Theory Summary of Hard and Electromagnetic Probes at QM2014

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Outline

Topics are widely chosen

- Heavy Quark
- Quarkonium

Topics are highly selected

- Photon & Dilepton
- ~~Jet~~ (I planned at first but gave up)

I have too many slides. I will stop 40 minutes later.

Please ask questions during my talk.

感想

- 今回はあまり大きな（派手な）進展はない。１年半ごとに理論の進歩が見られる分野などない、と開き直ろう。
- ジェットのほうで専門外から見ると発展（color decoherenceやqhatのくりこみ）があったように感じたが、フォローしきれず。
- Heavy Quarkはエネルギー損失や拡散現象の現象論が盛り沢山。チャームの完全熱化シナリオの線が、逆にすっきりしていて得られる情報が明確であったりする。
- Quarkoniumは相変わらずポテンシャル虚部の物理的意味の勘違いが見受けられる。有限温度ポテンシャルは何故いつも二択（自由／内部エネルギー）なのか？
- 光子・レプトン対の高次の摂動計算は見事。光子の大きな異方性は未解決。

Heavy Quark

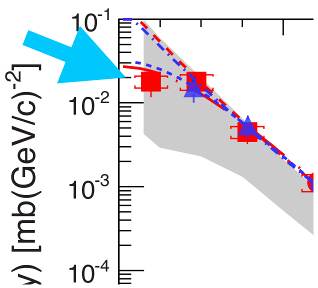
- Talk slides from
  - Kweon (plenary)
  - Beraudo (plenary)
  - Kaczmarek (parallel)
- Topics
  - Do we really understand pp and p(d)A collisions?
  - Which is which? Phenomenology at AA collisions
  - Is charm quark heavy enough?
  - Transport coefficient on the lattice

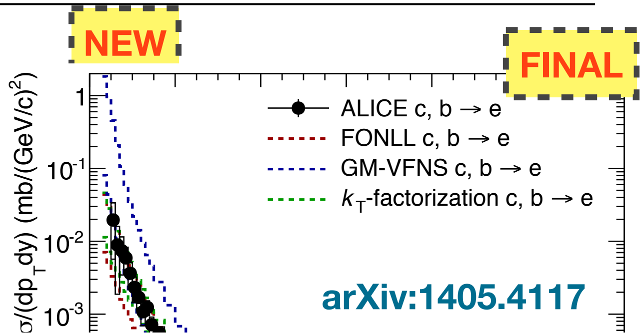
Do we really understand pp and p(d)A collisions?

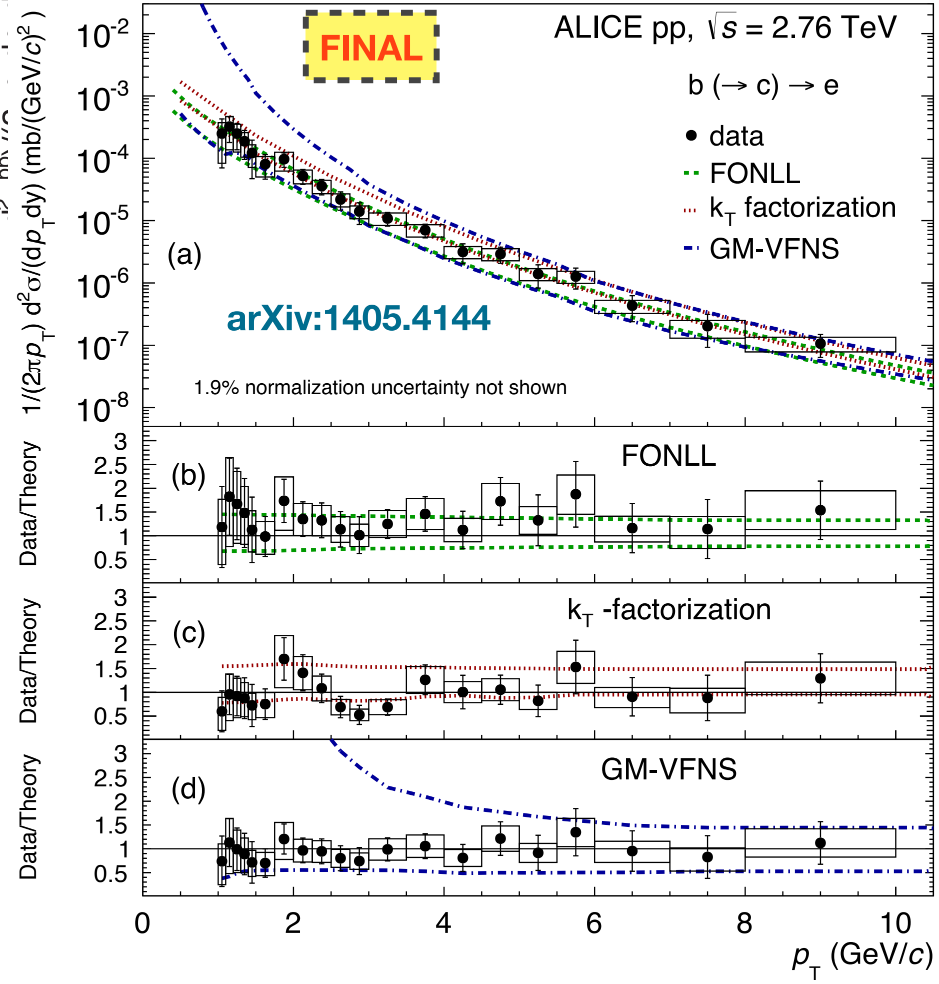
陽子衝突における重クォーク生成
p_T-differential cross sections in pp collisions

- Heavy flavour cross section measurements: **extended kinetic reaches, beam energy dependences**

- pQCD-based calculations (FONLL, GM-VFNS, k_T factorization) compatible with data
  - ◉ D^0, D^{*+} (mid rapidity, down to p_T~0.4 GeV/c at 200 GeV) at **200 & 500 GeV** STAR
  - ◉ D^0, D^+, D^{*+} mesons (mid rapidity) at 2.76 & 7 TeV ALICE
  - ◉ c,b→e (mid rapidity, down to p_T~0.5 GeV/c) at **2.76** & 7 TeV
  - ◉ c,b→μ (forward rapidity) at 2.76 & 7 TeV
  - ◉ b→e (mid rapidity, down to p_T~1 GeV/c) at **2.76** & 7 TeV ALICE



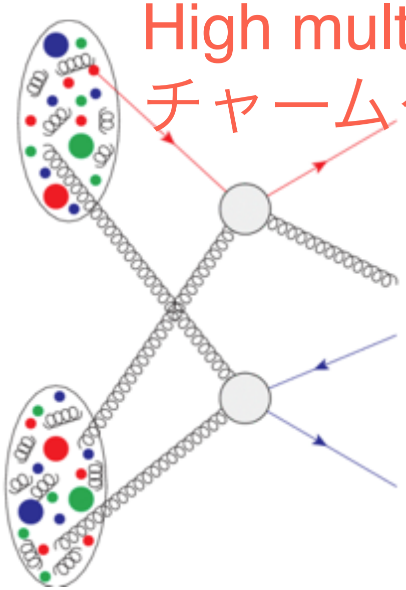




FONLL: JHEP 1210 (2012) 137, GM-VFNS: Eur. Phys. J. C 72 (2012) 2082, k_T factorisation: arXiv:1301.3033

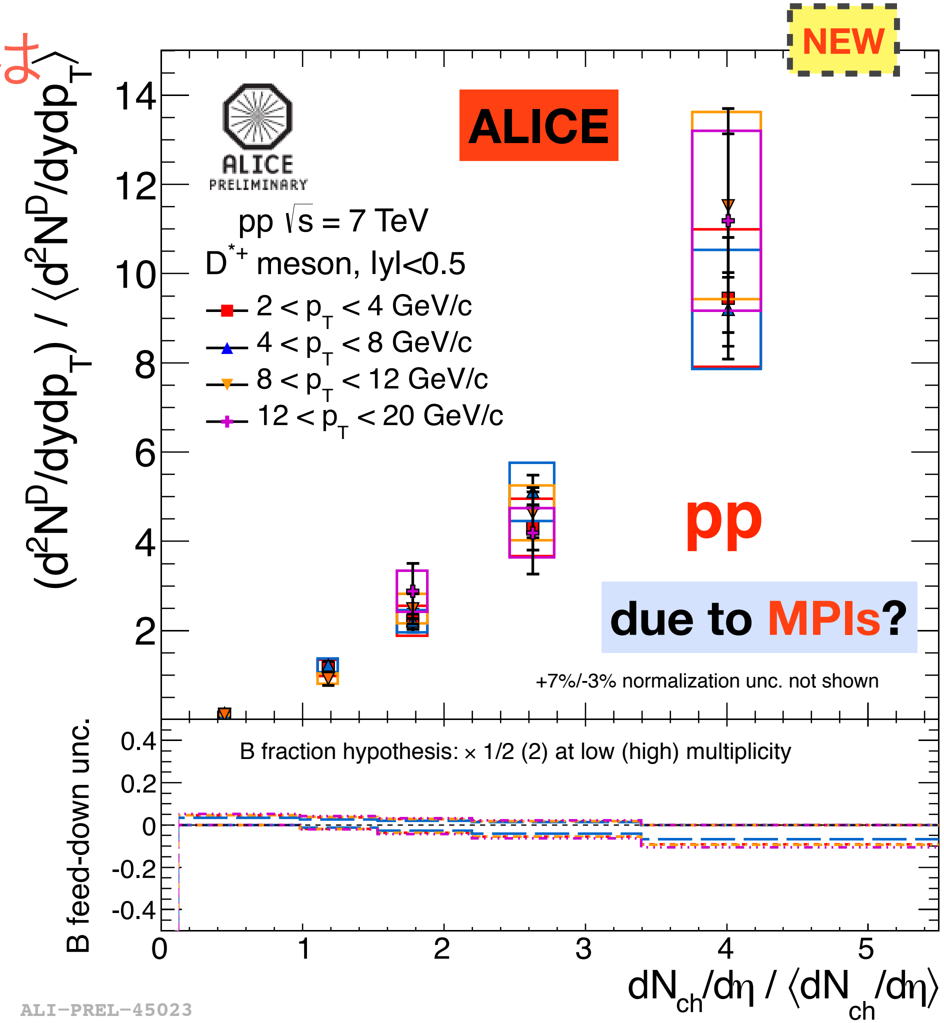
More on production mechanism:
Multiplicity dependences of charm production

High multiplicityの陽子衝突では
チャームクォーク生成も多い



Particle production in pp collisions at LHC shows **better agreement with models including MPIs**

Eur. Phys. J. C 73 (2013) 2674



For heavy flavours:

- LHCb: double charm production agrees better with models including double parton scattering

J. High Energy Phys., 06 (2012) 141

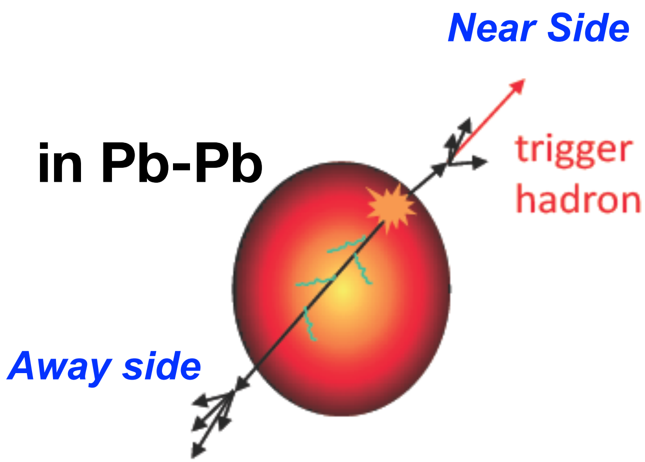
MPIs involving only light quarks and gluons?

- D-meson yields increase with charged-particle multiplicity

→ presence of MPI and contribution on the a harder scale?

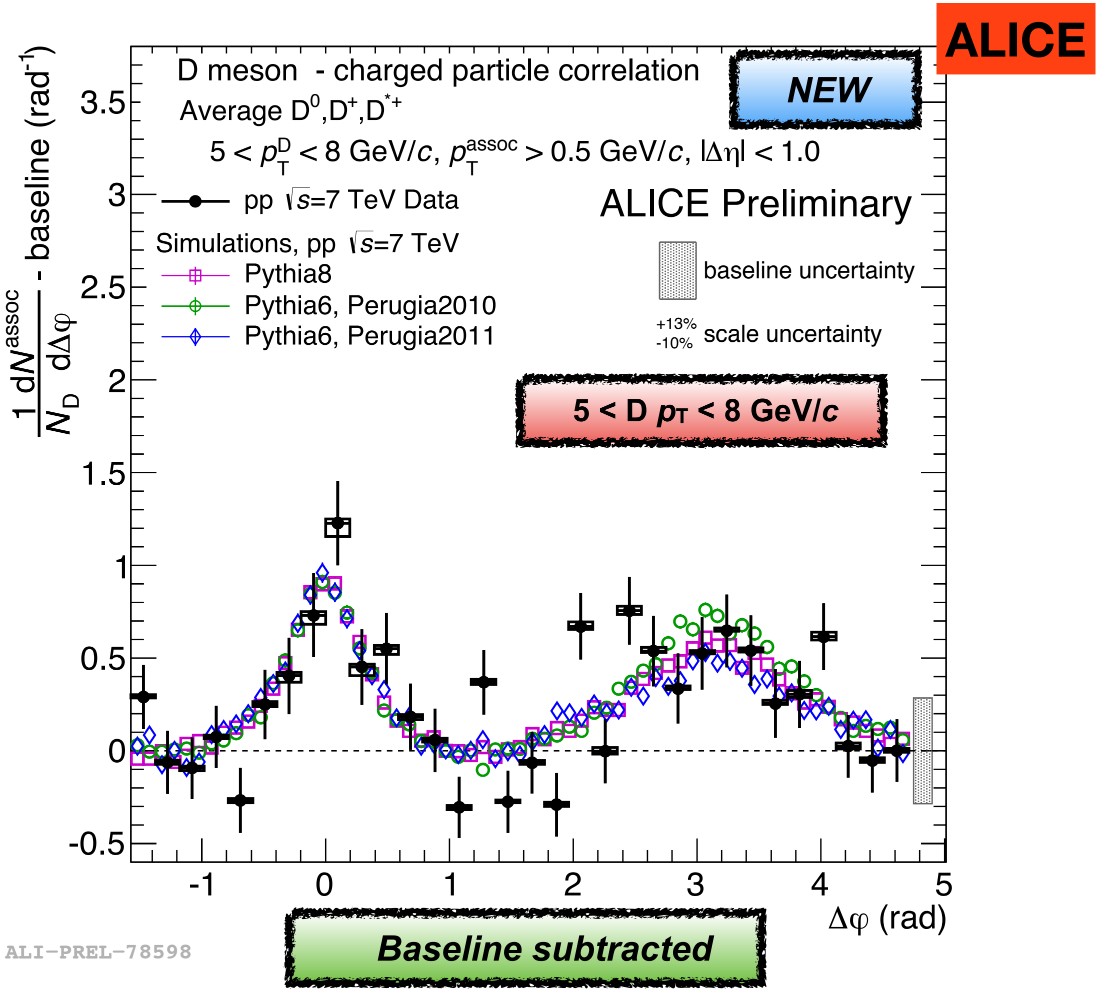
More differential information:
Heavy flavour correlations

Heavy flavour jet properties



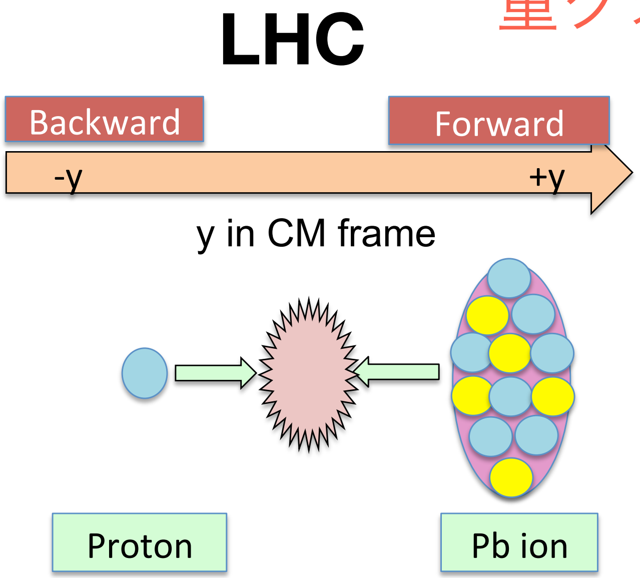
Path length dependence

陽子衝突を説明できることが、QGPを通過した重クォーク対の角度相関を調べる時に重要

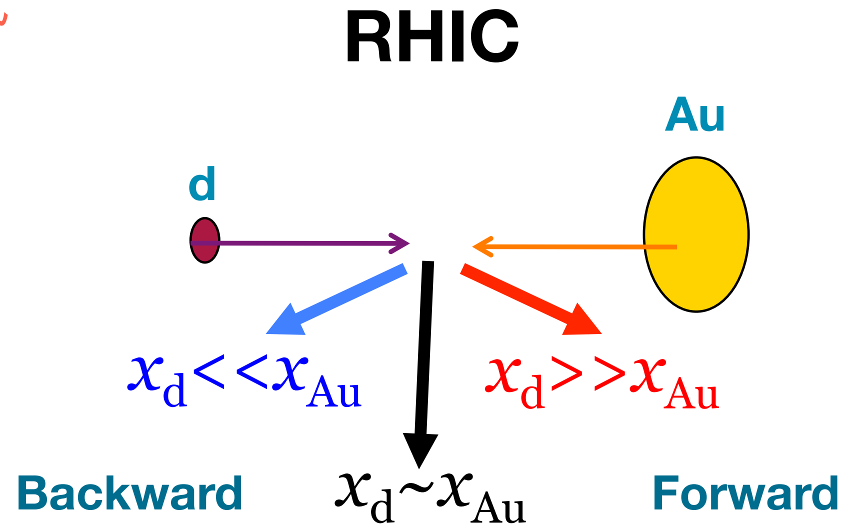


- D-hadron correlations in pp show good agreement with expectations from Pythia (different tunes)

(重)陽子-原子核衝突における重クォーク生成



y_{CMS} = 0.465 in the p-beam direction



p-A collisions at √s = 0.2 and 5.02 TeV

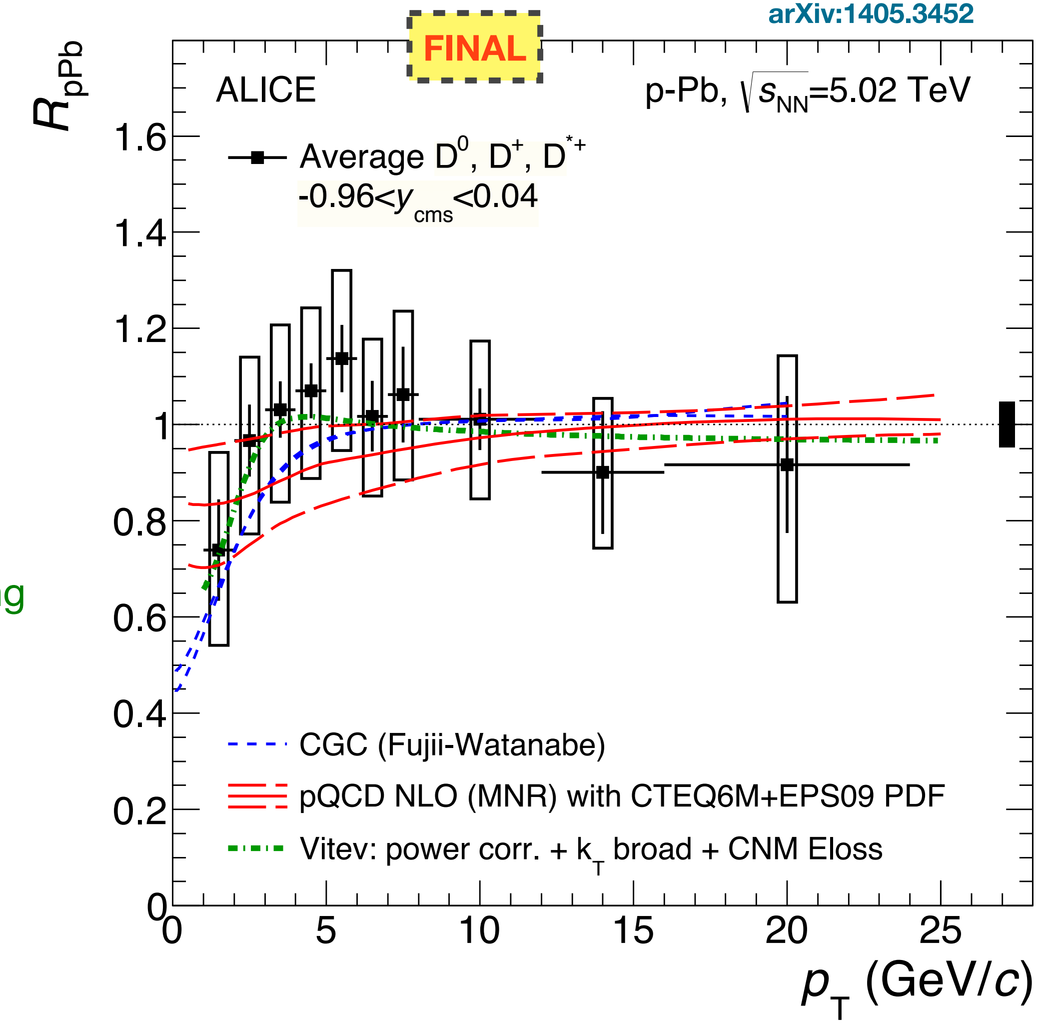
d-Au, p-Pb
Cold nuclear matter effect

$$\frac{dN^D_{PbPb}}{dp_T} = PDF(x_1)PDF(x_2) \otimes \frac{d\hat{\sigma}^c}{dp_T} \otimes P(\Delta E) \otimes D_{c \to D}(z)$$

Heavy flavour in p-Pb at LHC (at 5.02 TeV)

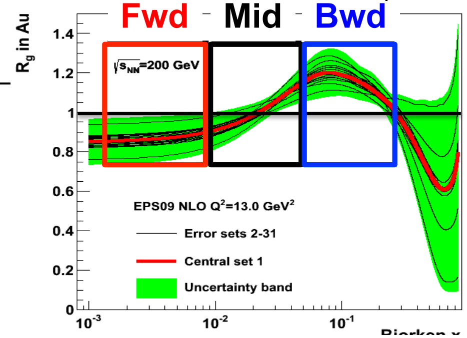
- R_{pPb} measured in various channels
- R_{pPb} consistent with unity within uncertainties

ALICE ◉ D^0, D^+, D^{*+} mesons (mid rapidity): can be described by CGC calculations, pQCD calculations with EPS09 nuclear PDF and a model including energy loss in cold nuclear matter, nuclear shadowing and k_T-broadening

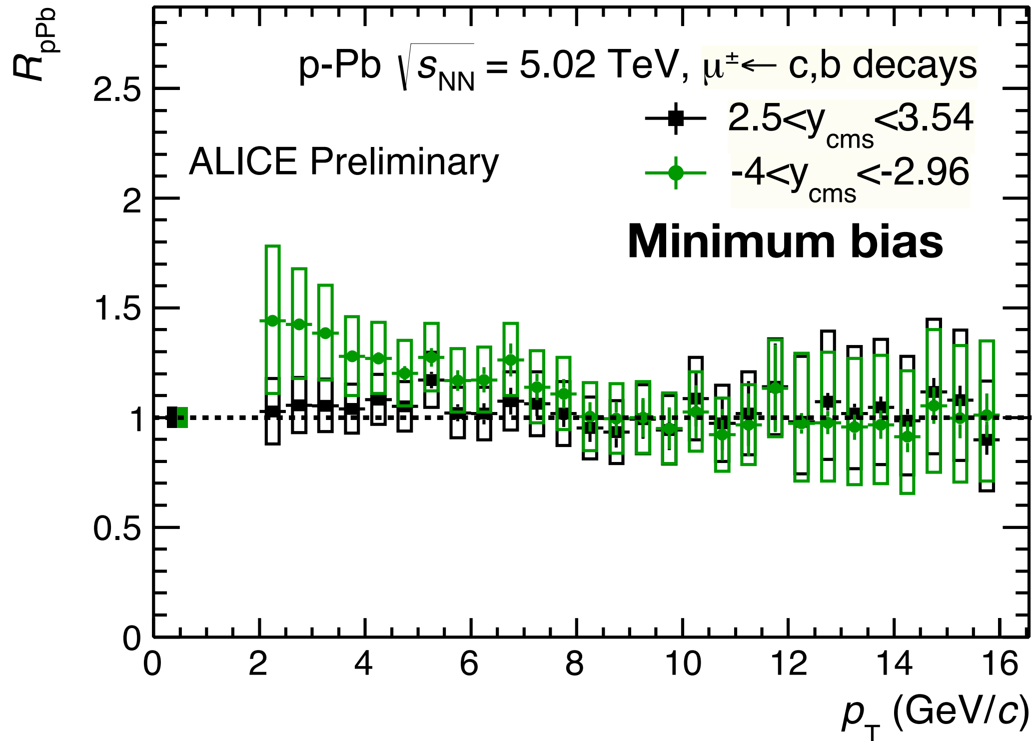


Mid-rapidityでは理論計算が実験と合っている

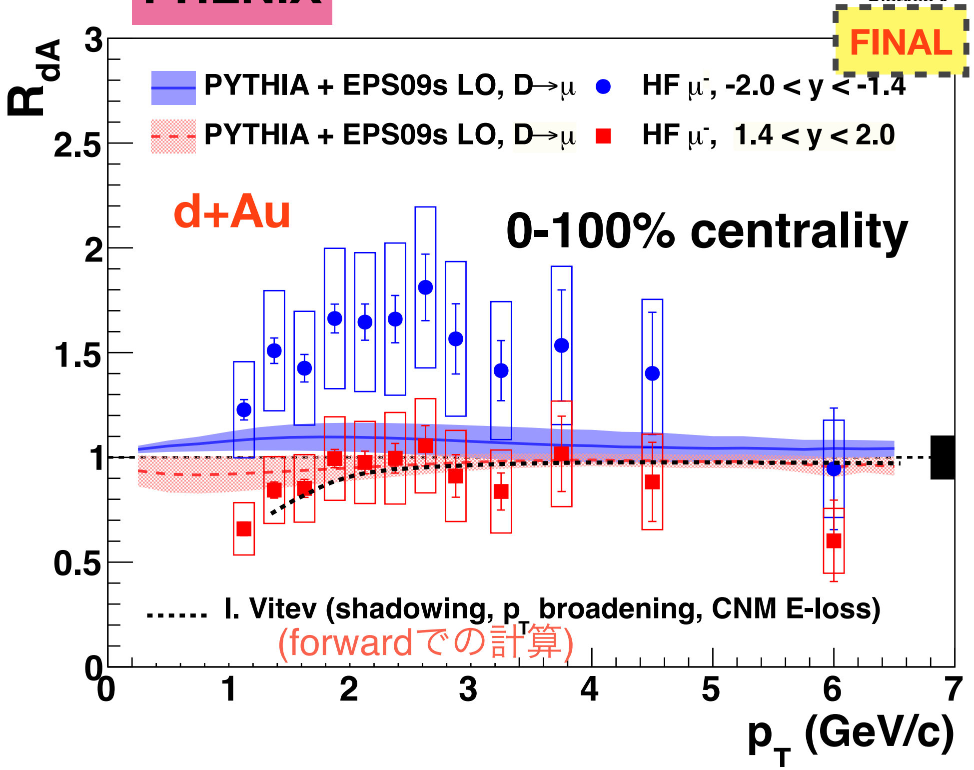
Heavy flavour in pA at LHC and RHIC



ALICE



PHENIX

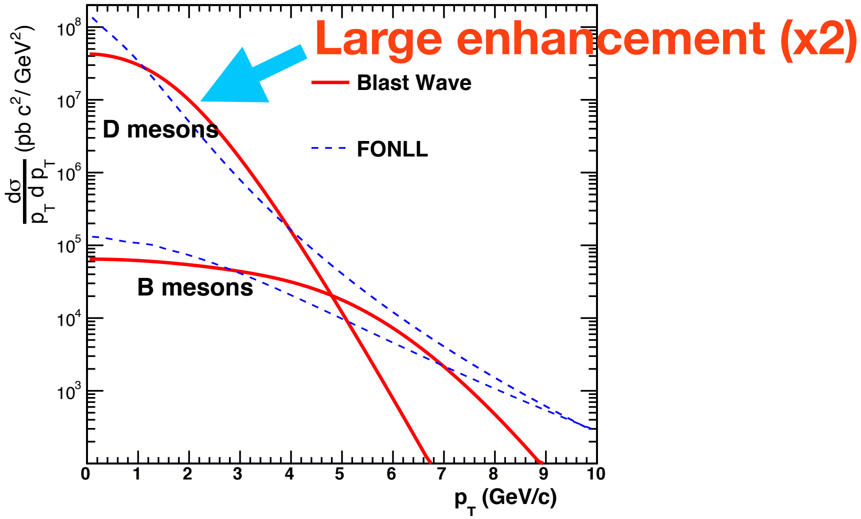


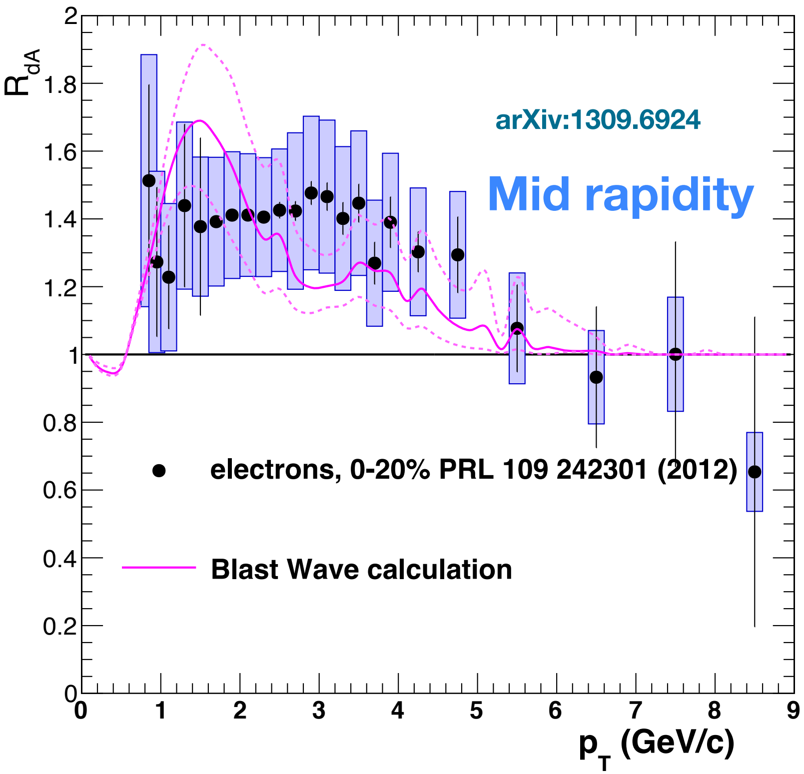
LHCではpQCD+EPS09で説明できる(別スライド)。RHICでは、forward, backwardともD中間子のスペクトルを説明できない。ForwardでCNM効果が重要？

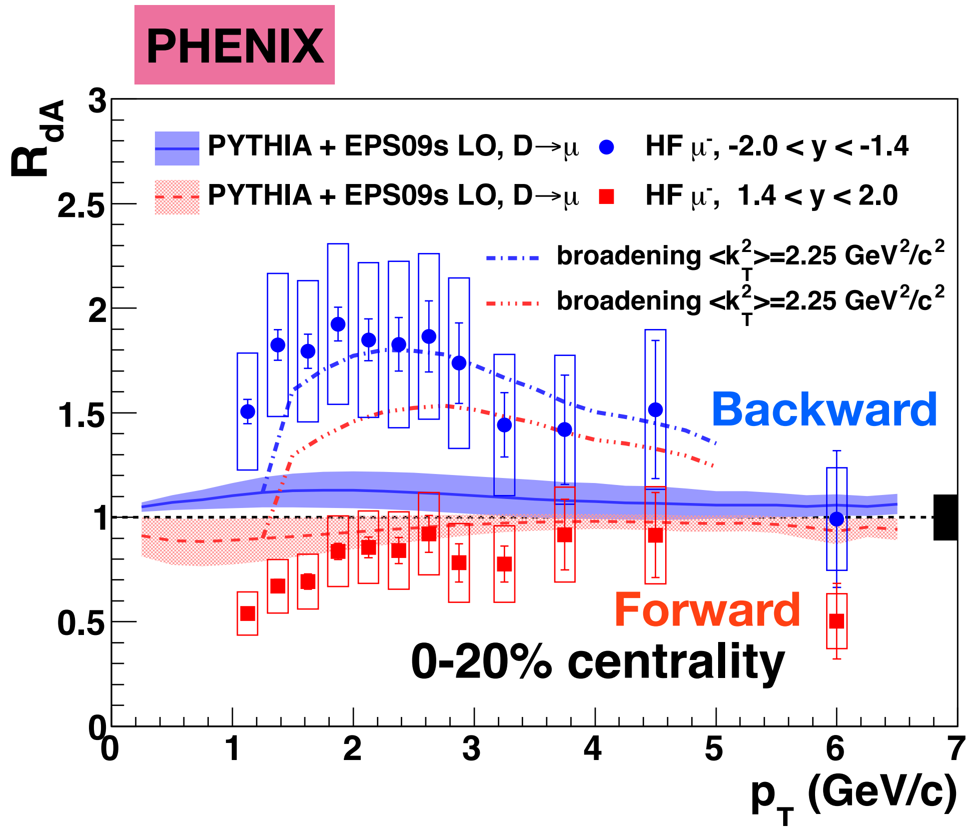
At RHIC, fail to reproduce the data at both rapidity simultaneously

arXiv:1310.1005

Enhancement in central d+Au







← **Radial flow qualitatively reproduces the data!**

RHICのdAのmid-とbackwardで流体？？

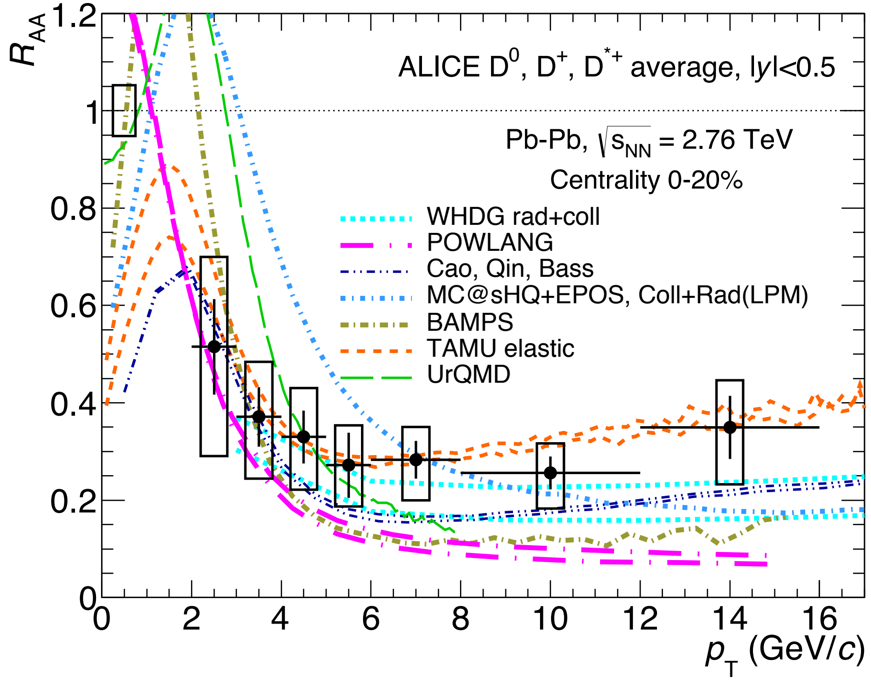
Enhancement at mid- and backward rapidity possibly due to hydrodynamics?

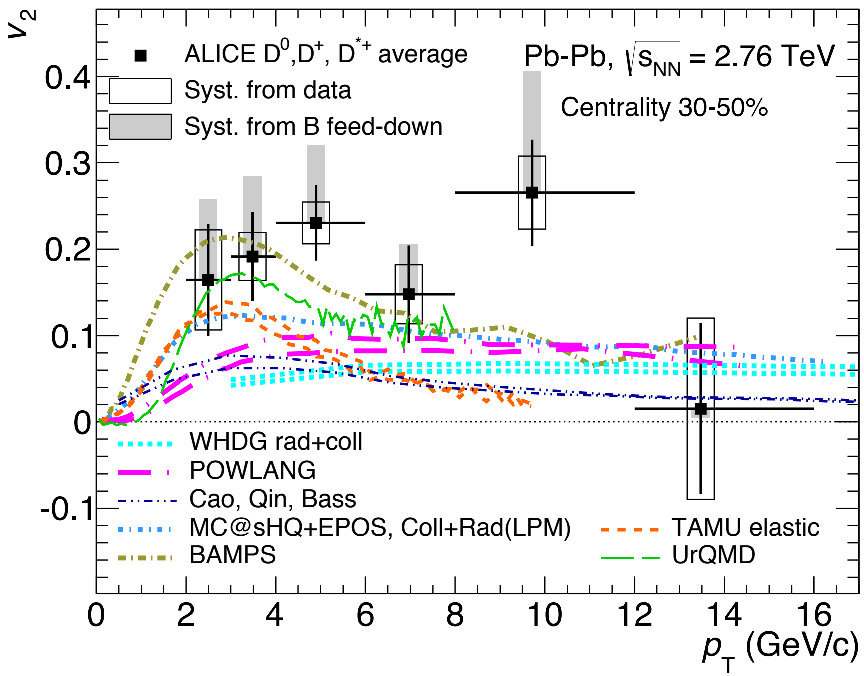
でも何故RHICだけ？チャームだけだから？

Which is which?
Phenomenology at AA collisions

Results vs experimental data

7グループの計算。依然としてR_AAとv2の両方を説明するのは難しい。

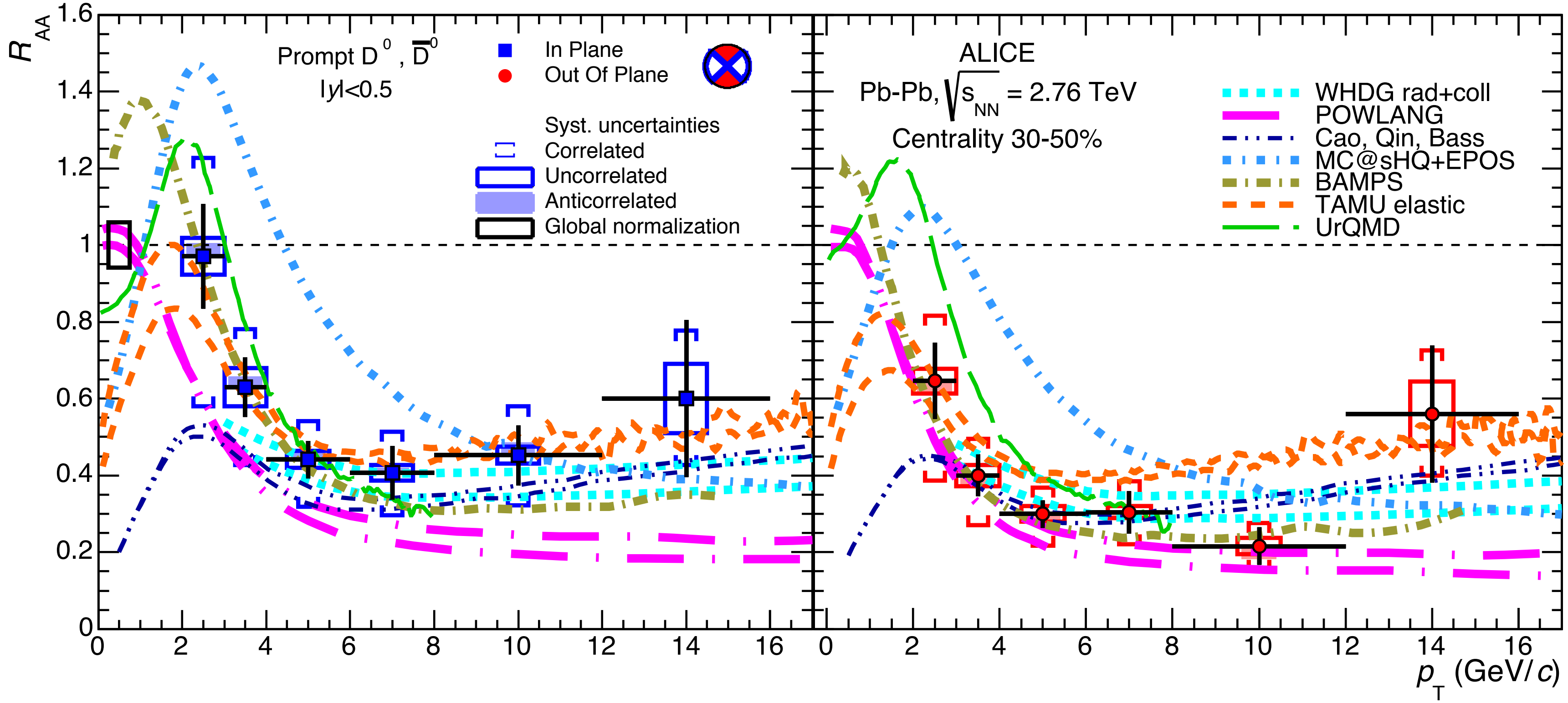




ALICE data so far cover a higher-p_T region

- Models are challenged to reproduce both R_{AA} and v_2

Results vs experimental data

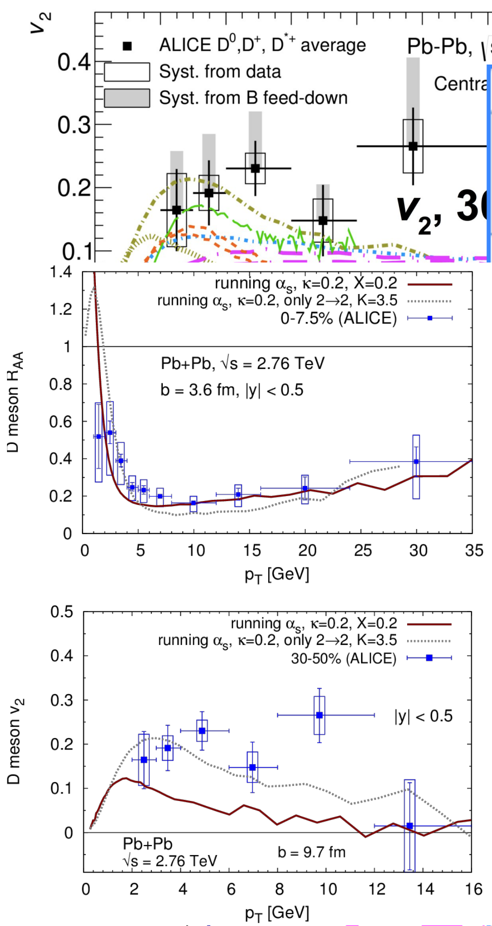


ALICE data so far cover a higher-p_T region

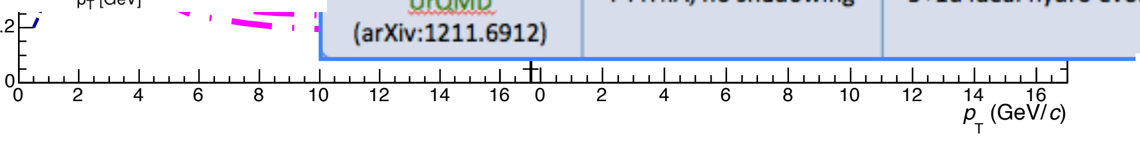
- Models are challenged to reproduce both R_{AA} and v_2
- R_{AA} vs EP allows the study of *path-length* dependence of energy-loss

Observables constraining models

7グループの違い。



	HQ production	Medium Modeling	Heavy quarks interactions	Hadronization
WHDG (AIP Conf Proc. 1441 (2012) 889	FONLL, no shadowing	Glauber model collision geometry, no hydro evolution	radiative + collisional energy loss	fragmentation
POWLANG (J. Phys. G 38 (2011) 124144)	POWEG (NLO) + EPS09 shadowing	2+1d expanding medium with viscos hydro evolution	HQ transport (Langevin) + collisional energy loss	fragmentation
Cao, Quin, Bass (Phys Rev C 88 (2013) 044907)	LO pQCD + EPS09 shadowing	2+1d expanding medium with viscous hydro evolution	HQ transport (Langevin) + quasi elastic scattering + radiative energy loss	recombination + fragmentation
MC@sHQ+EPOS2 (Phys Rev C 89 (2014) 014905)	FONLL, no shadowing	3+1d fluid dynamical expansion (EPOS)	HQ transport (Boltzmann) + radiative + collisional energy loss.	recombination + fragmentation
BAMPS (Phys Lett B 717 (2012) 430)	MC@NLO, no shadowing	3+1d fully dynamic parton transport model	HQ transport (Boltzmann) + collisional energy loss (w/ & w/o radiative)	fragmentation
TAMU elastic (arXiv:1401.3817)	FONLL + EPS09 shadowing	transport + 3+1d ideal hydro evolution	HQ transport (Langevin) + collisional energy loss + diffusion in hadronic phase	recombination + fragmentation
UrQMD (arXiv:1211.6912)	PYTHIA, no shadowing	3+1d ideal hydro evolution	HQ transport (Langevin) + collisional energy loss	recombination + fragmentation



Summarized by Davide Caffarri

- TAMU elastic: arXiv:1401.3817
- Djordjevic: arXiv:1307.4098
- Cao, Qin, Bass: PRC 88 (2013) 044907
- WHDG rad+coll: Nucl. Phys. A 872 (2011) 265
- MC@sHQ+EPOS: PRC 89 (2014) 014905
- Vitev, rad+dissoc: PRC 80 (2009) 054902
- POWLANG: JPG 38 (2011) 124144
- BAMPS: PLB 717 (2012) 430

Various observables provide constraints for the models

Is charm quark heavy enough?

Transport theory: the Boltzmann equation

Time evolution of HQ phase-space distribution $f_Q(t,\mathbf{x},\mathbf{p})$[3]:

$$\frac{d}{dt}f_Q(t,\mathbf{x},\mathbf{p}) = C[f_Q]$$

- Total derivative along particle trajectory

$$\frac{d}{dt} \equiv \frac{\partial}{\partial t} + \mathbf{v}\frac{\partial}{\partial \mathbf{x}} + \mathbf{F}\frac{\partial}{\partial \mathbf{p}}$$

Neglecting $\mathbf{x}$-dependence and mean fields: $\partial_t f_Q(t,\mathbf{p}) = C[f_Q]$

- Collision integral:

$$C[f_Q] = \int d\mathbf{k}[\underbrace{w(\mathbf{p}+\mathbf{k},\mathbf{k})f_Q(\mathbf{p}+\mathbf{k})}_{\text{gain term}} - \underbrace{w(\mathbf{p},\mathbf{k})f_Q(\mathbf{p})}_{\text{loss term}}]$$

$w(\mathbf{p},\mathbf{k})$: HQ transition rate $\mathbf{p} \to \mathbf{p}-\mathbf{k}$

運動量変化 << HQの運動量

[3] Approach implemented in codes like BAMPS (J. Uphoff talk at this conf.)

From Boltzmann to Fokker-Planck

Expanding the collision integral for *small momentum exchange*[4] (Landau)

$$C[f_Q] \approx \int d\mathbf{k} \left[k^i \frac{\partial}{\partial p^i} + \frac{1}{2} k^i k^j \frac{\partial^2}{\partial p^i \partial p^j} \right] [w(\mathbf{p}, \mathbf{k}) f_Q(t, \mathbf{p})]$$

The Boltzmann equation reduces to the *Fokker-Planck equation* (approx. to be quantitatively tested!)

$$\frac{\partial}{\partial t} f_Q(t, \mathbf{p}) = \frac{\partial}{\partial p^i} \left\{ A^i(\mathbf{p}) f_Q(t, \mathbf{p}) + \frac{\partial}{\partial p^j} [B^{ij}(\mathbf{p}) f_Q(t, \mathbf{p})] \right\}$$

where

$$A^i(\mathbf{p}) = \int d\mathbf{k}\, k^i w(\mathbf{p}, \mathbf{k}) \longrightarrow \underbrace{A^i(\mathbf{p}) = A(p)\, p^i}_{\text{friction}}$$

$$B^{ij}(\mathbf{p}) = \frac{1}{2} \int d\mathbf{k}\, k^i k^j w(\mathbf{p}, \mathbf{k}) \longrightarrow \underbrace{B^{ij}(\mathbf{p}) = \hat{p}^i \hat{p}^j B_0(p) + (\delta^{ij} - \hat{p}^i \hat{p}^j) B_1(p)}_{\text{momentum broadening}}$$

衝突項から、A,B0,B1が
独立に得られる

Problem reduced to the *evaluation of three transport coefficients*

[4] B. Svetitsky, PRD 37, 2484 (1988)

The relativistic Langevin equation

The Fokker-Planck equation can be recast into a form suitable to follow the dynamics of each individual quark: the Langevin equation

$$\frac{\Delta p^i}{\Delta t} = -\underbrace{\eta_D(p)p^i}_{\text{determ.}} + \underbrace{\xi^i(t)}_{\text{stochastic}},$$

A(p)は一般にはEinstein関係式を満たさないが、ここではA(p)を用いる。

with the properties of the noise encoded in

$$\langle \xi^i(\mathbf{p}_t)\xi^j(\mathbf{p}_{t'})\rangle = b^{ij}(\mathbf{p}_t)\frac{\delta_{tt'}}{\Delta t} \qquad b^{ij}(\mathbf{p}) \equiv \kappa_\parallel(p)\hat{p}^i\hat{p}^j + \kappa_\perp(p)(\delta^{ij} - \hat{p}^i\hat{p}^j)$$

Transport coefficients (to *derive from theory*):

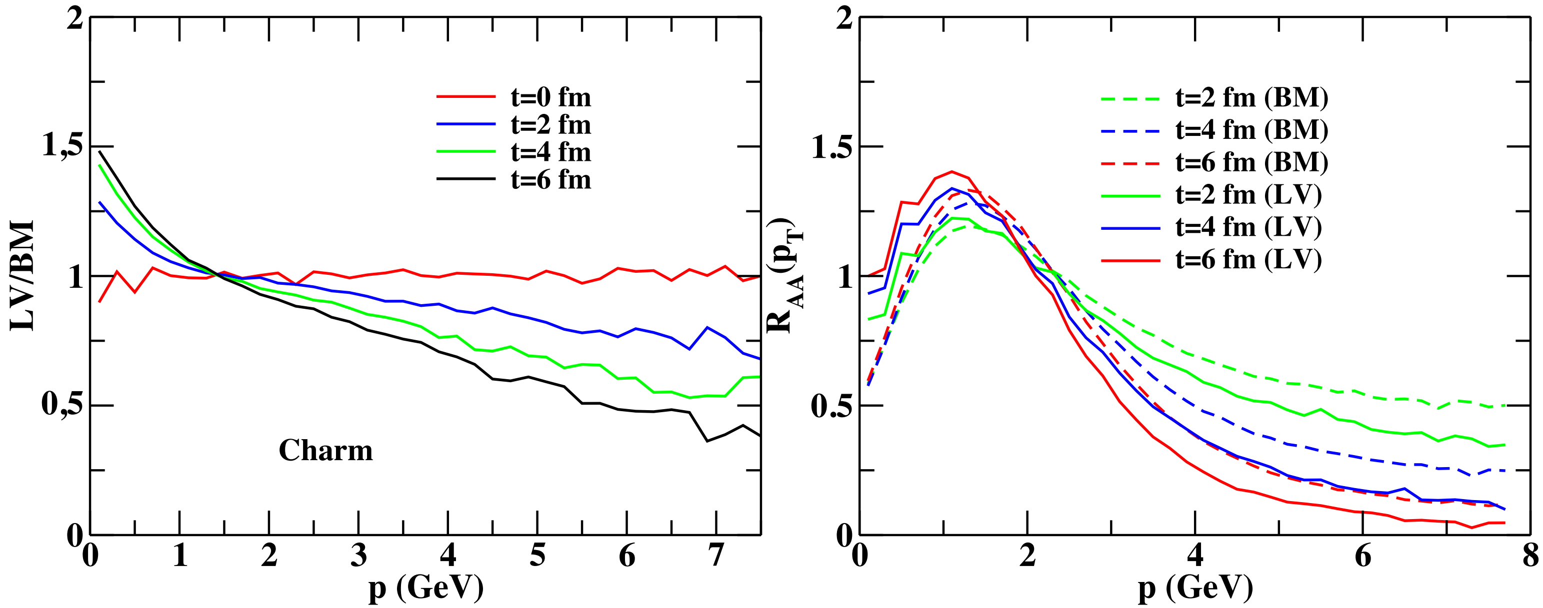
- *Momentum diffusion* $\kappa_\perp \equiv \frac{1}{2}\frac{\langle \Delta p_\perp^2 \rangle}{\Delta t}$ and $\kappa_\parallel \equiv \frac{\langle \Delta p_\parallel^2 \rangle}{\Delta t}$;
- *Friction* term (dependent on the discretization scheme!)

$$\eta_D{}^{\text{Ito}}(p) = \frac{\kappa_\parallel(p)}{2TE_p} - \frac{1}{E_p^2}\left[(1-v^2)\frac{\partial \kappa_\parallel(p)}{\partial v^2} + \frac{d-1}{2}\frac{\kappa_\parallel(p) - \kappa_\perp(p)}{v^2}\right]$$

fixed in order to assure approach to equilibrium (Einstein relation):

The Langevin/FP approach: a critical perspective

Although the Langevin approach is a very convenient numerical tool and allows one to establish a link between observables and transport coefficients derived from QCD... it is nevertheless based on a *soft-scattering expansion* of the collision integral $\mathcal{C}[f]$ truncated at second order (friction and diffusion terms), which may be *not always justified*, in particular for charm, possibly affecting the final R_{AA} (V. Greco *et al.*, arXiv:1312.6857 [nucl-th] and F. Scardina poster)



チャームは十分に重くない？

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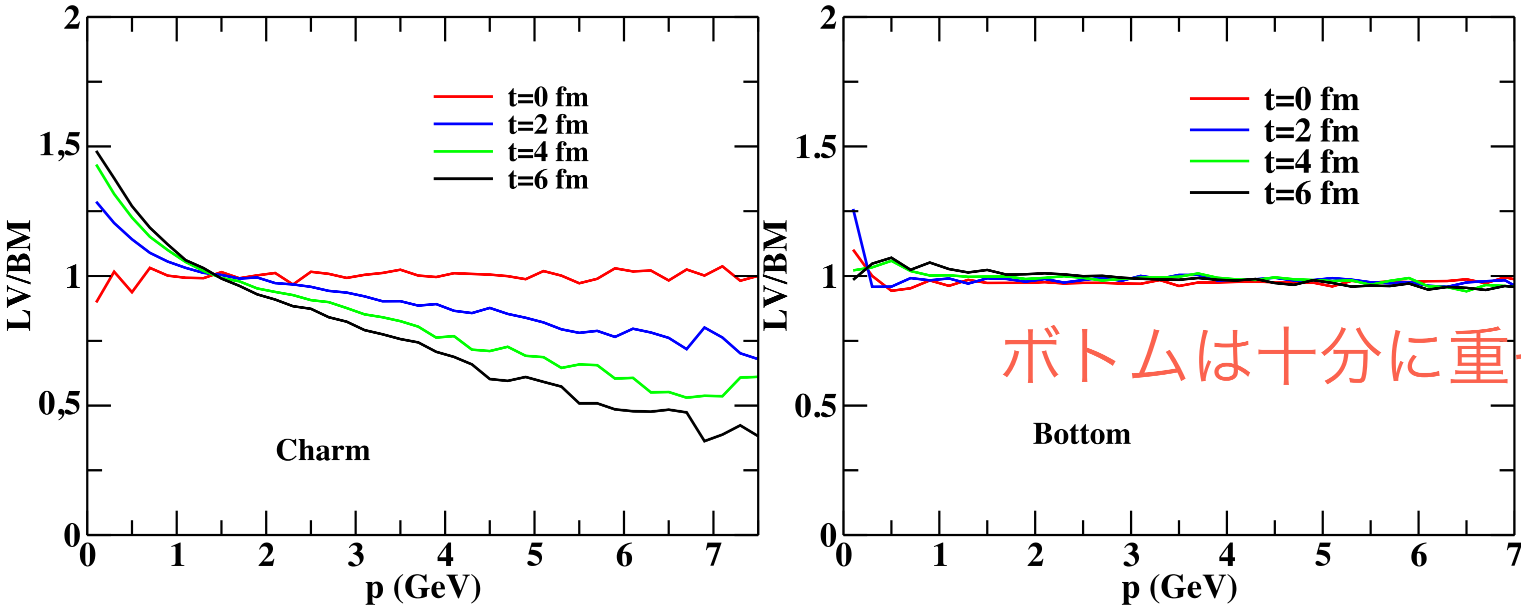


ボトムは十分に重そう。

For beauty on the other hand Langevin≡Boltzmann!

Transport coefficient on the lattice

Lattice-QCD transport coefficients: setup

Non perturbative information on HF transport coefficients can be obtained from lattice-QCD simulations, so far treating the HQ's as static ($M=\infty$) color sources placed in a thermal bath.
One consider the non-relativistic limit of the Langevin equation:

輸送係数を非摂動的に定義しよう！

$$\frac{dp^i}{dt} = -\eta_D p^i + \xi^i(t), \quad \text{with} \quad \langle \xi^i(t)\xi^j(t')\rangle = \delta^{ij}\delta(t-t')\kappa$$

運動量拡散係数は、"力"の時間相関で表される。

Hence, in the $p\to 0$ limit:

$$\kappa = \frac{1}{3}\int_{-\infty}^{+\infty} dt \langle \xi^i(t)\xi^i(0)\rangle_{\rm HQ} \approx \frac{1}{3}\int_{-\infty}^{+\infty} dt \underbrace{\langle F^i(t)F^i(0)\rangle_{\rm HQ}}_{\equiv D^>(t)}$$

In the static limit the force is due to the color-electric field:

$$\mathbf{F}(t) = g\int d\mathbf{x} Q^\dagger(t,\mathbf{x}) t^a Q(t,\mathbf{x})\mathbf{E}^a(t,\mathbf{x})$$

κ is then given by the $\omega\to 0$ limit of the *spectral density* $\sigma(\omega)$ of the above E-field correlator

$$\kappa \equiv \lim_{\omega\to 0}\frac{D^>(\omega)}{3} \equiv \lim_{\omega\to 0}\frac{1}{3}\frac{\sigma(\omega)}{1-e^{-\beta\omega}} \underset{\omega\to 0}{\sim} \frac{1}{3}\frac{T}{\omega}\sigma(\omega)$$

Lattice-QCD transport coefficients: results

The spectral function $\sigma(\omega)$ has to be reconstructed starting from the *euclidean electric-field correlator*

$$D_E(\tau) = -\frac{\langle \mathrm{Re}\,\mathrm{Tr}[U(\beta,\tau)gE^i(\tau,\mathbf{0})U(\tau,0)gE^i(0,\mathbf{0})]\rangle}{\langle \mathrm{Re}\,\mathrm{Tr}[U(\beta,0)]\rangle}$$

虚時間方向の電場相関

according to

$$D_E(\tau) = \int_0^{+\infty} \frac{d\omega}{2\pi} \frac{\cosh(\tau-\beta/2)}{\sinh(\beta\omega/2)}\sigma(\omega)$$

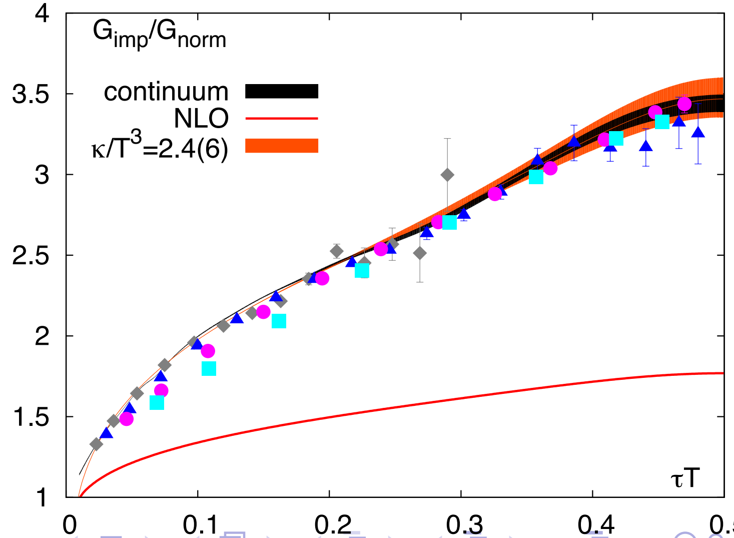
Y.A., Hatsuda, Hirano ('09)

One gets (D. Banerjee *et al.*, PRD 85 (2012) 014510; A. Francis *et al.*, PoS LATTICE2011 202 and arXiv:1311.3759 [hep-lat])

$$\kappa/T^3 \approx 2.4(6) \ (\textit{quenched QCD},\ \textit{cont.lim.})$$

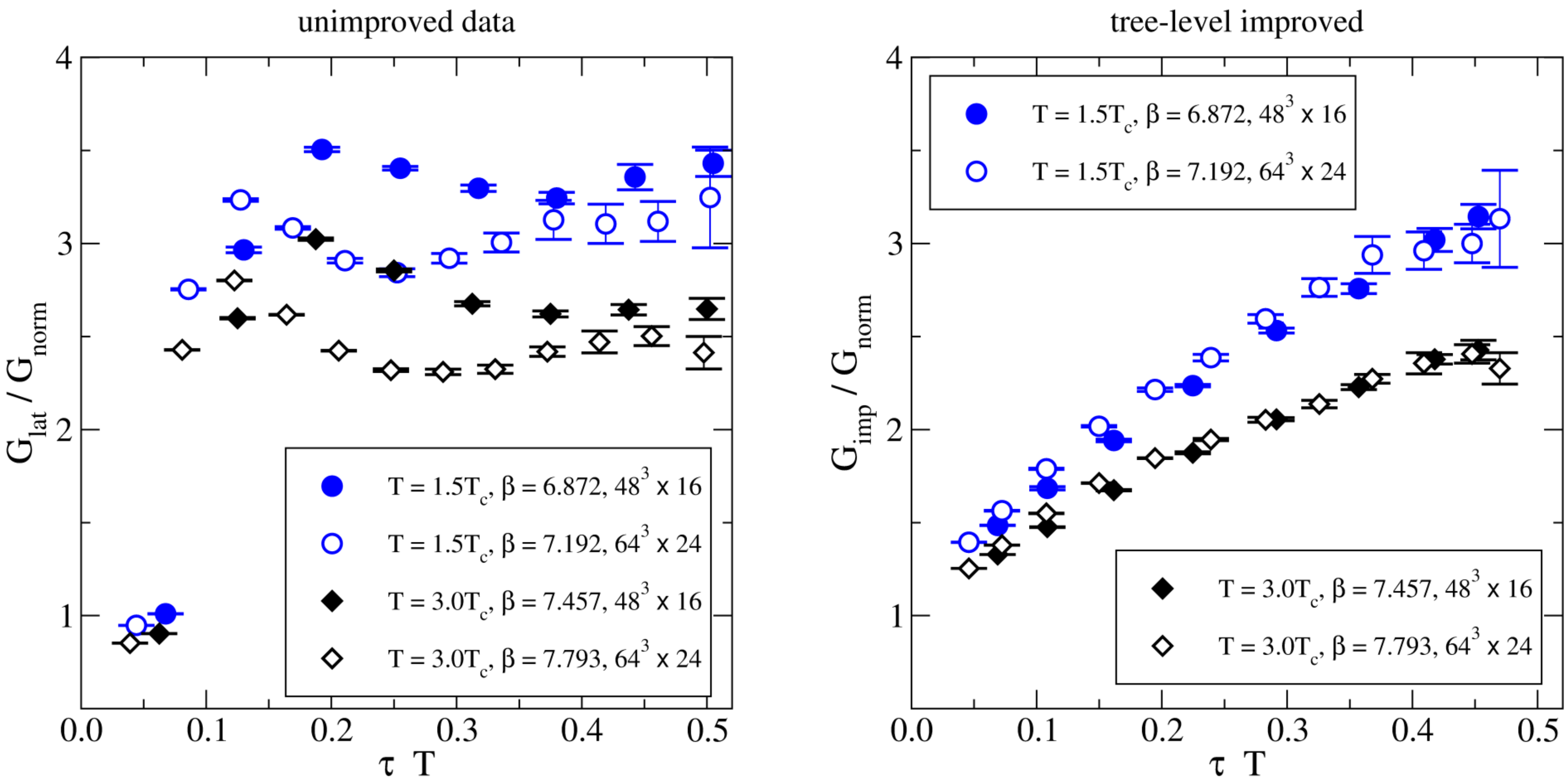
~3-5 times larger then the perturbative result (W.M. Alberico *et al*, EPJC 73 (2013) 2481). Challenge: approaching the continuum limit in full QCD (see Kaczmarek talk)!

κ/T^3 ~ 2.4(6)は現象論から見積もられた値(~4)に比較的近い。



Heavy Quark Momentum Diffusion Constant – Tree-Level Improvement

[A.Francis,OK,M.Laine,J.Langelage, arXiv:1109.3941 and arXiv:1311.3759]



lattice cut-off effects visible at small separations (left figure)

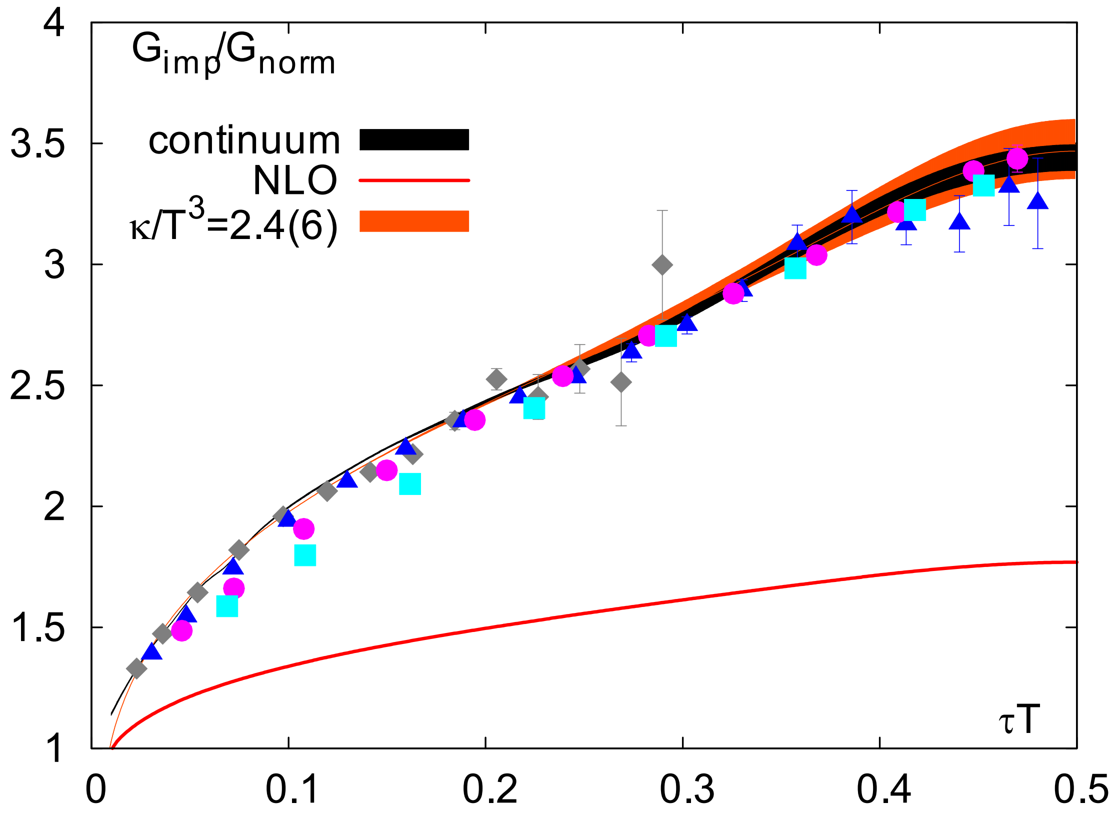
→ **tree-level improvement** (right figure) to reduce discretization effects

$$G^{\mathrm{LO}}_{\mathrm{cont}}(\overline{\tau T}) = G^{\mathrm{LO}}_{\mathrm{lat}}(\tau T)$$

連続極限への補正を横軸方向で考える。

leads to an effective reduction of cut-off effect for all τT

Heavy Quark Momentum Diffusion Constant – Model Spectral Function



result of the fit to $\rho_{model}(\omega)$

with three parameters: κ,A,B

連続極限の虚時間相関関数から κを読み取る。スペクトル関数の形を仮定。

Model spectral function: transport contribution + NLO + correction

$$\rho_{\rm model}(\omega) \equiv \max\left\{A\rho_{\rm NLO}(\omega) + B\omega^3, \frac{\omega\kappa}{2T}\right\}$$

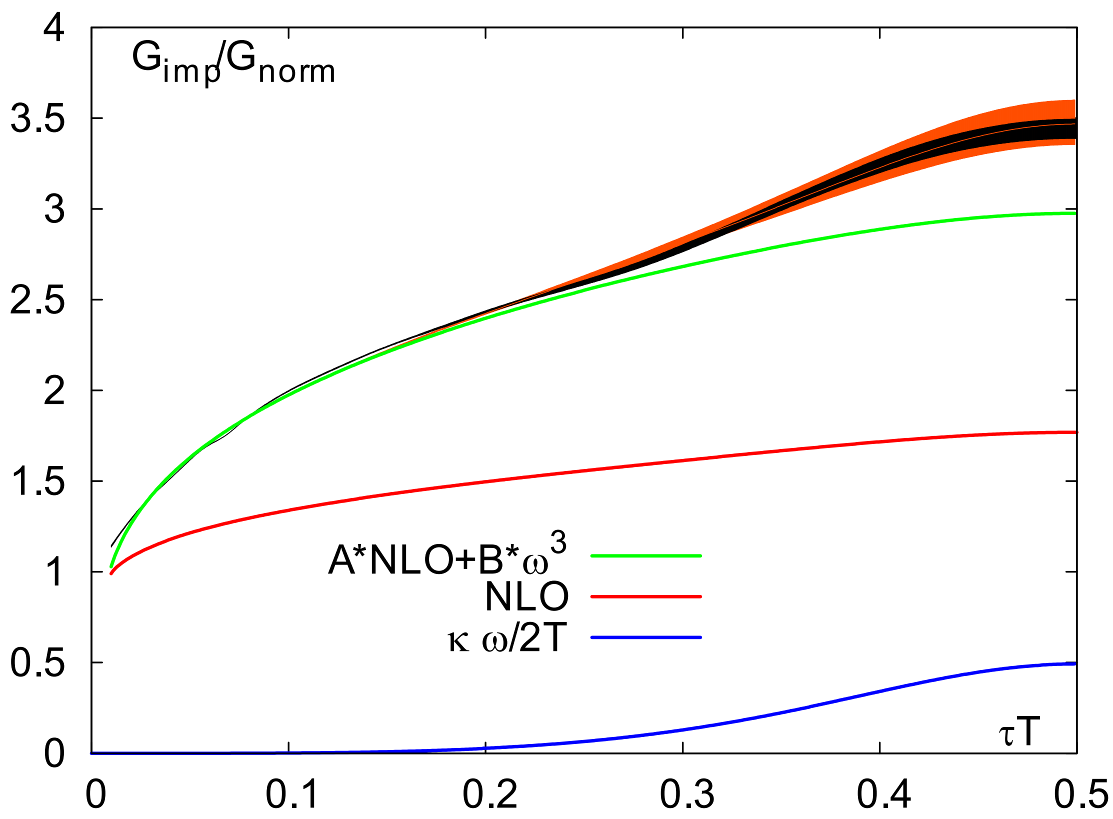
$$G_{\rm model}(\tau) \equiv \int_0^\infty \frac{{\rm d}\omega}{\pi}\rho_{\rm model}(\omega)\frac{\cosh\left(\frac{1}{2}-\tau T\right)\frac{\omega}{T}}{\sinh\frac{\omega}{2T}}$$

used to fit the continuum extrapolated data

→ **first continuum estimate of κ :**
(still preliminary)

$$\kappa/T^3 = \lim_{\omega\to 0}\frac{2T\rho_{\rm E}(\omega)}{\omega} \simeq 2.4(6)$$

Heavy Quark Momentum Diffusion Constant – Model Spectral Function



result of the fit to $\rho_{model}(\omega)$

A $\rho_{NLO}(\omega)$ + B w^3

NLO perturbation theory

$\frac{\omega\kappa}{2T}$ small but relevant contribution at $\tau T > 0.2$!

Model spectral function: transport contribution + NLO + correction

$$\rho_{\rm model}(\omega) \equiv \max\left\{A\rho_{\rm NLO}(\omega) + B\omega^3, \frac{\omega\kappa}{2T}\right\} \qquad G_{\rm model}(\tau) \equiv \int_0^\infty \frac{d\omega}{\pi}\rho_{\rm model}(\omega)\frac{\cosh\left(\frac{1}{2}-\tau T\right)\frac{\omega}{T}}{\sinh\frac{\omega}{2T}}$$

used to fit the continuum extrapolated data

→ **first continuum estimate of κ : (still preliminary)**

$$\kappa/T^3 = \lim_{\omega\to 0}\frac{2T\rho_{\rm E}(\omega)}{\omega} \simeq 2.4(6)$$

Quarkonium

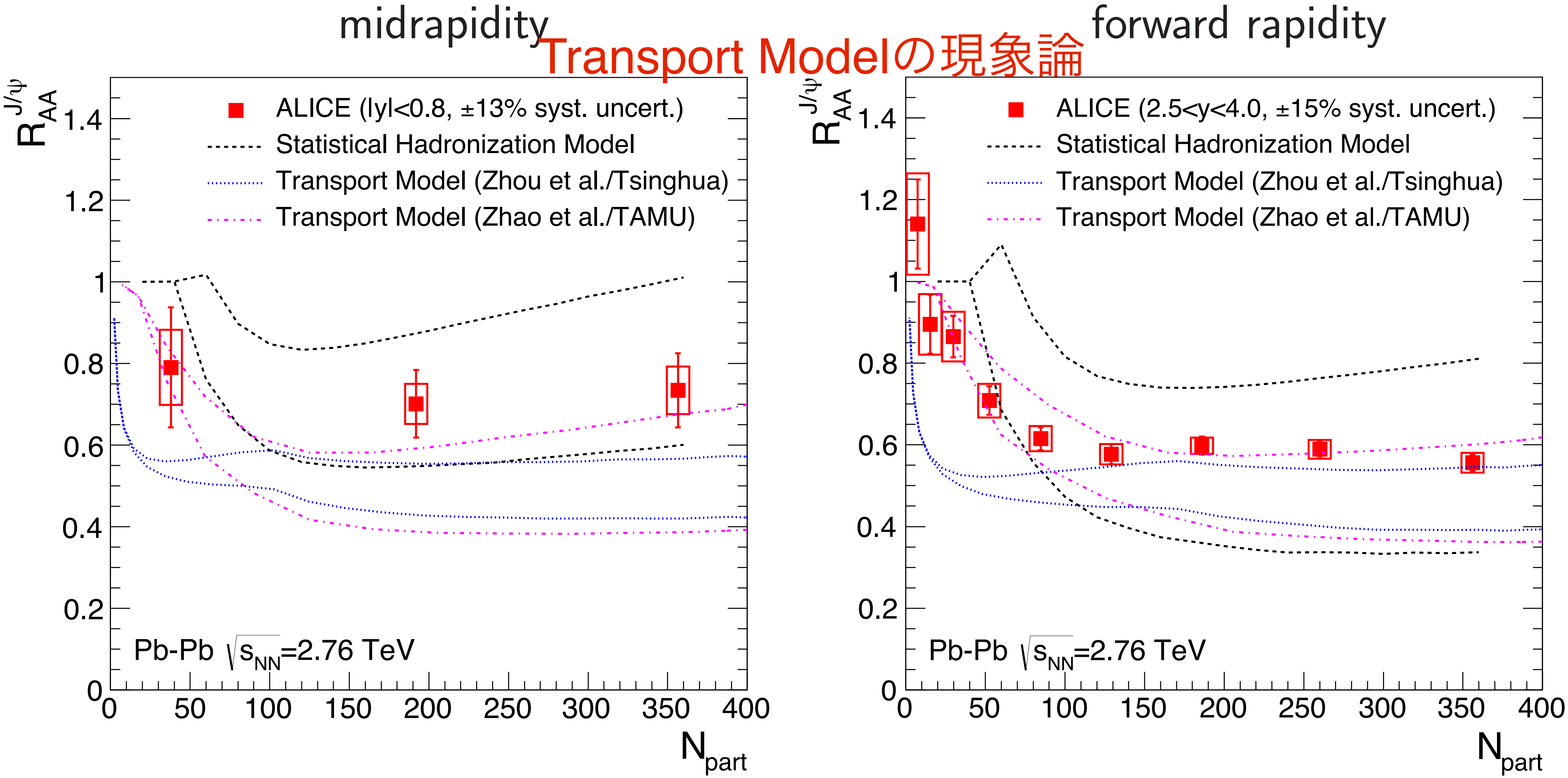
- Talk slides from
  - Andronic (plenary)
  - Zhuang (parallel)
  - Song (parallel)
  - Kopeliovich (parallel)
- Topics
  - Phenomenology at AA collisions
  - Transport model
  - QCD sum rule and heavy quark potential
  - Quarkonium at high pT

Phenomenology at AA collisions

Model comparisons for the LHC

A.Andronic@GSI.de

Statistical Hadronization Modelと
Transport Modelの現象論

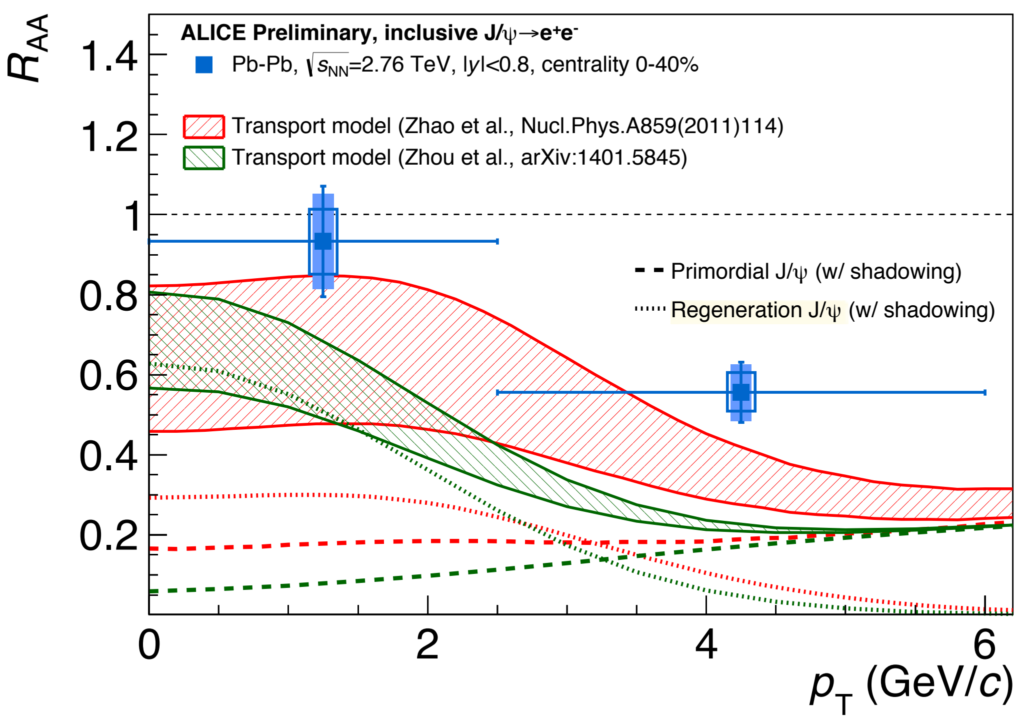


Both model categories reproduce the data ...$\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y$ values rather different:
midrapidity: Stat. Hadr.: 0.3-0.4 mb
Transport: 0.5-0.75 mb (TAMU), 0.65-0.8 mb (Tsinghua)

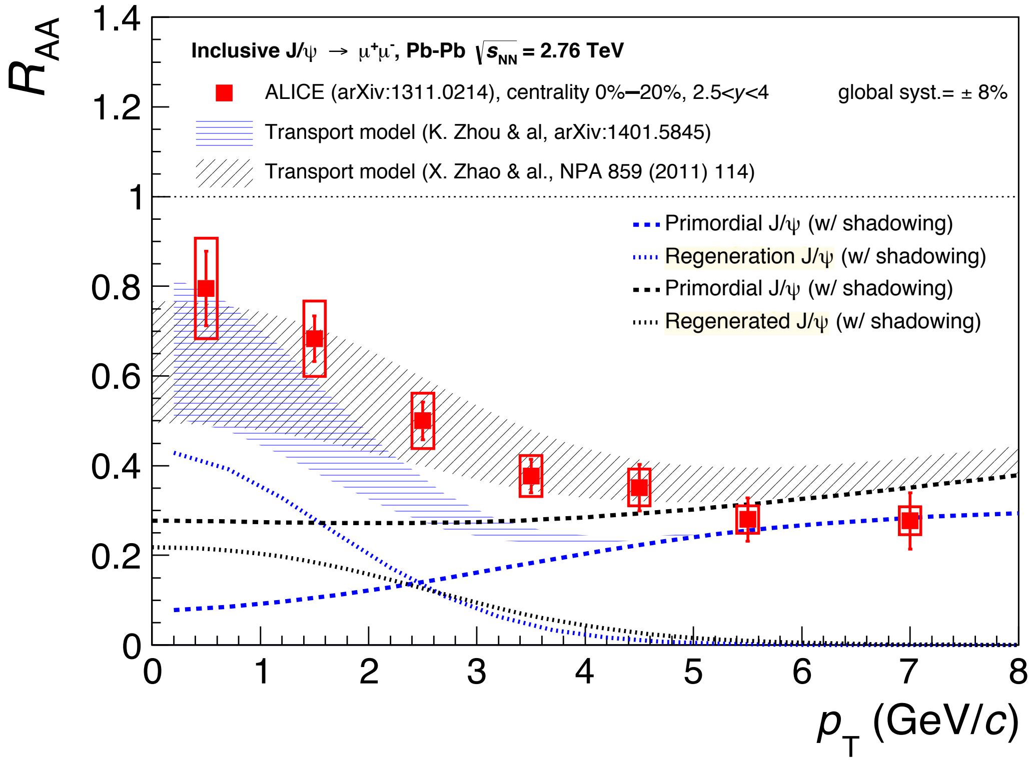
J/ψ vs. p_T - data and models

A.Andronic@GSI.de

midrapidity



forward rapidity

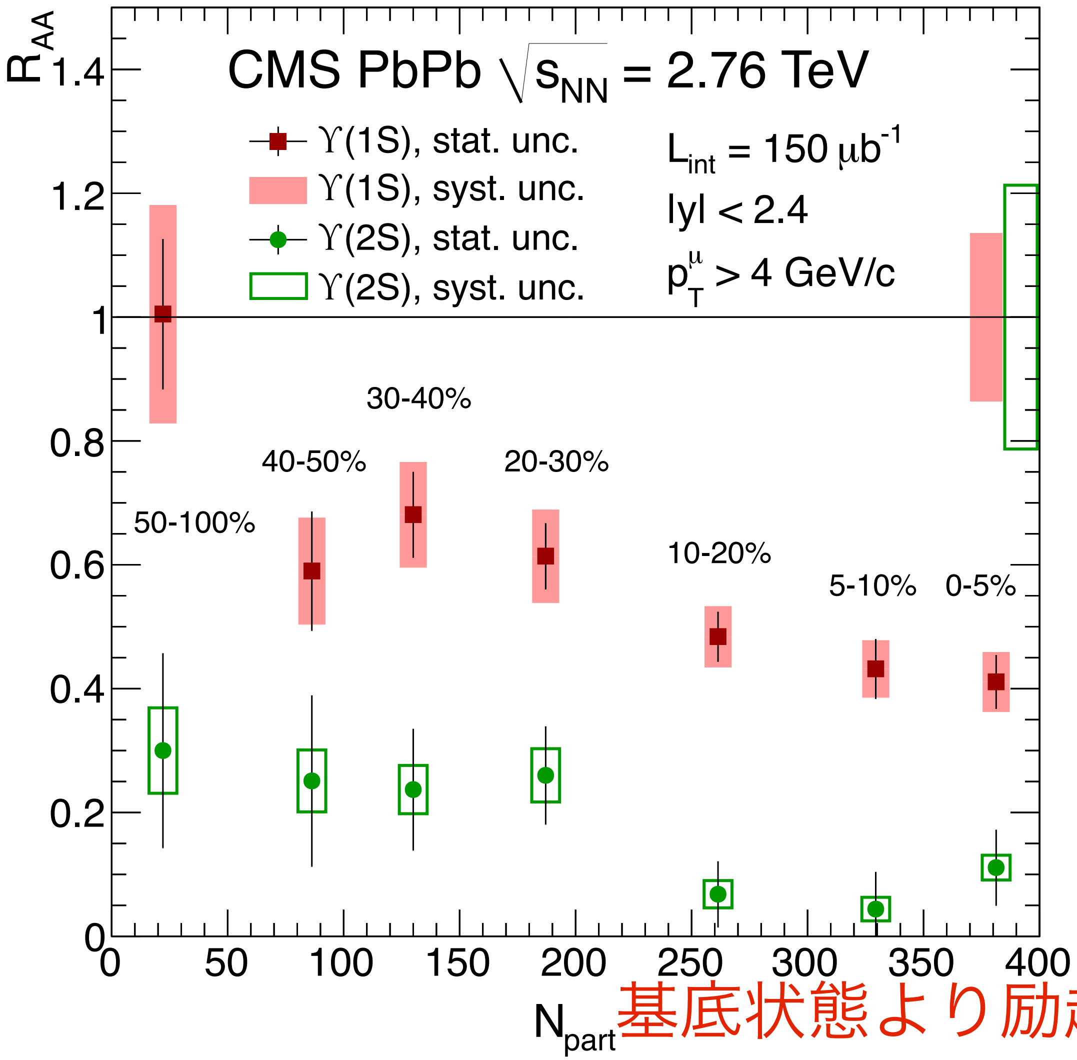


(re)generation models describe the LHC data well ...with a healthy fraction of J/ψ newly produced

ALICE, arXiv:1311.0214 (& prelim., Book, HF 4)

LHCでのlow pTのJ/Ψは、
regenerationが主な生成メカニズム。

A.Andronic@GSI.de



CMS, PRL 109 (2012) 222301

interpreted as effect of (almost:) full dissoc. of $\Upsilon(2S)$, $\Upsilon(3S)$, χ_b

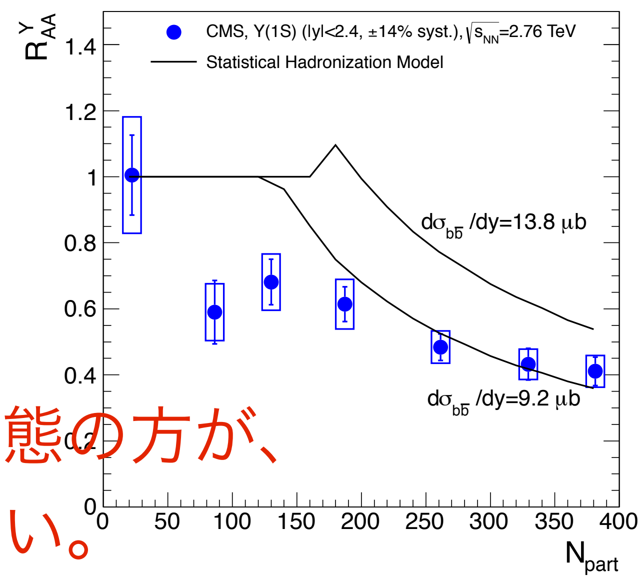
Transport models:

Emerick et al./TAMU, EPJA 48 (2012) 72

Zhuang, HF 6

(re)gen. component small ($\lesssim$10%),

Stat. Hadr. model



基底状態より励起状態の方が、
媒質効果を受けやすい。

Bottomonium at RHIC

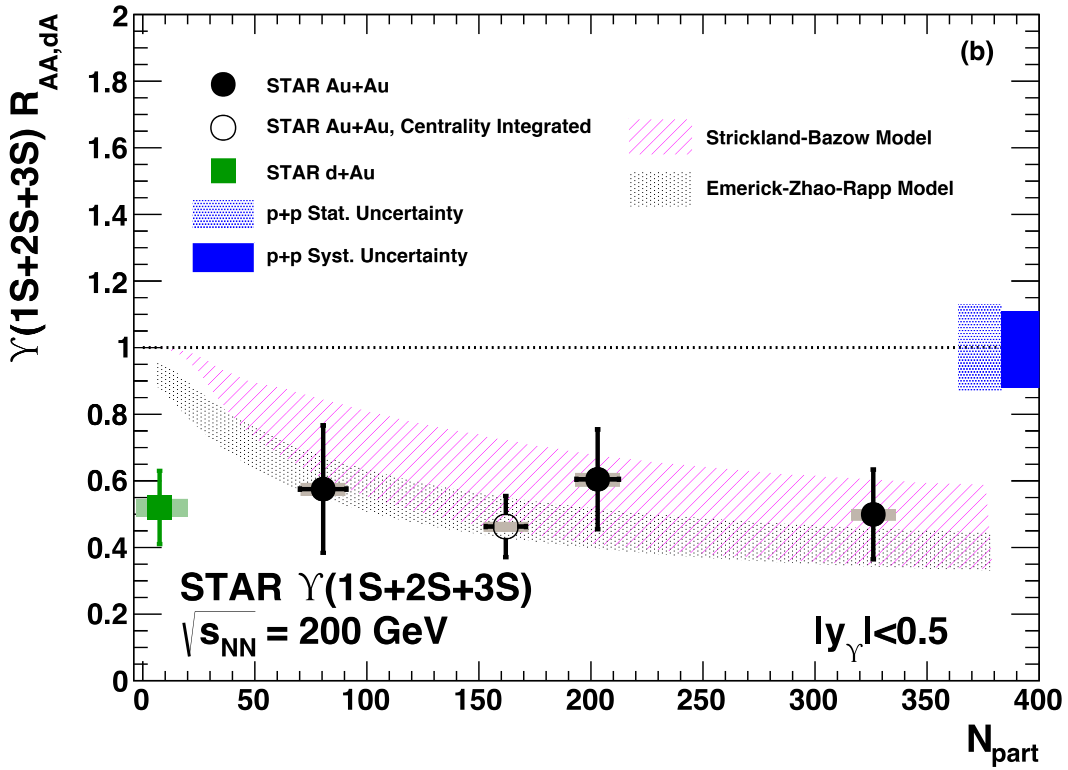
A.Andronic@GSI.de

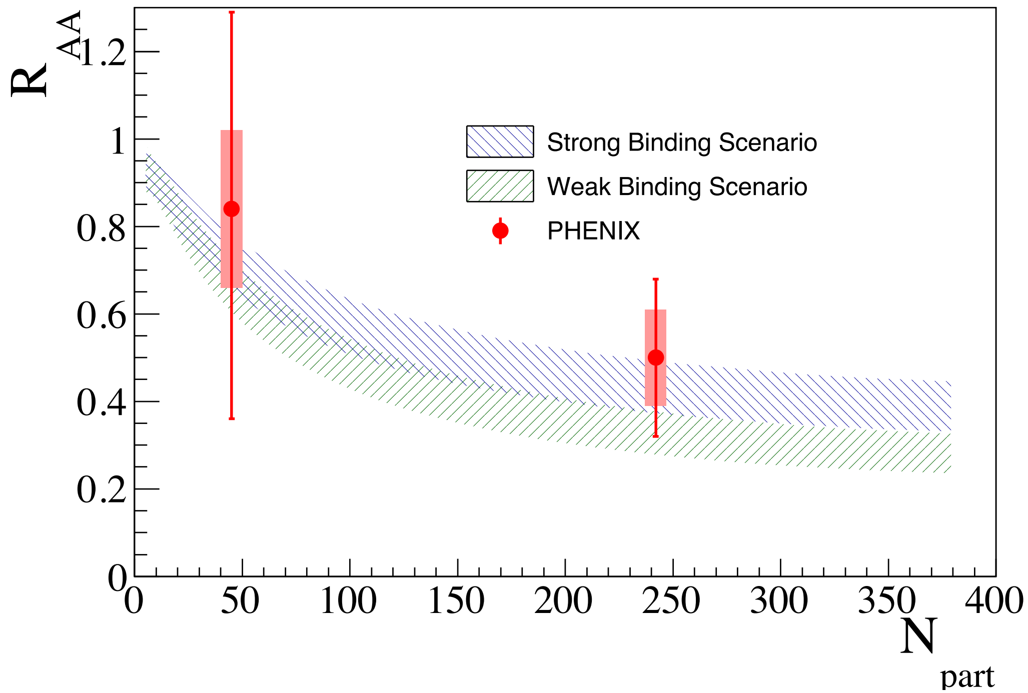
STAR, arXiv:1312.3675

(Zha, HF 4)

PHENIX, arXiv:1404.2246

(da Silva, HF 6)





複素ポテンシャルをそのまま使った計算もある。

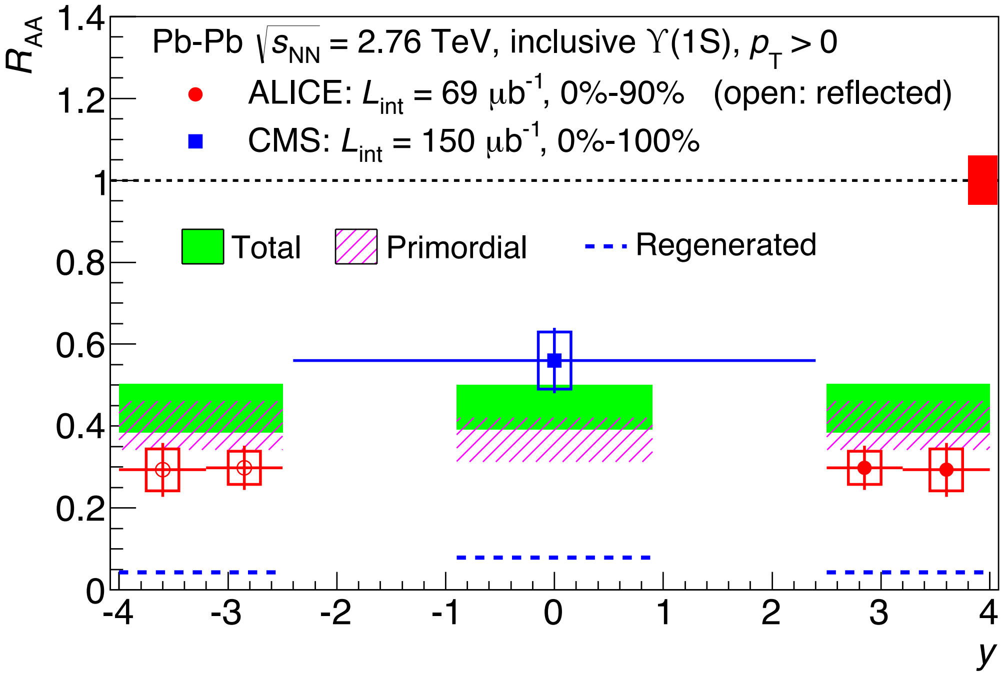
Emerick et al./TAMU, EPJA 48 (2012) 72; Strickland, Bazow, NPA 879 (2012) 25

is the charmonium story SPS–RHIC repeating with bottomonium RHIC–LHC?

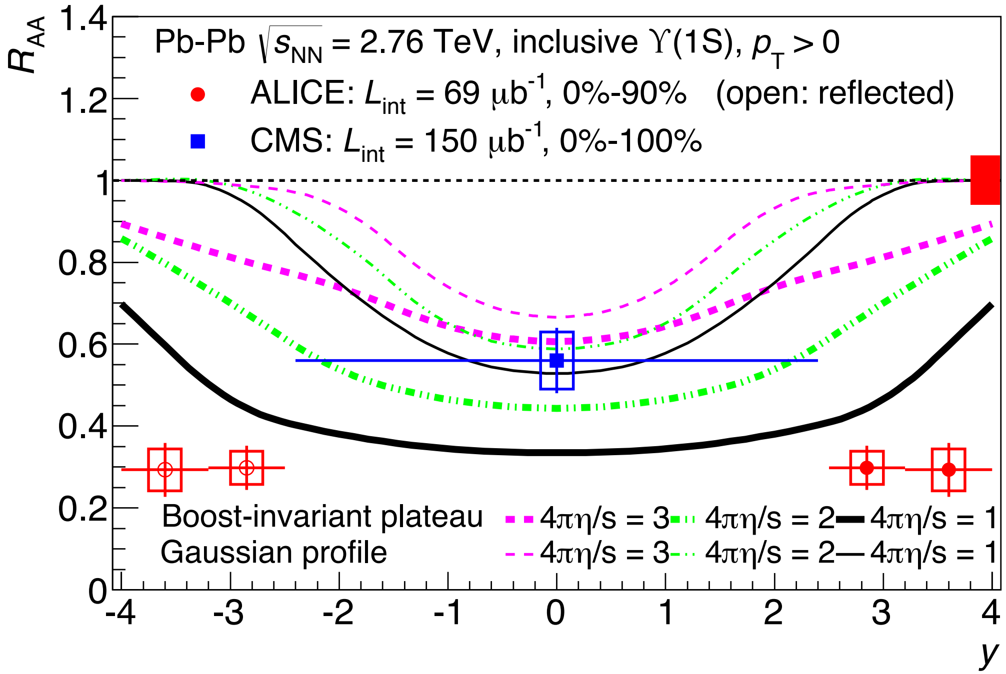
More bottomonium at the LHC

A.Andronic@GSI.de

ALICE arXiv:1405.4493 (Castillo, talk HF 6)



Emerick et al./TAMU, EPJA 48 (2012) 72



Strickland, Bazow, NPA 879 (2012) 25

no model does very well

ラピディティー分布は、どのモデルも説明できていない。

...recall the shocking R_{AA} vs. y of J/ψ? (PHENIX, 2006)

Transport model

A Dynamic Transport Approach for Quarkonia in HIC

QuarkoniumのTransportの模型

- **QGP evolution**

$$\partial_\mu T^{\mu\nu} = 0, \quad \partial_\mu n^\mu = 0$$ **+ equation of state**

- **quarkonium motion** $(\Psi = J/\psi,\ \psi',\ \chi_c)$

$$\partial f_\Psi / \partial \tau + \mathbf{v}_\Psi \cdot \nabla f_\Psi = -\alpha_\Psi f_\Psi + \beta_\Psi .$$

$$\alpha_\Psi(\mathbf{p}_t, \mathbf{x}_t, \tau|\mathbf{b}) = \frac{1}{2E_\Psi} \int \frac{d^3\mathbf{p}_g}{(2\pi)^3 2E_g} W_{g\Psi}^{c\bar{c}}(s) f_g(\mathbf{p}_g, \mathbf{x}_t, \tau) \Theta\left(T(\mathbf{x}_t, \tau|\mathbf{b}) - T_c\right),$$

$$\beta_\Psi(\mathbf{p}_t, \mathbf{x}_t, \tau|\mathbf{b}) = \frac{1}{2E_\Psi} \int \frac{d^3\mathbf{p}_g}{(2\pi)^3 2E_g} \frac{d^3\mathbf{p}_c}{(2\pi)^3 2E_c} \frac{d^3\mathbf{p}_{\bar{c}}}{(2\pi)^3 2E_{\bar{c}}} W_{c\bar{c}}^{g\Psi}(s) f_c(\mathbf{p}_c, \mathbf{x}_t, \tau|\mathbf{b}) f_{\bar{c}}(\mathbf{p}_{\bar{c}}, \mathbf{x}_t, \tau|\mathbf{b}) \times (2\pi)^4 \delta^{(4)}(p + p_g - p_c - p_{\bar{c}}) \Theta\left(T(\mathbf{x}_t, \tau|\mathbf{b}) - T_c\right),$$

gluon dissociation cross section by OPE and quarkonium size by potential model

$$\sigma(T) = \sigma(0) \langle r^2 \rangle (T) / \langle r^2 \rangle (0)$$

detailed balance

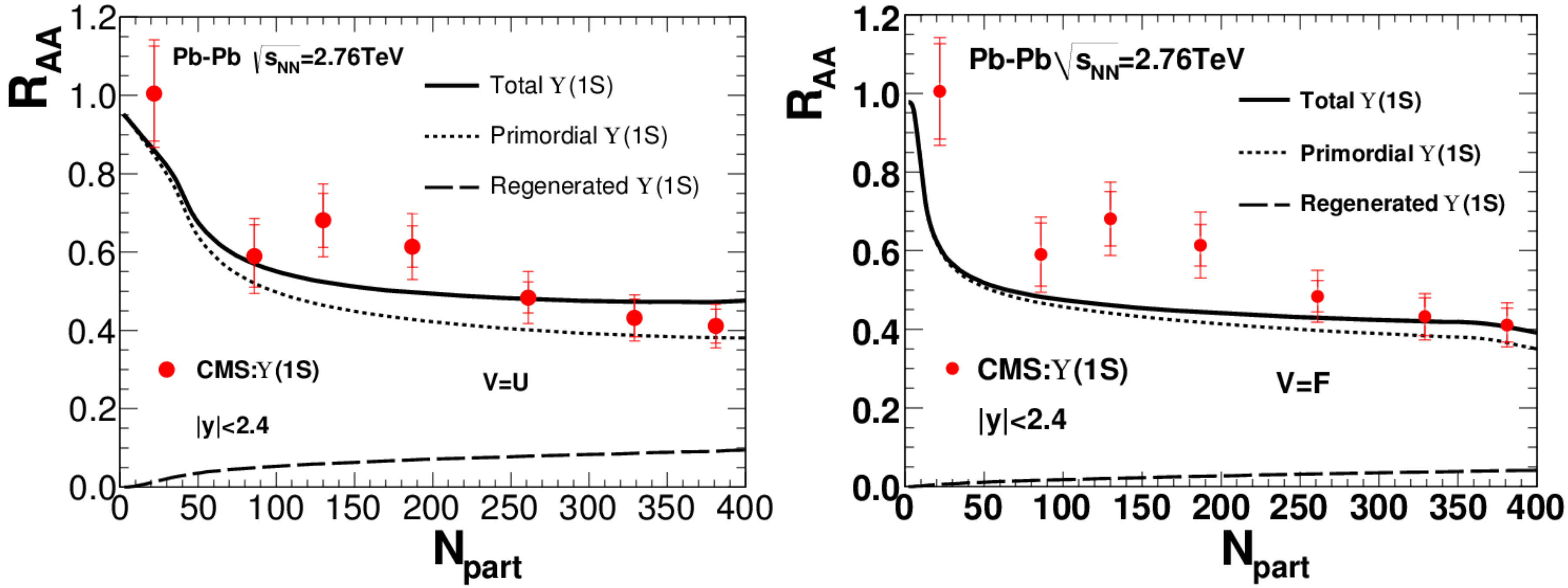
- ***cold medium effects (for instance, EKS98) modify not only the initial quarkonium distribution but also the regeneration!***

- ***assumption: thermalized gluon and heavy quark distributions***

HQの数が変われば、
regenerationの頻度も変わる。

（注）Bottomも熱平衡分布を仮定するのがどれくらい正しいのか？

Upsilon(1s) at mid rapidity



dσ(1s)/dy=40 nb (PYTHIA, CDF(1.8TeV) and CMS(7 TeV))
dσ(bb)/dy=20 ub (FONLL)
CMS data: NPA910, 91(2013)

反応率を計算するために、ポテンシャル（U or F）と束縛状態の波動関数が必要。

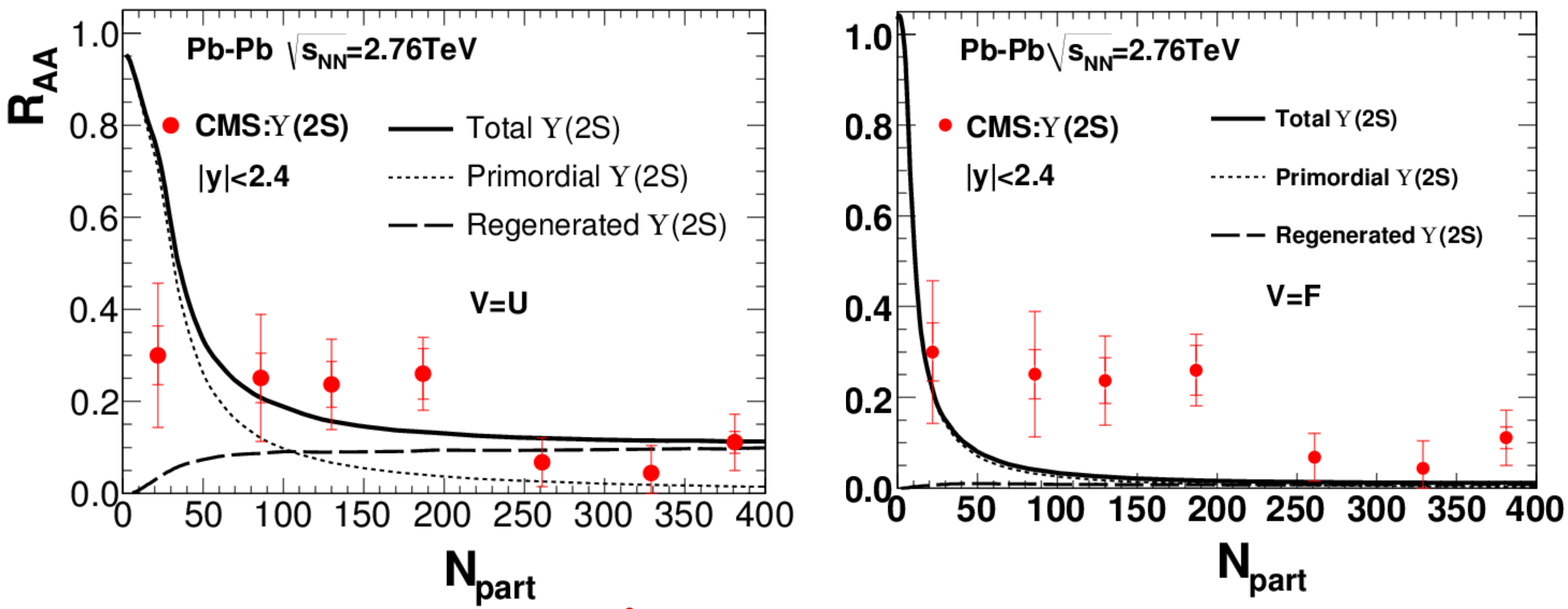
in central collisions:

1) T(2s)<T<T(1s) for both V=U and V=F, excited states are eaten up but ground state is not affected, R_AA=0.5;

2) small regeneration.

ground state is not sensitive to the hot medium !

Upsilon(2s) at mid rapidity



ポテンシャルは、UのほうがFより深いので。

in central collisions:

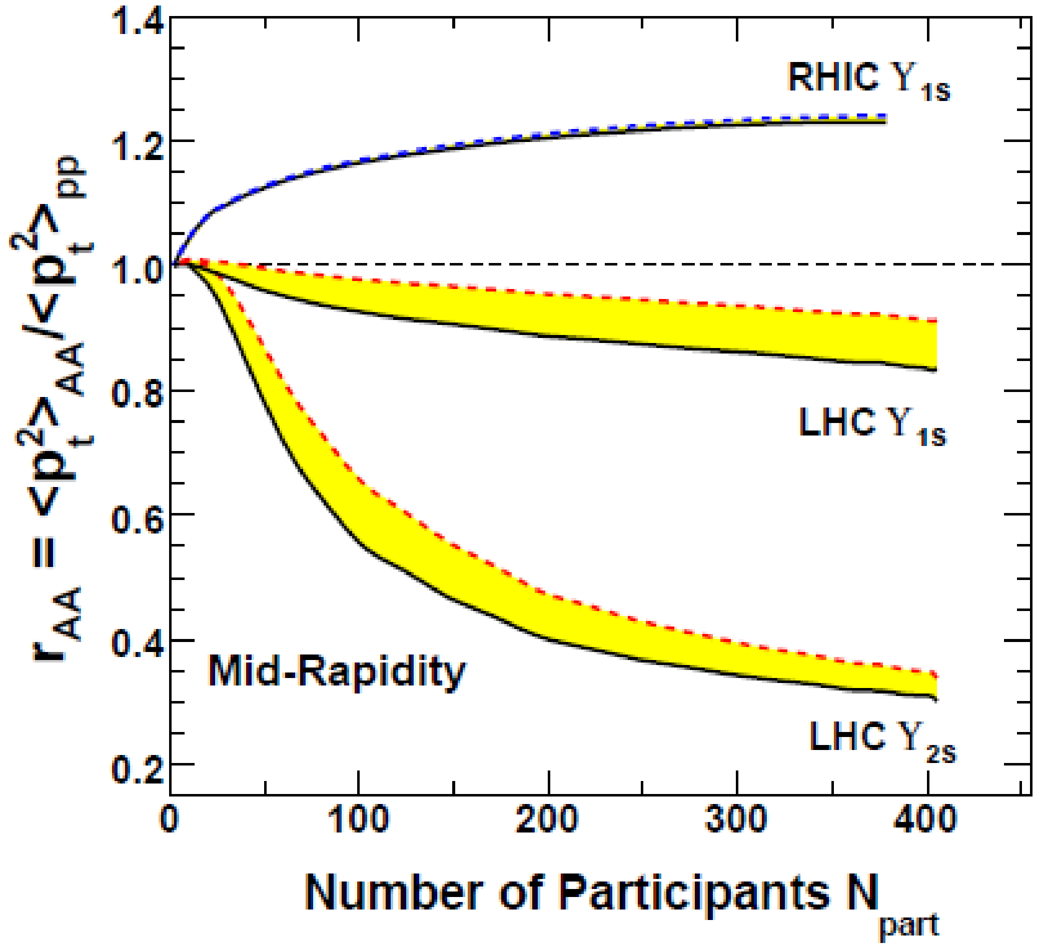
1) initial production is eaten up by the hot medium, the small regeneration becomes dominant!

2) for V=F, T(2s)~Tc, regenerated Upsilon(2s) is again eaten up by the medium !

3) the data favor V=U.

excited states are sensitive to the hot medium !

P_t Ratio (Upsilon)



the excited Upsilon states are sensitive to the hot medium !

QCD sum rule and heavy quark potential

Dispersion relation

左辺を有限温度のGluon凝縮で評価、

右辺はスペクトル関数：Quarkoniumの媒質中のダイナミクス

$$\mathrm{Re}\ \Pi(q^2) = \frac{1}{\pi}\int \frac{\mathrm{Im}\ \Pi(s)}{s-q^2} ds$$

- QCD parameters

$$m_c, \alpha_s,$$
$$\left\langle \frac{\alpha_s}{\pi} G^2 \right\rangle, \left\langle \frac{\alpha_s}{\pi} G^a_{\mu\alpha} G^{a\alpha}_{\nu} \right\rangle$$

- Physical parameters

$$m_{J/\psi}, \Gamma,$$
$$f_0 = \frac{12\pi}{m_{J/\psi}} |\psi(0)|^2$$

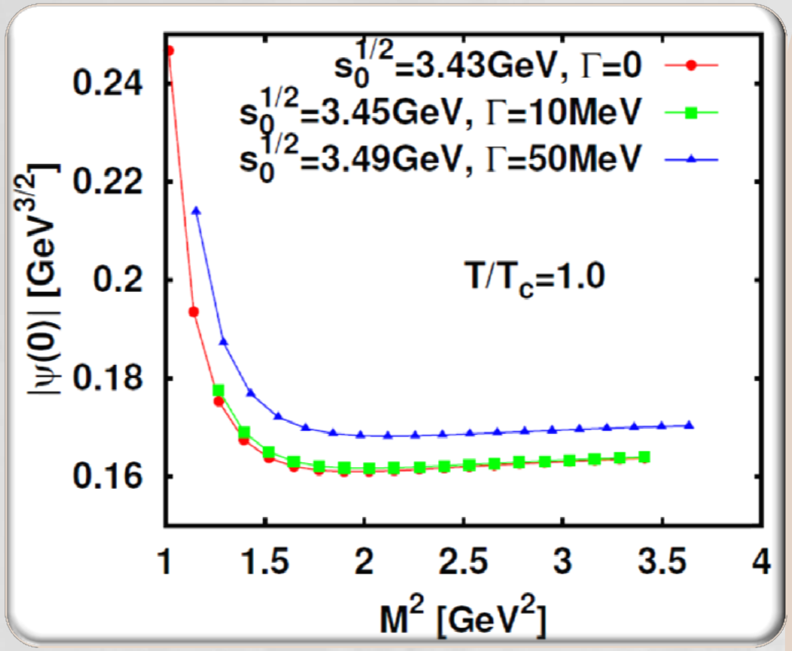
波動関数の原点

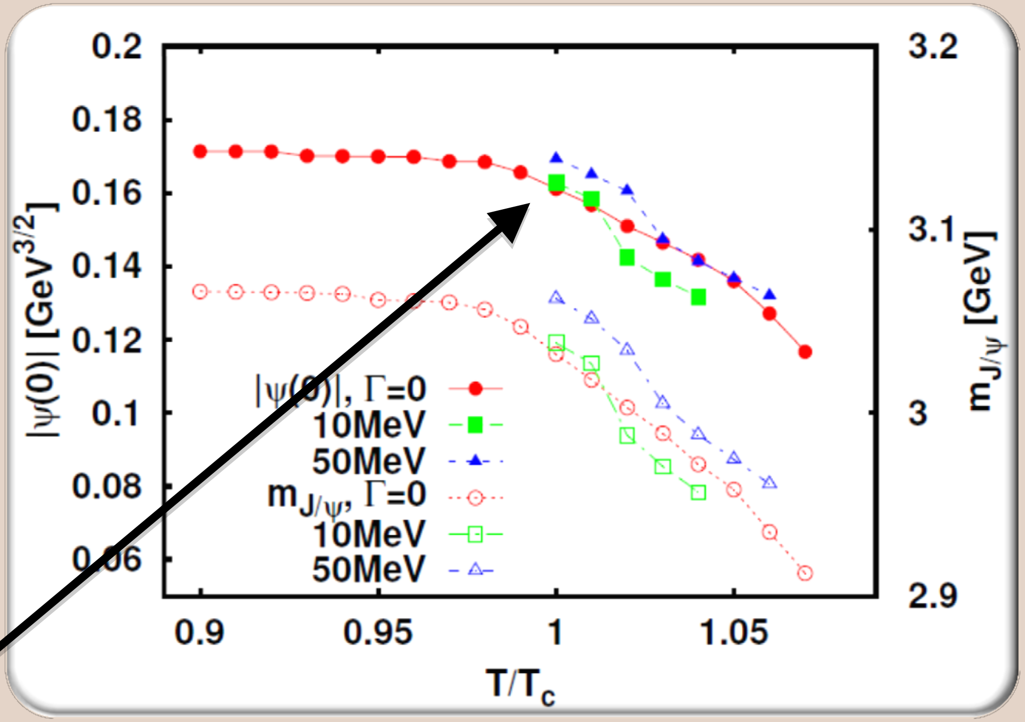
~QとQbarが対消滅する確率。

J/Ψ wavefunction |Ψ(0)|

波動関数の原点での値をポテンシャルモデルで計算。

$$f_0 = \frac{12\pi}{m_{J/\psi}} |\psi(0)|^2 = \exp\left[\frac{m_{J/\psi}^2(M^2)}{M^2}\right] \times [\Pi^{OPE}(M^2) - \Pi^{cont}(M^2; s_0)]$$



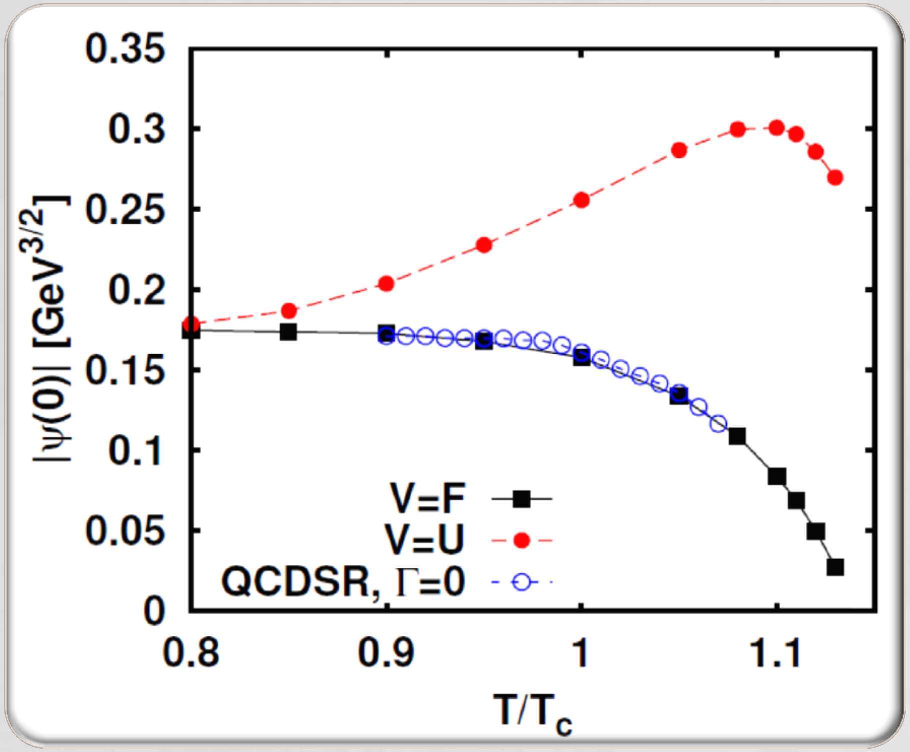


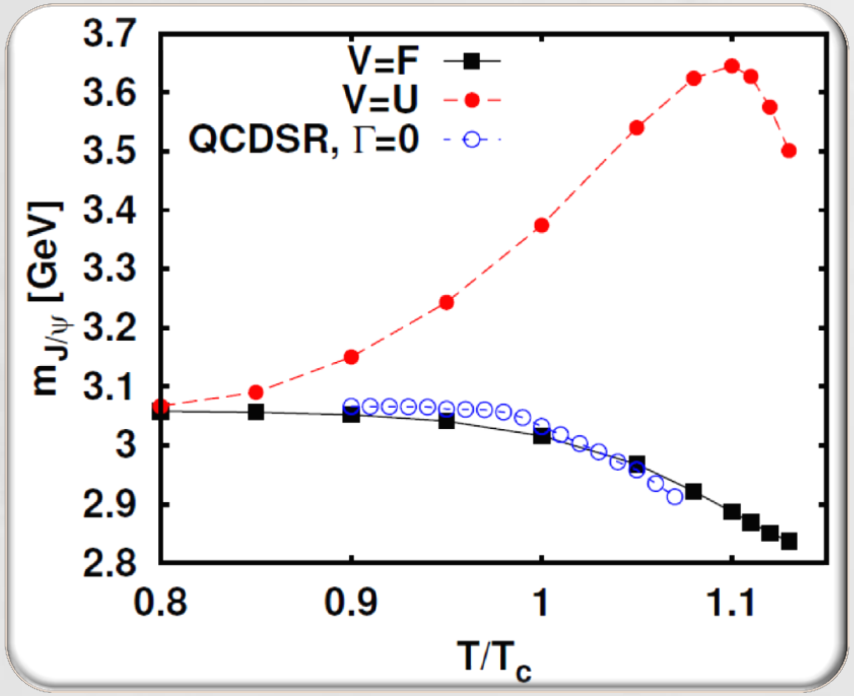
Borel windowでの値：

|Ψ(0)|~0.16-0.17@T=Tc

1. Both |Ψ(0)| and J/Ψ mass decrease with T
2. Width effect is small

5. Comparison of the results from QCD sum rule & Schrödinger equation





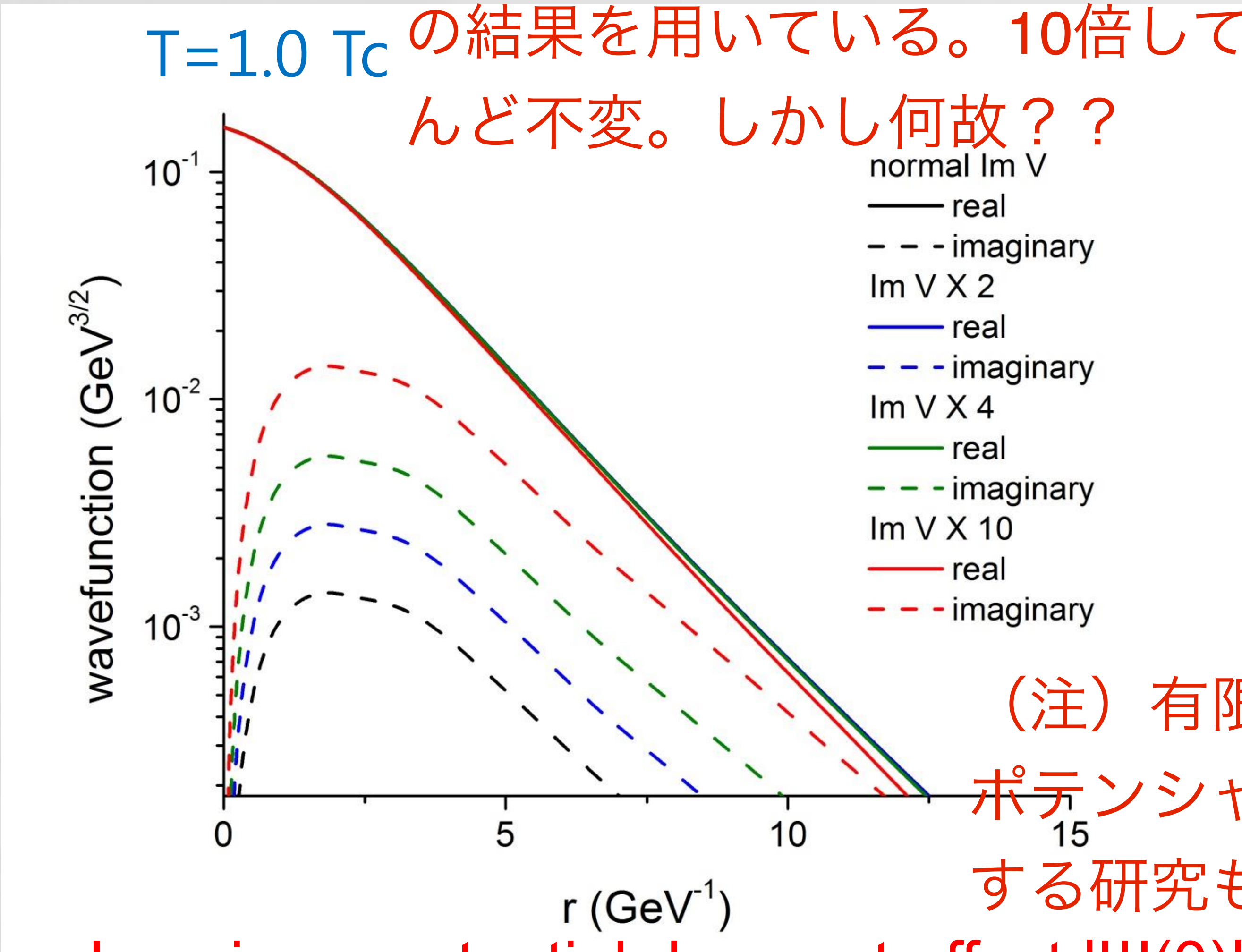
|Ψ(0)| as well as J/Ψ mass from QCD sum rule closely follow those from free energy potential.

QCD和則から求めたIΨ(0)Iは、V=Fとしたポテンシャルモデルと良く合う。

J/Ψ wavefunction

from the complex Schrödinger equation

この計算では、ポテンシャル虚部にHTL摂動論の結果を用いている。10倍してもIΨ(0)Iはほとんど不変。しかし何故？？



Rothkopf, Hatsuda, Sasaki (2012)

（注）有限温度中の複素ポテンシャルを直接計算する研究もある。

Imaginary potential does not affect |Ψ(0)| !!

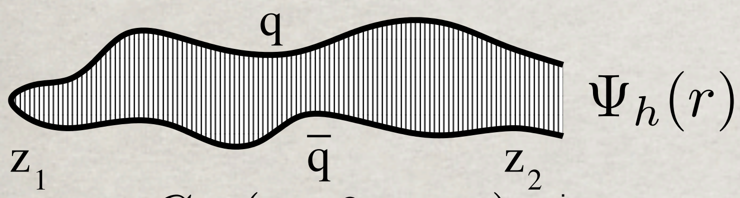
Quarkonium at high pT

High pTのQuarkonium

Charmonium propagation through a hot medium

Path integral technique

B.G.Zakharov & B.K. PRD44(1991)3466



$$G_{\bar{q}q}(z_1, 0; z_2, r)$$

$$\left[i\frac{d}{dz} - \frac{m_c^2 - \Delta_{r_\perp}}{E_\Psi/2} - V_{\bar{q}q}(z, r_\perp) \right] G_{\bar{q}q}(z_1, r_{\perp 1}; z, r_\perp) = 0$$

The Green function $G_{\bar{q}q}(z_1, r_1; l_2, r_2)$ describes propagation of the dipole between longitudinal coordinates $z_{1,2}$ with initial and final transverse (2D) separations $r_{1,2}$.

The imaginary part of the light-cone potential describes absorption,

$$\mathrm{Im}V_{\bar{q}q}(z, r_\perp) = -\frac{v}{4}\,\hat{q}(z)\,r_\perp^2$$

Transport coefficient $\hat{q}$, the rate of broadening, is related to the medium temperature, $\hat{q} \approx 3.6\,T^3$ $(T > T_c)$ and is to be adjusted to data.

$\mathrm{Re}V_{\bar{q}q}(z, r)$ corresponding to the binding potential, is known only in the rest frame of the dipole, and it also depends on longitudinal dipole separation r_L

It cannot be properly described with this 2-dimensional Schrödinger equation. Debye screening corrections make it even more challenging.

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Solving the equation

$$\mathbf{ReU_{\bar{q}q}(r_\perp,\zeta) = \frac{M_\psi}{p_\psi^+} V\left(\sqrt{r_\perp^2+\zeta^2}\right)}$$ - rest frame potential

This is the main result, a simple replacement: $\mathbf{r_L \Rightarrow \zeta}$

In the rest frame the usual Schrödinger equation is recovered.

$\mathbf{ImU_{\bar{q}q}(r_\perp,\zeta) = -\frac{1}{4}\, v\, \hat{q}\, r_\perp^2}$ controls absorption and is independent of ζ

Lightcone座標でのポテンシャル？
このように定義すれば良いらしい。

Screened potential.

$$\mathbf{V_{\bar{c}c}\left(r=\sqrt{r_\perp^2+\zeta^2}\right) = \frac{\sigma}{\mu(T)}\left(1-e^{-\mu(T)r}\right) - \frac{\alpha}{r}e^{-\mu(T)r}}$$

$$\mathbf{\mu(T) = g(T)T\sqrt{1+\frac{N_f}{6}}, \qquad g^2(T) = \frac{24\pi^2}{33\ln\left(19T/\Lambda_{\overline{MS}}\right)}}$$

F. Karsch, M. T. Mehr and H. Satz, Z. Phys. C 37, 617 (1988)

The equation is solved numerically with $\mathbf{\hat{q} = q_0 \frac{n_{part}(\tilde{\tau},\tilde{b})}{n_{part}(0,0)}\frac{t_0}{t}; \qquad q_0 = 1\,fm}$

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問題設定は面白い。

これは波動関数ではないと、
何回も言っているのに・・・。

Results

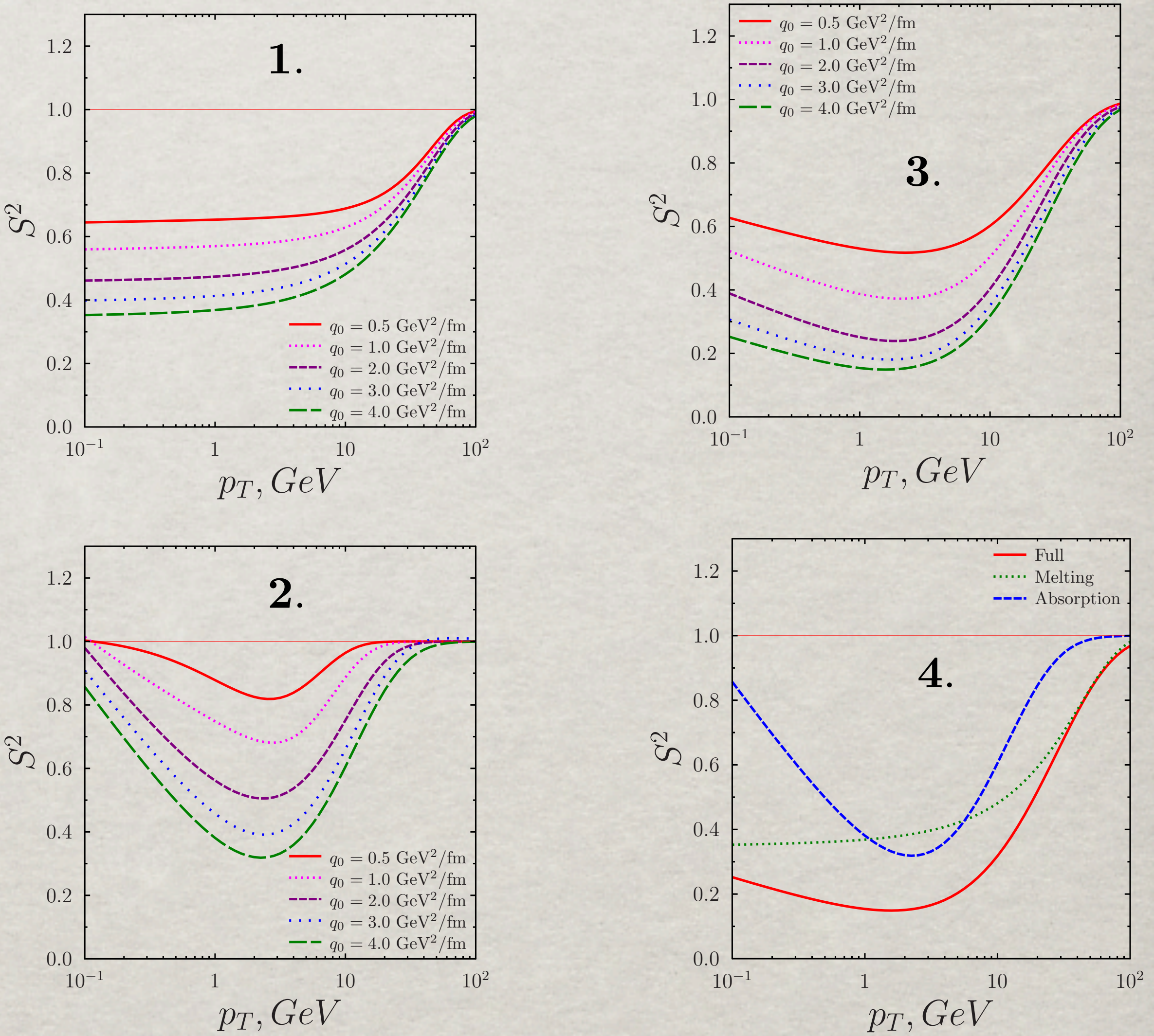
流体静止系にいるQuarkonium
の描像から連続的にどう移るか？

Survial probability amplitude

$$\mathbf{S(z_2, z_1) = \int d\zeta_2 d\zeta_1 d^2r_2 d^2r_1 \Psi_{J/\psi}(r_2, \zeta_2)}$$
$$\mathbf{\times G(r_2, \zeta_2, z_2; r_1, \zeta_1 . z_1) \Psi_{in}(r_1, \zeta_1)}$$

Calculations are done for central Pb-Pb collisions with realistic nuclear density. No ISI effects are added.

1. **Net melting:** $\mathbf{ReU \neq 0; ImU = 0.}$
2. **Net absorption:** $\mathbf{ReU = 0; ImU \neq 0.}$
3. **Total suppression:** $\mathbf{ReU \neq 0; ImU \neq 0.}$
4. $\mathbf{q_0 = 2\,GeV^2/fm}$



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Photon and Dilepton

- Talk slides from
  - Bratkovskaya (plenary)
  - Ghiglieri (plenary)

- Topics
  - Direct photon flow
  - Rate in NLO perturbation

Direct photon flow

1. Hydro: Influence of e-b-e fluctuating initial conditions

➔ From smooth Glauber initial conditions
to event-by-event hydro with fluctuating initial conditions

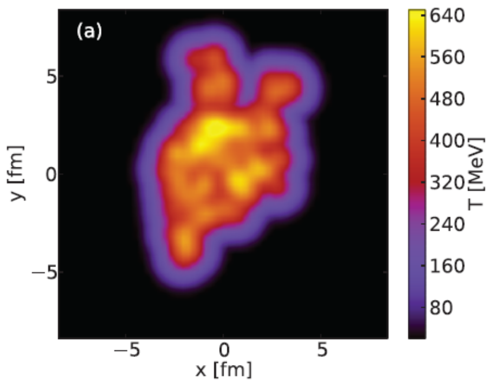
光子のv2@RHIC, LHC

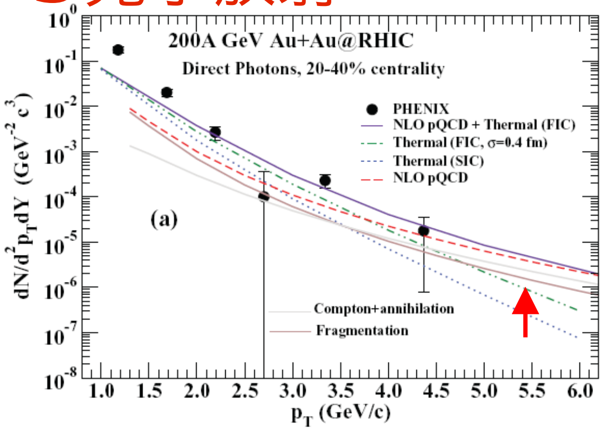
各Eventの完全流体発展から光子放射

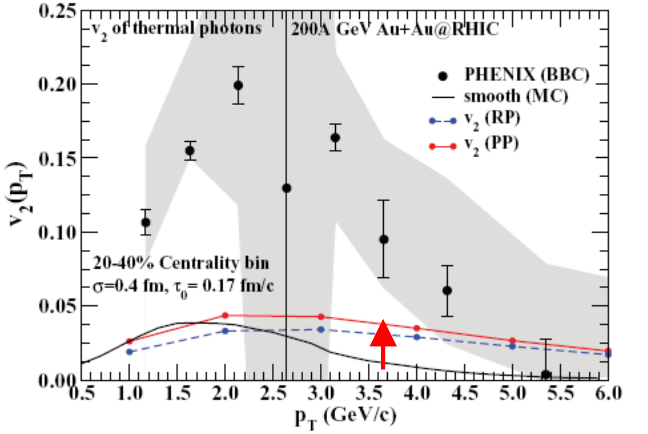
❑ **Jyväskylä ideal hydro**

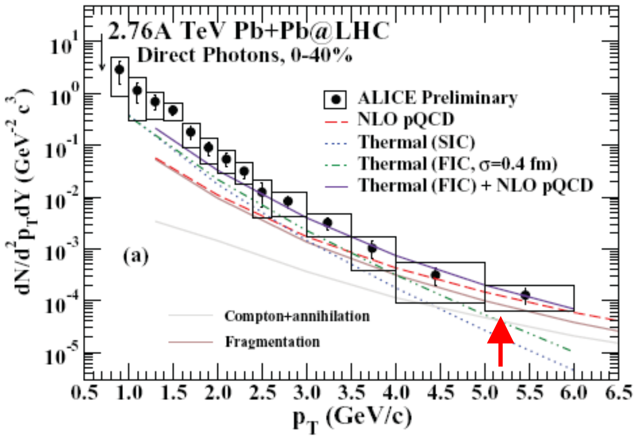
- **Ideal QGP and HG fluid**
- **Initial: ‚bumpy' ebe MC Glauber**
- **EoS: lQCD**

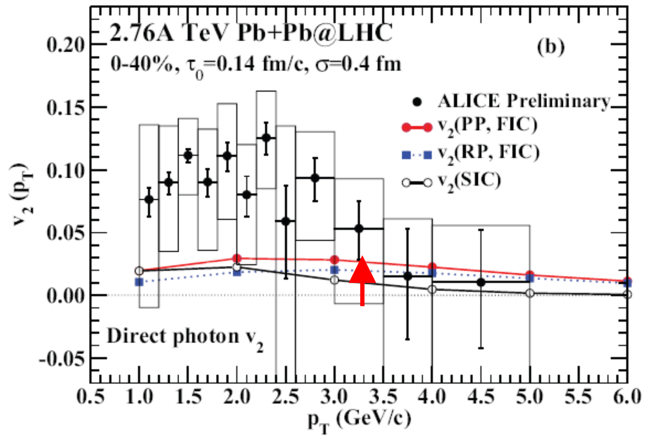
Talk by R. Chatterjee@QM'14, PRC 88, 034901 (2013)











➔ Fluctuating initial conditions: **slight increase at high p_T for yield and v_2**
small effect, right direction!

2. From ideal to viscous hydro: direct photons as a QGP viscometer?

The thermal photon emission rates with viscous corrections:

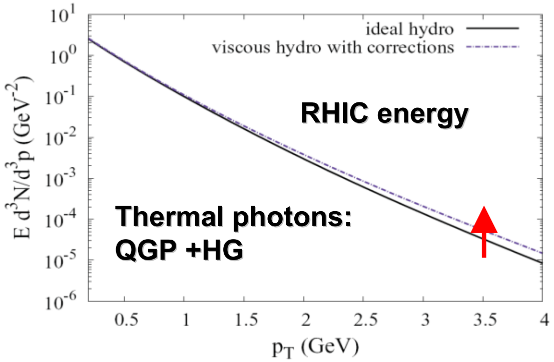
粘性による分布関数のゆがみの効果

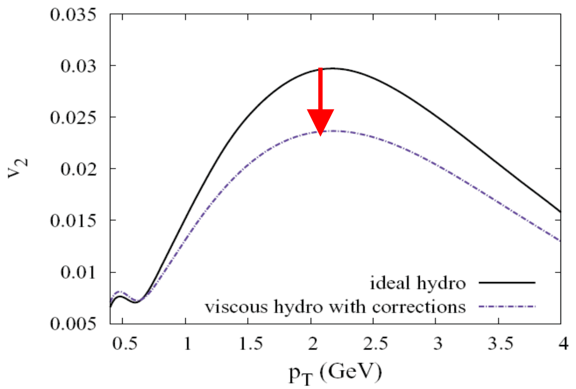
$$q\frac{dR}{d^3q}(q,T) = \Gamma_0(q,T) + \frac{\pi^{\mu\nu}}{2(e+P)}\Gamma_{\mu\nu}(q,T),$$

equilibrium contribution — first order viscous correction

(3+1)D MUSIC (McGill):
M. Dion et al., PRC84 (2011) 064901

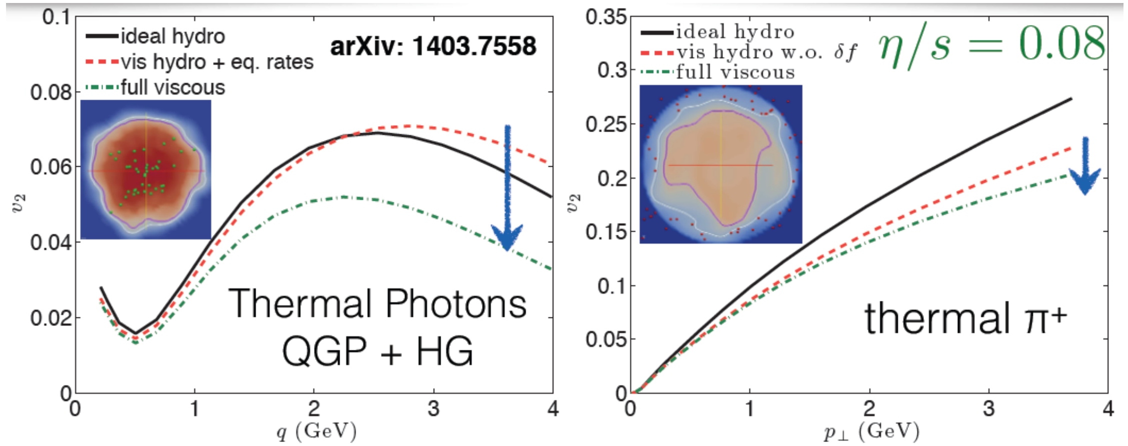
- viscous QGP and HG fluid
- Initial: ‚bumpy' ebe from IP-Glasma
- EoS: lQCD





(2+1)D VISH2+1 (Ohio State) :
C. Shen et al., arXiv:1308.2111, arXiv:1403.7558; Talk by C. Shen @ QM2014

- viscous QGP and HG fluid
- Initial: ‚bumpy' ebe from MC Glauber /KLN
- EoS: lQCD



➔ Effect of shear viscosity:
* small enhancement of the photon yield
* suppression of photon v_2
* effect on v_2 for photons is stronger than for hadrons

Important!

3. Influence of Glasma initial conditions with initial flow

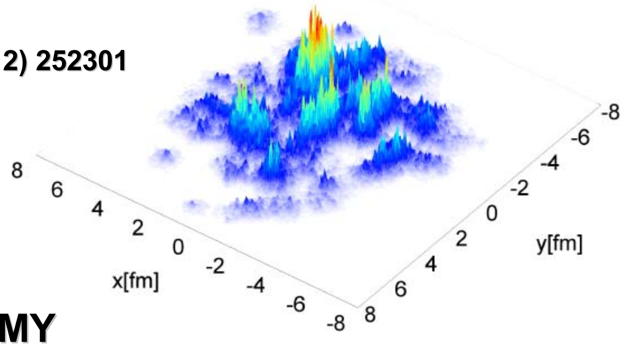
❑ **(3+1)D MUSIC - 2014:**
J-F. Paquet et al. (2014)

IPグラズマ初期条件

- viscous QGP and HG fluid ($\eta/s=0.22$)

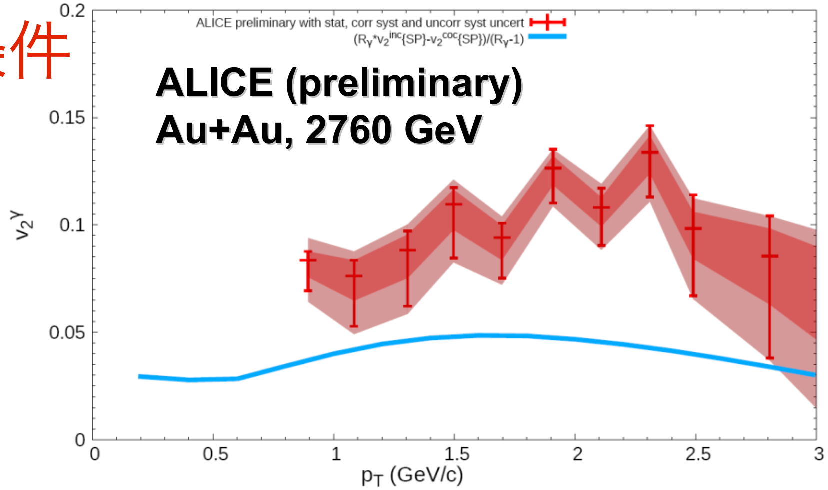
- **Initial: ‚bumpy' ebe from IP-Glasma ➔ generate initial flow due to fluctuations of IC**

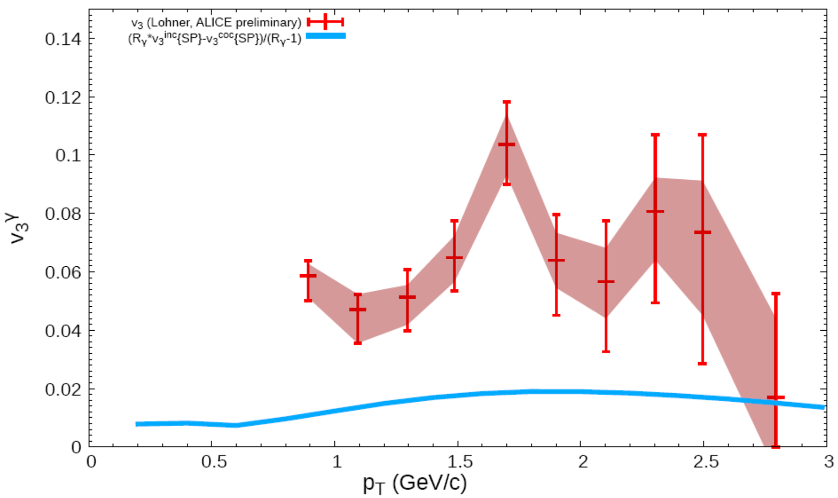
IP-Glasma:
Schenke et al., PRL108 (2012) 252301



- **EoS: lQCD**
- **QGP photon rate: AMY**
- **HG photon rate: TGR for meson gas with viscous corrections + Rapp spectral function for ρ-mesons to account for the baryonic contributions**

■ **MUSIC with IC-Glasma describes v_n of hadrons at RHIC & LHC, however, missing v_2, v_3 of photons!**





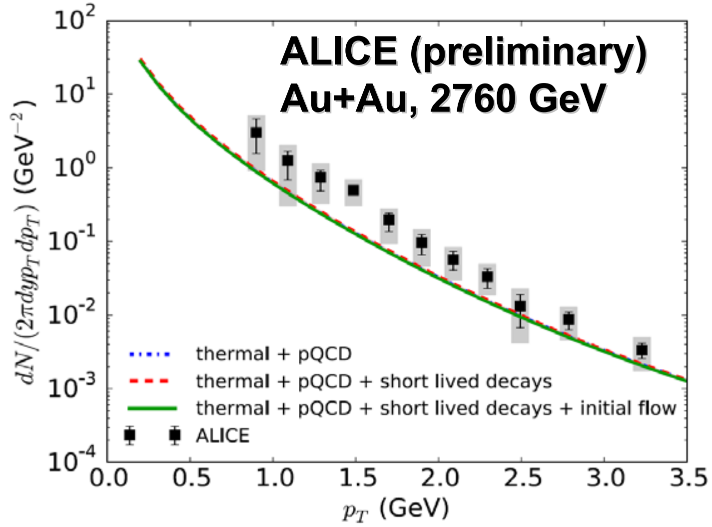
➔ **‚Bumpy' ebe from IP-Glasma - small effect**

4. Hydro with pre-equilibrium flow 初期条件における有限フローの効果

- ❑ **‚Initial' flow:** rapid increase of bulk v_2 in fireball model
  van Hees, Gale, Rapp, PRC84 (2011) 054906

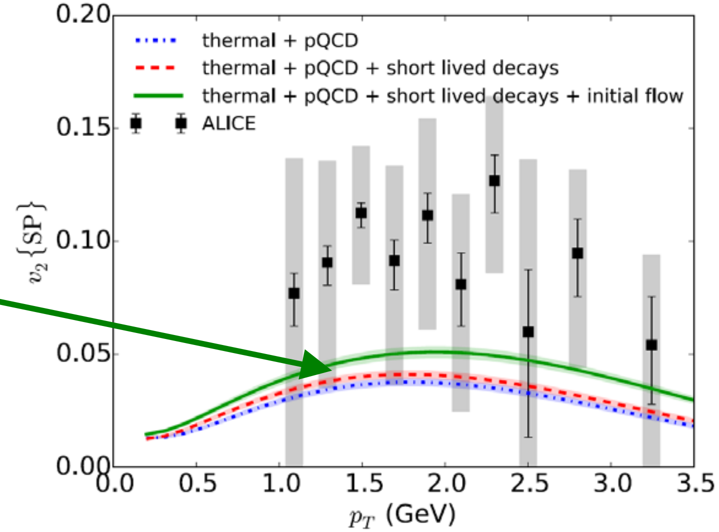
- ❑ **pre-equilibrium flow in (2+1)D VISH2+1 - 2014:**
  C. Shen et al., arXiv:1308.2111, arXiv:1403.7558; Talk by C. Shen @ QM'2014

- viscous QGP and HG fluid ($\eta/s=0.18$)
- Initial: ‚bumpy' ebe from MC Glauber /KLN
- EoS: lQCD
- QGP photon rate: AMY
- HG photon rate: TGR for meson gas with viscous corrections



• Generation of pre-equilibrium flow:
using free-streaming model to evolve the partons right after the collisions to 0.6 fm/c
+ Landau matching to switch to viscous hydro

➔ quick development of momentum anisotropy with saturation near T_C



➔ **Pre-equilibrium flow:**
- small effect on photon spectra
- slight increase of v_2

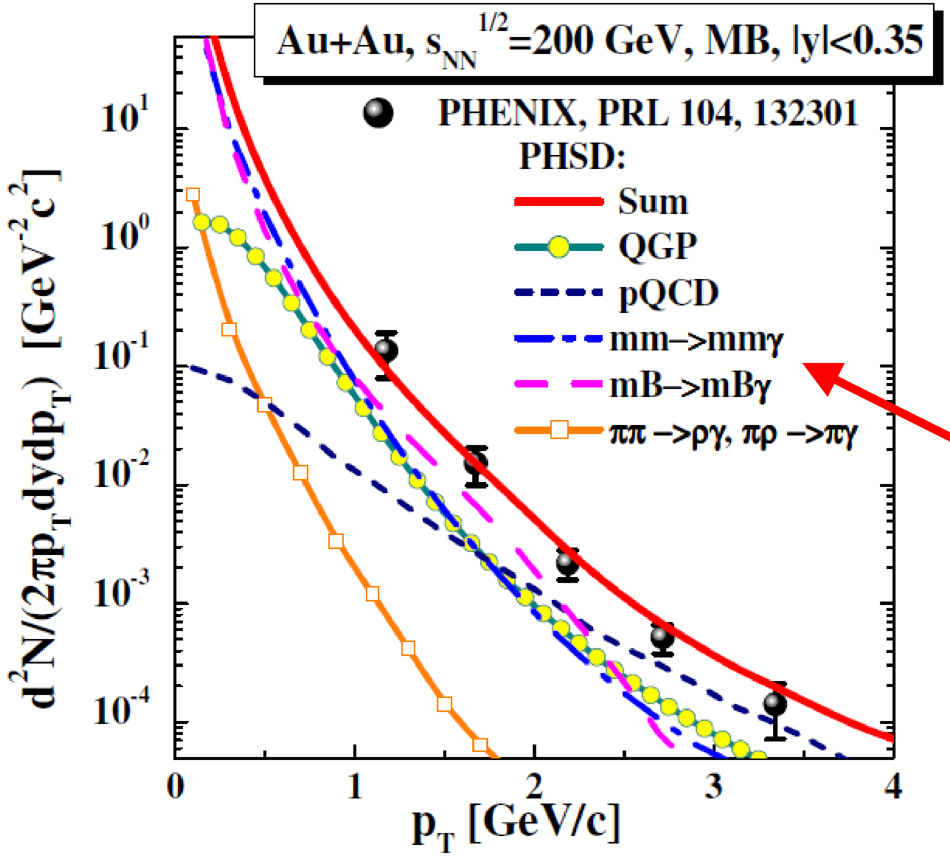
Warning: results can be considered as upper limit for the pre-equilibrium flow effect!

PHSD: photon spectra at RHIC: QGP vs. HG ?

Parton-Hadron-String Dynamicsの計算

Linnyk et al., PRC88 (2013) 034904; PRC 89 (2014) 034908

- **Direct photon spectrum (min. bias)**



The slope parameter T_{eff} (in MeV)			
PHSD			PHENIX
QGP	hadrons	Total	[38]
260 ± 20	200 ± 20	220 ± 20	233 ± 14 ± 19

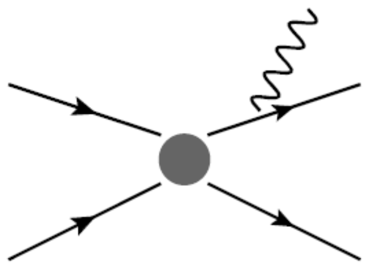
PHSD:

- **QGP gives up to ~50% of direct photon yield below 2 GeV/c**

! sizeable contribution from hadronic sources – meson-meson (mm) and meson-Baryon (mB) bremsstrahlung

$$m+m \rightarrow m+m+\gamma,$$

$$m+B \rightarrow m+B+\gamma\,,$$



$m=\pi,\eta,\rho,\omega,K,K^*,\ldots$

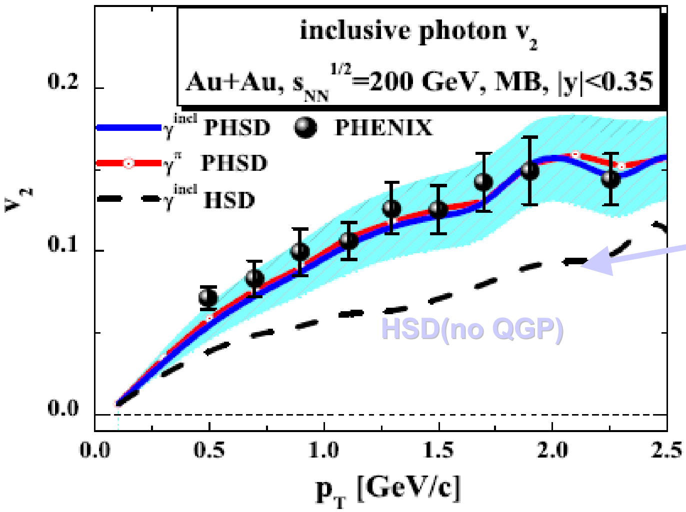
$B=p$

!!! mm and mB bremsstrahlung channels can not be subtracted experimentally !

Are the direct photons a barometer of the QGP?

❑ Do we see the **QGP pressure** in $v_2(\gamma)$ if the photon productions is **dominated by hadronic sources?**

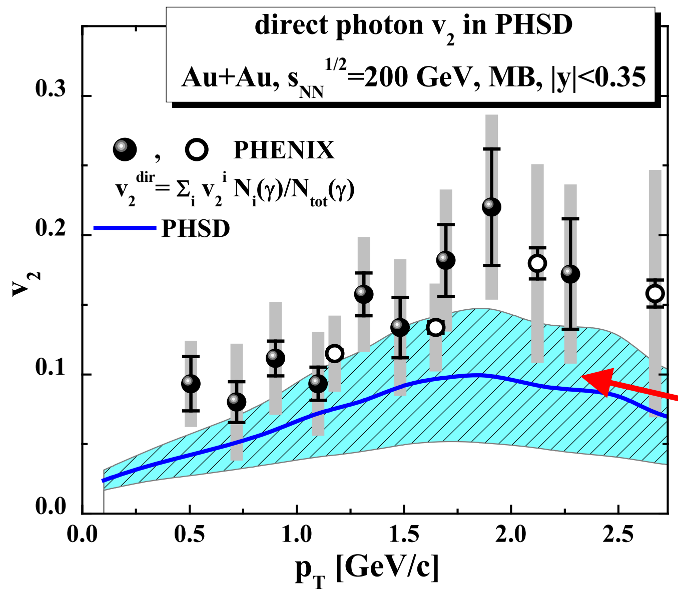
PHSD: Linnyk et al.,
PRC88 (2013) 034904;
PRC 89 (2014) 034908



1) $v_2(\gamma^{incl}) = v_2(\pi^0)$ - **inclusive photons** mainly come from π^0 decays

- HSD (without QGP) underestimates v_2 of hadrons and inclusive photons by a factor of 2, wheras the PHSD model with QGP is consistent with exp. data

➔ The **QGP causes the strong elliptic flow of photons indirectly**, by enhancing the v_2 of final hadrons due to the partonic interactions



Direct photons (inclusive(=total) – decay):

2) $v_2(\gamma^{dir})$ of **direct photons** in PHSD underestimates the PHENIX data :

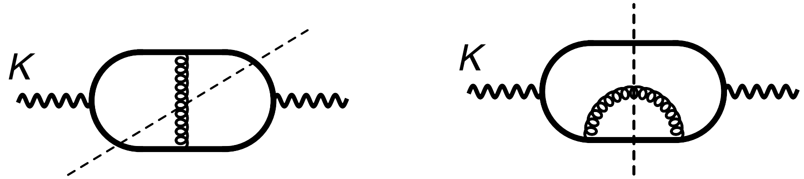
$v_2(\gamma^{QGP})$ **is very small**, but QGP contribution is up to 50% of total yield ➔ lowering flow

➔**PHSD:** $v_2(\gamma^{dir})$ comes from **mm and mB bremsstrahlung !**

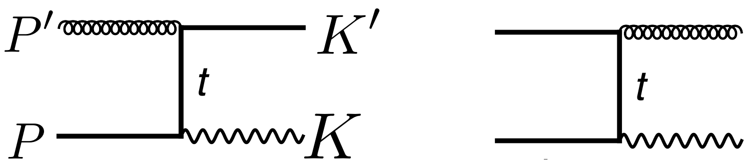
Rate in NLO perturbation

2↔2 processes

- Cut two-loop diagrams ($\alpha_{\rm EM}\, g^2$)



2↔2 processes (with crossings and interferences):



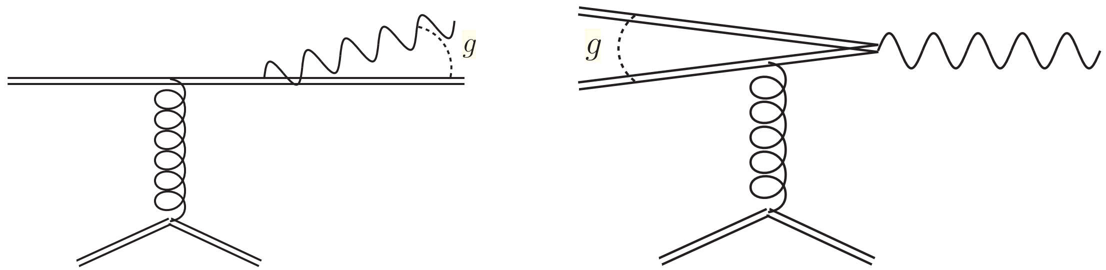
$$\int_{\rm ph.\,space} f(p)f(p')(1\pm f(k'))|\mathcal{M}|^2\delta^4(P+P'-K-K')$$

- Equivalence with kinetic theory: distributions x matrix elements

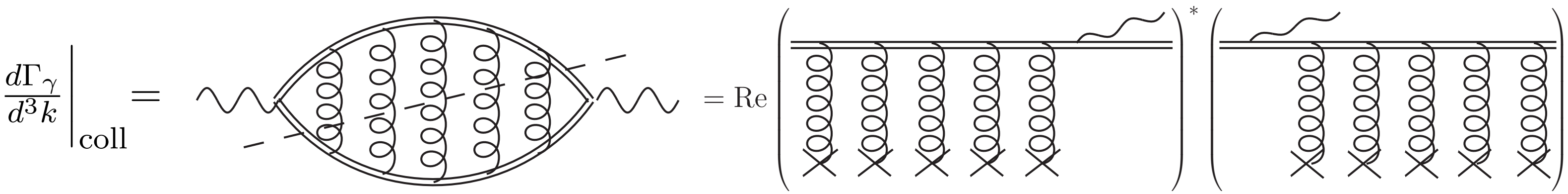
HTLで赤外正則化

- IR divergence (Compton) when t goes to zero

Collinear processes



- These diagrams contribute to LO if small (g) angle radiation/ annihilation Aurenche Gelis Kobes Petitgirard Zaraket 1998-2000
- Photon formation times is then of the same order of the soft scattering rate $\Rightarrow$ interference: *LPM effect*
- Requires resummation of infinite number of ladder diagrams



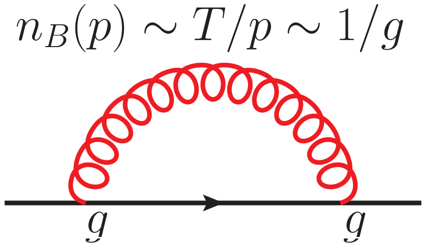
AMY (Arnold Moore Yaffe) **JHEP** 0111, 0112, 0226 (2001-02)

Beyond leading order

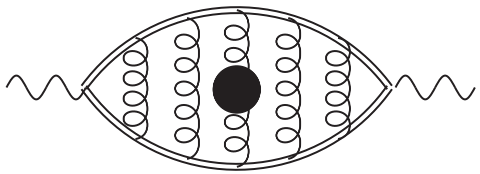
- The soft scale gT introduces $O(g)$ corrections

3種類の寄与

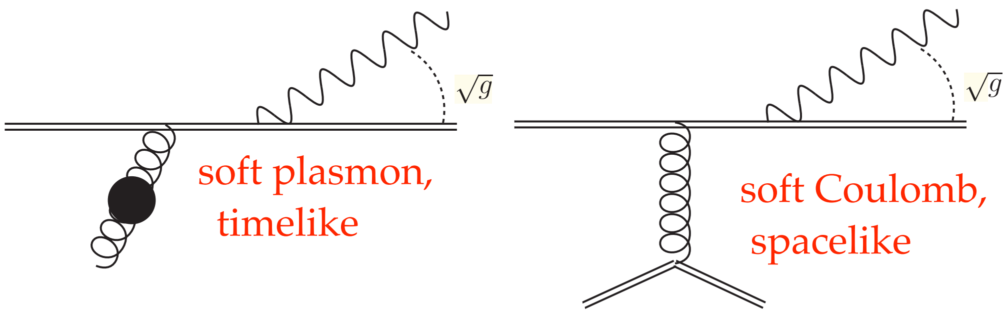
(correction from soft scale / collinear / semi-collinear)



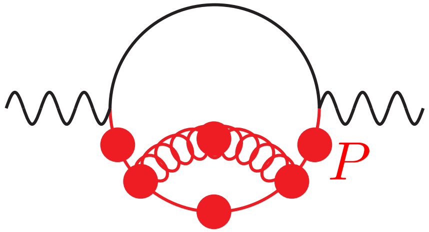
- In the collinear sector: account for 1-loop rungs (related to NLO qhat). Euclidean (EQCD) evaluation
Caron-Huot **PRD79**, talks by Panero, Meyer

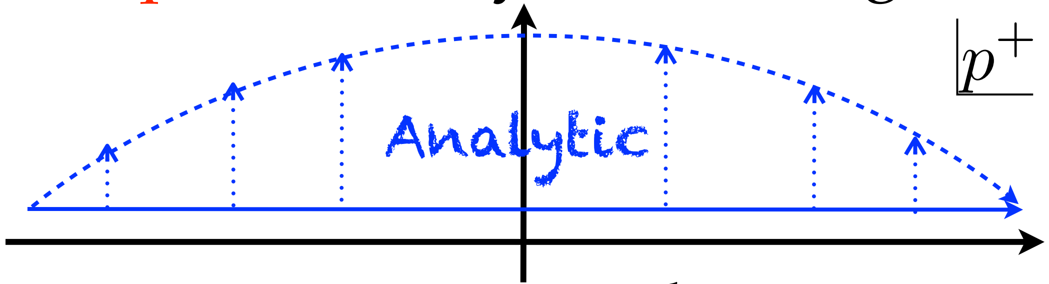


- New semi-collinear processes: larger angle radiation, NLO in collinear radiation approx. Requires a "*modified qhat*", relevance for jets too



- Add soft gluons to soft quarks: nasty all-HTL region





- Analyticity allows us to take a detour in the complex plane away from the nasty region $\Rightarrow$ compact expression

- Summing all contributions: good convergence, but with large cancellations between contributions: error estimate of LO

  JG Hong Kurkela Lu Moore Teaney **JHEP0503**