高エネルギー原子核衝突実験の最新結果 -国際会議QM2012から

Kobayashi-Maskawa Institute
for the Origin of Particles and the Universe

KMI/Department of Physics, Nagoya University
野中　千穂

August 22, 2012@熱場の量子論とその応用

Quark Matter 2012

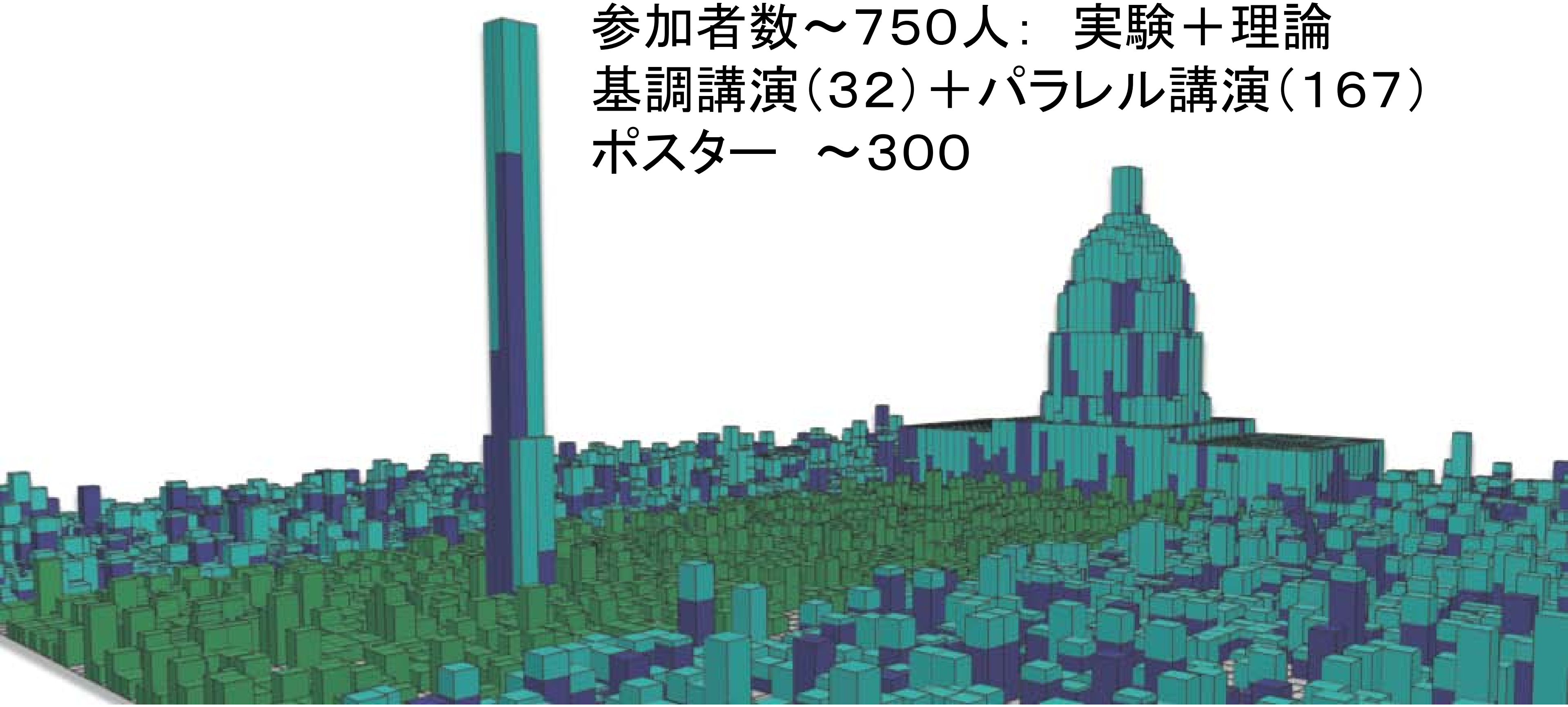
The XXIII International Conference on Ultrarelativistic Nucleus-Nucleus Collisions

August 13-18, 2012, Washington D.C.

参加者数～750人：　実験＋理論

基調講演（32）＋パラレル講演（167）

ポスター　～300



Quark Matter 2012

The XXIII International Conference on Ultrarelativistic Nucleus-Nucleus Collisions
August 13-18, 2012, Washington D.C.
http://qm2012.bnl.gov/default.asp

現在の目的

クォークマターの詳細な解析

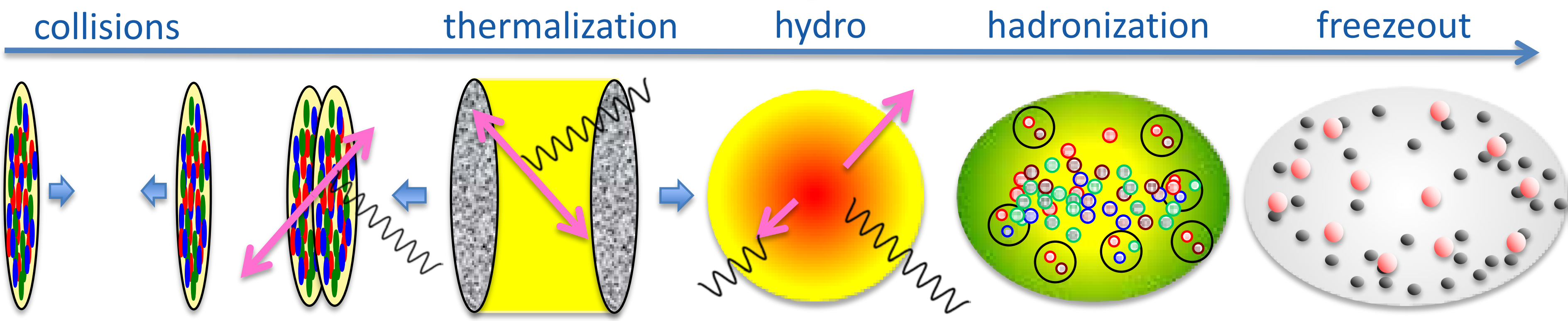
状態方程式、輸送係数

実験： LargeHadron Collider (LHC)
Relativistic Heavy Ion Collider (RHIC)

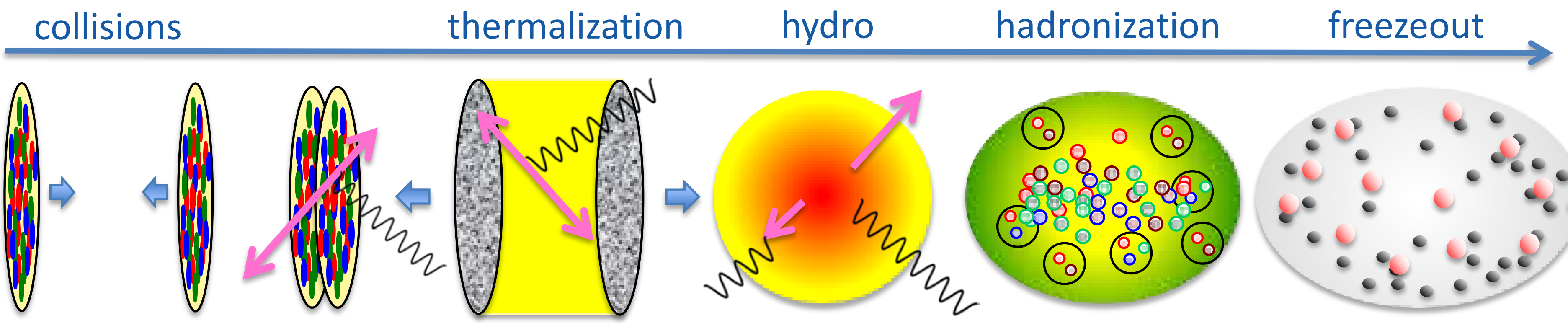
- クォークやグルーオンは直接観測不可
- クォークマターをどのように観測するのか？

➡ 様々なデータから包括的な理解をめざす
実験データが豊富

Relativistic Heavy Ion Collisions



Relativistic Heavy Ion Collisions



Pre-Equilibrium & Initial State

Global &Collective Flow

Correlations & Fluctuations

QCD at Finite Temperature and Density

QCD Phase Diagram

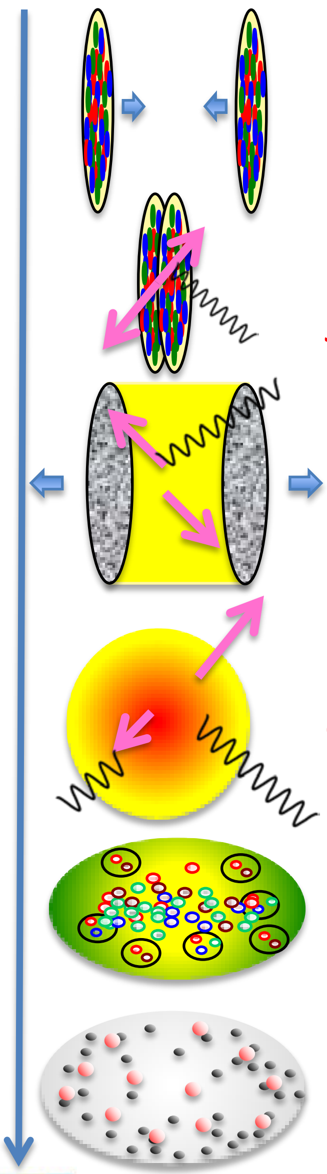
Hadron Thermodynamics and Chemistry

Electro-Weak Probes
Jets
Heavy flavor &Quarkonia

New Theoretical /Experimental Developments

C. NONAKA

Talk について概観



- Pre-equilibrium,Initial state
- Jets, high Pt
- Electro-weak probes
- Heavy flavor
- Global& Collective flow
- Correlations & fluctuations
- QCD at T≠0, m≠0
- QCD phase diagram
- Hadron thermodynamics

Tue 1	Tue 2	Wed 3	Wed 4	Thu 5	Fri 6	Fri 7
		✓	✓		✓	
✓	✓	✓	✓	✓		
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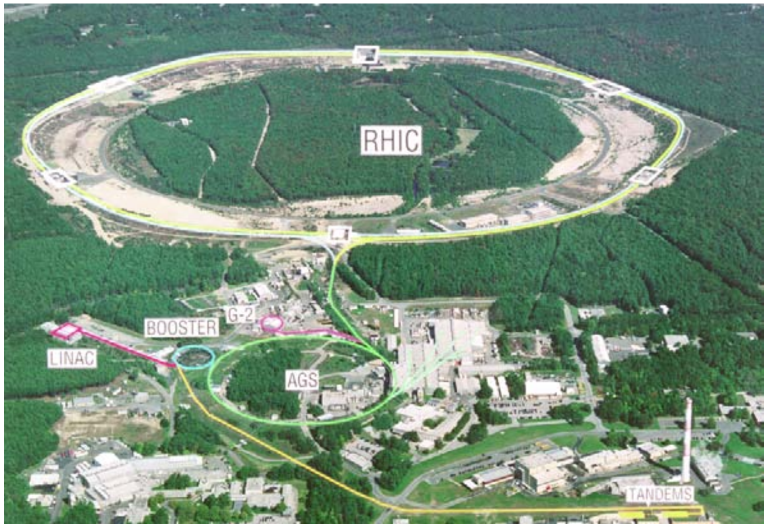
					✓	✓

Relativistic Heavy Ion Collisions

RHIC@ブルックヘブン国立研究所



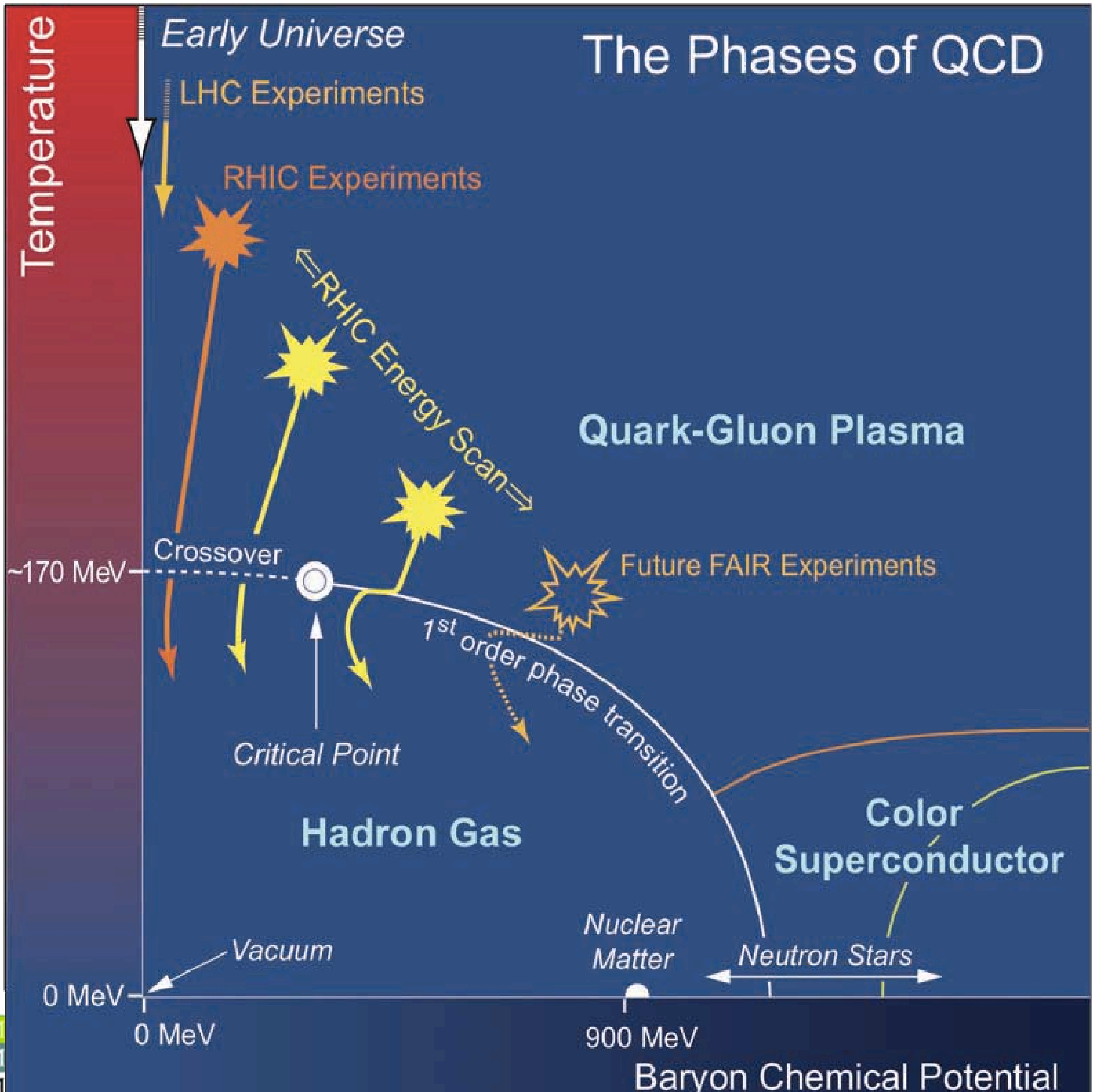
PHENIX, STAR から
Au+Au: エネルギースキャン
7.7, 19.6, 27, 39, 62, 200 GeV
U+U 193 GeV
Cu+Au 200 GeV

LHC@CERN

ALICE, CMS, ATLAS から
Pb+Pb 2.76 TeV

RHIC and LHC

- QCD Phase Diagram



RHIC: Au+Au 200 GeV
強結合QGPの発見

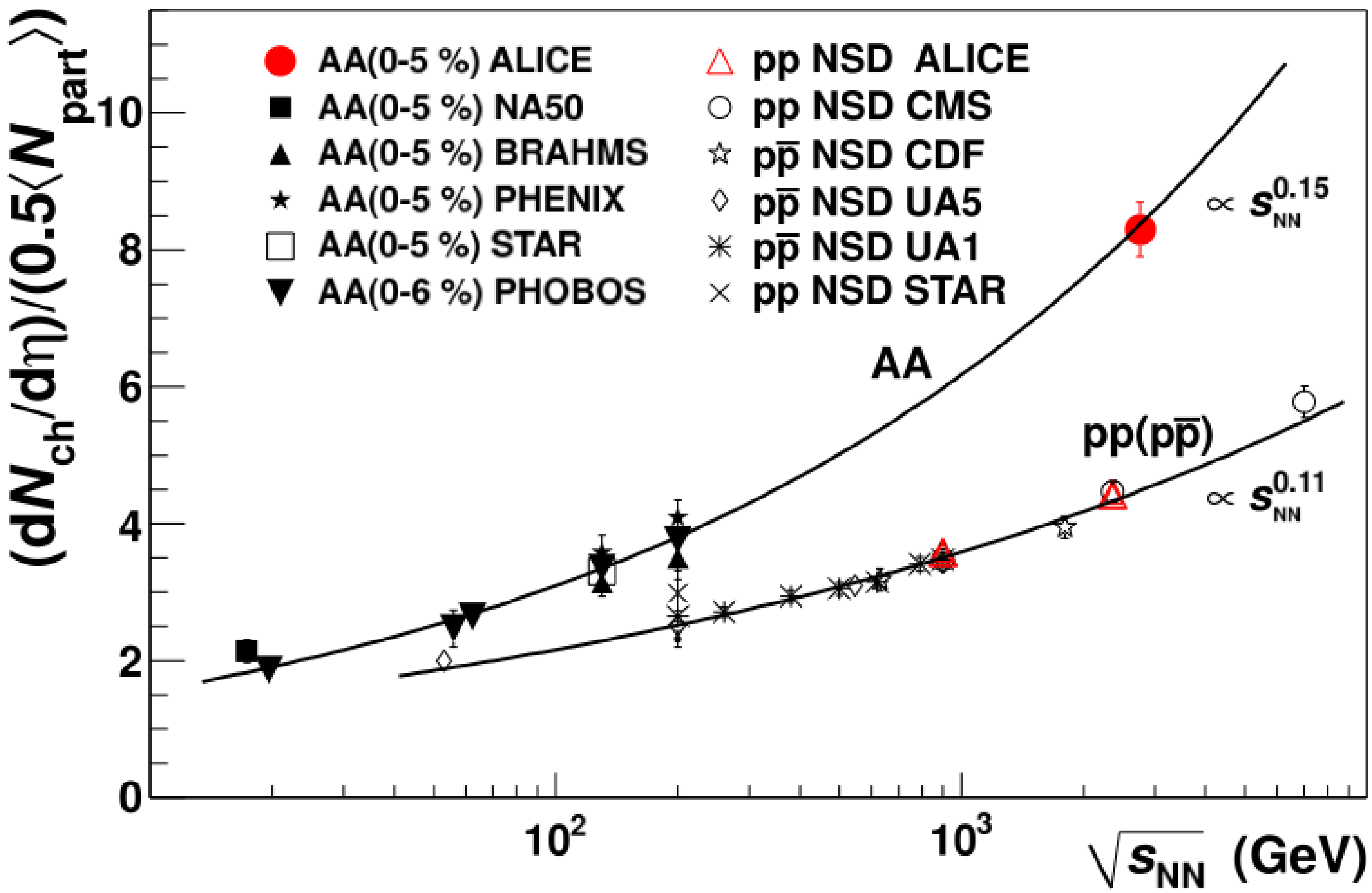
RHIC:エネルギースキャン
有限密度方向
QCD相図の詳細な理解

LHC:QGP相の奥へ
強結合QGP？

RHIC and LHC

- 生成粒子数の違い

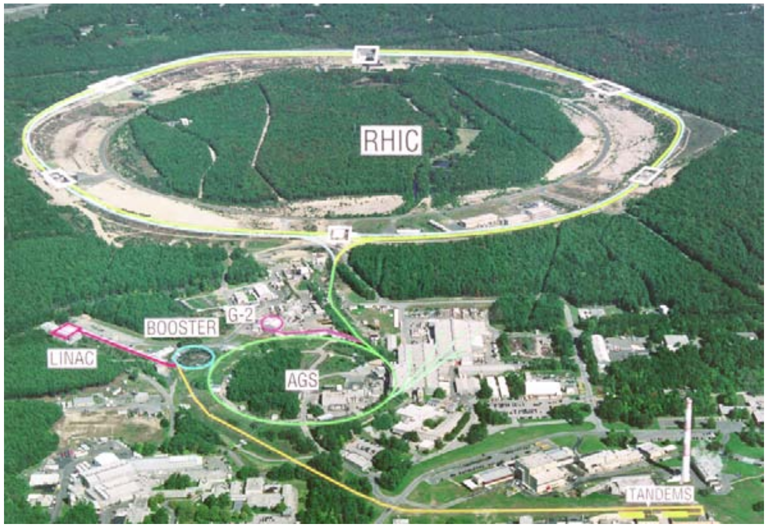
大きな増大



ALICE:arXiv:*1011.1916*

Relativistic Heavy Ion Collisions

RHIC@ブルックヘブン国立研究所



PHENIX, STAR から
Au+Au: エネルギースキャン
7.7, 19.6, 27, 39, 62, 200 GeV
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LHC@CERN

ALICE, CMS, ATLAS から
Pb+Pb 2.76 TeV

PHENIX@RHIC

- d+Au@200 GeV
  - Direct photons (R_{dA} vs P_T)
  - Jet probes: central dependence of R_{dA}
  - ψ□: R_{dA} vs N_{coll}: strong suppression

$$R_{AB} = \boxed{\frac{1}{N_{\rm coll}}} \frac{dN_{A+B}/dP_T}{dN_{p+p}/dP_T}$$

normalization

- Collision geometry: U+U, Cu+Au
  - U+U: v_2 vs P_T: strong radial flow @central
  - Cu+Au: v_1, v_2 vs P_T ; R_{AA} of J/ψ vs N_{coll} stronger suppression
- Hard probes
  - γ-h correlation
  - Fractional momentum loss $\delta P/P$ in π_0 spectra, energy dependence
  - Single electrons, R_{AA}(c➔e, b➔e, heavy flavor➔e)

STAR@RHIC

- Initial Conditions
  - d+Au collisions: search for CGC
- sQGP property
  - Centrality dependence of v_2 for identical particles, Au+Au 200 GeV
  - Charge asymmetry, charge separation at U+U collisions
    : chiral magnetic effect
  - Dielectrons at Au+Au 200 GeV, energy dependence
  - Reconstructed jet v_2
  - open charm hadrons
  - Non-photonic electrons
- Beam Energy Scan 7.7, 19.6, 27, 39, 62 Au+Au
  - Number of constituent quark scaling, R_{cp} suppression
  - Directed flow of proton, HBT, higher moments

ALICE@LHC

- Particle identification, low-mass tracker, low P_T (~100MeV)
- Bulk property
  - P_T spectra, R_{AA} of π, K, p, p/π ratio vs P_T centrality dependence
  - v_2 for identified particles: check hydro, recombination model
  - v_2, v_3 vs η, v_2, v_3, v_4 vs P_T
  - baryon HBT
- Hard probes
  - Jet structure, R_{AA} and R_{CP} vs P_T
- Heavy Flavor
  - R_{AA}, v_2 of D meson, R_{AA}, v_2 of e(μ), D_s
  - R_{AA} of J/ψ, centrality dependence, v_2 of J/ψ

$$R_{AB} = \boxed{\frac{1}{N_{\text{coll}}}} \frac{dN_{A+B}/dP_T}{dN_{p+p}/dP_T}$$

normalization

$$R_{CP} = \frac{N_{\text{coll}}^{\text{periph}} dN_{A+B}^{\text{central}}/dP_T}{N_{\text{coll}}^{\text{central}} dN_{A+B}^{\text{periph}}/dP_T}$$

ATLAS@LHC

- Collective flow
  - v_2-v_6 vs P_T, v_2-v_6 centrality, centrality dependence of v_1 vs P_T
  - v_2 fluctuations vs P_T, centrality dependence of v_n distributions
- Electro weak probes
  - Measurement of $Z \to e^+e^-, \mu^+\mu^-$, P_T spectra
  - Prompt photon, P_T spectra
- Medium sensitive probes
  - Open heavy flavor, muon R_{CP}
  - Jet size and centrality dependence of R_{CP}
  - Jet fragmentation
  - Centrality dependence of $R_{\Delta\phi}$ vs P_T
  - Jet v_2
  - γjet correlations

$$R_{CP} = \frac{N_{\rm coll}^{\rm periph} dN_{A+B}^{\rm central}/dP_T}{N_{\rm coll}^{\rm central} dN_{A+B}^{\rm periph}/dP_T}$$

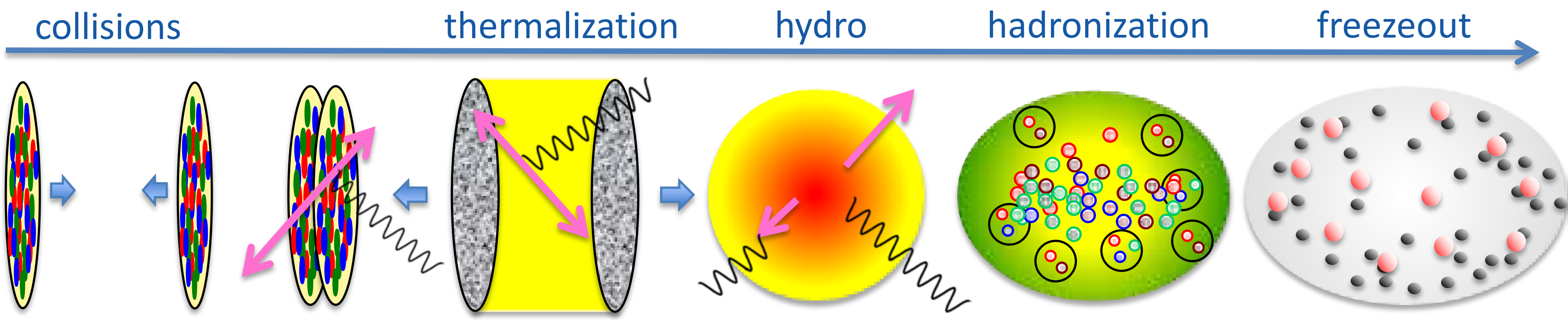
CMS@LHC

- Ultra-central collisions (0-2 % central)
  - Hierarchy of v_n ← hydro
- Anisotropy at high P_T
  - $V_{2,}$ v_3 vs P_T up to 50 GeV
- Jet quenching
  - R_{AA} of photons, Z^0, no suppression
  - R_{AA} of charged particles, suppression
  - R_{AA} of inclusive jets, suppression
- Parton Identification
- Anatomy of jets
  - Ratio of PbPb/pp differential jet shapes
- Dimuons
  - Sequential Upsilon suppression
  - R_{AA}vsN_{part} and R_{AA}vs biding energy

$$R_{AB} = \boxed{\frac{1}{N_{\rm coll}}} \frac{dN_{A+B}/dP_T}{dN_{p+p}/dP_T}$$

normalization

Relativistic Heavy Ion Collisions



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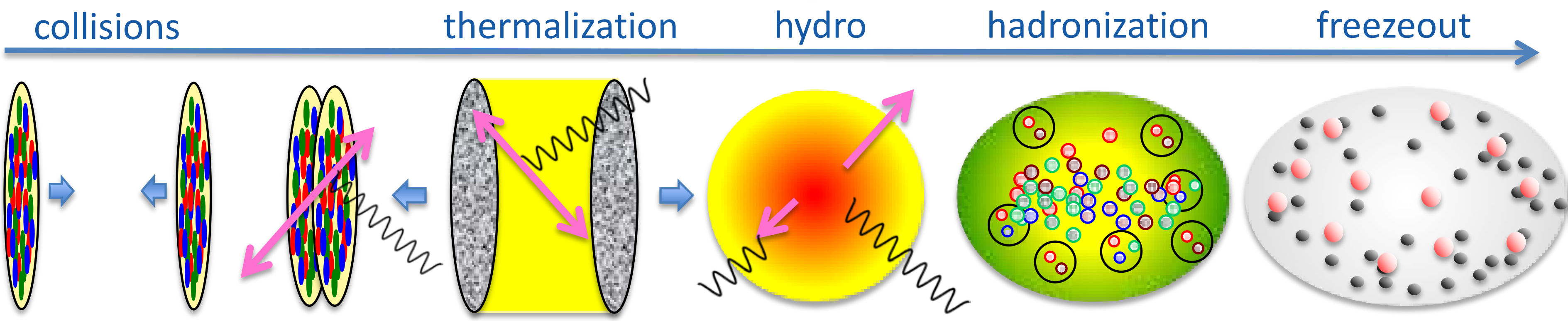
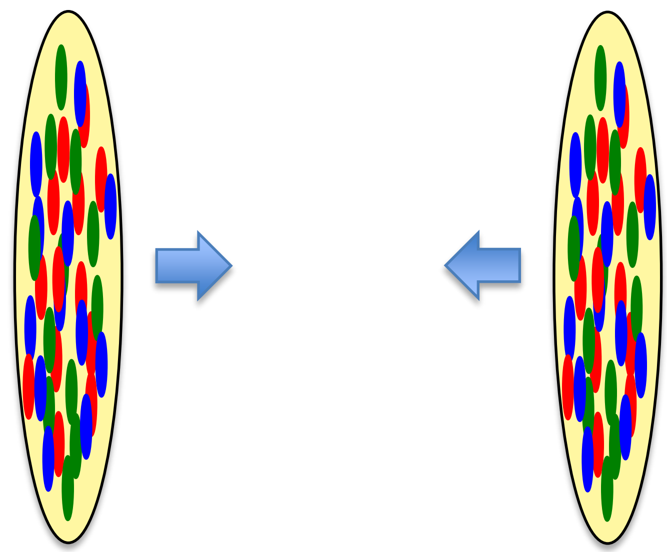
Relativistic Heavy Ion Collisions

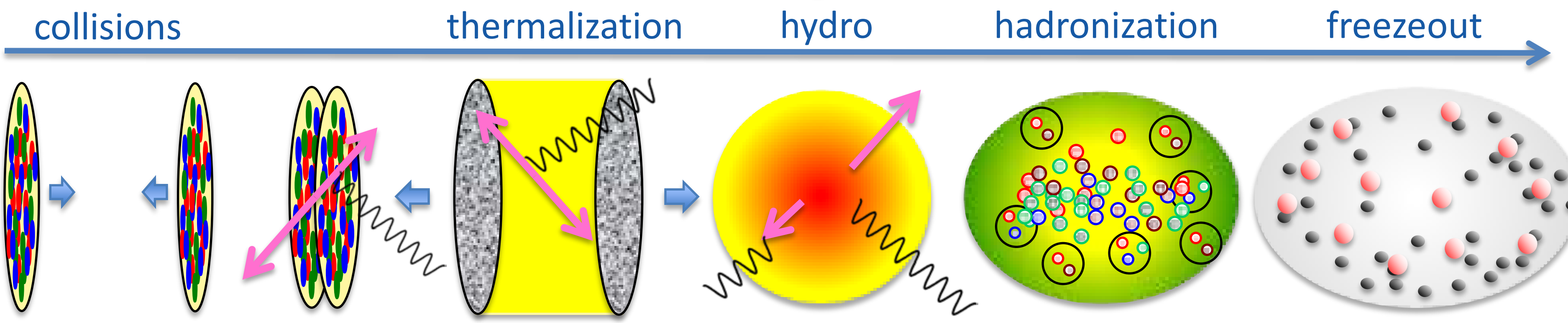


Pre-Equilibrium & Initial State



Static color charge, classical gluon field

Relativistic Heavy Ion Collisions



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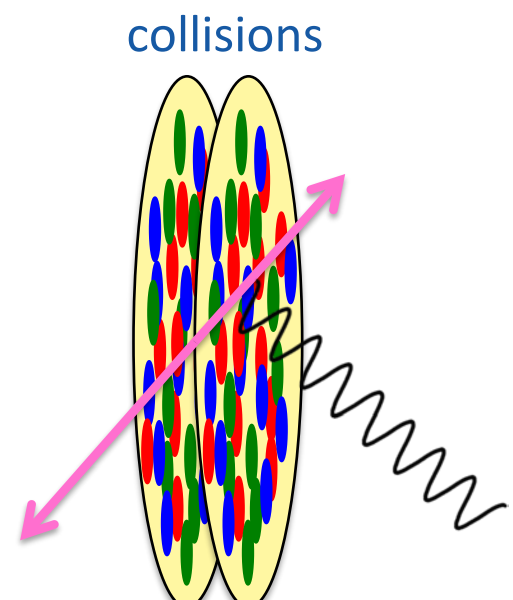
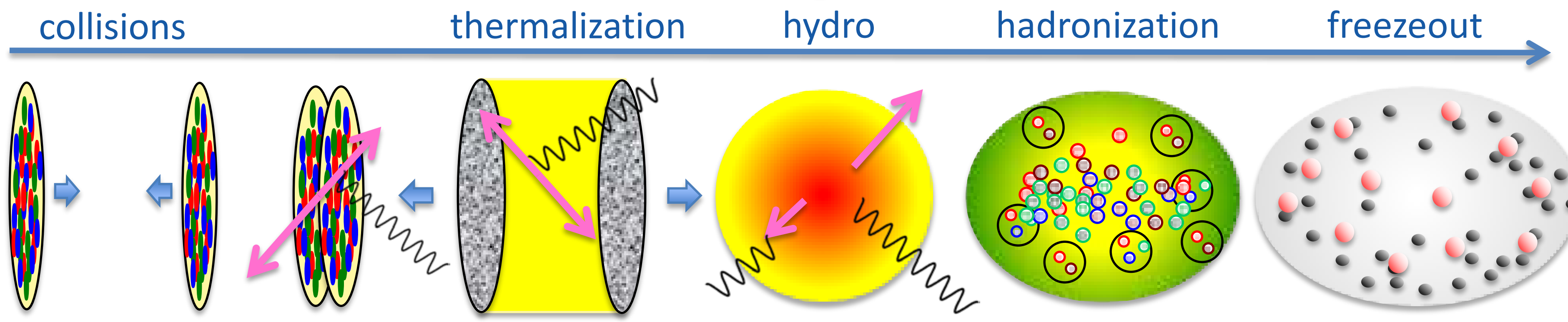


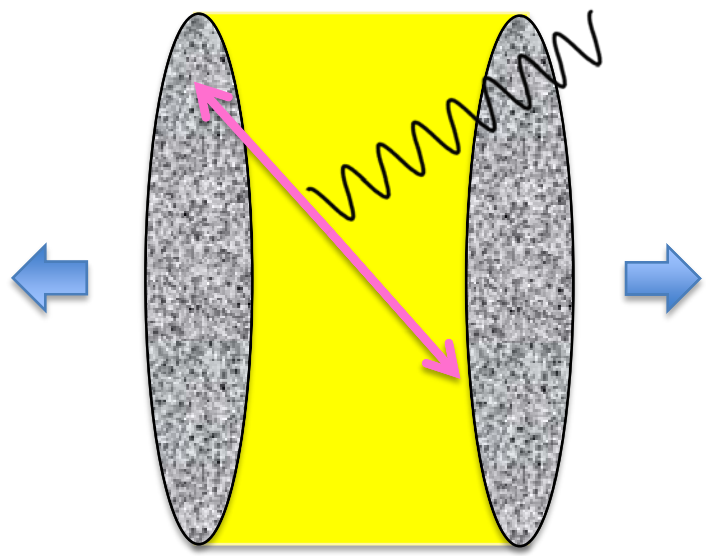
high energy photons, hard scattering

Relativistic Heavy Ion Collisions



to thermalization

Pre-Equilibrium & Initial State



photons, entropy

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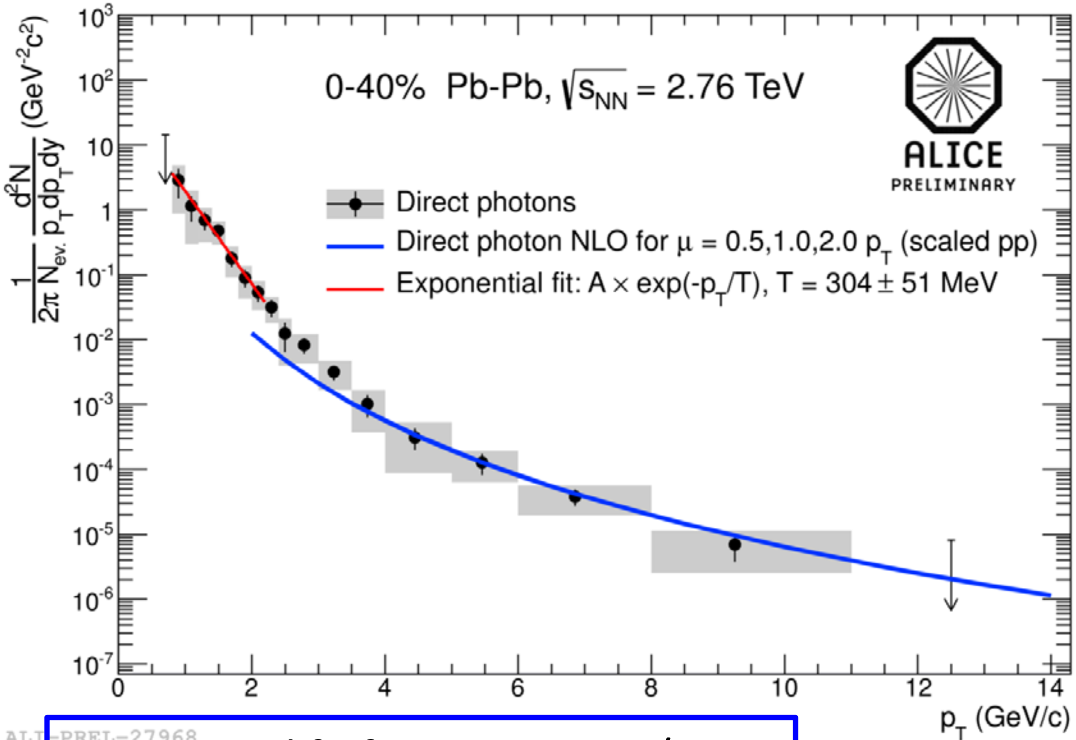
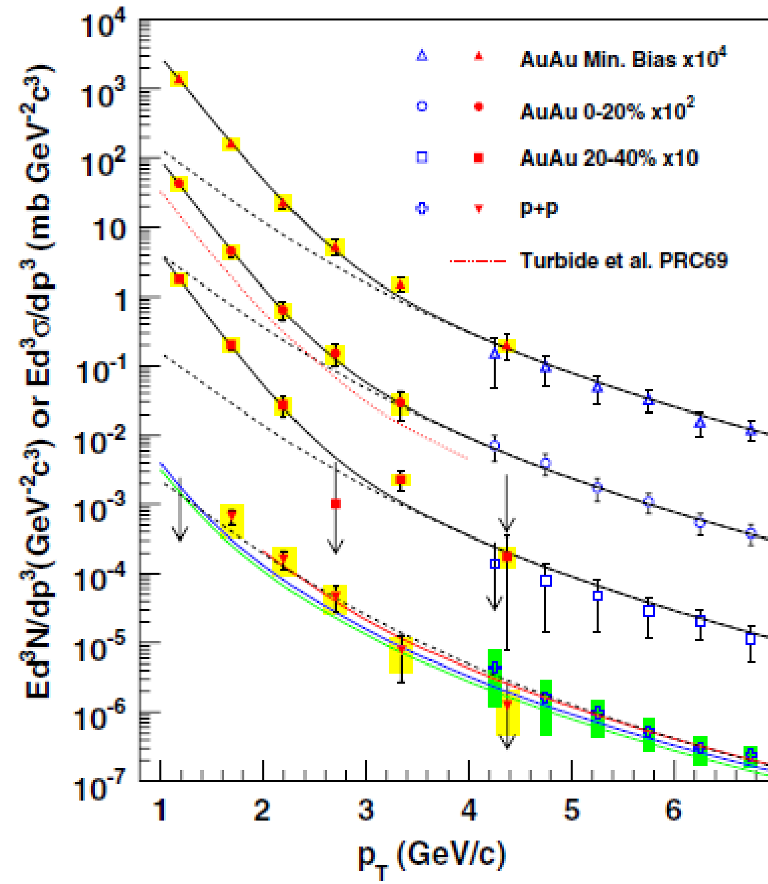
Achieved Temperature

ALICE



PHENIX

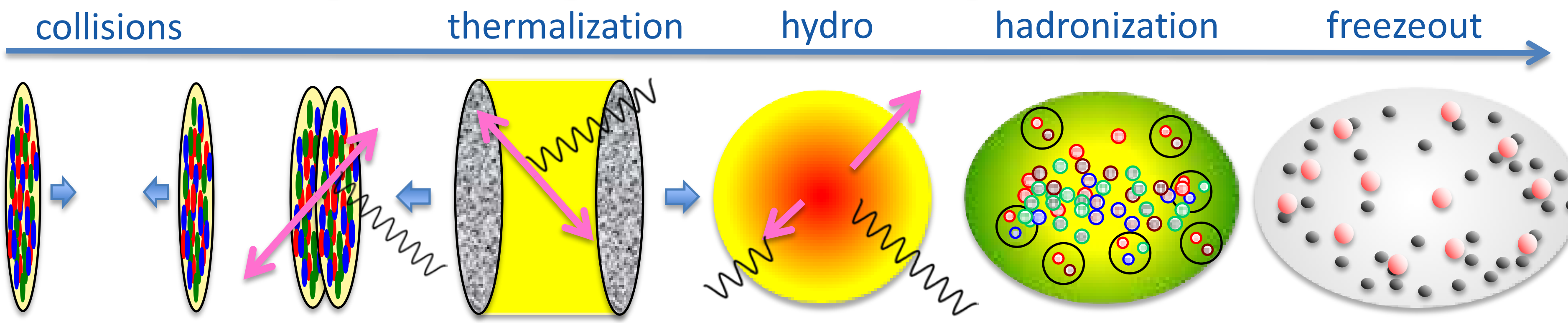


Exponential fit for p_T< 2.2 GeV/c
inv. slope T = 304±51 MeV
for 0–40% Pb–Pb at √s 2.76 TeV
PHENIX: T = 221±19±19 MeV
for 0–20% Au–Au at √s 200 GeV

Safarik@QM2012

流体模型の初期温度というよりも
全時間発展の平均温度

Hydrodynamic Expansion



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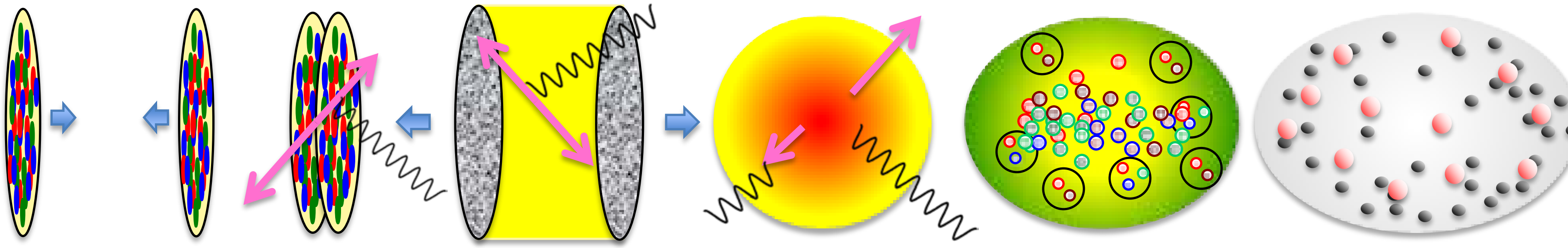
Hydrodynamic Expansion

collisions thermalization hydro hadronization freezeout



Global &Collective Flow

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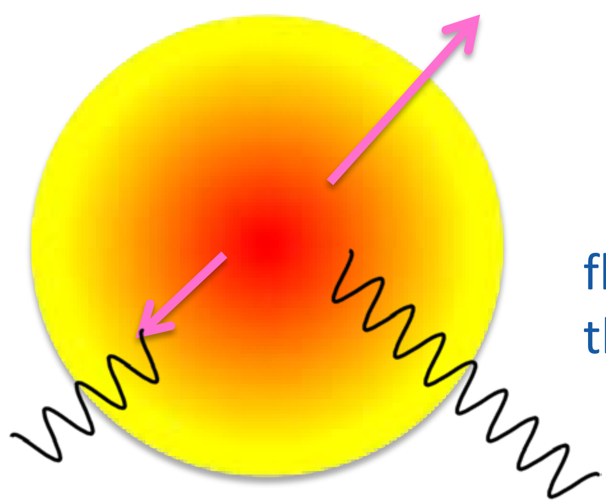

flow, jet quenching
thermal photons

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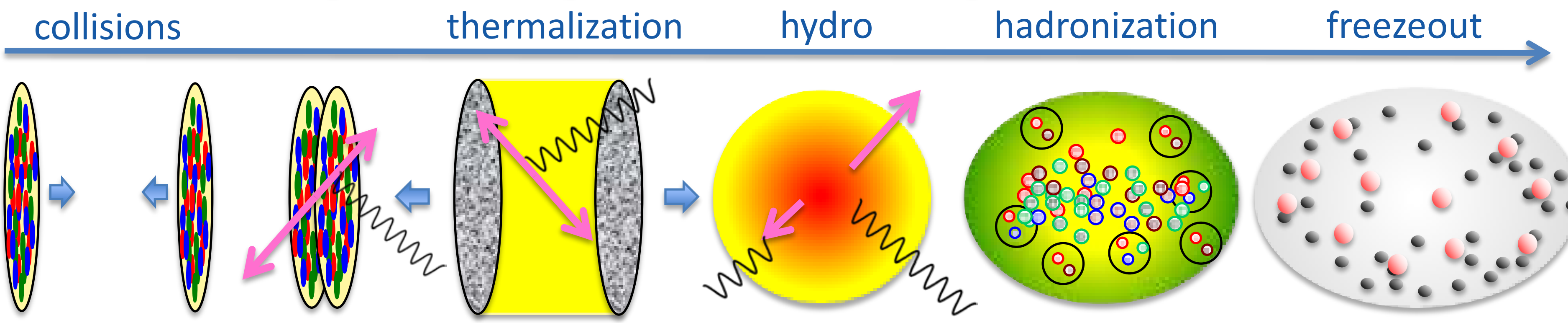
Hydrodynamic Expansion



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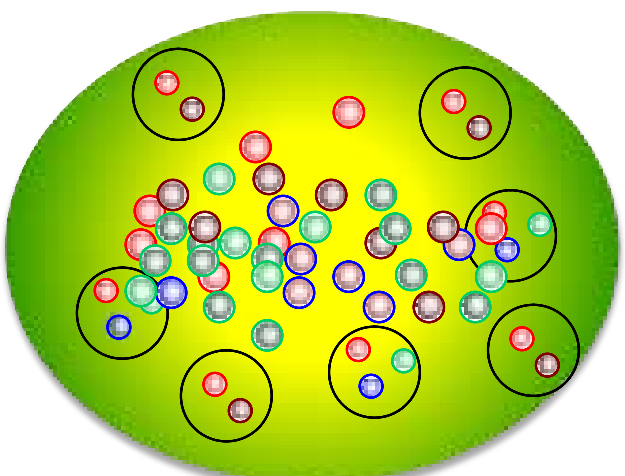

recombination, fragmentation

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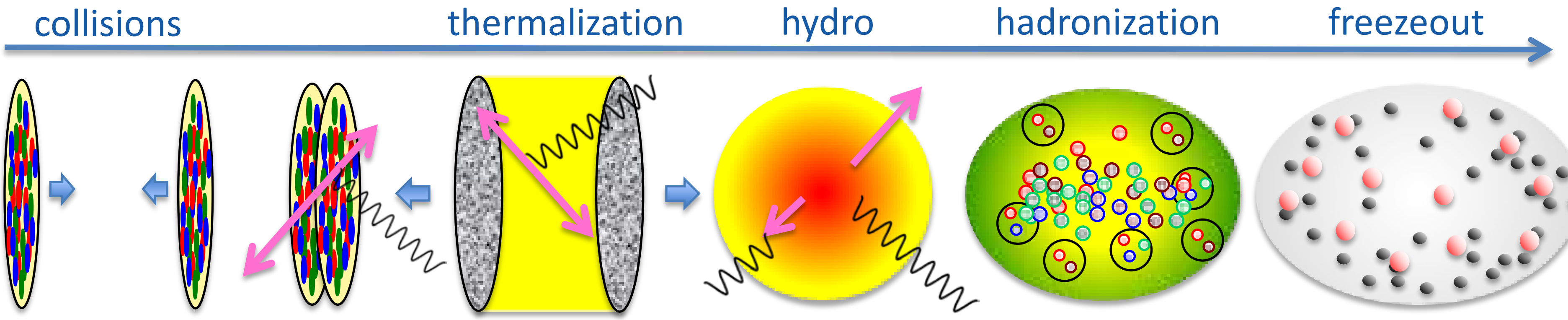
Hydrodynamic Expansion



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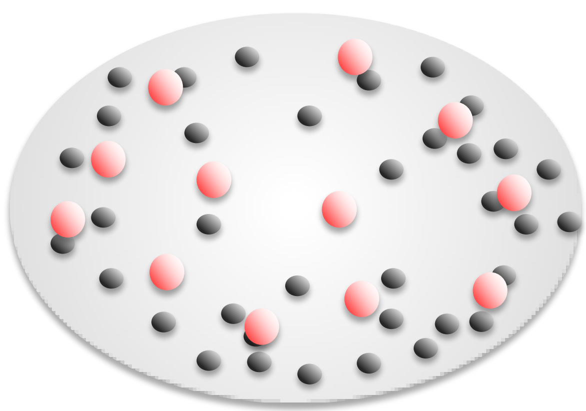

final state interactions

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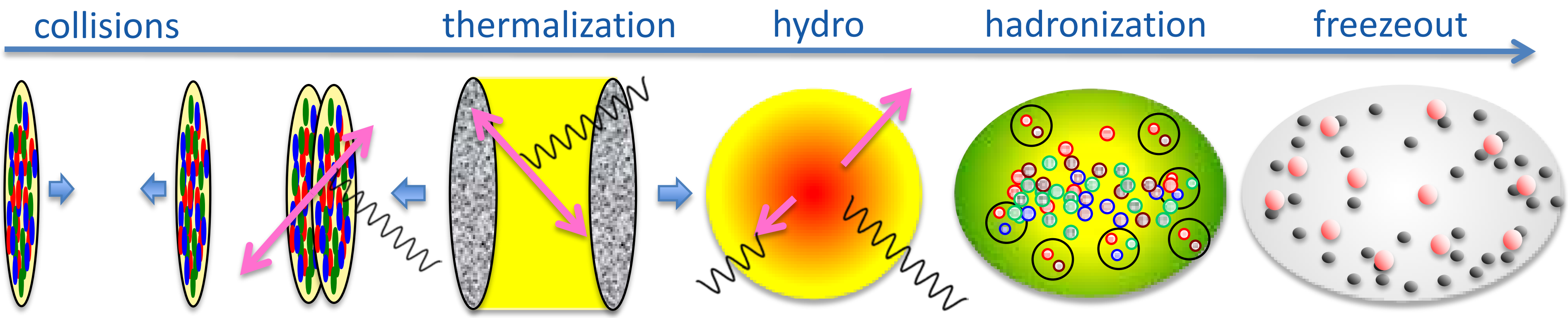
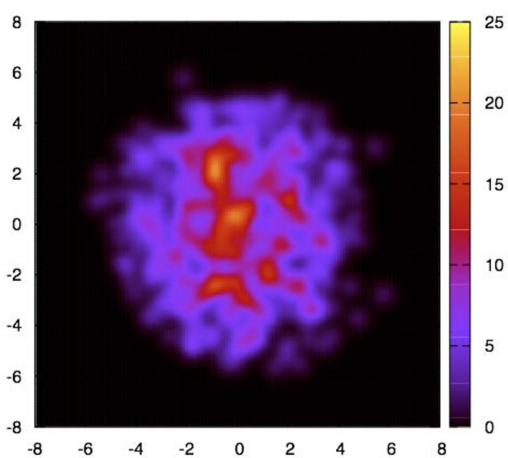
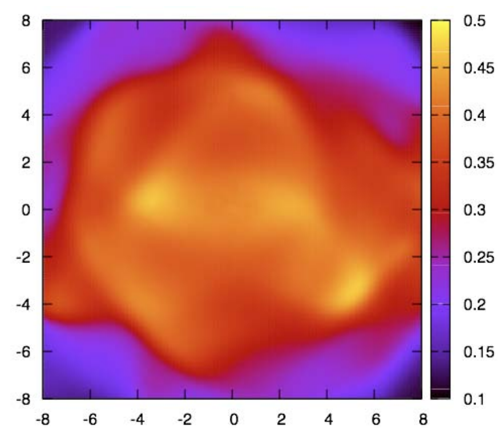
Development of Hydrodynamic Model



Fluctuated initial conditions + 3D relativistic viscous hydrodynamics + after burner





Hadron based event generator

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Hydrodynamic Model

Author/Presenter	QM2012	arXiv	initial fluctuations	3+1d	viscous	afterburner
Huichao Song	1D	1207.2396			✓	✓
Teaney/Yan	1A	1206.1905			✓	
Chun Shen	1A	1202.6620			✓	
Sangyong Jeon	2A		✓	✓	✓	✓
Matt Luzum	2A				✓	
Piotr Bozek	2C	1204.3580	✓	✓	✓	
Björn Schenke	3A	1109.6289	✓	✓	✓	
Dusling/Schaefer	3A	1109.5181			✓	
Chiho Nonaka	3A	1204.4795	✓	✓	✓	
Ryblewski/Florkowski	3D	1204.2624		✓		
Longgang Pang	4D	1205.5019	✓	✓		
Hannah Petersen	VA	1201.1881	✓	✓		✓
Fernando Gardim	6D	1111.6538	✓	✓		
Zhi Qiu	29	1208.1200	✓		✓	
Gardim/Grassi	52	1203.2882	✓	✓		
Katya Retinskaya	57	1203.0931			✓	
Hirano/Murase	255	1204.5814	✓	✓		✓
Holopainen/Huovinen	284	1207.7331	✓			
Asis Chaudhuri		1112.1166	✓		✓	
Iurii Karpenko		1204.5351		✓		✓
Yu-Liang Yan		1110.6704		✓		✓
Josh Vredevoogd		1202.1509		✓	✓	
Ron Soltz		1208.0897			✓	✓
Rafael Derradi de Souza		1110.5698	✓	✓		

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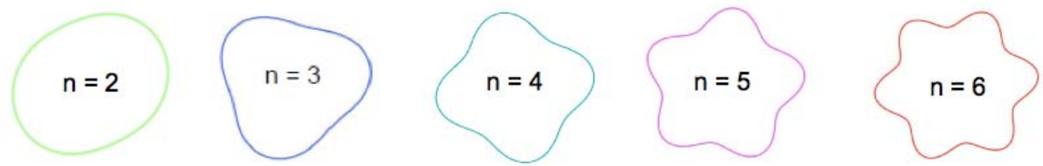
Higher Harmonics

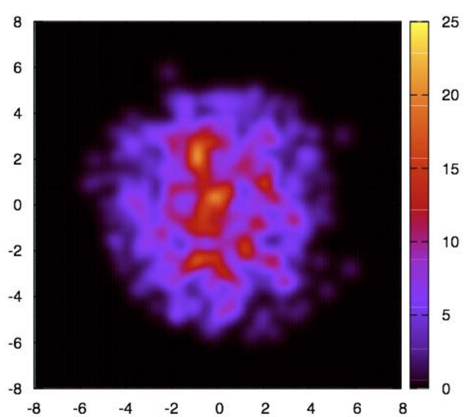
- Transport property

Ex. WMAP for big bang

$$\frac{dN}{dyd\phi} \propto 1+2v_1\cos(\phi-\Theta_1)+2v_2\cos 2(\phi-\Theta_2)+2v_3\cos 3(\phi-\Theta_3)+2v_4\cos 4(\phi-\Theta_4)+\cdots$$



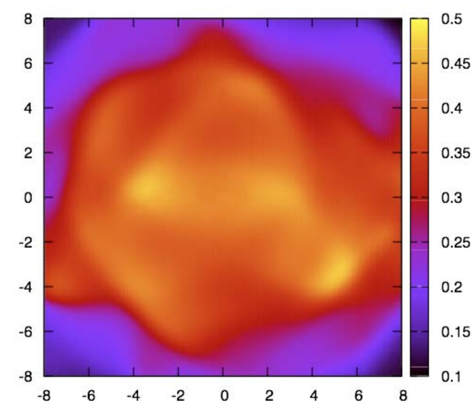
Initial geometry



hydrodynamics

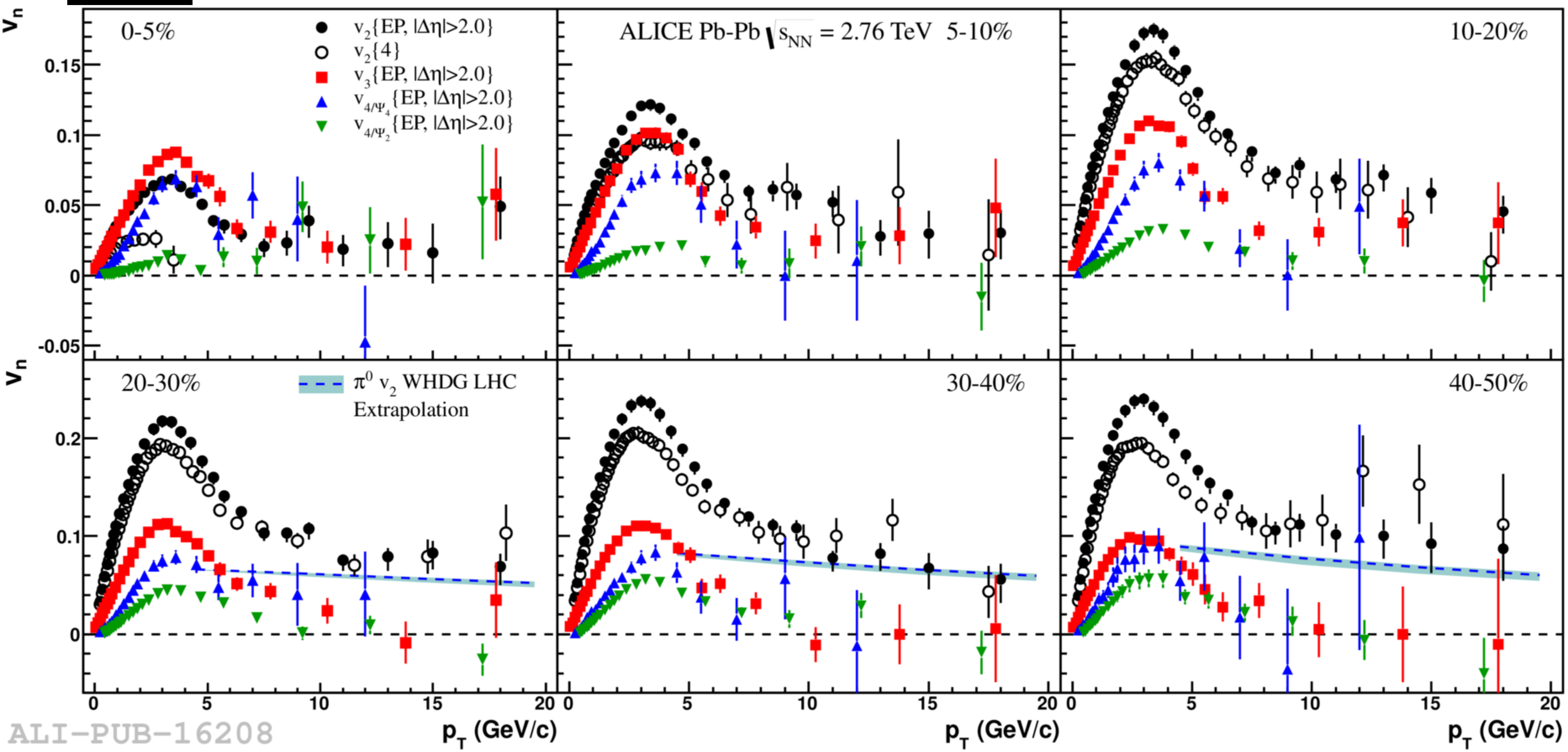
QGP property
Transport coefficients

Final flow distributions



Centrality Dependence of $v_n(P_T)$

ALICE



Most central collision: v_3 is dominant.
Mid central-peripheral colisions: v_2 is dominant.

→ Initial conditions, transport coefficients

ultra-central collisions 0-2 %

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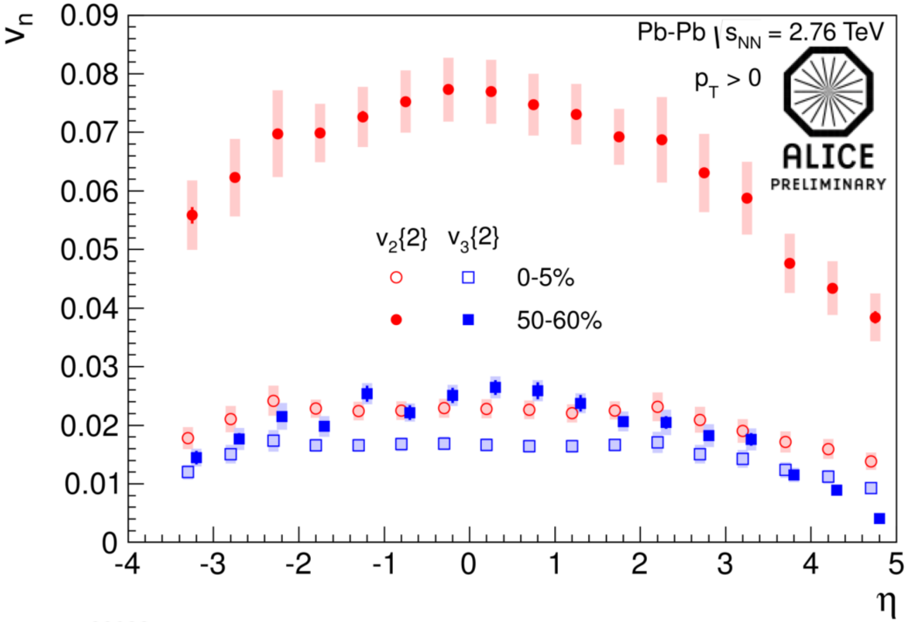
v_n vs η



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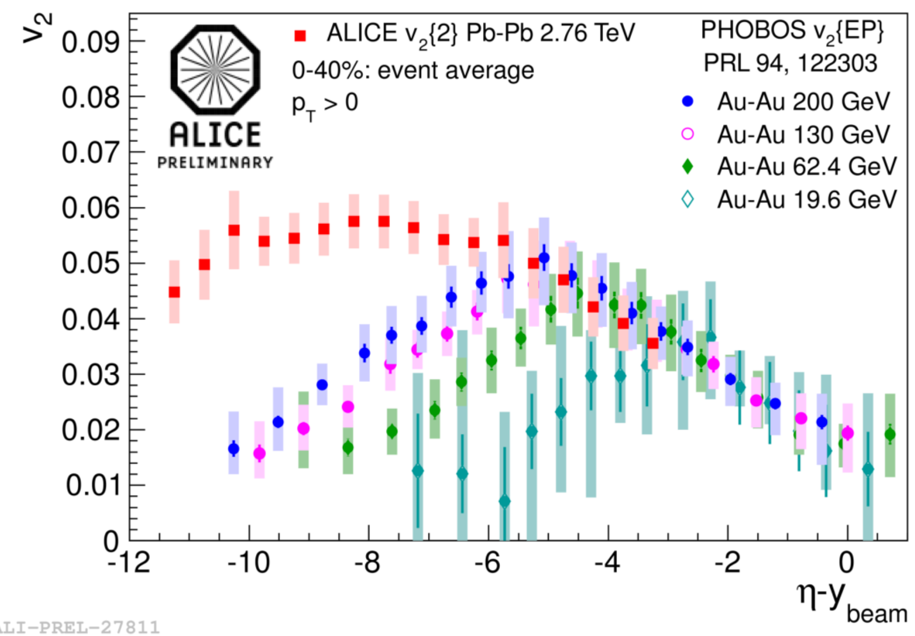

ALI-PREL-27811

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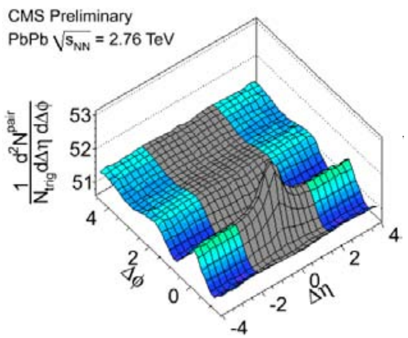
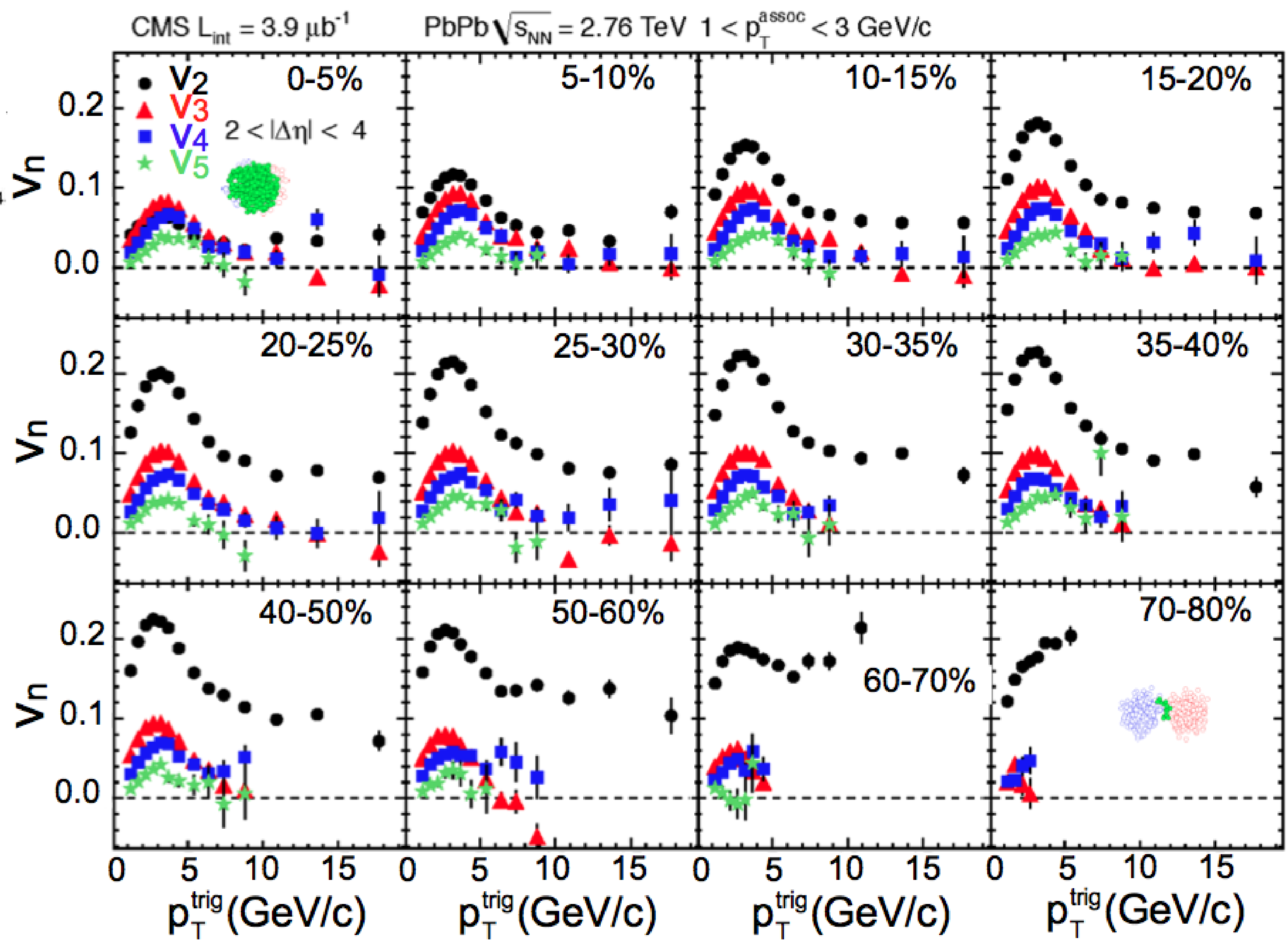
v_n at large η



Ridge structure



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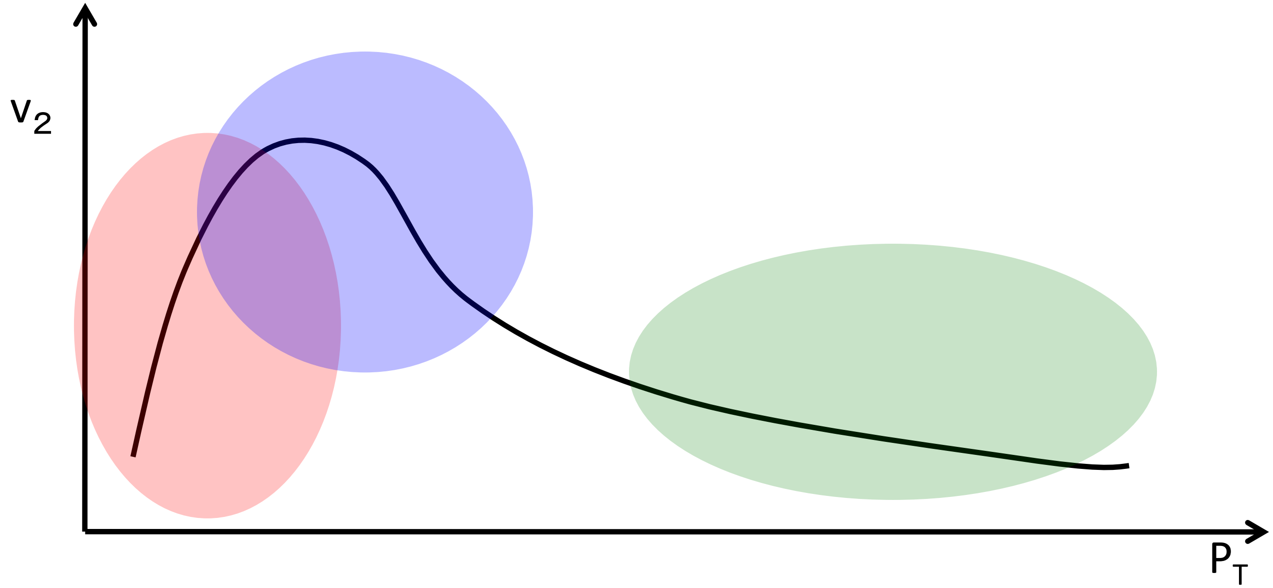
Flow

- 横運動量領域ごと



低横運動量領域
相対論的流体模型
mass ordering
π, K, p, ϕ, …

中横運動量領域
リコンビネーション模型
クォーク数スケーリング
メソンとバリオンの関係

高横運動量領域
ジェットクェンチング機構
ジェットのパスの長さに
依存？

ϕ: メソン、質量ほぼp
ストレンジネス

強結合QGP生成の証拠
RHICトップエネルギーでは観測
低いエネルギーでは？LHCでは？

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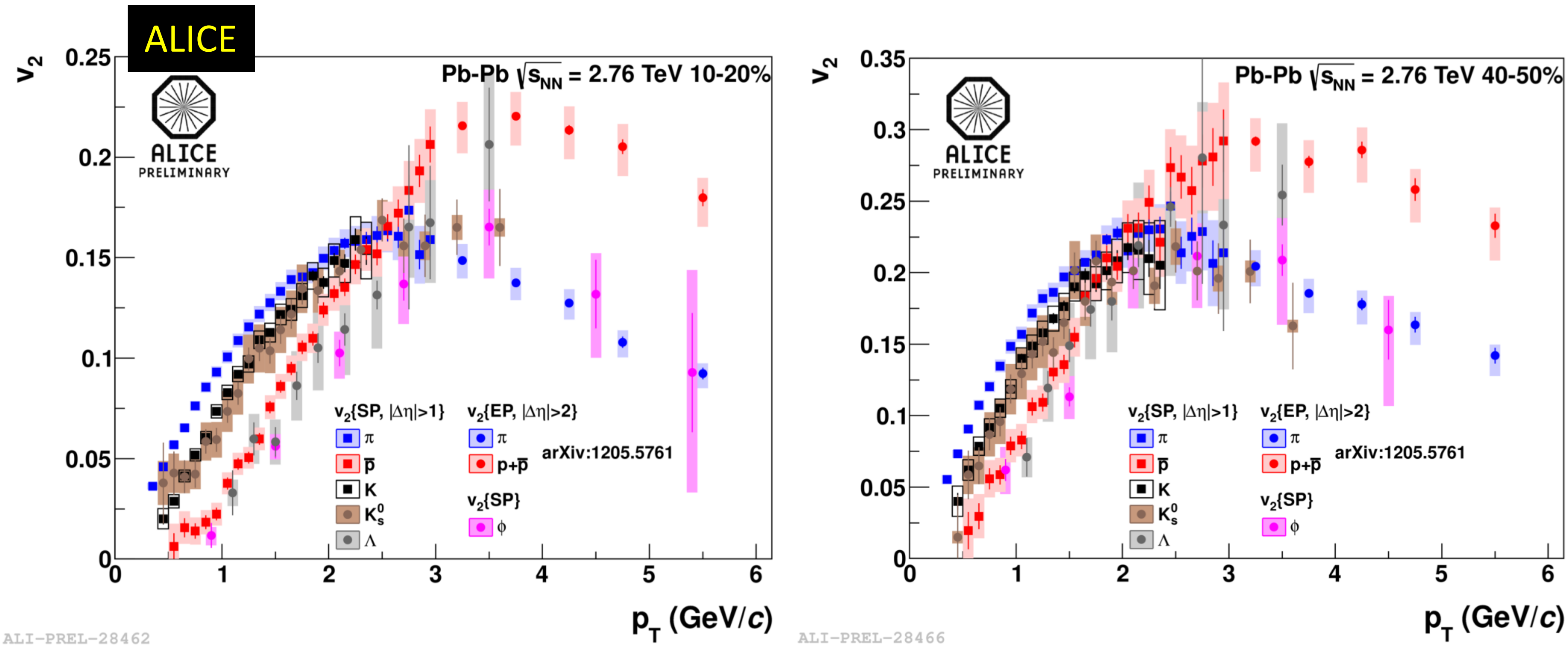
V_2 @ low P_T



ϕ: mass ordering に従っている
P_Tが高くなるとπに一致

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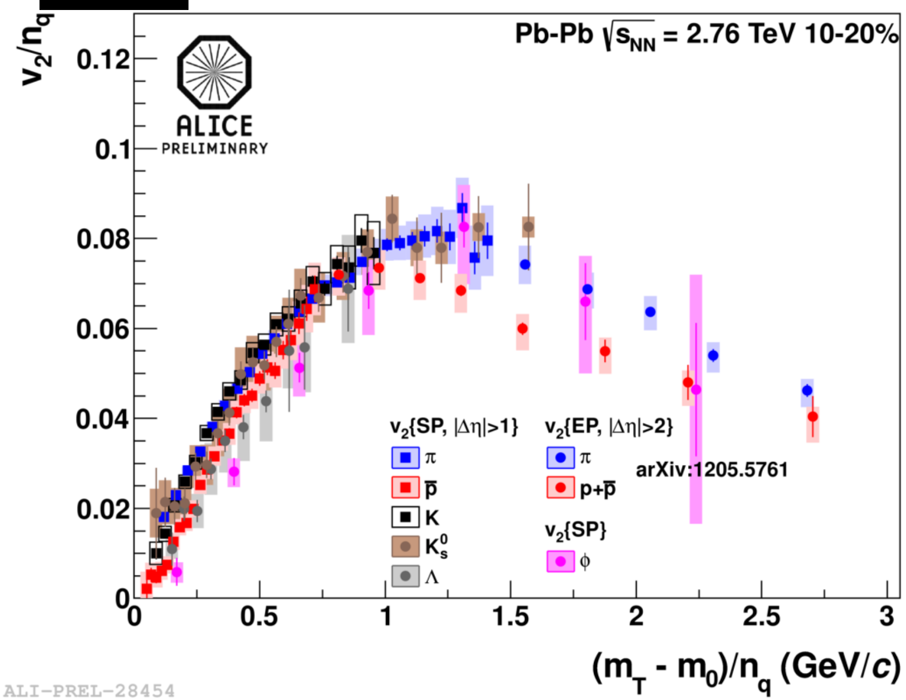
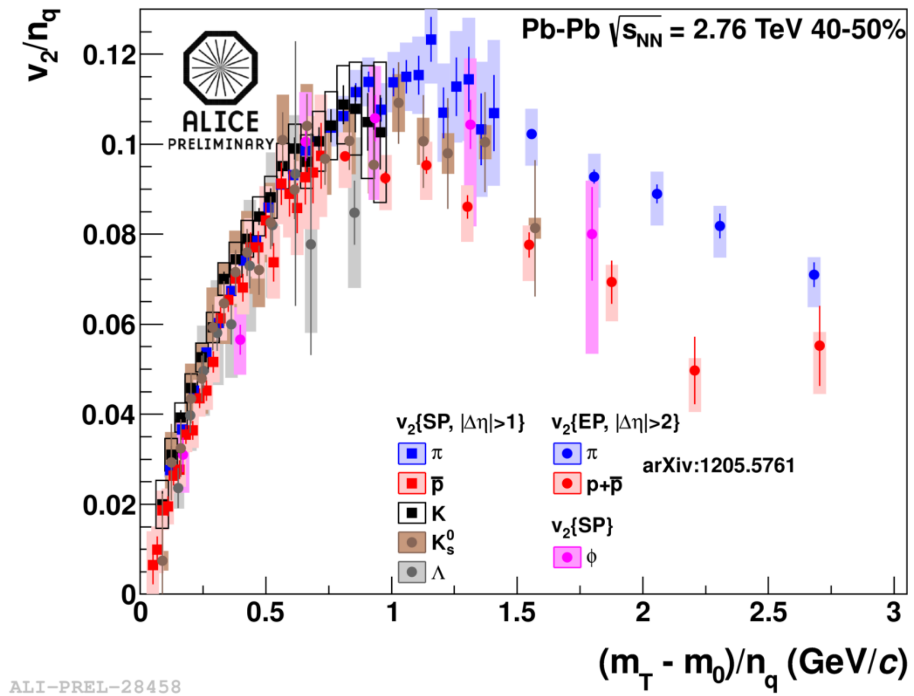
Quark Number Scaling@LHC

ALICE



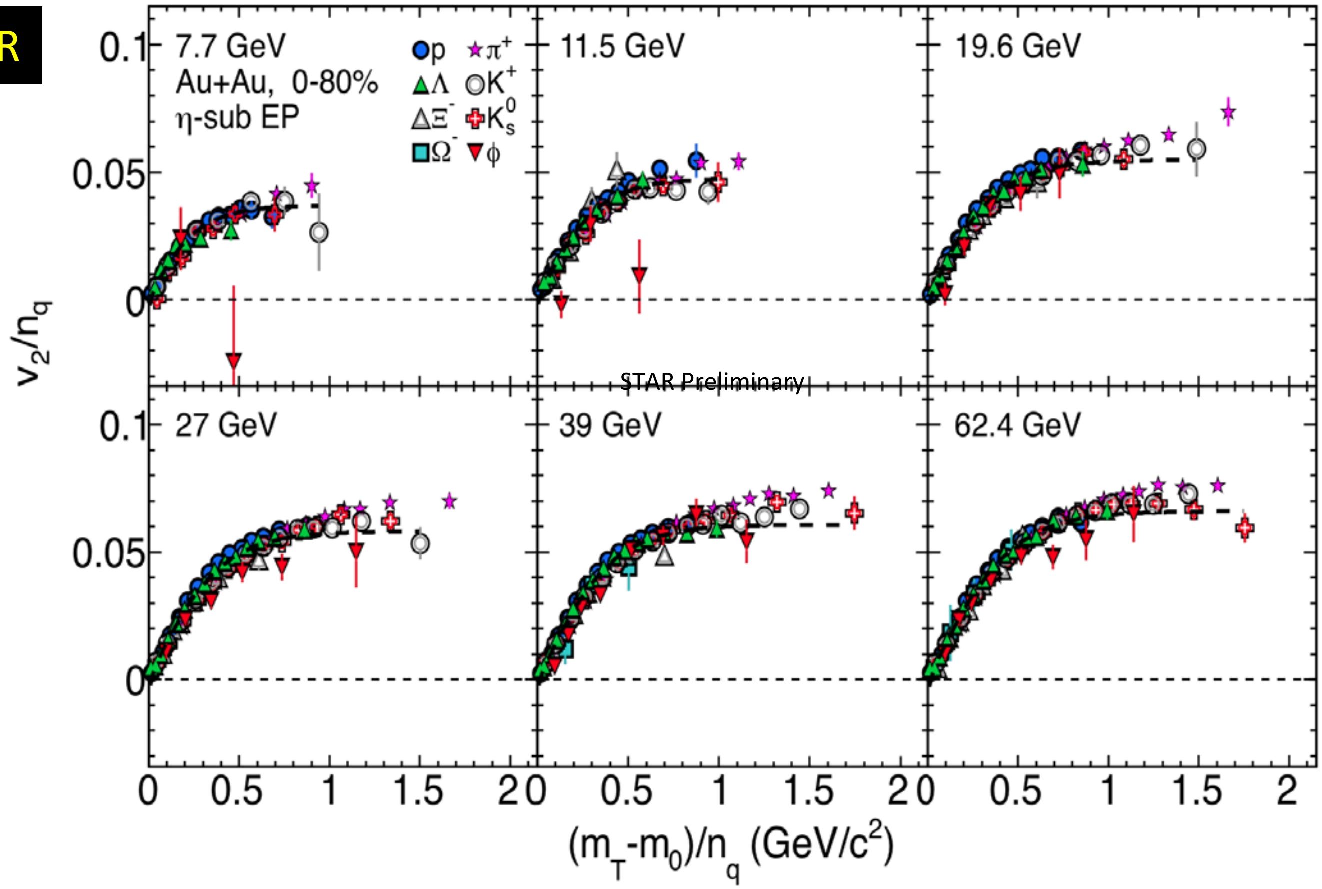


RHICよりも悪くなっている？

Quark Number Scaling @RHIC

- Energy Scan

STAR



Deviation from quark number scaling appears below 11.5 GeV

v_2 of ϕ ?

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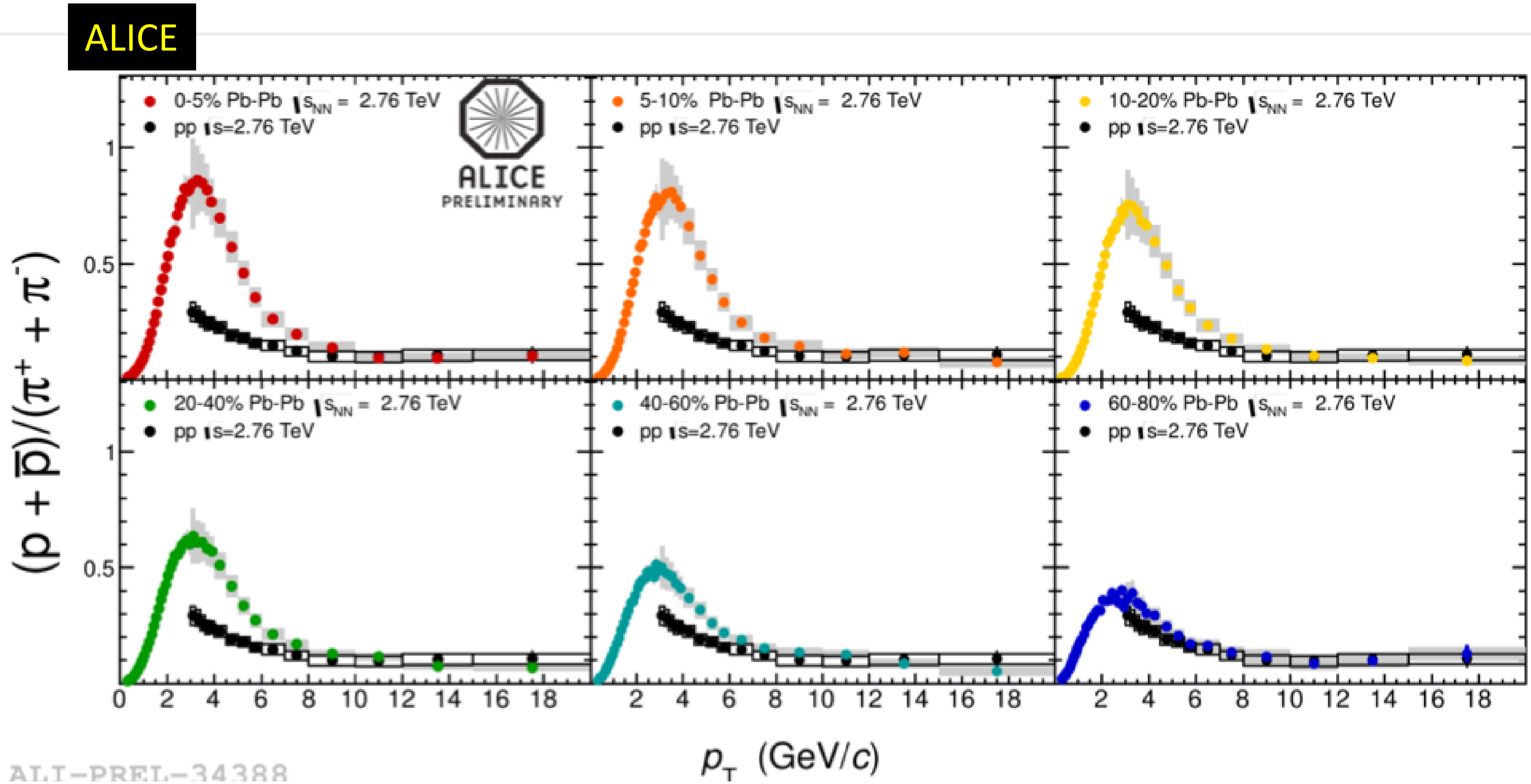
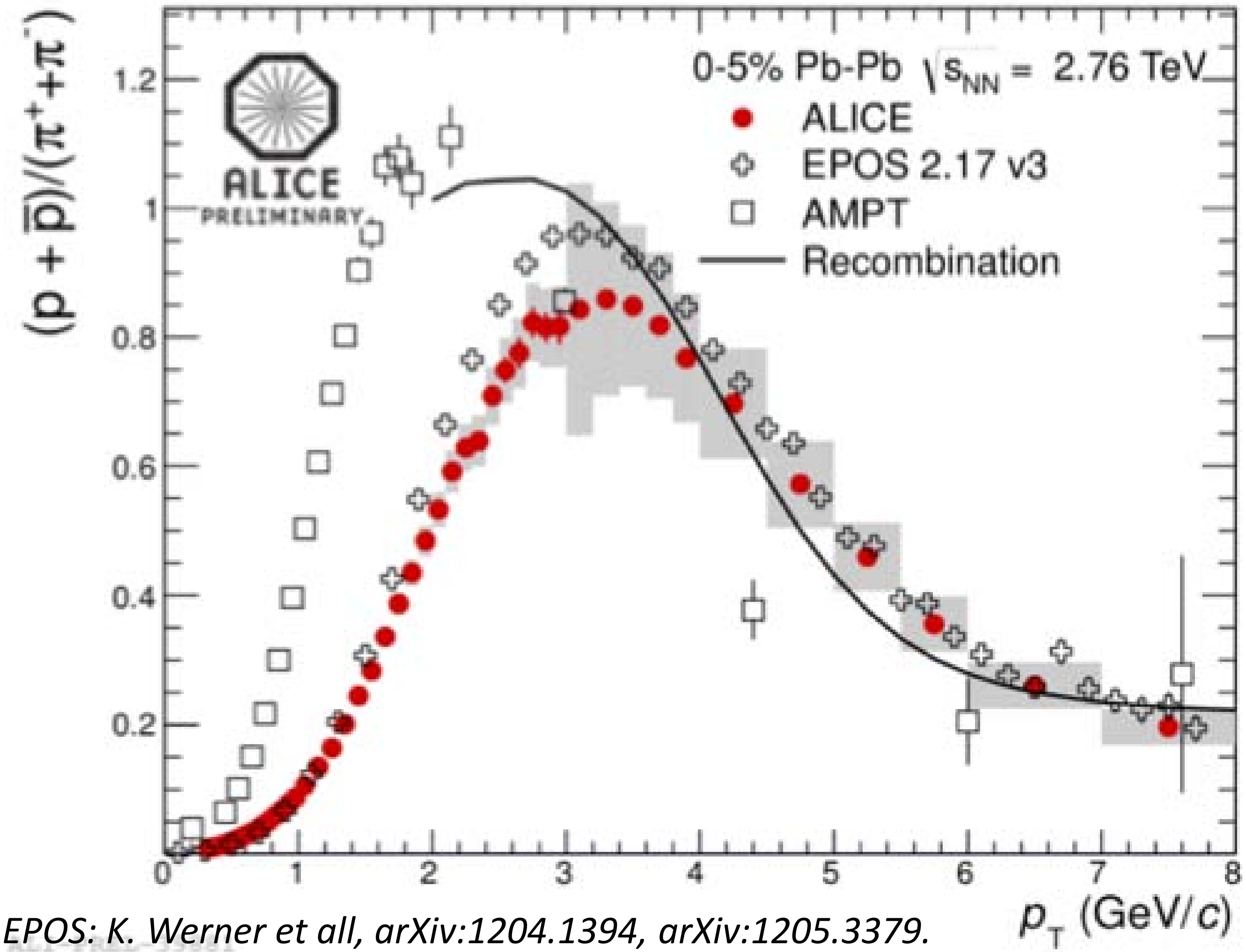
Baryon/Meson ratios



- Intermediate P_T
  Baryon enhancement: recombination
- High P_T
  Fragmentation

Comparison with Theory



EPOS: K. Werner et all, arXiv:1204.1394, arXiv:1205.3379.
AMPT: J. Xu and Che Ming Ko, Phys. Rev. C 83, 034904 (2011).
Recombination: R.J.Fries, B.Muller, C.Nonaka and S.A.Bass, Phys. Rev. C 68, 044902 (2003)

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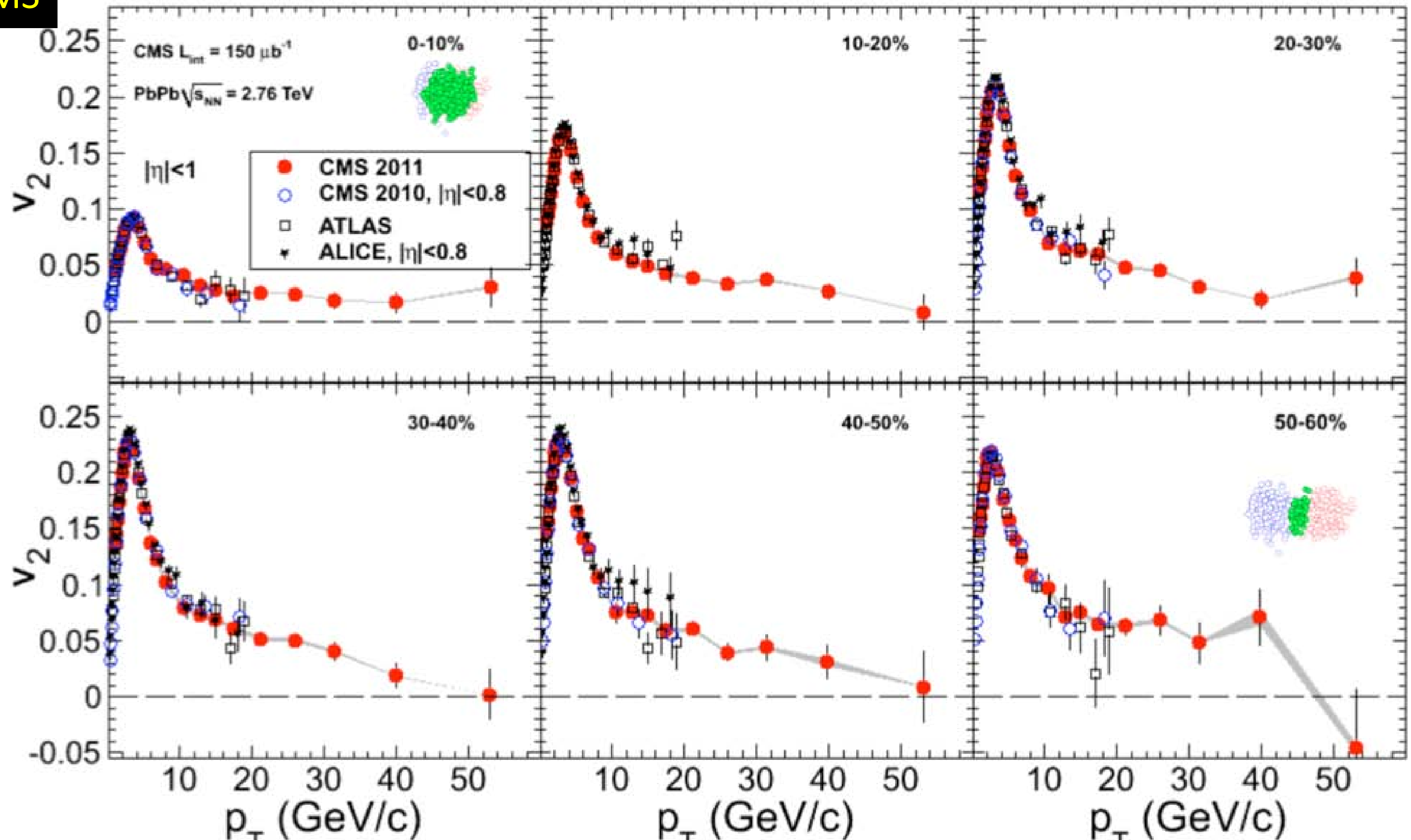
V_2 @ High P_T

CMS



P_T=40 GeVでも有限の値。ジェット抑制機構の解明へ大きな手がかり

v_3, v_4についてもhight P_Tの測定

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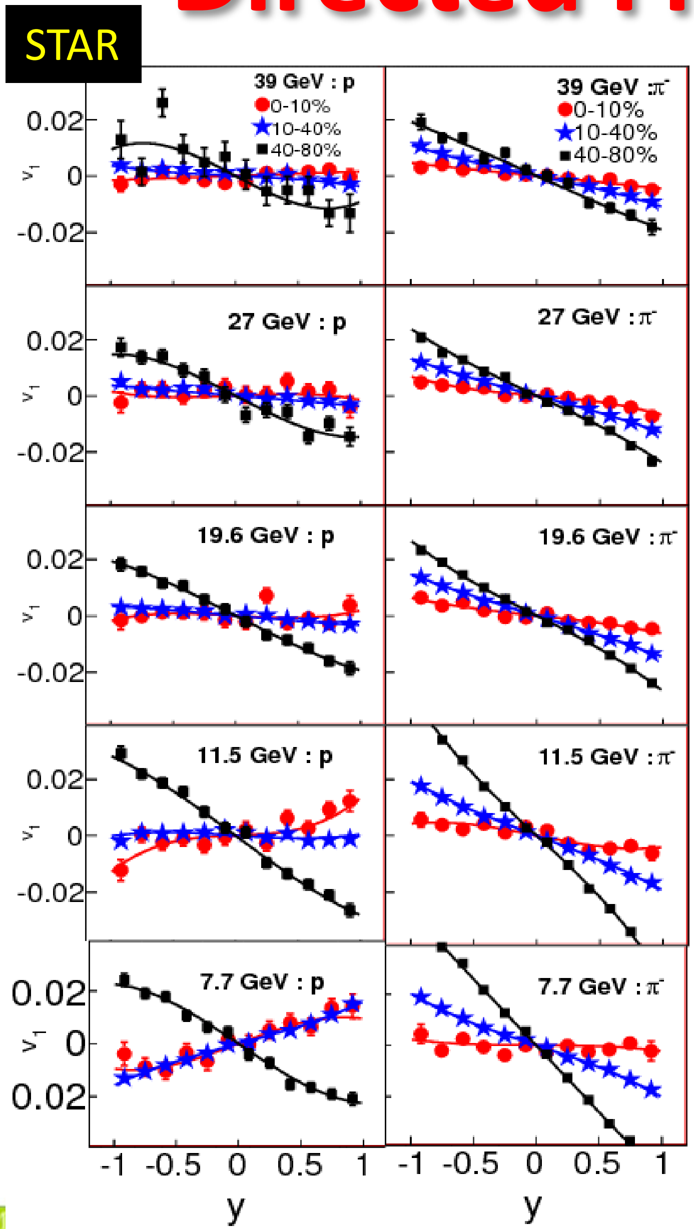
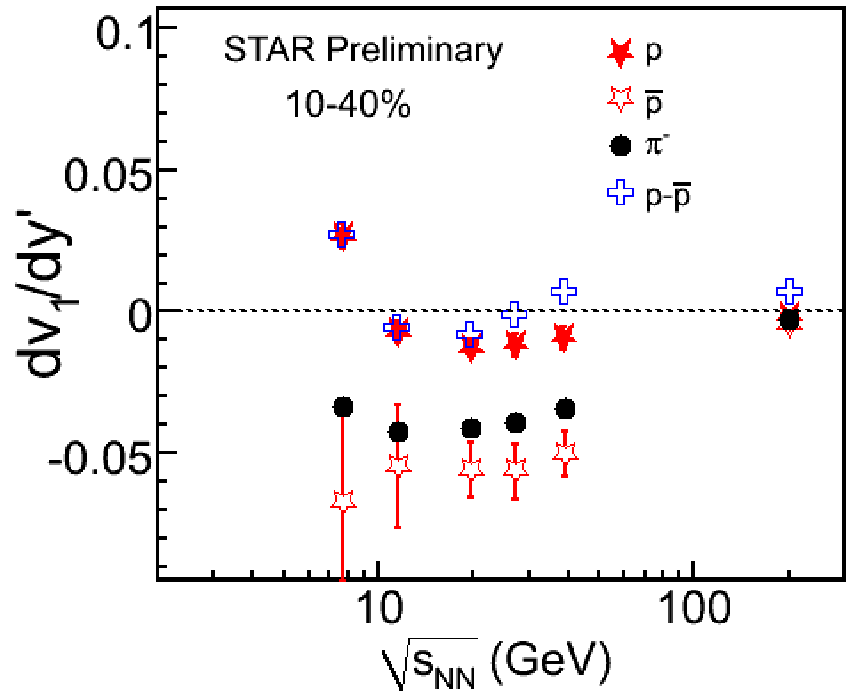
Directed Flow in Energy Scan





Pion v_1 slopes are negative
Proton $v_1$slple changes sign between 11.5 GeV and 7.7 GeV.

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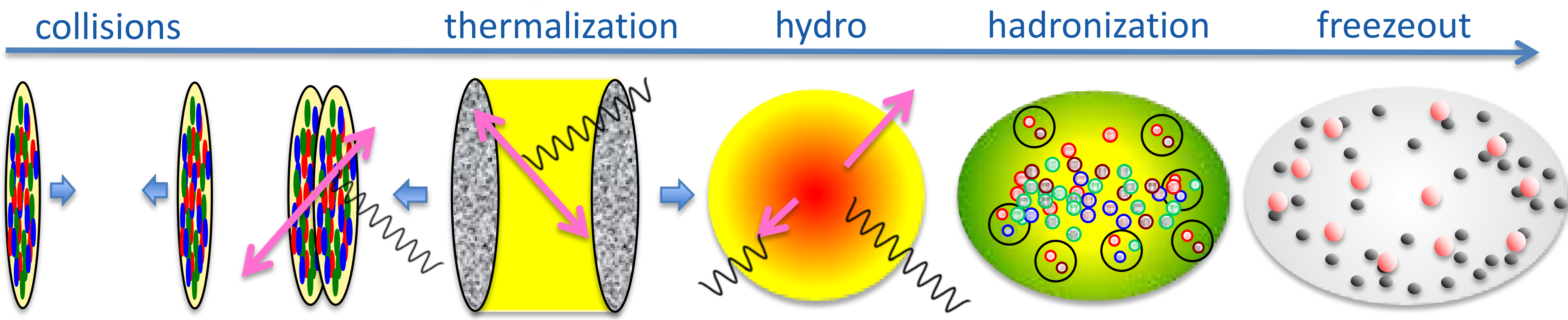
Jets, Heavy Flavor, Electro-Weak



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Jets
Heavy flavor &Quarkonia

New Theoretical /Experimental Developments

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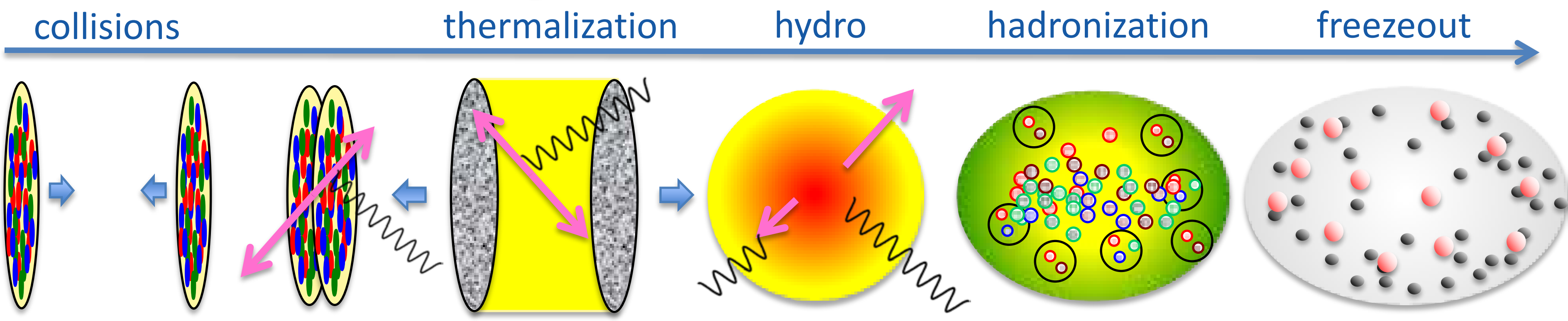
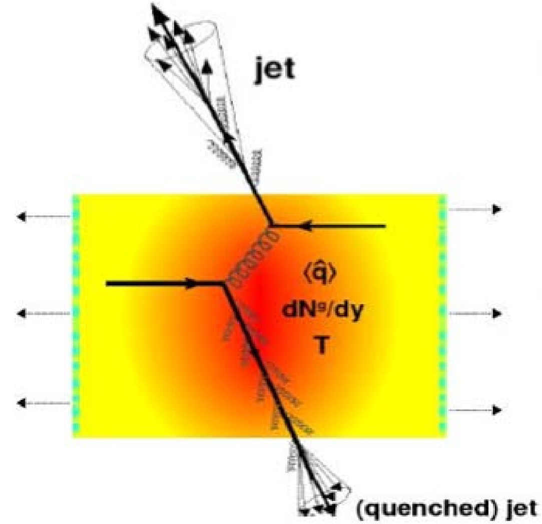
Jets, Heavy Flavor, Electro-Weak



Electro-Weak Probes
Jets
Heavy flavor &Quarkonia

Jets

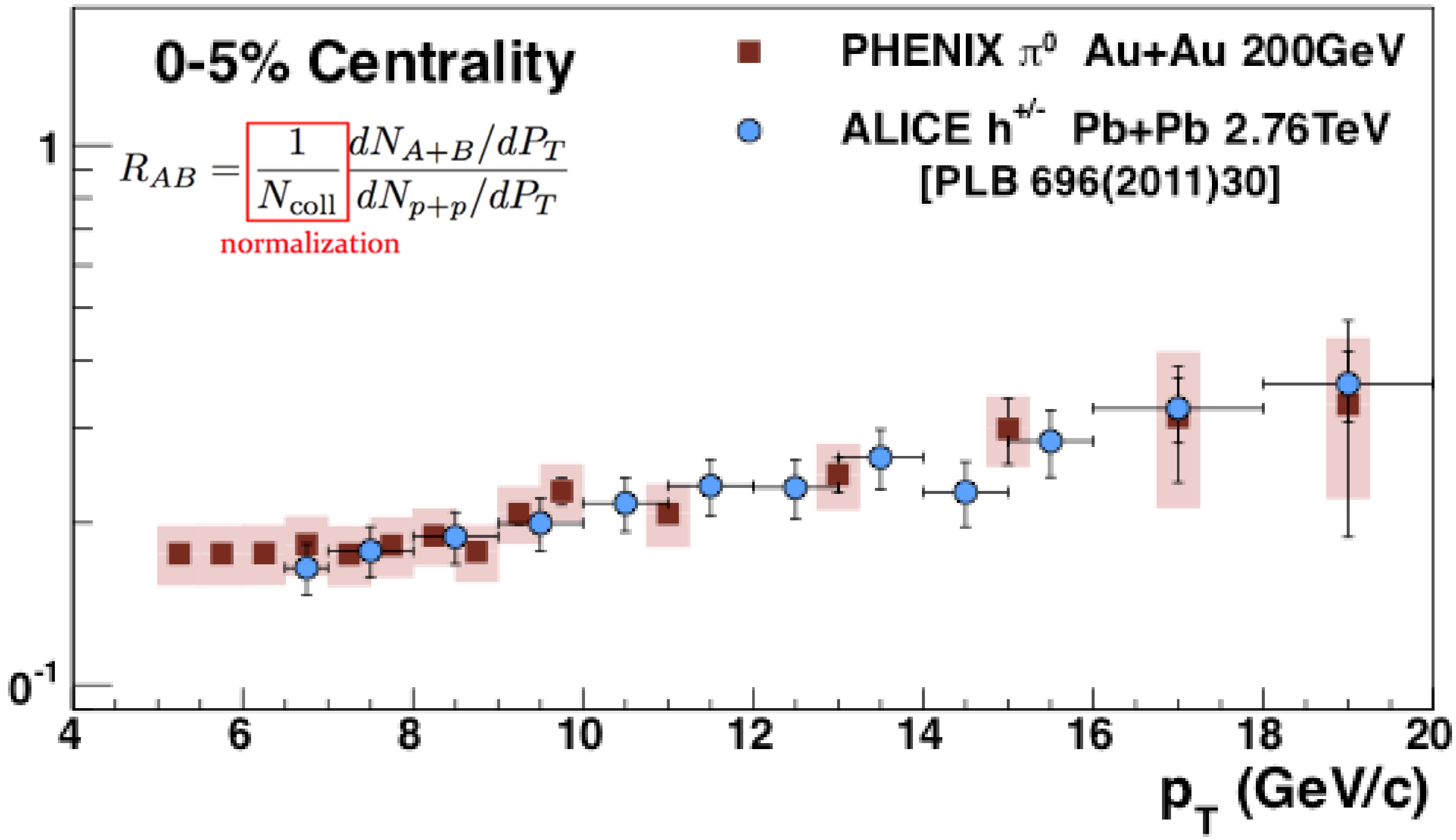


- Jets in medium
  - Properties of QGP
- Jet quenching mechanism
  - 4 approaches based on pQCD

Model	Assumption about the medium and kinematics	Scales	Resummation
GLV	static scattering centers (Yukawa), opacity expansion	$E \gg k_T \sim \mu$, $x \ll 1$	Poisson
ASW	static scattering centers, multiple soft scattering (harmonic oscillator approximation)	$E \gg k_T \sim \mu$, $x \ll 1$	Poisson
HT	observable matrix elements at scale Λ (thermalized or non-thermalized medium)	$E \gg k_T \gg \Lambda \sim \mu$	DGLAP
AMY	perturbative, thermal, $g << 1$ (asymptotically large T)	$E > T \gg gT \sim \mu$	Fokker-Planck

sQGP➔ model

R_{AA} @ RHIC and LHC

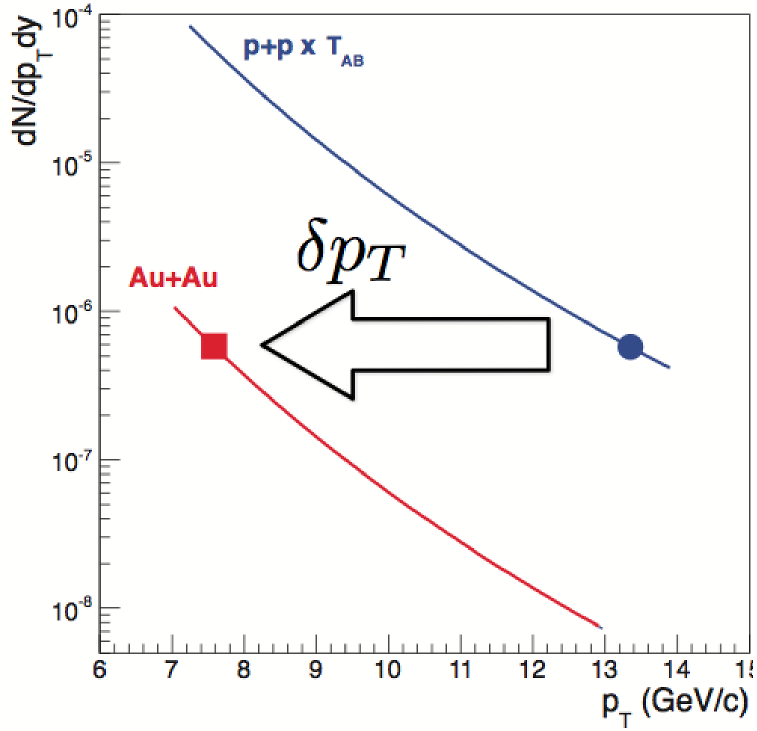


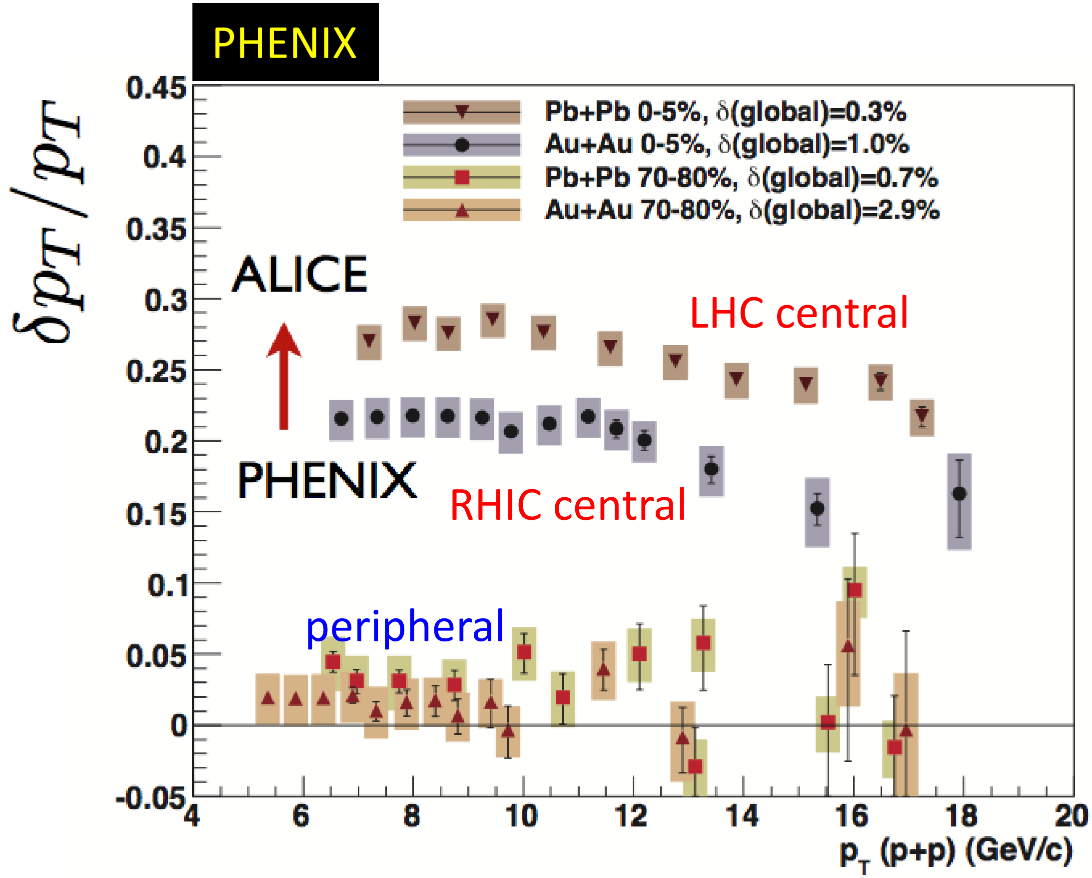
R_{AA} @ LHC is almost the same as R_{AA} @RHIC.

➡ Fractional momentum loss

Sakaguchi

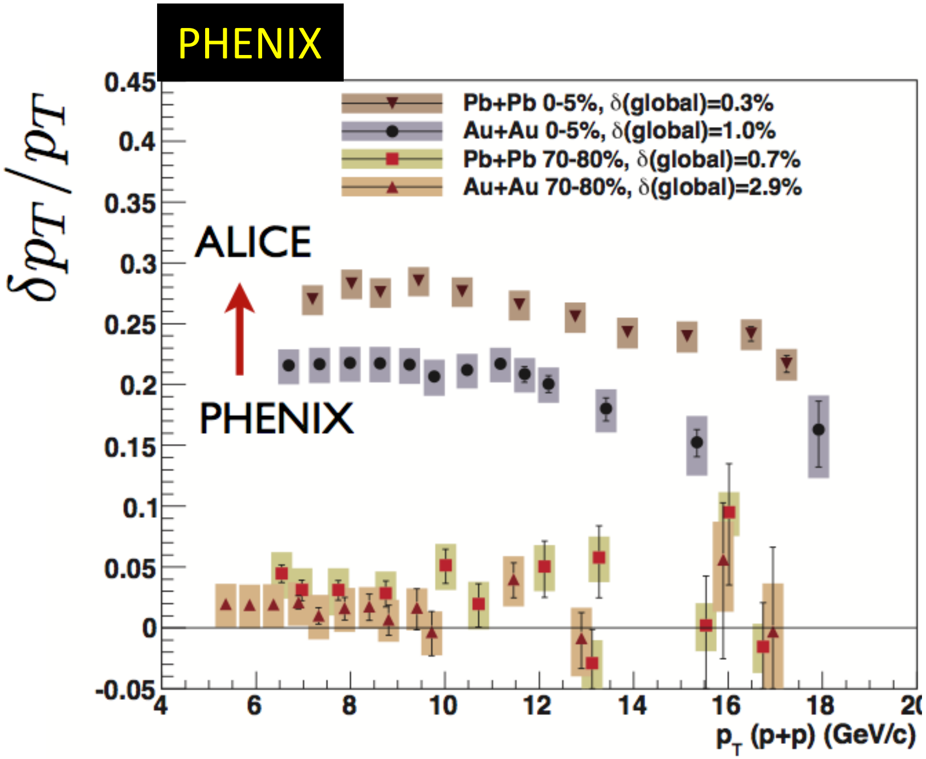
Fractional Momentum Loss

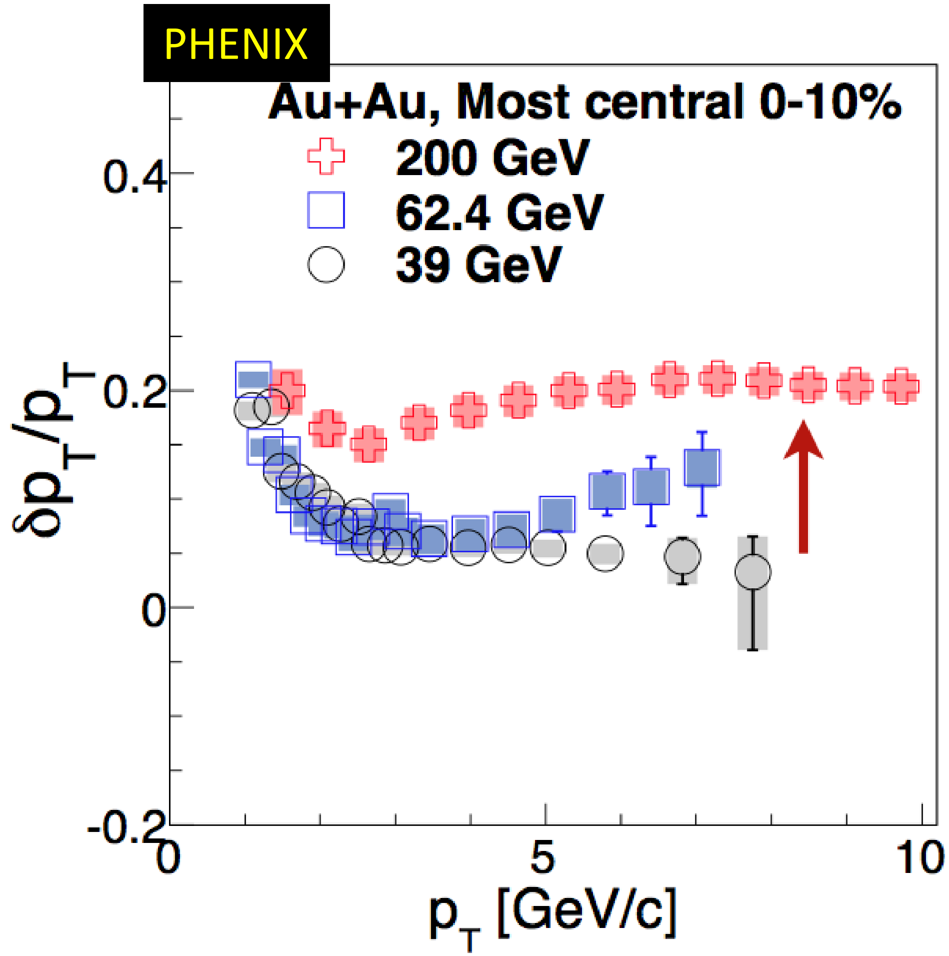




Fractional momentum loss @ LHC is larger than that @ RHIC.

Collision Energy Dependence

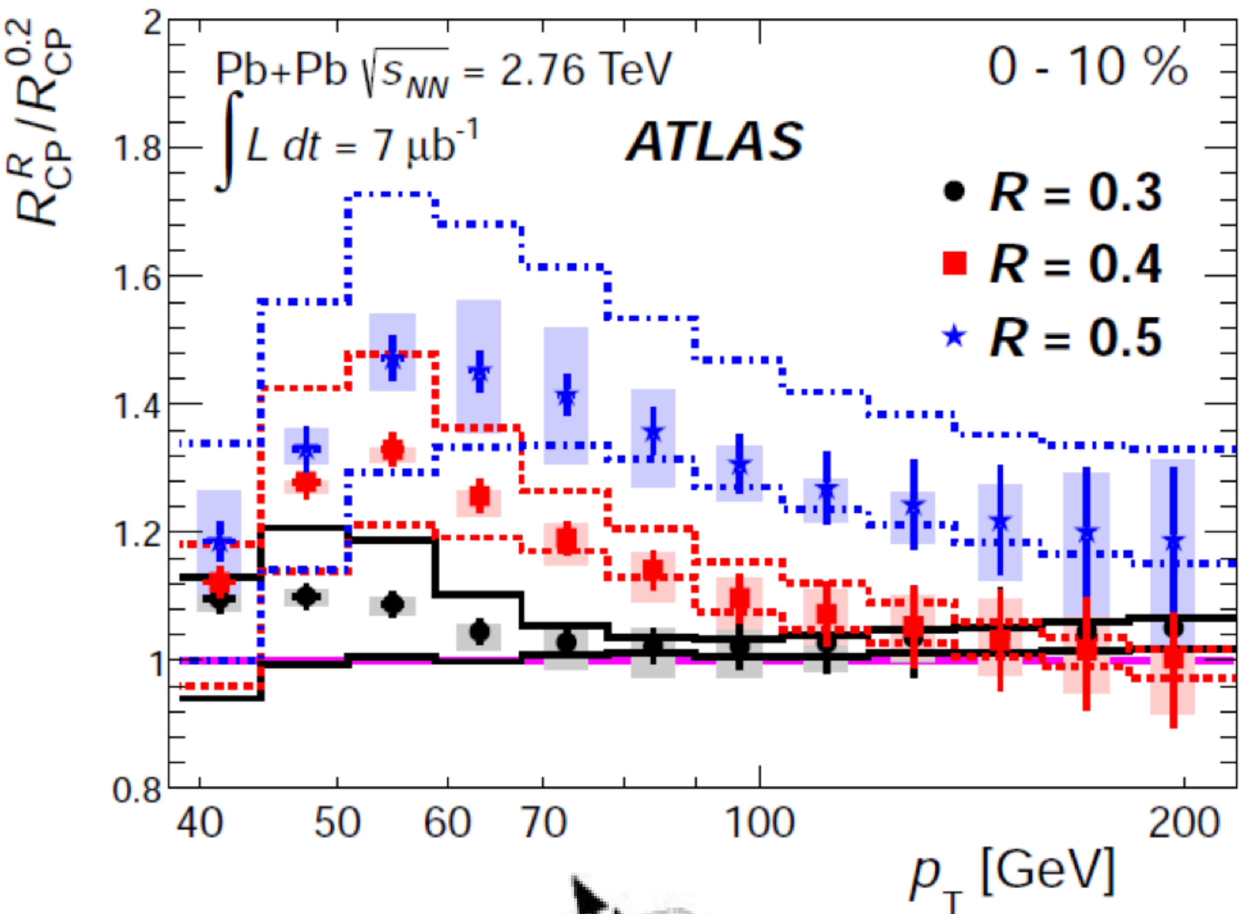




Jet Radius Dependence of R_{CP}

ATLAS

Inclusive jets



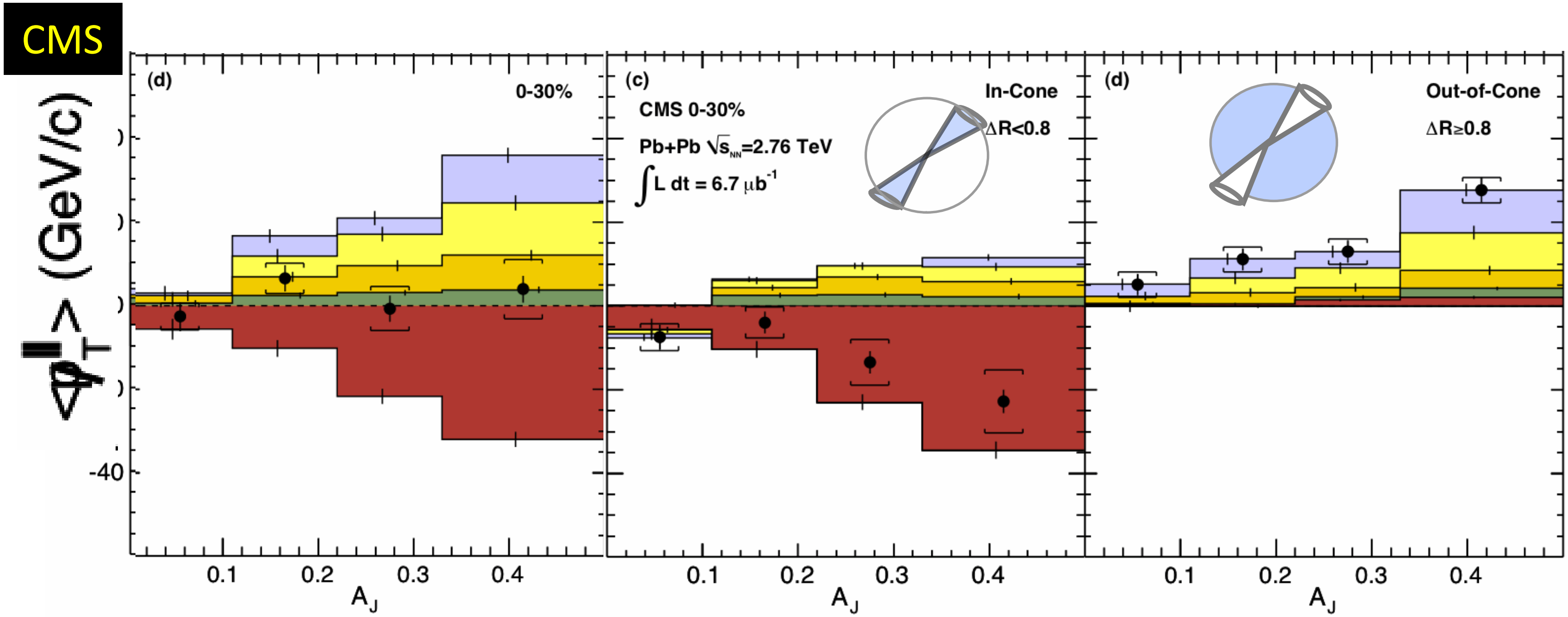
$$R_{CP} = \frac{N_{coll}^{periph} dN_{A+B}^{central}/dP_T}{N_{coll}^{central} dN_{A+B}^{periph}/dP_T}$$

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

Stronger suppression of smaller jets

CMS@QM2011

- Momentum balance in the dijet
  - Near side: high momentum
  - Away side: low momentum



$A_J = (p_{T,1}-p_{T,2})/(p_{T,1}+p_{T,2})$

$$\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

Jet Fragmentation

ATLAS

$$D(p_T)(p_T^{jet}) = \frac{1}{N_{jet}}\frac{1}{\epsilon}\frac{dN}{dp_T}(p_T^{jet}) =$$

Spectra of charged particles in jets

$$= \frac{1}{N_{jet}(p_T^{jet})}\frac{1}{\epsilon(p_T,\eta)}\left(\frac{\Delta N_{ch}(p_T,p_T^{jet})}{\Delta p_T} - \frac{\Delta N_{ch}^{UE}(p_T,p_T^{jet})}{\Delta p_T}\right)$$

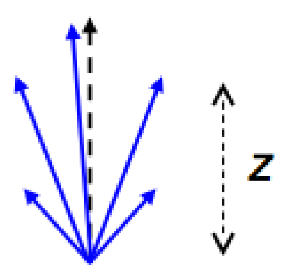
"Fragmentation function"

Tracking efficiency corrected

Underlying event subtracted

$$D(z)(p_T^{jet}) = \frac{1}{N_{jet}}\frac{1}{\epsilon}\frac{dN}{dz}(p_T^{jet}) =$$

$$= \frac{1}{N_{jet}(p_T^{jet})}\frac{1}{\epsilon(p_T,\eta)}\left(\frac{\Delta N_{ch}(z,p_T^{jet})}{\Delta z} - \frac{\Delta N_{ch}^{UE}(z,p_T^{jet})}{\Delta z}\right)$$

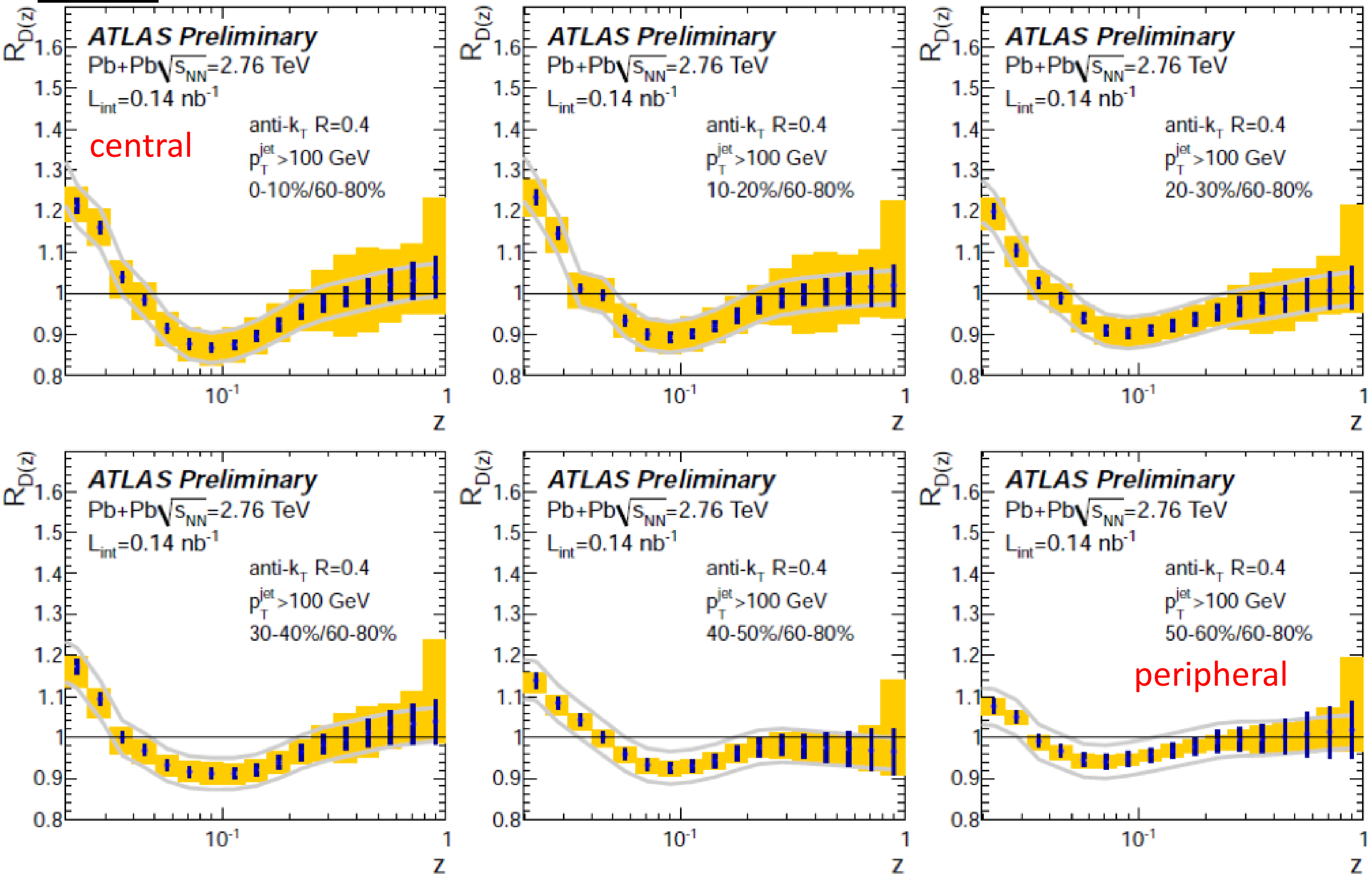


$$z = p_T/p_T^{jet}\cos\Delta R$$

$$R_{D(z)} = \frac{D(z)|_{cent}}{D(z)|_{60-80\%}}$$

Central Dependence of $R_{D(z)}$

ATLAS



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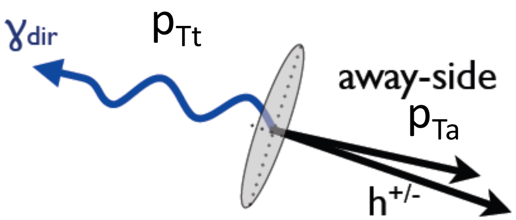
Modification of jet fragmentation with increasing of centrality

γ-h correlation in Au+Au

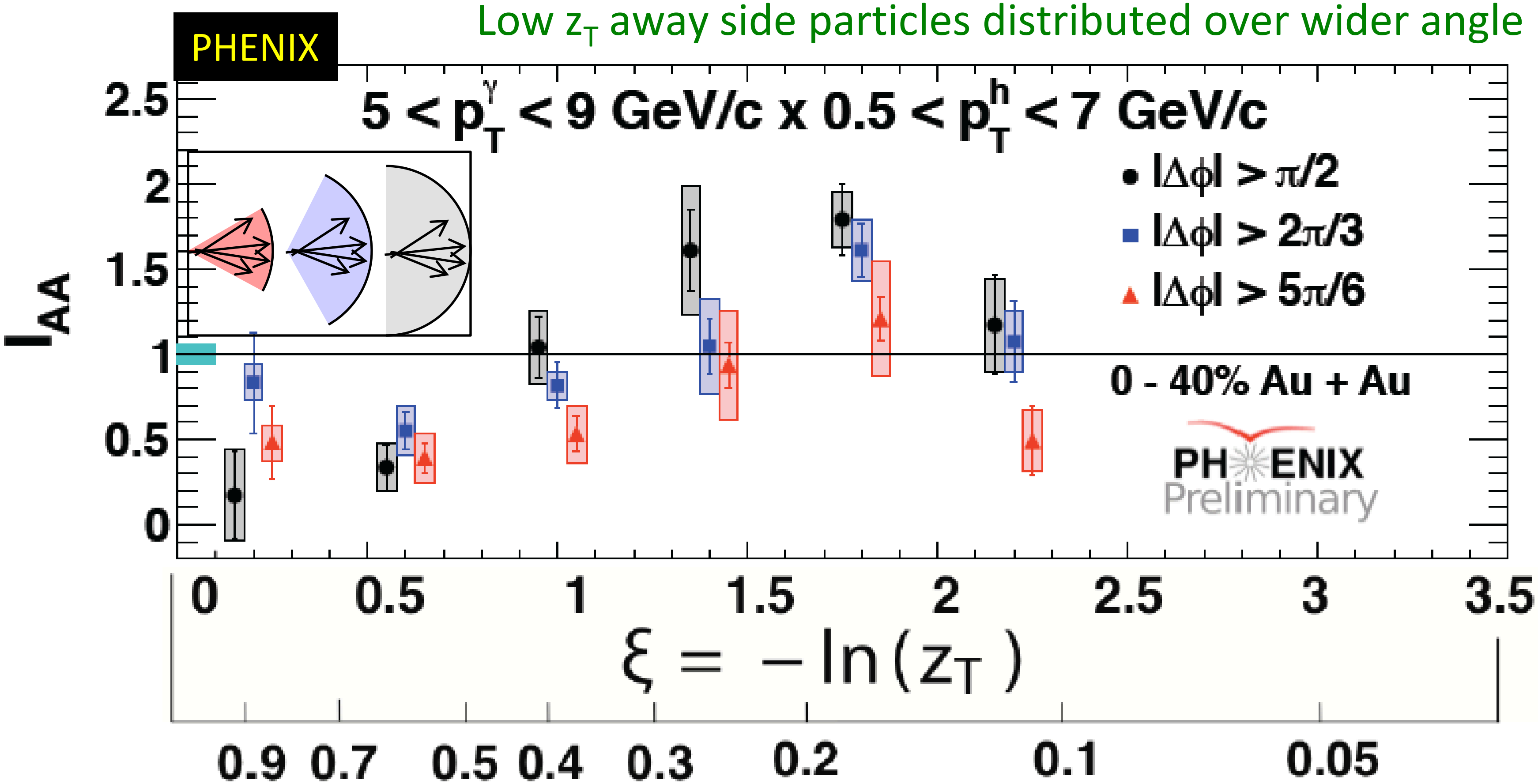


$z_T = p_{Ta}/p_{Tt}$

$\xi = \ln(1/z_T)$

$$I_{AA} \equiv \frac{(1/N_{trig}dN/d\xi)_{AA}}{(1/N_{trig}dN/d\xi)_{pp}}$$

Low z_T away side particles distributed over wider angle



z_T → Large energy loss

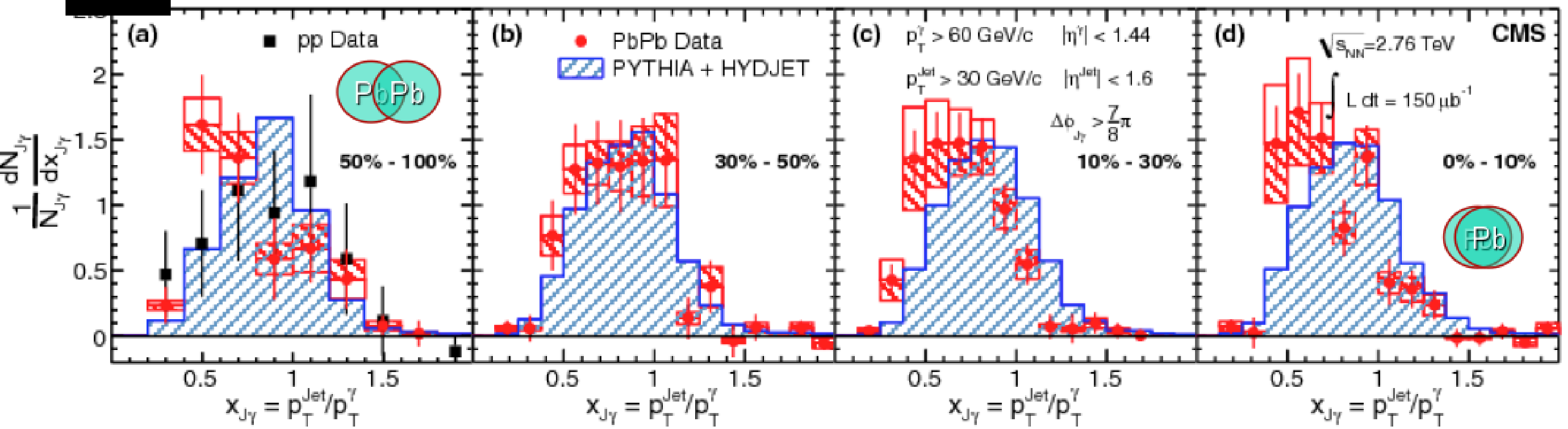
Sakaguchi

γ-jet Correlations

- Direct measure of the energy loss

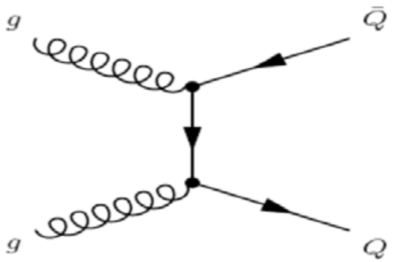
$x_{J\gamma} = p_T^{jet}/p_T^{\gamma}$

CMS



Small centrality dependence

Heavy Flavor



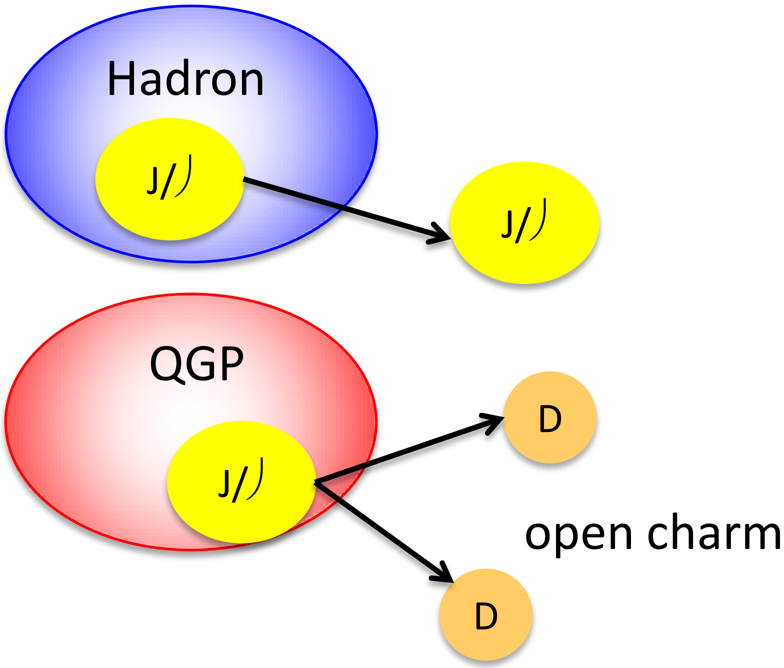
- Production
  - Gluon fusion
  - Initial gluon density and distribution
- Interactions with medium
  - Thermalization: medium transport properties
  - Energy loss: gluon bremsstrahlung radiation, collisional energy loss, collision dissociation…
- Cold Nuclear Effect
  - Gluon shadowing, color glass condensate
- Regeneration

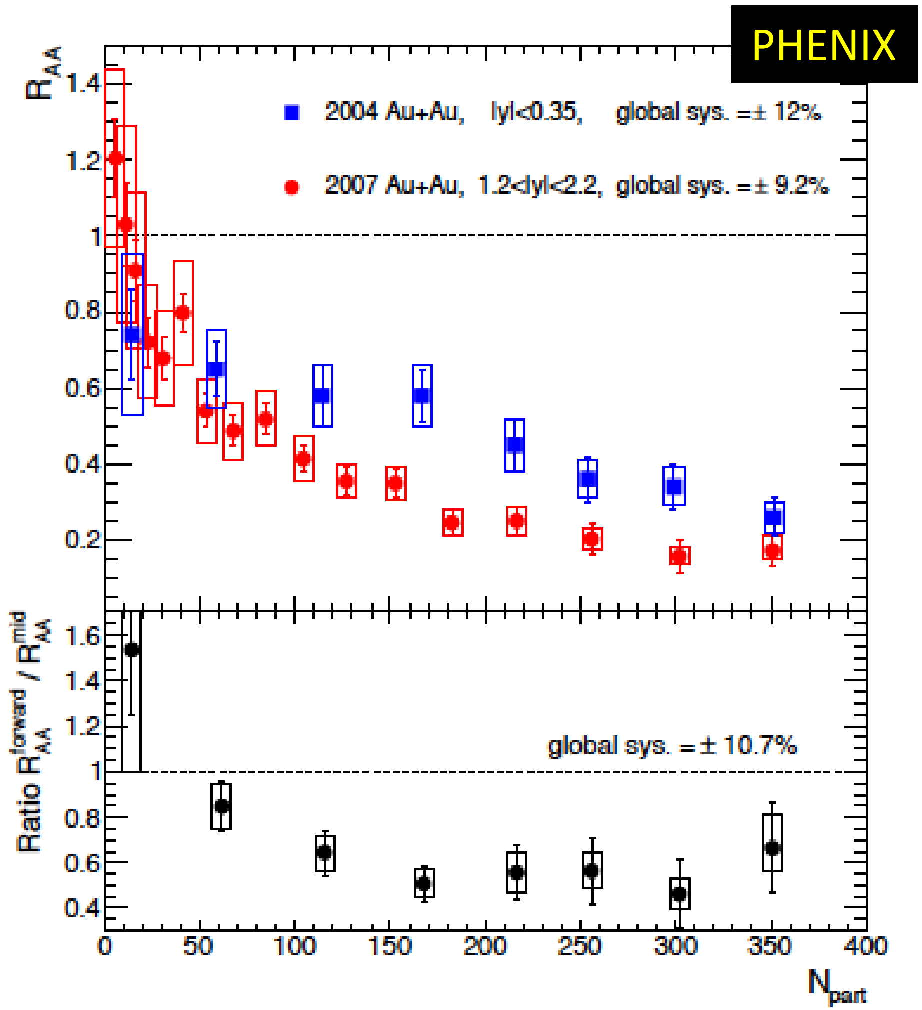
Heavy Flavor

- J/Ψ
  - J/Ψ 抑制：QGP生成のシグナル *Matsui, Satz, Miyamura … '86*

$$R_{AB} = \boxed{\frac{1}{N_{\rm coll}}} \frac{dN_{A+B}/dP_T}{dN_{p+p}/dP_T}$$

normalization





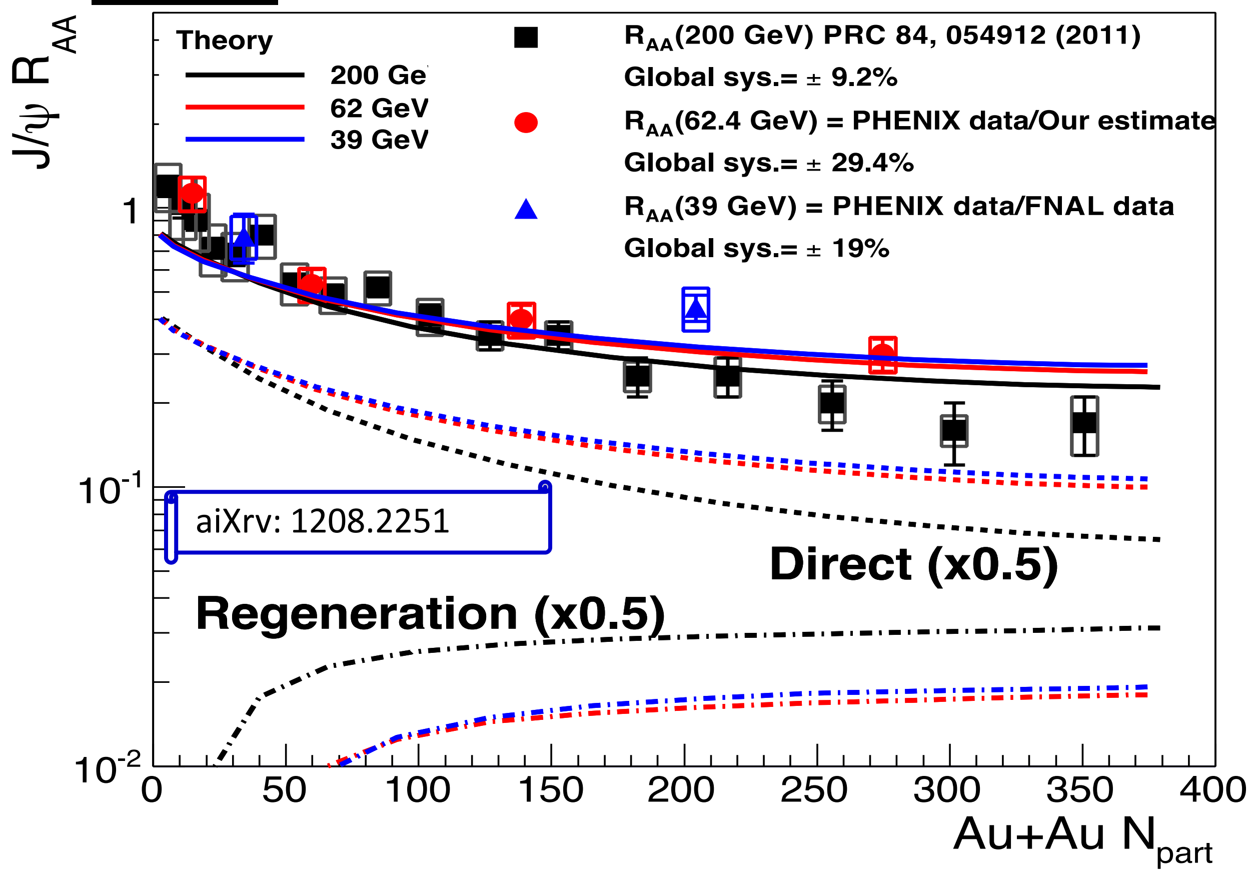
Regeneration of J/Ψ

X. Zhao, R. Rapp

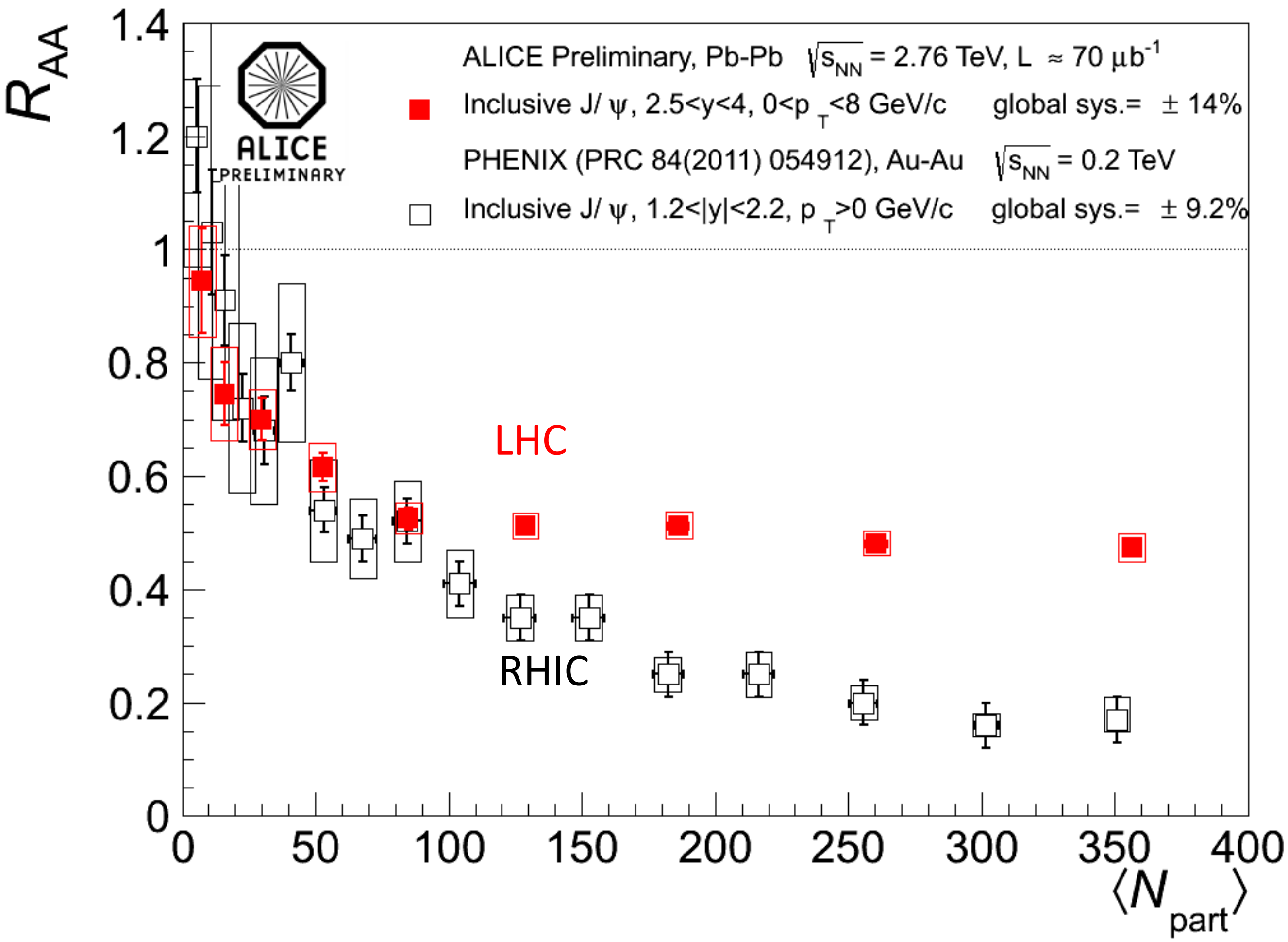
PHENIX Phys Rev C82 064905 (2010)

$$R_{AB} = \frac{1}{N_{coll}} \frac{dN_{A+B}/dP_T}{dN_{p+p}/dP_T}$$

normalization



R_{AA} of J/ψ @ LHC and RHIC



$$R_{AB} = \frac{1}{N_{\rm coll}} \frac{dN_{A+B}/dP_T}{dN_{p+p}/dP_T}$$

normalization

R_{AA} @ LHC is larger than R_{AA} @ RHIC

Larger regeneration?

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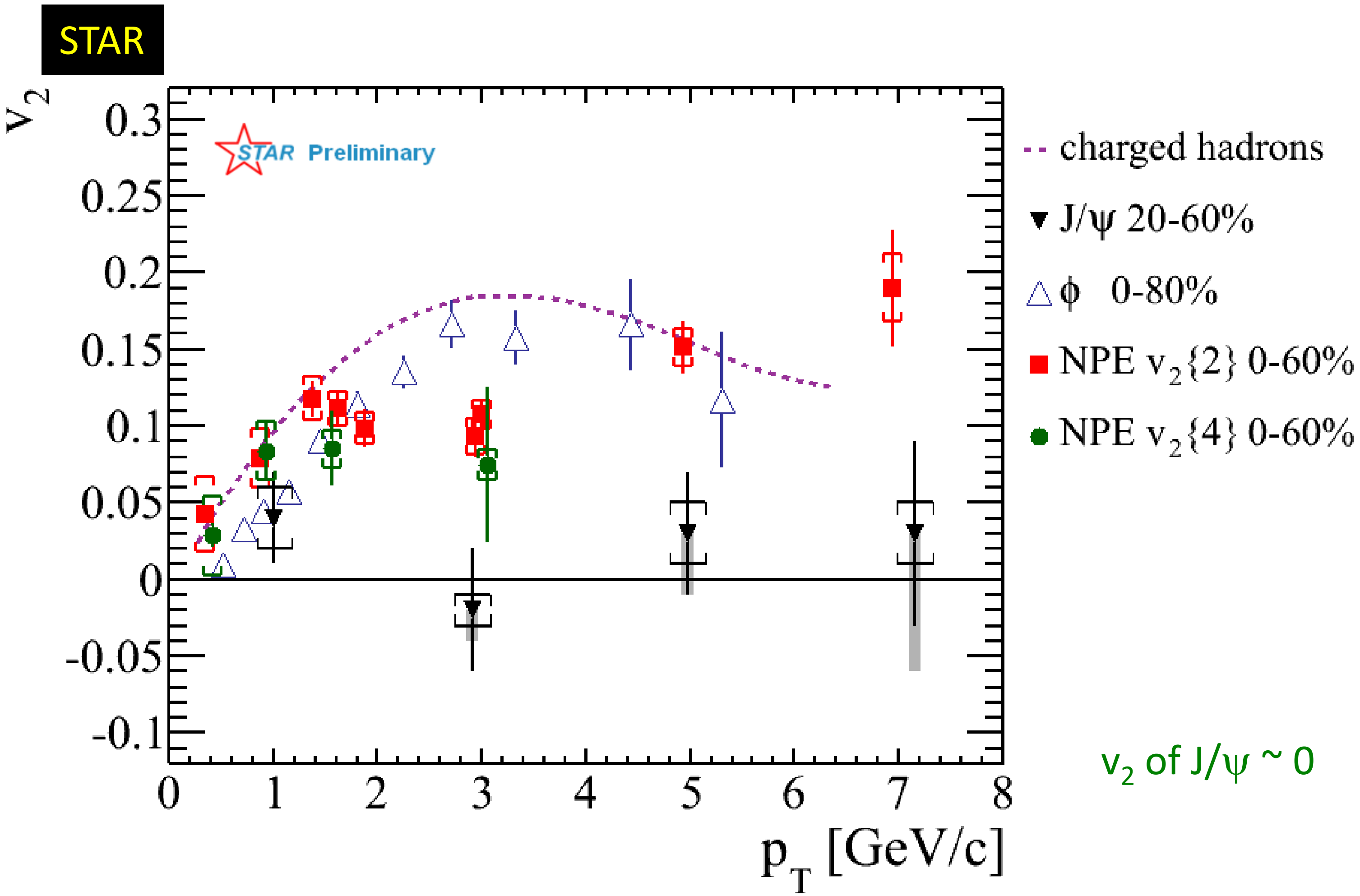
J/ψ Elliptic Flow @ RHIC



v_2 of J/ψ ~ 0

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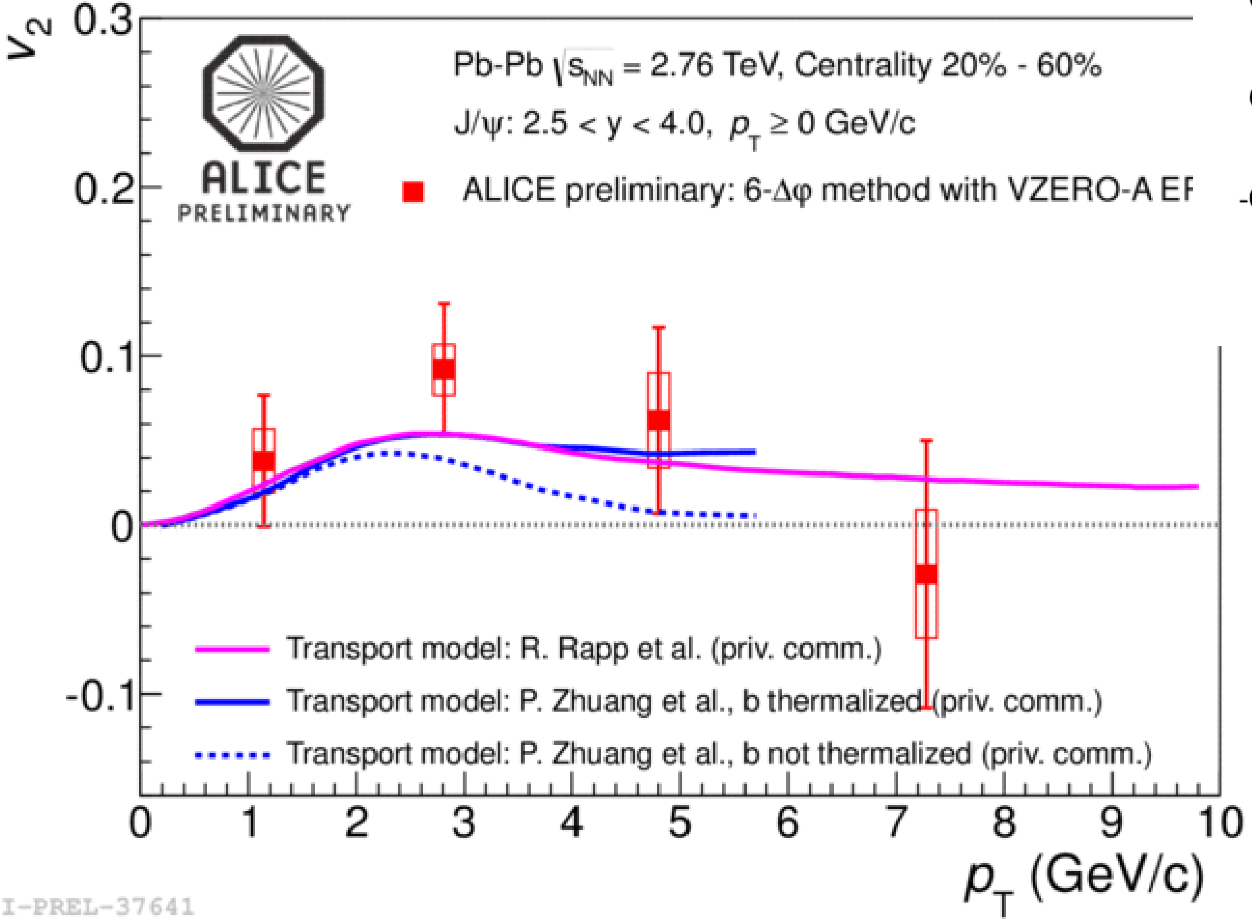
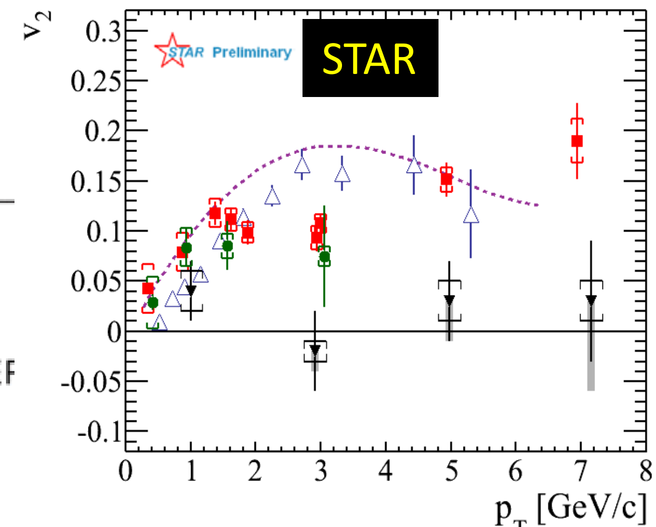
J/ψ Elliptic Flow @ LHC

ALICE



STAR



v_2 of J/ψ ≠ 0

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R_{AA} of bottom

$$R_{AB} = \boxed{\frac{1}{N_{coll}}} \frac{dN_{A+B}/dP_T}{dN_{p+p}/dP_T}$$

normalization

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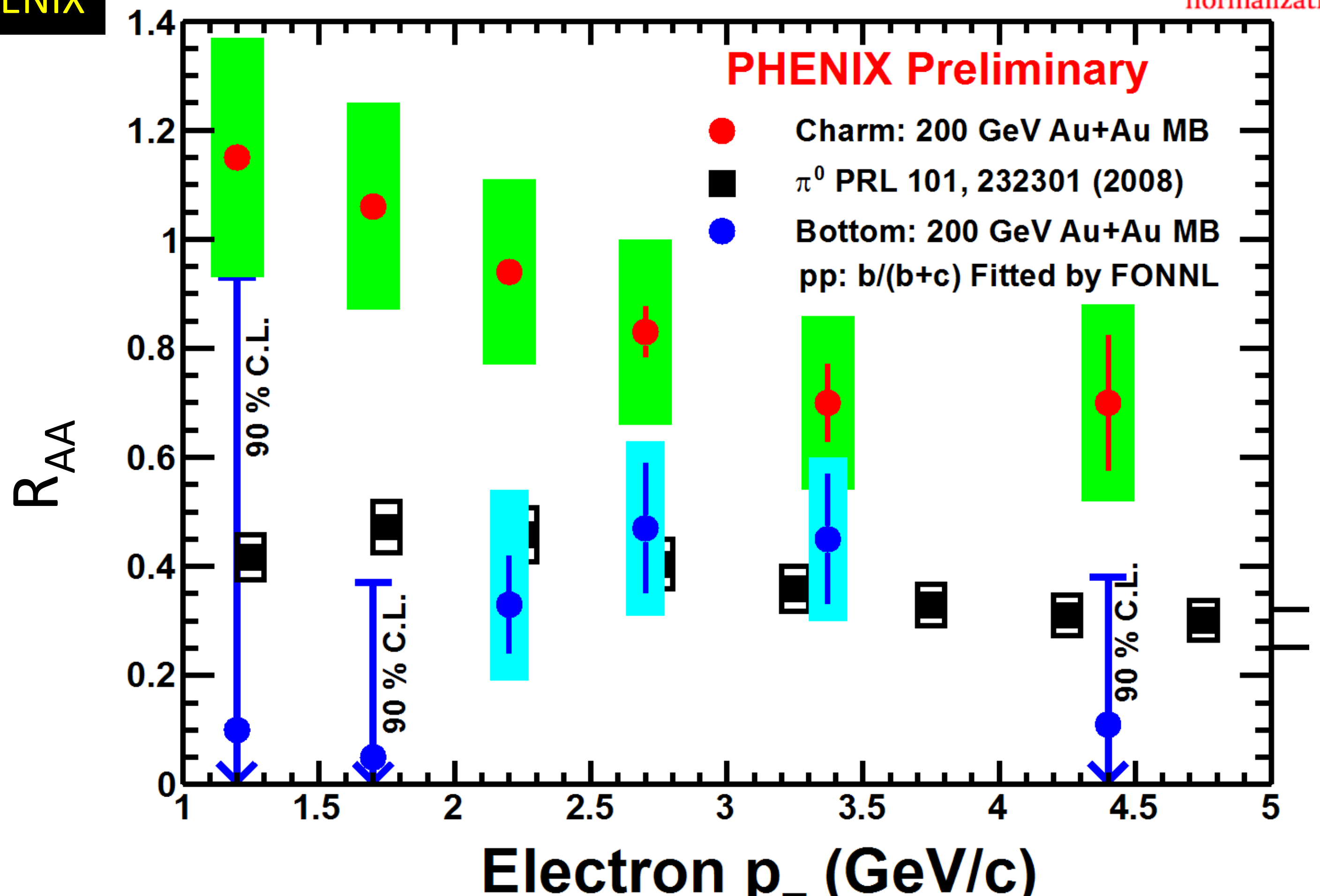
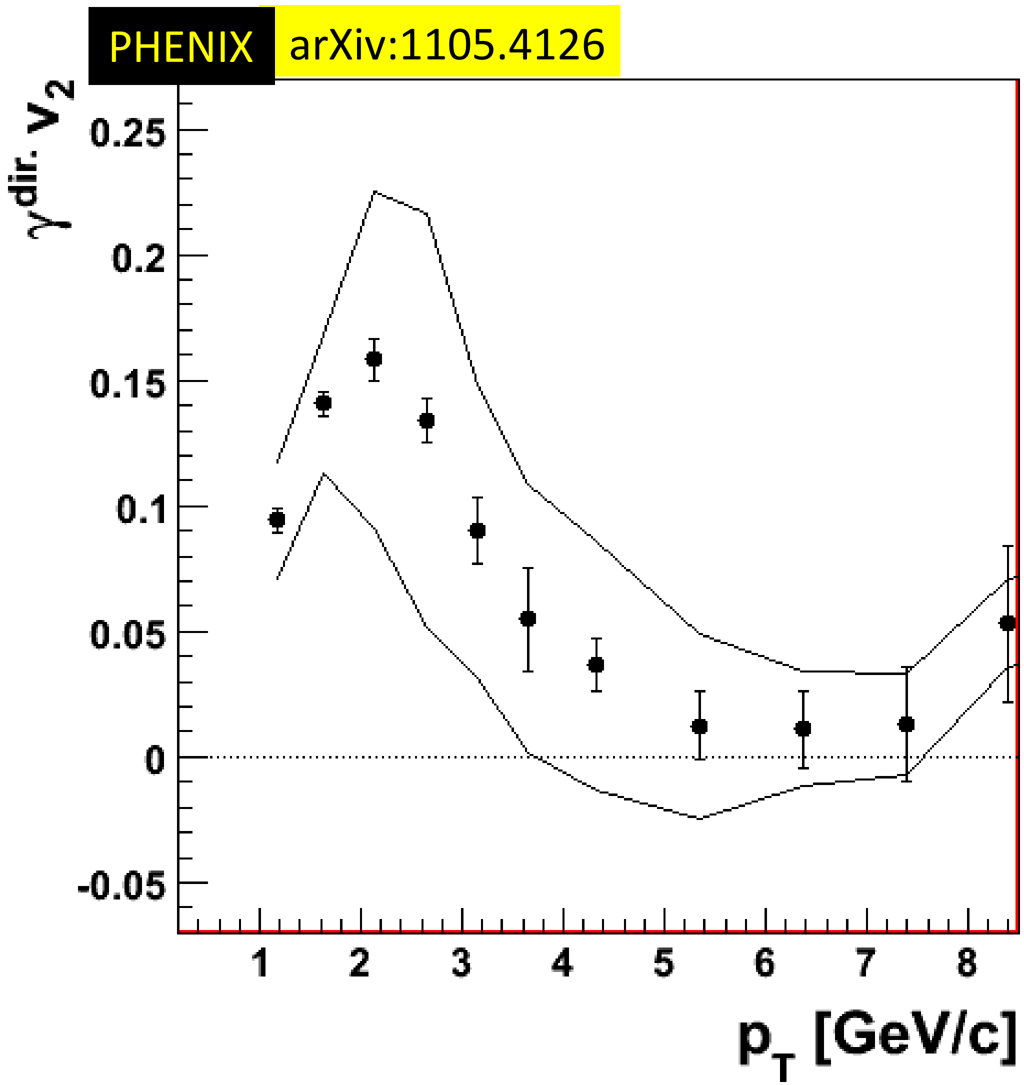


R_{AA}: jet energy loss, heavy flavor ?

A complicated mechanism may be hidden?

Direct Photon v_2



P_T< 4 GeV : large v_2

P_T> 4 GeV : v_2 ~ 0

Dileptons

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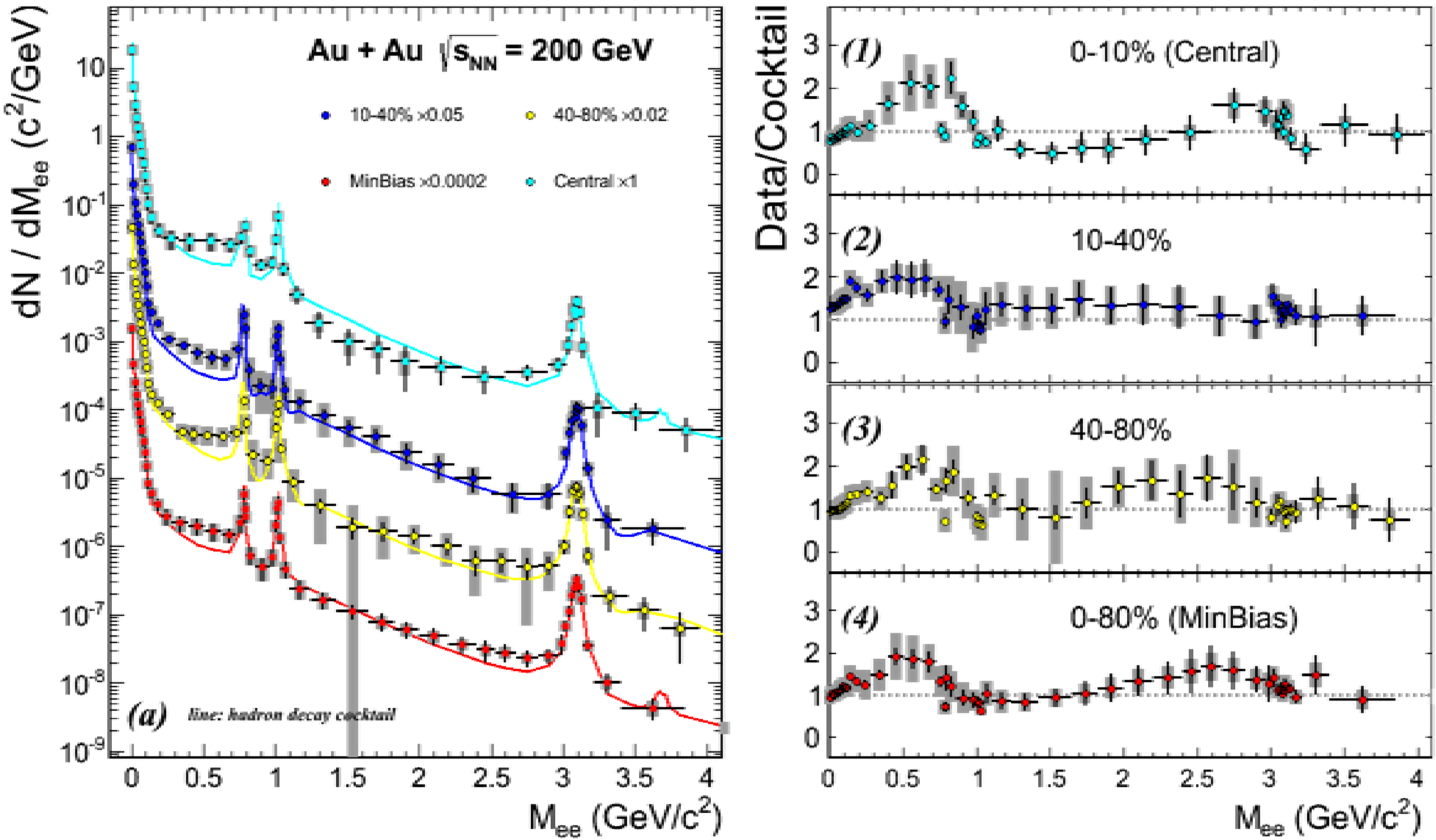
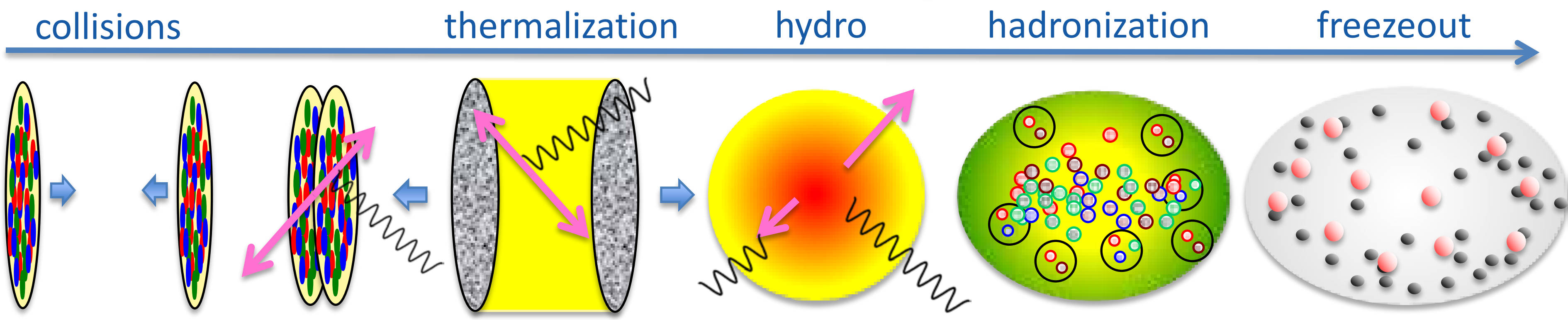


Low mass: enhancement → ρ meson in medium?

Summary



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Hadron Thermodynamics and Chemistry

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New Theoretical /Experimental Developments

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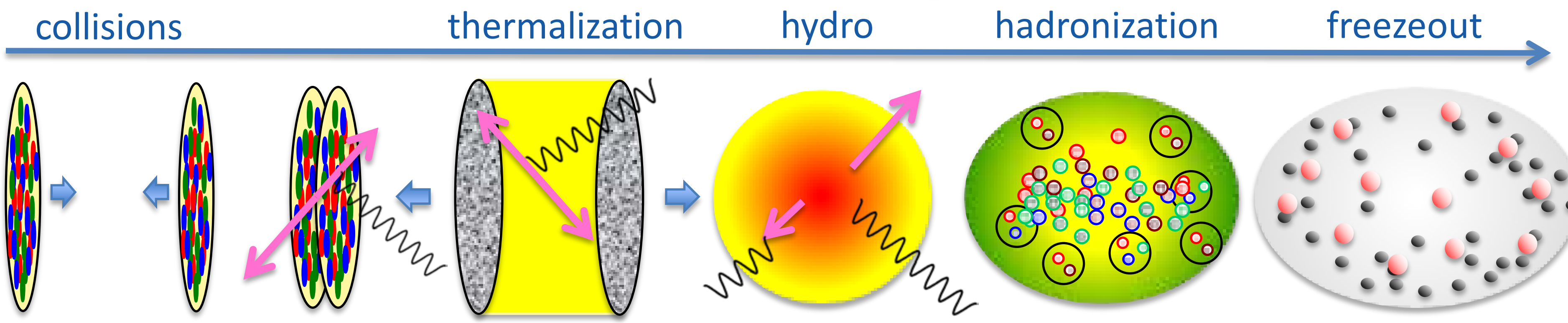

- QGP状態の解明をめざし大規模で精密な実験が行われている。
- 多角的な研究からQGPについての統一的な知見が得られつつある。
- 定量的な解明には理論からの理解が不可欠。

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