

色眼鏡でみるpA 衝突

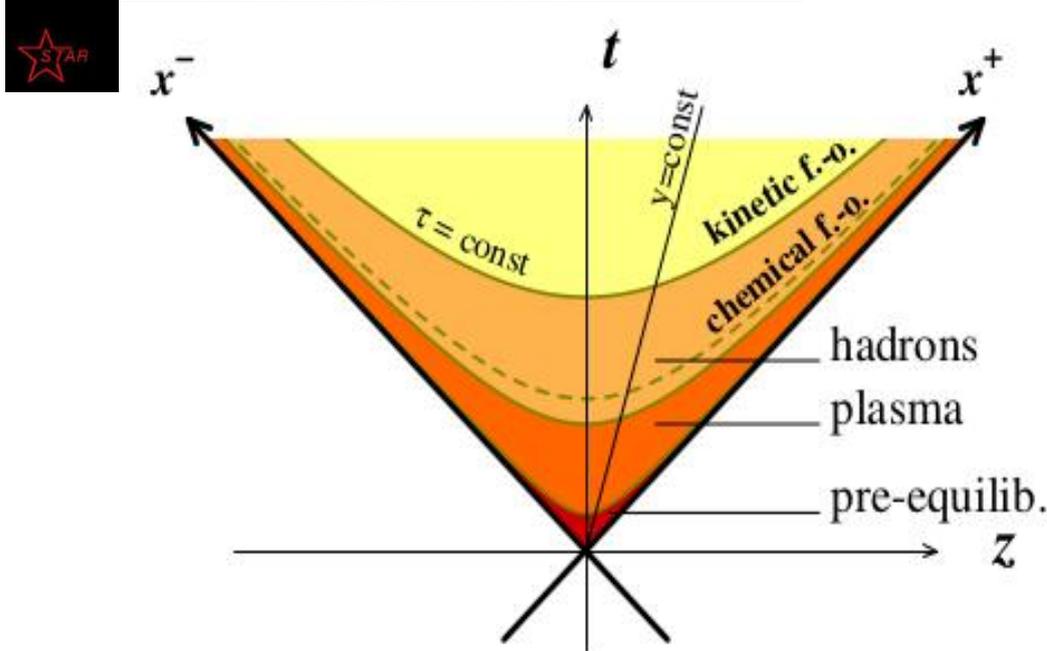
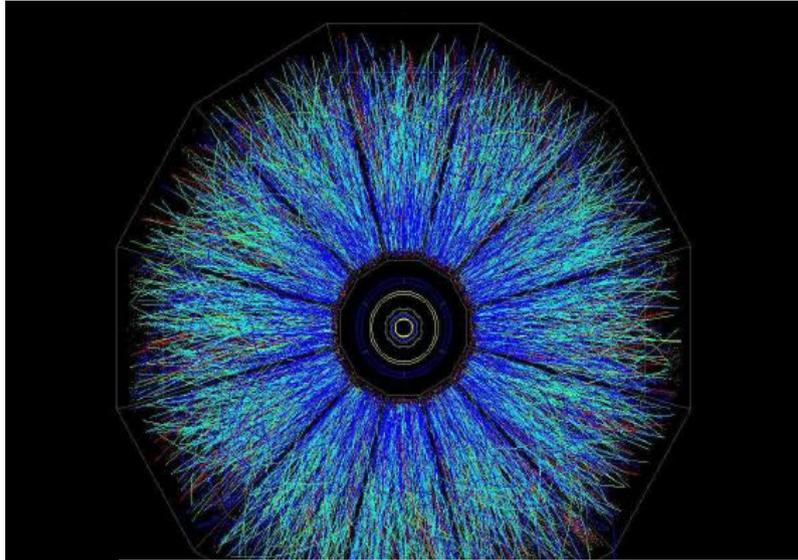
藤井 宏次

U Tokyo, Komaba

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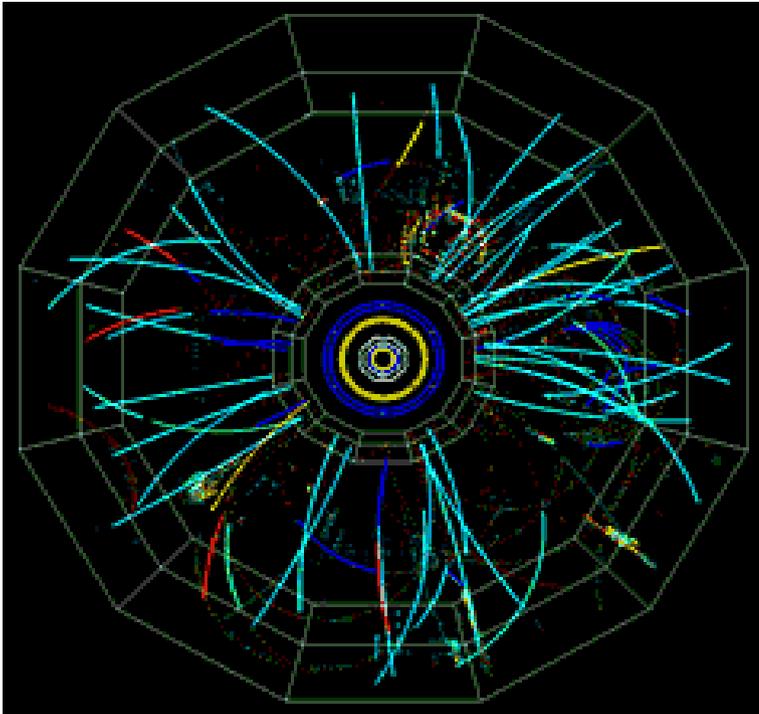
- カラーガラス凝縮の枠組み — pA衝突
- ハドロン生成
- 二粒子相関 -- 峰構造
- 重いクォーク
- まとめ

高エネルギー重イオン衝突



- 粒子観測
- 運動学的凍結
- 粒子種比凍結
- ハドロンカスケード
- 流体的プラズマ
- 早期平衡化？
- 核内パートンビーム

高エネルギー $p(d)+A$ 衝突



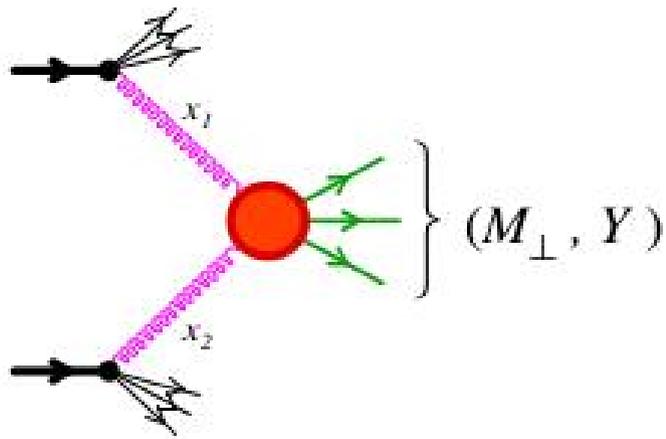
Brookhaven National Lab / RHIC-STAR

An end view of collision between deuterons and gold ions captured by the STAR detector at Brookhaven.

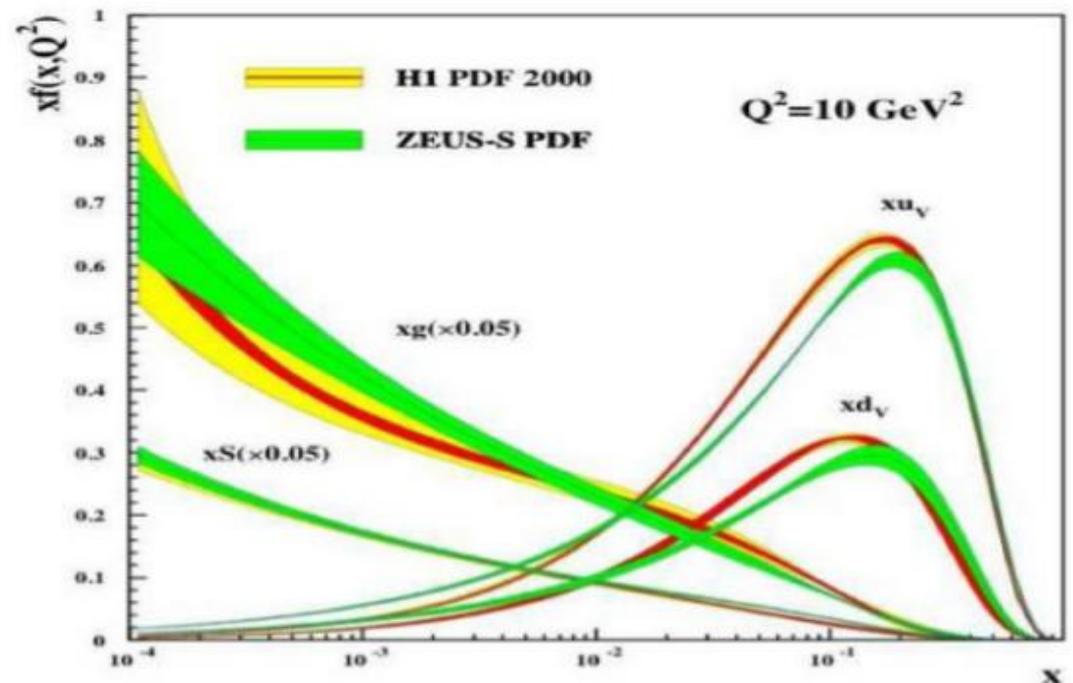
- 粒子観測
-
-
-
-
-
- 初期散乱
- 核内パートンビーム

初期条件 = dense small-x gluons

- 99%以上の粒子は $< 2\text{GeV}/c$ に生成

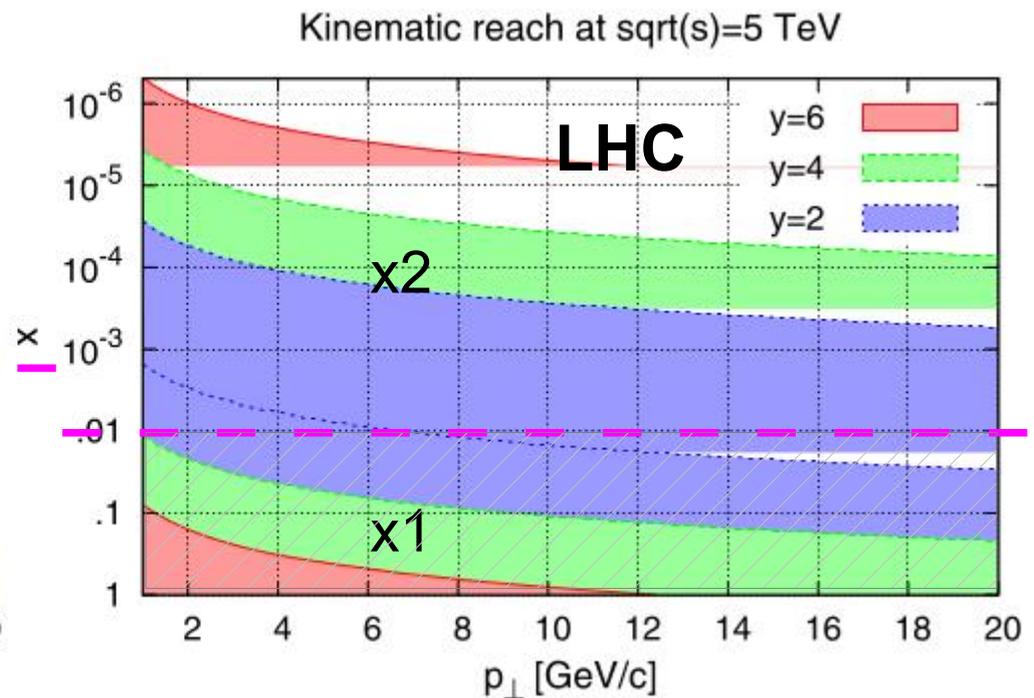
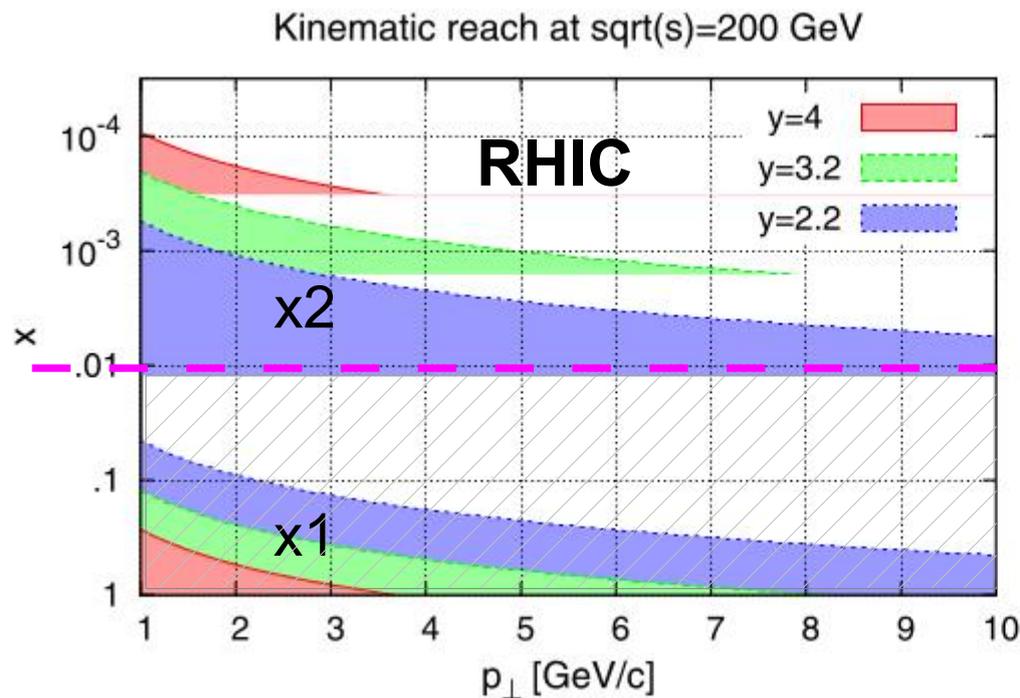


$$\left\{ \begin{array}{l} x_1 = M_{\perp} e^{+Y} / \sqrt{s} \\ x_2 = M_{\perp} e^{-Y} / \sqrt{s} \end{array} \right.$$



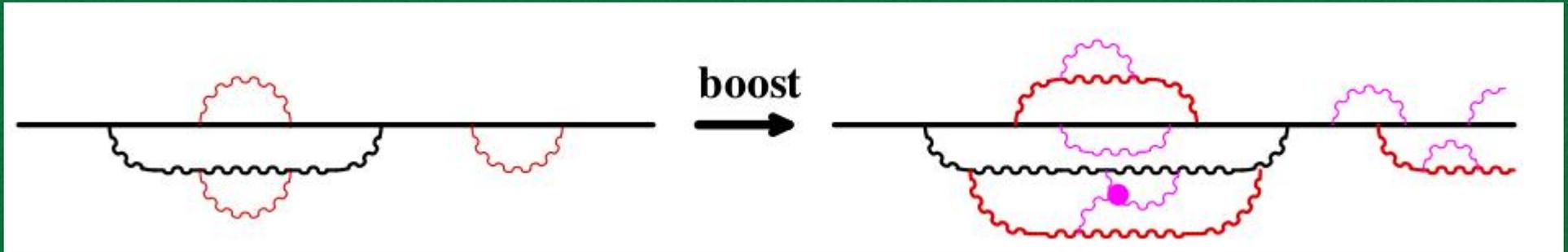
初期条件 = dense small-x gluons

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グルーオン飽和

$$\Delta E \sim k^- = \frac{k_{\perp}^2}{2k^+} = \frac{k_{\perp}^2}{2xP^+}$$



- 親パートンから娘パートンが生成
- 娘パートンから孫パートンが生成
- ...
- 濃密なグルーオン系の出現
- パarton再結合が重要になる
- 非線形なx発展

$$\sim \alpha_s \ln \frac{1}{x}$$
$$\sim \left(\alpha_s \ln \frac{1}{x} \right)^2$$



グルーオン飽和

Gribov-Levin-Ryskin (1983)

- グルーオンの面密度

$$\rho \sim \frac{x G_A(x, Q^2)}{\pi R_A^2}$$

- グルーオン結合

$$\sigma_{g g \rightarrow g} \sim \frac{\alpha_s}{Q^2}$$

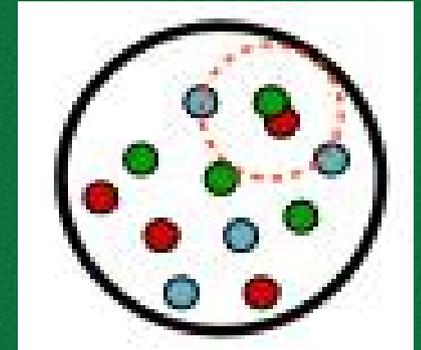
- 確率が1になるとき

飽和運動量スケール

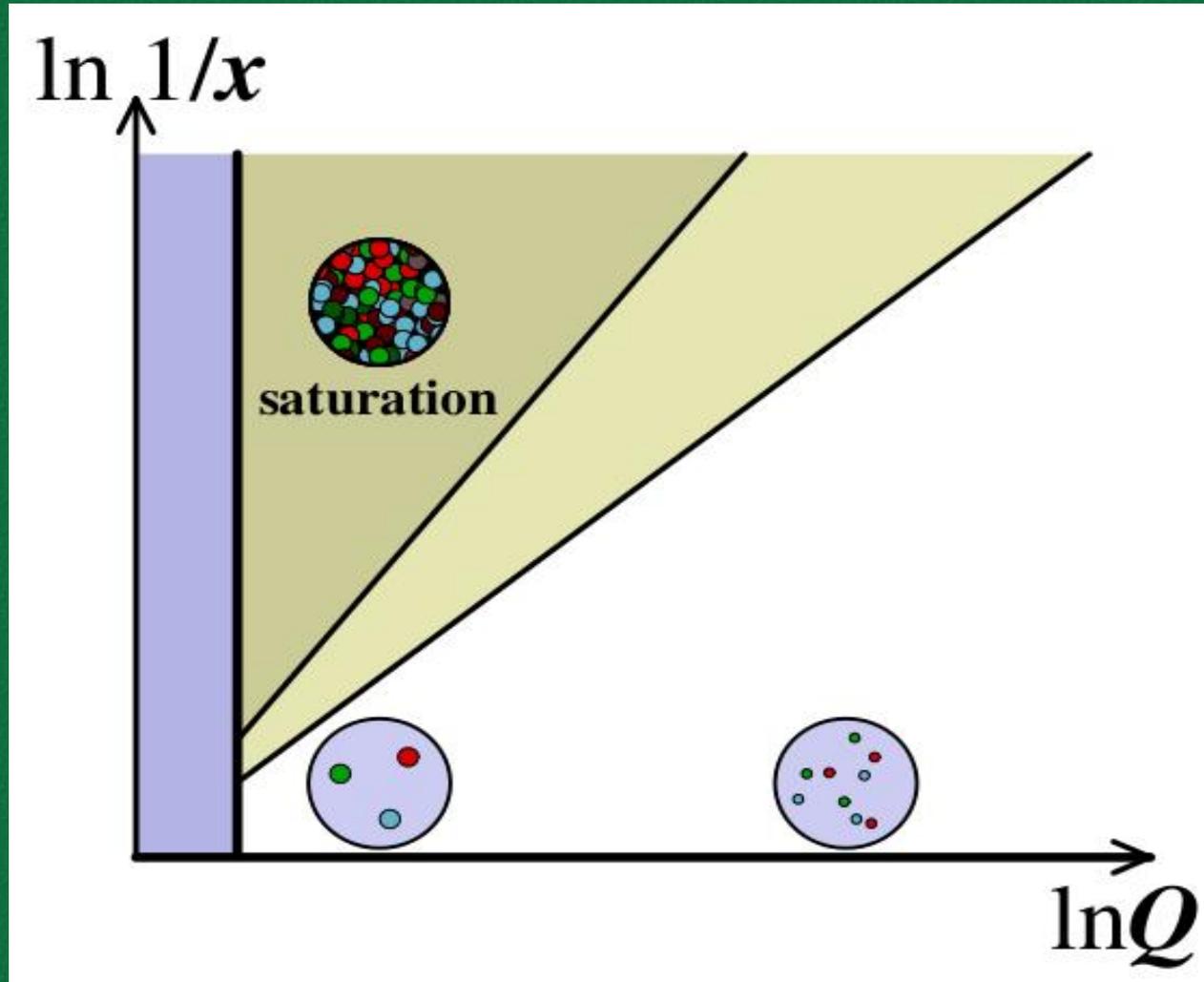
$$Q_s^2 \sim \frac{\alpha_s x G_A(x, Q_s^2)}{\pi R_A^2} \sim A^{1/3} \frac{1}{x^{0.3}}$$

- この時の相空間密度

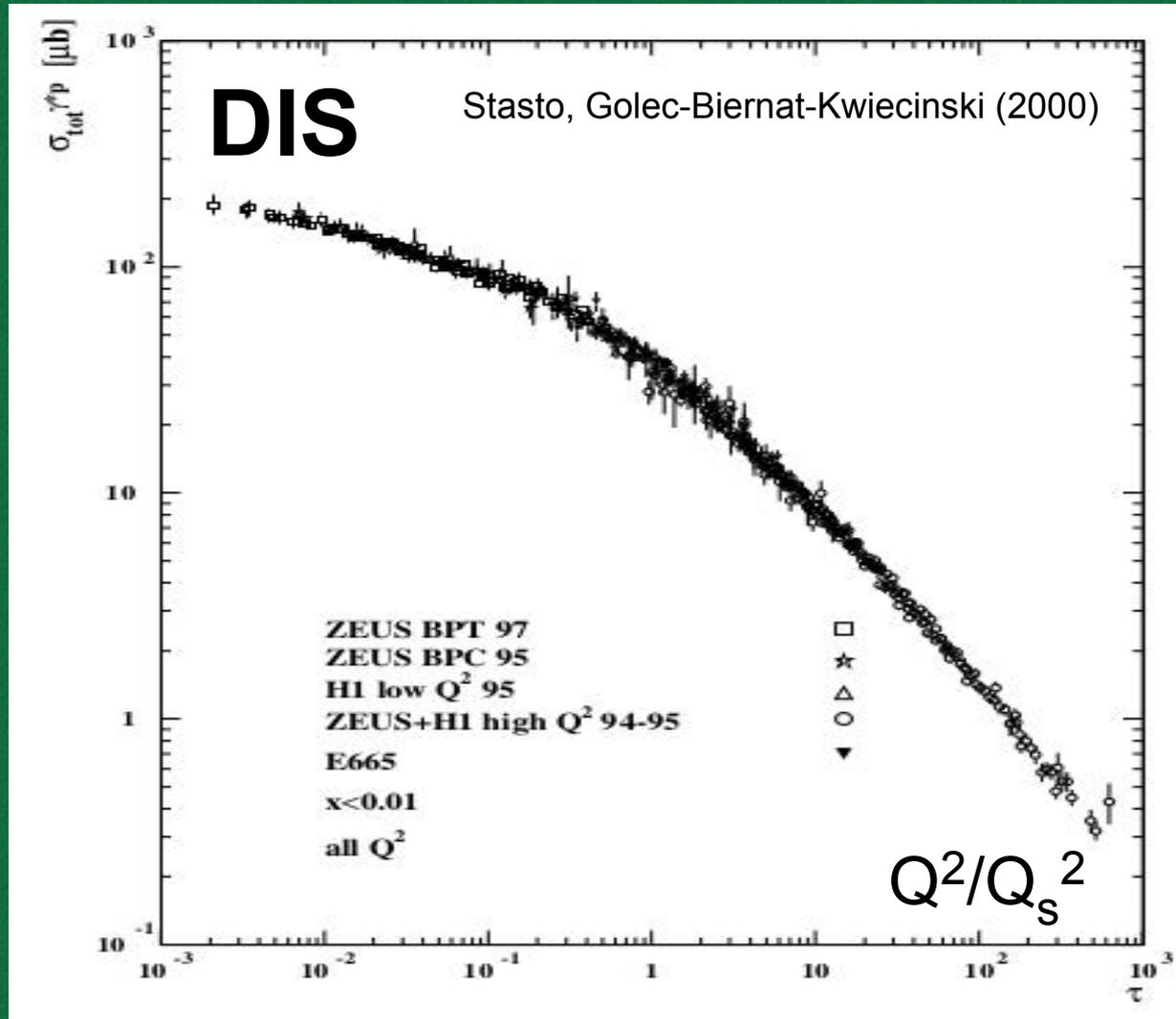
$$\frac{dN}{d^2 p d^2 x} \sim \frac{\rho}{Q_s^2} \sim \frac{1}{\alpha_s}$$



グルーオン飽和



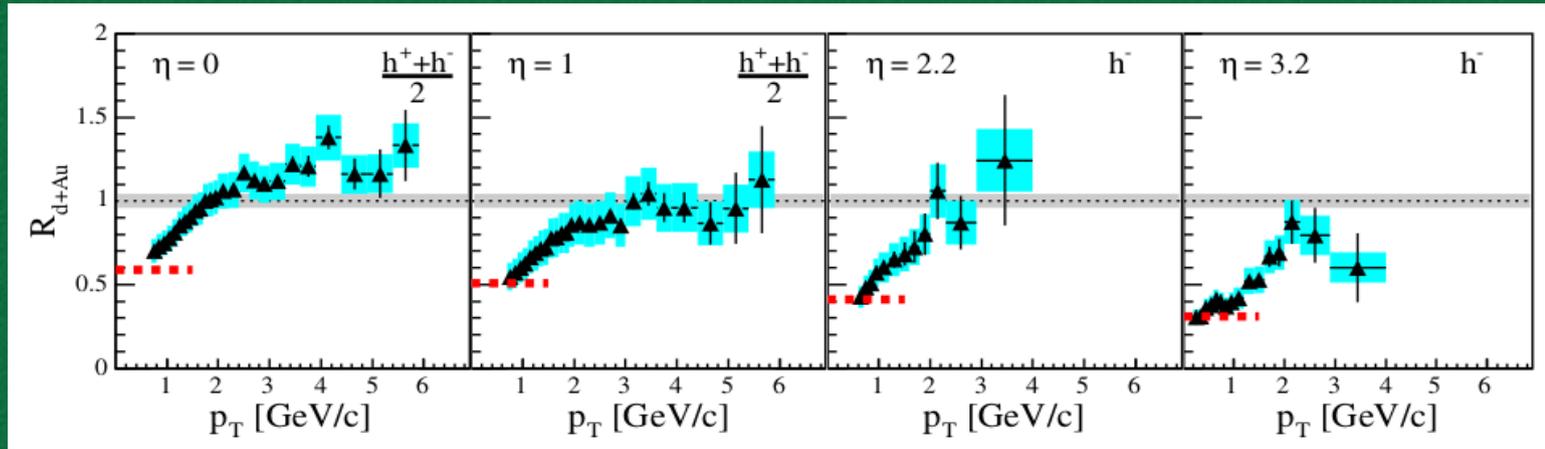
グルーオン飽和



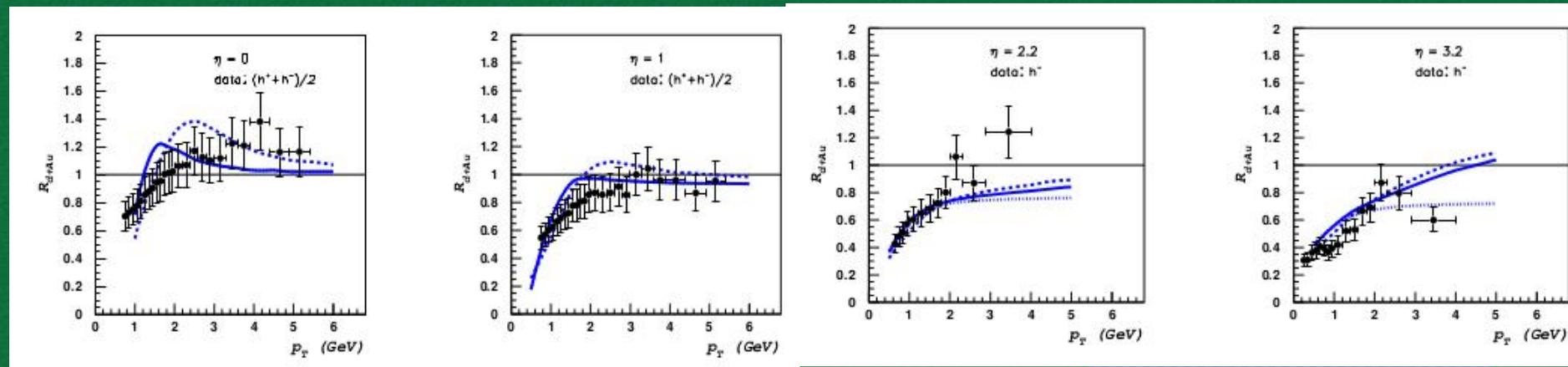
ハドロン生成

- RHIC-BRAHMS実験

$$R_{dAu} \equiv \frac{1}{N_{\text{coll}}} \frac{\left. \frac{dN}{dp_{\perp} d\eta} \right|_{dAu}}{\left. \frac{dN}{dp_{\perp} d\eta} \right|_{pp}}$$

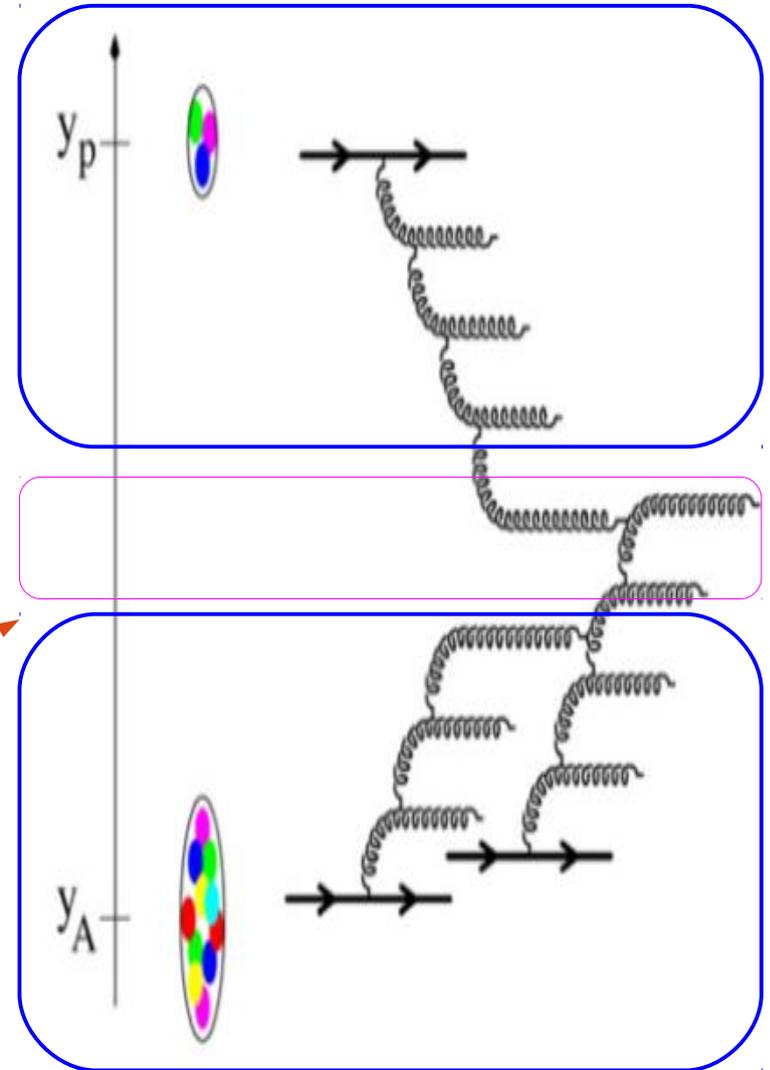


Khazzev-Kovchegov-Tuchin (2005) w/ model uGD



カラーガラス凝縮アプローチ

- $Q_s(x) \gg \Lambda_{\text{QCD}} \Rightarrow$ weak coupling
- 自由度の分離
- **higher-x** : 強いカラーソース
 - ローレンツ効果で凍結
- **lower-x** : ソース下の量子場
- 分離スケールの任意性 = JIMWLK eqn.



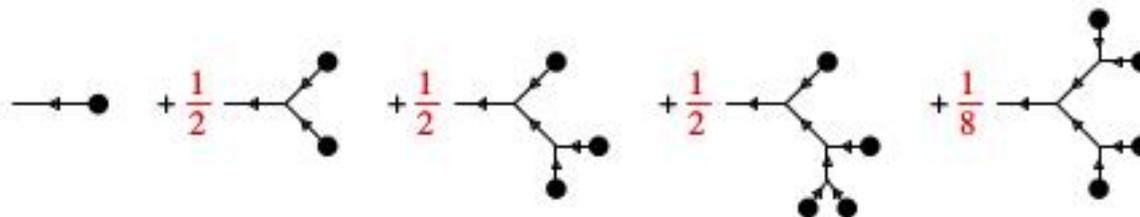
グルーオン生成 LO

- 強いソース $J=O(1/g)$ の下での包含粒子生成は、LOでは運動方程式を満たす場の古典解 A で表される

$$[D_\mu, F^{\mu\nu}] = J^\nu \quad [D_\mu, J^\nu] = 0$$

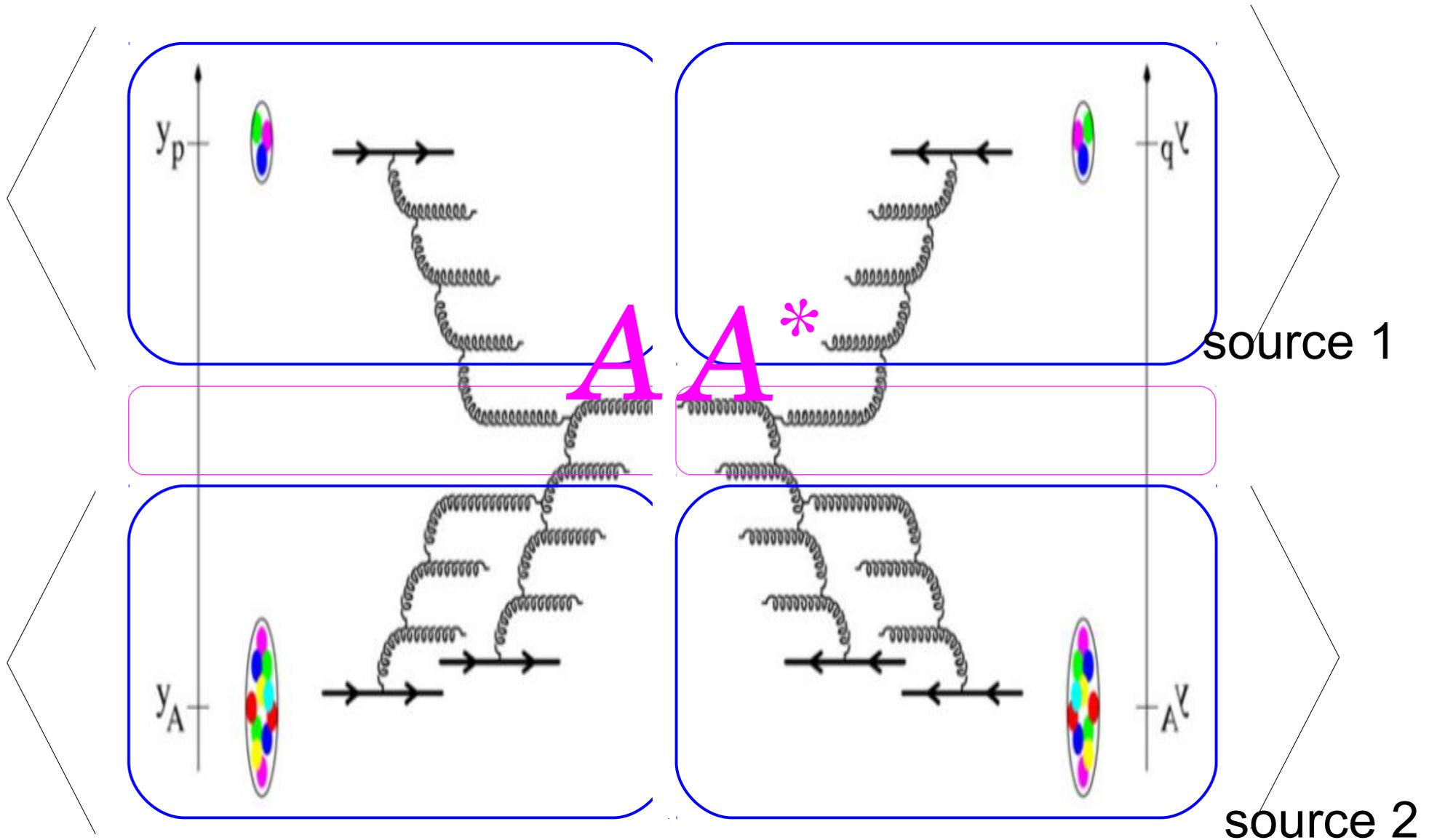
$$J_a^\nu = \delta^{\nu+} \delta(x^-) g \rho_{1,a}(\mathbf{x}_\perp) + \delta^{\nu-} \delta(x^+) g \rho_{2,a}(\mathbf{x}_\perp)$$

- スカラー理論での例



F. Gelis, lecture in NFQCD2013

グルーオン生成 LO



グルーオン生成 LO

$$\frac{d\bar{N}_g(\mathbf{q})}{d^3\mathbf{q}} = \frac{1}{(2\pi)^3 2E_q} \sum_{\lambda} \langle |q^2 A^{\mu}(q) \epsilon_{\mu}^{(\lambda)}(\mathbf{q})|^2 \rangle$$

$$\frac{d\bar{N}_g^2(\mathbf{q}, \mathbf{p})}{d^3\mathbf{q} d^3\mathbf{p}} \sim \langle |q^2 A(q) \cdot \epsilon \ p^2 A(p) \cdot \epsilon|^2 \rangle$$

...

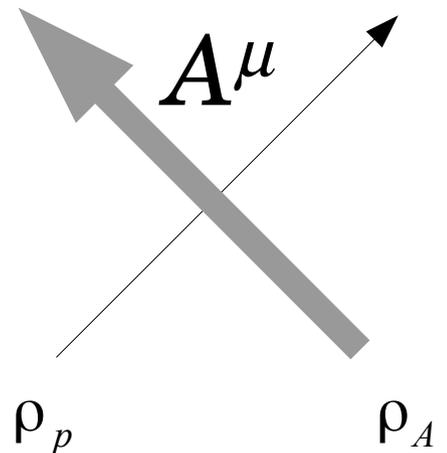
$$\langle O \rangle = \int D\rho_1(y_1) D\rho_2(y_2) W_1[\rho_1] W_2[\rho_2] O[\rho_1, \rho_2]$$

CGC アプローチ

- カラーソースからコヒーレントな粒子生成
 - 運動方程式を満たす古典場 = 強いソース効果の再和
 - ループグラフ = 量子補正
- カラーソースの x 依存性
 - BFKL 量子補正、グルーオン飽和効果 (普遍性)
 - 飽和スケール $Q_s(x)$

pA 衝突からグルーオン生成

- 希薄ソース・濃密ソース
 - ρ_A について足し上げ (EoM)
 - kT 因子化表式が導かれる



$$\frac{d\bar{N}_g}{d^2\mathbf{q}_T dy} = \frac{1}{2(2\pi)^3} \sum_{\lambda} \langle |q^2 A^{\mu}(\mathbf{q}) \epsilon_{\mu}^{(\lambda)}(\mathbf{q})|^2 \rangle$$

$$\sim \frac{\alpha N}{\pi^4 d_A S_T q_T^2} \int_k \varphi_p(\mathbf{k}, y_1) \varphi_A(\mathbf{q} - \mathbf{k}, y_2)$$

<hard> <proton uGD> <nuclear “uGD”>

$\varphi_A(\mathbf{q}_T) \sim q_T^2 \text{ F.T. } \langle U^+(0) U(\mathbf{x}_T) \rangle$...Wilson line... 多重散乱効果

small- x gluon 分布関数 uGD

- 汎関数カラーソースの x 依存性 ; JIMWLK eqn.
- 2pt fn (dipole) に制限 ; BK eqn. (large N)

$$\frac{\partial \mathcal{N}_F(r, x)}{\partial \ln(x_0/x)} = \int d^2 r_1 K^{\text{run}}(\underline{r}, \underline{r}_1, \underline{r}_2) [\mathcal{N}_F(r_1, x) + \mathcal{N}_F(r_2, x) - \mathcal{N}_F(r, x) - \mathcal{N}_F(r_1, x)\mathcal{N}_F(r_2, x)],$$

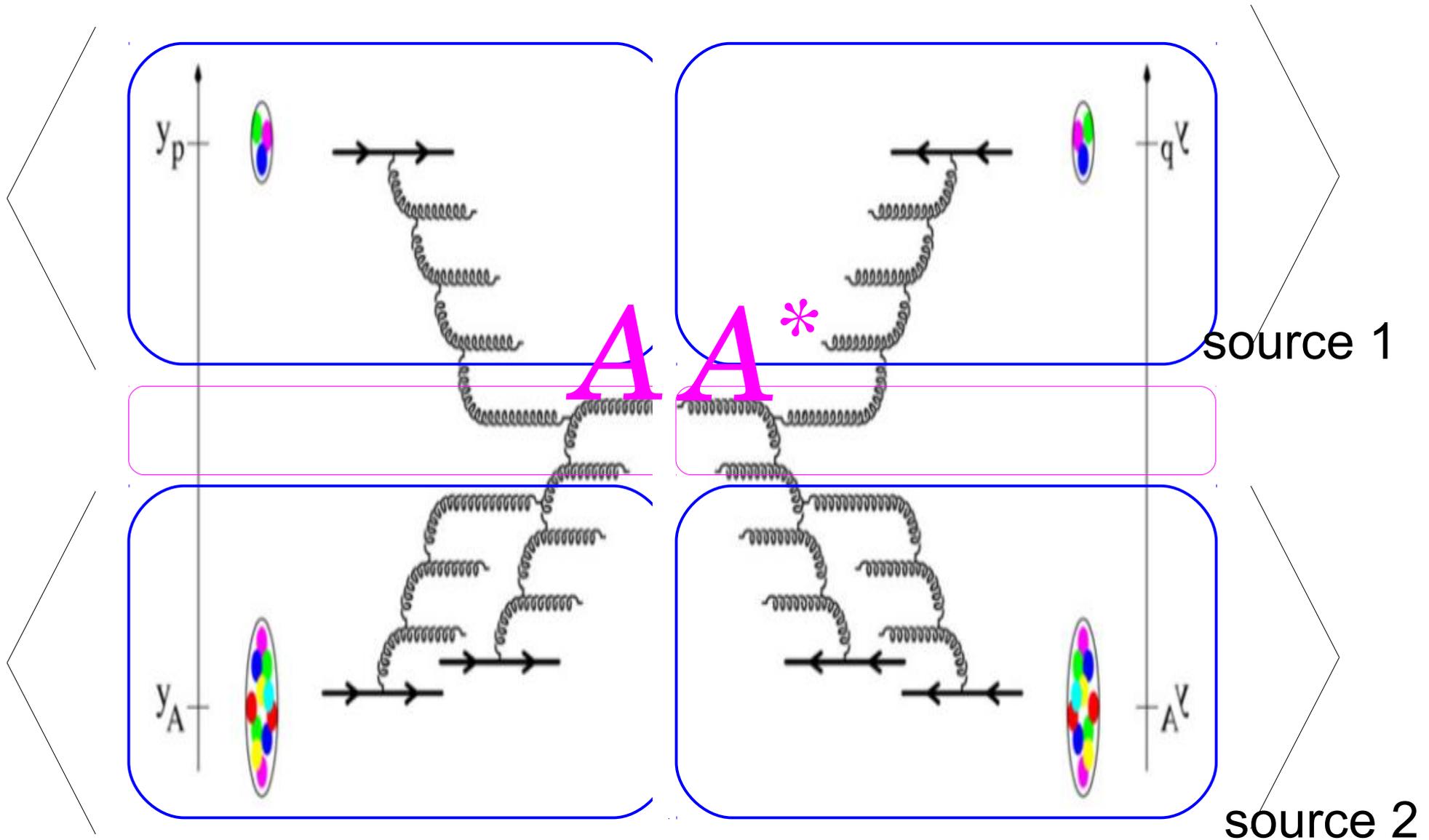
- **BFKL ladder + unitarity**

$$\mathcal{N}_F(r, x) = 1 - \langle U^+(0) U(\mathbf{x}_T) \rangle$$

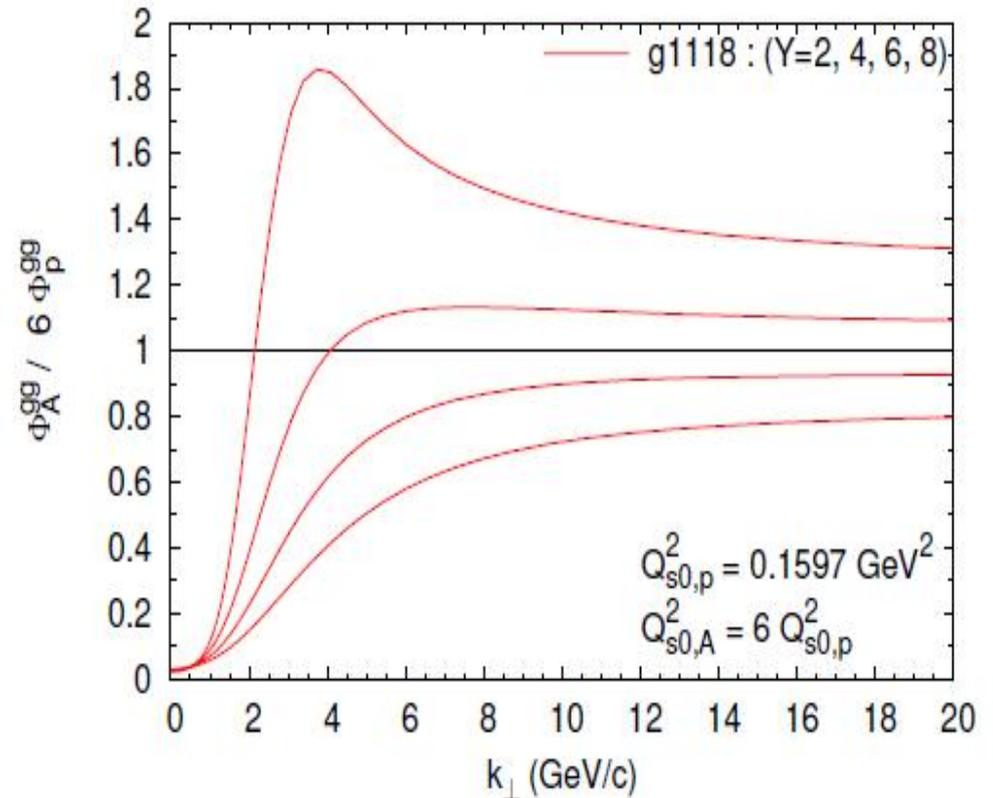
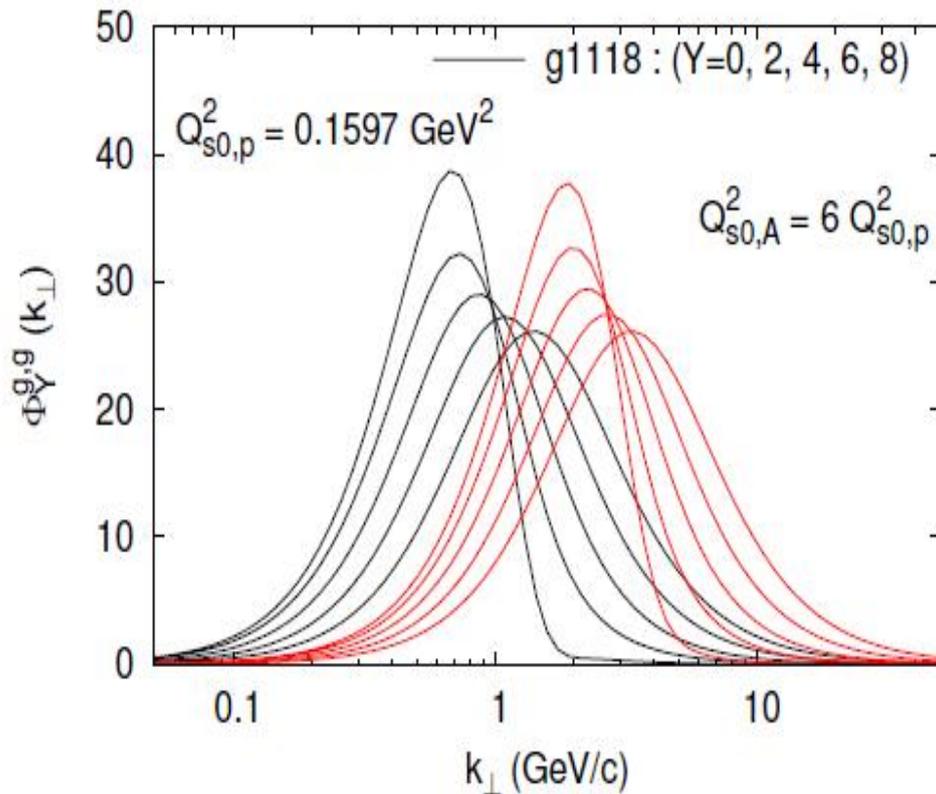
- **初期条件@ x_0 ← 標的依存性**

$$\mathcal{N}_F(r, x=x_0) = 1 - \exp \left[-\frac{(r^2 Q_{s0, \text{proton}}^2)^\gamma}{4} \ln \left(\frac{1}{\Lambda r} + e \right) \right]$$

グルーオン生成 LO



Gluon distributions for p and A



AAMQS: HERA-DIS dataとrcBK eqnを用いてuGDを構成
 g1118; AAMQS に準じて、J.Albaceteが準備した一つのセット

phenomenology

- kT factorized formula for dense-dense

$$\frac{d\sigma^{A+B \rightarrow g}}{dy d^2p_t d^2R} = K^k \frac{2}{C_F} \frac{1}{p_t^2} \int \frac{d^2k_t}{4} \\ \times \int d^2b \alpha_s(Q) \varphi_P \left(\frac{|p_t + k_t|}{2}, x_1; b \right) \varphi_T \left(\frac{|p_t - k_t|}{2}, x_2; R - b \right)$$

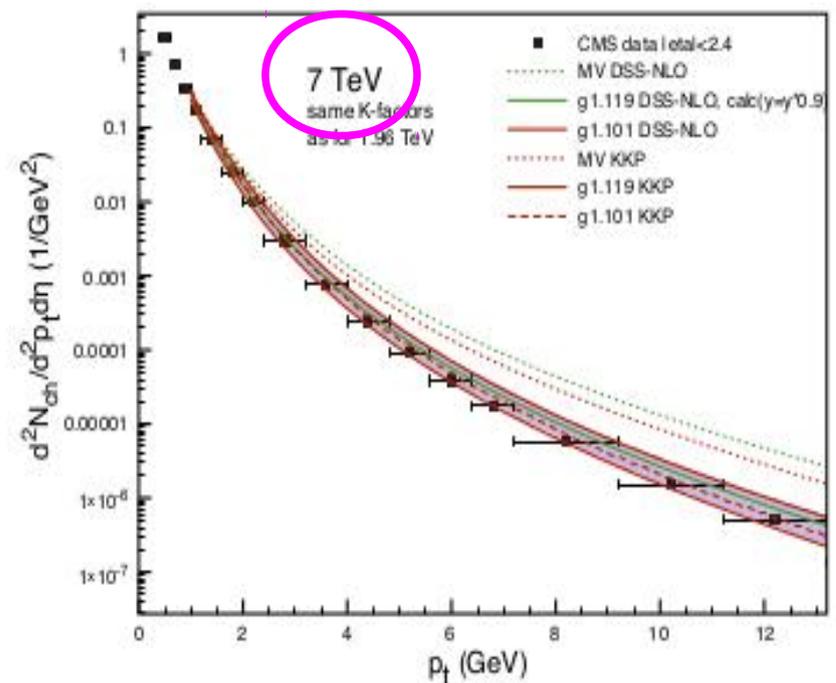
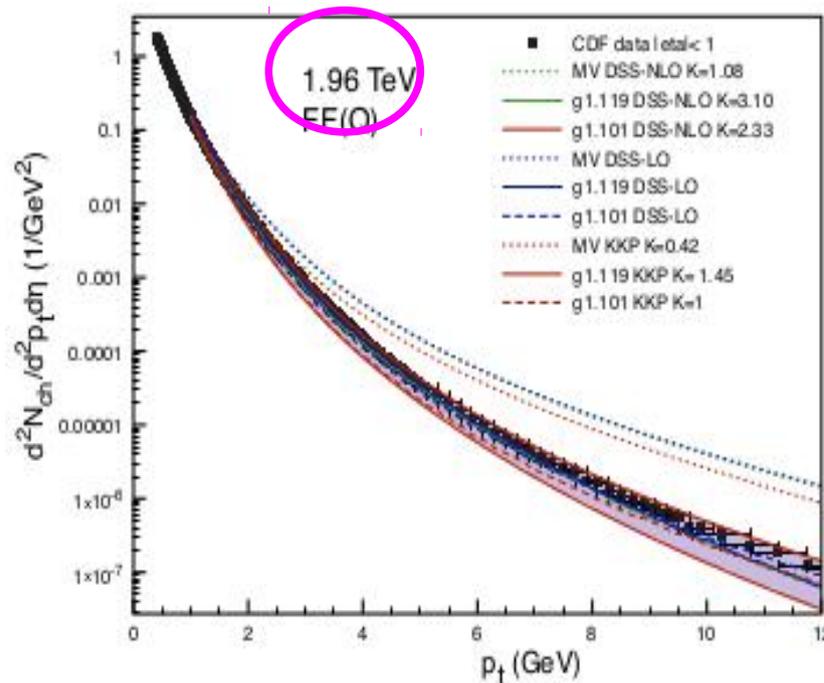
- DHJ's hybrid formula for dilute-dense

$$\left[\frac{dN_h}{d\eta d^2k} \right]_{\text{el}} = \frac{1}{(2\pi)^2} \int_{x_F}^1 \frac{dz}{z^2} \left[\sum_q x_1 f_{q/p}(x_1, Q^2) \tilde{N}_F \left(x_2, \frac{k}{z} \right) D_{h/q}(z, Q^2) \right. \\ \left. + x_1 f_{g/p}(x_1, Q^2) \tilde{N}_A \left(x_2, \frac{k}{z} \right) D_{h/g}(z, Q^2) \right],$$

Particle production from CGC

- in kT factorized model

$$\frac{d\sigma^{A+B \rightarrow g}}{dy d^2p_t d^2R} = K^k \frac{2}{C_F} \frac{1}{p_t^2} \int \frac{d^2k_t}{4} \times \int d^2b \alpha_s(Q) \varphi_P\left(\frac{|p_t + k_t|}{2}, x_1; b\right) \varphi_T\left(\frac{|p_t - k_t|}{2}, x_2; R - b\right)$$



$dN/d\eta$ in pA at the LHC

ALICE: Phys.Rev.Lett. 110 (2013) 032301

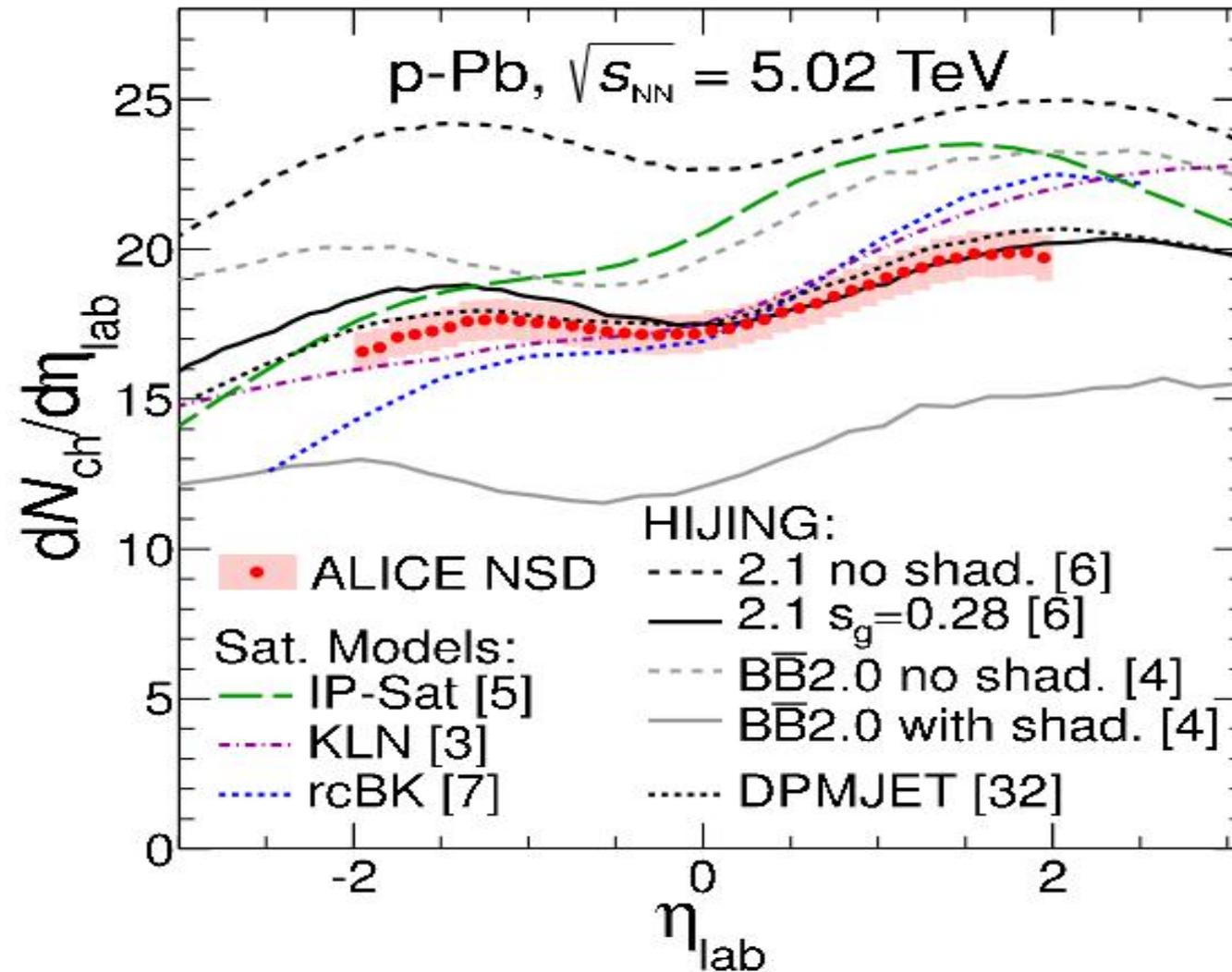
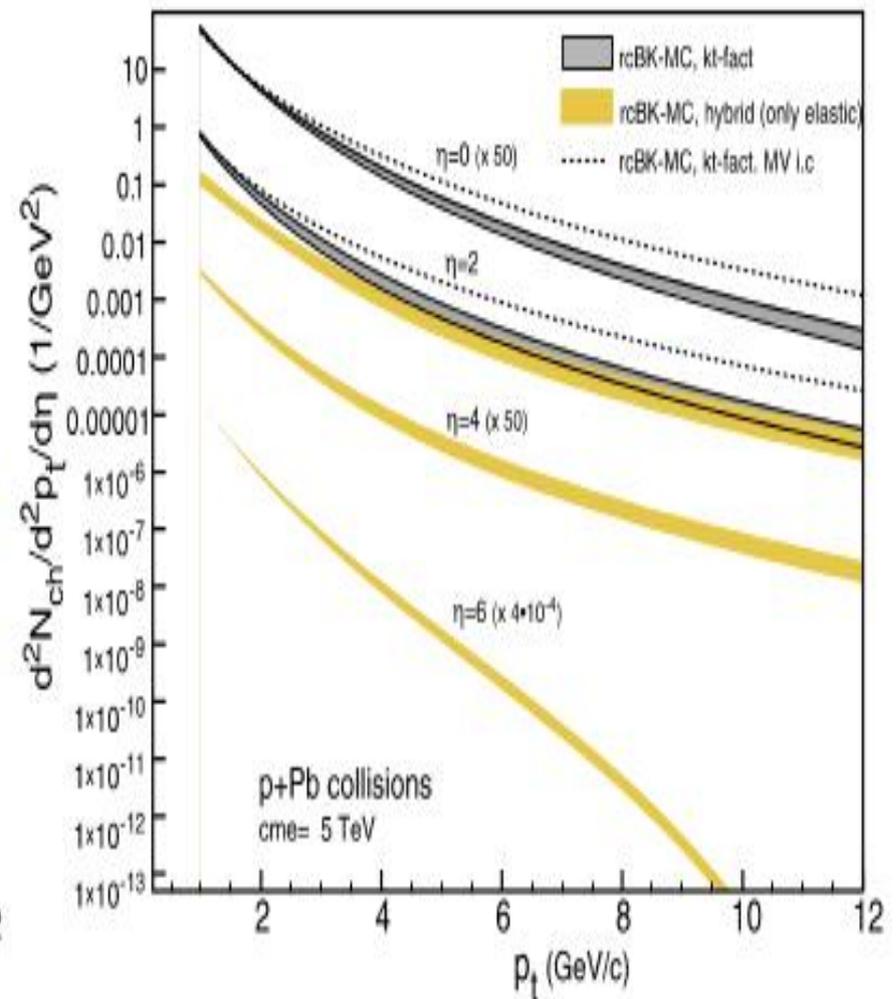
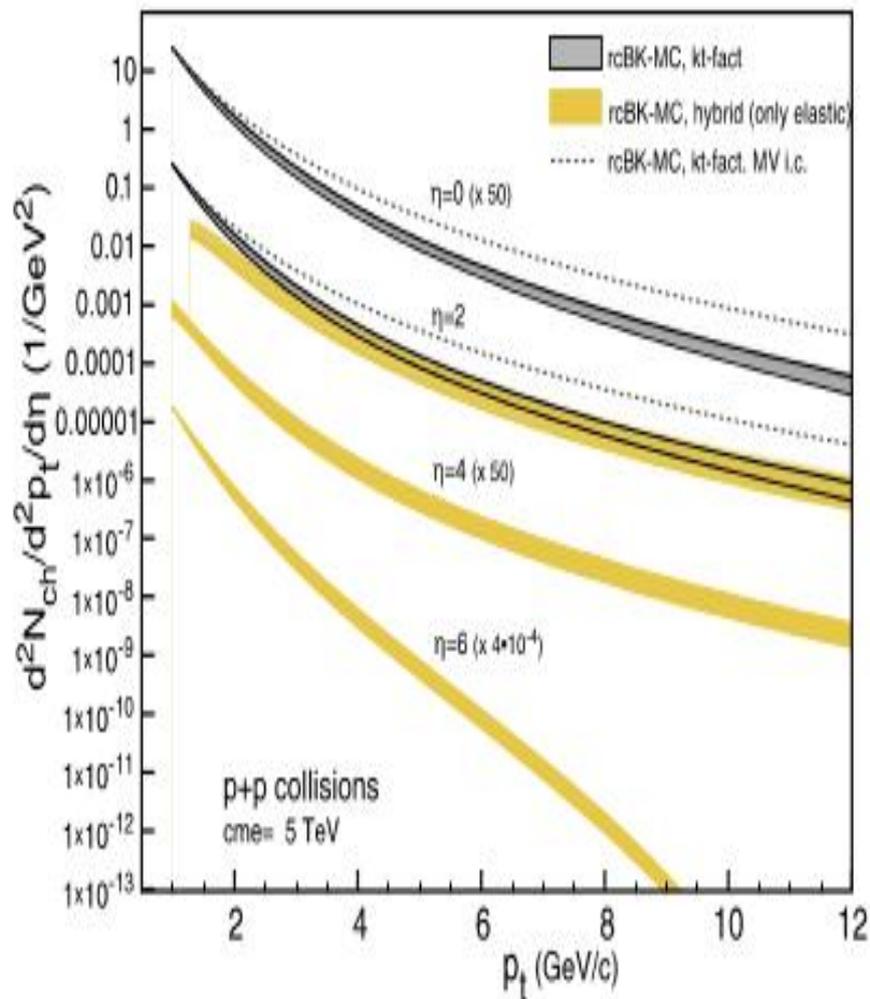


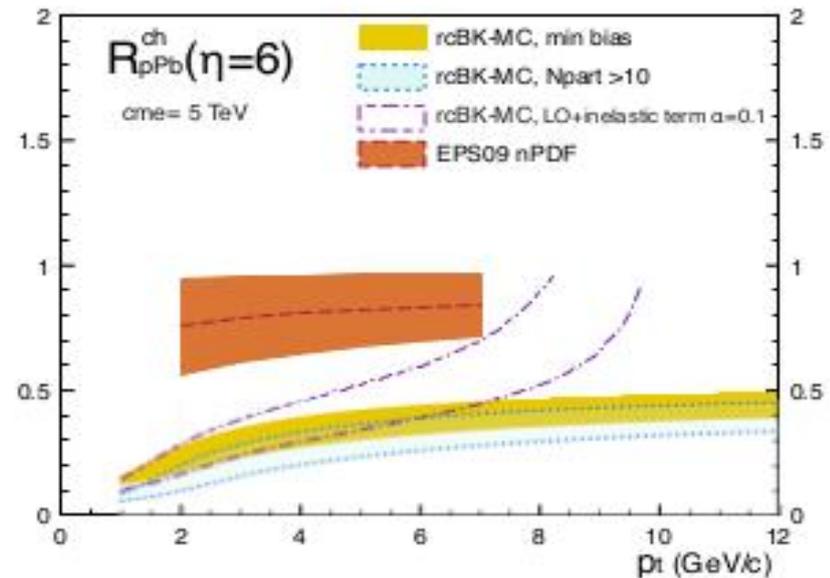
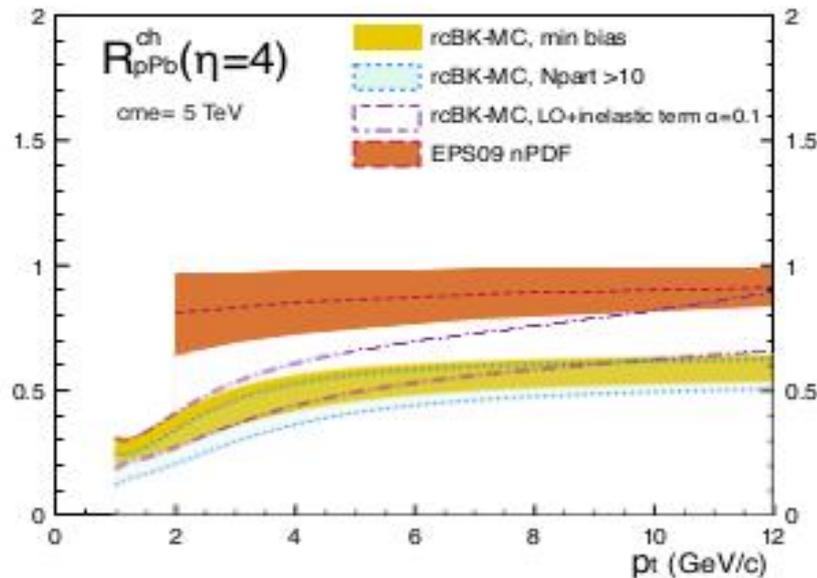
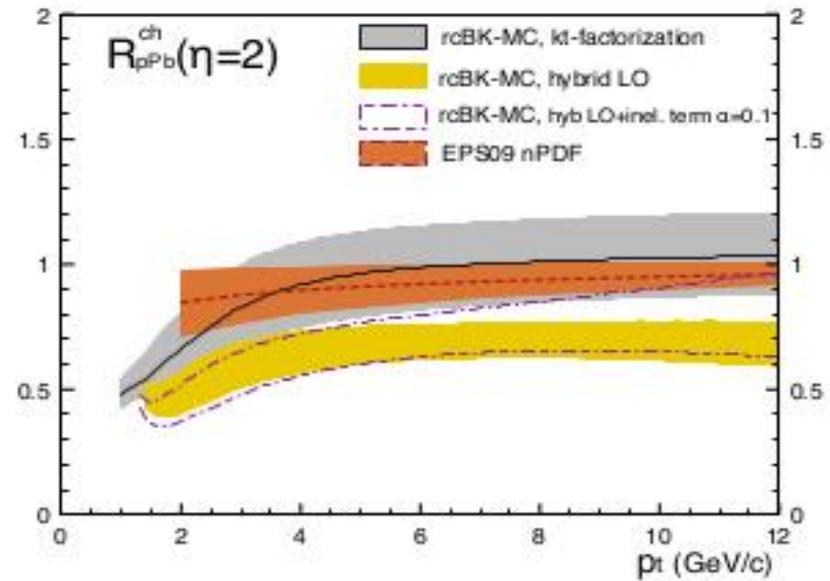
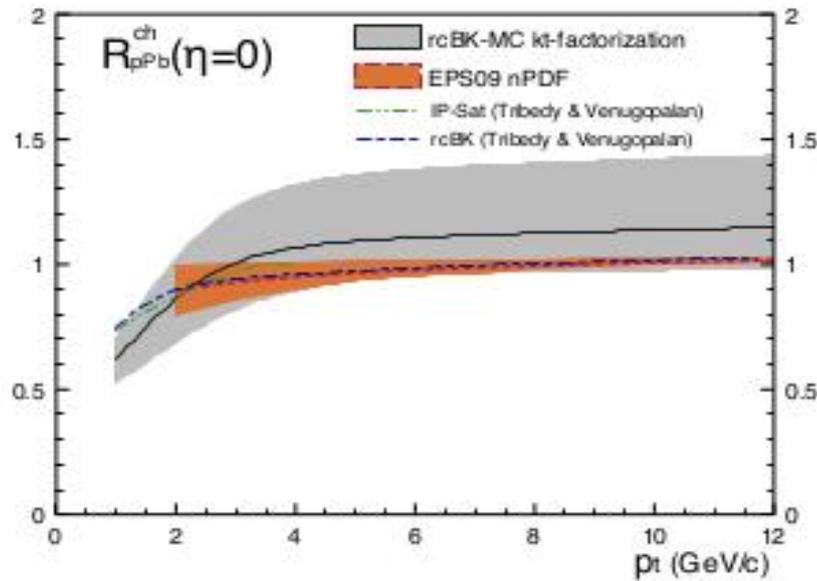
Fig. 1: Pseudorapidity density of charged particles measured in NSD p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV compared to theoretical predictions [3-7]. The calculations [4,5] have been shifted to the laboratory system.

pT spectrum in pp and pA at 5 TeV



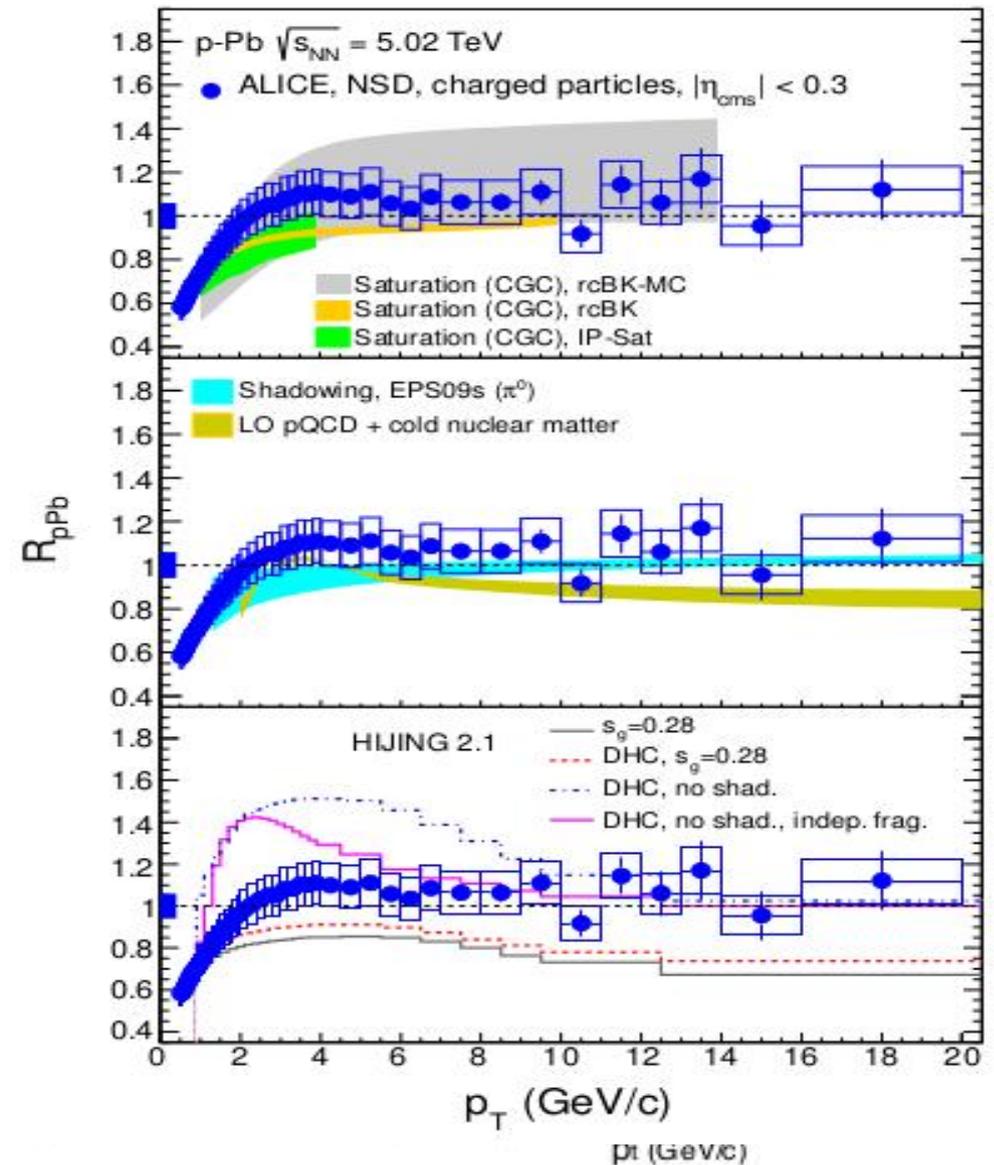
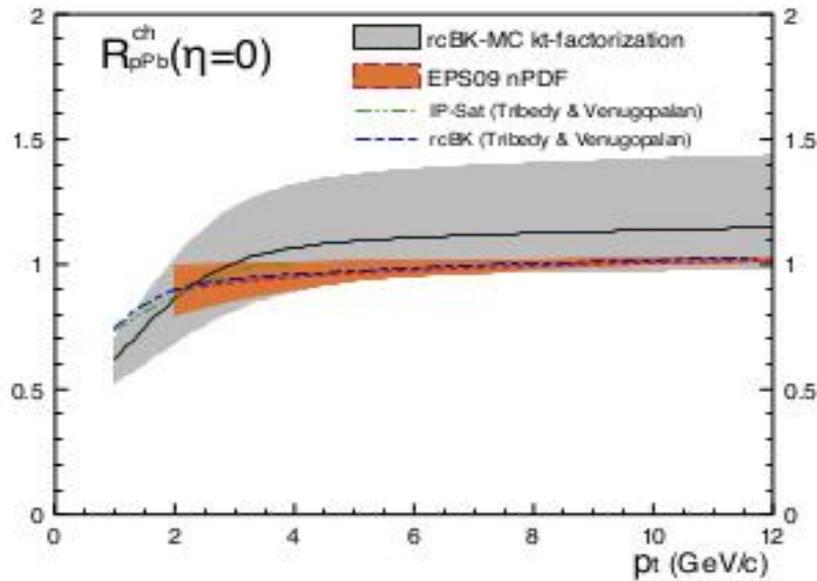
RpA at 5 TeV

$$R_{p+Pb}(p_{\perp}) \equiv \frac{1}{\langle N_{\text{coll}} \rangle} \frac{dN_{\text{ch}}^{P+Pb}/d\eta d^2p_{\perp}}{dN_{\text{ch}}^{P+P}/d\eta d^2p_{\perp}}$$



RpA at 5 TeV

$$R_{p+Pb}(p_{\perp}) \equiv \frac{1}{\langle N_{\text{coll}} \rangle} \frac{dN_{\text{ch}}^{P+Pb}/d\eta d^2p_{\perp}}{dN_{\text{ch}}^{P+P}/d\eta d^2p_{\perp}}$$



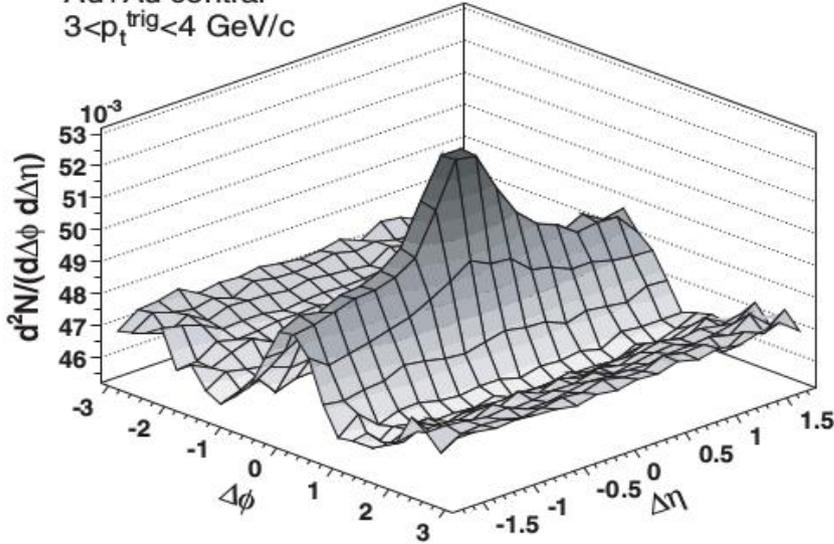
2 グルーオン生成 LO

$$\frac{d\bar{N}_g^2(\mathbf{q}, \mathbf{p})}{d^3\mathbf{q} d^3\mathbf{p}} \sim \langle |q^2 A(q) \cdot \epsilon \ p^2 A(p) \cdot \epsilon|^2 \rangle$$

二粒子相関

STAR, PRC 80, 064912 (2009)

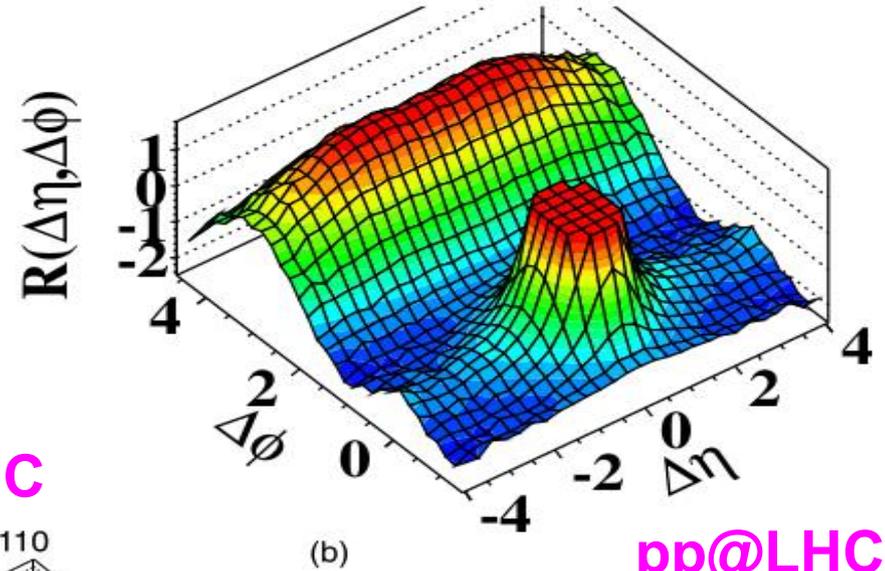
Au+Au central
 $3 < p_t^{\text{trig}} < 4 \text{ GeV}/c$



AA@RHIC

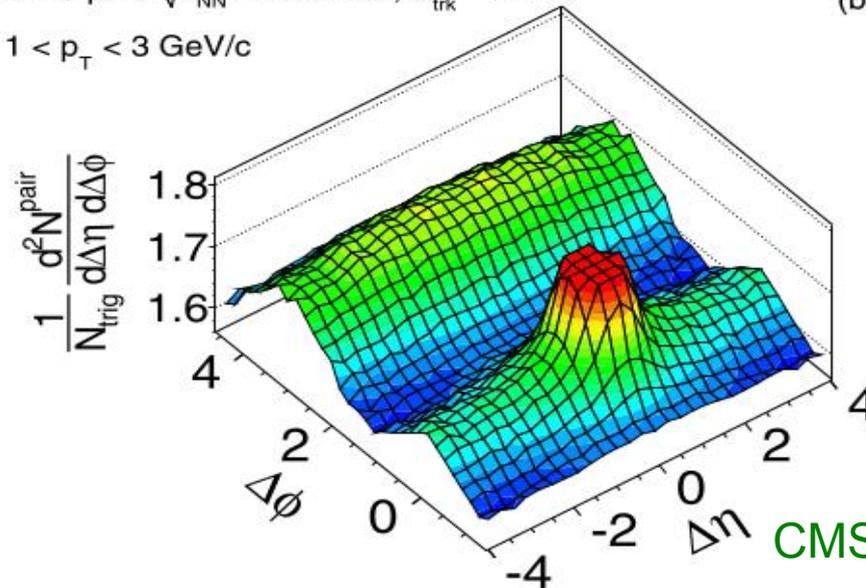
CMS, JHEP 09 (2010), 091

(d) CMS $N \geq 110$, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



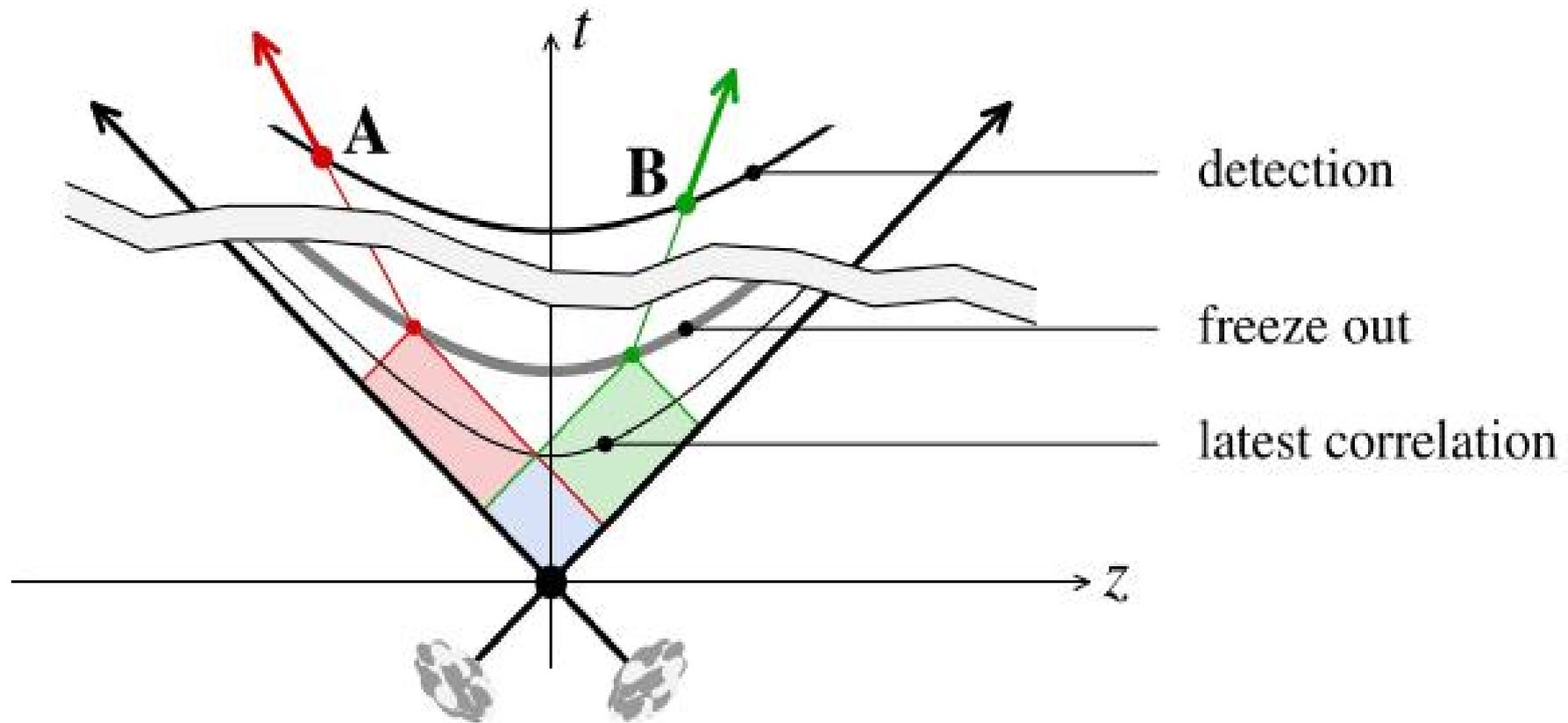
pA@LHC

CMS pPb $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, $N_{\text{trk}}^{\text{offline}} \geq 110$
 $1 < p_T < 3 \text{ GeV}/c$



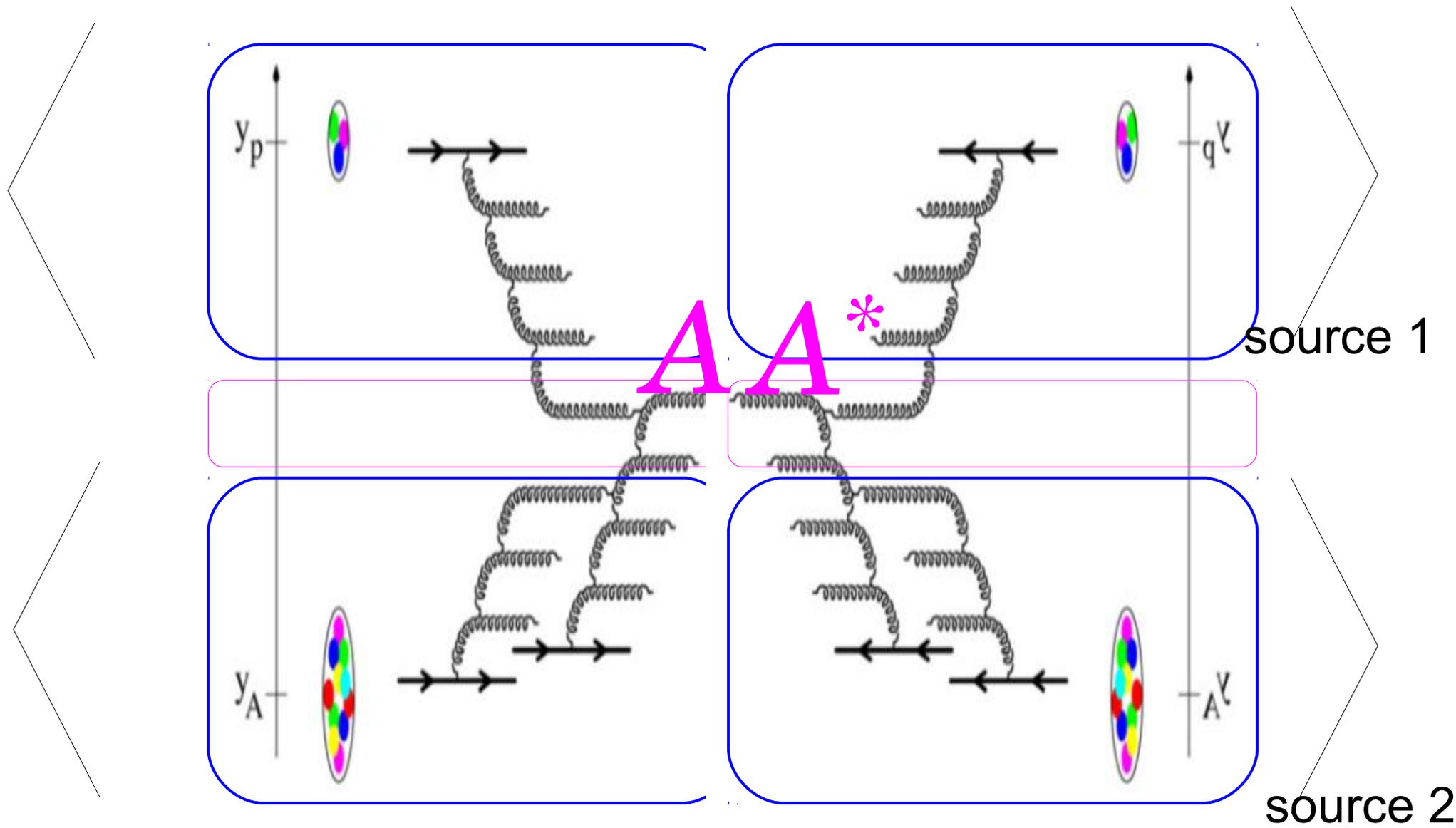
pp@LHC

二粒子相関

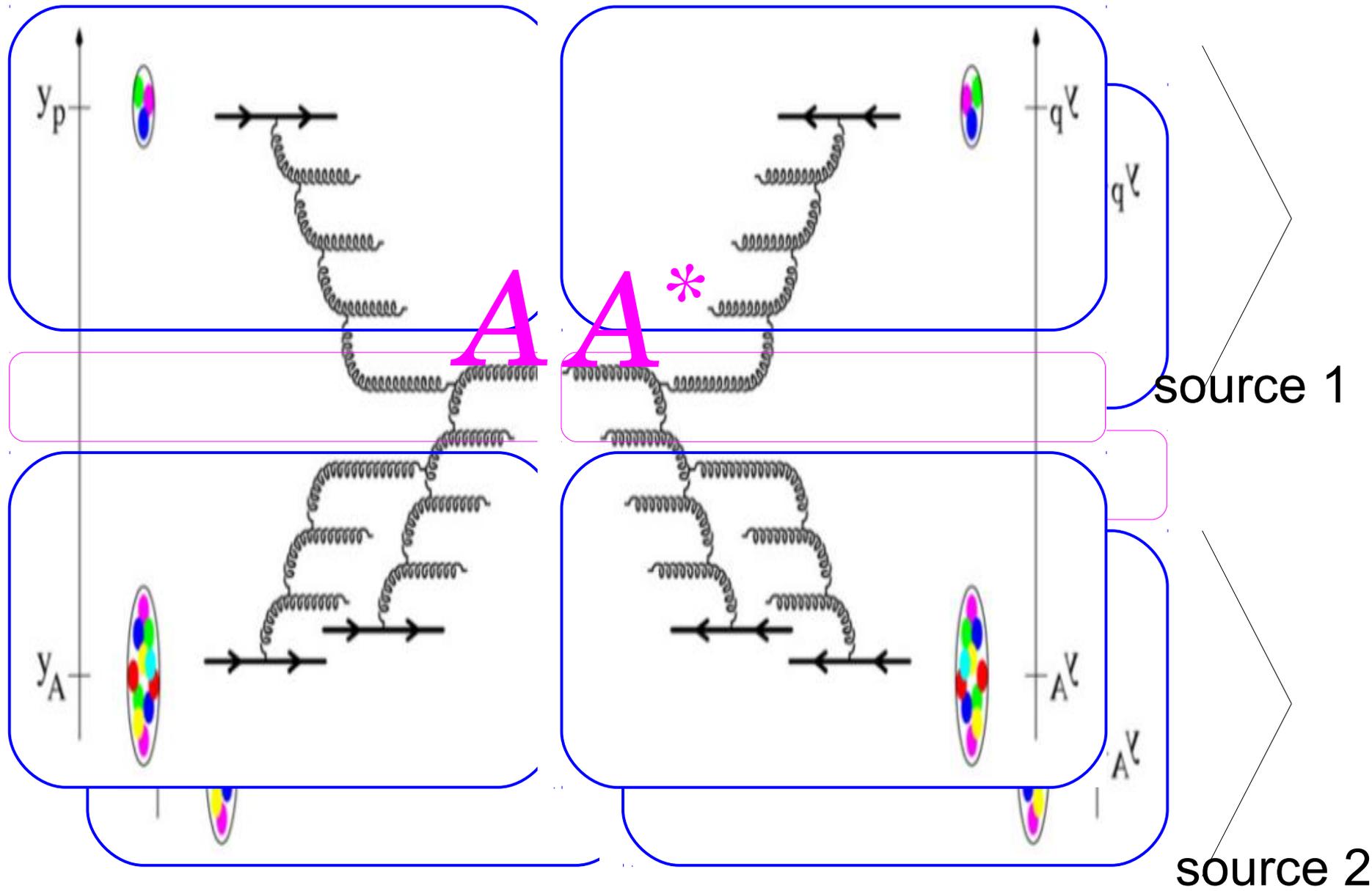


A. Dumitru et al. / Nuclear Physics A 810 (2008) 91–108

1グルーオン生成



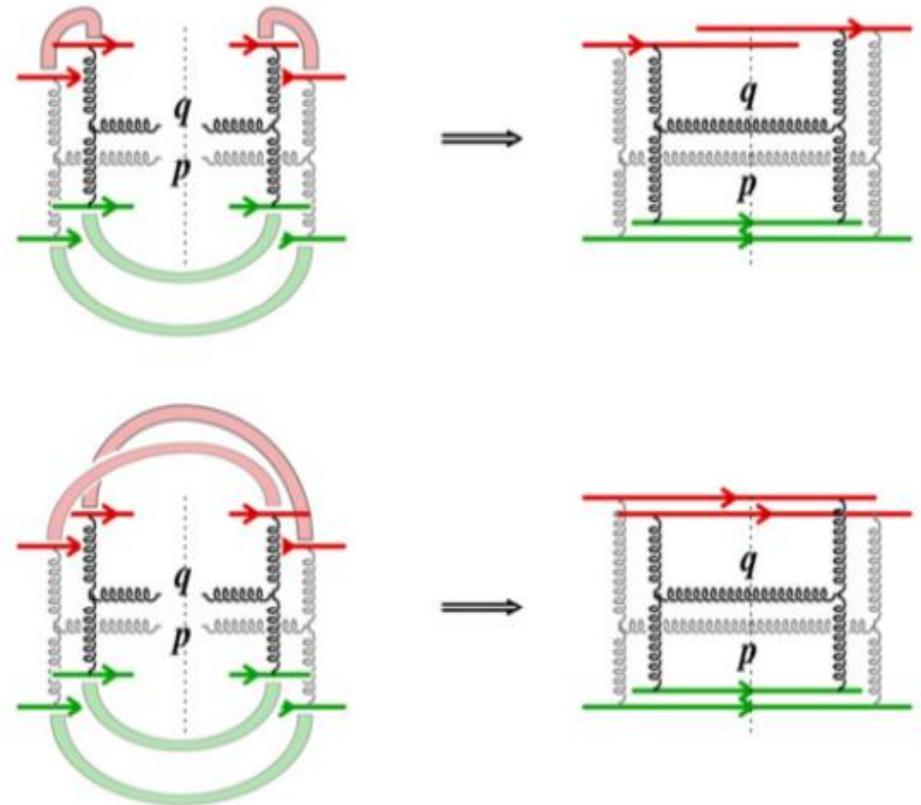
2 グルーオン生成



ソース相関 ⇒ 粒子相関

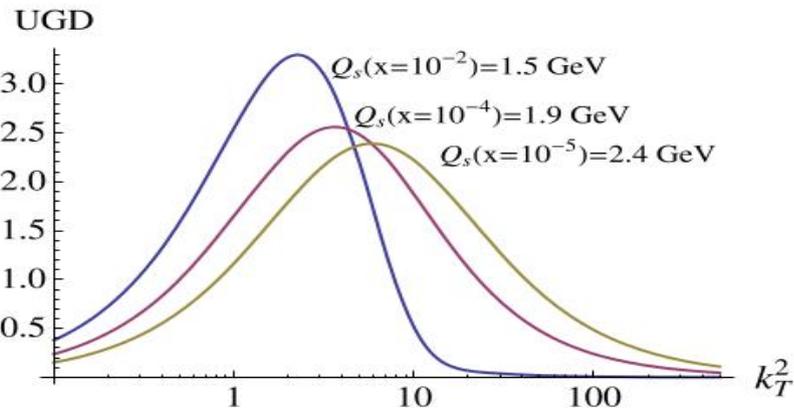
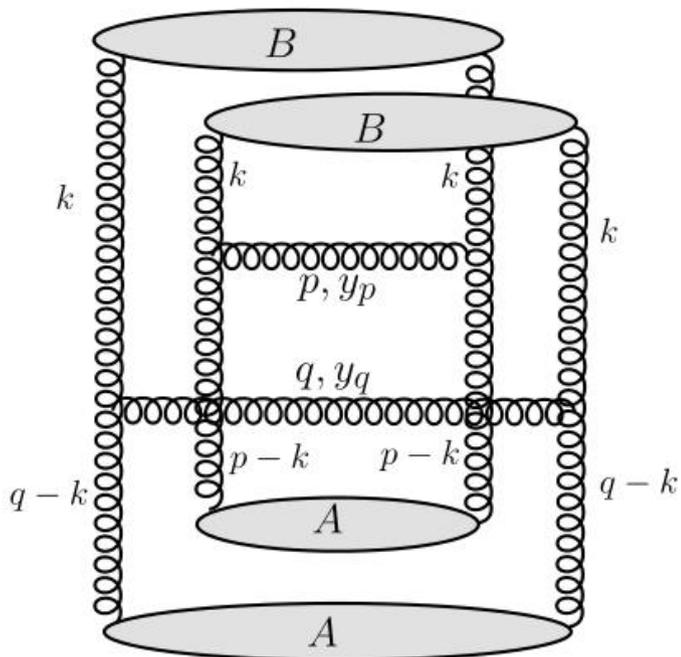
$$C(\mathbf{p}, \mathbf{q}) \equiv \left\langle \frac{dN_2}{dy_p d^2 \mathbf{p}_\perp dy_q d^2 \mathbf{q}_\perp} \right\rangle - \left\langle \frac{dN}{dy_p d^2 \mathbf{p}_\perp} \right\rangle \left\langle \frac{dN}{dy_q d^2 \mathbf{q}_\perp} \right\rangle$$

- 非自明なソース相関
 - single diffraction
 - interference
 - 粒子相関のy依存性 = 標的の内ソースのy依存性

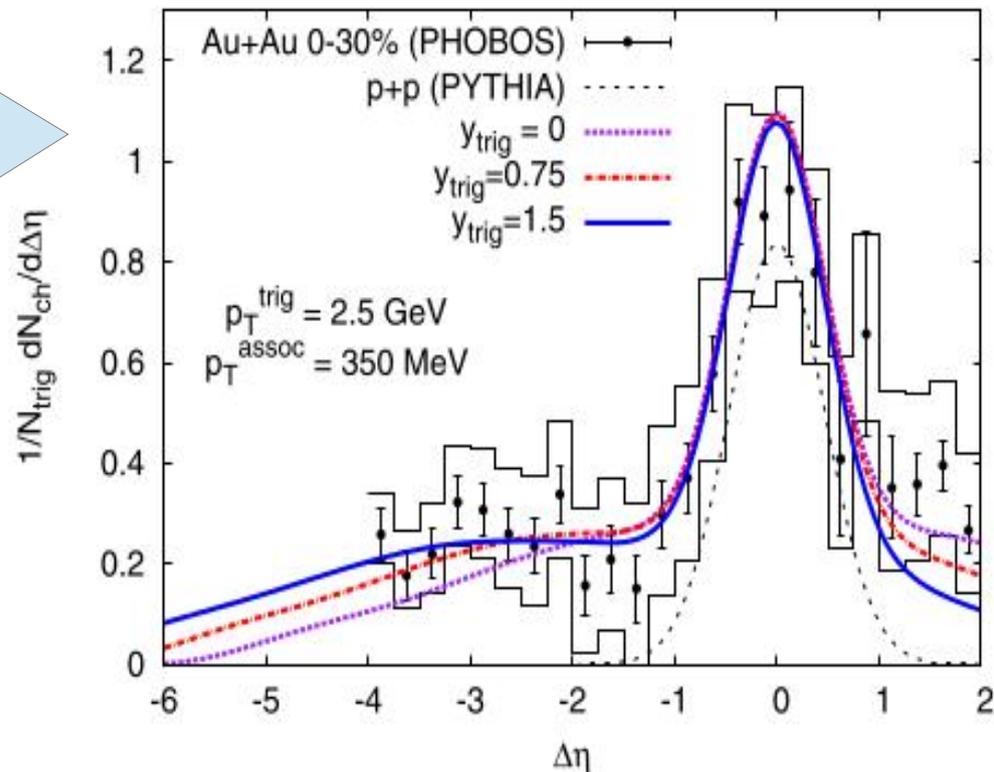


- + 流体膨張による ϕ 依存

干渉項の生む角度相関



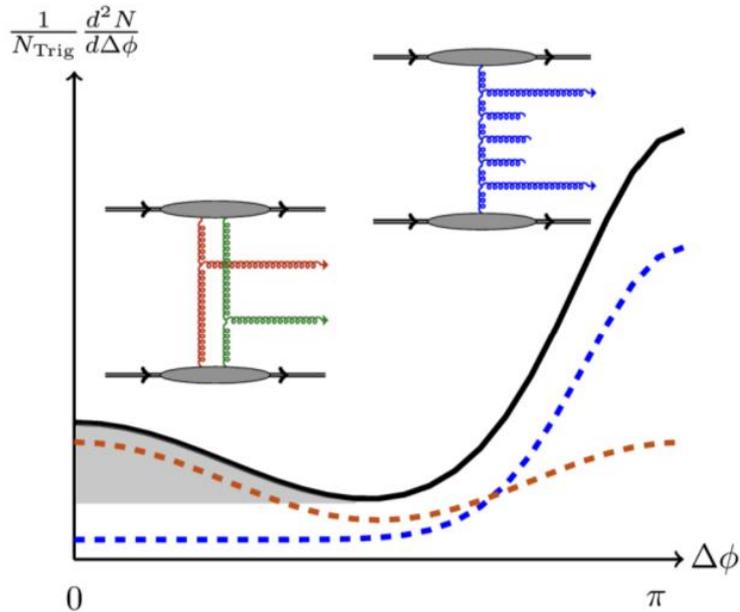
+ pythia



- 運動量保存
- uGD に主要な運動量 $k \sim |q-k| \sim |p-k| \sim Q_s$

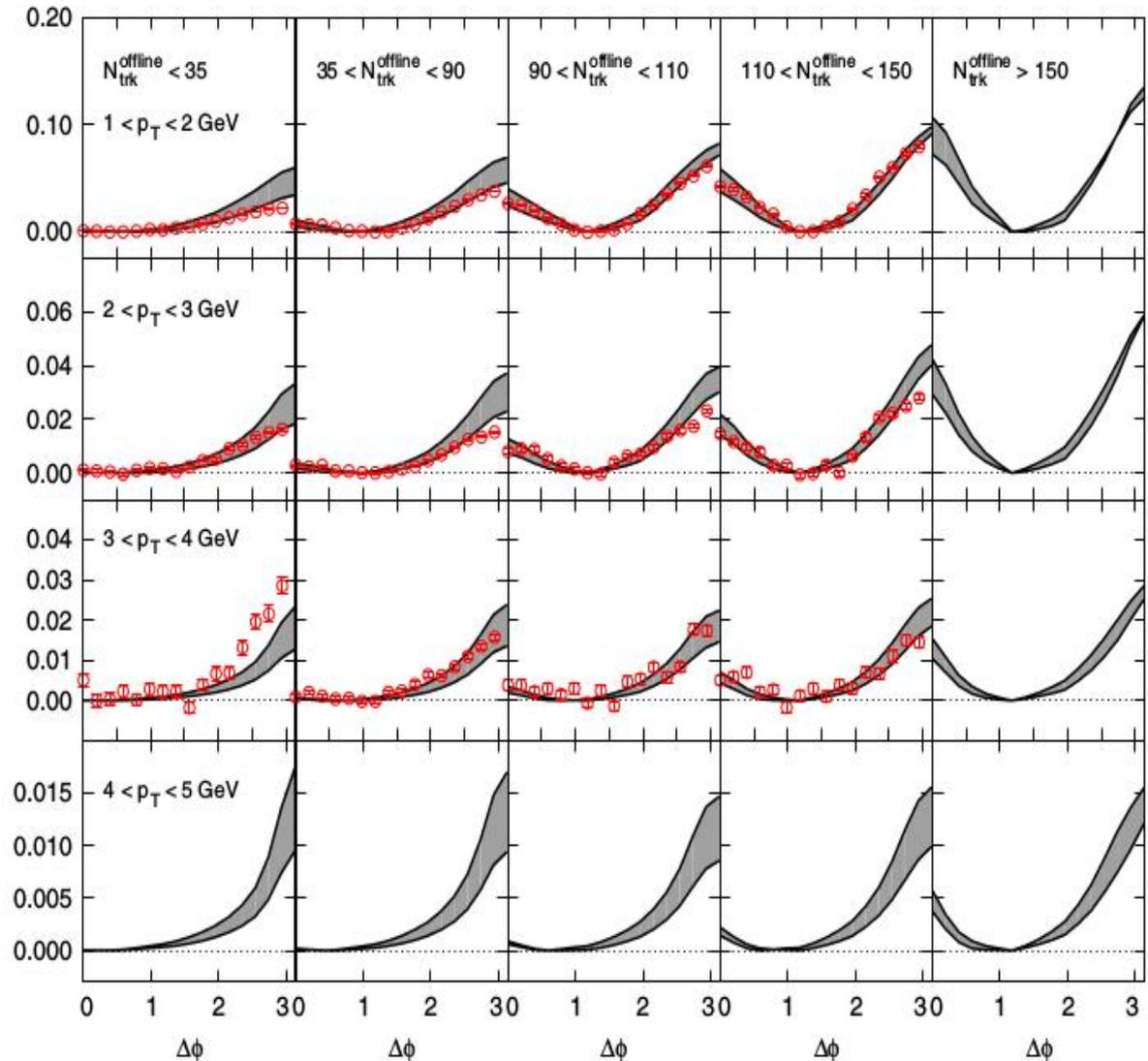
Glasma + BFKL

Dusling-Venugopalan, PRD 87, 054014 (2013)



CMS pA dataとの比較

$2 < \Delta\eta < 4$



重いクオーク生成

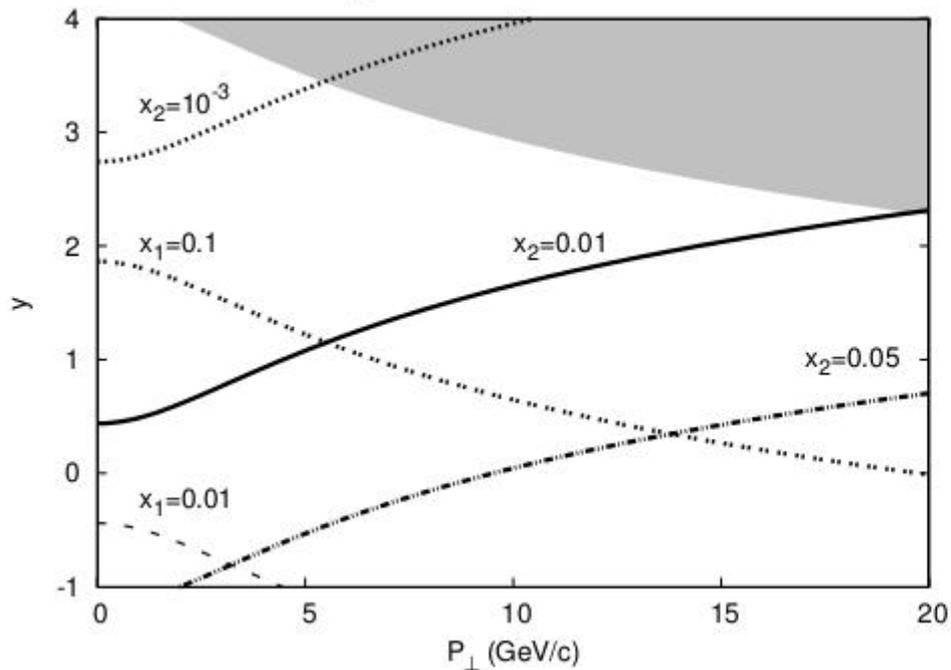
HF+K.Watanabe, NPA (2013)

重いクォーク生成

- $gg \rightarrow$ Quarkonium

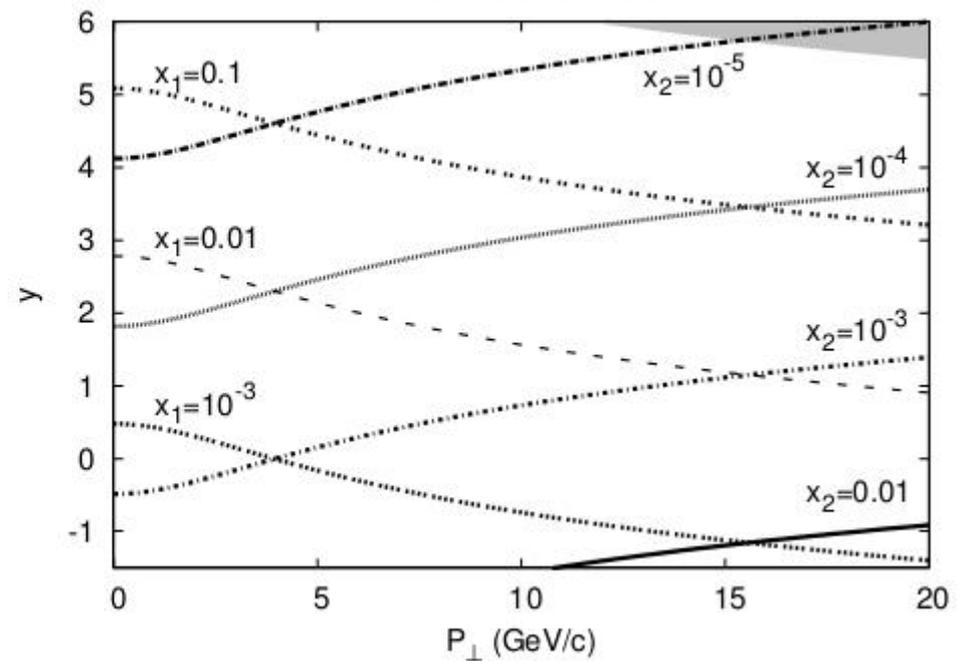
RHIC

(a) $\sqrt{s}=200\text{GeV}$, $M=3.1\text{GeV}$



LHC

(b) $\sqrt{s}=5.02\text{TeV}$, $M=3.1\text{GeV}$

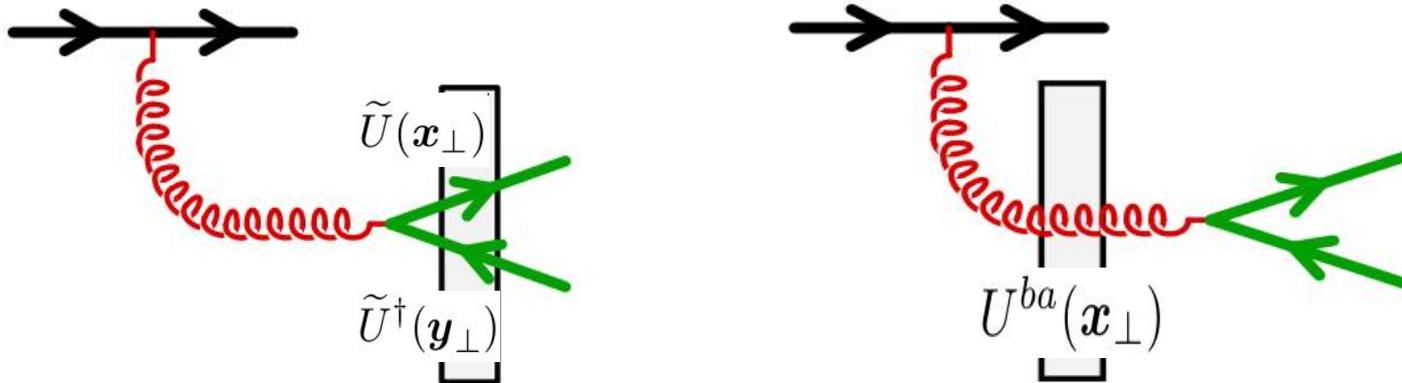


Quark pair production amplitude

Blaizot-Gelis-Venugopalan (2004)

$$\mathcal{M}_F(\mathbf{q}, \mathbf{p}) = g^2 \int \frac{d^2 \mathbf{k}_{1\perp}}{(2\pi)^2} \frac{d^2 \mathbf{k}_\perp}{(2\pi)^2} \frac{\rho_{p,a}(\mathbf{k}_{1\perp})}{k_{1\perp}^2} \int d^2 \mathbf{x}_\perp d^2 \mathbf{y}_\perp e^{i\mathbf{k}_\perp \cdot \mathbf{x}_\perp} e^{i(\mathbf{p}_\perp + \mathbf{q}_\perp - \mathbf{k}_\perp - \mathbf{k}_{1\perp}) \cdot \mathbf{y}_\perp}$$

$$\times \bar{u}(\mathbf{q}) \left\{ T_{q\bar{q}}(\mathbf{k}_{1\perp}, \mathbf{k}_\perp) [\tilde{U}(\mathbf{x}_\perp) t^a \tilde{U}^\dagger(\mathbf{y}_\perp)] + T_g(\mathbf{k}_{1\perp}) [t^b U^{ba}(\mathbf{x}_\perp)] \right\} v(\mathbf{p}),$$

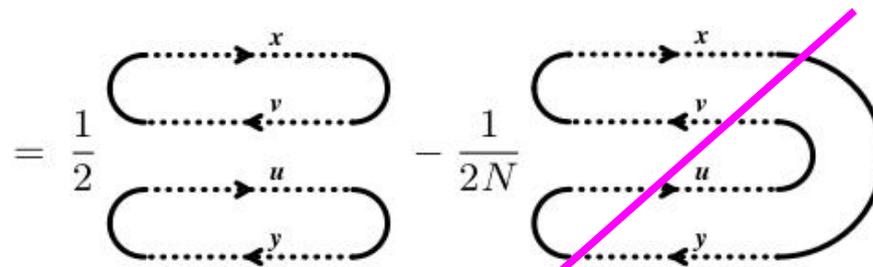


Cross-section in large N

$$\frac{dN_{q\bar{q}}}{d^2\mathbf{p}_\perp d^2\mathbf{q}_\perp dy_p dy_q} = \frac{1}{\pi R_A^2} \frac{\alpha_s^2 N}{8\pi^4 d_A} \frac{1}{(2\pi)^2} \int_{\mathbf{k}_{2\perp}, \mathbf{k}_\perp} \frac{\Xi(\mathbf{k}_{1\perp}, \mathbf{k}_{2\perp}, \mathbf{k}_\perp)}{k_{1\perp}^2 k_{2\perp}^2} \phi_{A, y_2}^{q\bar{q}, g}(\mathbf{k}_{2\perp}, \mathbf{k}_\perp) \varphi_{p, y_1}(\mathbf{k}_{1\perp})$$

- 振幅の2乗から 4-点関数が必要になる (kT fact breaking)
- large N 極限では、2点関数の積になる

$$C(\mathbf{x}_\perp, \mathbf{y}_\perp; \mathbf{u}_\perp, \mathbf{v}_\perp) \equiv \text{tr}_c \langle \tilde{U}(\mathbf{x}_\perp) t^a \tilde{U}^\dagger(\mathbf{y}_\perp) \tilde{U}(\mathbf{u}_\perp) t^a \tilde{U}^\dagger(\mathbf{v}_\perp) \rangle$$



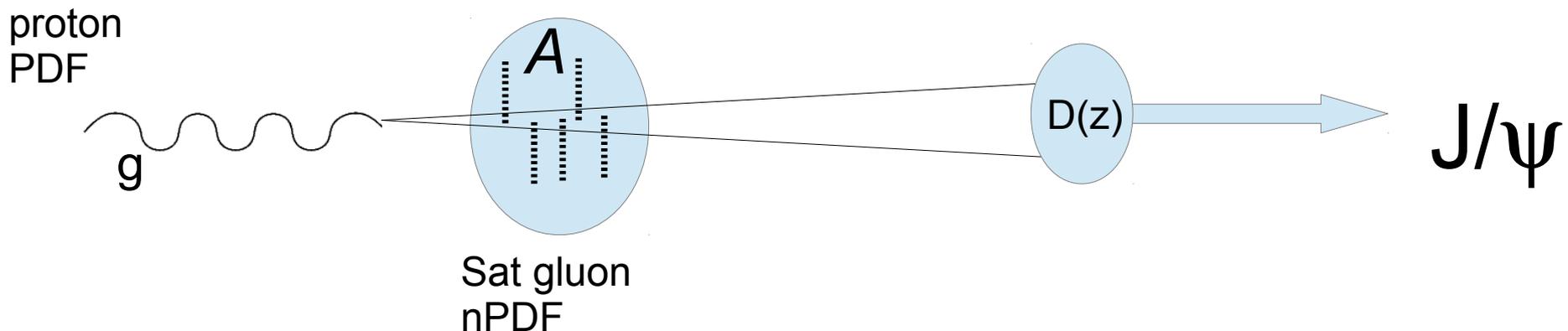
Quarkonium in Color Evaporation Model (CEM)

$$\frac{dN_{J/\psi}}{d^2\mathbf{P}_\perp dy} = F_{J/\psi} \int_{4m_c^2}^{4M_D^2} dM^2 \frac{dN_{c\bar{c}}}{d^2\mathbf{P}_\perp dM^2 dy}$$

- 仮定:

しきい値以下のクォーク対は、初期カラー状態に依らない一定の確率で、標的の外で非摂動的に J/ψ に束縛する

- **原子核効果 = グルーオン飽和 + 多重散乱**



open heavy flavors

- クォークスペクトルから破砕関数を用いて変換

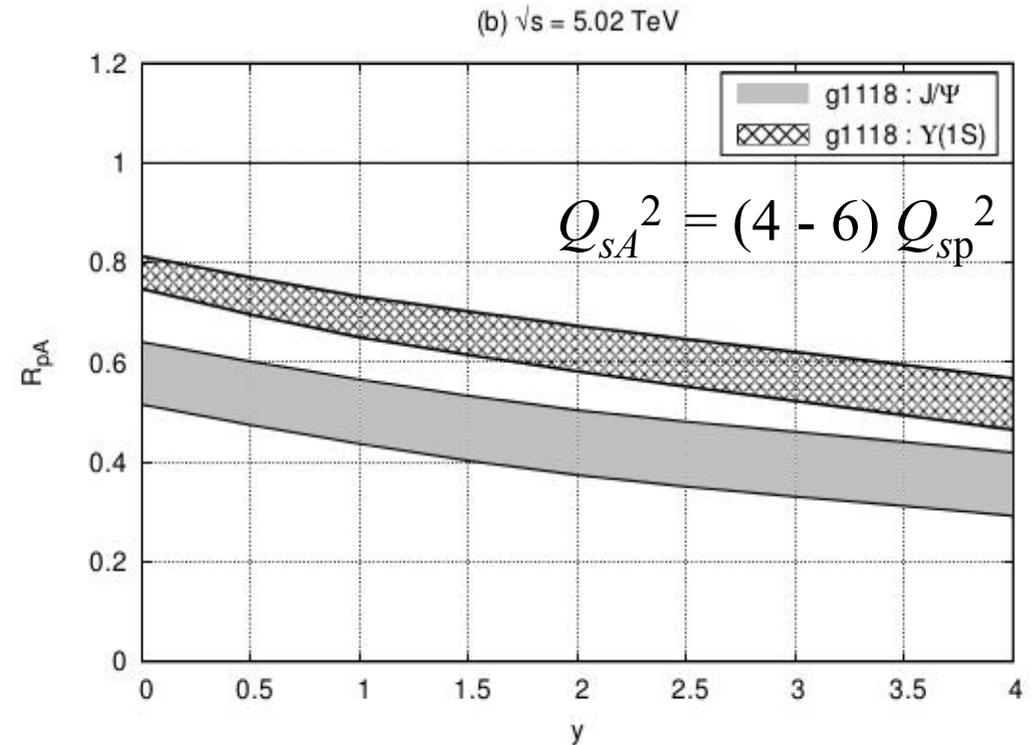
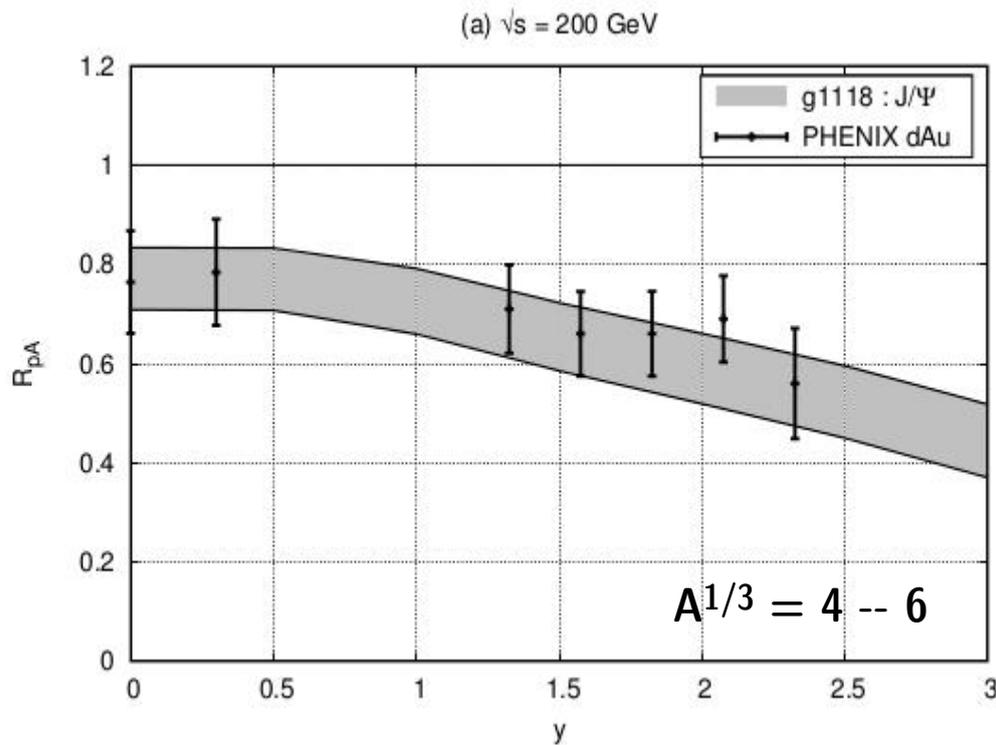
$$\frac{d\sigma_h}{d^2\mathbf{p}_{h\perp} dy} = f_{q\rightarrow h} \int_{z_{\min}}^1 dz \frac{D_q^h(z)}{z^2} \frac{d\sigma_q}{d^2\mathbf{q}_{\perp} dy}$$

$$D_q^h(z) = (\alpha + 1)(\alpha + 2)z^\alpha(1 - z)$$

$R_{pA}(y)$ for J/ψ at RHIC & LHC

$$R_{pA} = \frac{dN_{J/\psi}/d^2P_{\perp} dy|_{pA}}{N_{\text{coll}} dN_{J/\psi}/d^2P_{\perp} dy|_{pp}} \quad N_{\text{coll}} = A^{1/3}$$

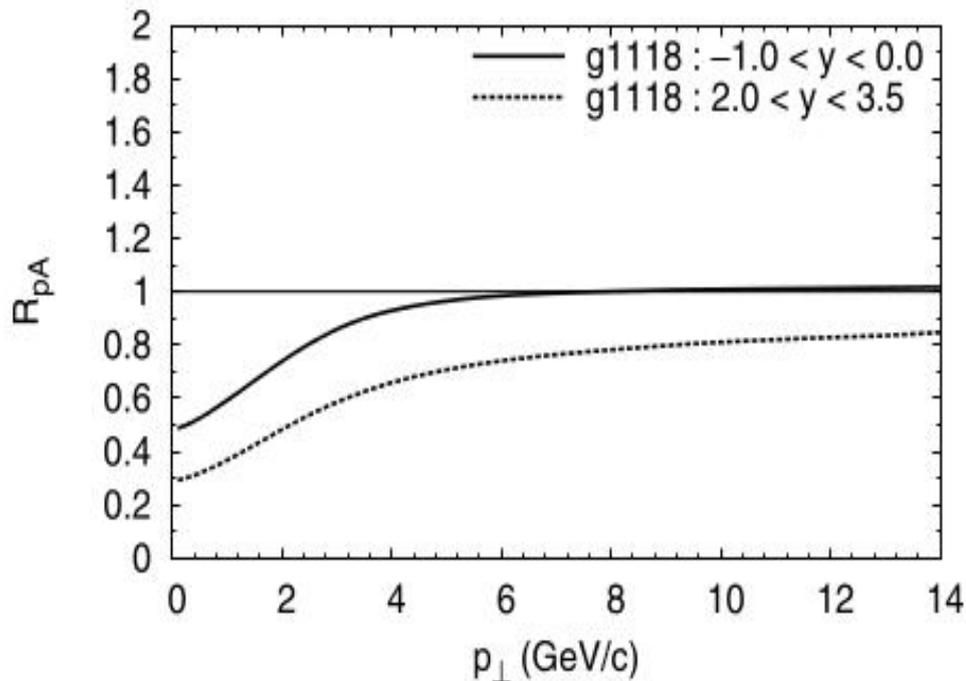
- グルーオン飽和はRHICよりLHCで顕著のはず。。。。



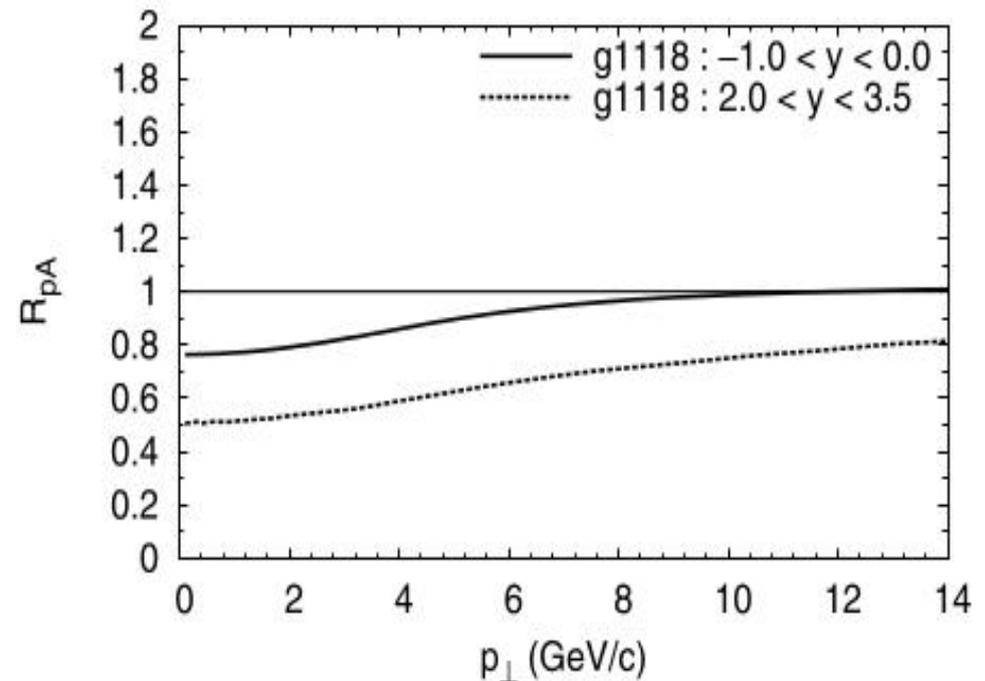
$R_{pA}(p_T)$ for open heavy flavors

- 小さい p_T で抑制が見える
- 大きい p_T では 1 に漸近

(a) D : $\sqrt{s} = 5.02$ TeV

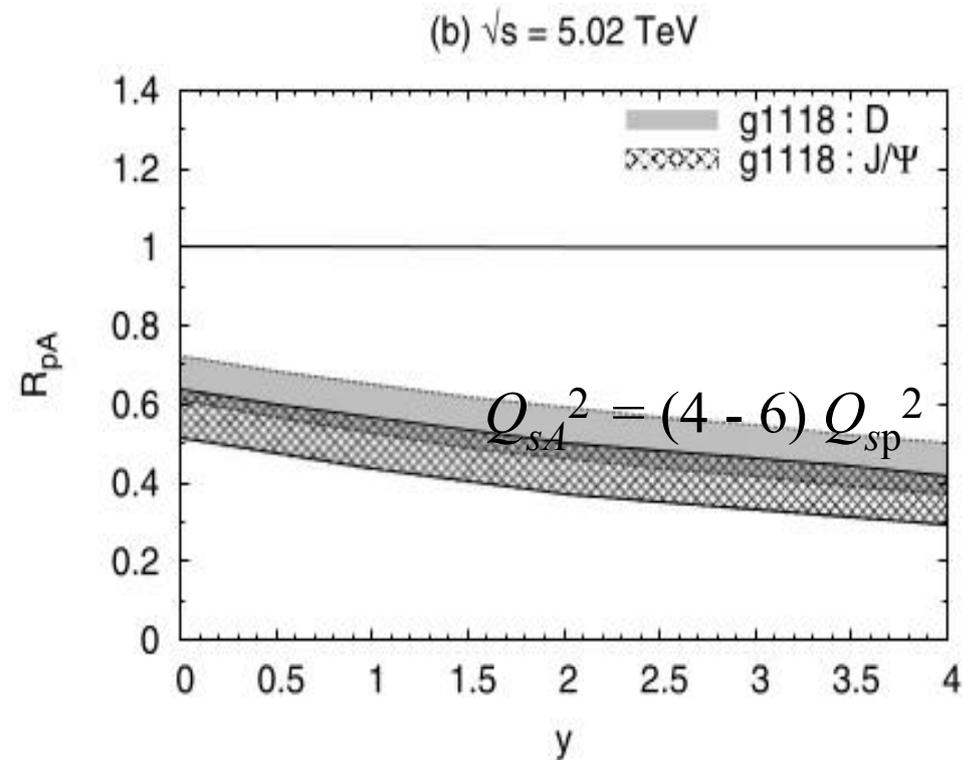
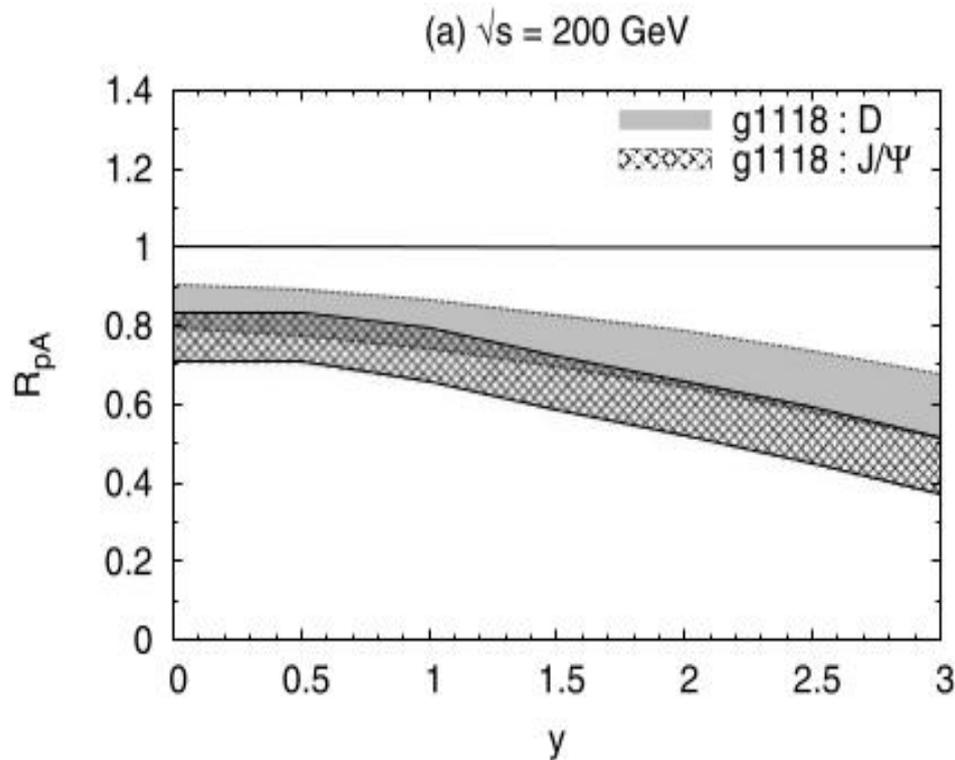


(b) B : $\sqrt{s} = 5.02$ TeV



Comparison: quarkonium vs open charm

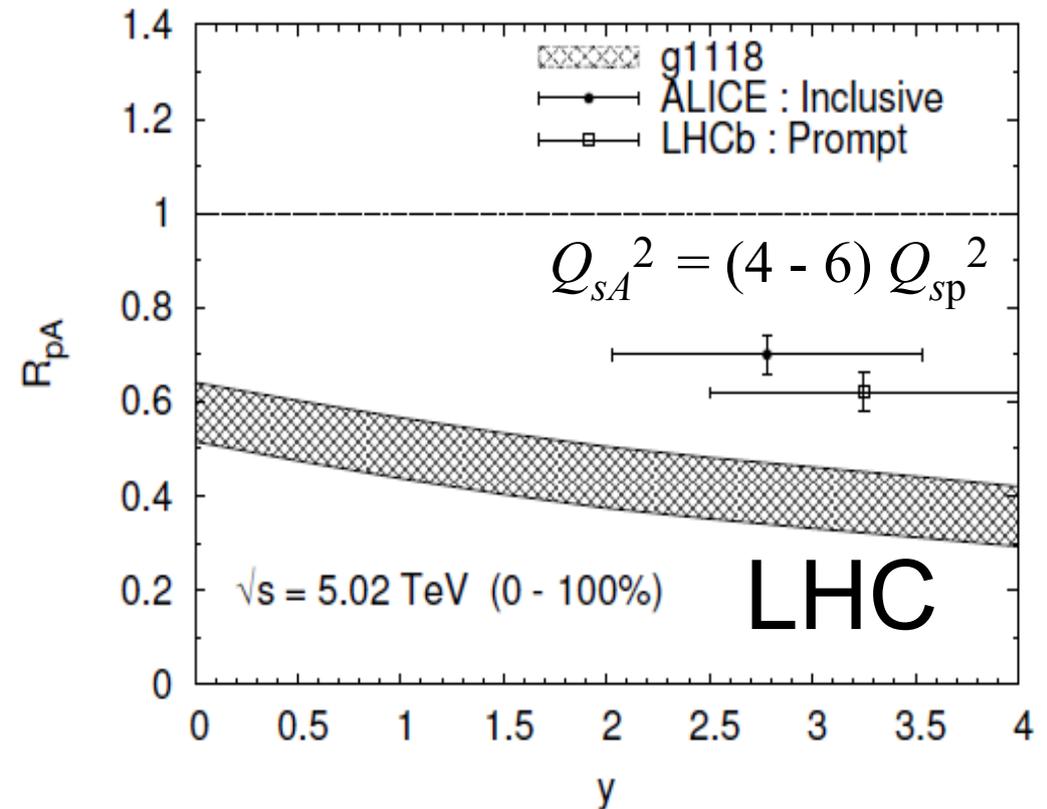
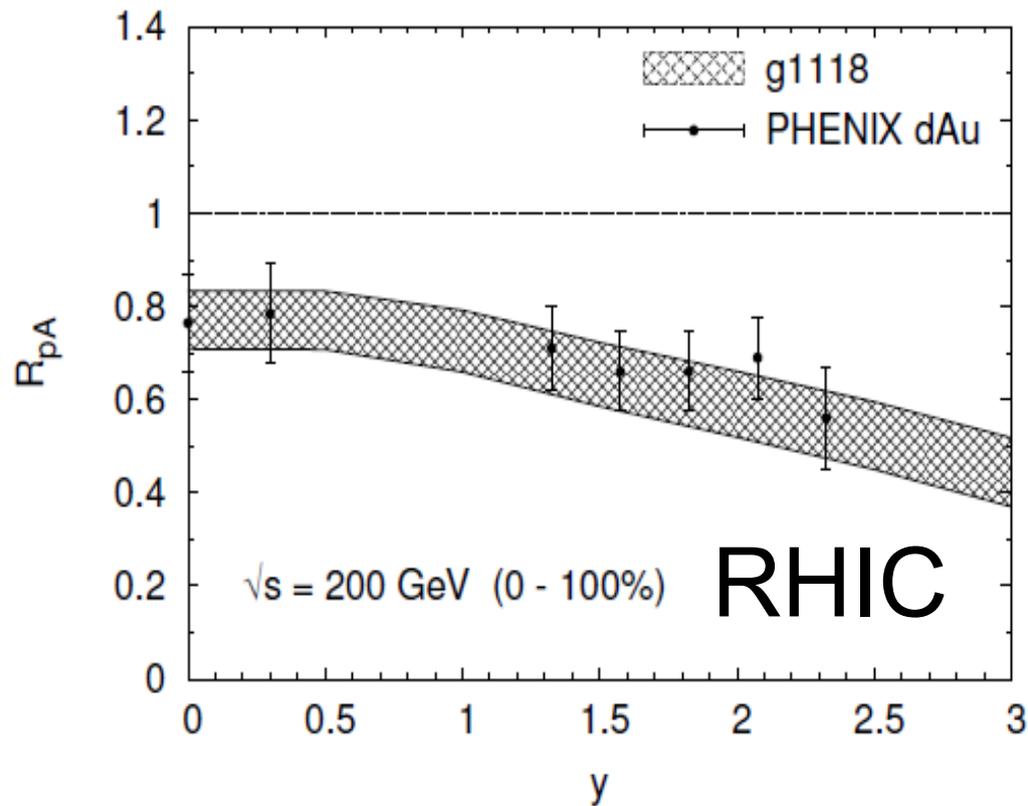
- 前方抑制 = グルーオン飽和効果
- クォークニウム抑制 = + 多重散乱



データとの比較

ALICE, 1308.6726

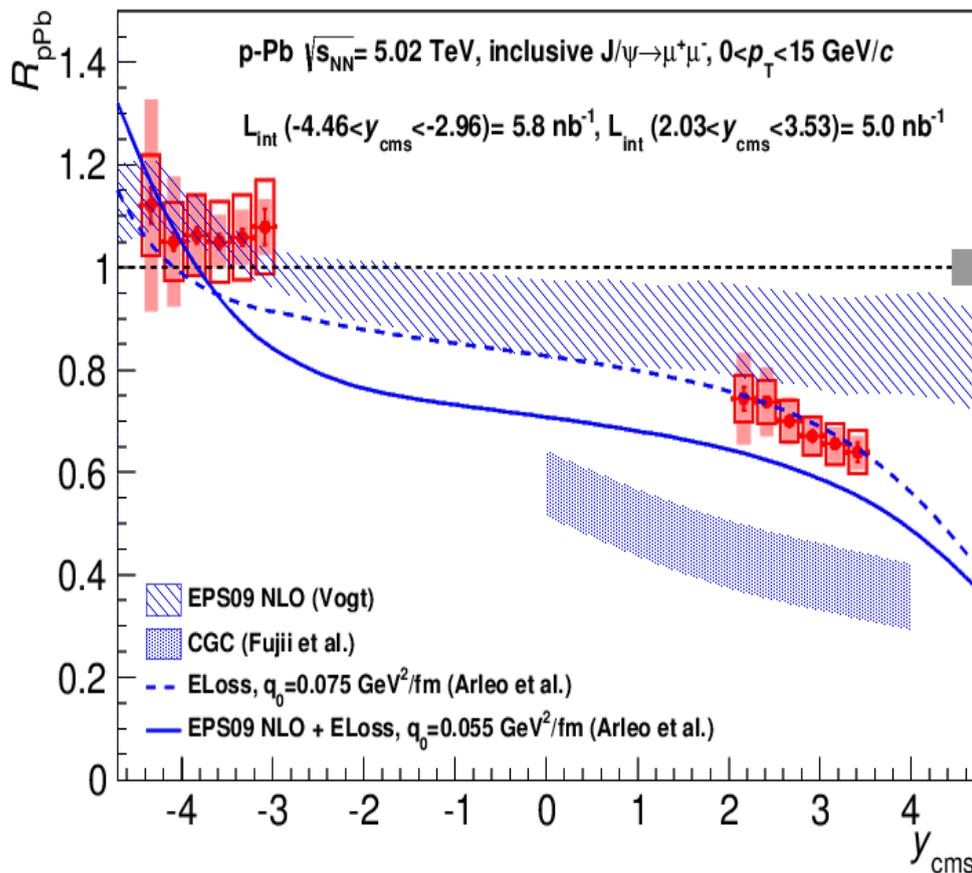
J/ψ



データとの比較

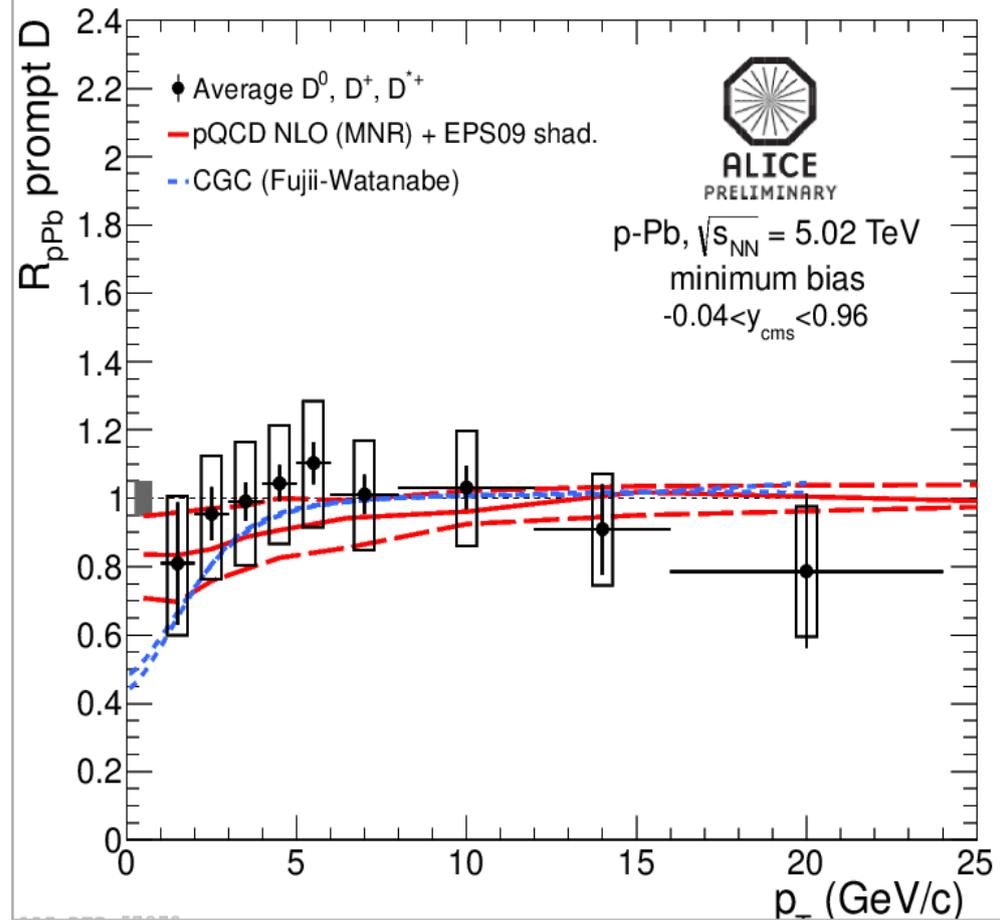
J/ψ

ALICE, 1308.6726



D

ALICE, 1310.1714

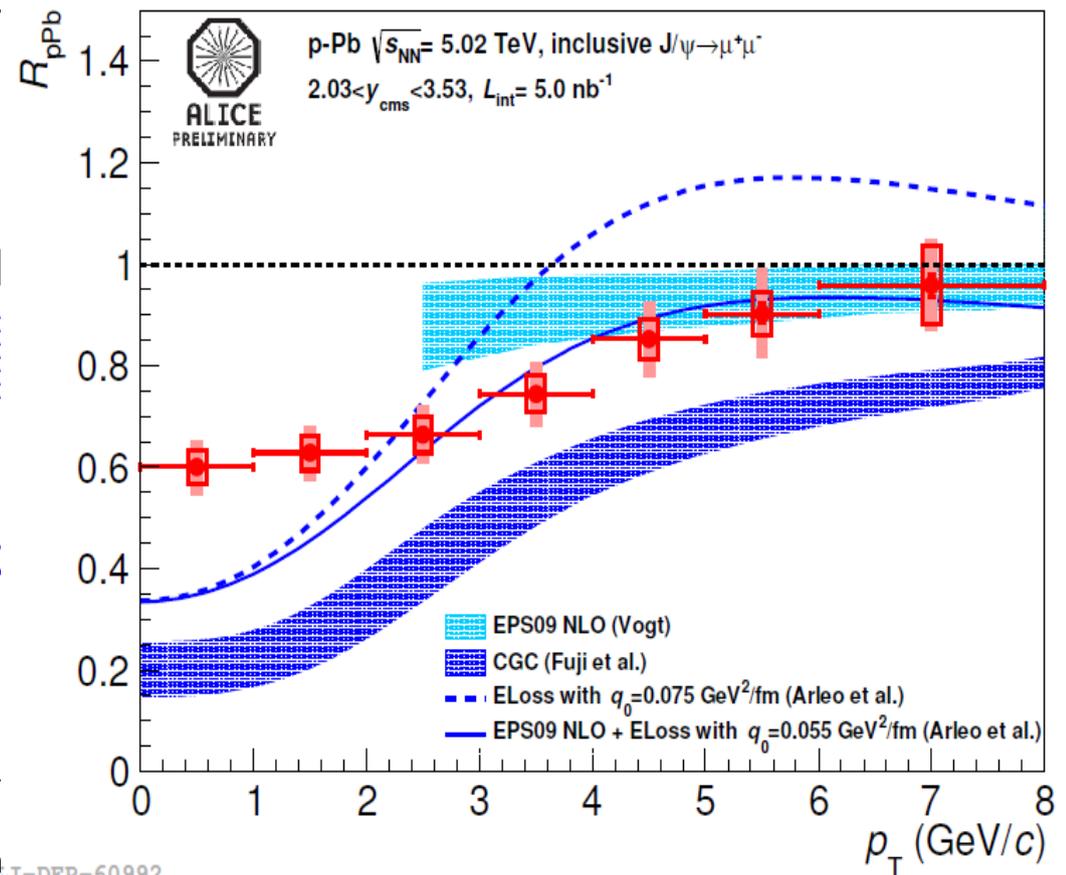
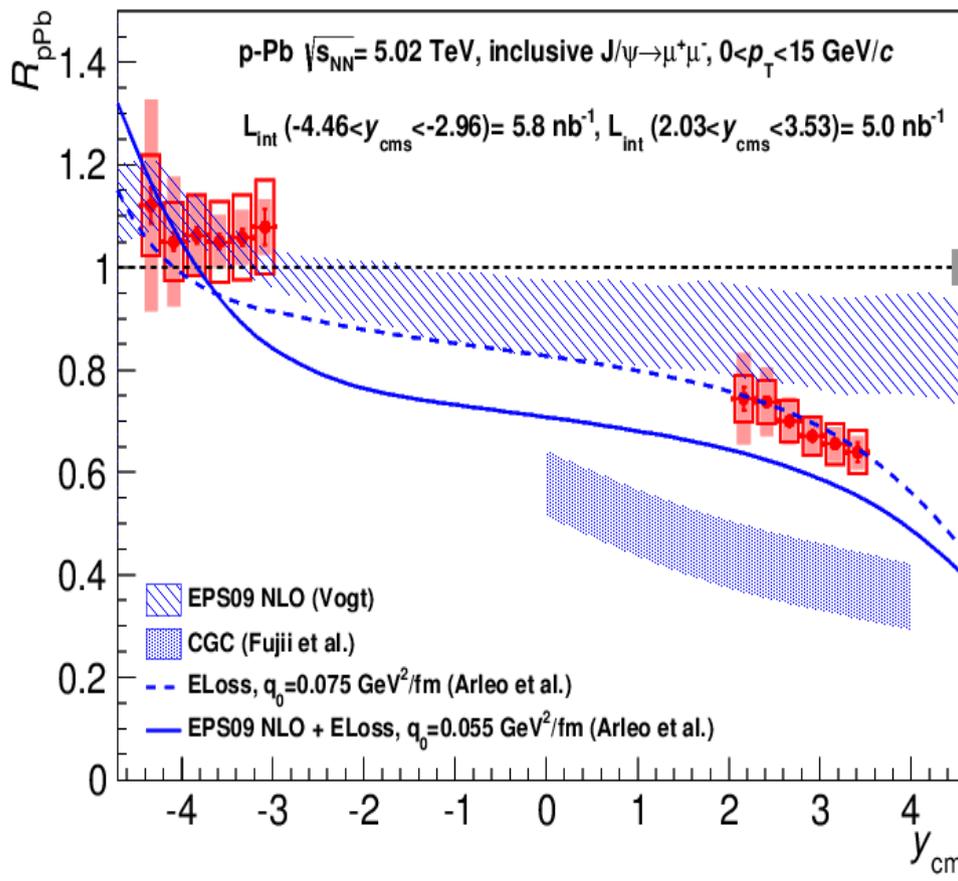


データとの比較

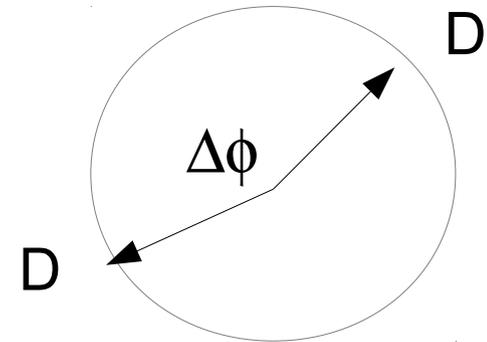
J/ψ

ALICE, 1308.6726

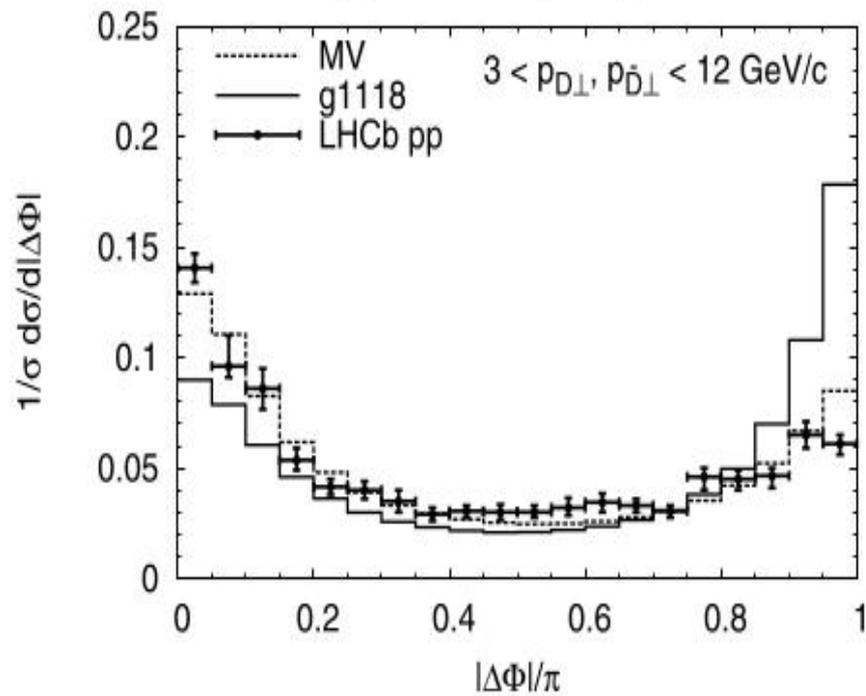
ALICE, 1404.1615



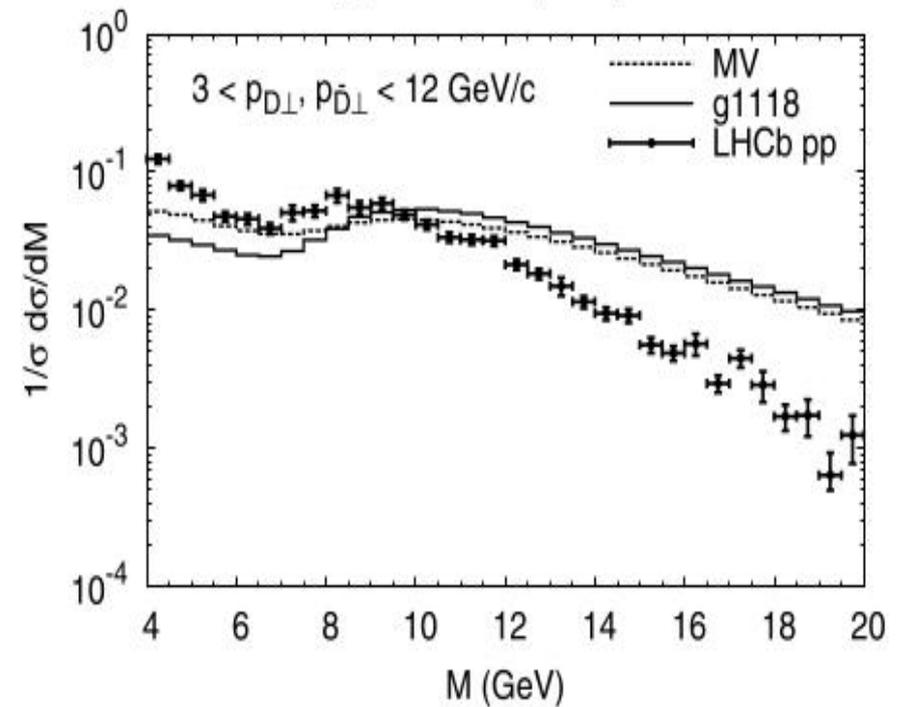
Dメソン相関



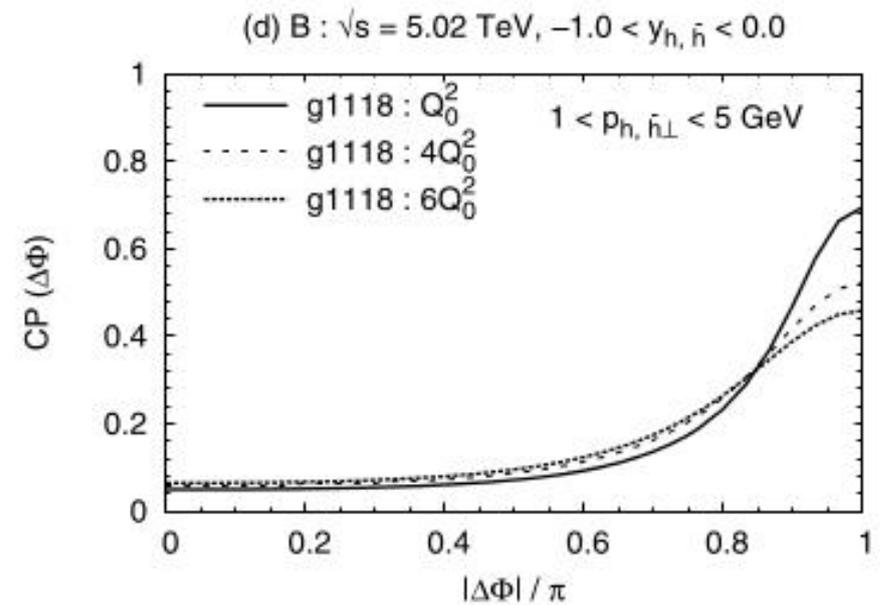
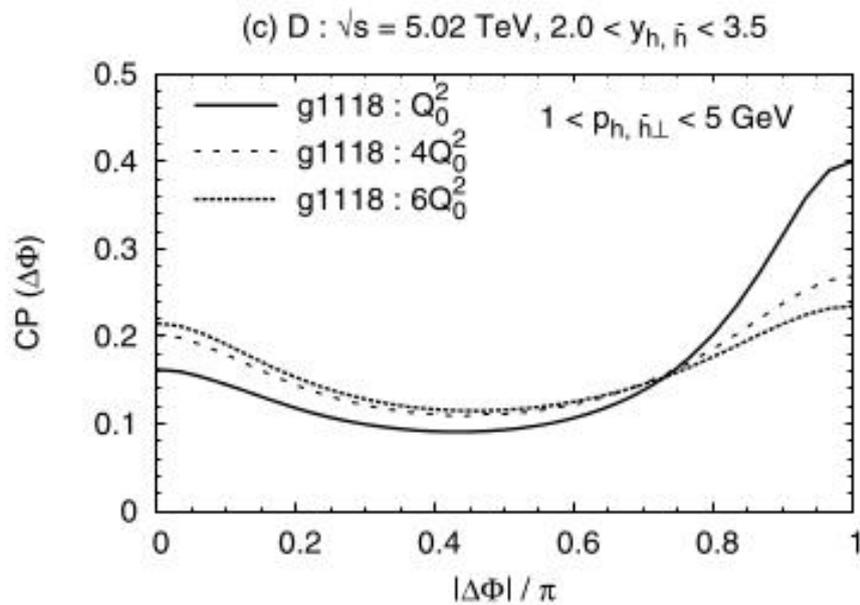
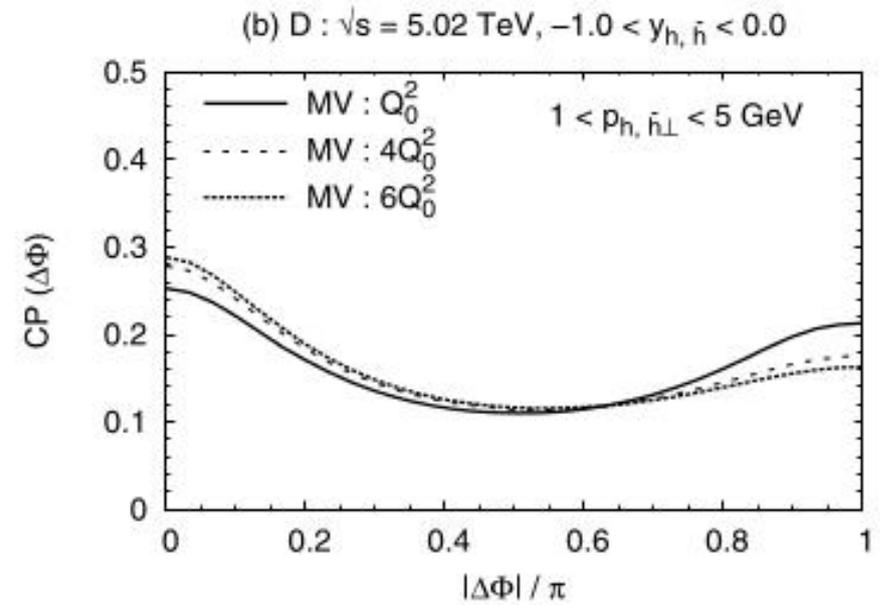
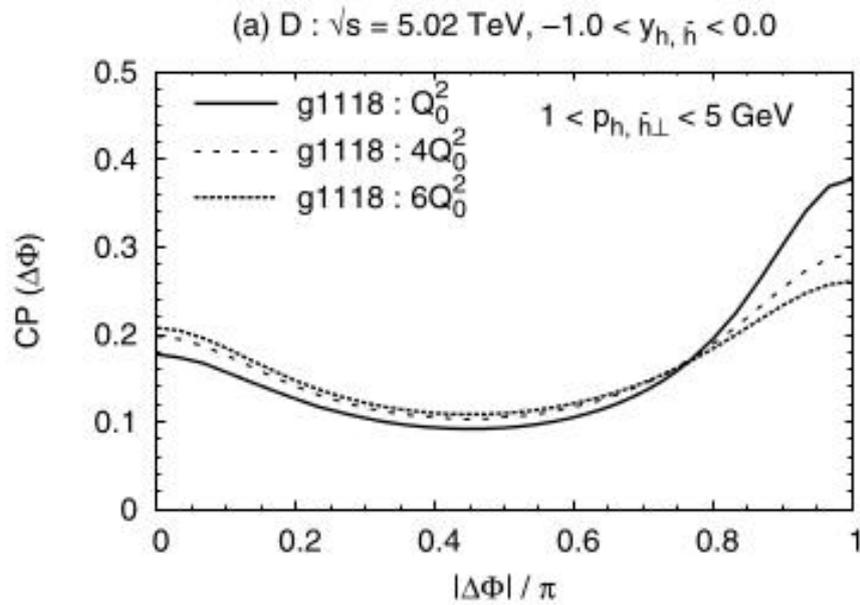
(a) $\sqrt{s} = 7 \text{ TeV}, 2 < y < 4$



(b) $\sqrt{s} = 7 \text{ TeV}, 2 < y < 4$



Dメソン関連



まとめ

- 高エネルギーハドロン反応の初期過程として、カラーグラス凝縮有効理論に基づく粒子生成を概観した
- pA@LHCでの、一粒子スペクトルを示した。パートン飽和効果によって、前方生成に強い抑制が期待される。
- CGCの枠組みで、二粒子相関に峰構造が現れる可能性をレビューした。
- 核内パートン分布のプローブとして、重いクォーク生成を評価した。

展 望

- CGC (モデル) 計算は、nuclear DIS, 二粒子相関を含むハドロン生成、ジェット、光子生成など、多くの過程に適用・研究されているが、ここではカバーできない。
- CGC理論としては、一貫性のあるNLOの計算が試みられつつことを始め、理論の進化・進展に期待。
- pp, pA, AA@LHCから興味深いデータが続々と提供され、small-x の原子核、陽子構造の研究が非常に興味深い。