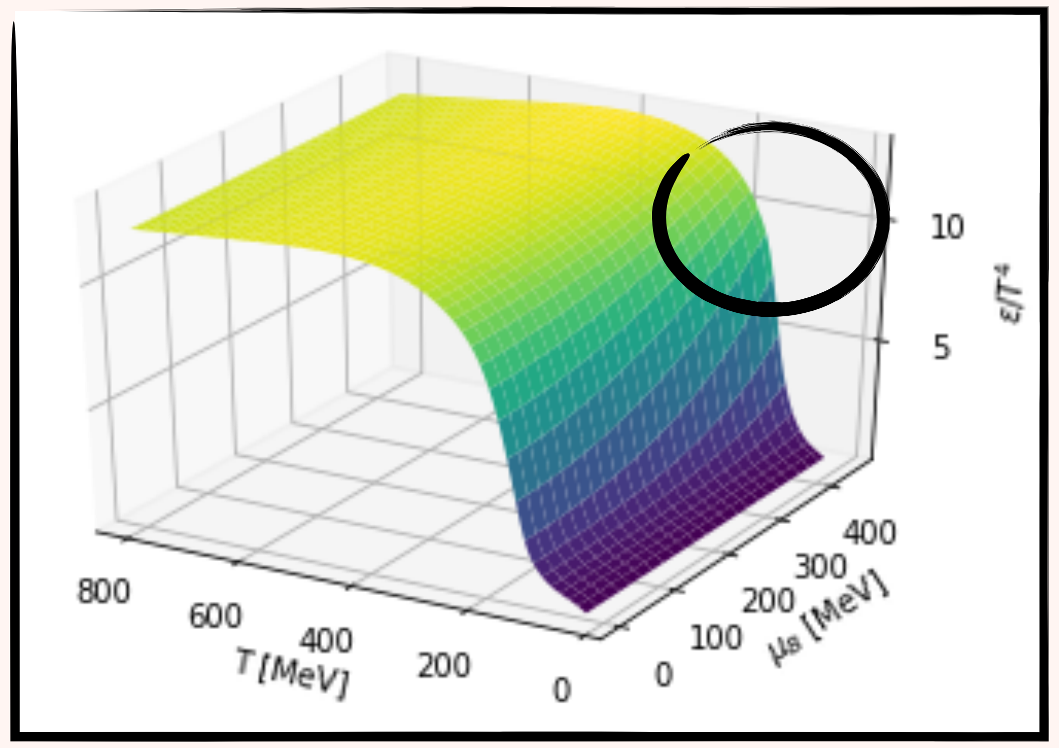
BEST 2: PAR 155 -0.0149 350 90 4 1



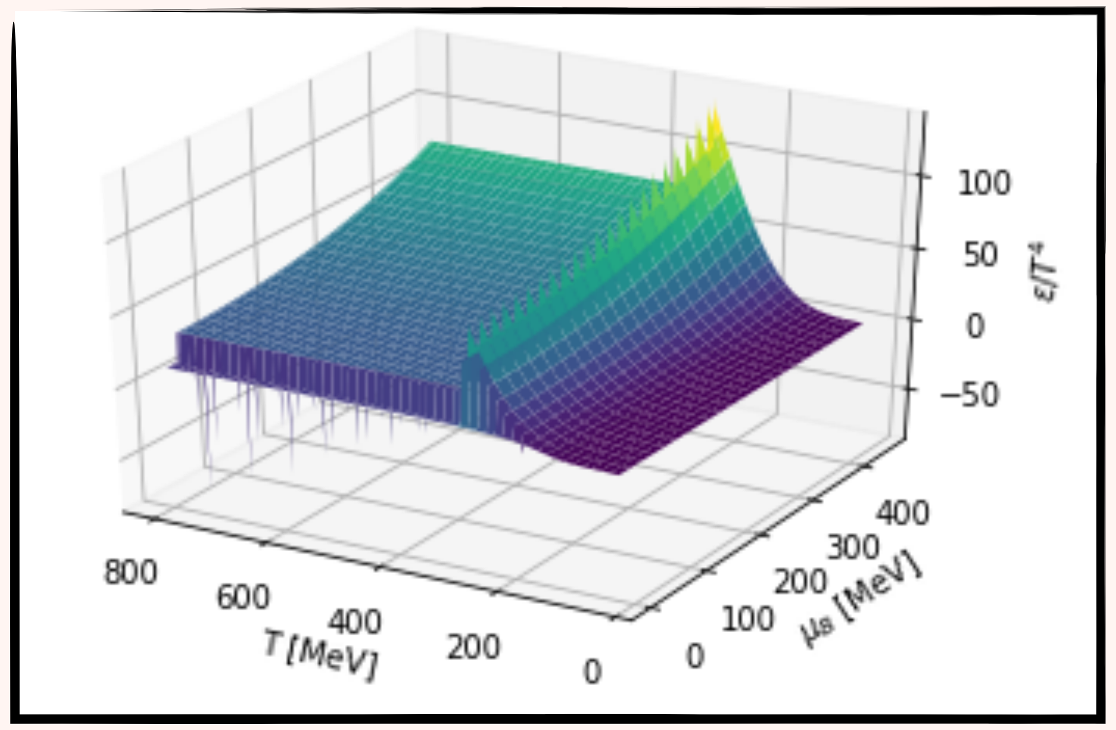
BEST 3: PAR 155 -0.0149 420 90 0.75 2



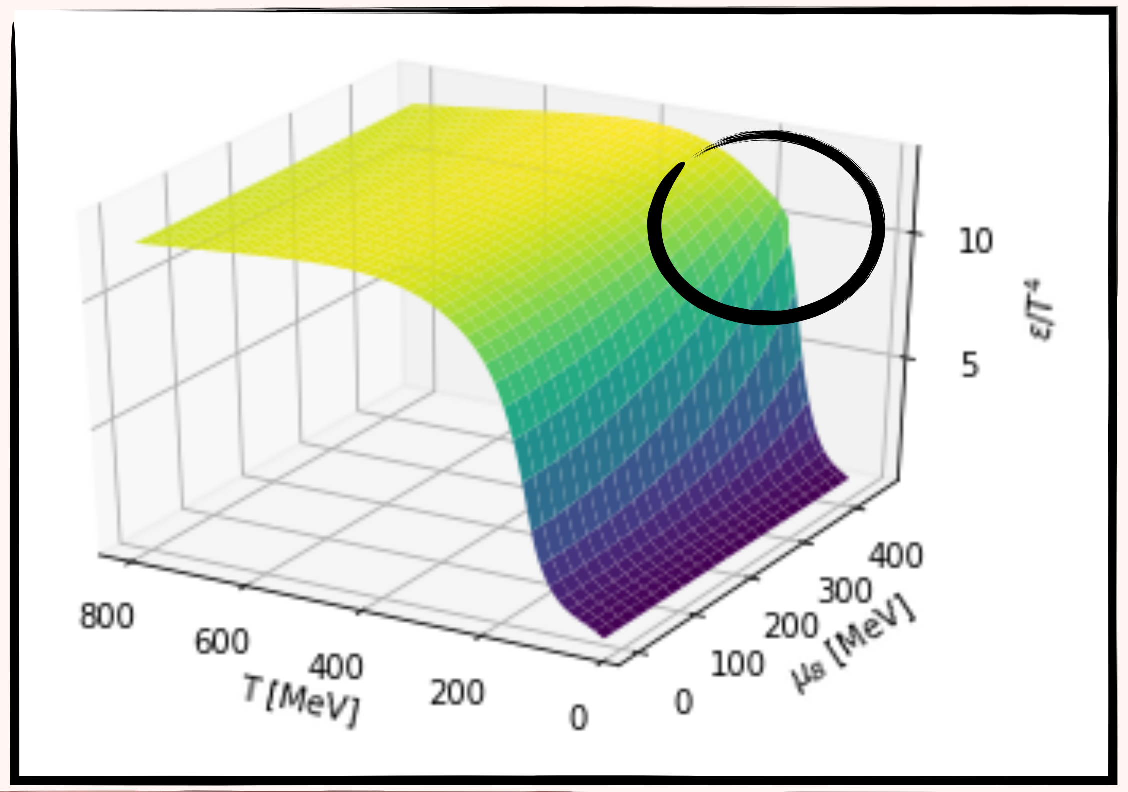
BEST 4: PAR 155 -0.0149 350 90 10 1



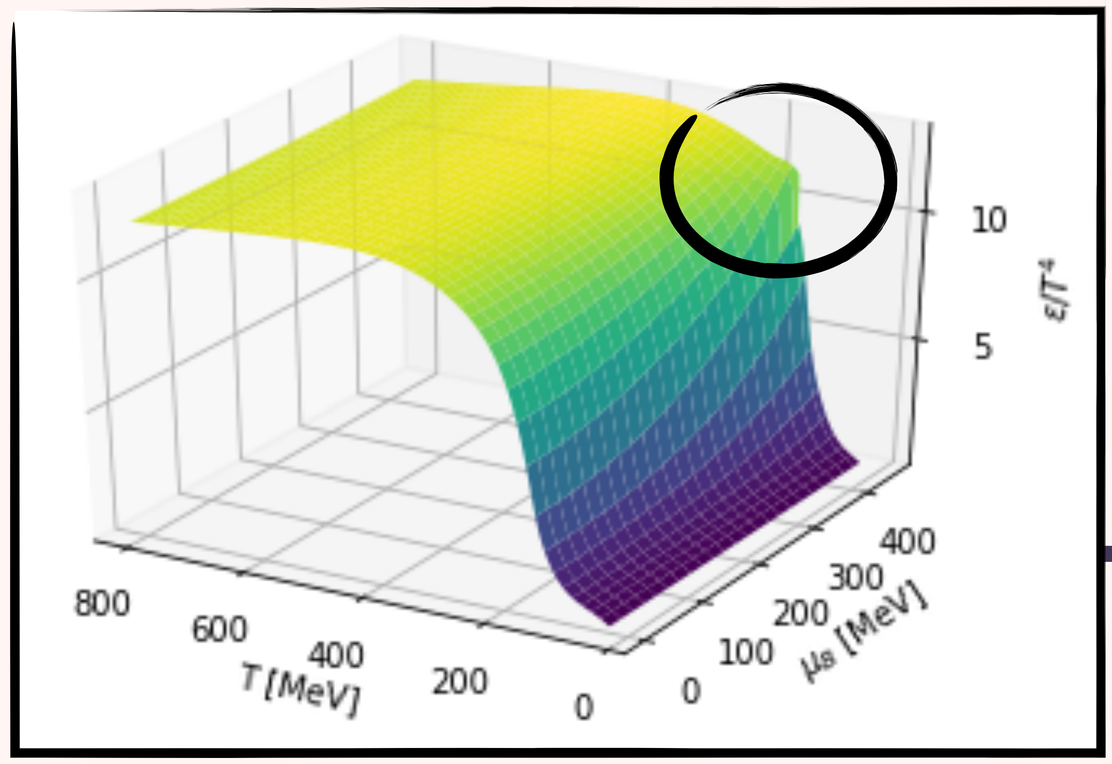
BEST 5: PAR 169 -0.0149 420 90 0.25 2



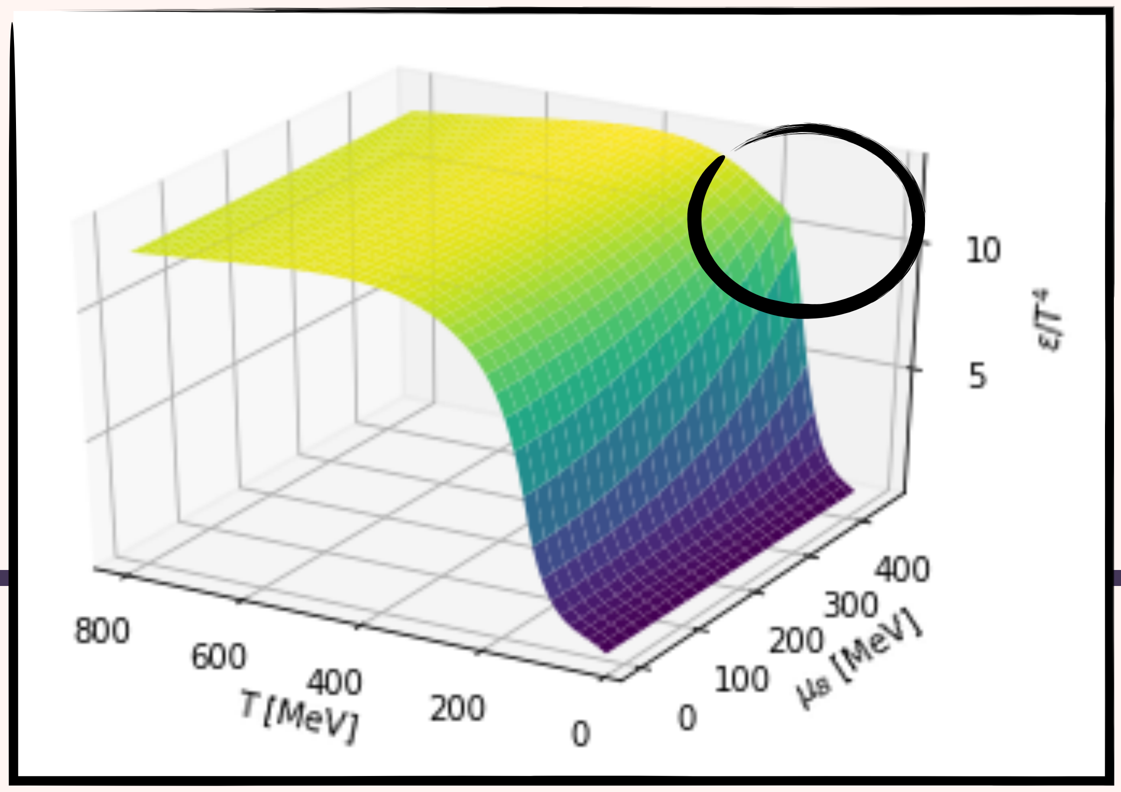
BEST 6: PAR 169 -0.0149 420 90 1 1



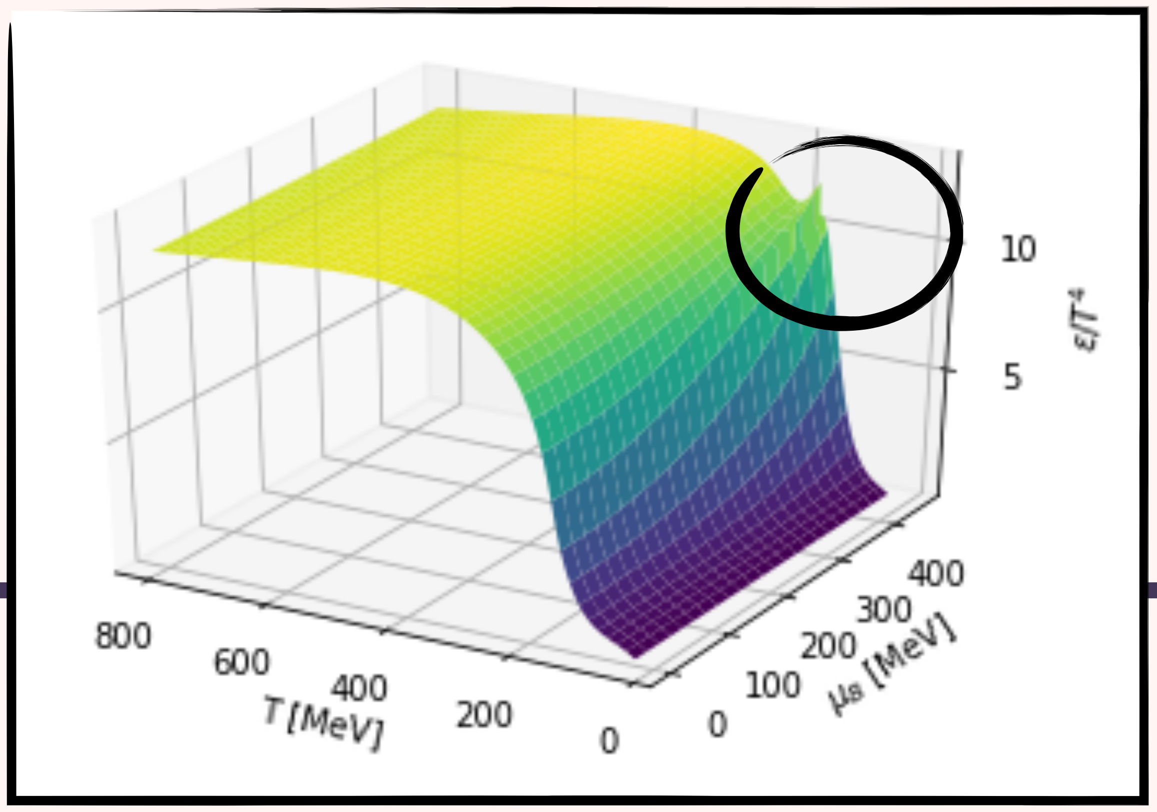
BEST 7: PAR 169 -0.0149 420 90 0.5 1



BEST 8: PAR 174 -0.0149 440 90 1 1

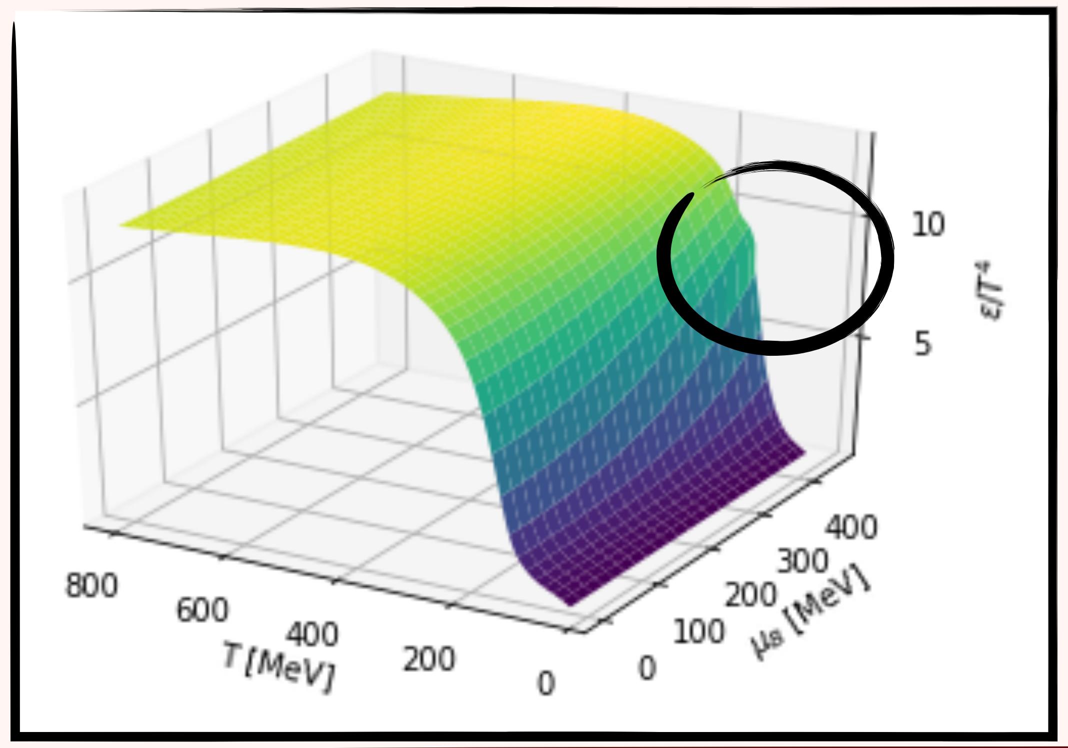


BEST 9: PAR 178 -0.0149 300 90 1 1

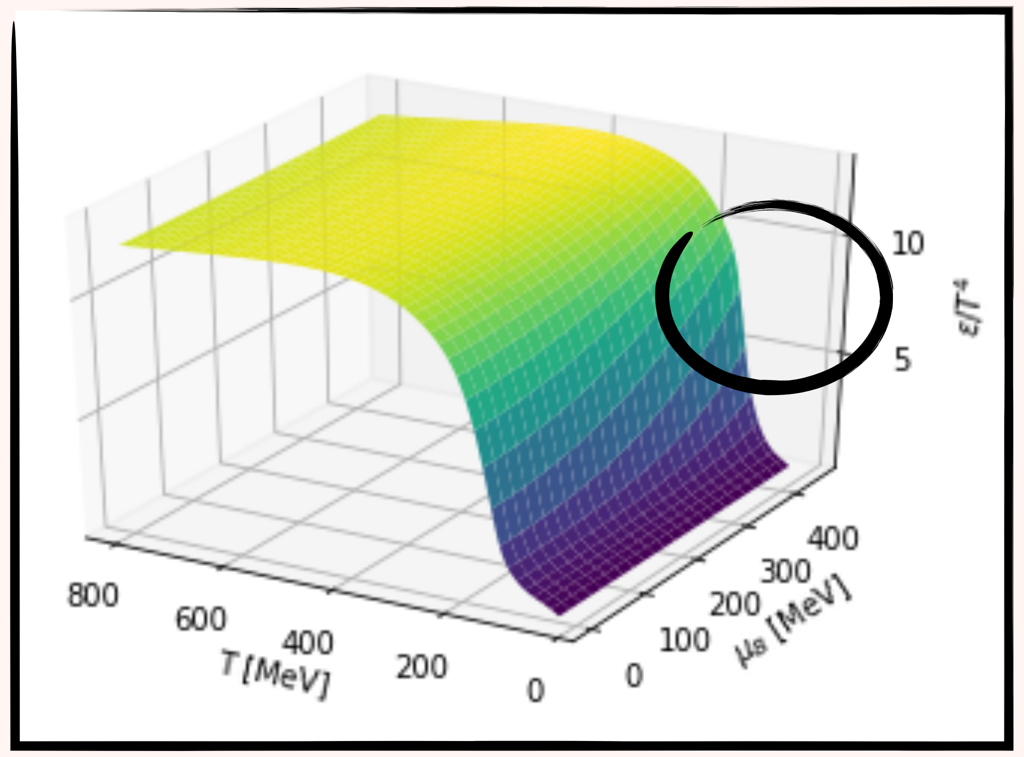


ϵ/T^4

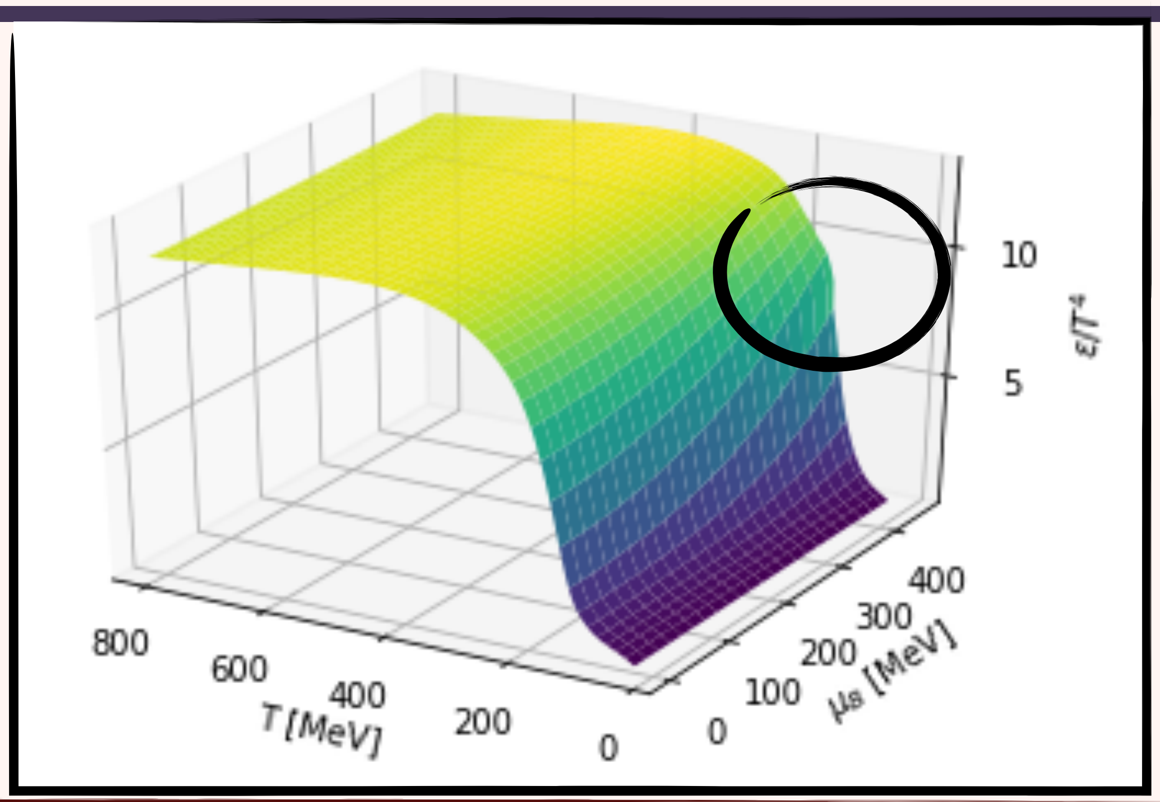
BEST 1: PAR 155 -0.0149 350 90 1 2



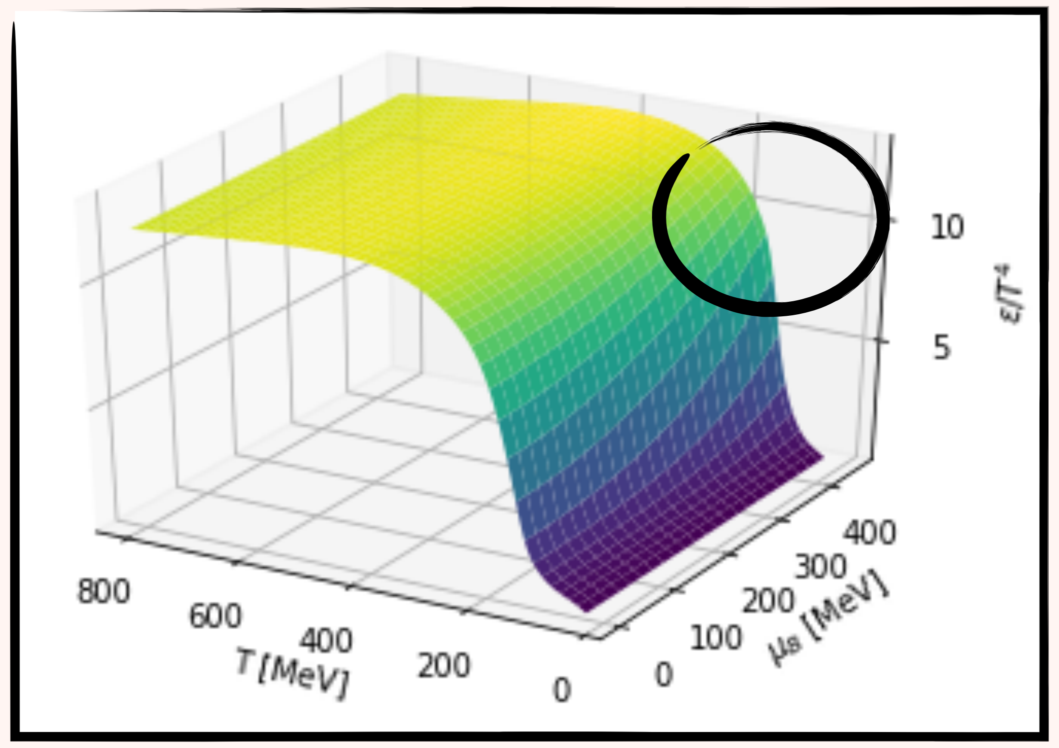
BEST 2: PAR 155 -0.0149 350 90 4 1



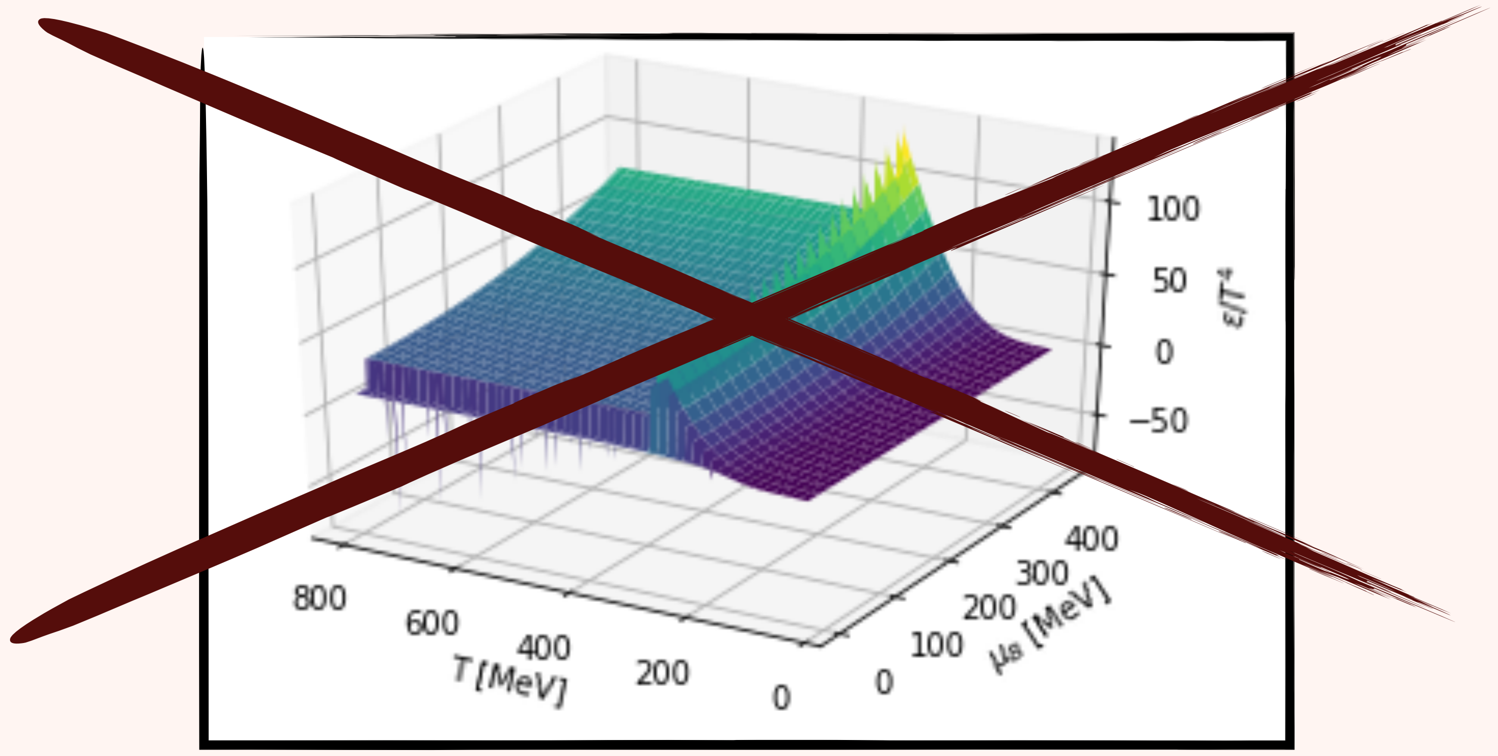
BEST 3: PAR 155 -0.0149 420 90 0.75 2



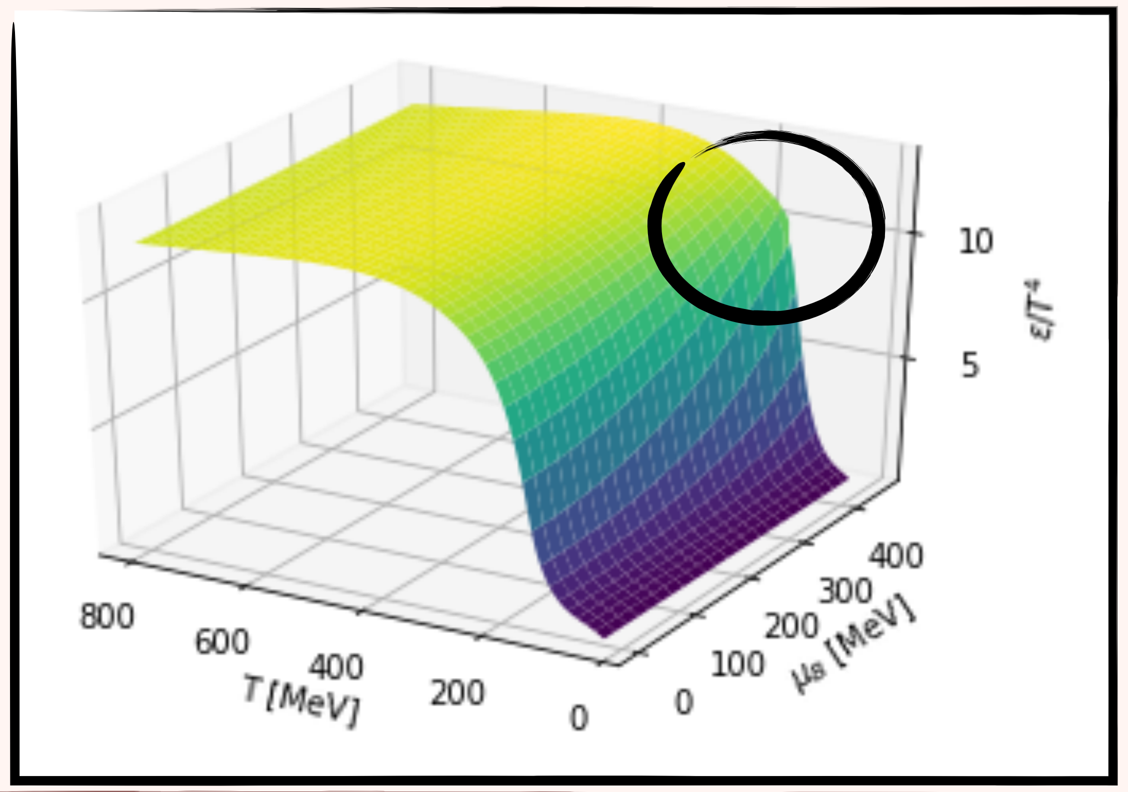
BEST 4: PAR 155 -0.0149 350 90 10 1



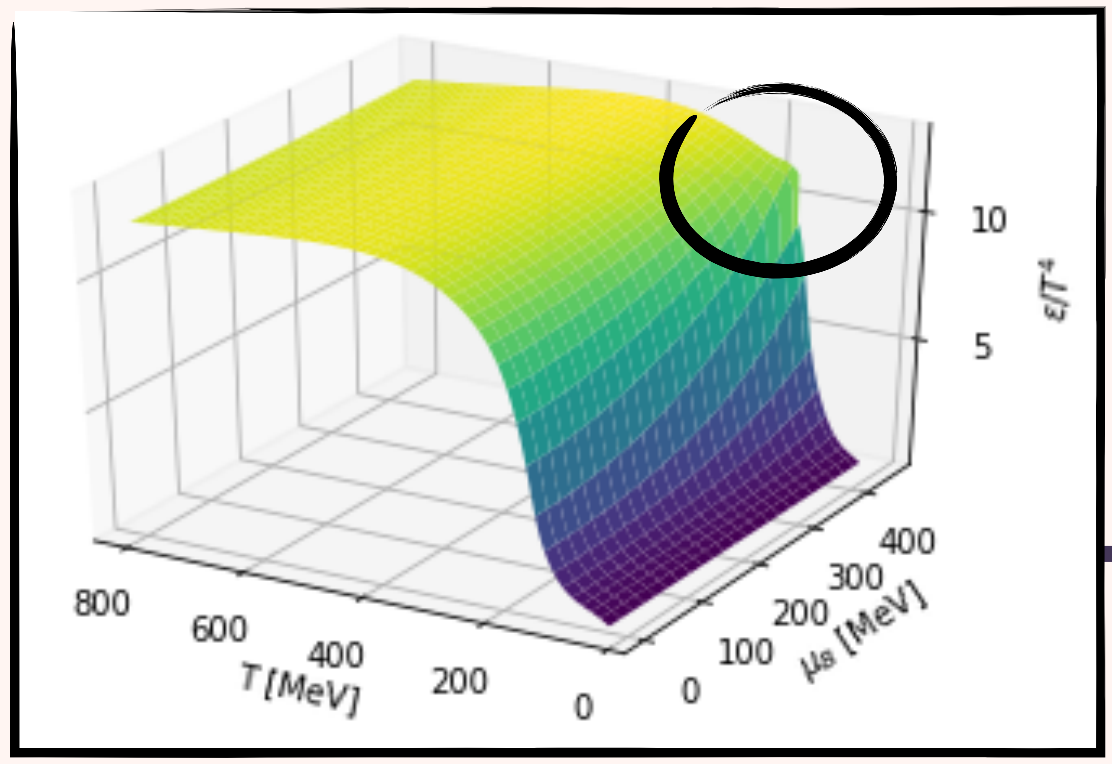
BEST 5: PAR 169 -0.0149 420 90 0.25 2



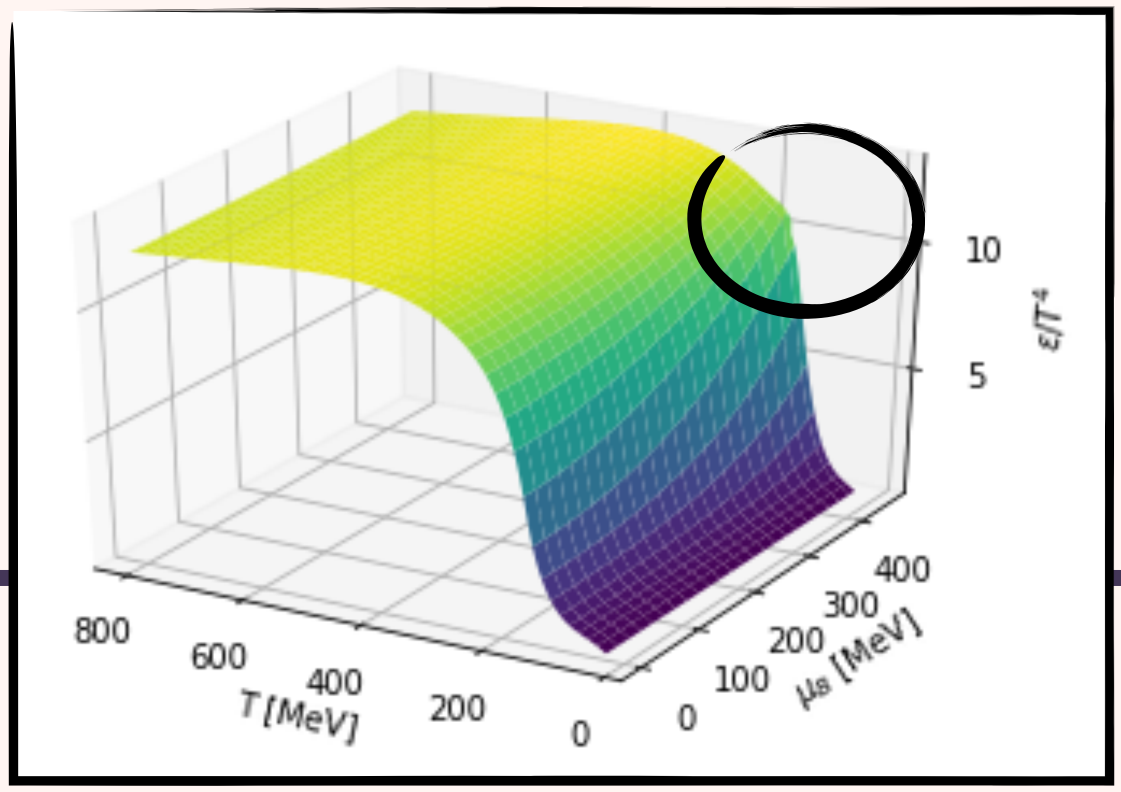
BEST 6: PAR 169 -0.0149 420 90 1 1



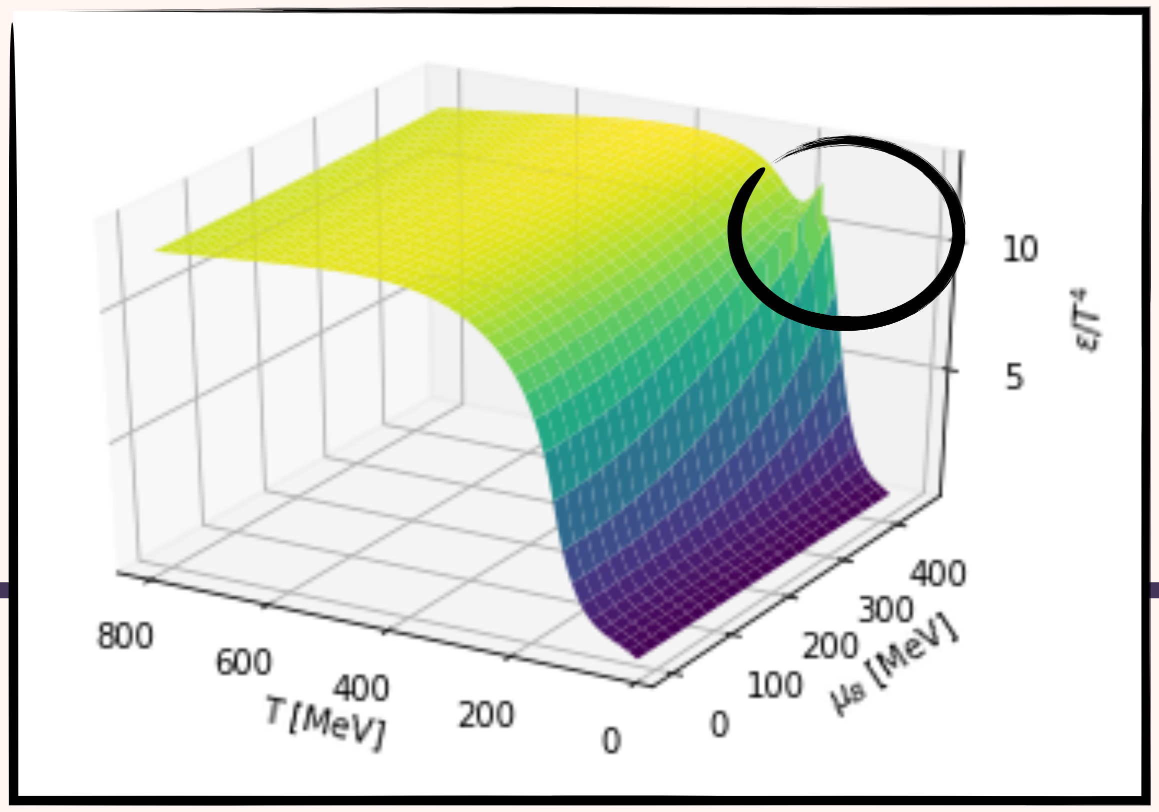
BEST 7: PAR 169 -0.0149 420 90 0.5 1



BEST 8: PAR 174 -0.0149 440 90 1 1

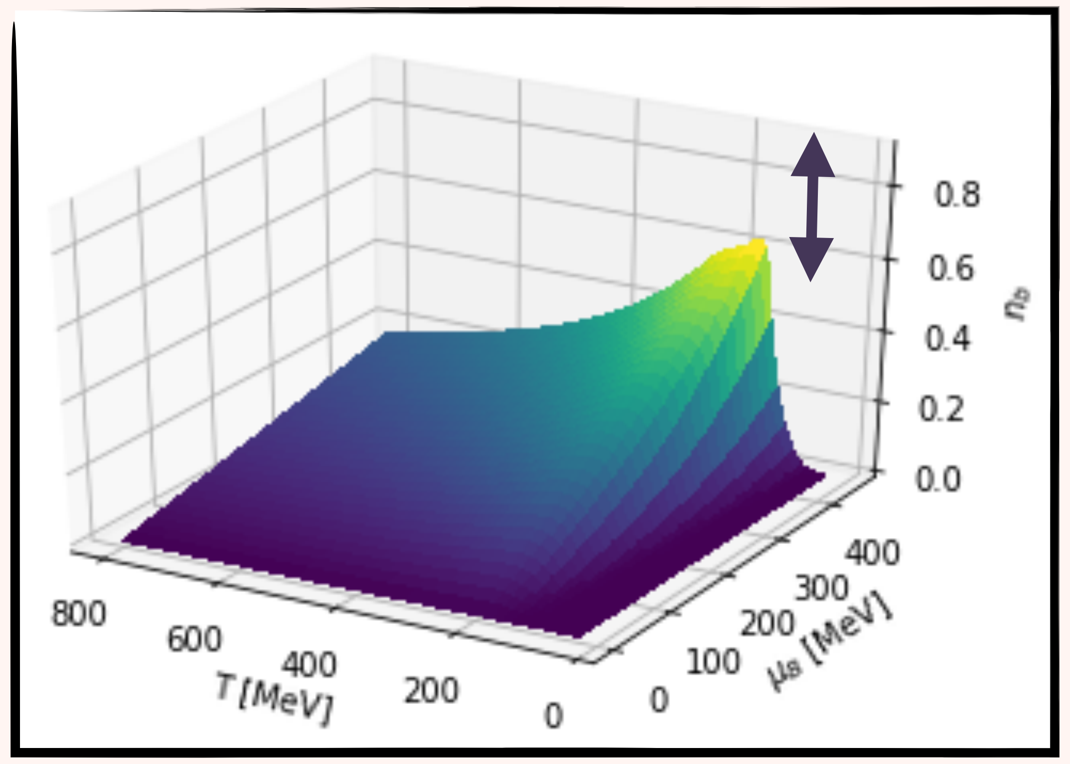


BEST 9: PAR 178 -0.0149 300 90 1 1

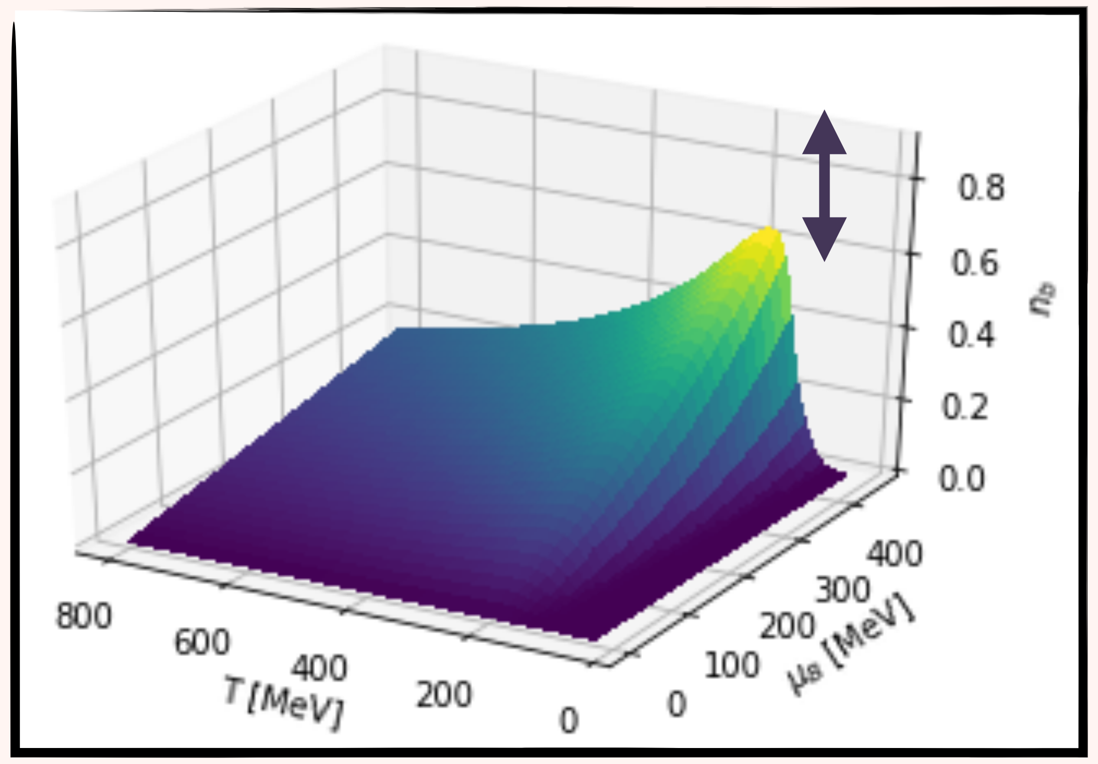


n_B

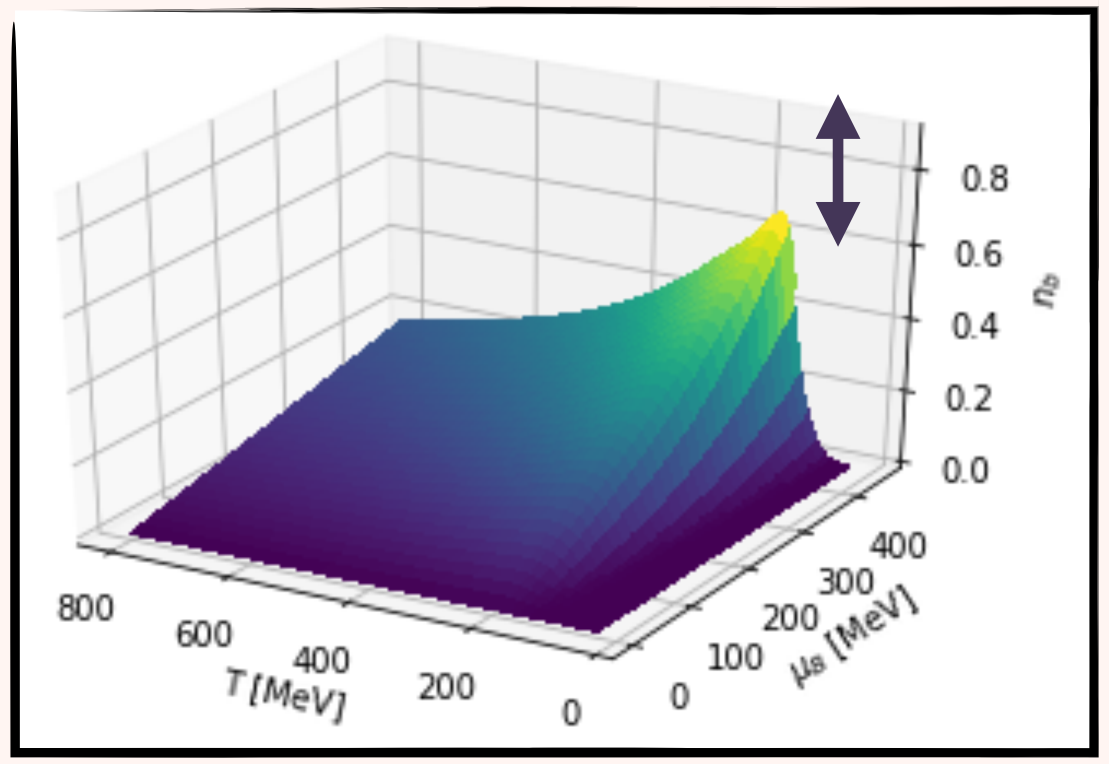
BEST 1: PAR 155 -0.0149 350 90 1 2



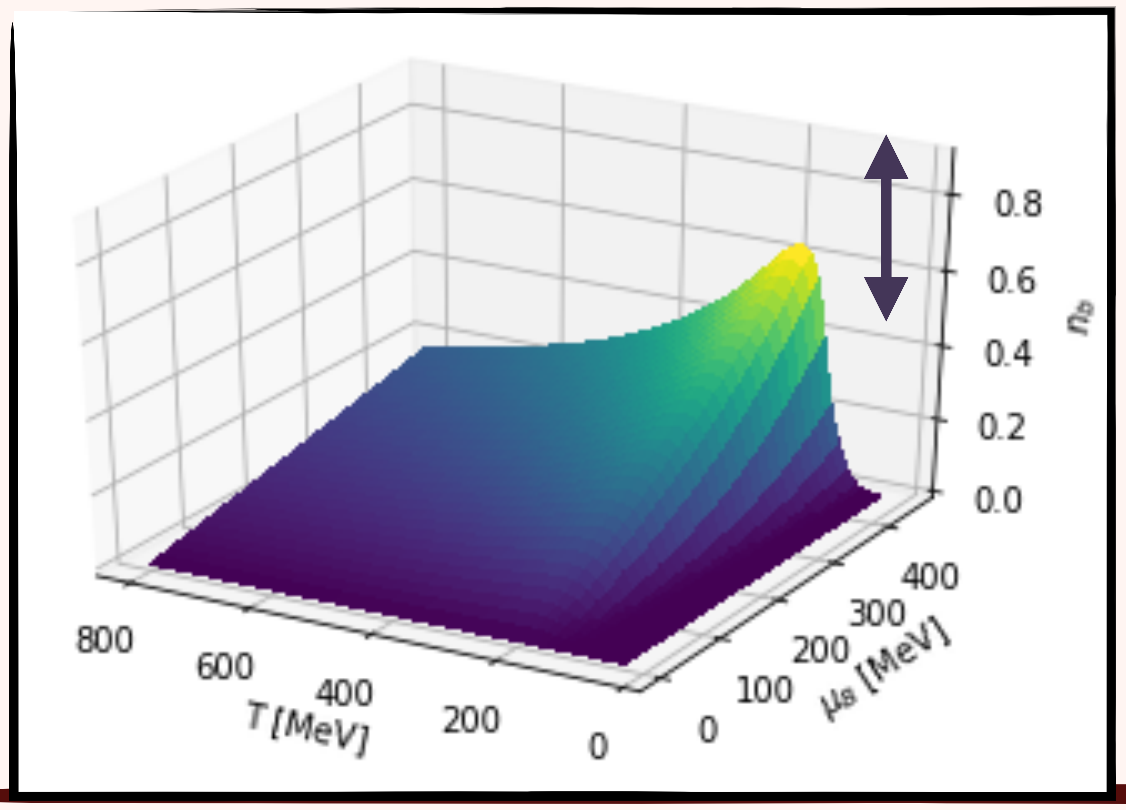
BEST 2: PAR 155 -0.0149 350 90 4 1



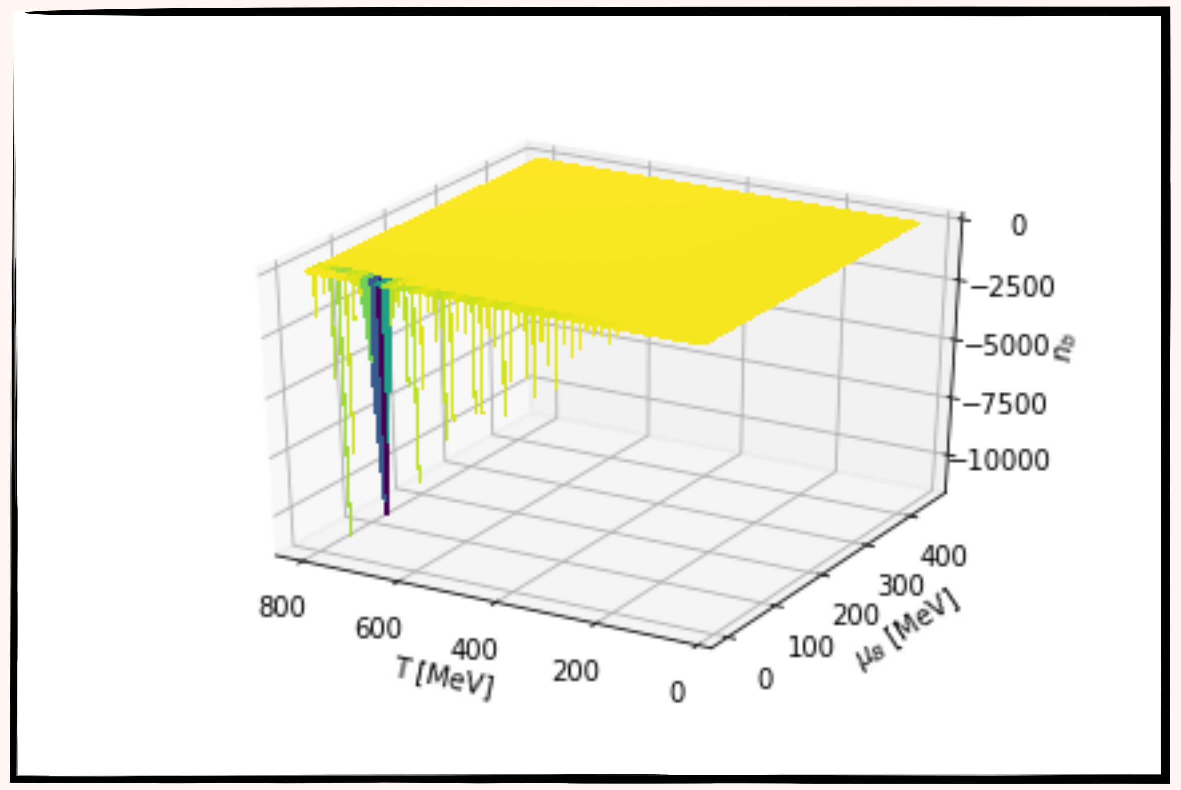
BEST 3: PAR 155 -0.0149 420 90 0.75 2



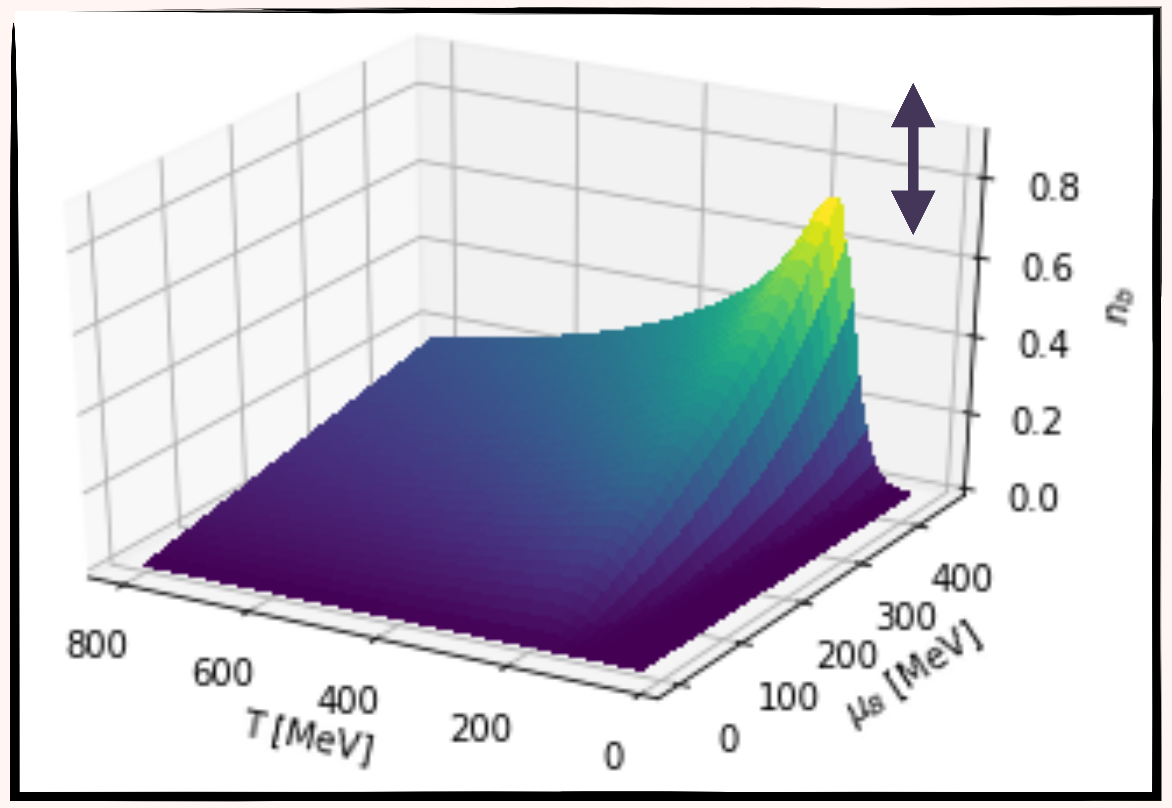
BEST 4: PAR 155 -0.0149 350 90 10 1



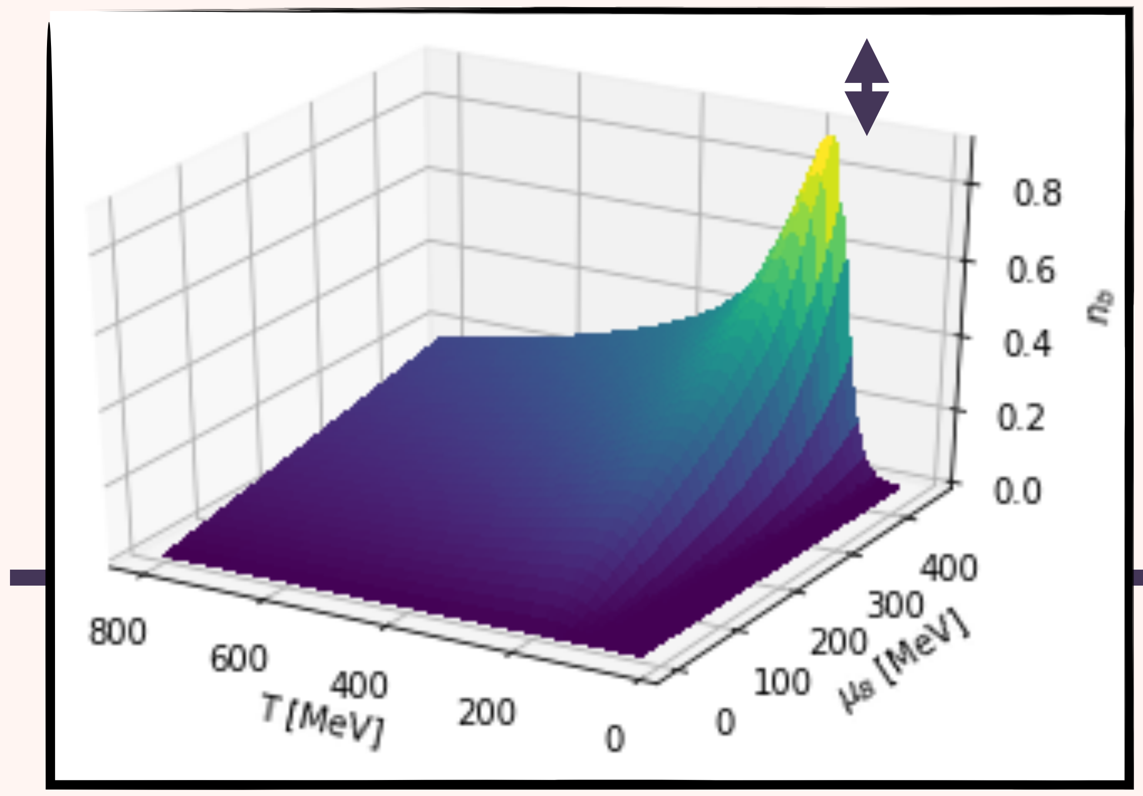
BEST 5: PAR 169 -0.0149 420 90 0.25 2



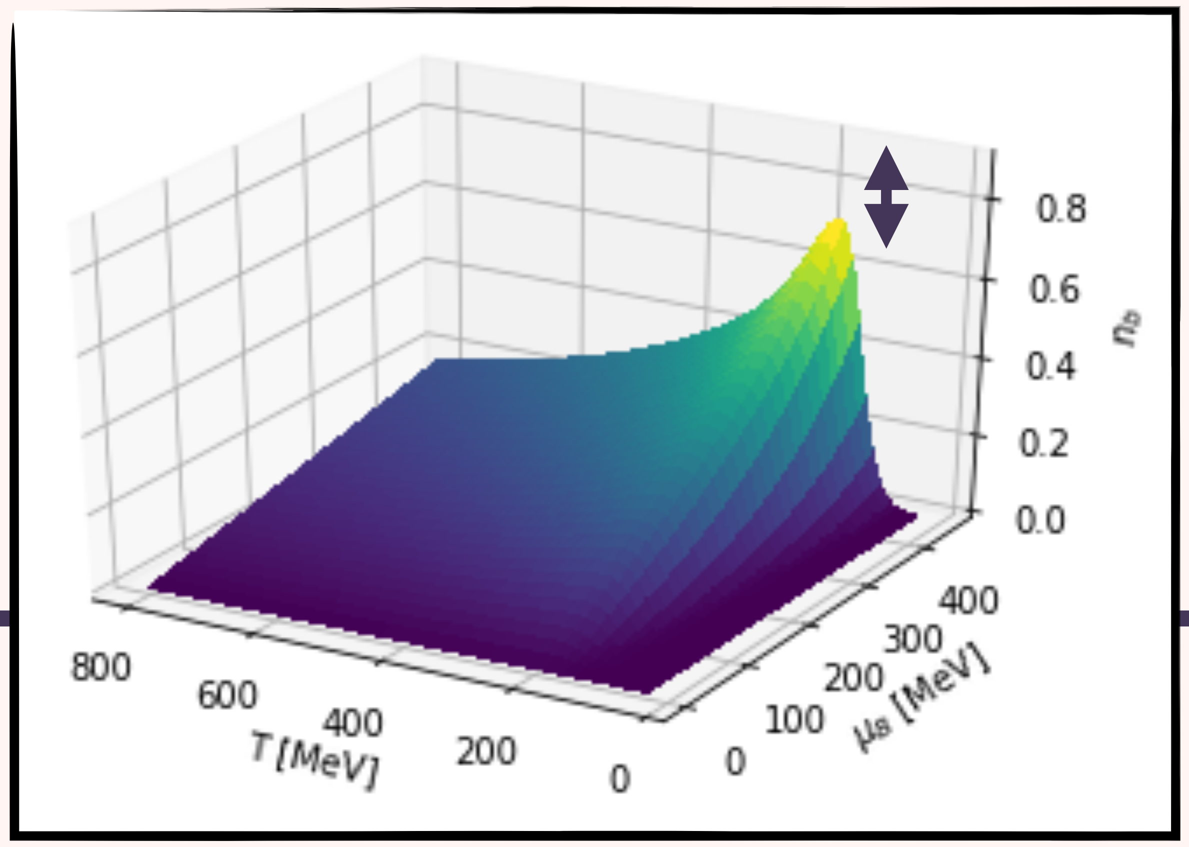
BEST 6: PAR 169 -0.0149 420 90 1 1



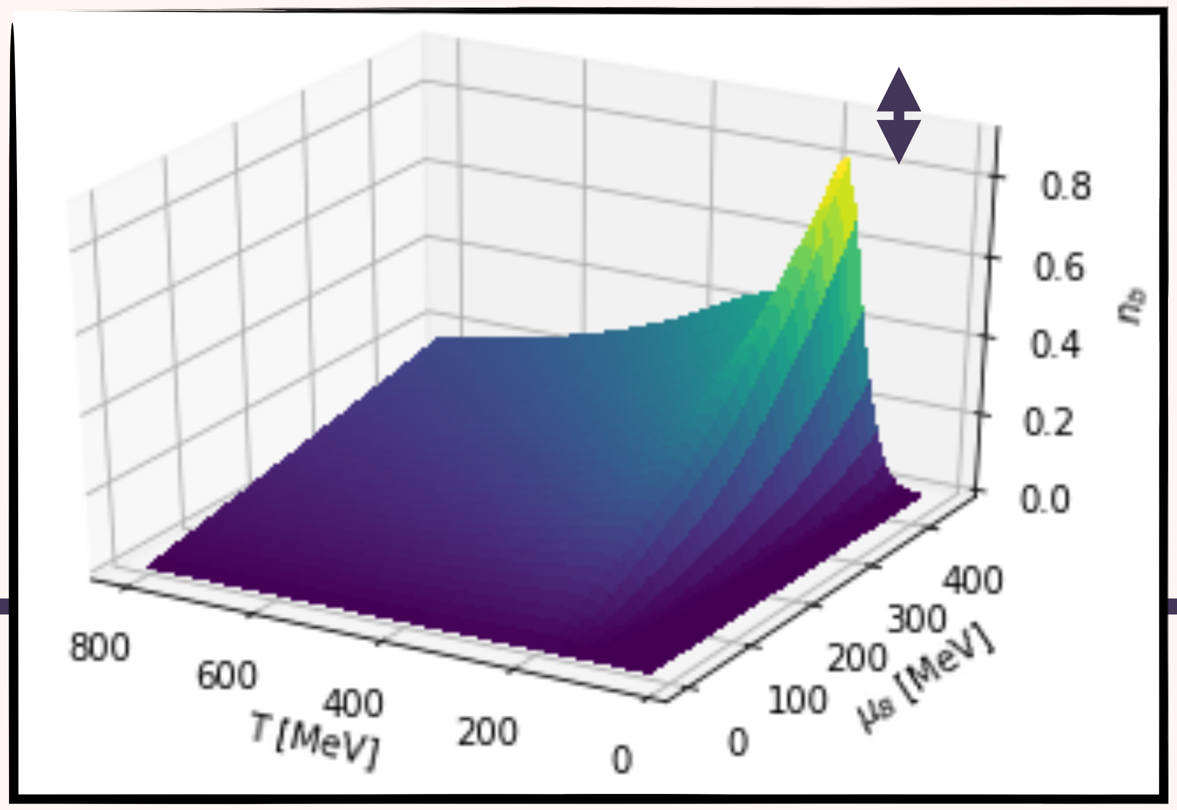
BEST 7: PAR 169 -0.0149 420 90 0.5 1



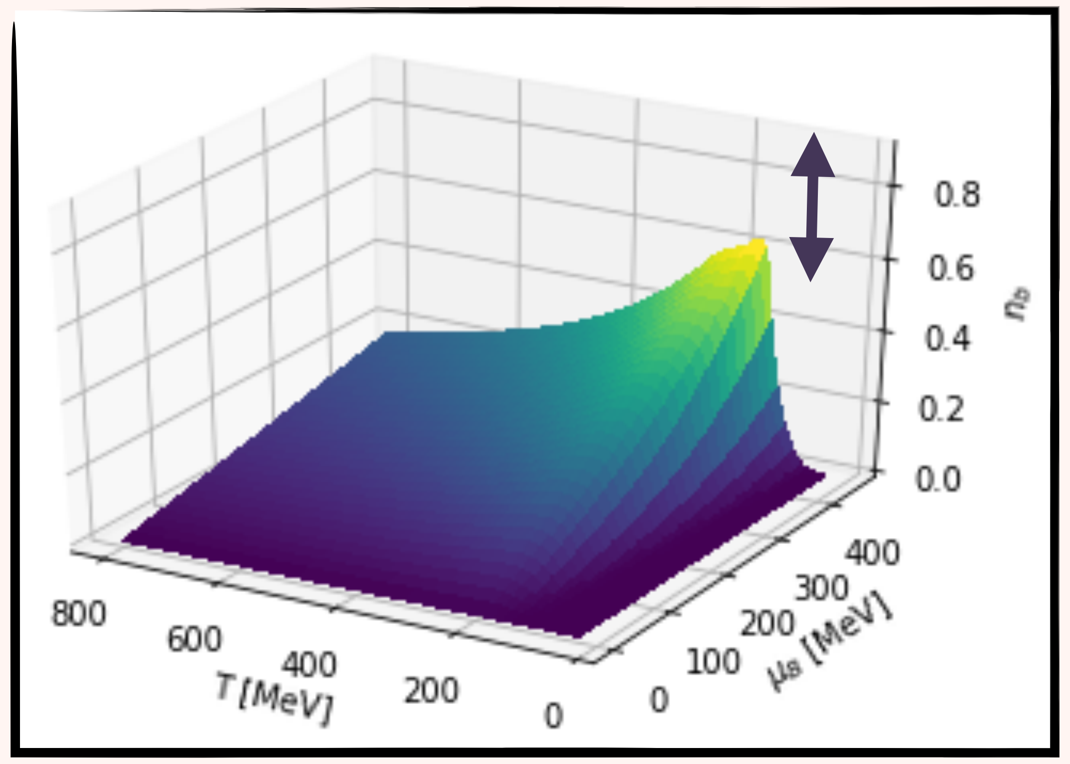
BEST 8: PAR 174 -0.0149 440 90 1 1



BEST 9: PAR 178 -0.0149 300 90 1 1

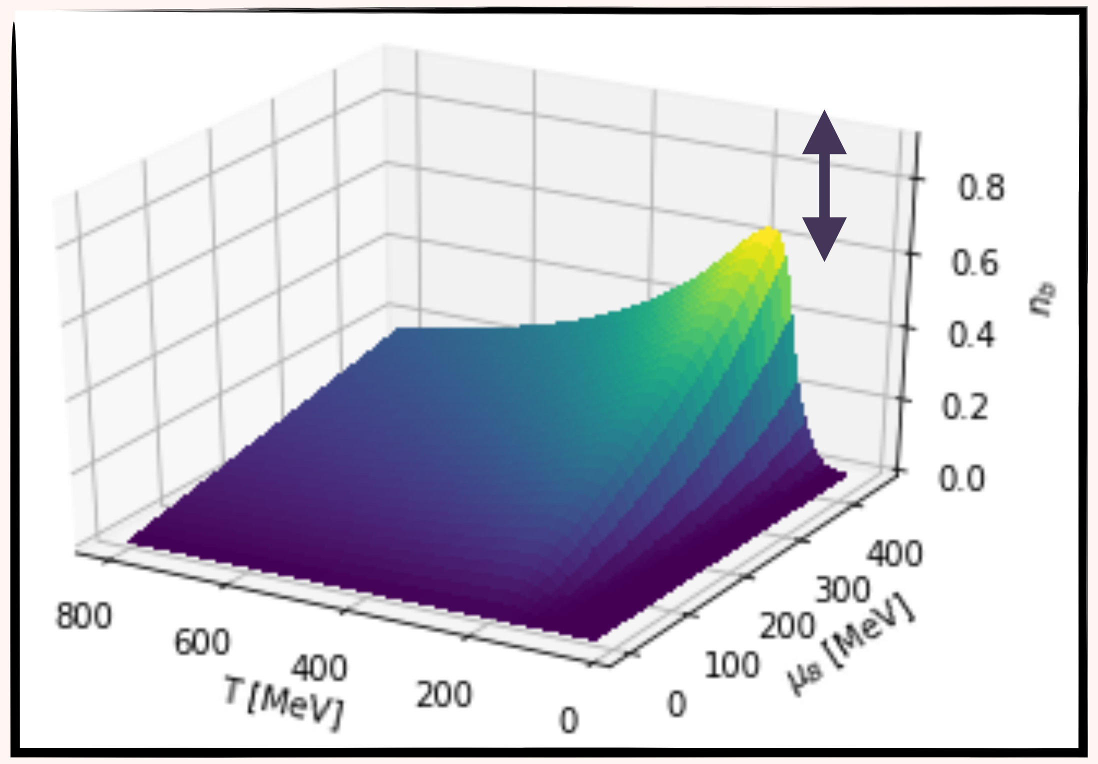


BEST 1: PAR 155 -0.0149 350 90 1 2

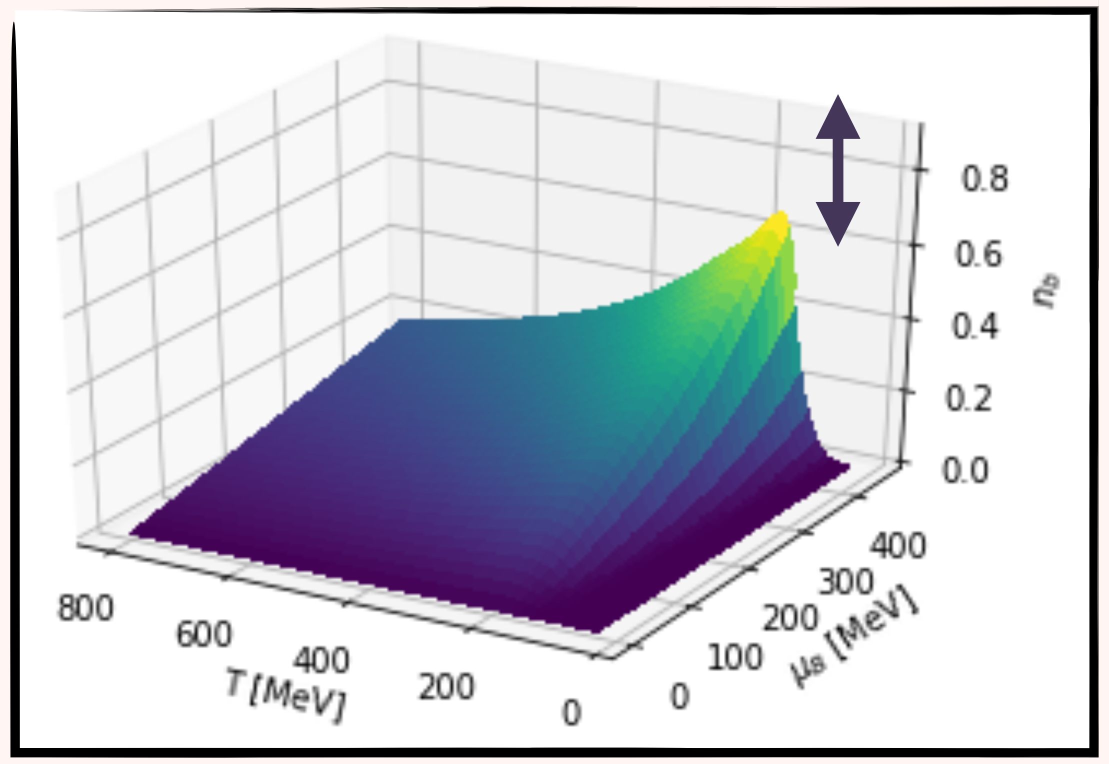


n_B

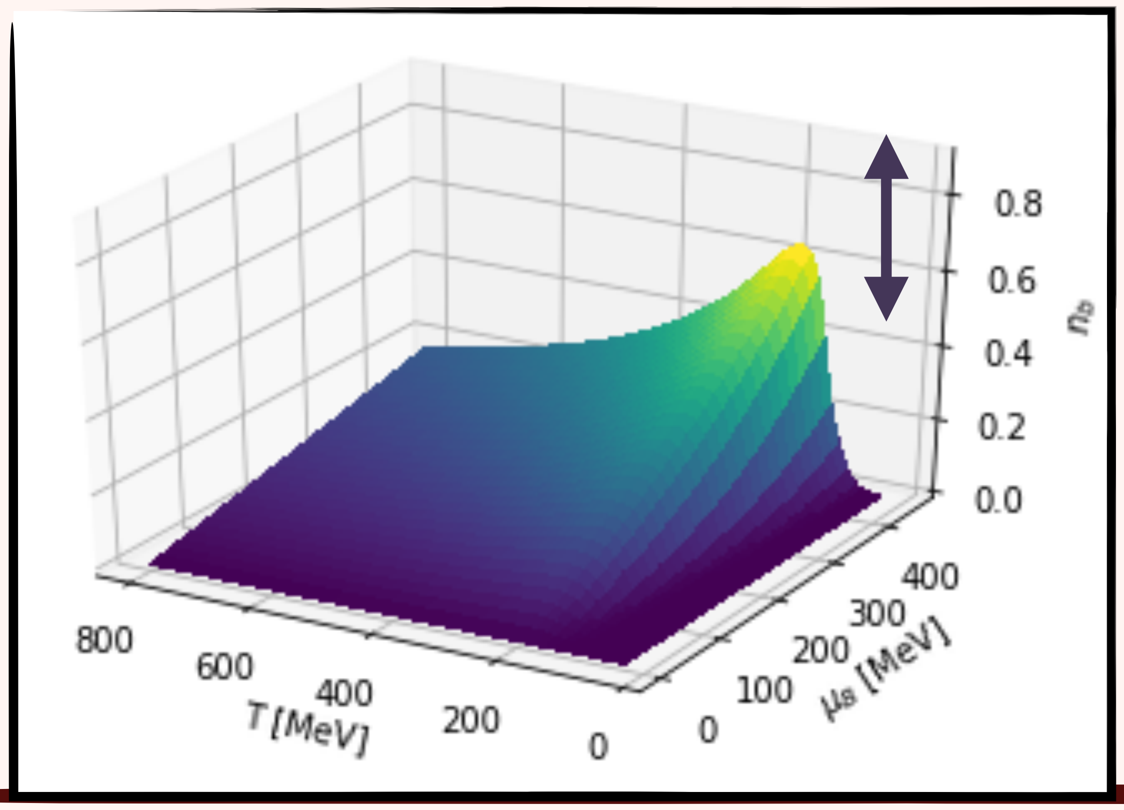
BEST 2: PAR 155 -0.0149 350 90 4 1



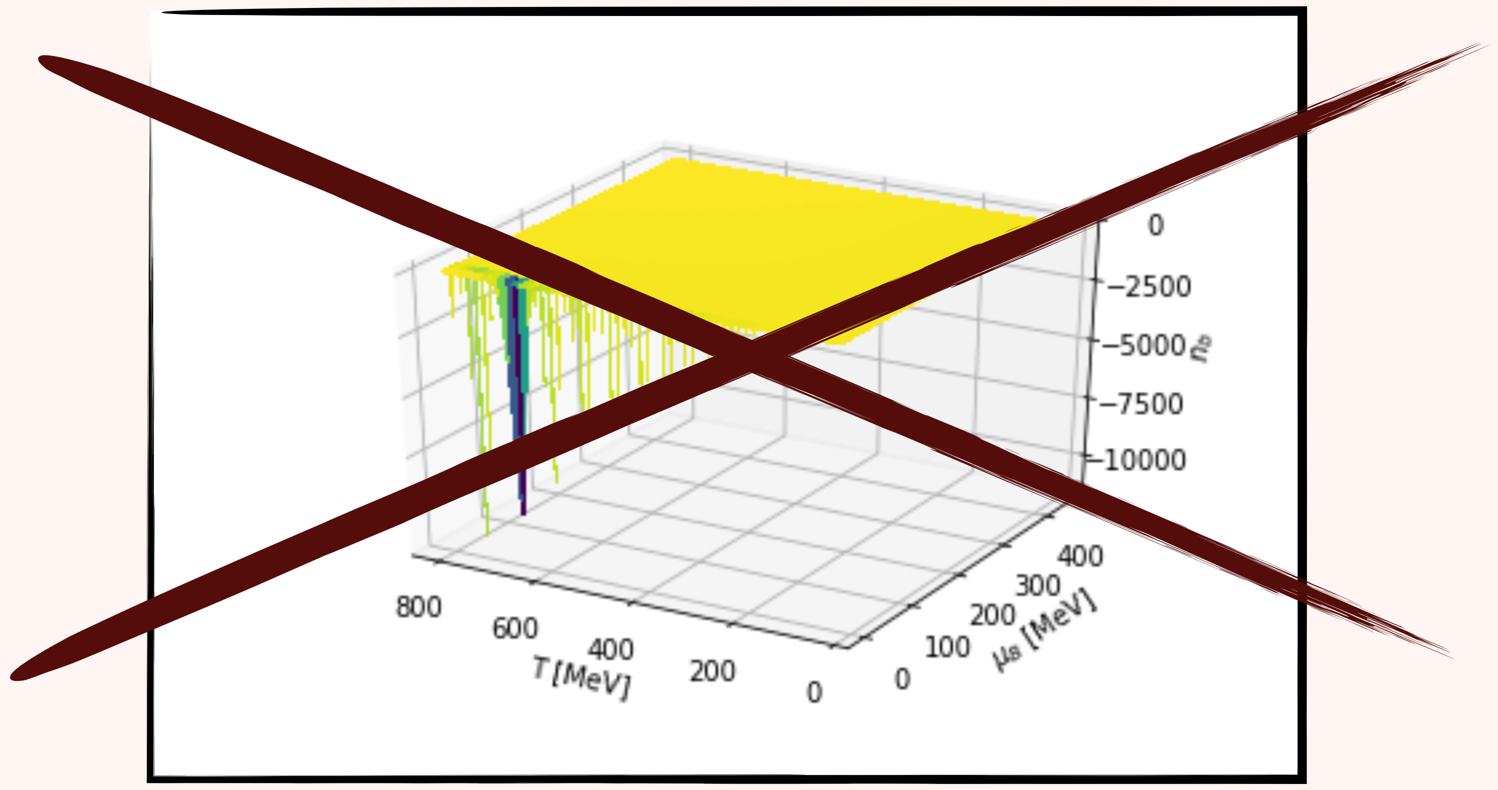
BEST 3: PAR 155 -0.0149 420 90 0.75 2



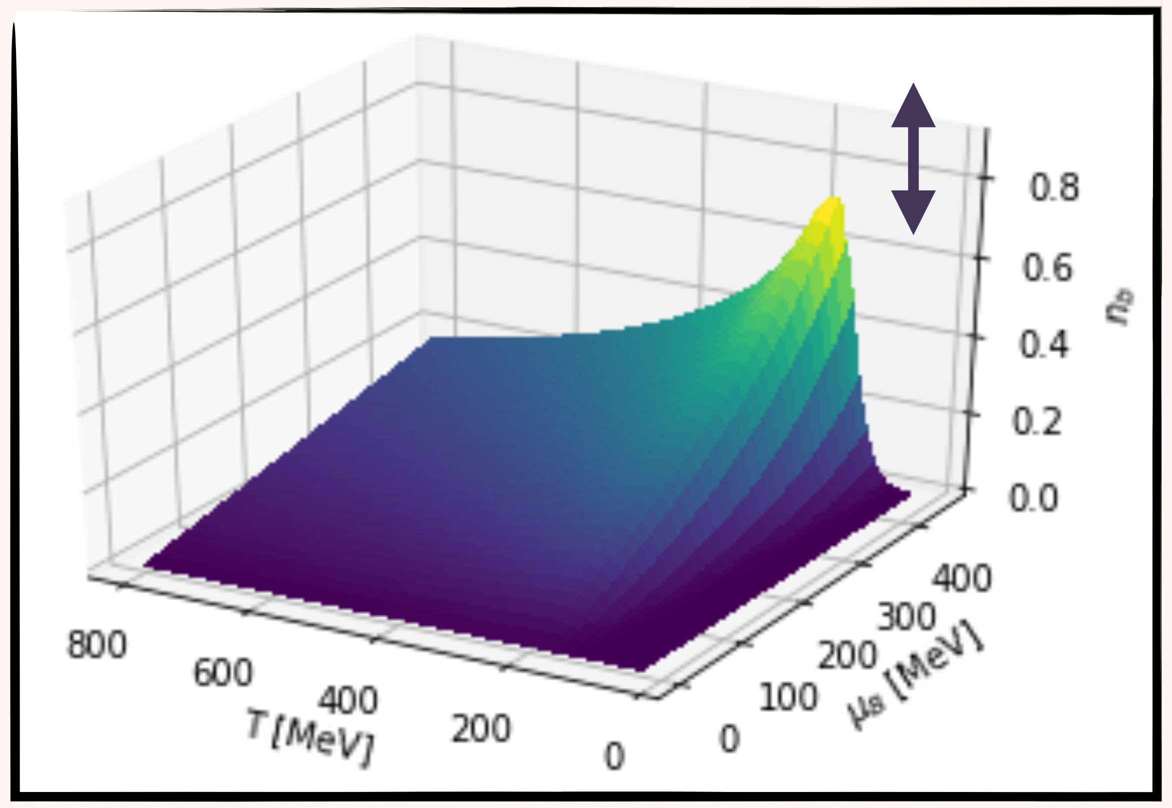
BEST 4: PAR 155 -0.0149 350 90 10 1



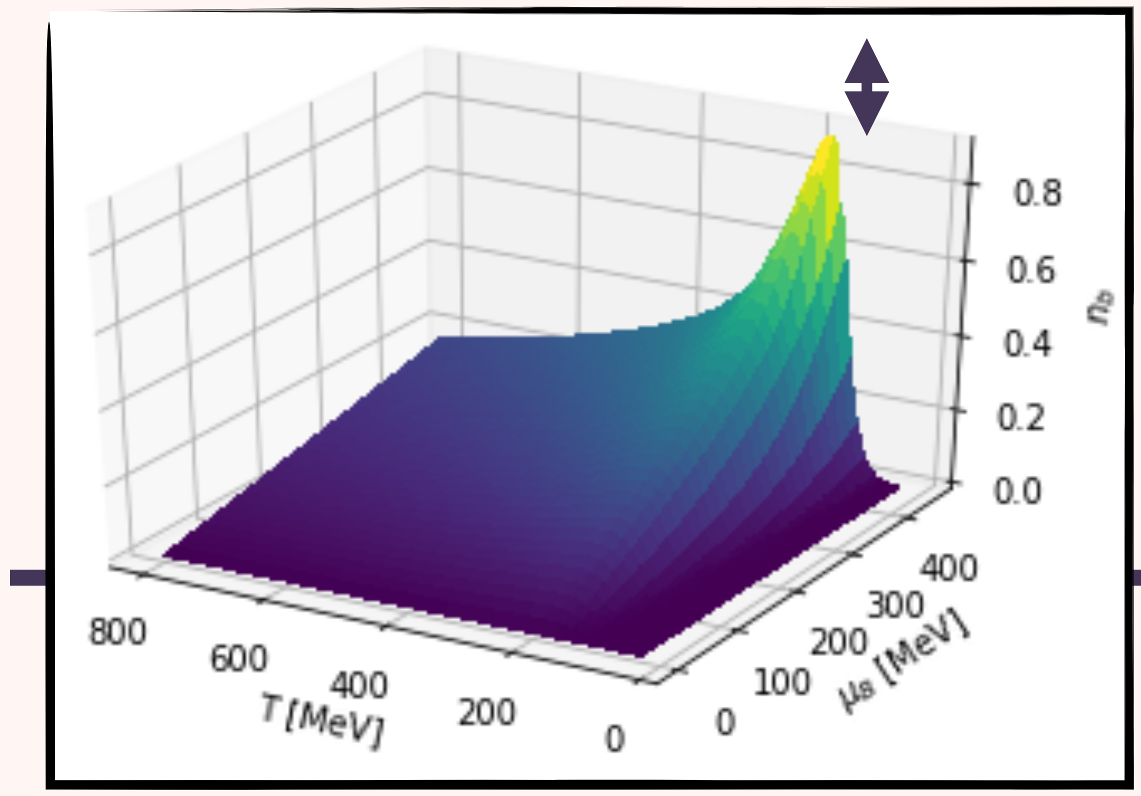
BEST 5: PAR 169 -0.0149 420 90 0.25 2



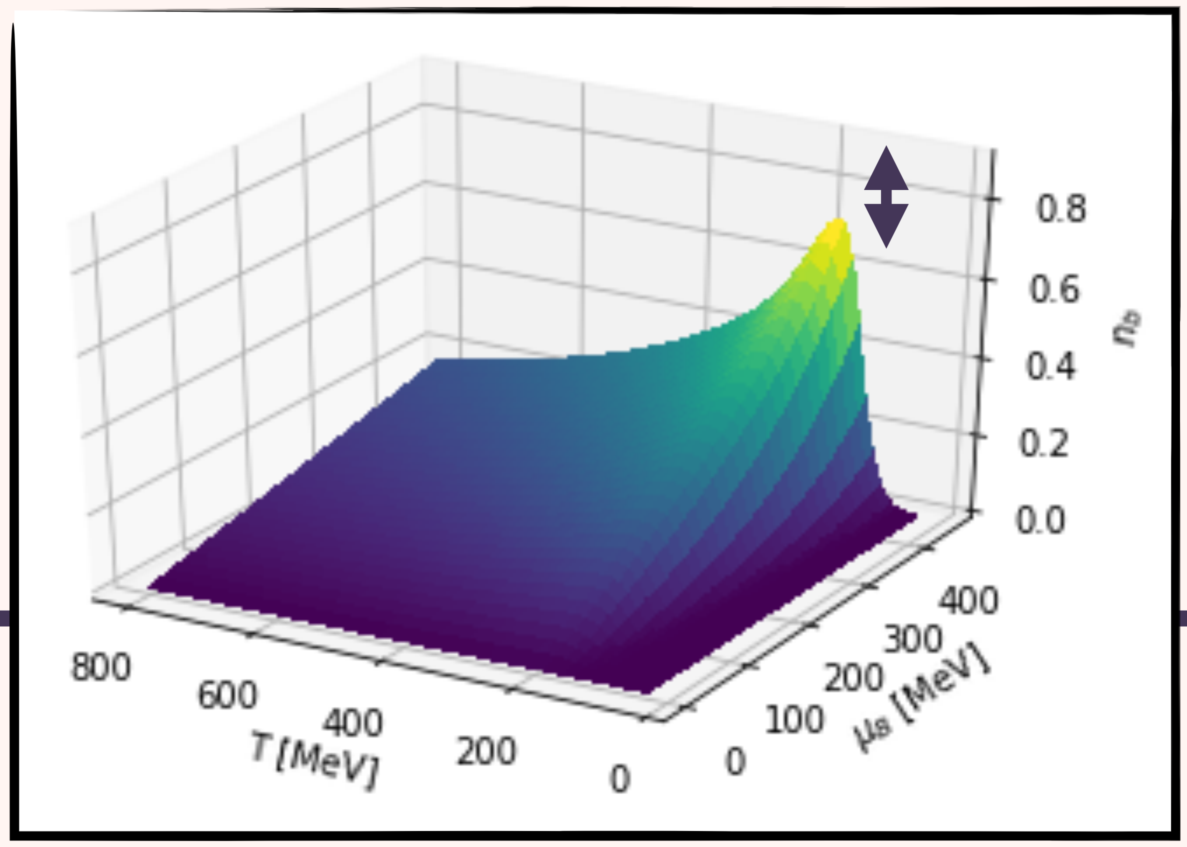
BEST 6: PAR 169 -0.0149 420 90 1 1



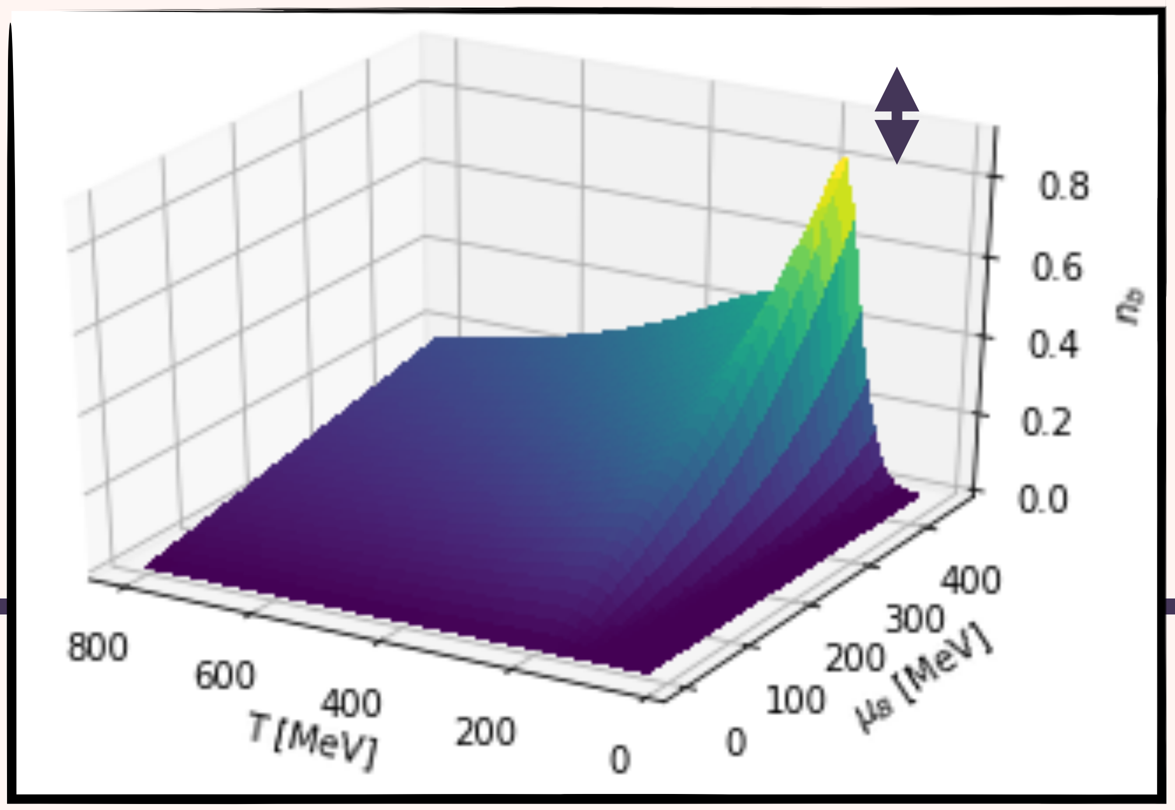
BEST 7: PAR 169 -0.0149 420 90 0.5 1



BEST 8: PAR 174 -0.0149 440 90 1 1



BEST 9: PAR 178 -0.0149 300 90 1 1

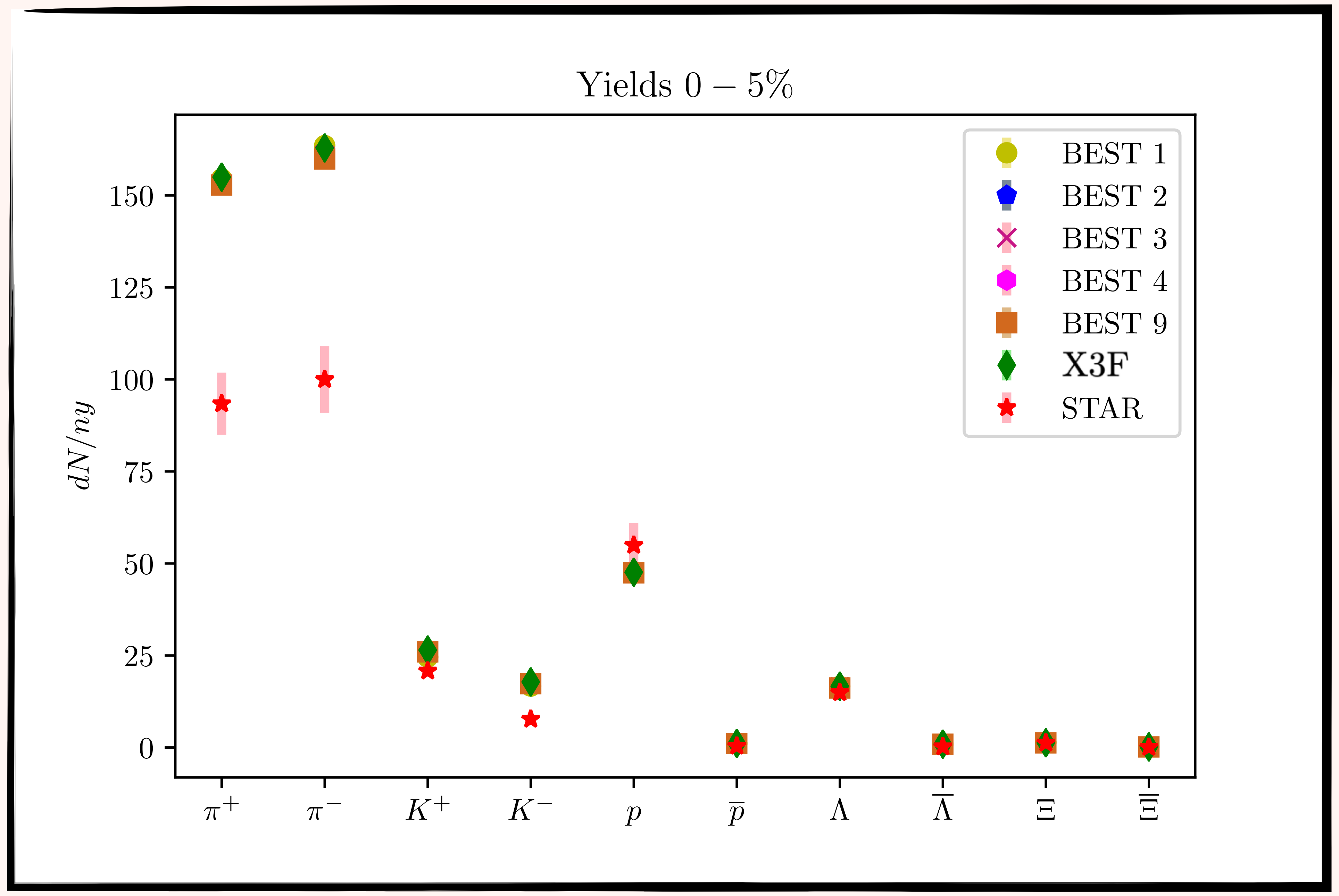


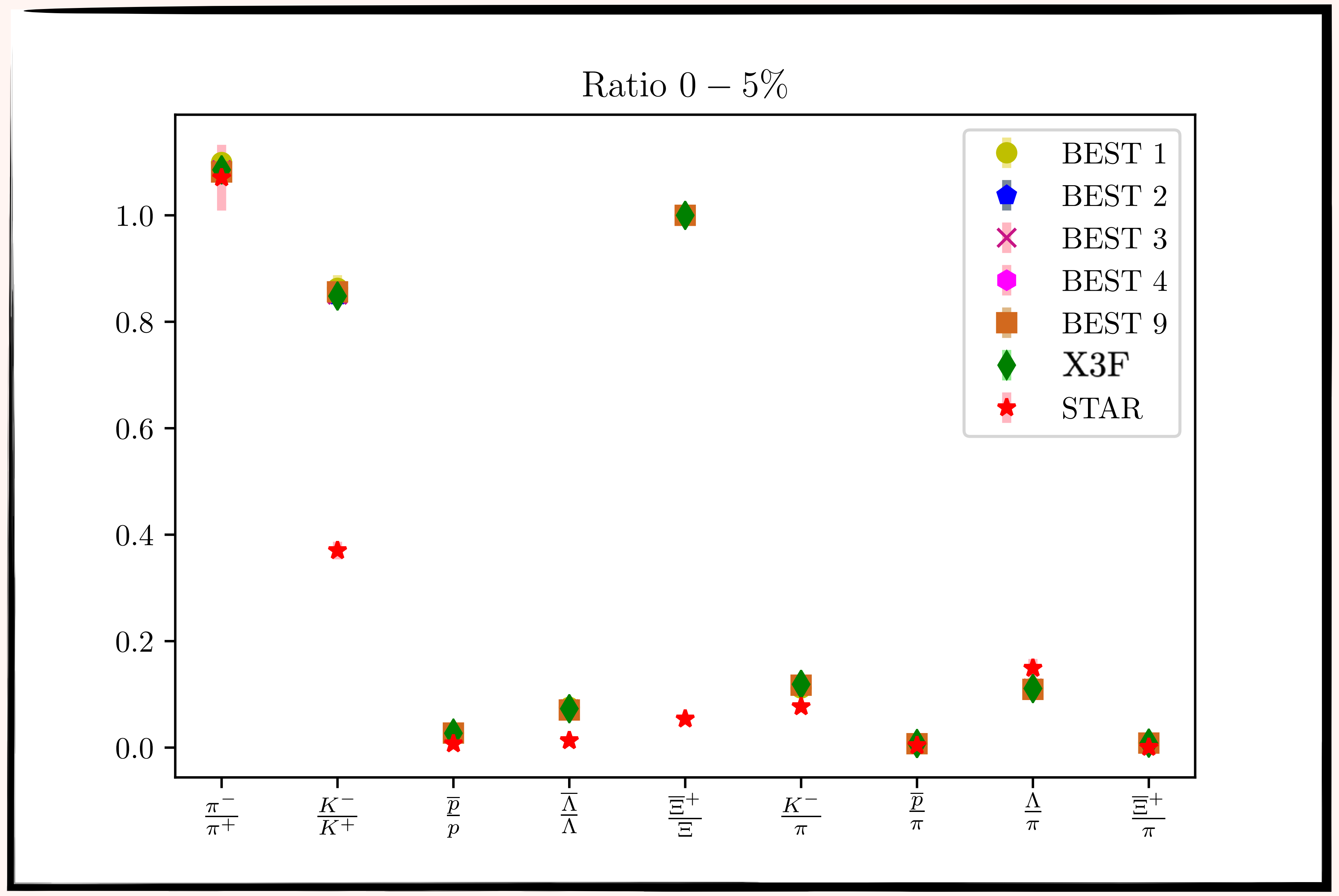
BEST EOS WITH CP

Parabola	T	curvature	μ_{BC}	$\alpha_1 - \alpha_2$	ω	ρ

- **BEST 1: PAR 155 -0.0149 350 90 1 2**
- **BEST 2: PAR 155 -0.0149 350 90 4 1**
- **BEST 3: PAR 155 -0.0149 420 90 0.75 2**
- **BEST 4: PAR 155 -0.0149 350 90 10 1**
- **BEST 9: PAR 178 -0.0149 300 90 1**
- **X3F (Cross-over 3 flavour conservation)**
- **STAR: *Phys.Rev.C* 96 (2017) 4, 044904**

YIELDS : Au+Au @ $\sqrt{s_{NN}}$ = 7.7GeV

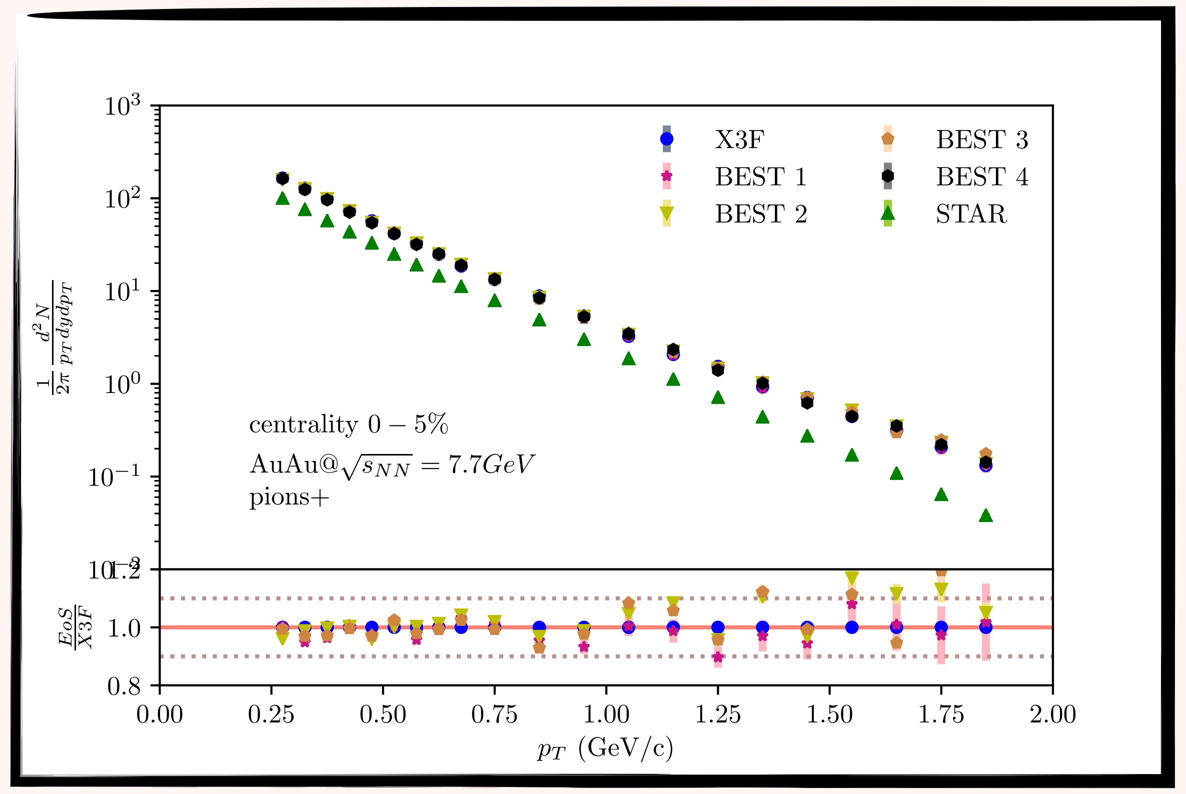


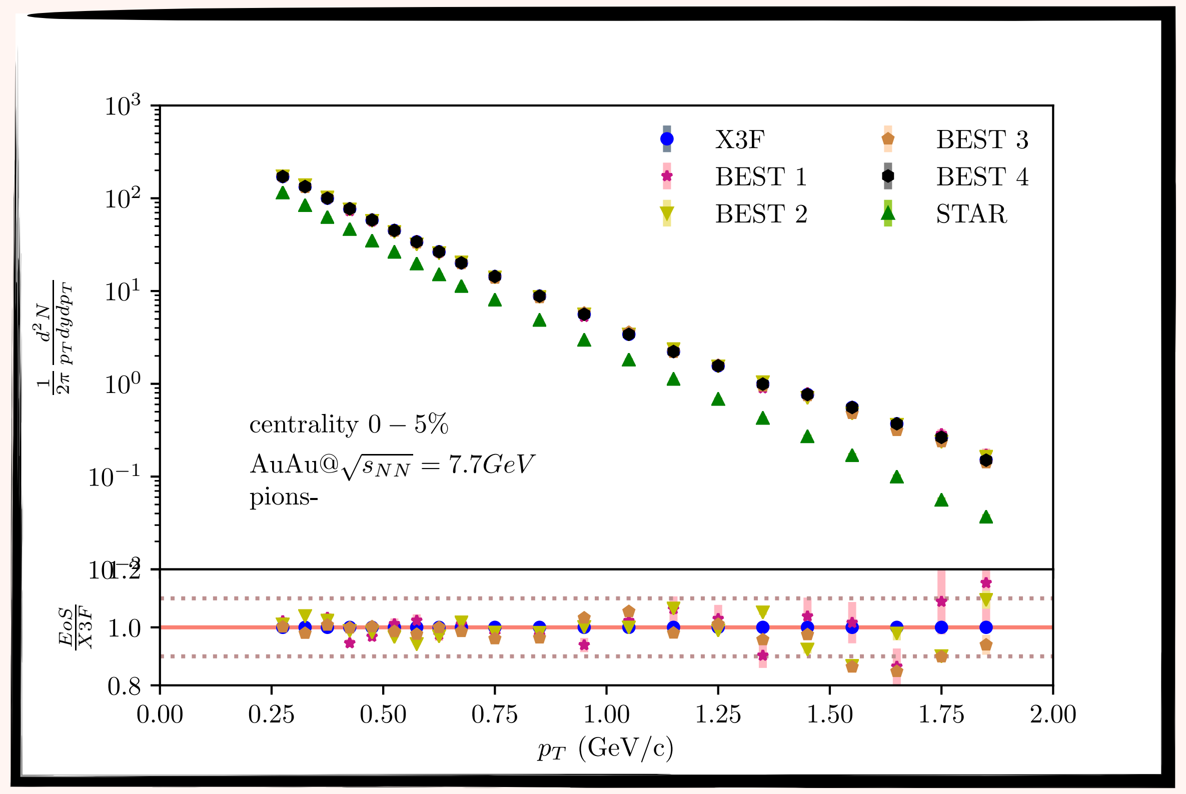


- **<u>The change of the EoS does NOT influence relevantly the production of the particles</u>**
- The ratio of **π+/π-** is in agreement with data, although separately in EPOS much more **π+** and **π-**

p_T spectra : Au+Au @ $\sqrt{s_{NN}}$ = 7.7GeV, centrality 0-5%

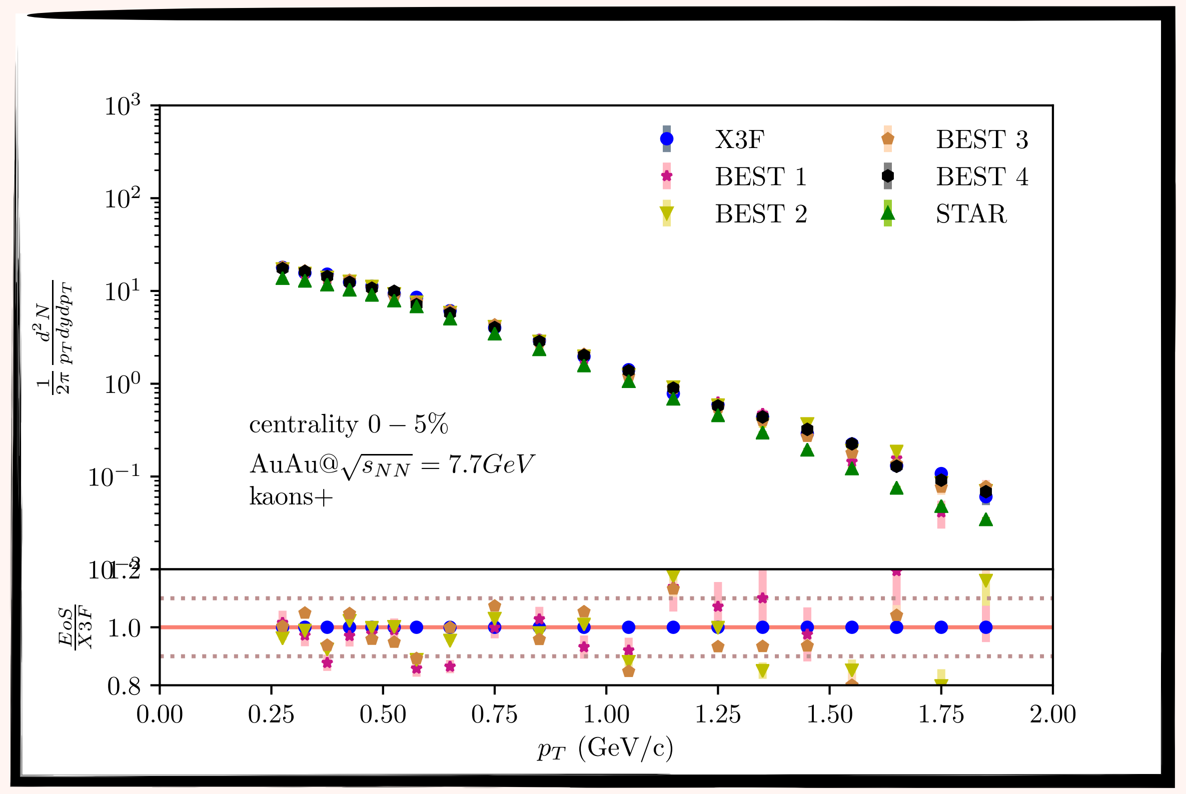
STAR: Phys.Rev.C 96 (2017) 4, 044904

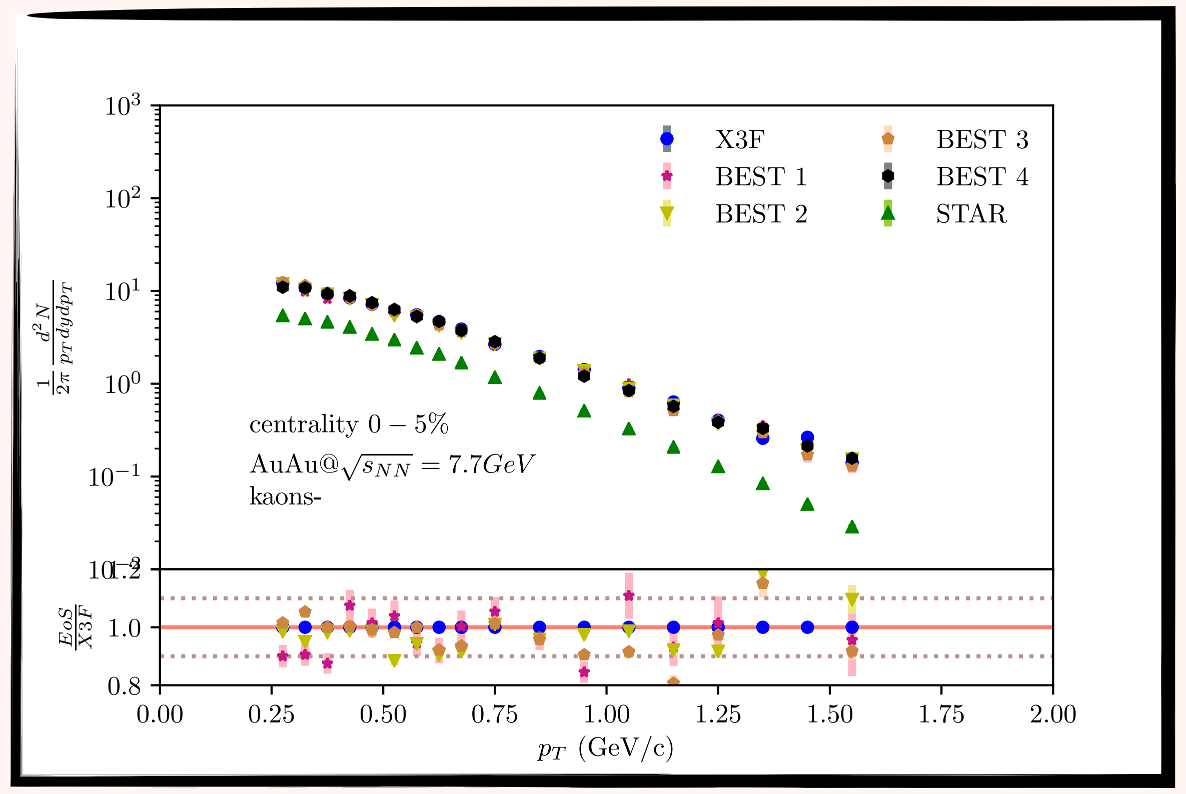




PIONS:

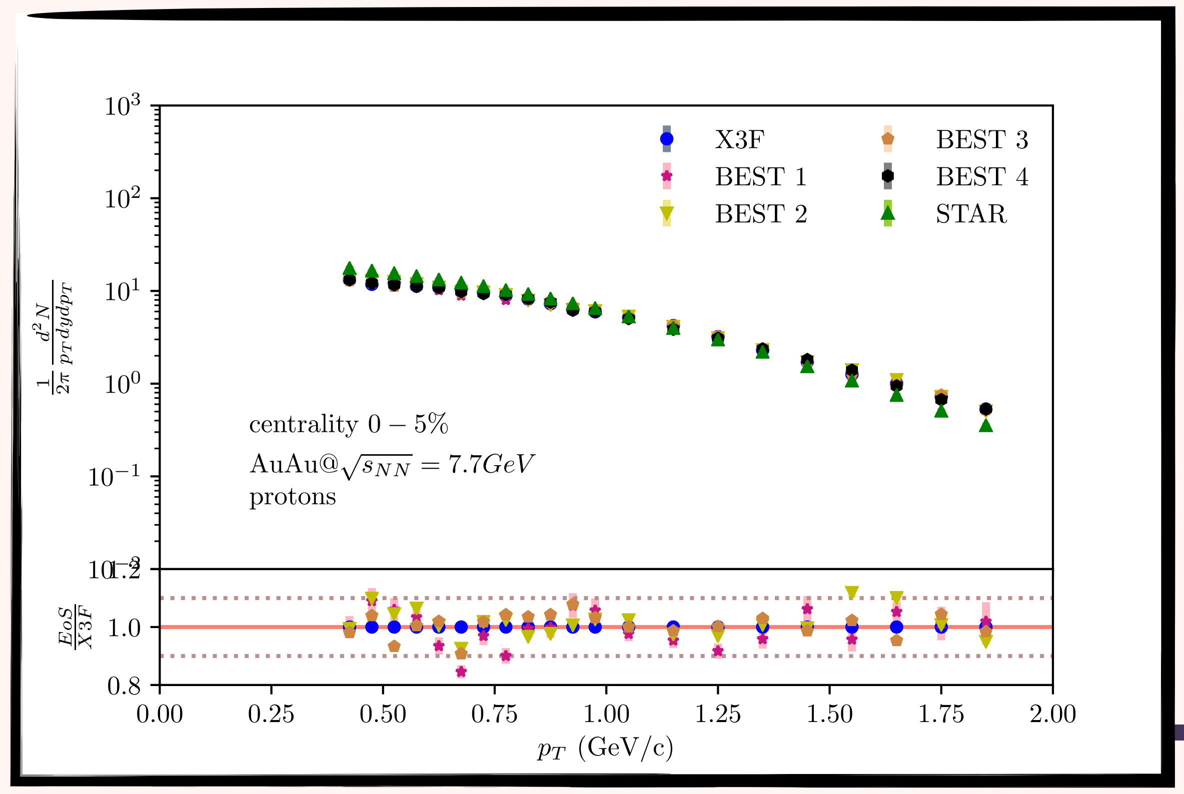
- **Differences between EoS for p_T > 1 GeV/c up to 10%**
- The EPOS data sets higher in the whole range than STAR - too many pions (in back up *yields* plots)

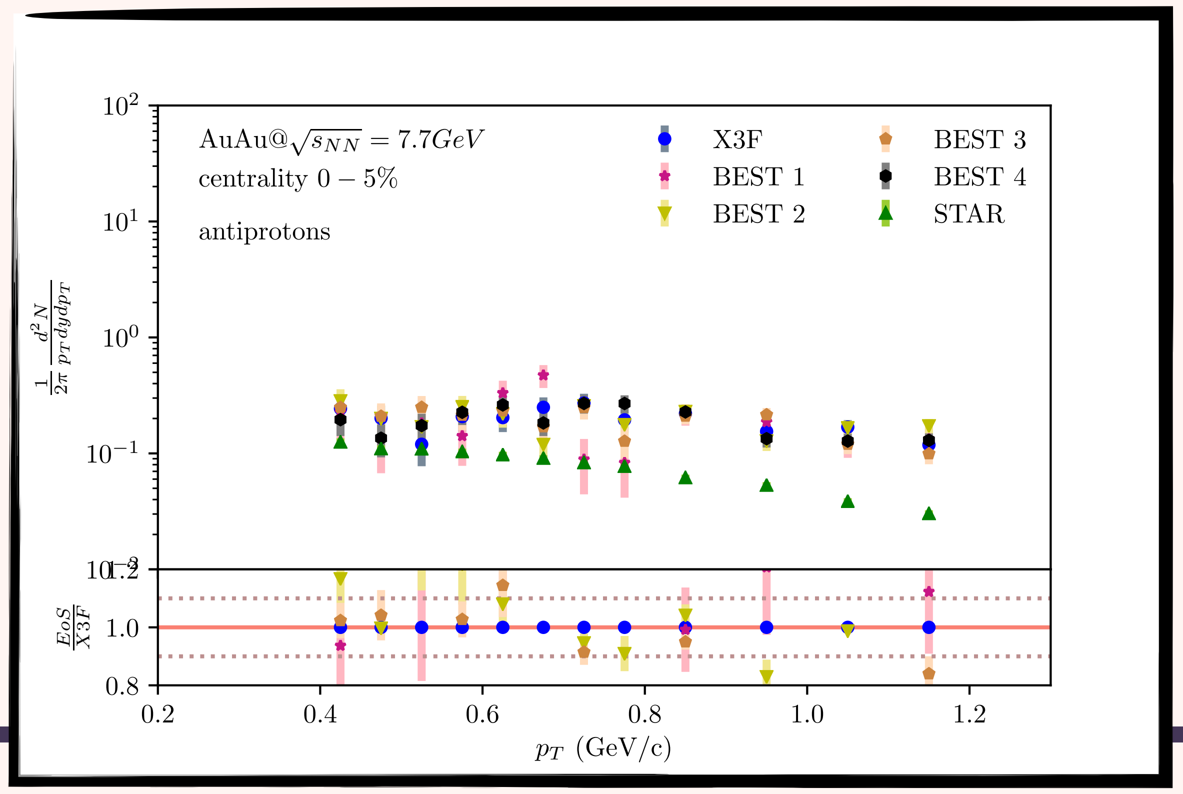




KAONS:

- **Differences between EoS up to 10% in whole range of p_T mostly fluctuating**
- In case of K+ close to STAR data



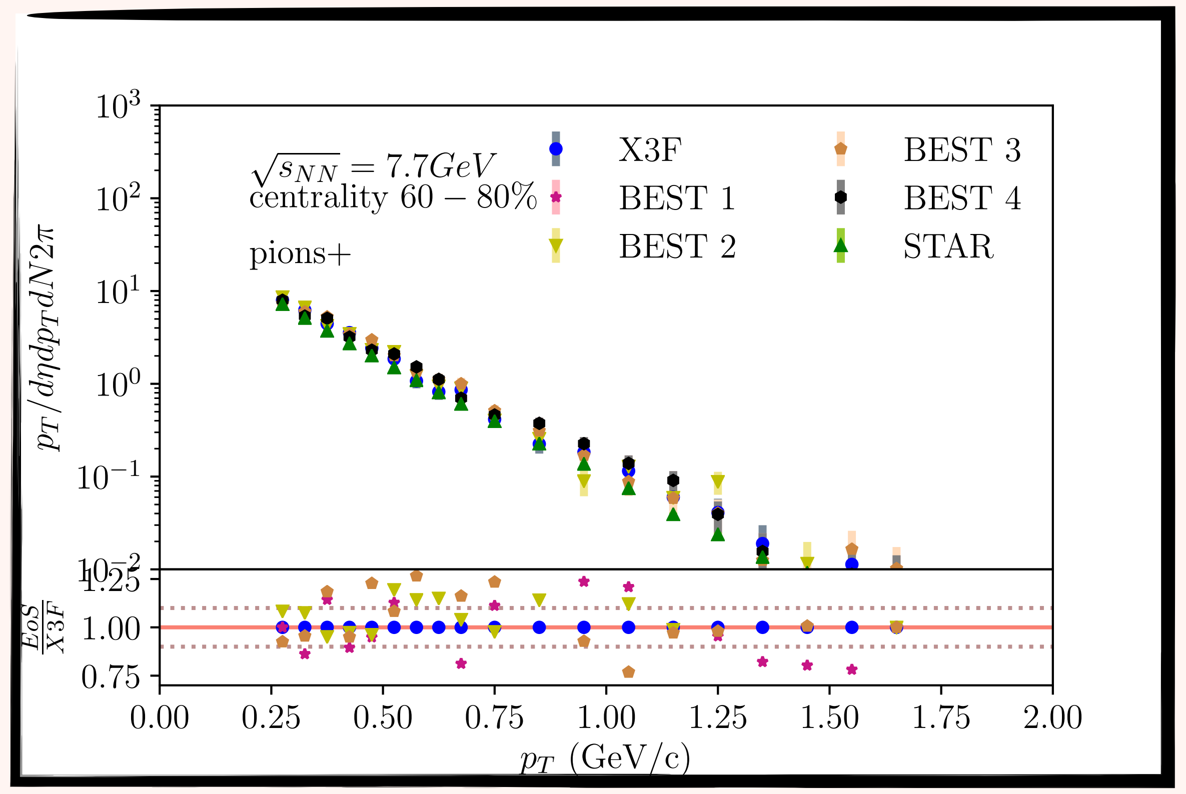


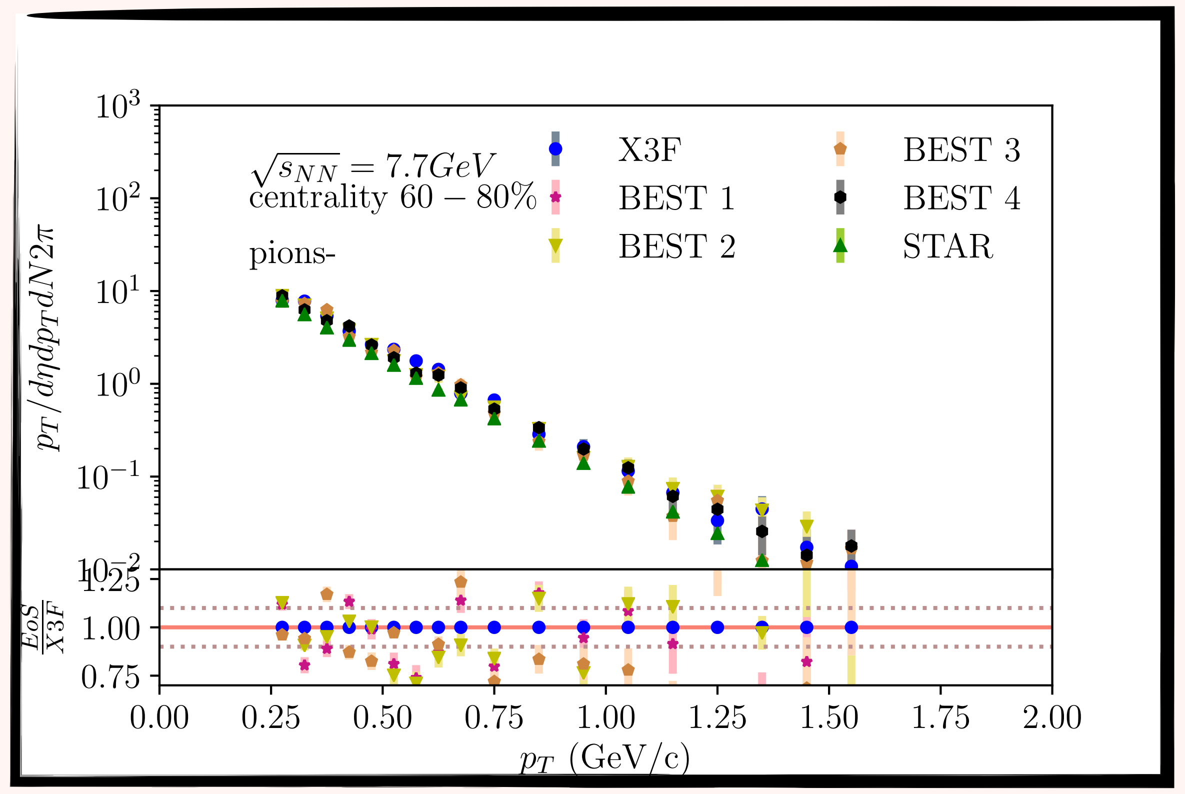
PROTONS:

- **Differences between EoS up to 10% in whole range of p_T mostly fluctuating**
- Agreement between protons' spectra simulated and experimental

p_T spectra : Au+Au @ $\sqrt{s_{NN}}$ = 7.7GeV, centrality 60-80%

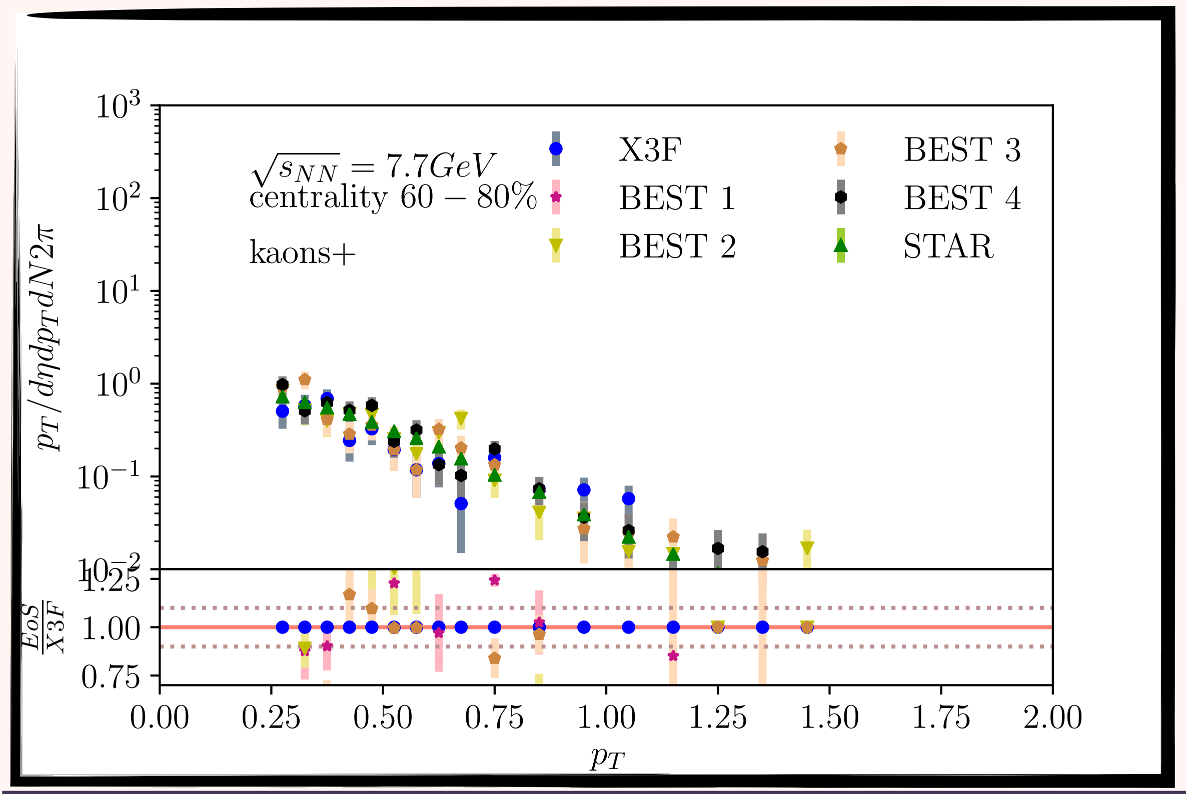
STAR: Phys.Rev.C 96 (2017) 4, 044904

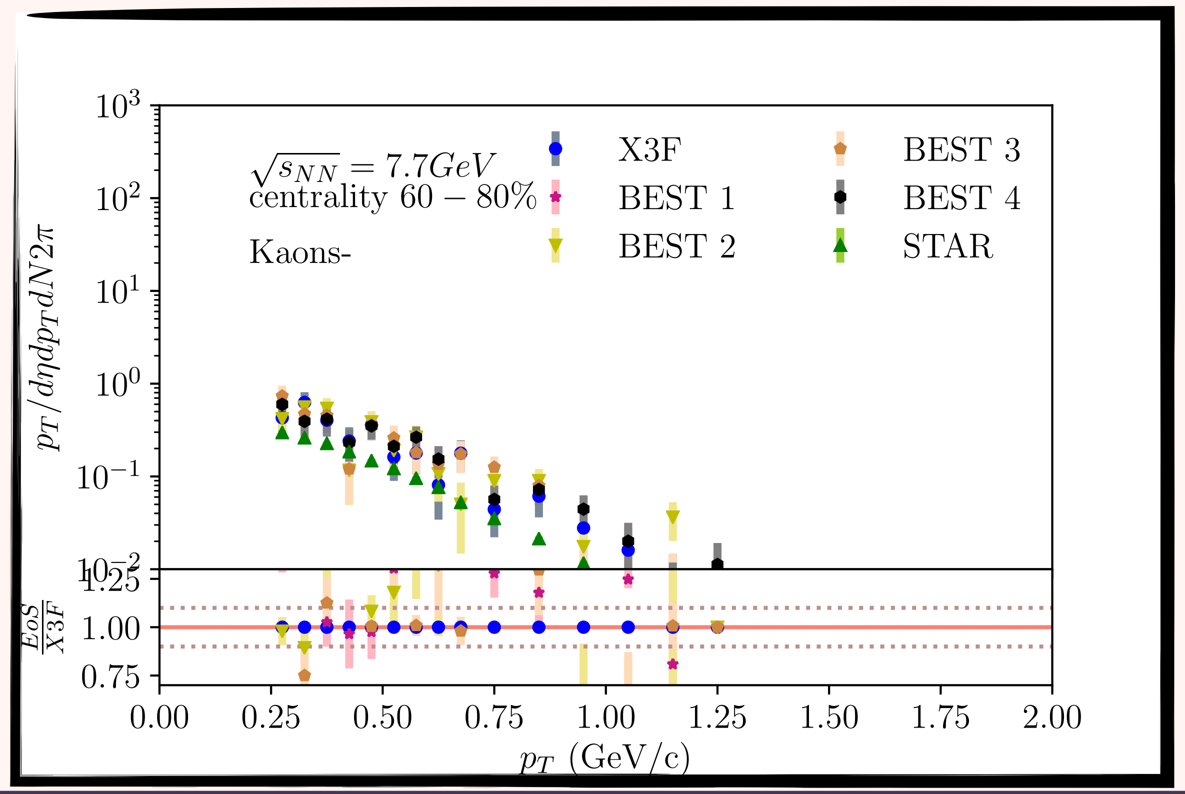




PIONS:

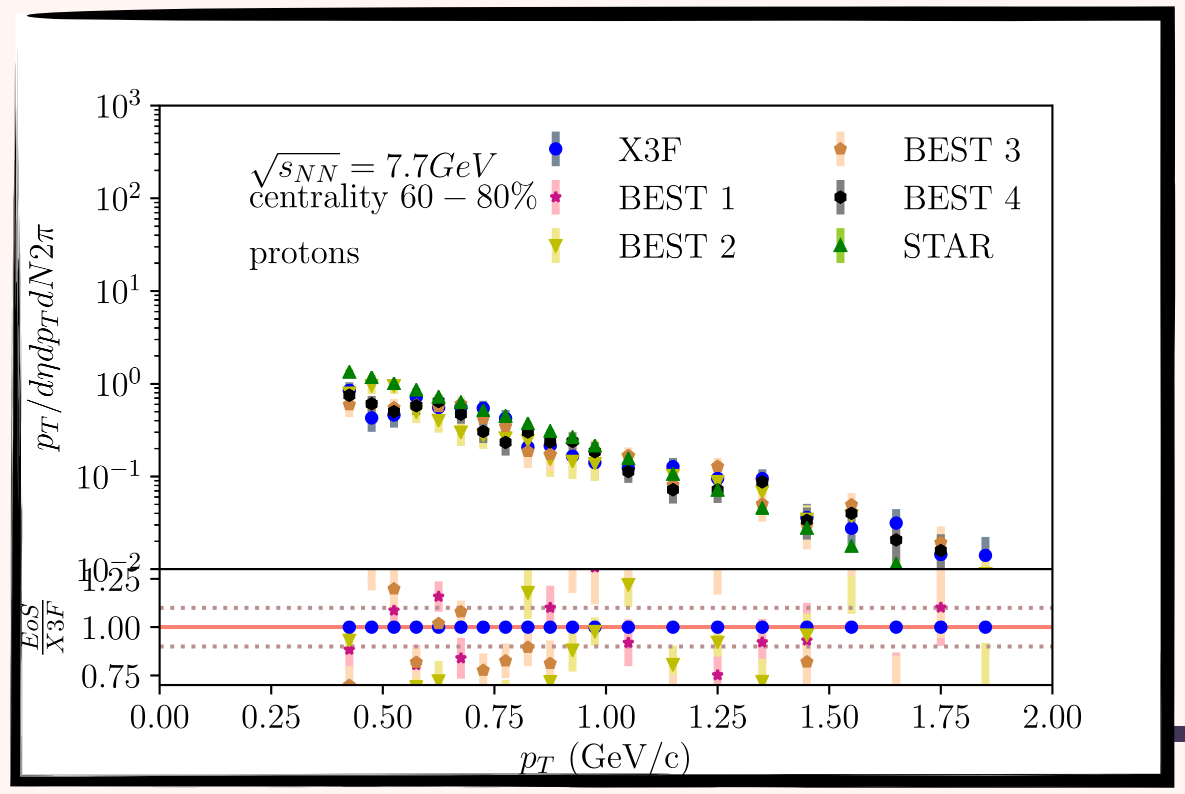
- **Differences between EoS more than 10% in whole range of p_T mostly fluctuating**
- EPOS spectra slightly overestimates the experimental

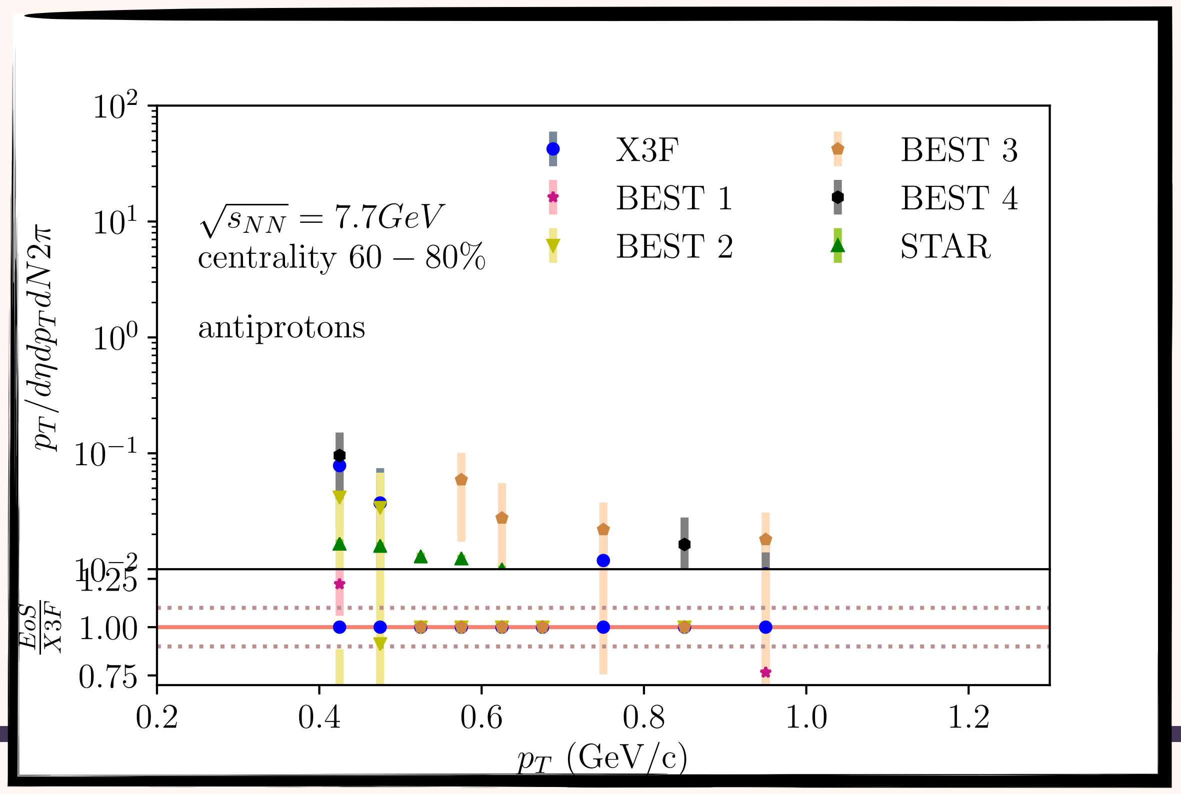




KAONS:

- **Differences between EoS more than 10% in whole range of p_T mostly fluctuating**
- Both data sets within the statistical uncertainty

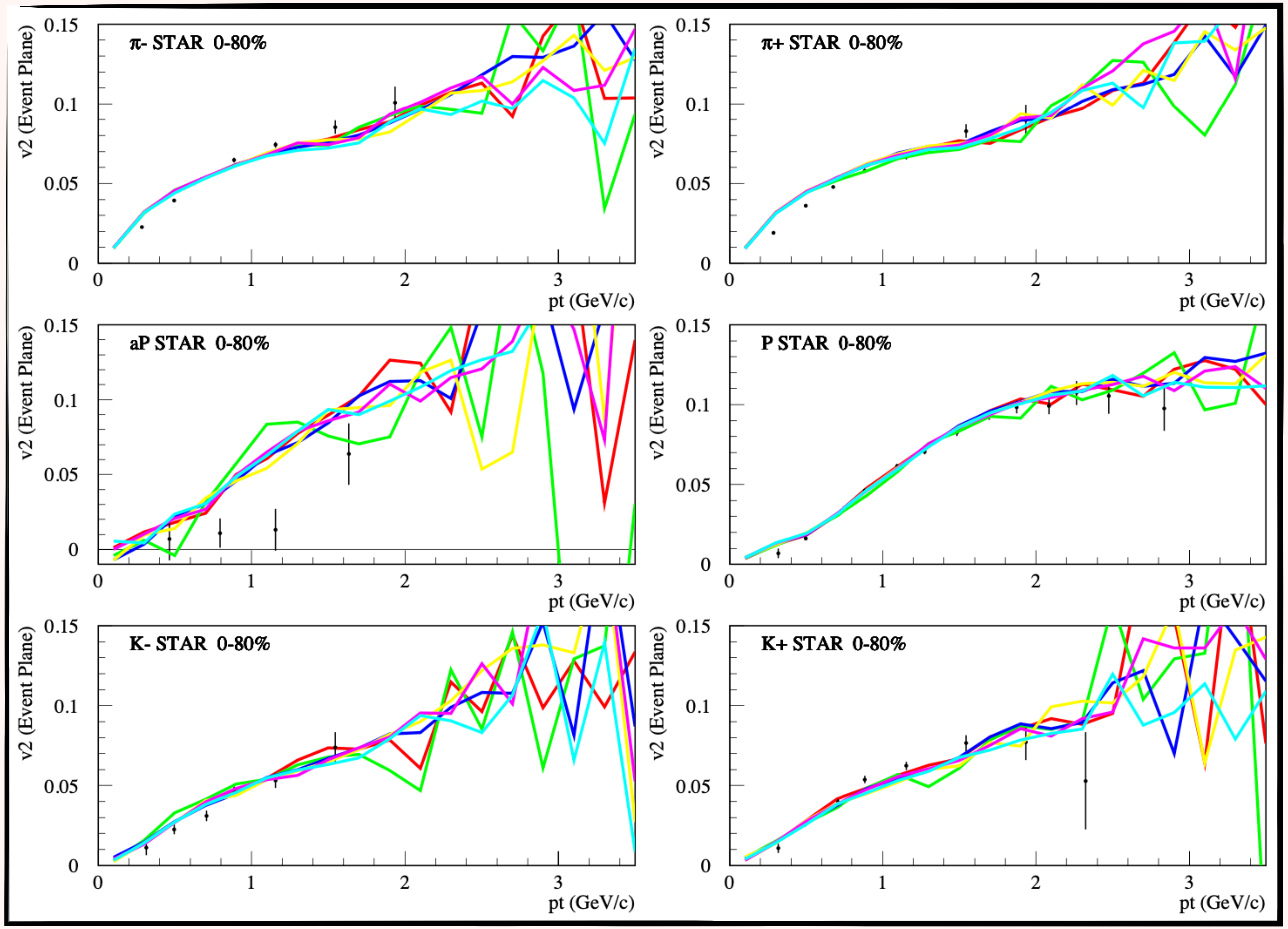




PROTONS:

- **Differences between EoS more than 10% in whole range of p_T mostly fluctuating**
- Both data sets within the statistical uncertainty

v_2 EP : Au+Au @$\sqrt{s_{NN}}$ = 7.7 GeV, centrality 0-80%

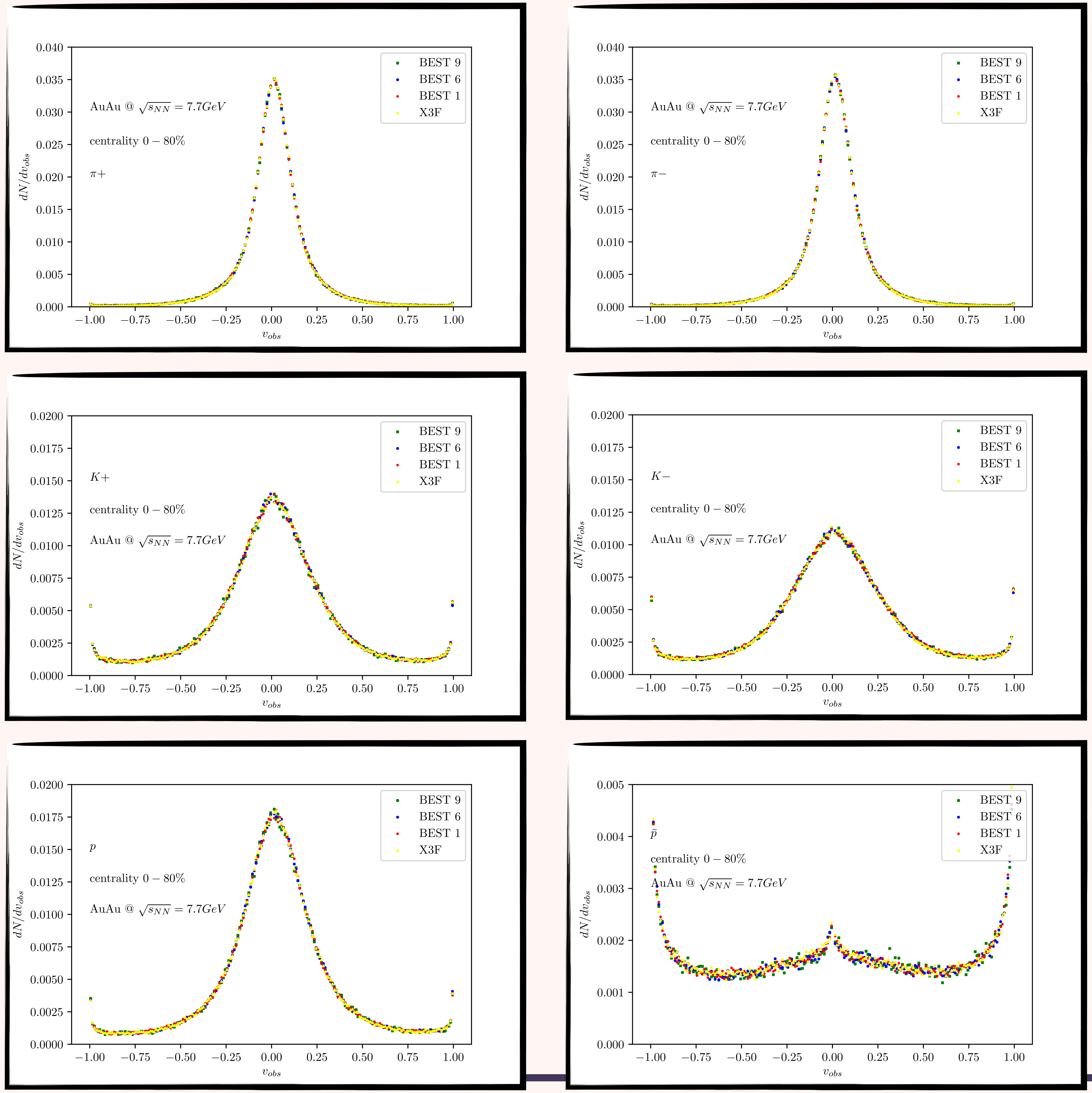


1) PAR_143_350_3_93_143_286
3) PAR_138_420_4_94_103_207
4) PAR_143_350_3_93_1432_1432
6) PAR_153_420_4_94_153_153
9) PAR_170_300_2_92_170_170
X3F

✱ STAR: Phys. Rev. C 88 (2013) 14902

- Quite reasonable reproduction of STAR data
- **No vital differences between EoS**

v_2^{obs}: Au+Au $\sqrt{s_{NN}}$ = 7.7GeV, centrality 0-80%



$$v_2^{obs}(p_T, y) = \langle \cos[2(\phi_i - \Phi_2)] \rangle$$

Event-by-Event v_2^{obs}

Not averaged studies of elliptic flow

does **not** emphasise the differences between EoS

SUMMARY:

- ☑ The new EoS was successfully implemented into EPOS 3.4
- ☑ Changes of parameters in BEST EoS depicted on basic plots of thermodynamical dependencies
- ☑ Simulation of collisions AuAu @ $\sqrt{s_{NN}} = 7.7 GeV$ with EPOS 3.4 using various EoS parameters
- ☑ Half of sets of parameters tested with analysis such as:
  - ☑ yields
  - ☑ p_T spectra
  - ☑ elliptic flow
    - ☑ first ebe check
  - ☐ triangular flow

Some variations between EoS for pT spectra!

SUMMARY:

- ☑ The new EoS was successfully implemented into EPOS 3.4
- ☑ Changes of parameters in BEST EoS depicted on basic plots of thermodynamical dependencies
- ☑ Simulation of collisions AuAu @ $\sqrt{s_{NN}} = 7.7 GeV$ with EPOS 3.4 using various EoS parameters
- ☑ Half of sets of parameters tested with analysis such as:
  - ☑ yields
  - ☑ p_T spectra
  - ☑ elliptic flow
    - ☑ first ebe check
  - ☐ triangular flow
- ☐ More studies of event-by-event observables? *S.Vogel, G.Torrieri, M. Bleicher: Phys.Rev.C 82 (2010) 024908*
- ☐ What about HBT? *P. Batyuk, at all: Phys. Rev. C 96, 024911 (2017)*
- ☐ Look into Freeze-out variables

Some variations between EoS for pT spectra!

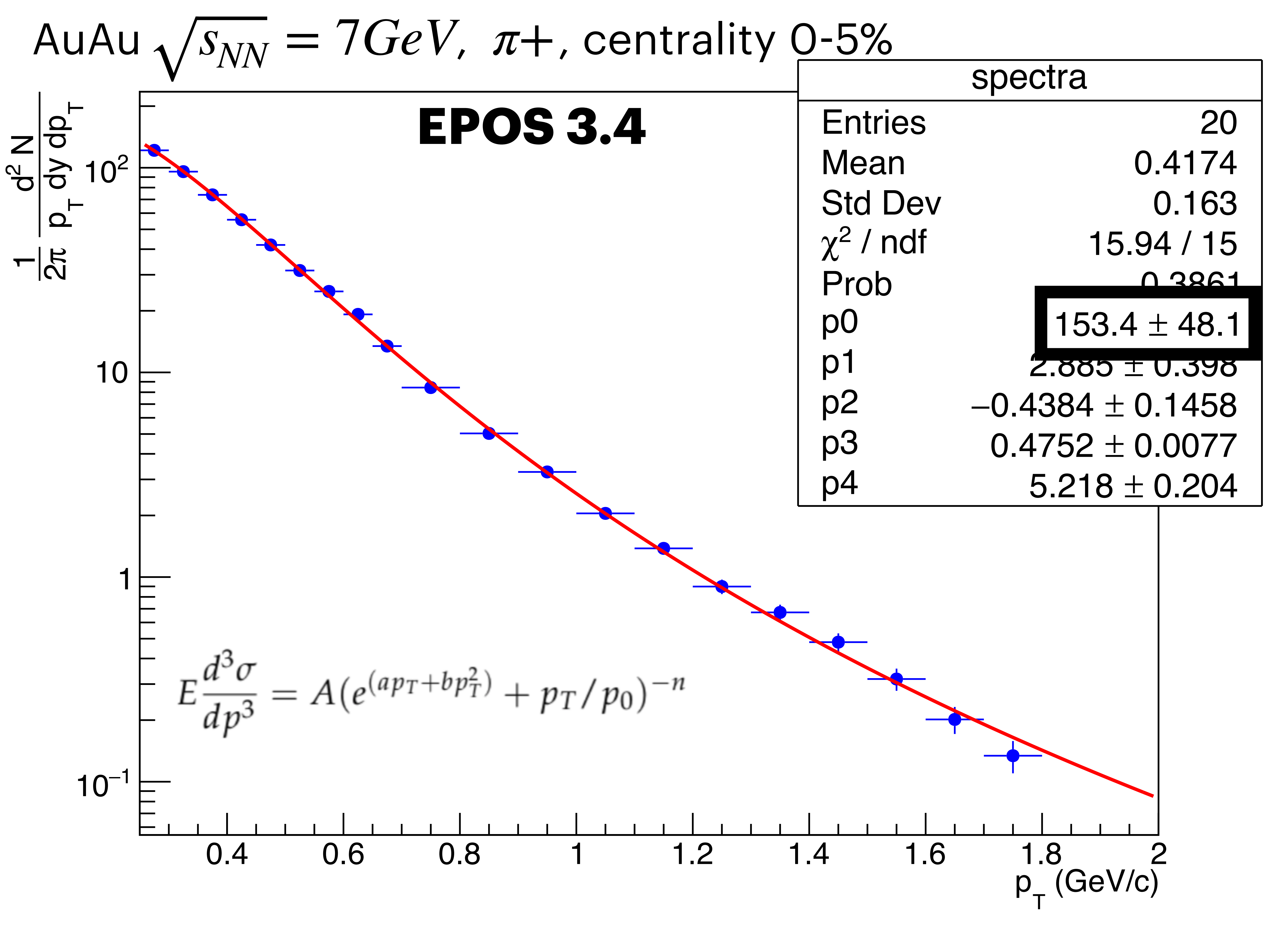
THANK YOU FOR ATTENTION

THANK YOU FOR ATTENTION

My question: Is there snow already in Budapest ?

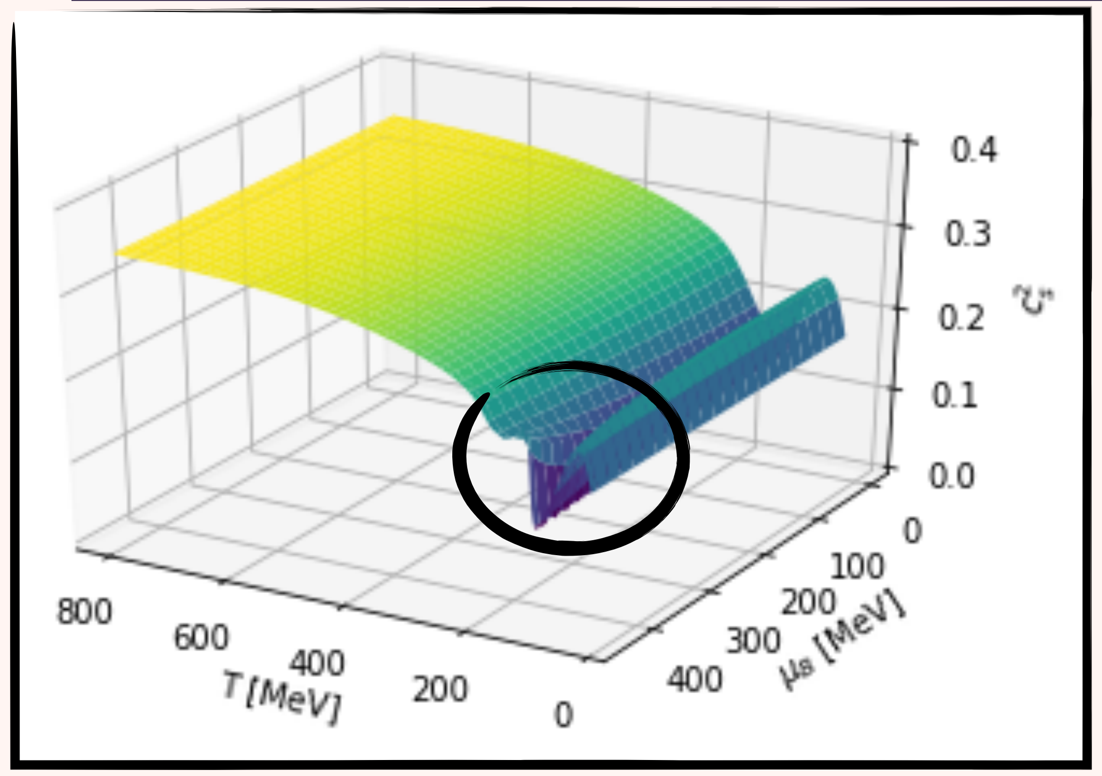
BEST EOS WITH CP

Locate approximately „where we are"



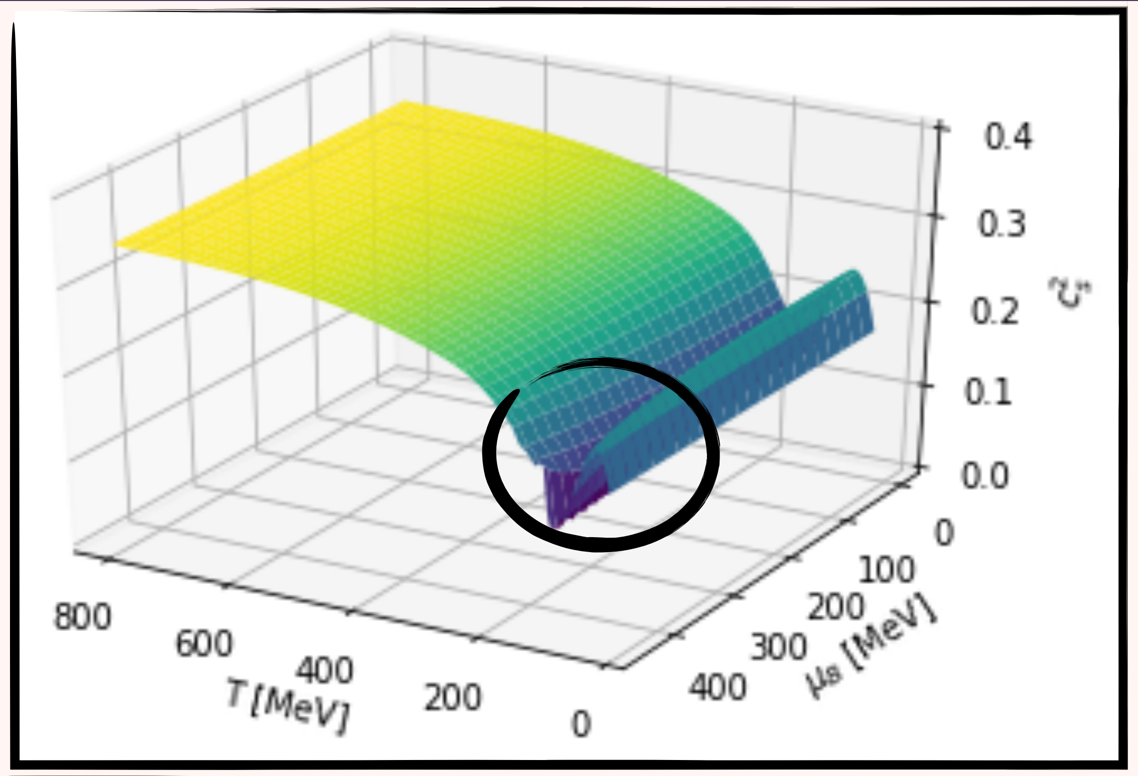
Temperature of chemical freeze-out

BEST 1: PAR 155 -0.0149 350 90 1 2

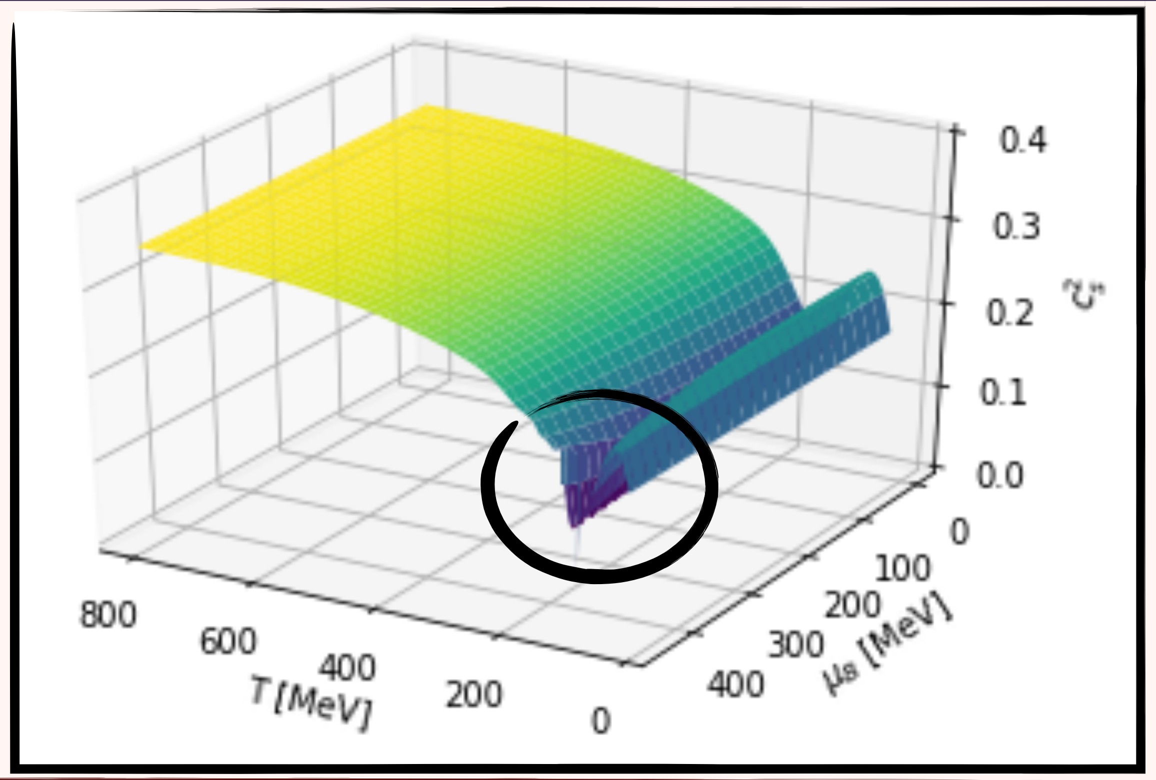


c_s^2

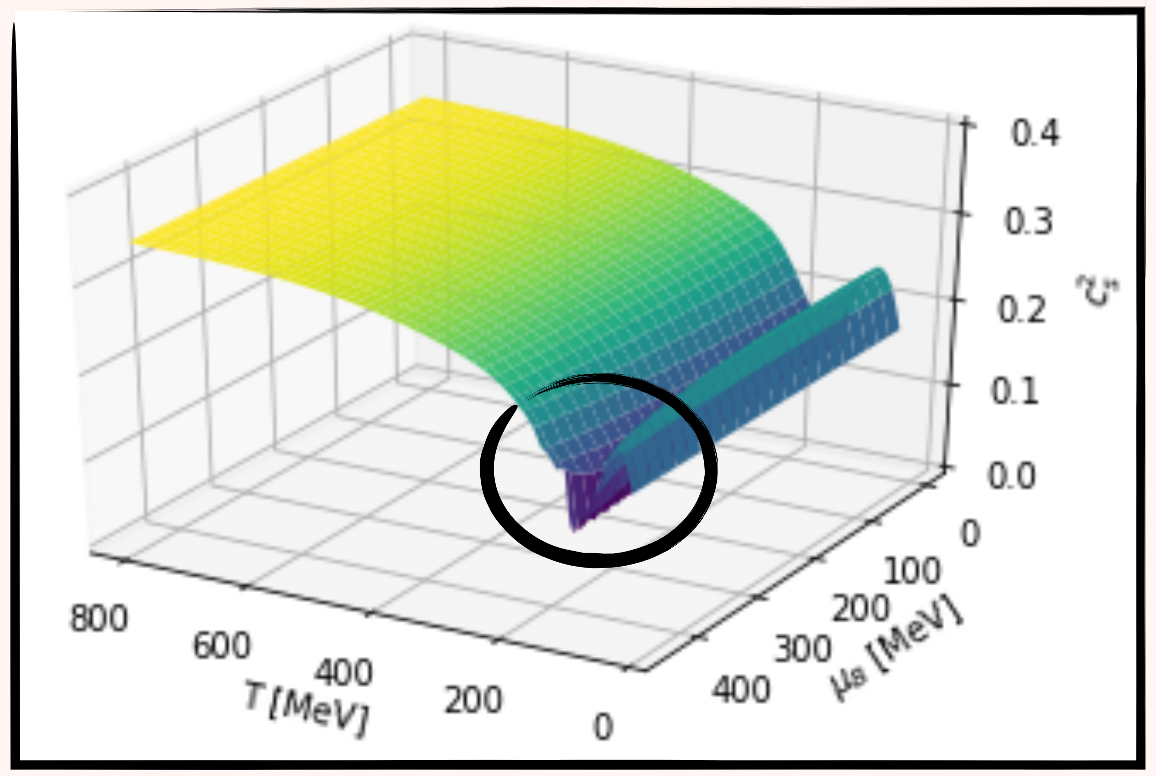
BEST 2: PAR 155 -0.0149 350 90 4 1



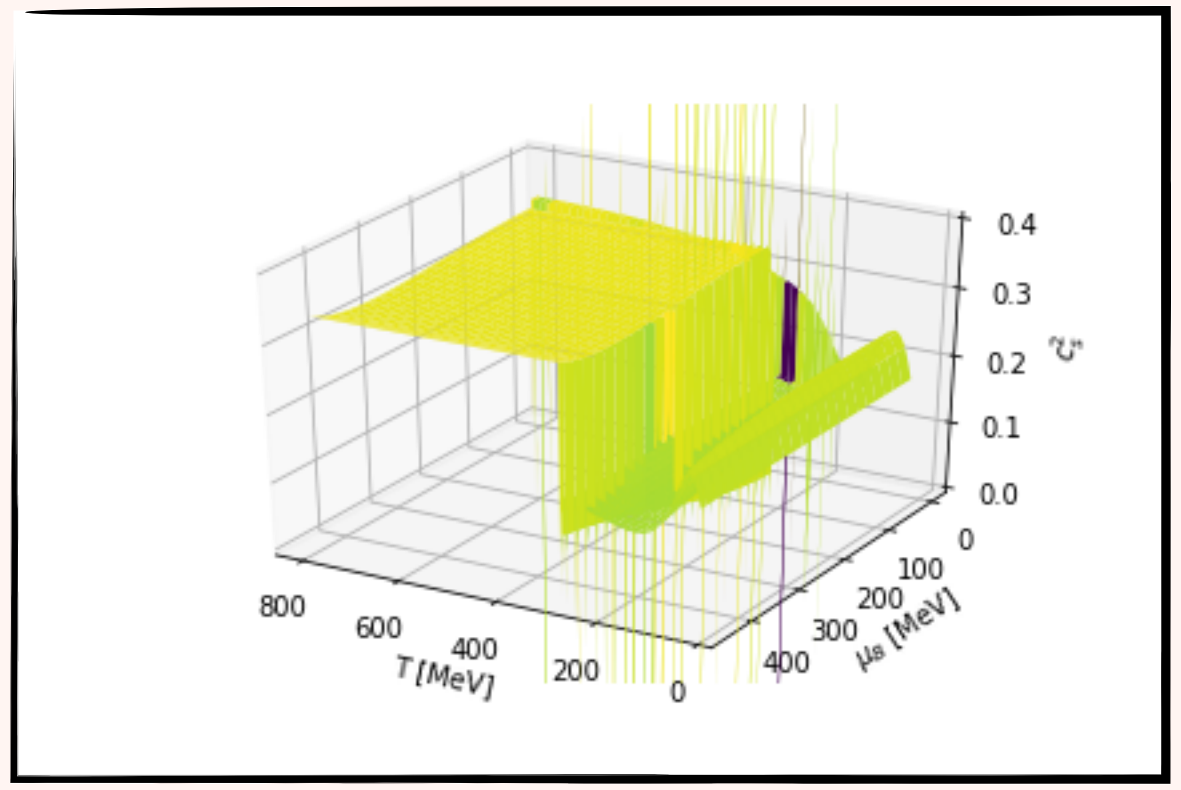
BEST 3: PAR 155 -0.0149 420 90 0.75 2



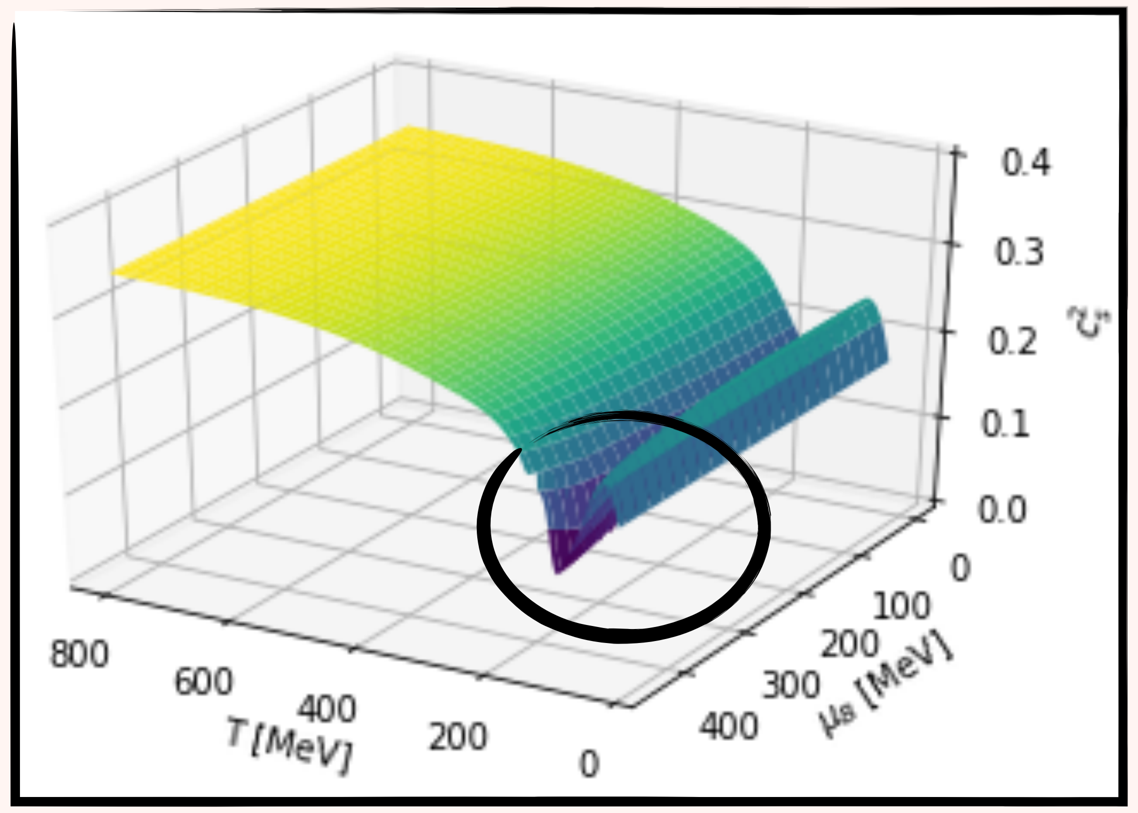
BEST 4: PAR 155 -0.0149 350 90 10 1



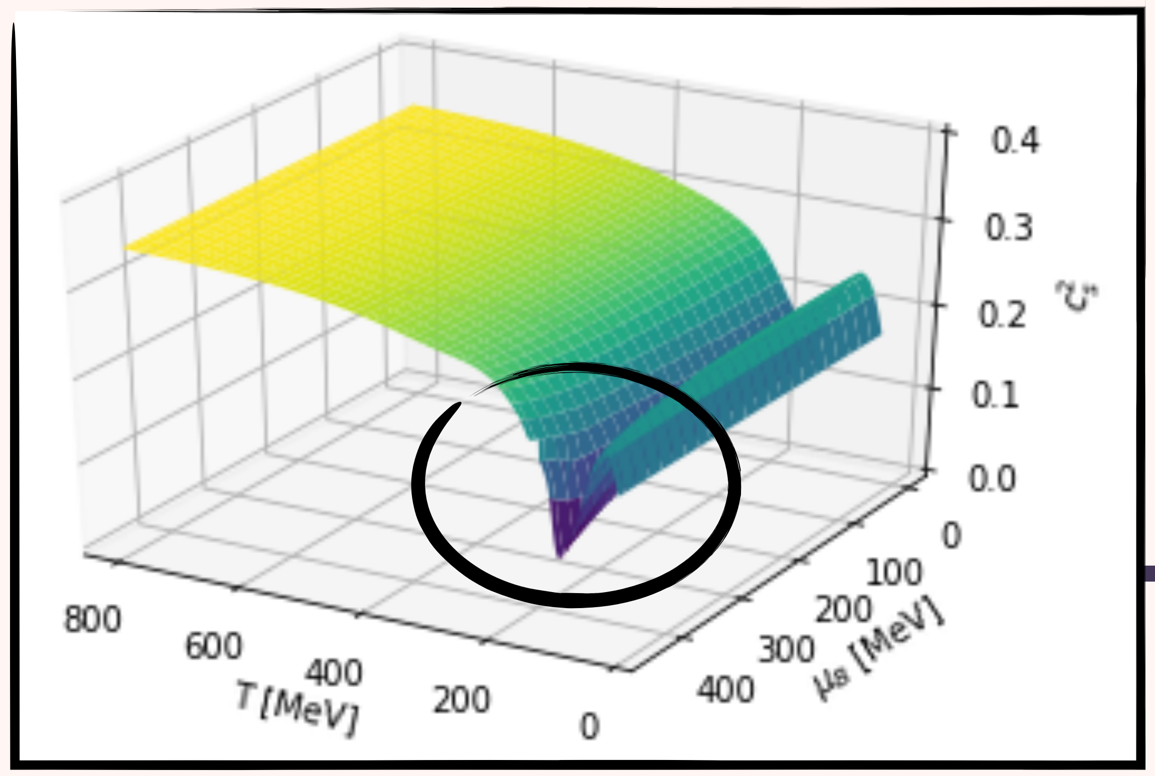
BEST 5: PAR 169 -0.0149 420 90 0.25 2



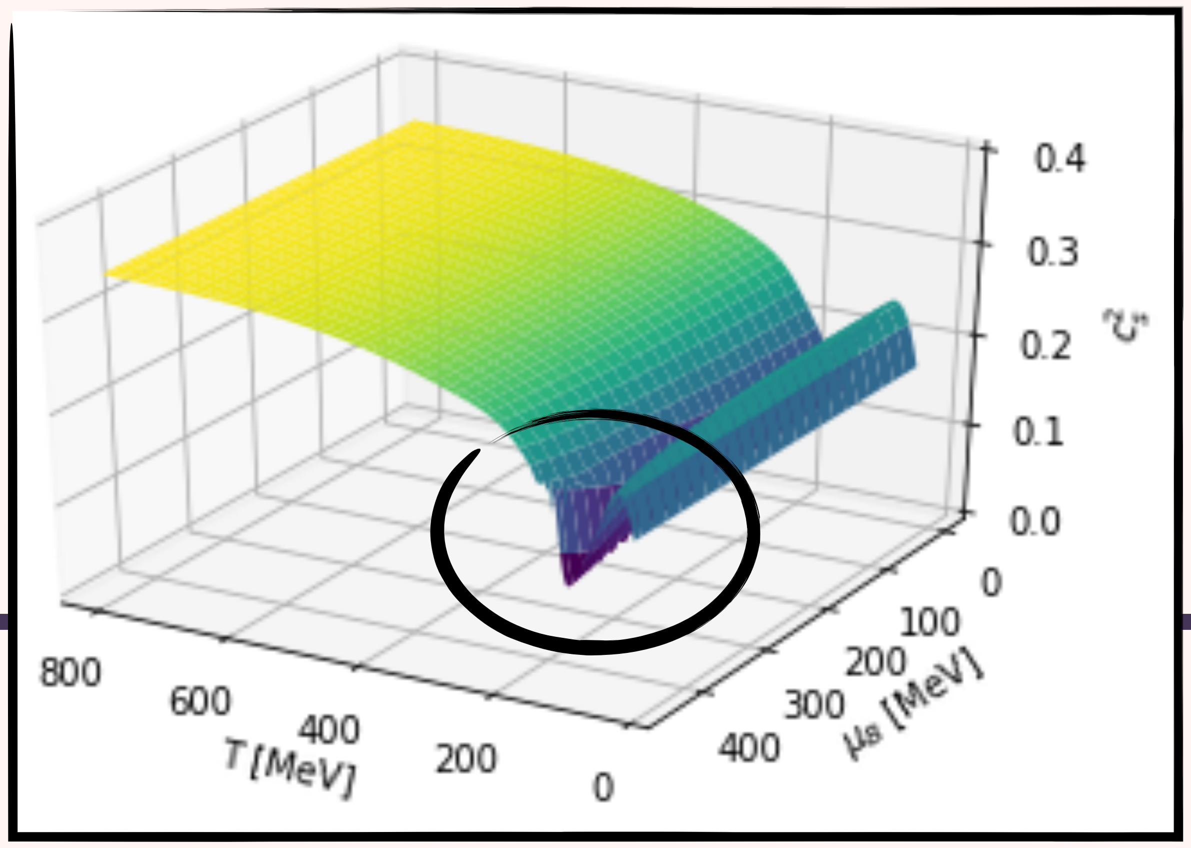
BEST 6: PAR 169 -0.0149 420 90 1 1



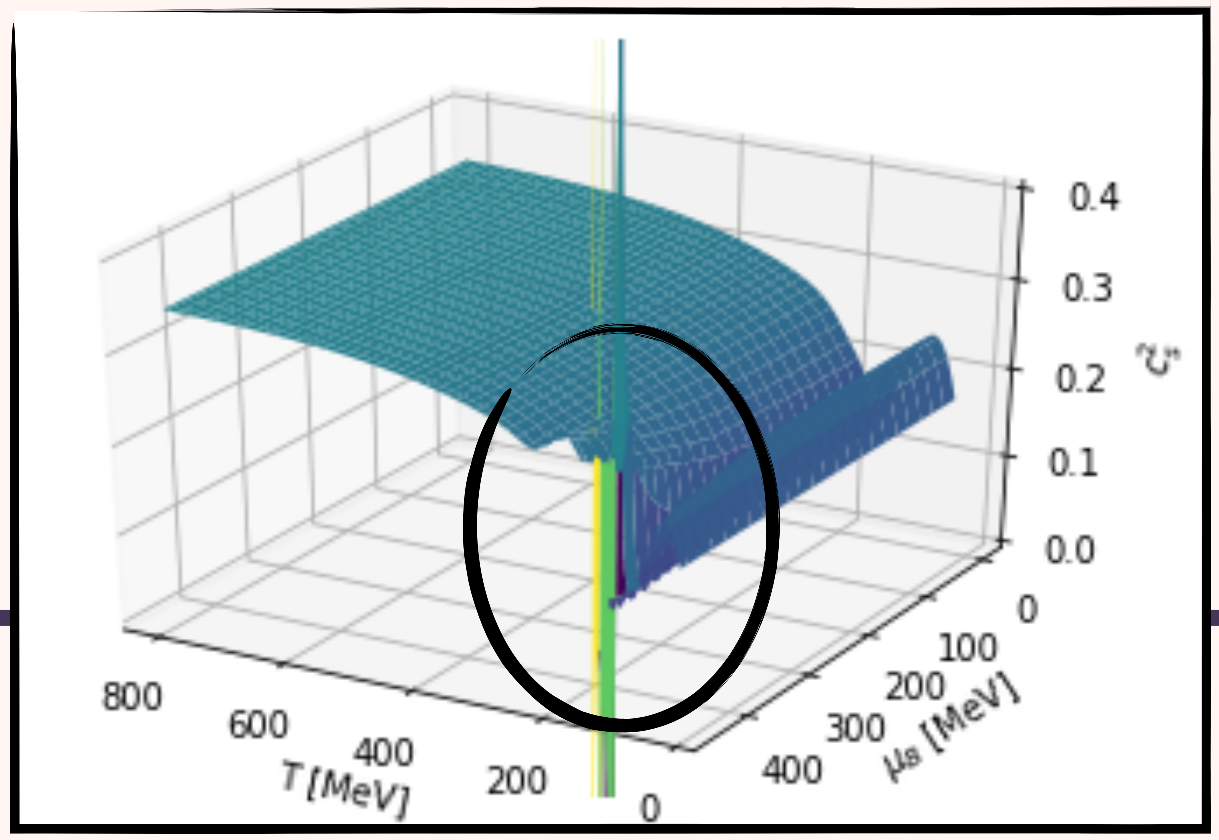
BEST 7: PAR 169 -0.0149 420 90 0.5 1



BEST 8: PAR 174 -0.0149 440 90 1 1

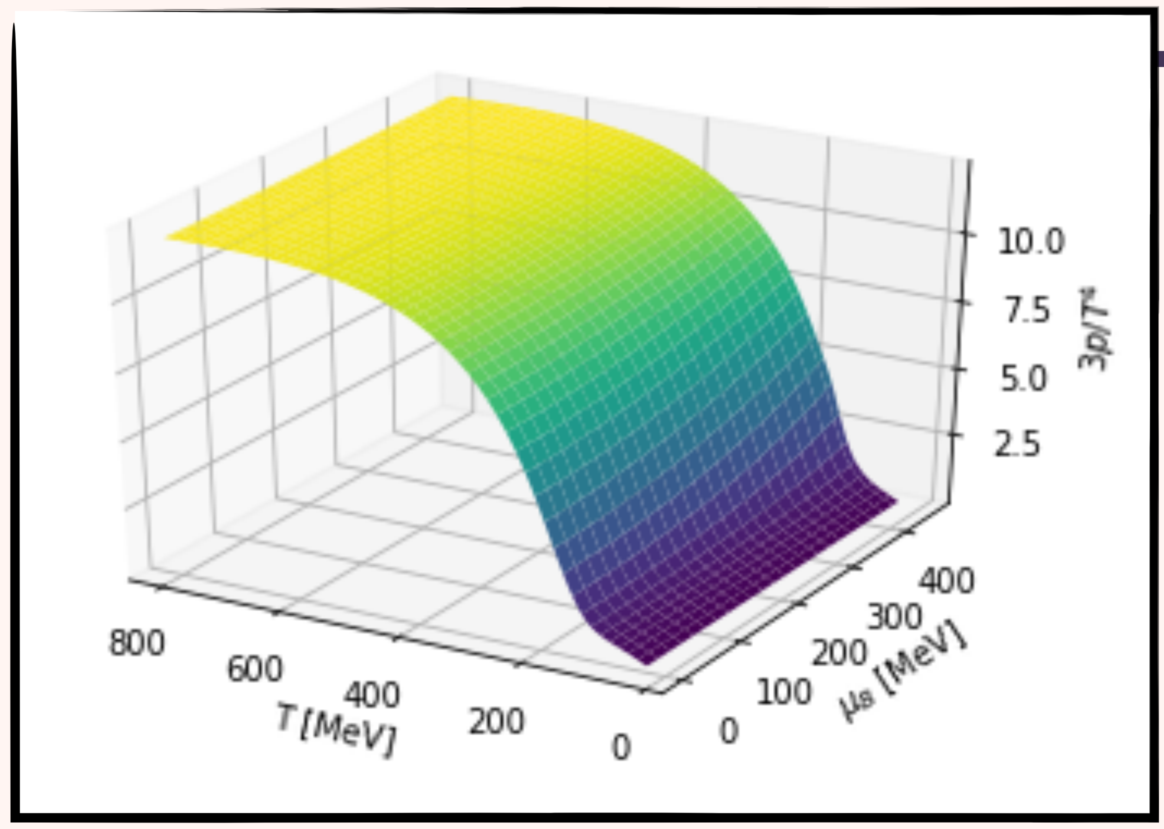


BEST 9: PAR 178 -0.0149 300 90 1 1

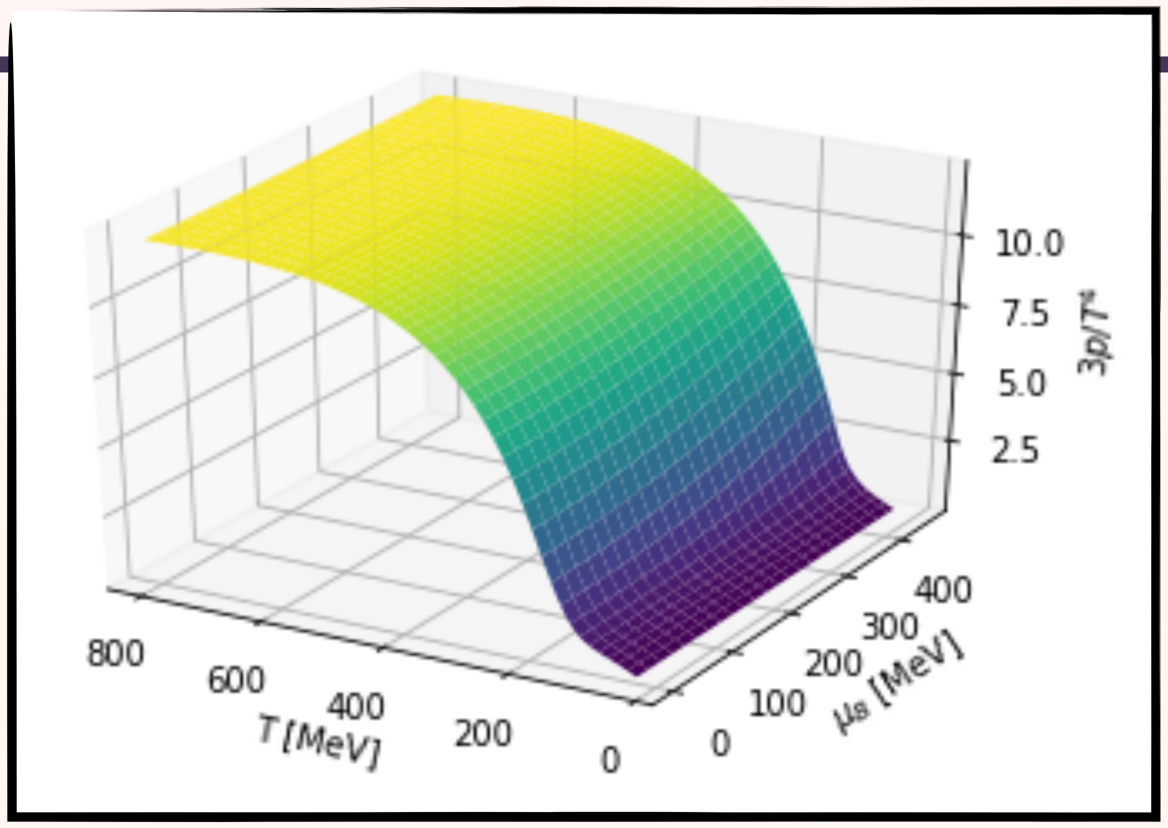


$3p/T^4$

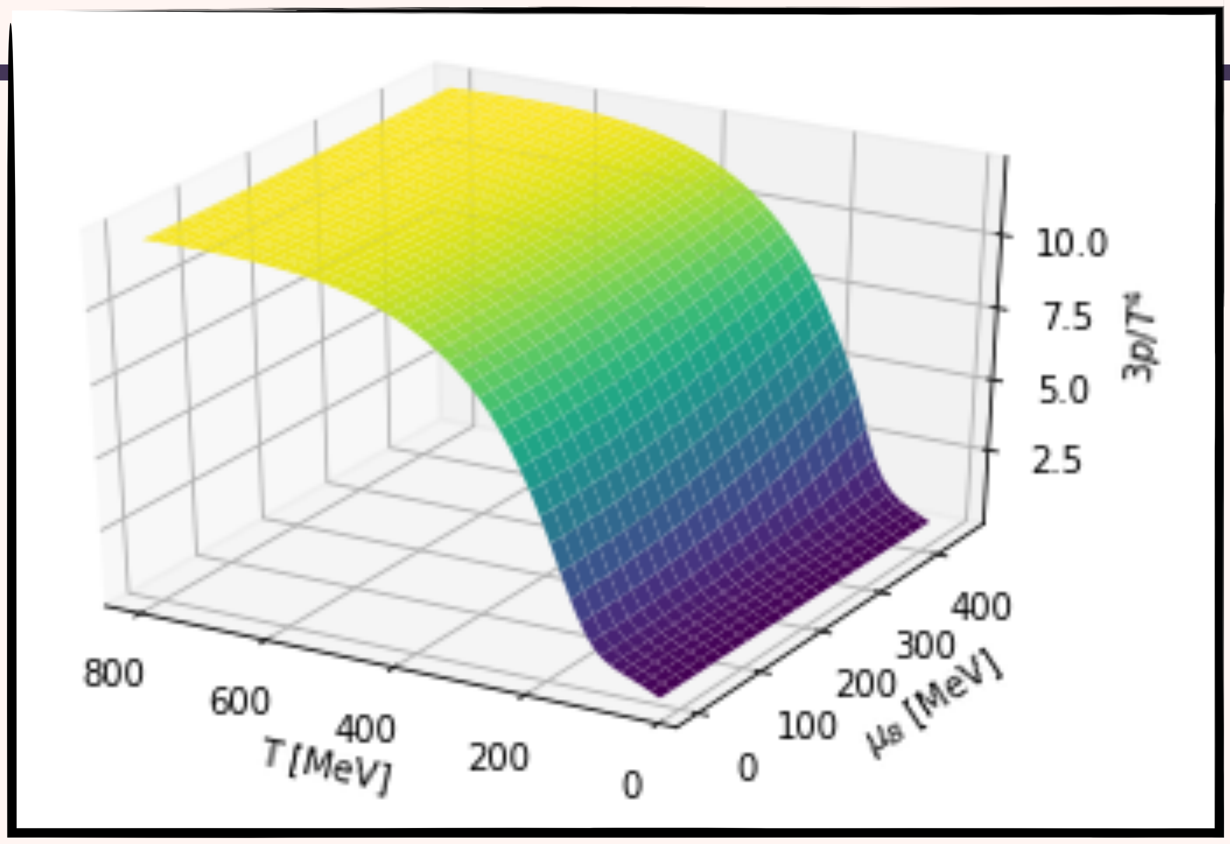
BEST 1: PAR 155 -0.0149 350 90 1 2



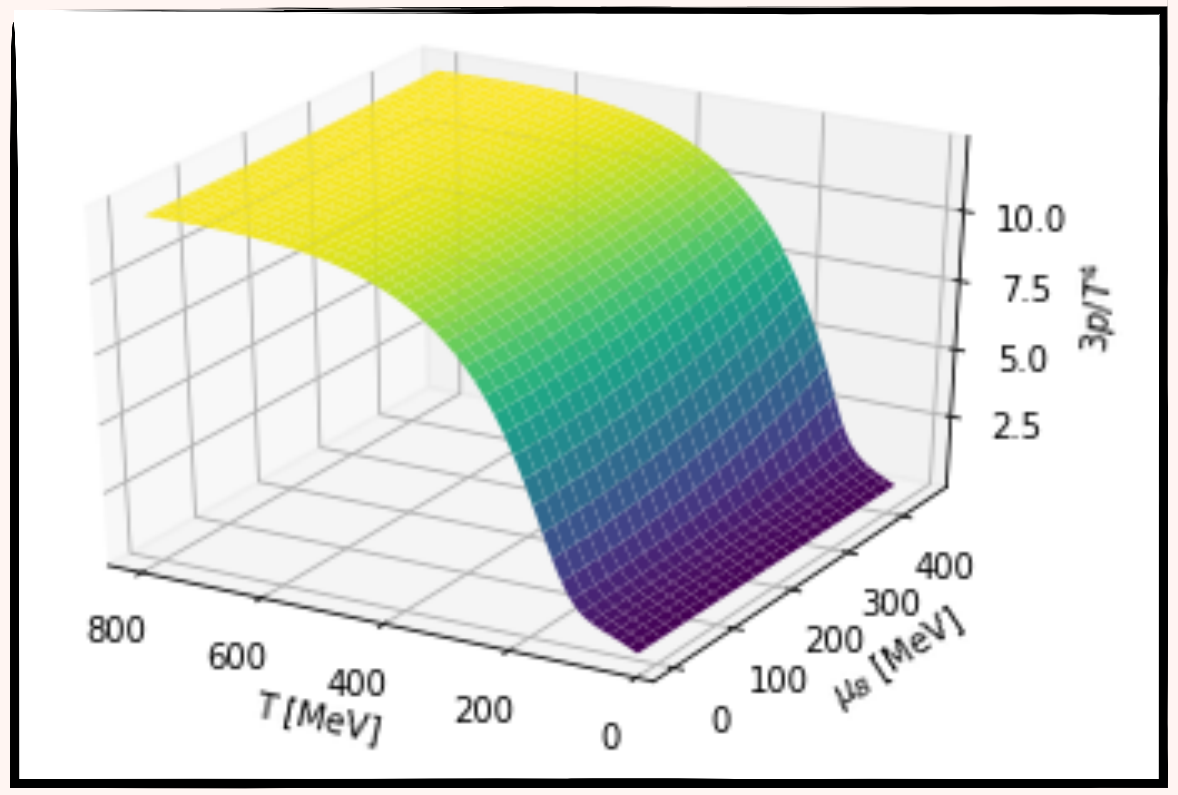
BEST 2: PAR 155 -0.0149 350 90 4 1



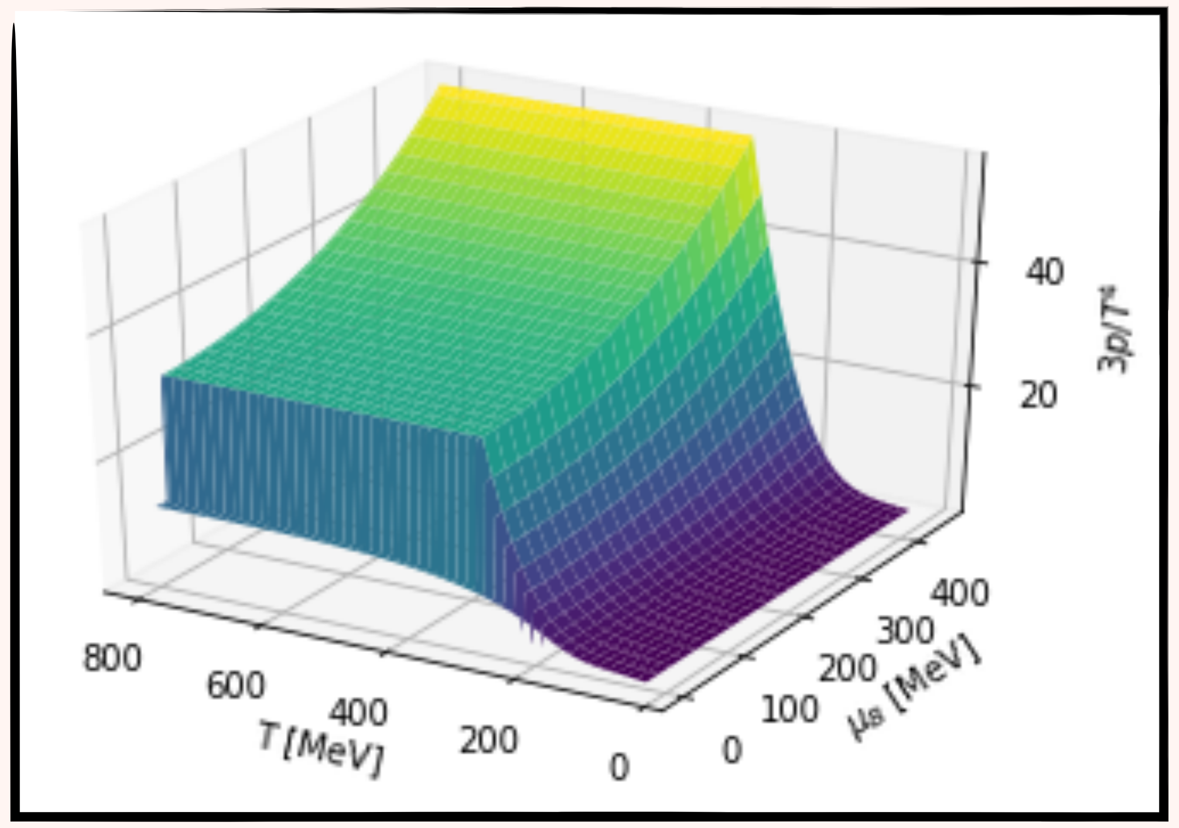
BEST 3: PAR 155 -0.0149 420 90 0.75 2



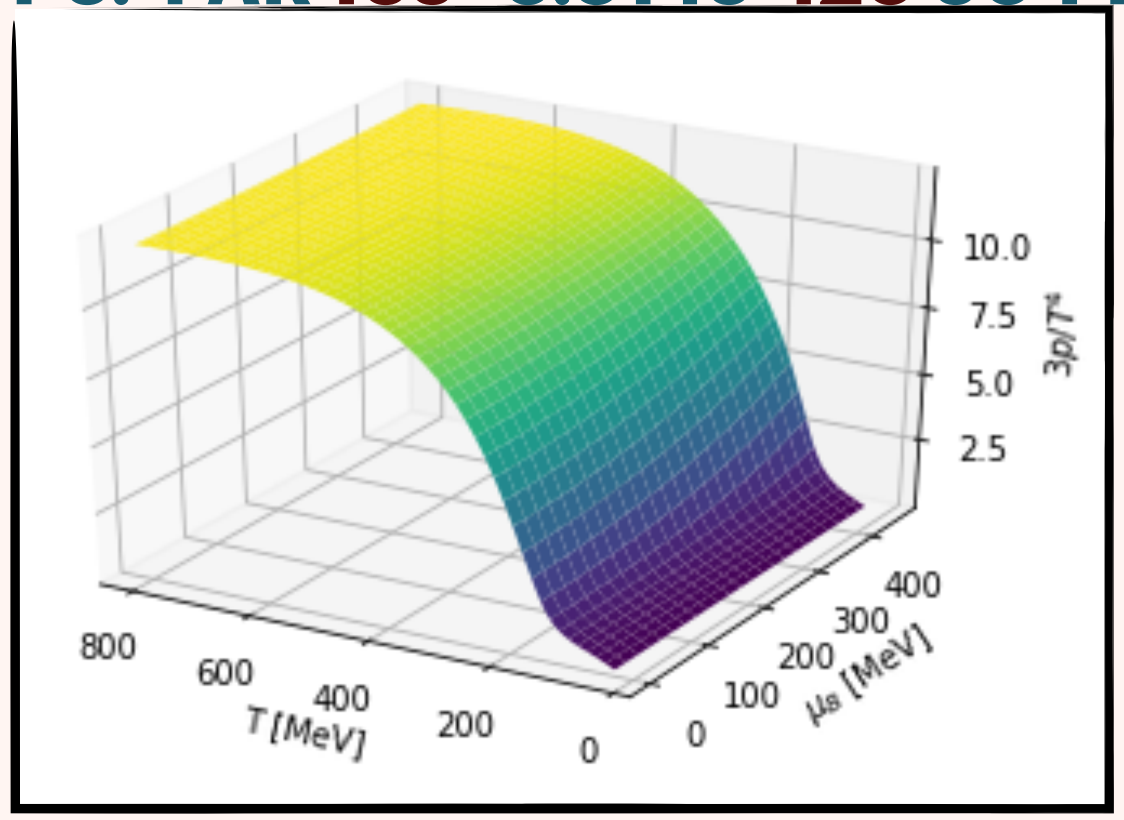
BEST 4: PAR 155 -0.0149 350 90 10 1



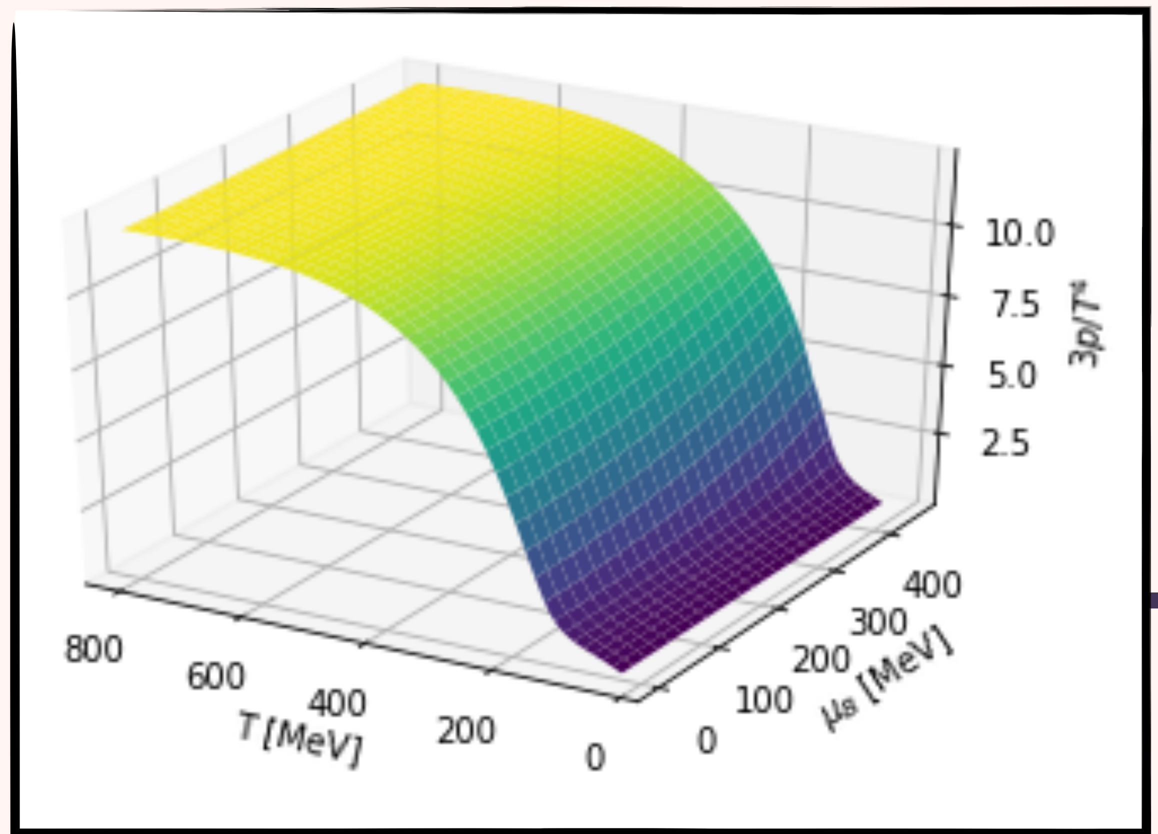
BEST 5: PAR 169 -0.0149 420 90 0.25 2



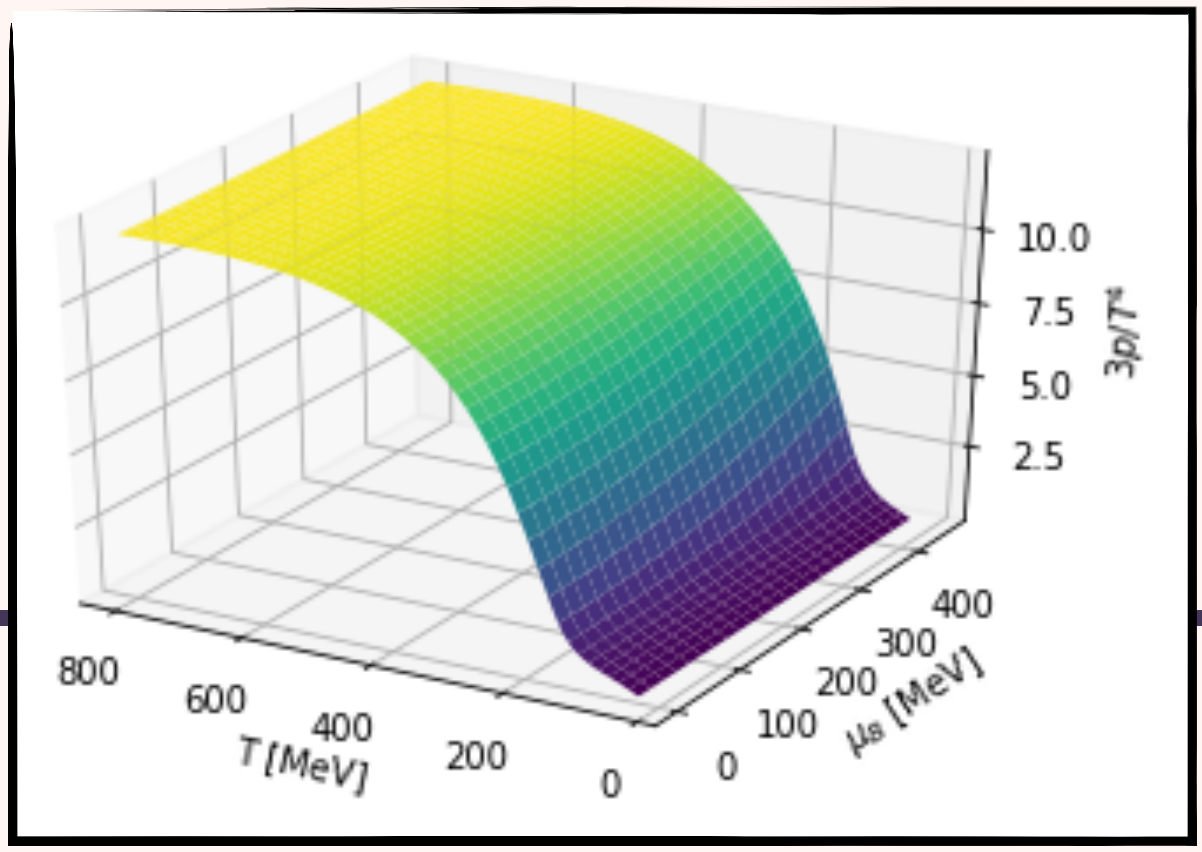
BEST 6: PAR 169 -0.0149 420 90 1 1



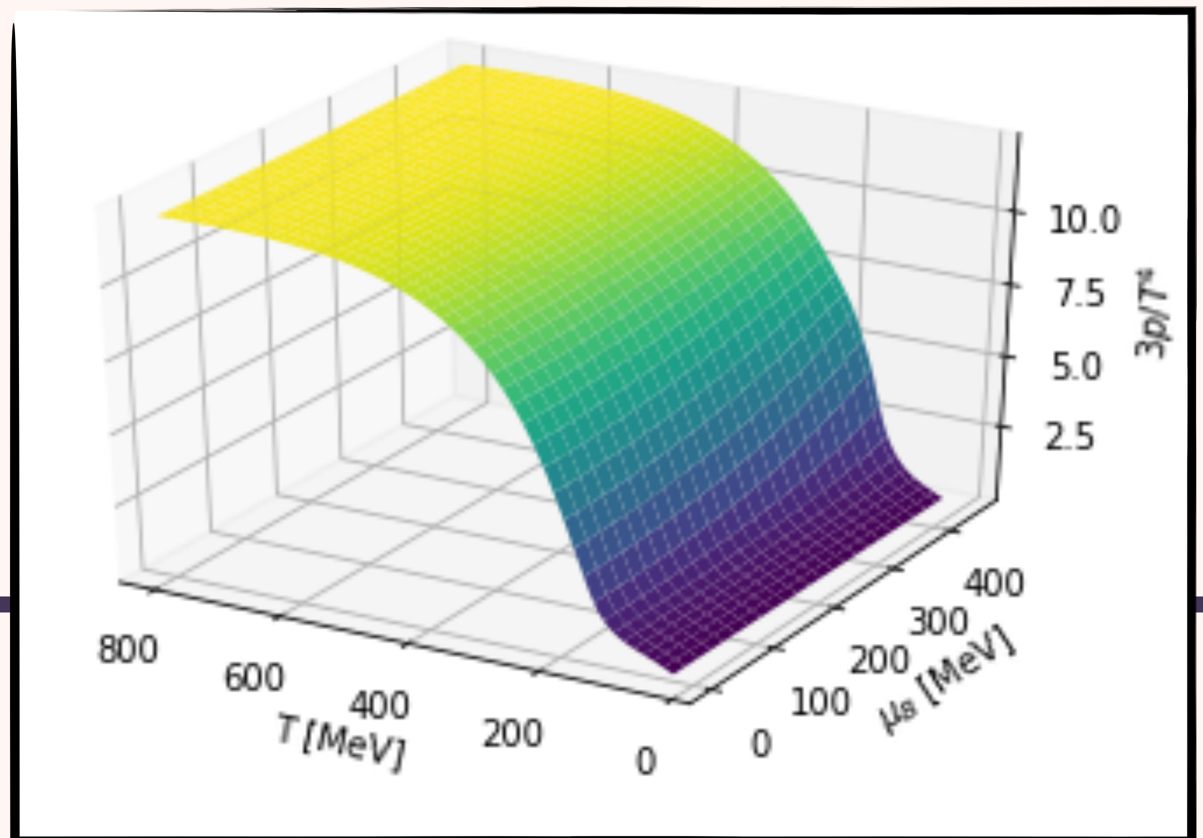
BEST 7: PAR 169 -0.0149 420 90 0.5 1



BEST 8: PAR 174 -0.0149 440 90 1 1



BEST 9: PAR 178 -0.0149 300 90 1 1



BEST EOS WITH CP

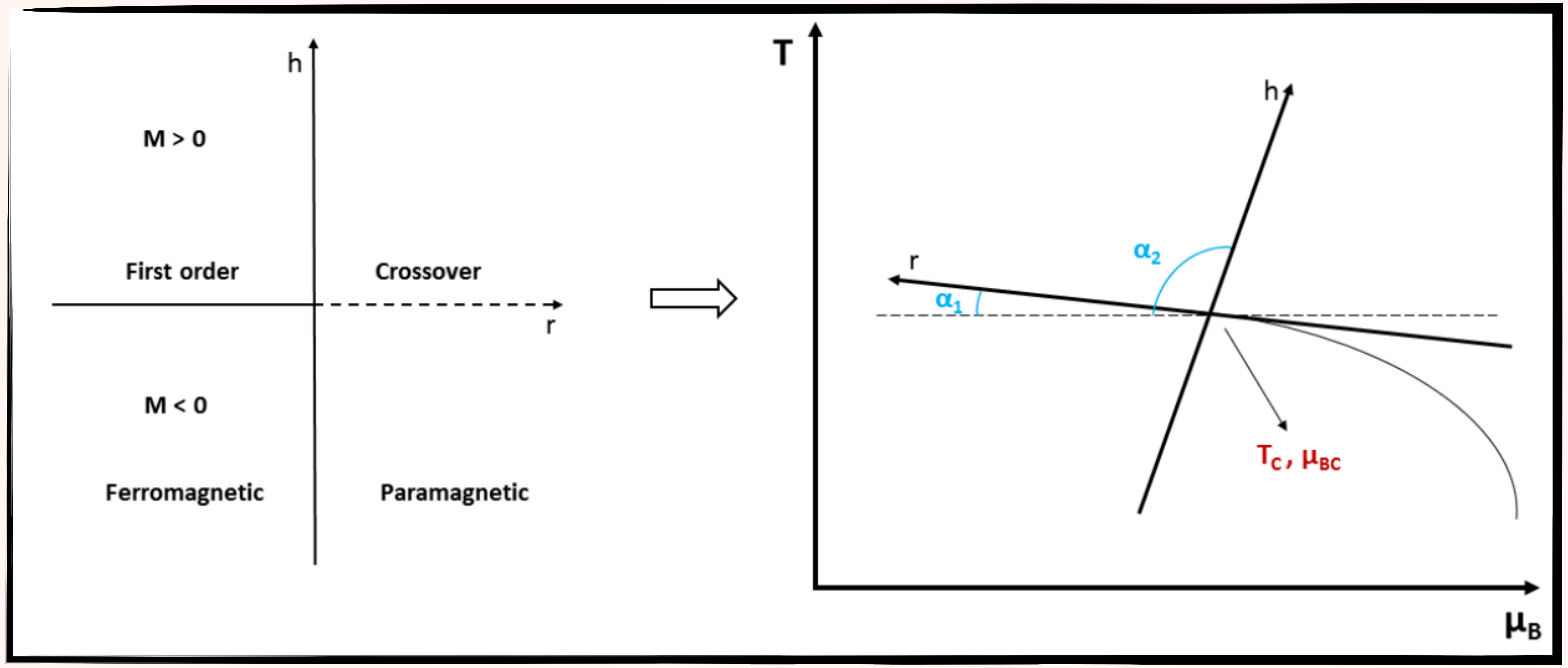
* Phys. Rev. C 101, 034901 (2020)
* Nucl. Phys. A 982 (2019)

$$\frac{T-T_C}{T_C} = \omega(r\rho\sin\alpha_1 + h sin\alpha_2)$$

$$\frac{\mu_B-\mu_{BC}}{T_C} = \omega(-r\rho\cos\alpha_1 - h cos\alpha_2)$$

ω - the global scaling parameter in the mapping

ρ - the relative scaling in the mapping



BEST EOS WITH CP

PAR	155	-0.0149	350	90	4	1
Parabola	T	curvature	μ_{BC}	$\alpha_1 - \alpha_2$	ω	ρ

1) PAR 155 -0.0149 350 90 1 2 ➜ PAR_143_350_3_93_143_286
2) PAR 155 -0.0149 350 90 4 1 ➜ PAR_143_350_3_93_572_572
3) PAR 155 -0.0149 420 90 0.75 2 ➜ PAR_138_420_4_94_103_207
4) PAR 155 -0.0149 350 90 10 1 ➜ PAR_143_350_3_93_1432_1432
5) PAR 169 -0.0149 420 90 0.25 2 ➜ PAR_165_3_86_179_23599_6749314
6) PAR 169 -0.0149 420 90 1 1 ➜ PAR_153_420_4_94_153_153
7) PAR 169 -0.0149 420 90 0.5 1 ➜ PAR_153_420_4_94_76_76
8) PAR 174 -0.0149 440 90 1 1 ➜ PAR_157_440_4_94_157_157
9) PAR 178 -0.0149 300 90 1 1 ➜ PAR_170_300_2_92_170_170

BEST EOS WITH CP

Parabola	T	curvature	μ_{BC}	$\alpha_1 - \alpha_2$	ω	ρ
PAR	155	-0.0149	350	90	4	1

1) PAR 155 -0.0149 350 90 1 2 ➜ PAR_143_350_3_93_143_286
2) PAR 155 -0.0149 350 90 4 1 ➜ PAR_143_350_3_93_572_572
3) PAR 155 -0.0149 420 90 0.75 2 ➜ PAR_138_420_4_94_103_207
4) PAR 155 -0.0149 350 90 10 1 ➜ PAR_143_350_3_93_1432_1432
~~5) PAR 169 -0.0149 420 90 0.25 2 ➜ PAR_165_0_86_179_23599_6749314~~
6) PAR 169 -0.0149 420 90 1 1 ➜ PAR_153_420_4_94_153_153
7) PAR 169 -0.0149 420 90 0.5 1 ➜ PAR_153_420_4_94_76_76
8) PAR 174 -0.0149 440 90 1 1 ➜ PAR_157_440_4_94_157_157
9) PAR 178 -0.0149 300 90 1 1 ➜ PAR_170_300_2_92_170_170