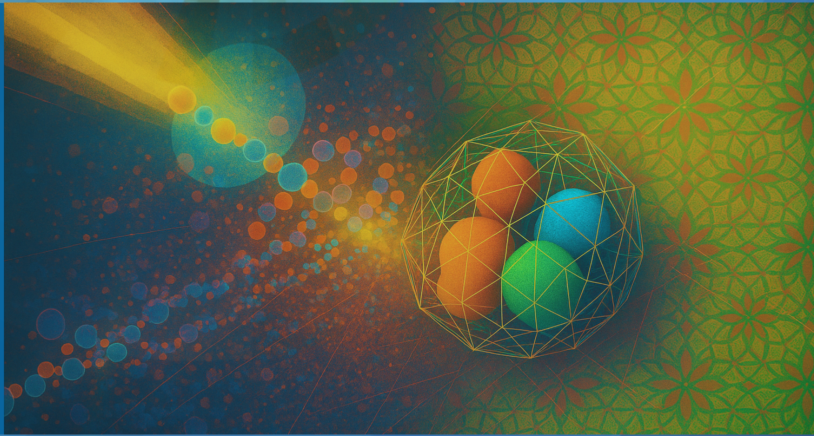
JUNE 25, 2025

THERMAL AND NON-THERMAL PRODUCTION OF FINAL STATE HADRONS ACROSS DIFFERENT COLLISION SYSTEMS

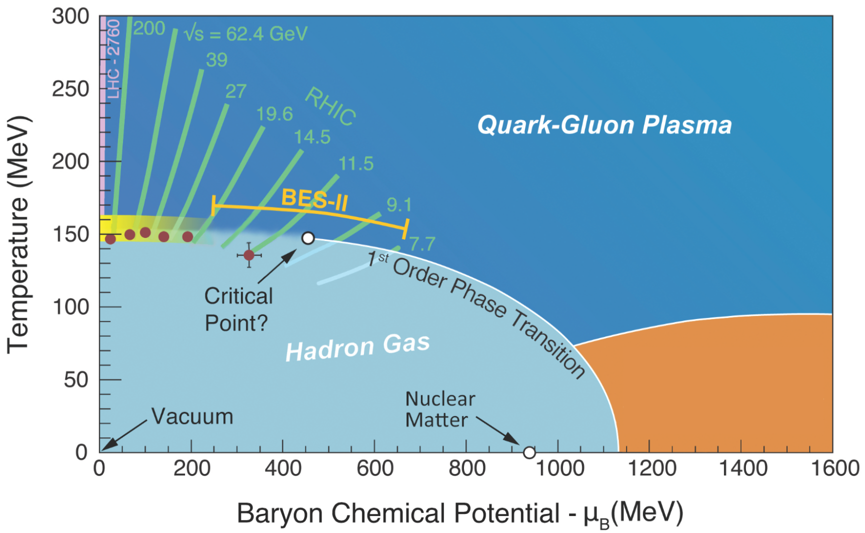


FERNANDO ANTONIO FLOR
Postdoctoral Appointee
fflor@anl.gov

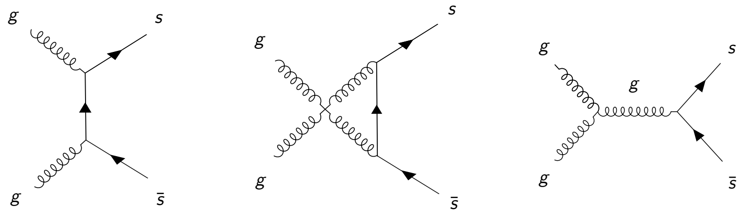
2025 Light Ion Physics in the EIC Era Summer School
Miami, Florida

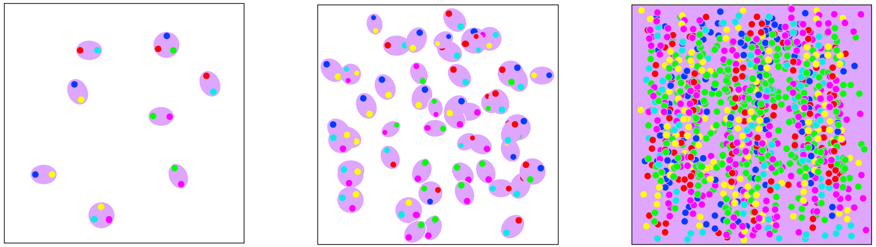
STRANGE BEGINNINGS

B. Müller. *Phys. Rev. Lett.* **56** (1986)
S. Mukherjee. *Brookhaven National Lab* (2016)



- *The enhanced production* of **strange** and **multi-strange** hadrons was the first suggested signature of a *deconfined state of quarks and gluons*
  - Above a characteristic temperature, $s\bar{s}$ pair production from *gg* fusion is highly favorable
    - Not the case from purely hadronic phase





$T < T_C$ $T \sim T_C$ $T > T_C$

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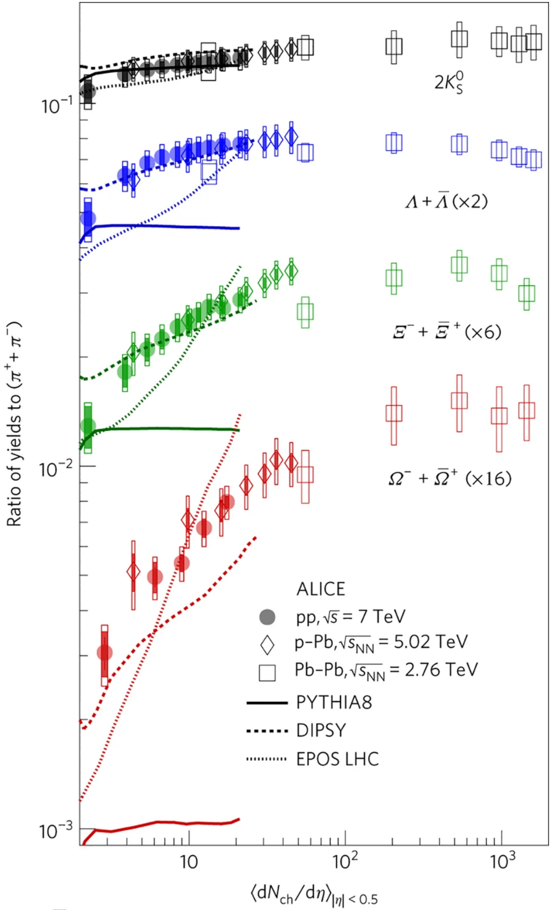
ALICE Collaboration. *Nature Phys.* **13** (2017)



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"Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions"

- Strange hadron to π yield ratios show increased enhancement WRT strangeness content
  - Rising slope parameters as strangeness increases
  - Saturation just above high-multiplicity pp limit
  - Smooth trend apparent as function of system size

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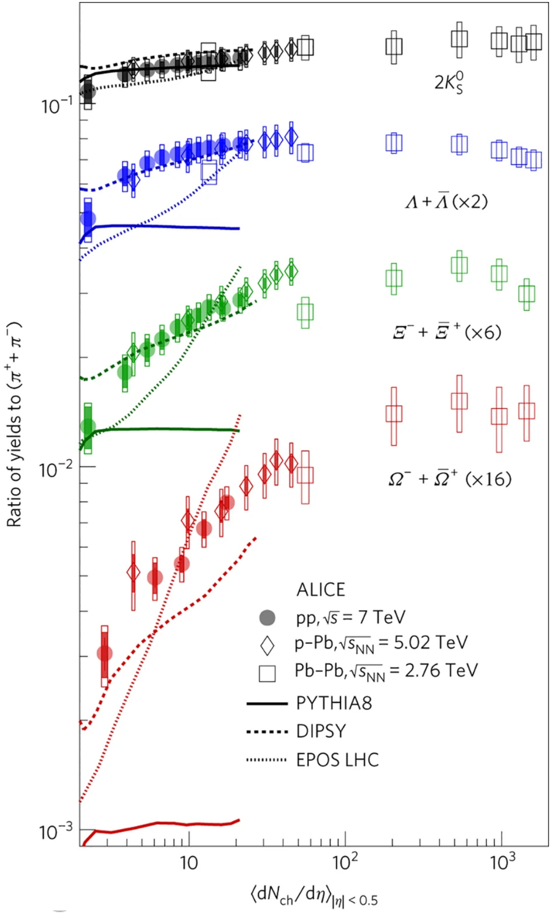

|S| = 1

|S| = 2

|S| = 3

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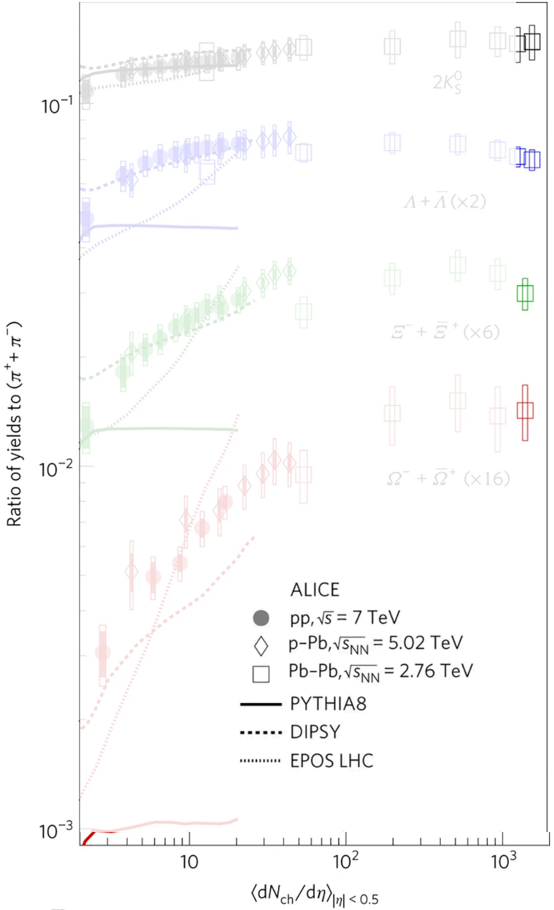

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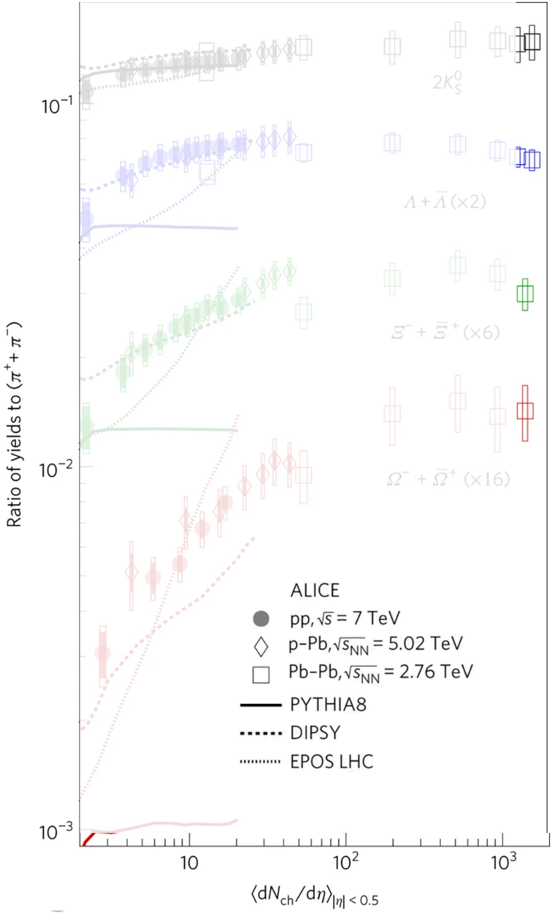

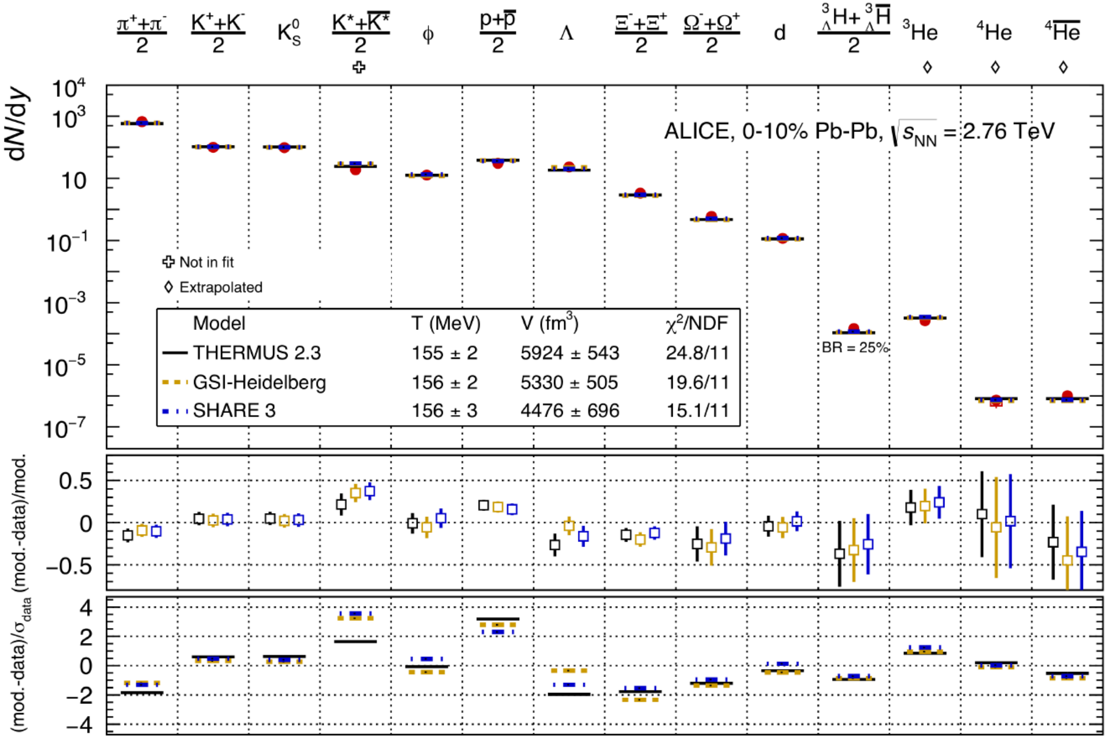

STATISTICAL HADRONIZATION

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ALICE Collaboration. *Nucl. Phys. A.* **971** (2018)

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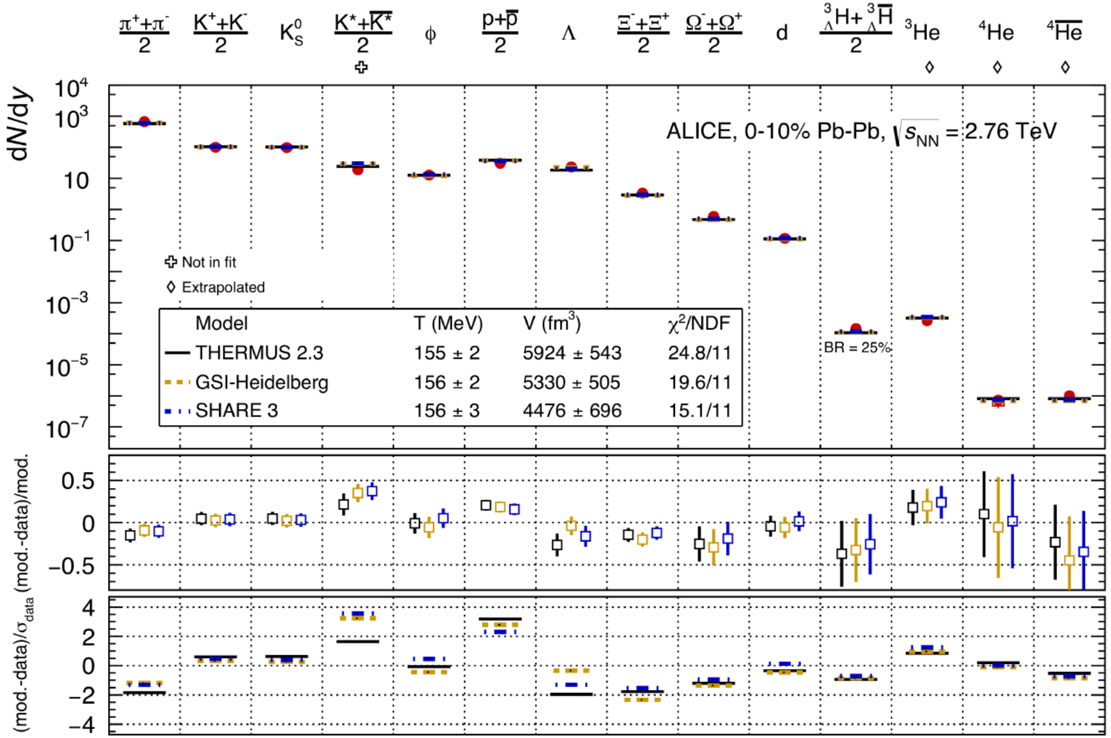


STATISTICAL HADRONIZATION

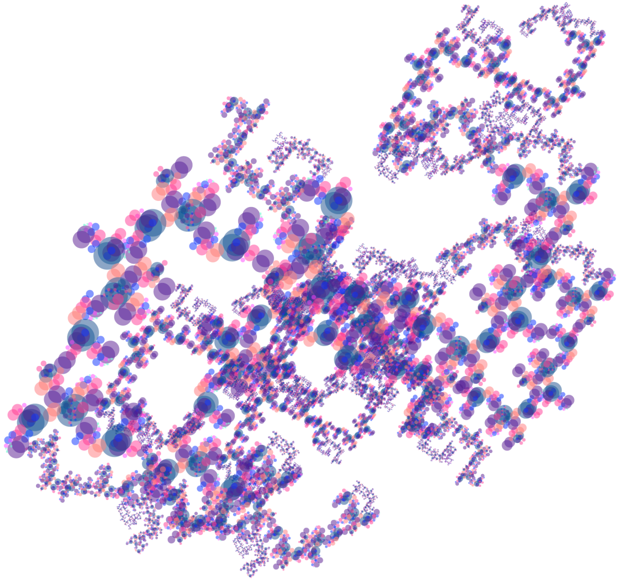
- Basic Assumptions
  - Thermally Equilibrated System at chemical freeze-out
  - Freeze-out temperature (T_{ch}), volume (V), chemical potential (μ) and particle yields (N_i) are constant

- By knowing N_i, one can calculate T_{ch}, V and μ
- Conversely, knowing T_{ch}, V and μ, N_i is calculated

$$p(T,\mu) = \sum_i p_i^{ideal}(T,\mu_i)$$

$$p_i^{ideal}(T,\mu_i) = \frac{d_i}{6\pi^2}\int_0^\infty \frac{k^4 dk}{\sqrt{k^2+m_i^2}}\left[exp\left(\frac{\sqrt{k^2+m_i^2}-\mu_i}{T}+\eta_i\right)\right]^{-1}$$

$$N_i = V\frac{d_i m_i^2 T}{2\pi^2}K_2\left(\frac{m_i}{T}\right)exp\left(\frac{\mu_i}{T}\right)$$

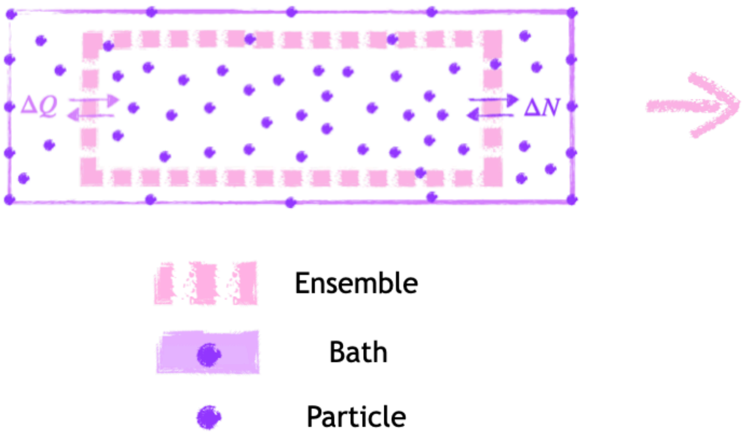


FAF. *Copy of a…* **Yale Cushing Whitney Medical Library** (2024)

à la Hagedorn: Highly interacting ground state hadrons can be well-described via a non-interacting (ideal) gas of hadrons and hadronic resonances due to the self-similarity of the system at every stage of its evolution

STATISTICAL HADRONIZATION

WLOG, a time averaged system ensemble can be equally represented by *infinitely* many system ensembles averaged at one instant in time



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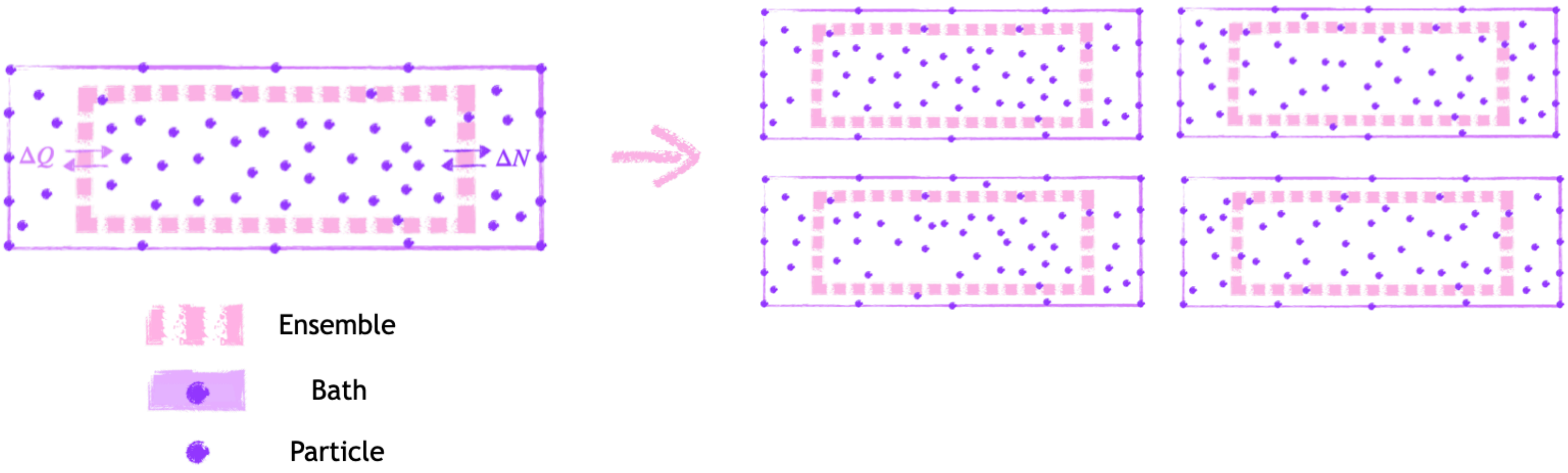

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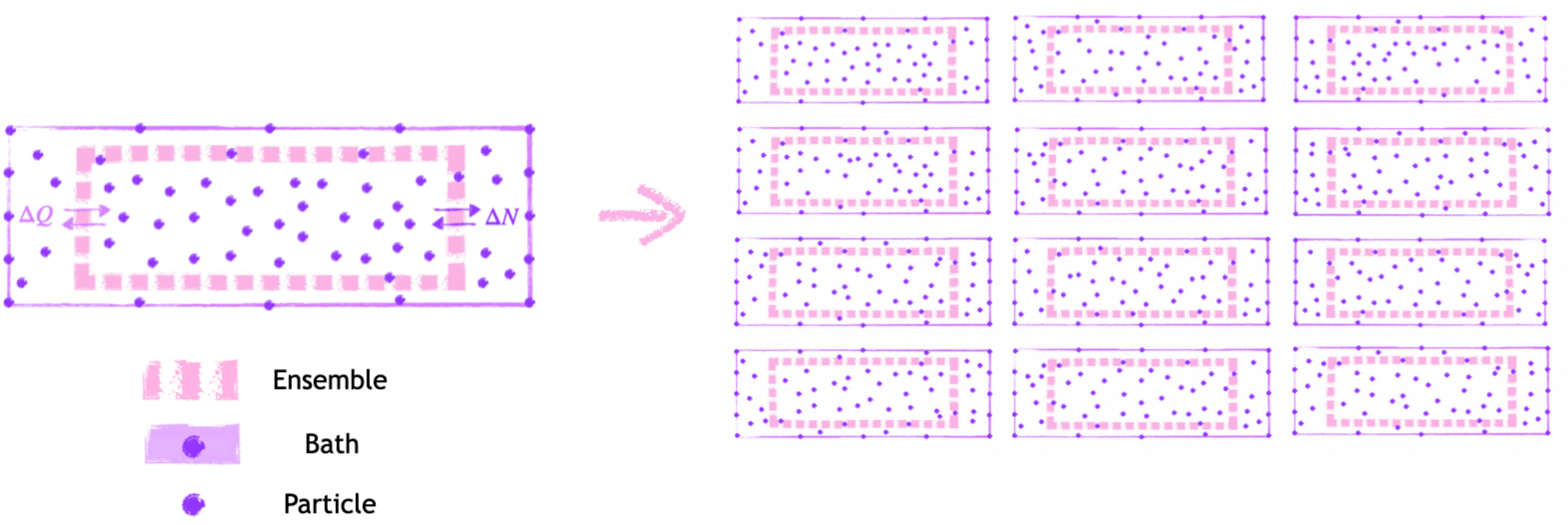

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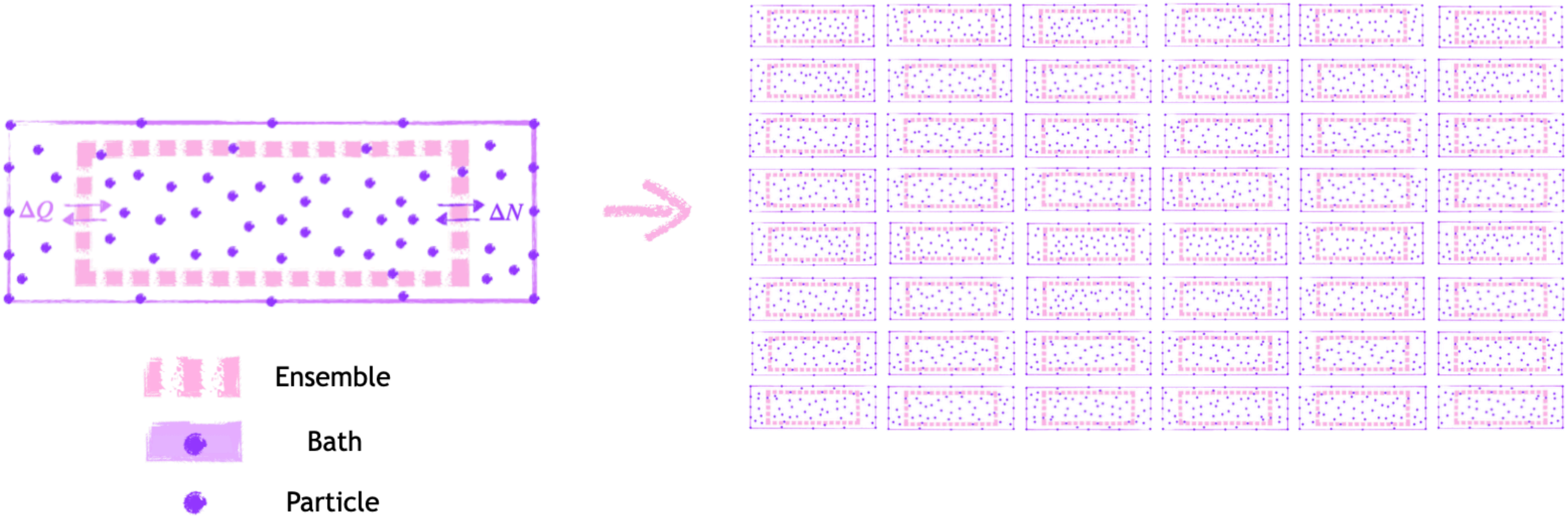

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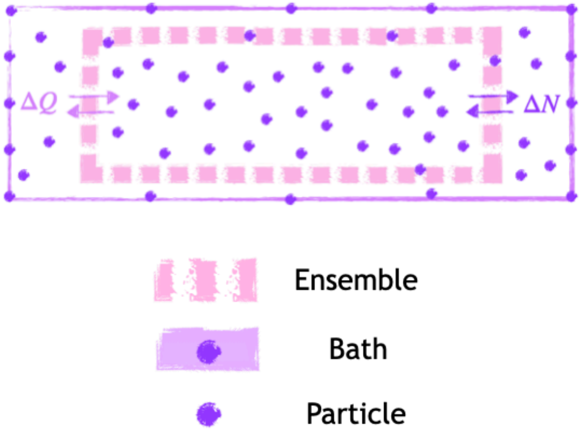

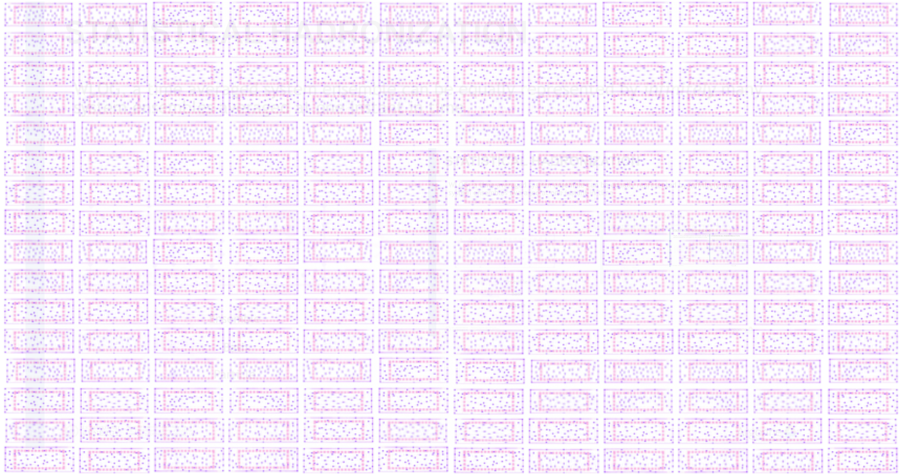

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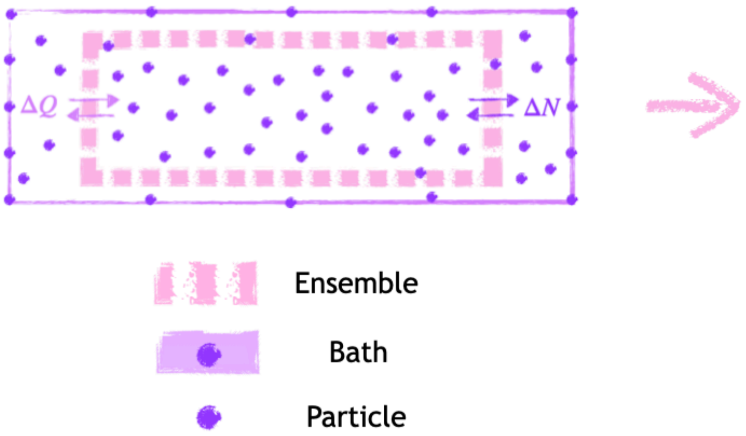

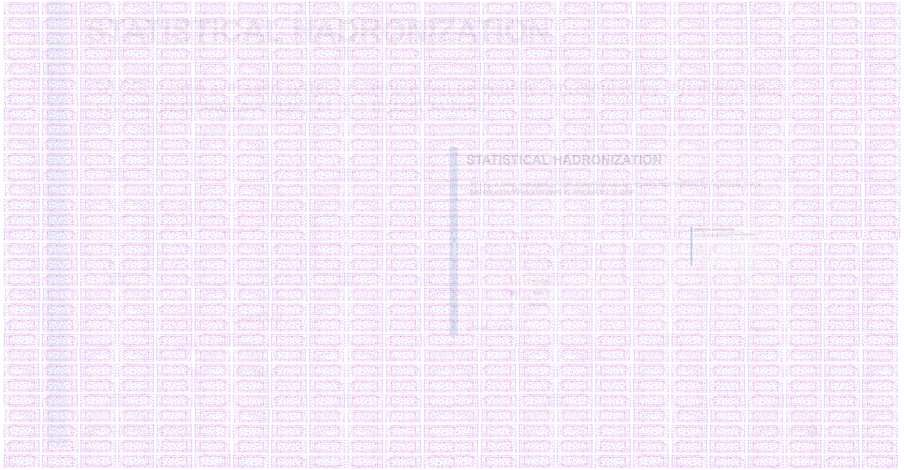

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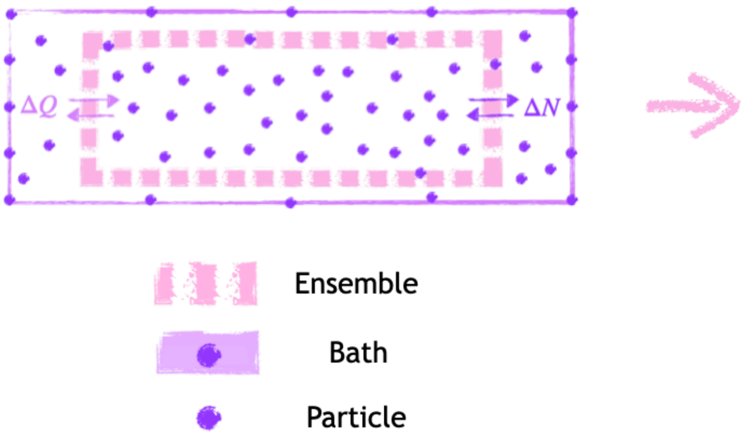

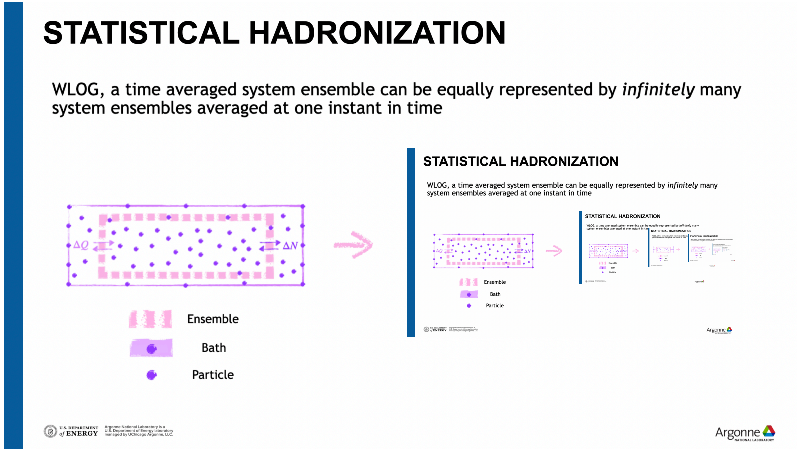

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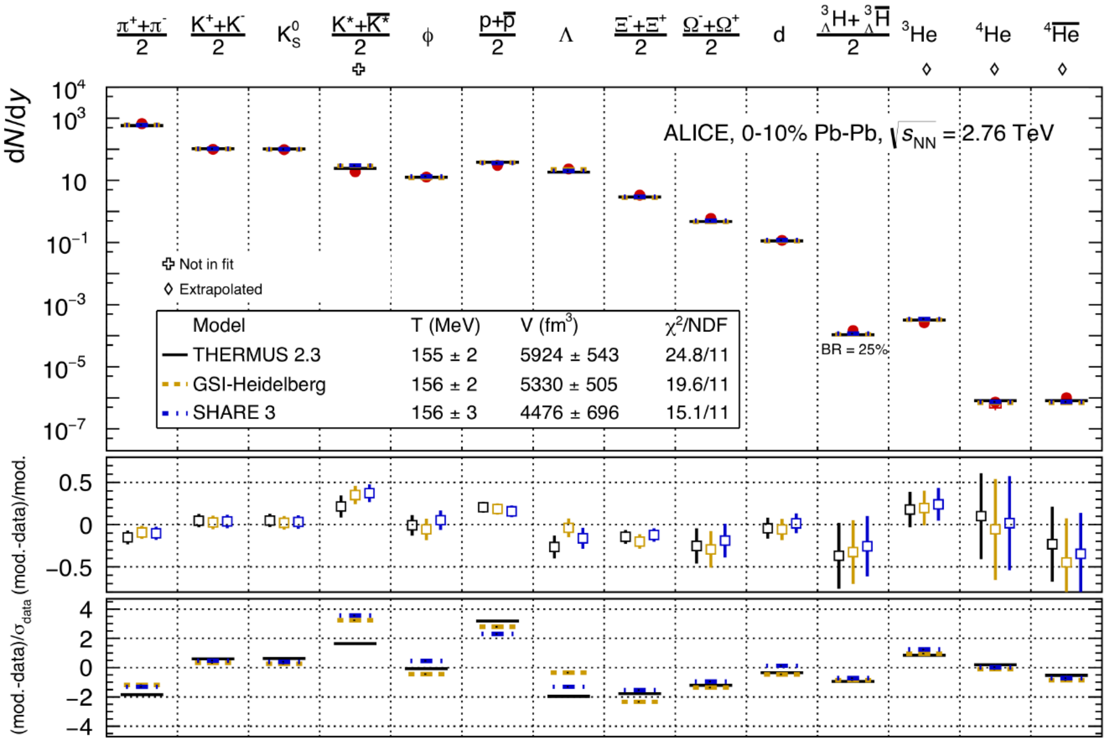

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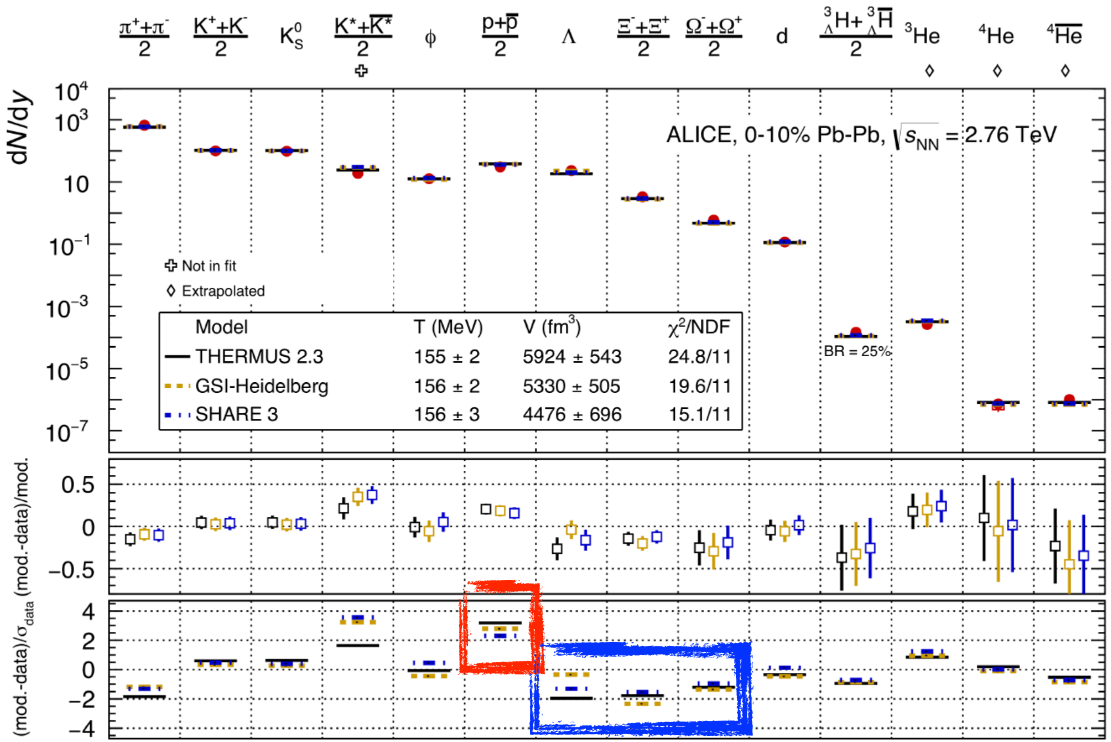

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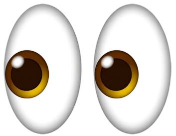

FAF et al. *Phys. Lett B.* **814** (2021)

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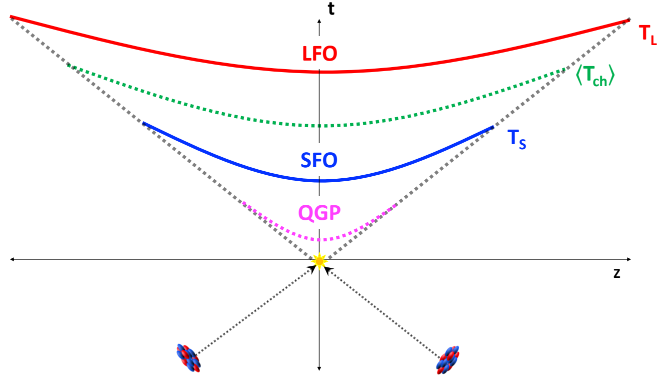

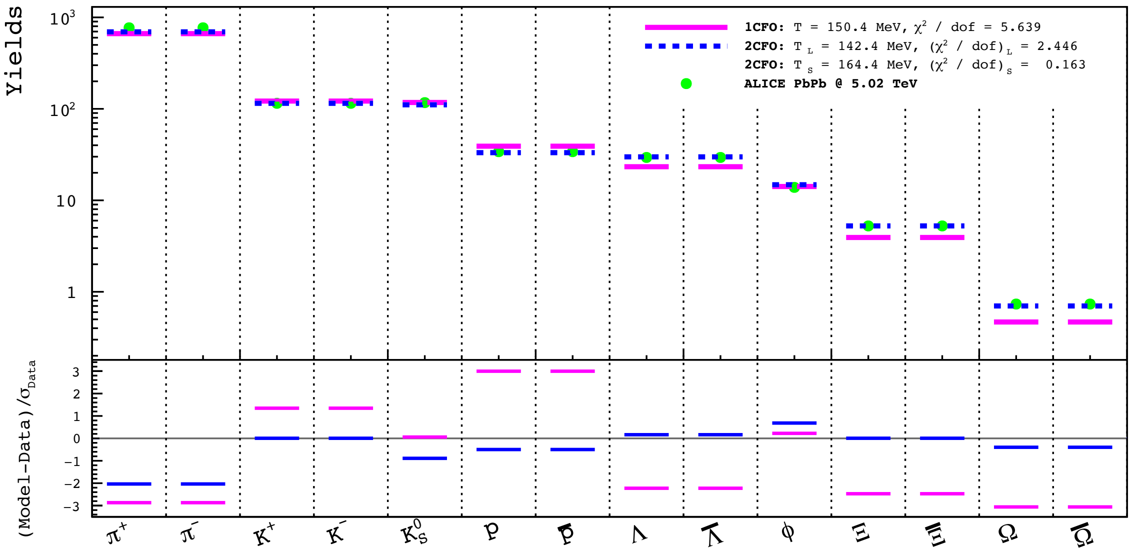

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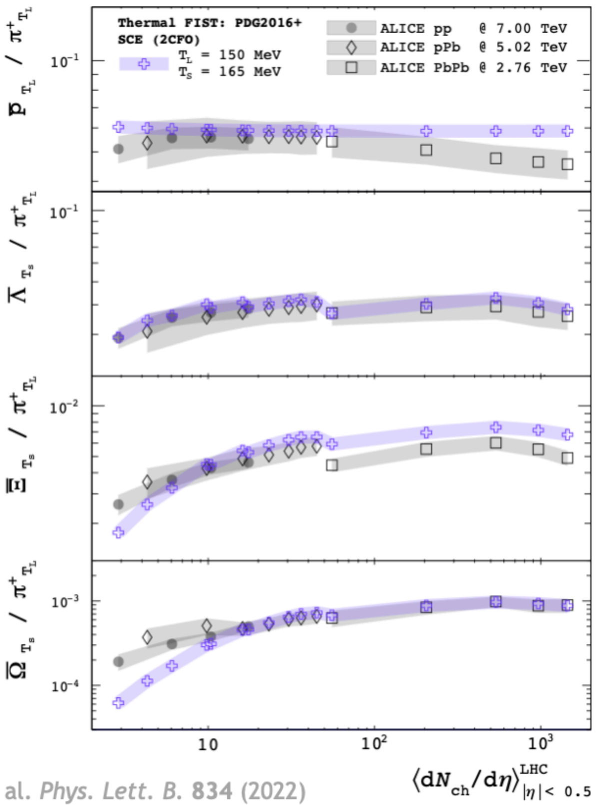
T_{light} = 142 ± 2 MeV

$T_{strange}$ = 164 ± 2 MeV

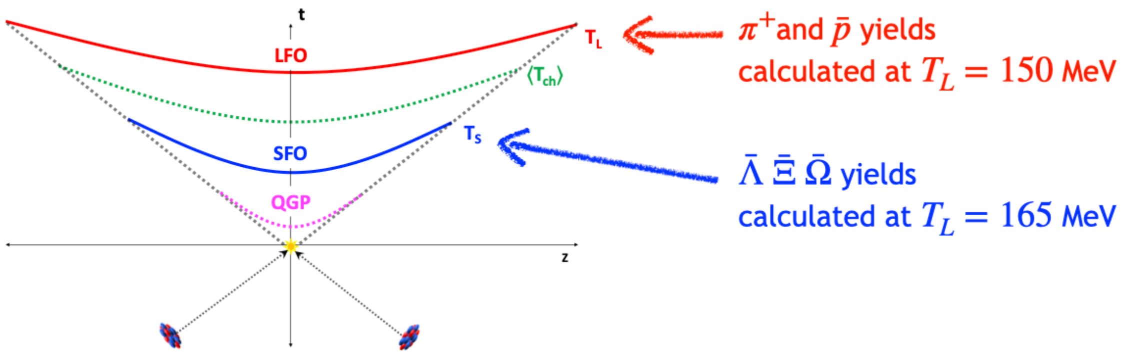
FAF et al. *Phys. Lett B.* **814** (2021)

2CFO THERMAL MODEL YIELDS AT ALICE



FAF et al. *Phys. Lett. B.* **834** (2022)

Experimental data in grey while the SHM calculations via the 2CFO approach in purple



Strangeness Enhancement at ALICE can be well described with two different freeze-out temperatures

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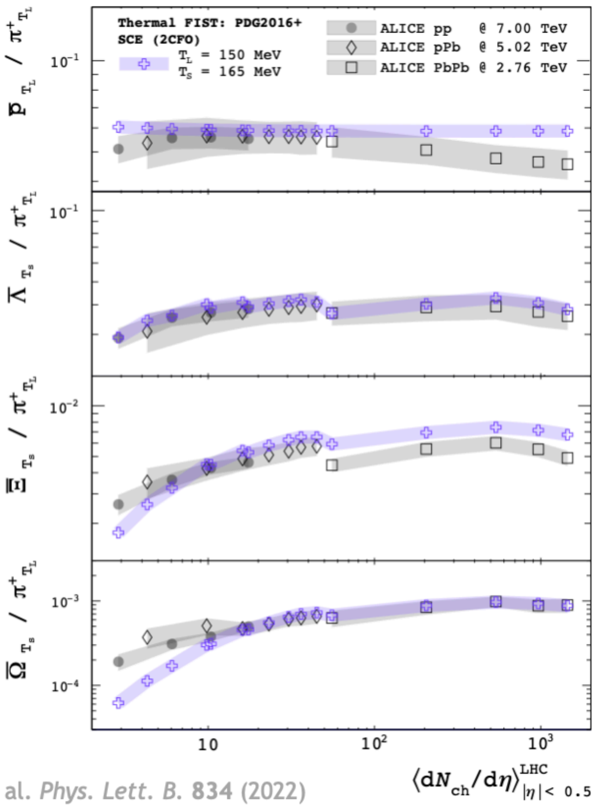

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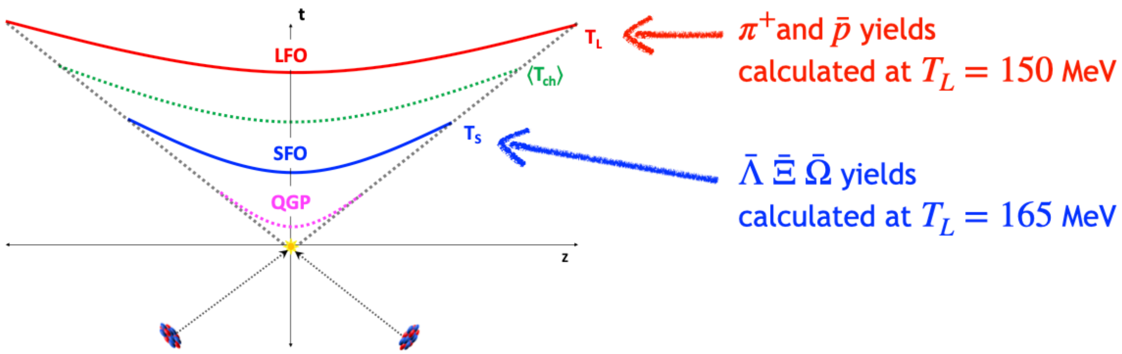

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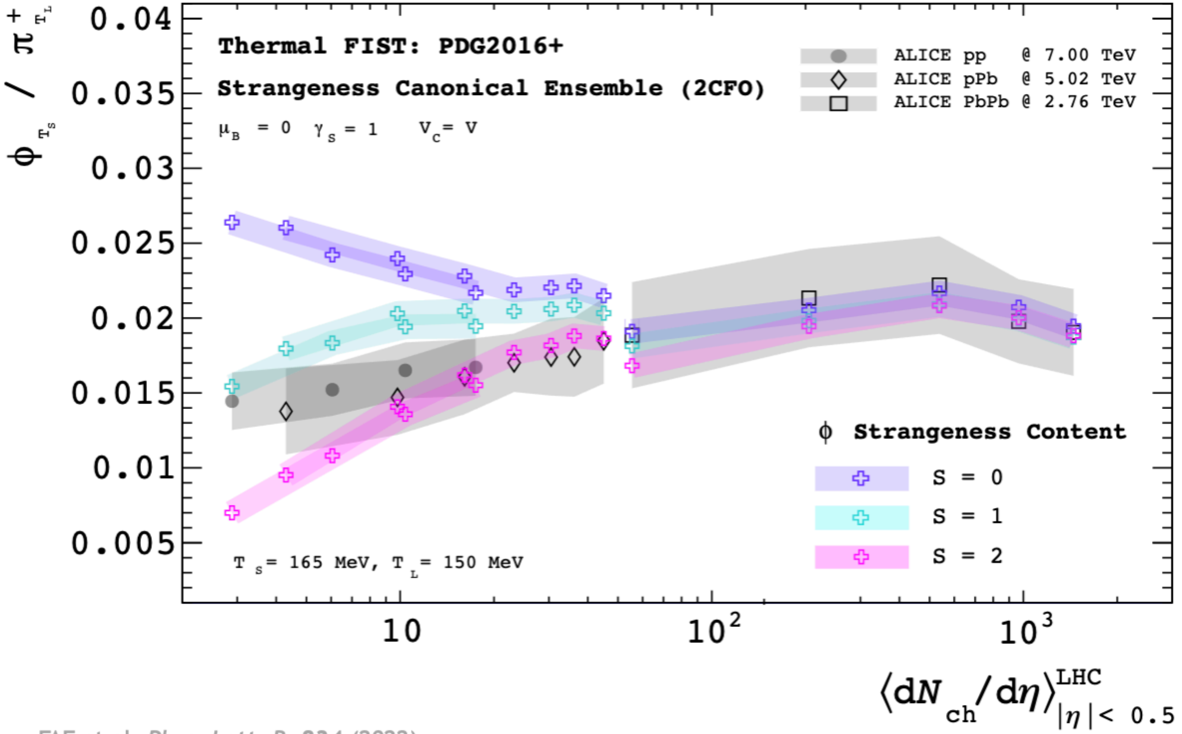
What about the ϕ meson?

2CFO THERMAL MODEL ϕ YIELDS AT ALICE



ϕ/π ratios only well-described in the Pb+Pb system when treating ϕ's as strangeness neutral objects (**S = 0**)

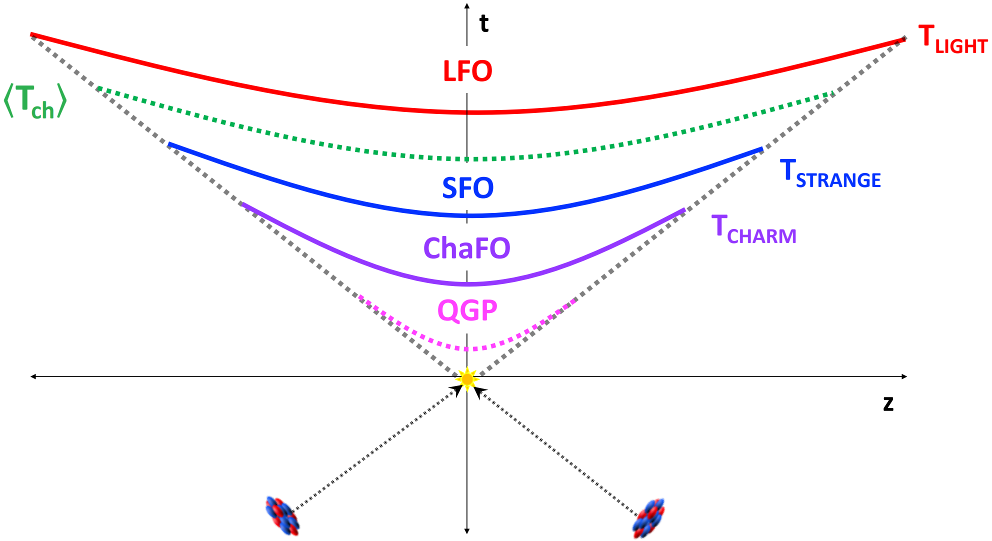
By fixing **S = 1** for ϕ's, the ratios improve but are still **over-calculated** in the smaller collision systems

However, by fixing **S = 2**, the ratios improve but are now **under-calculated** in the smaller collision systems…

FAF et al. *Phys. Lett. B.* **834** (2022)

3CFO THERMAL MODEL AT ALICE?

3CFO THERMAL MODEL YIELDS AT ALICE!



$T_{charm} > T_{strange} > T_{light}$

Given that charm (anti-)quarks are produced in the initial had scattering of incoming partons — due to their large masses — it is necessary to modify the Boltzmann factors associated with each individual charmed particle densities

$$e^{\mu_i/T} \longrightarrow e^{\mu_i/T}\gamma_c^{|c_i|}$$

In this manner, the charm fugacity (γ_c) is treated as an out of equilibrium pseudo impurity which remains constant throughout the lifetime of the collision fireball.

Assuming the total number of charm (anti-)quarks is constant until hadronization, we can model final state heavy flavor yields within the SHM framework

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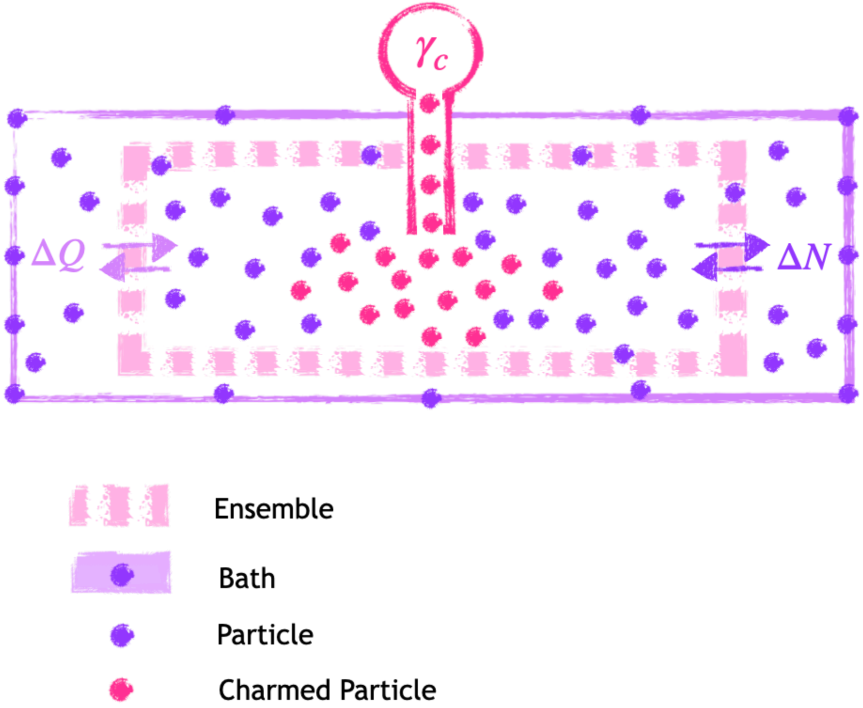

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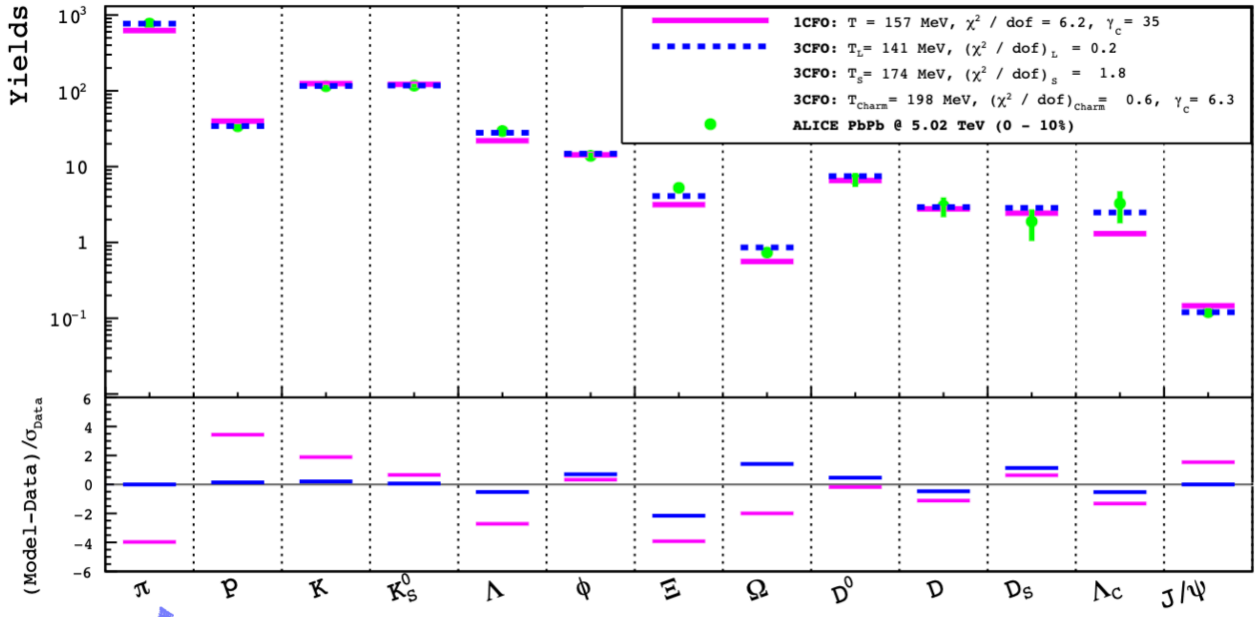


Shorthand is used to represent the arithmetic mean of hadrons and their respective anti-hadrons

We then used a flavor-dependent freeze-out (3CFO) while fixing $\mu_B = 1$ MeV

Charm fugacity was determined based on the temperature when only fitting charmed hadron yields

T_{charm} = 198 MeV and $\gamma_c = 6.3$

$T_{strange}$ = 174 MeV

T_{light} = 141 MeV

We observe a considerable improvement in the combined reduced goodness-of-fit values of all thee fits when compared to the 1CFO result

6.2 vs. 2.6

QUO VADIS?

J/ψ PHOTOPRODUCTION AT JLAB

J/ψ at threshold:

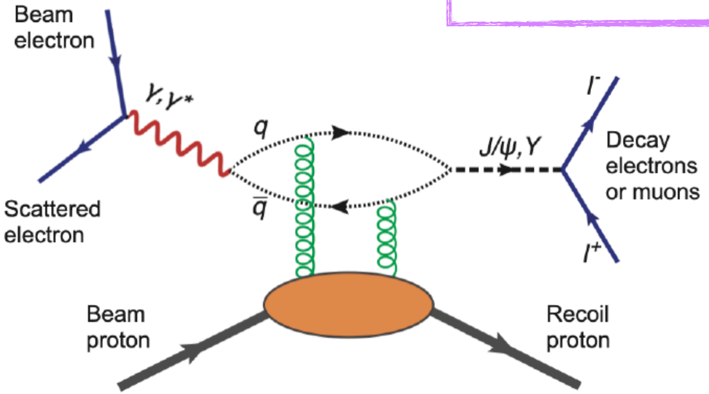
$E_\gamma^{lab} \approx 8.2$ GeV

$t \approx 2.1$ GeV^2

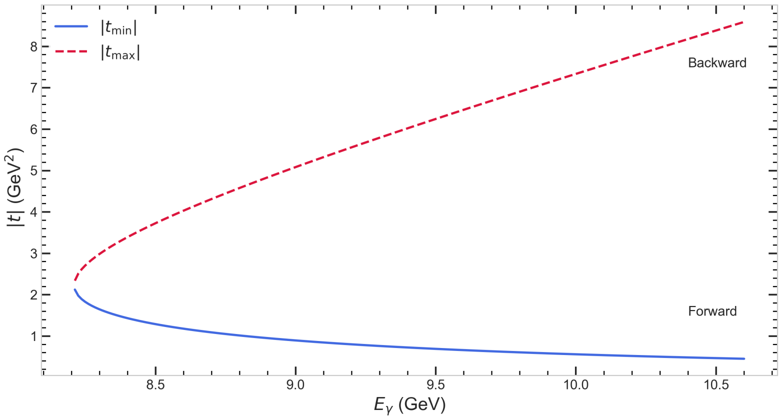
$W \approx 4.04$ GeV

- Due to the heavy mass of the charm quark (~ 1 GeV), exclusive J/ψ photoproduction proceeds dominantly via gluonic exchange

- Reaction t-dependence, determined by proton vertex, used as probe of gluon form factors



|t| limits for $\gamma p \to J/\psi\, p$ process



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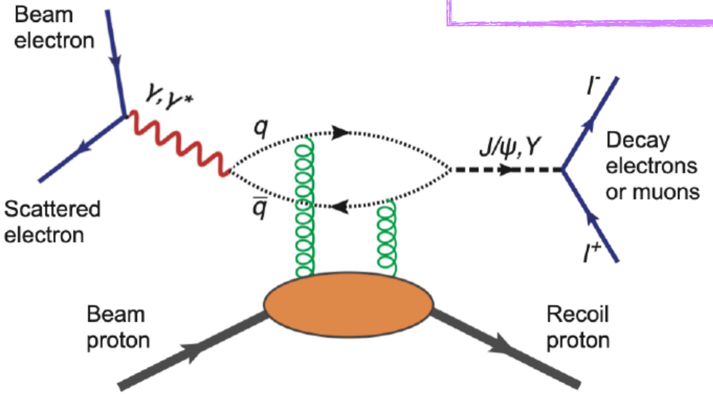
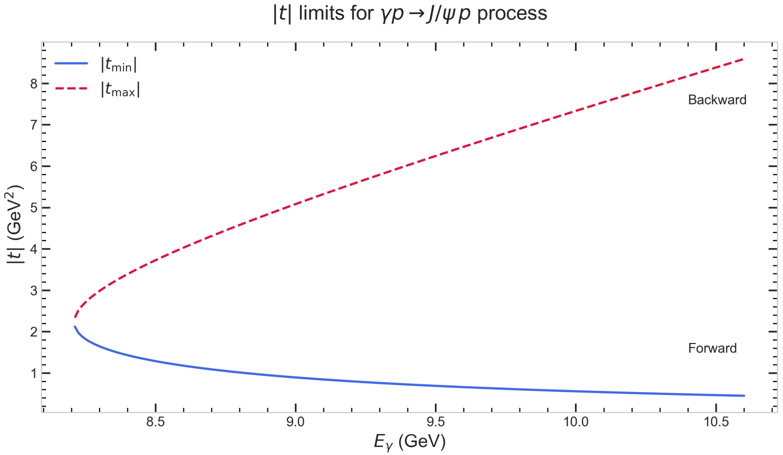
- Heavy quarkonia can treated as a *color* dipole in order to probe gluons in the production process

- Gravitational form factors are constrained in near-threshold J/ψ photoproduction

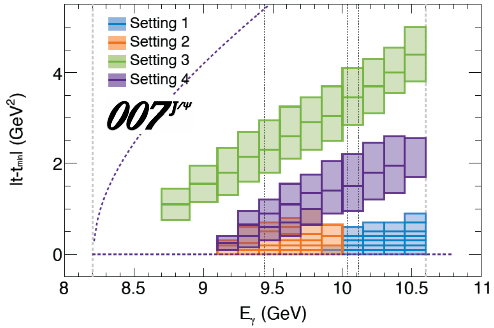


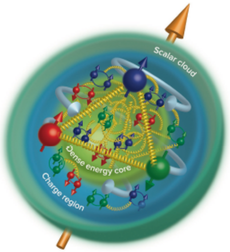


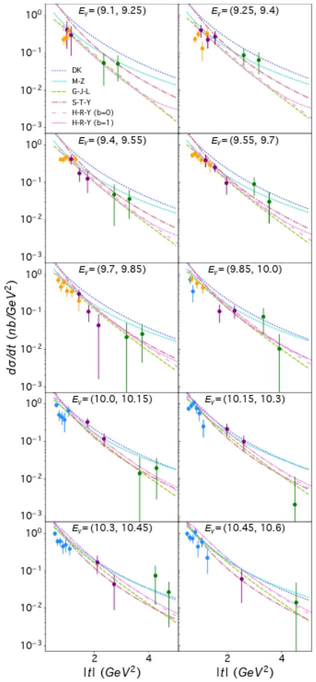
Nature **615**, 813-816 [2023]

J/ψ PHOTOPRODUCTION AT JLAB

- *J/ψ*-007 experiment in Hall C unfolded 2D cross section
  - Ten E_γ slices in 9.1 - 10.6 GeV range
  - Showed determination of the proton radius in three regions
    - Mass radius > charge radius
    - Scalar gluonic cloud surrounds charge region at around 1 fm

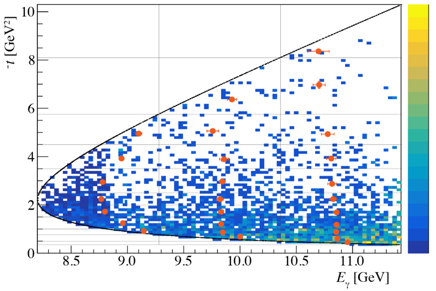


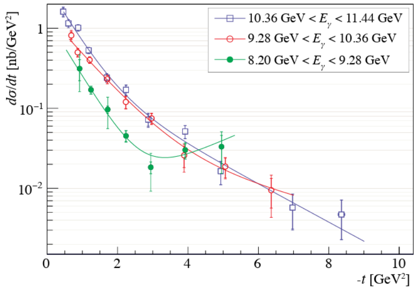




- 2023 GlueX results in the near-threshold region extract the 2D differential cross section in E_γ ~ 8.2 - 11.4 GeV
  - Observe *enhancement* of the differential cross-section in the lowest E_γ region
  - *"Can be interpreted as an s-channel or u-channel contribution"*

GlueX: PRC **108**, 025201 [2023]





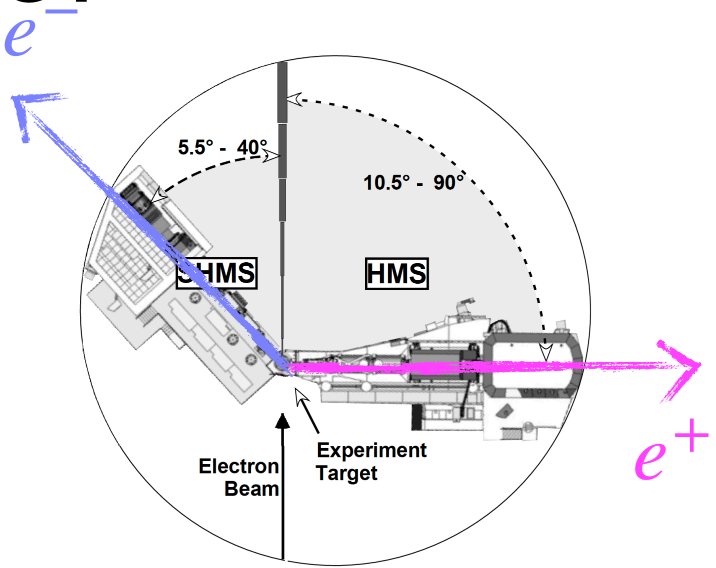
S. Joosten, lAger (https://eicweb.phy.anl.gov/monte_carlo/lager/)
Approach à la arXiv:1609.00676

lAger MC CAMPAIGN STRATEGY

- Based on the simplest Hall C setup, with HMS and SHMS, identify areas in t vs. E_γ phase space with large event rate (at least comparable to sample size from J/ψ-007)

- Focus on areas of higher skewness value (ξ)
  - Preferably also regions overlapping with values of E_γ below the J/ψ-007 range
  - In principle, attempt to cover same space shown by Glue-X (PRC **108**, 025201 [2023])

- Brute-force optimization approach had few constraints from start, getting more strict along each step…

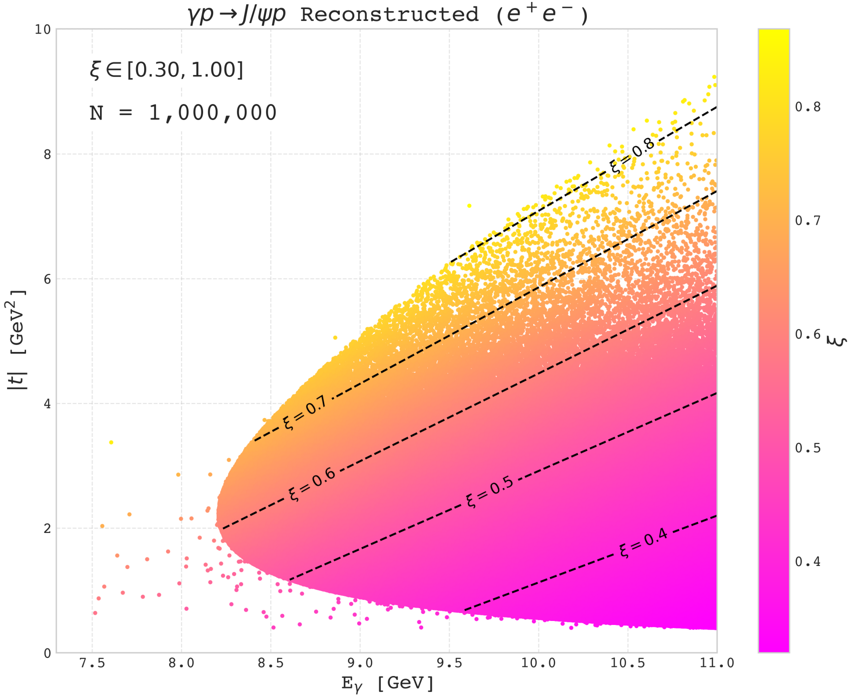


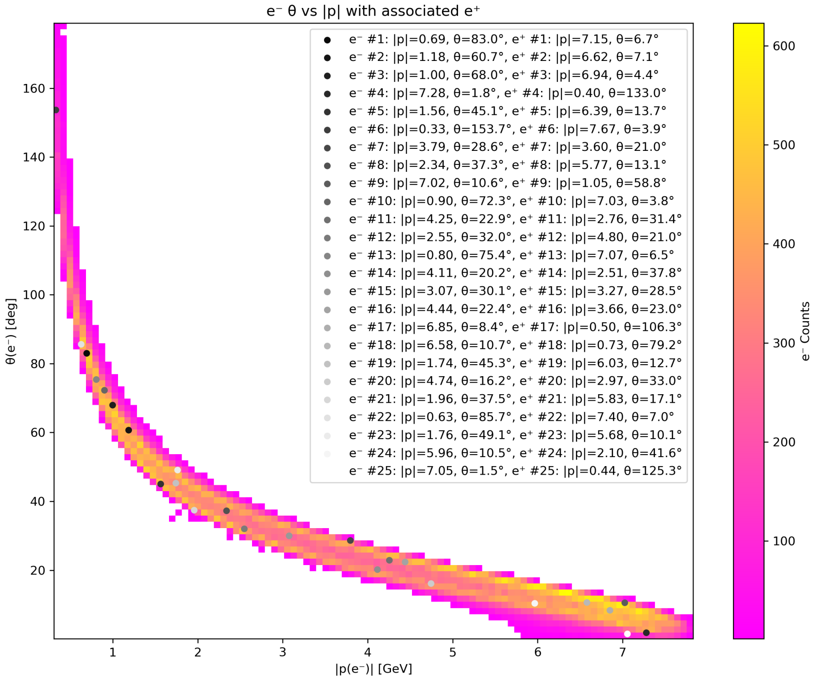
Parameter	*HMS Performance*	*SHMS Specification*
Range of Central Momentum	0.4 to 7.4 GeV/c	2 to 11 GeV/c
Momentum Acceptance	±10%	-10% to +22%
Momentum Resolution	0.1% – 0.15%	0.03% – 0.08%
Scattering Angle Range	10.5° to 90°	5.5° to 40°
Target Length Accepted at 90°(HMS)/45° (SHMS)	10 cm	25 cm
Horizontal Angle Acceptance	±32 mrad	±18 mrad
Vertical Angle Acceptance	±85 mrad	±45 mrad

lAger MC CAMPAIGN

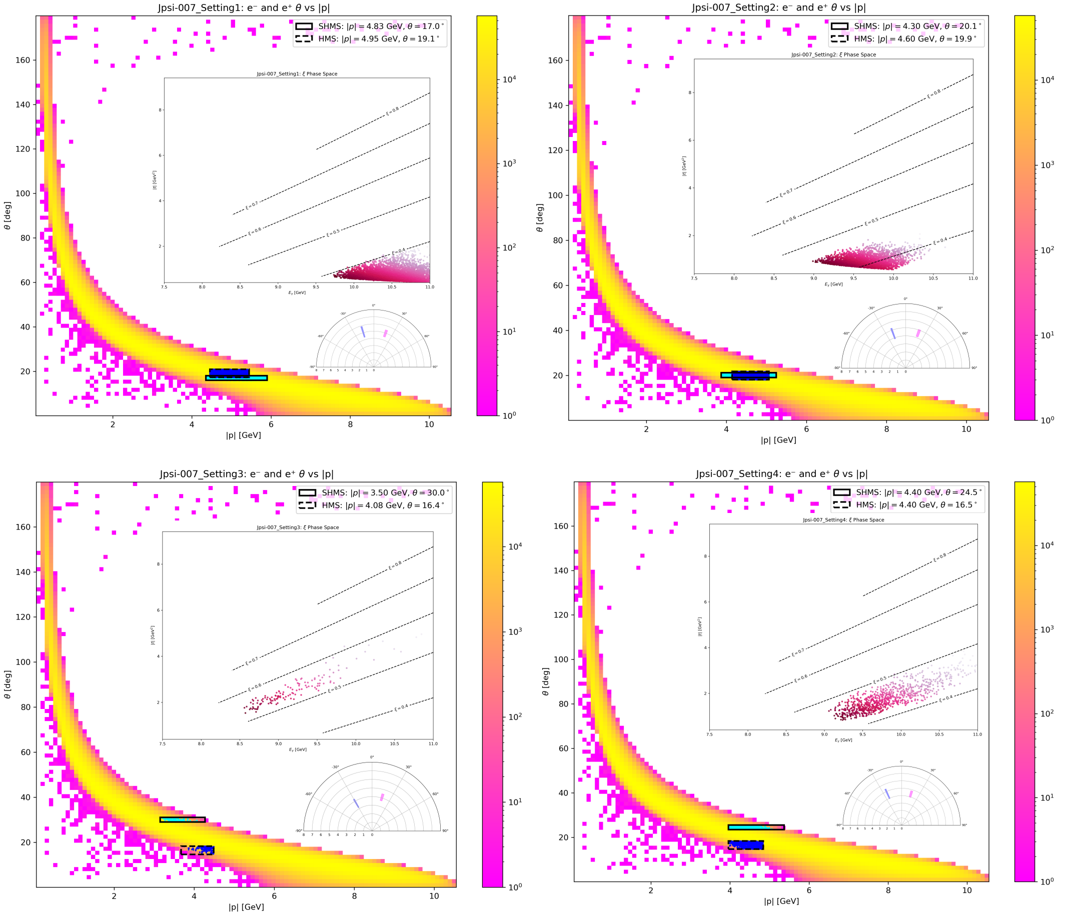
Hall C Parameters (1M Events): No Cuts

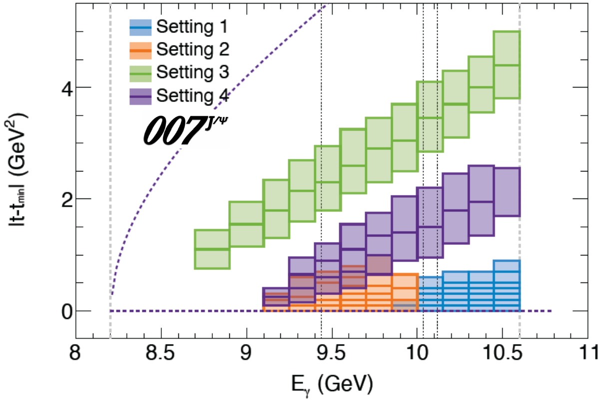
$$\xi \approx \frac{t - M_{J/\psi}^2}{2M_p^2 + M_{J/\psi}^2 - t - 2W}$$





007$^{J/\psi}$ SETTINGS MC CROSS-CHECK





Nature **615**, 813-816 [2023]

S. Joosten, lAger (https://eicweb.phy.anl.gov/monte_carlo/lager/)

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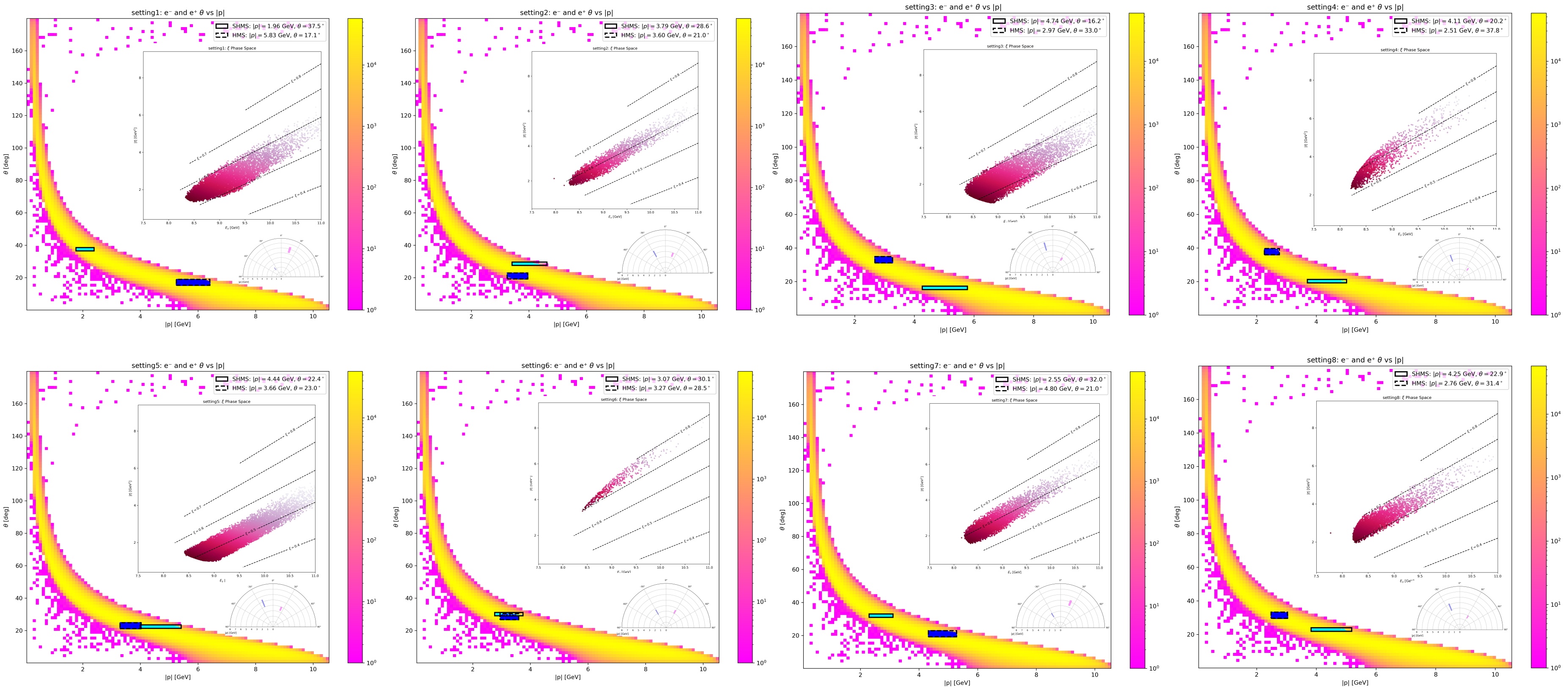
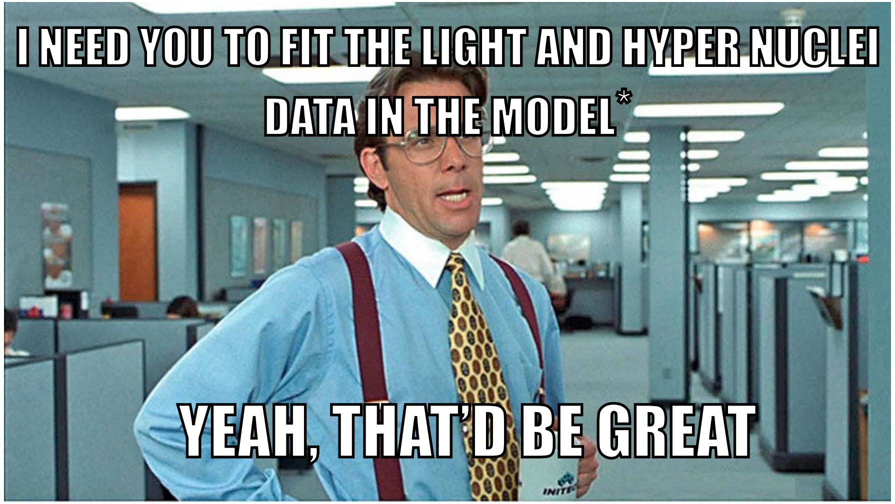
PRELIMINARY HALL C SETTINGS (TOP 8)

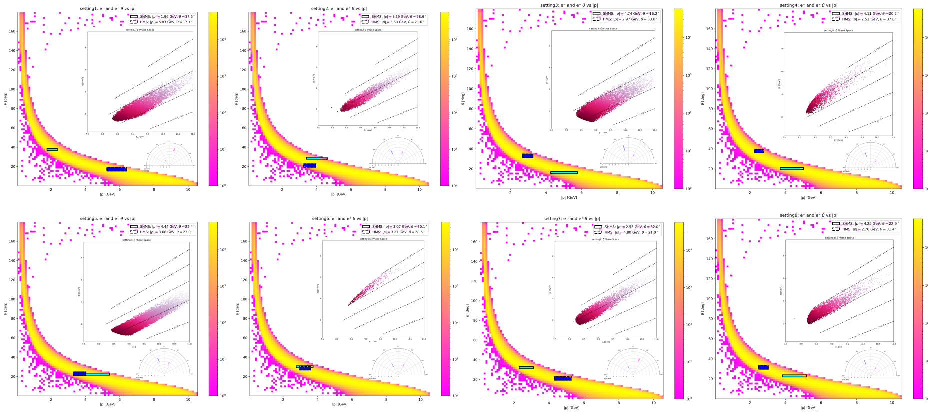


GENERAL OUTLOOK

- Final state yields of various flavors and baryon number from different collision systems across various energies can be described via simple thermal models
  - Minimal assumptions and parameters
  - Additional parameters to fit allows for *non-bulk hadrons* to be treated pseudo-thermally
    - Lest we forget von Neumann's elephant 🙃



- Path to EIC is non-linear: Getting lost along the way is part of the process
  - Keep collaborators close along the way to periodically touch grass
  - Be open to change and to make yourself uncomfortable
  - It is normal to switch experiments as your career progresses
    - Opportunities turn up when least expected



*For SHM fits to light nuclei (and hyper-nuclei) at ALICE and STAR see FAF et al. arXiv: 2412.20517

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SEQUENTIAL STRANGENESS HADRONIZATION

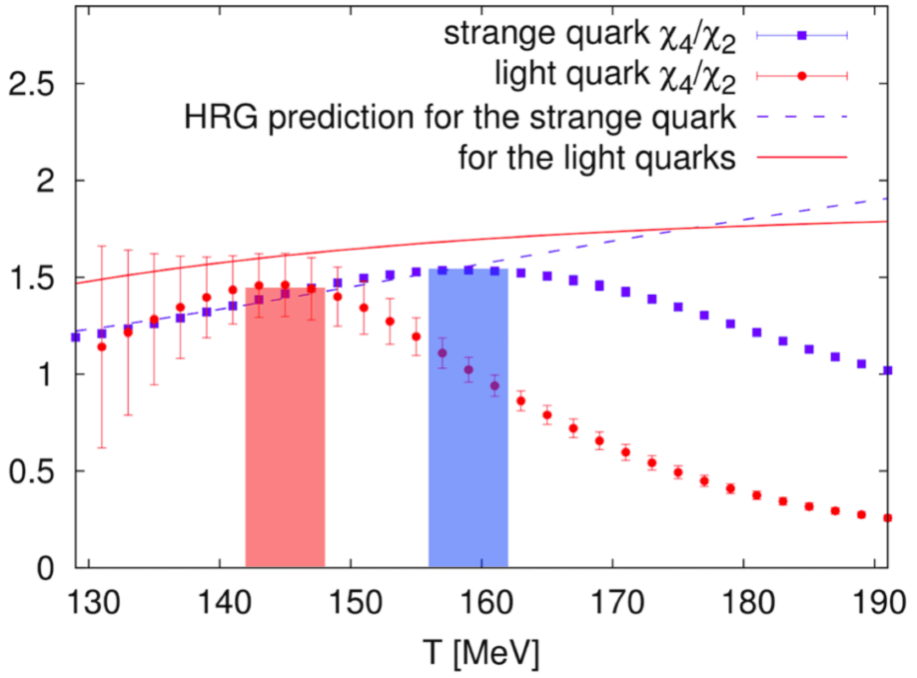
Continuum extrapolated Lattice QCD χ_4/χ_2 calculations for light and strange quarks at vanishing baryochemical potential (μ_B)

- Depict different results between light and strange flavors
  - Flavor-specific "kinks" at particular temperatures
  - Deviations of lattice curves in coincidence with kinks
- Suggest flavor separation of characteristic temperatures
  - ~ 15 MeV lower for light flavor quarks

The derivatives of the QCD pressure (P) WRT to the chemical potentials of baryon number (B), electric charge (Q), strangeness (S) and charm (C) give rise to the susceptibilities:

$$\chi_{klmn}^{BQSC} = \frac{\partial^{(k+l+m+n)}[P(\hat{\mu}_B, \hat{\mu}_Q, \hat{\mu}_S, \hat{\mu}_C)/T^4]}{\partial\hat{\mu}_B^k \partial\hat{\mu}_Q^l \partial\hat{\mu}_S^m \partial\hat{\mu}_C^n} \Big|_{\vec{\mu}=0}$$

Determine how "susceptible" a system is to changes to the chemical potential



R. Bellwied and W.B. Collaboration. *Phys. Rev. Lett.* 111 (2013)

SEQUENTIAL CHARM HADRONIZATION

Recall:

$$\chi^{BQSC}_{klmn} = \frac{\partial^{(k+l+m+n)}[P(\hat{\mu}_B, \hat{\mu}_Q, \hat{\mu}_S, \hat{\mu}_C)/T^4]}{\partial\hat{\mu}^k_B \partial\hat{\mu}^l_Q \partial\hat{\mu}^m_S \partial\hat{\mu}^n_C} |_{\vec{\mu}=0}$$

Partial pressures of charmed mesons, baryons and quarks are given by:

$$P_C(T, \vec{\mu}) = P^C_M(T, \vec{\mu}) + P^C_B(T, \vec{\mu}) + P^C_q(T)\cosh\left(\frac{2}{3}\hat{\mu}_Q + \frac{1}{3}\hat{\mu}_B + \hat{\mu}_C\right)$$

In terms of generalized susceptibilities:

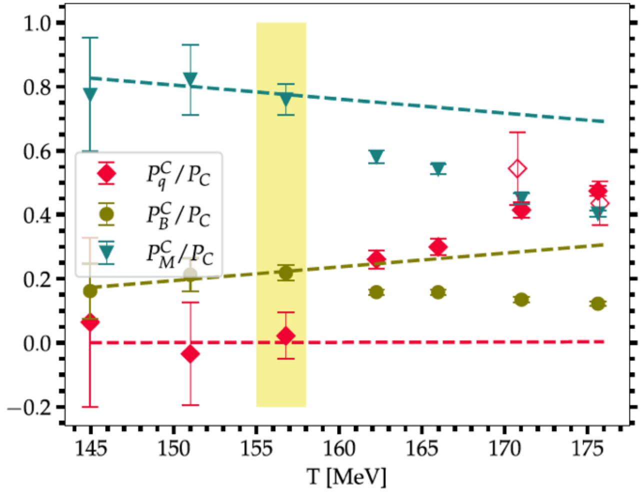
$$P^C_q = 9\left(\chi^{BC}_{13} - \chi^{BC}_{22}\right)/2,$$

$$P^C_B = \left(3\chi^{BC}_{22} - \chi^{BC}_{13}\right)/2,$$

$$P^C_M = \chi^C_4 + 3\chi^{BC}_{22} - 4\chi^{BC}_{13}$$

Total charm pressure:

$$P_C = \chi^C_4$$



- Beyond the crossover region, the lattice begins to deviate from the HRG baseline (dashed lines)
- Above $T > 175$ MeV, charmed hadron partial pressures drop while the partial pressure of charm quarks rise

A. Bazavov et al. *Phys. Lett. B.* **850** (2024)

SEQUENTIAL CHARM HADRONIZATION

Recall:

$$\chi_{klmn}^{BQSC} = \frac{\partial^{(k+l+m+n)}[P(\hat{\mu}_B, \hat{\mu}_Q, \hat{\mu}_S, \hat{\mu}_C)/T^4]}{\partial\hat{\mu}_B^k \partial\hat{\mu}_Q^l \partial\hat{\mu}_S^m \partial\hat{\mu}_C^n}\Big|_{\vec{\mu}=0}$$

Partial pressures of charmed mesons, baryons and quarks are given by:

$$P_C(T, \vec{\mu}) = P_M^C(T, \vec{\mu}) + P_B^C(T, \vec{\mu}) + P_q^C(T)\cosh\left(\frac{2}{3}\hat{\mu}_Q + \frac{1}{3}\hat{\mu}_B + \hat{\mu}_C\right)$$

In terms of generalized susceptibilities:

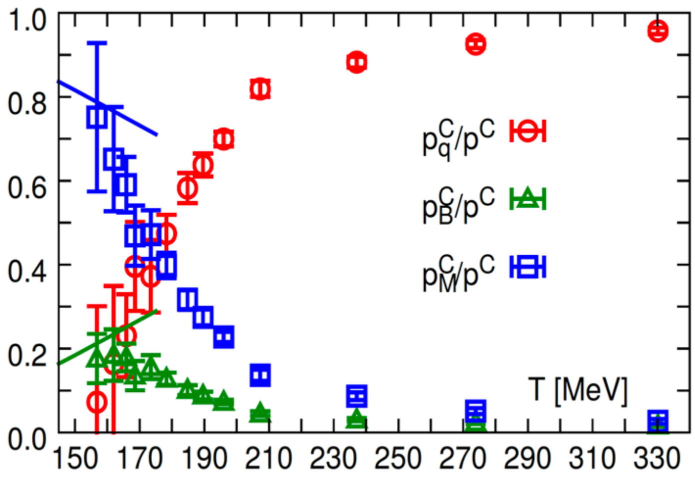
$$P_q^C = 9\left(\chi_{13}^{BC} - \chi_{22}^{BC}\right)/2,$$

$$P_B^C = \left(3\chi_{22}^{BC} - \chi_{13}^{BC}\right)/2,$$

$$P_M^C = \chi_4^C + 3\chi_{22}^{BC} - 4\chi_{13}^{BC}$$

Total charm pressure:

$$P_C = \chi_4^C$$

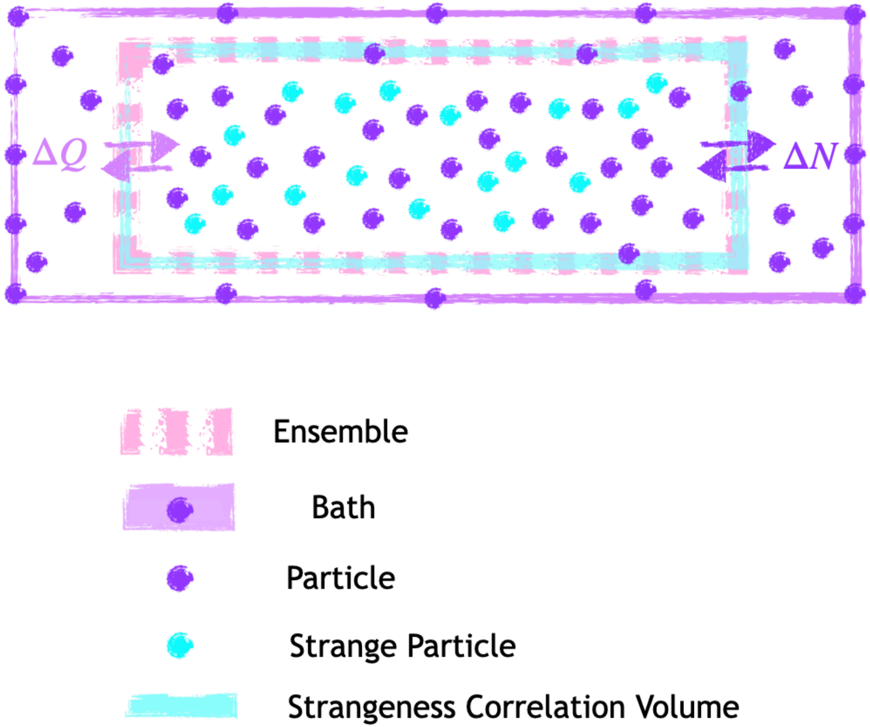


- Beyond the crossover region, the lattice begins to deviate from the HRG baseline (dashed lines)

- Above $T > 175$ MeV, charmed hadron partial pressures drop while the partial pressure of charm quarks rise
  - Flattening out somewhere around $T > 250$ MeV

S. Mukherjee et al. *Phys. Rev. D.* **93** (2016)

STRANGENESS CANONICAL ENSEMBLE



INTEGRATED LUMINOSITY (24 HRS)

$$N_{EVENTS} = \sigma \cdot \mathscr{L}_{24hrs} \cdot \epsilon \ni$$

σ_{10M} = cross-section from lAger *
$\mathscr{L}_{INT} = \mathscr{L}_{INST} \cdot t$
ϵ = efficiency/acceptance

$$\mathscr{L}_{INST} = \frac{N_{EVENTS}}{\sigma \cdot \epsilon \cdot t} \Leftrightarrow t = \frac{N_{EVENTS}}{\sigma_{10M} \cdot \epsilon \cdot \mathscr{L}_{INST}}$$

$I_{beam}\,(\mu A)$	$\mathscr{L}_{INST}\,(cm^{-2}s^{-1})$	$t_{10M}\,(s)$	$t_{10M}\,(Hours)$
25	$6.59 \cdot 10^{37}$	$2.66 \cdot 10^{5}$	74.1
50	$1.317 \cdot 10^{38}$	$1.33 \cdot 10^{5}$	37.0
75	$1.976 \cdot 10^{38}$	$8.88 \cdot 10^{4}$	24.7
100	$2.637 \cdot 10^{38}$	$6.66 \cdot 10^{4}$	18.5

* For e^+e^- B.R.: $\sigma_{10M} = 5.69921 \cdot 10^{4}\, nb = 5.69921 \cdot 10^{-37} cm^2$

007$^{J/\psi}$ DELIVERED LUMINOSITY AND CHARGE

	N_{EVENTS}	$\mathscr{L}\,(nb^{-1})$	$Q\,(C)$	$t_{50\mu A}\,(hrs)$
Setting 1	863	$1.3 \cdot 10^{10}$	5.1	28.3
Setting 2	1041	$2.2 \cdot 10^{10}$	8.3	46.1
Setting 3	113	$3.4 \cdot 10^{10}$	13	72.2
Setting 4	300	$1.7 \cdot 10^{10}$	6.6	36.7
				183.3 (7.6 days) ✔

- Check the conversion factor between your MC events/beam time and the J/ψ-007 actual beam time
- Run the MC (different seeding and check the HMS and SHMS settings)
- Run the MC (different seeding and radiator) to cover GlueX phase space (PRC **108**, 025201 [2023])

INSTANTANEOUS LUMINOSITY

- Estimate for beam time for different beam currents

$$\mathscr{L}_{INST} = \frac{I \cdot n \cdot \ell}{e} \ni$$

I = beam current
ℓ = target length
n = # density of hydrogen atoms
$e = 1.602 \cdot 10^{-19} C$

$$n = \frac{\rho_{LH_2}}{M_{LH_2}} \cdot N_A \ni$$

$\rho_{LH_2} \approx 0.0708\ g/cm^3$
$M_{LH_2} \approx 2.01588\ g/mol$
$N_A = 6.022 \cdot 10^{23}\ mol^{-1}$

$I_{beam}\,(\mu A)$	$\mathscr{L}_{INST}\,(cm^{-2}s^{-1})$	$\mathscr{L}_{24hrs}\,(cm^{-2})$	$\mathscr{L}_{24hrs}\,(ab^{-1})$
25	$6.25 \cdot 10^{37}$	$5.69 \cdot 10^{42}$	5.69
50	$1.32 \cdot 10^{38}$	$1.14 \cdot 10^{43}$	11.4
75	$1.97 \cdot 10^{38}$	$1.70 \cdot 10^{43}$	17.0
100	$2.63 \cdot 10^{38}$	$2.27 \cdot 10^{43}$	22.7

GRAVITATIONAL FORM FACTORS (GFFS)

Towards observables for the matter structure of the proton

GFFs are the form factors of the QCD energy-momentum tensor (EMT) for quarks and gluons

$$\langle N' \mid T^{\mu,\nu}_{q,g} \mid N\rangle = \bar{u}(N')\left(A_{g,q}(t)\gamma^{\{\mu}P^{\nu\}} + B_{g,q}(t)\frac{iP^{\{\mu}\sigma^{\nu\}}\rho\Delta_\rho}{2M} + C_{g,q}(t)\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{M} + \bar{C}_{g,q}(t)Mg^{\mu\nu} \right) u(N)$$

GFFs encode mechanical properties of the proton:

- $A_{g,q}(t)$: Related to quark and gluon momenta, $A_{g,q}(0) = \langle x_{q,g}\rangle$
- $J_{g,q}(t) = 1/2\left(A_{g,q}(t) + B_{g,q}(t)\right)$: Related to angular momentum, $J_{\text{tot}}(0) = 1/2$
- $D_{g,q}(t) = 4C_{g,q}(t)$: Related to pressure and shear forces