Direct photon production and jet interaction in small systems

QUARK MATTER 2015

Sep. 27 – Oct. 3, 2015 Kobe, Japan

Charles Gale
McGill University

[Image: physics.org]

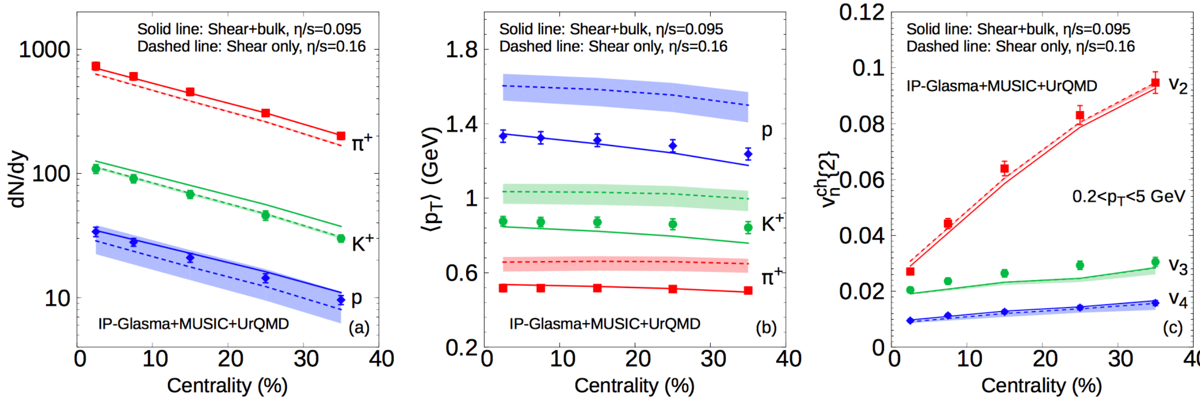
Outline

- Fluid behaviour in small systems at RHIC & LHC
- Photon production from small systems at RHIC & LHC
- Jet modification in small systems

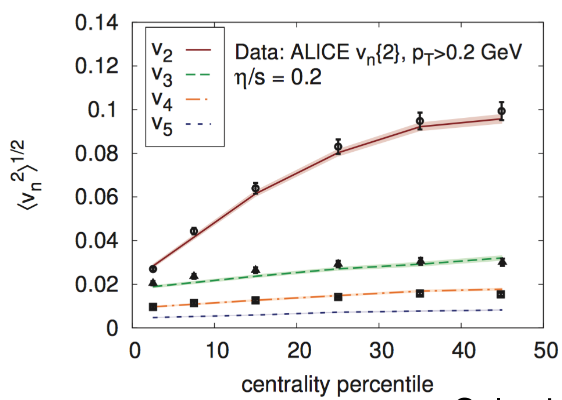
Gabriel Denicol
Sangyong Jeon
Jean-François Paquet
Chanwook Park
Chun Shen

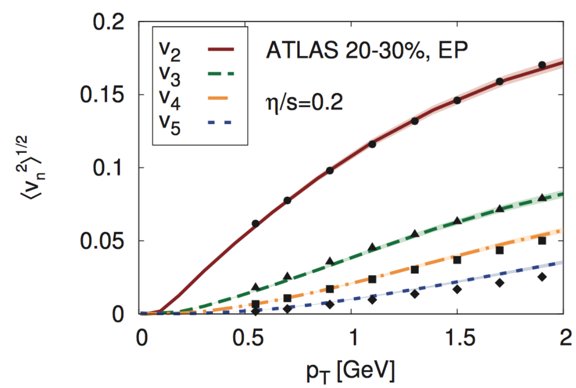
Collectivity in large systems

In AA collisions, collectivity has been quantified by its flow characteristics, and by the behaviour of global observables:



S. Ryu *et al.*, PRL (2015)

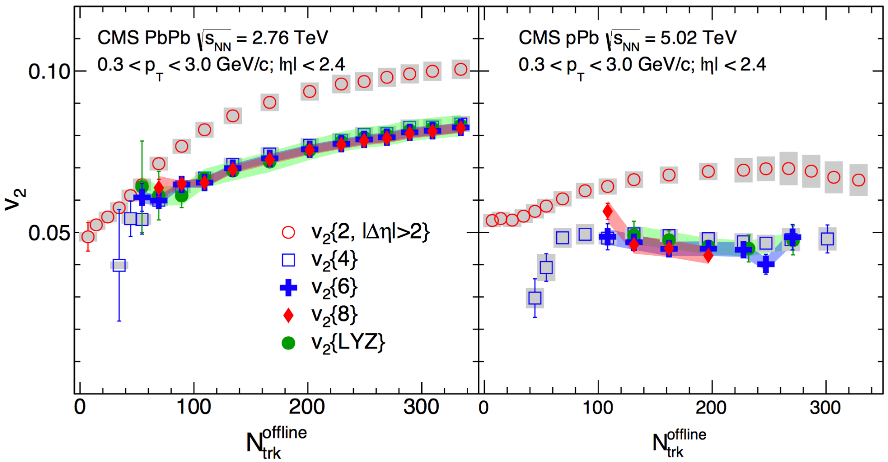




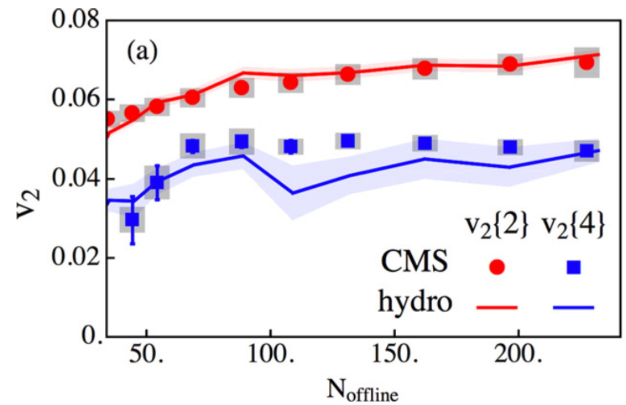
Gale, Jeon, Schenke, Int. J. Mod. Phys. A (2013)

See Gabriel Denicol's talk on Thursday

Collectivity in small systems?



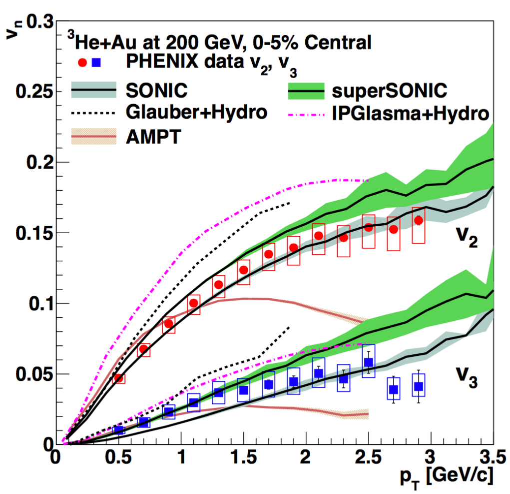
CMS Collab., PRL 2015



LHC

Kozlov *et al.*, NPA (2014)

RHIC



PHENIX Collab., arXiv:1507.06273

- Magnitude and behaviour of flow coefficients consistent with fluid-dynamical modelling
- Pair correlation variable $r_n(p_T^a, p_T^b)$ confirmed by measurements (CMS)
- Some tension between AA and pA hydro calculations
- Initial state correlations
- Details of the shape of the proton/deuteron
- … (a lot more this week)

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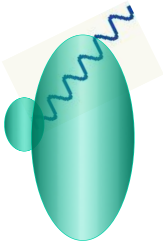
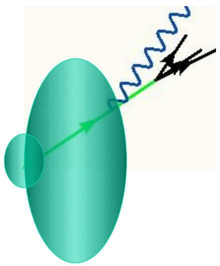
Help from a complementary observable: Photons

A penetrating probe (tomography), with little final-state interaction:

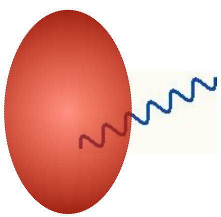
Photons (real and/or virtual)



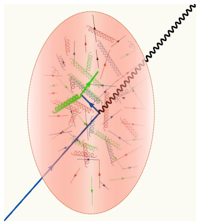
Hard direct photons. pQCD with shadowing
Non-thermal



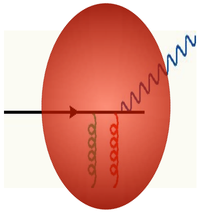
Fragmentation photons. pQCD with shadowing
Non-thermal



Thermal photons
Thermal



Jet-plasma photons
Thermal



Jet in-medium bremsstrahlung
Thermal

An additional, penetrating probe could help validate hydrodynamic behaviour in small systems

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Help from a complementary observable: Photons

A <u>penetrating probe</u> (tomography), with little final-state interaction:

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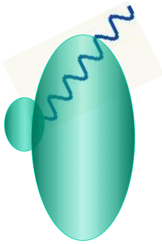

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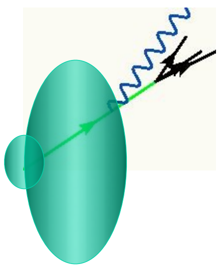

Fragmentation photons. pQCD with shadowing
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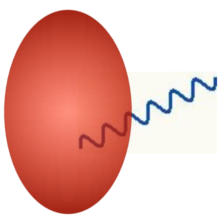
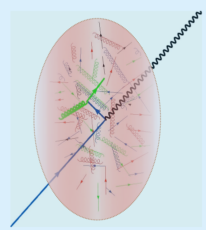


Thermal photons
Thermal



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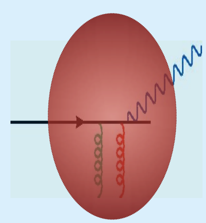


Jet in-medium bremsstrahlung
Thermal

An additional, penetrating probe could help validate hydrodynamic behaviour in small systems

Electromagnetic emissivity

$$\omega \frac{d^3R}{d^3k} = -\frac{g^{\mu\nu}}{(2\pi)^3} \mathrm{Im}\Pi^R_{\mu\nu}(\omega,k) \frac{1}{e^{\beta\omega}-1}$$

- Partonic rates @ LO: Arnold, Moore, Yaffe, JHEP (2001); Partonic rates @ NLO: J. Ghiglieri et al., JHEP (2013)
- Hadronic rates: Turbide et al., PRC (2004); Heffernan et al., PRC (2015)

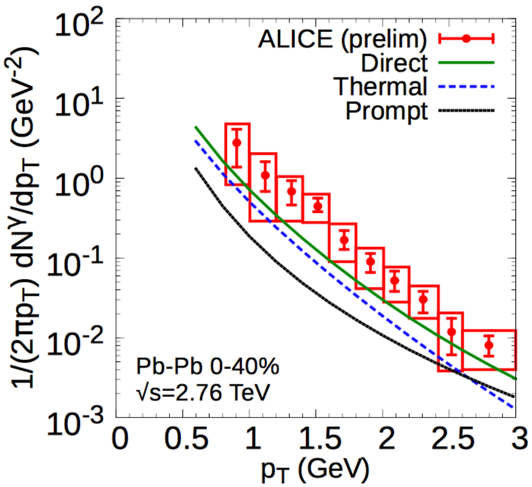
$$\mathcal{L} = \frac{1}{8}F_\pi^2 \,\mathrm{Tr}\, D_\mu U D^\mu U^\dagger + \frac{1}{8}F_\pi^2 \,\mathrm{Tr}\, M\left(U + U^\dagger\right)$$
$$-\frac{1}{2}\mathrm{Tr}\left(F^L_{\mu\nu}F^{L\mu\nu} + F^R_{\mu\nu}F^{R\mu\nu}\right) + m_0^2 \mathrm{Tr}\left(A^L_\mu A^{L\mu} + A^R_\mu A^{R\mu}\right)$$
$$+ \text{ non-minimal terms}$$

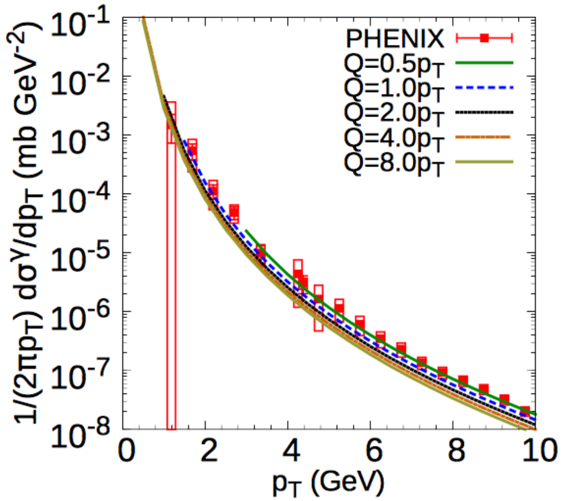
$$\left.\begin{array}{l} X + Y \rightarrow Z + \gamma \\ \rho \rightarrow Y + Z + \gamma \\ K^* \rightarrow Y + Z + \gamma \end{array}\right\} X, Y, Z \in \{\rho, \pi, K^*, K\}$$

$$\pi\pi \rightarrow \pi\pi\gamma,\ \Sigma \rightarrow \Lambda\gamma,\ f_1(1285) \rightarrow \rho^0\gamma \ldots$$

+ viscous corrections

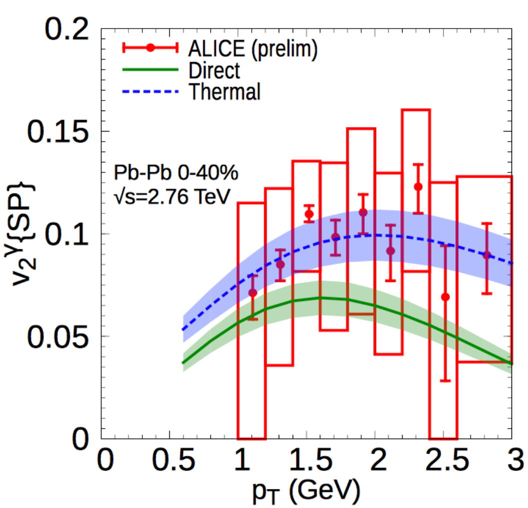
Photons and hydro calculations?
The photon "elliptic flow puzzle" in AA?





Prompt, pQCD pp photons@NLO

Paquet *et al.*, arXiv: 1509.06738



- LHC: Hydro calculation consistent with ALICE measurements, considering the statistical and systematic uncertainties
- RHIC and discussion of the details: J.-F. Paquet's parallel session talk on Wednesday
- See Chun Shen's plenary talk on Friday
- See experimental presentations at this meeting

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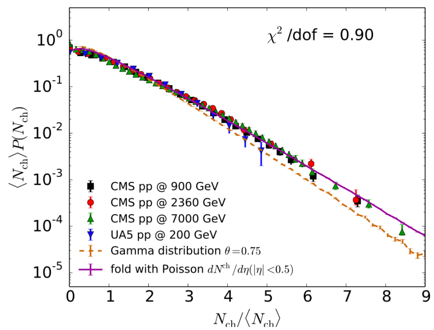
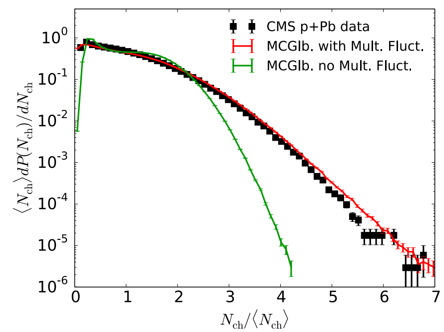
Fluid-dynamical simulation

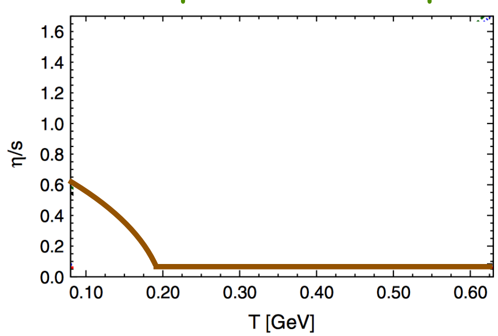
- Event-by-event simulations
- Initial state entropy density fluctuates according to a Gamma distribution





C. Shen *et al.*, arXiv:1409.8164

- Temperature-dependent shear viscosity



H. Niemi *et al.*, PRL (2011)

- Owing to compact fireball sizes (v.s. AA) pA collisions have larger pressure gradients, driving a larger expansion rate

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The limits of hydrodynamics

One indicator, the Knudsen number, Kn $\mathrm{Kn} = \frac{\ell_{\mathrm{micro}}}{L_{\mathrm{macro}}}$

For a dilute gas $\ell_{\mathrm{micro}} = \lambda_{\mathrm{mfp}} \sim \tau_\pi = 5\frac{\eta}{\epsilon + P}$

For L_{macro}, use the local fields ϵ, u^μ to construct all possibilities

Denicol *et al.*, PRD (2012); Niemi, Denicol, *arXiv:1404.7327*

$\frac{1}{L^\theta_{\mathrm{macro}}} = \theta,\ \frac{1}{L^\epsilon_{\mathrm{macro}}} = \frac{1}{\epsilon}\sqrt{\nabla_\mu \epsilon \nabla^\mu \epsilon}$ are the larger ones $\left(\theta = \nabla_\mu u^\mu\right)$

$$\mathrm{Kn} = \frac{\tau_\pi}{L}, \quad L = \min\left(L^\theta_{\mathrm{macro}}, L^\epsilon_{\mathrm{macro}}\right)$$

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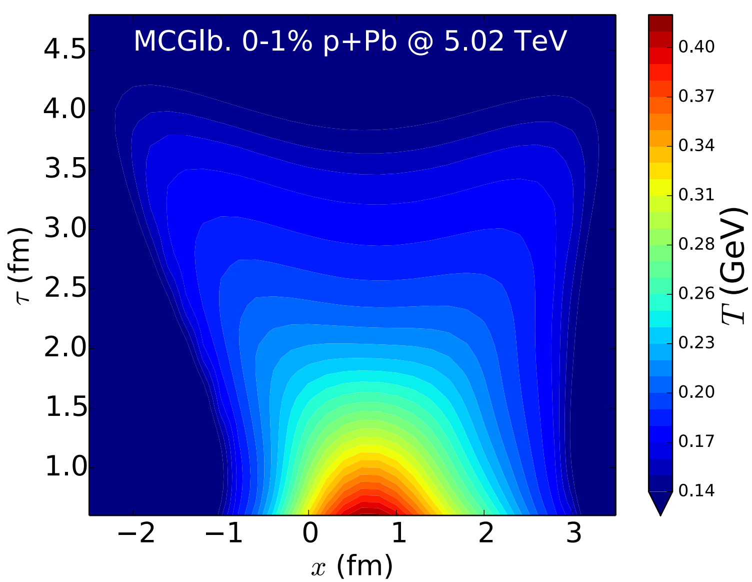

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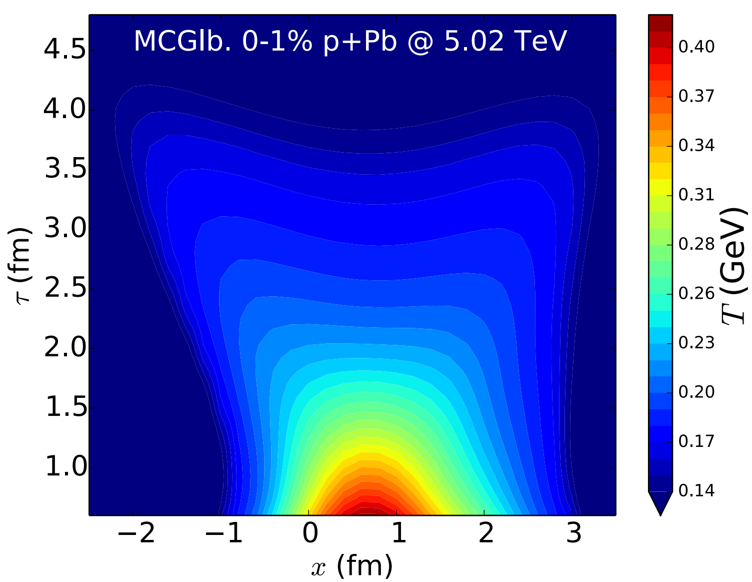

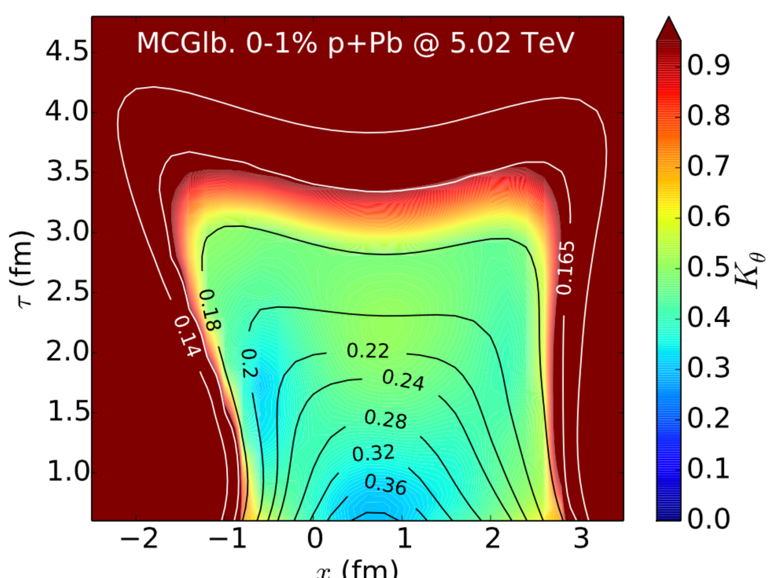

$\mathrm{Kn} > 1$

$\mathrm{Kn} \sim 1$

$\mathrm{Kn} < 1$

The limits of hydrodynamics

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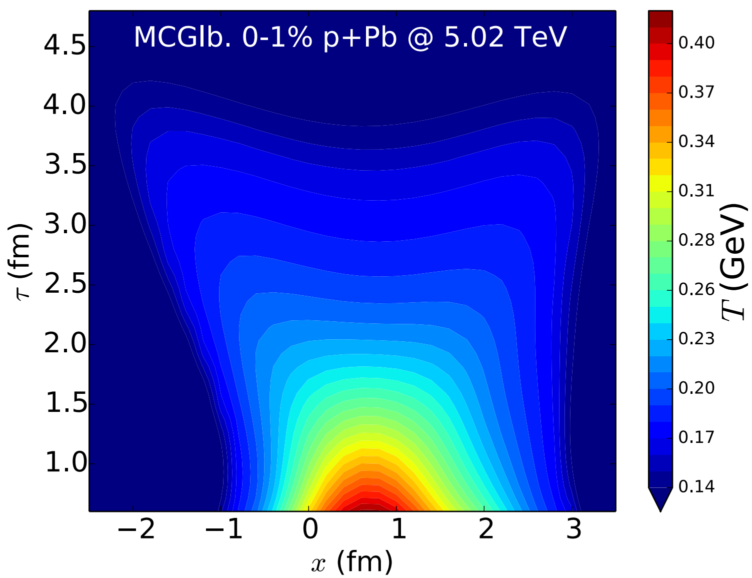
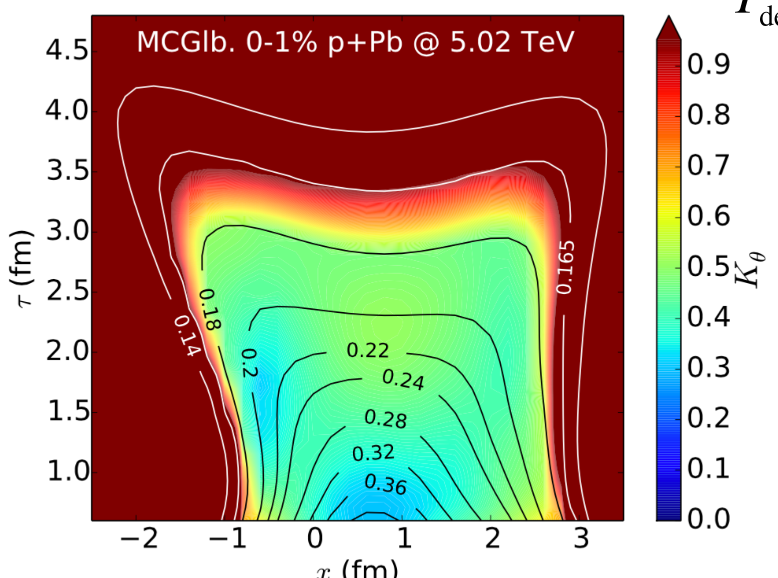
Stop at $T_{\text{dec}} = 165\ \text{MeV}$





$\mathrm{Kn} > 1$

$\mathrm{Kn} \sim 1$

$\mathrm{Kn} < 1$

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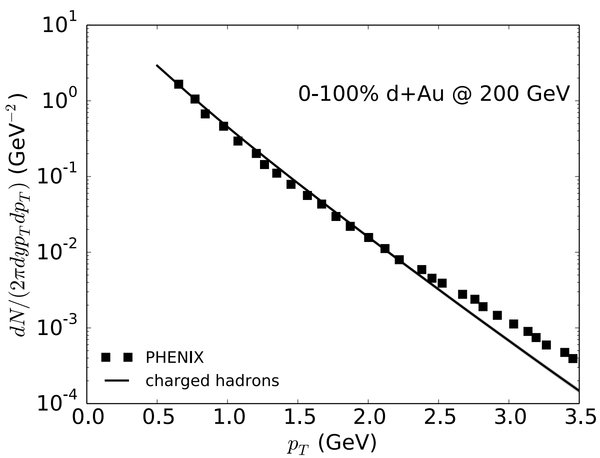
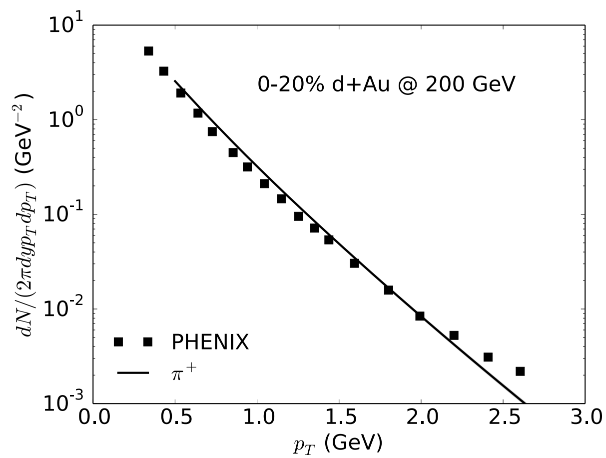
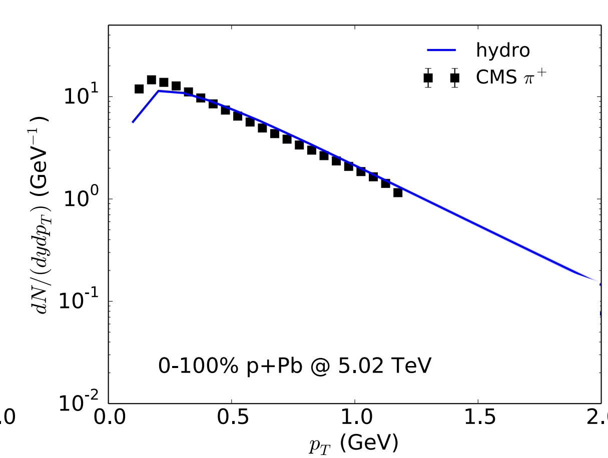
Soft hadrons @ RHIC and @ LHC

p+Pb @ 5.02 TeV	$\langle N_{\rm coll} \rangle$	$\frac{dN^{\rm ch}}{d\eta}\Big\|_{\|\eta\|<0.5}$	$\langle p_T \rangle (\pi^+)$ (GeV)	$v_2^{\rm ch}\{2\}$	$v_3^{\rm ch}\{2\}$
0-1%	15.4 ± 0.03	57.6 ± 0.3	0.59 ± 0.01	0.056 ± 0.001	0.018 ± 0.001
0-100%	6.6 ± 0.01	16.6 ± 0.3	0.51 ± 0.02	0.034 ± 0.001	0.007 ± 0.001
d+Au @ 200 GeV	$\langle N_{\rm coll} \rangle$	$\frac{dN^{\rm ch}}{d\eta}\Big\|_{\|\eta\|<0.5}$	$\langle p_T \rangle (\pi^+)$ (GeV)	$v_2^{\rm ch}\{2\}$	$v_3^{\rm ch}\{2\}$
0-100%	8.05 ± 0.01	8.85 ± 0.19	0.46 ± 0.02	0.025 ± 0.001	0.003 ± 0.001



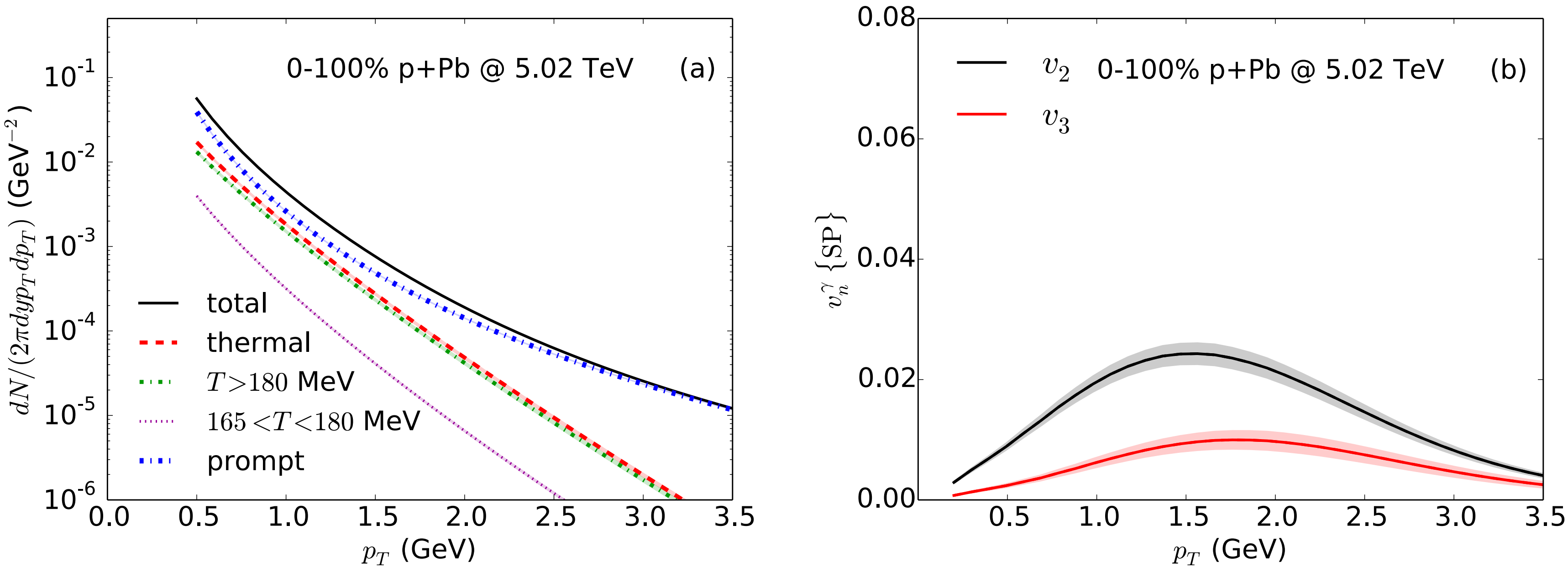




- Reasonable agreement between theory and measurement
  $< p_T >$ values in agreement within 10%

Photon results

Min. bias



- For minimum bias p+Pb collisions, thermal photons are suppressed w.r.t. prompt photons, but are still visible in the total yield
- Prompt photons: NLO pQCD
- There is however a clear photon elliptic flow, and a photon triangular flow

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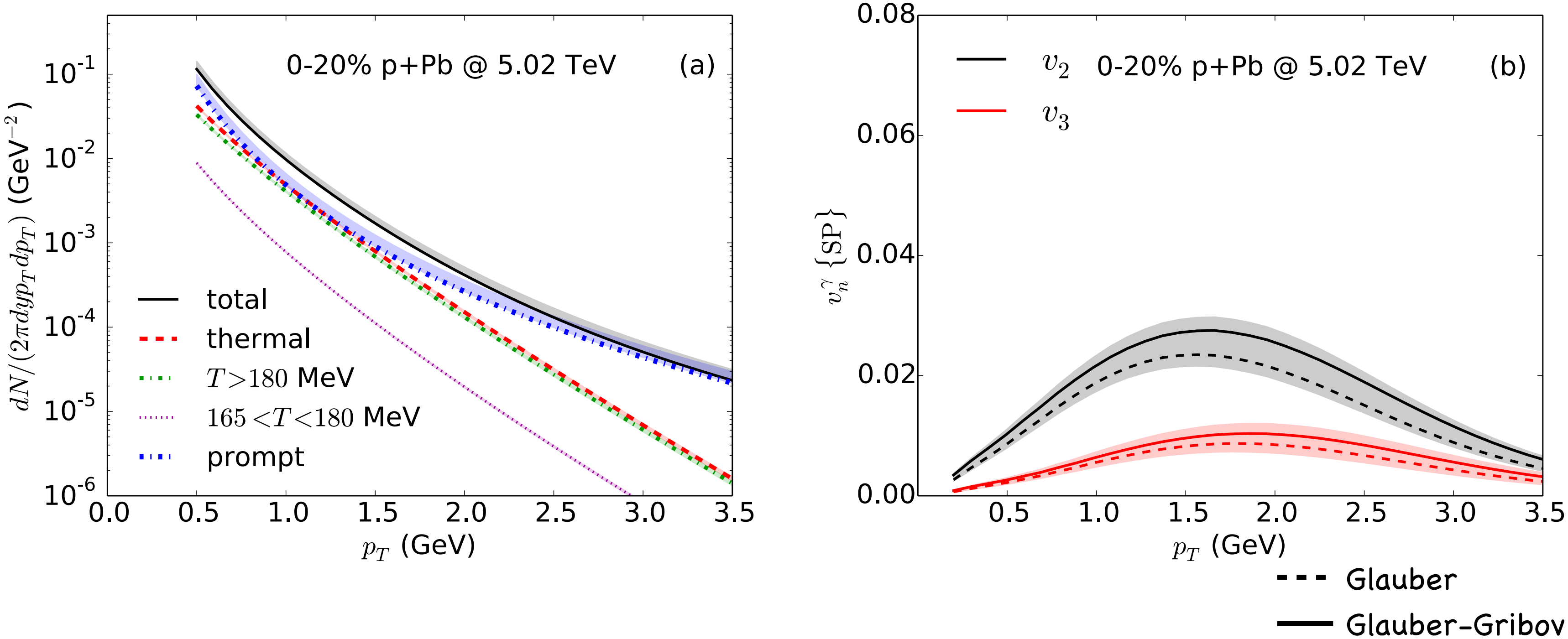
Photon results

0-20%



- In the 0-20% centrality range, the thermal photons compete with the prompt, up to intermediate p_T
- Larger elliptic and triangular flows

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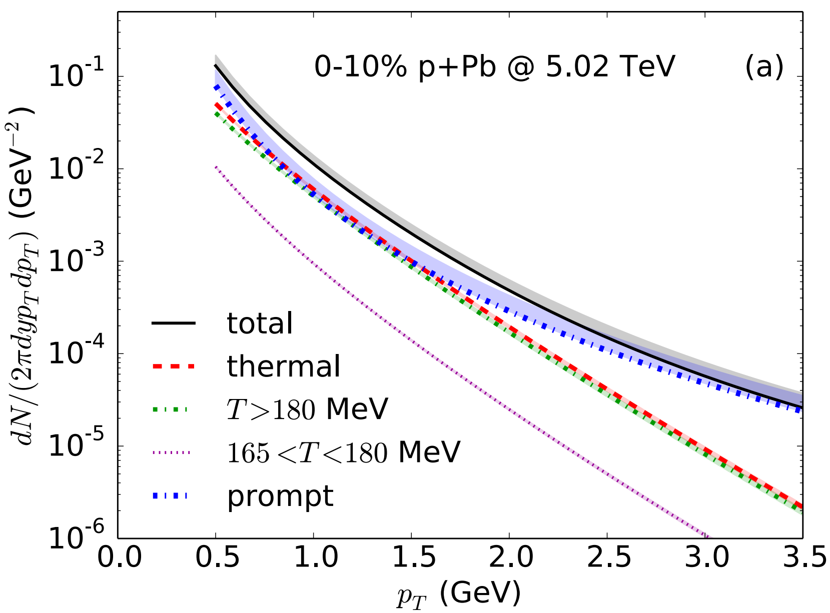
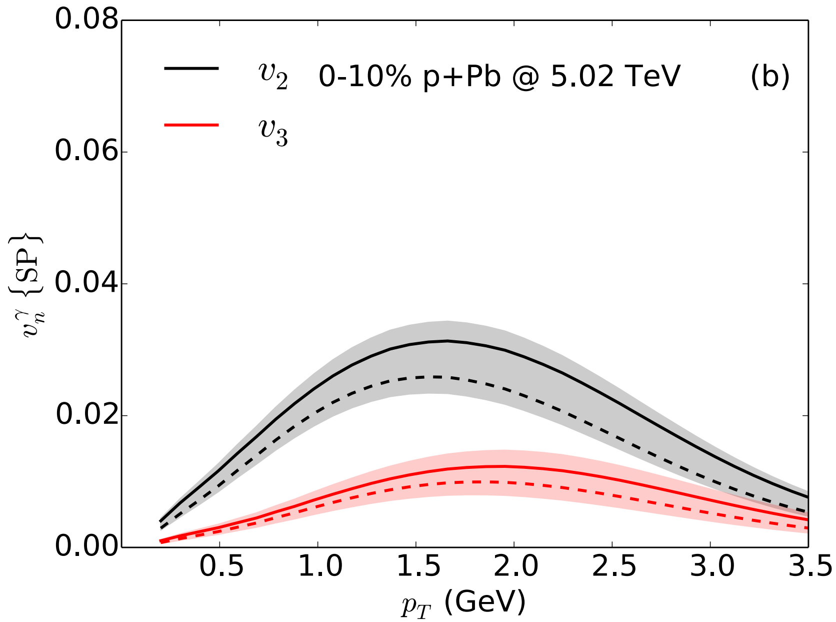
Photon results

0-10%

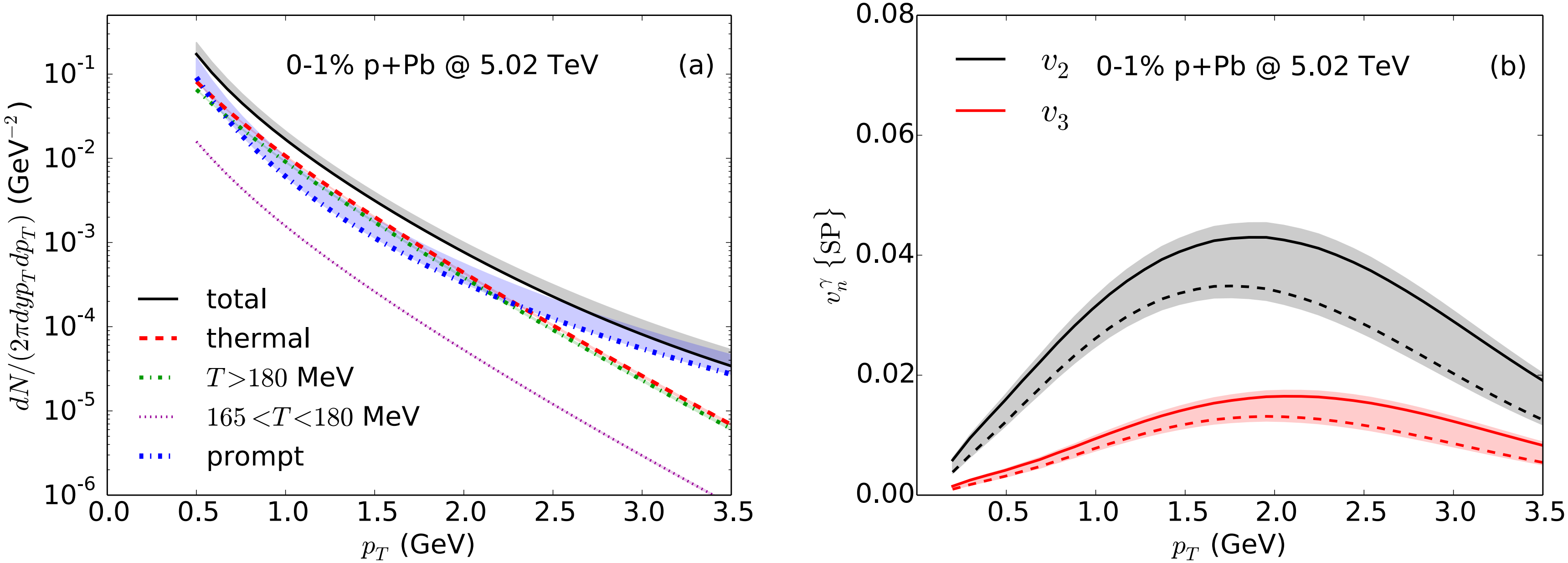




- In the 0-10% centrality range, the thermal photons compete with the prompt, up to intermediate p_T
- Larger elliptic and triangular flows

Photon results

0-1%



- In the 0-1% centrality range, a clear thermal photon signal over the prompt photon contribution; a factor of 3 @ 1.5 GeV
- There is a clear photon elliptic flow, and a photon triangular flow
- T_{dec} is kept high: arguably even a lower limit to the thermal contributions

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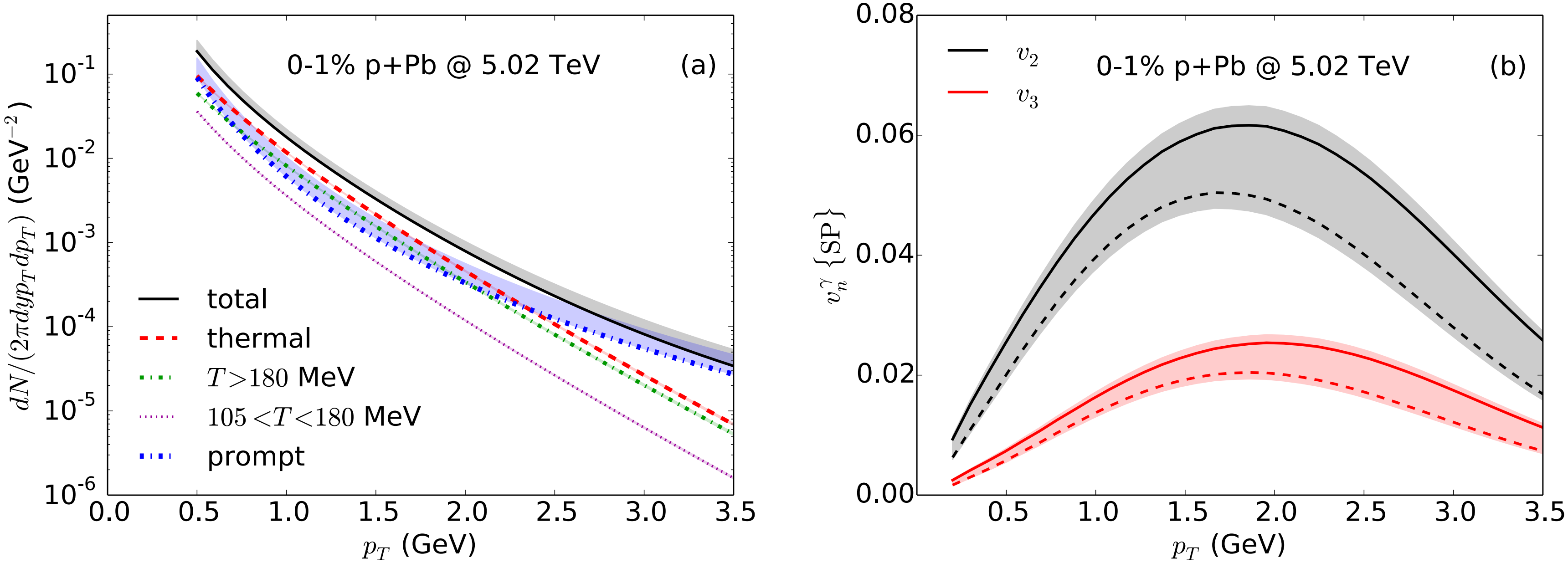
Photon results

0-1%



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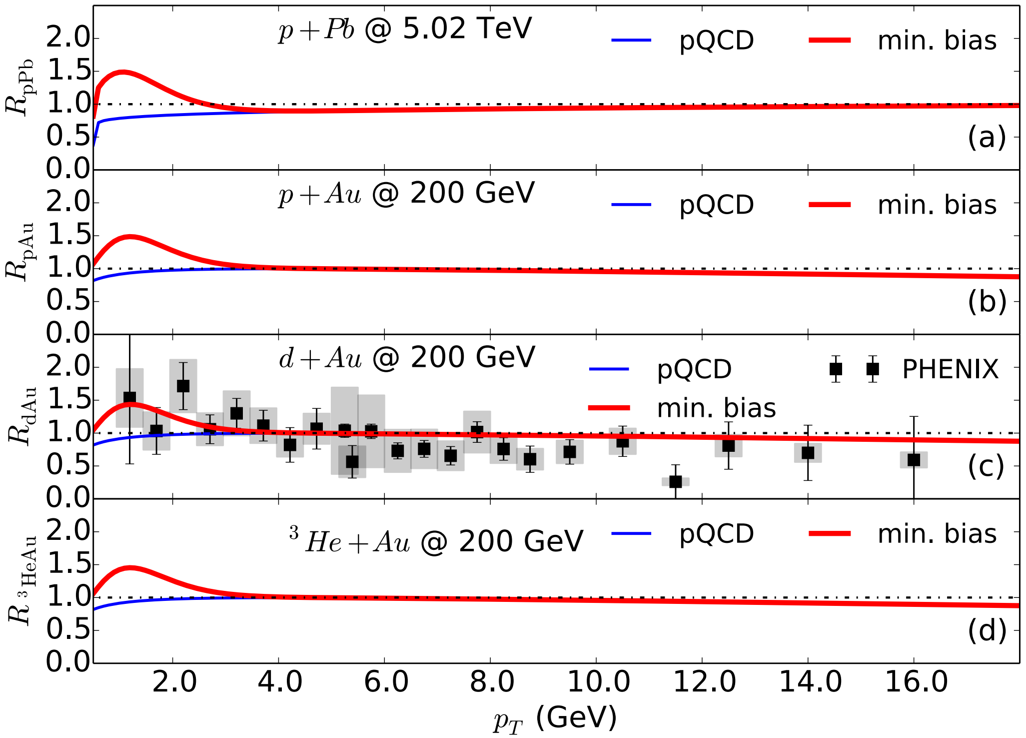
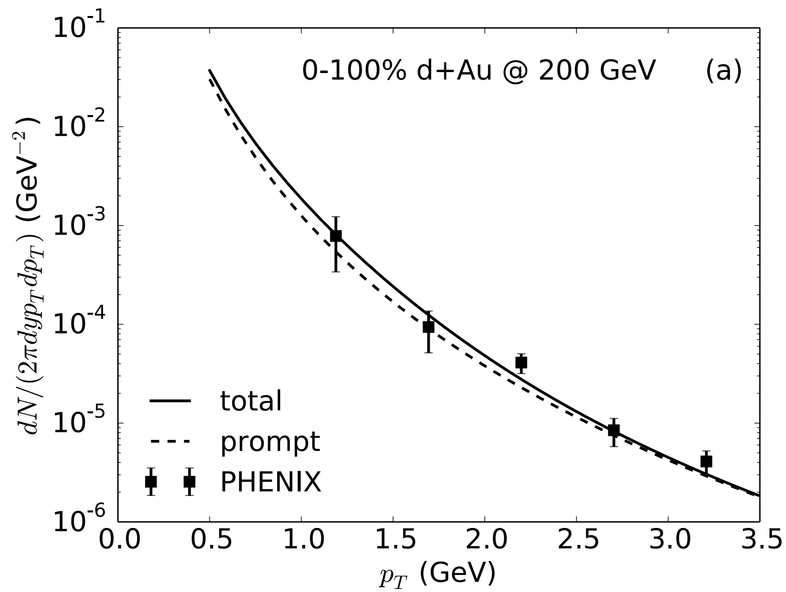
Comparing against what is currently known, and some predictions





- Thermal radiation can leave a measurable imprint even on min. bias $R^{\gamma}_{\rm pPb}$
- An additional empirical support to the existence of a medium with collectivity features

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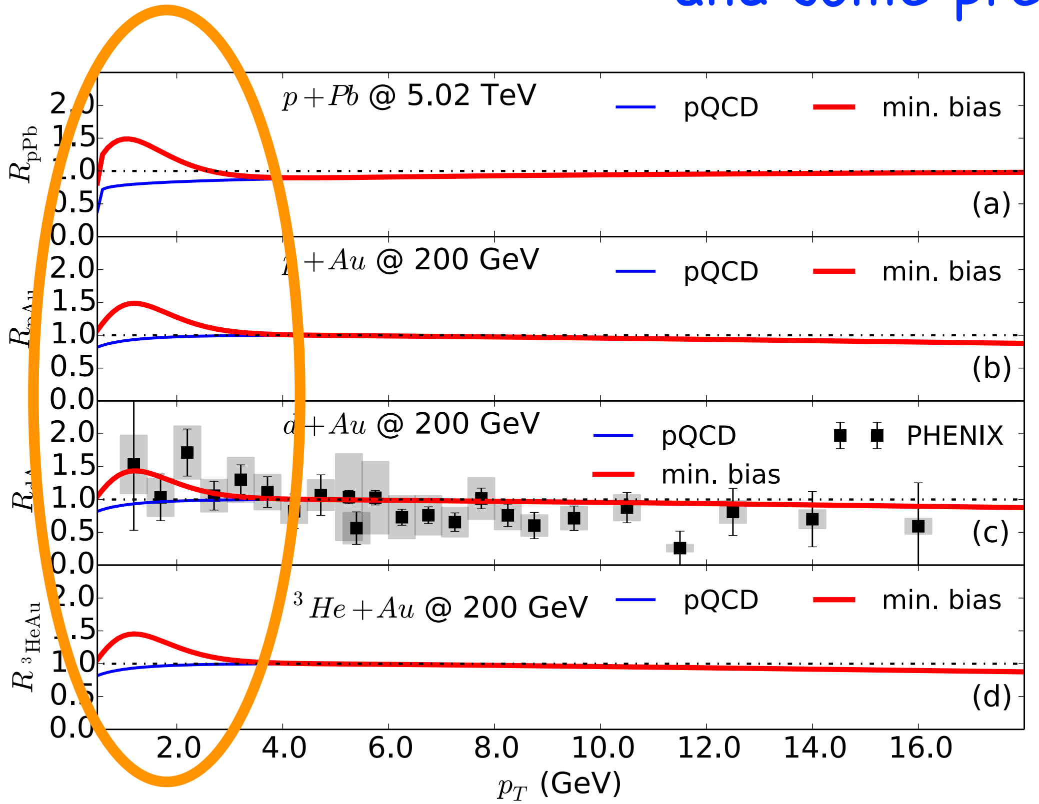
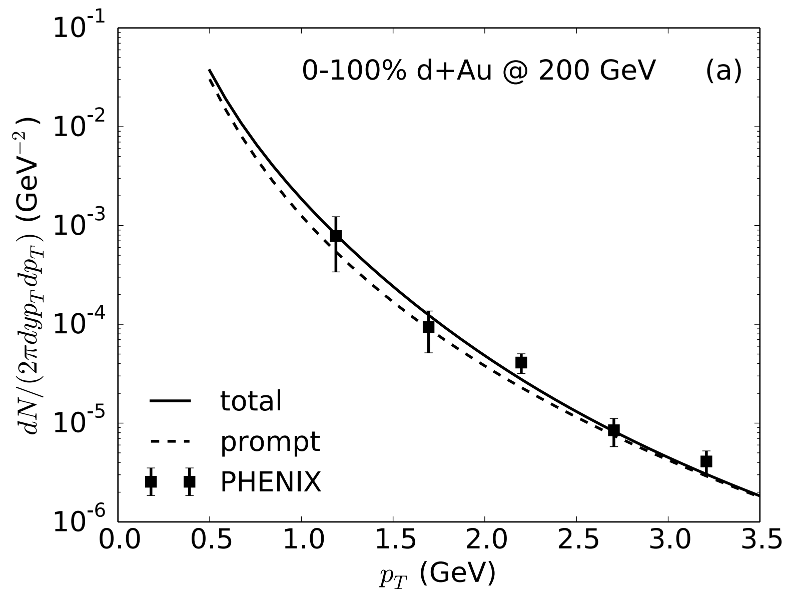
Comparing against what is currently known, and some predictions





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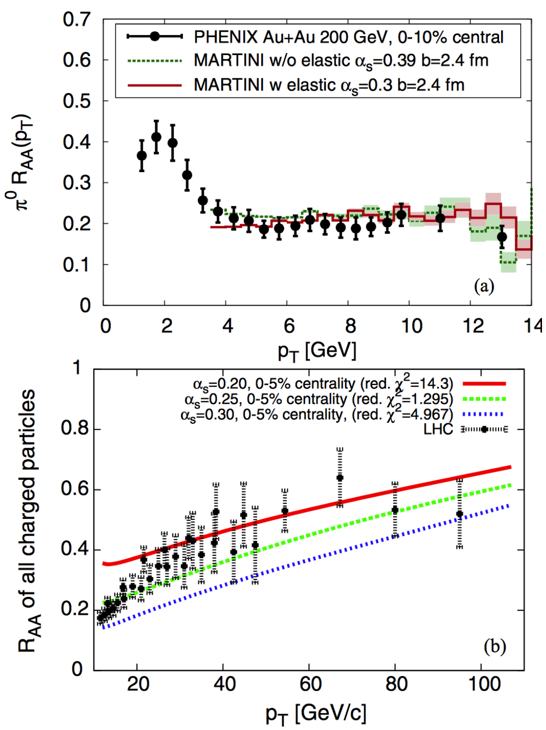
Jets in the pA medium?

Martini: Combines PYTHIA, MUSIC (relativistic viscous hydro, jet-medium interaction (inelastic & elastic, AMY). Modular.

Schenke *et al.*, PRC (2009)

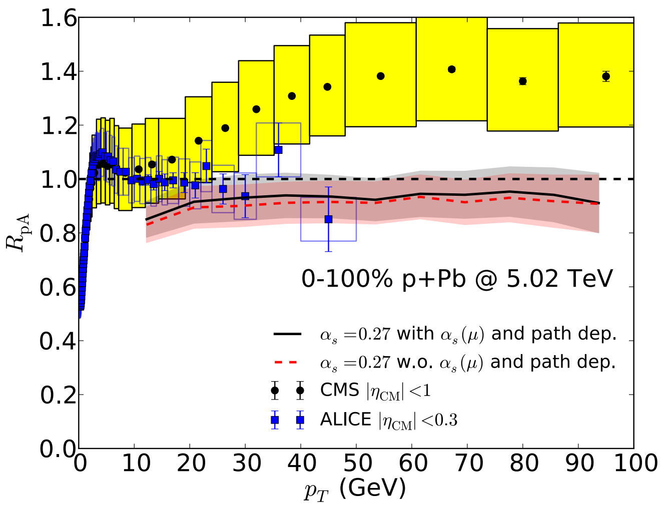
Running α_s, finite-size effects

Caron-Huot, Gale, PRC (2010)



Burke *et al.*, PRC (2014)

Jets in the pA medium?
Here, charged hadrons



- Situation in min. bias pA clearly sensitive to the value of α_s
- Some possibility of suppression @~10-20 GeV, but data mostly 1

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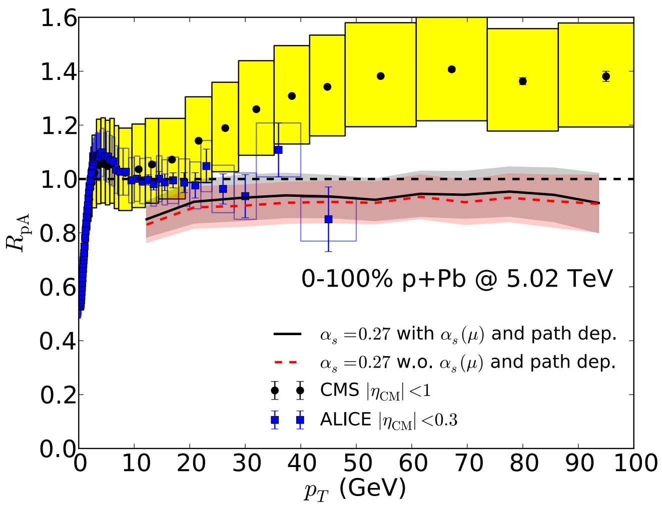

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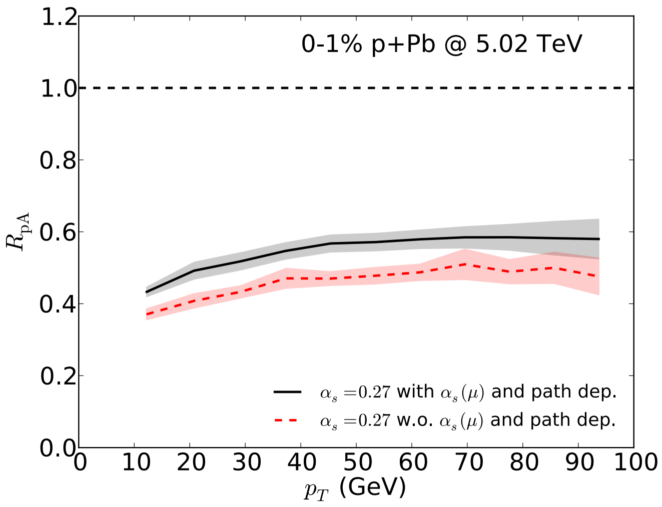

- A large(r) effect in central collisions
- Enhanced sensitivity to physical conditions and model characteristics (medium size and granularity)
- Much more to do: y, jet R_{pA}...
- A clear manifestation of the medium in pA collisions

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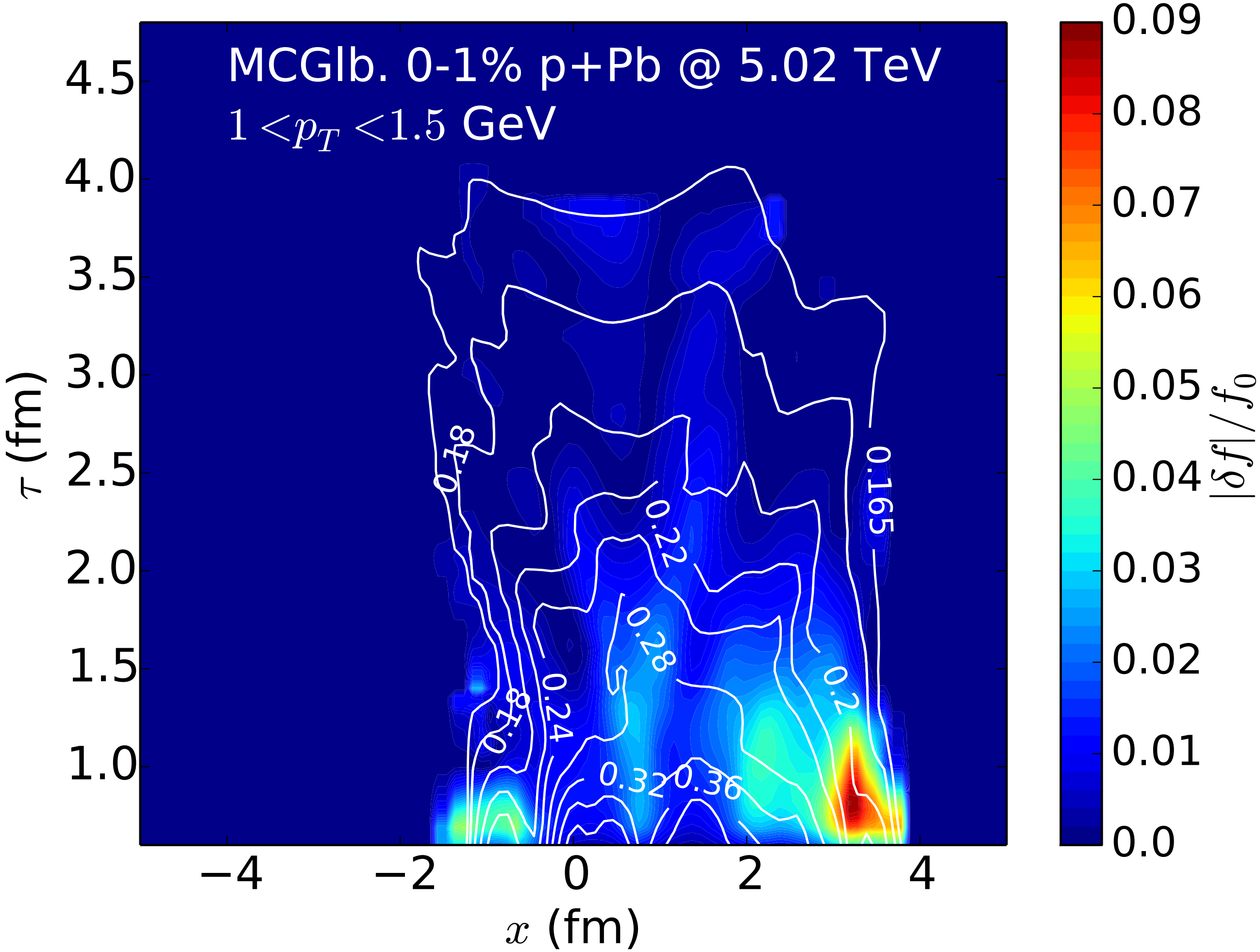
Conclusions

- pA/dA/HeA systems explore the limits of fluid dynamical modelling
- Ideal to study non-equilibrium features
- Photons in pA collisions offer the opportunity to confirm fluid behaviour in small systems
- Photon yield and flow (elliptic & triangular) large in central collisions
  - Much to explore (jet-medium photons, photon-hadron correlations…)
- pA systems do offer a medium for QCD jets to interact
  - Next, jet reconstruction
- High centrality measurements are/will be revealing; even min bias data still contains signature for photons, some for hadrons

Charles Gale
McGill

$|\delta f| / f_0$



MCGlb. 0-1% p+Pb @ 5.02 TeV
$1 < p_T < 1.5$ GeV
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
τ (fm)
−4
−2
0
2
4
x (fm)
0.18
0.165
0.22
0.28
0.2
0.24
0.32
0.36
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.0
$|\delta f| / f_0$