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QGP formation time and direct photon production

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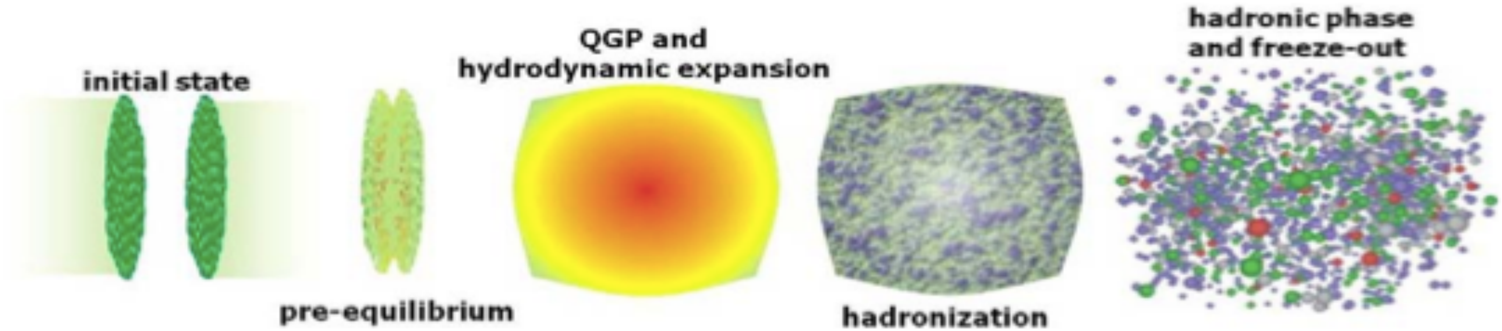
The 9th Relativistic Aspects of Nuclear Physics Workshop (RANP2013)

Sep. 23-27, 2013, Rio de Janeiro, Brazil

What's the matter in the system?



- Hadronic phase: statistical models, hadron cascade, PDG for decays.
- Partonic phase :
  - Bulk hadrons may constrain space-time evolution.
  - How and when QGP forms, and hadronization are unknown.
  - Monitor the contents of the system with EM probes.

Outline

- Photon production in AA

  Pt spectra and v2 of direct photons

  Au+Au at 200 GeV

  Pb+Pb at 2.76TeV

- Photon production in pp

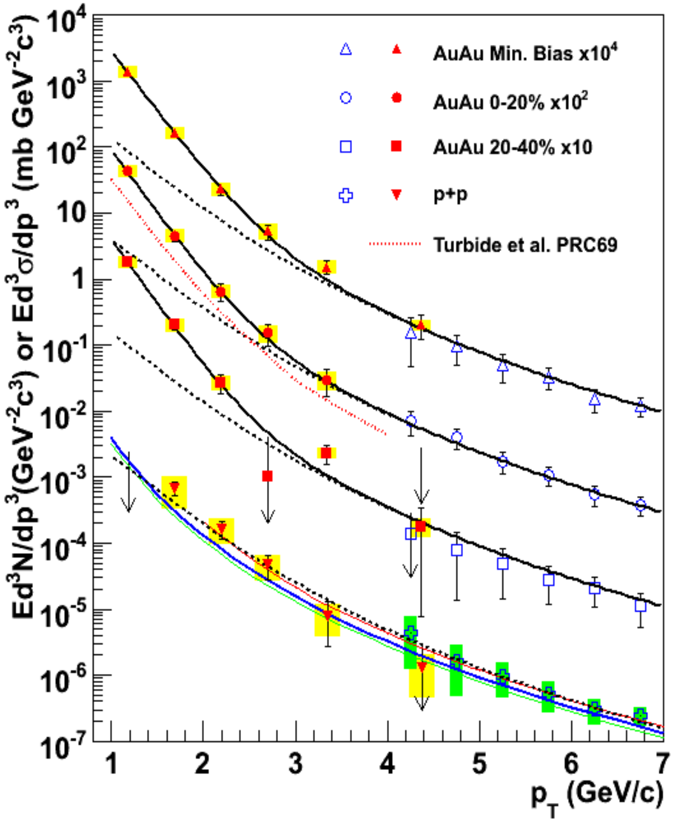
  Ridge in p+p at 7TeV

  Construct p+p collision system

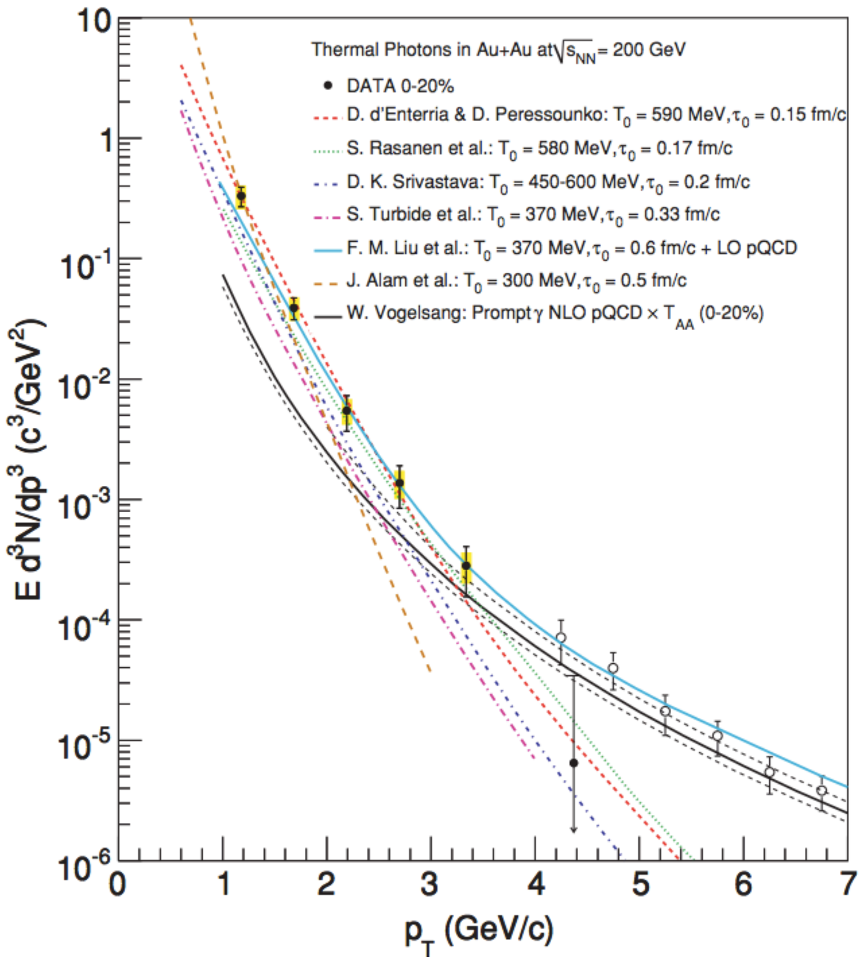
  photons, flow, QGP?

AuAu➔ photons, Pt spectra

PHENIX, Phys. Rev. Lett. 104, 132301 (2010)

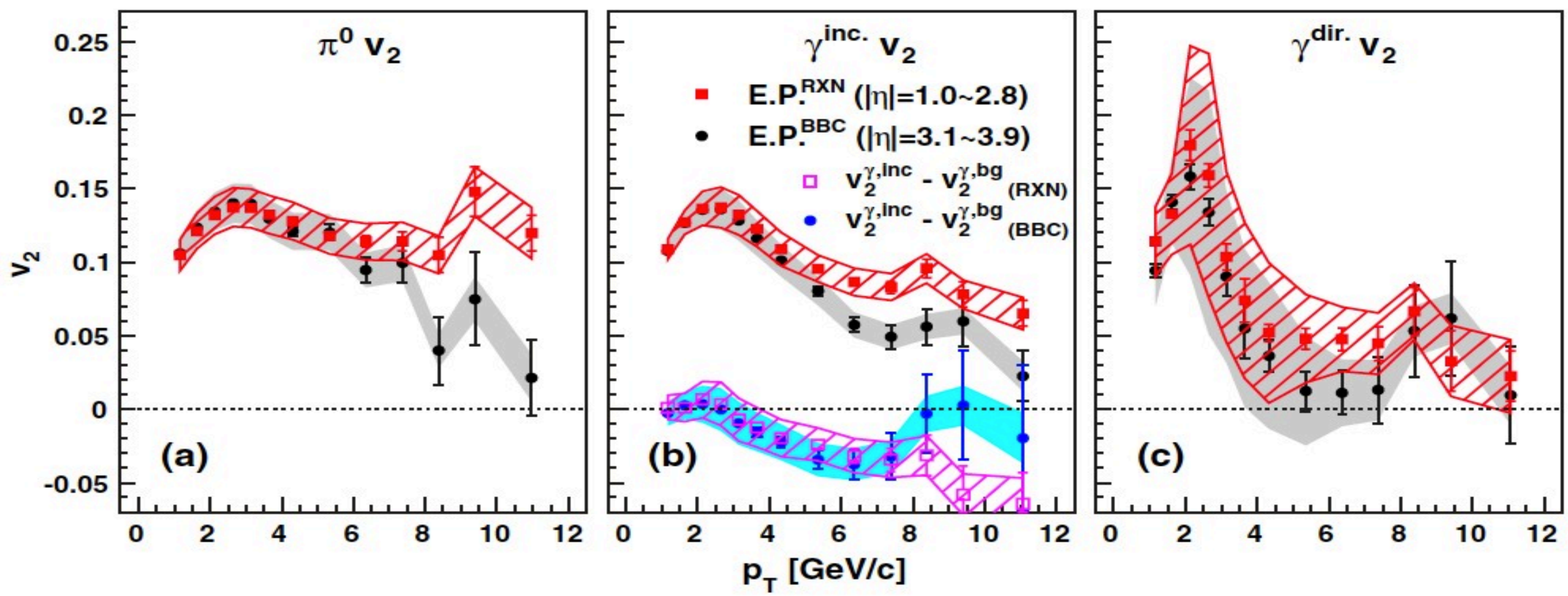


PHENIX, Phys. Rev. C81, 034911 (2010)

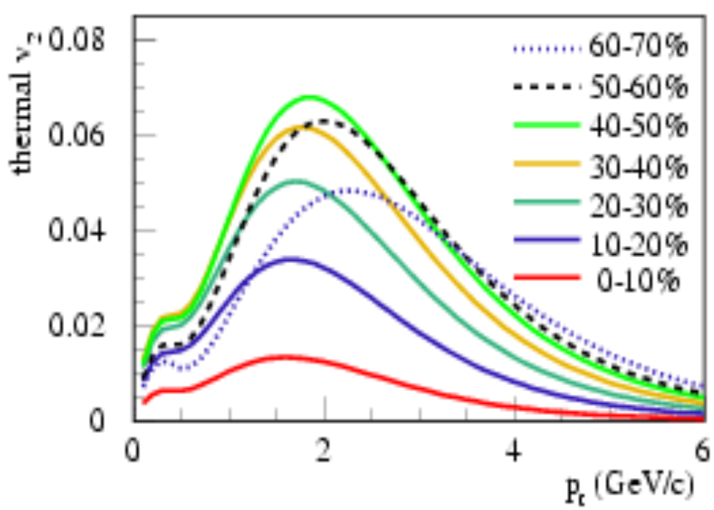


Puzzle: Large v2 observed

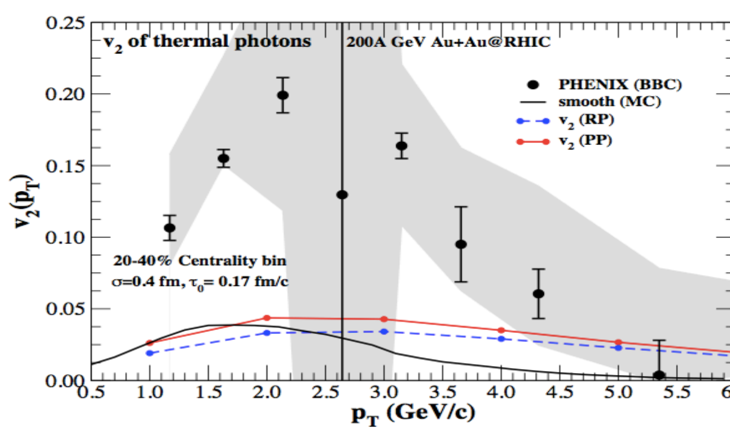
PHENIX, Phys. Rev. Lett. 109, 122302 (2012)



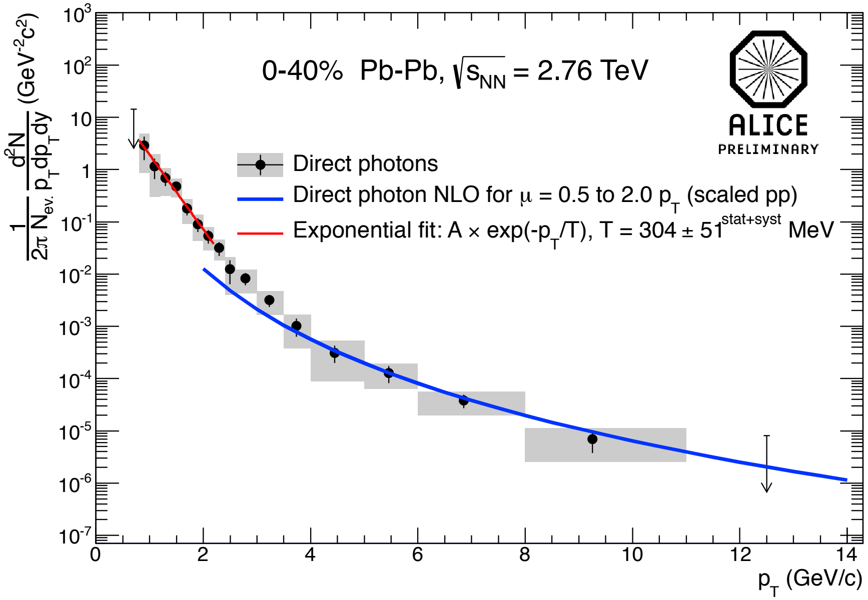
FML et al. Phys.Rev.C80:034905,2009

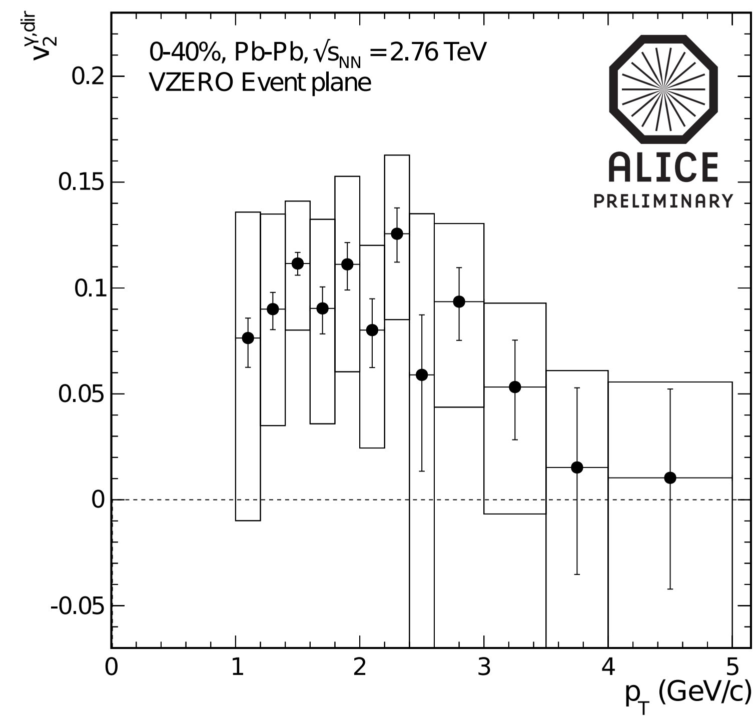


Chatterjee et al, arXiv:1305.6443



Large v_2 of direct photons at LHC!



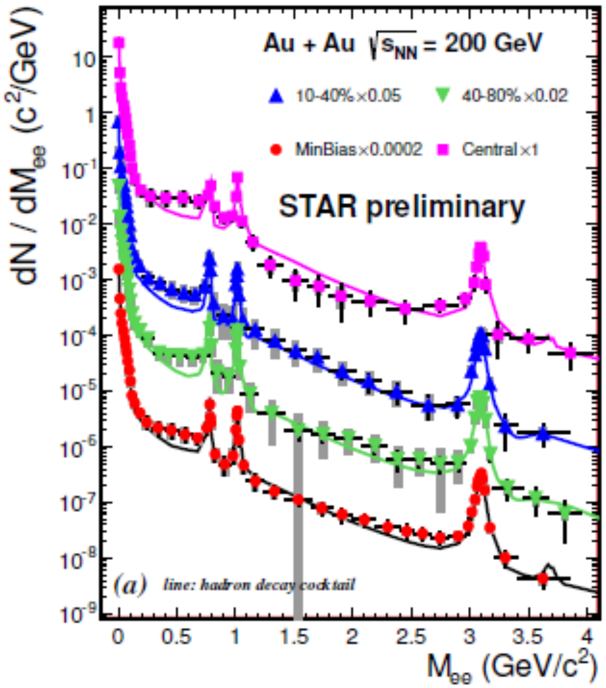


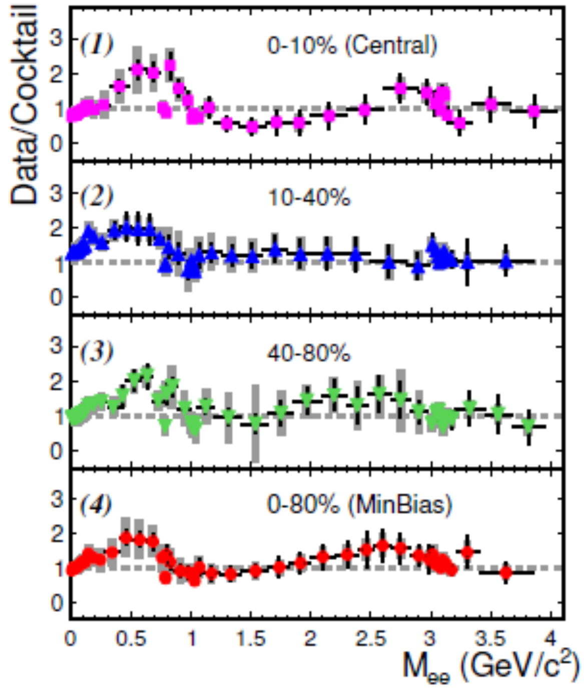
Quark Matter 2012

ArXiv: 1212.3995

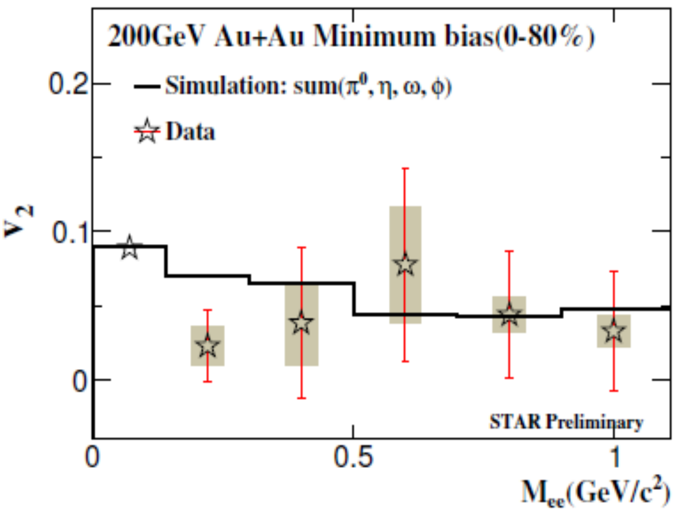
Raa =1 at high pt !

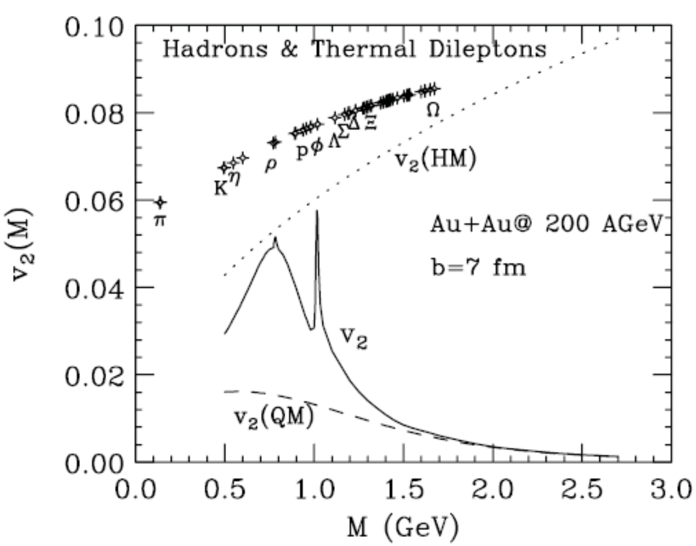
Dileptons, also puzzling





STAR: arXiv:1305.5447





Rupa Chatterjee, et al.,

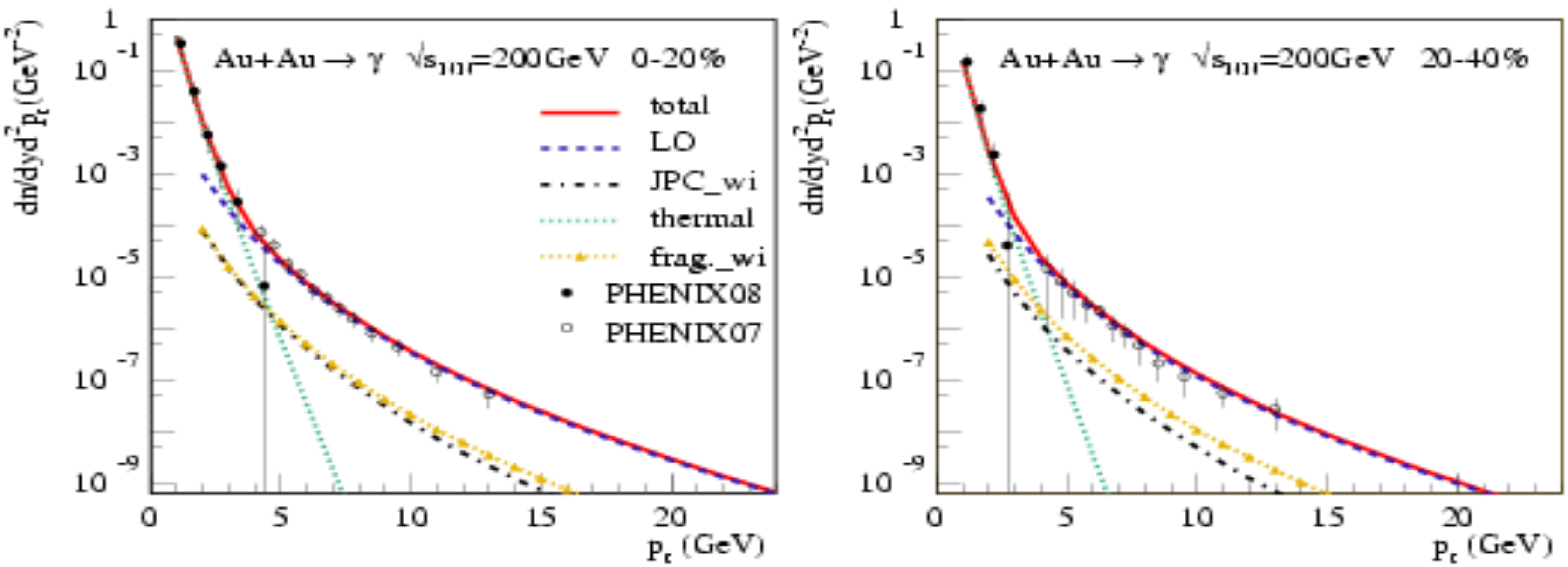
Phys ReV C 75, 054909 (2007)

Check photon calculation

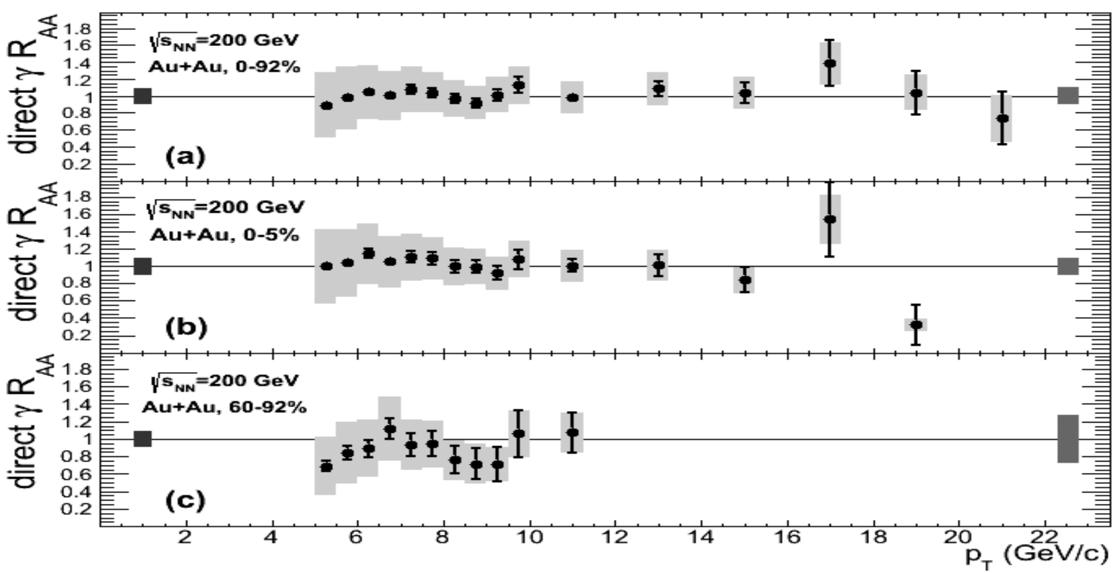
1. Sources of direct photons
2. Photon emission rates
3. Hydro evolution & QGP formation time
4. E-b-E fluctuation and high order harmonics

Sources of Direct photons

F.M. Liu, T.Hirano, K.Werner, Y. Zhu, Phys.Rev.C79:014905,(2009)

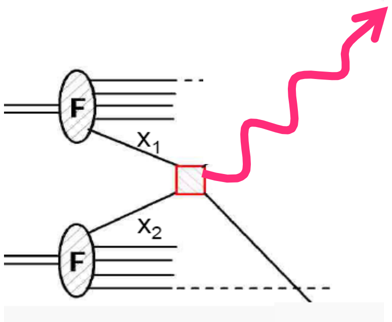


PHENIX,
Phys. Rev. Lett.
109, 152302 (2012)



Main sources of Direct photons

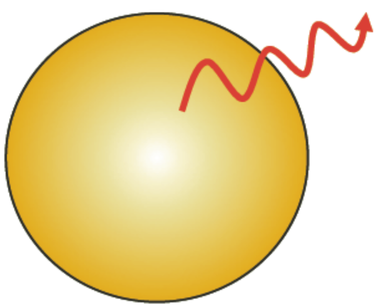
1. Prompt photons at the early stage ➔ **zero v2**



$$\frac{d\sigma^{\text{Prompt}}}{dy d^2 p_t} = \sum_{ab} dx_a dx_b G_{a/p}(x_a, M^2) G_{b/p}(x_b, M^2) \frac{\hat{s}}{\pi} \frac{d\sigma}{d\hat{t}}(ab \to cd) \delta(\hat{s} + \hat{t} + \hat{u})$$

$$+ \sum_{c=q,g} \int dz_c \frac{d\sigma^c}{dy d^2 p_t} \frac{1}{z_c^2} D^0_{\gamma/c}(z_c, Q^2)$$

2. Thermal photons from the plasma ➔ **v2, later and outer makes bigger**



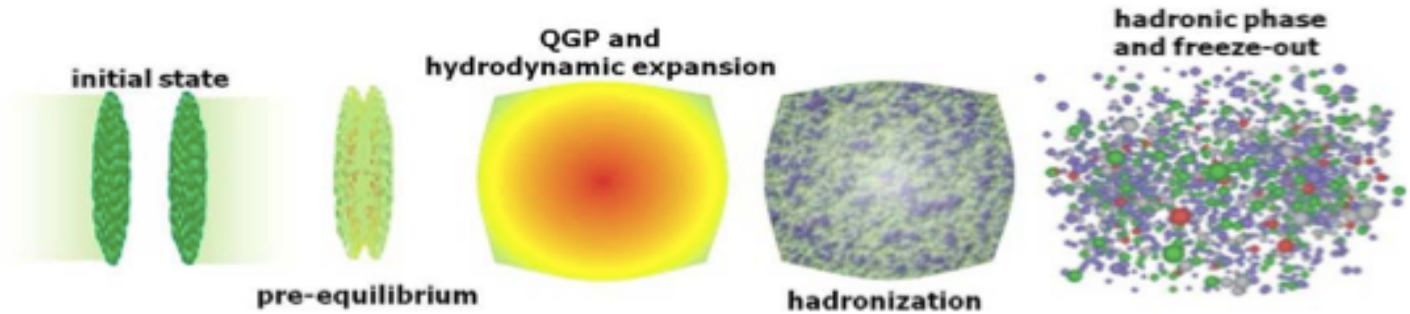
$$\frac{dN^{\text{thermal}}}{dy d^2 p_t} = \int d^4 x \Gamma_{\text{thermal}}(E^*, T), \quad E^* = p^\mu u_\mu$$

$$\Gamma_{\text{thermal}}(E^*, T) = f_{\text{QGP}} \Gamma_{\text{QGP}\to\gamma} + (1 - f_{\text{QGP}}) \Gamma_{\text{HG}\to\gamma}$$

.

f_{QGP} : QGP fraction

Space-time evolution $\varepsilon, u^{\mu}, s, B, \ldots(\tau, x, y, z)$



Initial condition: Glauber model or event generator $T^{\mu\nu}_{\rm hydro}(\tau_0, \vec{r})$ τ_0

Evolution: $\partial_\mu T^{\mu\nu} = 0$ EoS: 1st -order phase transition

EoS: Lattice QCD (S. Borsanyi, arXiv: 1007.2580)

Freeze-out: $e^{th} = 0.08 \mathrm{GeV/fm^3}$ or $T^{th} \sim 100 \mathrm{MeV}$

AuAu at 200 GeV, T.Hirano, et al, PRC77, 044909(2008)

PbPb at 2.76 TeV, EPOS, K.Werner, et al, PRC85, 064907 (2012)

pp at 7TeV, EPOS, K.Werner, et al. Phys. Rev. Lett. 106(2011) 122004.

Thermal photon emission rates

$$\Gamma^{\mathrm{QGP}\to\gamma}(E^*,T)=\frac{6}{9}\frac{\alpha\alpha_s(T)}{2\pi^2}T^2\frac{1}{e^{E^*/T}+1}C_{\mathrm{AMY}}$$

$q\bar{q}\to g\gamma, qg\to\gamma q, LPM$

$\Gamma^{\mathrm{HG}\to\gamma}(E^*,T)$: Kapusta et al, 1991

R. Rapp et al, 2004   Hadronic form factor

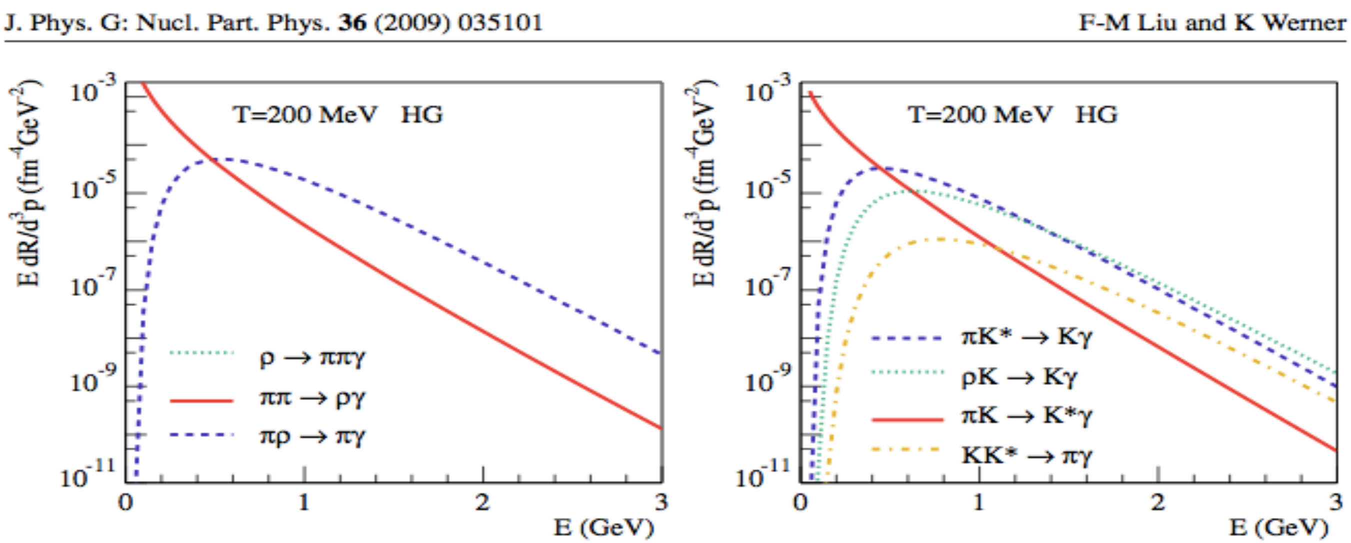
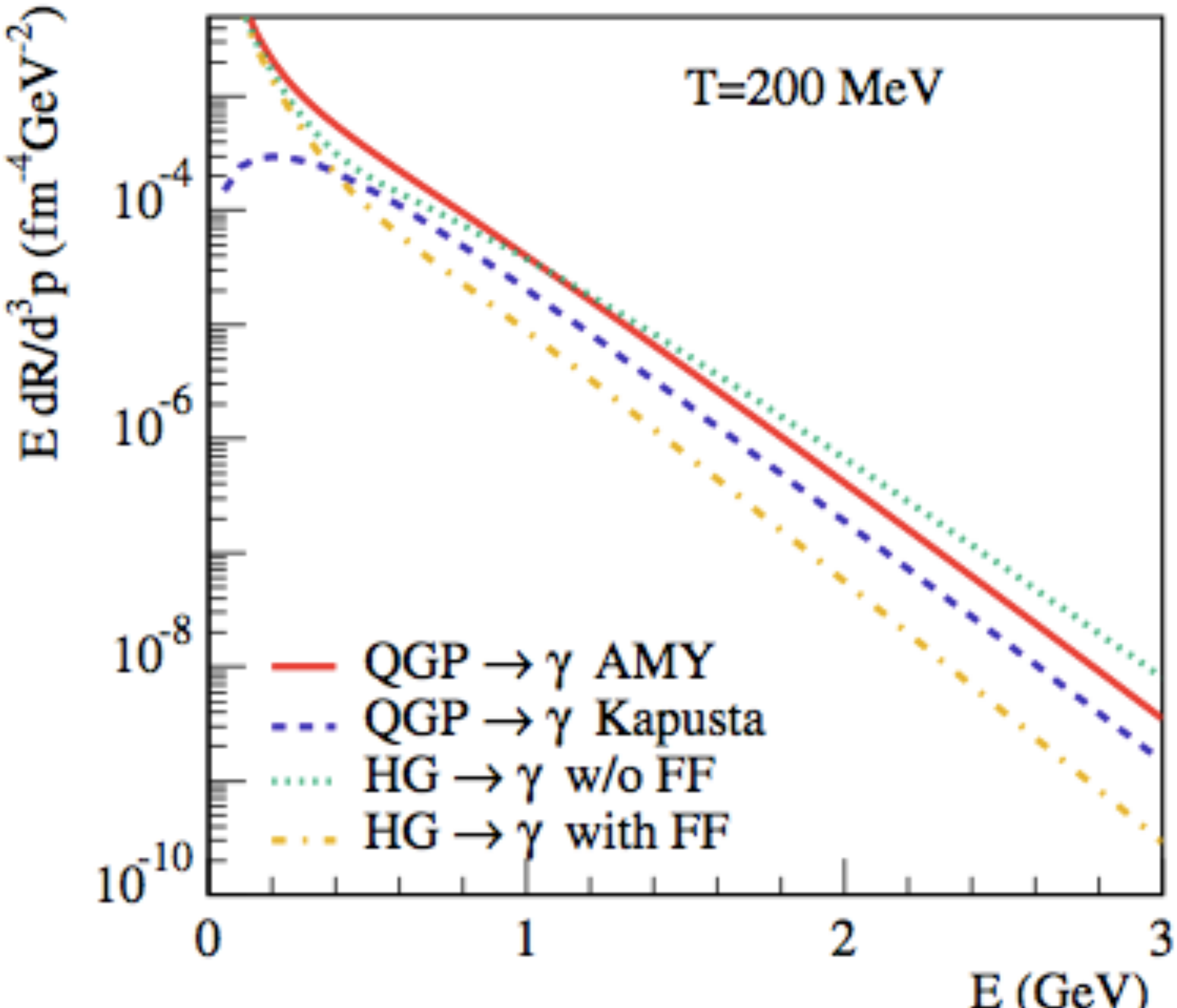


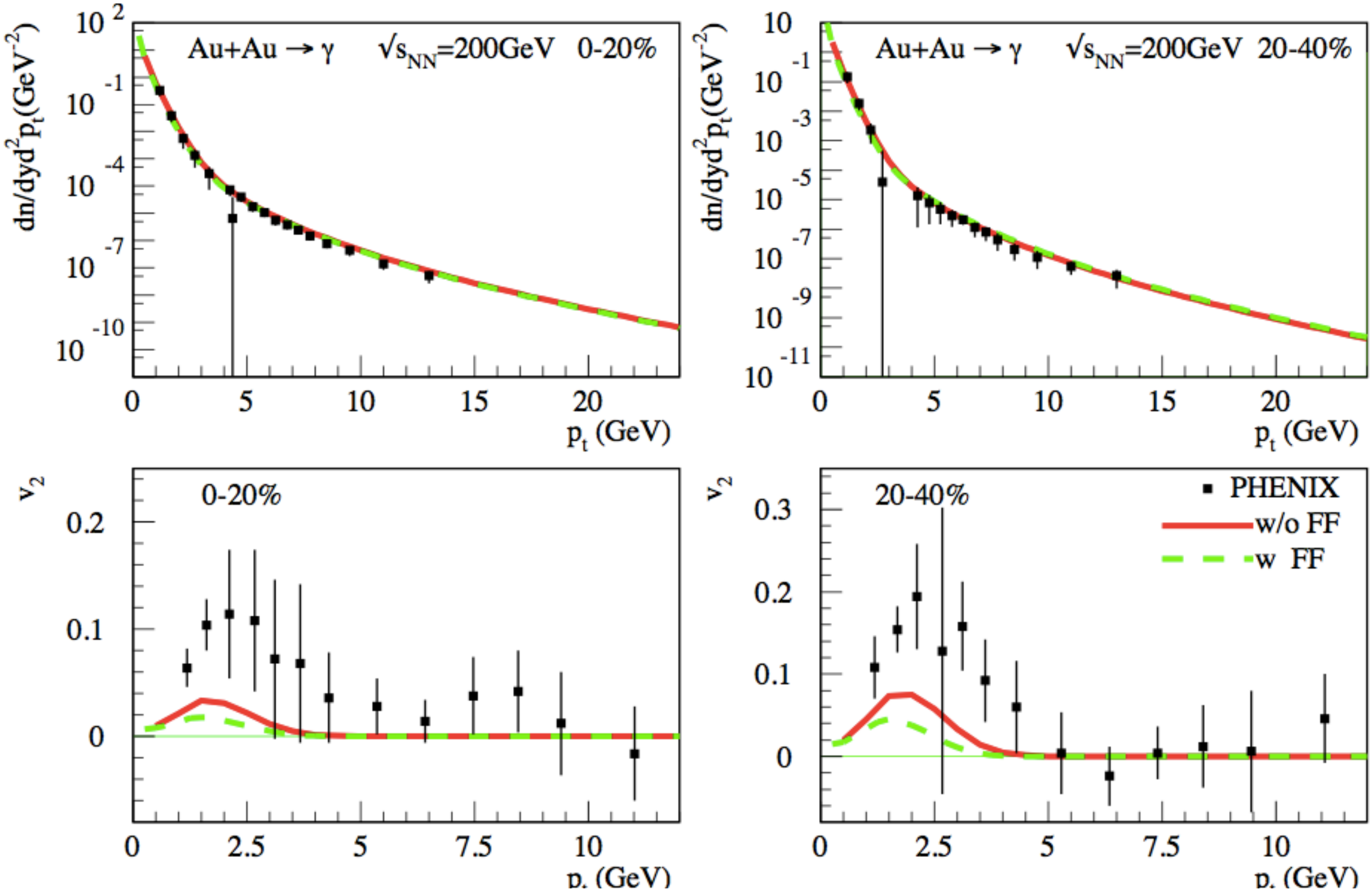
Figure 1. Photon emission rates from a HG from the different reactions (bare graphs, no hadronic form factor).

Thermal photon emission rates

Hadronic form factor is a delicate issue.



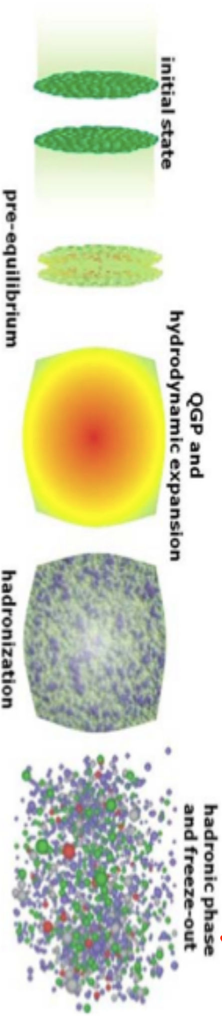
Effect of Hadonic FF



No need FF. v2 is still too small!

Space-time evolution

Shuryak, PRL (1992). Start from glue-dominate sys. PDF
F.M. Liu, arXiv: 1212.6587 longitudinal color tubes



0 Prompt γ like in pp, zero v_2

τ_g *local thermalization*

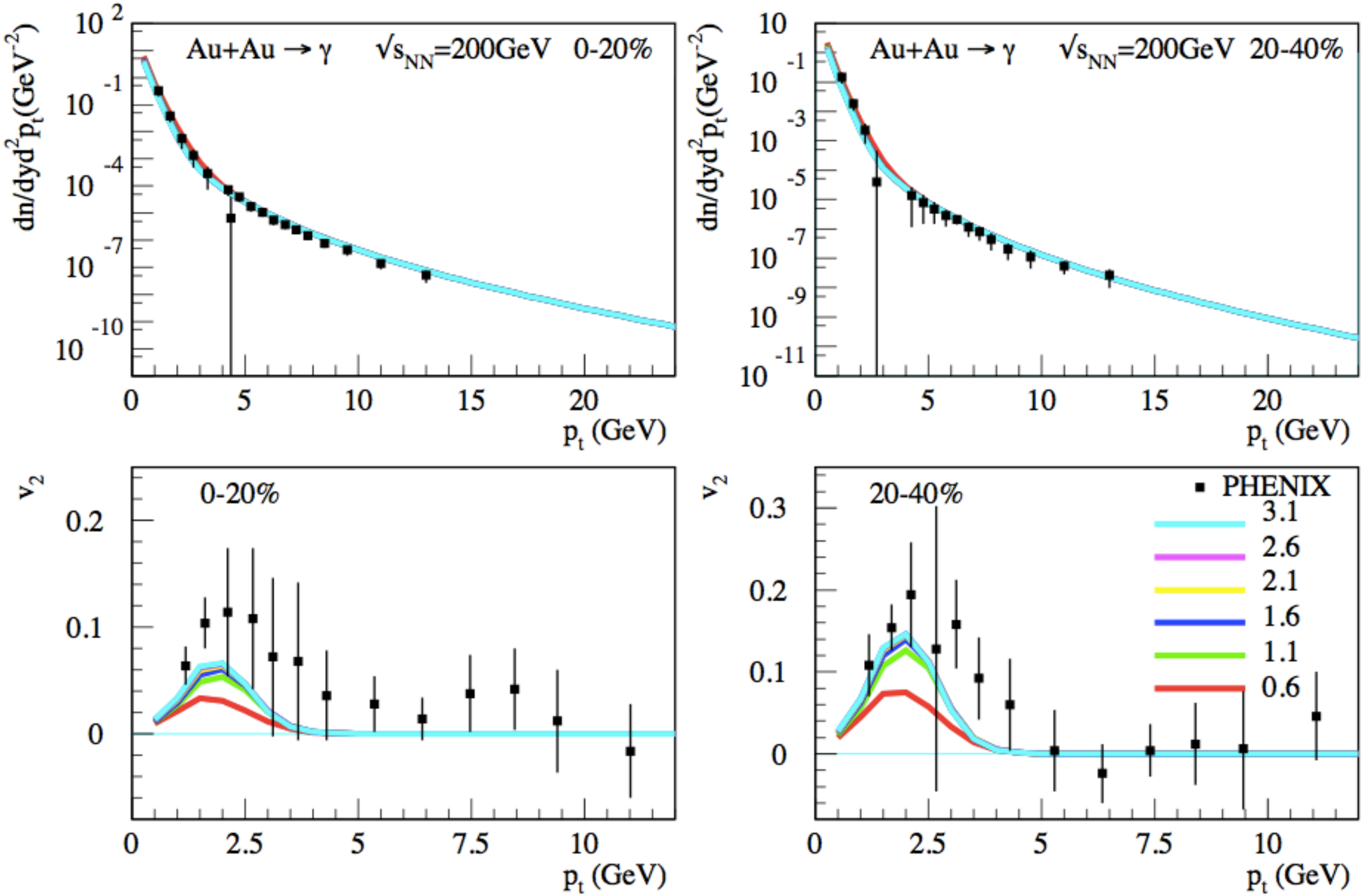
τ_{QGP} $\Gamma_\gamma = \xi\Gamma_{Comp} + \xi^2\Gamma_{anni}$ $\varepsilon \sim d_g T^4 + \xi d_q T^4$ ξ: Quark fugacity

$\Gamma^{QGP\to\gamma}(E^*, T)$: AMY rate

$\Gamma^{HG\to\gamma}(E^*, T)$: R. Rapp et al, 2004, no FF

Take photon data to estimate τ_{QGP}

QGP formation time

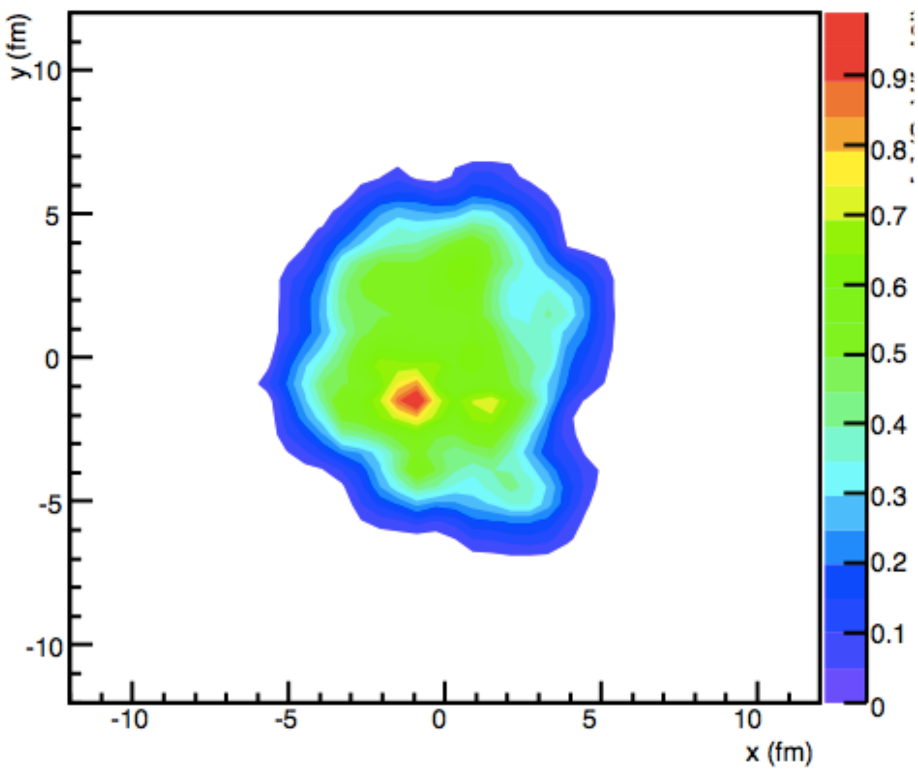


What do we learn

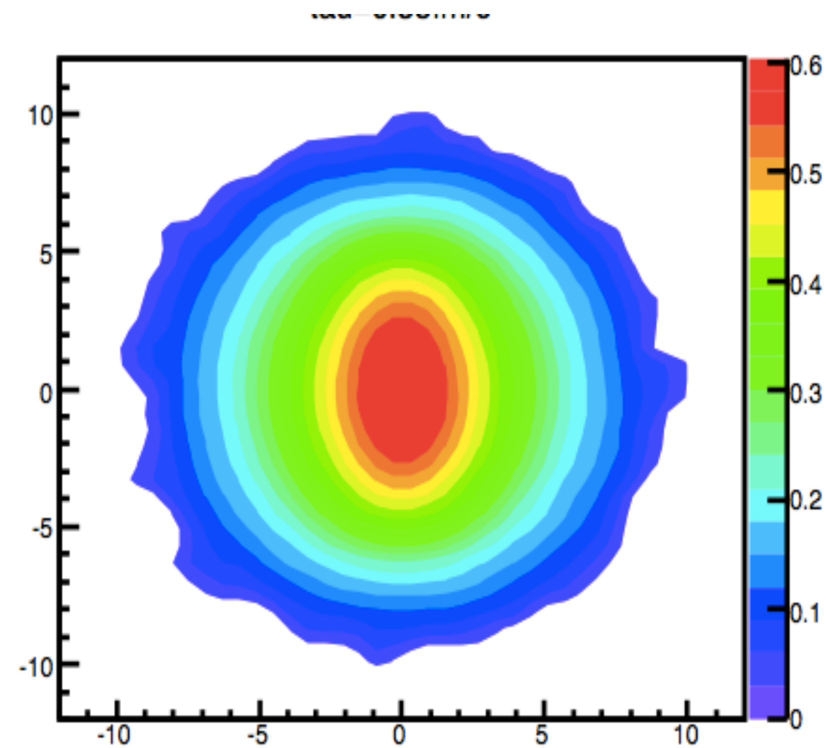
- Pt spectrum of direct photons are not sensitive either to hadronic form factor or to QGP formation time.
- Elliptic flow is more sensitive.
- For $\tau_0 = 0.6$ fm/c, τ_{QGP} is later than 1fm/c.
- Other τ_0? Fluctuation effect?

Pb+Pb at 2.76TeV with EPOS

- E-by-E initial condition



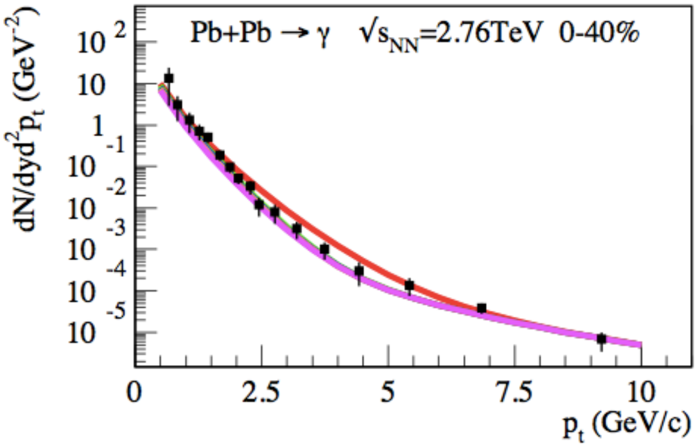
- Averaged initial conditon

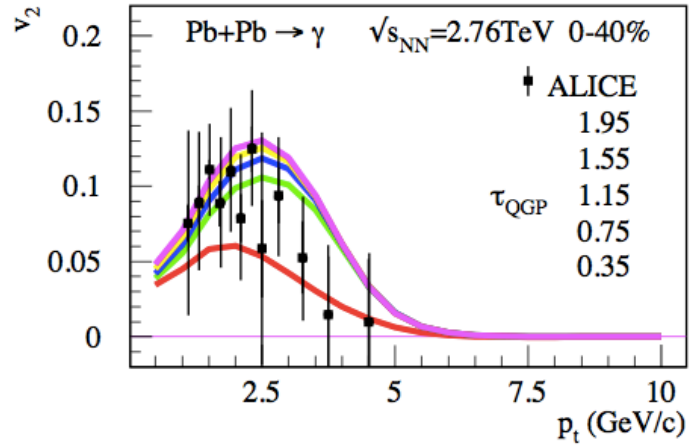


K.Werner, et al, PRC85, 064907 (2012)

EPOS hydro for PbPb 2.76TeV

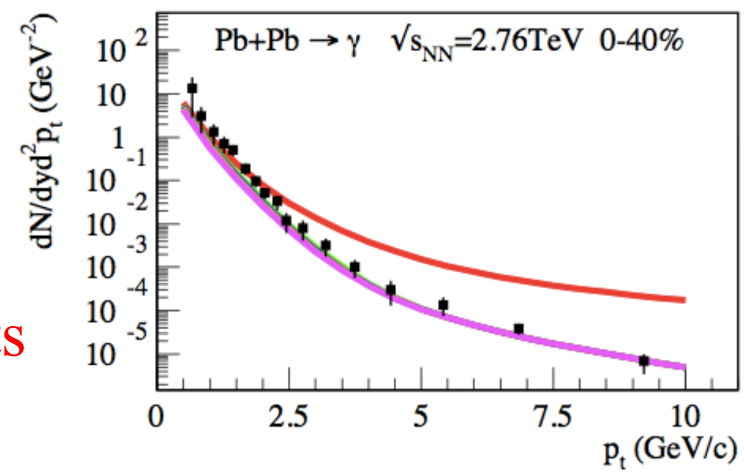
- Averaged initial condition, fixed EP $v_2 = \langle \cos 2\phi \rangle$

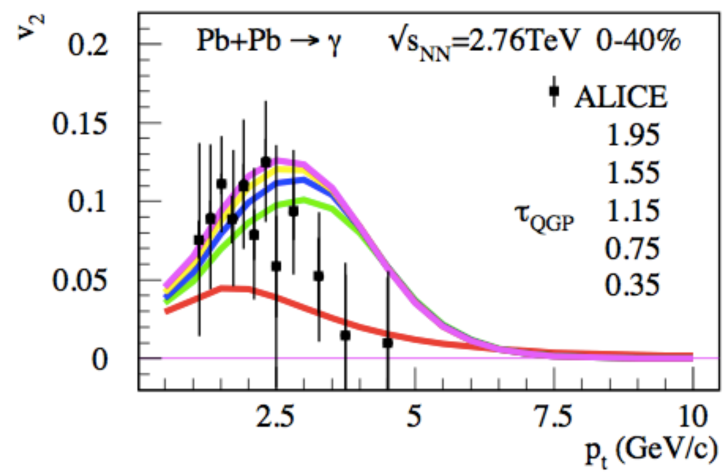




- E-by-E case $v_n = \sqrt{\langle \cos n\phi \rangle^2 + \langle \sin n\phi \rangle^2}$

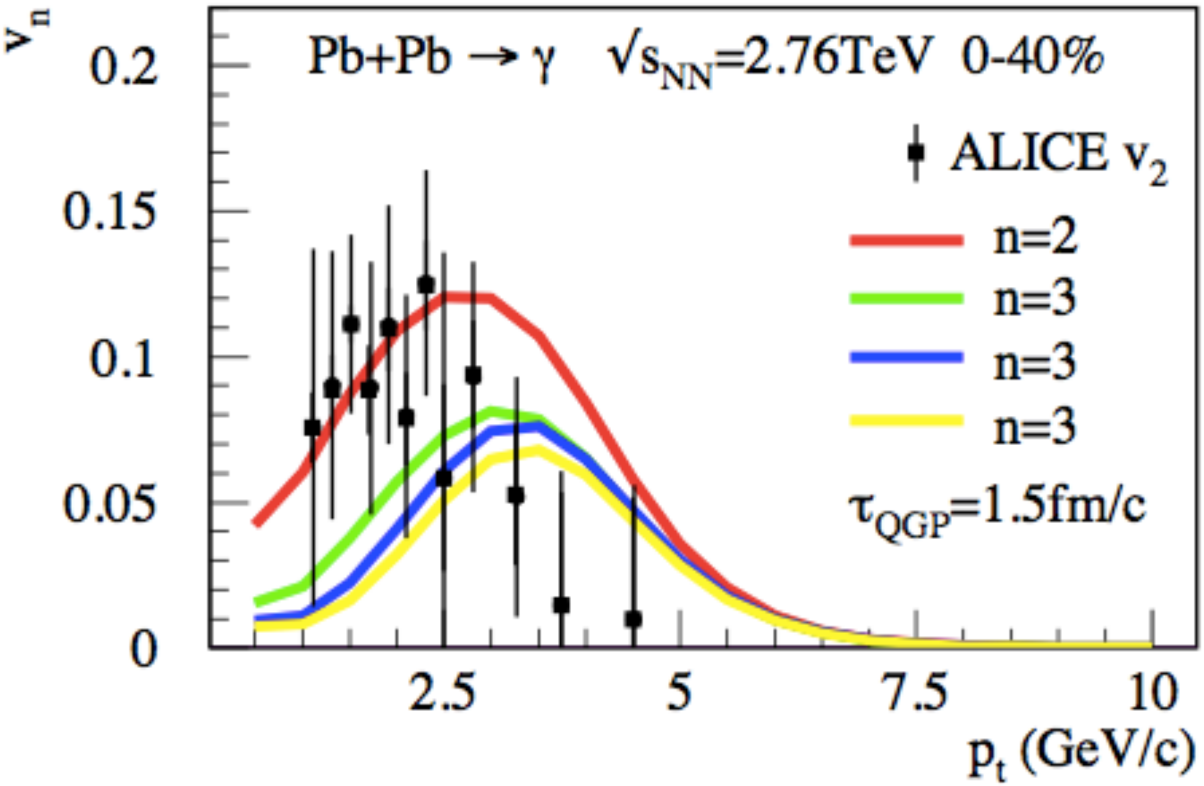
Hot spots





High order Flow harmonic

- E-by-E fluctuation



Summery: AA➔ photons

- The large elliptic flow of directons looks explainable.

- Partonic phase: earlier (local) thermal equilibrium & later chemical equilibrium
  There is a stage dominant by gluons with little photon emission, before tau0.

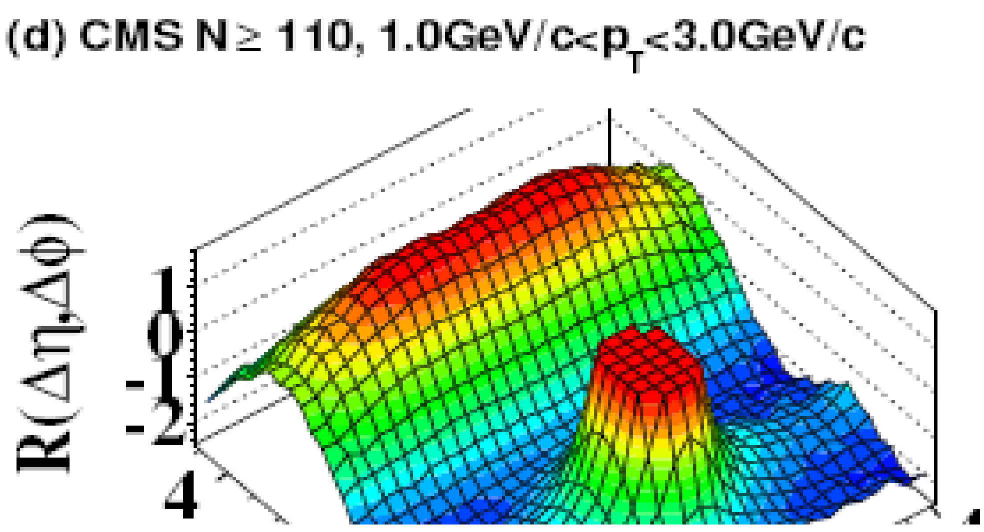
- Hadronic phase: more work is needed for emission rate

- PP → photons

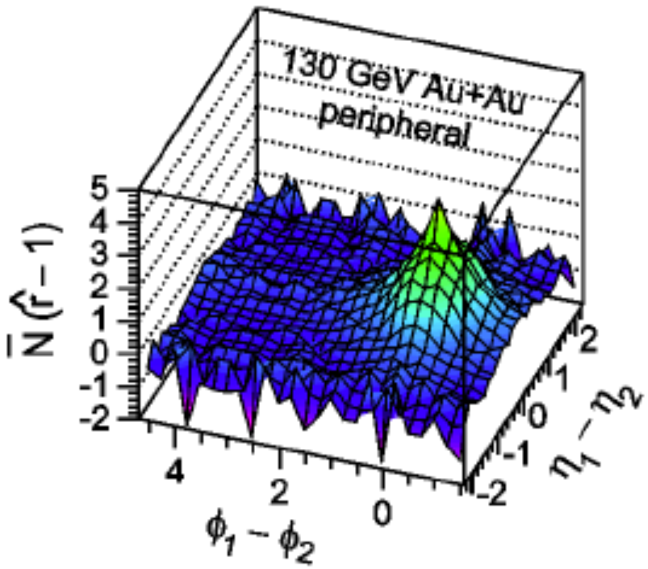
(motivated by ridge in pp and ppb)

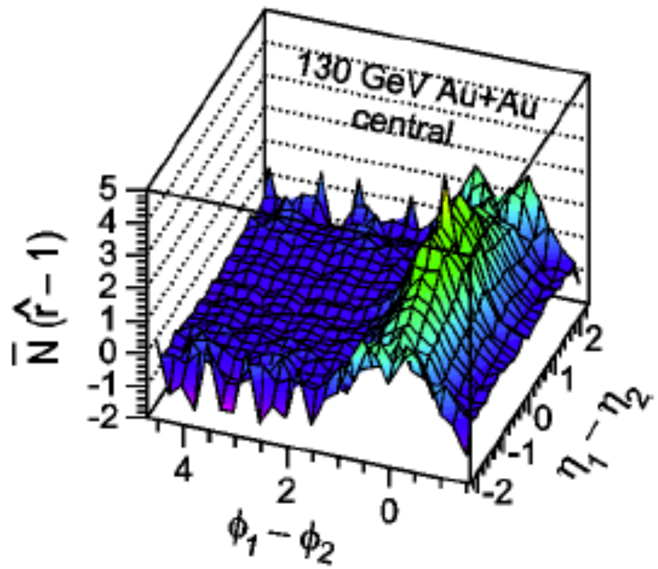
Can we see photons from QGP in pp?

Ridge in pp at 7TeV



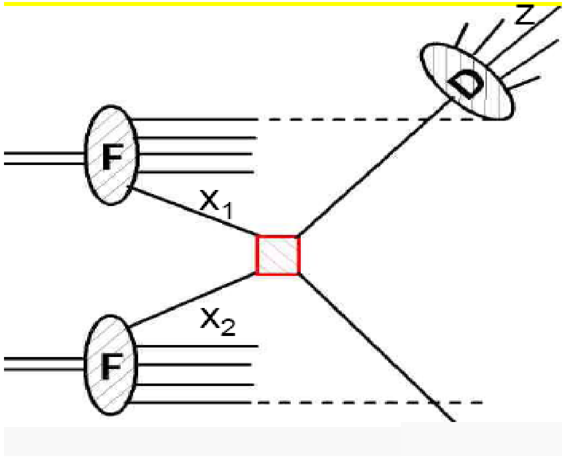
STAR Collaboration / Nuclear Physics A 757 (2005) 102–183



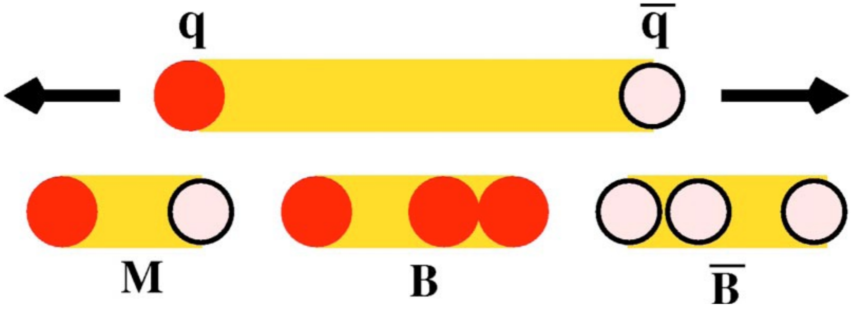


Modeling pp collisions

Hard sector:

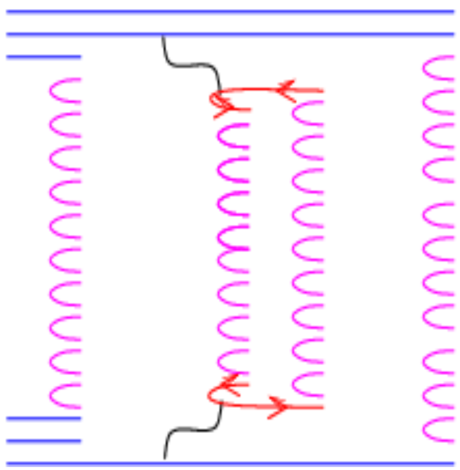


Soft sector:



Multiple scattering in pp (EPOS)

Multiple elementary interactions (Pomerons) happen in parallel!
Both soft and hard strings are accommodated in Pomerons!



Energy conservation
Flavour conservation
Pomeron number has a distribution

NeXuS:

H.J.Drescher *et al*, Phys.Rept.**350**,93 (2001);

F.M.Liu *et al*, PRD **67**, 034011 (2003).

Condition of particle production:

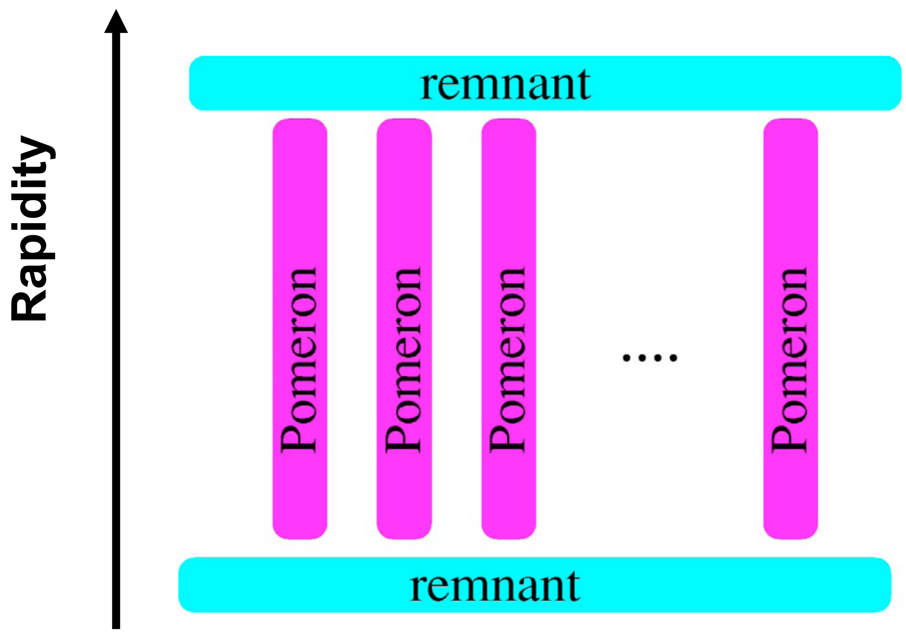
$$x^{+}x^{-}\sqrt{s} > E_{0} \sim 1\text{GeV}$$

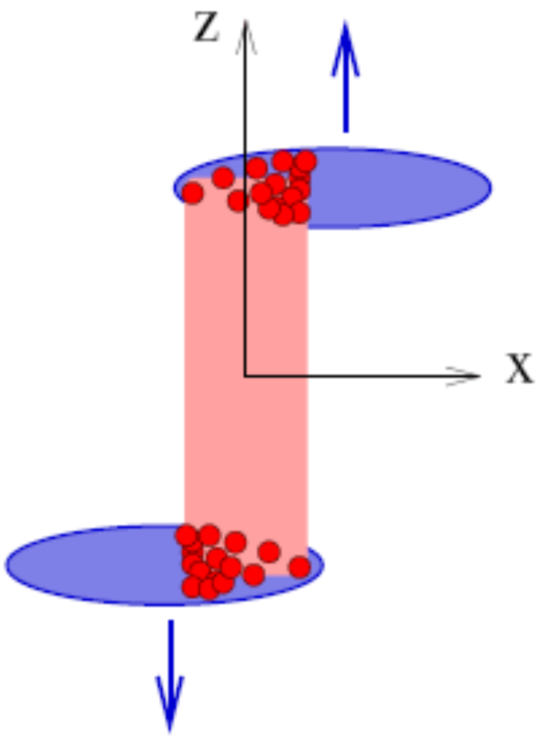
$$\sqrt{s} = 7\text{TeV}$$

Gluons at small x become active!

Many secondary interactions!

Similarity between pp and AA





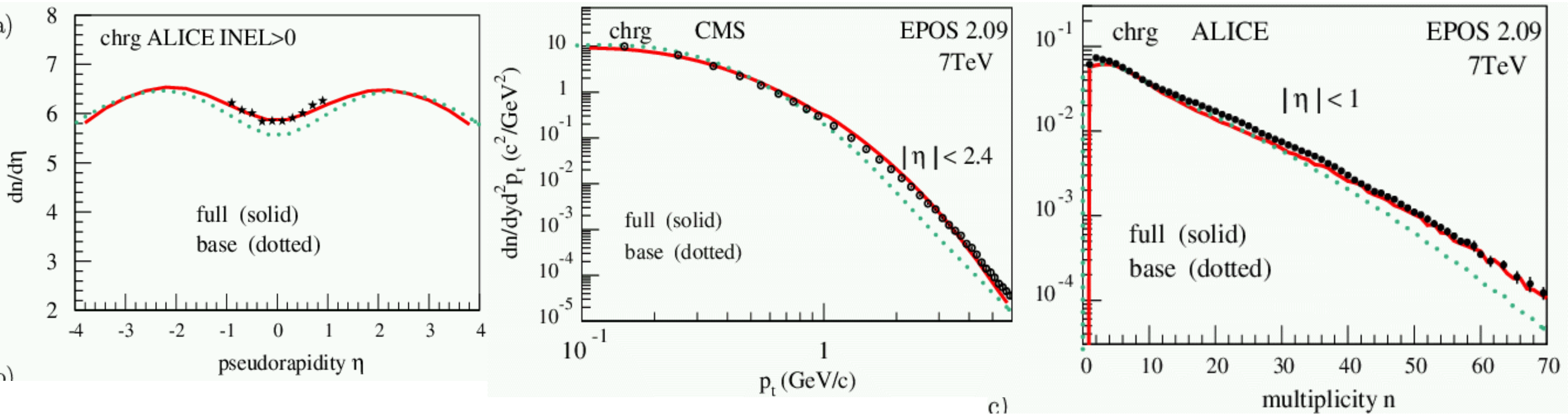
Centrality in AA: Glauber model
in pp: Gribov-like theory

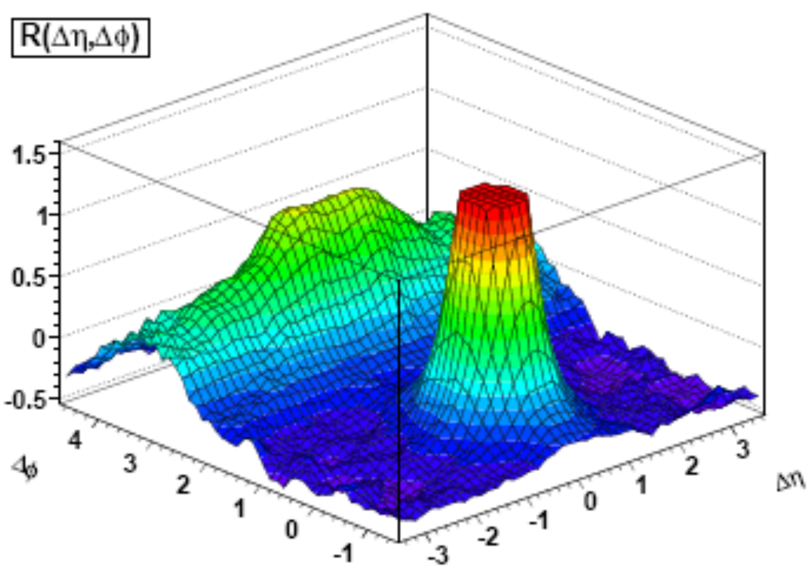
Pomerons

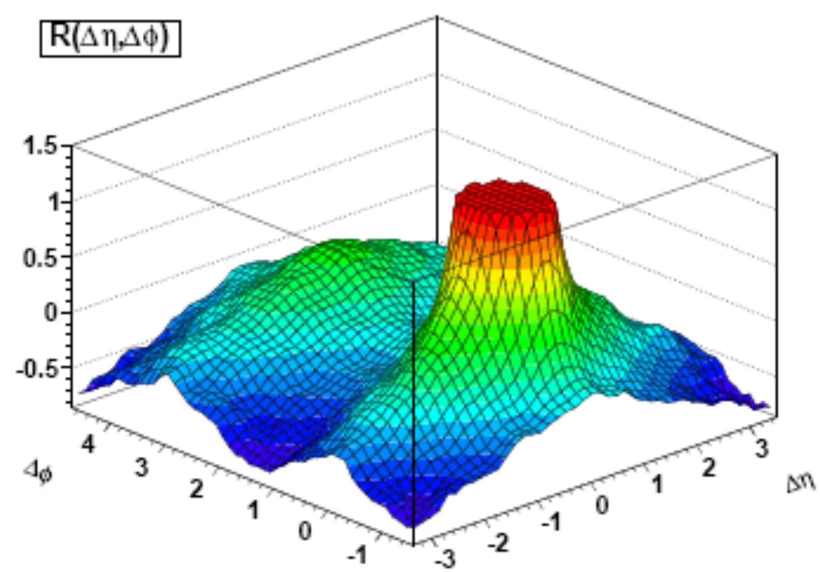
Strings in pp makes the initial condition for hydro!

Constrain plasma with hadron data

K.Werner, Iu.Karpenko, T.Pierog, Phy.Rev.Lett.106, (2011) 122004.

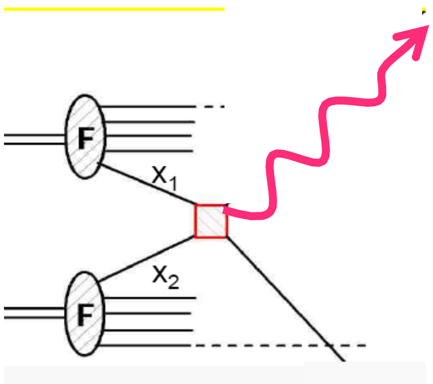






Direct photon production in pp

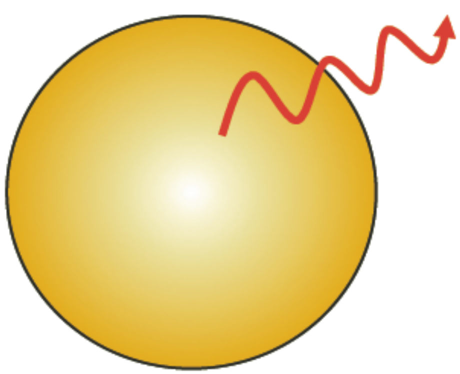
1. Prompt photons at the early stage



$$\frac{d\sigma^{\text{Prompt}}}{dy\,d^2p_t} = \sum_{ab} dx_a dx_b G_{a/p}(x_a, M^2) G_{b/p}(x_b, M^2) \frac{\hat{s}}{\pi} \frac{d\sigma}{d\hat{t}}(ab \to cd)\,\delta(\hat{s}+\hat{t}+\hat{u})$$

$$+ \sum_{c=q,g} \int dz_c \frac{d\sigma^c}{dy\,d^2p_t} \frac{1}{z_c^2} D^0_{\gamma/c}(z_c, Q^2)$$

2. Thermal photons

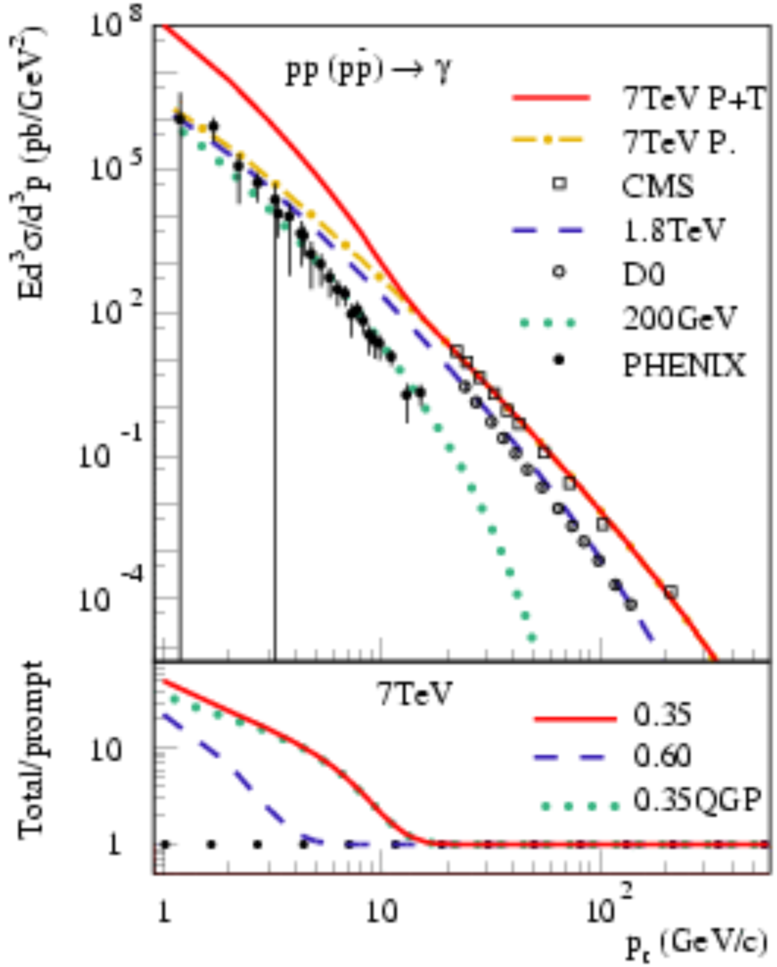


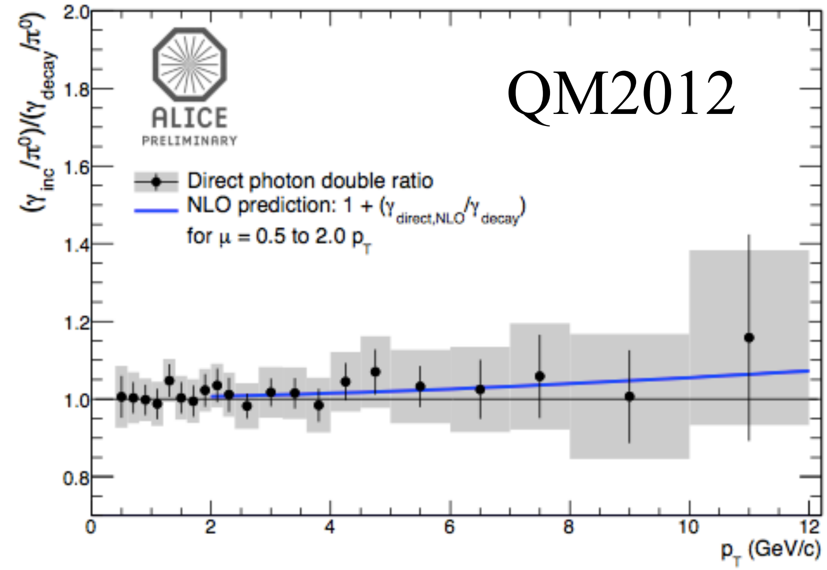
$$\frac{dN^{\text{thermal}}}{dy\,d^2p_t}(\nu) = \int d^4x\,\Gamma_{\text{thermal}}(E^*, T), \quad E^* = p^\mu u_\mu$$

$$\frac{d\sigma^{\text{thermal}}}{dy\,d^2p_t}(\text{MB}) = \sigma_{pp}^{\text{inel}} \cdot \sum_{\nu} \frac{dN^{\text{thermal}}}{dy\,d^2p_t}(\nu) \cdot \text{Prob}(\nu)$$

Direct photons from pp

F.M.Liu, K.Werner,Phys.Rev.Lett.106:242301,(2011)



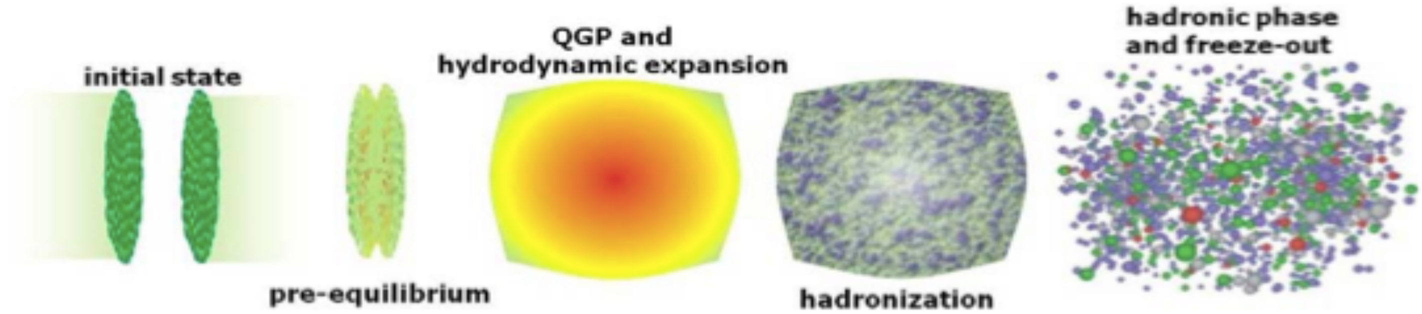


Flow doesn't mean QGP formation.

Consistent with AA (big v2)!

The excess at low pt tells QGP formation!

Conclusion



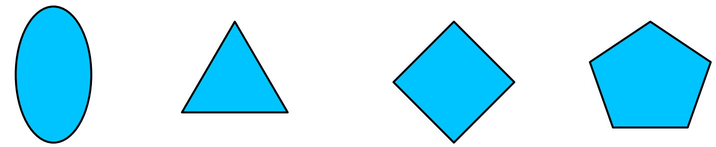
- A simple picture that $\tau_0 = \tau_{QGP}$ doesn't work.
- A gluon(-dominant) region appears in the early stage.
- Ridge in pp and pA tells something.

To get known, we'd better check spontenously
photons, identified hadrons, jet quenching ,…

Thank you!

High order harmonics in E-b-E

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + \sum_n 2v_n \cos n(\phi - \psi_n)\right]$$



- Experimentally, usually obtained via
  - RP, SP, PP,…. (planes)
  - Particle correlation (comulants)

- Averaged IC with $\psi_2 = 0$

$$v_2 = \frac{1}{N}\int_0^{2\pi} \frac{dN}{d\phi}\cos 2\phi \, d\phi = \langle \cos 2\phi \rangle$$

$\langle \cdots \rangle$: average over all particles in single event

- In E-b-E case, ψ_n vary.

However, it is easy to show

$$\langle \cos n\phi \rangle = v_n \cos n\psi_n$$

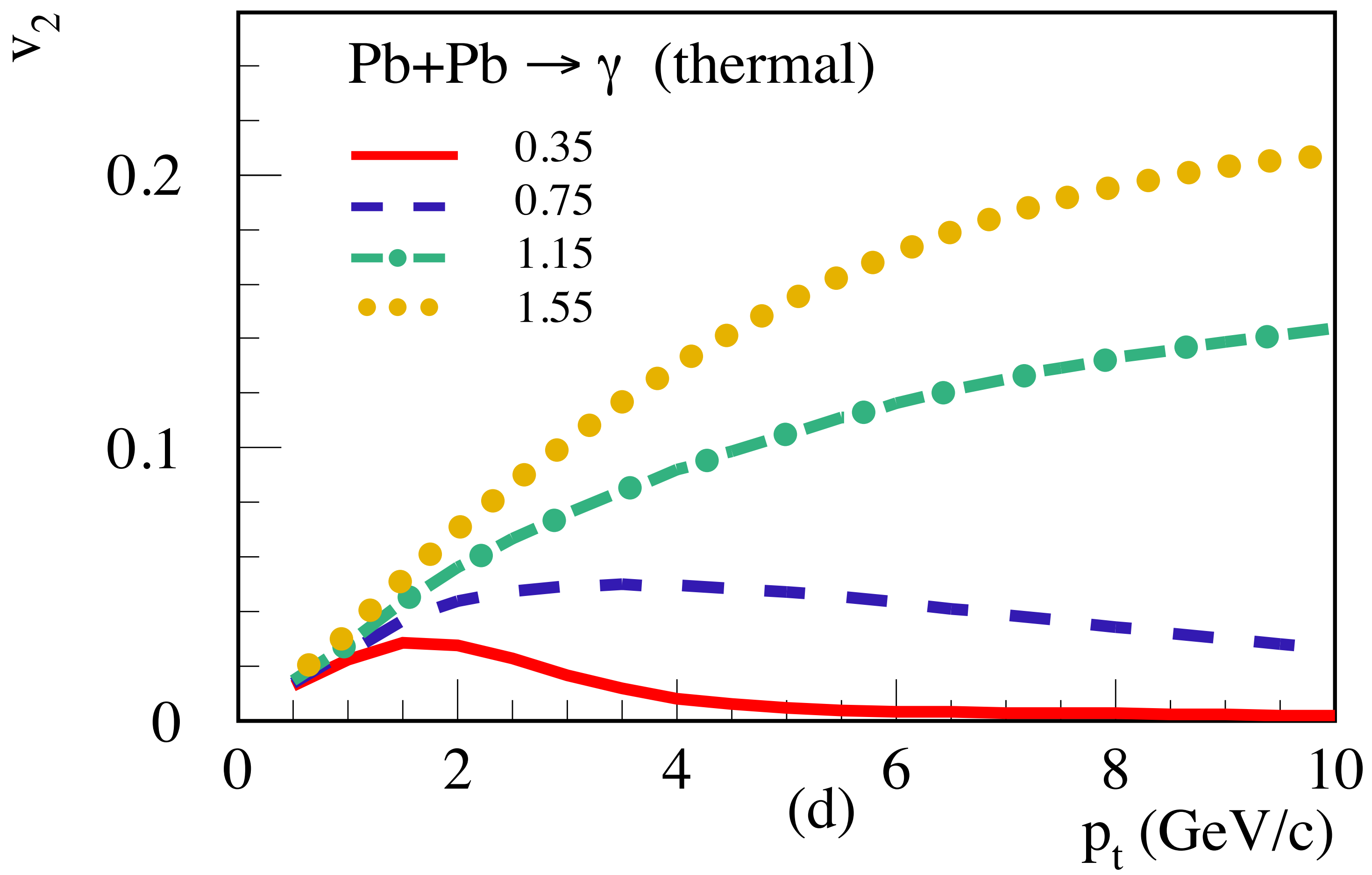
$$\langle \sin n\phi \rangle = v_n \sin n\psi_n$$

So without known ψ_n, we can get for each event,

$$v_n = \sqrt{\langle \cos n\phi \rangle^2 + \langle \sin n\phi \rangle^2}$$

then event average.
Easy for both exp. and theo.!

thermal photon v2

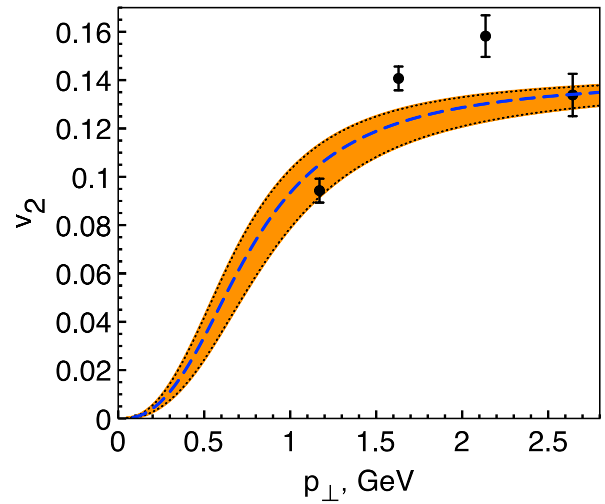


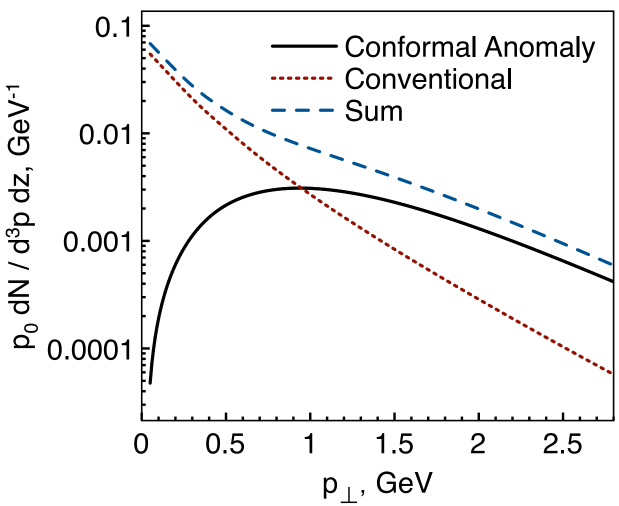
Flow generates with time, so does v2.

Suggestion 1: new photon sources

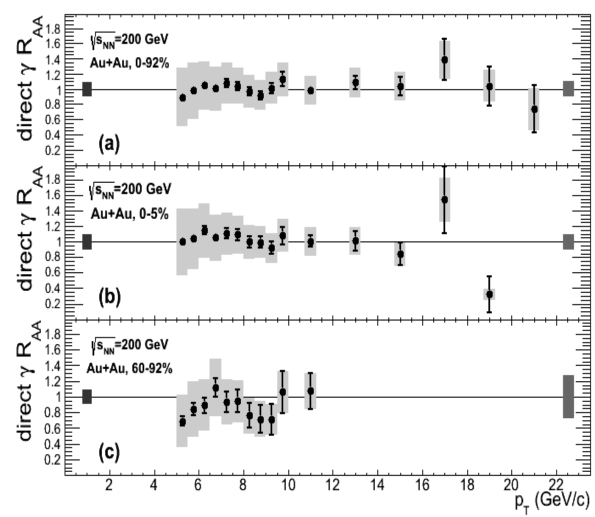
- Conformal anomaly as a photon source (Basar, Kharzeev, Skokov, PRL2012)

$$q_0 \frac{d\Gamma_B}{d^3 q} = 2\left(\frac{g_{\sigma\gamma\gamma}}{\pi f_\sigma m_\sigma^2}\right)^2 \times \frac{(B_y^2 - B_x^2) q_x^2 + q_\perp^2 B_x^2}{\exp(\beta q_0) - 1} \rho_\theta(q_0 = |\boldsymbol{q}|).$$



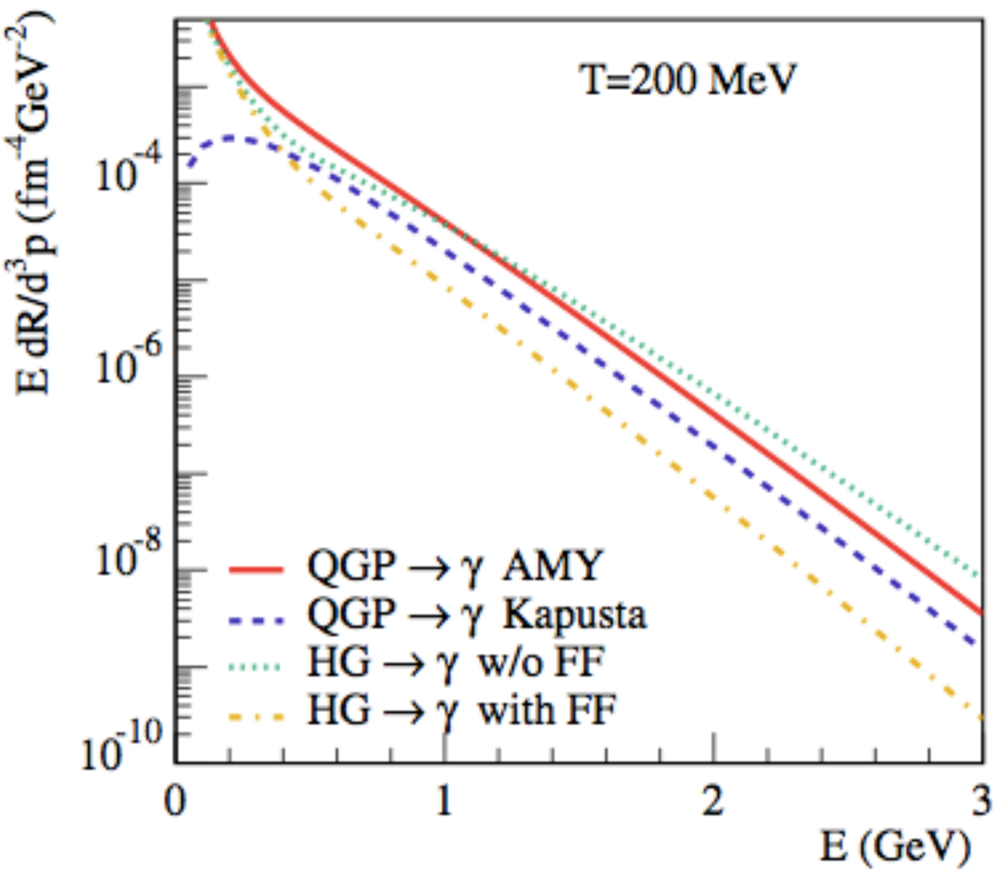


Problem: Not vanish at large pt.



PHENIX, Phys. Rev. Lett. 109, 152302 (2012)

Thermal photon emission rates



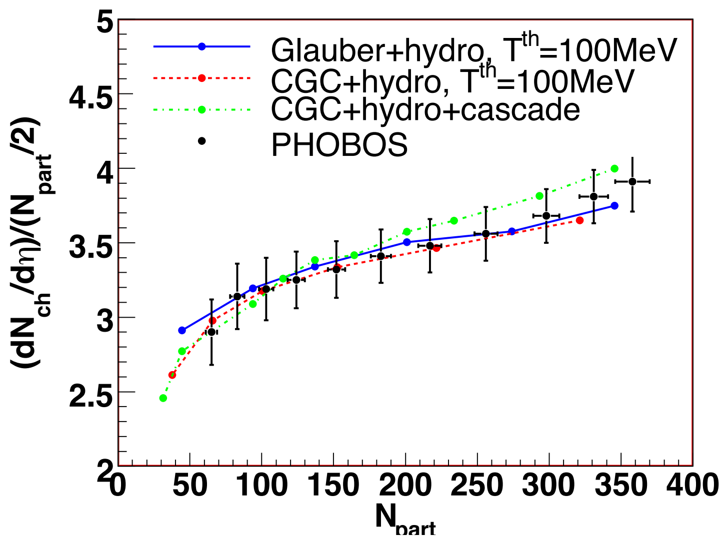
Hadronic Form Factor

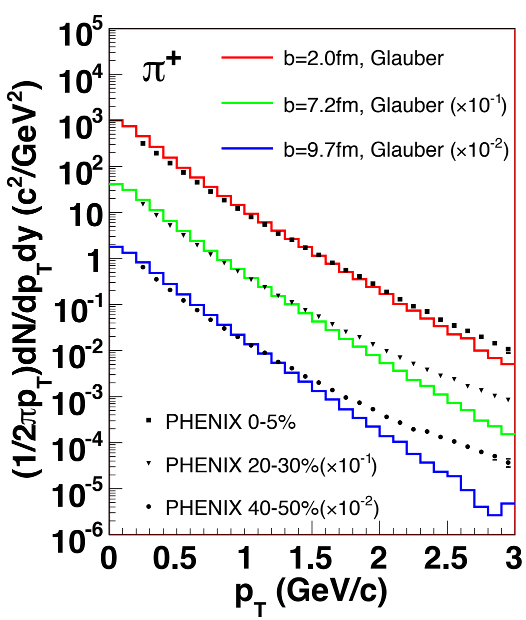
R. Rapp et al, 2004

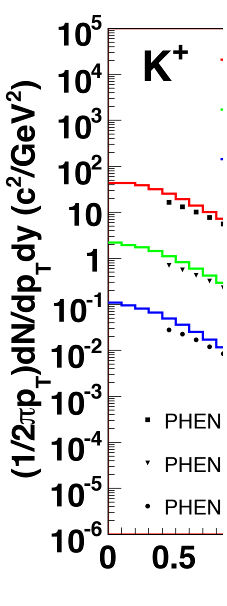
$$F(\bar{t}) = \left(\frac{2\Lambda^2}{2\Lambda^2 - \bar{t}} \right)^2$$

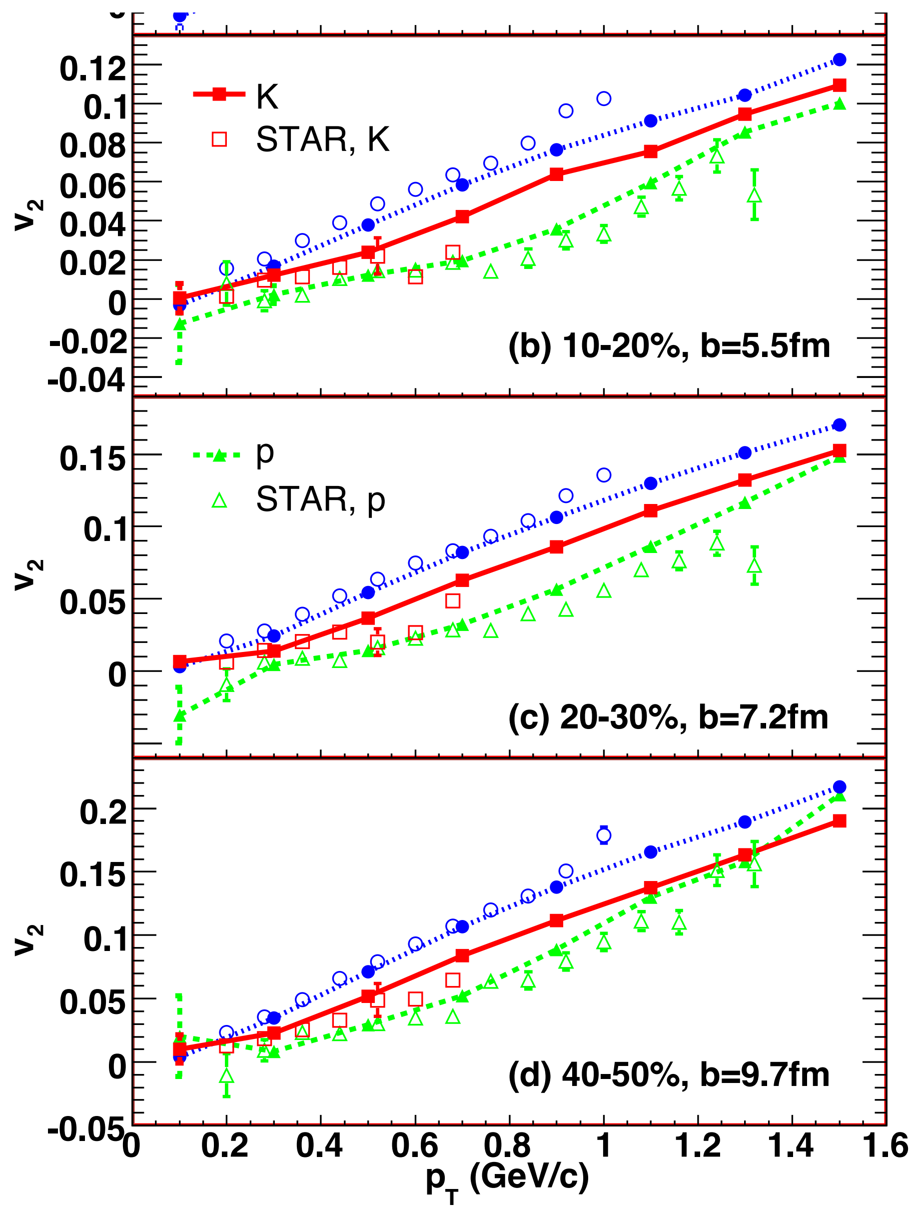
$$\bar{t} = -2Em_X$$

Constrain system evolution (RHIC)







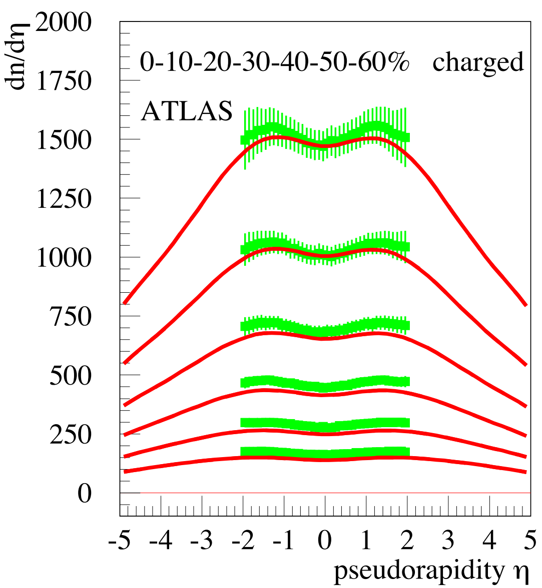


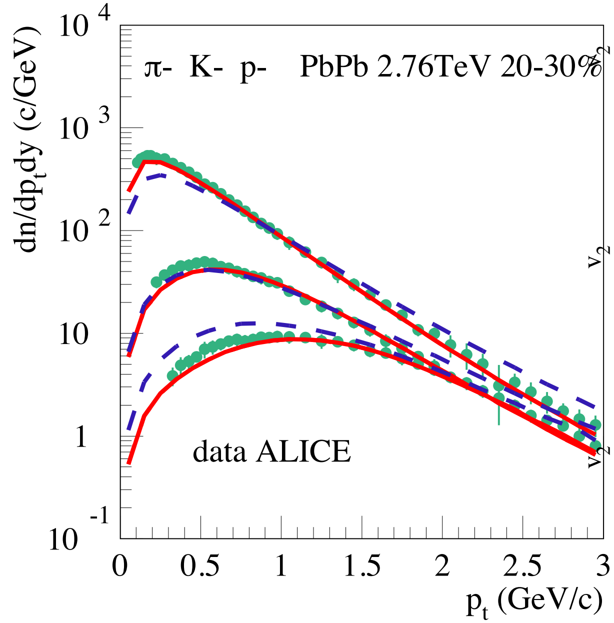
Constrain system evolution (LHC)

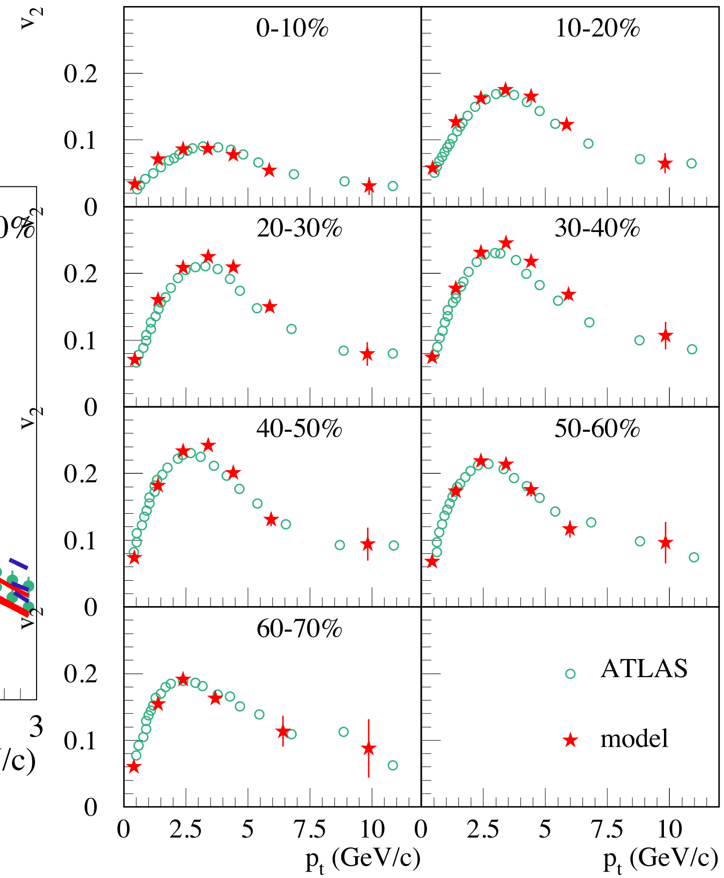
K.Werner, et al, PRC85, 064907 (2012)

Hydro equation: $\partial_\mu T^{\mu\nu} = 0$

Parameters fixed with hadron data







Tau0=0.35 fm/c.

Hadron data is more sensitive to freeze-out than to initialization.