

ハードプローブで探るQGP物性

HIC & HIP 合同研究会

蜂谷 崇

奈良女子大学 & 理研BNLセンター



2018/6/30

ハードプローブで探るQGP物性 蜂谷 崇



QM2018の結果を振り返る前に

- 取り扱う内容 : ハードプローブ
 - Open heavy flavor, Quarkonia, Jetの測定結果です。
 - 独断と偏見とプレナリーで選んだプロットを見せます。
- 2015 チュートリアル研究会「重イオン衝突の物理:基礎から最先端まで」
 - このスライドから絵とスライドを借りてきてます。
 - ウェブサイトが壊れてるので直してほしいです

N talks

HQ : 18 (5CMS, 2ATLAS, 3LHCb, 3ALICE, 2STAR, 2PHENIX, NA61)

QQ : 8 (2ALICE, 2CMS, ATLAS, LHCb, STAR, PHENIX)

JET : 17 (5ALICE, 5CMS, 4ATLAS, PHENIX, STAR,)

ハードプローブを使ってQGPを見る

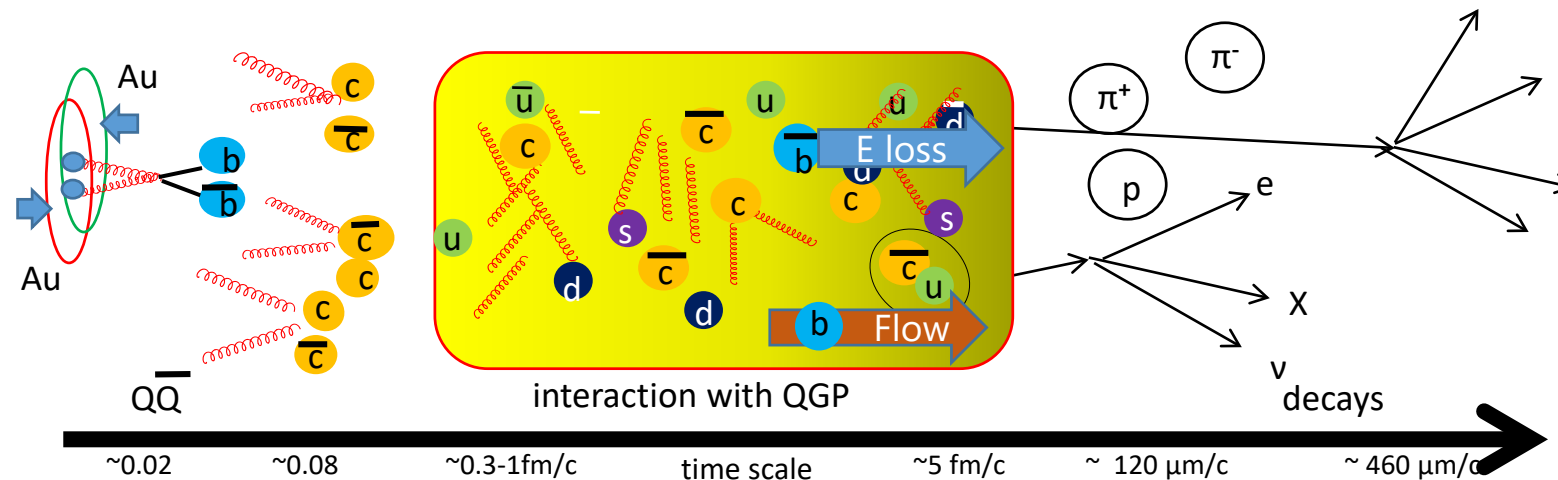
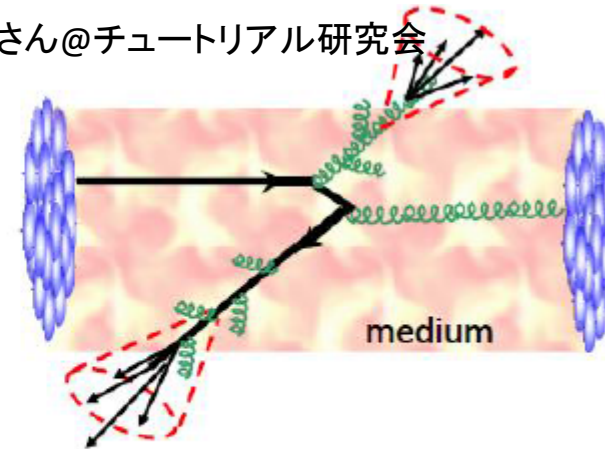
板倉さん@チュートリアル研究会

はじめに

ハードプローブの重要性

QGPを「外から」プローブすることはできない

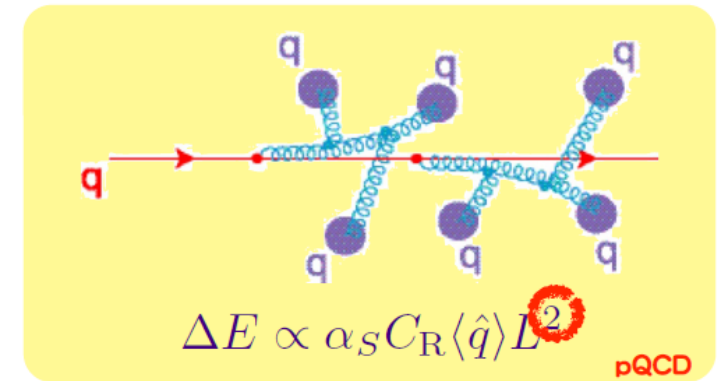
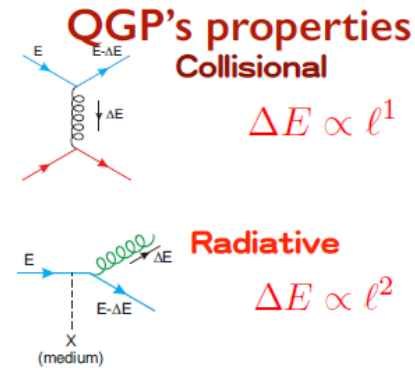
→ しかし、生成したクォーク・グルーオンの全てがQGPになるわけではない。
QGPが生成されたとき、QGPになっていない成分が存在することを利用



- 性質の分かっているプローブ (ppなどで) が、QGPとの相互作用でどのように変化するかを調べる。

ハードプローブを使って、何を調べるのか

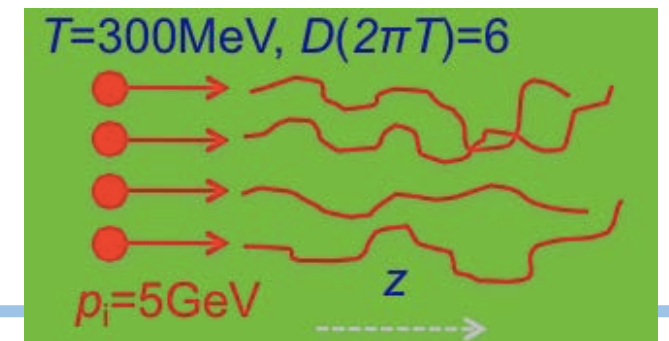
- QGPの性質: medium response
 - Eloss: q -hatの値や、 dE/dx のL依存性 (high pT particleやJet)



• Dominant energy loss is gluon radiation $\hat{q} \equiv m_D^2/\lambda = m_D^2 \rho \sigma$

- η/s : low pTのRAA, v_2 や2粒子相関 $dE \sim l^3$ (Ads/CFT)
 - Heavy quarkはQGPの輸送係数($\sim \eta/s$)に敏感

- 温度T:
 - Quarkoniaの融解を測定



データが増えました。



ALICE@LHC

System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010-2011	2.76	$\sim 75 \mu\text{b}^{-1}$
	2015	5.02	$\sim 250 \mu\text{b}^{-1}$
	by end of 2018	5.02	$\sim 1 \text{nb}^{-1}$
Xe-Xe	2017	5.44	$\sim 0.3 \mu\text{b}^{-1}$
p-Pb	2013	5.02	$\sim 15 \text{nb}^{-1}$
	2016	5.02, 8.16	$\sim 3 \text{nb}^{-1}, \sim 25 \text{nb}^{-1}$
pp	2009-2013	0.9, 2.76, 7, 8	$\sim 200 \mu\text{b}^{-1}, \sim 100 \text{nb}^{-1}, \sim 1.5 \text{pb}^{-1}, \sim 2.5 \text{pb}^{-1}$
	2015, 2017	5.02	$\sim 1.3 \text{pb}^{-1}$
	2015-2017	13	$\sim 25 \text{pb}^{-1}$

RHIC

- 2014-2016の高統計Au+Au
- 2015 pp, pAl, pAu

- シリコン検出器によるHF測定

ハードプローブは生成量が少ないので、実験データの統計を増やすことで精度向上が可能

- 衝突核種、Centrality, Reaction Plane, 運動量などの軸で、生成量などの変化を調べることができる

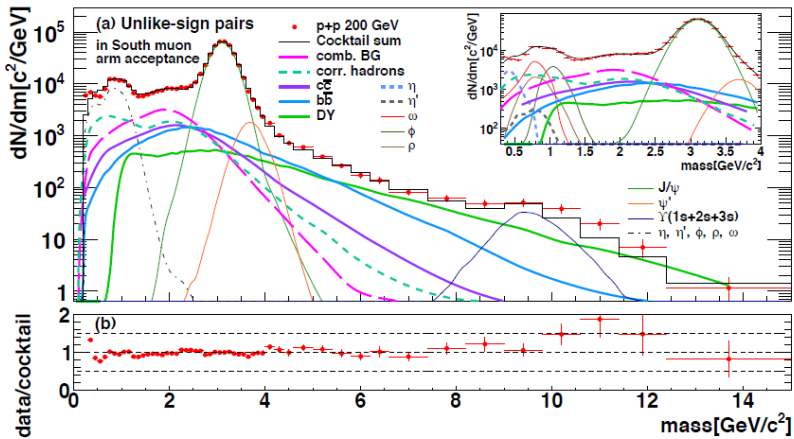
Heavy Quark

- p+p : baseline 測定
 - HQ生成についての理解
- p+A : CNM効果
 - Initial state interaction
- A+A: Hot-matter効果 (Final state interaction)
 - Charm: RAA, v_2
 - Bottom: RAA, v_2

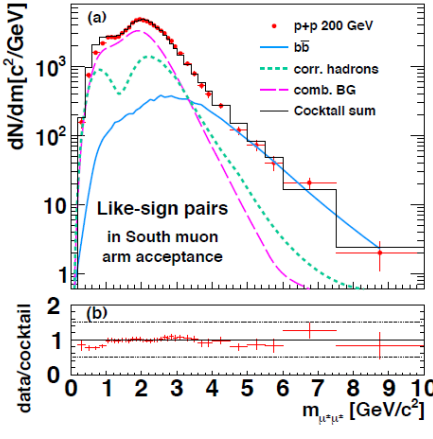
実験的に、生成メカニズムを理解するための測定

First measurement of the dimuon continuum at RHIC PHENIX

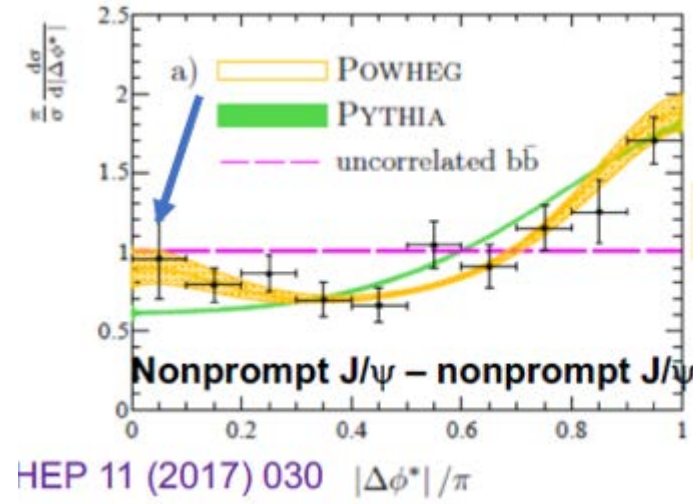
Unlike-sign pairs



Like-sign pairs



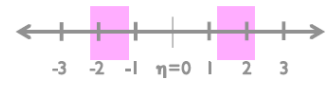
arXiv:1805.02448



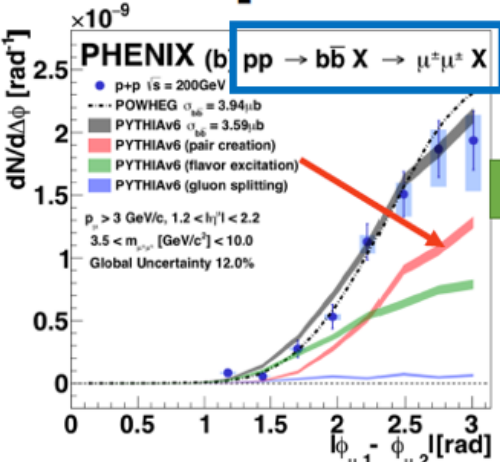
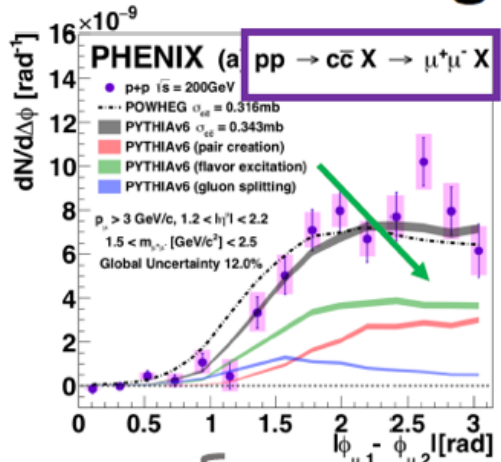
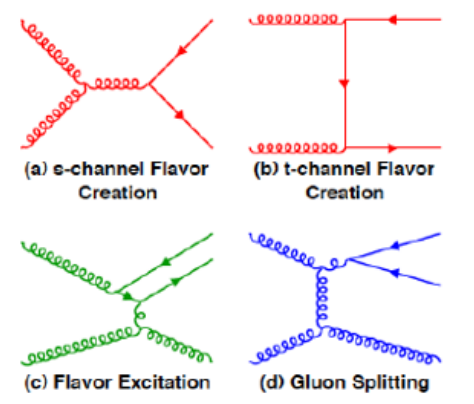
pp $\sqrt{s}=7$ TeV

B.P. Malecki

- Simultaneous fitting in mass- p_T using unlike- and like-sign spectra
- Cocktail describes unlike-sign data and like-sign data well



Angular correlations: investigate HF production



Final

arXiv: 1805.02448
arXiv: 1805.04075

- RHICではHQ生成(特にb)は、PCの効果が主で分かりやすい。
- LHCでも傾向は同じ。

Y.H. Leung (Wed 15:40)

pp $\sqrt{s}=200$ GeV

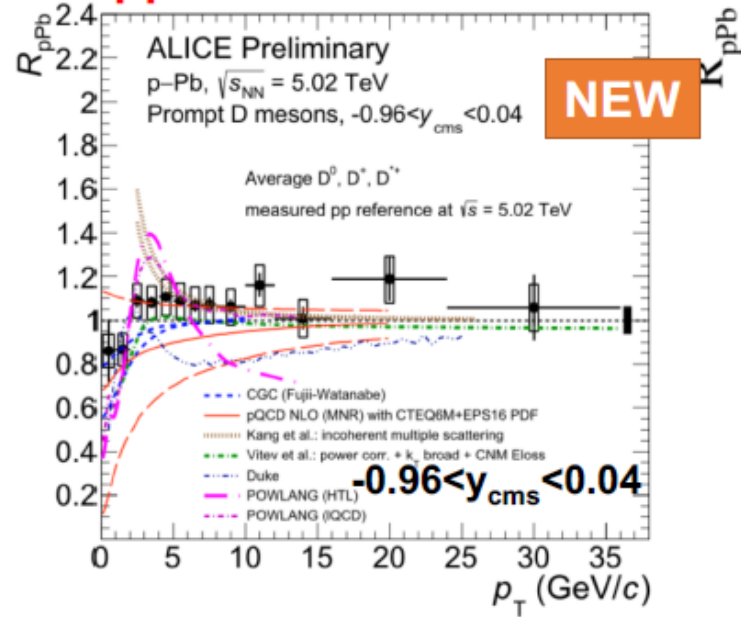
Charm mainly produced by flavor excitation
Beauty mainly produced by pair creation

Based on
PYTHIA 8

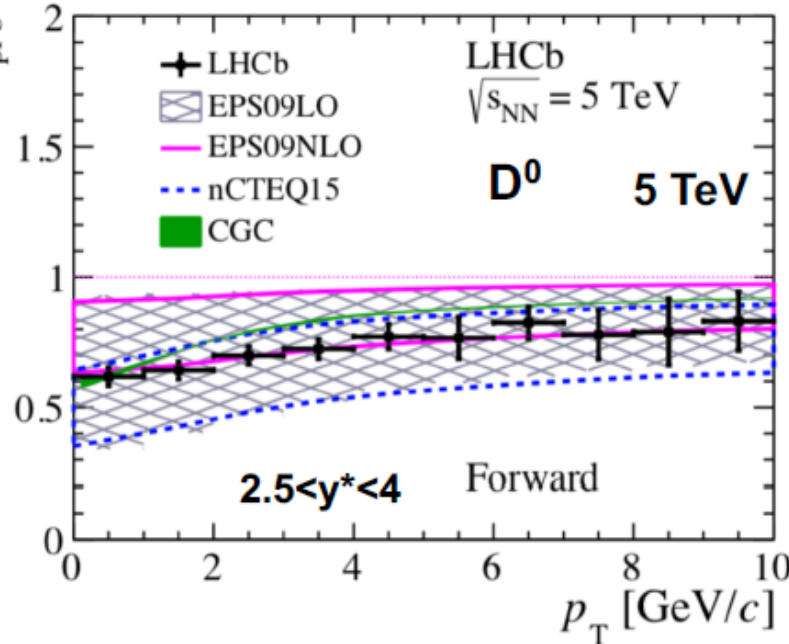
2018/6/30

p(d)-A : constrain CNM effects

New pp reference at 5.02 TeV!

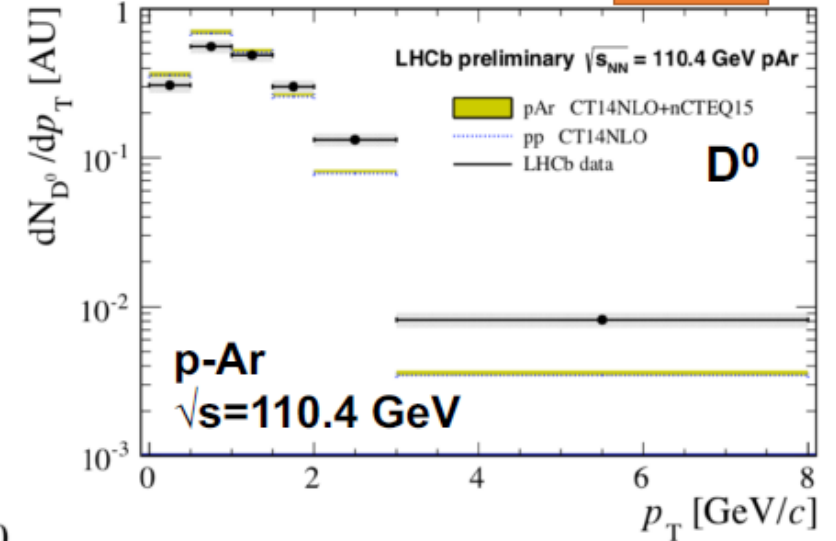


JHEP 1710 (2017) 090



LHCb fixed target

NEW



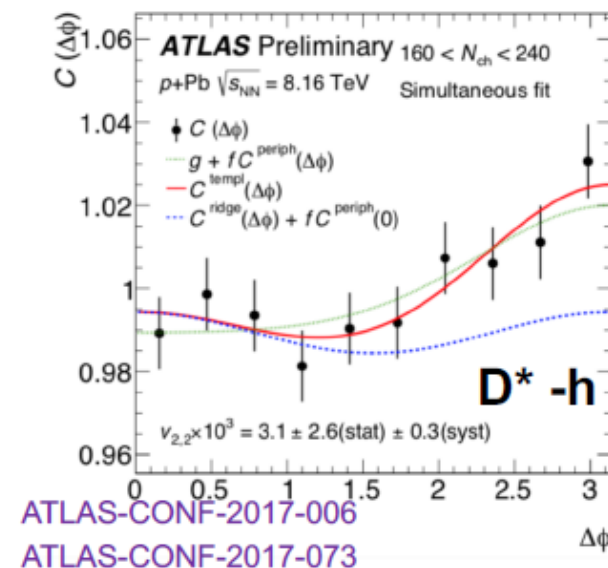
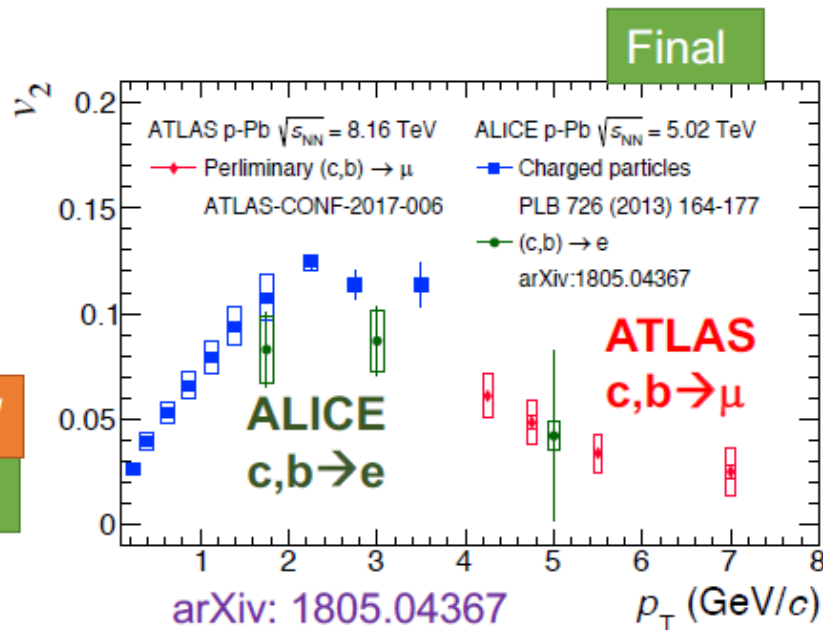
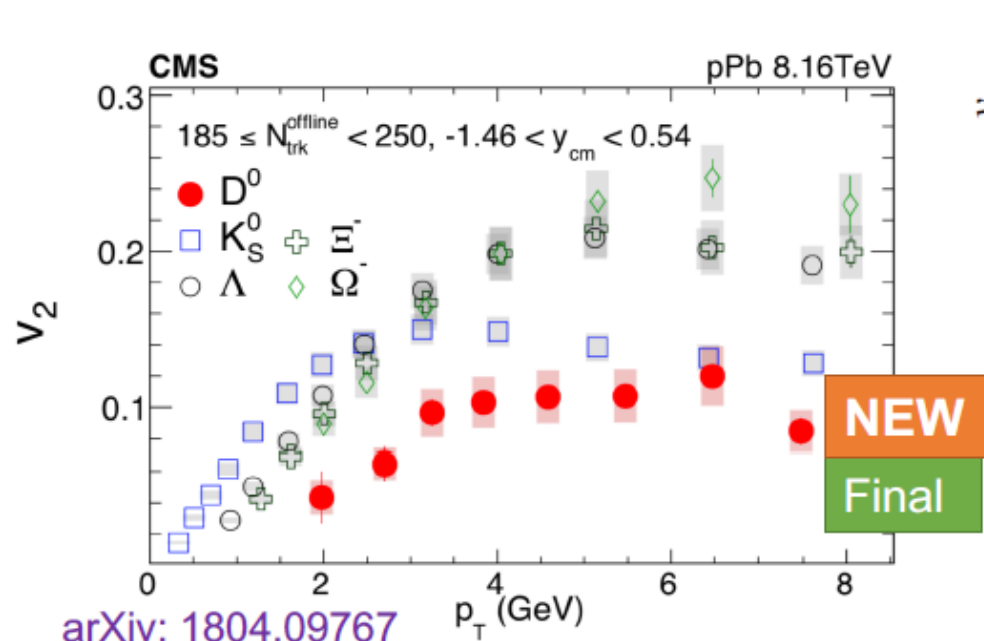
Mid-rapidity: $R_{pA} = 1$ within uncertainties

Forward rapidity: $R_{pA} < 1$, exploring shadowing region

Can assess p_T and rapidity dependence of CNM effects

H. Zanolini (Wed 15:20)
 J. Sun (Wed 14:40)
 S. Chen (Tue 12:50)

Collectivity in p(d)-A?

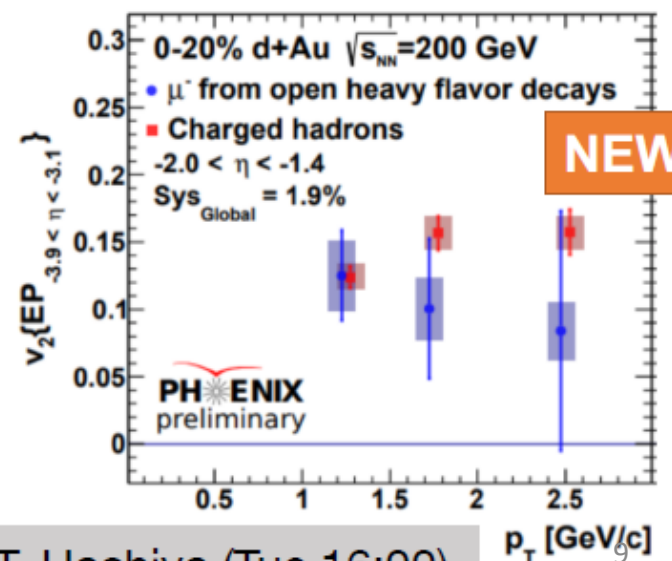


Positive v_2 for HF particles (D^0 , D^* mesons, e^\pm and μ^\pm from HF) from 2-particle correlations in high-multiplicity p-Pb

D^0 v_2 persists up to high p_T , weaker than that of light flavors

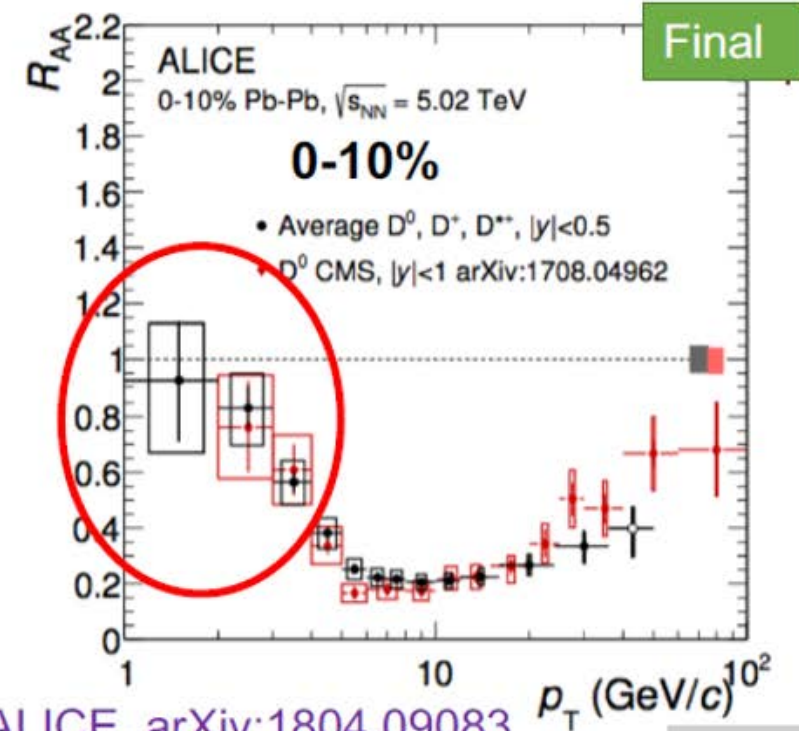
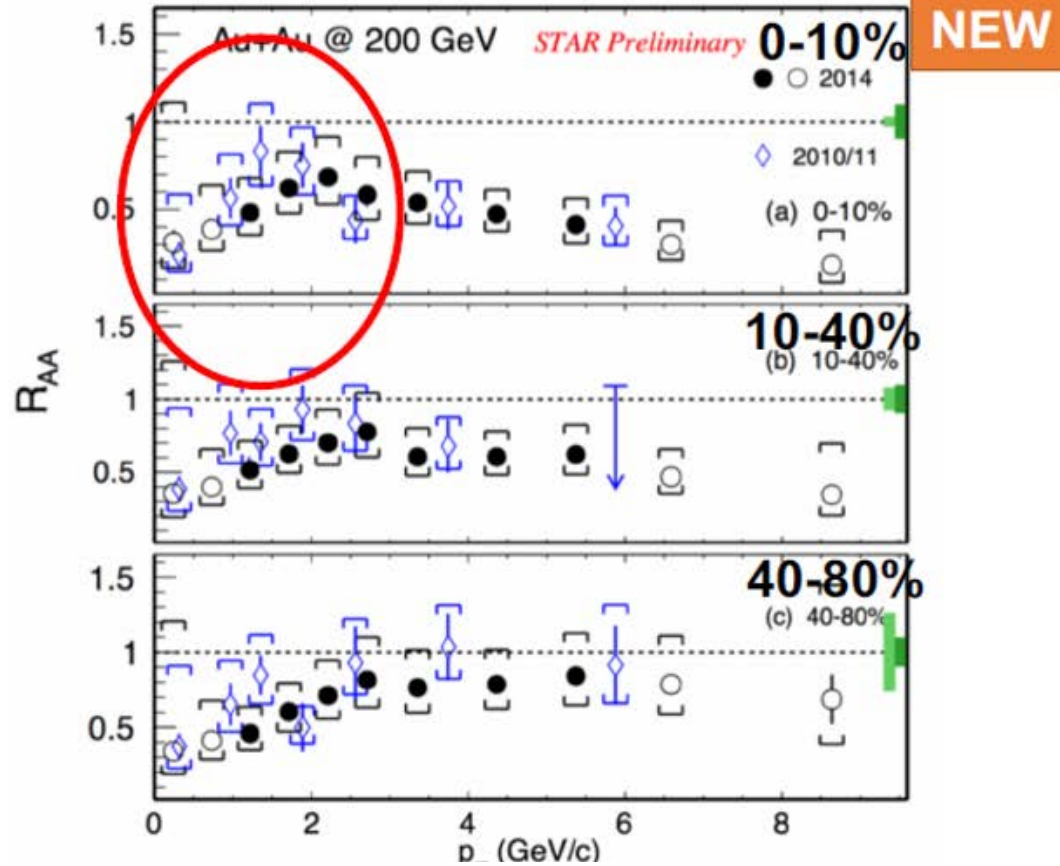
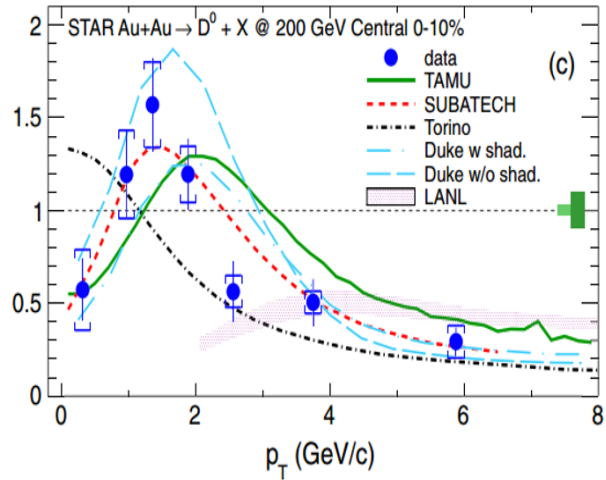
AAで見られるcharmの v_2 とは異なる。

First measurement of $v_2(c,b \rightarrow \mu^\pm)$ in d+Au at RHIC!



D meson RAA at RHIC and LHC

PRL 113, 142301 (2014)



ALICE, arXiv:1804.09083
CMS, arXiv:1708.04962

S. Raa
X. Per
Z. Shi

$D^0 R_{AA} < 1$ down to $p_T = 0$ at RHIC (2014 data + re-analysis 2010/2011)

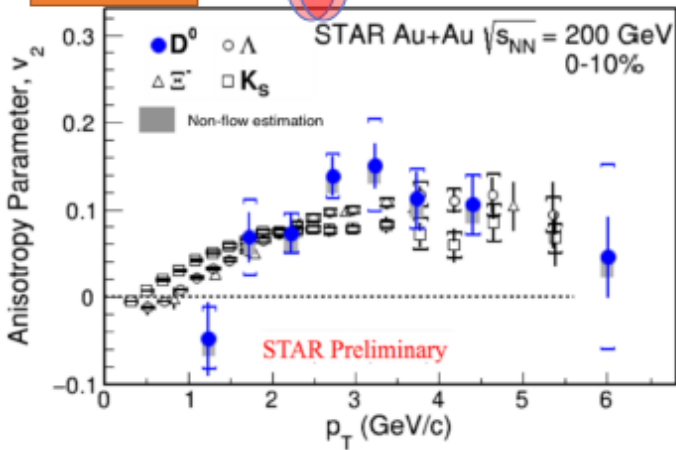
High p_T : similar suppression at RHIC and LHC

Low p_T : $R_{AA}(D)_{RHIC} \approx R_{AA}(D)_{LHC} \rightarrow$ interplay of p_T shapes, radial flow, recombination

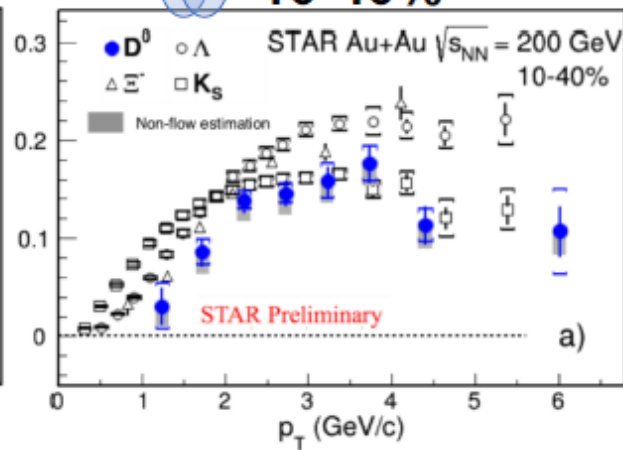
Charm elliptic flow

NEW

0-10%



10-40%

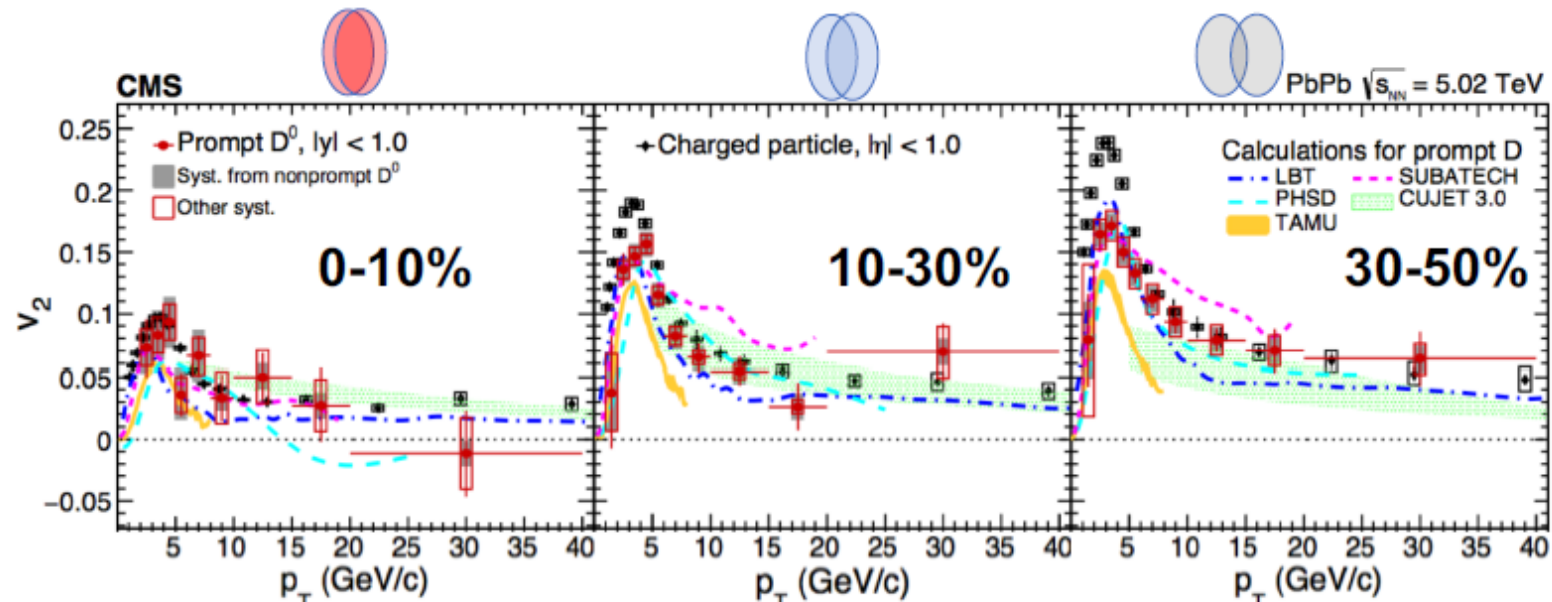
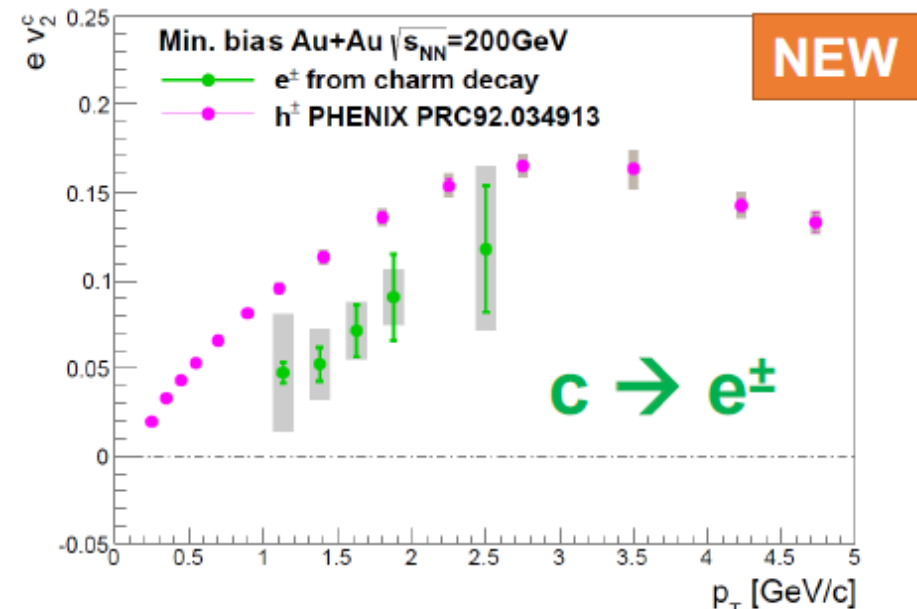


Significant charm v_2 at both RHIC and LHC

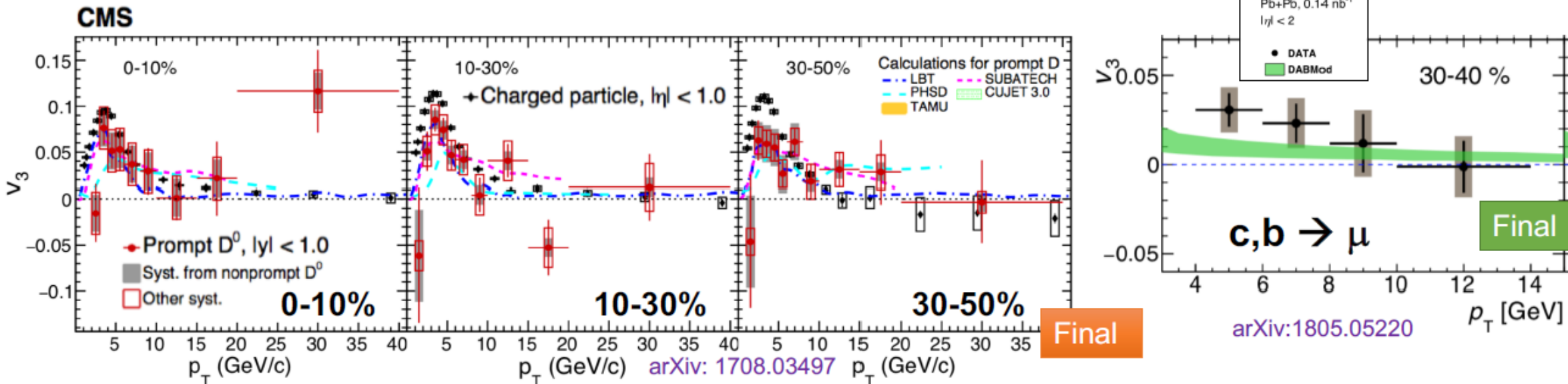
v_2 decreases with increasing centrality

Low p_T : v_2 (charged particles) $\gtrsim v_2$ (D)

High p_T : v_2 (charged particles) $\approx v_2$ (D)



Additional harmonics



Positive v_3 for HF !

Both v_2 and v_3 smaller for charm wrt light quarks: different degree of thermalization, recombination? $h + w/\text{baryon}$ を考えると、NCQ scale するとよく似た v_2, v_3 になるように見える。

R. Xiao (Wed 09:00), Q. Hu (Wed 15:00)

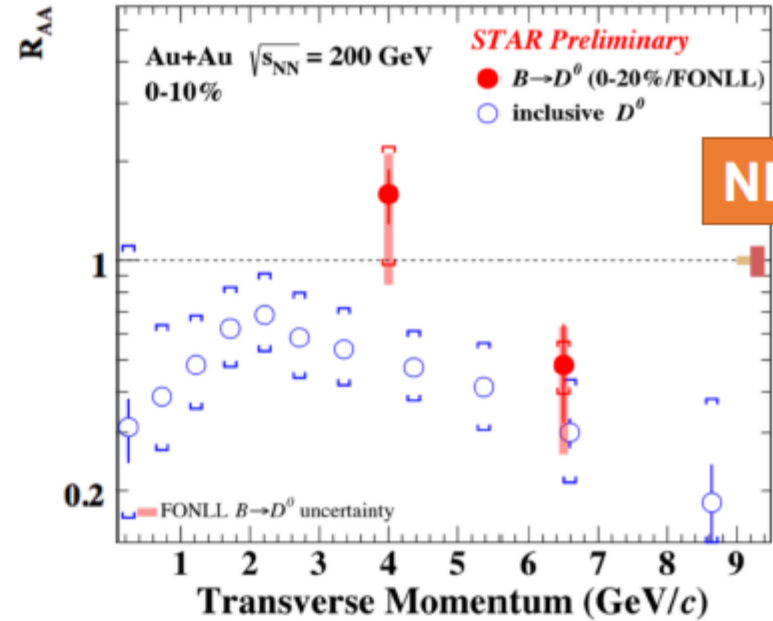
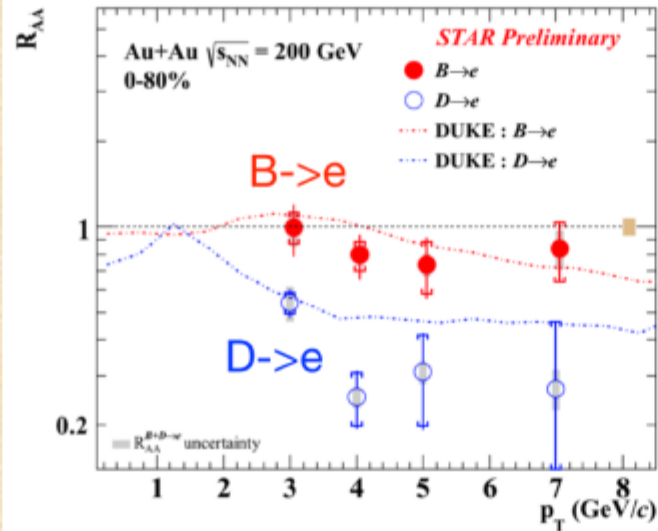
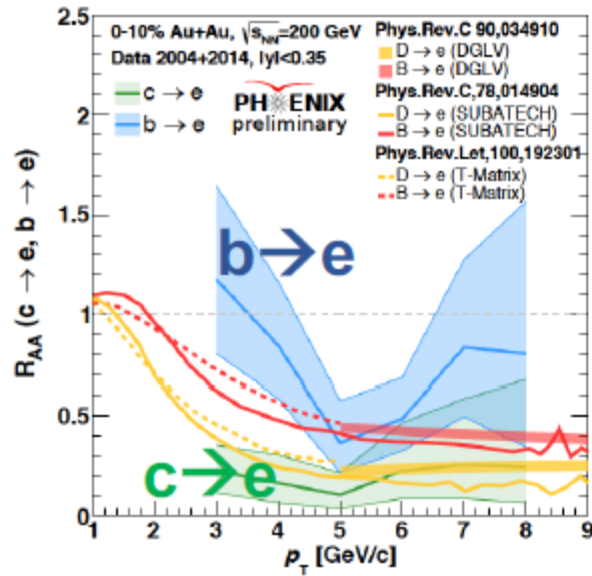
Very little centrality dependence: constant triangularity from geometrical fluctuations

Models (including charm re-scattering) qualitatively describe v_2 and v_3 data
 → **confirm that charm takes part in collective motion**



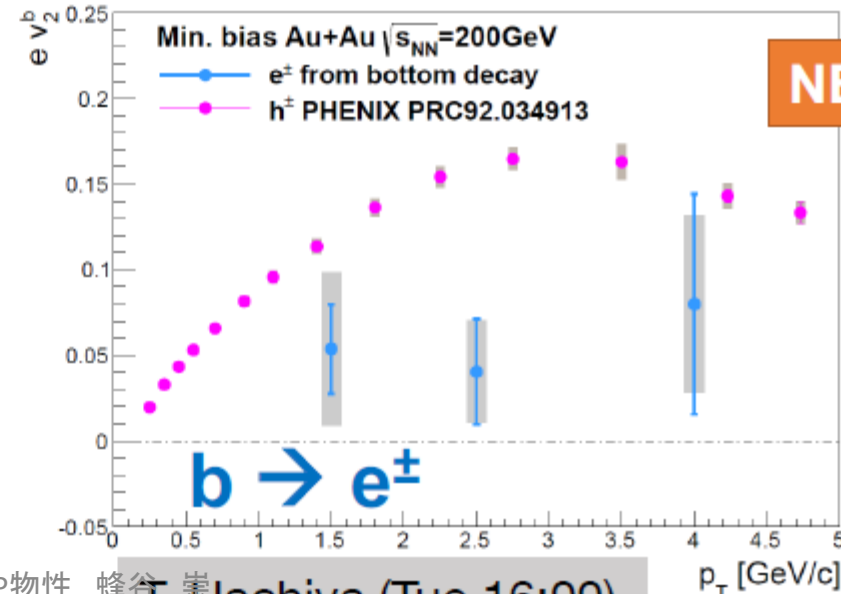
Beauty at RHIC

pre-QM18

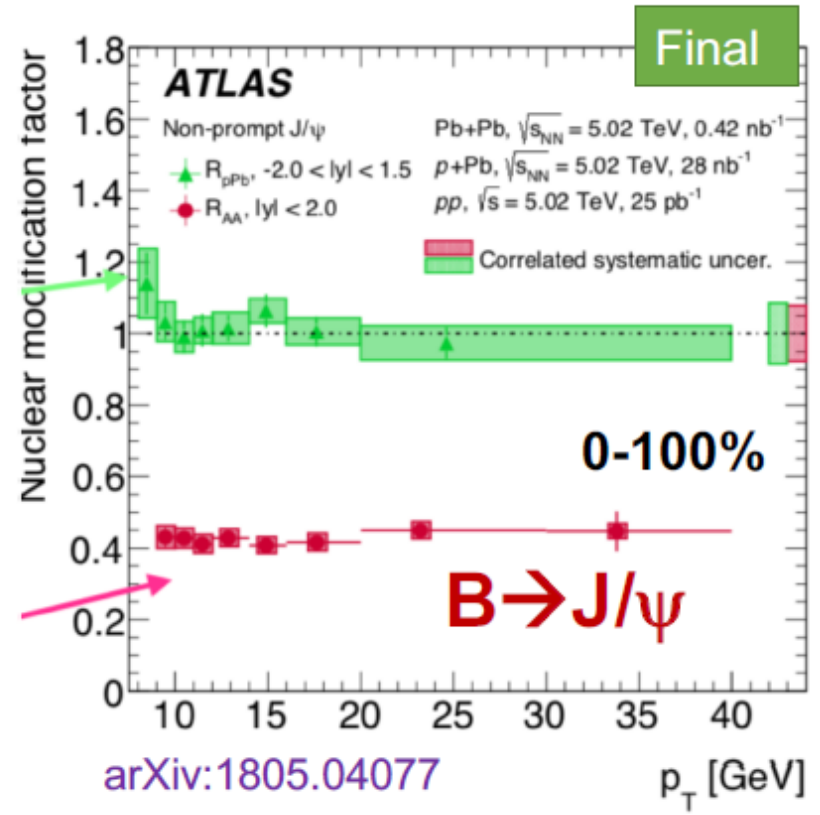
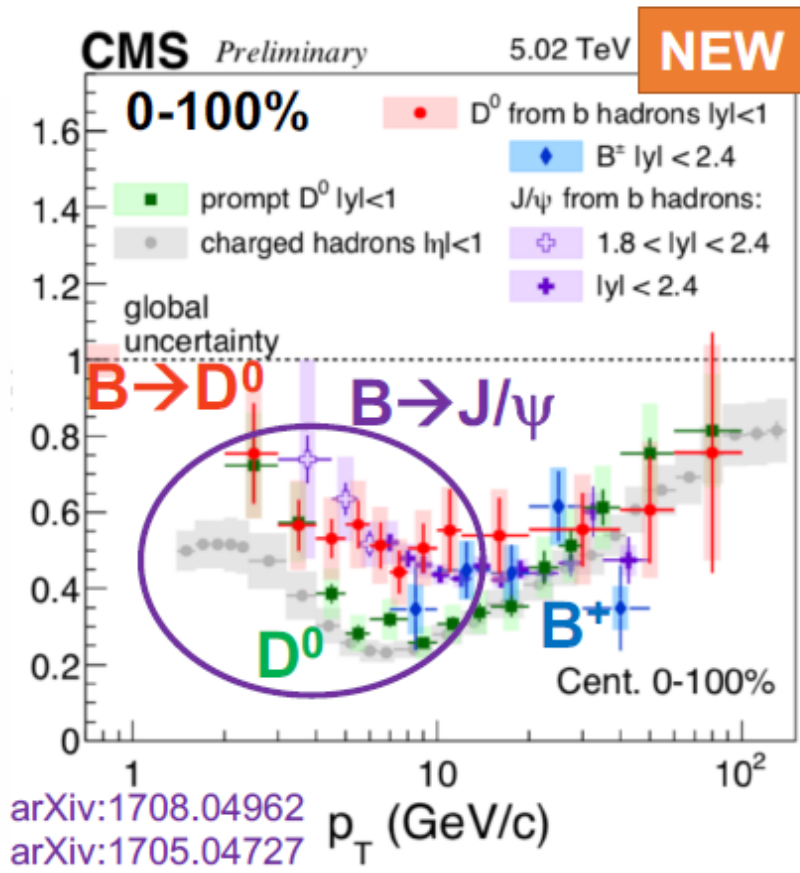
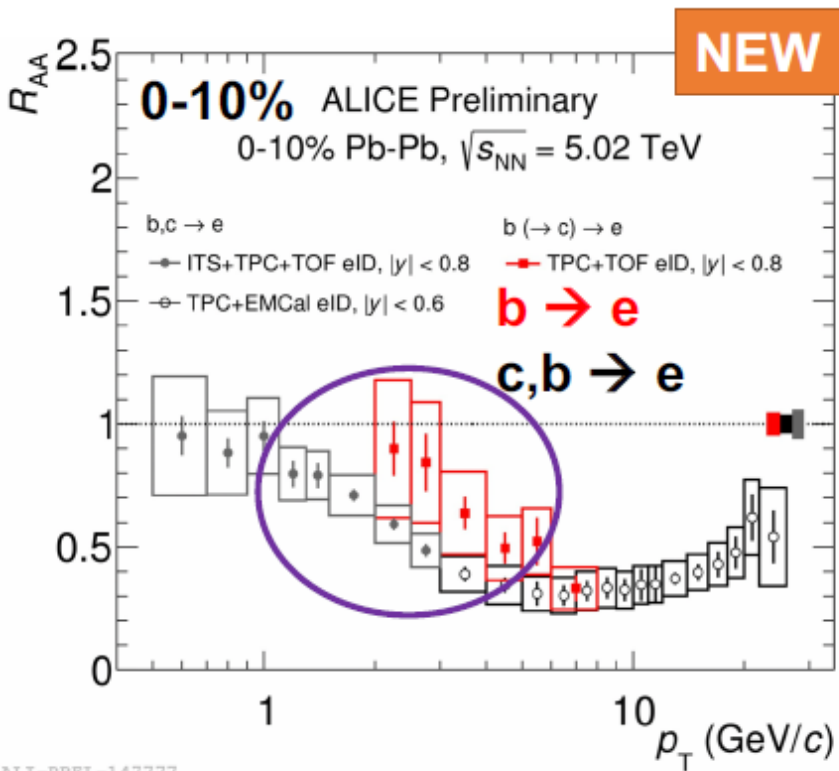


Smaller suppression for **electrons from B** than D at RHIC

First $v_2(b \rightarrow e)$ measurement at RHIC, consistent with zero within large uncertainty



Beauty at LHC



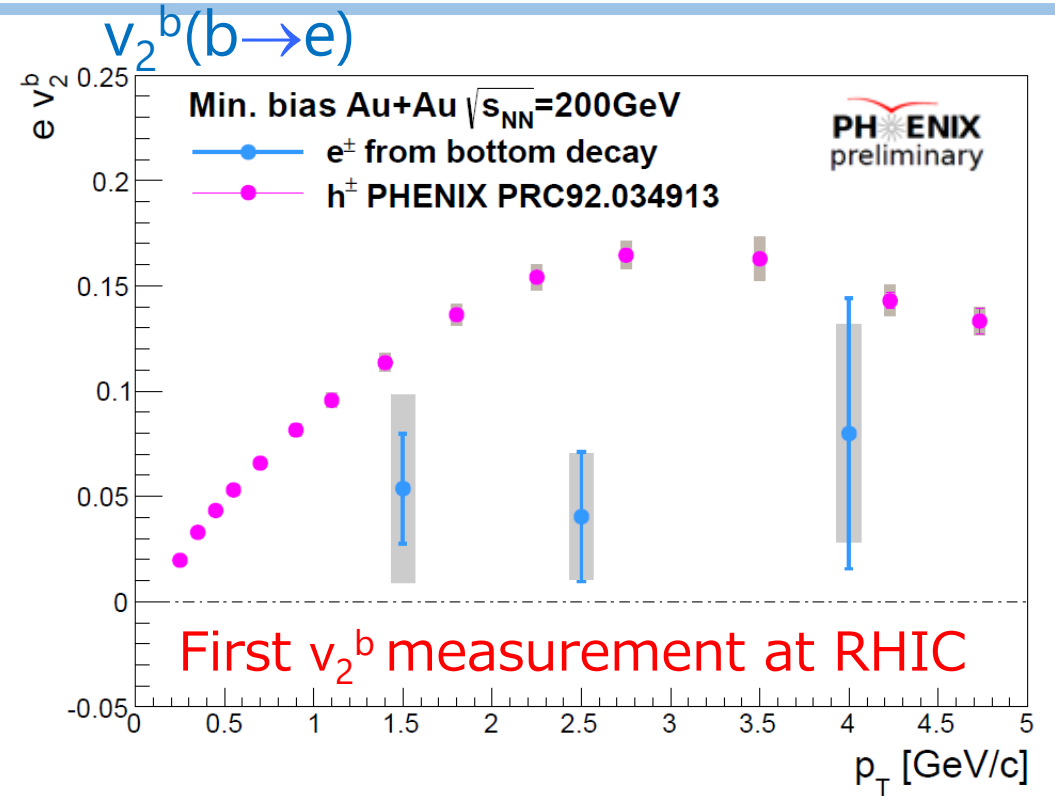
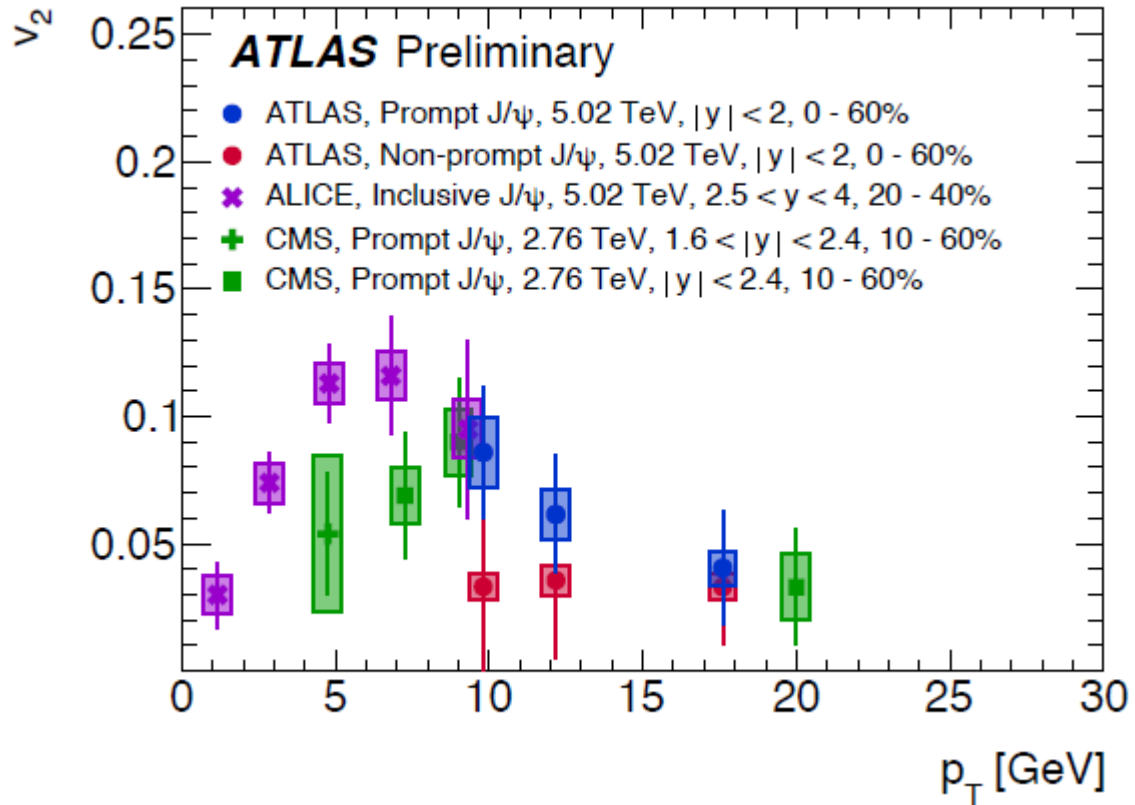
Hint of a **smaller suppression at low/intermediate p_T**

- **beauty-decay electrons** w.r.t electrons from charm+beauty
- **non-prompt J/ψ** and **non-prompt D^0** w.r.t D^0

Similar suppression at higher p_T . Flat suppression at high p_T ?

A. Dubla (Tue 15:00)
T-W. Wang (Wed 16:20)
Q. Hu (Wed 15:00)

B v2 @ LHC



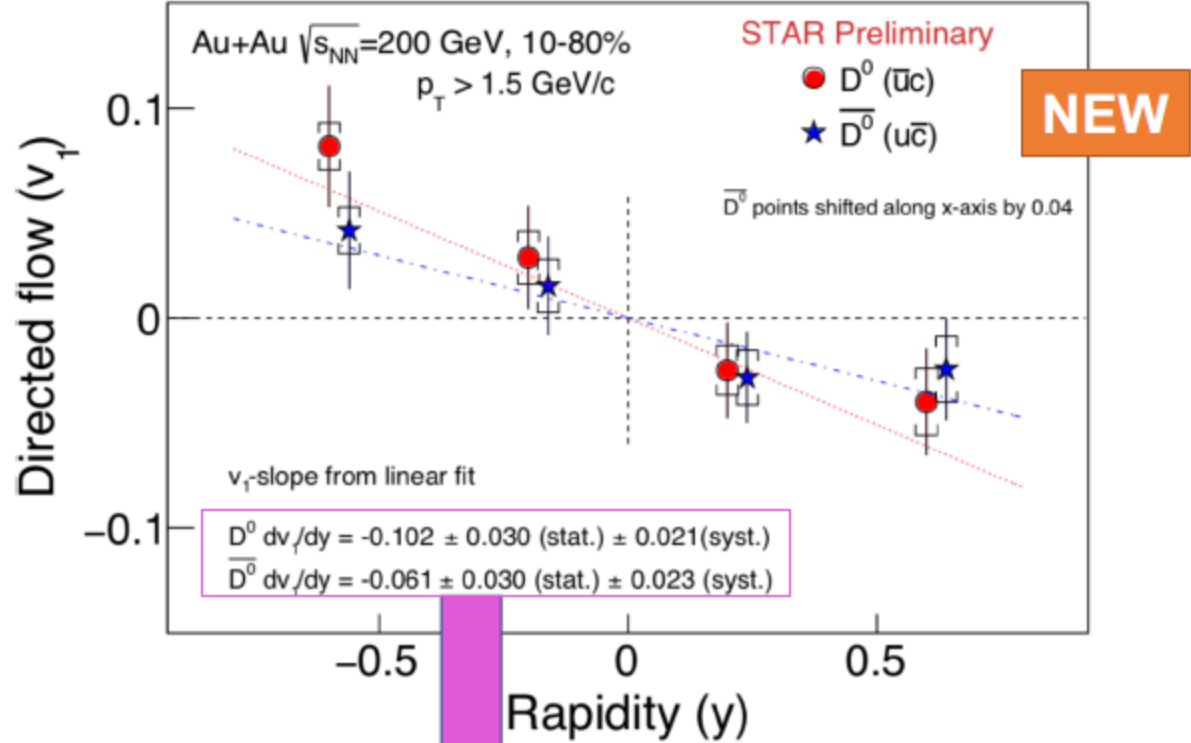
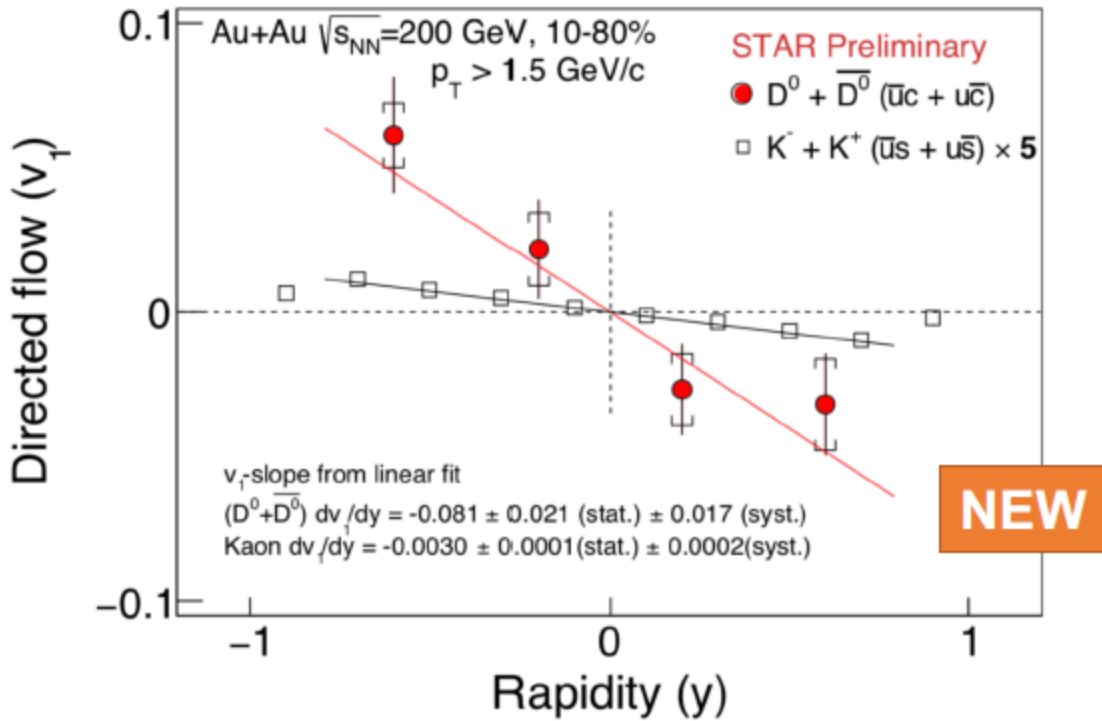
- b v2の測定もはじまり、 light partonのv2よりも小さい様子が見え始めている

Bottomの測定もRHIC, LHC共にかなり充実してきた。

PHENIX: electron, STAR: B→D

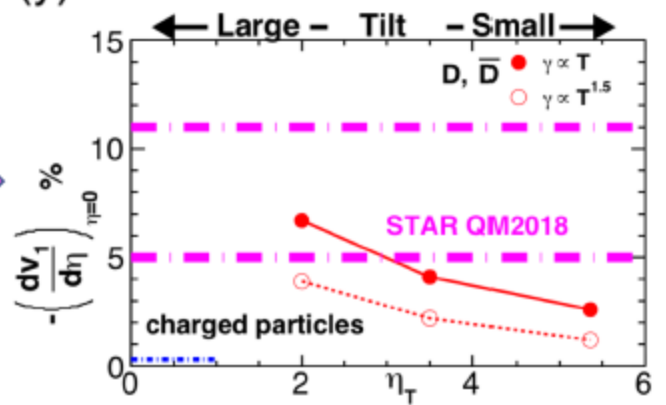
LHC: B→Jpsi, B→D

Directed flow v_1 with open heavy flavours



First observation of non-zero $D^0 v_1$
 $D^0 v_1$ -slope much larger than the kaons

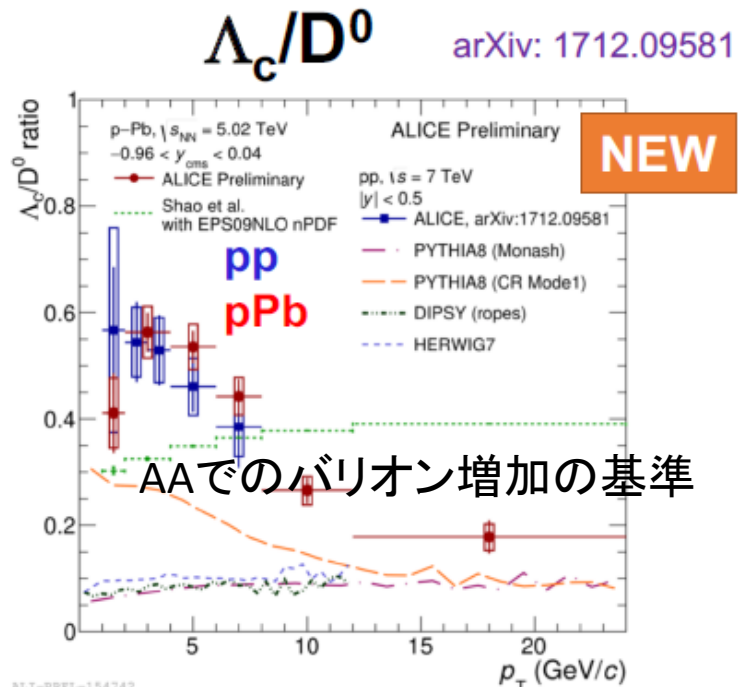
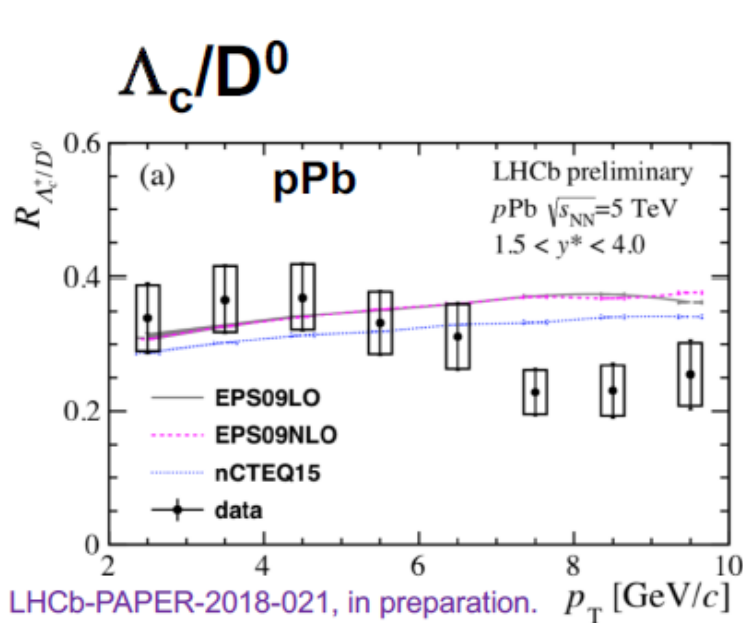
Qualitative trend in D^0 and $\bar{D}^0 v_1(y)$ close to interplay
 Hydro+EM model prediction



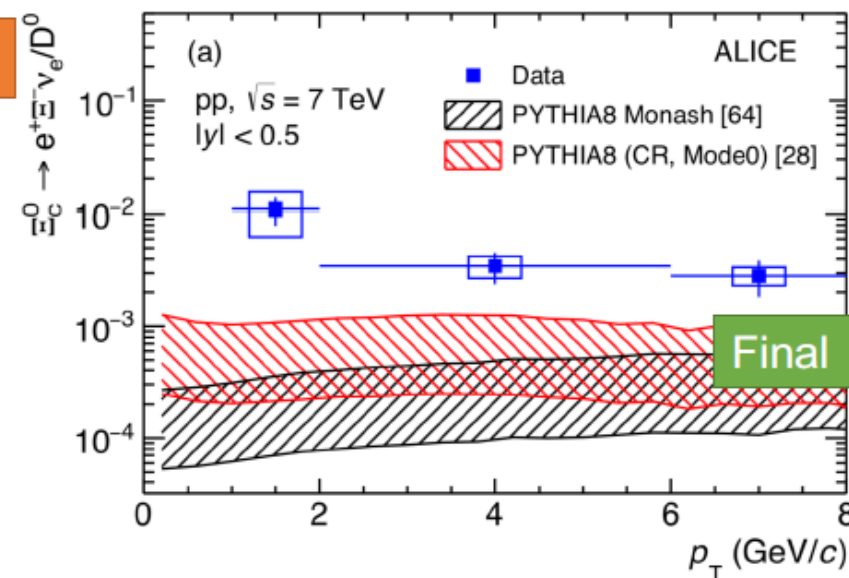
Chatterjee, Bozek, arXiv: 1804.04893

AAでのバリオン増加の基準

Charm baryons: understand hadronization



Ξ_c^0/D^0 Phys. Lett. B 781 (2018) 8



Λ_c^0/D^0 :

- compatible in **pp** and **p-Pb** collisions within uncertainties
- slight different in p-Pb at mid- and forward rapidity

LHCb@Fwd vs ALICE @ mid

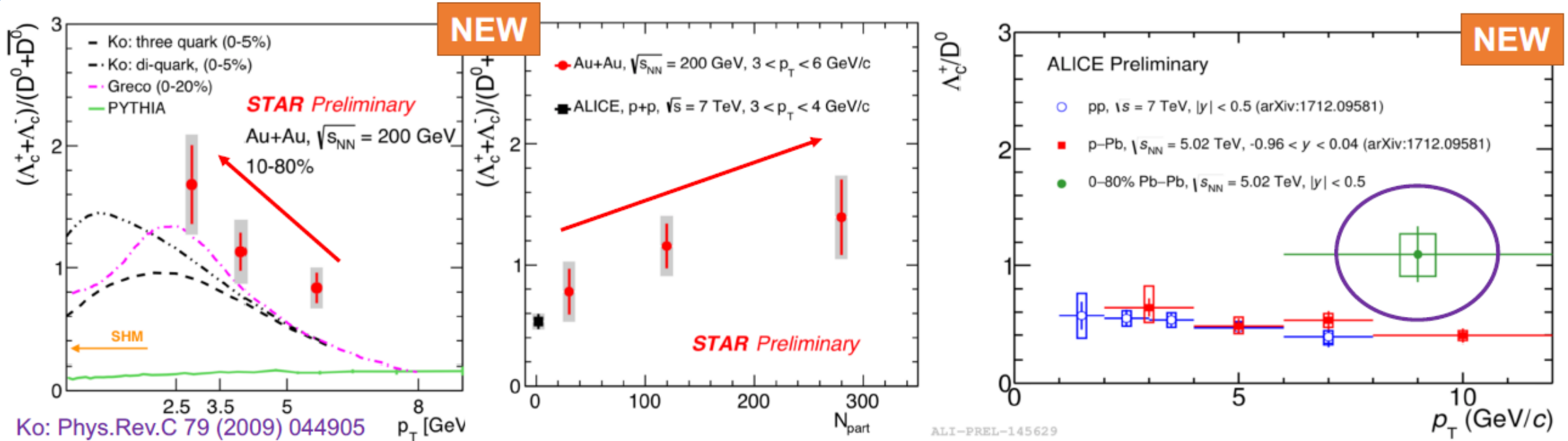
Λ_c^0/D^0 and Ξ_c^0/D^0

- At mid rapidity \rightarrow ratio higher than MC generators

Are we understanding **charm hadronization** ?

RHICや他のLHCでの測定が必要

Λ_c : insight into hadronization



Ko: Phys.Rev.C 79 (2009) 044905
 Greco: Eur.Phys.J.C (2018) 78:348
 SHM: Phys.Rev.C 79 (2009) 044905

Enhancement increases toward low p_T , increases from peripheral to central
 Similar Λ_c/D at RHIC and LHC (different p_T ranges)

Enhancement larger than models based on fragmentation + recombination

Crucial measurement to extract **total $c\bar{c}$ cross section !**

S. Radhakrishnan (Tue 15:50)
 X. Peng (Wed 09:20)

• その他のバリオン? Bバリオン?

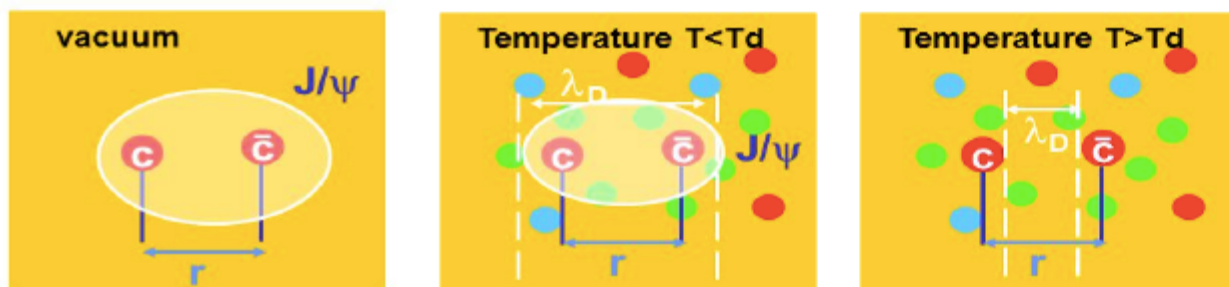
Heavy Flavor summary

- PP: 生成メカニズムの実験的な理解
 - RHIC: B: pair creation, D: Flavor excitation,
 - LHC: B: smaller gluon splitting, D:
- pA:
 - CNM効果 (No suppression)
- AA
 - Charm, Bottom のRAA、 v_2 の測定が充実してきた
 - $RAA(D) < RAA(B)$ @ mid-pTがRHIC, LHCの両方で見えている。
 - Charmの v_2 は、Light hadronとConsistent
 - Bottomの v_2 、
 - RHICでは初測定しかし、zero-consistent,
 - LHCでは、non-zero@High pT (energy loss効果のL依存)
- チャームバリオン増加
 - RHIC, LHCの両方で見られた。 Recombinationの結果と考えられる。

Quarkonia

Quarkonia as a QGP probe

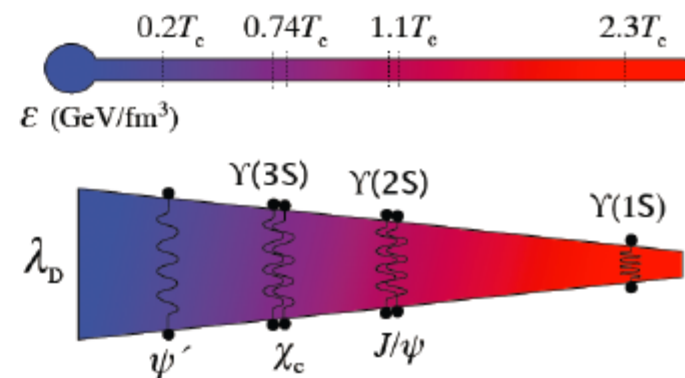
- **Early creation:** experience entire evolution of quark-gluon plasma
- **Proposed signature of deconfinement:** quark-antiquark potential color-screened by surrounding partons \rightarrow *dissociation*
 - **J/ψ suppression was proposed as a direct proof of QGP formation** T. Matsui and H. Satz PLB 178 (1986) 416



QGP中にとどまっているときの描像

$$r_{q\bar{q}} \sim 1 / E_{binding} > r_D \sim 1 / T$$

- **“Thermometer”:** different states dissociate at different temperatures \rightarrow *sequential suppression*



	J/ψ	ψ(2S)	Υ(1S)	Υ(2S)	Υ(3S)
E_b (MeV)	~ 640	~ 60	~ 1100	~ 500	~ 200

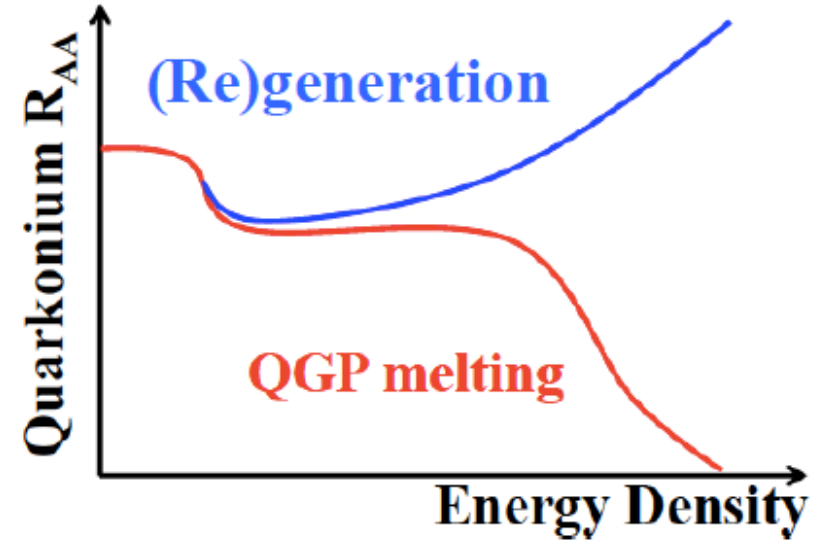
ややこしいこと

そもそもどうやって生成するのか、よくわかっていない。それでもp+p, p+A, A+Aの比較からQGP効果を読み取る

Other effects

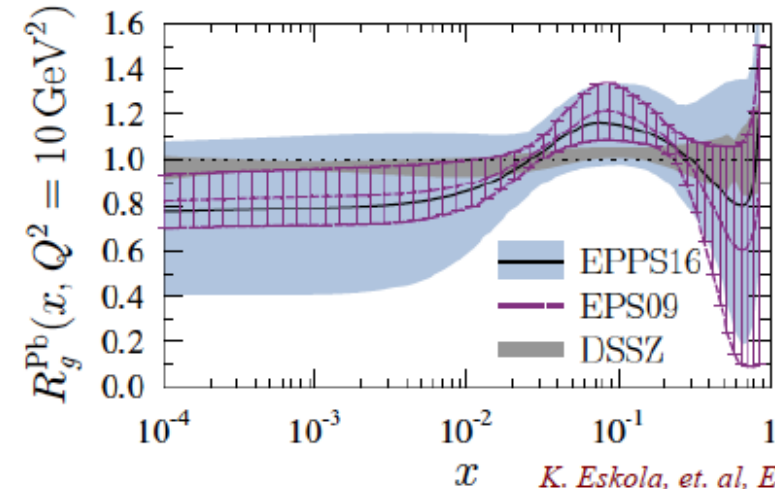
- **(Re)generation**
 - *Deconfinement is a prerequisite*
 - Depend on species, energy, p_T , etc
- Medium-induced energy loss
 - Color-octet states; parton fragmentation
- Formation time
- **Feed-down contributions**

チャームでは顕著。
ボトムにはない予想。



Cold nuclear matter effects (CNM)

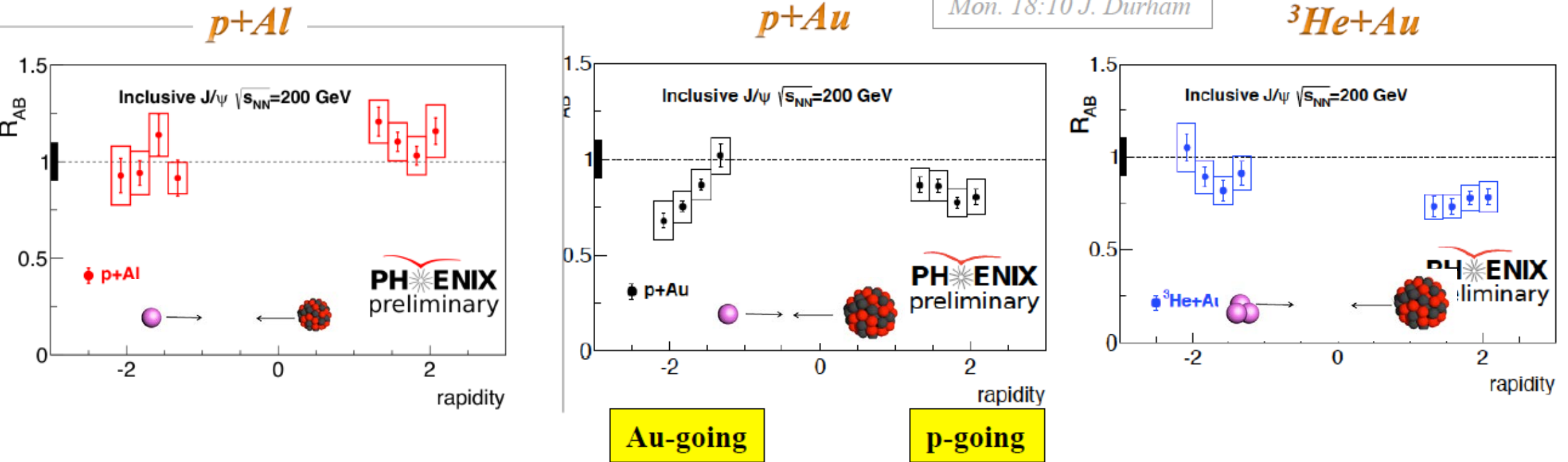
- nPDF: shadowing/anti-shadowing
- Coherent energy loss
- Nuclear absorption
- Interact with co-movers



K. Eskola, et. al, EPJC 77 (2017) 163

Large- y J/ψ in small system at RHIC

Mon. 18:10 J. Durham

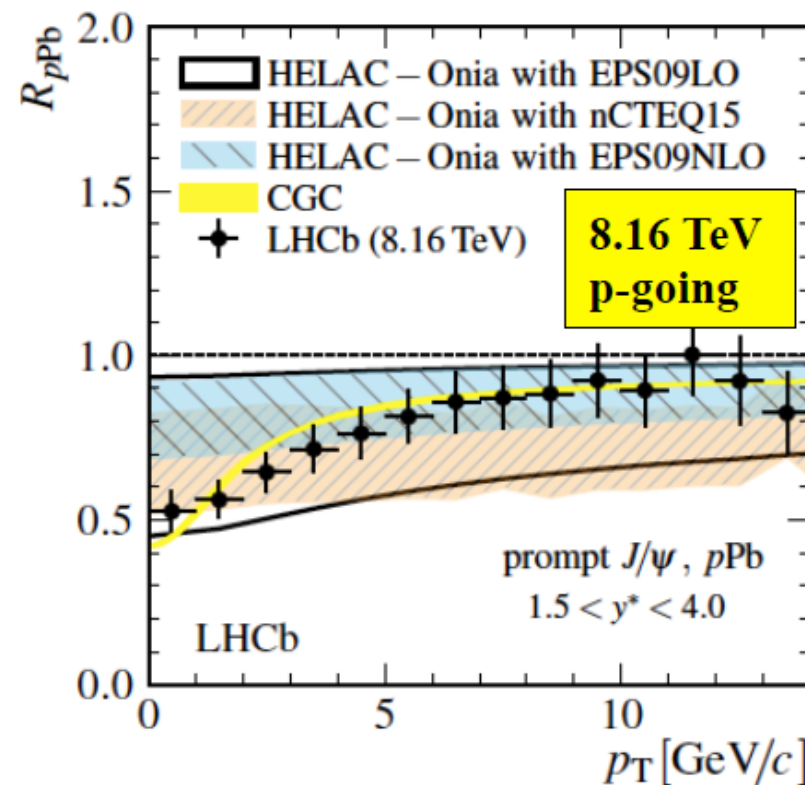
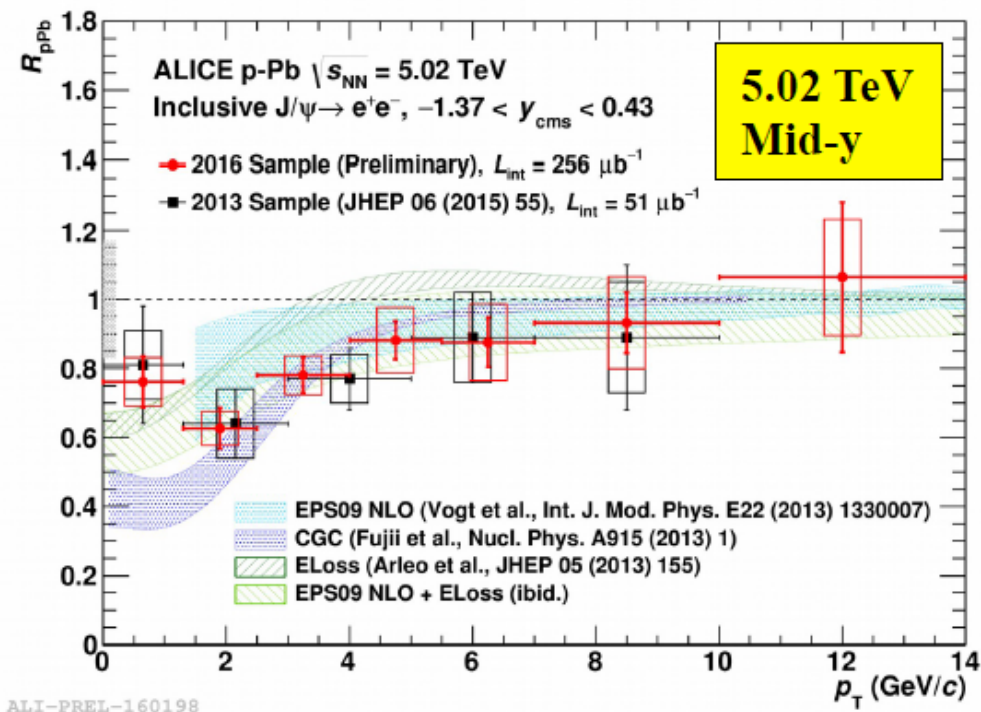


- $p/{}^3He$ -going: about 10-20% suppression with Au nuclei. Consistent with shadowing expectation
- Au/Al-going: indication of suppression in $p+Au$ collisions?

J/ψ Production in pPb

Wed. 16:50 B. Paul

Tue. 12:50 S. Chen



- Low p_T : significant suppression; High p_T : much smaller CNM effects
- While consistent with nPDF effects, data provide constraints on gluon distribution at low-x.

ALICE-PUBLIC-2018-007
 LHCb: PLB 774 (2017) 159

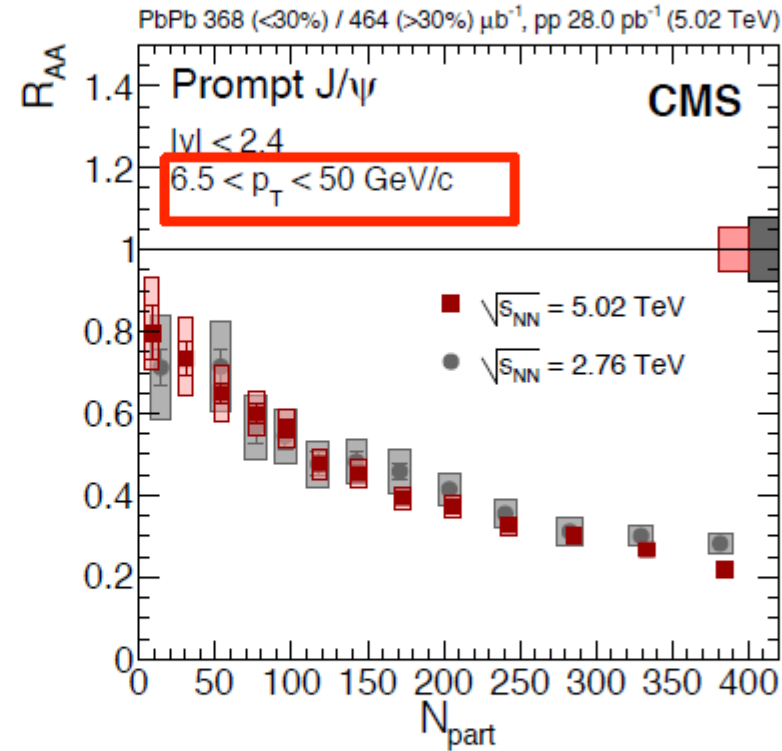
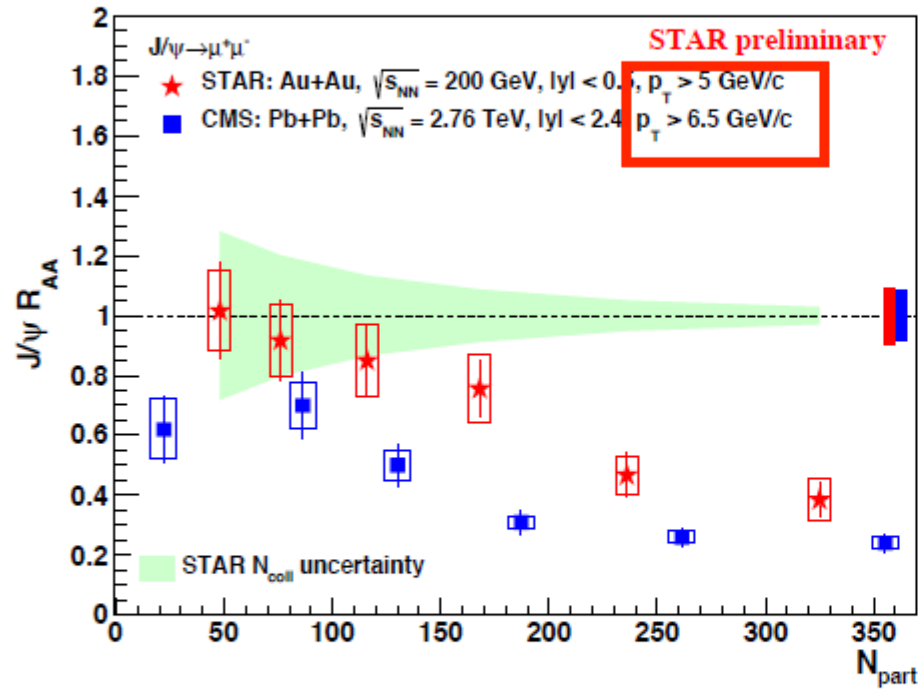
高統計データにより測定精度が向上

ハードプローブで探るQGP物性 蜂谷 崇

High- $p_T J/\psi$: RHIC vs. LHC

CMS: JHEP 05 (2012) 063

CMS: arXiv:1712.08959



- Unlike low p_T , R_{AA} decreases towards central collisions
 - CNM & regeneration effects small
- $R_{AA}^{RHIC} \gtrsim R_{AA}^{LHC/2.76TeV} \gtrsim R_{AA}^{LHC/5.02TeV}$

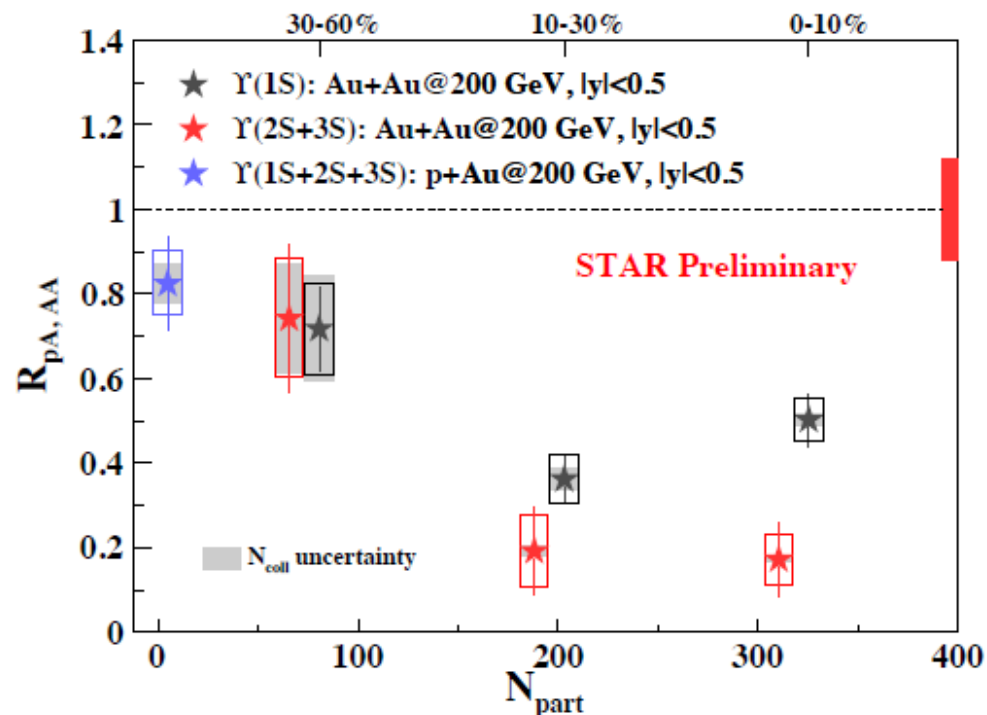


Dissociation
In Effect

Sequential Suppression for Bottomonium

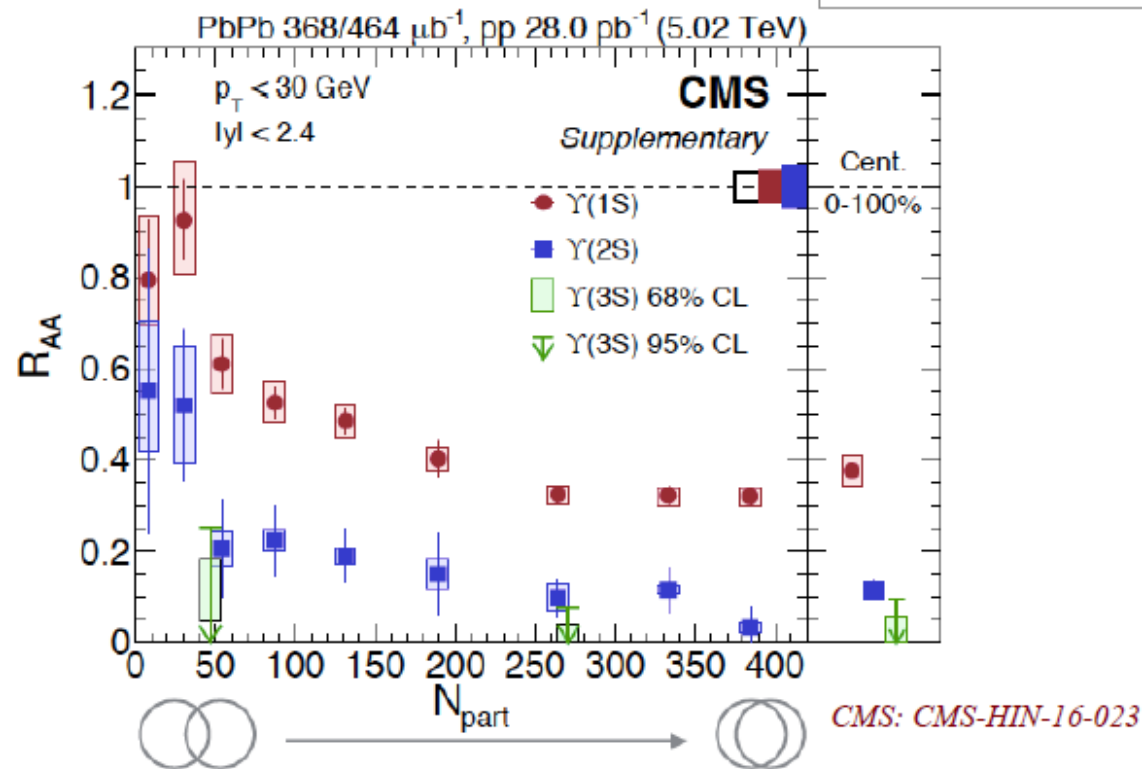
Tue. 11:10 P. Wang

Au+Au @ 200 GeV

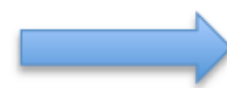


Pb+Pb @ 5.02 TeV

Tue. 11:30 S. Tuli



- $R_{AA}^{peri} > R_{AA}^{cent}$: increasing hot medium effects
- RHIC: $R_{AA}^{Y(2S+3S)} < R_{AA}^{Y(1S)}$ in 0-10% central
- LHC: $R_{AA}^{Y(3S)} < R_{AA}^{Y(2S)} < R_{AA}^{Y(1S)}$ in all centrality

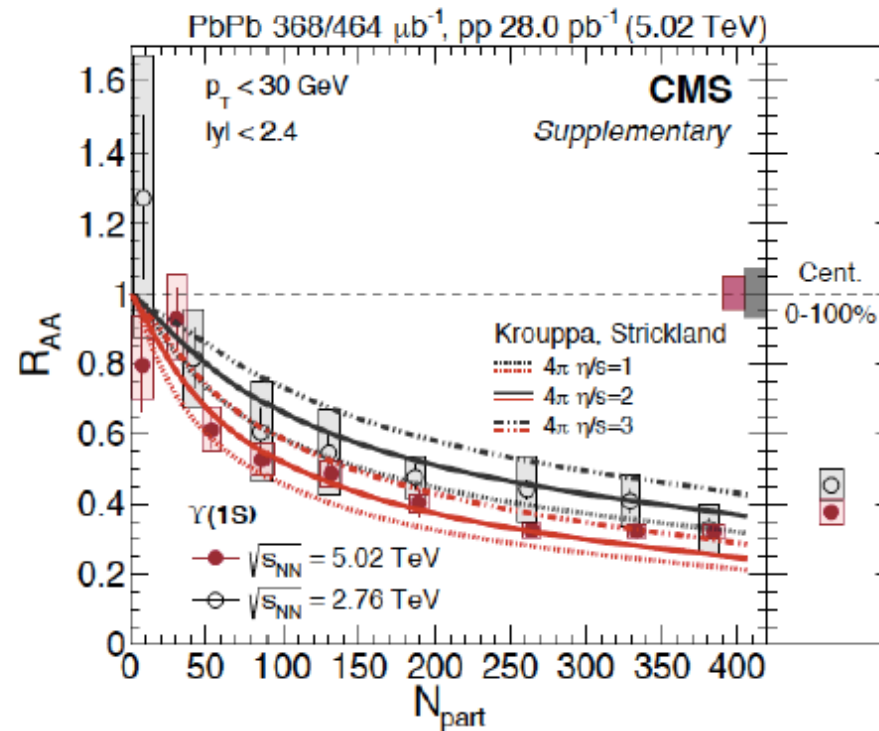
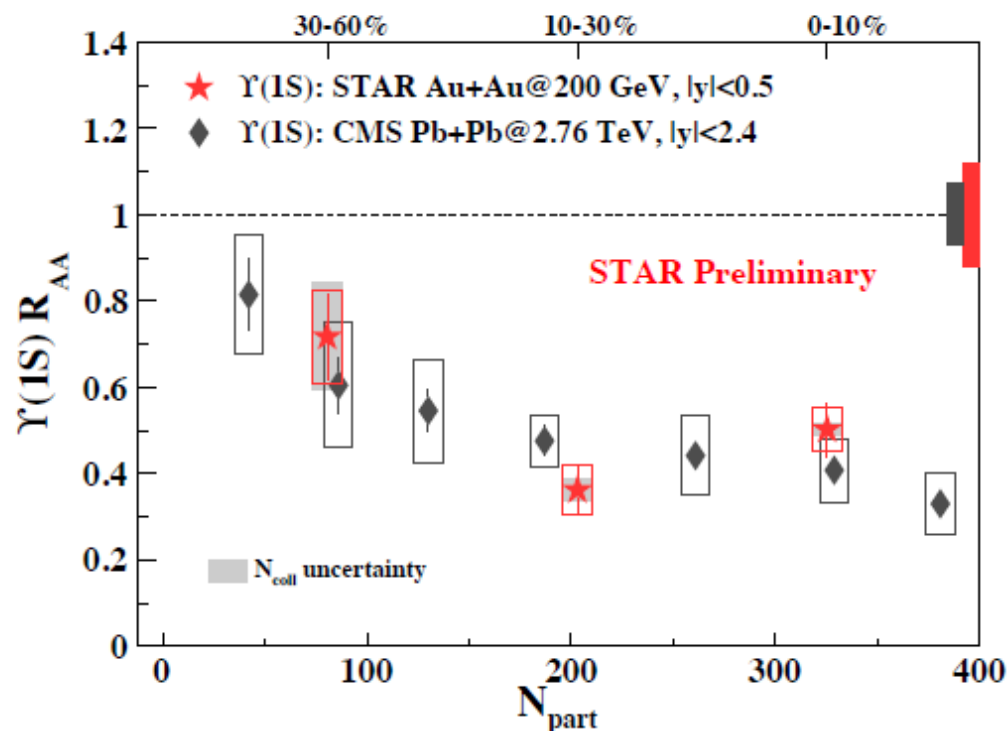


**sequential
suppression**

Inclusive $\Upsilon(1S) R_{AA}$: RHIC vs. LHC

0.2 TeV vs. 2.76 TeV vs. 5.02 TeV

CMS: CMS-HIN-16-023
CMS: PLB 770 (2017) 357

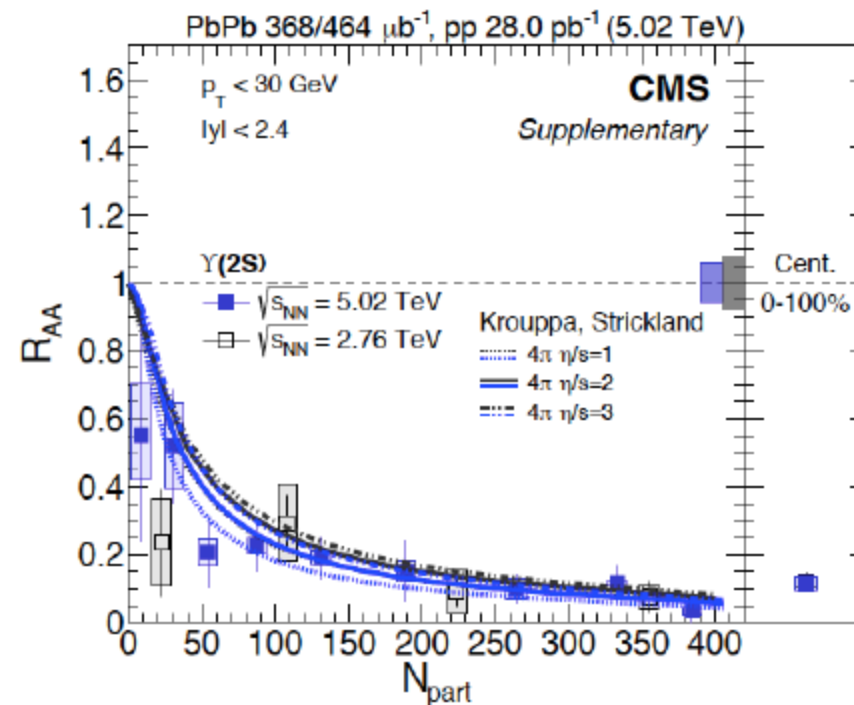
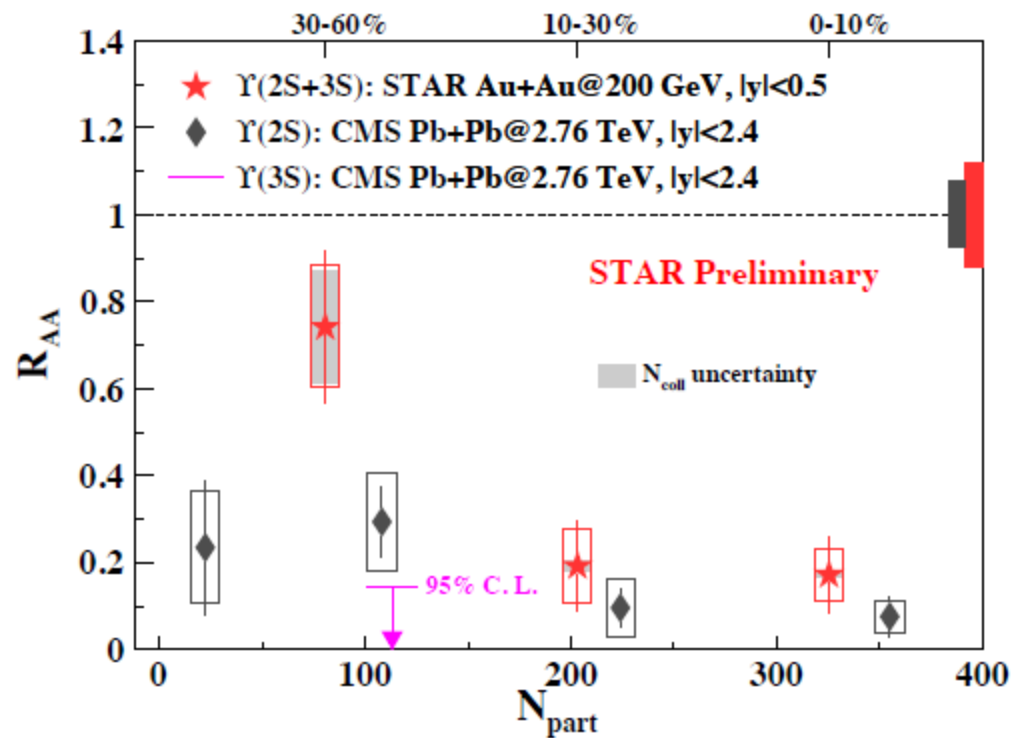


- $R_{AA}^{\text{RHIC}} \sim R_{AA}^{\text{LHC}/2.76\text{TeV}}$: likely due to CNM + suppression of excited states
- $R_{AA}^{\text{LHC}/2.76\text{TeV}} > \sim R_{AA}^{\text{LHC}/5.02\text{TeV}}$: onset of direct $\Upsilon(1S)$ suppression?

Excited ΥR_{AA} : RHIC vs. LHC

0.2 TeV vs. 2.76 TeV vs. 5.02 TeV

CMS: CMS-HIN-16-023
CMS: PLB 770 (2017) 357

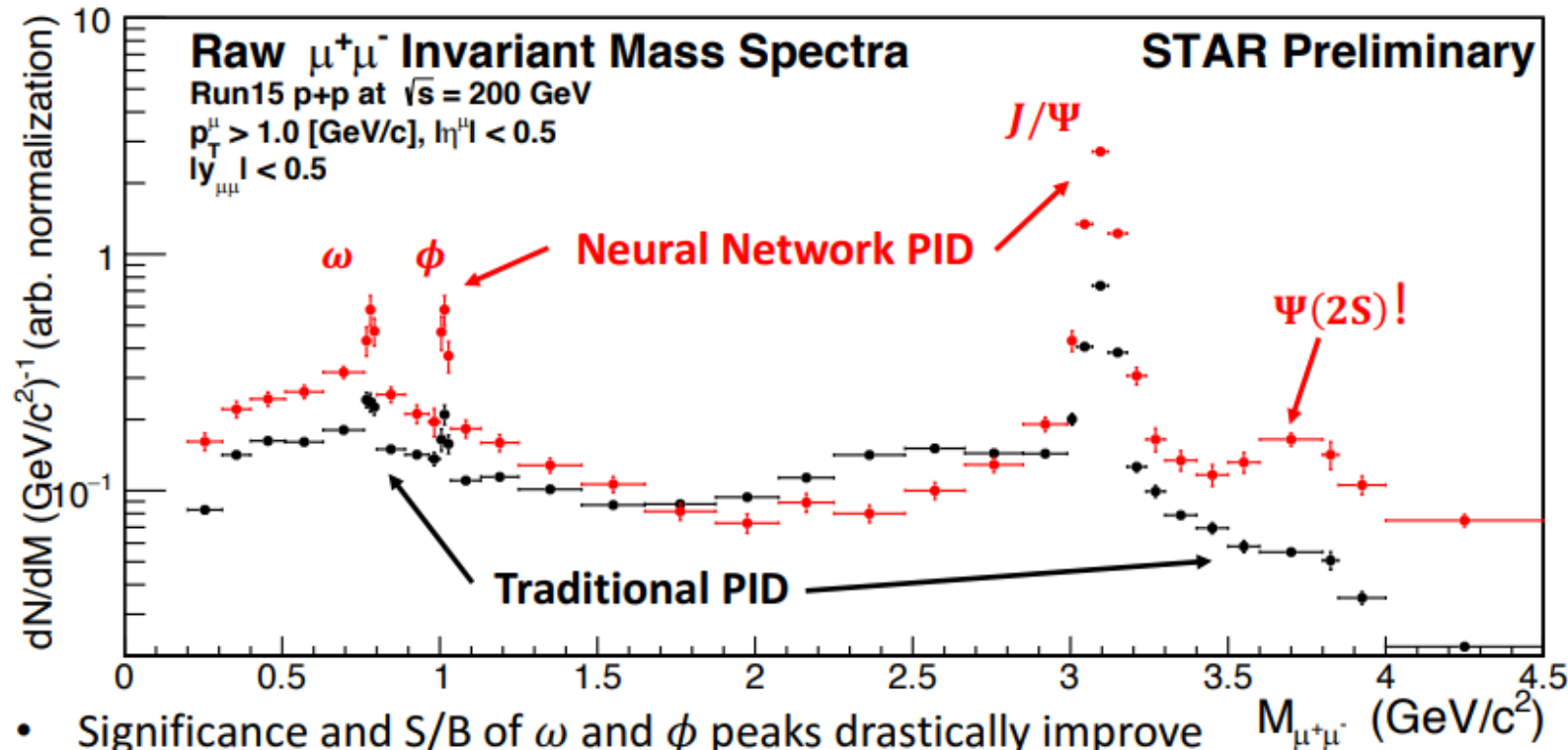
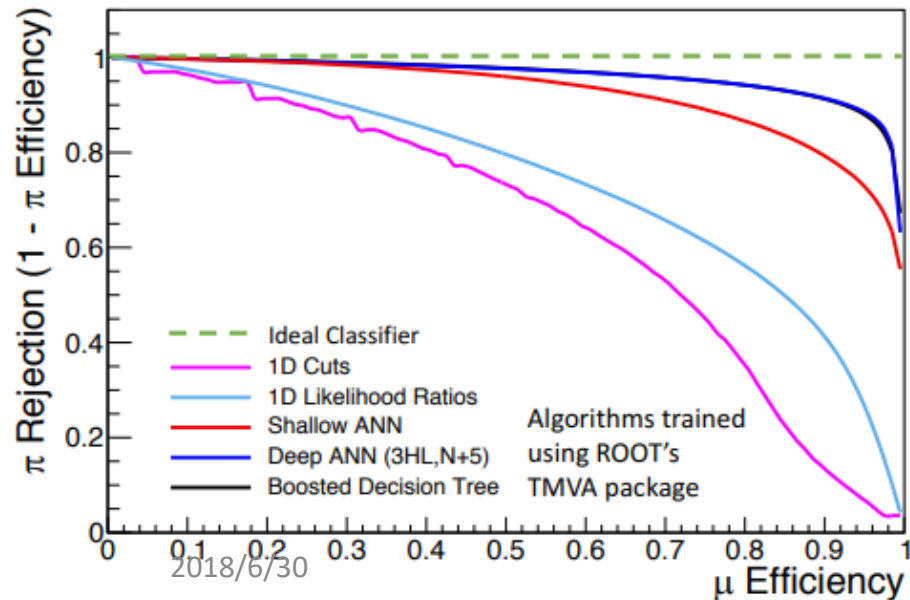
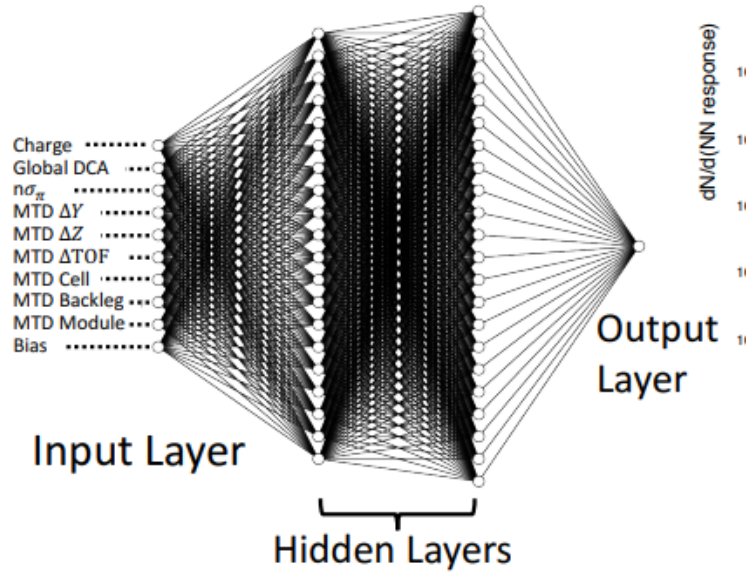


- $R_{AA}^{\text{RHIC}} > \sim R_{AA}^{\text{LHC}/2.76\text{TeV}}$: indication of less melting at RHIC peripheral?
- $R_{AA}^{\text{LHC}/2.76\text{TeV}} \sim R_{AA}^{\text{LHC}/5.02\text{TeV}}$: complete dissociation in the medium

Quarkonia summary

- pA
 - Low p_T での抑制が見えている。 CNM効果。 AAの解釈に反映。
 - (見せていない) : Non-zero J/ψ v_2
- AA
 - High p_T J/ψ : more suppression at central collisions
 - Sequential melting of Upsilon at RHIC and LHC w/ improved precision
 - Direct $Y(1s)$ の抑制が見えているかも@5TeV
 - (見せていない) J/ψ in Xe+Xe
 - (見せていない) J/ψ non-zero v_2
 - J/ψ vs $\Psi(2s)$ at RHIC?

Analysis improved by new NN PID

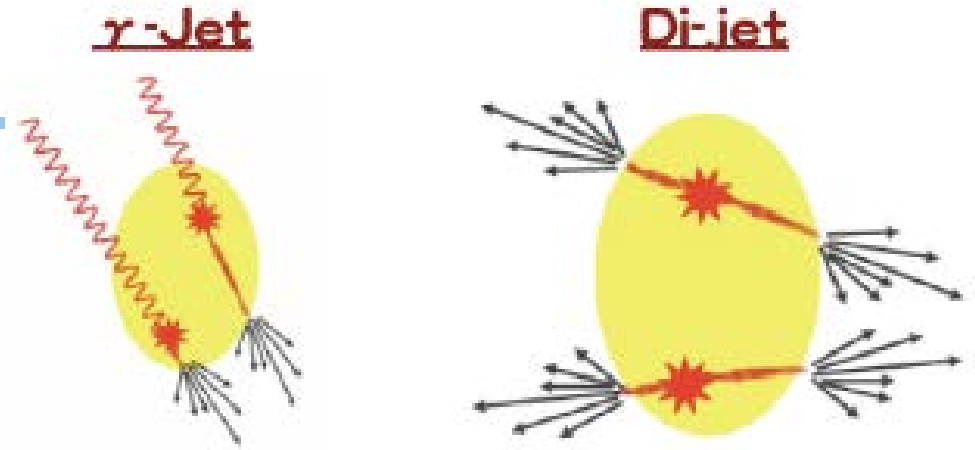


- Significance and S/B of ω and ϕ peaks drastically improve
- Measurement of $\Psi(2S)$ possible with neural net PID
- ➔ Neural network clearly out-performs traditional identification techniques

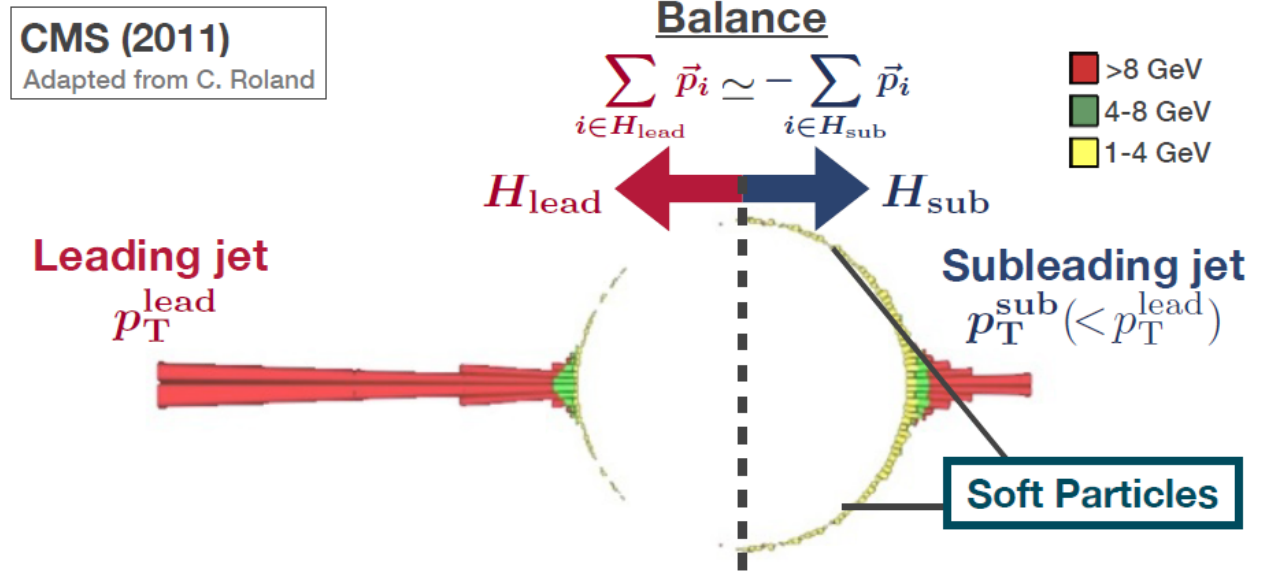
Jet

JET測定

- QGP物質中でどれくらい変わるかを測定する
 - 量が減るか
 - 形が変わるか
- Fragmentation FunctionやJet Balanceの変化
 - Single Jet
 - Di-Jet
 - Gamma – Jet (理想的なプローブ)
- Jet mass
 - VirtualityがQGP中で変わるか？



Redistribution of the jet energy and momentum



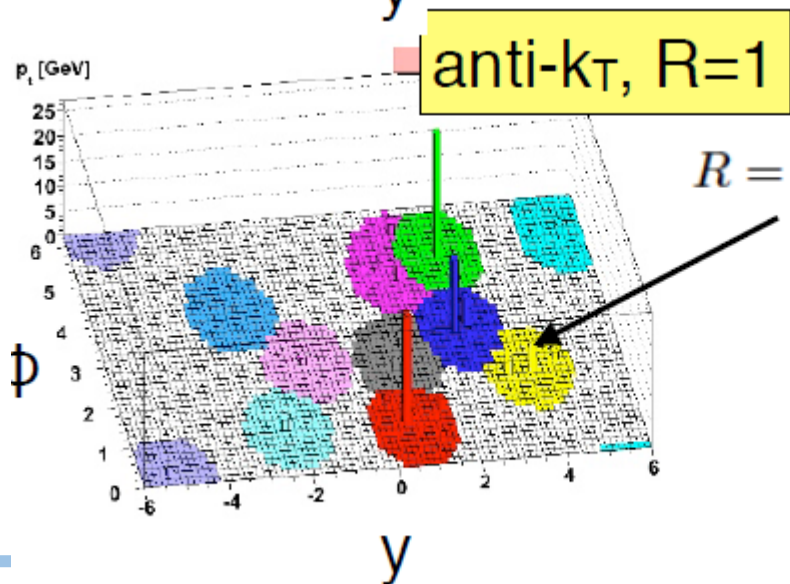
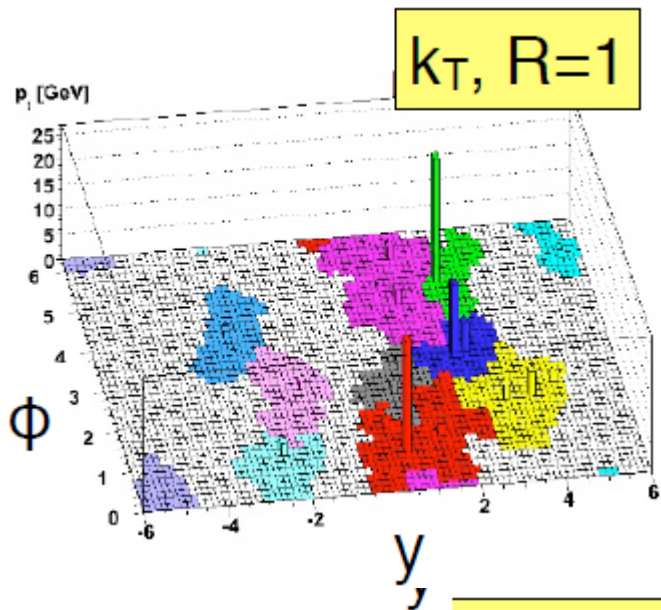
Result from entire processes in jet quenching

Jet測定

2. Sequential recombination algorithm:

- Cluster pairs of objects close in relative p_T
- Define "distance" between pairs
- ◆ k_T algorithm
 - Starting from low p_T particle
 - Standard algorithm for BG estimation
- ◆ anti- k_T algorithm
 - Starting from high p_T particle
 - Standard algorithm in HIC

Radius parameter:
decide the resolution scale



$$R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

Large radius parameter

Small radius parameter
→ jet splitting

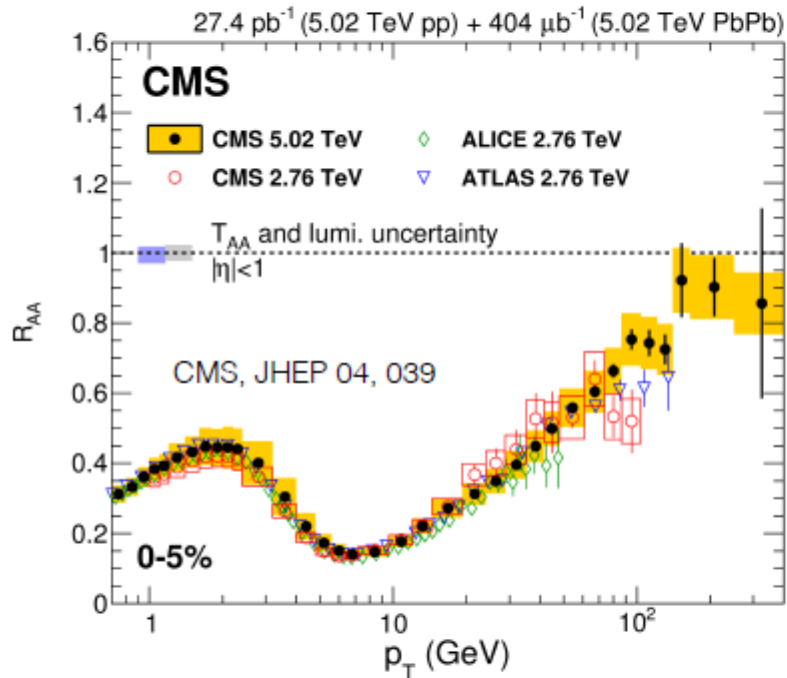


$\Delta R = 0.2, 0.3, 0.4, 0.5$ are used in LHC analyses

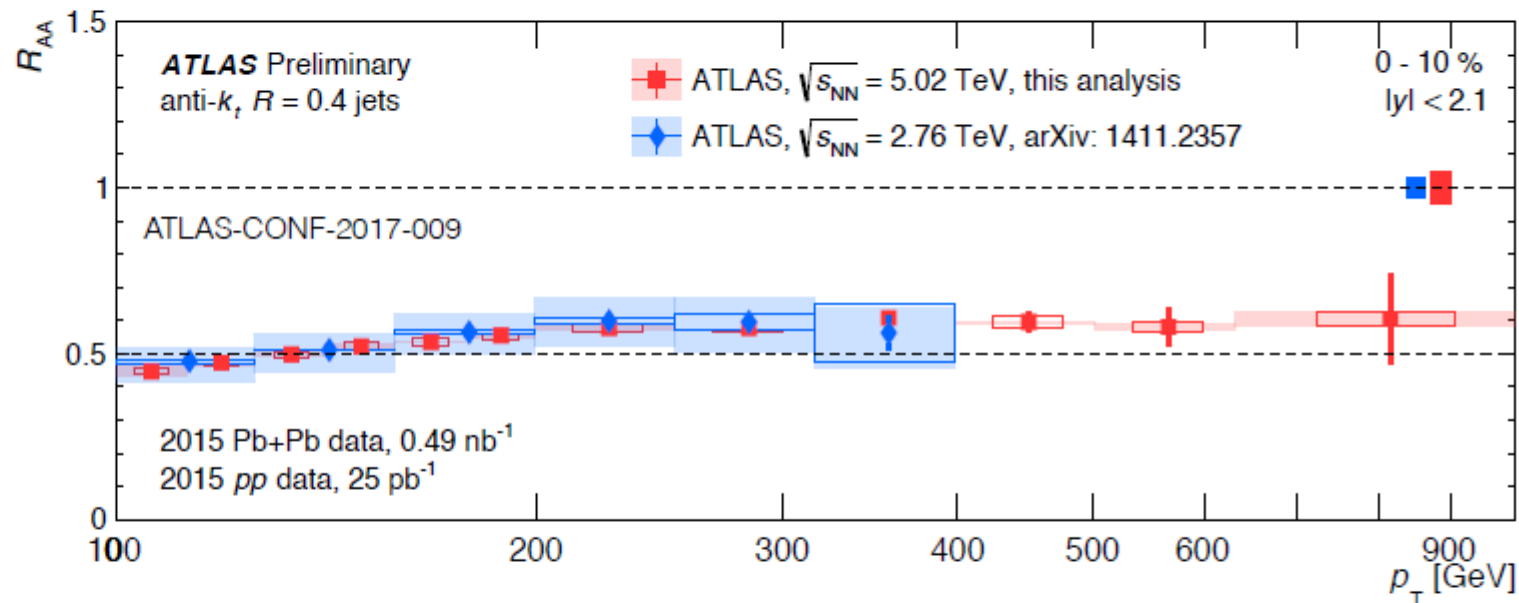
R:大 Jet全体=最初期のパートン
R:小 部分Jet=ちぎれたジェットの一部

High- p_T jets vs hadrons

Charged particle R_{AA}



Jet R_{AA}



Jets: $R_{AA} < 1$ out to high p_T

p_T -dependence:

Single particles: consistent with expected constant ($\log E$) dependence

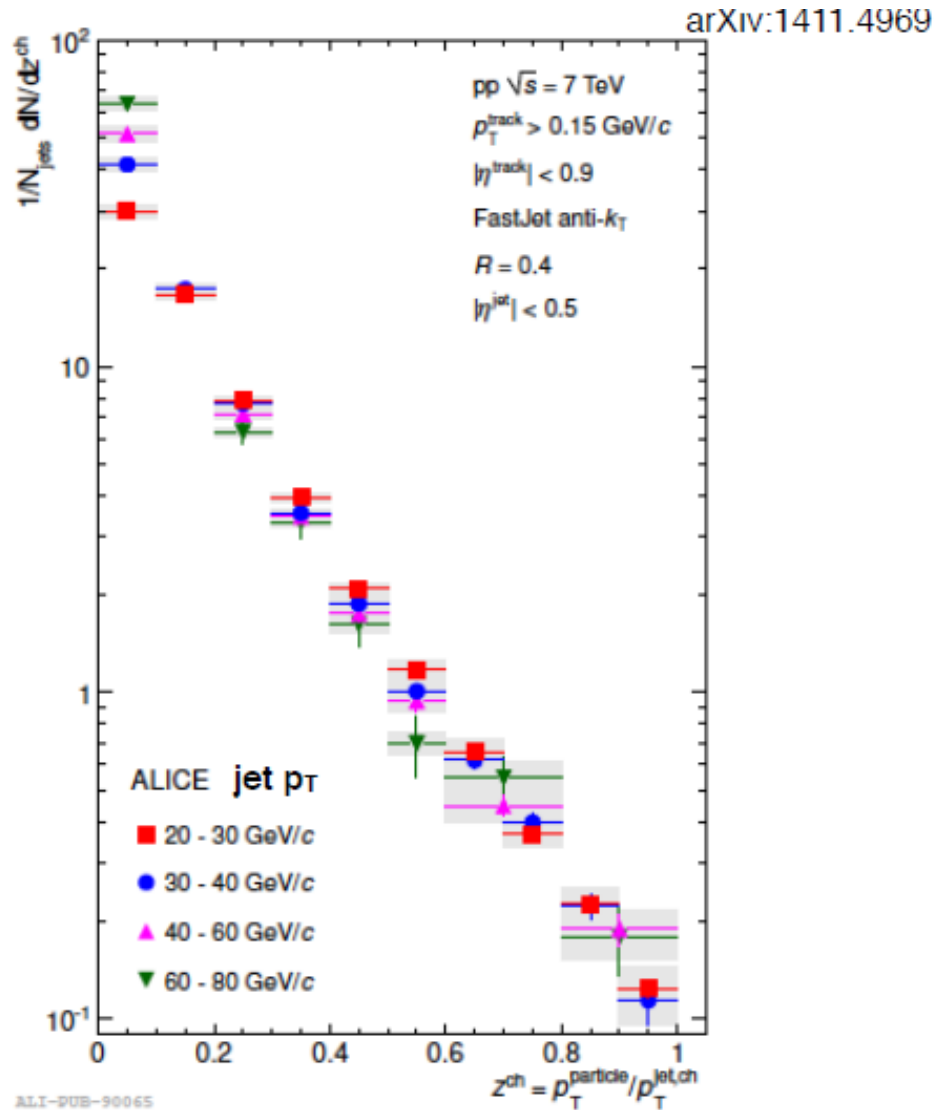
Jets: suggest increase of ΔE vs E

Tentative interpretation: in jets, multiple partons lose energy; more partons in high- E jets \Rightarrow more E -loss

- High p_T で分布がshallowになるため、 dE が同じ場合、 R_{AA} は小さくなるはず。

Fragmentation Function in pp

$$D_{h|k}(z), z = p_h/p_k$$



右下がりの分布

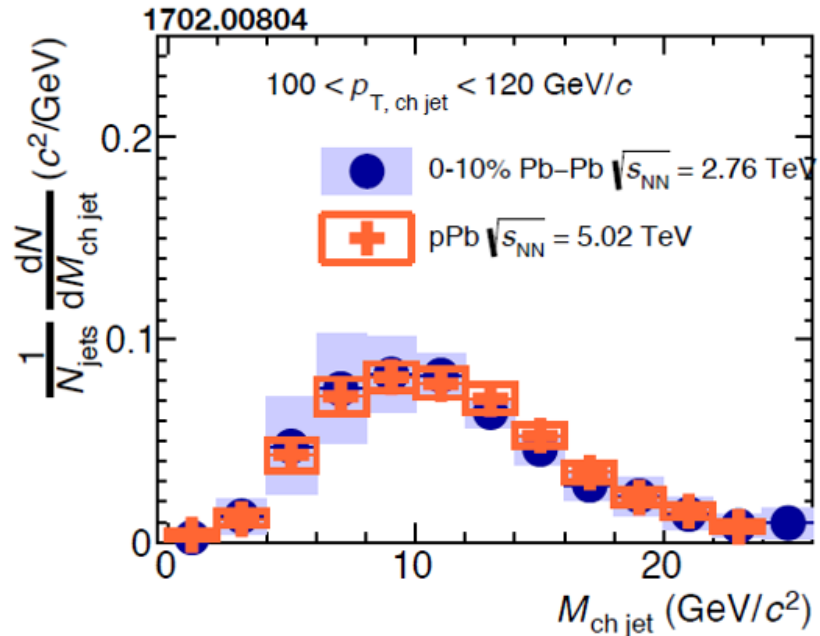
AAとPPを比較する

R_Z : FFのAAとPPとの比

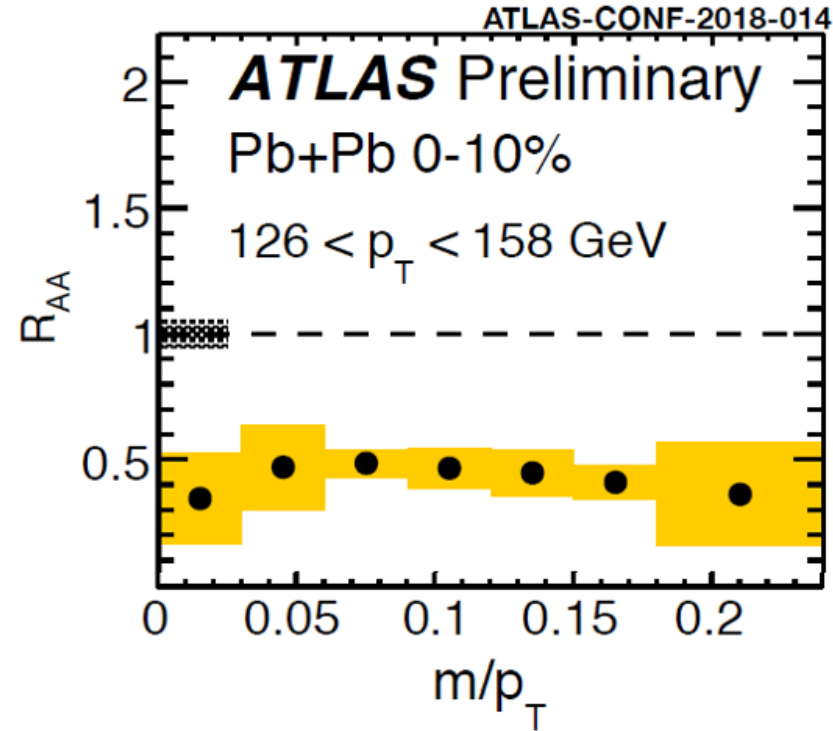
Jet Mass = Virtuality: jetの太さ

mass of the jet

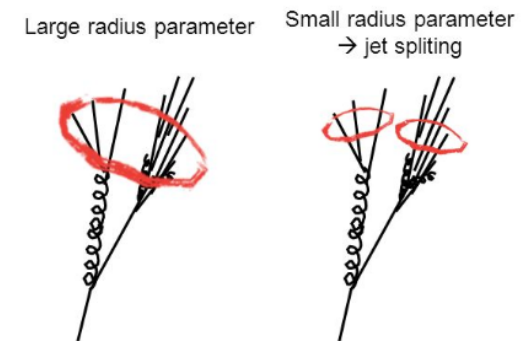
ALICE: mass from charged particles



ATLAS: mass from calorimeter towers



Radius parameter:
decide the resolution scale



$\Delta R = 0.2, 0.3, 0.4, 0.5$ are used in LHC analyses

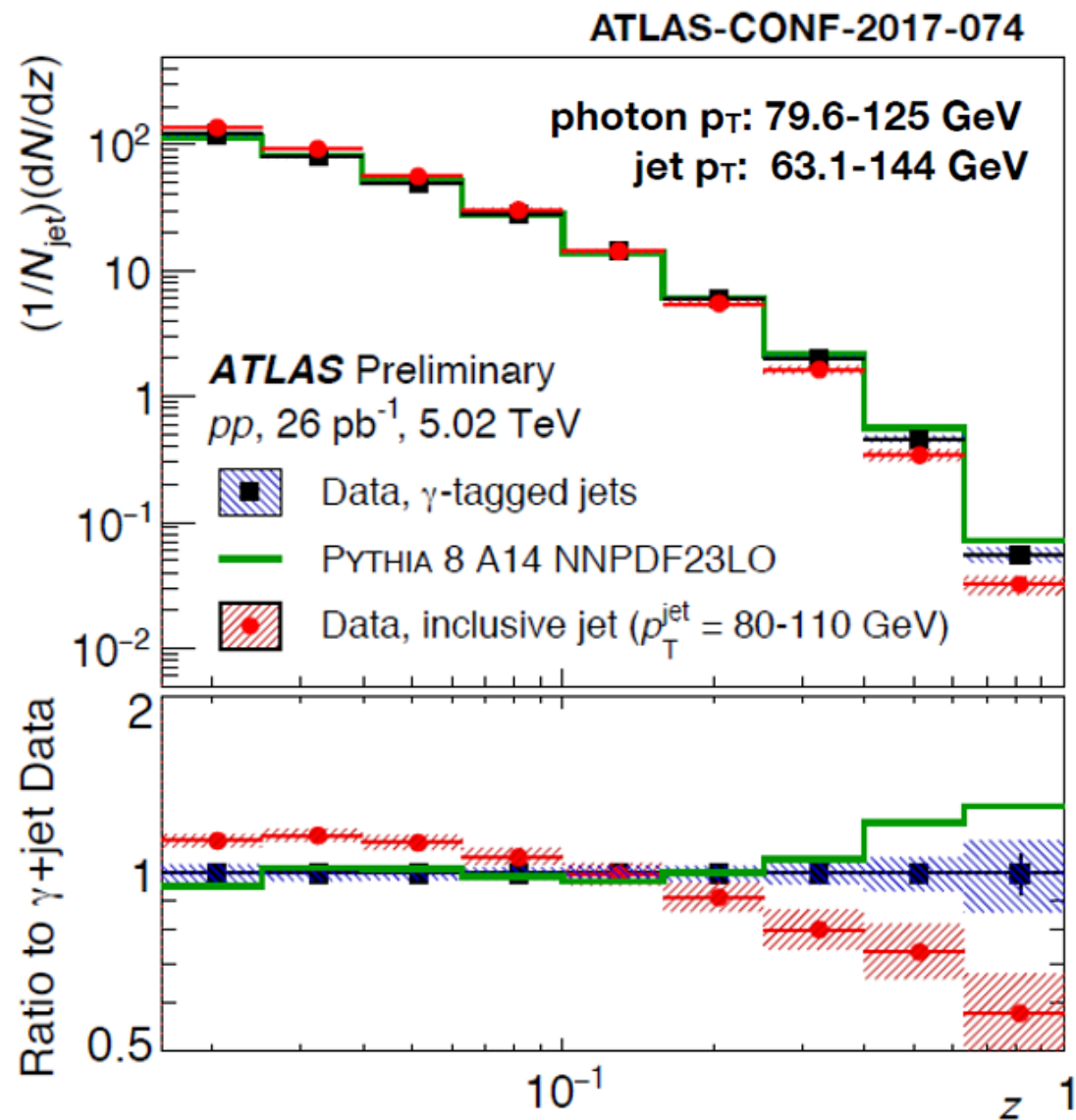
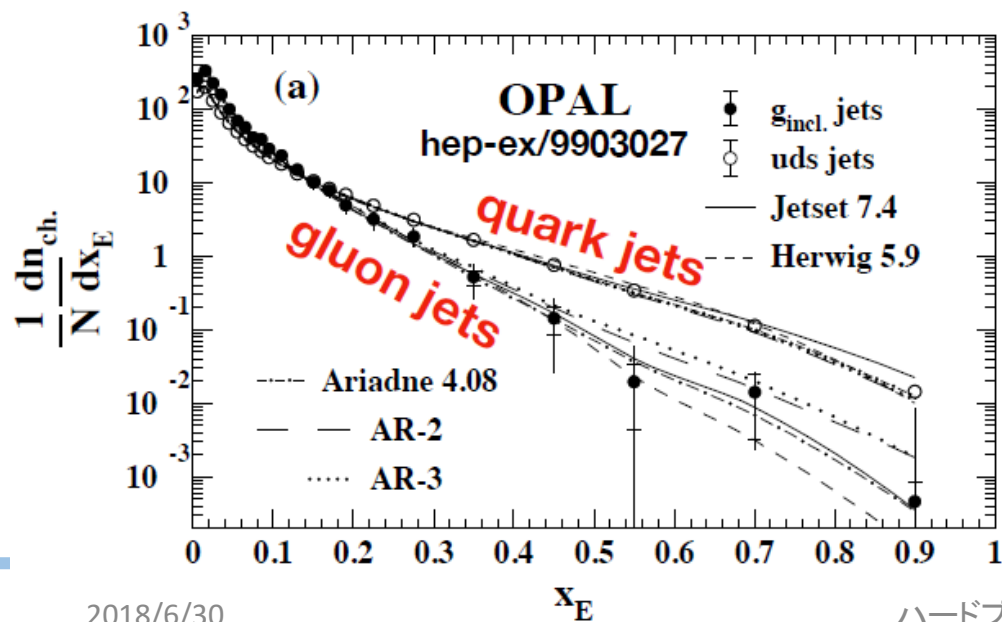
- Jetの構造をみるためのパラメータ。
- パートン-QGPの相互作用により、変化すると予想。
- 結果

- AAとpAが一致。 → R=0.4は小さく、QGPを抜けた後のJETを見ている可能性

Photon- Jet measurement

- photon-jet events dominated by $q + g \rightarrow q + \gamma$ process
- changes the flavor mix with respect to inclusive jets

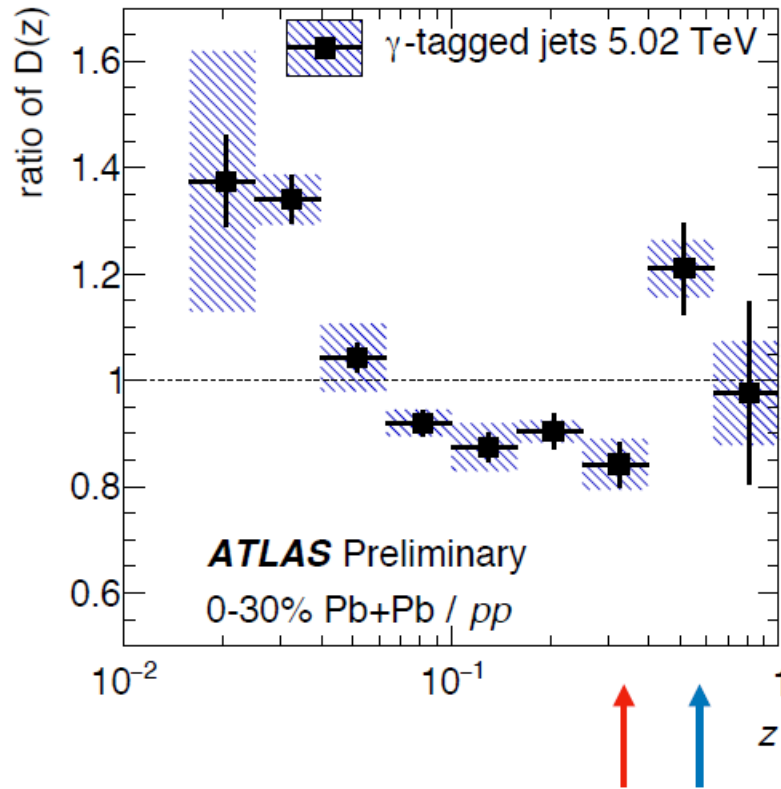
Inclusive Jet : gluon dominant
 Photon- Jet : quark dominant



- significant difference between **inclusive** and **γ -tagged** fragmentation functions

photon-jet fragmentation functions

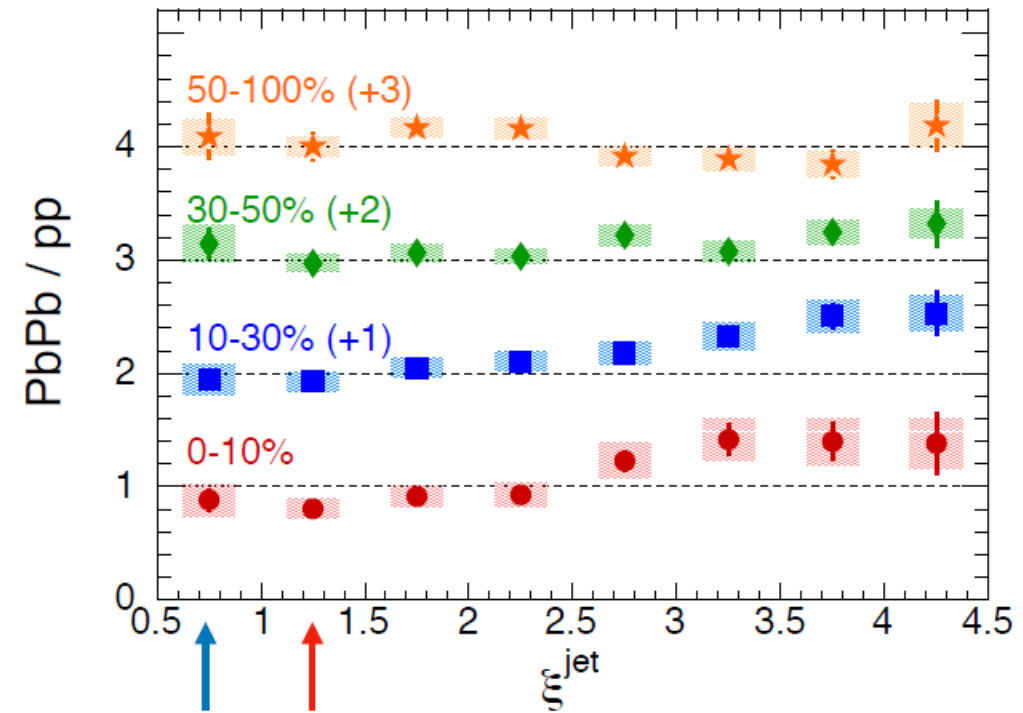
photon p_T : 79.6-125 GeV
jet p_T : 63.1-144 GeV



ATLAS-CONF-2017-074

$$\xi_{\text{jet}} = \ln(1/z)$$

photon p_T : > 60 GeV
jet p_T : > 30 GeV



Kaya Tatar, Tuesday CMS: 1801.04895

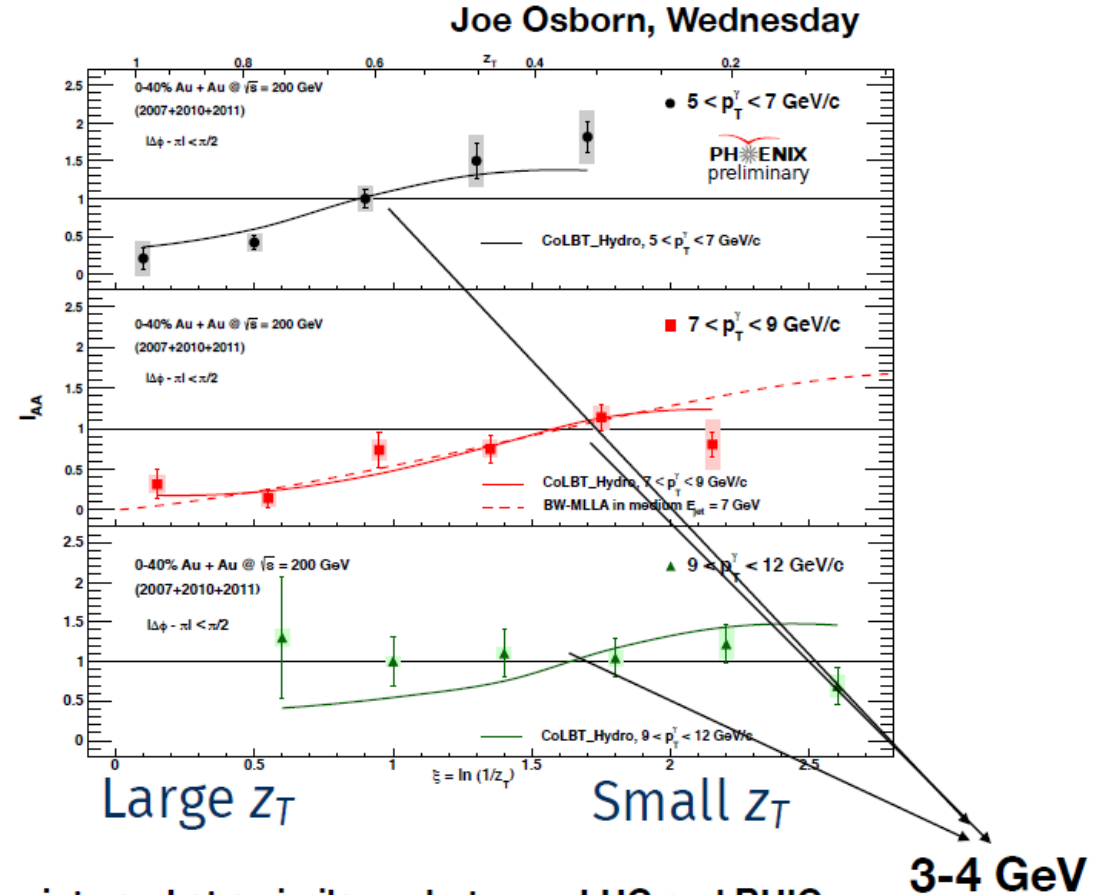
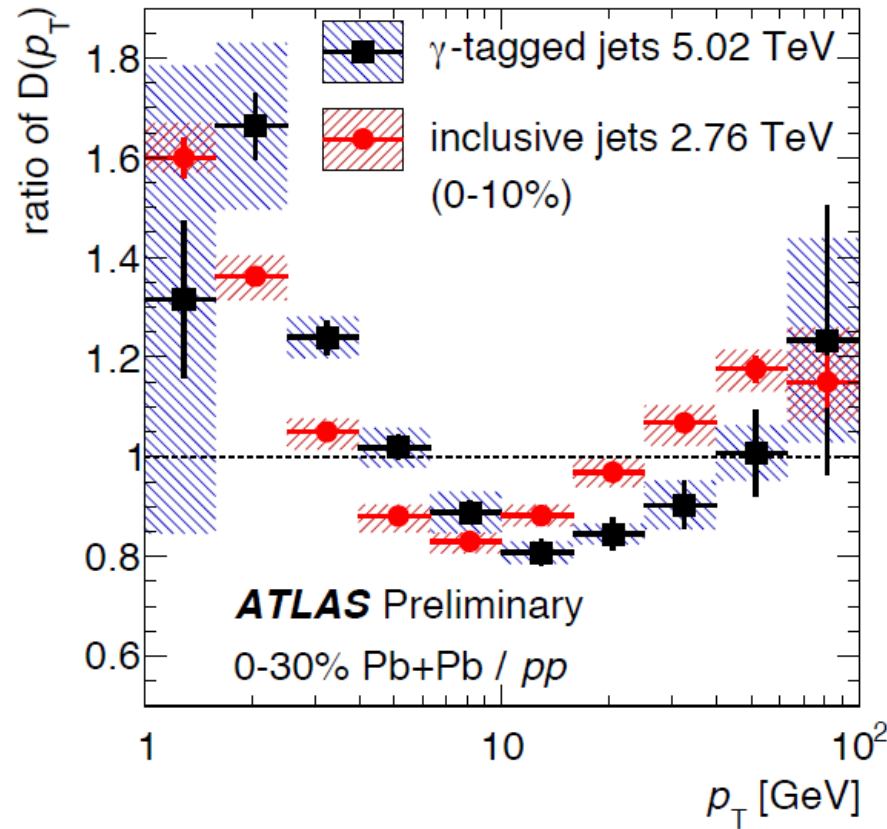
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- Hi-Z : R_z はフラット : high p_T 粒子の E_{loss} は一定
- Low-Z: R_z の増加 : Low p_T 粒子の増加 ~ 損失 E の再分配の結果

photon-tagged fragmentation functions

photon p_T : 79.6-125 GeV
jet p_T : 63.1-144 GeV

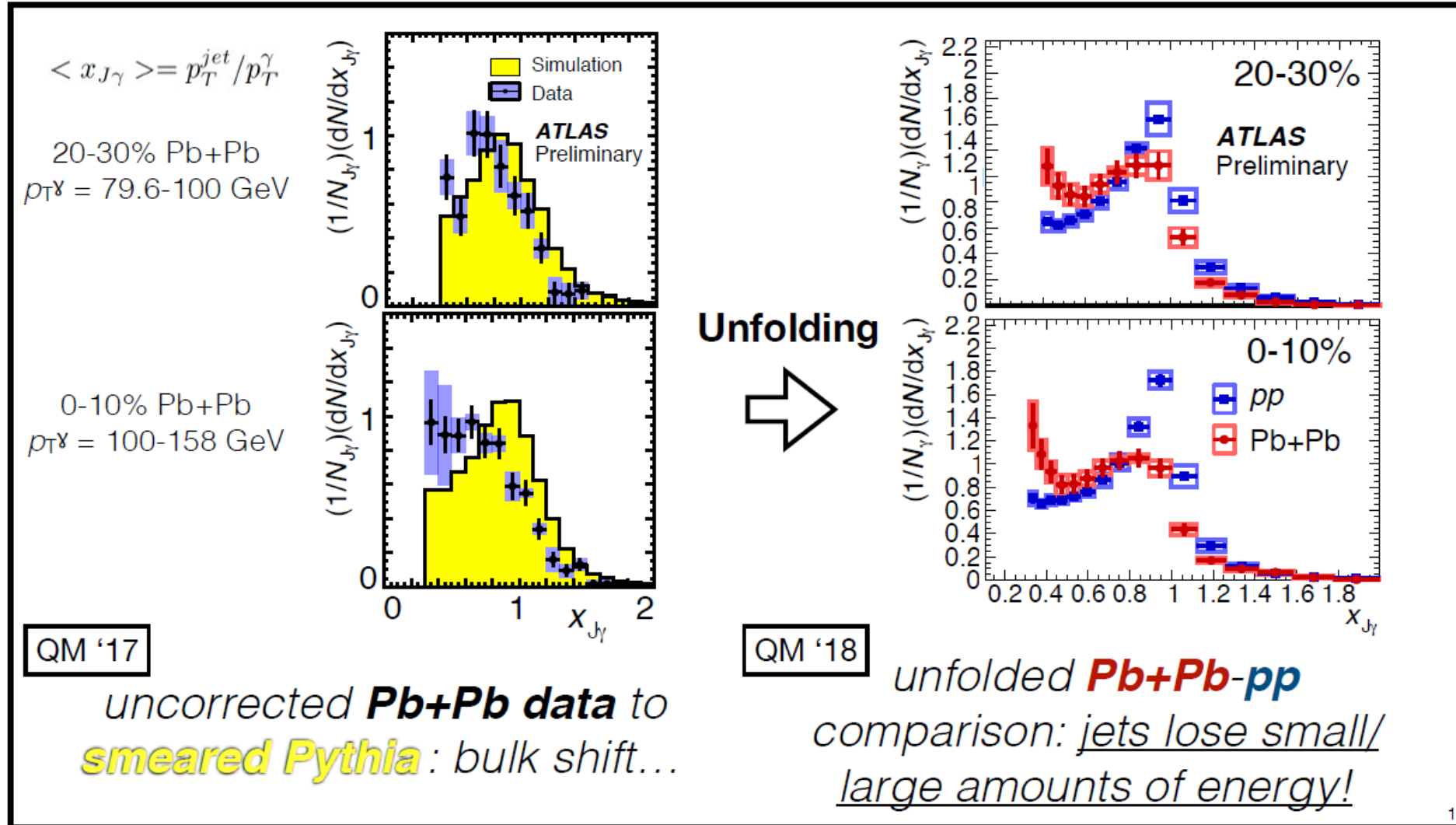
γ -hadron correlations at 200 GeV AuAu collisions



low p_T enhancement begins at a similar p_T to inclusive jets and at a similar p_T between LHC and RHIC

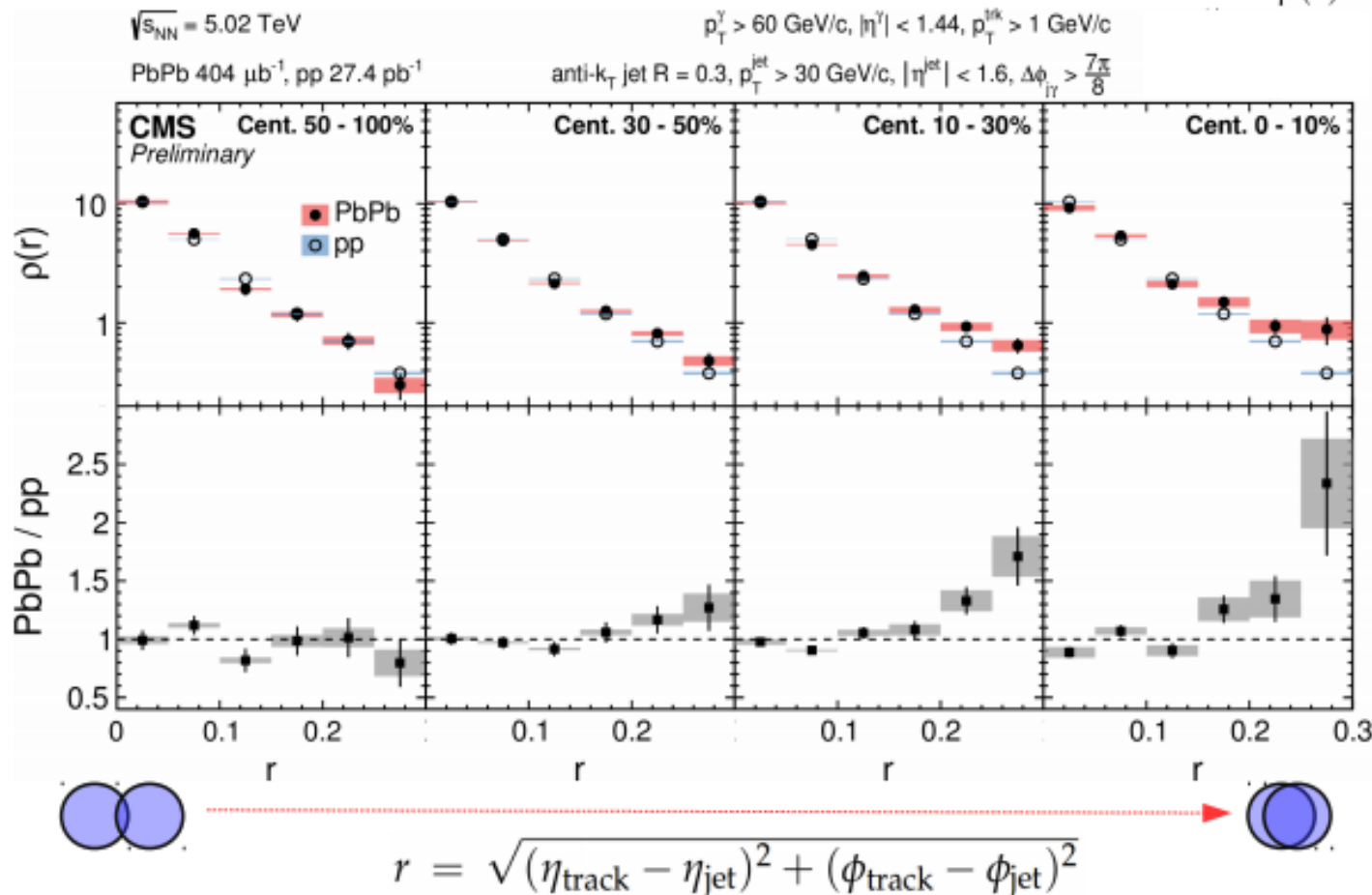
looking forward to precision measurements with reconstructed jets at sPHENIX!

- Inc-Jetとgamma-jetでは、q-jet, g-jetの違いがあるが、 R_z の増加 p_T は同じ
 - Jet効果ではなく、medium効果であることを示唆。

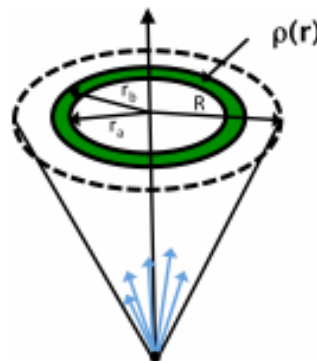


Unfoldingによる検出器効果の補正により、形の違いが顕著に

- Pp: $x_{j\gamma} \sim 1$ にピーク構造: Gamma-Jetがバランスしている
 - R-size (+ Jet reco. algorithm)により $x_{j\gamma} < 1$ にtailがある
- AA: $x_{j\gamma} \sim 1$ のピーク構造が無くなり、 $x_{j\gamma} < 0.4$ に新しいピークが出現。



$$\rho(r) = \frac{1}{\delta r} \frac{\sum_{\text{jets}} \sum_{\text{trk} \in [r_a, r_b]} (p_T^{\text{trk}} / p_T^{\text{jet}})}{\sum_{\text{jets}} \sum_{\text{trk} \in [0, r_f]} (p_T^{\text{trk}} / p_T^{\text{jet}})}$$



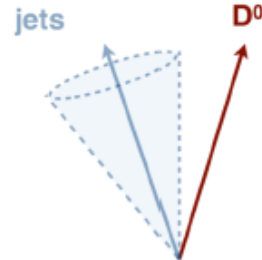
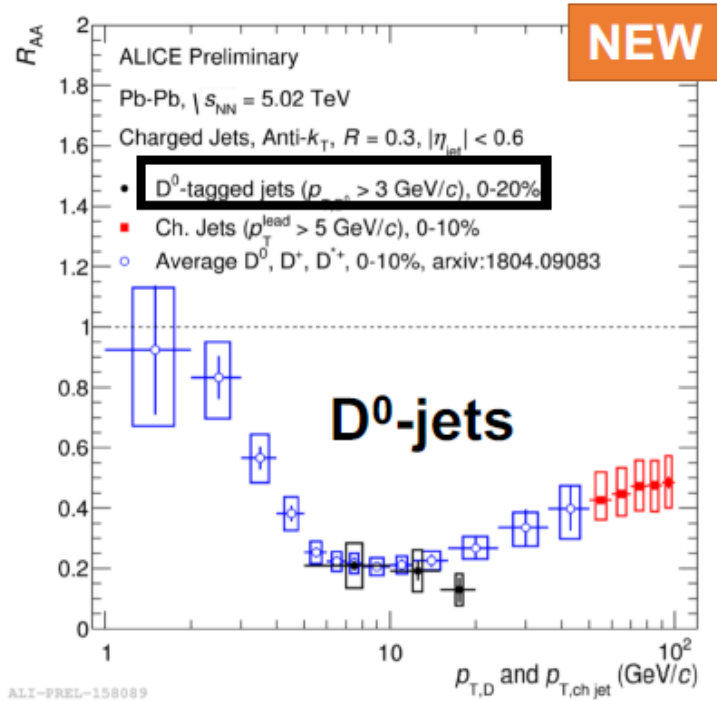
$\rho(r)$ normalized to unity over $r < 0.3$.

Results are corrected for detector resolution, particle reco.

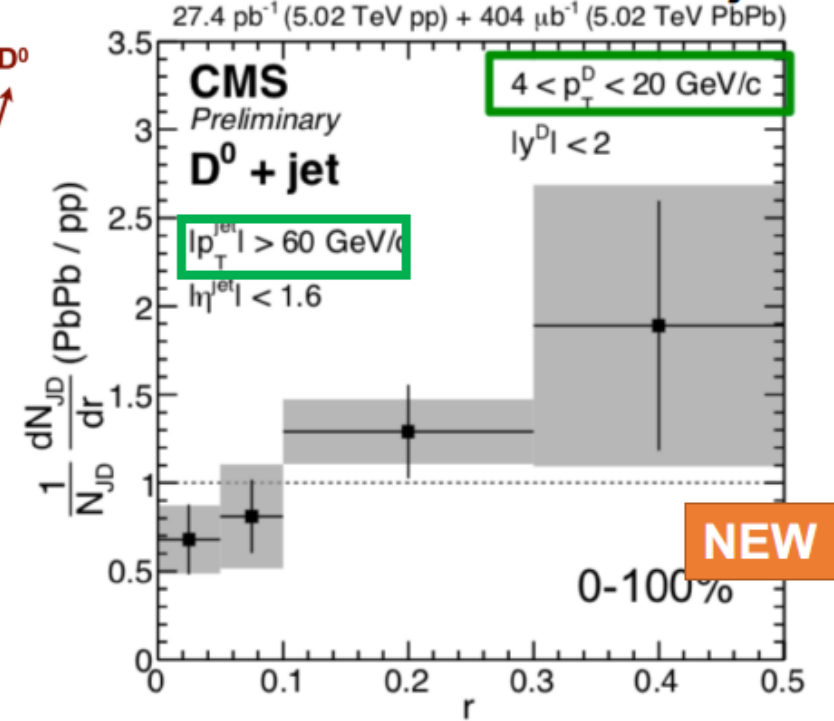
pp results are **NOT** smeared.

Central PbPb collisions \rightarrow a larger fraction of jet energy at large distances from the jet axis.

Jets: complementary to single particles



Radial correlations D⁰ and jets



Strong **suppression of D⁰-tagged jets** in central Pb-Pb at low/intermediate p_T, consistent with D

Hint of **D⁰ at low p_T appearing at large angles**. Not seen for inclusive jets at this p_T !

- ジェット測定と粒子測定が一致。
- ジェット収量・抑制の測定は理解が進んだ。
- FFやJetバランスなどジェット構造などの測定により、より詳細な情報を得る。

Jet summary

- Jet, gamma-Jetの測定が改善してきた。
 - Jet抑制だけでなく、ジェットの形の変化、損失エネルギーの行方などについても、測定データが見えてきている。
 - 特にGamma-Jet (最良のチャンネルと思う)を使った測定がLHC, RHICに置いて進んでいる。
- 現在の手法で、RP依存のGamma-Jet相関などを再度行うことで、より情報を測定の精度が上がるか？

Summary

- 改善

- 統計、検出器の理解、測定手法 (Unfolding, Neural Net) の全ての点で改善してきている。

- RHIC & LHCで

- Heavy Quark (チャーム、ボトムともに) 充実してきた。
- $Y(1s, 2s, 3s)$ の分離した測定ができています。
- Jet (Gamma-Jet) の測定で、Jetの形の変化や、Imbalanceなどが精度よく見え始めた。

- 今後

- これらのデータを使って、QGPのパラメータを決定したい。
 - 理論の人たちとの協力がこれまでより重要。
 - 実験屋もイベントジェネレータで遊びたい！
- QGPの統一的な理解