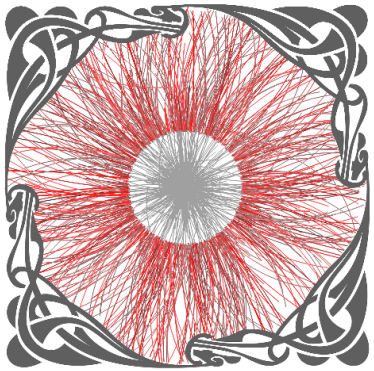


XXIV
QUARK
MATTER
DARMSTADT
2014

Quark Matter 2014報告
(Heavy flavor)

林　真一（東大CNS）

HIP/HIC合同研究会

2014.06.06

Heavy flavor in heavy ion collisions

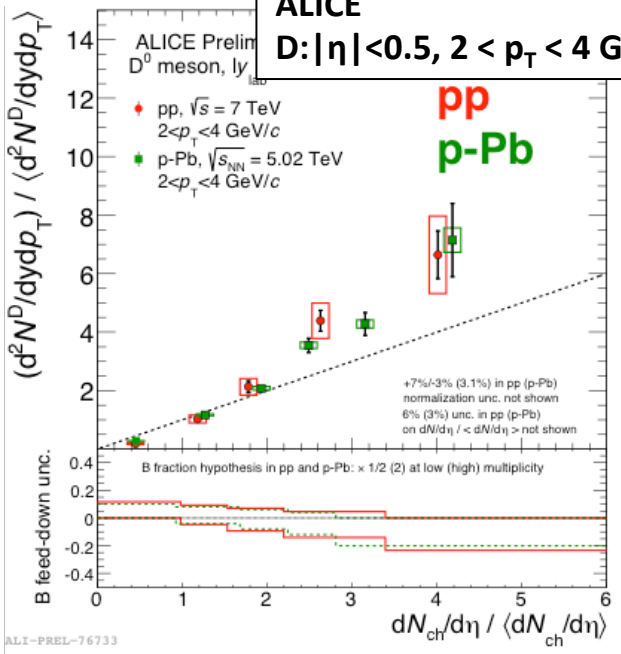
- **Open heavy flavor:D, B, e, μ ← D, e,μ ←B**
  - Energy loss
  - Thermalization
  - Cold nuclear matter effects
- **Quarkonia: J/ψ, ψ', Υ**
  - Melting
  - Regeneration
  - Cold nuclear matter effects
- **(Exotic state?)**
  - Charmed baryon, tetra quarks, penta quarks…

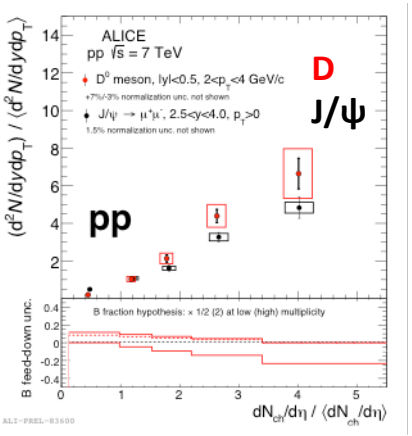
Spectrum, $R_{AA}/R_{pA}(Q_{pPb})$, v_2, angular correlation…
Rapidity, p_T, event activity, system energy, system size…

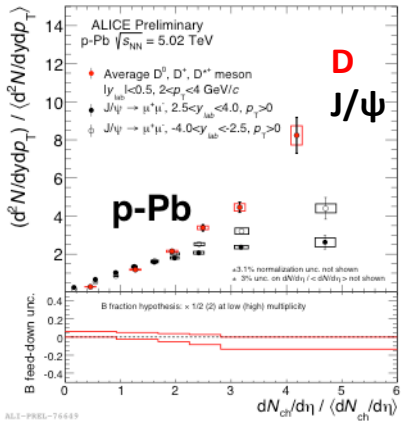
D, J/ψ, Υ multiplicity dependence

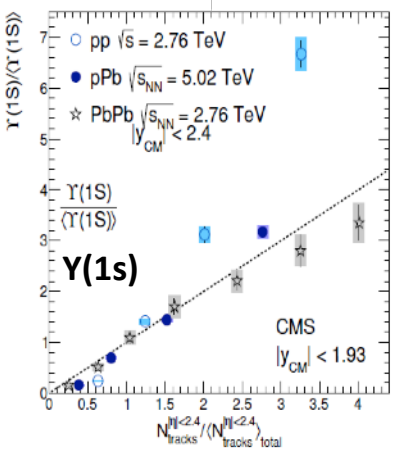
- pp、p–Pb
  - 強いmultiplicity依存性を確認
  - J/ψ,Υでも同様の依存性
  - Pythia(6.4, Perugia 2011)では再現しない
- 定性的には、p–Pbではbinary collisionの増加とconsistent
- p–pでは？
  - Multiple parton interaction？

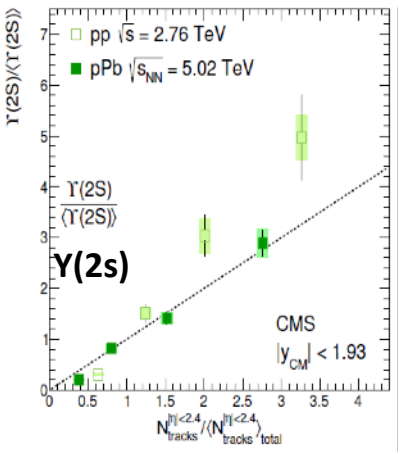
ALICE
D:|η|<0.5, 2 < p_T < 4 GeV/c









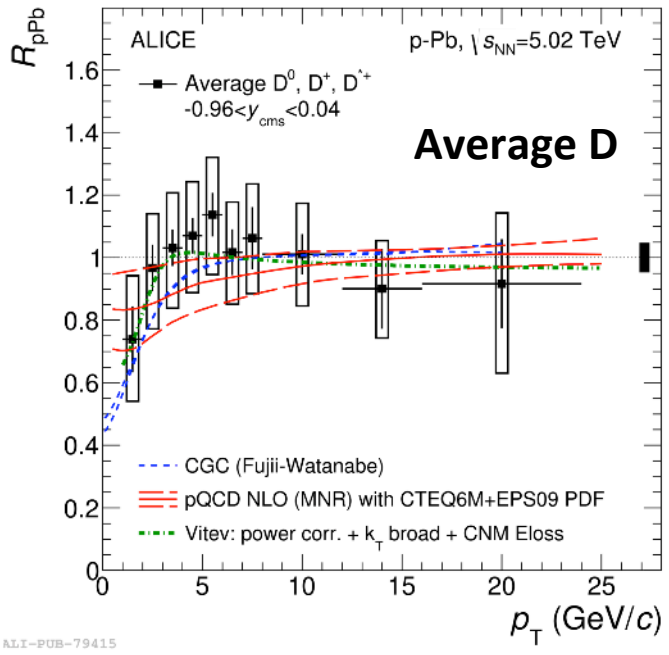


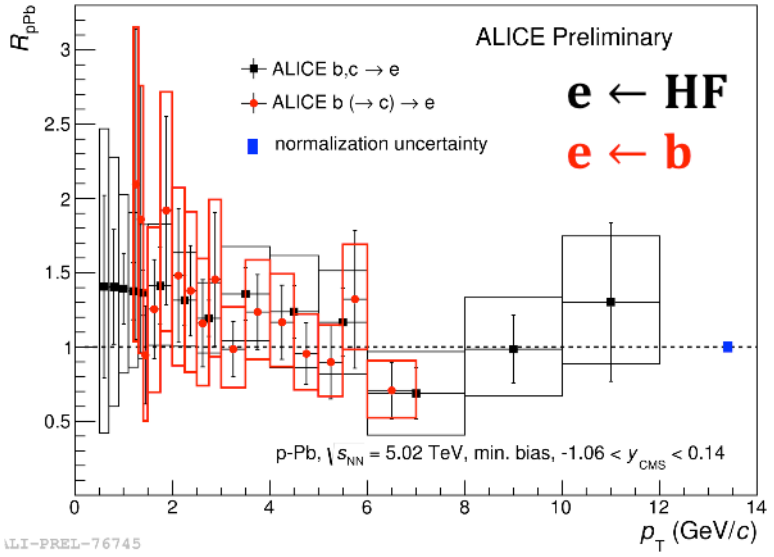
Open heavy flavor

Open Heavy flavor at mid-rapidity in p-Pb

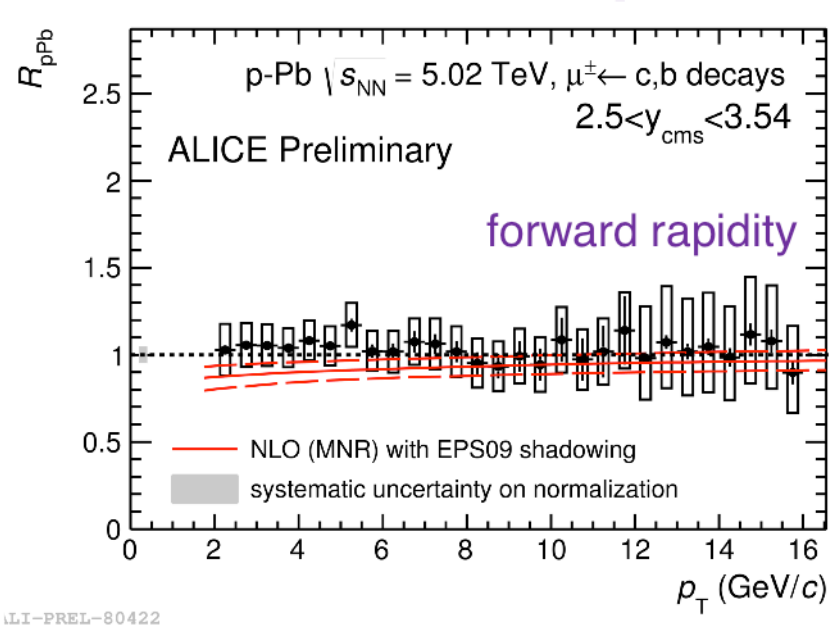
- D meson R_{pA}(mid-rapidity)
  - CGC
  - pQCD(EPS09)
  - Shadowing + energy losss + k_T broading(Vitev)

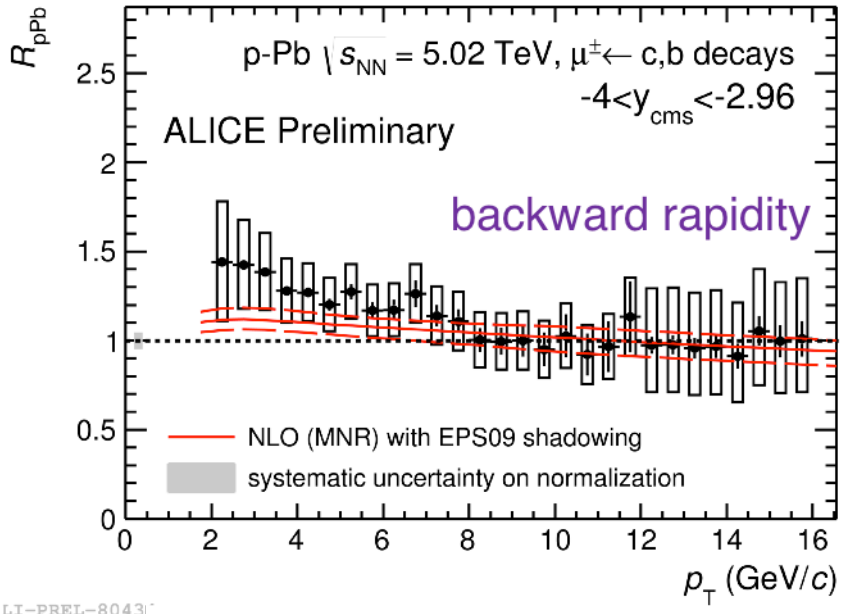
  ともに一致
- Heavy flavor electron in midrapidity (-1.06 < y <0.14)
  - Enhancement 確認されず



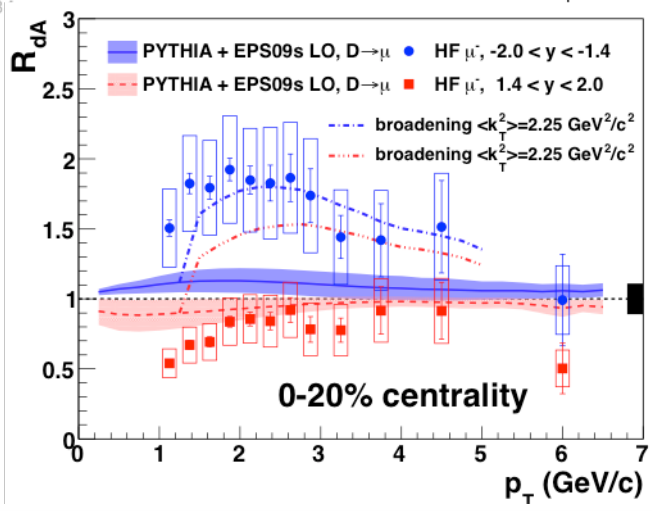


Heavy flavor at forward/backword in p-Pb





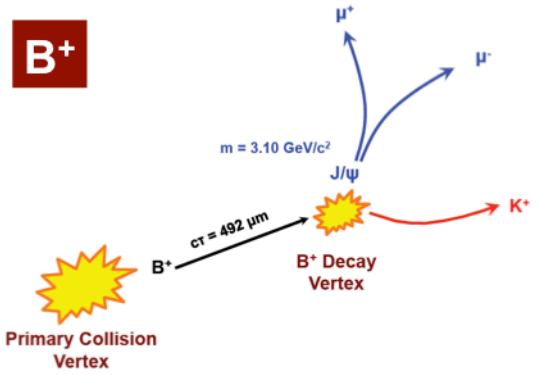
- Forward：変化は見られず
- Backward: low p_Tでenhancement
- pQCD計算(Pythia NLO tune, EPS09)と一致
  - Anti-shadowingの効果
- しかし、RHICではEPS09では一致せず (PYTHIAのparametrizationは違う)

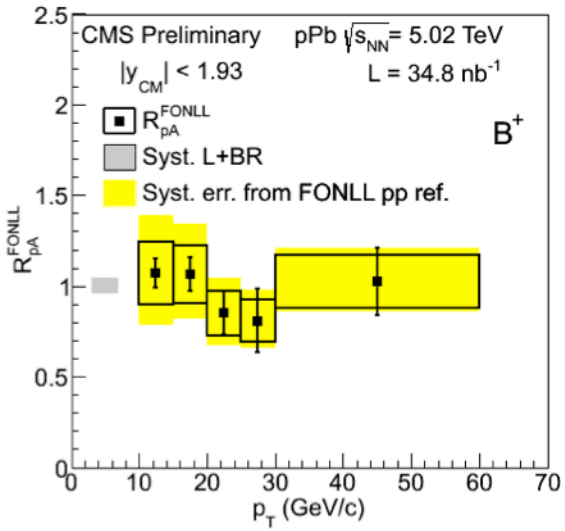


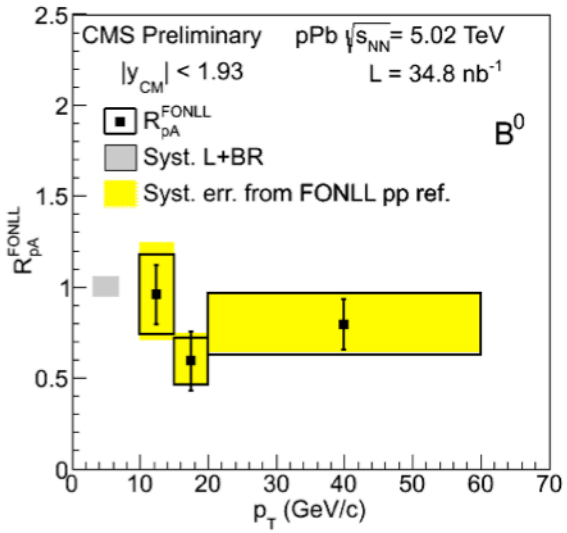
R_{pPb} for B meson

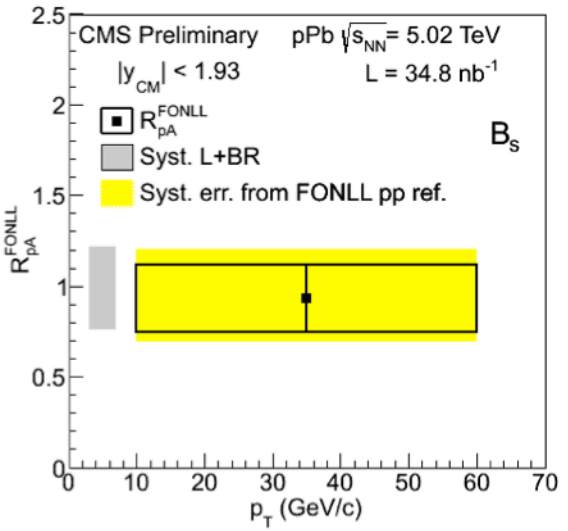
- B-meson reconstructed by combination of
  - J/ψ (decay to muon pair)
  - tracks (charged pion or kaon)

- CMSがp-Pb でのB (→ J/ψ+X)を測定
  - pp reference
    - FONLL 計算を使用
    - http://www.lpthe.jussieu.fr/~cacciari/fonll/fonllform.html
  - R_{pPb}はp_T > 10 GeV/c で1



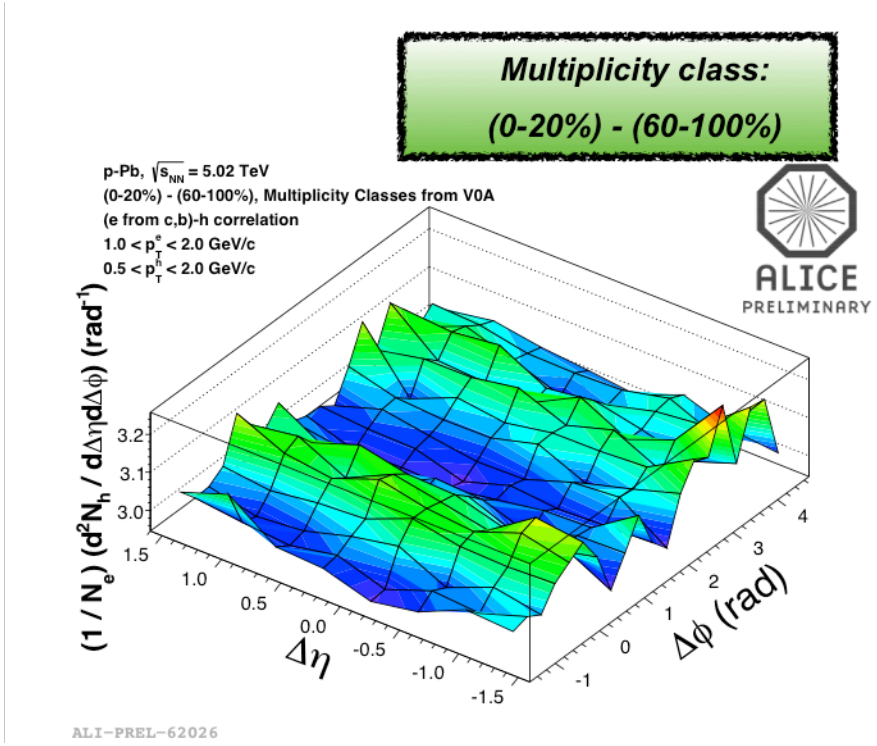


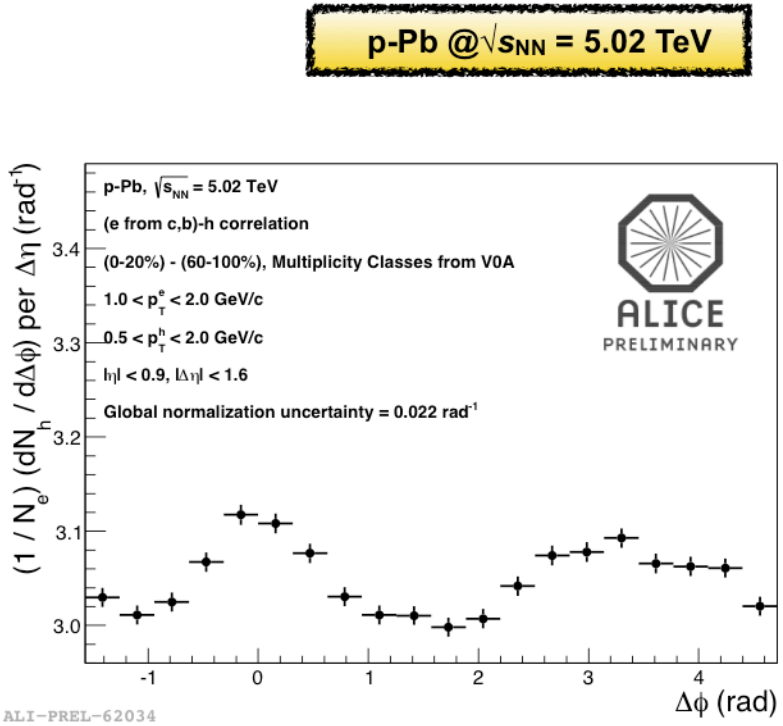




Double ridge for Heavy flavor electron

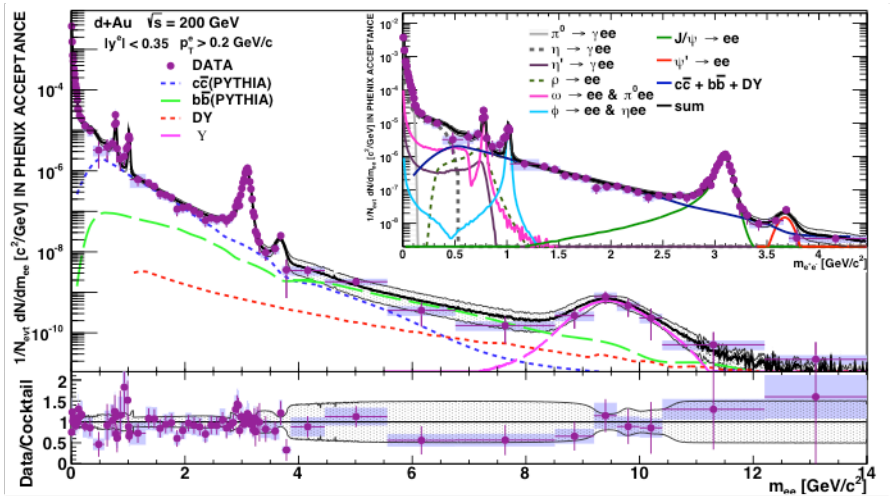
- Electron-hadron(from D, B) correlation
  - Double ridge structureを確認
  - CGC? Hydrodynamics?

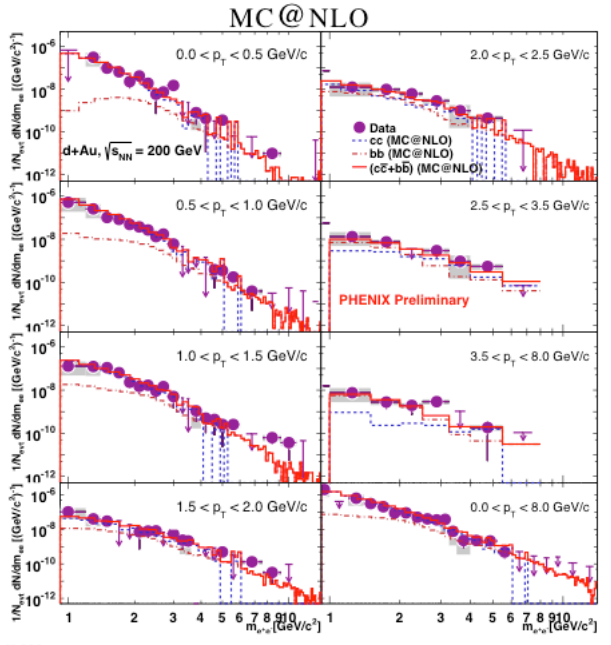




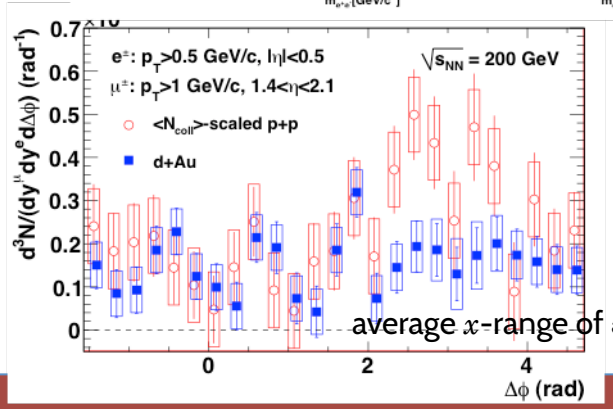
dilepton in d+Au at RHIC

- Dielectron
  - High mass, low mass high p_Tでbからの寄与がdominant
  - Pythia(CTEQ5L), MCNLO（CTEQ6L）で一致
    - $\sigma_{bb} = 3.4 \pm 0.28(stat) \pm 0.46(sys)\mu b$

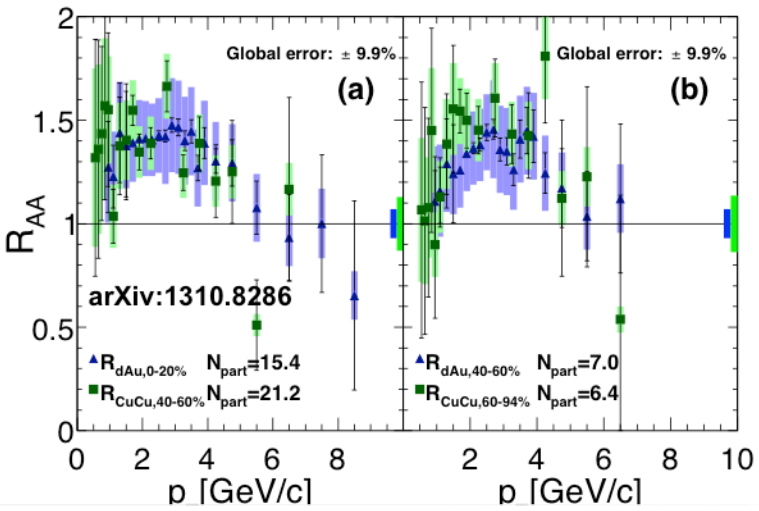


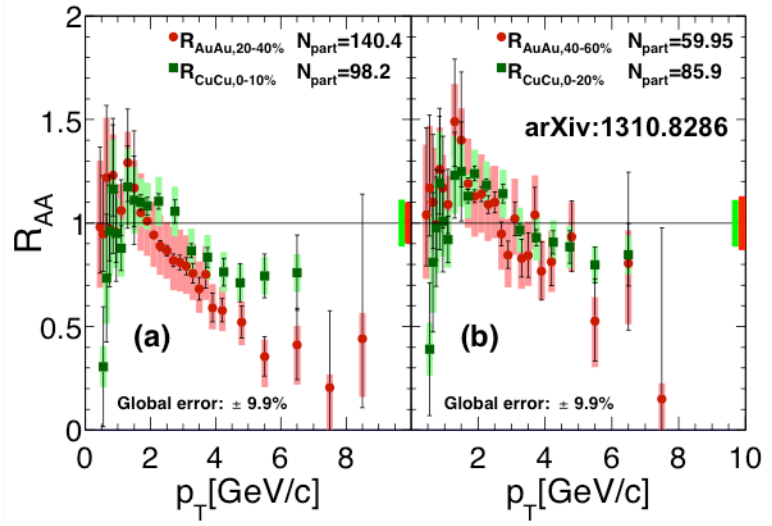


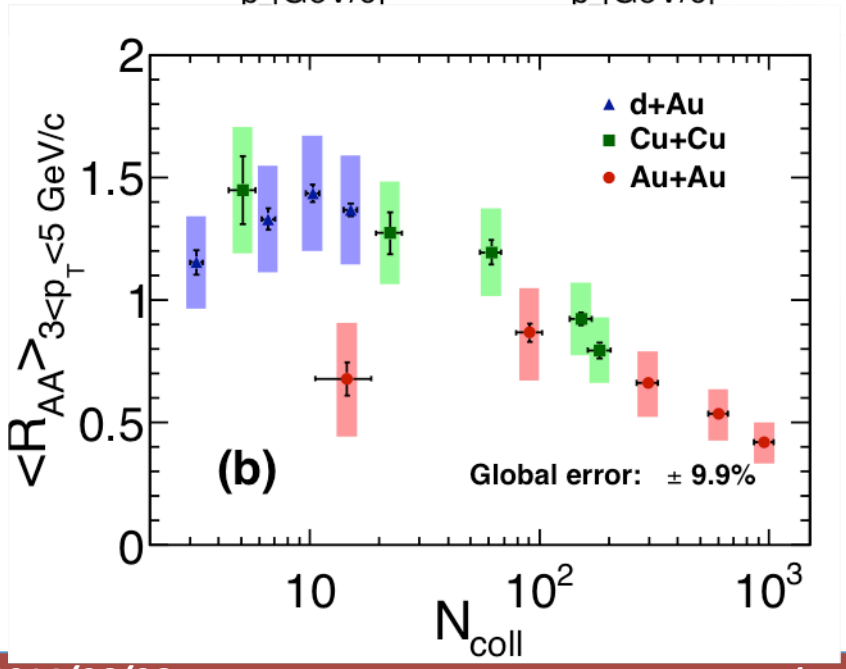
- e-μ correlation(central-forward)
  - Away sideの相関が消失
  - Gluon shadowing? Saturation?



HF R_{AA}: Au+Au vs. Cu+Cu





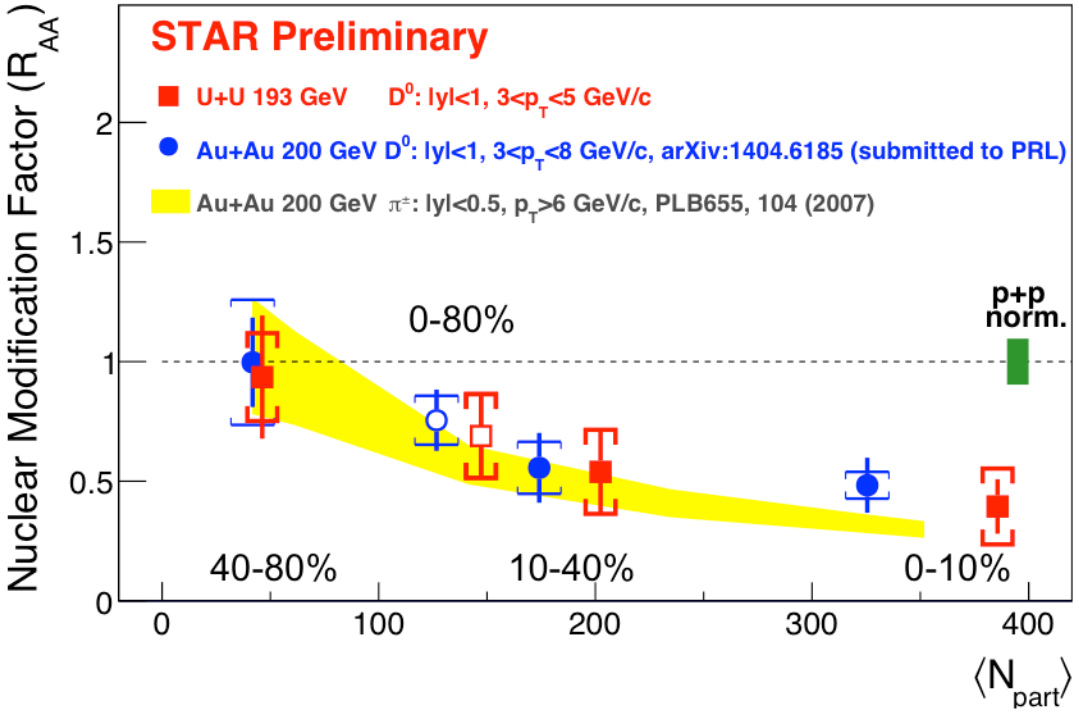


Cu+Cu@PHENIX

- Peripheral: enhancement
  ～central d+Au
- Central: suppression
  ～peripheral Au+Au

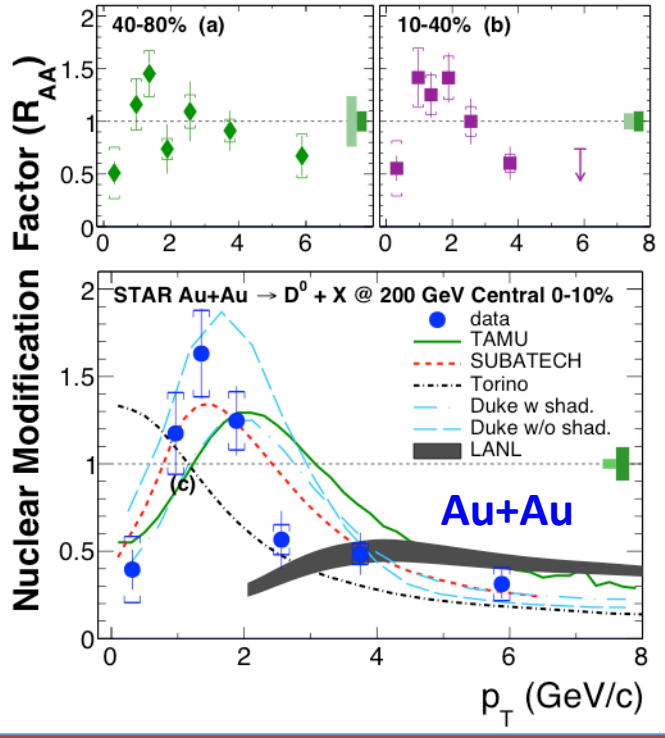
D meson R_{AA}: Au+Au vs. U+U

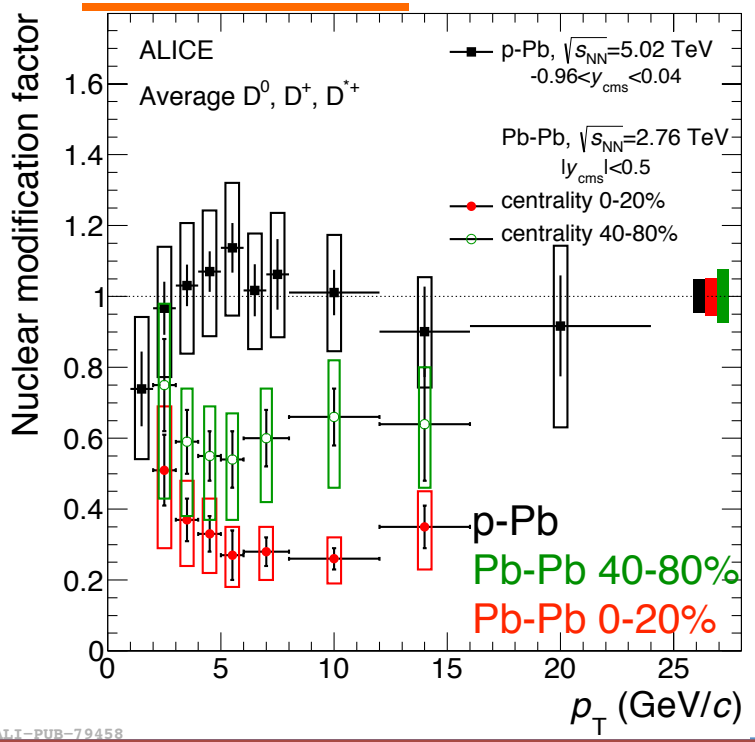
- U+U
  - tip-tipでAu+Auよりエネルギー密度20 %増加
  - Au+Auと誤差の範囲内で同様のcentrality 依存性



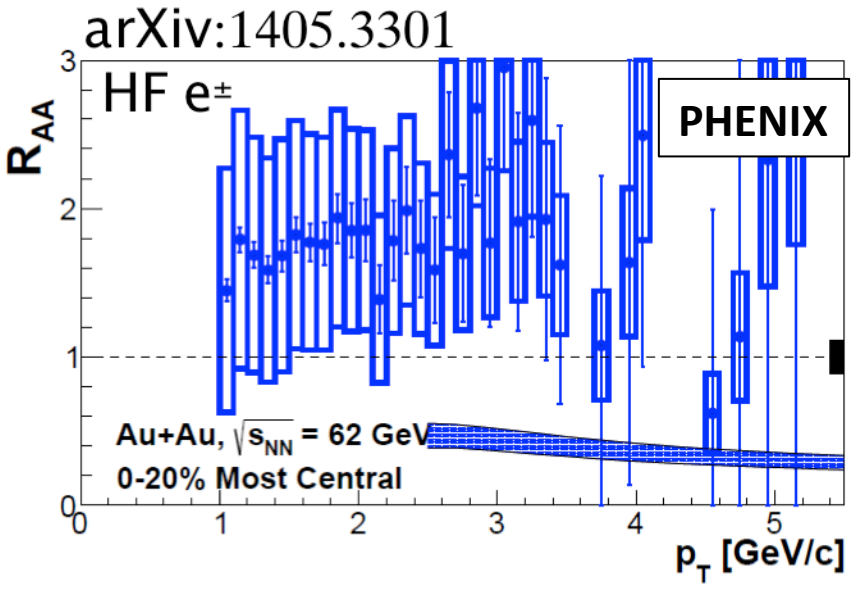
D meson R_{AA}: R_{AA} vs. p_T (RHIC & LHC)

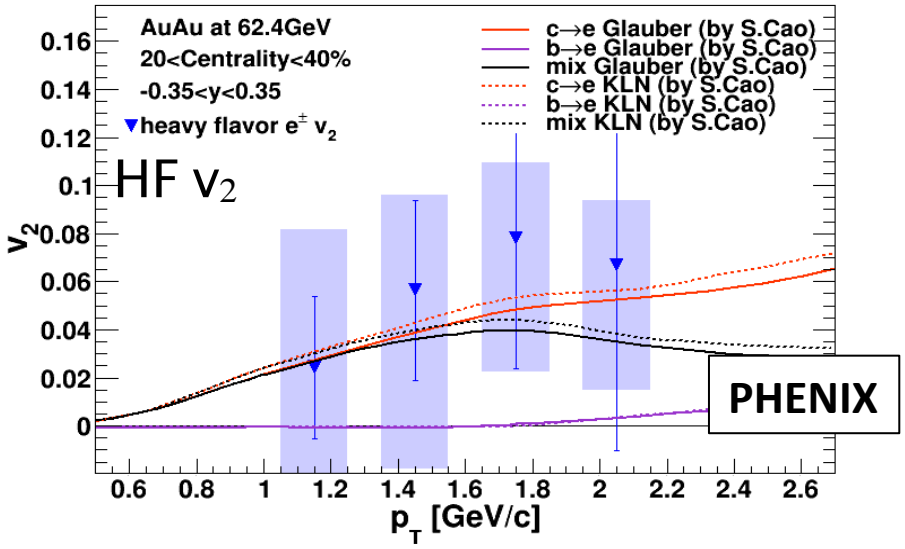
- Au+Au
  - High p_T でsuppression
  - Low p_Tでenhancement：recombination? Shadowingの効果？Radial flow?
- Pb-Pb
  - p-Pb に比べ明らかなsuppression→medium中でのenergy loss
  - Low p_Tでenhancementは見られない（RHICとは異なる振る舞い）



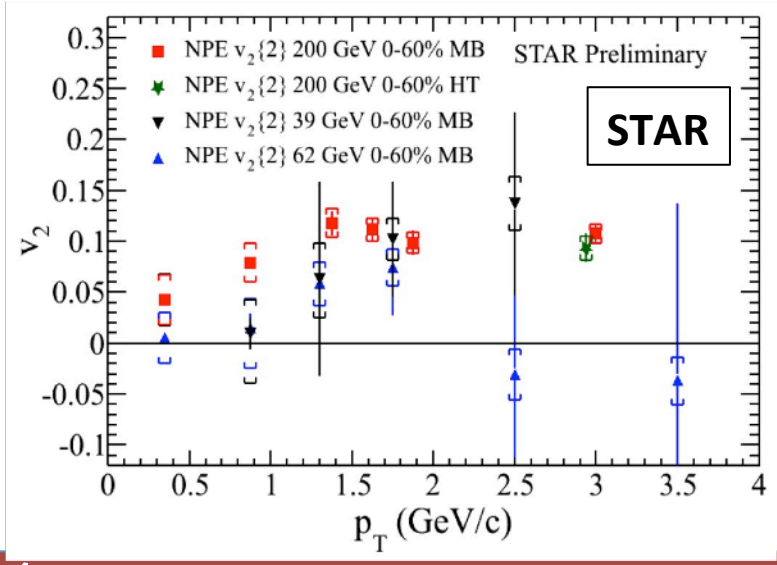


HF R_{AA} and v_2 vs. $\sqrt{s}$



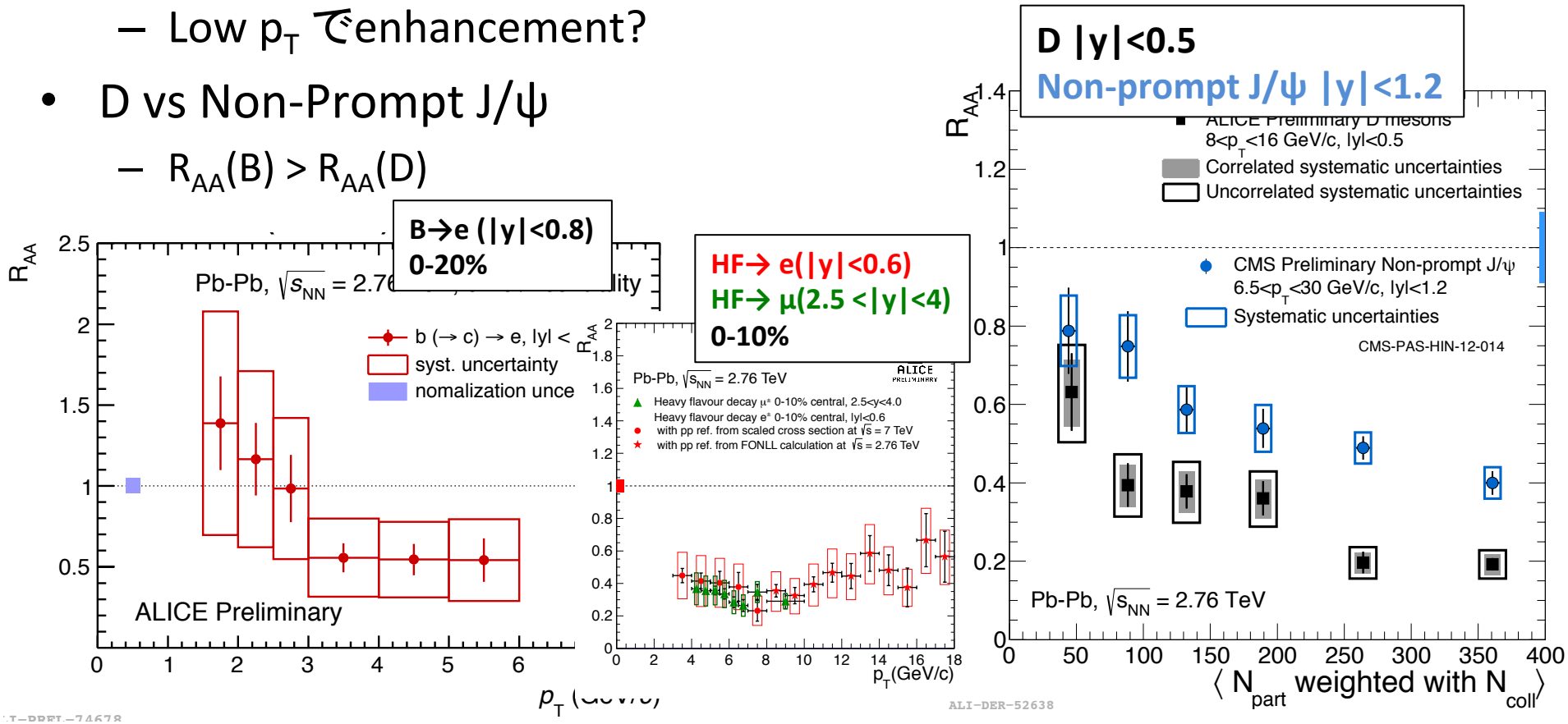


- R_{AA} enhancement
  - Energy lossとは矛盾
  - Light hadronではsuppression確認
- v_2
  - Low p_TでSTARではzero consistentか？
  - PHENIXではnon-zero?

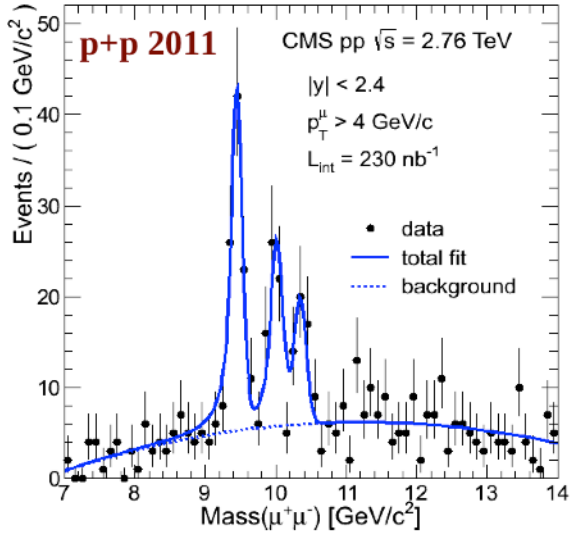


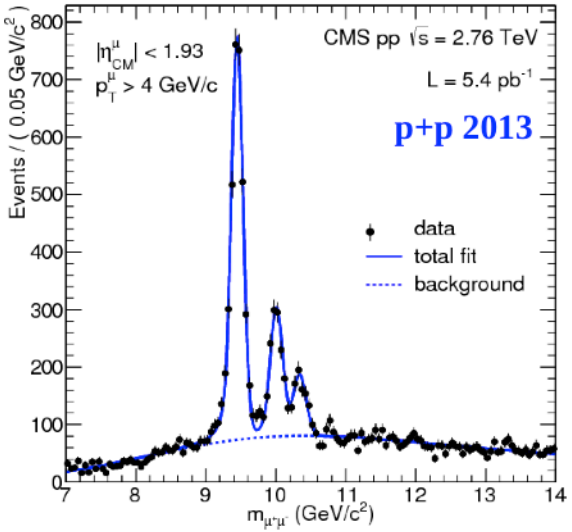
R_{AA} (B) AND R_{AA}(D)

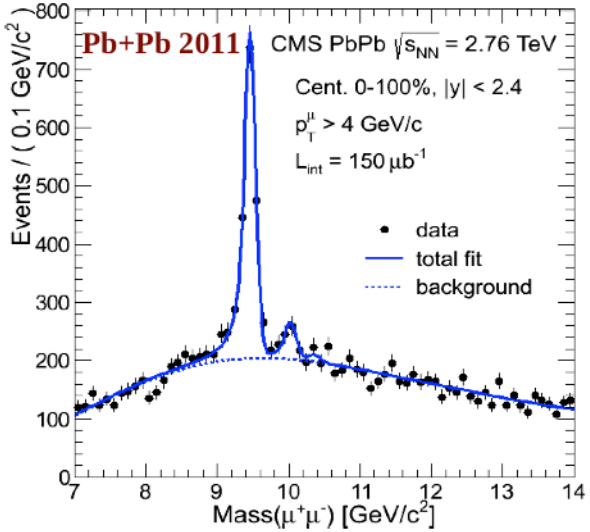
- B→e
  - Pb–Pb： p_T > 3 GeV/c でsuppresion（HF→eと同程度？）
  - Low p_T でenhancement?
- D vs Non-Prompt J/ψ
  - R_{AA}(B) > R_{AA}(D)

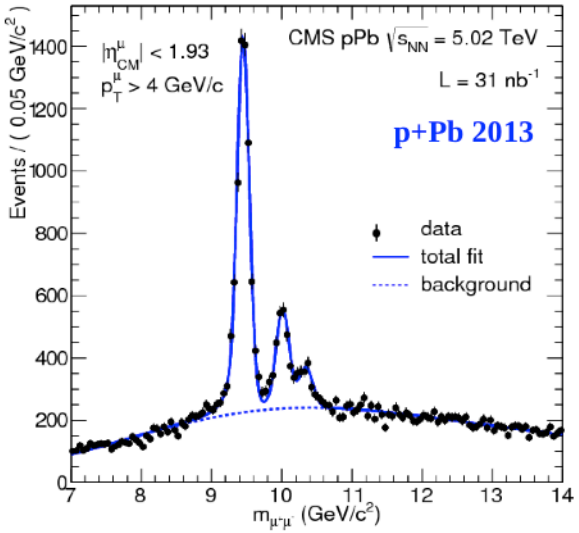


Quarkonia


p+p 2011
CMS pp √s = 2.76 TeV
|y| < 2.4
p_T^μ > 4 GeV/c
L_int = 230 nb^-1
data
total fit
background
Events / (0.1 GeV/c^2)
Mass(μ+μ-) [GeV/c^2]

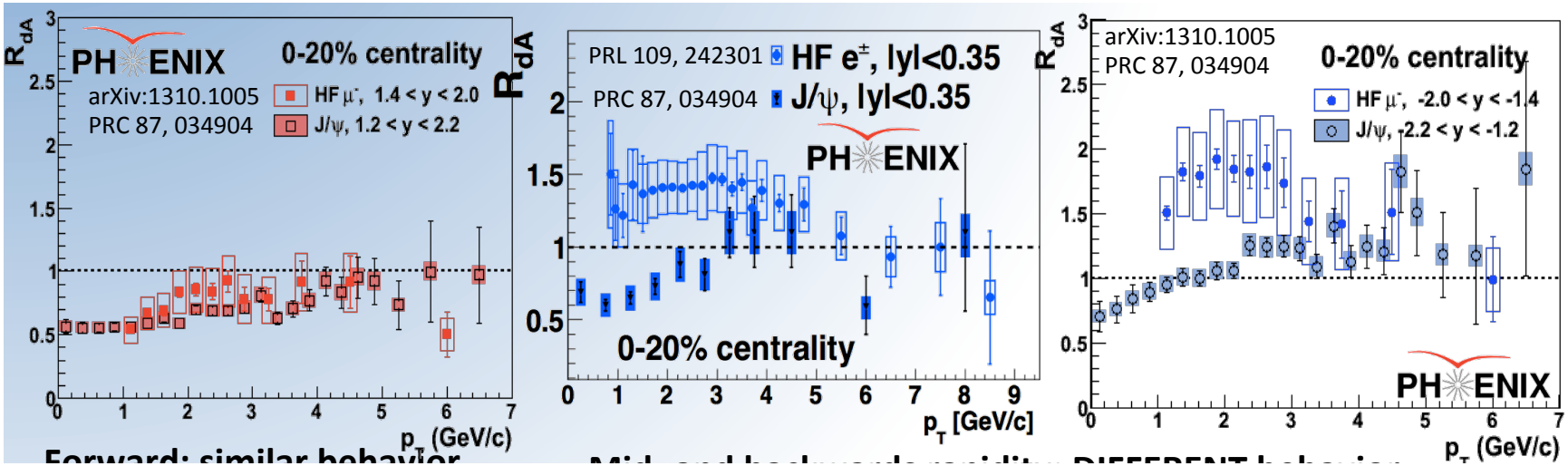

|η^μ_CM| < 1.93
p_T^μ > 4 GeV/c
CMS pp √s = 2.76 TeV
L = 5.4 pb^-1
p+p 2013
data
total fit
background
Events / (0.05 GeV/c^2)
m_μ+μ- (GeV/c^2)


Pb+Pb 2011
CMS PbPb √s_NN = 2.76 TeV
Cent. 0-100%, |y| < 2.4
p_T^μ > 4 GeV/c
L_int = 150 μb^-1
data
total fit
background
Events / (0.1 GeV/c^2)
Mass(μ+μ-) [GeV/c^2]

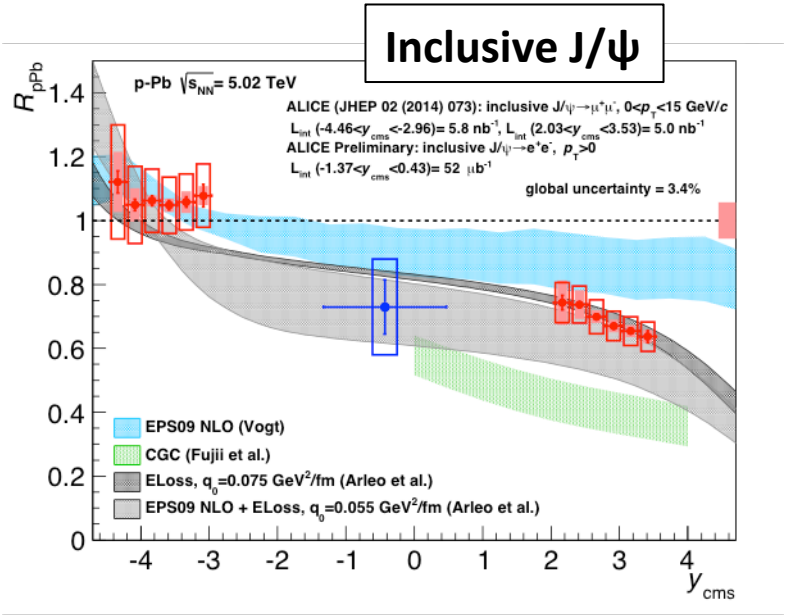

|η^μ_CM| < 1.93
p_T^μ > 4 GeV/c
CMS pPb √s_NN = 5.02 TeV
L = 31 nb^-1
p+Pb 2013
data
total fit
background
Events / (0.05 GeV/c^2)
m_μ+μ- (GeV/c^2)

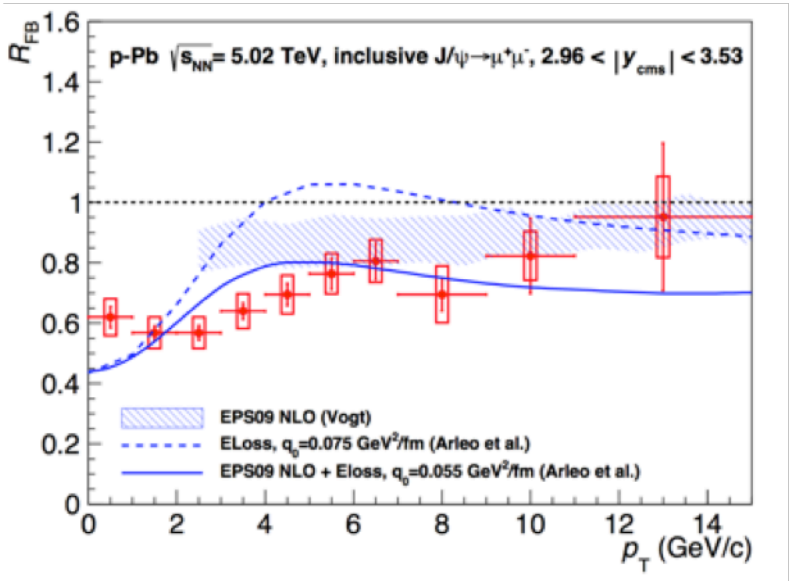
J/ψ vs. open heavy flavor in d+Au

- Forward
  - J/ψ, open heavy flavorで同程度のsuppression
- mid-rapidity, Backward
  - Open heavy flavorのenhancement(cronin?)に対しJ/ψではenhancementは確認されず



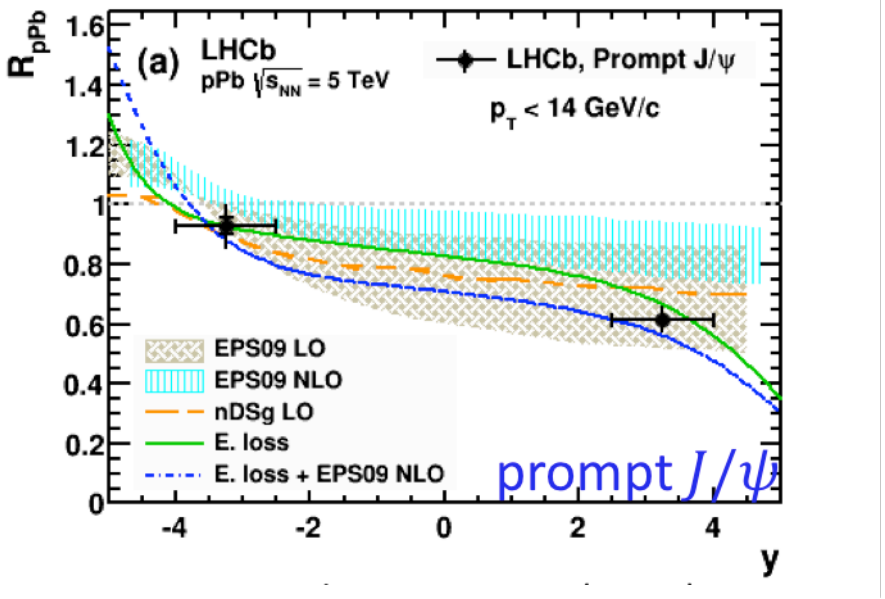
J/ψ in p-Pb@ALICE

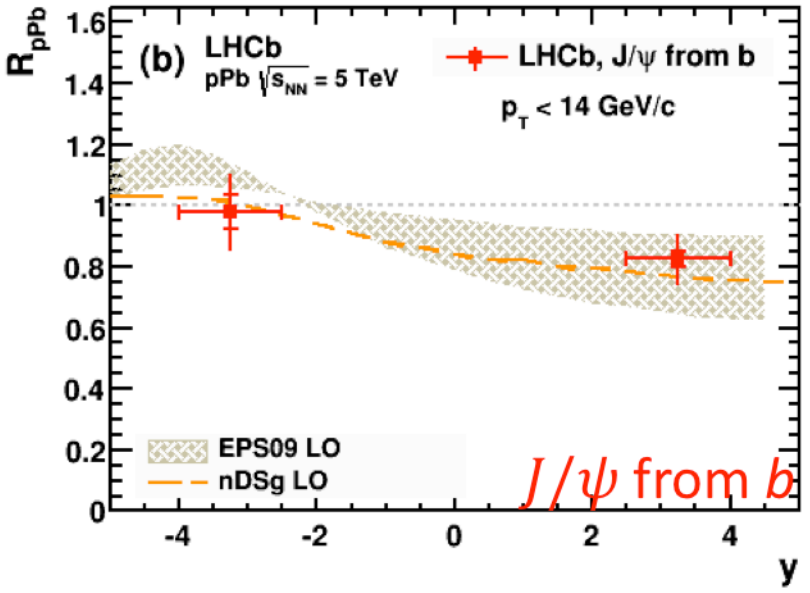




- rapidity依存性
  - Forwardでsuppression、Backwardでenhancement
  - Energy lossを含む模型(Arleo.et.al) が最も結果を再現
- $R_{FB,}$ p_T 依存性
  - Low p_Tで振る舞いは再現できず？

J/ψ in p-Pb@LHCb

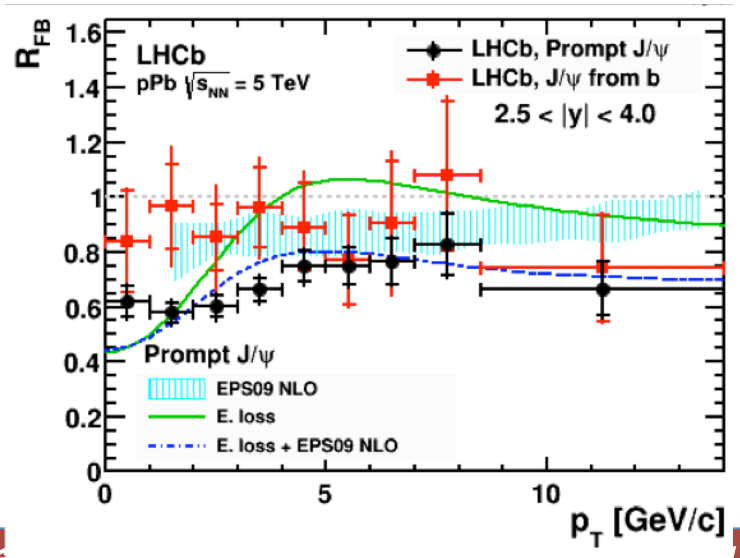




Pseudo proper timeによりPrompt J/ψ とNon-prompt J/psiを選別

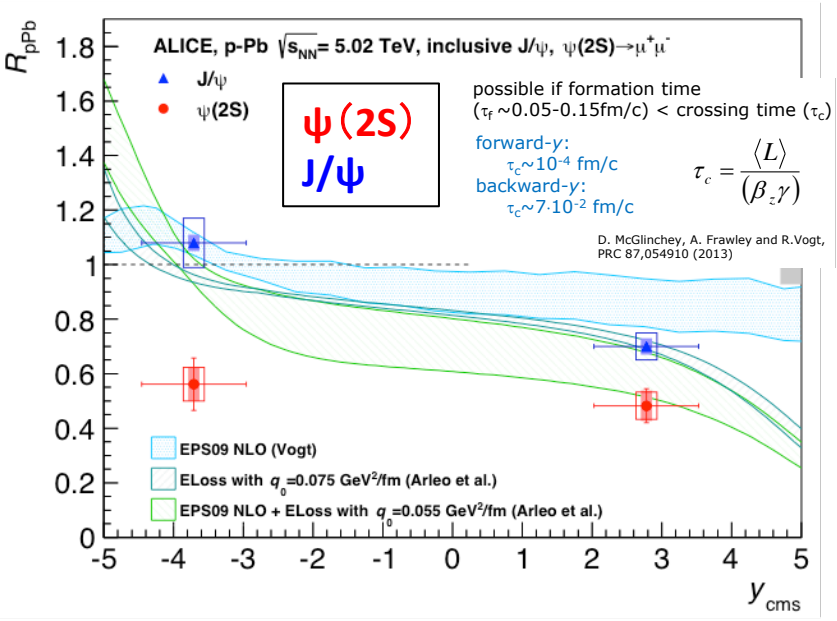
Prompt J/ψ
– ALICEの結果とほぼ一致

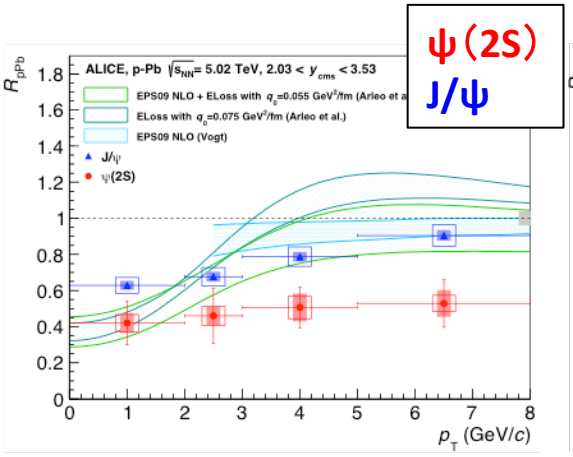
Non-Prompt J/ψ
– pQCD計算とコンシステント

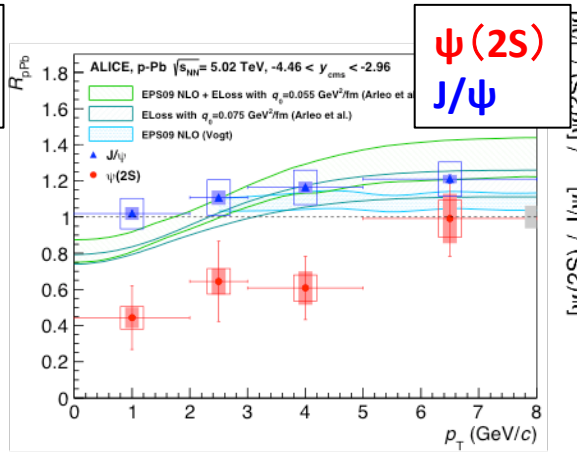


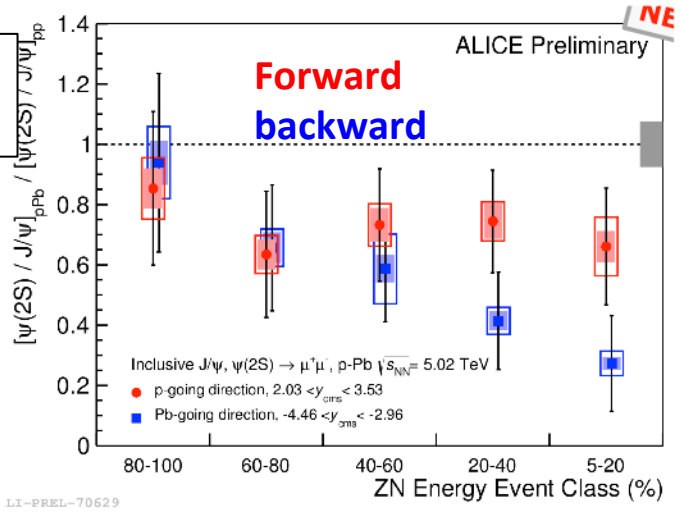
ψ(2S) in p-Pb

- Backward でも抑制確認
  - PHENIX(mid rapidity)でも確認
  - Initial state effectsはJ/ψと変わらない
  - 核内でのbreakupは考えにくい ($\tau_c < \tau_{form}$)
  - Co-mover hadronによるbreakup?
- J/ψとのdouble ratio
  - Forward suppressionに比べbackwardでより強いcentrality 依存性

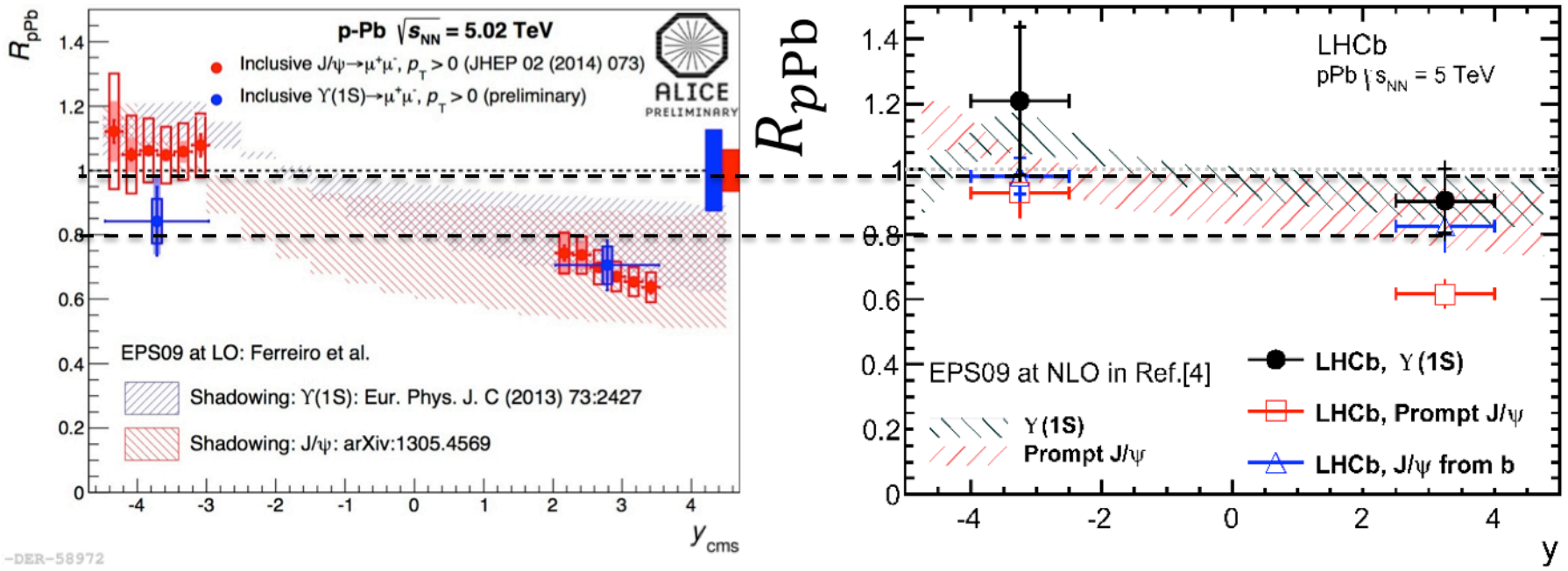








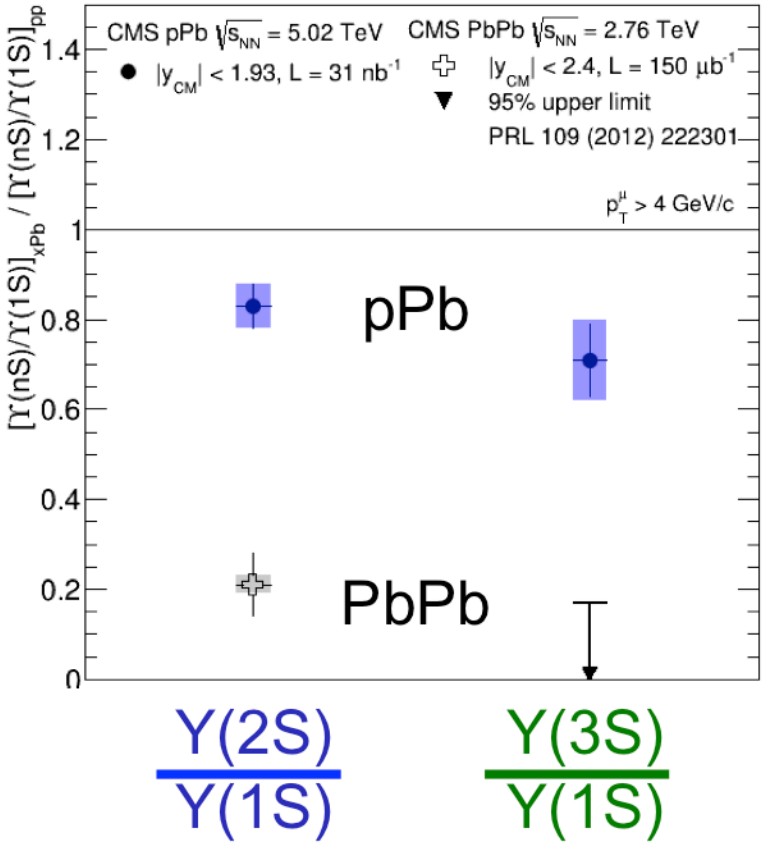
Υ(1S) in p-Pb

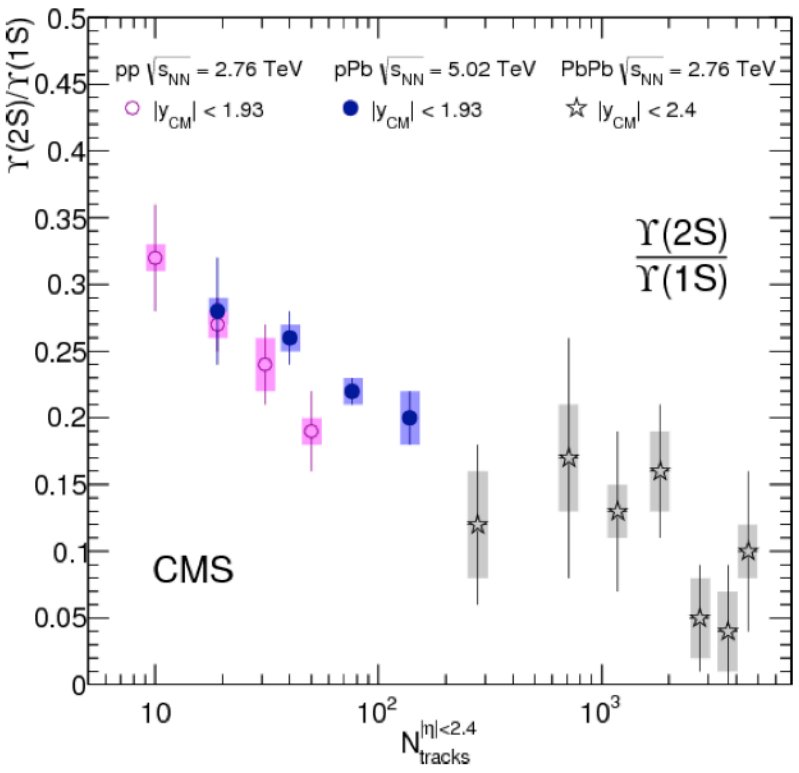


- ALICEとLHCbでinconsistent?
  - 誤差の範囲内では一致？
  - ALICE：forwardでJ/ψ程度のsuppression，backwardでも依然suppression
  - LHCb:J/ψに比べsuppressionが少ない、backwardでenhancement
  - ppのInterpolation の仕方が異なる

Y(nS) in p-Pb

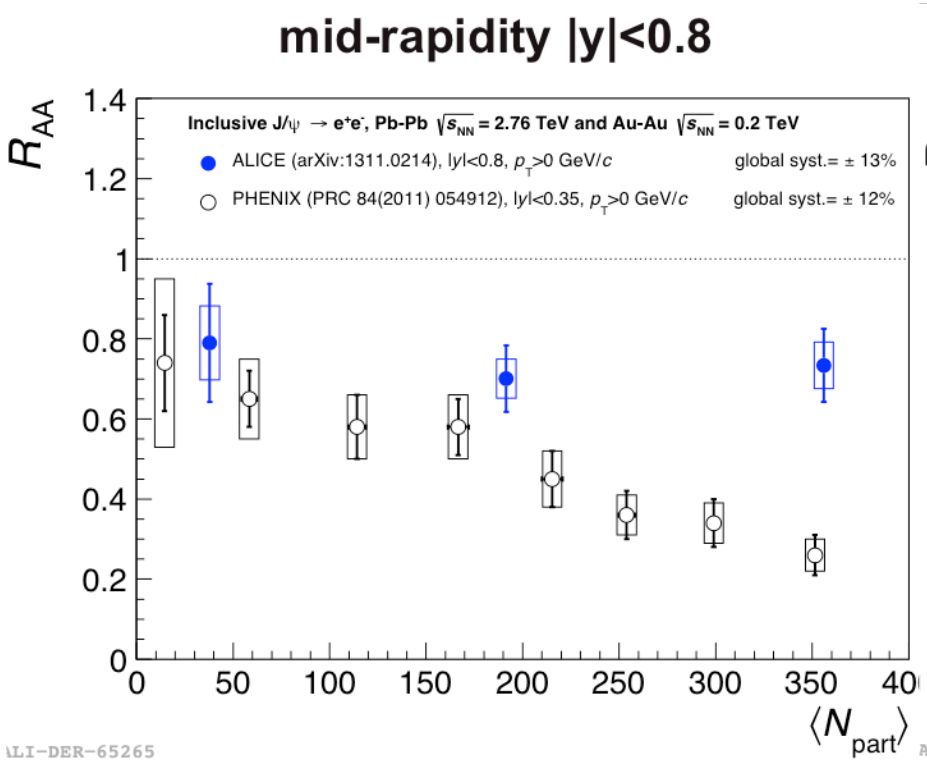
- Pb-Pbほどのsuppressionは見られず
  - Pb-Pbのsuppressionはsequential melting？
  - 定性的にはhigh multiplicityでより強いsuppression

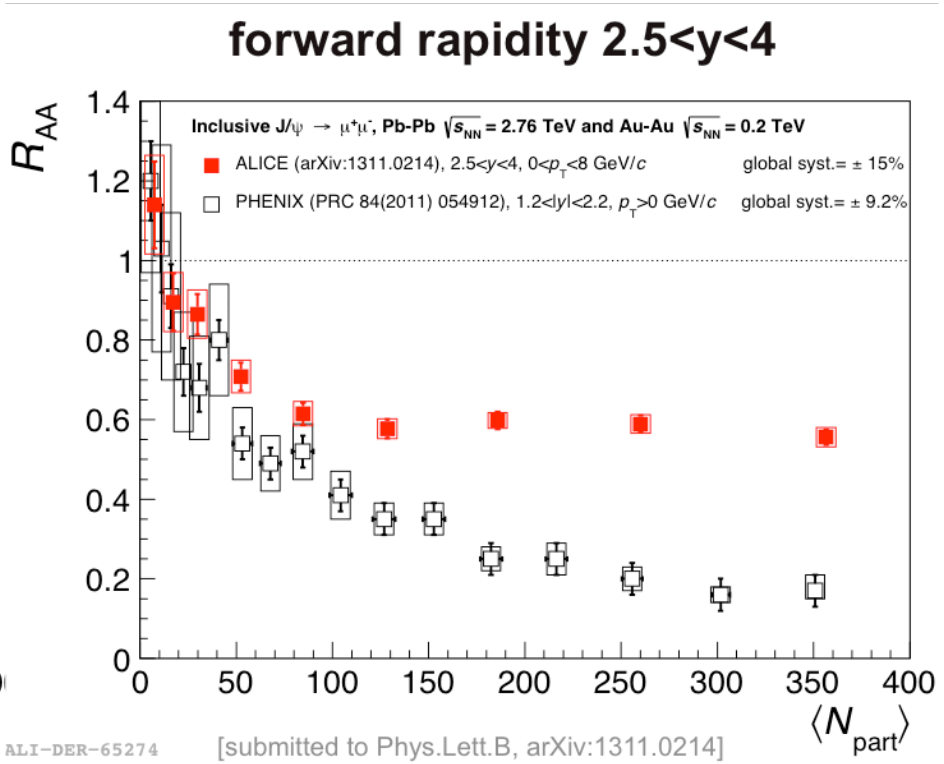




J/ψ R_{AA}: centrality dependence

- ALICEとPHENIXの比較（inclusive J/ψ）
  - LHCではRHICほど抑制されていない
  - LHCではrecombinationが効いている

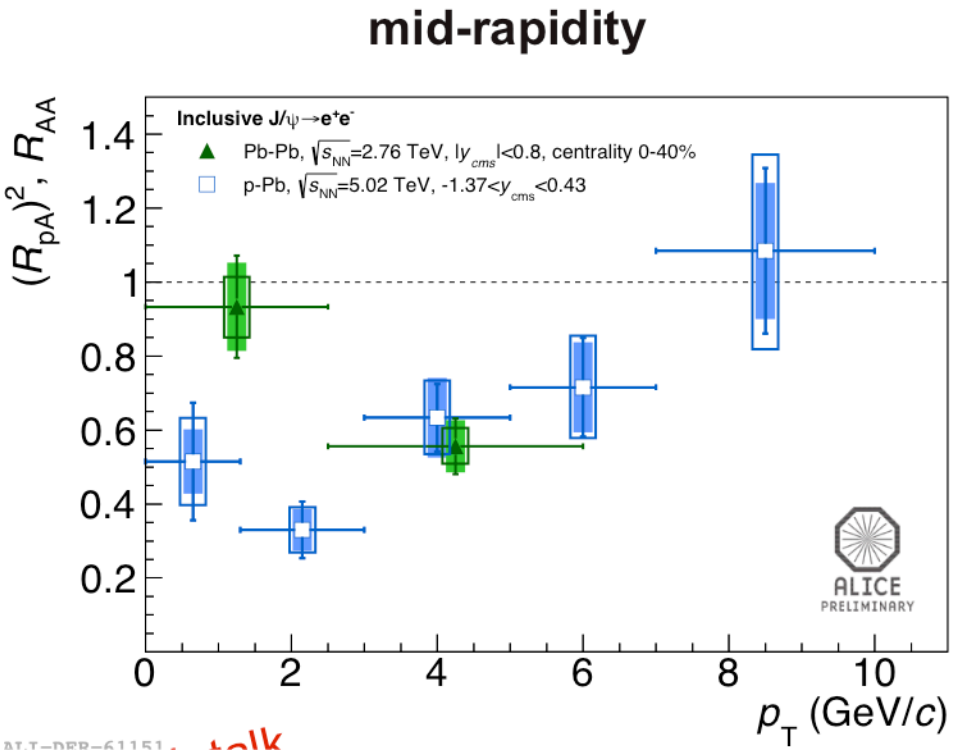


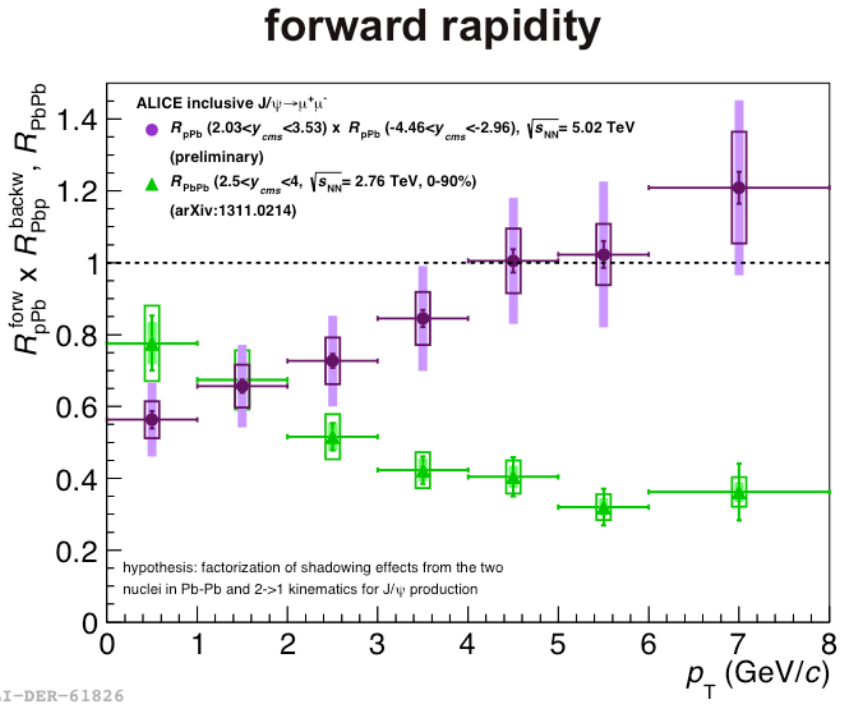


[submitted to Phys.Lett.B, arXiv:1311.0214]

J/ψ R_{AA}: comparison to R_{pPb}

- Low p_Tでenhancement
  - Recombinationとconsistent
- High p_Tではsuppression



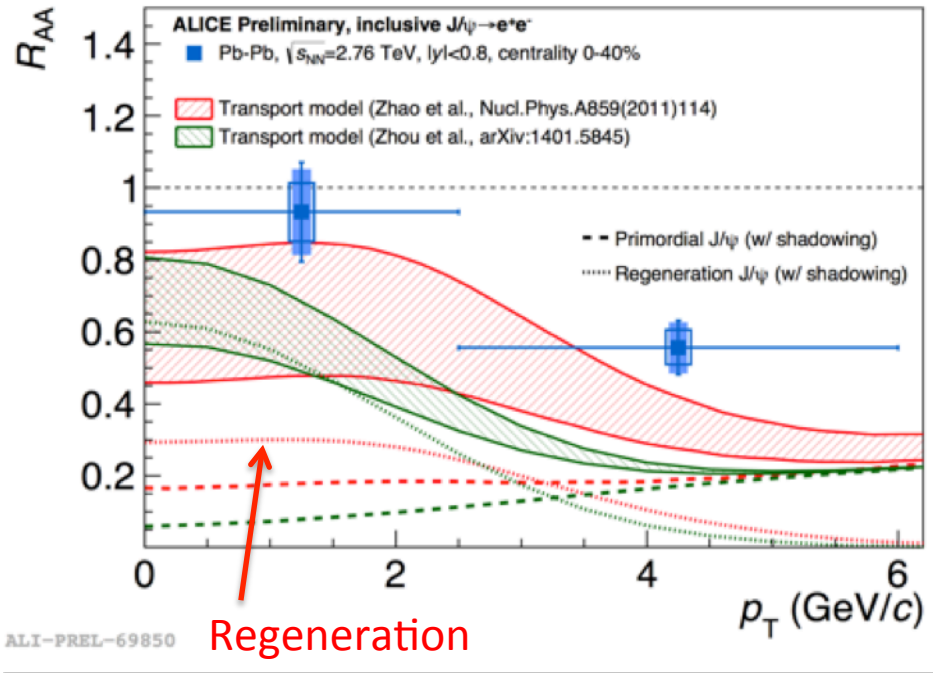


LI-DER-61826

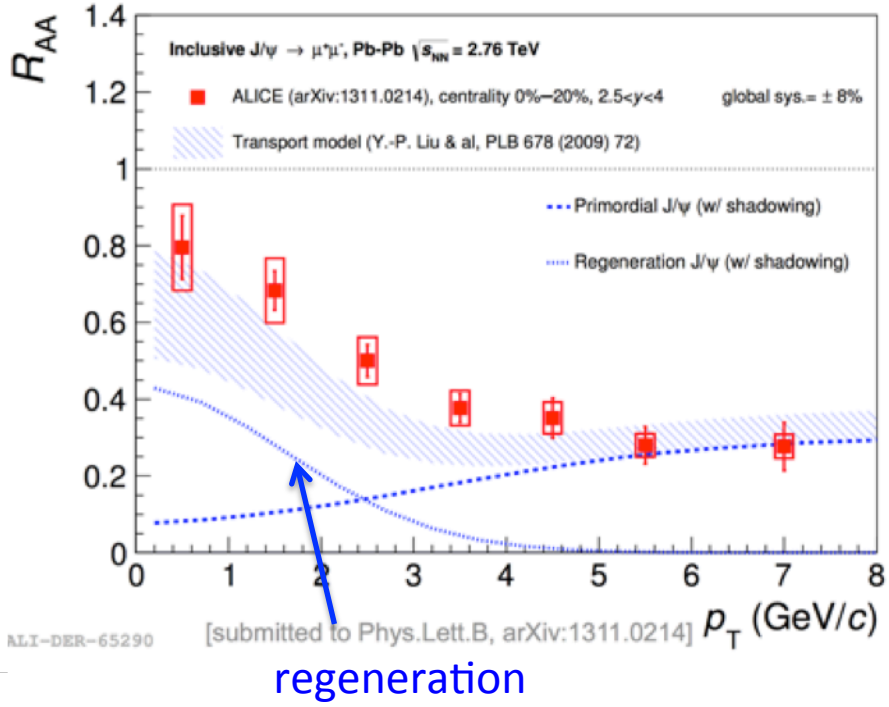
J/ψ R_{AA}: comparison to models

- Regeneration模型が実験結果を再現

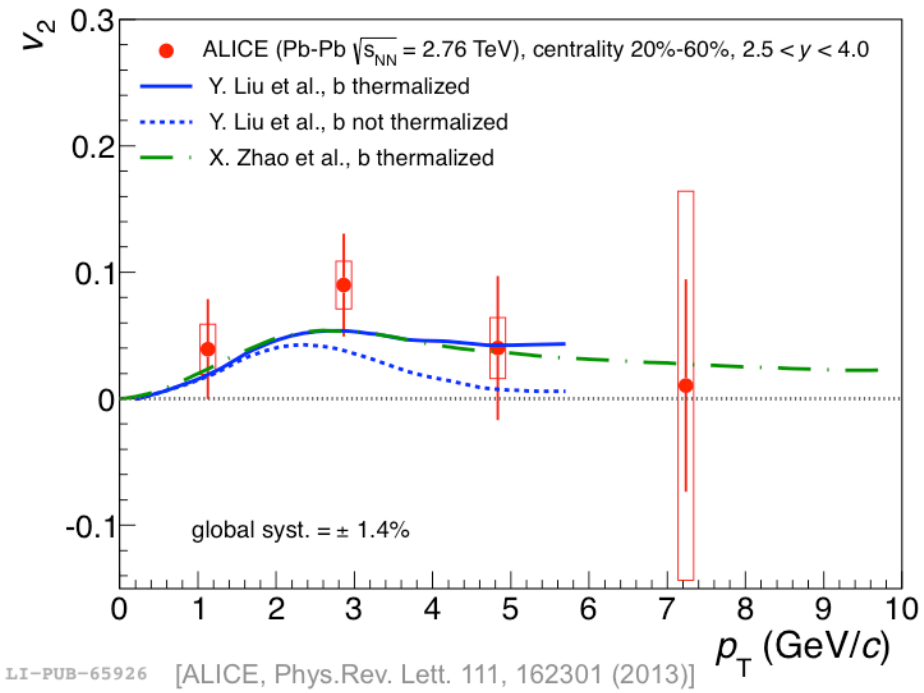
mid-rapidity |y|<0.8



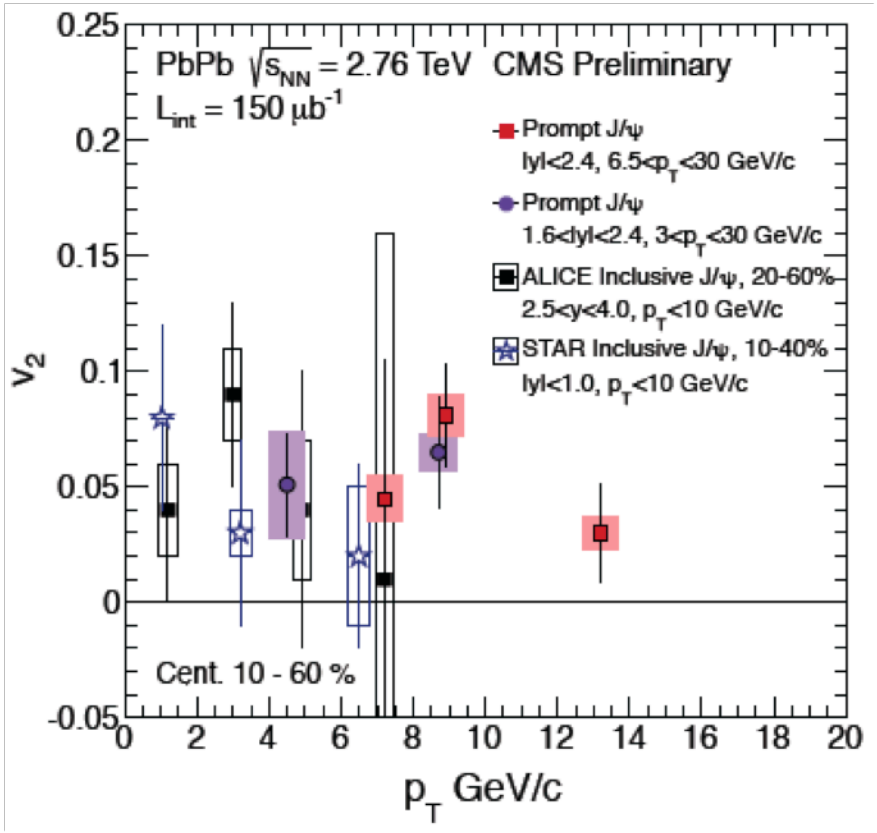
Forward rapidity 2.5 < y < 4



J/ψ v2



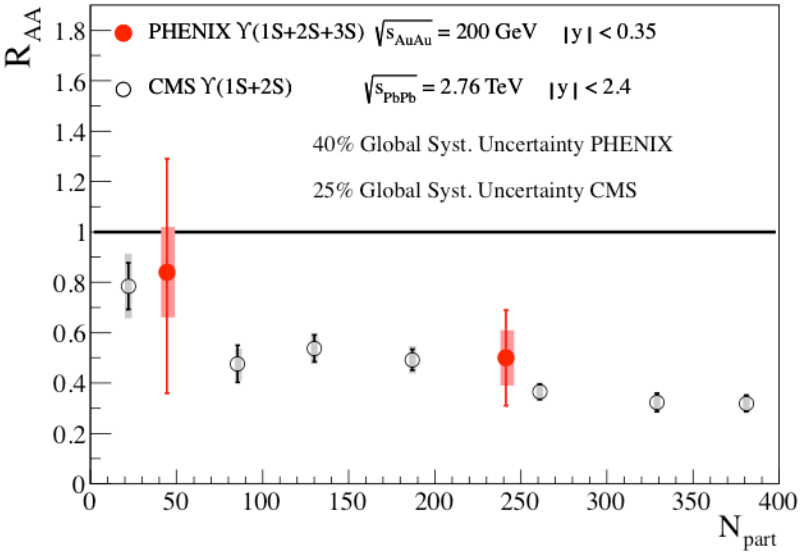
LI-PUB-65926 [ALICE, Phys.Rev. Lett. 111, 162301 (2013)]

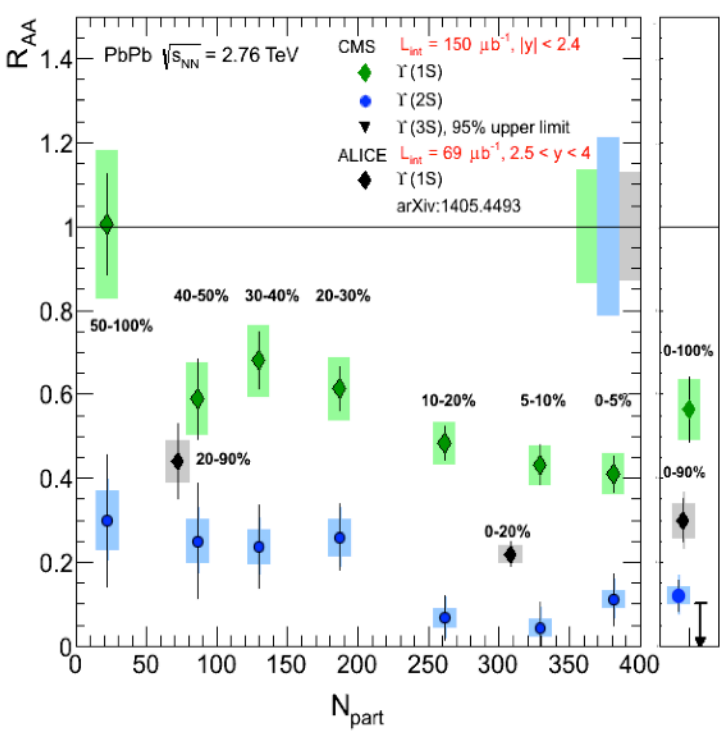


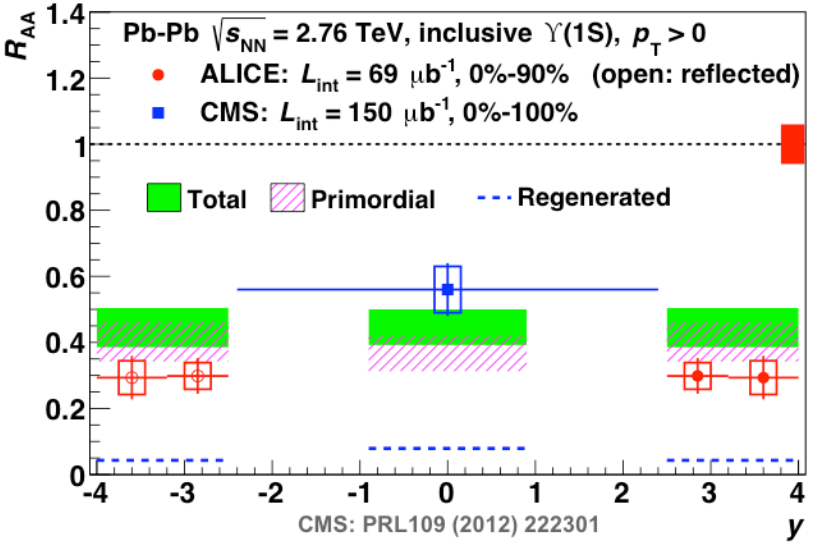
- ALICE
  - Non-zero v_2確認
  - Recombinationとconsistent
- CMS
  - High p_T J/ψでもnon-zero v_2(～v_{2had}～v_{2D}) : Path length依存性？

Bottomonium R_{AA}

- RHIC, LHCともにmid rapidity で同程度のsuppressionを確認
- LHCでラピディティ依存性を確認







Summary

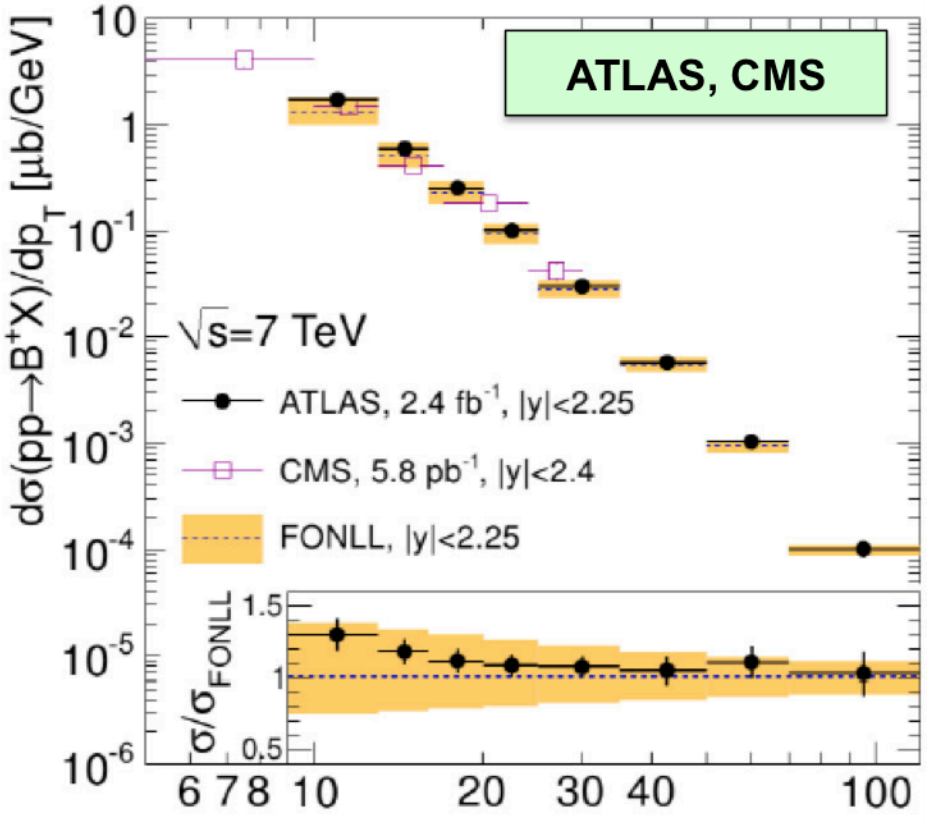
p-Aと重イオン衝突の結果の比較が可能
→今まで見えていた現象の解釈
Low energy, p/d-A自身についても興味深い結果

- Open heavy flavor
  - p-p Multiplicity dependence: Multiple parton interaction?
  - R_{pPb}: 原子核効果見られず-> R_{AA} suppression はenergy loss
  - Double-ridge in p-Pb: CGC? Hydro?
  - energy dependence: enhancement, nonzero v_2 at √s=64 GeV
  - $R_{AA}(B) > R_{AA}(D)$
- Quarkonium
  - ψ(2S) suppression at backward→ co-mover breakup?
  - J/ψ R_{pPb} vs R_{AA}: enhancement at low p_T → regeneration
  - High p_T J/ψ v_2
  - Y(nS)/Y(1S) in p-Pb: Pb-Pbほどのsuppression見られず→Sequential melting
  - Y R_{AA}: rapidity 依存性?

Back up

B meson in p-p

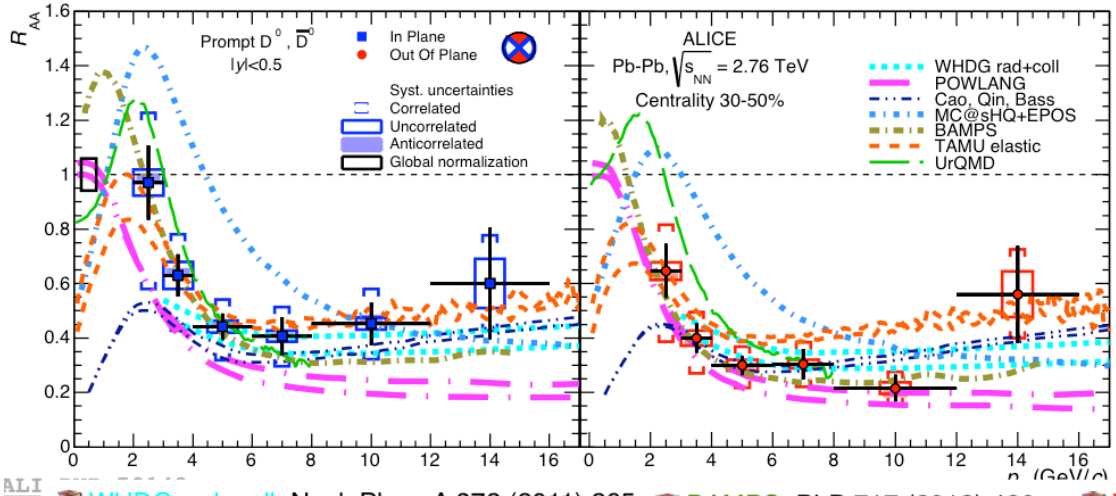
- FONLL 計算



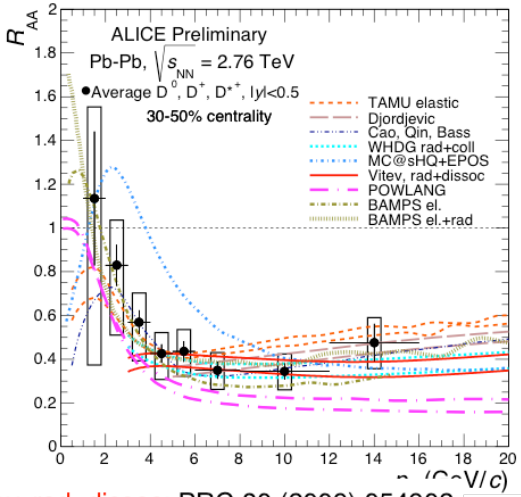
Model constraint

D⁰ R_{AA} (30-50%)

In-plane Out-of-plane



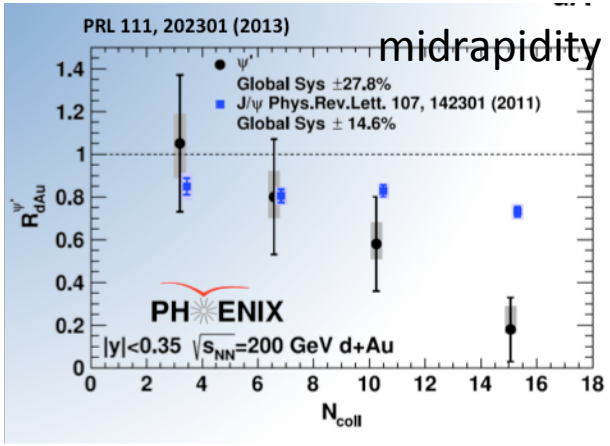
Average R_{AA} (30-50%)

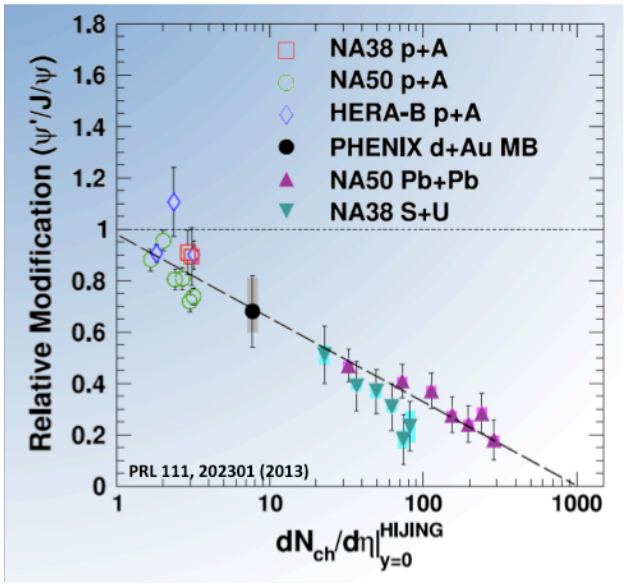


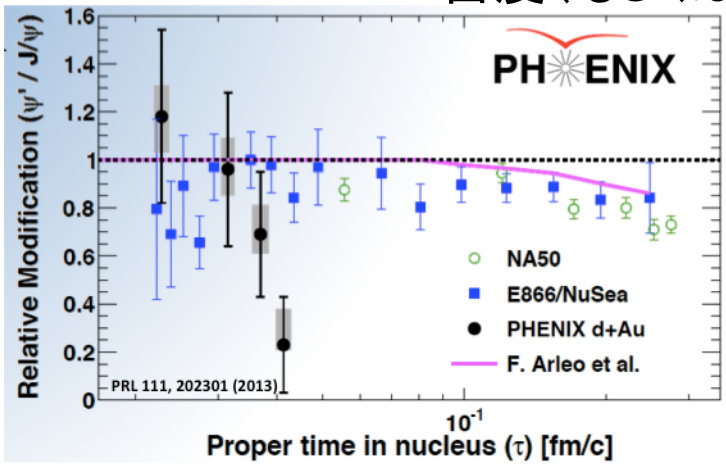
WHDG rad+coll: Nucl. Phys. A 872 (2011) 265
POWLANG: JPG 38 (2011) 124144
Cao, Qin, Bass: PRC 88 (2013) 044907
MC@sHQ+EPOS: PRC 89 (2014) 014905
BAMPS: PLB 717 (2012) 430
TAMU elastic: arXiv:1401.3817
UrQMD: J. Phys. Conf. Ser. 426 (2013) 012032
Djordjevic: arXiv:1307.4098
Vitev, rad+dissoc: PRC 80 (2009) 054902

ψ'@RHIC

- J/ψに比べcentrality が大きいところでで強いsuppression
- Crossing timeは十分短い
  - τ_{form}～0.05-0.15fm/s
  - Inside breakup は考えにくい
  - Co-mover によるbreakup?
- Multiplicity 依存性
  - Co-mover hadron密度（もしくは

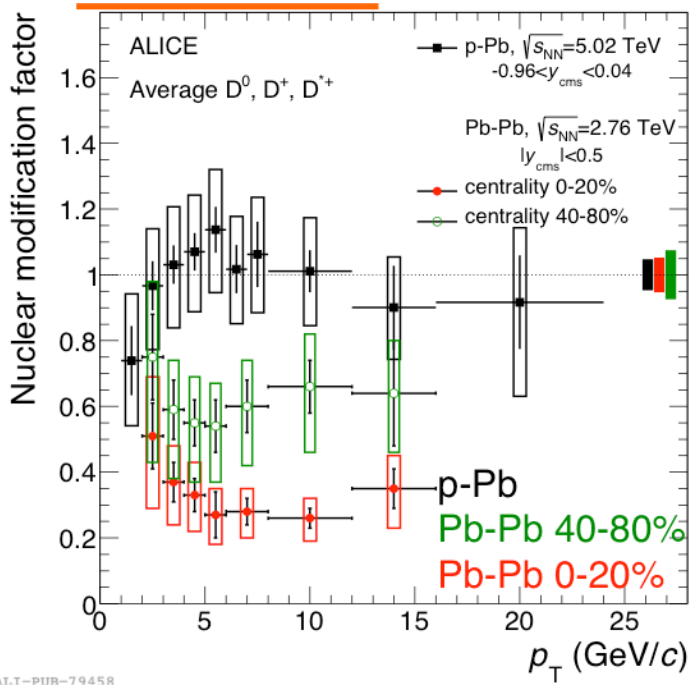


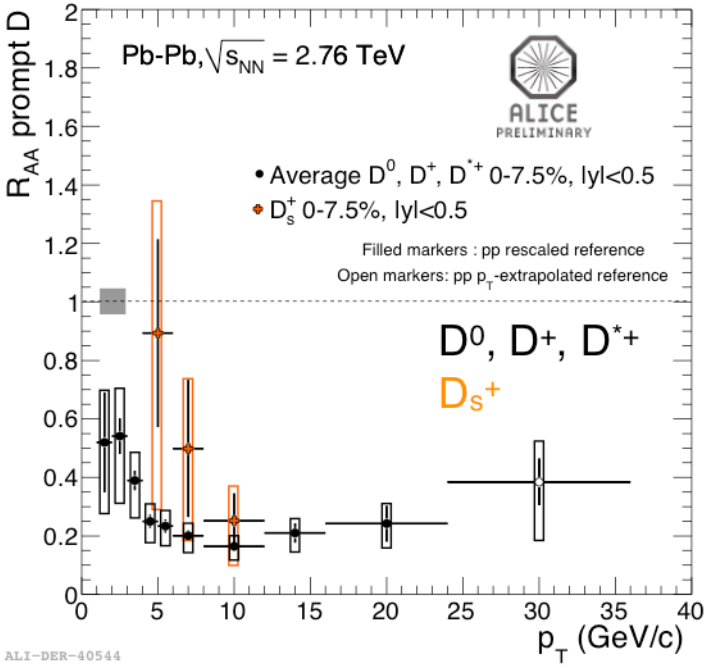




D meson R_{AA}@LHC

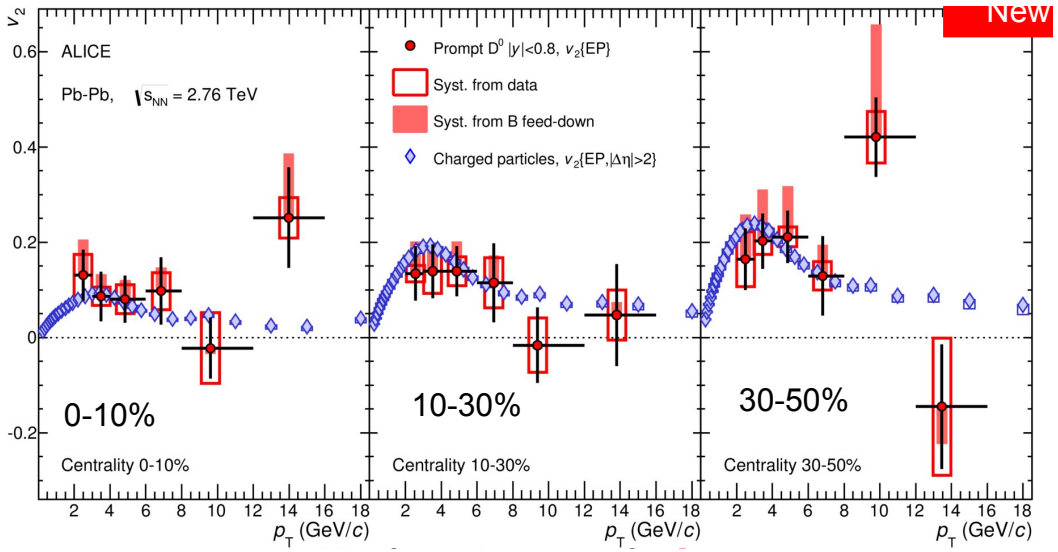
- R_{pPb}に比べ明らかなsuppression
  - medium中でのenergy lossによるもの
- D_S測定

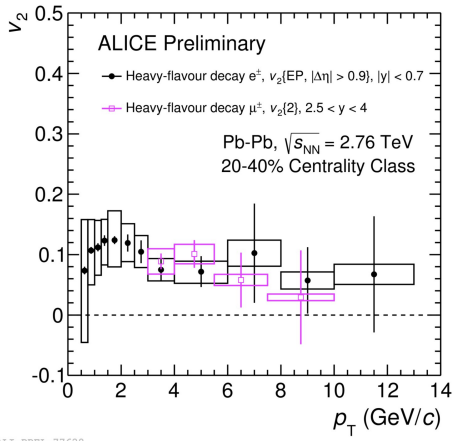


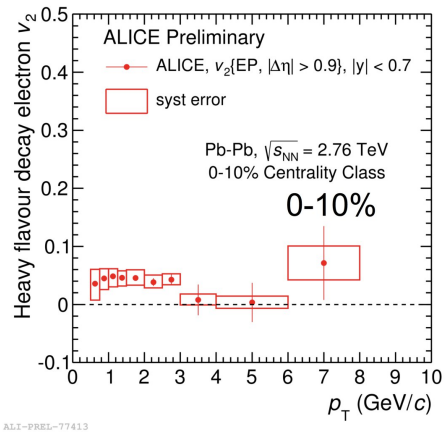


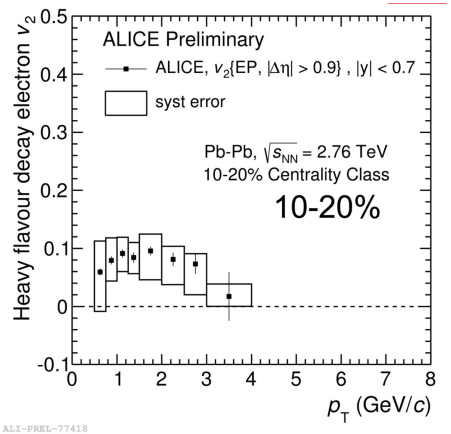
D meson flow

- Non-zero v2を確認
  - p_T > 2 GeV/cでcharged hadron と同程度
  - Single electron/muonでもv_2を確認
- Charm quarkの熱平衡化?

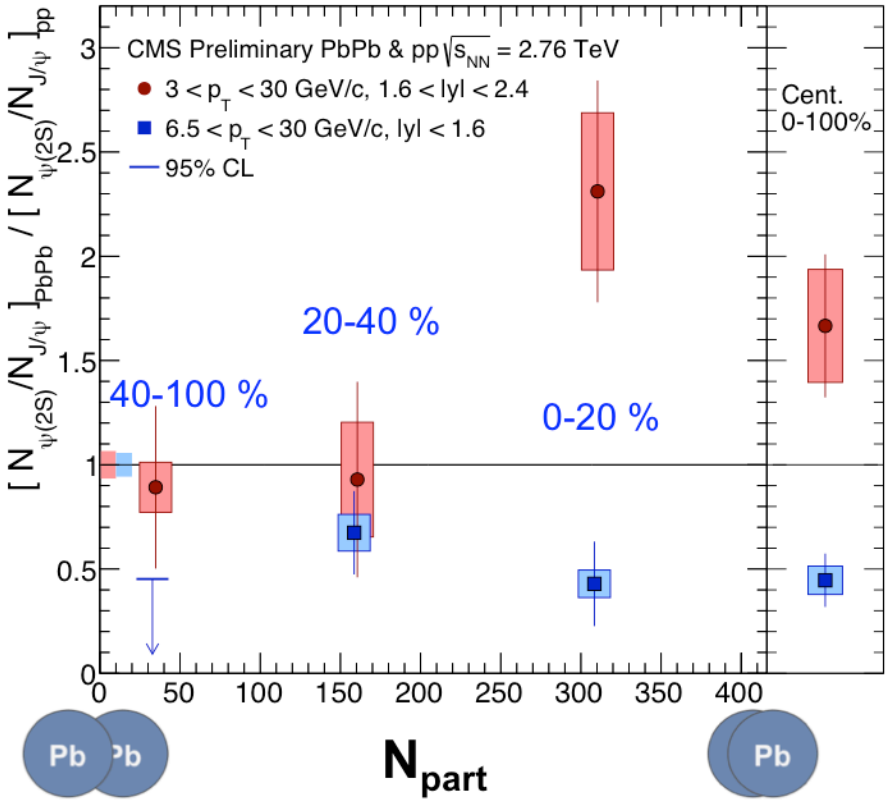








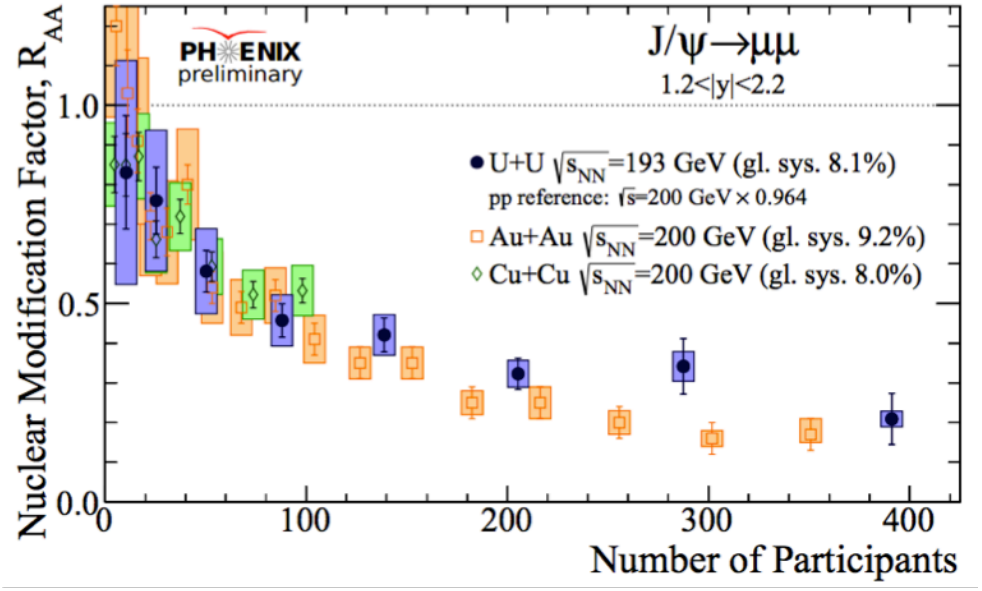
ψ(2S):PbPb



- High p_T suppression
  - Melting
- Inclusive ψ(2S)
  - Recombination と consistent

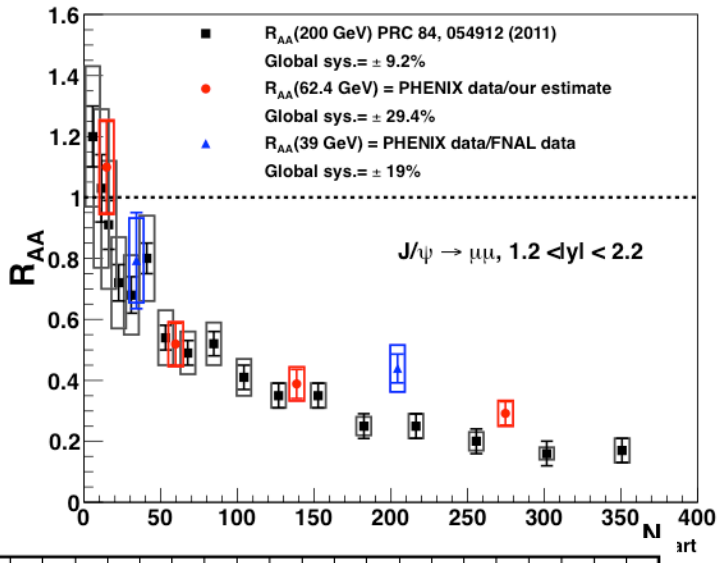
J/ψ System size依存性

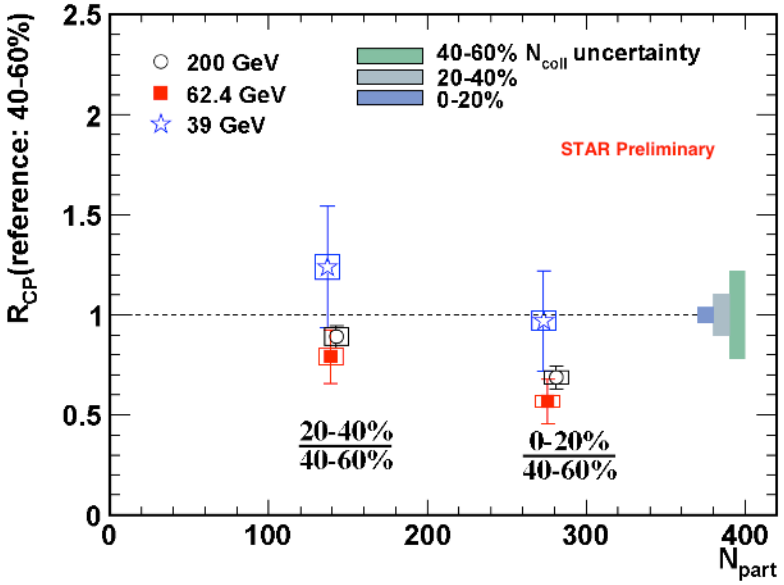
- 緩やかなsuppression傾向
- 核種依存性は見られず

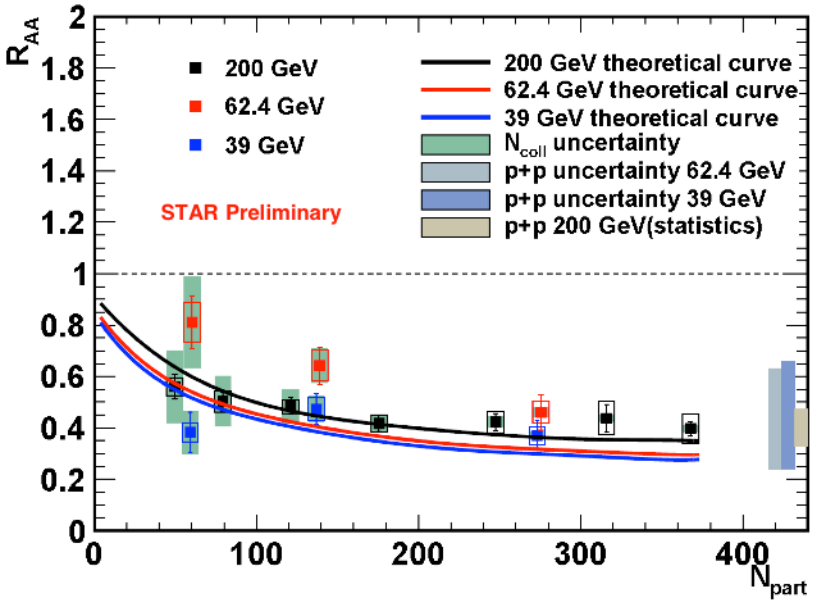


J/ψ at low energy

- STAR PHENIXともにLow energy でも suppression を確認
- 200 GeVが最も顕著なsuppression
  - Recombination modelと逆の傾向





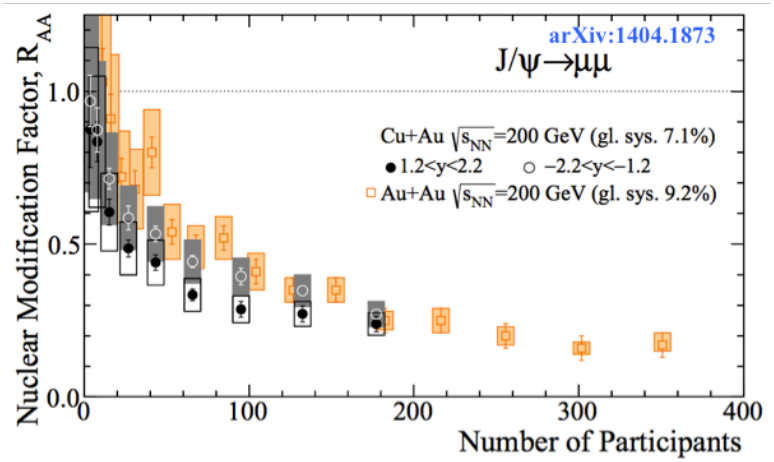


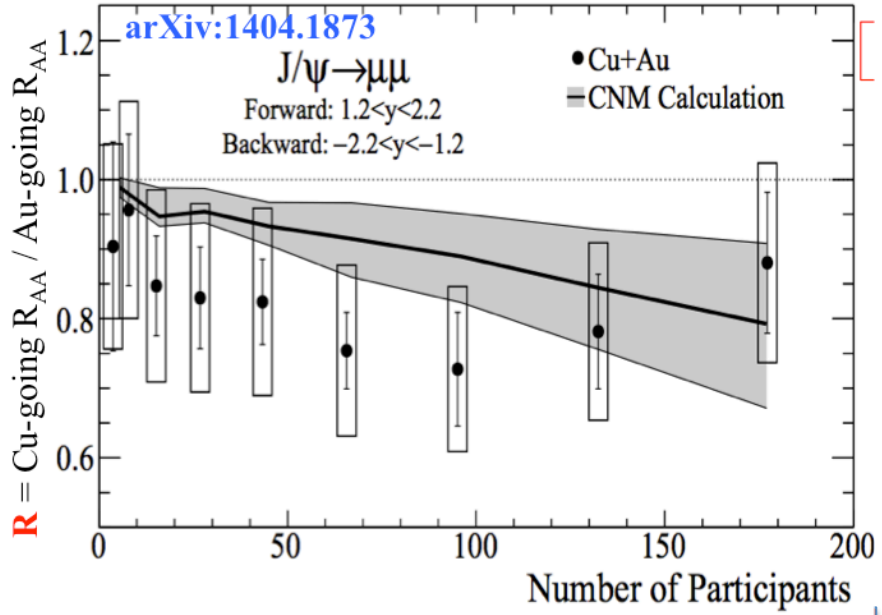
J/ψ in Cu+Au

- Cu-goingとAu-goingで異なるxをプローブ
  - Cu-going側はAu内のx(より小さいx)をプローブするためAu-goingに比べ原子核効果を受けやすい→Rは小さくなる
- Final state effect
  - Au-goingがよりsuppressされるはず→R は大きくなる

N_{part}>100でRは増加

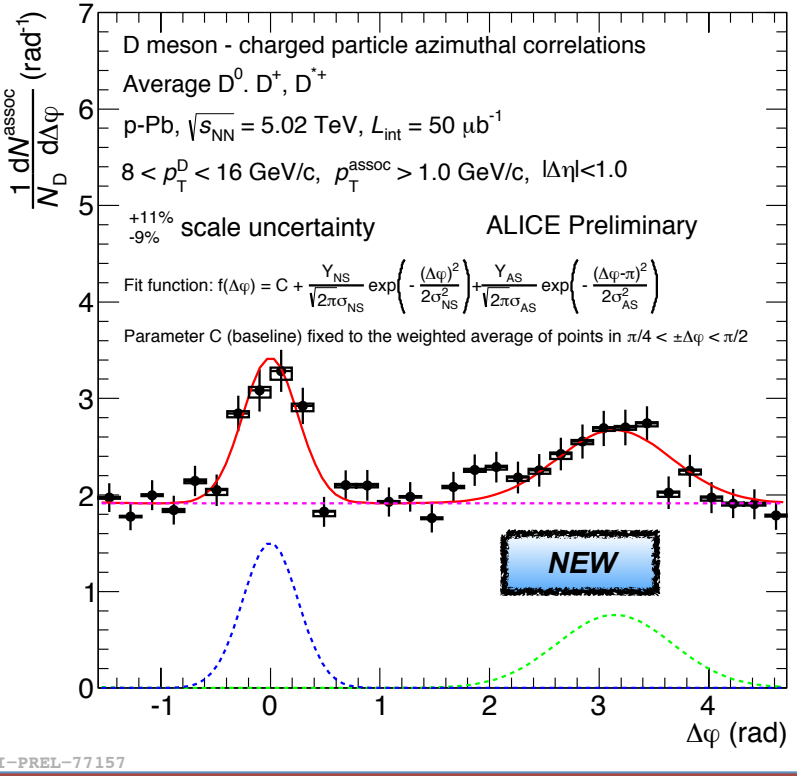
CNM: EPS09+ 4mb breakup

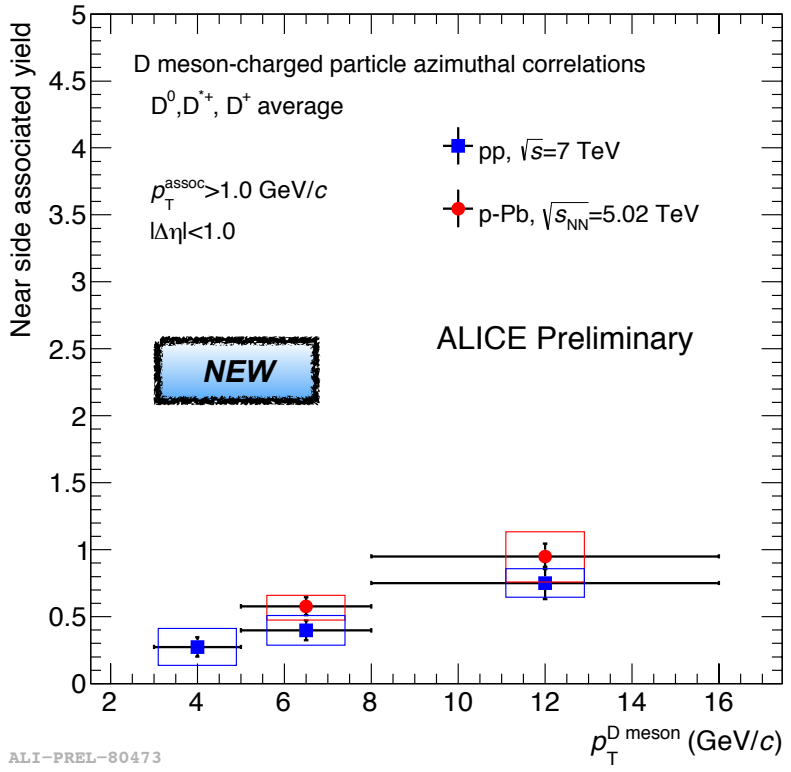




D-hadron correlation

- pp, p-PbでD-hadron相関を測定
  - Near side, away sideピークを確認
- Detector upgrade(2018～？)後に本格測定
  - Energy loss, thermalization
  - Cold nuclear matter effects　の検証



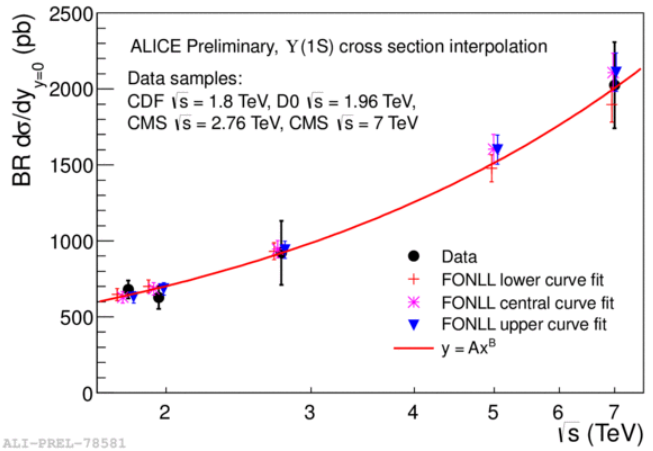


pp reference of Υ

- ALICE pp refference

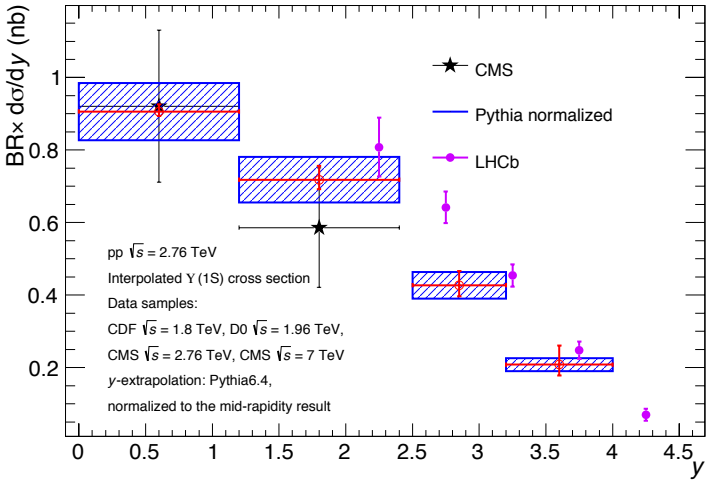
Approach used for preliminary results

- Energy interpolation at mid-rapidity
  - using CDF@1.8 TeV, D0@1.96 TeV, CMS@2.76 TeV, CMS@7 TeV data
  - and several "reasonable" functional forms
  - but also pQCD FONLL calculation
- Rapidity extrapolation
  - Test and select many Pythia tunes using CMS and LHCb data at 7 TeV
  - With selected tunes extrapolate the mid-rapidity point above to forward rapidity



Approach used for the publication

- Use data from LHCb [EPJC74 2835 (2014)]
- pp cross section at 2.76 TeV (2.5<y<4)
  - LHCb measurement: σ[Υ(1S)→μμ]=0.670±0.025 (stat.)±0.026 (syst.) nb
  - ALICE extrapolation: $\sigma[\Upsilon(1S)\rightarrow\mu\mu]=0.465^{+0.071}_{-0.045}$ (extrap.) ±0.041(norm.) nb



Outlook

- LHC
  - Run2 :来年５月から稼働
    - 約10倍の統計
  - Run3:
    - ALICE,Detector upgrade : ITS, TPC, MFT….
      - B, D-D correlation, Λ_c….
- PHENIX
  - Vertex の結果
  - sPHENIX
- STAR
  - HFT: B/D separation,
  - Muon telescope detector: e-μ correlation for heavy flavor correlation