p-A衝突における粒子相関

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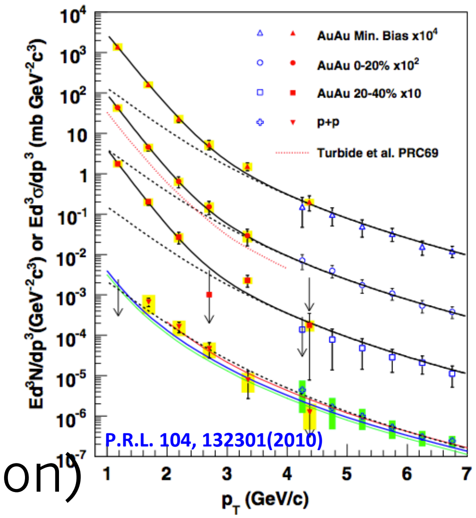
Outline

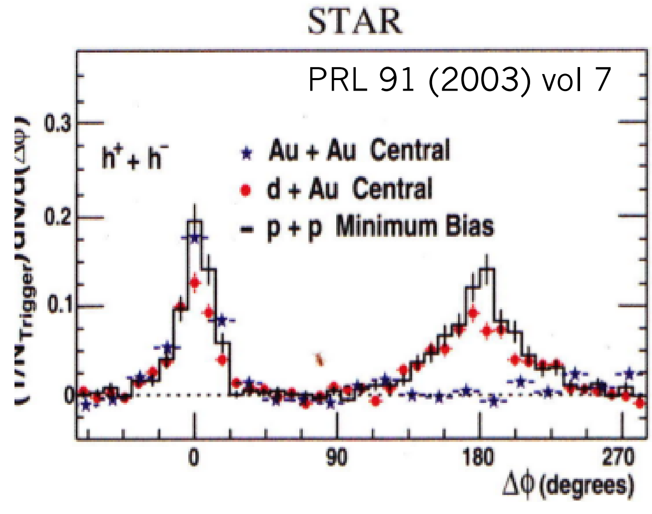
- Heavy Ion collisions
- p-Pb collisions
  - Particle correlation
  - Heavy flavor correlation
- Summary

Heavy Ion Collisions

HICにおけるこれまでの成果

- Large elliptic flow
  - Mass ordering
  - Quark number scaling?
- High p_T particle suppression
- Jet quenching
- Thermal photon?
- J/ψ suppression(&regeneration)
- Baryon enhancement
- Strange enhancement
- …

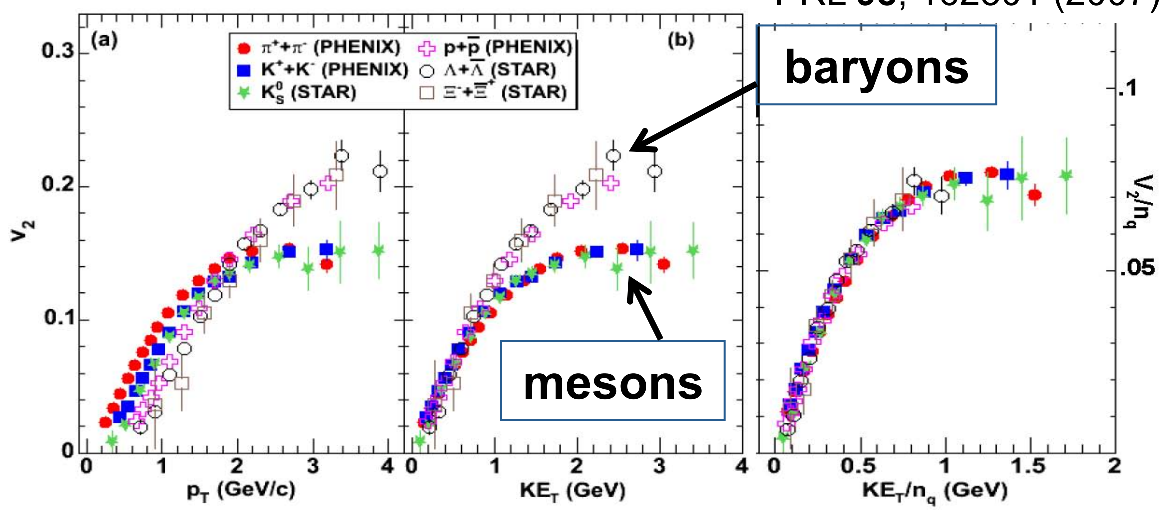




確からしいこと

- Ideal hydrodynamics
- 強結合性(sQGP)
- Coaleasence な粒子生成
- …

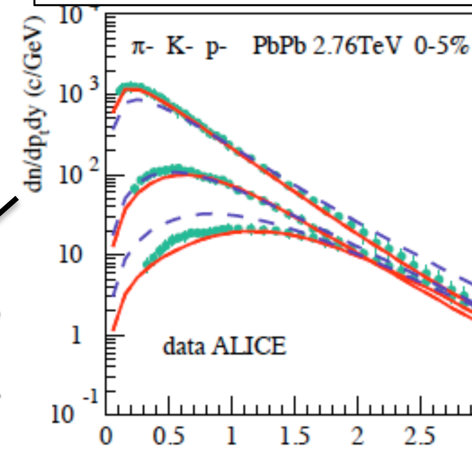
PRL **98**, 162301 (2007)



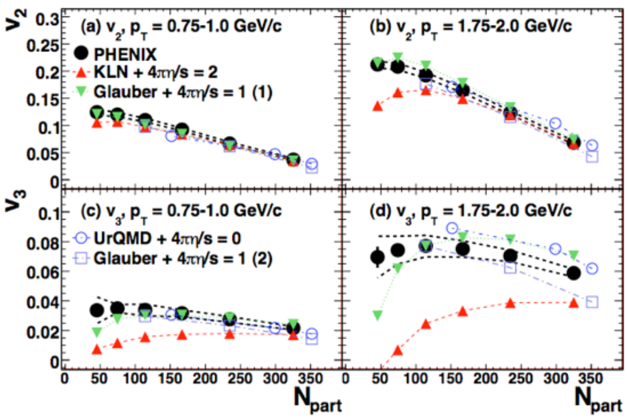
Time-space evolution of HIC

- 初期状態は物理量に影響を与える
  - Hadron相も

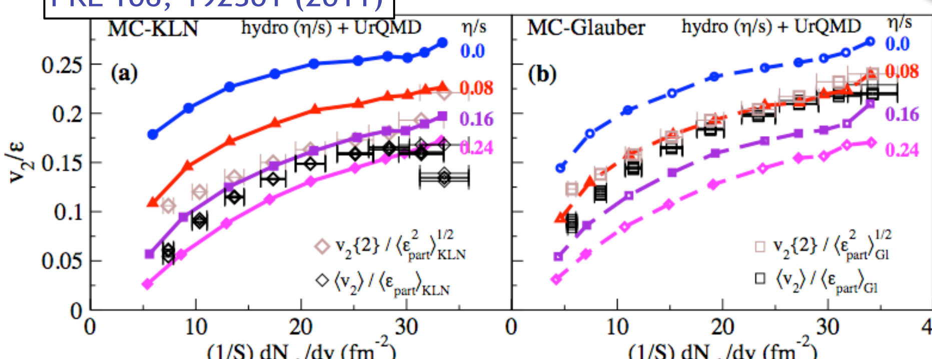
Rescattering in hadron phase

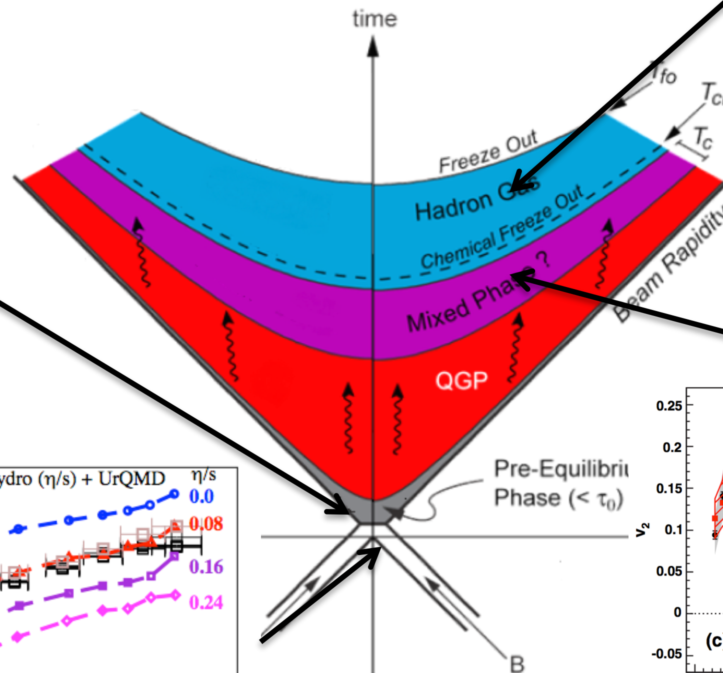


Werner et al, Phys.Rev. C85 (2012) 064907

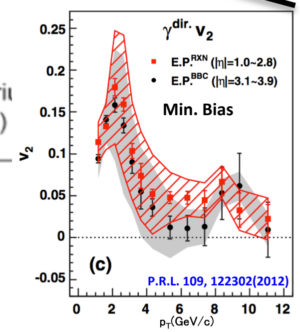


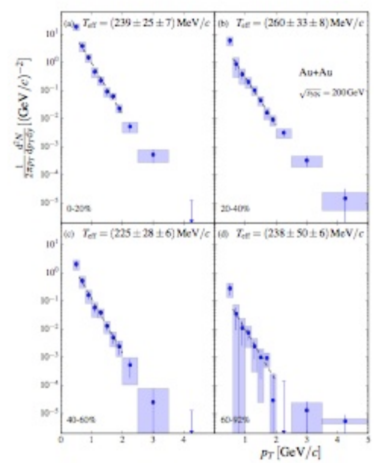
PRL 106, 192301 (2011)





?





- lifetime

t ~ 10 fm/c~ 10^{-23} s

- system size

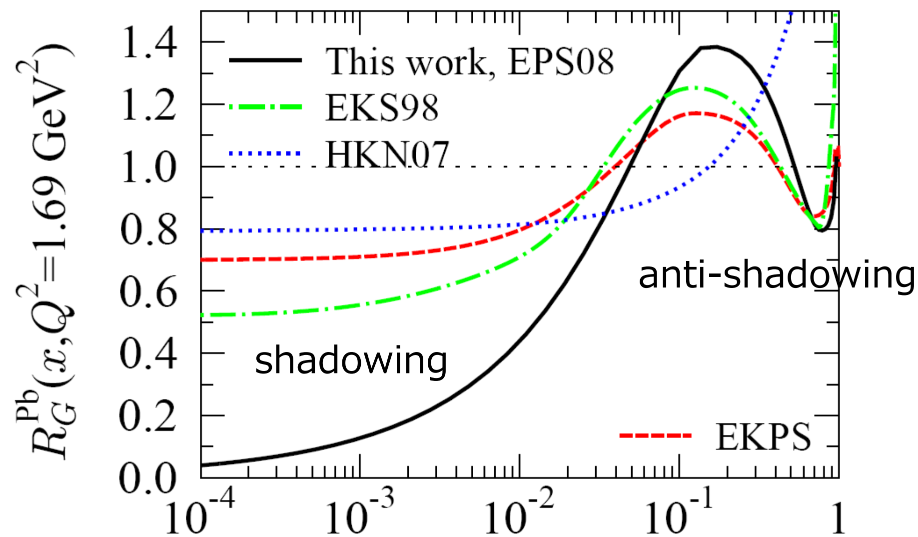
r ~ 10 fm~ 10^{-14} m

Initial state effect theories

- Glauber:
  - geometric model determining wounded nucleons based on the inelastic nucleon-nucleon cross section (whole family of variants)
- MC-KLN:
  - Color-Glass-Condensate (CGC) based model using k_T factorization
- IP-Glasma:
  - CGC based model using classical Yang-Mills evolution of early-time gluon fields, including fluctuations in the particle production
- pQCD+saturation:
  - calculate minijets using pQCD to get energy deposited in the collision region

p-A 衝突実験

- Initial state effectsの検証
  - Gluon shadowing
  - Gluon saturation
  - Cronin effect
    - <k_T> broadening
  - …



JHEP07 102

原子核核子中でのGluon PDFの変化、多重散乱

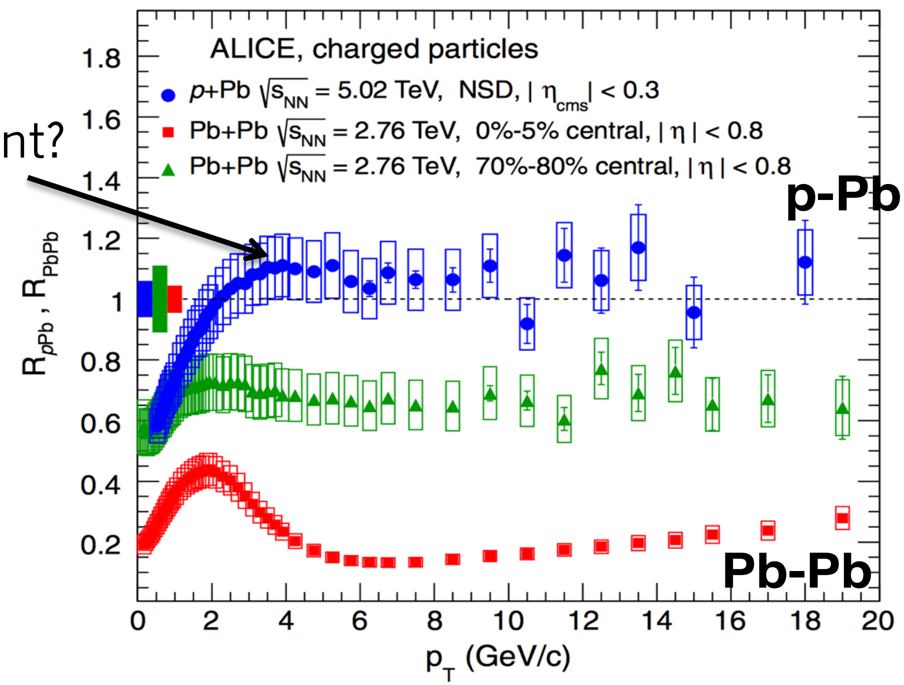
Other effects
Break up
Collectivity

Charged particles R_{pA}

- p-Aでsuppressionは見られない
- AAで見られる大きな収量抑制はfinal state effectによるもの
  - QGP中でのenergy loss

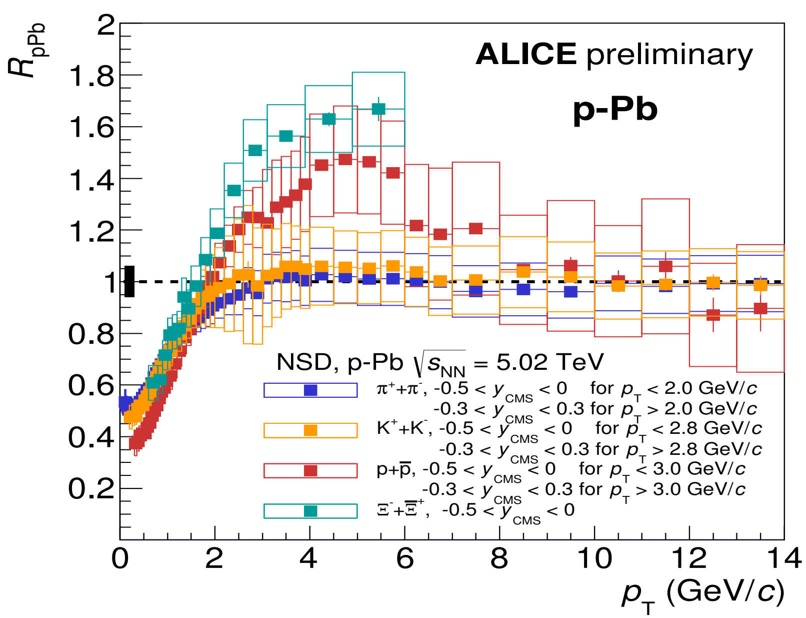
ALICE, PRL 110 (2013) 082302

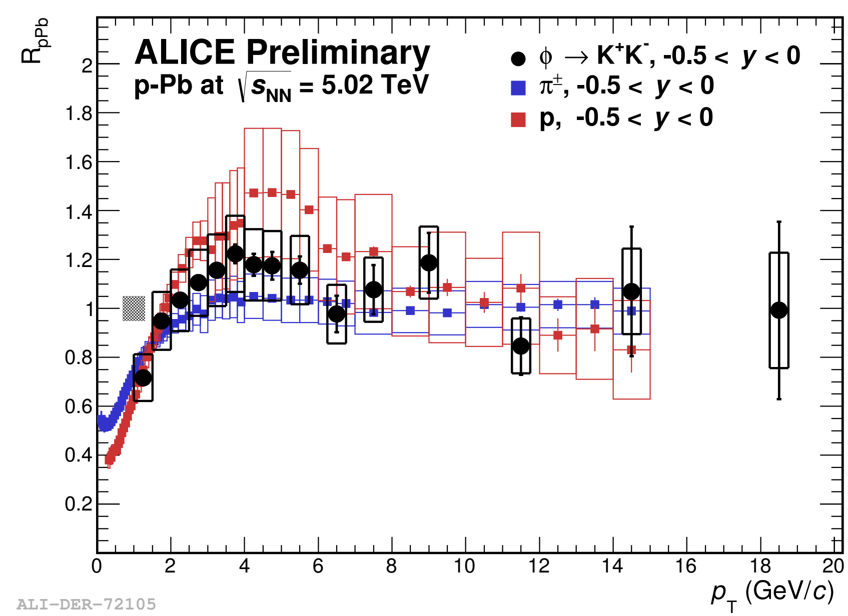
Cronin enhancement?



Hadron production in p-Pb

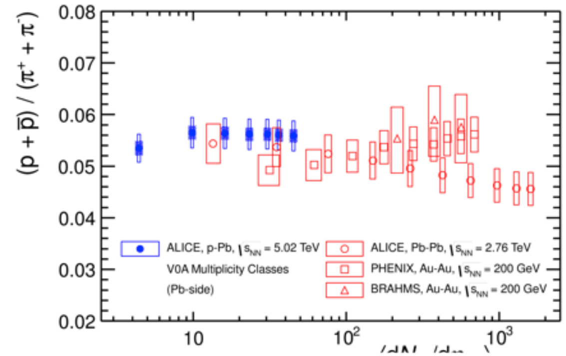
- Mass ordering ?
  - φもenhancement?
    - RHICでは見えていない
  - Baryon enhancement, strangeness enhancement?

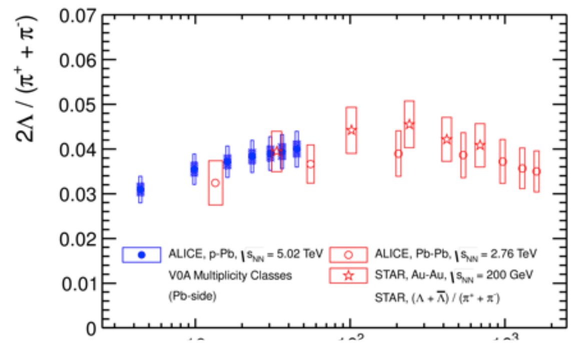




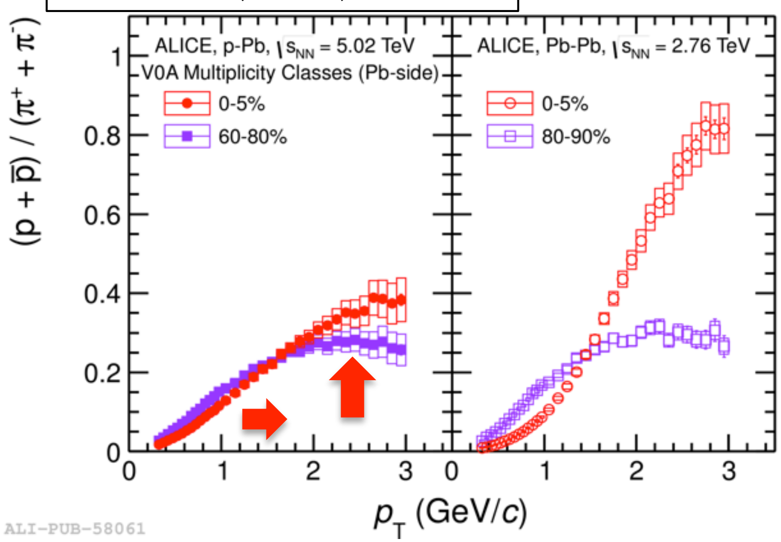
Particle ratio

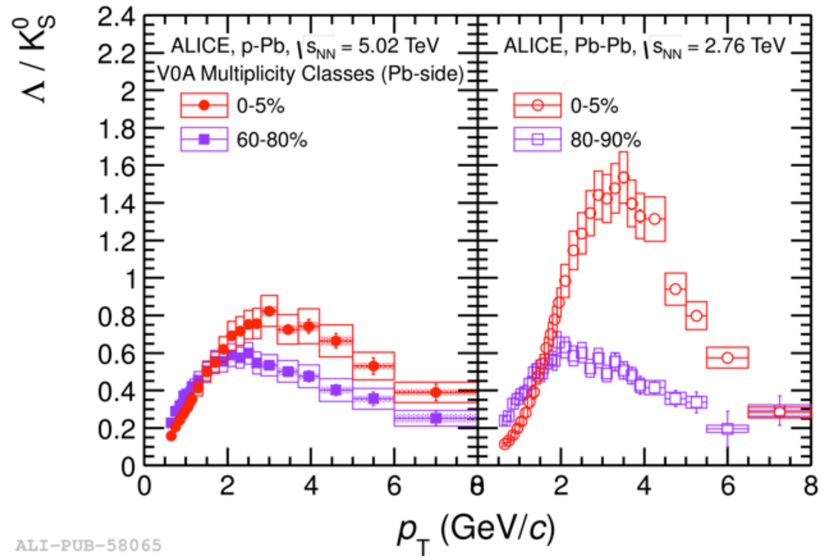
- p/πのoverall ratioは変わらない
  - Λ/πが緩やかに増加
- p_T 依存性
  - Baryon enhancement
  - Radial flow？Coaleascence?





PLB 728 (2014) 25–38

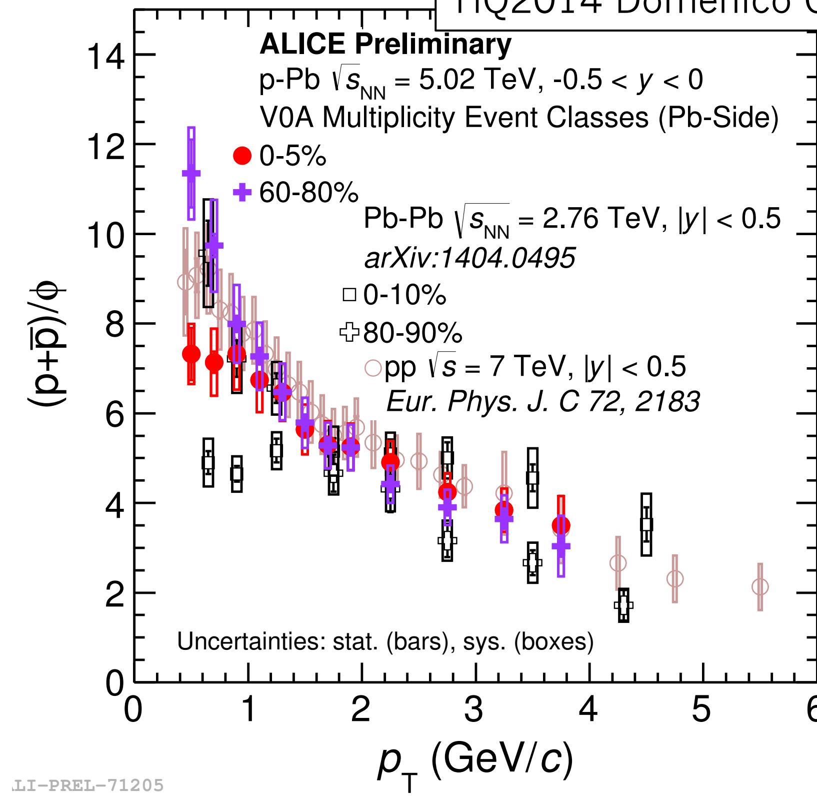




p/φ ratio

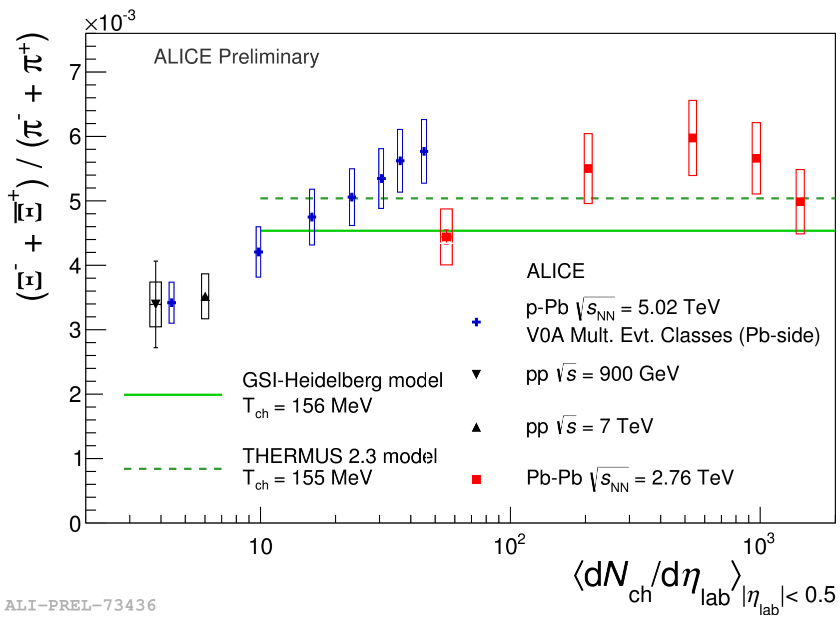
- High p_Tではevent activity依存性は見られない
- Central衝突でマグニチュードは異なるがLow p_Tでsuppress

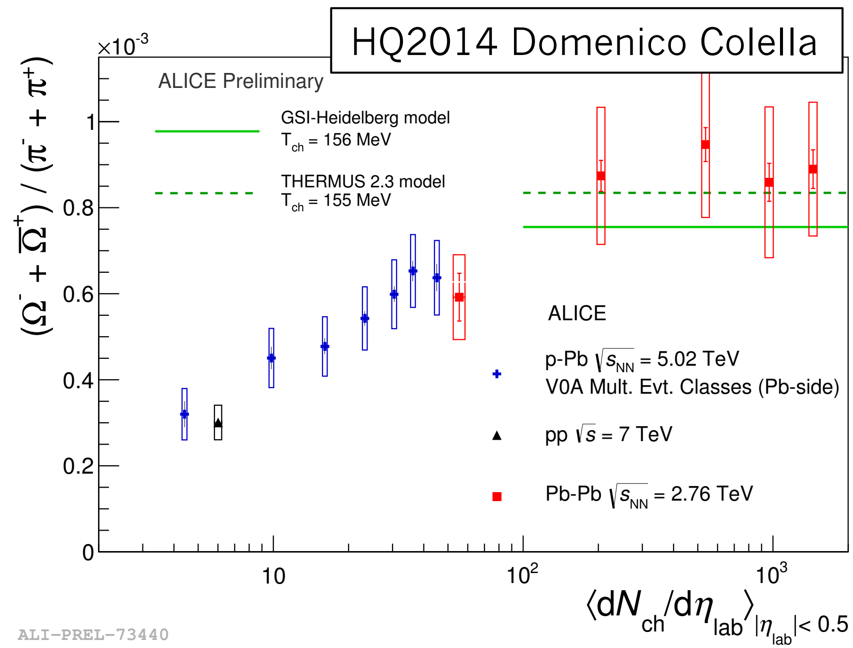
HQ2014 Domenico Colella



Strangeness enhancement

- Strangeness enhancementを確認
  - pp-pPb-PbPbとスムーズに増加
  - Ξ :Thermal modelの予想値と同程度
  - Ω:Thermal modelの予想値には達していない





Mean p_T in p-Pb

$$p_T^{flow} = p_T + m\beta_T^{flow}\gamma_T^{flow}$$

- pp
  - color reconnection を入れるとdataを再現
- p-Pb
  - saturate, mass 依存性
  - Radial flowによるpush?

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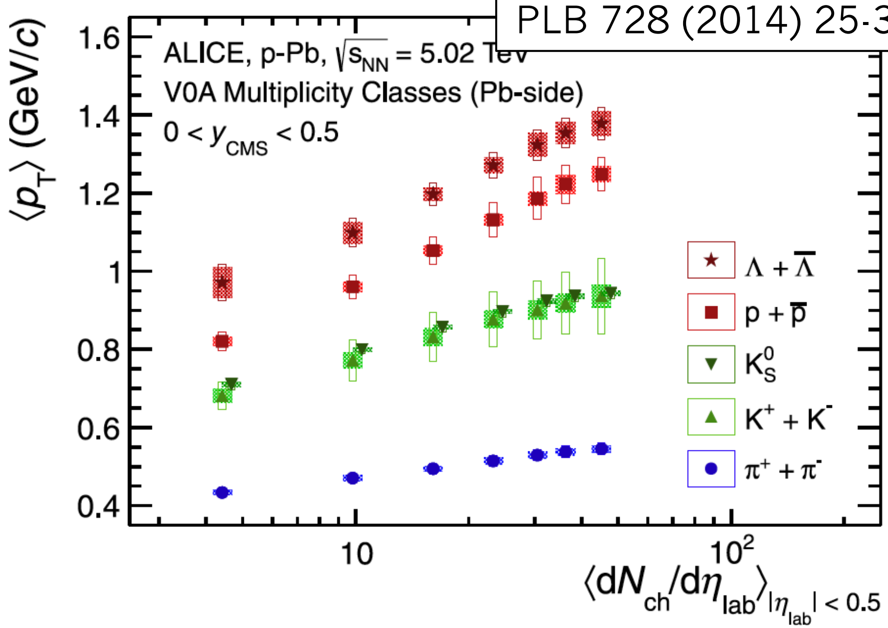
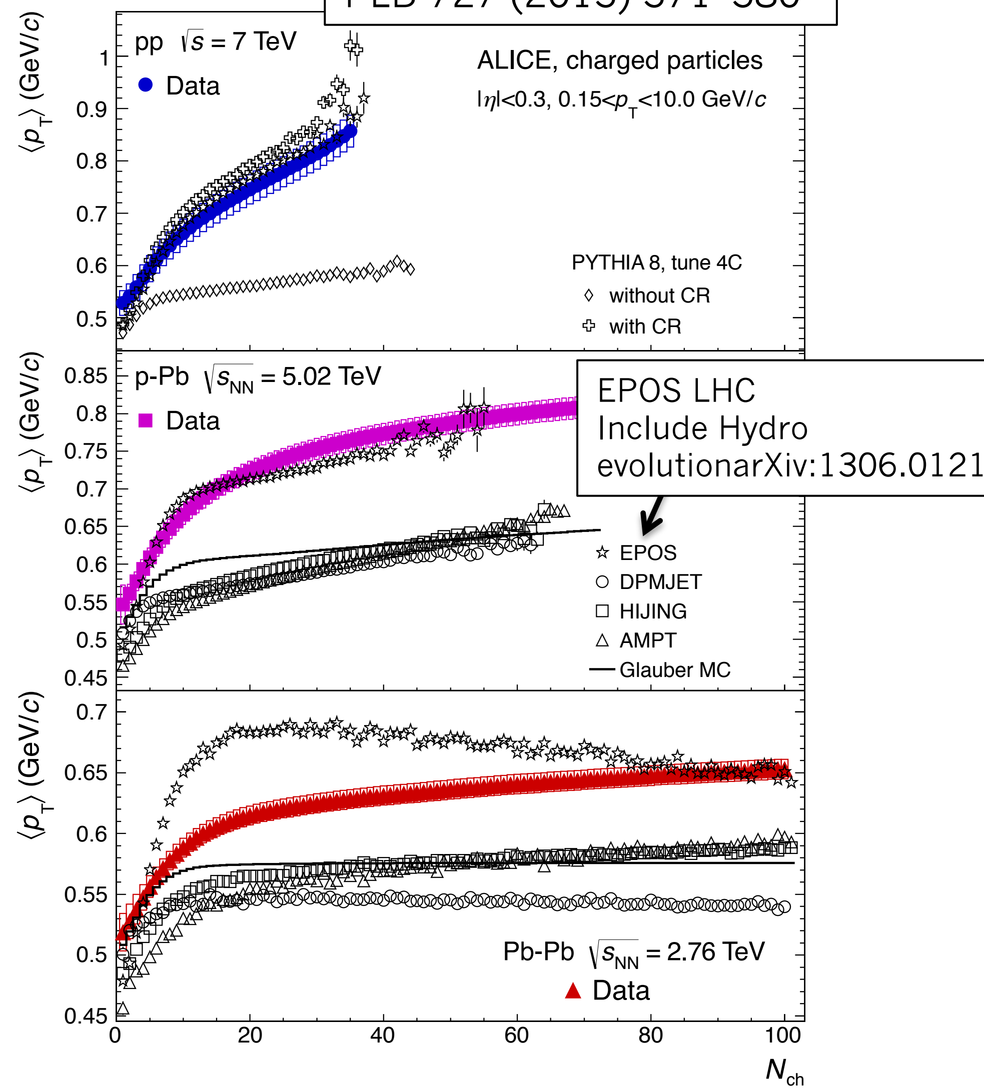


PLB 727 (2013) 371–380



Geometric scaling of mean p_T

$$Q_{\rm sat}^2 \sim \frac{dN}{dy}\frac{1}{S_{\rm T}}$$ S_T:transverse interaction area～$R^2\pi$

$$\langle p_{\rm T}\rangle_i = \frac{\int p_{\rm T}^2 dp_{\rm T}\, f(m_i, T_i^{\rm eff}, p_{\rm T})}{\int p_{\rm T} dp_{\rm T}\, f(m_i, T_i^{\rm eff}, p_{\rm T})} = \frac{m_i^2}{m_i + T_i^{\rm eff}} K_2\left(\frac{m_i}{T_i^{\rm eff}}\right) e^{m_i/T_i^{\rm eff}}$$

$$f(m_i, T_i^{\rm eff}, p_{\rm T}) \sim e^{-(m_T)_i/T_i^{\rm eff}} \qquad T_i^{\rm eff} = \kappa_i Q_{\rm p} = \kappa_i\sqrt{\frac{N_{\rm track}}{S_{\rm T}}}$$

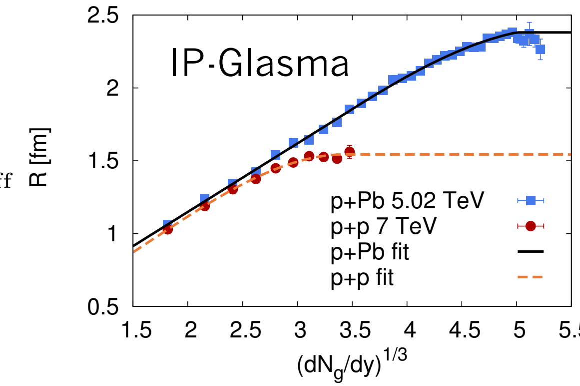
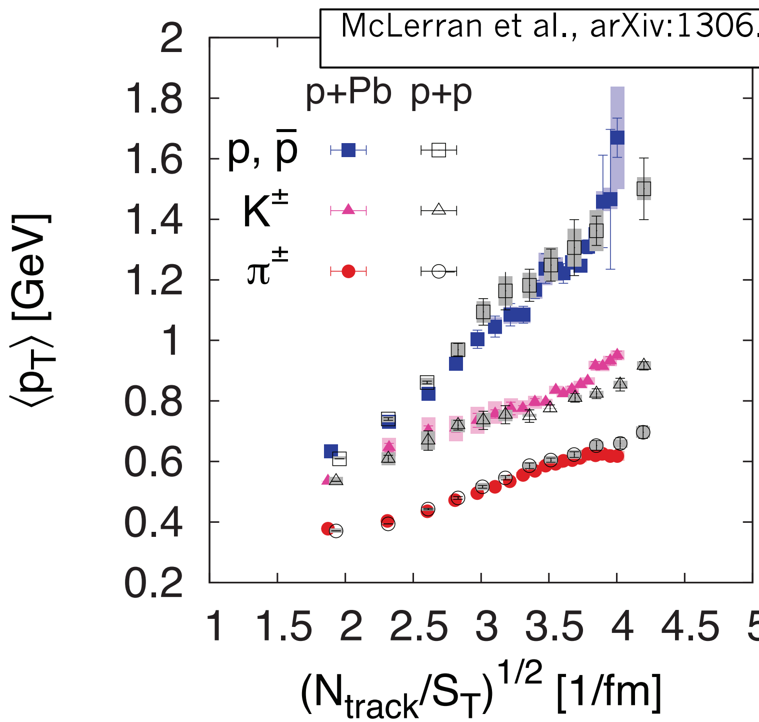
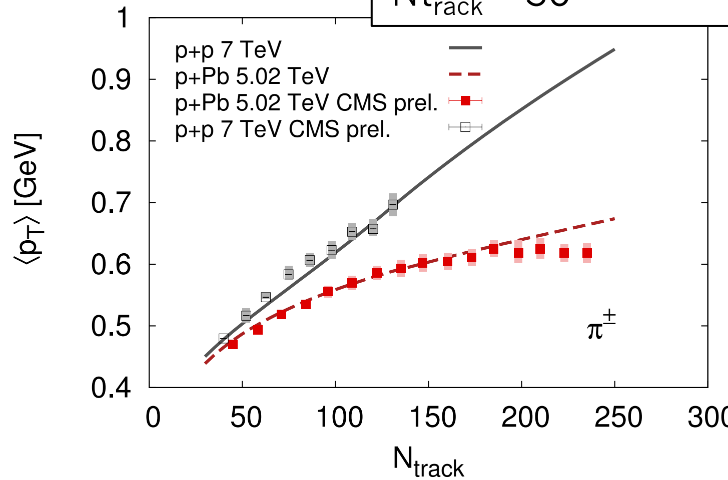


Figure 1: Radius $R_{\rm pPb} = \sqrt{S_{\rm pPb}/\pi}$ for pPb collisions and $R_{\rm pp} = \sqrt{S_{\rm pp}/\pi}$ for pp collisions vs $(dN_g/dy)^{1/3}$ as computed in the IP-Glasma model [23] together with the corresponding fits.



K_i obtained by fitting pp data
$Nt_{rack} \approx 30$



Dataをよく再現？

Blast wave fit

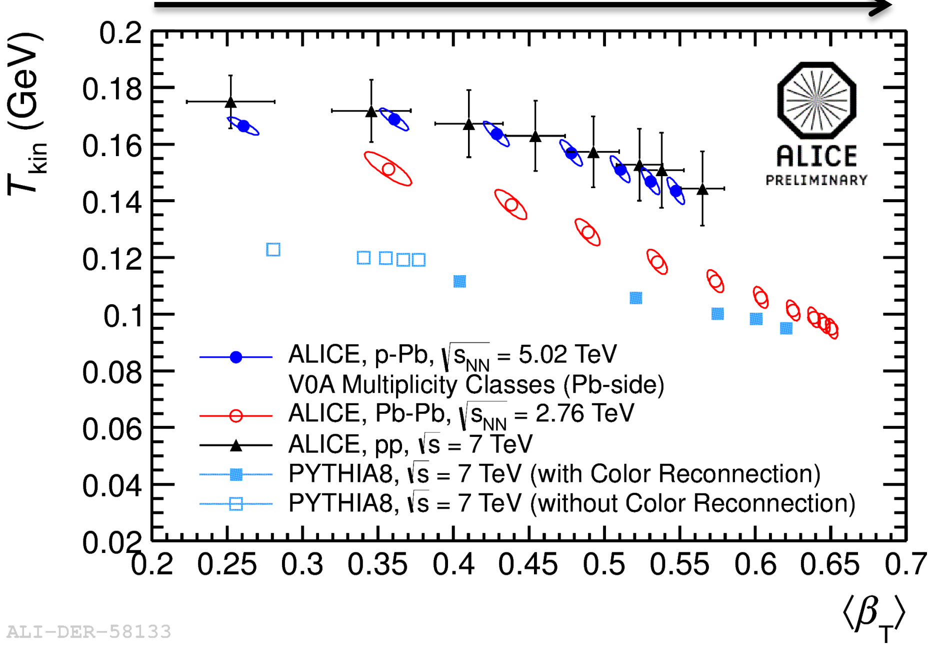
$$\frac{dN}{p_\perp dp_\perp} \propto \int_0^R r\,dr\,m_\perp I_0\left(\frac{p_\perp \sinh\rho}{T_{kin}}\right) K_1\left(\frac{m_\perp \cosh\rho}{T_{kin}}\right)$$

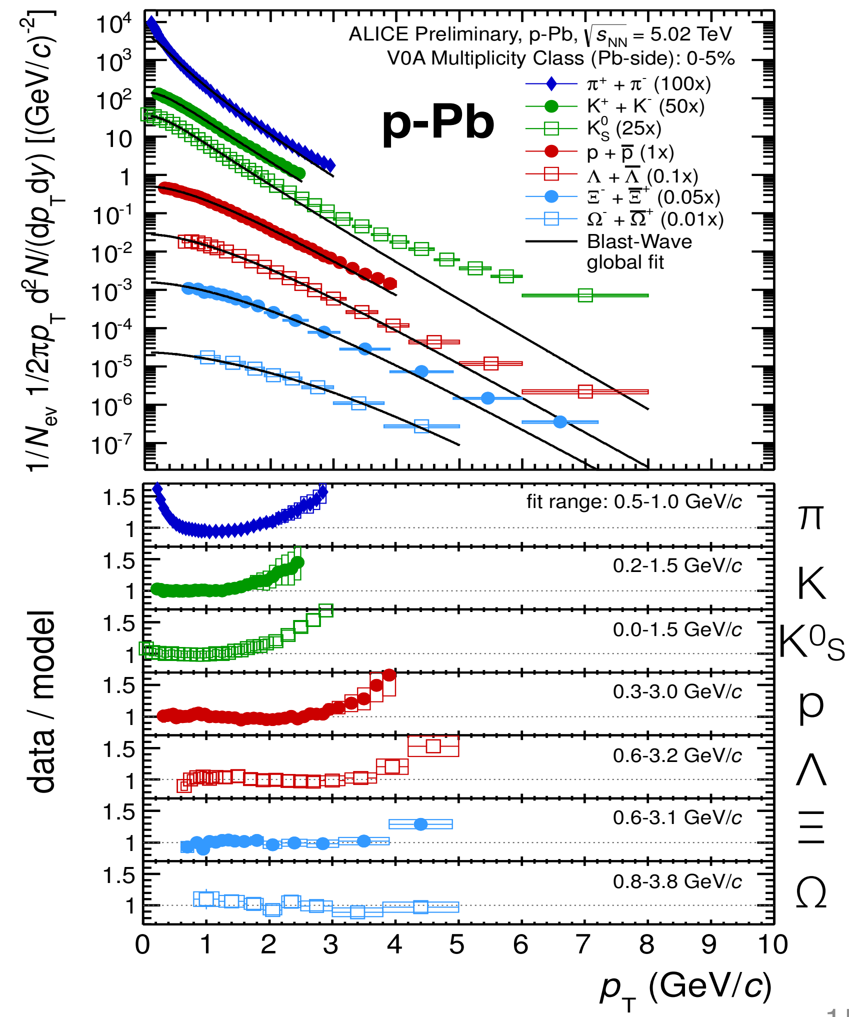
$$\rho = \tanh^{-1}\beta \qquad \beta = \beta_S(r/R)^n \qquad \langle\beta\rangle = \frac{2}{2+n}\beta_S$$

$<\beta_T>$	radial flow ($2\beta_s/(2+n)$)
T_{fo}	freeze-out temperature
n	velocity profile

- Dataをよく再現
  - Radial flowを示唆?
- ただしppも同じ傾向を示す
  - Fitting rangeは？(p_T, η)

Multiplicity → high





Ridge structure in p-Pb

- High Multiplicity p-Pb(pp)でもA-A衝突と同程度の長距離相関
- AAのridgeとの関係は？
  - Collective flow?

$$\frac{1}{N_{trig}}\frac{dN_{assoc}(\Delta\varphi)}{d\Delta\varphi} = a_0 + \sum_{n=1}^{\infty} 2a_n \cos(n\Delta\varphi)$$

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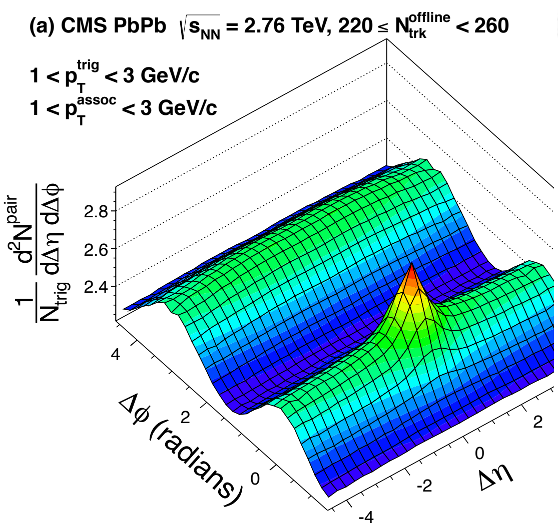
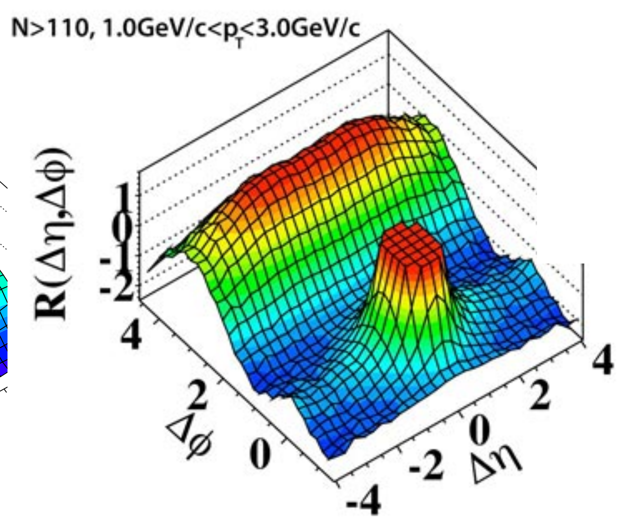
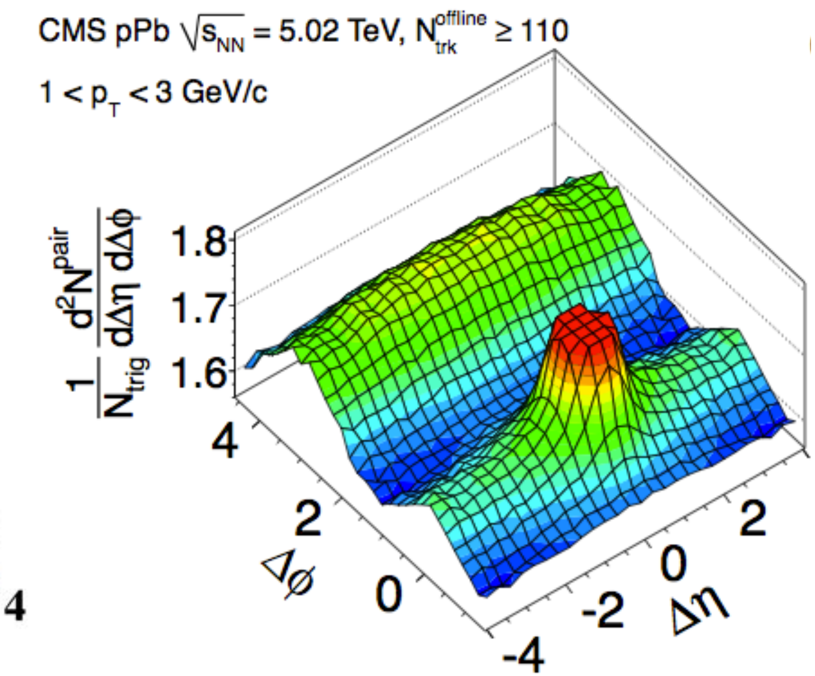
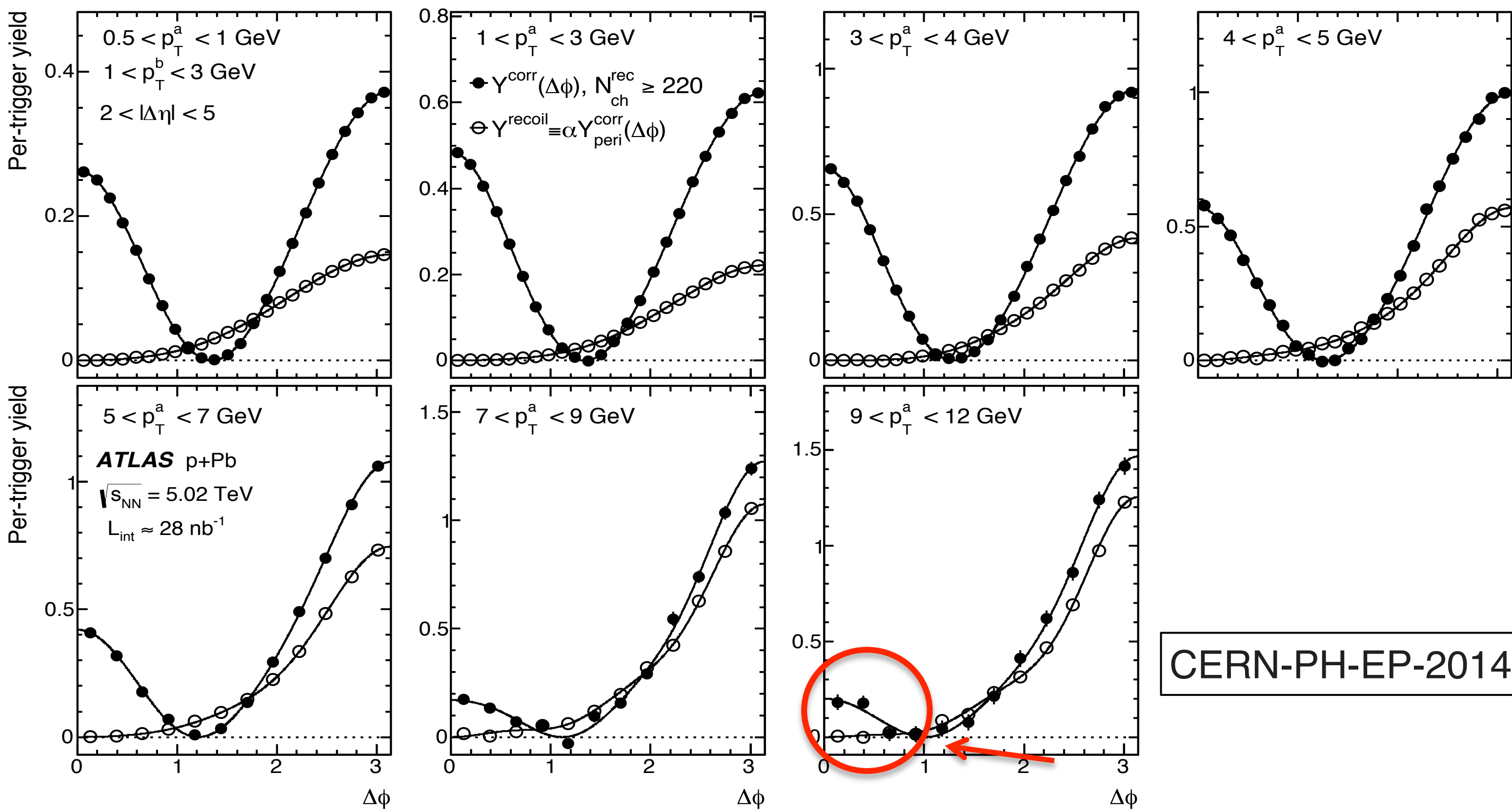






p_T dependence of ridge

- High multiplicity eventsでnear side, away sideともに大きな相関
- High p_T でも依然として相関が残っている

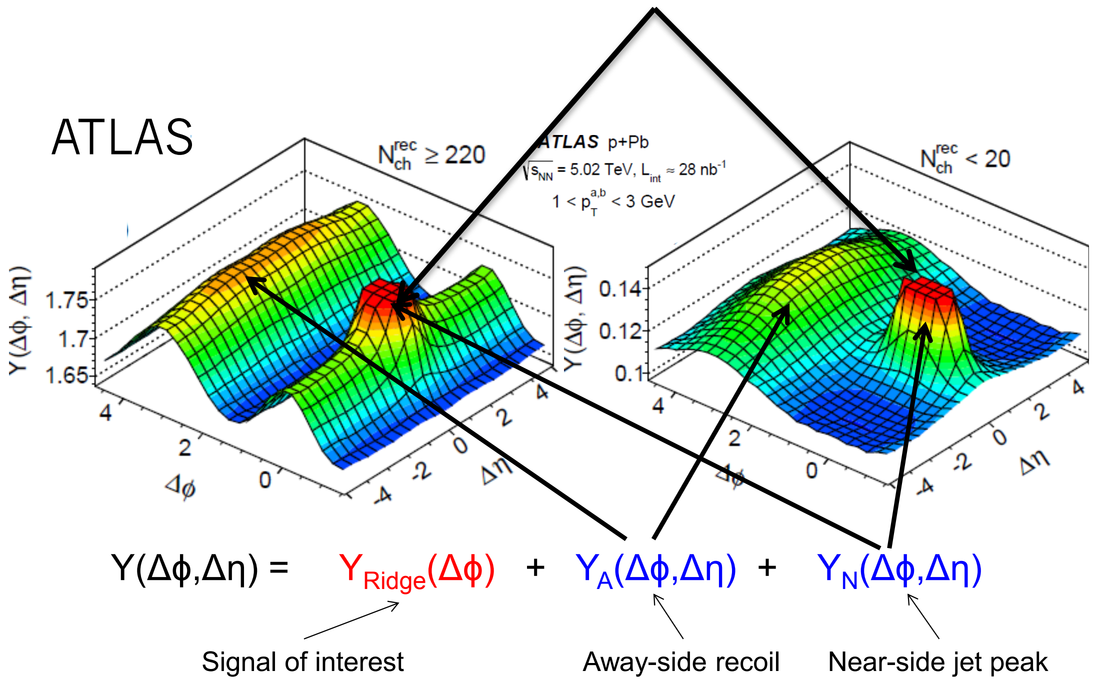


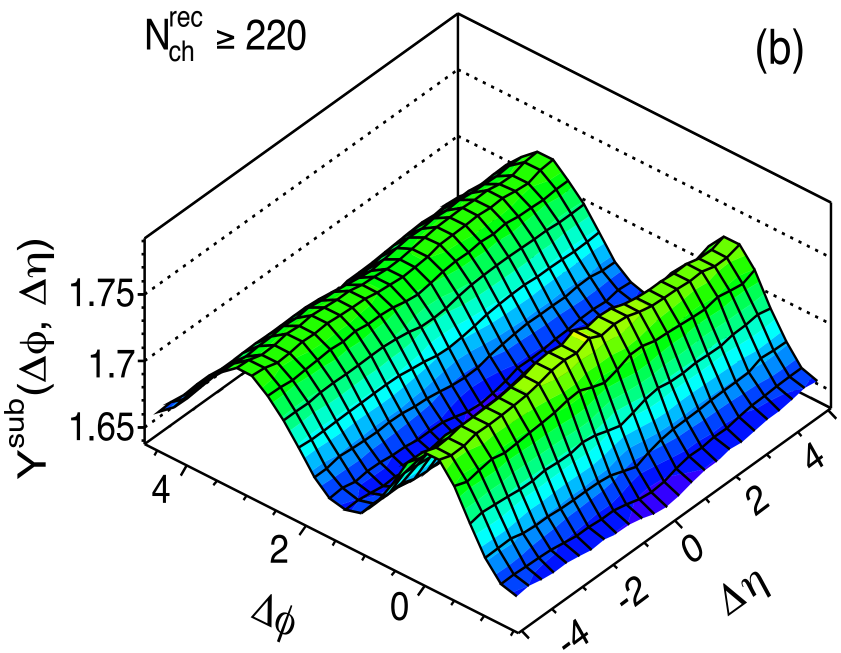
CERN-PH-EP-2014-201

Double-ridge structure

- Central – Peripheral
  - Assume no change of Jet(and recoil) structure
  - Double-ridge structure

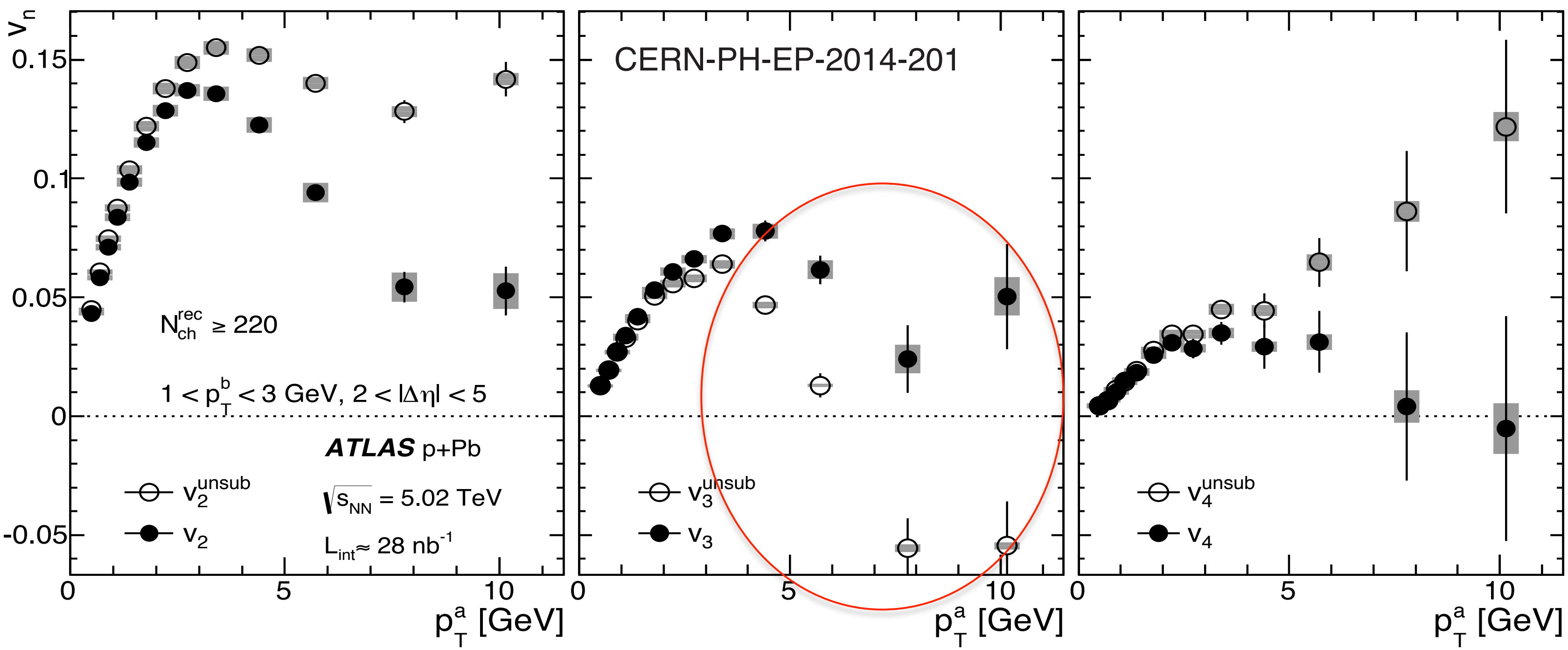
$$Y^{\mathrm{sub}}(\Delta\phi, \Delta\eta) = Y(\Delta\phi, \Delta\eta) - \alpha Y^{\mathrm{corr}}_{\mathrm{peri}}(\Delta\phi, \Delta\eta)$$





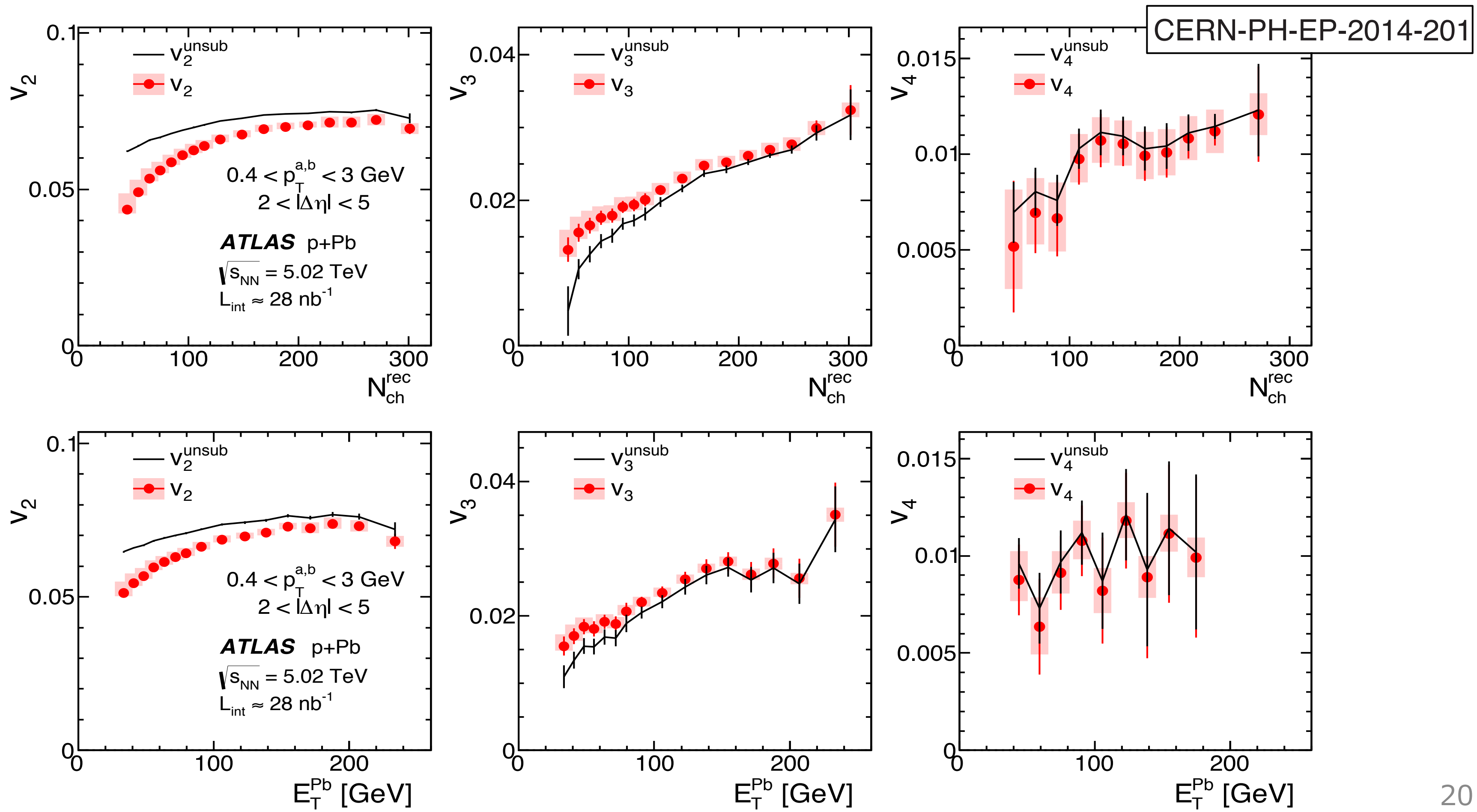
v_n extraction from 2PC

- Central collision からperipheral collisionの寄与を引きフーリエfit
  - v_3はJet biasが逆に現れる
  - High pTでもnon-zero v_2



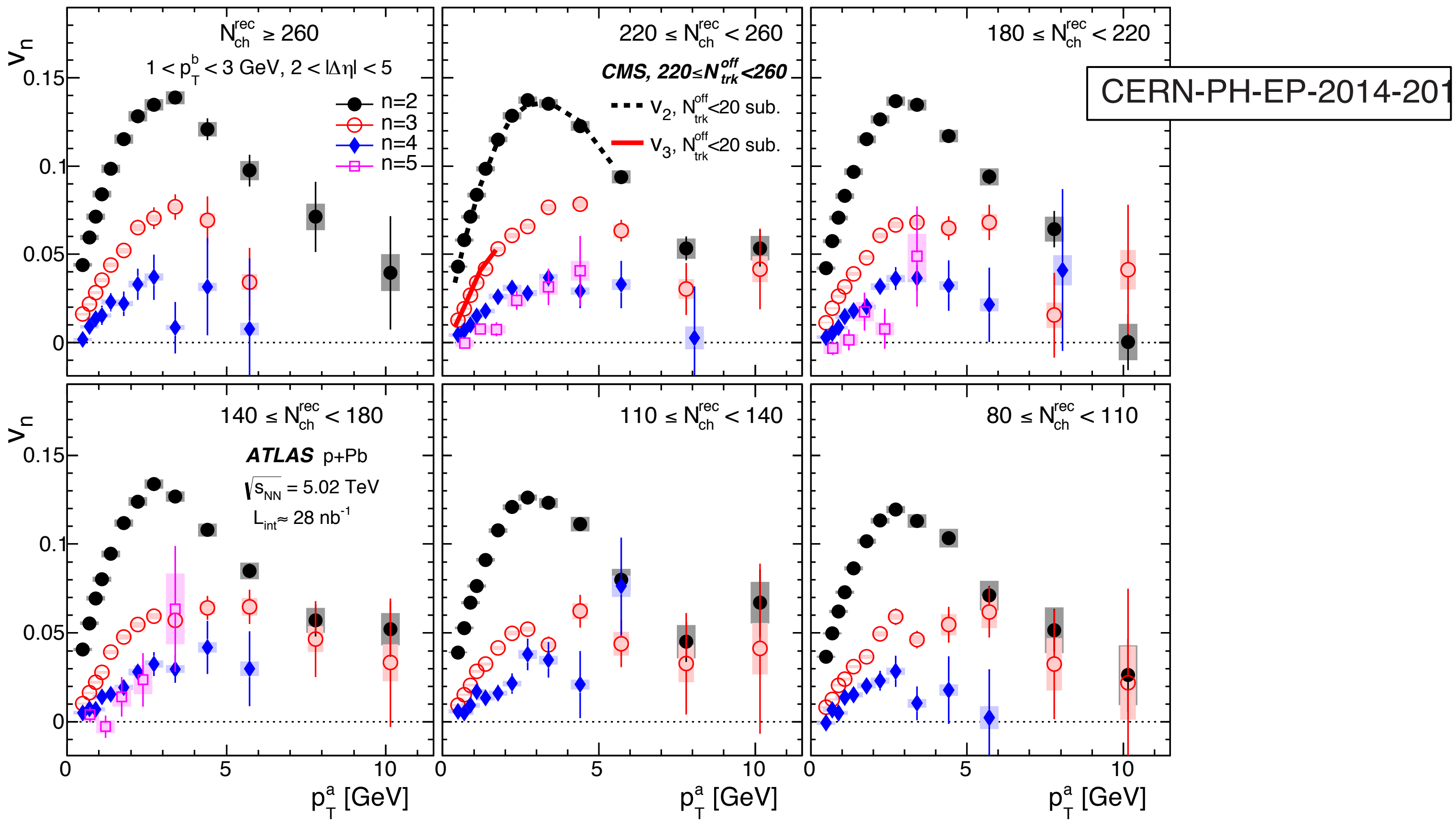
Multiplicity dependence of v_n

- Multiplicityに対して緩やかに増加



v_n ordering

- $v_2 > v_3 > v_4$
  - この領域ではv_nはmultiplicityにはよらない



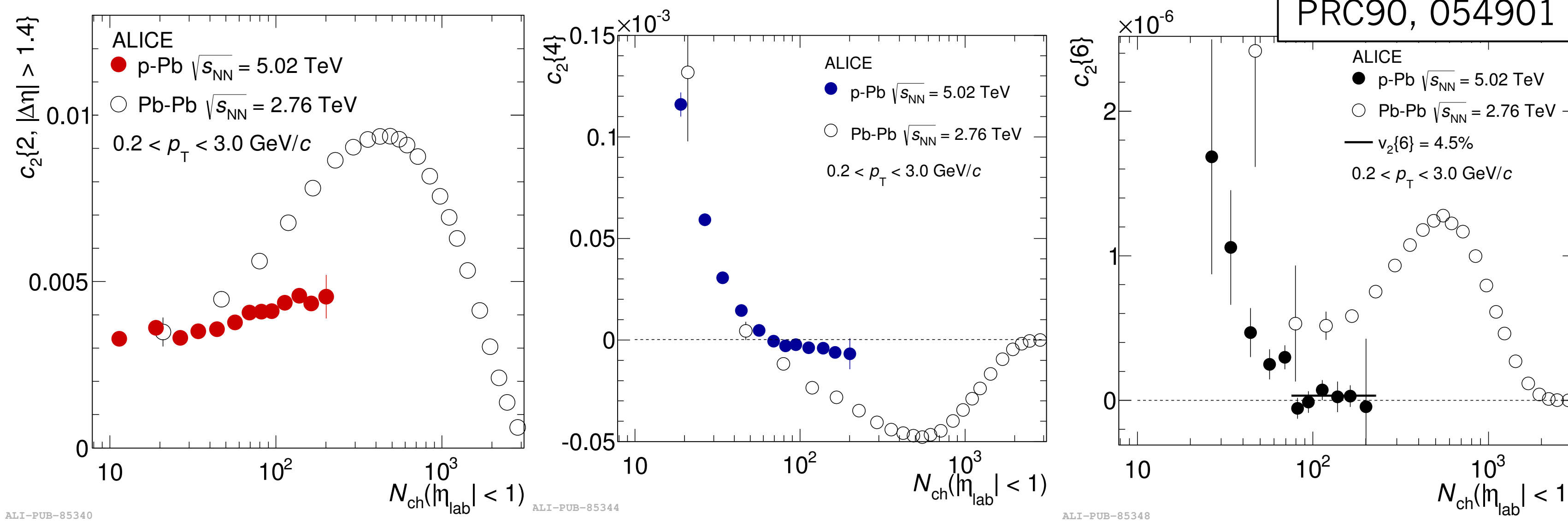
Multi-particle correlation

- Cumulants
  - N-particle correlation(excluding (n-1)-particle correlation)

$$\langle 2\rangle = \langle e^{in(\varphi_1-\varphi_2)}\rangle.$$
$$\langle 4\rangle = \langle e^{in(\varphi_1+\varphi_2-\varphi_3-\varphi_4)}\rangle.$$
$$\langle 6\rangle = \langle e^{in(\varphi_1+\varphi_2+\varphi_3-\varphi_4-\varphi_5-\varphi_6)}\rangle.$$

$$c_n\{2\} = \langle\langle 2\rangle\rangle$$
$$c_n\{4\} = \langle\langle 4\rangle\rangle - 2\langle\langle 2\rangle\rangle^2$$
$$c_n\{6\} = \langle\langle 6\rangle\rangle - 9\langle\langle 4\rangle\rangle\langle\langle 2\rangle\rangle + 12\langle\langle 2\rangle\rangle^3$$
$$c_n\{8\} = \langle\langle 8\rangle\rangle - 16\cdot\langle\langle 6\rangle\rangle\langle\langle 2\rangle\rangle - 18\cdot\langle\langle 4\rangle\rangle^2 + 144\cdot\langle\langle 4\rangle\rangle\langle\langle 2\rangle\rangle^2 - 144\langle\langle 2\rangle\rangle^4$$

PRC90, 054901 (2014)



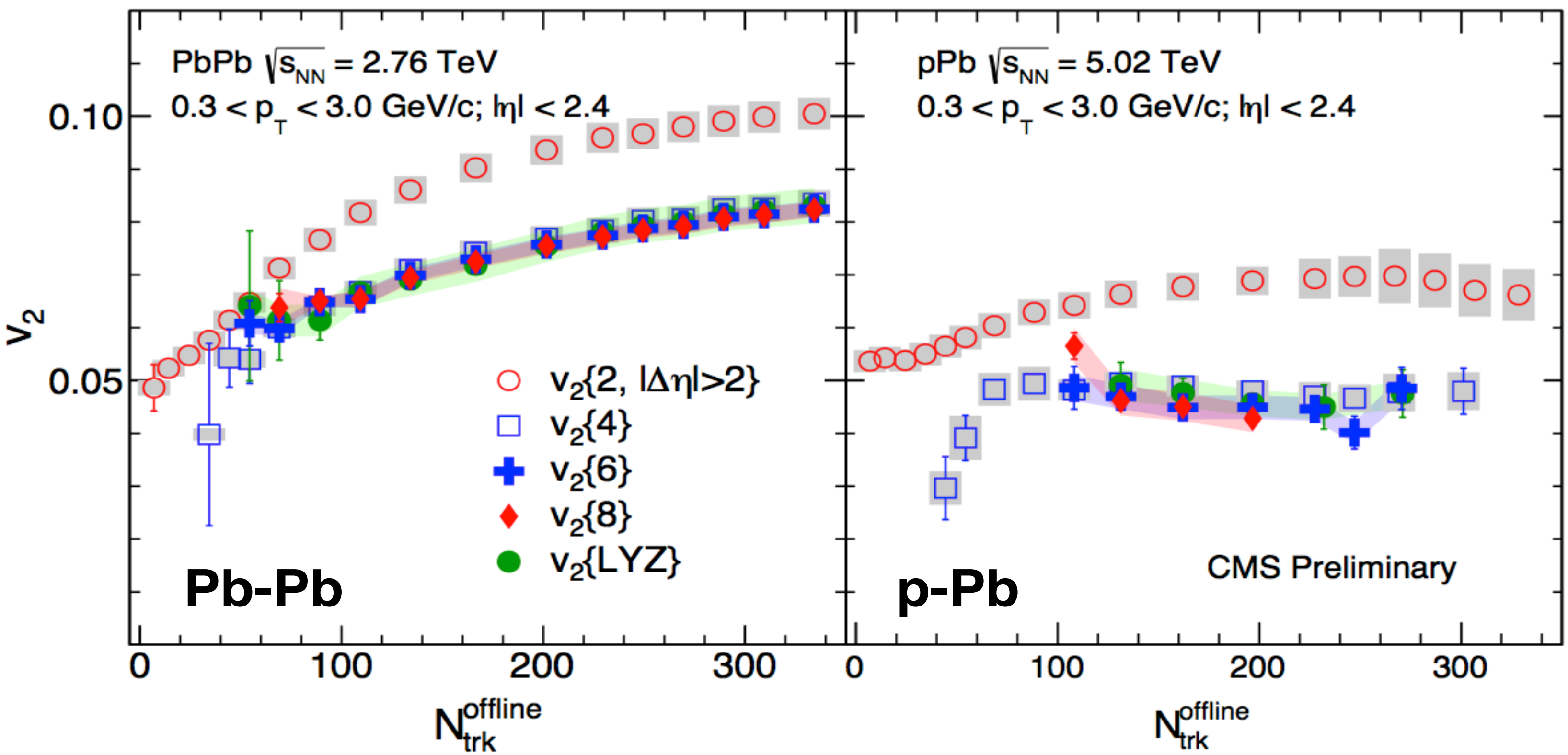
Pb−Pbと似た傾向？

Multi-particle correlation v_2

- $v_2\{4\}=v_2\{6\}=v_2\{8\}=v_2\{LYZ\}$
  - non-flow effects, flow fluctuationがなくなる
  - Collectivityの証拠？

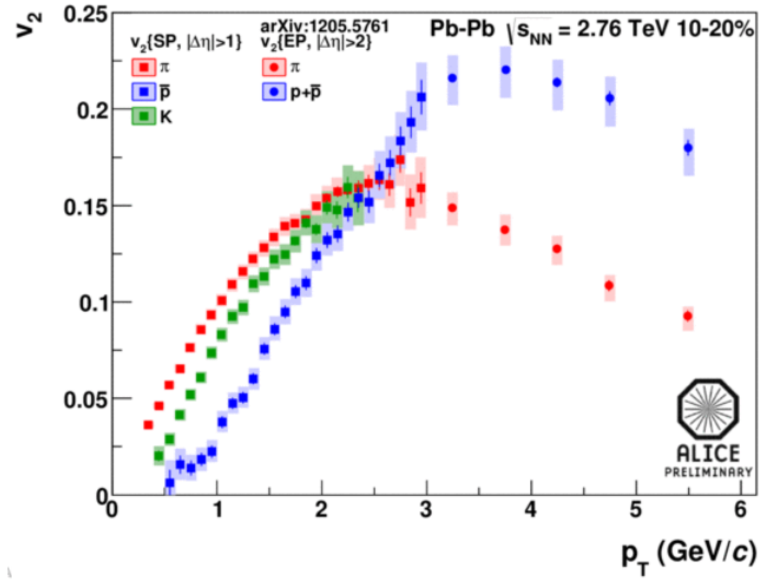
$$v_n\{2\} = \sqrt{c_n\{2\}},$$
$$v_n\{4\} = \sqrt[4]{-c_n\{4\}},$$
$$v_n\{6\} = \sqrt[6]{\frac{1}{4}c_n\{6\}}.$$
$$v_n\{8\} = \sqrt[8]{-\frac{1}{33}c_n\{8\}}$$

CMS, PAS HIN-14-006

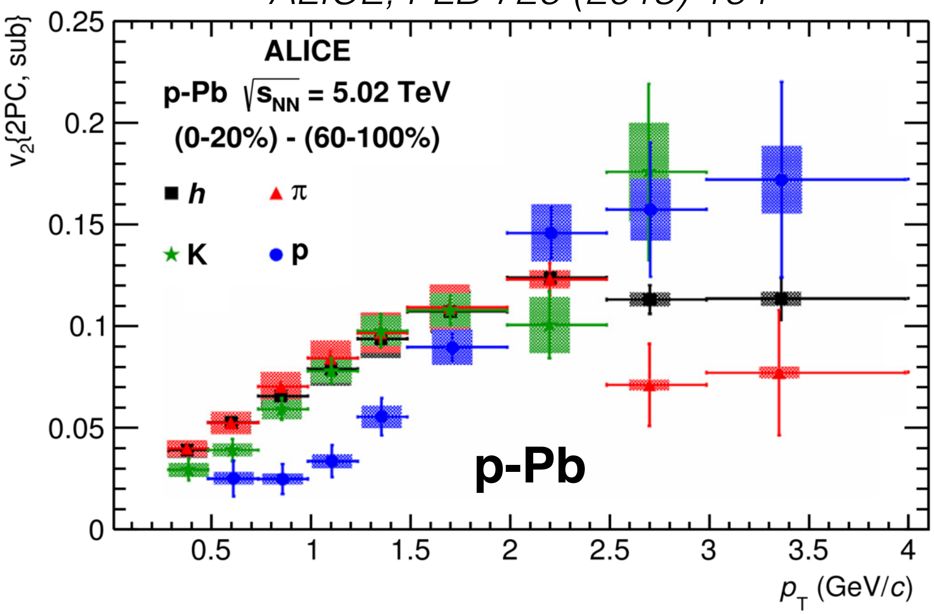


Identified v_2

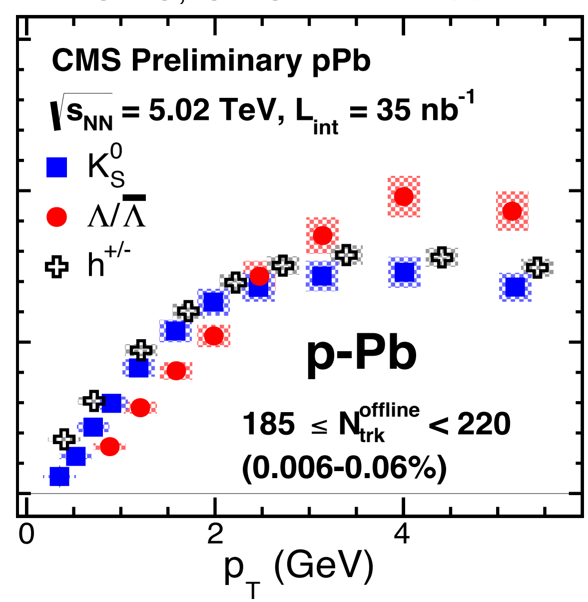
- Mass ordering
  - RHICd+Auでも確認
  - PbPbと似た傾向
  - Radial flow?



ALICE, PLB 726 (2013) 164

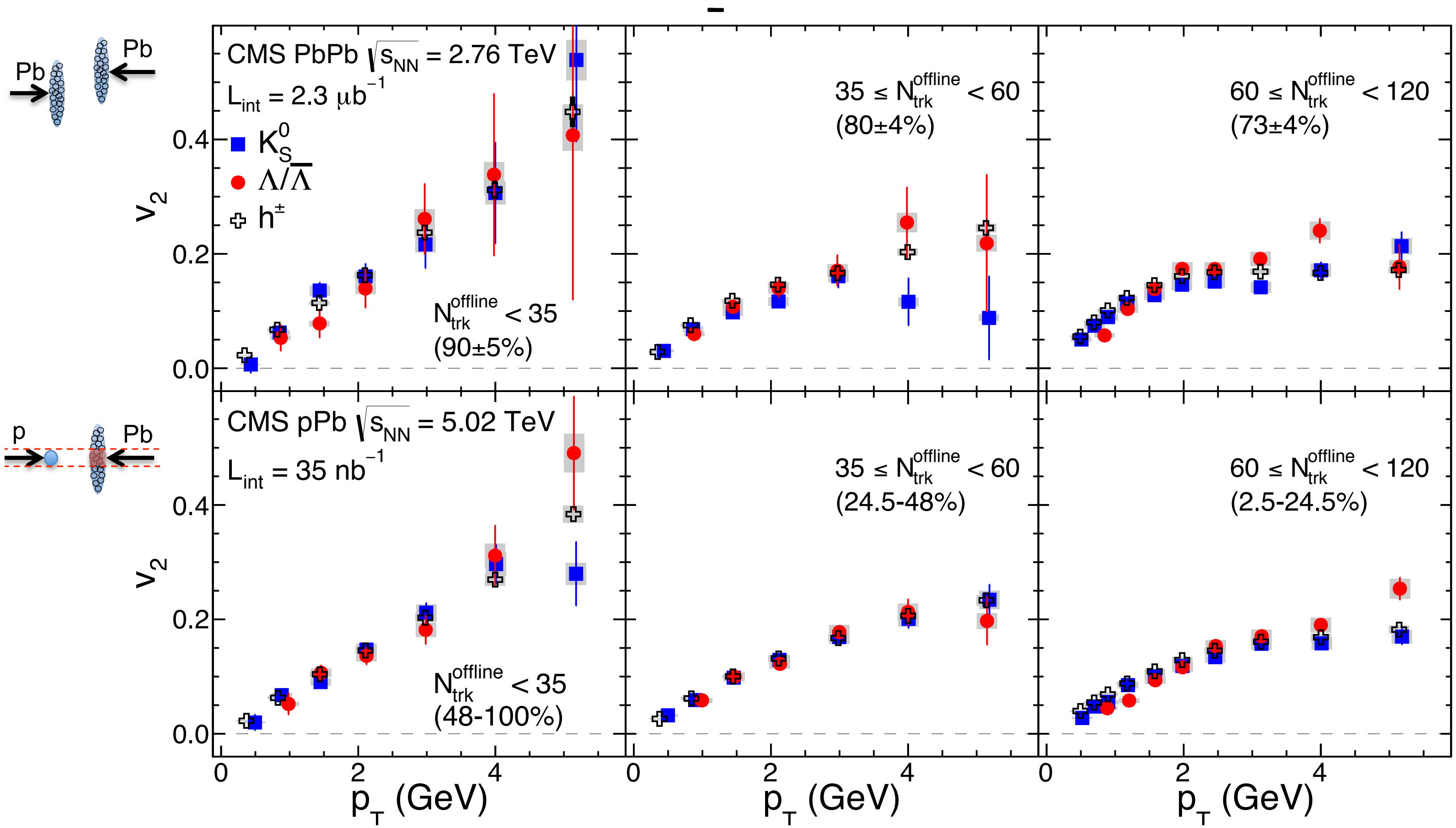


CMS, CMS-HIN-14-002



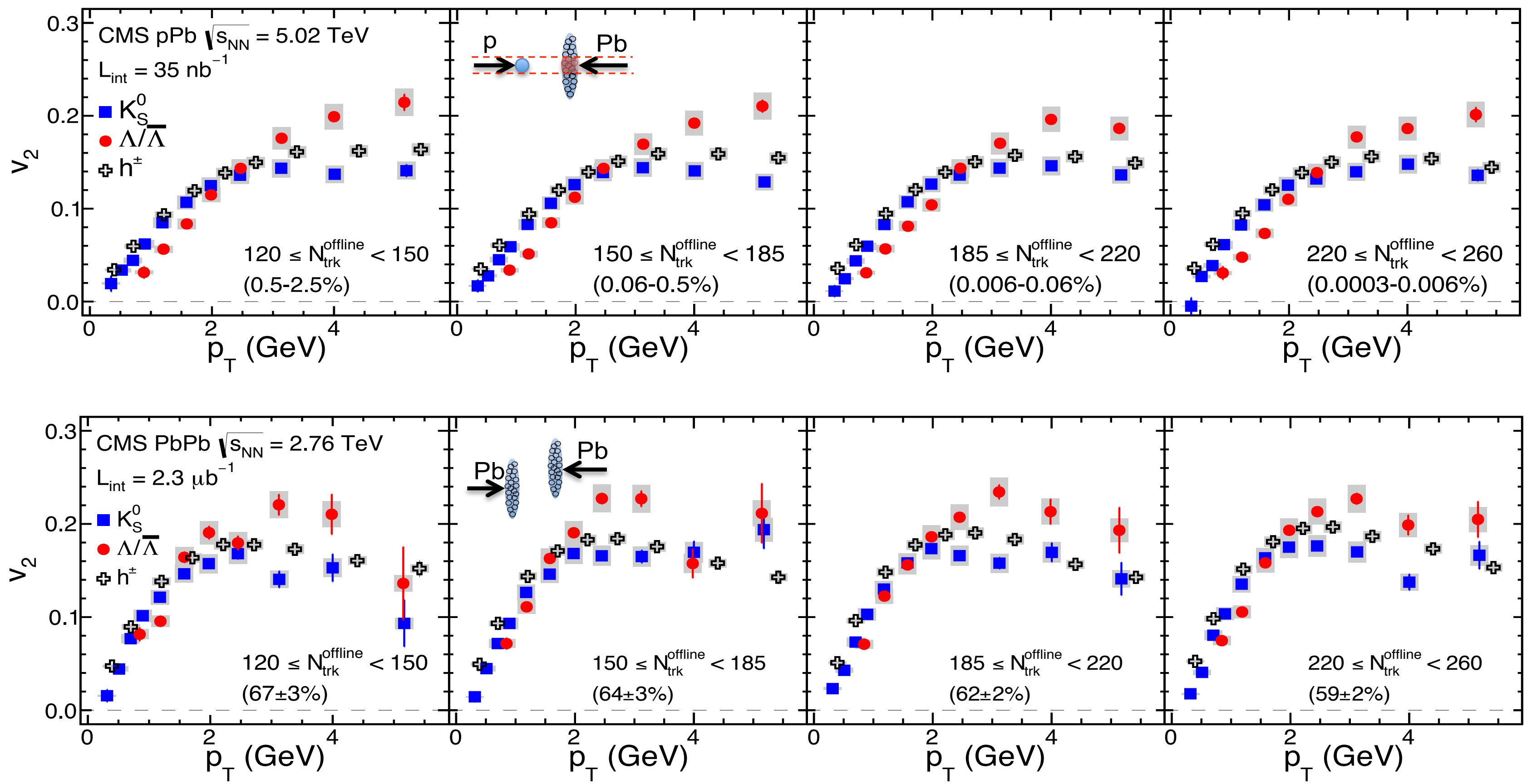
Identified v_2(2PC) in p-Pb and Pb-Pb

- Low multiplicityでは粒子依存性は見られない



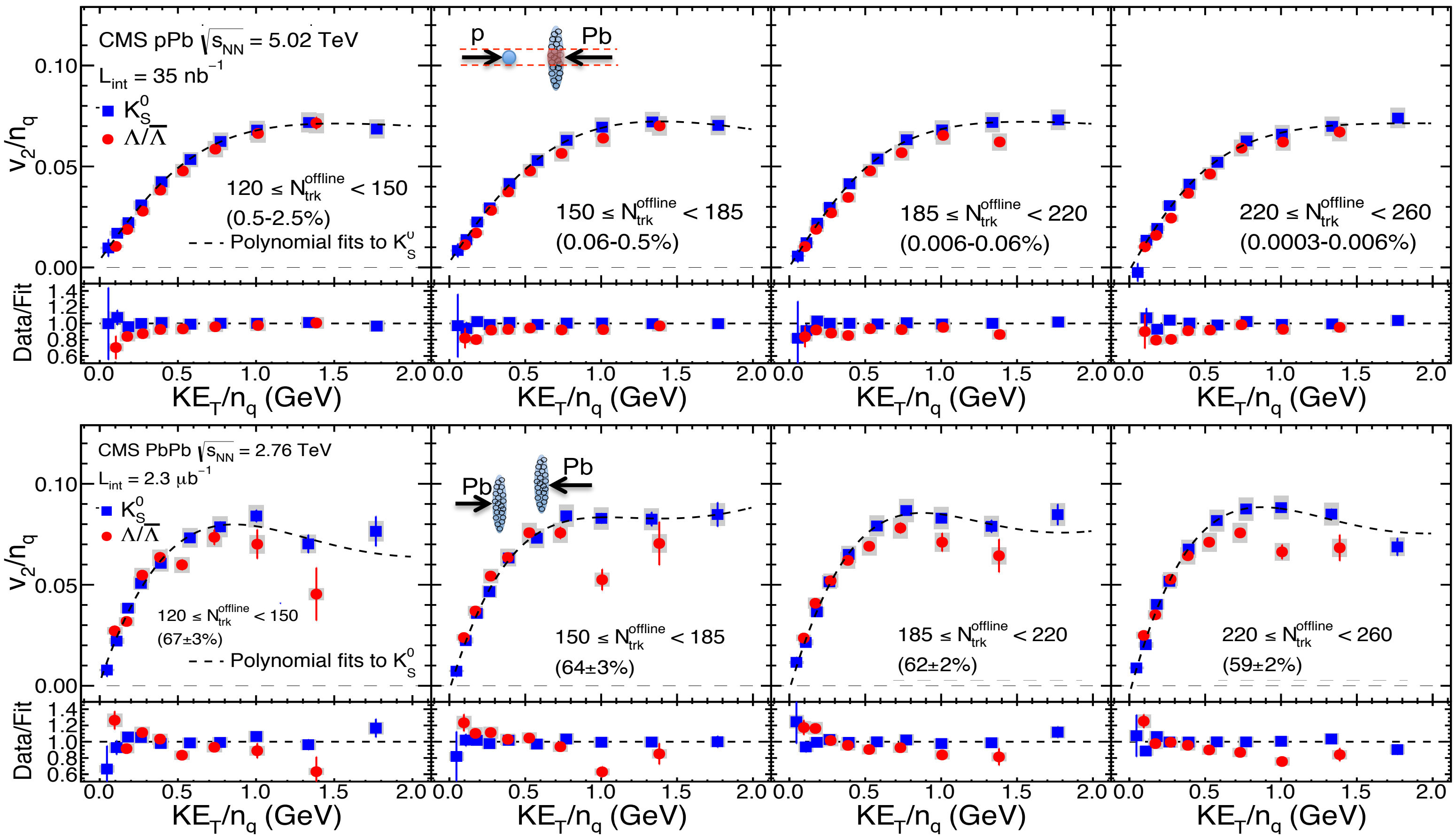
Identified v_2(2PC) in p-Pb and Pb-Pb

- p-Pb とPb-Pbで同じような傾向
  - 2GeV/c付近で交差



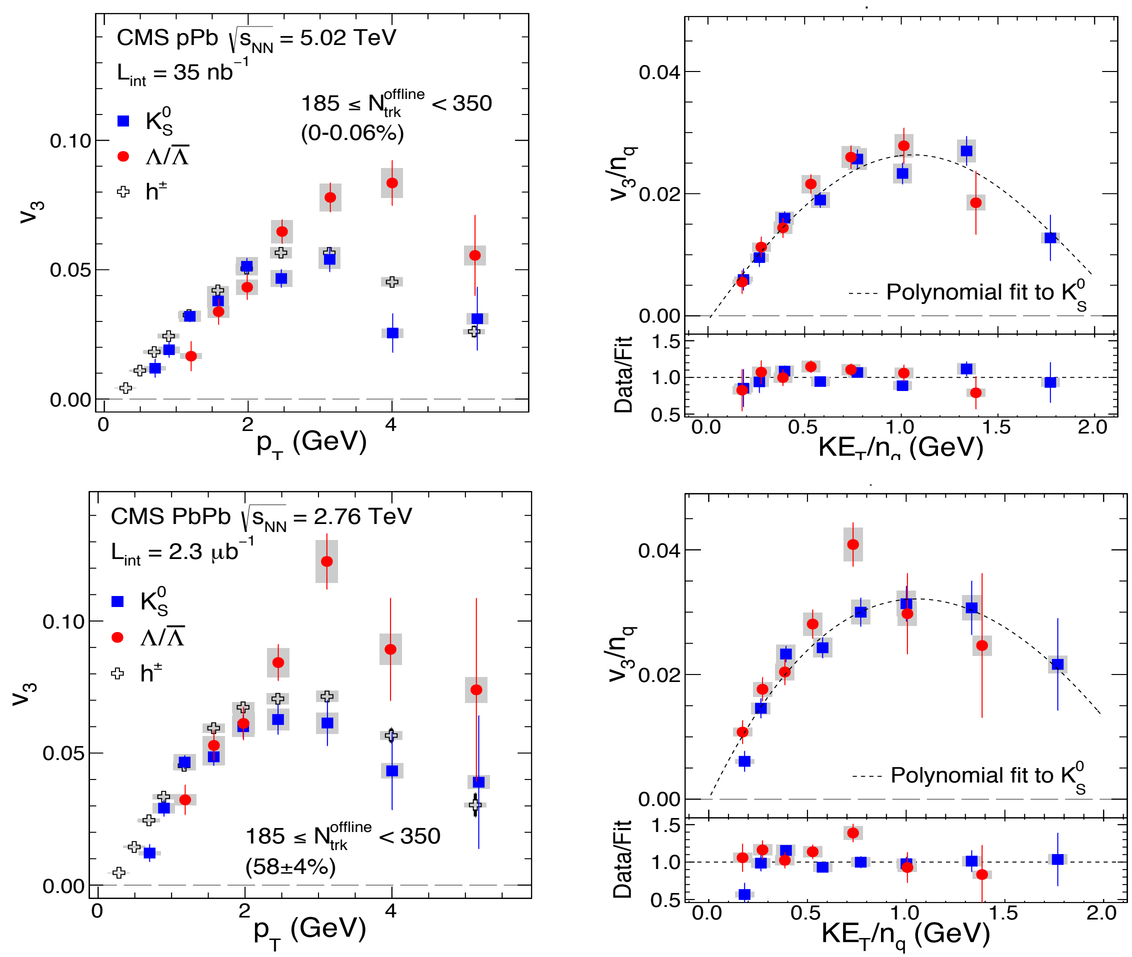
Quark number scaling of v_2

- Pb-Pb よりp-Pbでよく一致
  - Pb-Pb衝突ではhadron相での寄与が大きい？



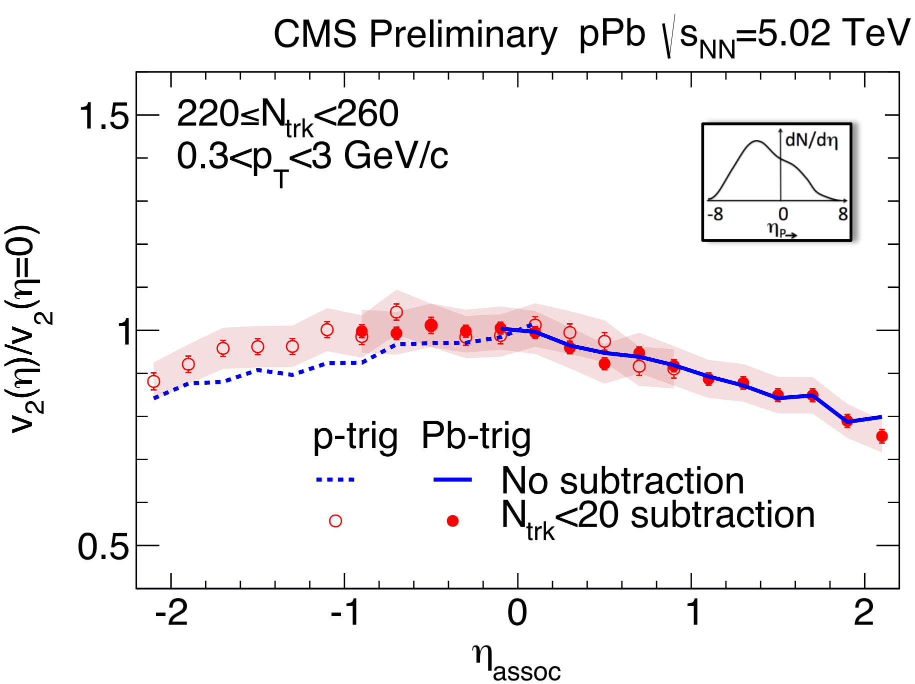
Quark number scaling of v_3

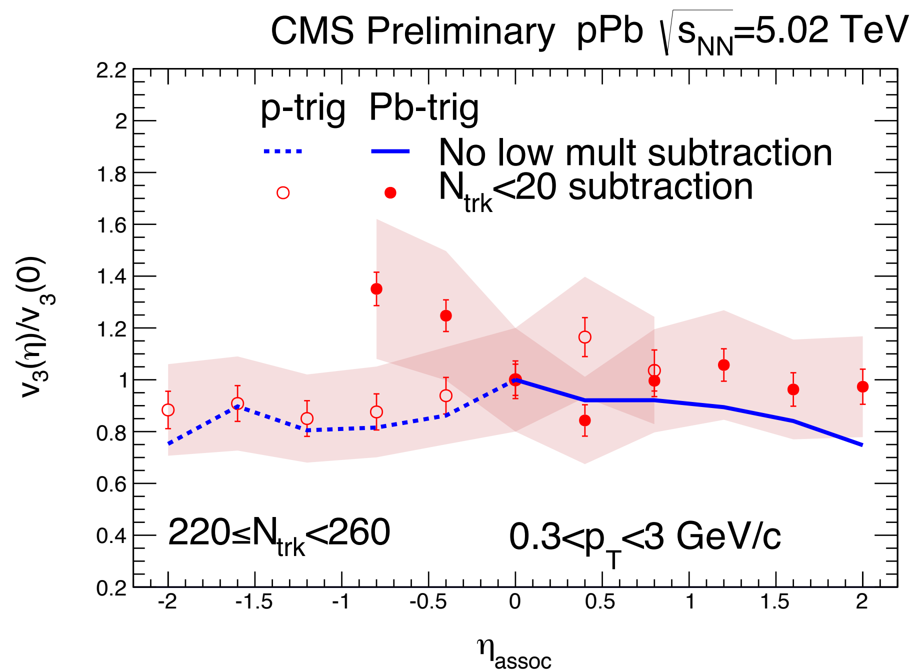
- Pb-Pbと同様の傾向
- v_3でもquark number scalingは成り立っているように見える



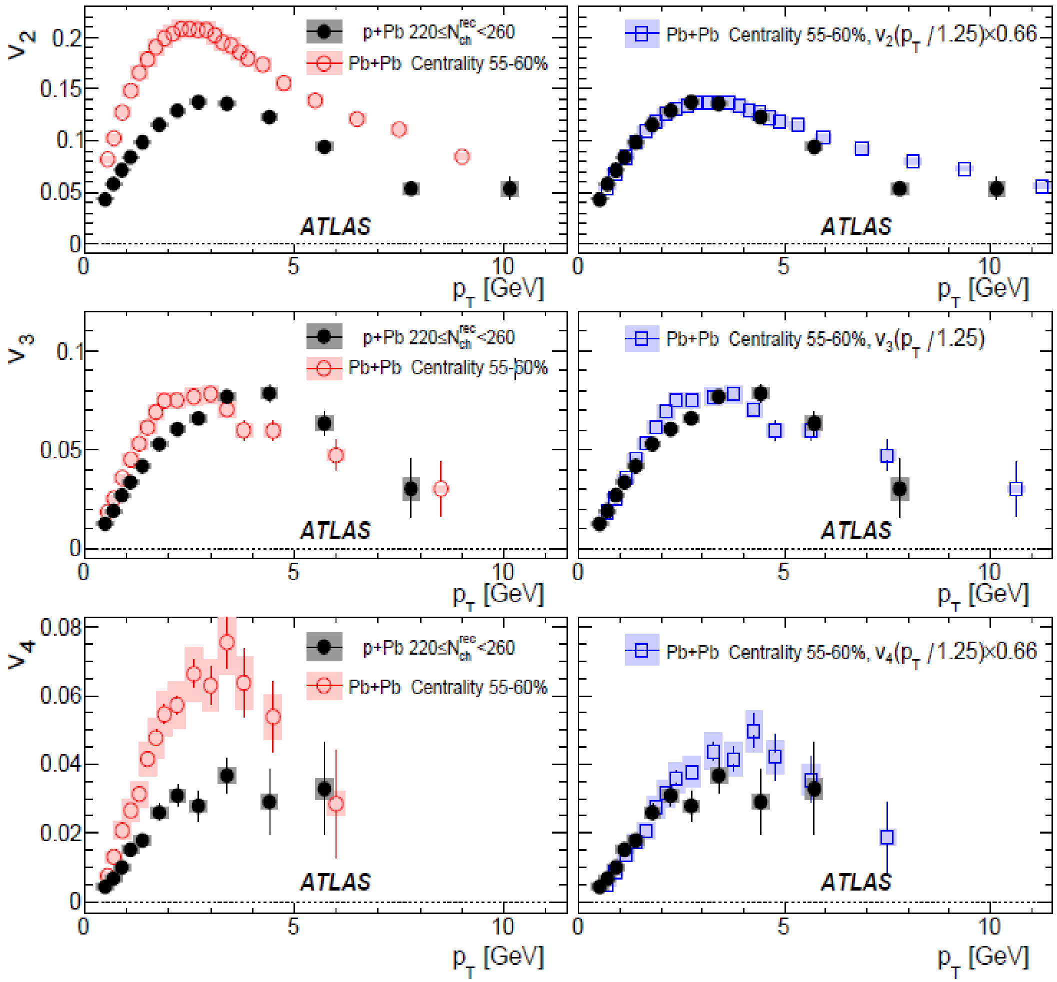
Eta dependence of ridge

- 異なる粒子密度
- Initial stateと他の効果の選別が可能?



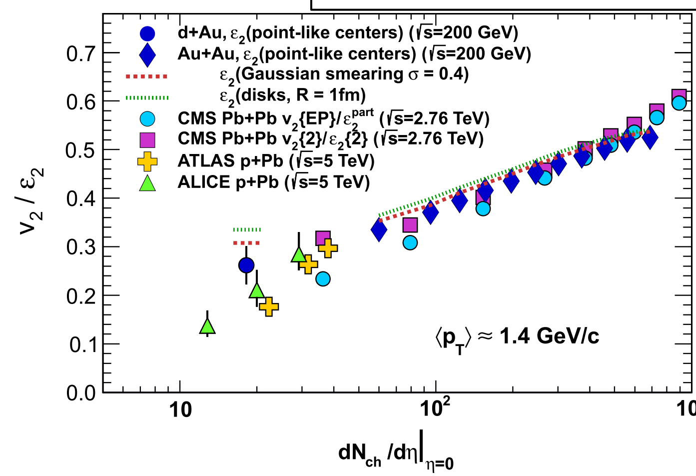


v_2 comparison with peripheral AA collisions



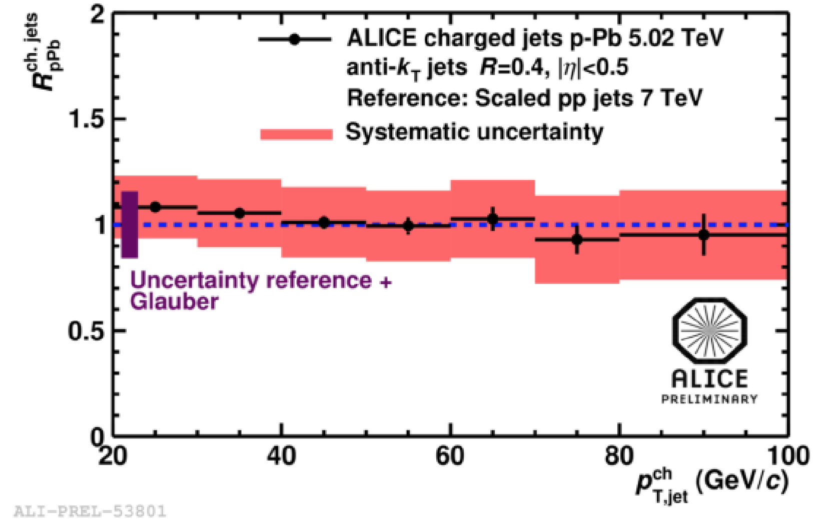
- Multiplicityは同程度
  - Pb-Pb:<N$_{ch}$> = 259 ± 13
  - p-Pb:<N$_{ch}$> = 259 ± 13
- v_3のみ同じマグニチュード
  - $v_2 v_4$:初期形状の効果？
- Mean p_T ratio(radial flowの効果？)で割って,さらに0.66でscaleさせるとほぼ一致する

PRL 111, 212301 (2013)

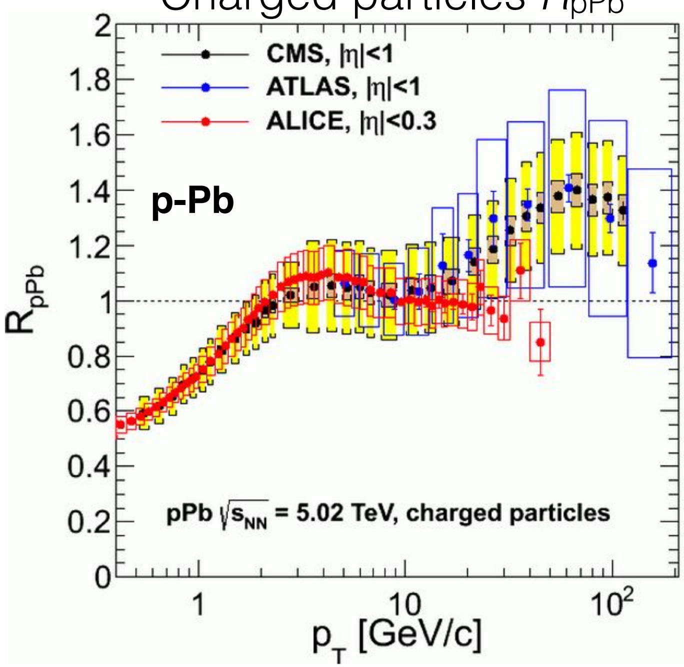


High p_T R_{pPb}

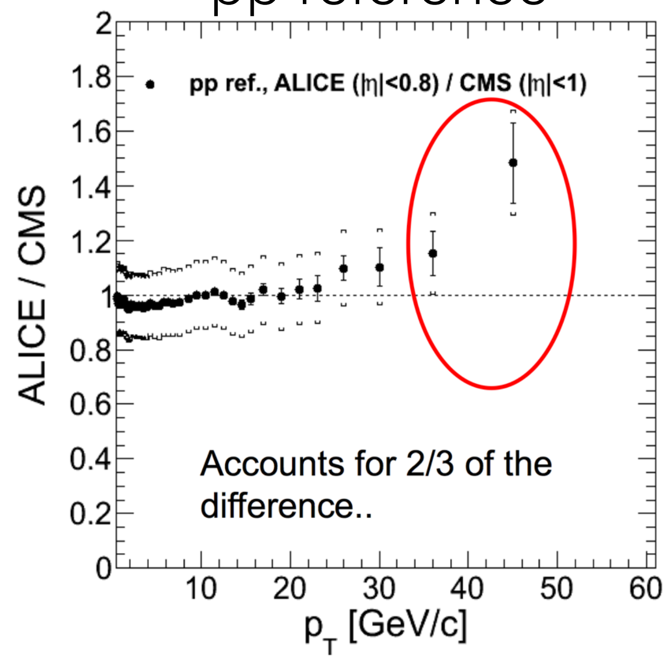
- Jet
  - Modification はない
- High p_T charged particle
  - ALICE, CMS, ATLASで違い
  - pp referenceの違い



Charged particles R_{pPb}



pp reference

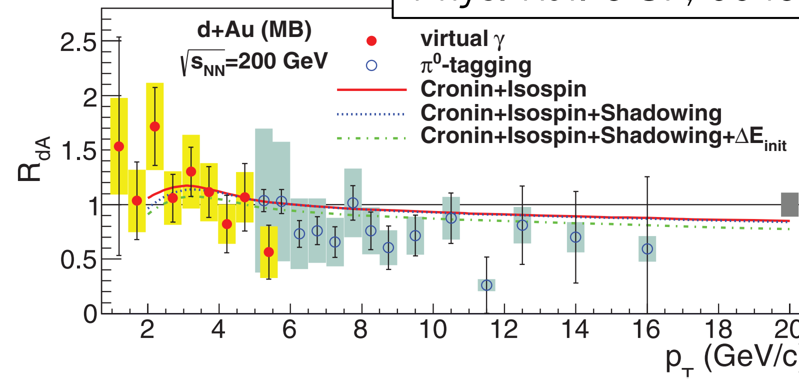


Electromagnetic probe

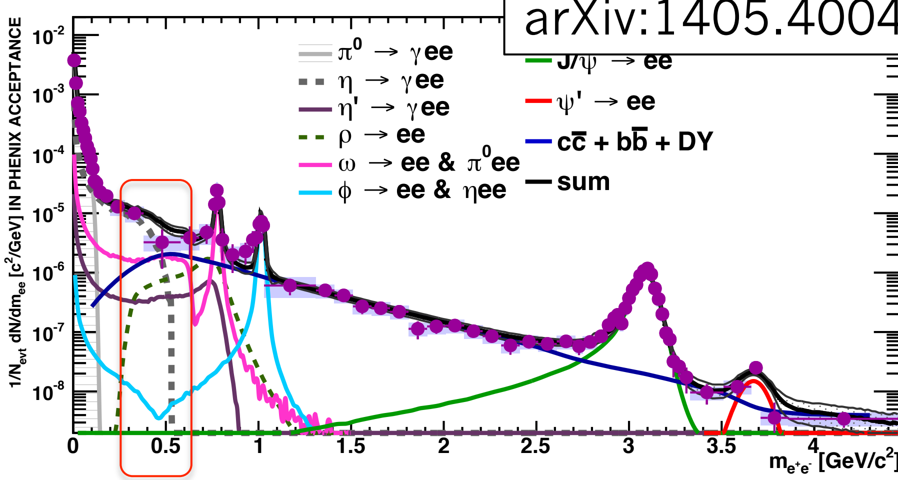
- Direct photon
  - Low p_T enhancement無し
- Low mass dielectron
  - Enhancement無し

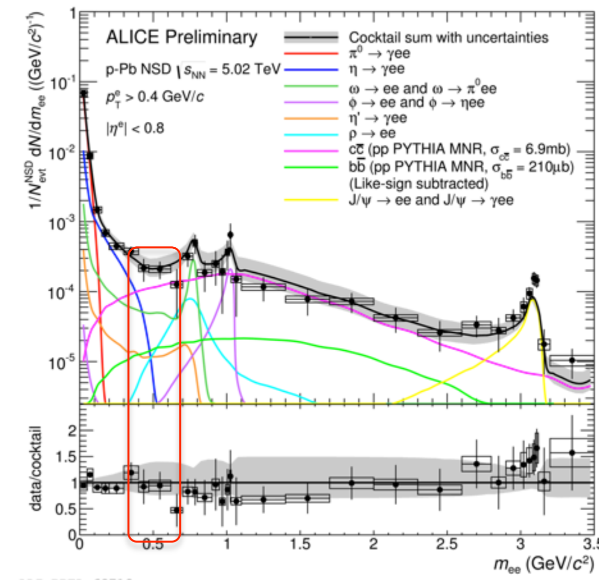
Thermal radiationはない？

Phys. Rev. C 87, 054907



arXiv:1405.4004





ここまでのまとめ

- ソフトなプローブに対してはcollectivityがあるように見える
  - CNM等他の効果がどの様に測定に効いてくるのかよく分からない
  - Thermal radiationは確認されず
- ハードなプローブ(Jet, high p_T particle)でppからの変化はない
  - Short path length？
  - Heavy quarkは？

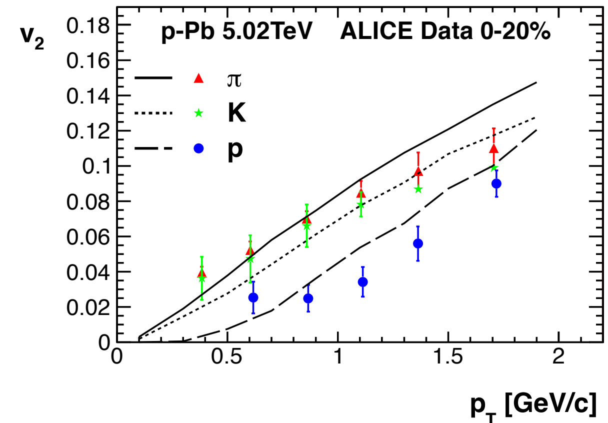
- p-Pb衝突からどのような知見が得られるか？
  - 原子核効果がないという訳ではない
  - QGPが出来ているとしても系のサイズ小さく、寿命は短い？

    → QGP, HRGからの寄与は相対的に小さい？
    - 果たして小さな系でも局所熱平衡に達するのか？
      - 熱化機構の検証？
    - v_2の起源は？ Initial fluctuation?
      - 観測量にはより大きなinitial state依存性が予想される

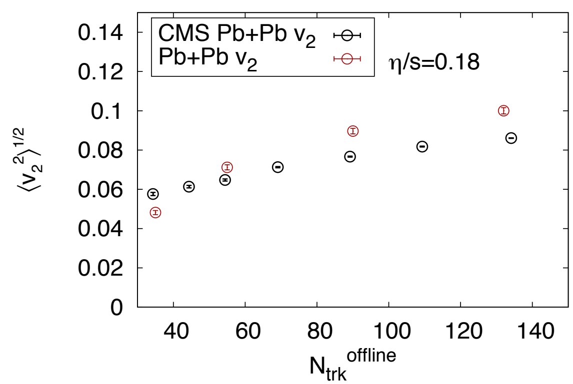
理論的理解に向けて

- Hydro calculation
  - Glauber-3+1D event-by-event viscous hyd
  - IP-Glasma+MUSIC

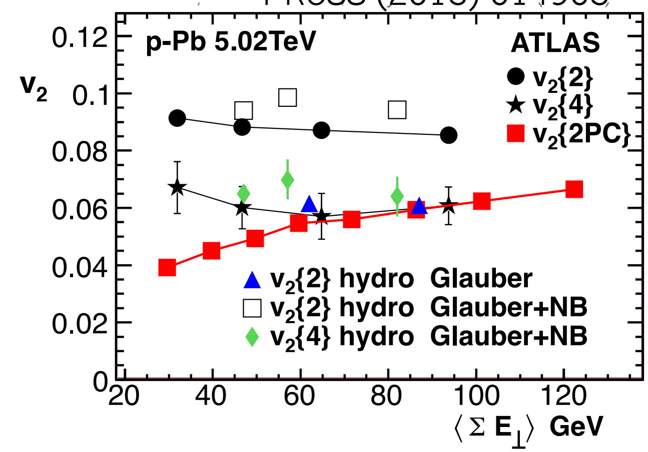
PRL 111 (2013) 1723030



PLB724 (2013) 213-240



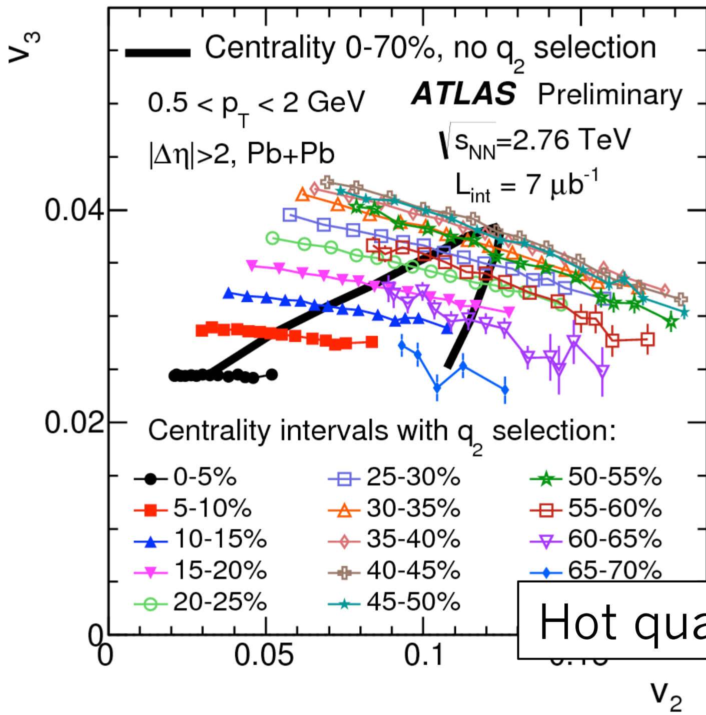
PRC88 (2013) 014903



- Thermalizationの問題
  - AdS/CFT calculation(PRL108 (2012) 201602)
    - describe early thermalization?pAでは？

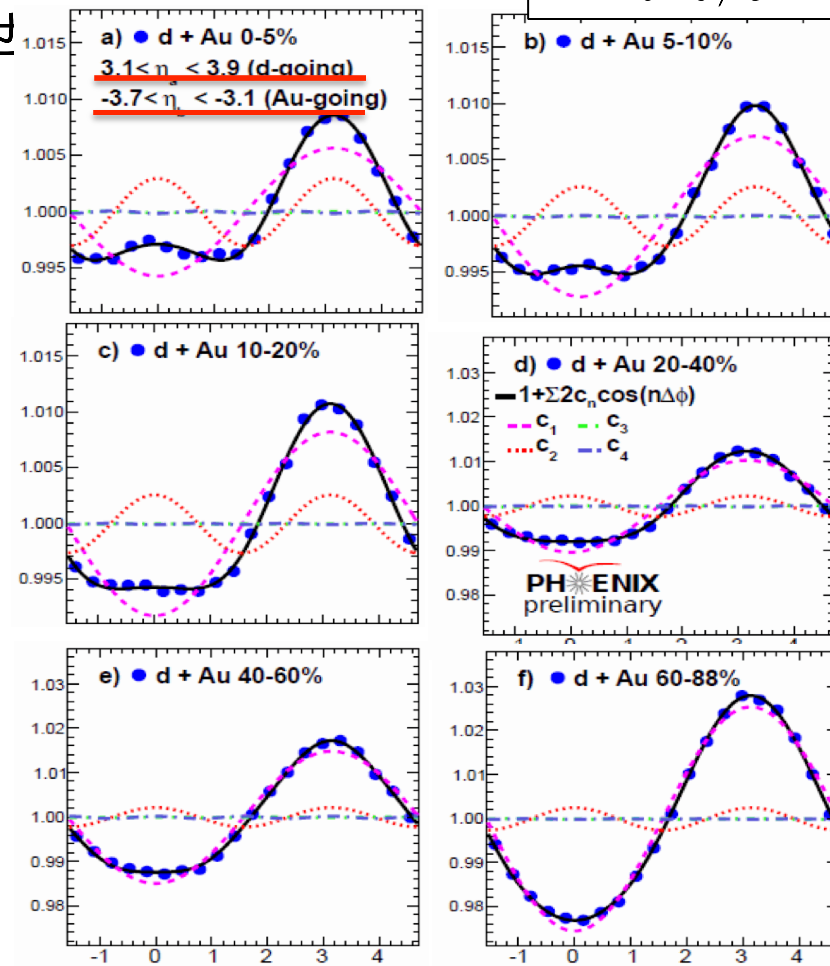
更なるridge構造の理解に向けて

- 結局起源はまだよく分からない
  - 恐らくいろいろな効果の足し合わせ
  - v_n相関, event plane相関と同等の測定は可能か？
  - よりlong-rangeでの相関？



Hot quark2014

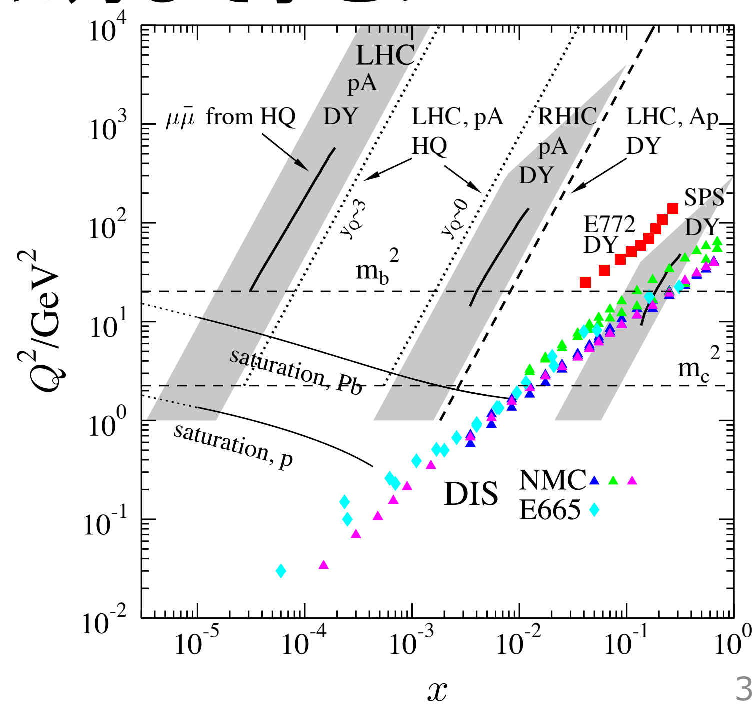
HP2013, S. Huang



Heavy flavors in p-Pb

Heavy flavorを用いた原子核効果の検証

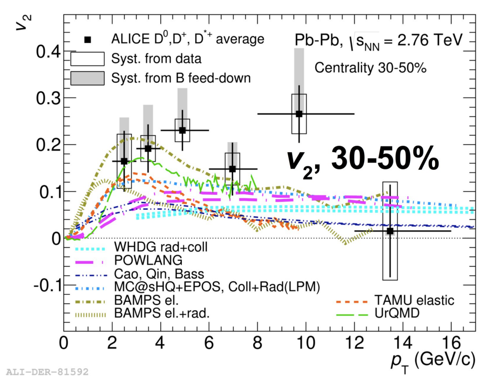
- p-Pb衝突は当初考えられていた初期状態の効果だけが反映されている訳ではなさそう？
- Charm quarkや Bottom quarkに対してはどうか？
  - CNM以外の影響は少ないはず
  - m_c(～1.4GeV/c^2)は飽和スケールに対して小さい
    - Q_s^2～3-10 GeV

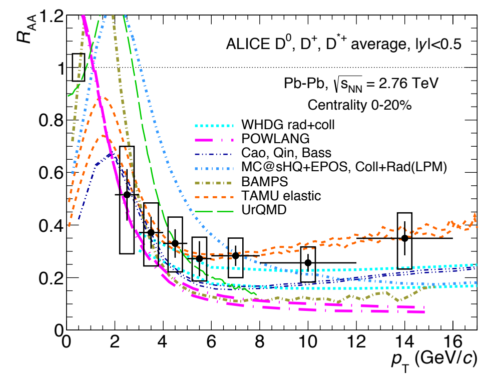


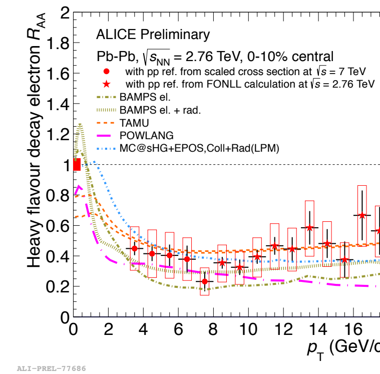
Heavy flavor measurement in PbPb

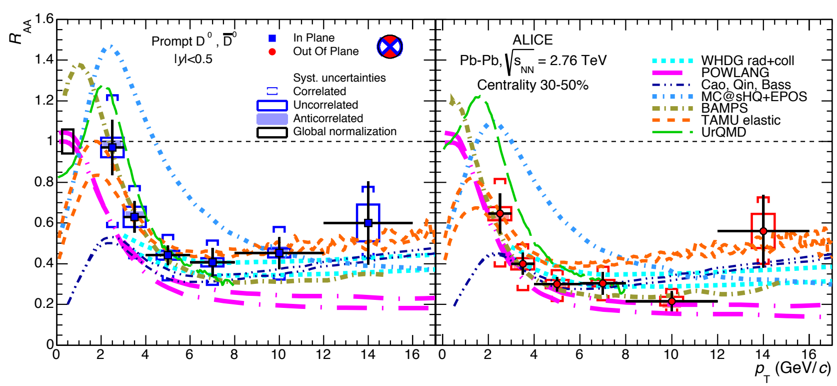
- 大きなsuppression, nonzero v_2
  - $R_{AA}(g) \sim R(D)$?
  - Recombination?

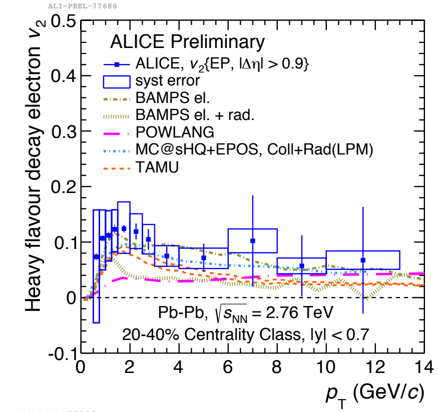
TAMU elastic: arXiv:1401.3817
Djordjevic: arXiv:1307.4098
Cao, Qin, Bass: PRC 88 (2013) 044907
WHDG rad+coll: Nucl. Phys. A 872 (2011) 265
MC@sHQ+EPOS: PRC 89 (2014) 014905
Vitev, rad+dissoc: PRC 80 (2009) 054902
POWLANG: JPG 38 (2011) 124144
BAMPS: PLB 717 (2012) 430





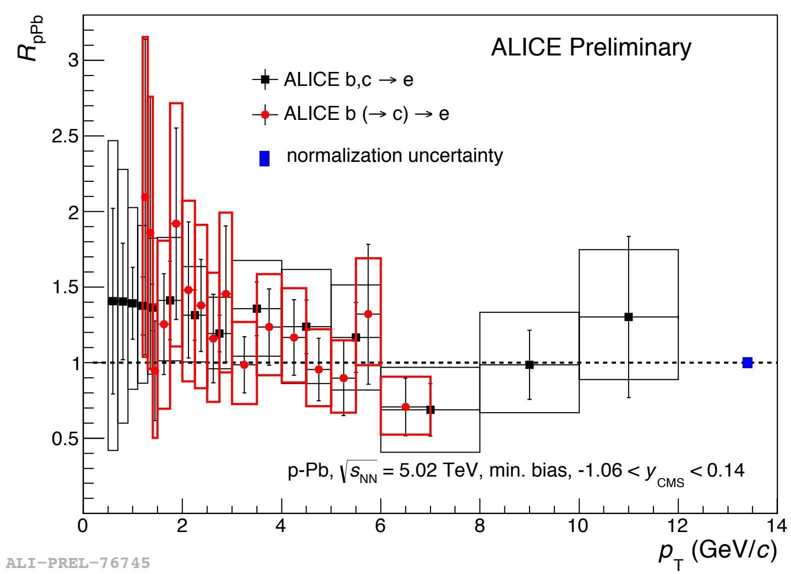


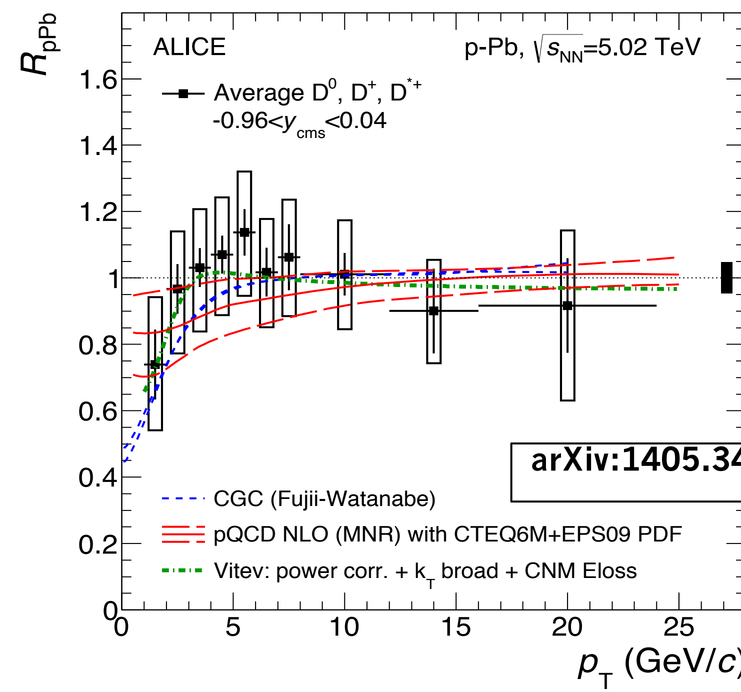




R_{pPb} of open heavy flavors

- 不定性の範囲内でppと一致
- 理論予想ではR_{pPb}に対する差は小さい
  - 不定性をのぞいてもsensitivityはない?
    - Event activity dependenceは？
- 新しい測定量->ペア相関

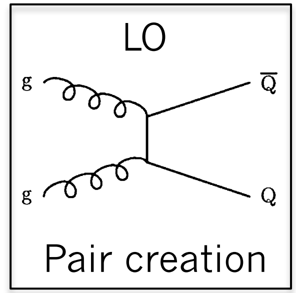


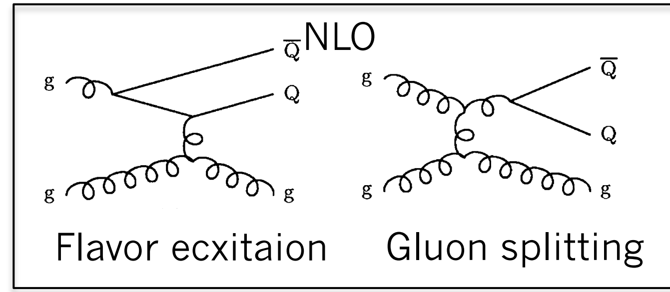


arXiv:1405.3452

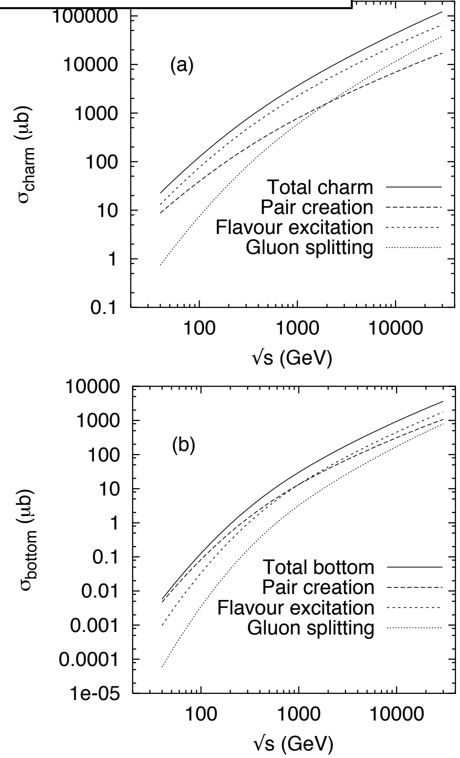
Heavy quarks pair production

- LHC energyではNLO dominant
  - FONLLと一致
  - 異なる相関
- MPIによる多重生成

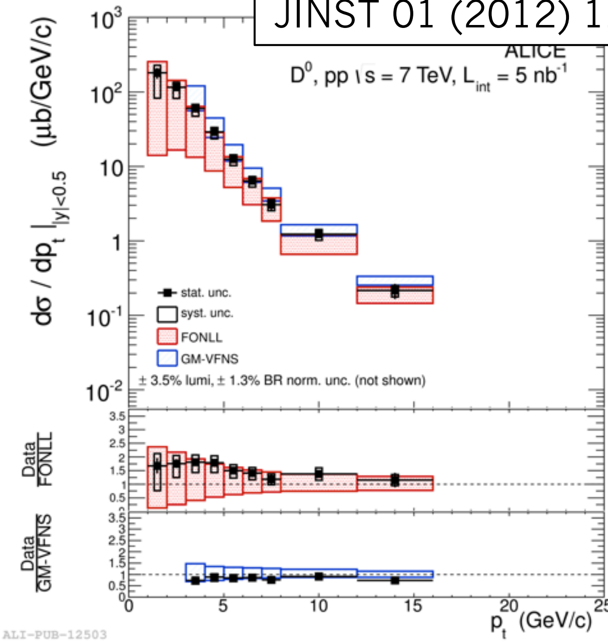


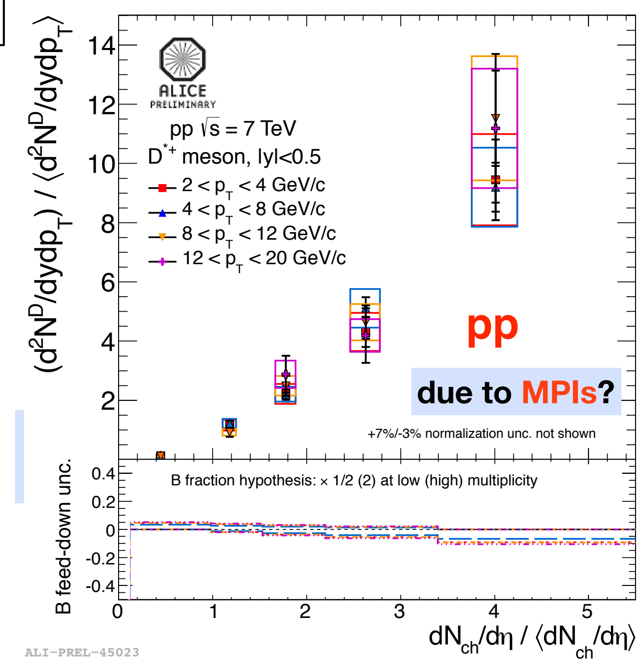


Eur. Phys. J. C 17, 137–161 (2000)



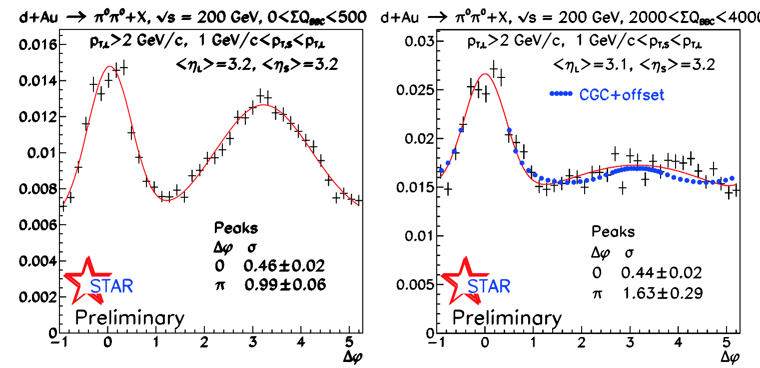
JINST 01 (2012) 128





Heavy flavor correlation

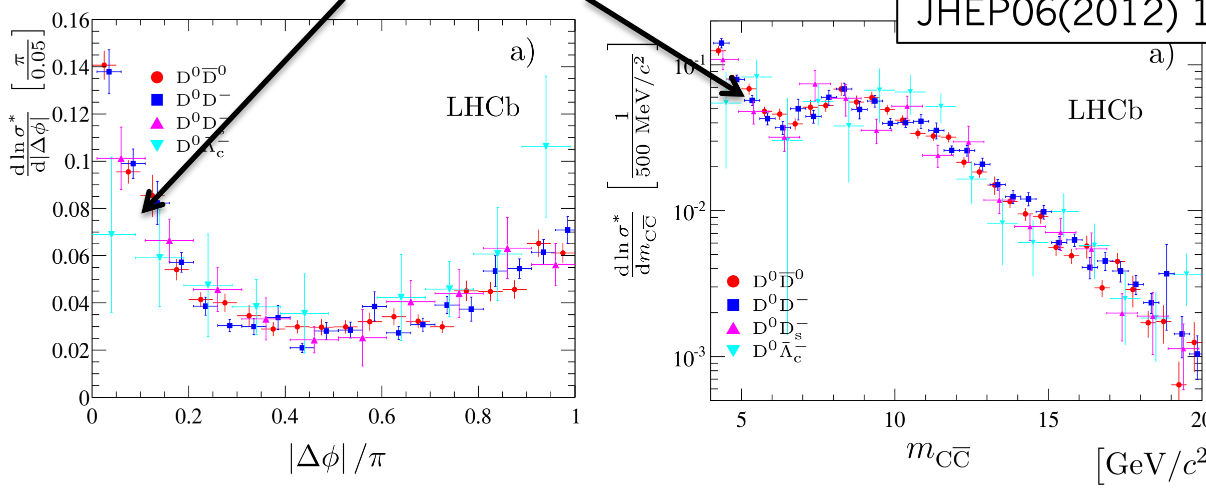
NPA 854 (2011) 168–174



- dihadron correlation in d+Au
  - Shadowing?CGC?
- Heavy quark pairに対しては？
  - i.e. CGC(Fujii, Watanabe)
- 測定可能か？
  - D/B-D/B
  - D/B-hadron
  - Lepton-hadron
  - Lepton-Lepton

Gluon splitting

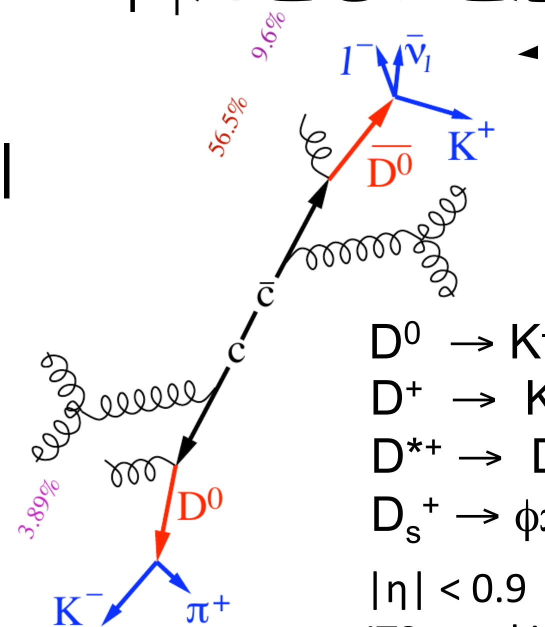
JHEP06(2012) 141



LHCb pp@√s = 7TeV, 2 < y < 4, 3 < p_T < 12 GeV/c

Heavy flavor analysis

- Direct reconstruction
  - 直接測定で感度はいい
  - しかしハドロンを用いた直接崩壊測定はbranch, 検出効率ともに悪い(10%以下@ALICE, Low p_Tだともっと悪い)
- Semi-leptonic decay channel
  - 間接的測定なので相関は弱まる
  - Branchはやや大きい(～10%)
  - 検出効率はいい
  - Trigger eventsが使える



Courtesy of David Tlusty

$D^0 \rightarrow K^- \pi^+$

$D^+ \rightarrow K^-\pi^+\pi^+$

$D^{*+} \rightarrow D^0\pi^+$

$D_s^+ \rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$

$|\eta| < 0.9$

ITS: tracking, vertexing

TPC: tracking, PID

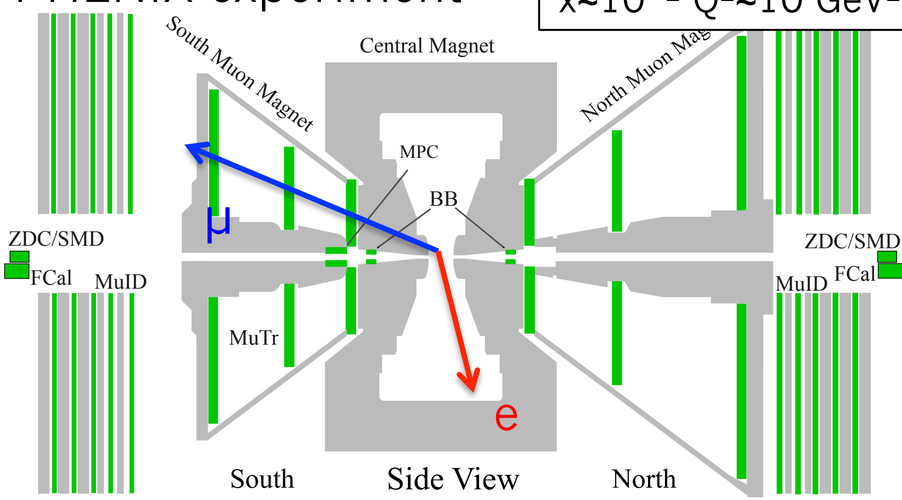
TOF: PID

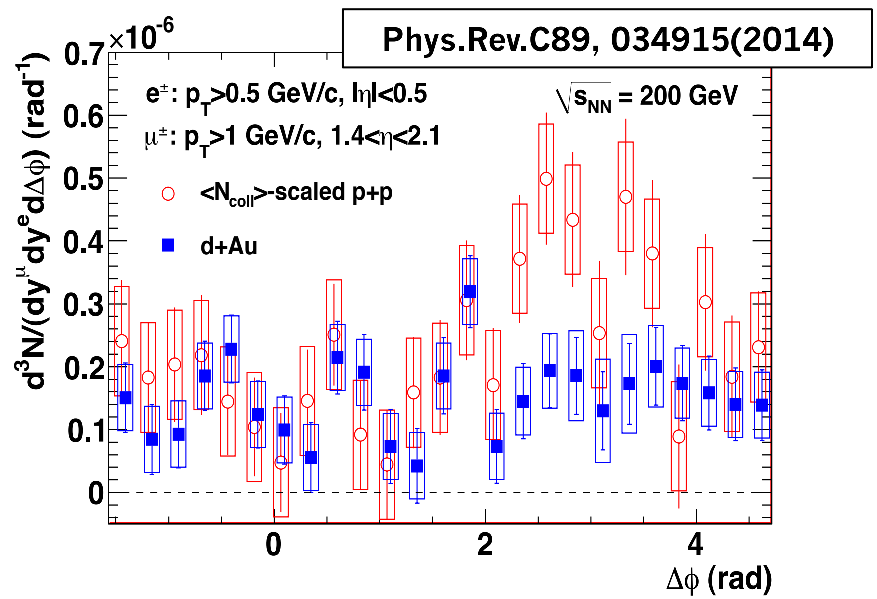
e-μ correlation in d+Au

- Forward-central相関
- ppで見えているback-to-backの相関がd+Auでは見えない
  - Shadowing effect?

PHENIX experiment

x≈10⁻² Q²≈10 GeV²

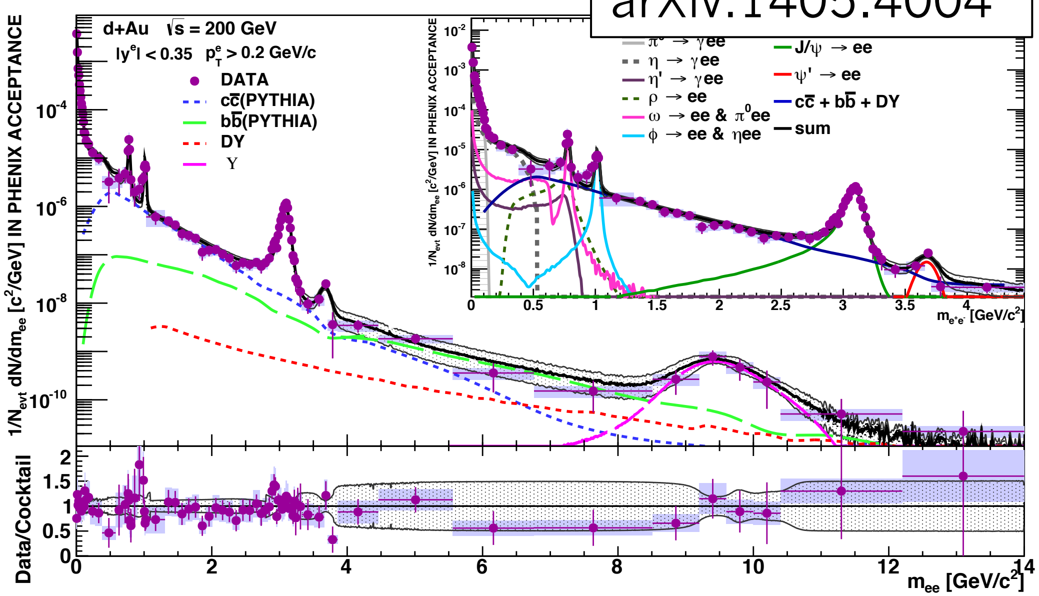


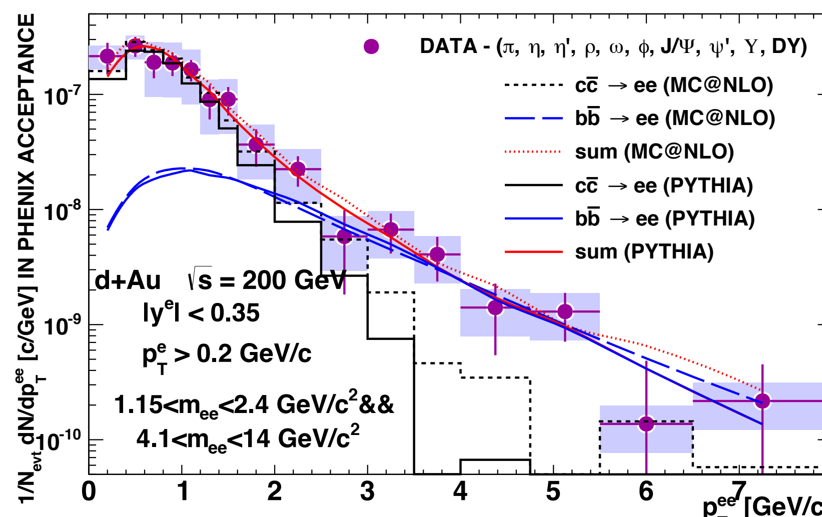


Dielectron in d+Au

- Mass とp_Tでcharmとbottomの寄与を選別
- bb cross sectionの導出
  - ppとの比較

arXiv:1405.4004

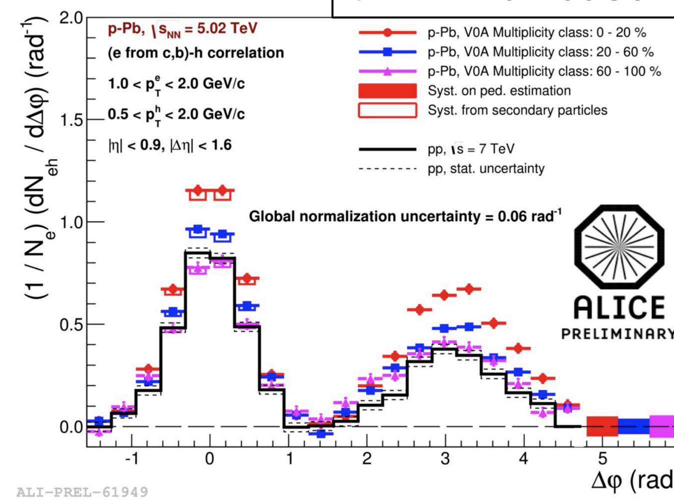


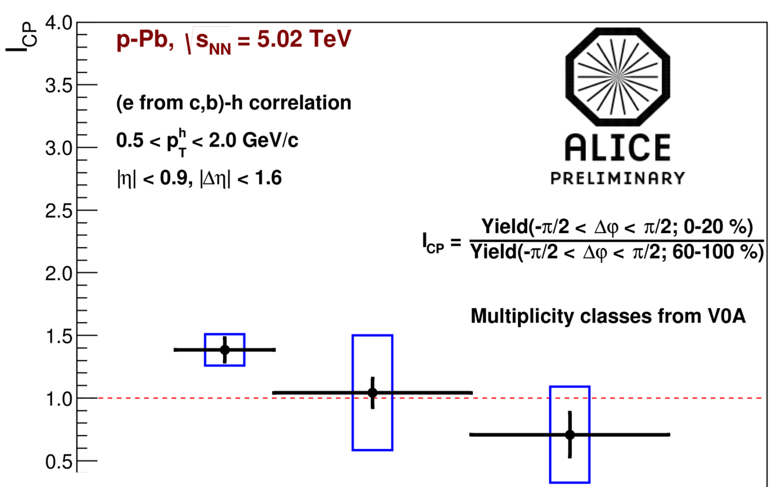


e-h correlation in p-Pb

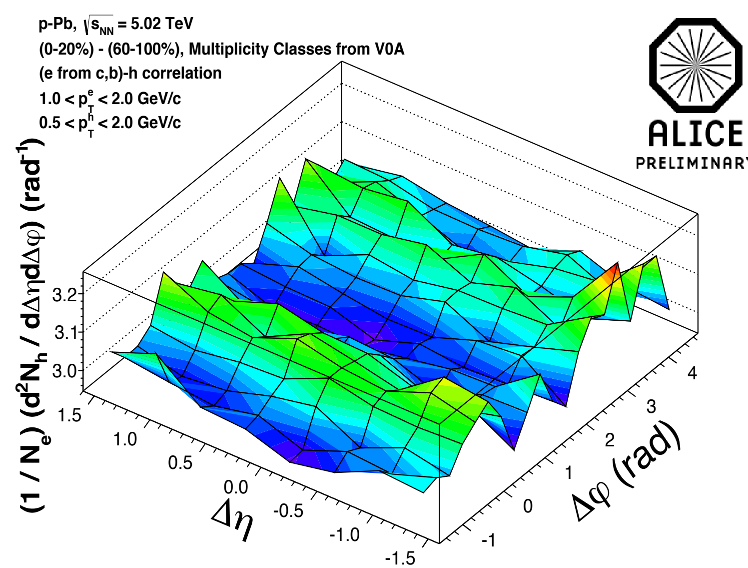
- electron-charged hadron
  - D/Bからのdecay
- Near side, away sideともcentralでenhancement
- Double ridge structure
  - Light flavor と同じ起源？

arXiv:1404.3983v2



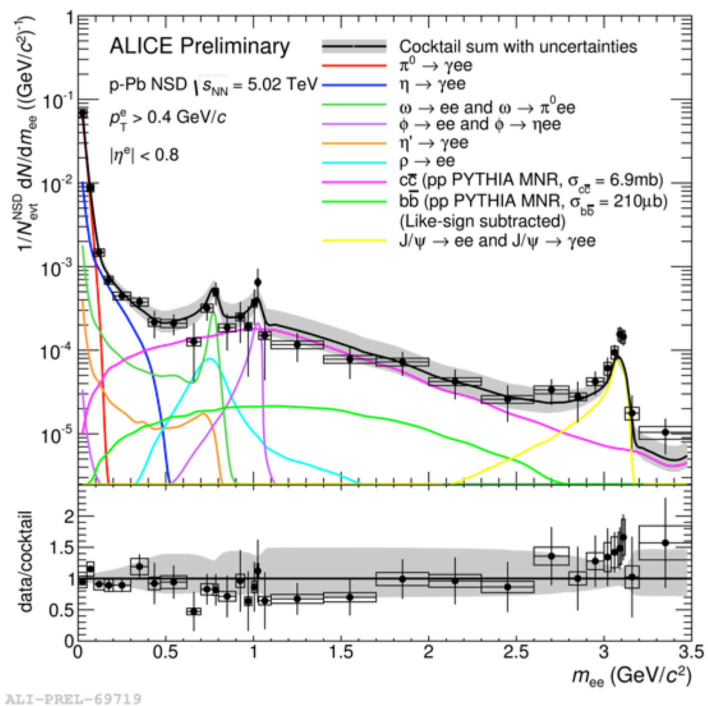


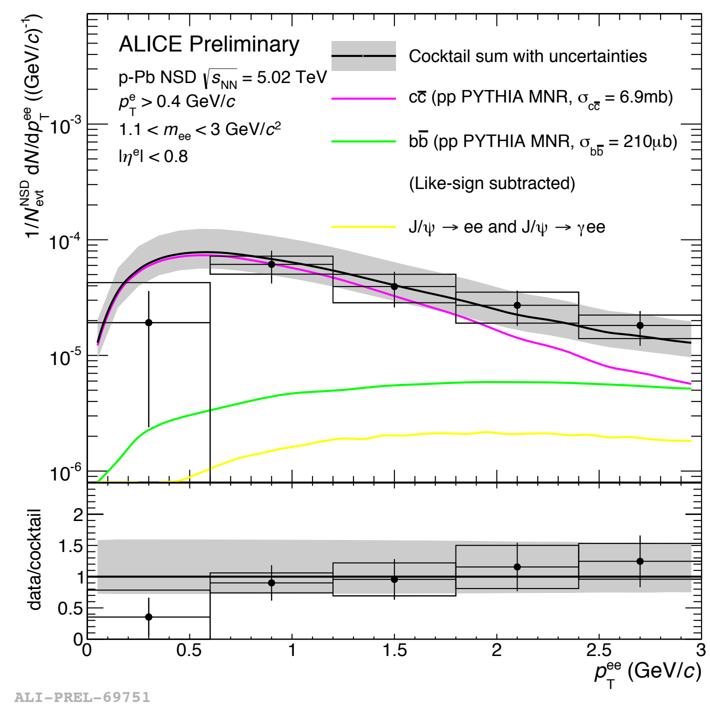
$$I_{CP} = \frac{Y(-\pi/2 < \Delta\varphi < \pi/2)_{0-20\%}}{Y(-\pi/2 < \Delta\varphi < \pi/2)_{60-100\%}}$$



Dielectron channel in p-Pb

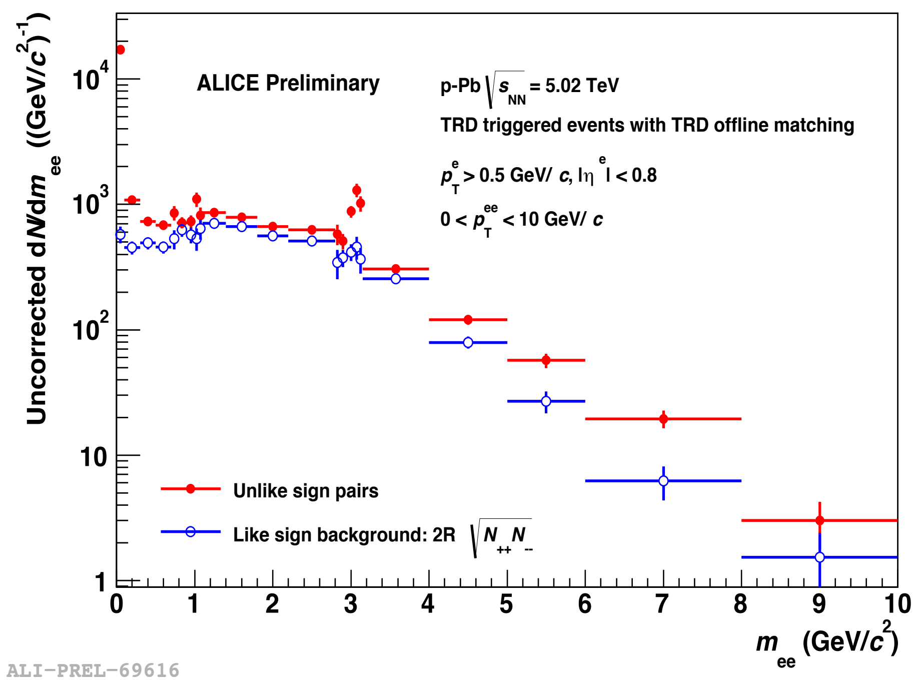
- Consistent with the hadronic cocktail calculation within the uncertainties
  - Charm and bottom pair production: based on Pythia(pp simulation)
  - T_{pPb} =0.0983±0.0035(mb^{-1}) scaling

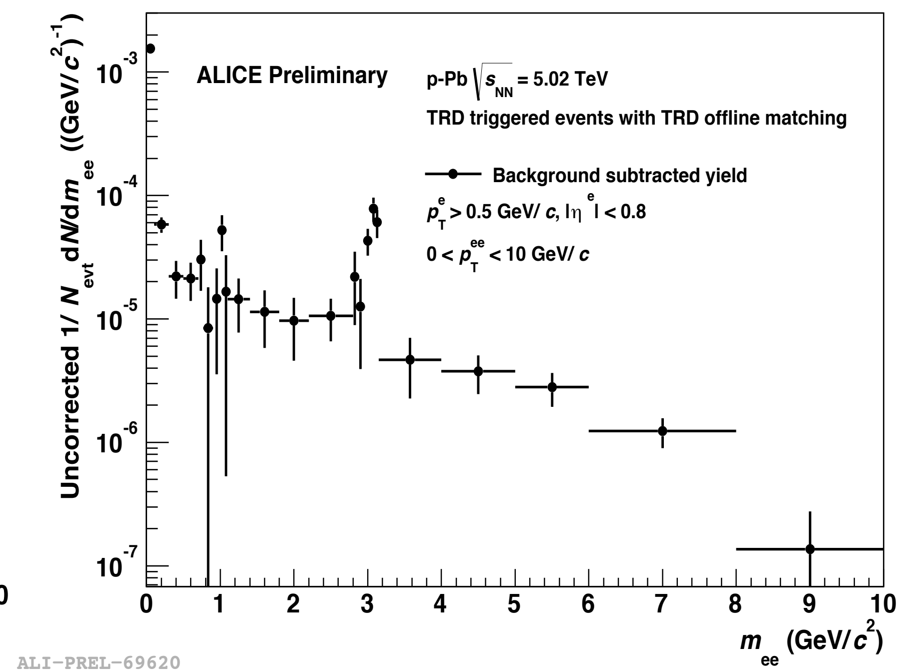




Dielectron channel in p-Pb

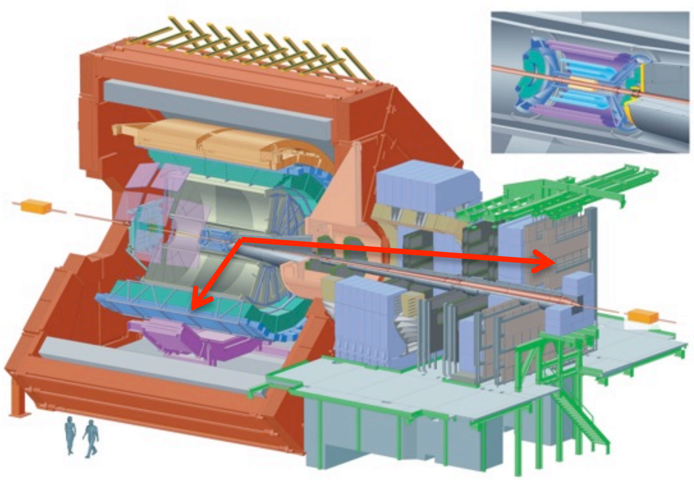
- How about higher mass and higher p_T?
  - Bottom quark pairs
- TRD/EMCAL triggerによりmass領域を拡張可能

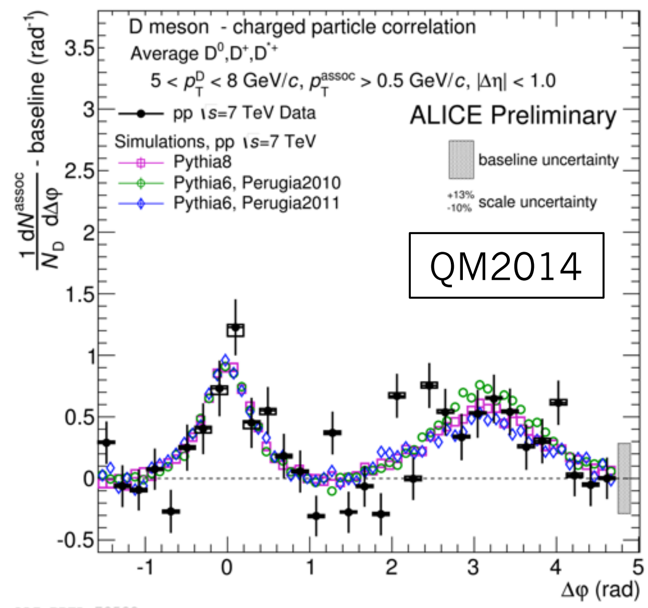




Future in LHC-ALICE

- e-μ correlation
  - Forward-backward correlation
- D-hadron
  - Promising after ALICE upgrade
  - 特に2018年以降のITS, TPC アップグレードで統計, 系統誤差ともに大幅改善





Summary

- pA衝突でのLong-range correlationの発見
  - AA衝突ridgeと似た傾向
    - Mass ordering
    - Quark number scaling
  - $v_2\{4\}=v_2\{6\}=v_2\{8\}=v_2\{LYZ\}$
    → collectivity?
- Initial state(CGC, fluctuation, thermalization)の理解がより重要
- Heavy quark pair生成におけるCNM効果の検証
  - e-μ in d+Au: back-to-back correlationの抑制
  - e-h in p-Pb: double ridge structure
  - Dielectron channel: ongoing
  - D-hadron: promising after ALICE upgrade

RHIC
He+Au: 異なる初期geometry
eRHIC, LHeC

Back up

Models for heavy quarks

- Various models

	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

Heavy flavor production in HIC

Charm and bottom quarks are created at the early stage of heavy-ion collisions through initial hard scattering.

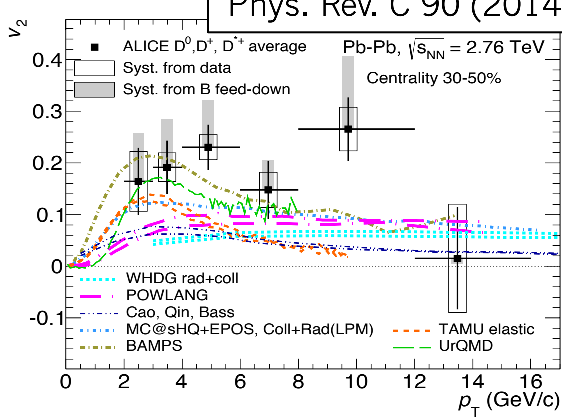
→ Good probe to study the properties of the medium

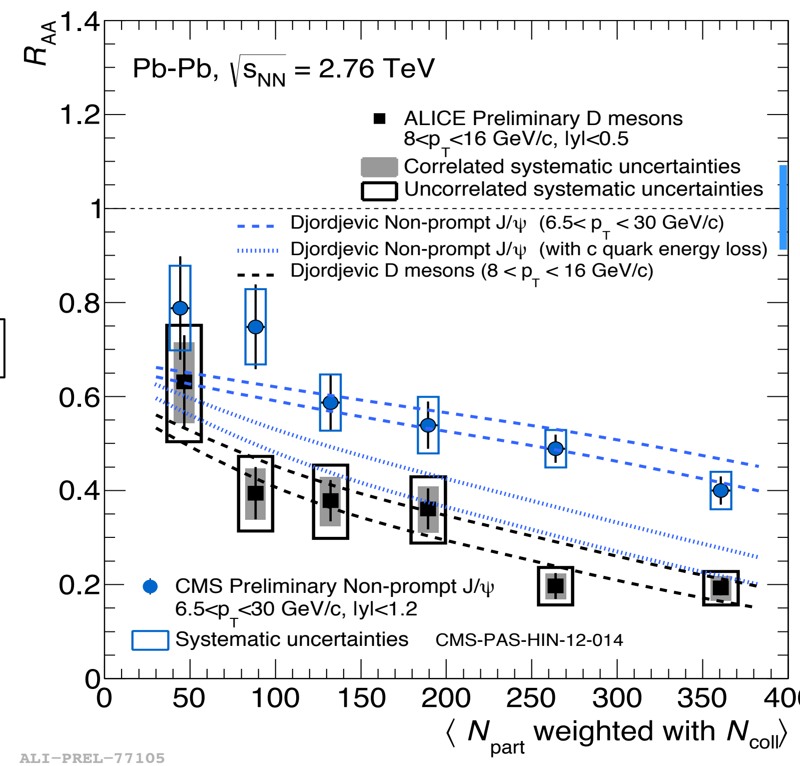
- Energy loss in medium
  - Gluon radiation
  - Collisional loss

  $\Delta E_g > \Delta E_c > \Delta E_b$ due to dead cone effect

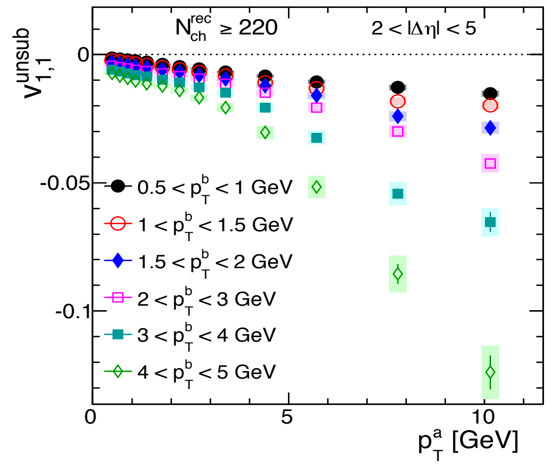
  Modification of heavy flavor correaltion
- Thermalization of charm quarks

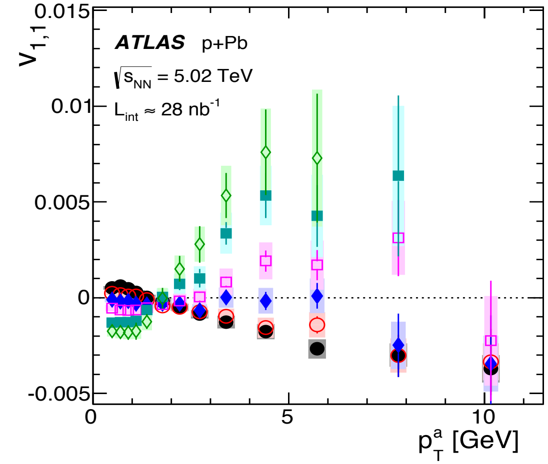
Phys. Rev. C 90 (2014) 034904





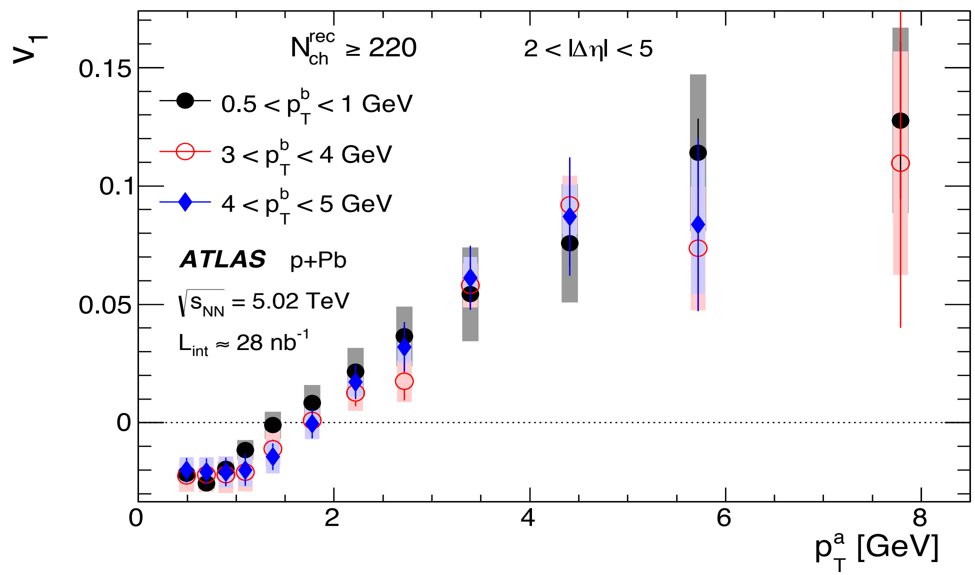
v_1 measurement





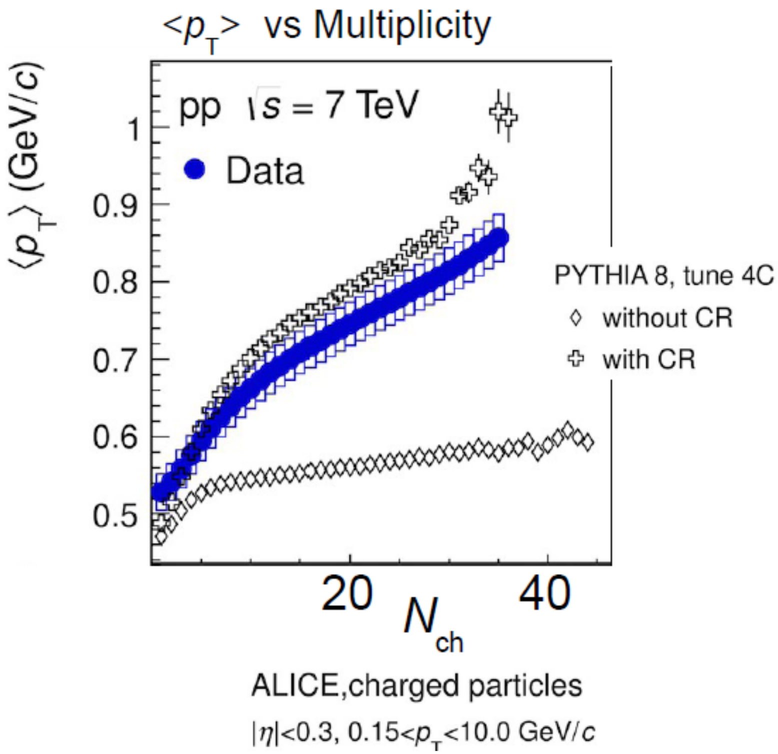
$$v_1(p_T^a) \equiv \frac{v_{1,1}(p_T^a, p_T^b)}{v_1(p_T^b)} \ ,$$

$$v_1(p_T^b) = \mathrm{sign}(p_T^b - p_T^0)\sqrt{\left|v_{1,1}(p_T^b, p_T^b)\right|} \ ,$$

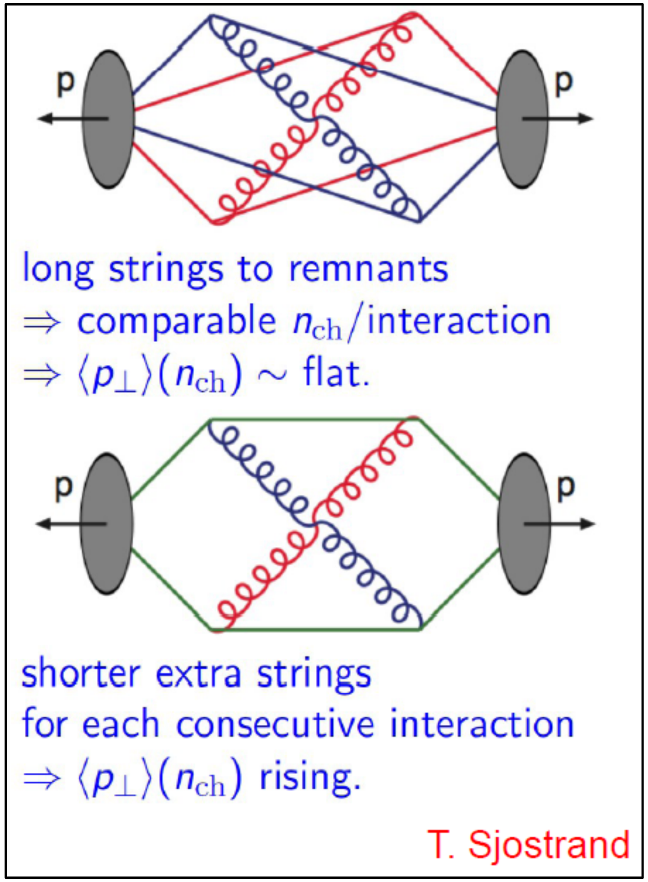


pp

ALICE, PLB 727 (2013) 371

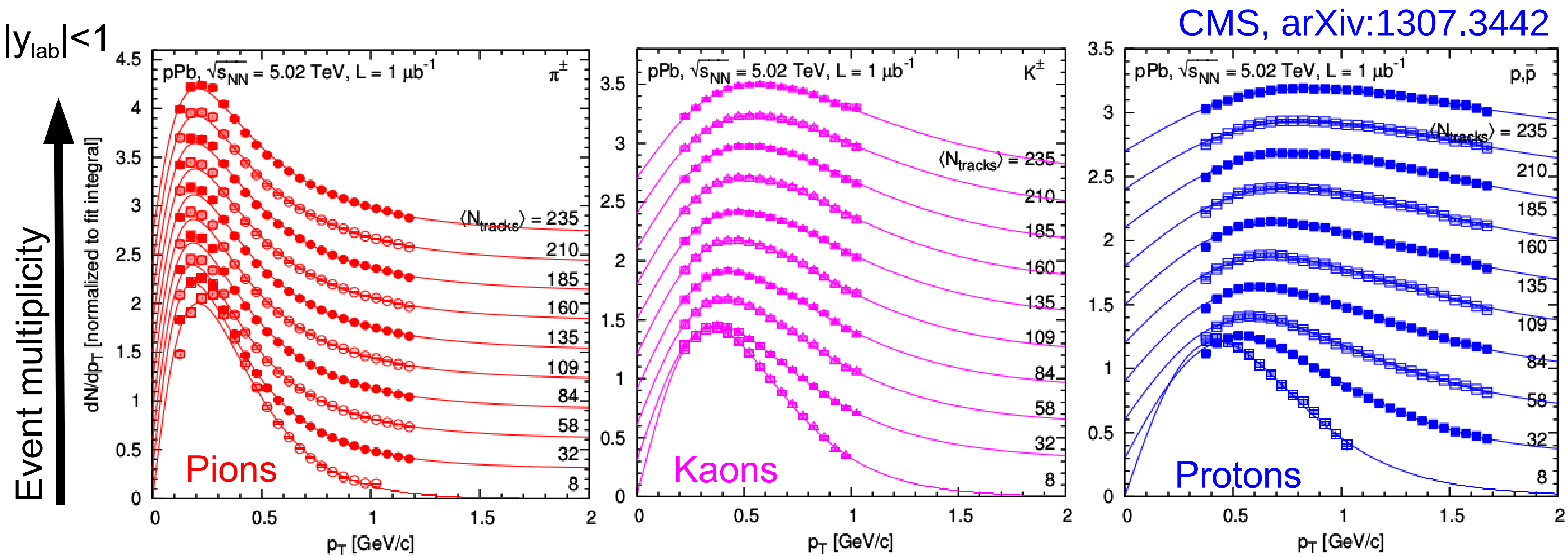


Rise of $<p_T>$ can not be reproduced by incoherent superposition of MPI



Particle spectra

- Radial flowを示唆？



Brast wave fit

Hydrodynamic-inspired model, that assumes

- hard sphere uniform density particle source with temperature T
- collective transverse radial flow velocity β

Schnedermann, PRC 48, 2462 (1993)

Transverse velocity distribution $\beta_r(r)$ for $0 < r < R$ parametrized with

- surface velocity β_s
- velocity profile n

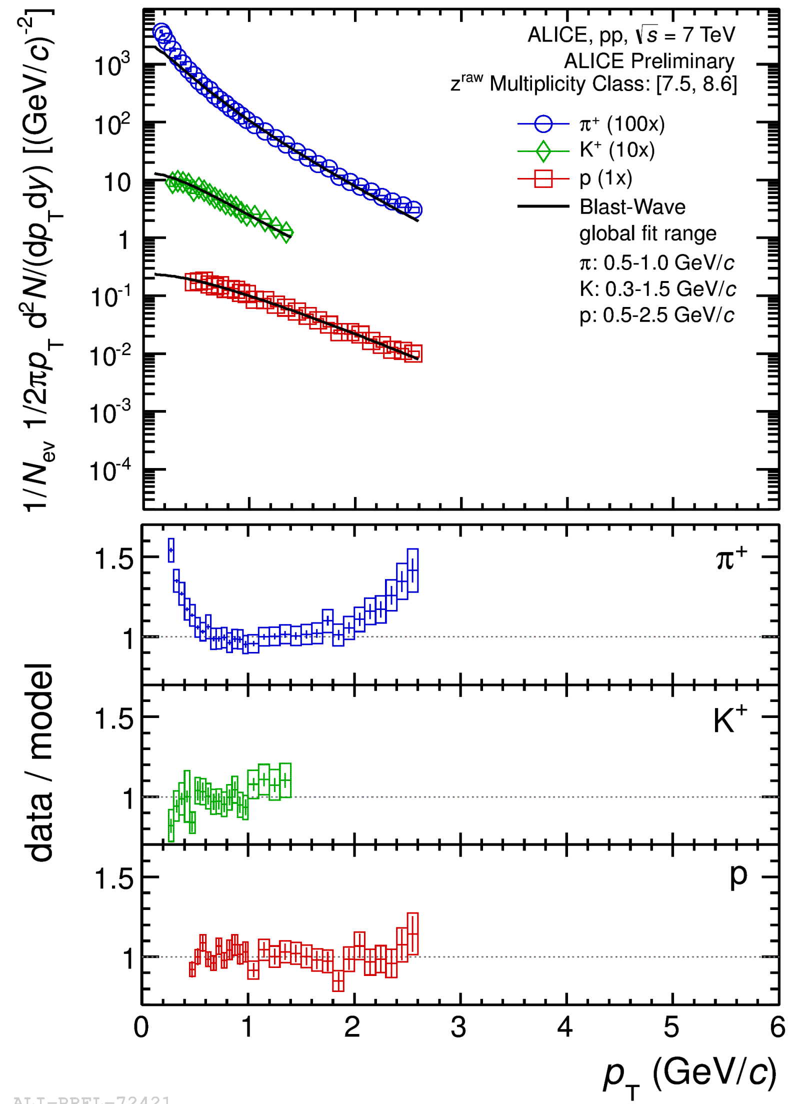
$$\beta_r(r) = \beta_s \left(\frac{r}{R}\right)^n$$

Resulting spectrum is superposition of the individual thermal components, each boosted with the boost angle ρ

$$\rho = \tanh^{-1} \beta_r$$

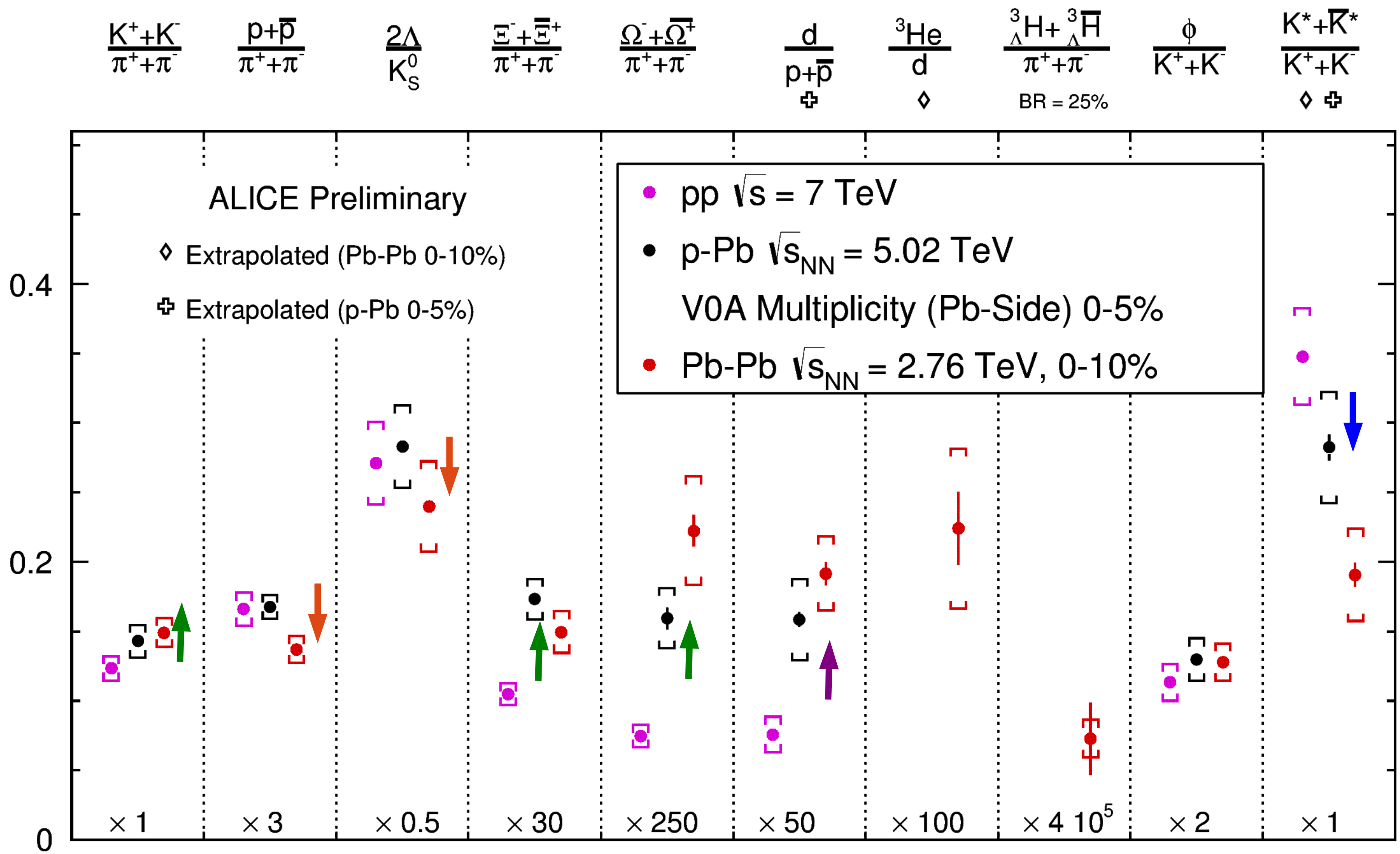
$$\frac{dn}{m_T dm_T} \propto \int_0^R r \; dr \; m_T I_0 \left(\frac{p_T \sinh \rho}{T}\right) K_1 \left(\frac{m_T \cosh \rho}{T}\right)$$

Blast wave fit in pp

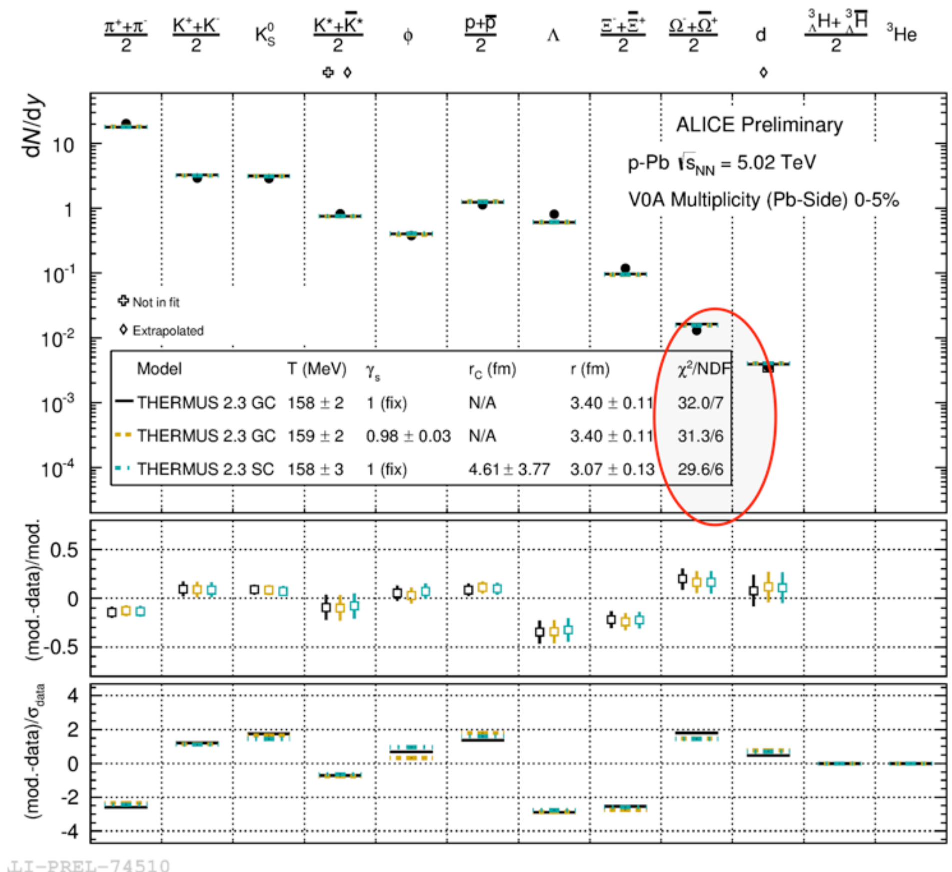


Thermal model

- Baryon suppression?



Thermal model



Initial state dependence on η/s