Angular distributions of hadrons and Using a Bethe Salpeter approach to study hadronization

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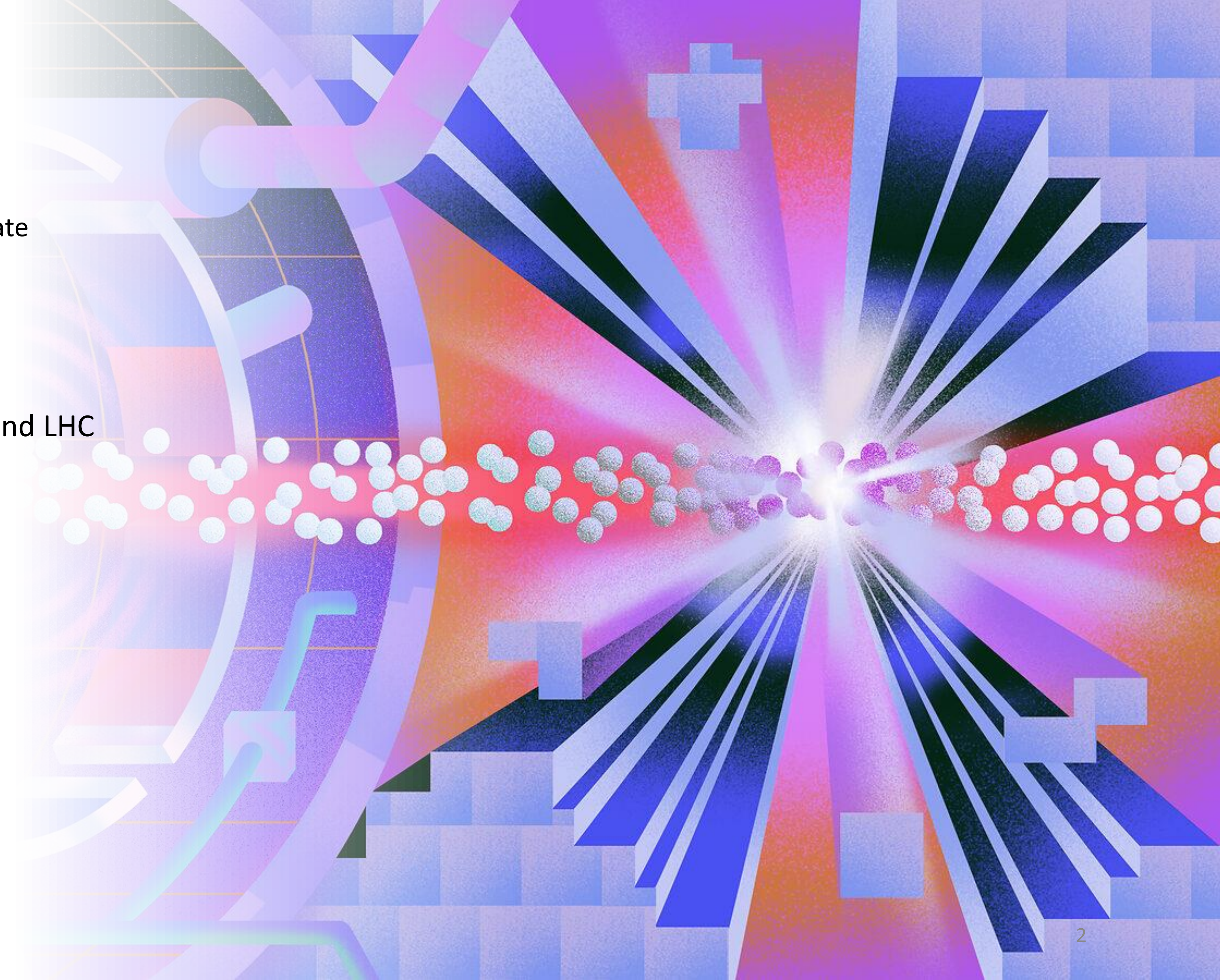
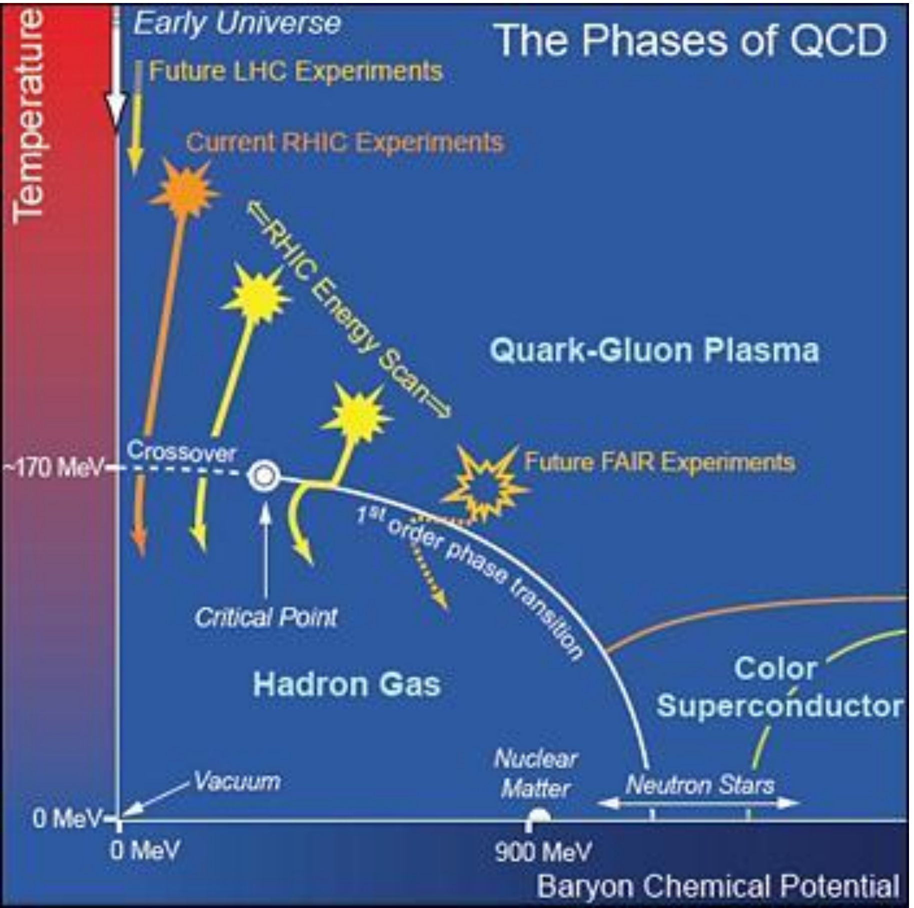
STRONG 2020
HFHF Helmholtz Forschungsakademie Hessen für FAIR

Outline

- Introduction
  - hadronization from the QGP state
  - Transport theory
  - Coalescence model
- Hadrons in AA collisions
  - p, π, Λ_C, D spectra at RHIC and LHC
- Angular distribution
- Bethe Salpeter approach to hadronization
- Conclusions



- Nuclear matter: Critical energy and temperature in the transition between confined and deconfined phase
- If $T > T_C$ colour charges are deconfined in a Quark Gluon Plasma
- Different value of T and ρ for deconfinement → Phase diagram



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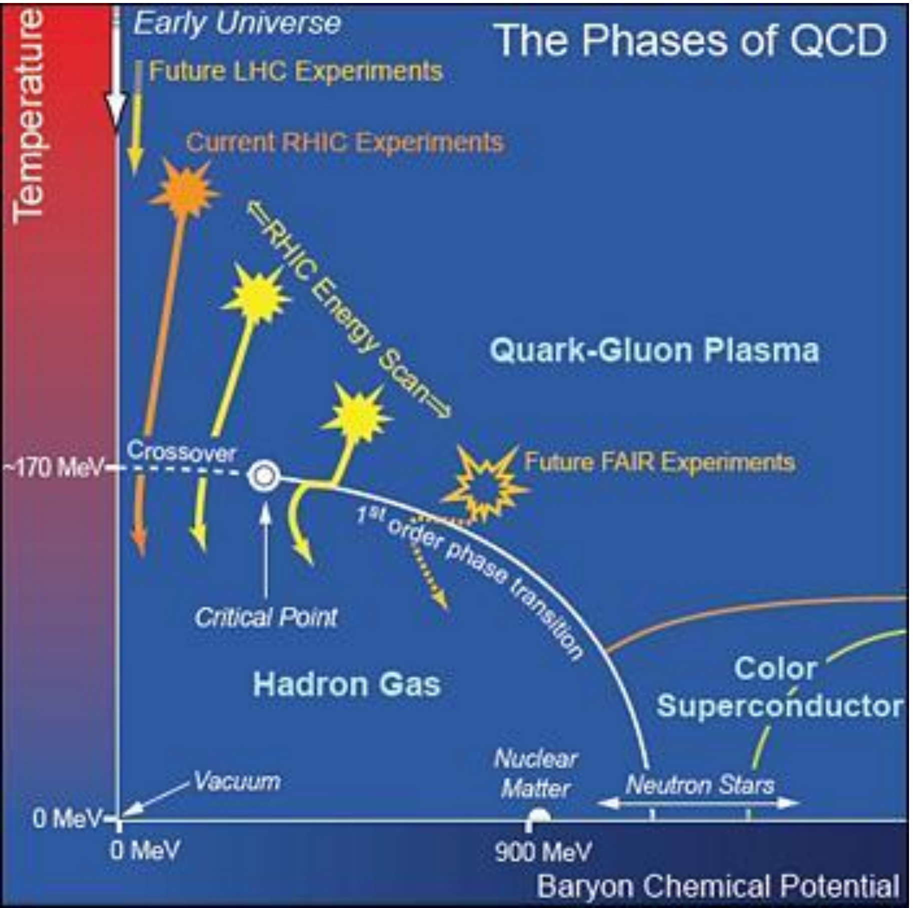
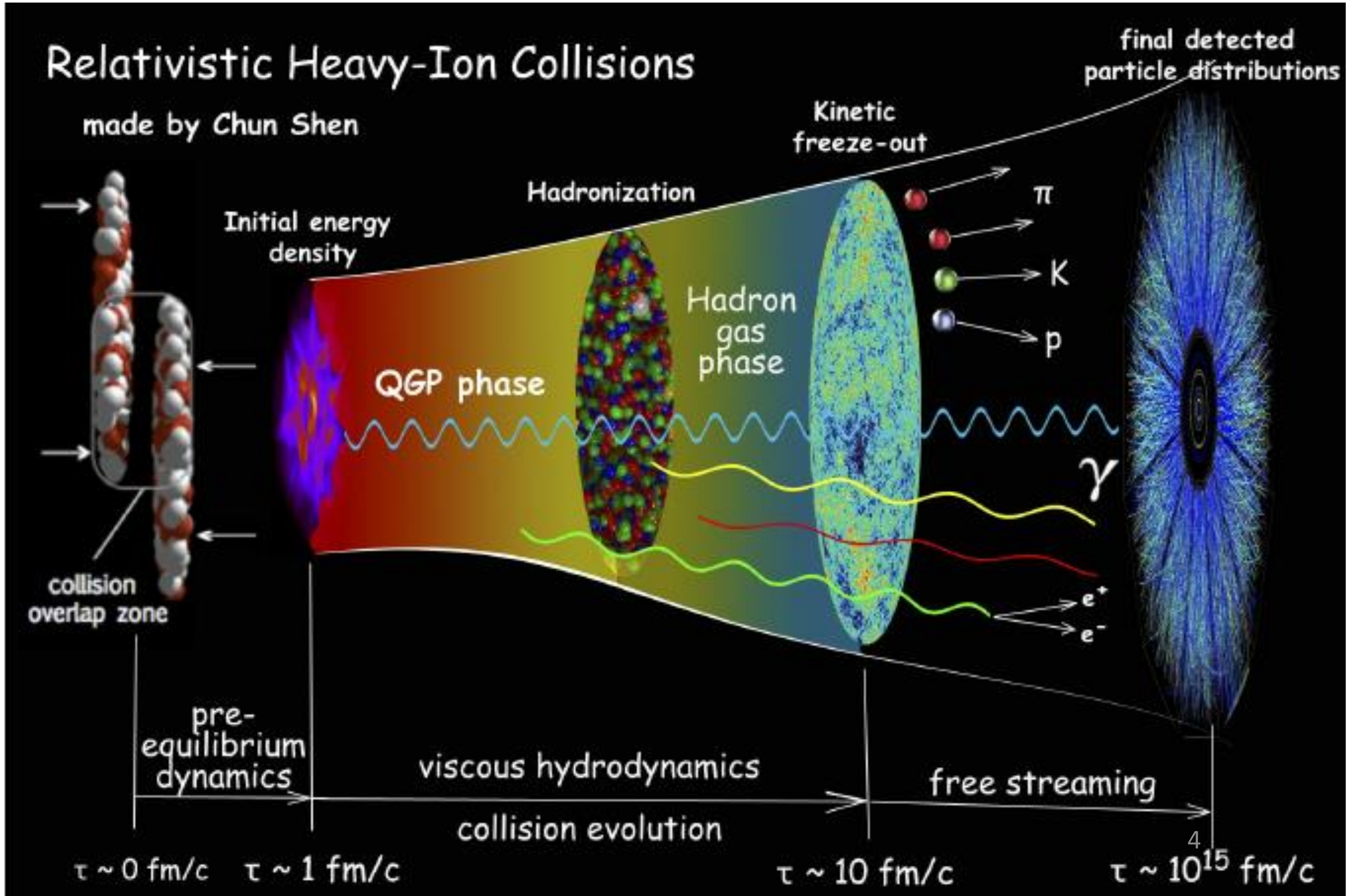


Quark Gluon Plasma in Ultrarelativistic Heavy-Ion collisions



Quark Gluon Plasma in Ultrarelativistic Heavy-Ion collisions

- $m_{c,b} \gg \Lambda_{QCD}$

produced by pQCD process (out of equilibrium)

- $m_{c,b} \gg T_0$

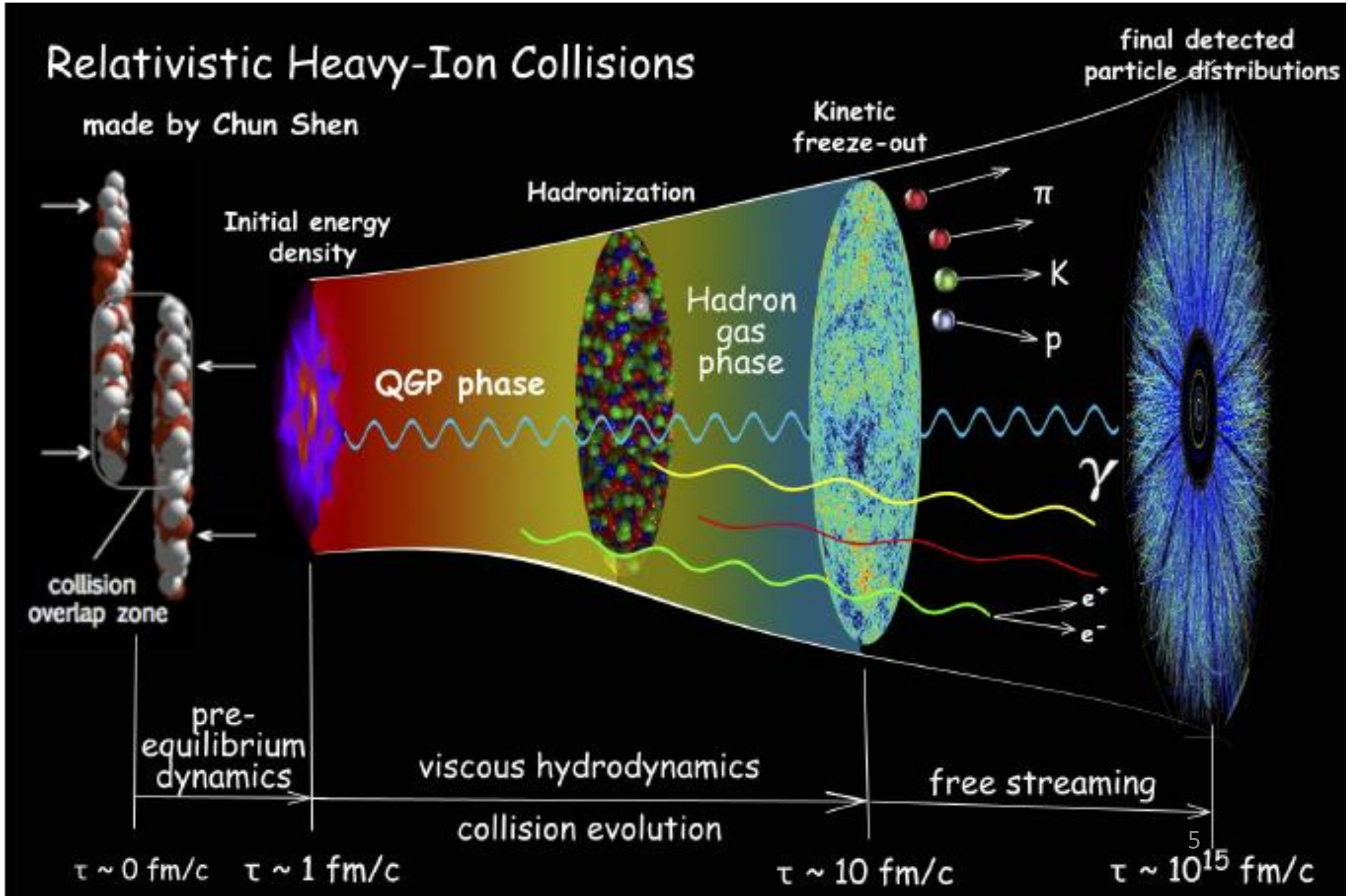
negligible thermal production

- $\tau_0 \ll \tau_{QGP}$

- $\tau_{therm.} \approx \tau_{QGP} \gg \tau_{g,q}$

HQs experience the full QGP evolution

Carry informations about initial stages, more than light quarks



Relativistic Boltzmann transport for finite $\frac{\eta}{s}$

Bulk Evolution

$$\underbrace{p^{\mu}\partial_{\mu}f_{q,g}(x,p)}_{\text{Free-streaming}} + \underbrace{M(x)\partial_{\mu}^{x}M(x)\partial_{p}^{\mu}f_{q,g}\,(x,p)}_{\text{Field interaction}} = \underbrace{C_{22}\left[f_{q,g}\right]}_{\text{Collision }\eta\neq 0}$$

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Heavy quark evolution

$$p^{\mu}\partial_{\mu}f_{Q}(x,p) = C[f_{q}, f_{g}, f_{Q}]$$

- Describes the evolution of the one body distribution function f(x,p)
- It is valid to study the evolution of both bulk and Heavy quarks
- Possible to include f(x,p) out of equilibrium

Coalescence model

Statistical factor colour-spin-isospin

Parton distribution function

Hadron Wigner function

$$\frac{dN_H}{d^2\boldsymbol{P}_T} = g_H \int \prod_{i=1}^{n} \frac{d^3p_i}{(2\pi)^3 E_i} p_i \cdot d\sigma_i f_{q_i}(x_i, p_i) f_W(x_1 ... x_n; p_1 ... p_n) \, \delta\left(\boldsymbol{P_T} - \sum_i^n p_{T,i} \right)$$

LIGHT

Thermal + flow for **u,d,s** ($p_T < 3\ GeV$)

$$\frac{dN_{q,\bar{q}}}{d^2p_T} \sim exp\left(-\frac{\gamma - p_T \cdot \beta \pm \mu_q}{T}\right)$$

$$\beta(r) = \frac{r}{R}\beta_{max}$$

$$\mathrm{V} = \pi r^2 \tau \cosh(y_z)$$

+ quenched minijets for **u,d,s** ($p_T > 3\ GeV$)

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Wigner function-Wave function

$$\Phi_M^W(\boldsymbol{r},\boldsymbol{q}) = \int d^3r' e^{-i\boldsymbol{q}\cdot\boldsymbol{r}'} \varphi_M(\boldsymbol{r} + \frac{\boldsymbol{r}'}{2}) \varphi_M^*(\boldsymbol{r} - \frac{\boldsymbol{r}'}{2})$$

where $\varphi_M(\boldsymbol{r})$ is the meson wave function

Assuming gaussian wave function

$$f_H(\dots) = \prod_{i=1}^{N_q-1} A_W \exp\left(-\frac{x_{ri}^2}{\sigma_{ri}^2} - p_{ri}^2\sigma_{ri}^2\right)$$

Wigner function width fixed by root-mean-square charge radius from quark model

C.-W. Hwang, EPJ C23, 585 (2002)
C. Albertus et al., NPA 740, 333 (2004)

$$\langle r^2 \rangle_{ch} = \frac{3}{2}\frac{m_2^2 Q_1 + m_1^2 Q_2}{(m_1+m_2)^2}\sigma_{r1}^2 + \frac{3}{2}\frac{m_3^2(Q_1+Q_2)+(m_1+m_2)^2 Q_3}{(m_1+m_2+m_3)^2}\sigma_{r2}^2$$

$$\sigma_{ri} = 1/\sqrt{(\mu_i\,\omega)} \qquad \mu_1 = \frac{m_1 m_2}{m_1+m_2} \qquad \mu_2 = \frac{(m_1+m_2)m_3}{m_1+m_2+m_3}$$

Meson	$\langle r^2\rangle_{ch}$	σ_{p1}	σ_{p2}
$D^+ = [c\bar{d}]$	0.184	0.282	—
$D_s^+ = [\bar{s}c]$	0.083	0.404	—
Baryon	$\langle r^2\rangle_{ch}$	σ_{p1}	σ_{p2}
$\Lambda_c^+ = [udc]$	0.15	0.251	0.424
$\Xi_c^+ = [usc]$	0.2	0.242	0.406
$\Omega_c^0 = [ssc]$	-0.12	0.337	0.53

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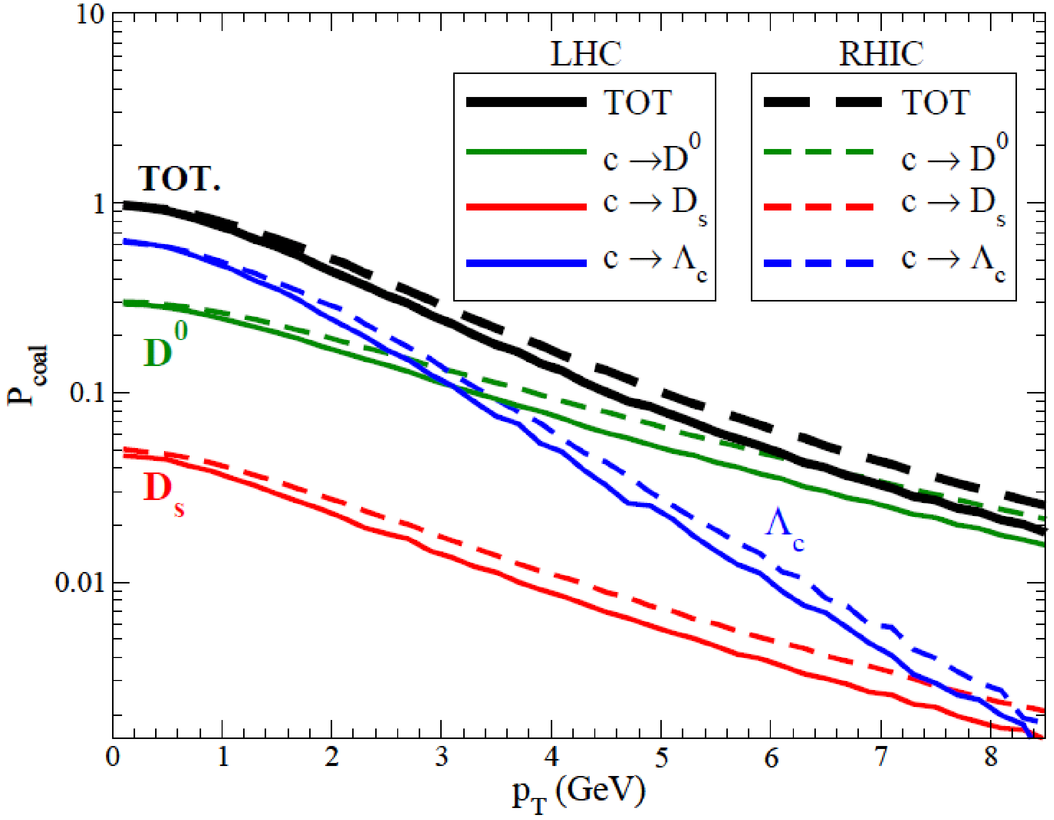

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Numerical implementation of coalescence integral

$$\frac{dN_M}{d^2\boldsymbol{p}_T} = g_M \sum_{i,j} P_q(i) P_{\bar{q}}(j) \delta^{(2)}(\boldsymbol{p}_T - \boldsymbol{p}_{iT} - \boldsymbol{p}_{jT}) f_M(x_i, x_j; p_i, p_j)$$

Meson

$$\frac{dN_M}{d^2\boldsymbol{p}_T} = g_B \sum_{i \neq j \neq k} P_q(i) P_q(j) P_q \delta^{(2)}(\boldsymbol{p}_T - \boldsymbol{p}_{iT} - \boldsymbol{p}_{jT} - \boldsymbol{p}_{kT}) f_M(x_i, x_j, x_k; p_i, p_j, p_k)$$

Baryon

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Baryon

$$p_x^{rel} = \frac{E_2 p_{x1}^{CM} - E_1 p_{x2}^{CM}}{E_1 + E_2}$$

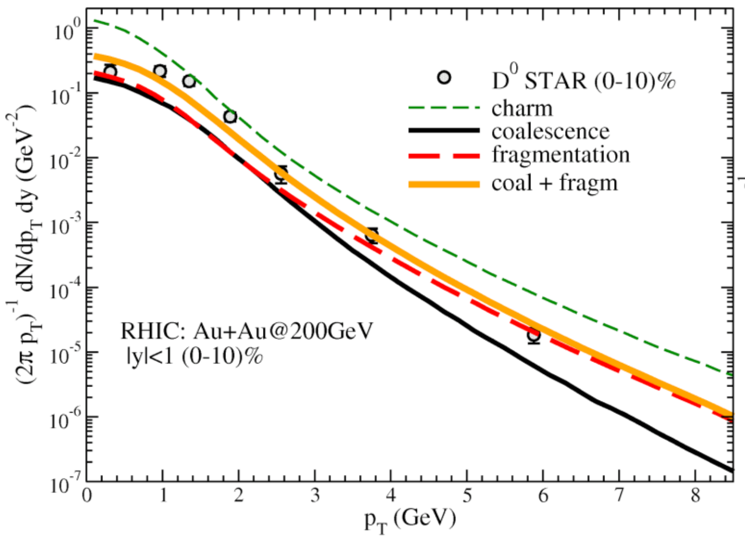
→ p_i^{rel} is independent of which weights we use

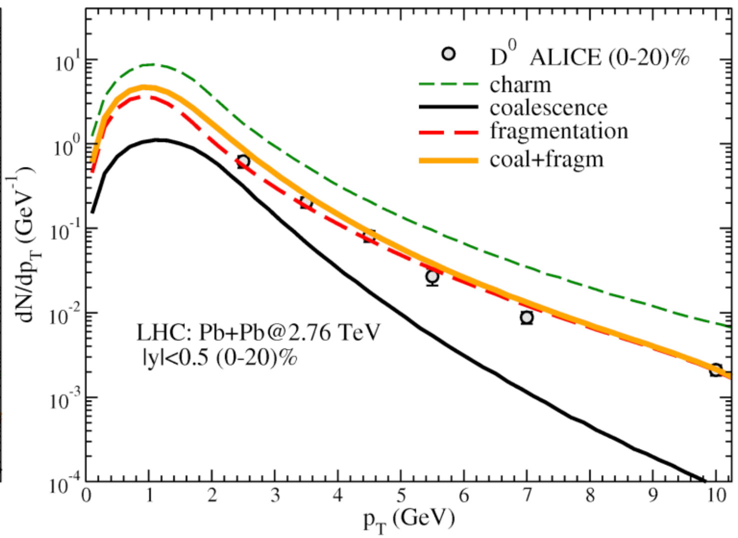
$$p_x^{rel} = \frac{m_2 p_{x1}^{CM} - m_1 p_{x2}^{CM}}{m_1 + m_2}$$

AA @ RHIC & LHC

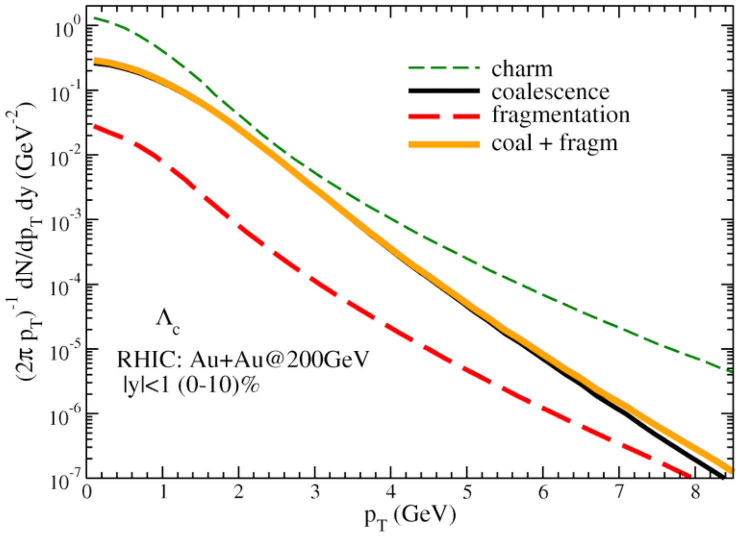
Wave function widths σ_p of baryon and mesons are the same at RHIC and LHC

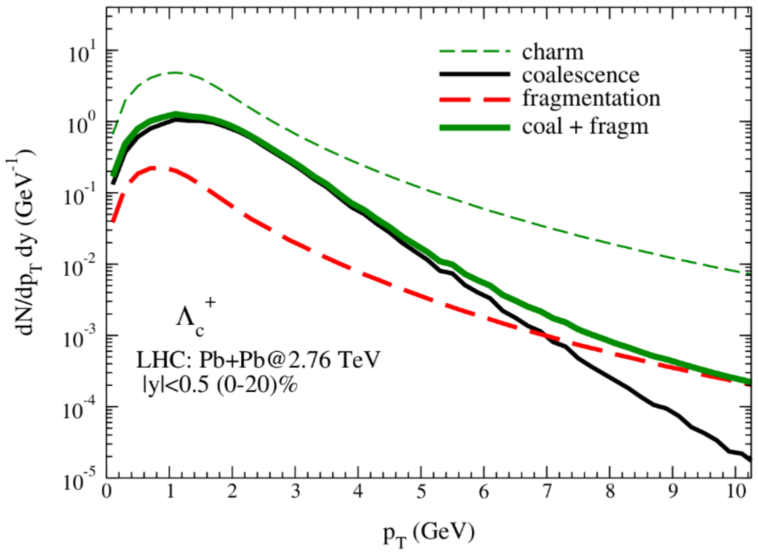
Data from: STAR Coll. PRL 113, 142301 (2014), ALICE Coll. JHEP 09 (2012) 112





D^0





Λ_C

RHIC LHC

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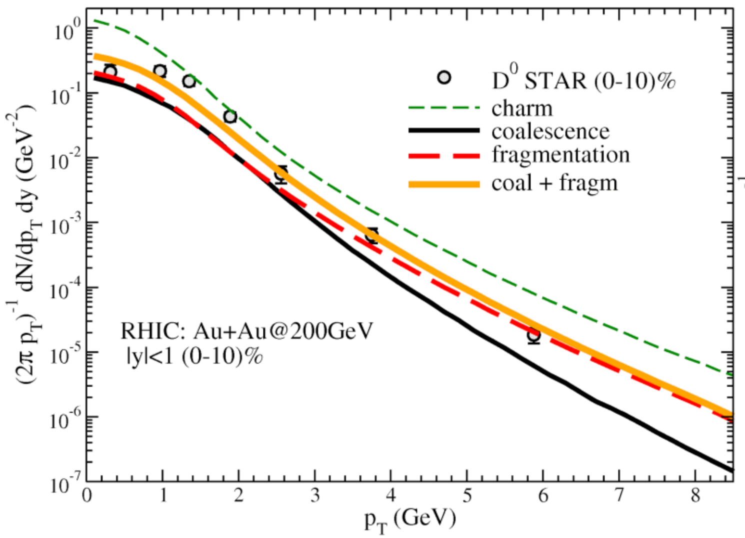
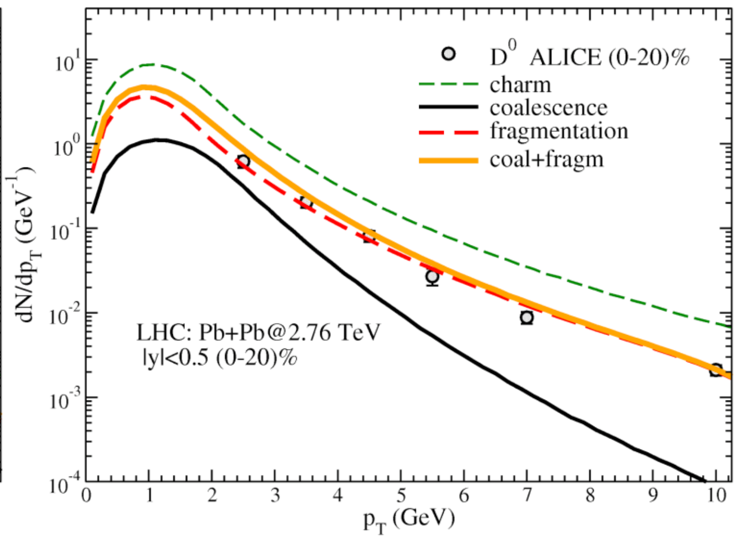
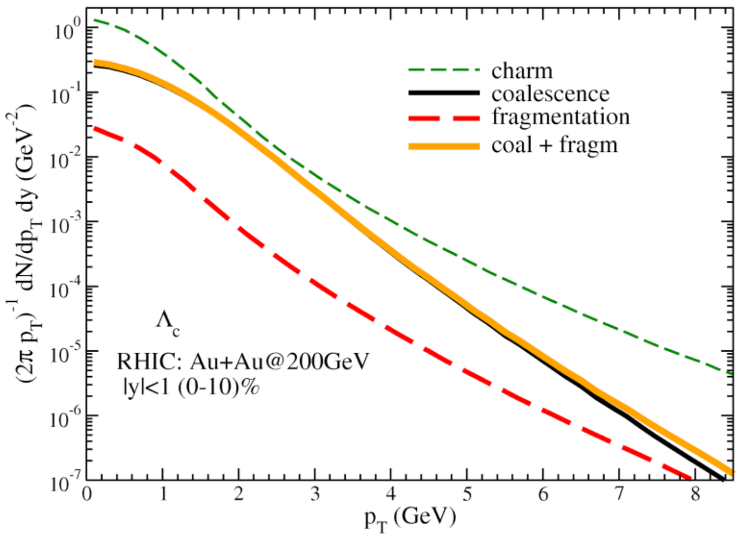


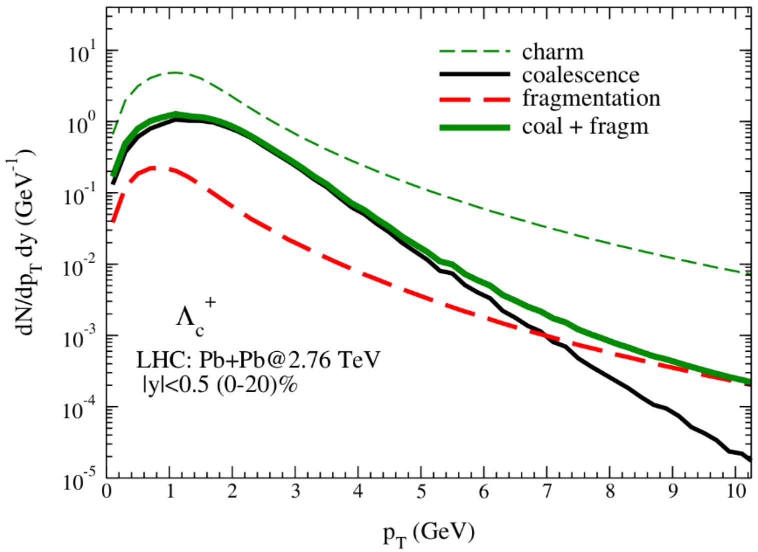


D^0

Coalescence lower at LHC then at RHIC

Main contribution: **Fragmentation**





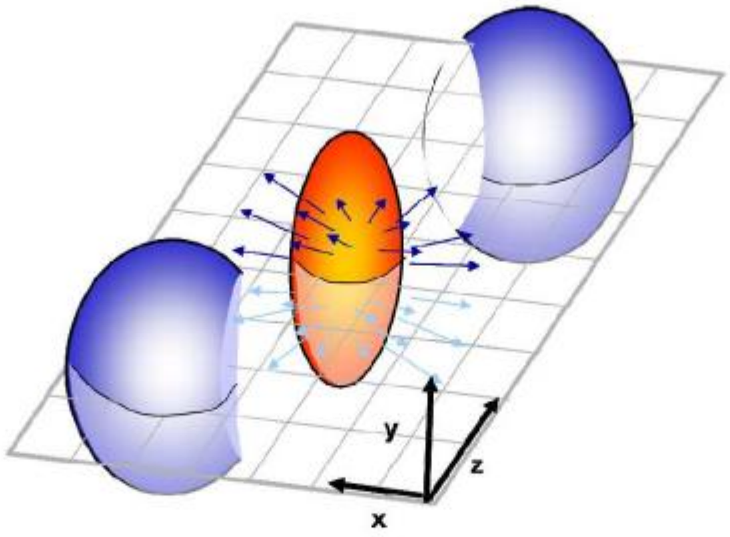
Λ_C

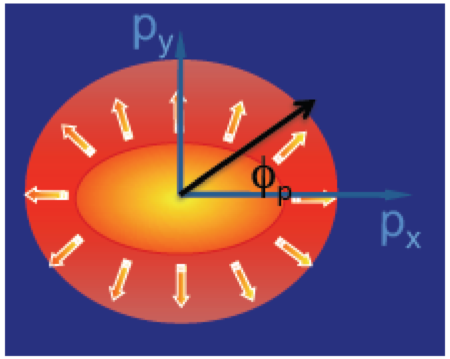
Coalescence lower at LHC then at RHIC

Main contribution: **Coalescence**

RHIC LHC

Elliptic Flow: v_2





Coordinate space: initial anisotropy → **Momentum space: final anisotropy**

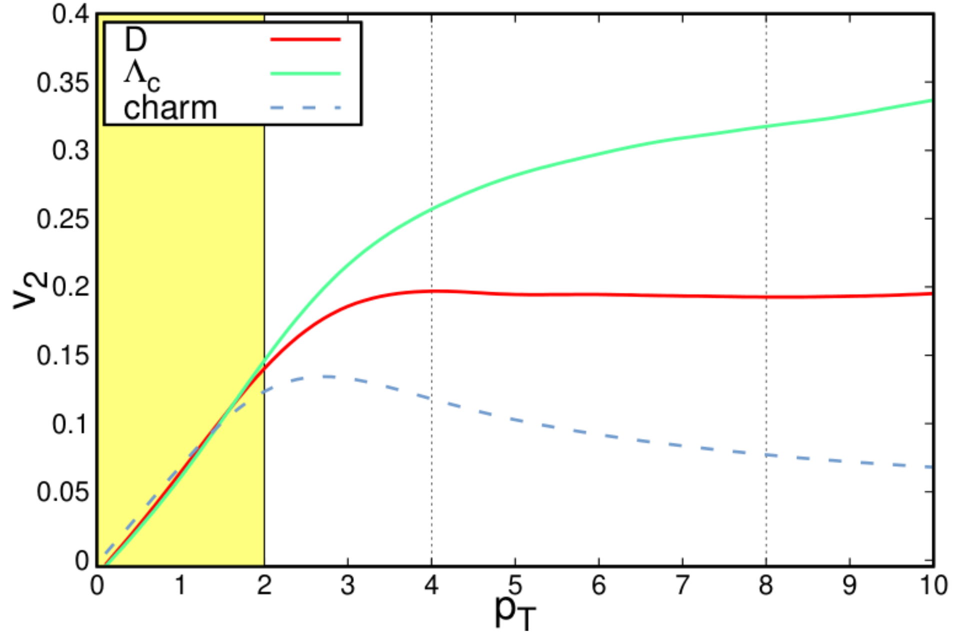
$$\varepsilon_x = \left\langle \frac{y^2 - x^2}{y^2 + x^2} \right\rangle$$

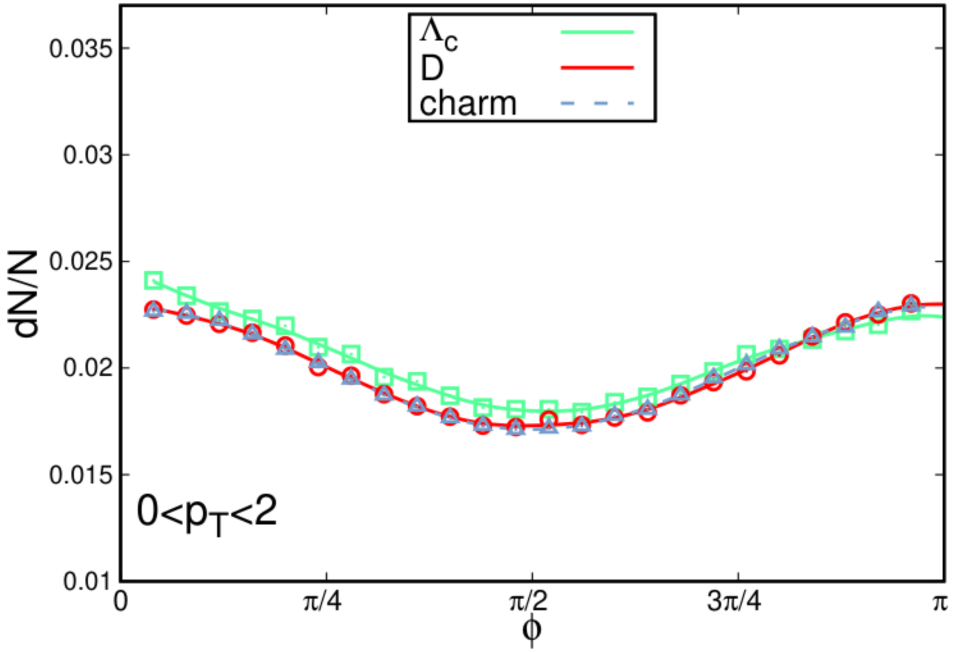
$\frac{v_2}{\varepsilon}$ mesure the efficiency in converting the eccentricity from coordinate to momentum space

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

$$\frac{dN}{dp_T d\phi} = \frac{dN}{dp_T}[1 + 2v_2 \cos(2\phi) + \cdots]$$

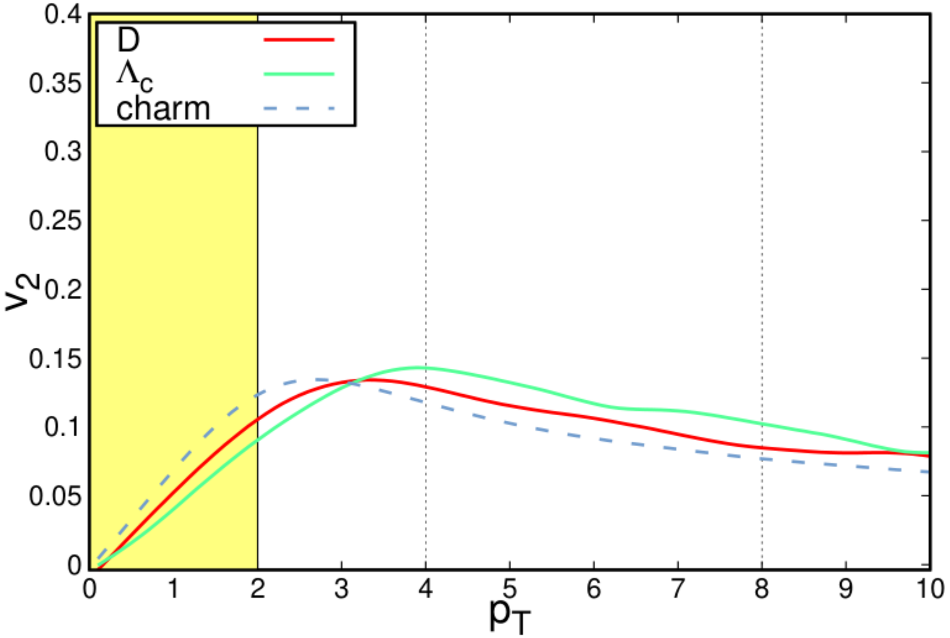
Angular distribution

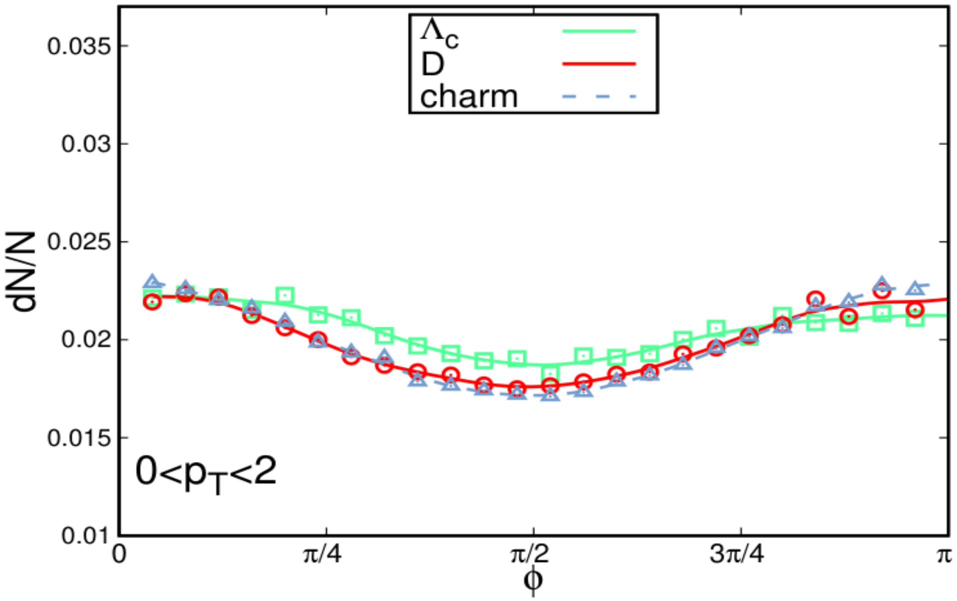




V2 charm **ON**

V2 bulk **ON**





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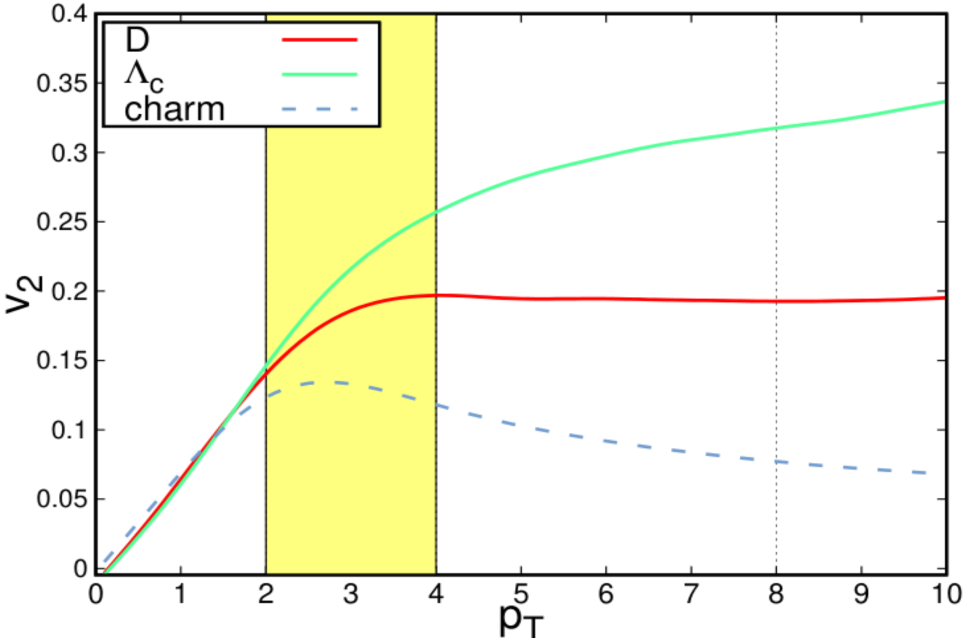
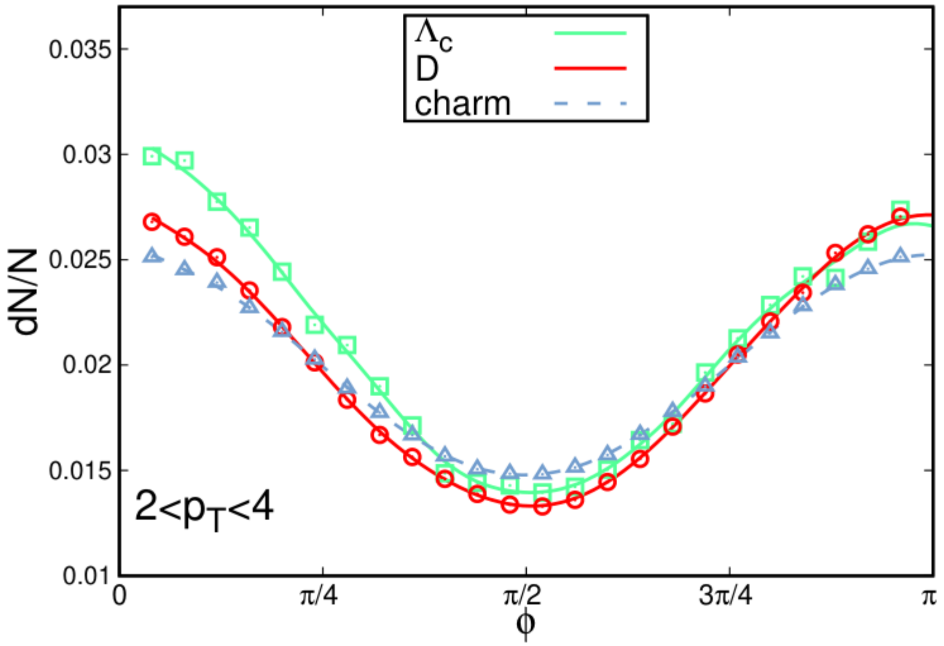
Angular distribution





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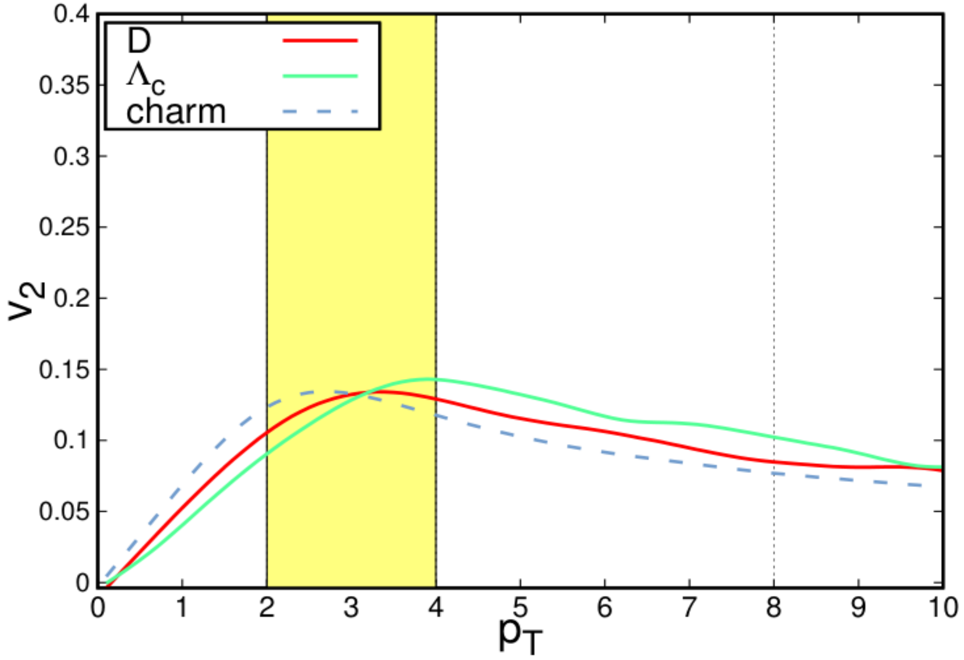

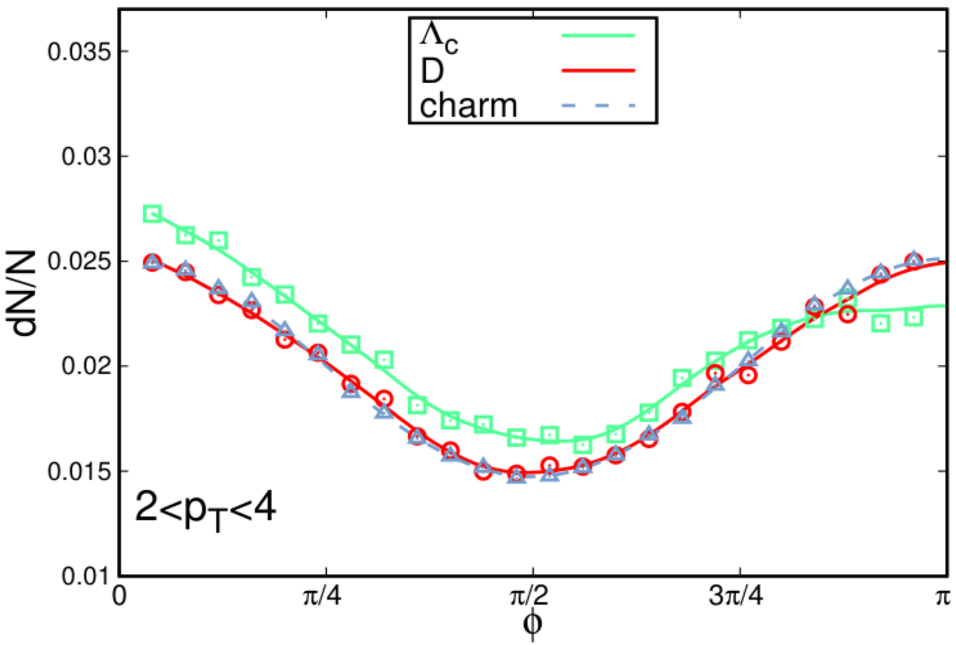

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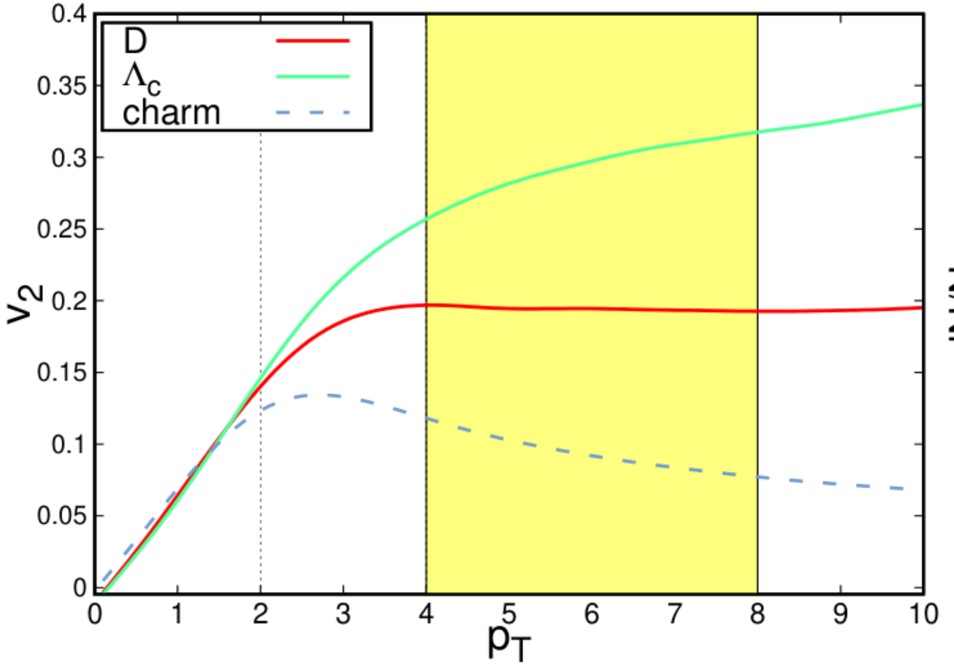

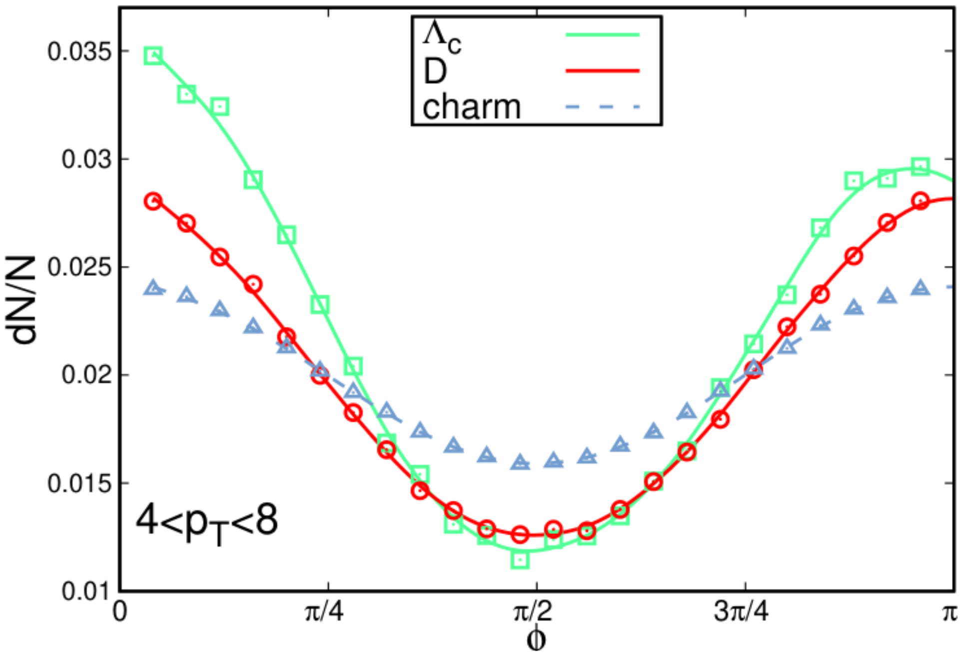

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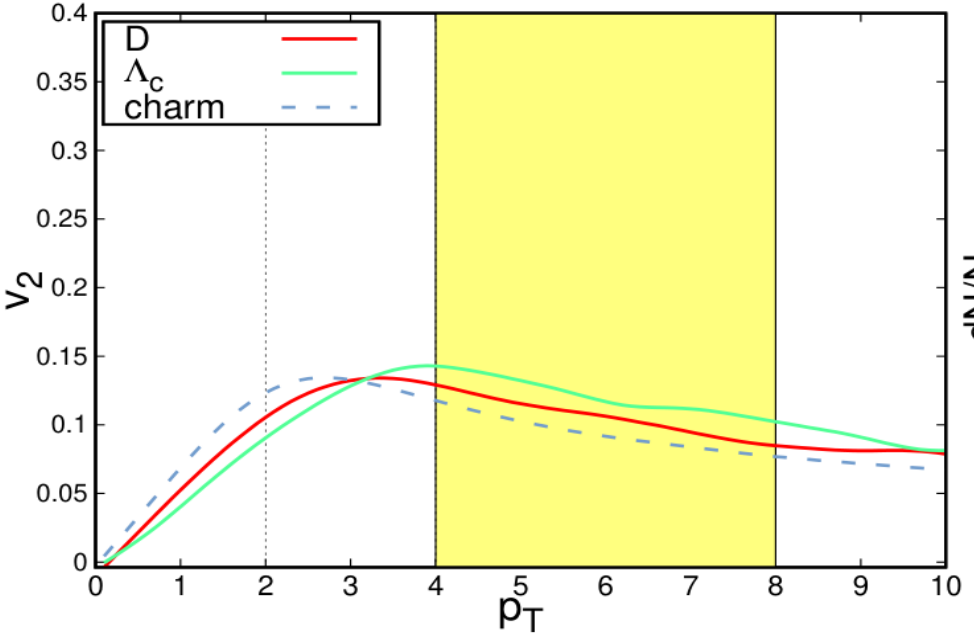

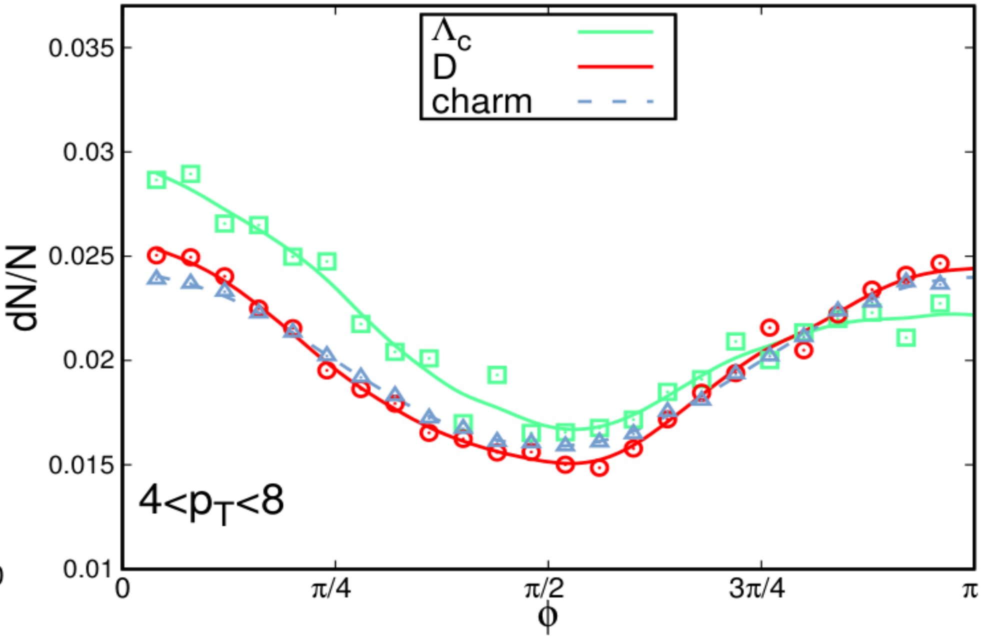

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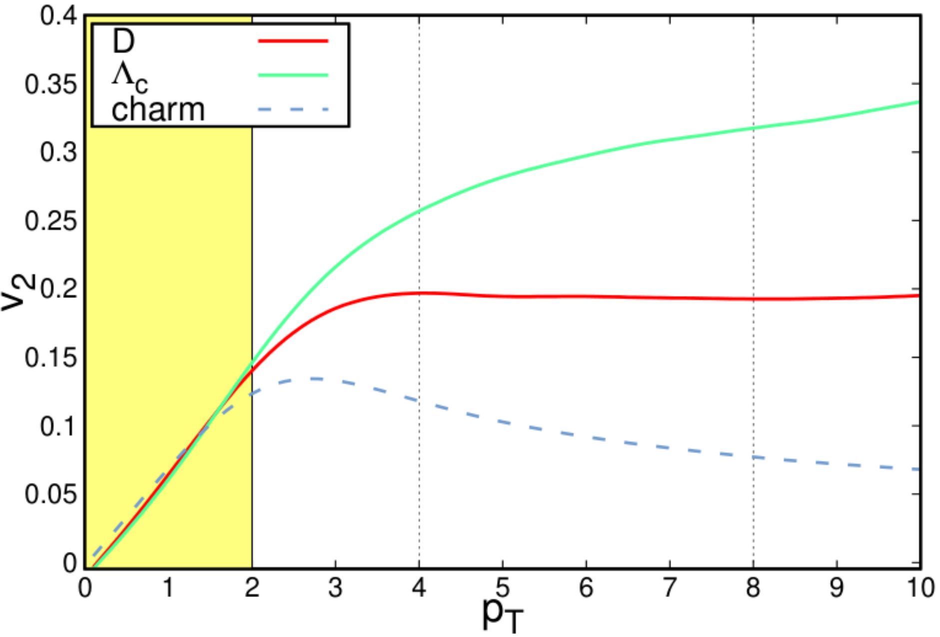

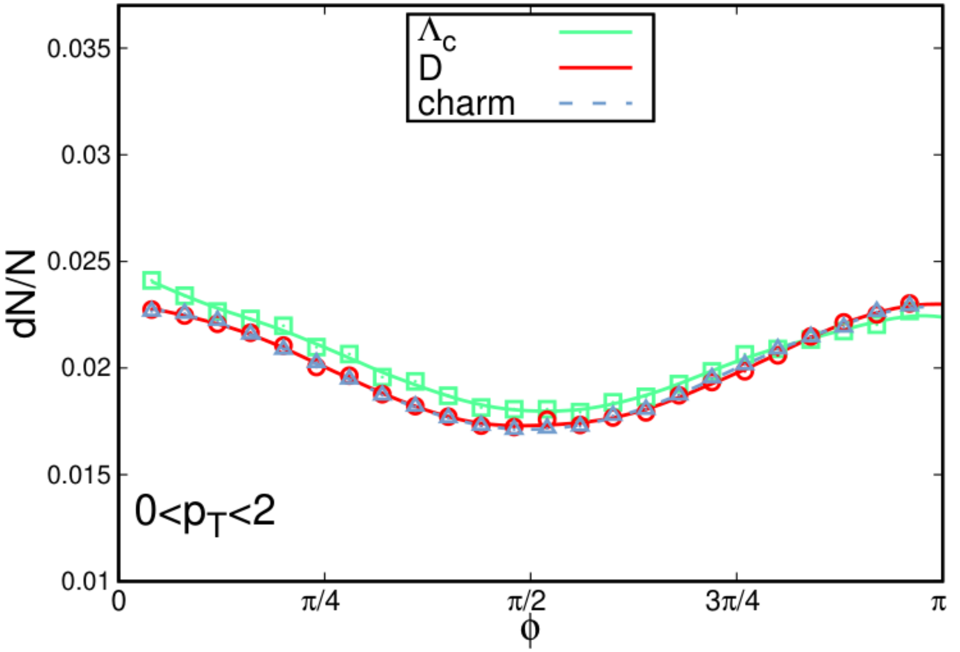

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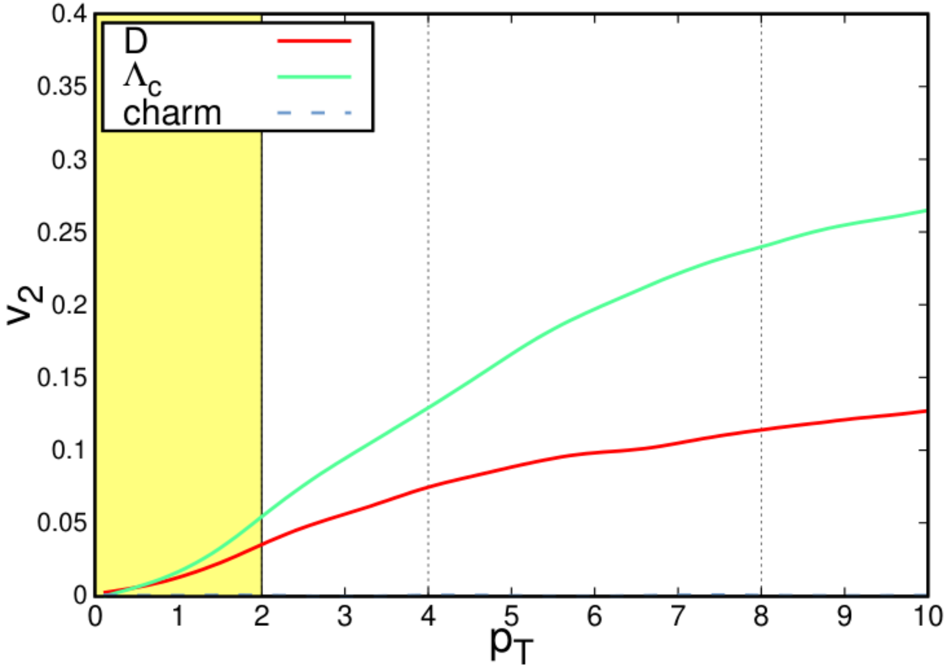

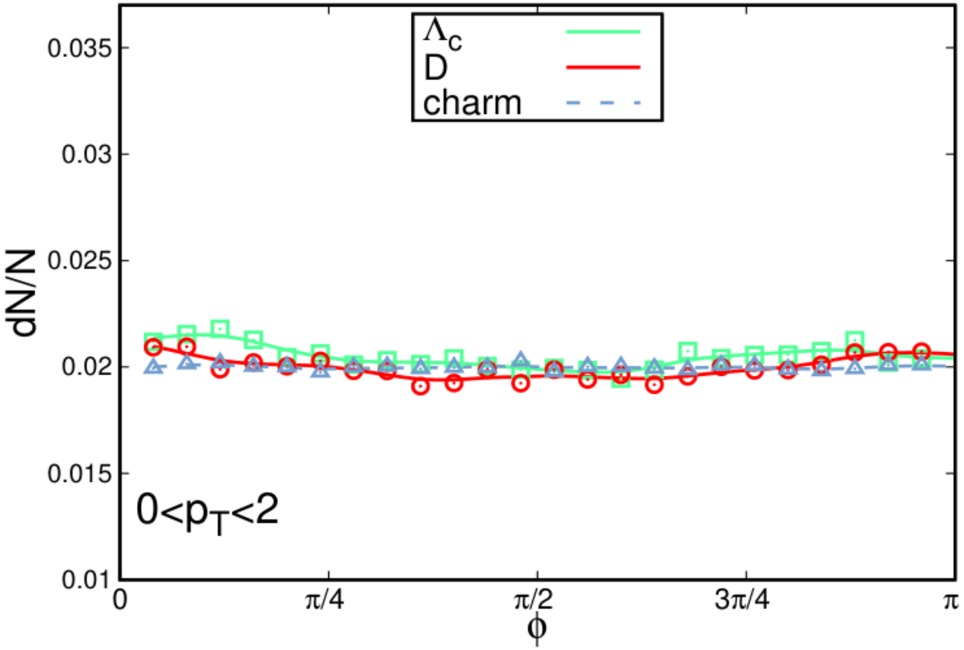

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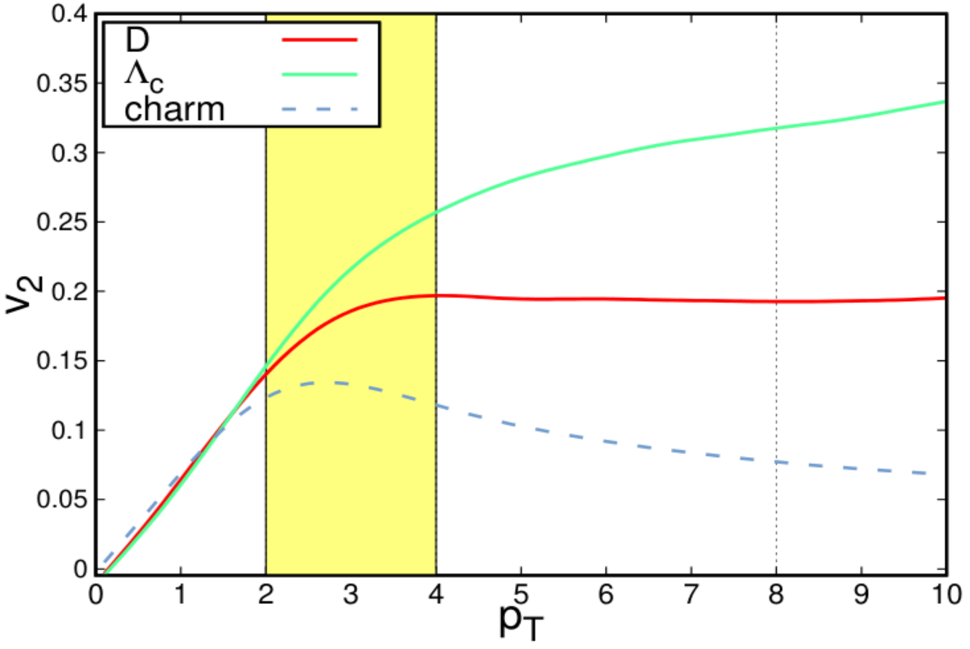

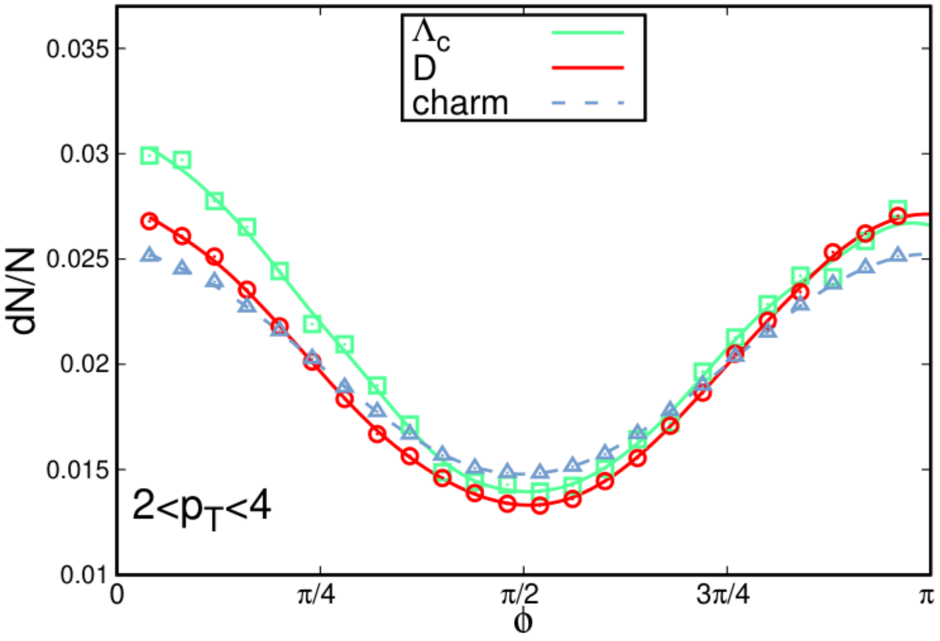

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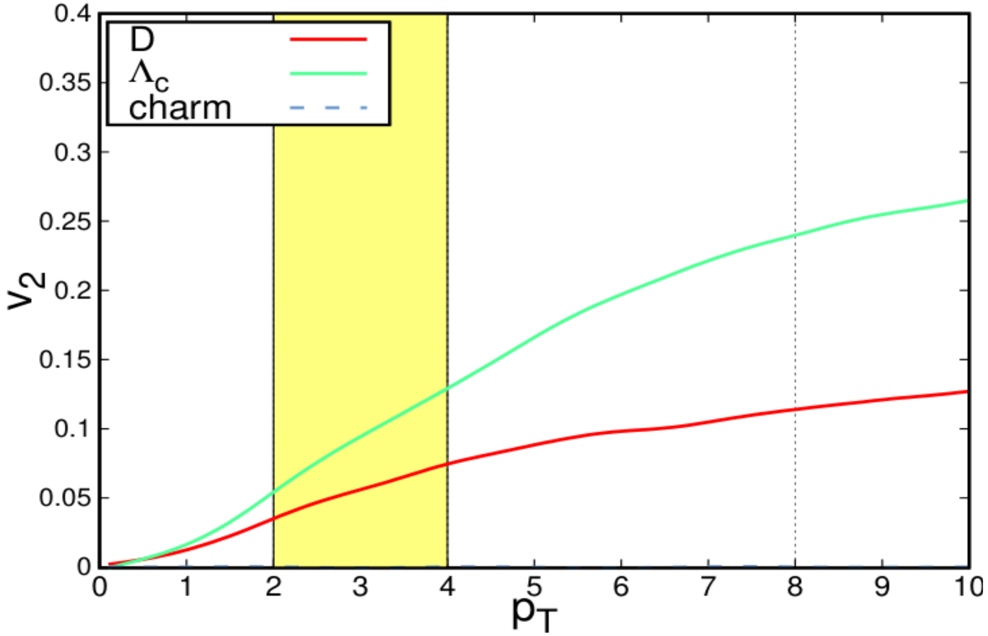

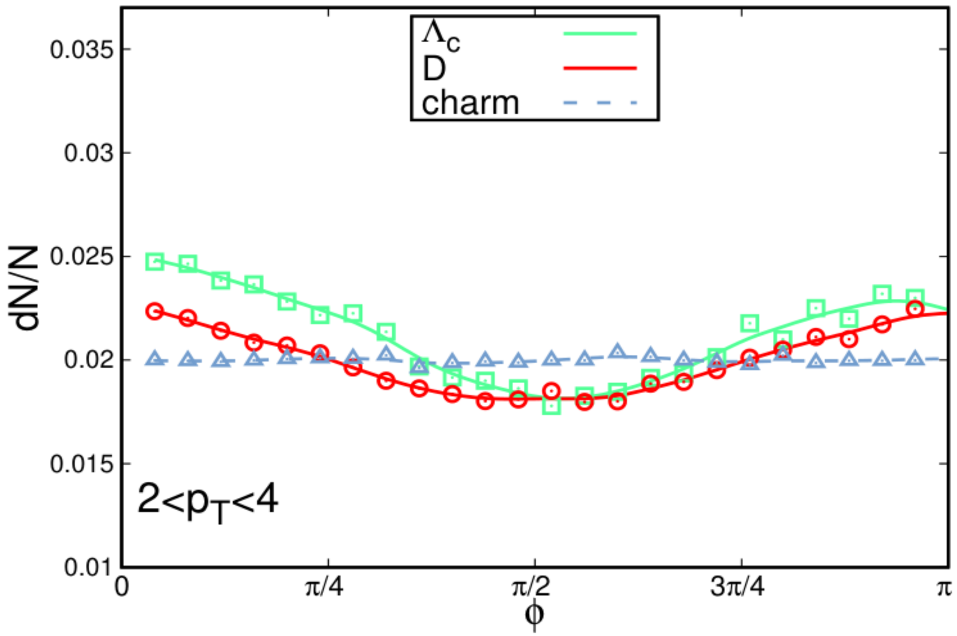

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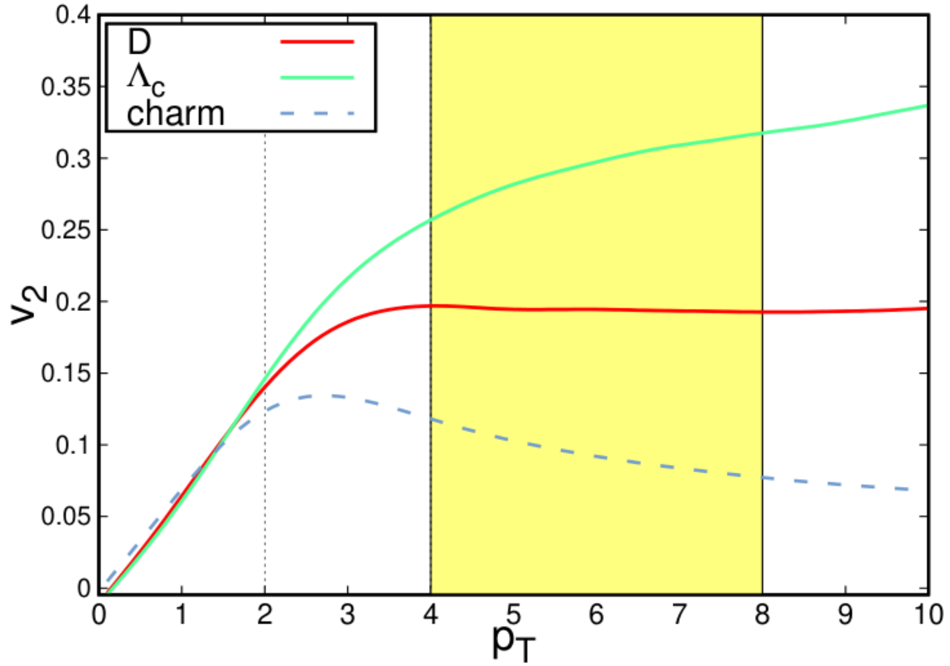

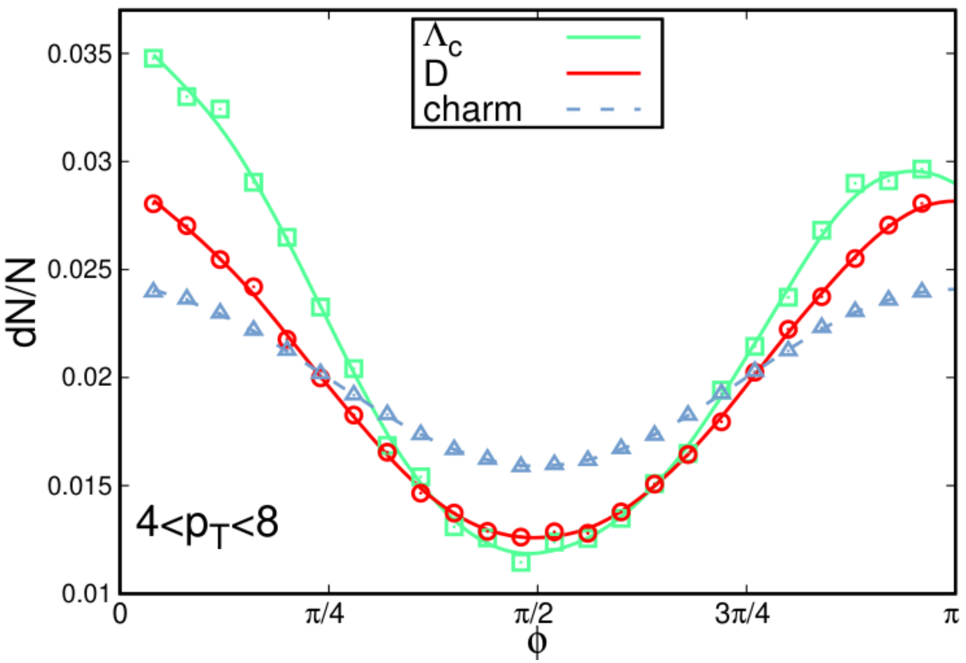

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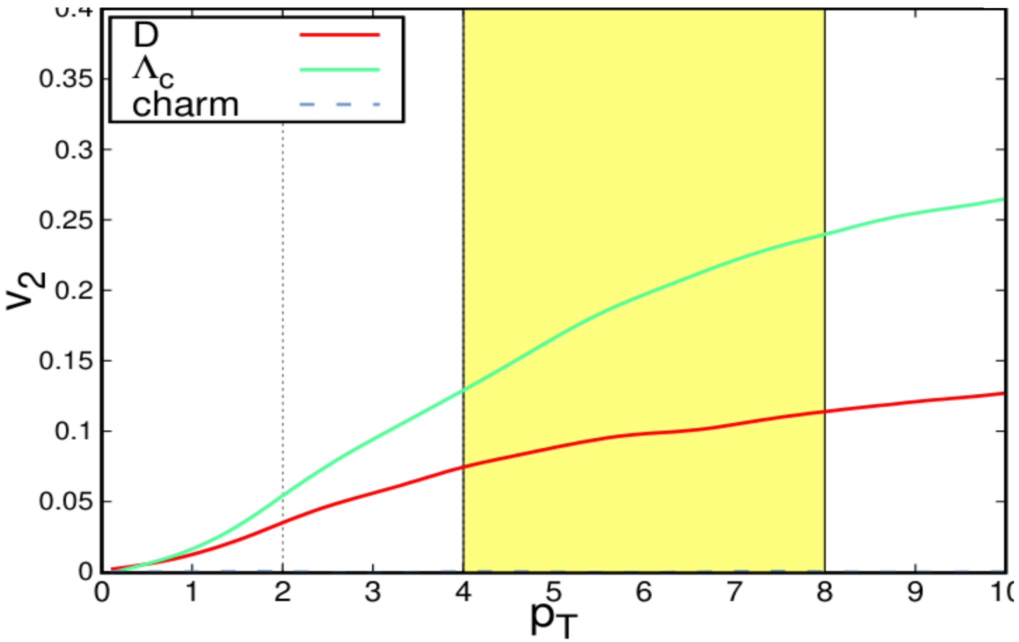

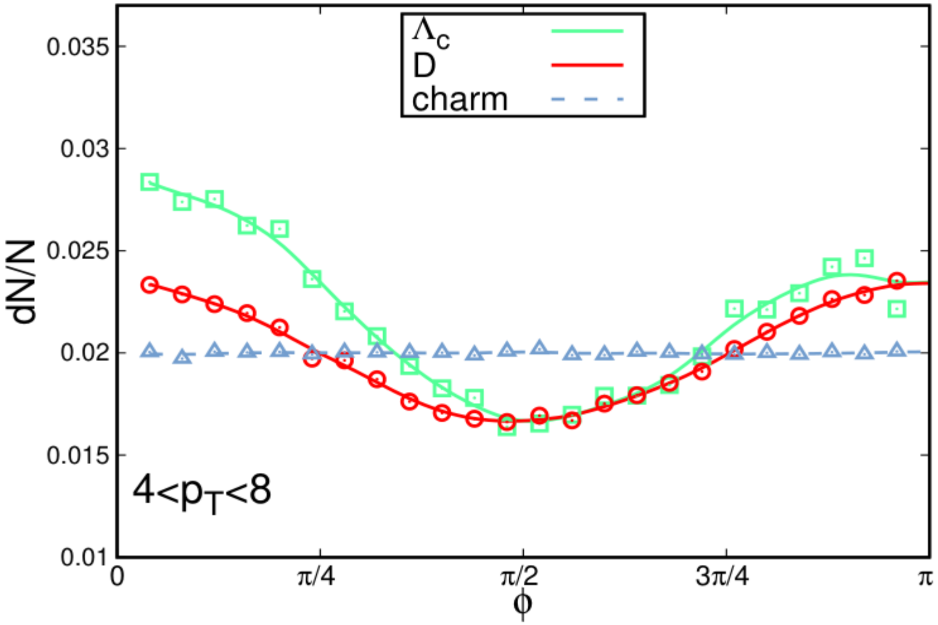

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Bethe-Salpeter approach to hadronization

The BS is a relativistic eq. which try to describe a bound system via a wave function called BS wave function. The idea come from Feynman treatment of interaction, and it was then formalized by Gell Mann. The idea is the following

$$\psi(\mathbf{x}_2, t_2) = \int K(\mathbf{x}_2, t_2; \mathbf{x}_1, t_1)\psi(\mathbf{x}_1, t_1) d^3\mathbf{x}_1$$

If we now add a weak potential $U(\boldsymbol{x}, t) we\ can\ expand\ the\ propagator$

$$K^{(1)}(2, 1) = -i \int K_0(2, 3) U(3) K_0(3, 1) d\tau_3$$

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$$K^{(1)}(2, 1) = -i\int K_0(2, 3)U(3)K_0(3, 1)d\tau_3$$

Continuing the perturbation expansion, we can write

$$K_+^{(A)}(2, 1) = K_+(2, 1) - i\int K_+(2, 3)A(3)K_+^{(A)}(3, 1)d\tau_3$$

Bethe-Salpeter approach to hadronization

The BS is a relativistic eq. which try to describe a bound system via a wave function called BS wave function. The idea come from Feynman treatment of interaction, and it was then formalized by Gell Mann. The idea is the following

$$\psi(\mathbf{x}_2, t_2) = \int K(\mathbf{x}_2, t_2; \mathbf{x}_1, t_1)\psi(\mathbf{x}_1, t_1)d^3\mathbf{x}_1$$

If we now add a weak potential $U(\boldsymbol{x}, t) we\ can\ expand\ the\ propagator$

$$K^{(1)}(2, 1) = -i\int K_0(2, 3)U(3)K_0(3, 1)d\tau_3$$

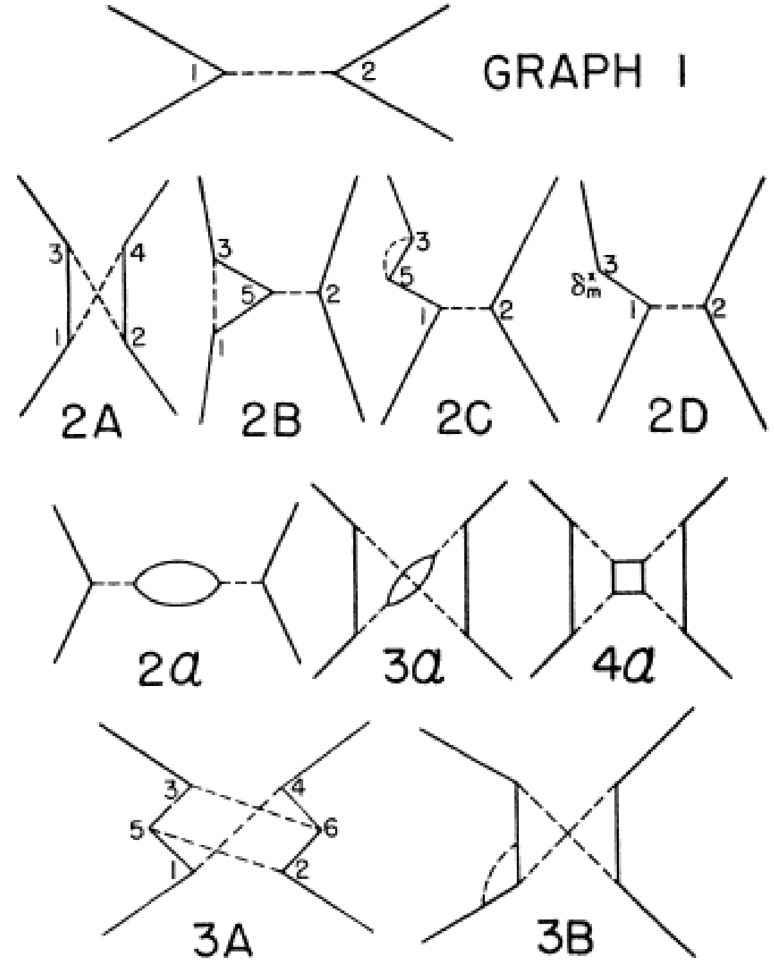
In the case in which we consider two particles in interaction

$$K^{(1)}(3, 4; 1, 2) = -ie^2\int\int K_{0a}(3, 5)K_{0b}(4, 6){r_{56}}^{-1} \times \delta(t_{56})K_{0a}(5, 1)K_{0b}(6, 2)d\tau_5 d\tau_6$$

Bethe-Salpeter approach to hadronization

In the case of two particles, we have to consider all the possible interactions

$$G^{(2A)}(1,2\,;3,4) = -i\Gamma_{a\sigma}\Gamma_{b\tau}K_{+a}(3,1)K_{+b}(4,2)$$
$$\times\Gamma_{a\tau}\Gamma_{b\sigma}G'(1,4)G'(2,3)$$



Bethe-Salpeter approach to hadronization

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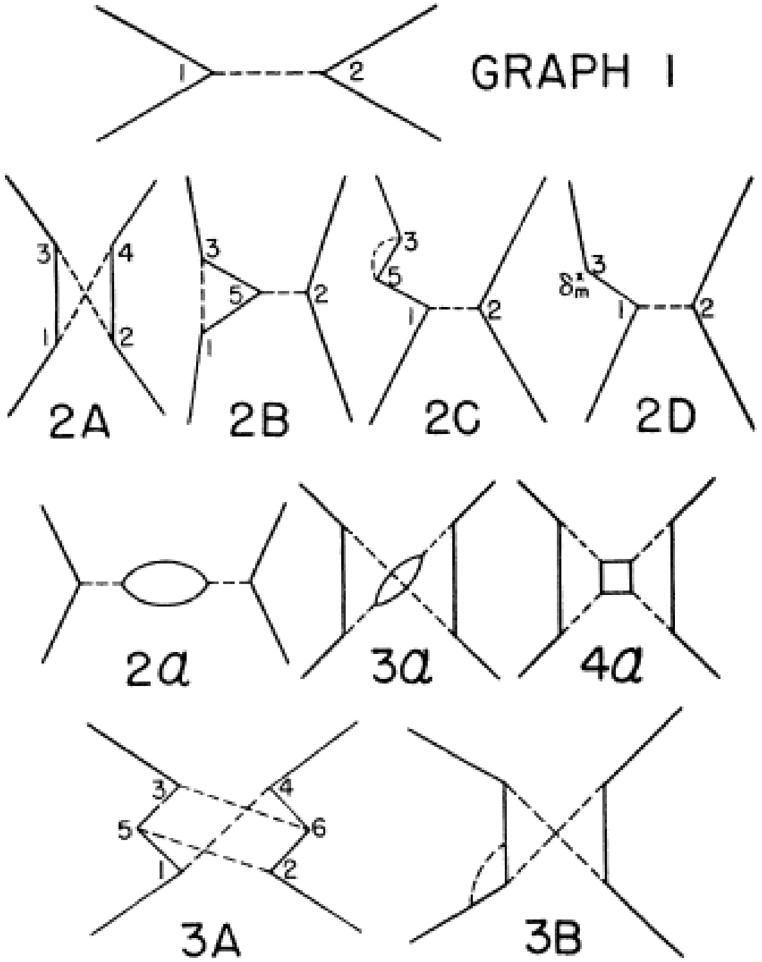

If we consider only the irreducible graphs

$$K^{(n)}(3,4;1,2)=-i\int\int\int\int d\tau_5 d\tau_6 d\tau_7 d\tau_8$$
$$\times K_{+a}(3,5)K_{+b}(4,6)G^{(n)}(5,6;7,8)$$
$$\times K_{+a}(7,1)K_{+b}(8,2)$$

Bethe-Salpeter approach to hadronization

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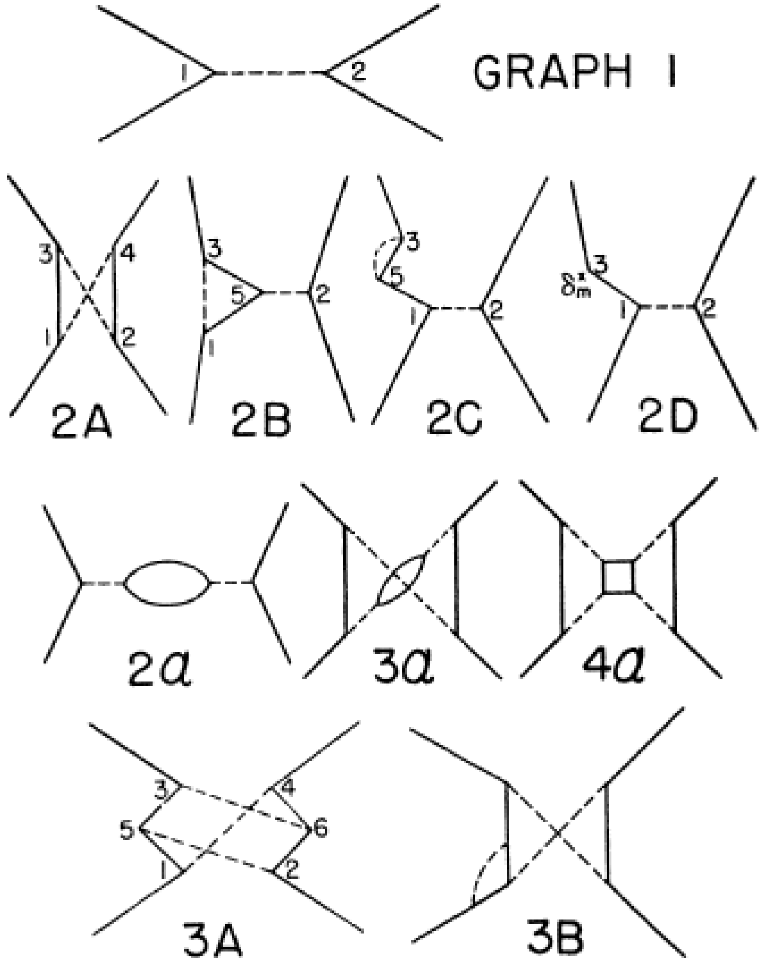
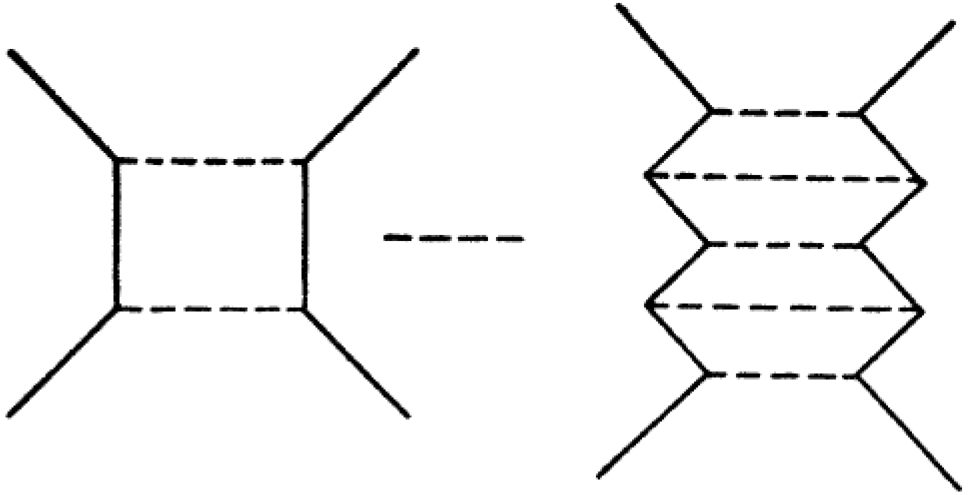


$$K^{(n)}(3,4;1,2) = -i\int\int\int\int d\tau_5 d\tau_6 d\tau_7 d\tau_8 \times K_{+a}(3,5)K_{+b}(4,6)G^{(n)}(5,6;7,8) \times K_{+a}(7,1)K_{+b}(8,2)$$

$$K(3,4;1,2) - K_{+a}(3,1)K_{+b}(4,2) = i\int\int\int\int d\tau_5 d\tau_6 d\tau_7 d\tau_8 K_{+a}(3,5)K_{+b}(4,6) \times \bar{G}(5,6;7,8)K(7,8;1,2)$$

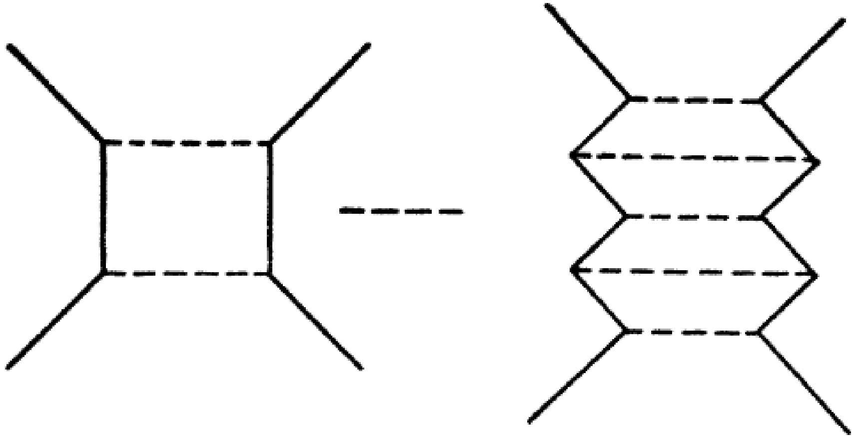
with $\bar{G} = \{G^{(1)} + G^{(2A)} + G^{(2B)} + G^{(2C)} + G^{(2D)} + G^{(2a)} + G^{(3A)} + \cdots\}$

Bethe-Salpeter approach to hadronization



If we chose only the $G(1)$ contribution, we are considering **Bound State**

Bethe-Salpeter approach to hadronization



If we chose only the $G(1)$ contribution, we are considering **Bound State**

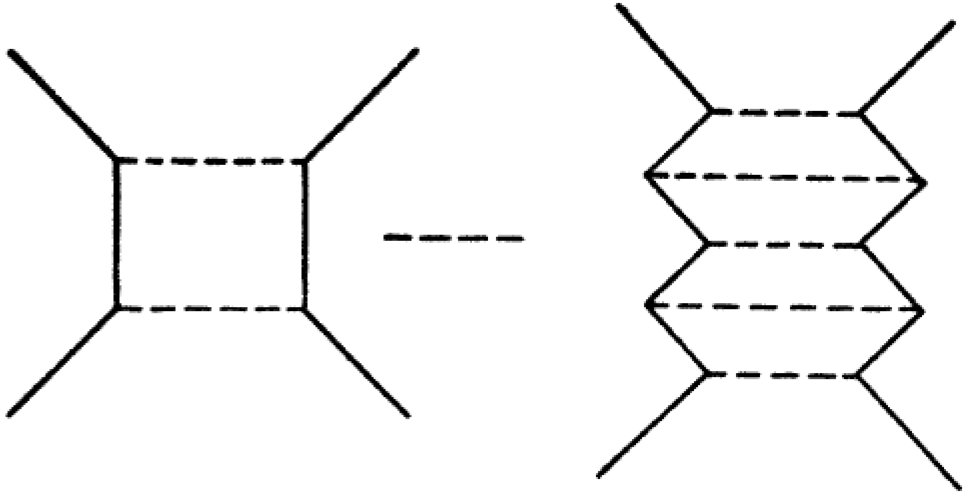
Now that we have the expansion of the propagator, we can use this in order to derive an integral equation for the wave function

$$K(3,4;1,2)-K_{+a}(3,1)K_{+b}(4,2) = i\int\int\int\int d\tau_5 d\tau_6 d\tau_7 d\tau_8 K_{+a}(3,5)K_{+b}(4,6) \times \bar{G}(5,6;7,8)K(7,8;1,2)$$

$\longrightarrow$

$$\psi(3,4) = -i\int\int\int\int d\tau_5 d\tau_6 d\tau_7 d\tau_8 K_{+a}(3,5) \times K_{+b}(4,6)\bar{G}(5,6;7,8)\psi(7,8)$$

Bethe-Salpeter approach to hadronization



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→

$$\mathfrak{F}\psi(p_\mu)=i\int d^4p'\bar{G}(p,p';K)\psi(p_\mu')$$

Salpeter, E. E., & Bethe, H. A. (1951). A relativistic equation for bound-state problems. *Physical Review*, *84*(6), 1232.

Bethe-Salpeter approach to hadronization

$$\mathfrak{F}\psi(p_\mu)=i\int d^4p'\bar{G}(p,p';K)\psi(p_\mu')$$

Since is very difficult to solve such an integral equation, a new equation is often used: **Quasi-Potential equation**

$$\left[4(\mathbf{p}^2+m^2)-E^2\right]\psi(\mathbf{p})-g^2\int\frac{d^3q}{(2\pi)^3}\frac{1}{\sqrt{\mathbf{q}^2+m^2}}\frac{\psi(\mathbf{q})}{(\mathbf{p}-\mathbf{q})^2+\mu^2}=0$$

Bethe-Salpeter approach to hadronization

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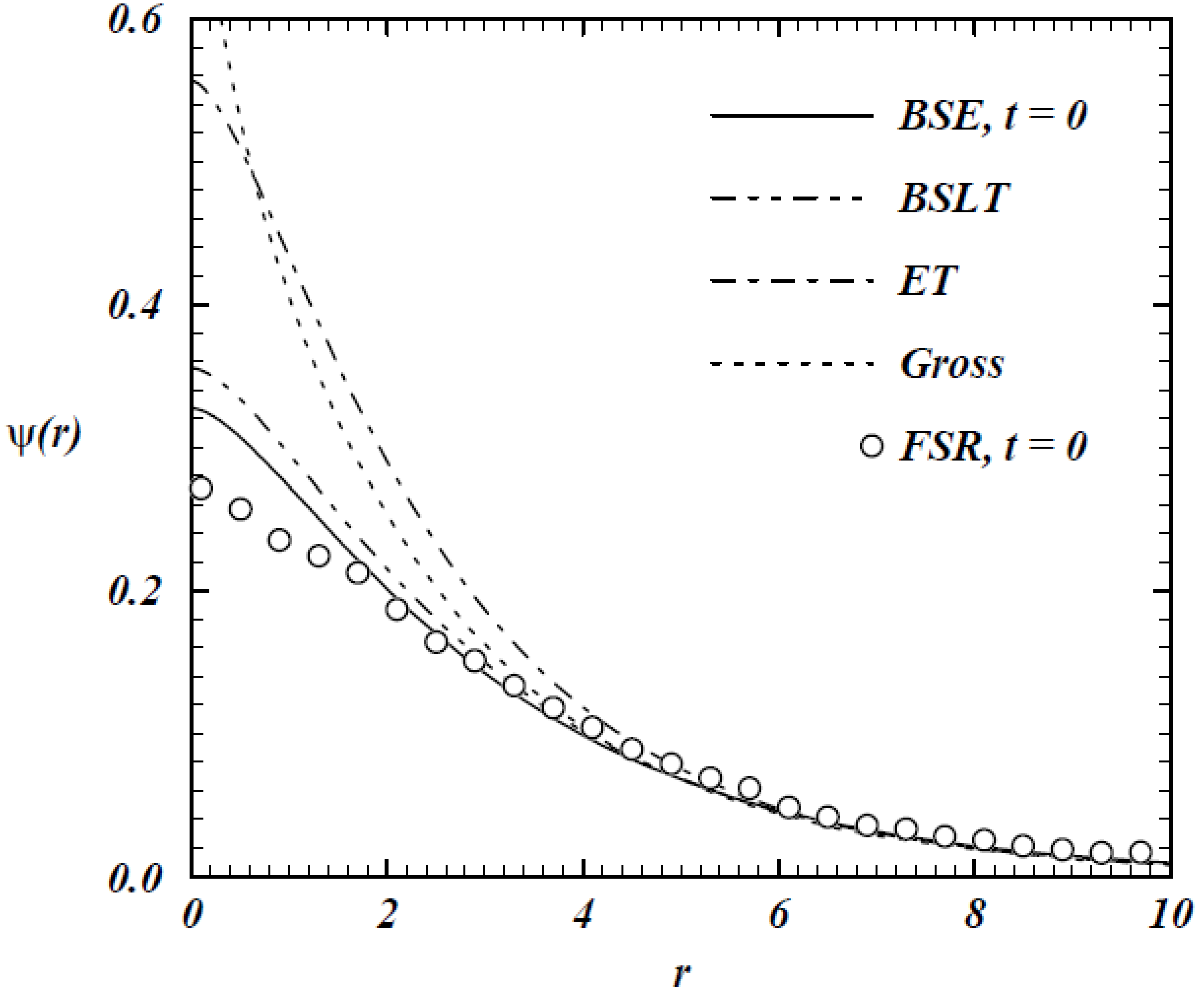

Bethe-Salpeter approach to hadronization

$$\langle x \,|\, q, \mathbf{p}_1\mathbf{p}_2\rangle = V^{-1} e^{i(\mathbf{p}_1\mathbf{x}_1 + \mathbf{p}_2\mathbf{x}_2)}$$

$$\langle x \,|\, M, \mathbf{P}\rangle = V^{-1/2} e^{i\mathbf{P}\cdot\mathbf{R}} \varphi_M(\mathbf{y})$$

The idea is to calculate the overlap of the two wave functions, in which the second is the BS Wave function, and insert the squared amplitude in a coalescence integral

Bethe-Salpeter approach to hadronization

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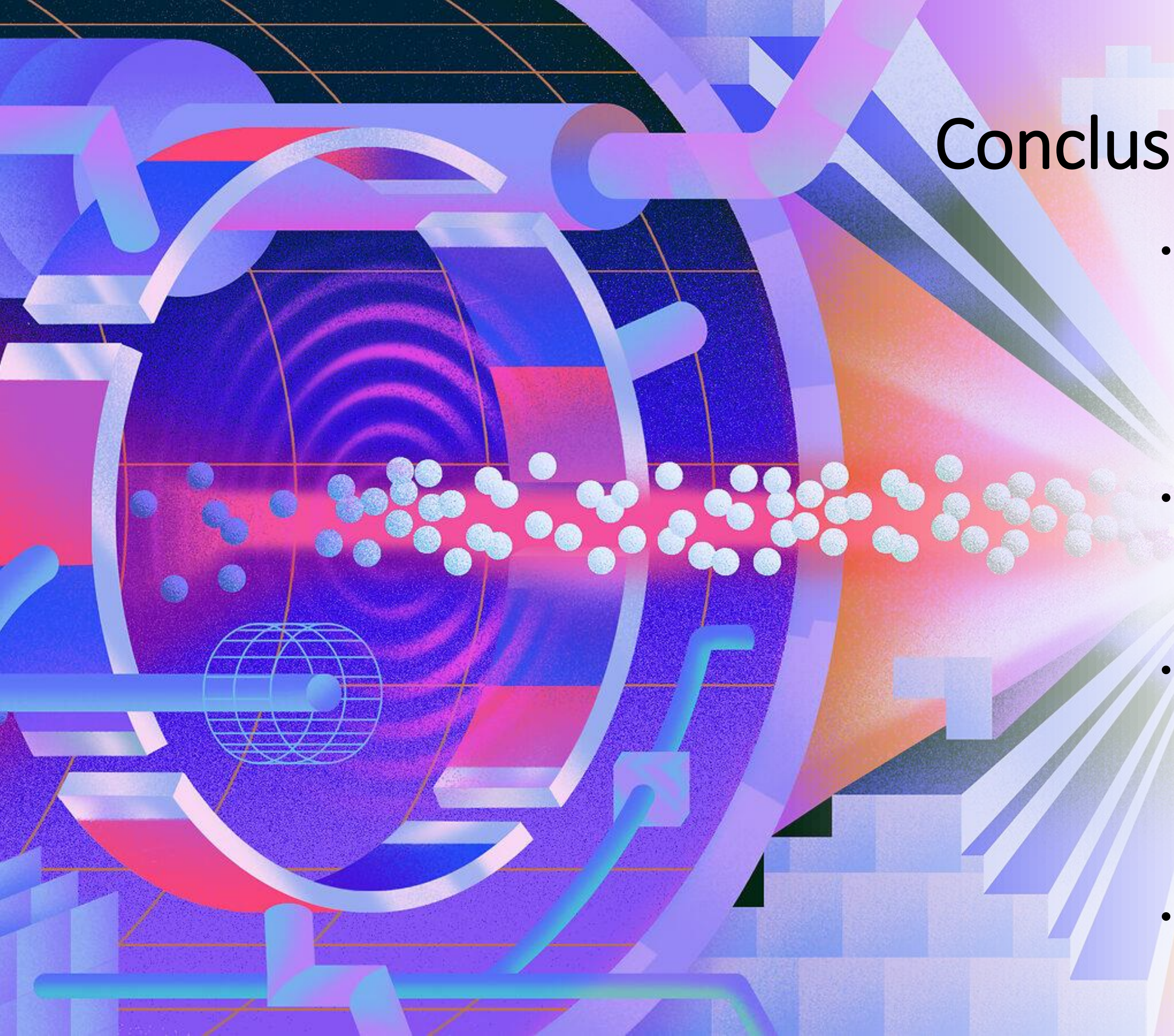
The idea is to calculate the overlap of the two wave functions, in which the second is the BS Wave function, and insert the squared amplitude in a coalescence integral

Link to coalescence approach

$$N_M = C_M V^3 \int \frac{d^3 P}{(2\pi)^3} \frac{d^3 p_1}{(2\pi)^3} \frac{d^3 p_2}{(2\pi)^3} \times w(\mathbf{p}_1) w(\mathbf{p}_2) \left| \langle q, \mathbf{p}_1 \mathbf{p}_1 \,|\, M, \mathbf{P} \rangle \right|^2$$



Conclusion(beginnings?)

- Study more deeply the motivations behind the fact that the elliptic flow of the light quarks contributes on the v_2 of Λ_C more than on the v_2 of the D mesons in [2,4] slice
- How the v_3 affect angular distributions in meson and baryon and how the v3 of Λ_C is generated
- Why when there is only the v_2 of the bulk turned on we see difference between the v_2 of meson and baryon already at low p_T
- Continue the development of the Bethe-Salpeter approach to coalescence

Meson	Mass(MeV)	I (J)	Decay modes	B.R.
$D^+ = \bar{d}c$	1869	$\frac{1}{2}(0)$		
$D^0 = \bar{u}c$	1865	$\frac{1}{2}(0)$		
$D_s^+ = \bar{s}c$	2011	$0(0)$		
Resonances				
D^{*+}	2010	$\frac{1}{2}(1)$	$D^0\pi^+$; D^+X	68%,32%
D^{*0}	2007	$\frac{1}{2}(1)$	$D^0\pi^0$; $D^0\gamma$	62%,38%
D_s^{*+}	2112	$0(1)$	D_s^+X	100%
Baryon				
$\Lambda_c^+ = udc$	2286	$0(\frac{1}{2})$		
$\Xi_c^+ = usc$	2467	$\frac{1}{2}(\frac{1}{2})$		
$\Xi_c^0 = dsc$	2470	$\frac{1}{2}(\frac{1}{2})$		
$\Omega_c^0 = ssc$	2695	$0(\frac{1}{2})$		
Resonances				
Λ_c^+	2595	$0(\frac{1}{2})$	$\Lambda_c^+\pi^+\pi^-$	100%
Λ_c^+	2625	$0(\frac{3}{2})$	$\Lambda_c^+\pi^+\pi^-$	100%
Σ_c^+	2455	$1(\frac{1}{2})$	$\Lambda_c^+\pi$	100%
Σ_c^+	2520	$1(\frac{3}{2})$	$\Lambda_c^+\pi$	100%
$\Xi_c'^{+,0}$	2578	$\frac{1}{2}(\frac{1}{2})$	$\Xi_c^{+,0}\gamma$	100%
Ξ_c^+	2645	$\frac{1}{2}(\frac{3}{2})$	$\Xi_c^+\pi^-$,	100%
Ξ_c^+	2790	$\frac{1}{2}(\frac{1}{2})$	$\Xi_c'\pi$,	100%
Ξ_c^+	2815	$\frac{1}{2}(\frac{3}{2})$	$\Xi_c'\pi$,	100%
Ω_c^0	2770	$0(\frac{3}{2})$	$\Omega_c^0\gamma$,	100%

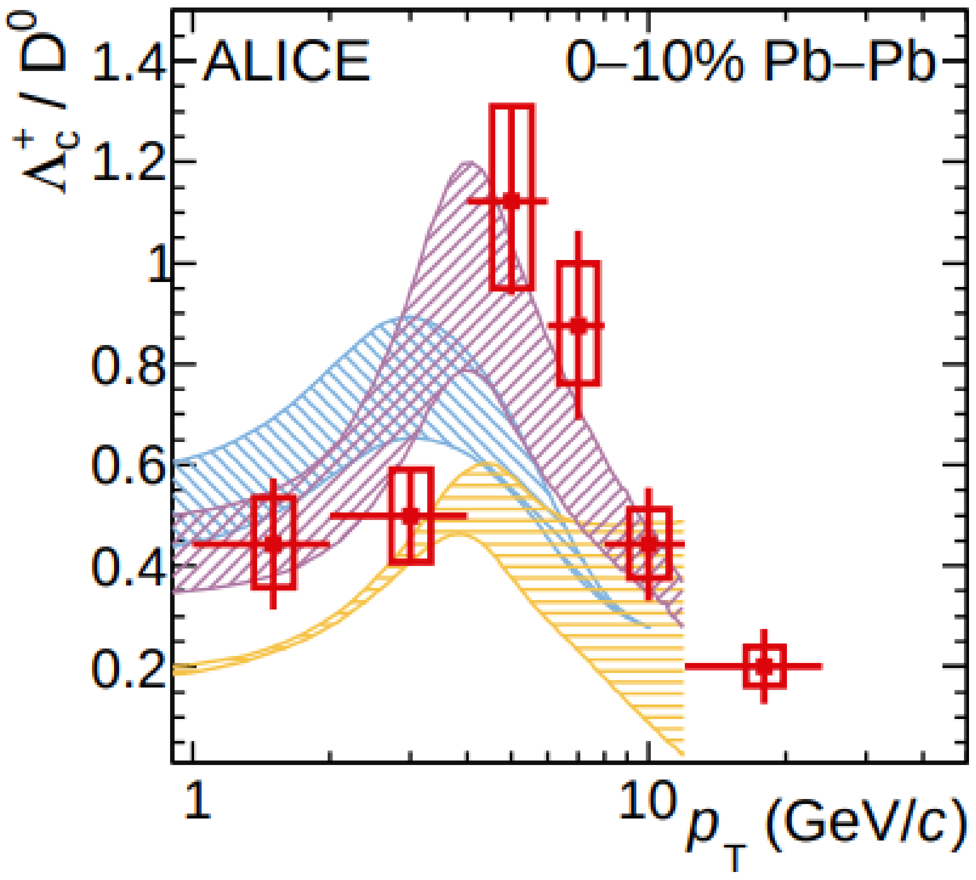
In our calculations we take into account hadronic channels including the ground states + first excited states

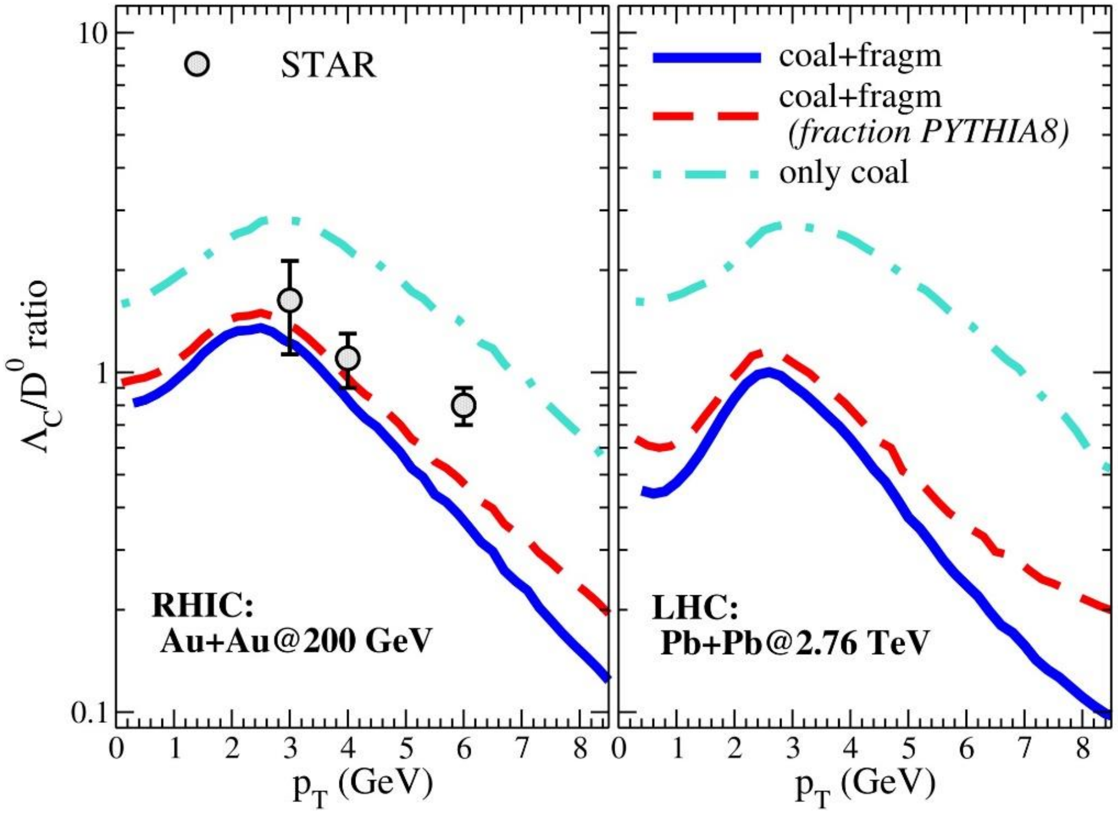
Statistical factor suppression for resonances

$$\frac{[(2J+1)(2I+1)]_{H^*}}{[(2J+1)(2I+1)]_H}\left(\frac{m_{H^*}}{m_H}\right)^{3/2} e^{-(m_{H^*}-m_H)/T}$$

AA @ RHIC & LHC

Wave function widths σ_p of baryon and mesons are the same at RHIC and LHC





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