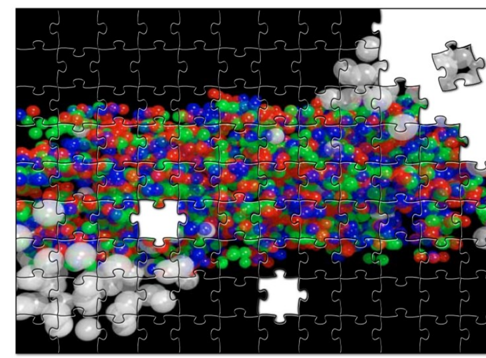
Filled and missing pieces in direct photon measurements in heavy ion collisions



Takao Sakaguchi
Brookhaven National Laboratory

Preface

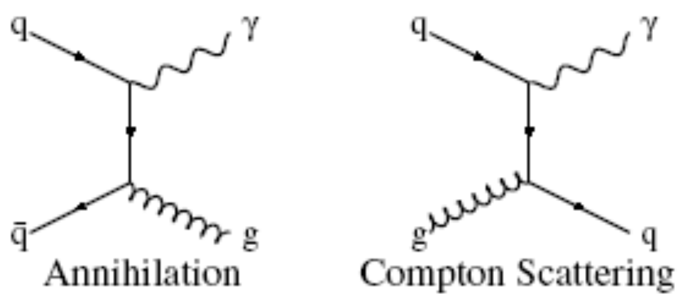
- I will mainly talk about EM radiation, specifically on (virtual) photons
- Prejudice and speculation are apparently existing
- Apology in advance if your theoretical/experimental works are not mentioned
  - *I appreciate for all the work related to EM radiation in HI physics, because they are not easy to get at all.*

Why photons?

- Photons are emitted from all the stages throughout the heavy ion collisions
- Photons escape the systems unscathed by strong interaction
- Therefore, photons carry out information about the states they are emitted

Photon production and rate

- Photon production rate can be written by photon self energy and Bose distribution
- At higher p_T (E>>T), the slope of the distribution tells the temperature of the system
  - When including hard component, one may have to use Tsallis function instead of Bose (McLerran and Schenke, 1504.07223)
- Absolute yield is dependent on production processes included
  - Self energy is weakly dependent on E/T



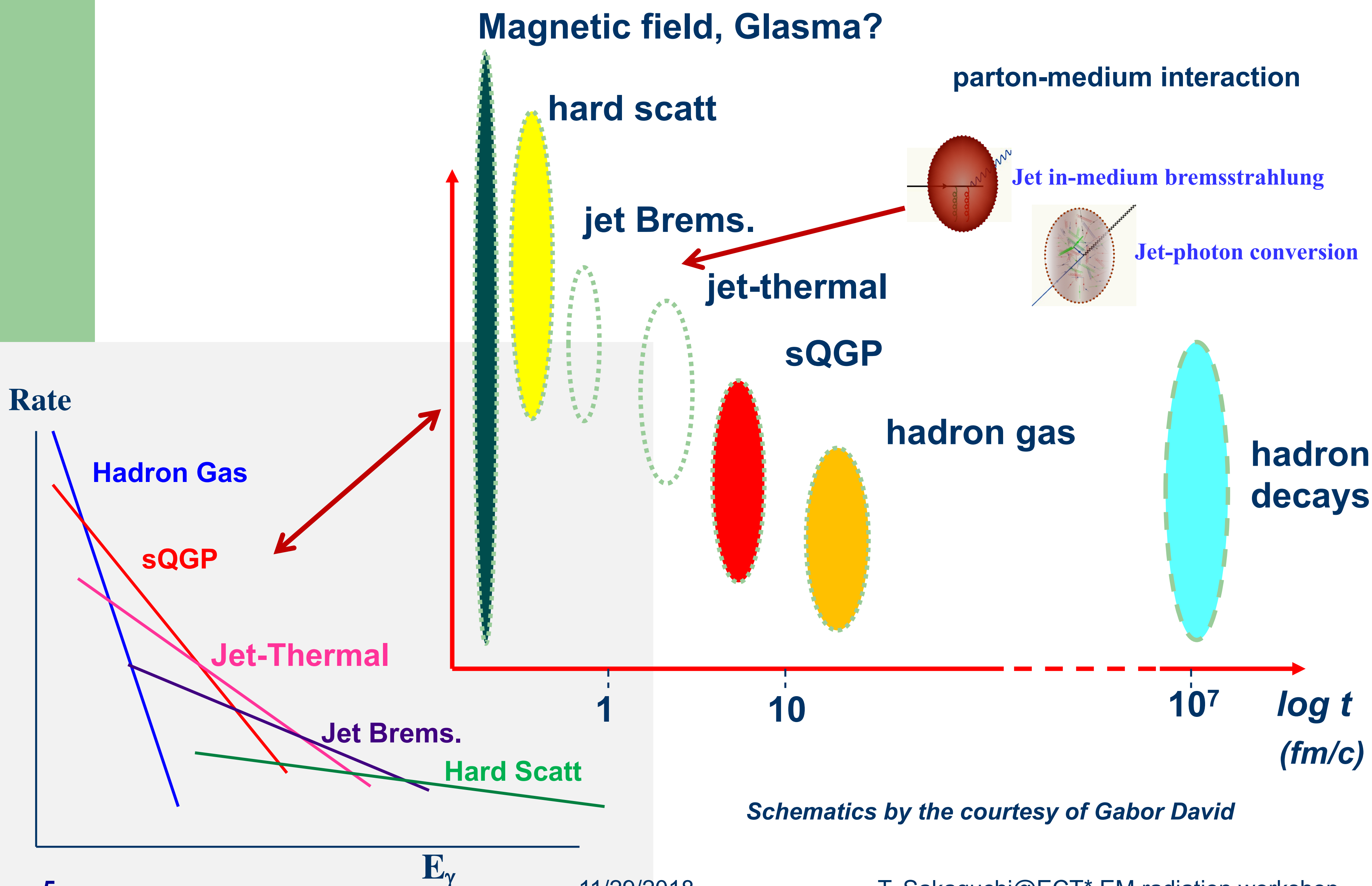
$$E\frac{dR_\gamma}{d^3p} = -\frac{\alpha_{em}}{\pi^2}\mathrm{Im}\Pi_{em}(\omega,k)\frac{1}{e^{E/T}-1}$$

Π_{em}: photon self energy

$$\mathrm{Im}\Pi_{em}(\omega,k) \approx \ln\left(\frac{\omega T}{(m_{th}(\approx gT))^2}\right)$$

QGP case:
Kapusta, Lichard, Seibert, PRD47, 4171 (1991)
Baier, Nakkagawa, Niegawa, Redlich, PRD45, 4323 (1992)

Photon production in a nutshell



Schematics by the courtesy of Gabor David

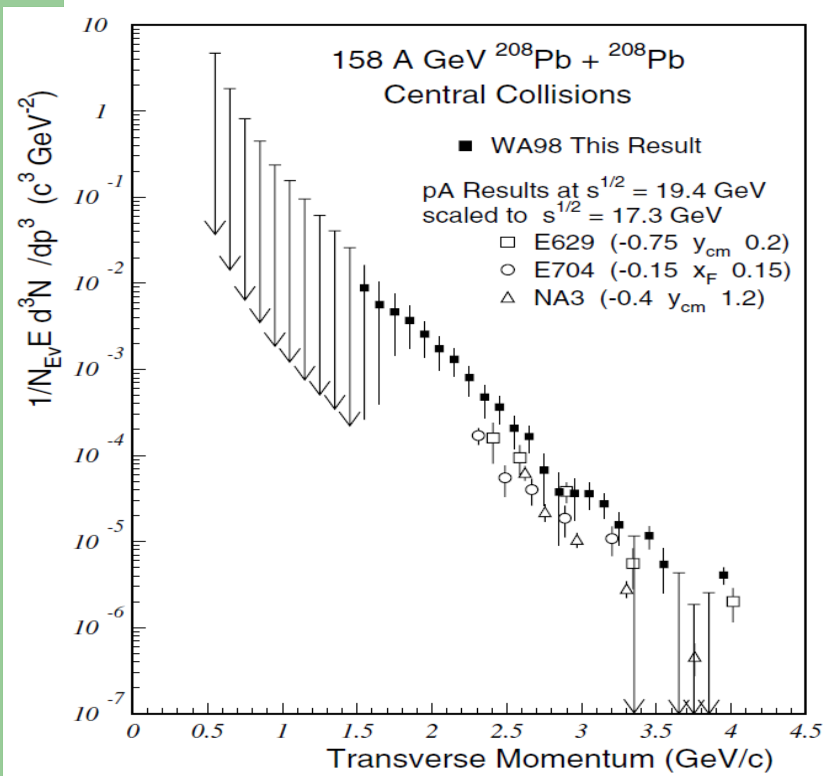
Various sources proposed

- More differential measurements would be needed to disentangle the photon production sources

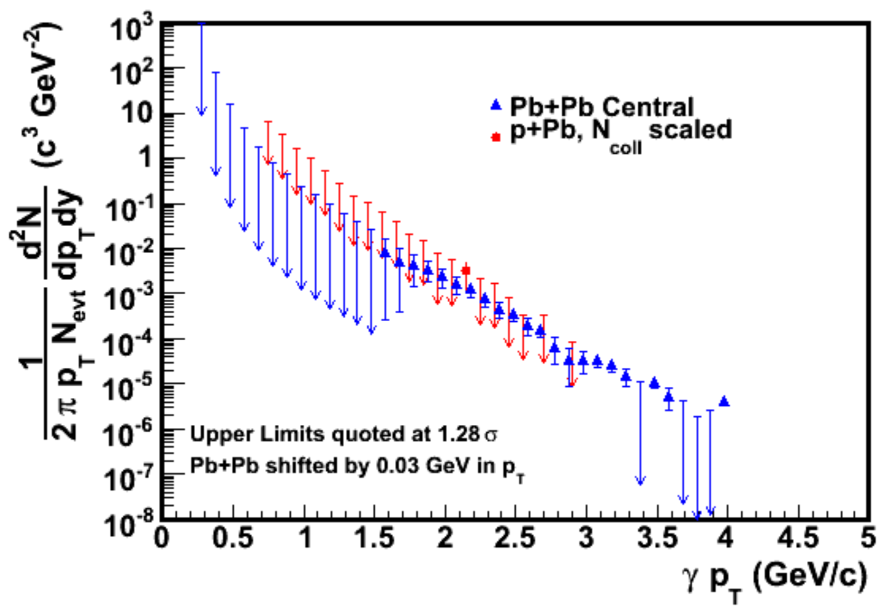
Sources	p_T	v_2	v_3	v_n t-dep.
Hadron-gas	Low p_T	Positive and sizable	Positive and sizable	→
QGP	Mid p_T	Positive and small	Positive and small	↗
Primordial (jets)	High p_T	~zero	~zero	→
Jet-Brems.	Mid p_T	Positive	?	↘
Jet-photon conversion	Mid p_T	Negative	?	↘
Magnetic field	All p_T	Positive down to p_T=0	Zero	→

Long-time efforts became fruition

- CERN results (WA98)
  - Third generation experiment, WA98, showed the first significant result
  - Pb+Pb $\sqrt{s_{NN}}$=17.3GeV, PRL85, 3595(2000).



p+Pb data shows initial nuclear effect

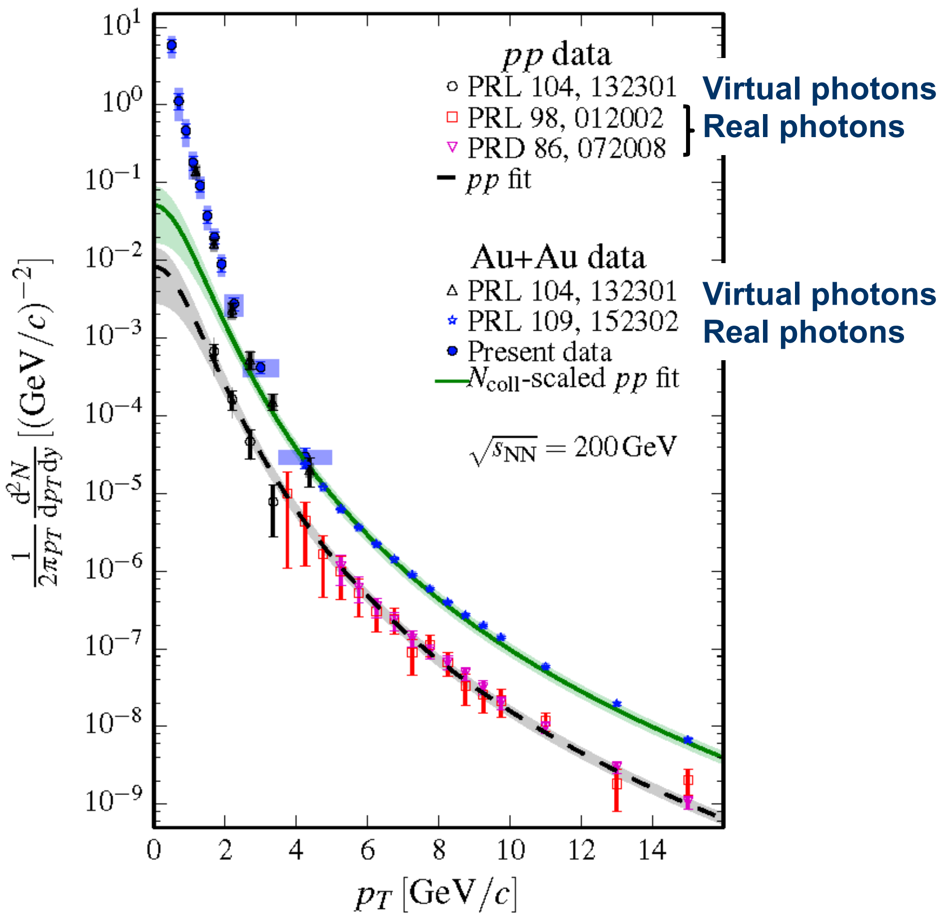


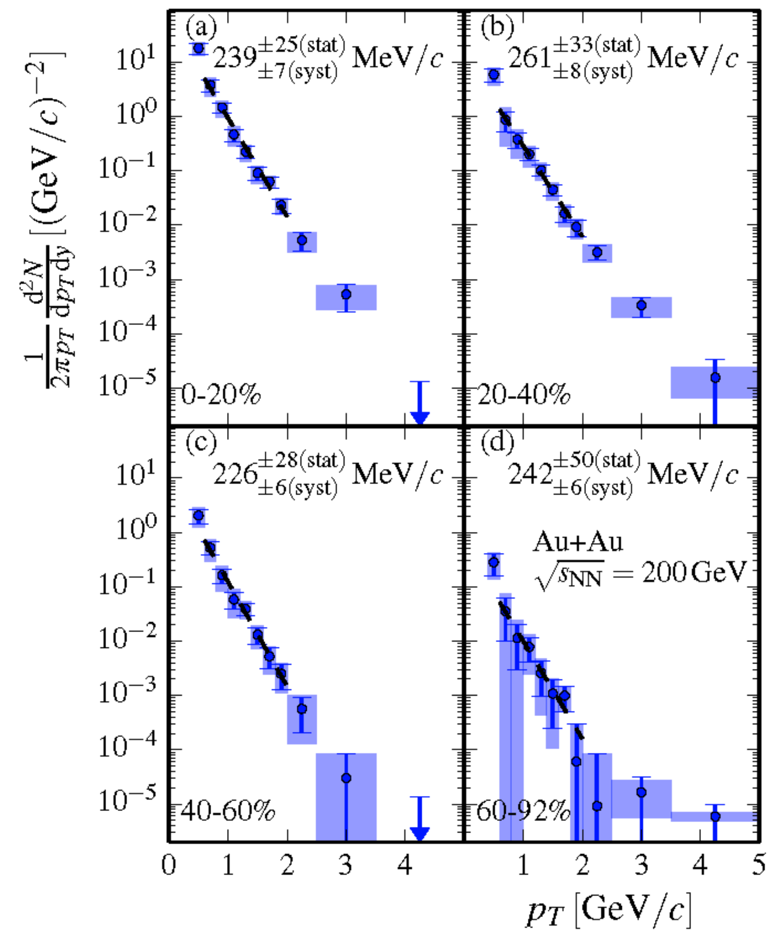
Baumann, QM2008

Long-time efforts became fruition

- RHIC results (PHENIX)
  - Real (direct or external conversion) and virtual photon analysis. T_{eff}~220MeV

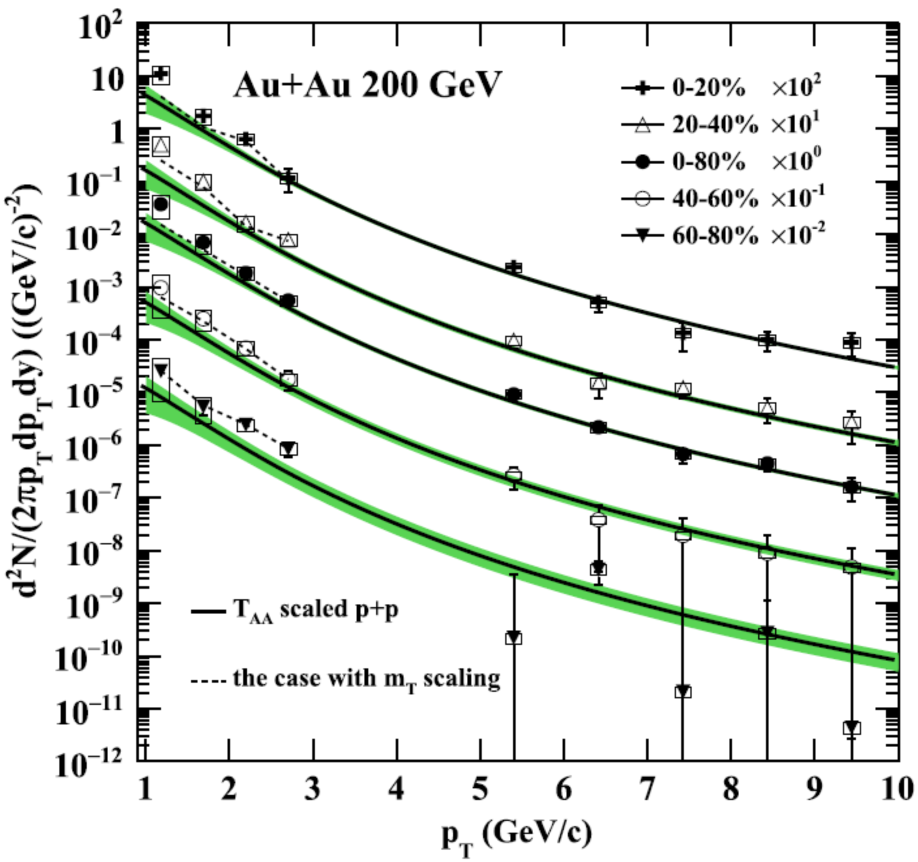
PRC91, 064904 (2015)

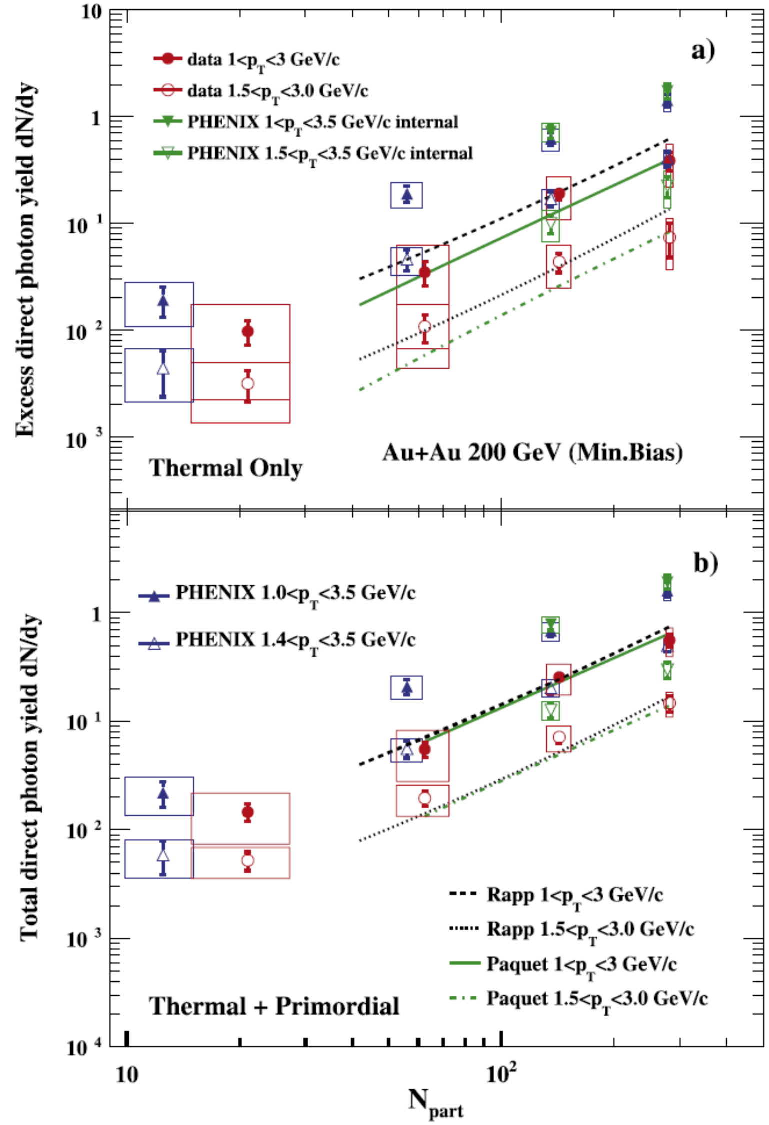




Long-time efforts became fruition

- RHIC results (STAR)
  - Virtual photon analysis

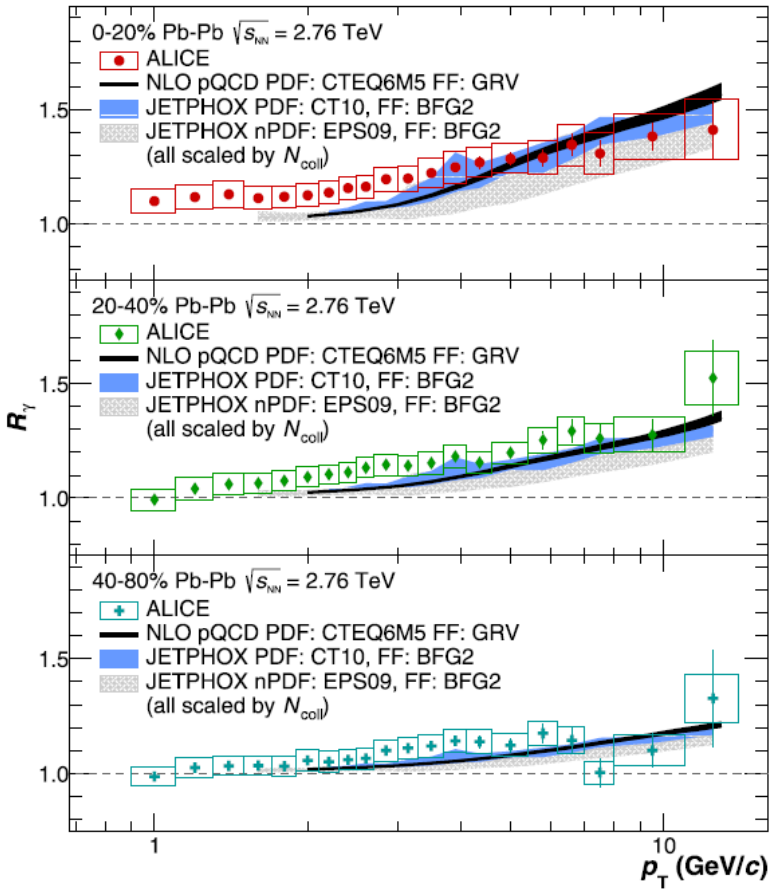




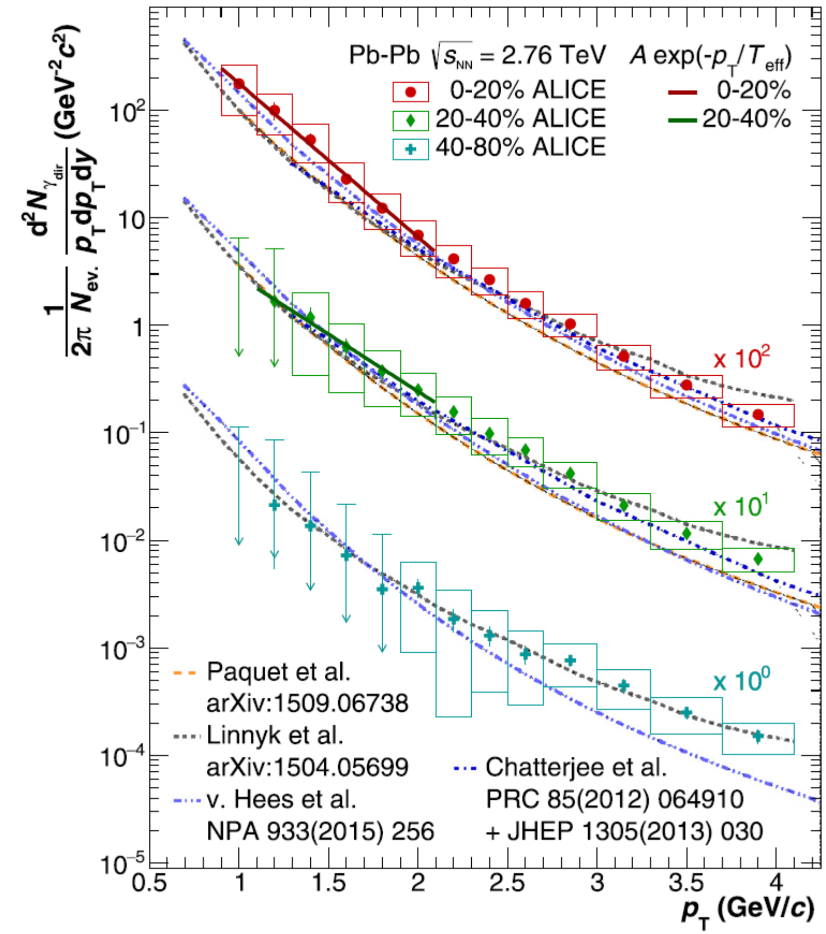
Physics Letters B 770 (2017) 451–458

Long-time efforts became fruition

- LHC results (ALICE)
  - Several methods are employed for solidifying the result
  - Higher T_{eff} was observed compared to RHIC: ~300MeV



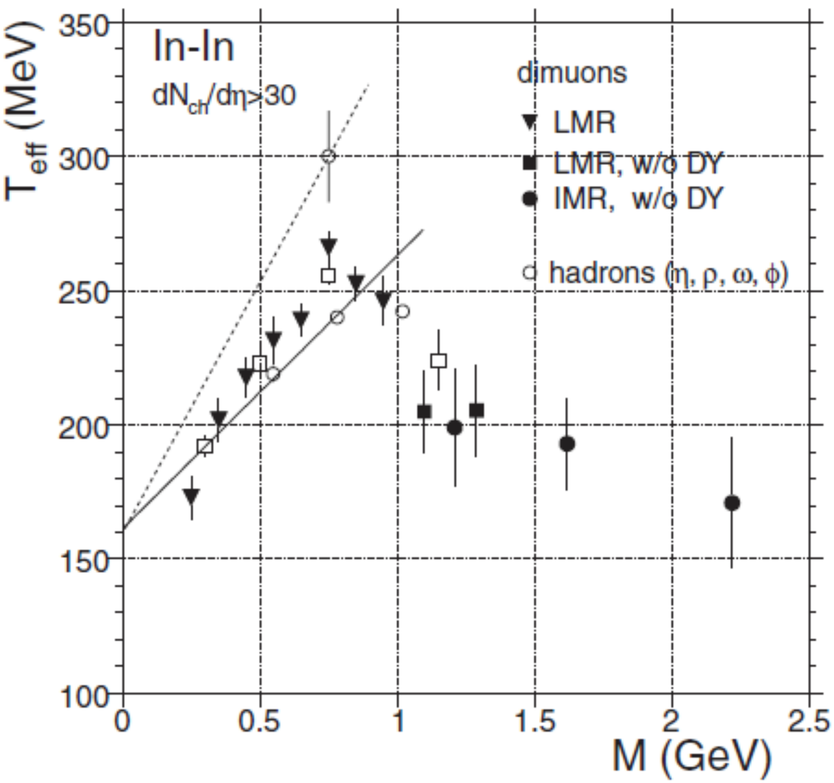
Phys. Lett. B 754 (2016) 235



Long-time efforts became fruition

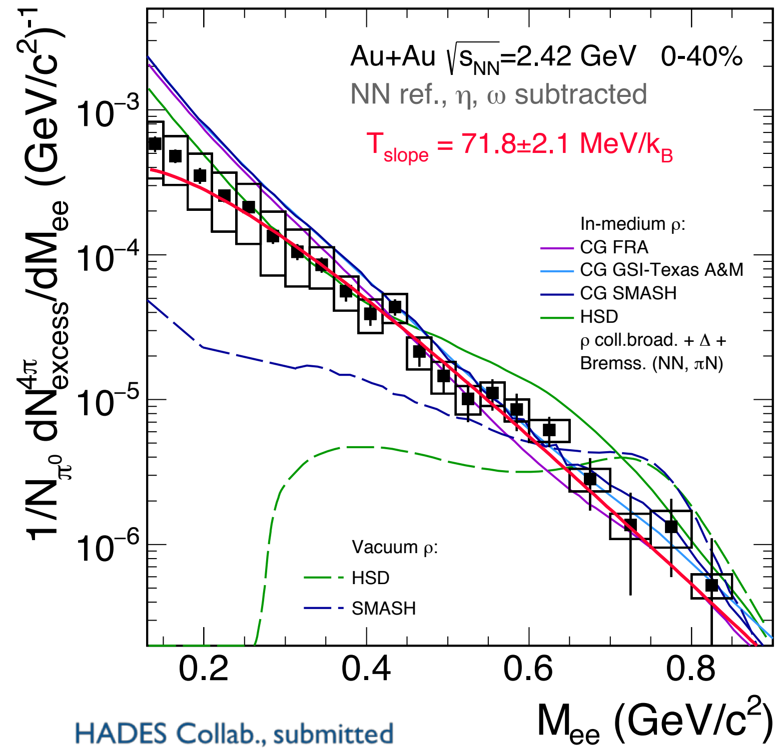
- More success has been seen in lower energies as well in RHIC/LHC era

NA60



PRL **100**, 022302 (2008)

HADES



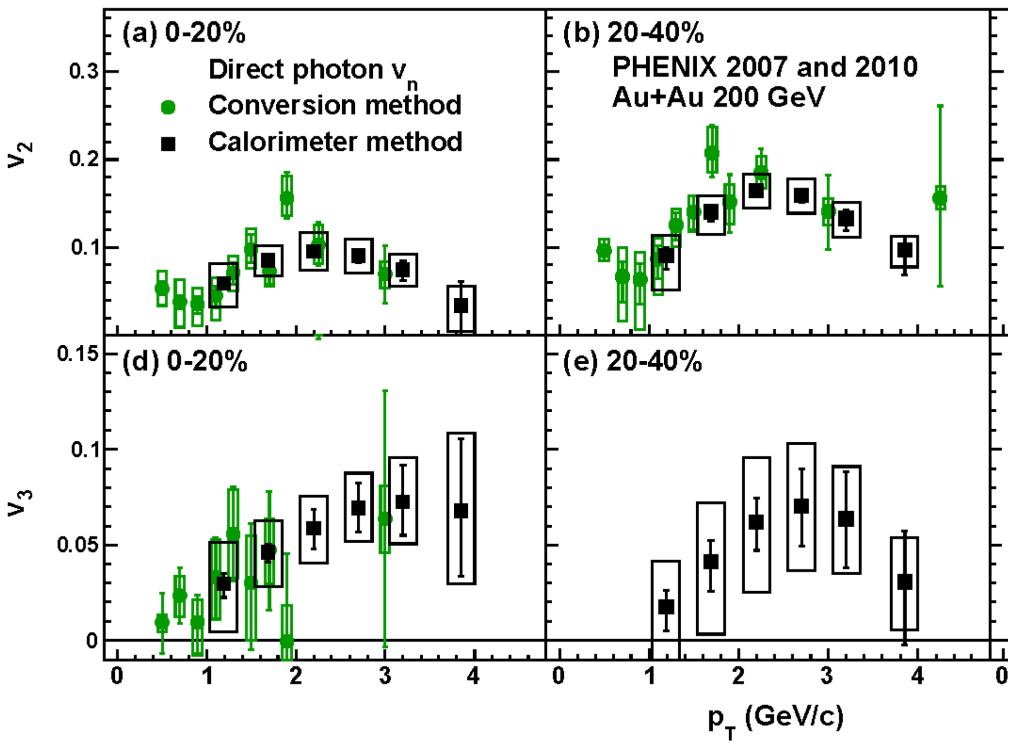
HADES Collab., submitted
CG FRA Endres et al.: PRC 92 (2015) 014911
CG GSI-Texas A&M TG et al.: Eur.Phys.J.A52 (2016) no.5, 131
CG SMASH: J. Staudenmaier et al., arXiv:1711.10297v1
HSD: Phys. Rev. C 87, 064907 (2013)

Two photon flow examples

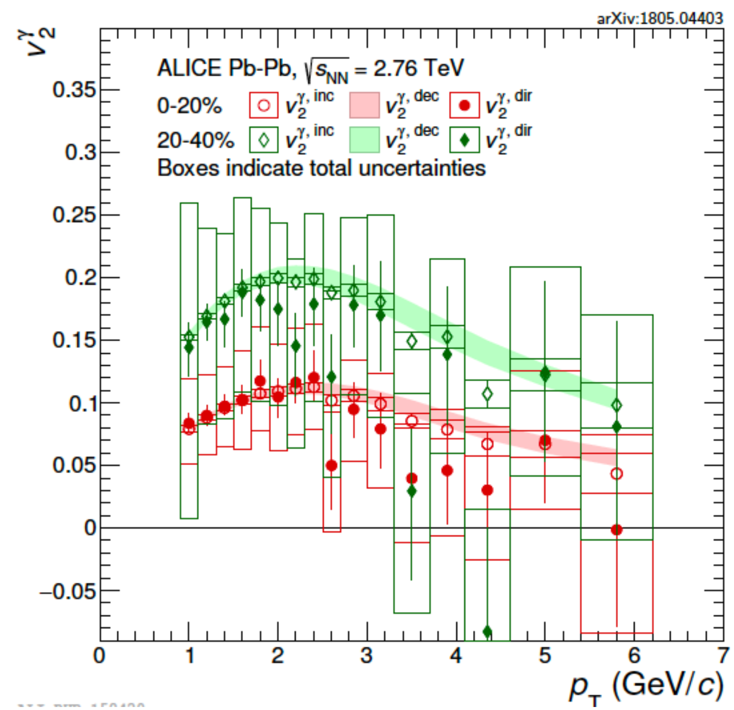
- PHENIX and ALICE data called a puzzle
  - **Large yield (**Emission from early stage where T is high)
  - **Large elliptic flow (v_2) (**Emission from late stage where the collectivity is sufficiently built up)

- Dilepton flow results exist (HADES, STAR)

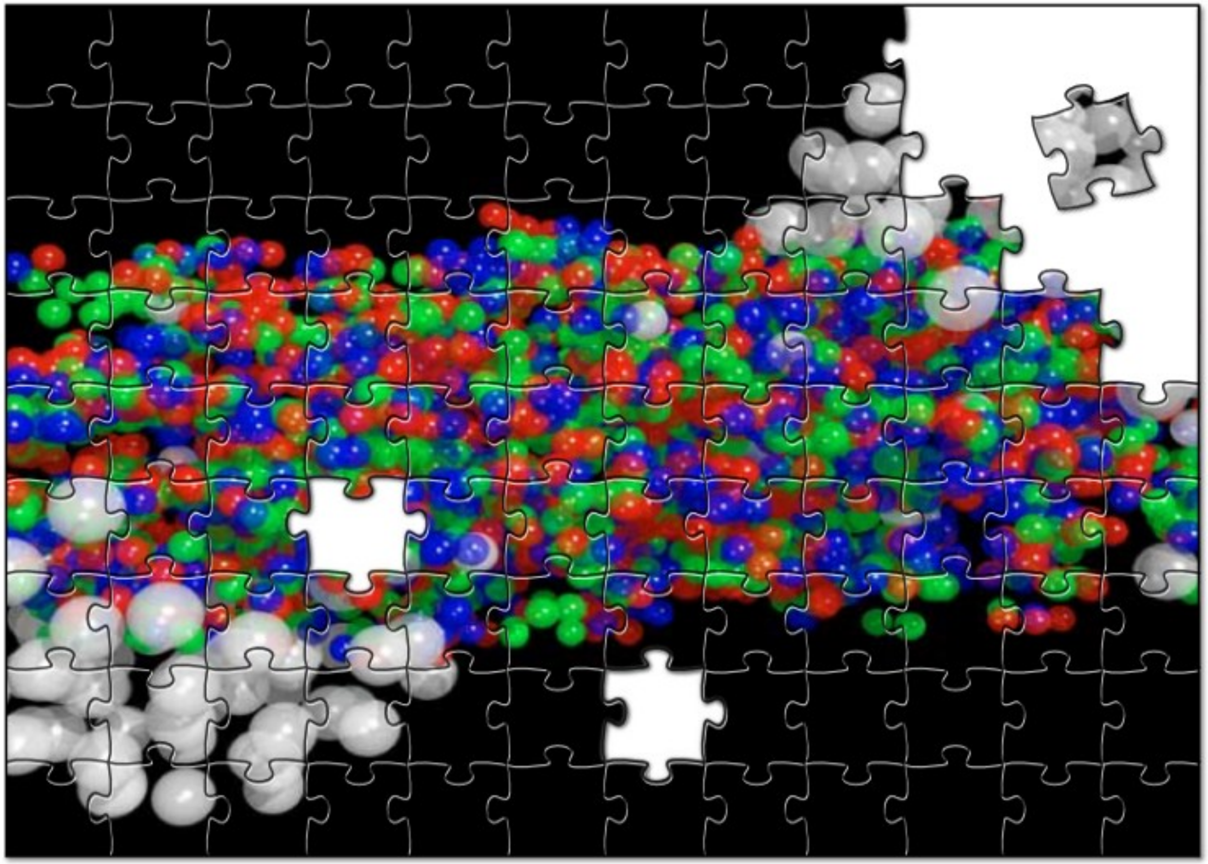
PHYSICAL REVIEW C 94, 064901 (2016)



Schmidt, HP2018



Filled and missing parts?



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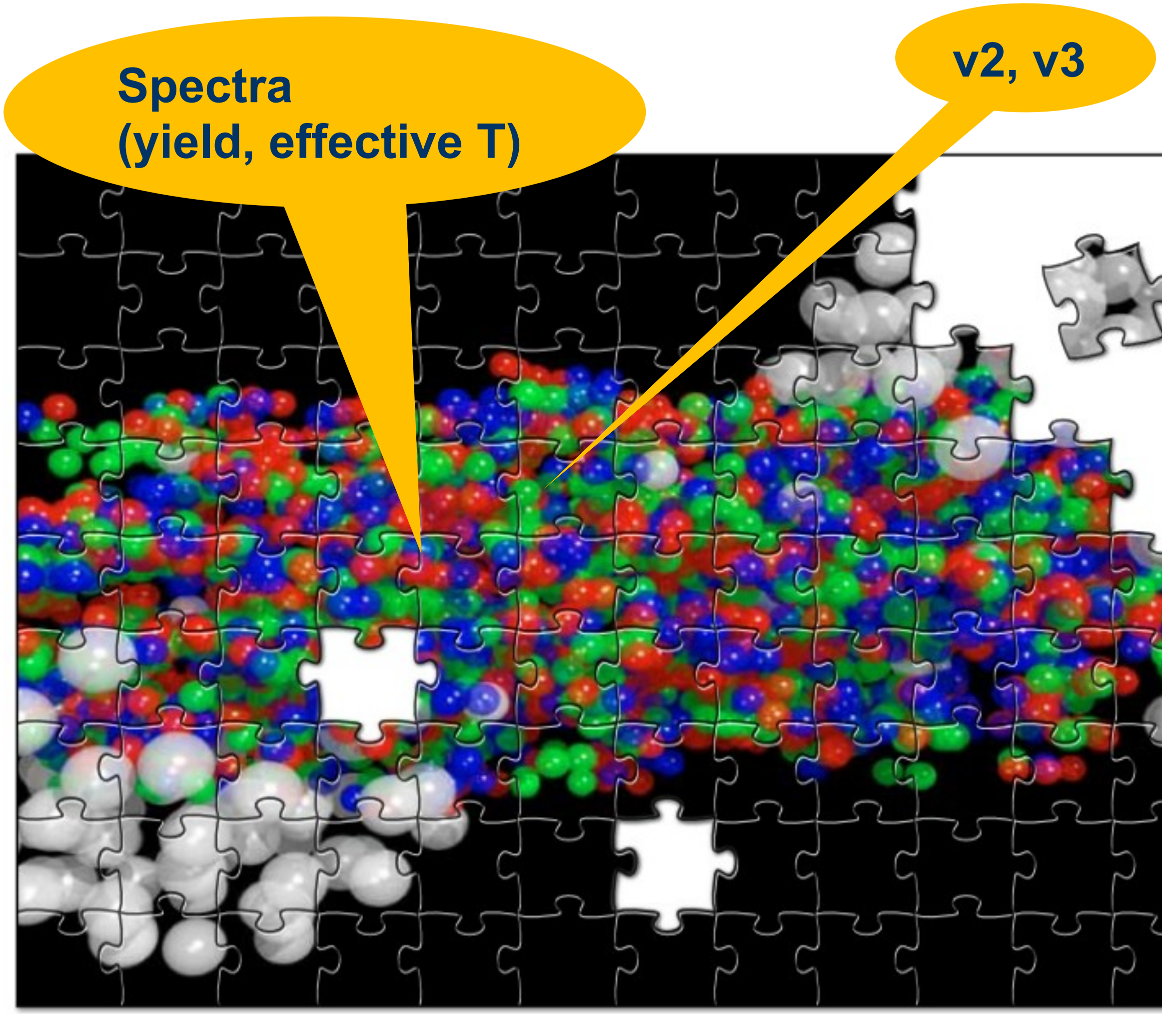

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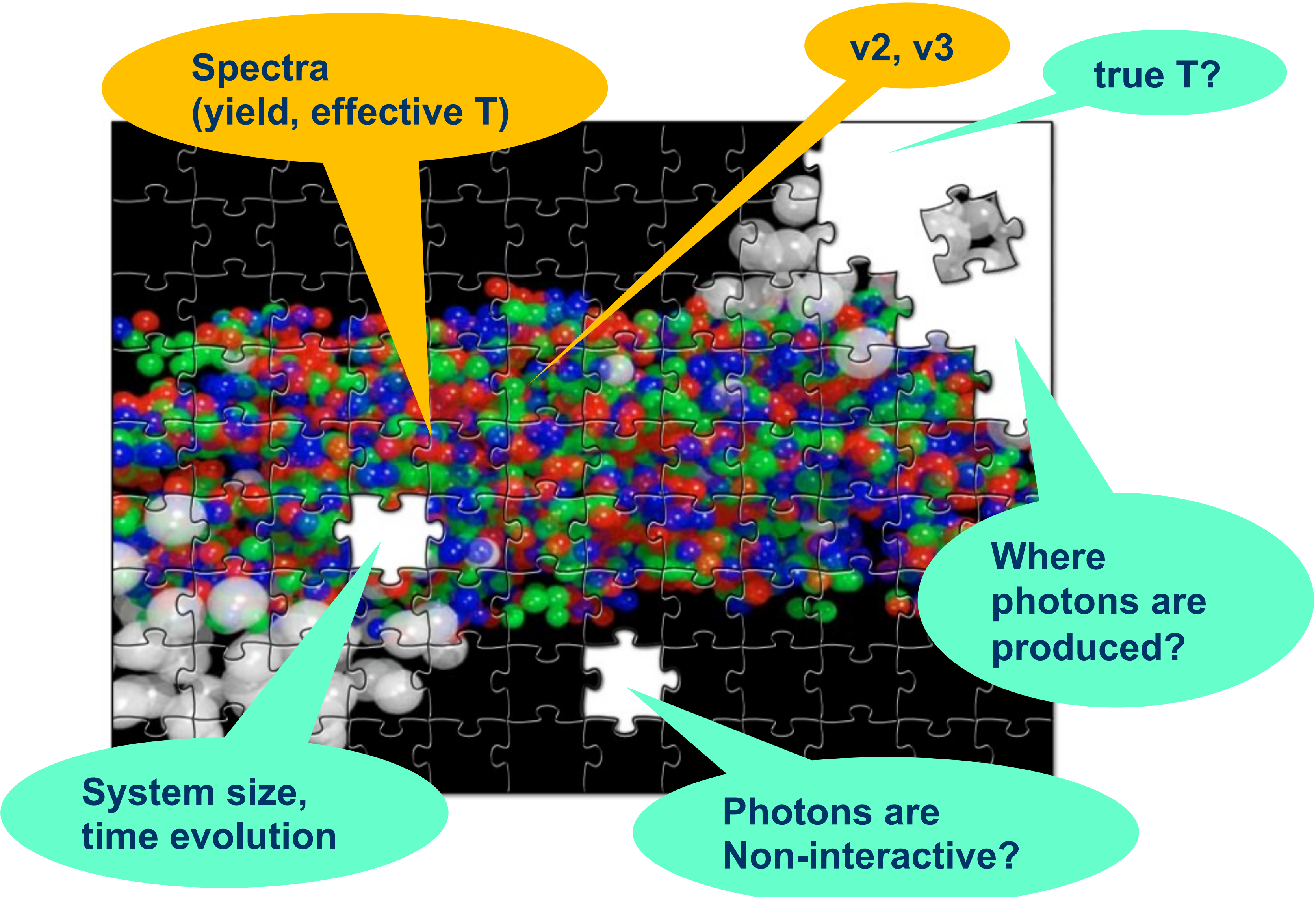
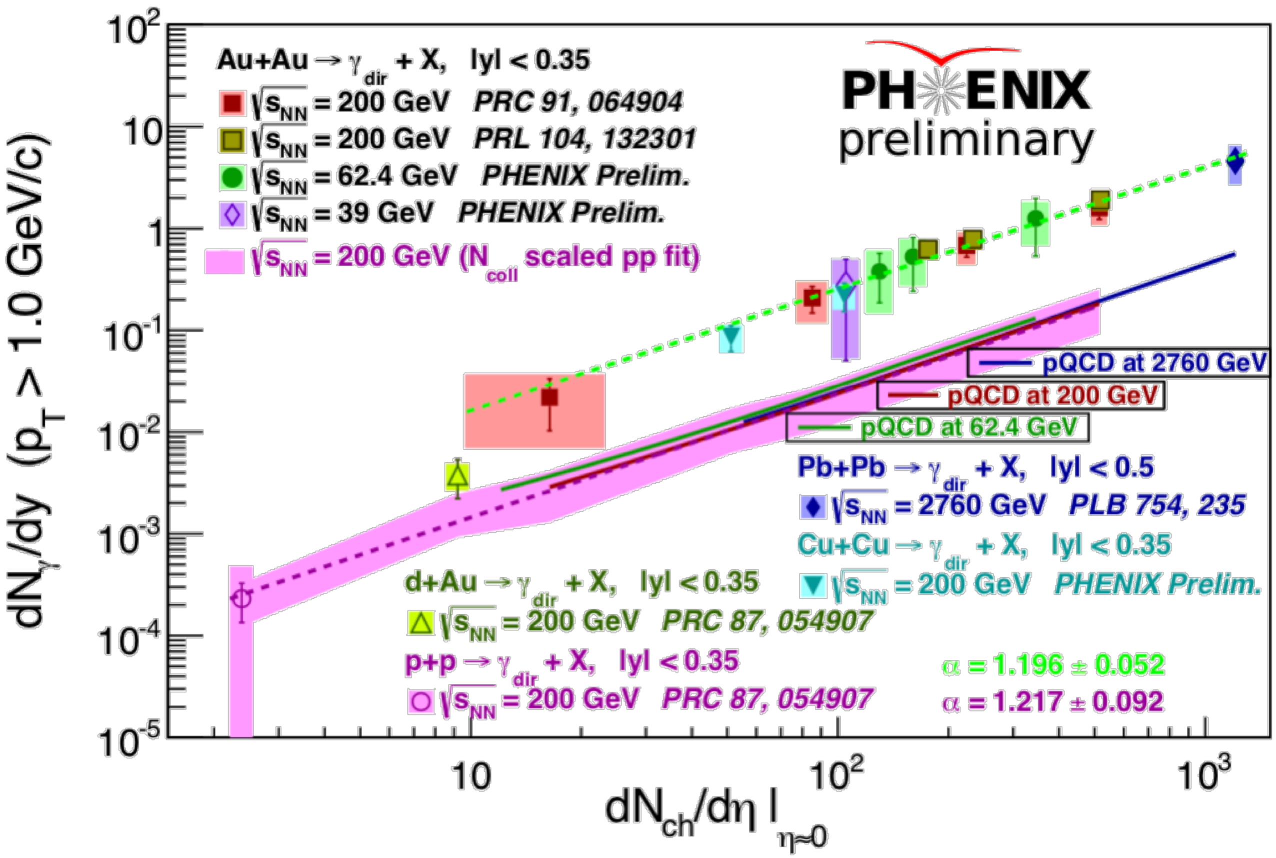


Time evolution of collision system

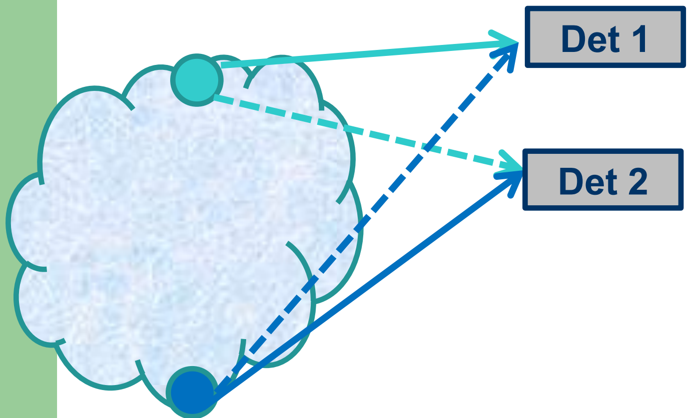
A photon yield scaling has been found

- Photon yield scales with $dN_{ch}/d\eta$ over wide
  - $dN_{ch}/d\eta$ ~ energy density * system size

- Both energy density and system size change as time goes; needs a handle on either (both) of them



One idea: size from Interferometry



$$A_{12} = \frac{1}{\sqrt{2}}[e^{ip_1\cdot(r_1-x)}e^{ip_2\cdot(r_2-y)}+e^{ip_1\cdot(r_1-y)}e^{ip_2\cdot(r_2-x)}]$$

$$P_{12} = \int d^4x d^4y |A_{12}|^2 \rho(x)\rho(y) = 1+|\tilde{\rho}(q)|^2 \equiv C_2(q)$$

- Interference of two identical particles from incoherent sources
  - First applied by Hanbury-Brown and Twiss for star size measurement
  - Hanbury-Brown Twiss (HBT) effect
- In heavy ion collisions, we use π, K, etc. as probes.
  - Measurement can be basically made at freezeout

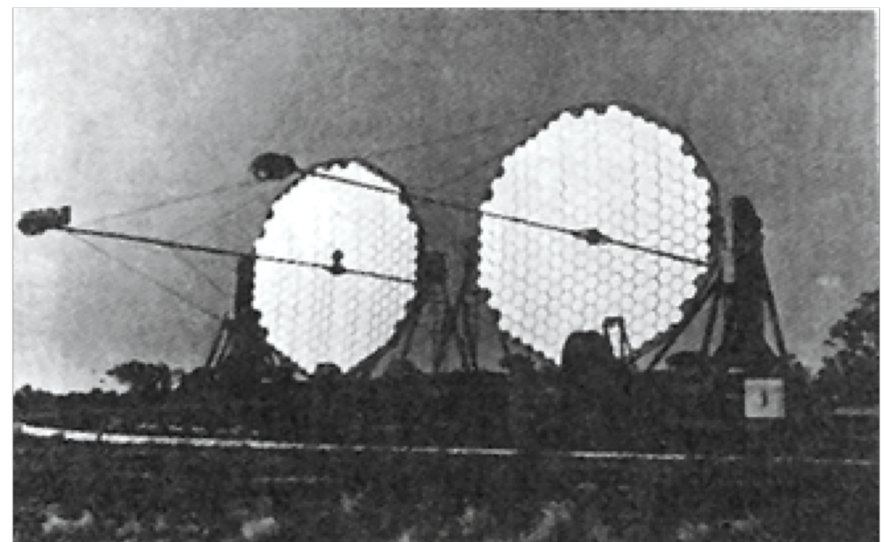
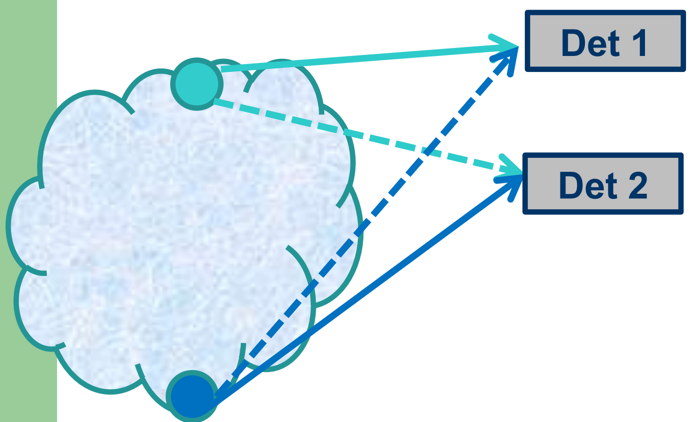


Figure 2. Picture of the two telescopes used in the HBT experiments. The figure was extracted from Ref.[1].

One idea: size from Interferometry



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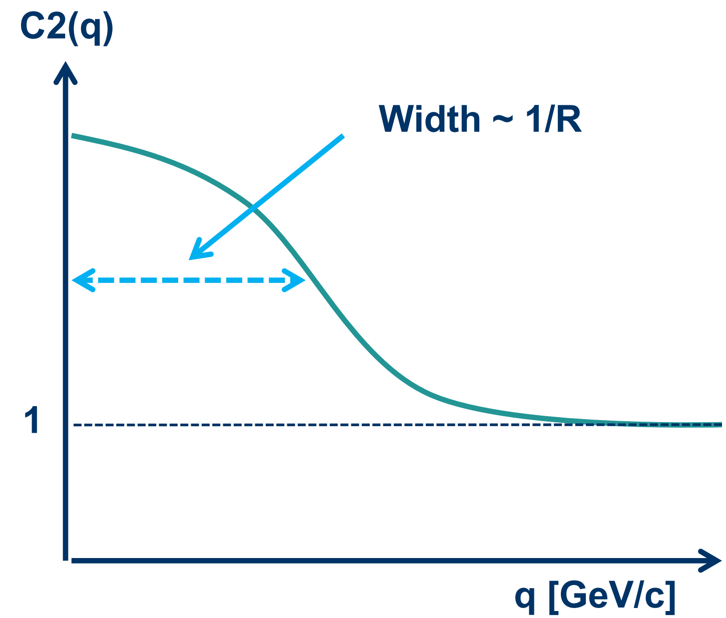

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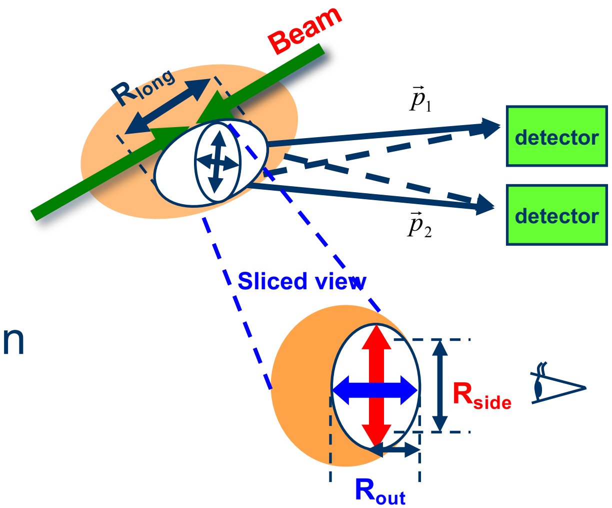
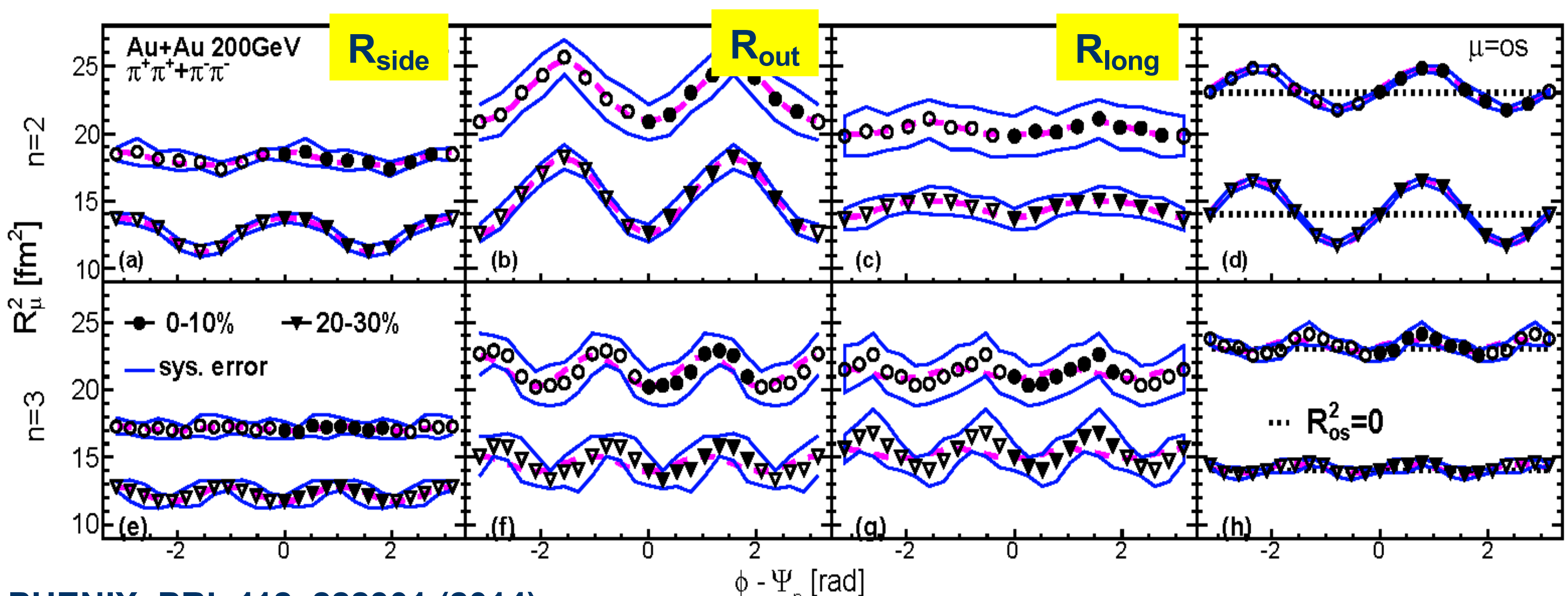
Dynamics seen from HBT

- HBT radii as a function of $\Delta\phi$ (ϕ-Ψ_n)
- PHENIX and STAR observed 2[nd] order modulation of HBT radii in 200GeV Au+Au collisions
  - source shape at freezeout and emission duration of particles have angular modulation



- PHENIX observed the triangular pattern, too

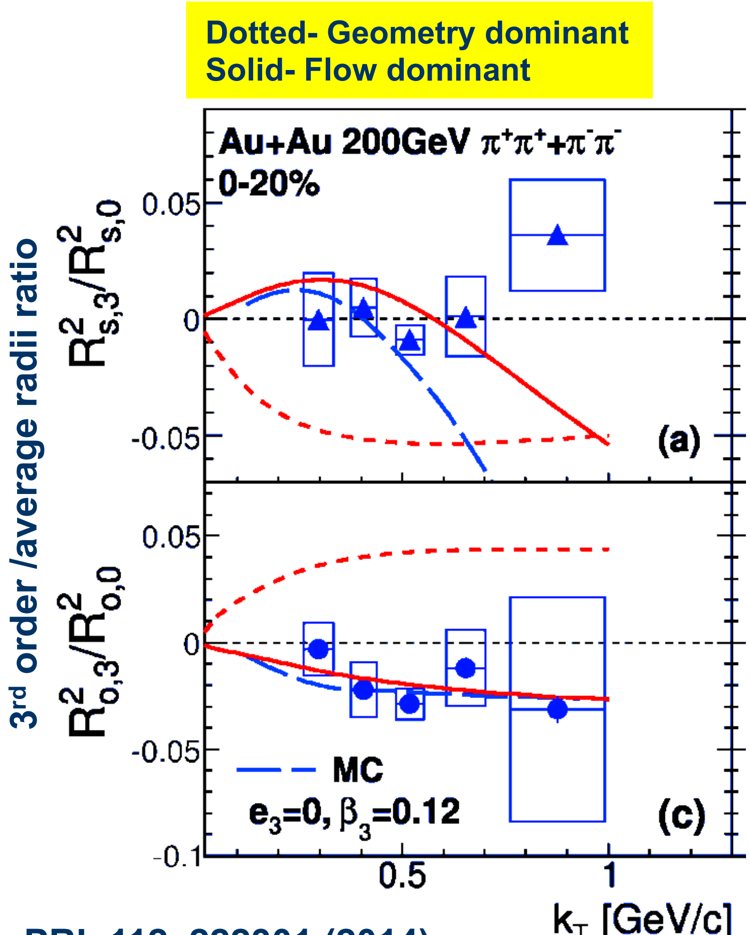


PHENIX, PRL 112, 222301 (2014)

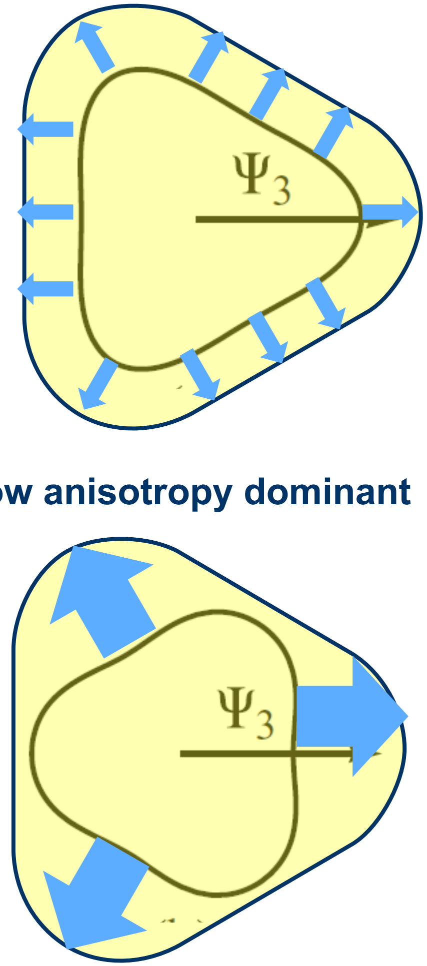
Geometry or flow dominant?

- Charged pion HBT results favor flow anisotropy dominant scenario

PRC88, 044914 (2013)

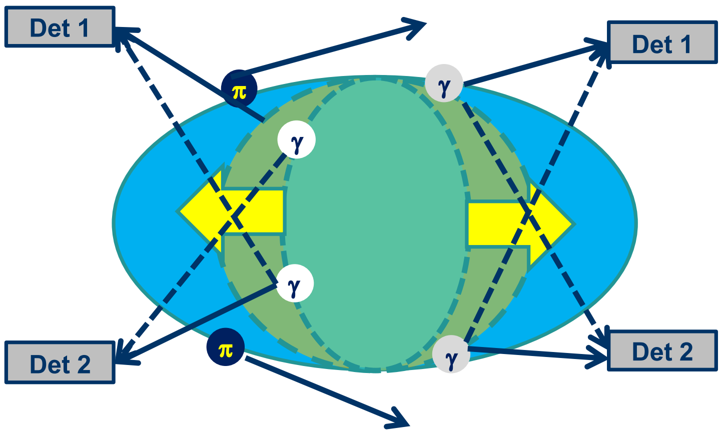


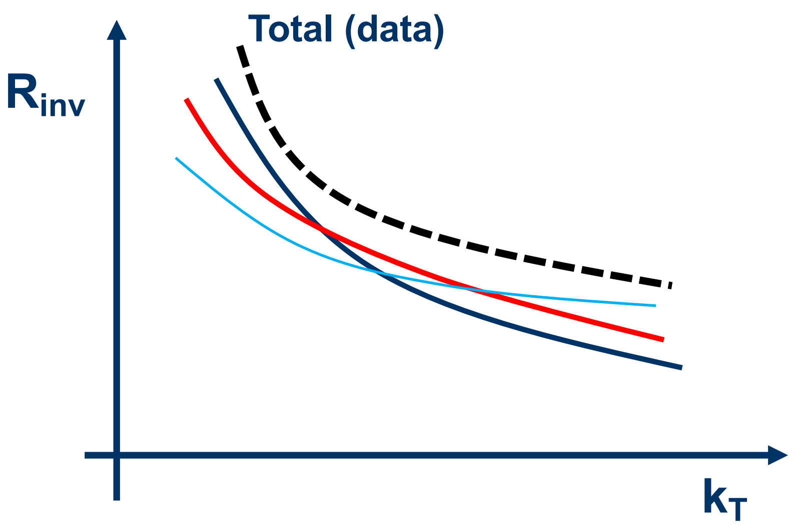
PRL 112, 222301 (2014)



Direct (virtual)photon HBT…?

- Very hard to measure. May need a new setup (e.g. ALICE Run4+)
- Using virtual photons may be a solution?
- One can study time-dependent size of the QGP
  - Photons penetrate systems. Momentum will tell the time they are emitted.
  - Angle dependent HBT → shape measurement
- Caveat: as opposed to hadrons, photons are decoupled anytime





Direct photon HBT measurement by now

- WA98 results (in Pb+Pb @ $\sqrt{s_{NN}}$=17.3GeV)
  - PRL 93, 022301 (2004)
  - 1D HBT

- Yield at lowest p_T was obtained from correlation length.

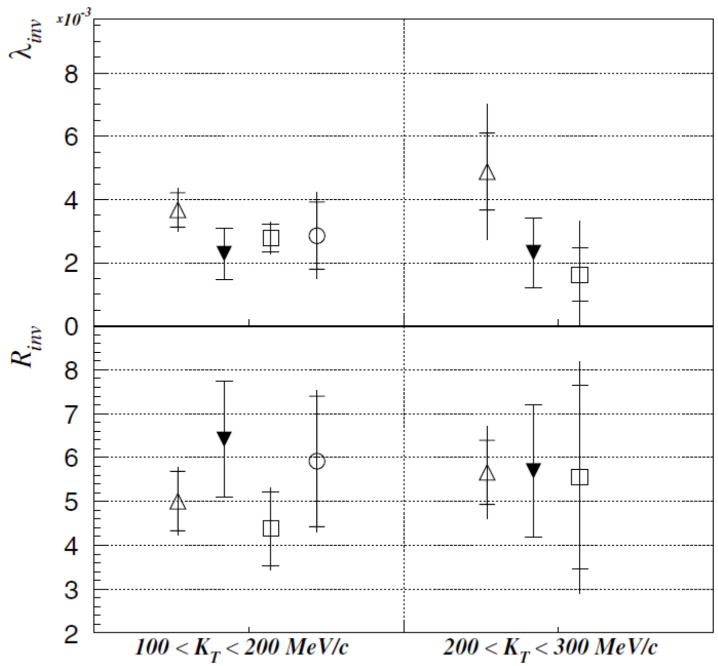
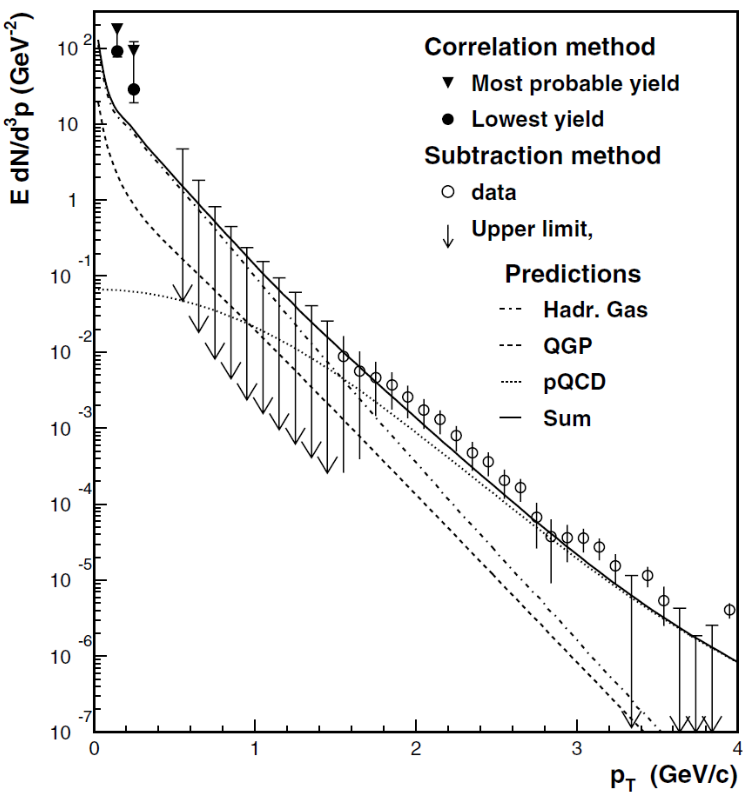


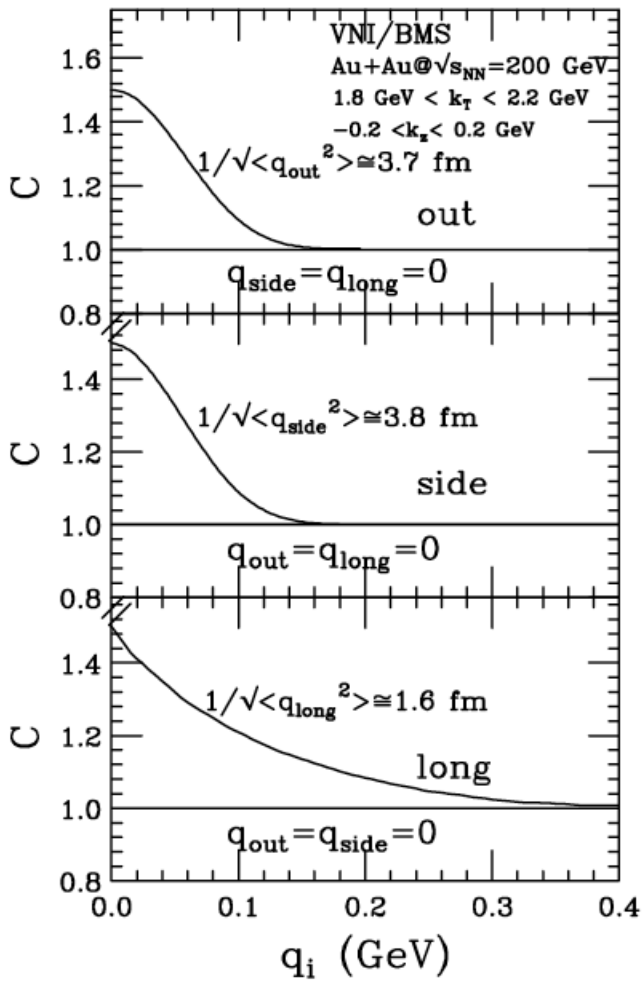
FIG. 3. Comparison of parameters of correlation functions with different particle identification criteria: △, all clusters; ▼, narrow electromagnetic; □, all neutral; ○, narrow neutral electromagnetic (no significant result for high K_T).



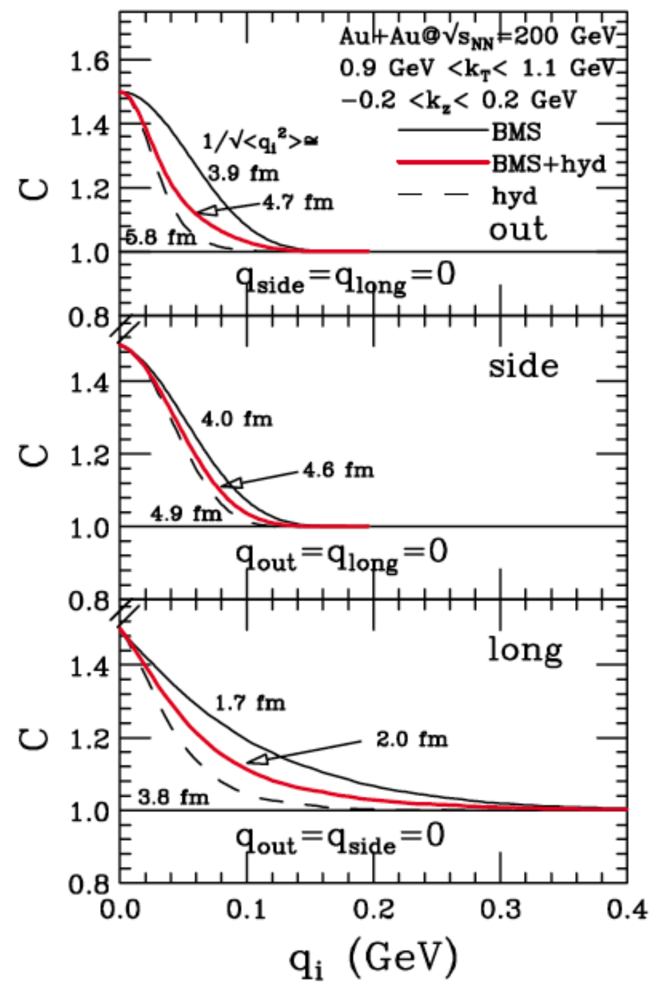
A Calculation

PhysRevLett.93.162301

k_T=2GeV



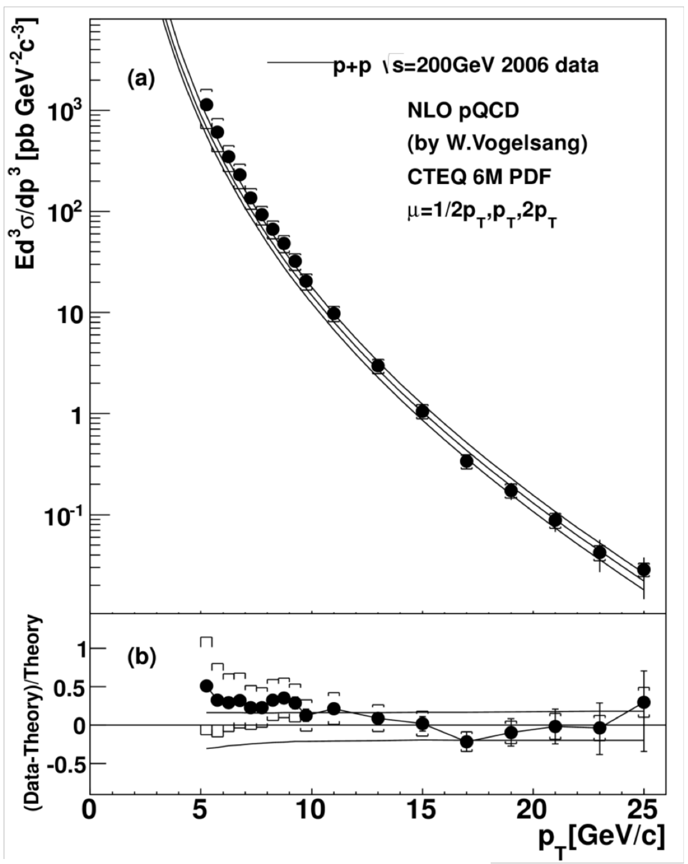
k_T=1GeV



Hard photons don't interact?

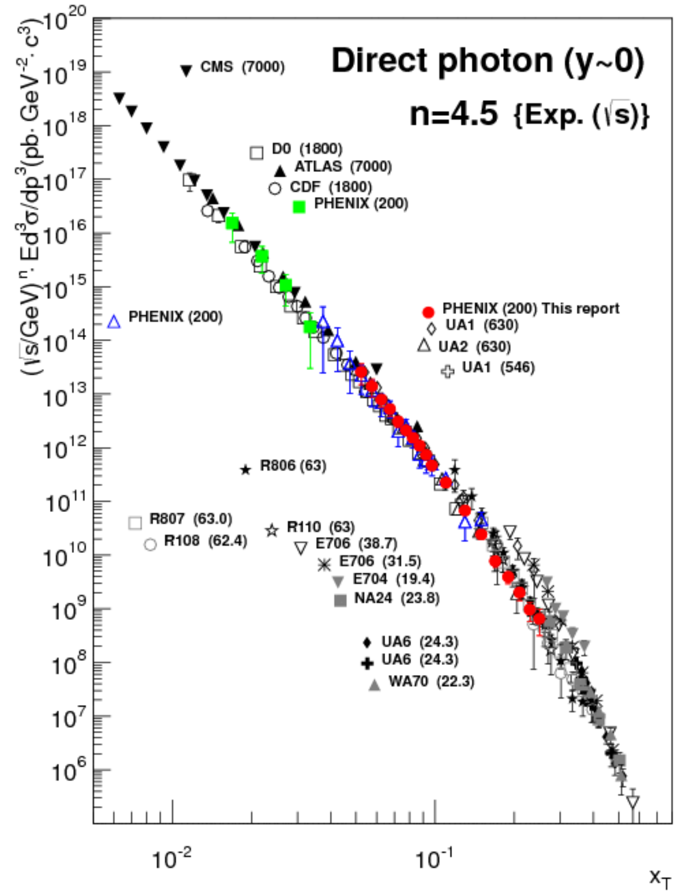
Primordial photon production

- Photons will be produced both from prompt and fragmentation
- Well scaled in x_T (n=4.5). n=4 for 2->2



PhysRevLett.93.162301

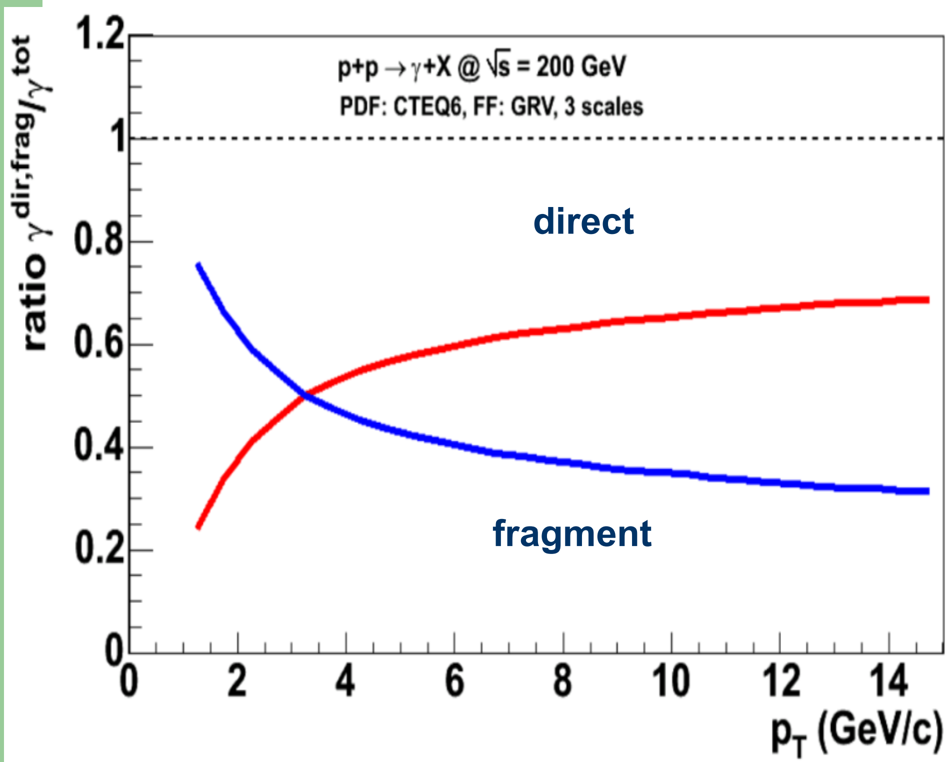
Phys.Rev. D86 (2012) 072008

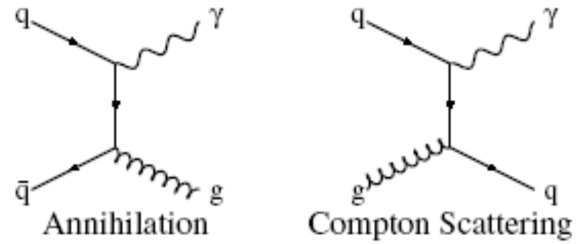


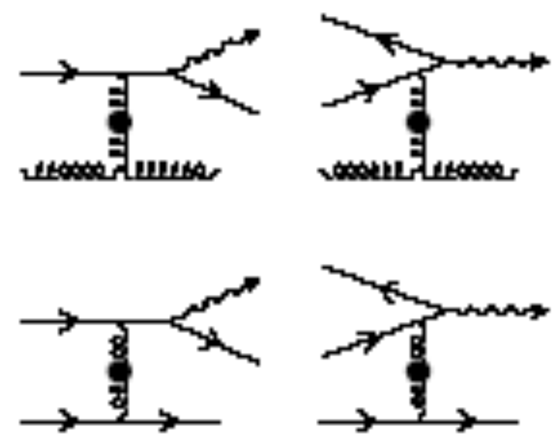
Process of primordial photon production

Small Rate: Yield $\propto \alpha\alpha_s$

- Production Process
  - Compton and annihilation (LO, direct)
  - Fragmentation (NLO)



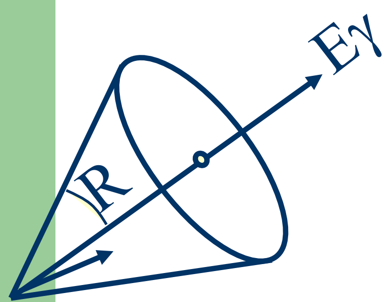




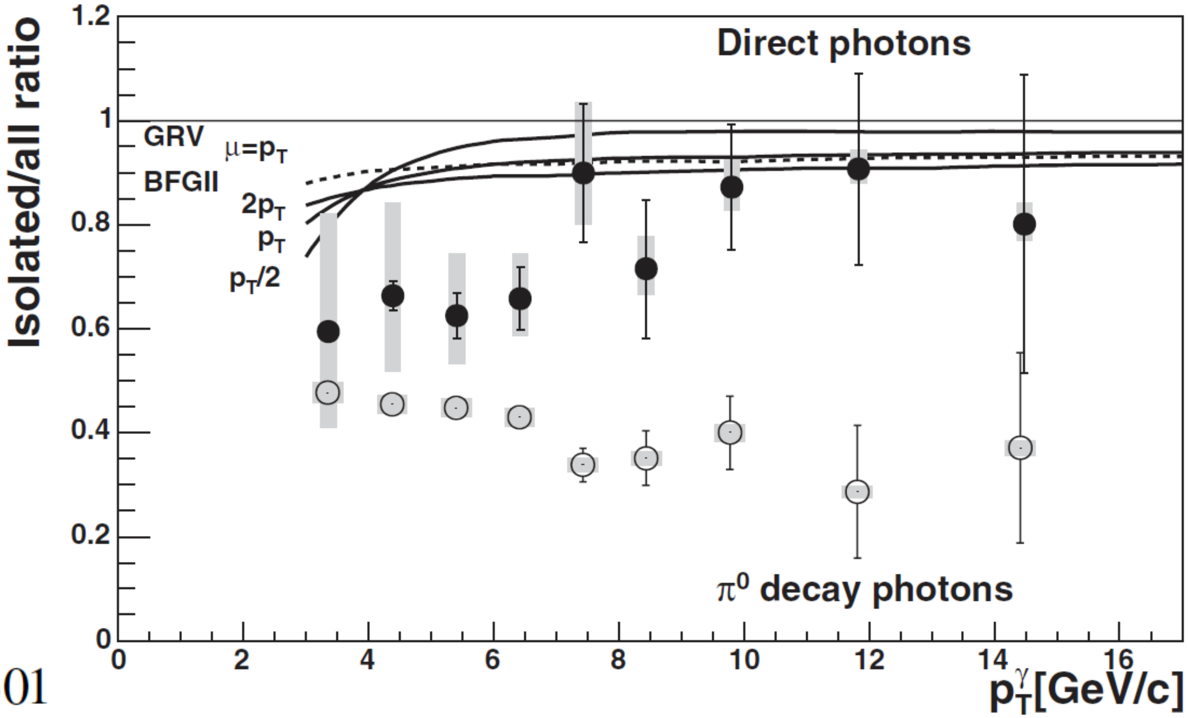
Gordon and Vogelsang, PRD48, 3136 (1993)

What the measurement says?

- Obviously, prompt and fragment component can't be separated in rigorous way
- PHENIX performed measurement for isolated/inclusive photon ratio down to low p_T
  - NLO pQCD describes the data reasonably?



γ(Isolated)/γ(all direct)

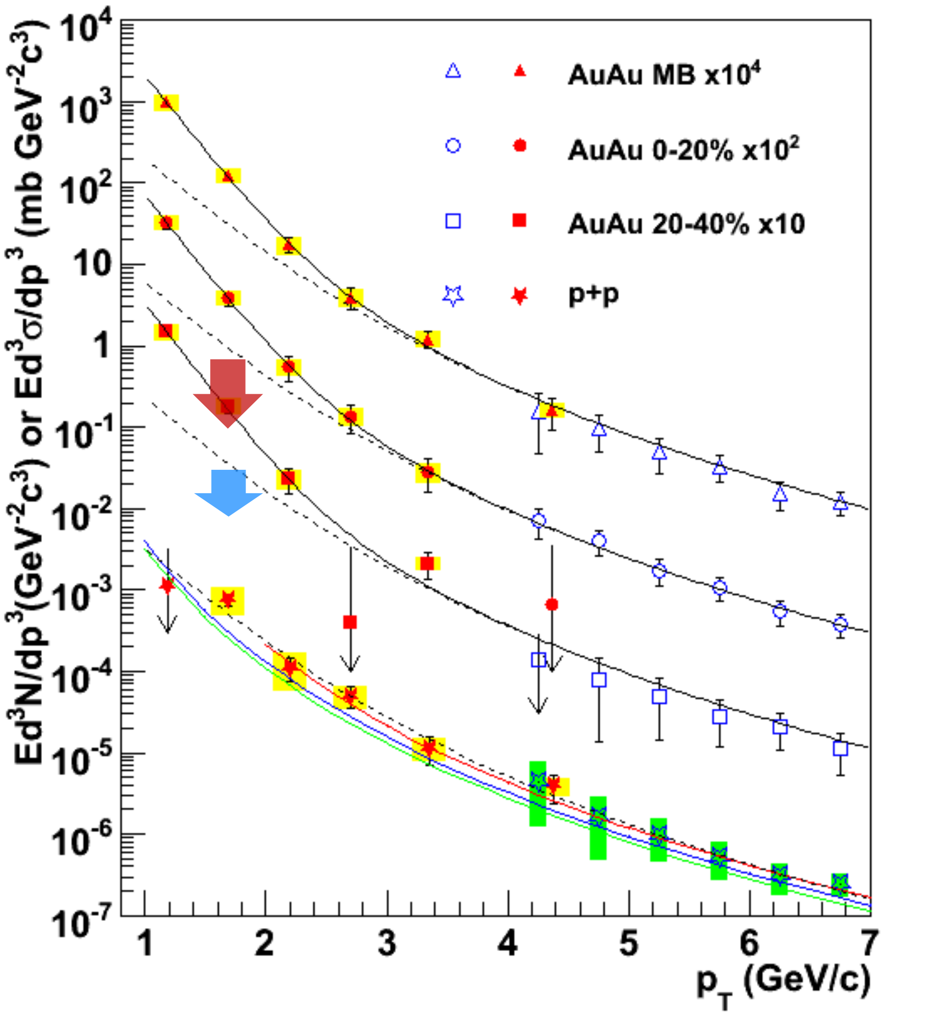


PhysRevLett.93.162301

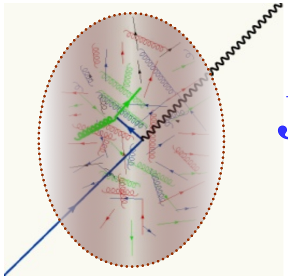
p+p baseline at low p_T

PHENIX, PRL. 104, 132301 (2010)

- p+p itself is OK, but can be linearly scaled to A+A by T_{AB}?
- Like leading hadrons, the fragmentation part of the NLO pQCD photons should be suppressed in A+A collisions?
  - It can be suppressed to be as much as 0.5 at p_T=1GeV/c
  - 0.75(frag)*0.3+0.25(dir)=~0.5
- Supposed to be more thermal contributions?
  - It's p_T-dependent
  - It may affect to T_{eff} rather than yield in the end.

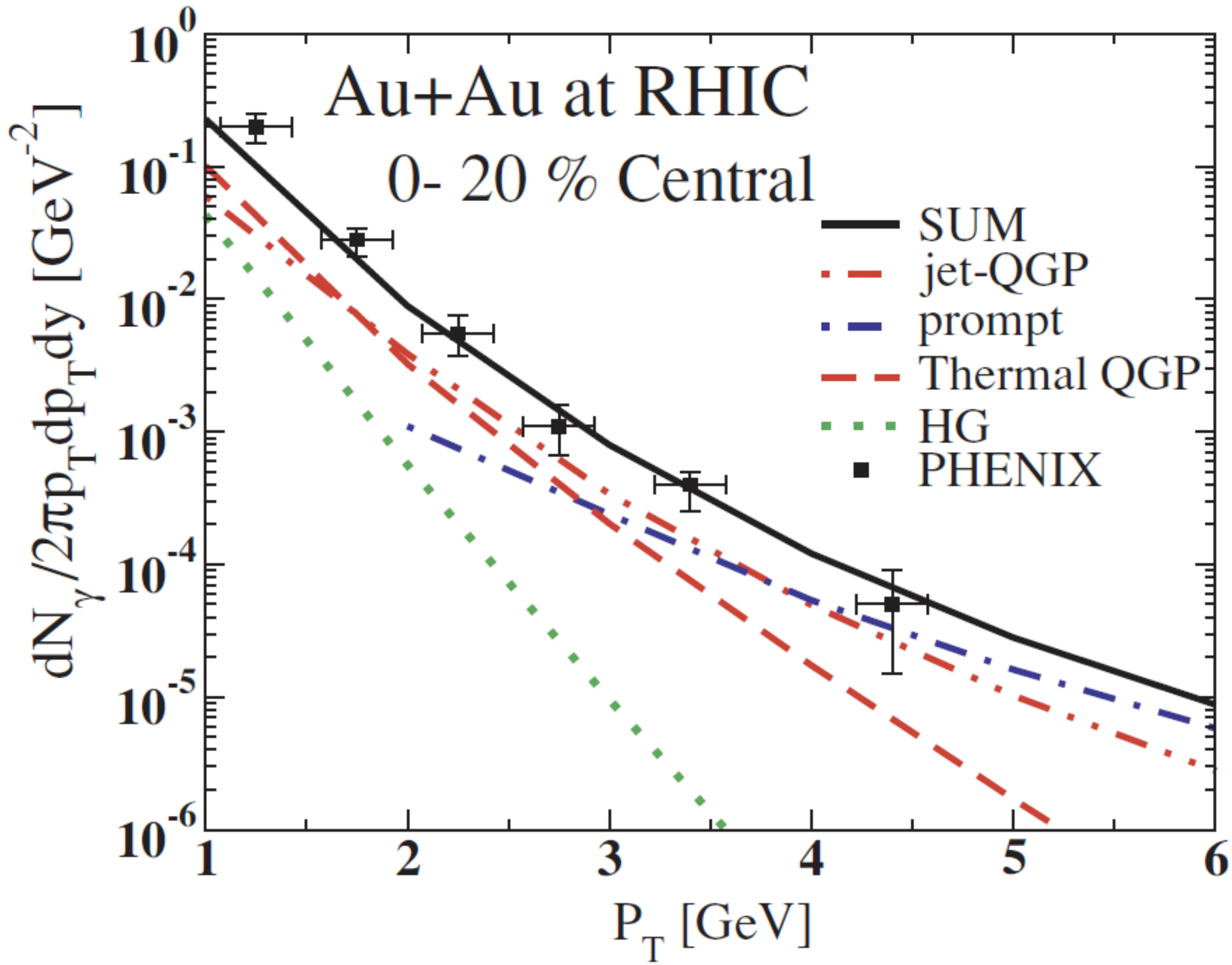


Photons from another process



Jet-photon conversion

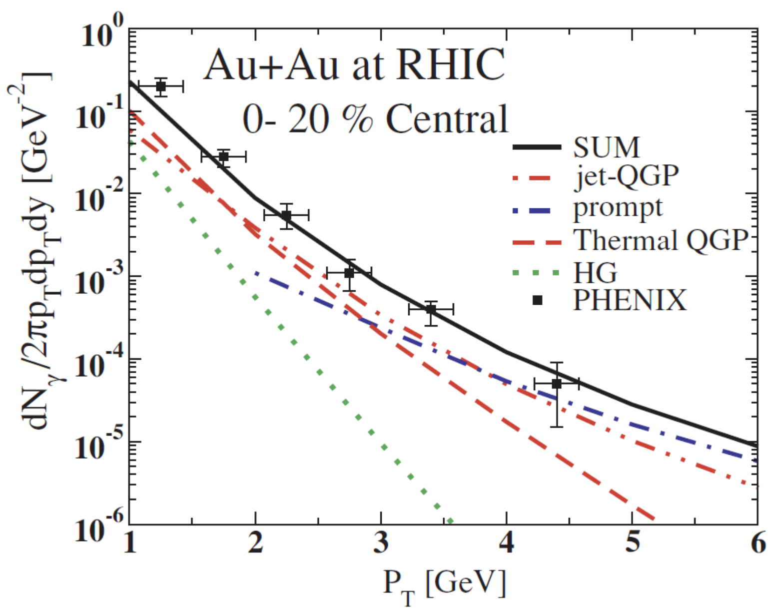
A model calculation



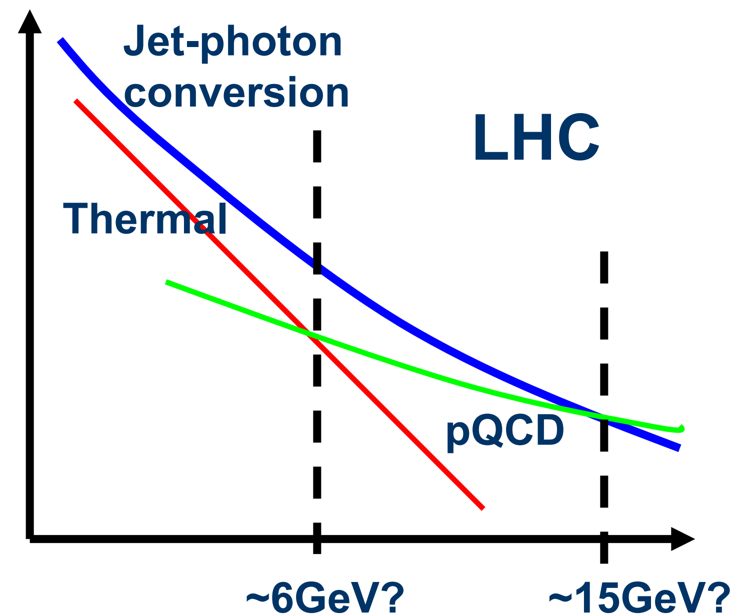
PHYSICAL REVIEW C 77, 024909 (2008)

My expectation for LHC was ….

- A calculation tells that even in low p_T region(p_T~2GeV/c), jet-photon conversion significantly contributes to total
- What do we expect naively (compared to RHIC)?
  - Jet-Photon conversions: a factor of ~30 increase in hard scattering
  - Thermal Photons: $(dN_{ch}/d\eta)$^1.25 → ~4 increase
  - ***Bet: Jet-photon conversion contribution dominates over thermal***



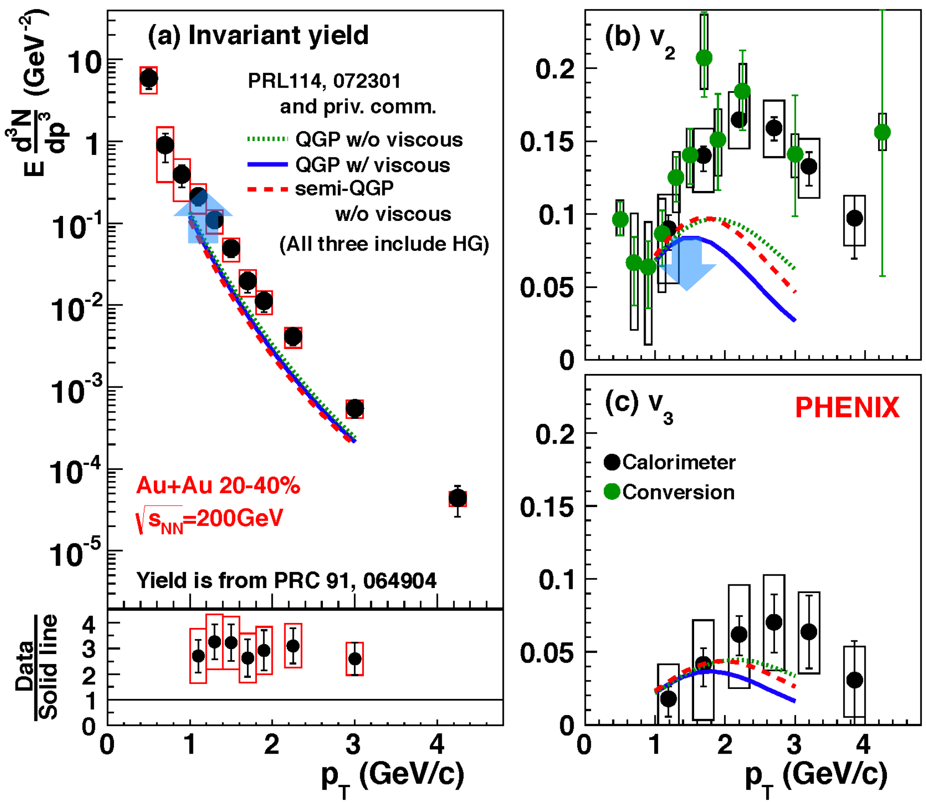
PHYSICAL REVIEW C 77, 024909 (2008)

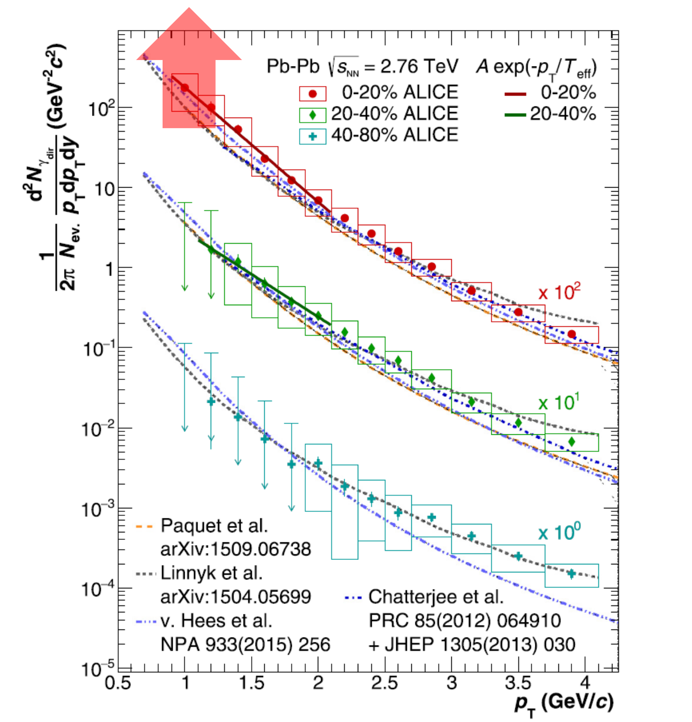


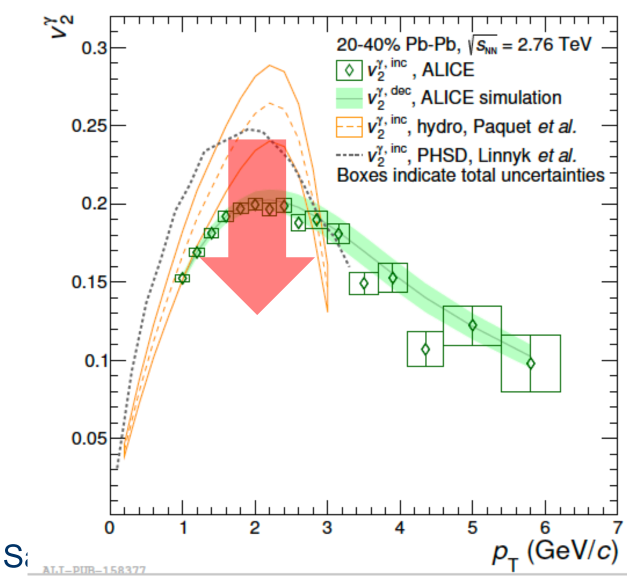
Then…

- Data don't move.
- It is exaggerated, but makes us happier?

Sources	p_T	v_2
Jet-photon conversion	Mid p_T	Negative







T. S

What can we do for jet-medium photons?

- Proof of its existence may be obtained rather high p_T
- A method to look for these photons

G. David, ECT2015

Jet-photon conversions: another clue to medium properties?

PRL 90, 132301 (2003)

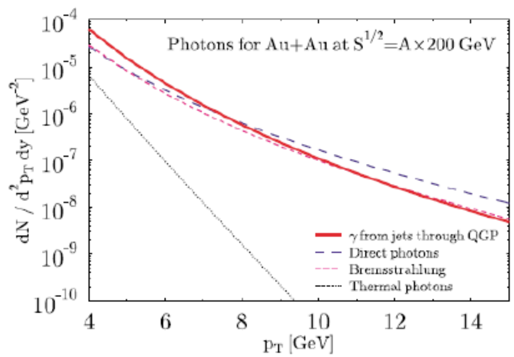
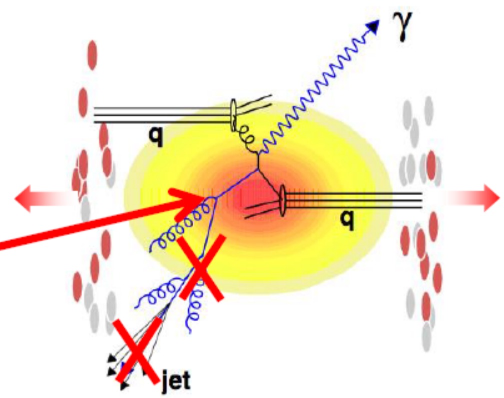


FIG. 1 (color online). Spectrum $dN/d^2p_\perp dy$ of photons at $y = 0$ for central collision of gold nuclei at $\sqrt{s_{NN}} = 200$ GeV at RHIC. We show the photons from jets interacting with the medium (solid line), direct hard photons (long dashed), bremsstrahlung photons (short dashed), and thermal photons (dotted).

Convert into a photon here!



An interesting experimental possibility:
look for two, high p_T back-to-back photons, both isolated
(The source would be hard Compton with the parton undergoing jet-photon conversion)
Huge penalty in rates, but no competing processes
Directly tied to the medium

Eur. Phys. J. C (2009) 61: 819–823

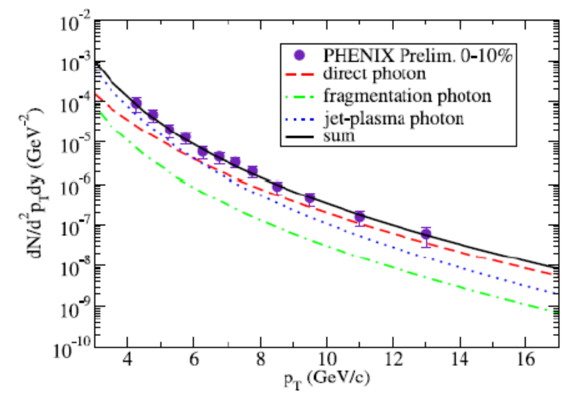


Fig. 3.1 The contributions from different channels to the photon production in Au + Au collisions at RHIC for $b = 2.4$ fm compared with most 0–10% PHENIX data

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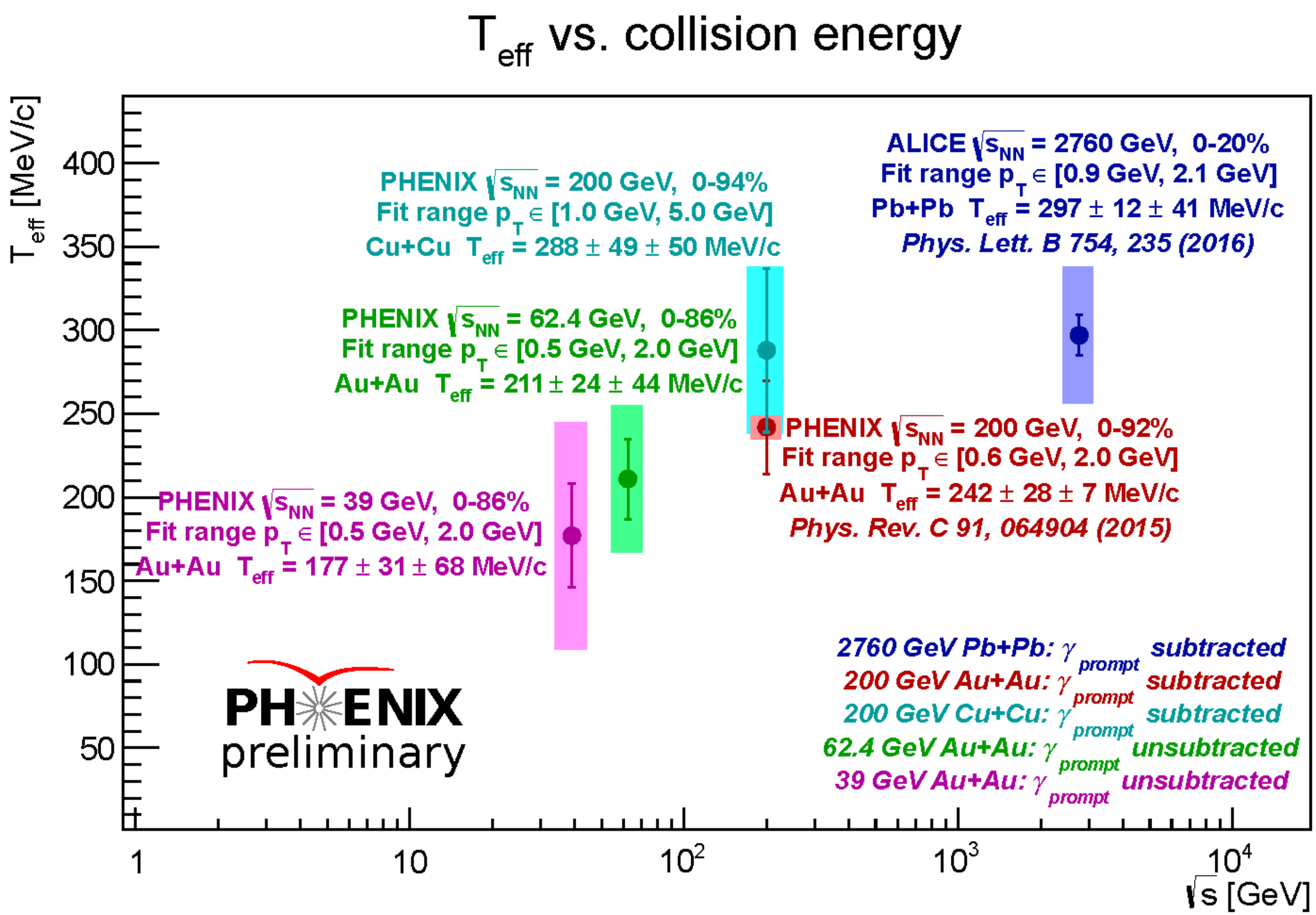
ECT, Trento, Dec. 2016 -- G. David, BNL*

True temperature

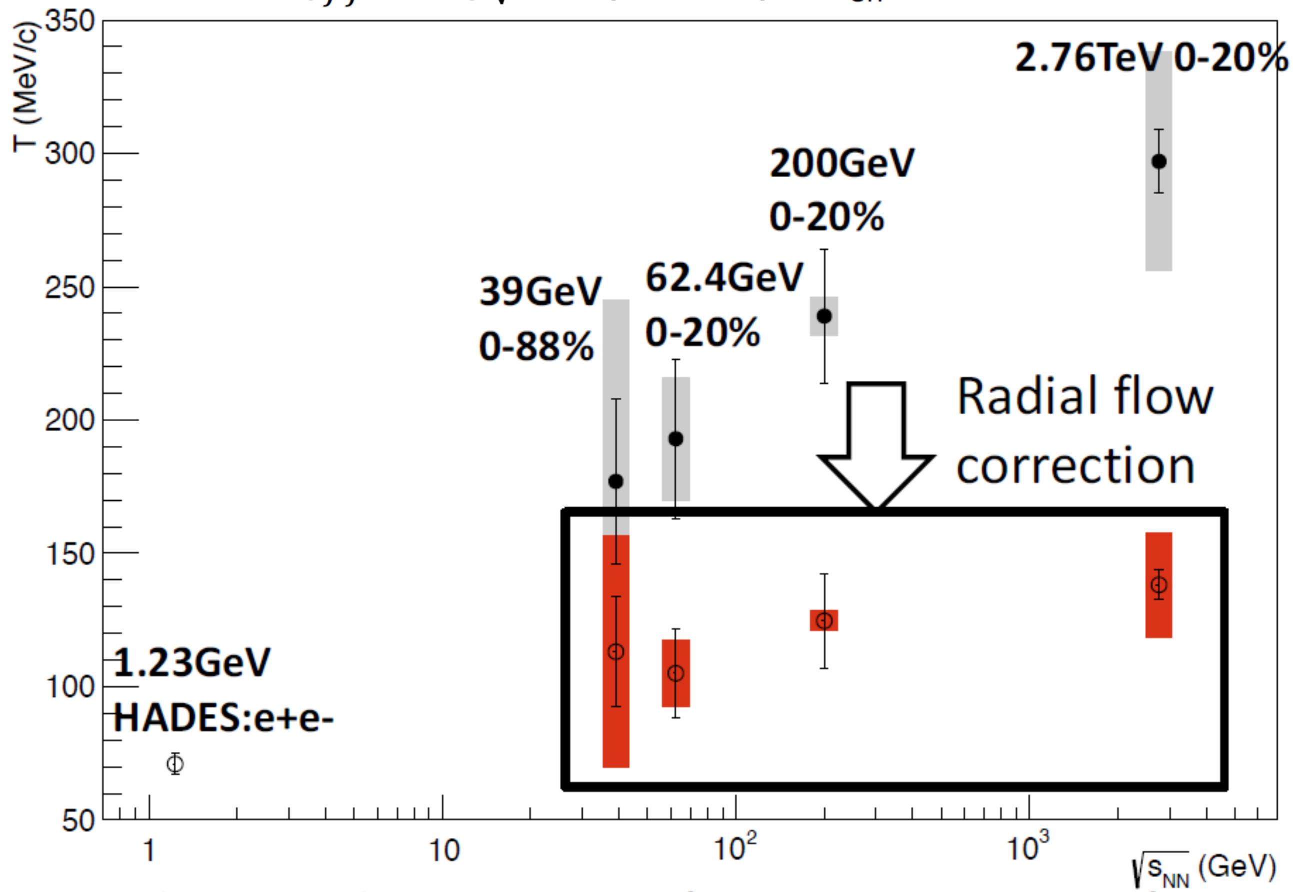
Temperature systematics



Temperature systematics

- Corrected for blue shift using radial boost parameters obtained from Blast-wave fit to hadrons
- Obviously misleading, and over-corrected

$T_{eff} = T_0\sqrt{1+\beta/1-\beta}$: T_{eff} from spectrum

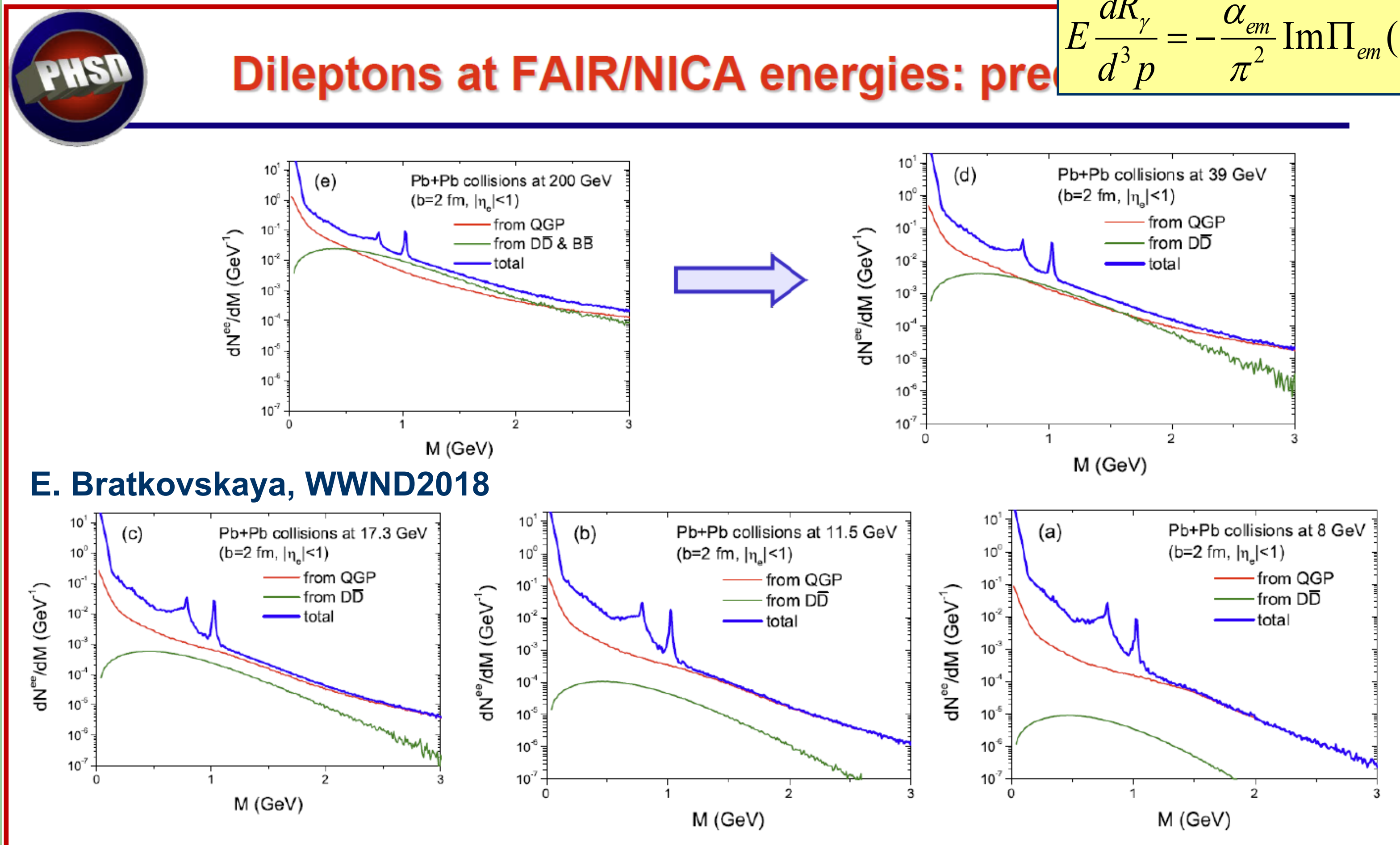


Plot by
Y. Yamaguchi

Sweet spots spread over wide energies

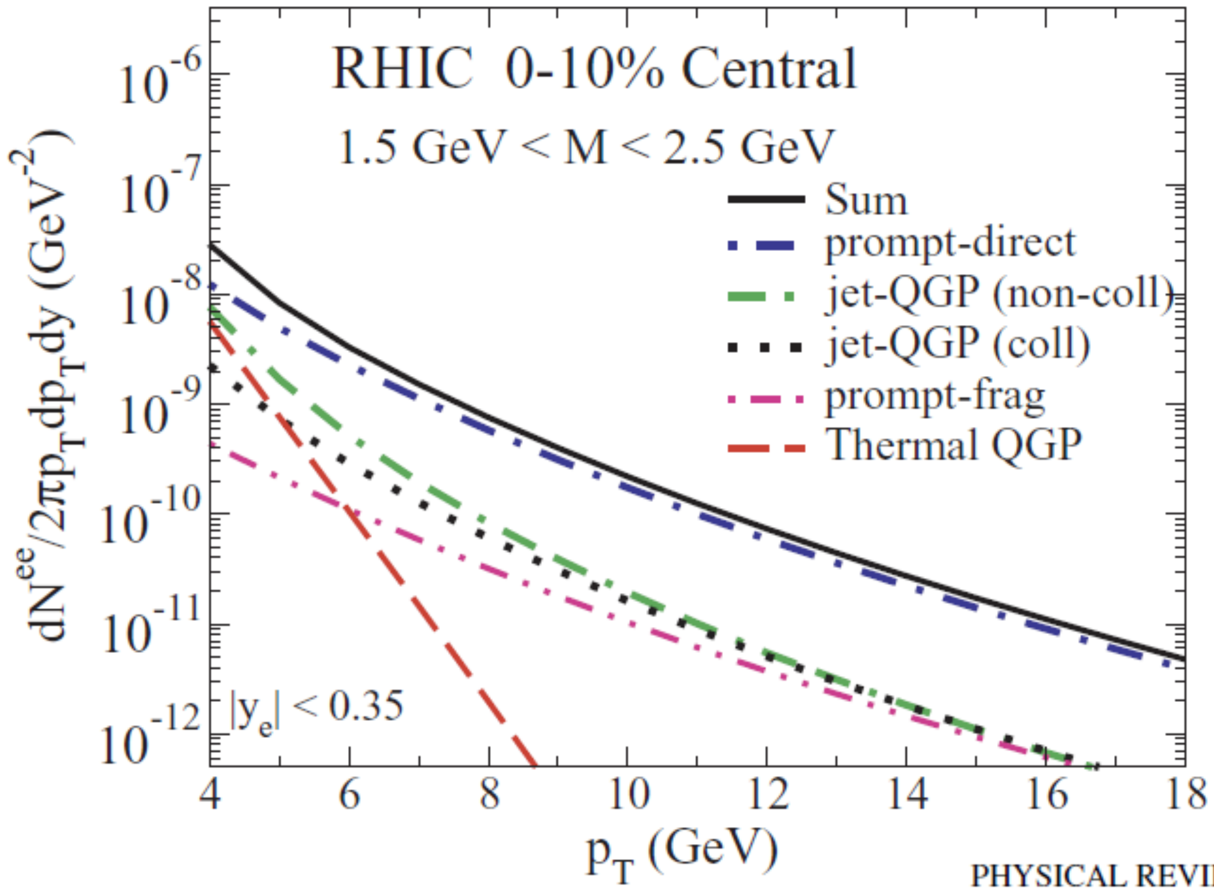
- Pure temperature via dileptons is expected in M=1-2GeV/c^2 ?
- Important measurement not only at LHC/RHIC/SPS, but also at FAIR/NICA/J-PARC

$$E\frac{dR_\gamma}{d^3p} = -\frac{\alpha_{em}}{\pi^2}\,\mathrm{Im}\Pi_{em}(\omega,k)\frac{1}{e^{E/T}-1}$$



QGP tomography by EM is underway

- (Virtual) photons have two axes (p_T and M). And η?
- Still a lot to do…



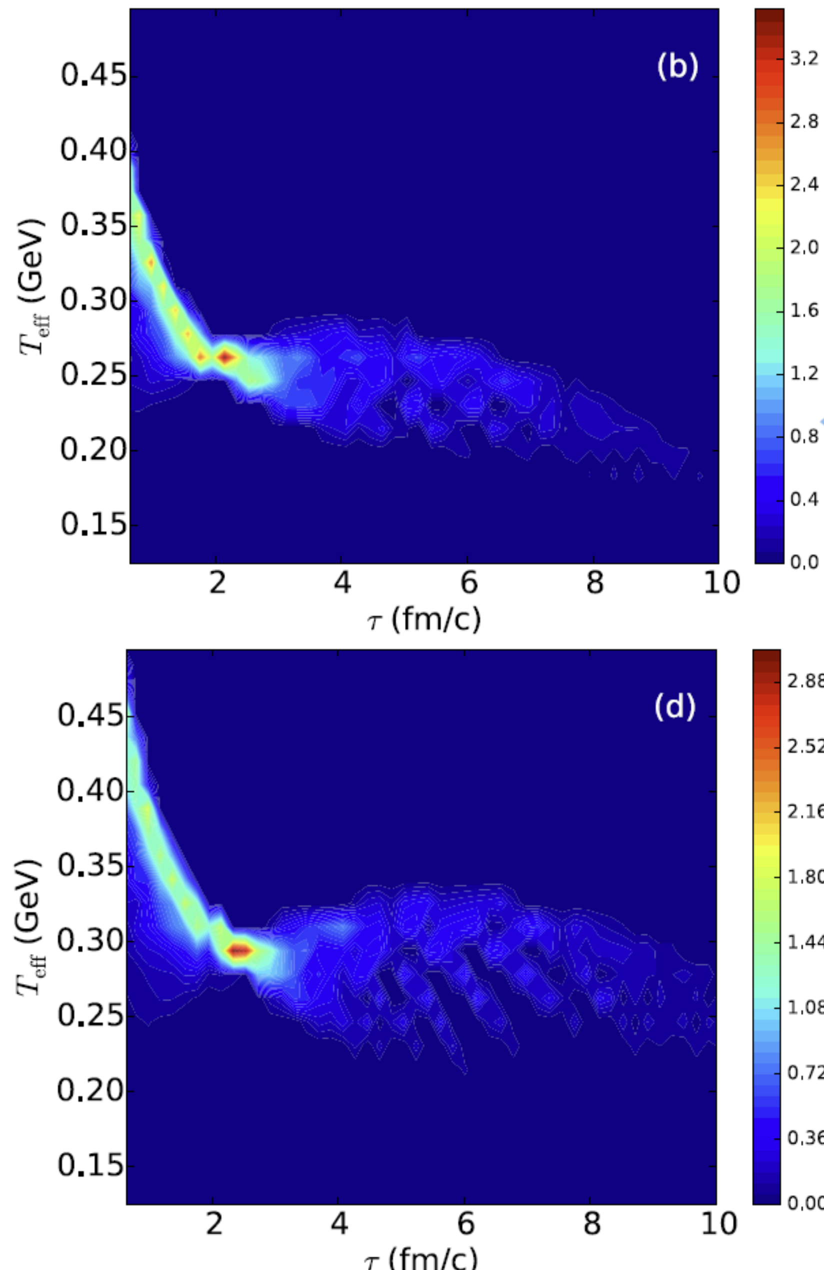
PHYSICAL REVIEW C 77, 024909 (2008)

Closing remark

- Photon physics became fruition after the decades of efforts both from experiment and theoretical sides
- Still several missing parts that have not been touched are existing
  - HBT, jet-photon, fragment photons in p+p, etc.
- Hanging these items on our mind would eventually make them realized

Backup

C. Shen, U. Heinz, J-F. Paquet and C. Gale, PRC89, 044910 (2014)



RHIC

PHENIX

LHC

LHC

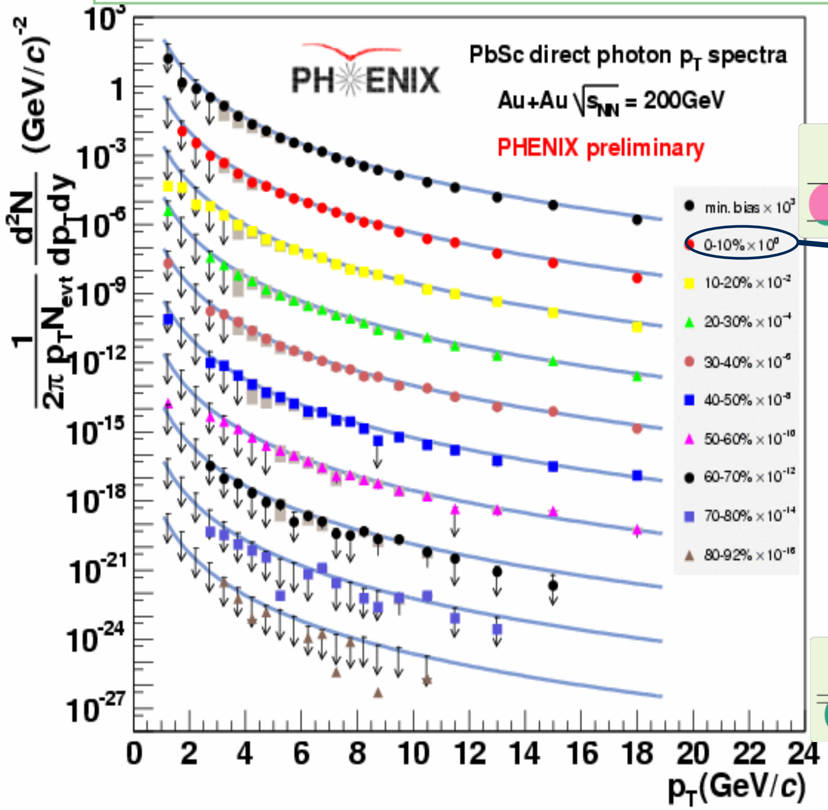
$$T_e = \sqrt{\frac{1+v}{1-v}}\,T$$

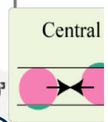
Doppler shift

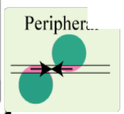
First γ_{dir} in Au+Au (hard scattering)

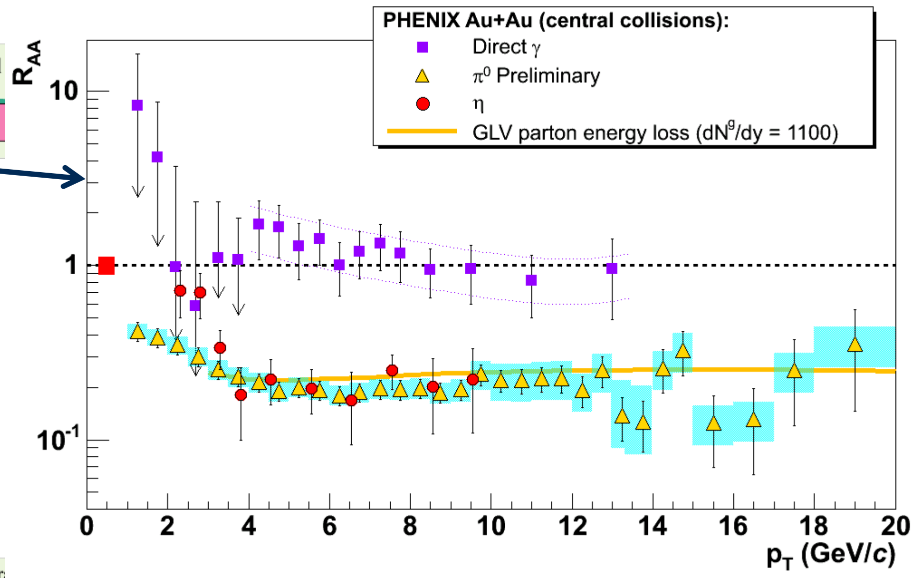
- Au+Au = p+p x T_{AB} holds – pQCD factorization works
- NLO pQCD works. → Non-pert. QCD may work in Au+Au system

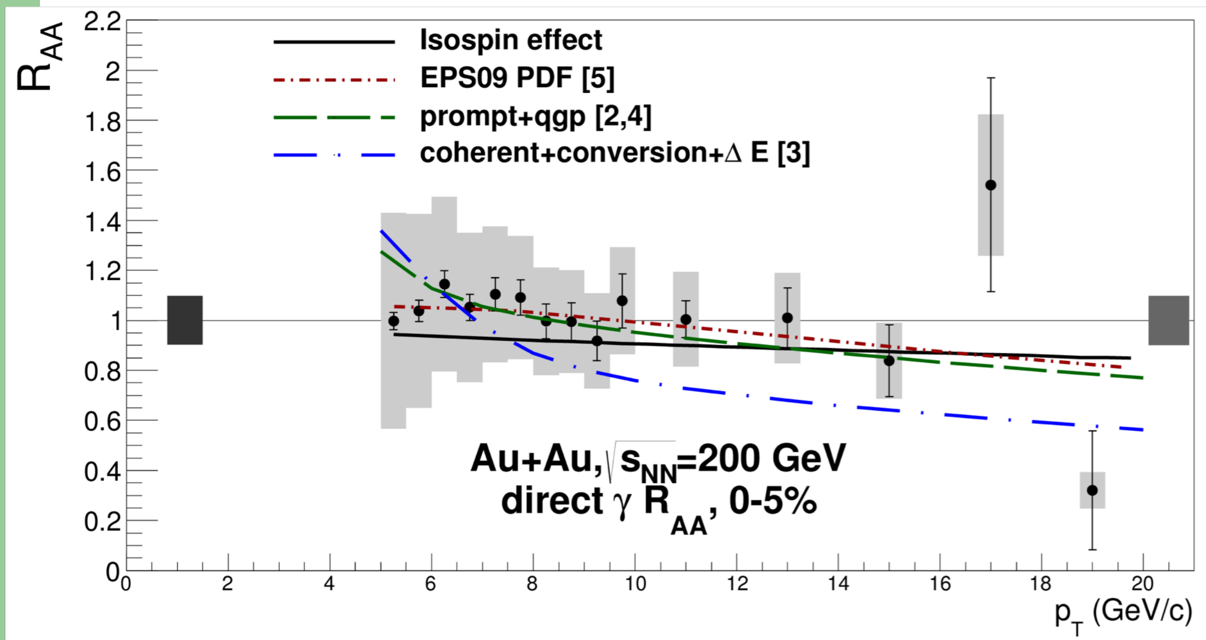
Blue line: N_{coll} scaled p+p cross-section











$$R_{AA} = \frac{\left(\frac{d^3N}{dp^3}\right)_{AA}}{T_{AA}\cdot\left(\frac{d^3\sigma}{dp^3}\right)_{pp}}$$

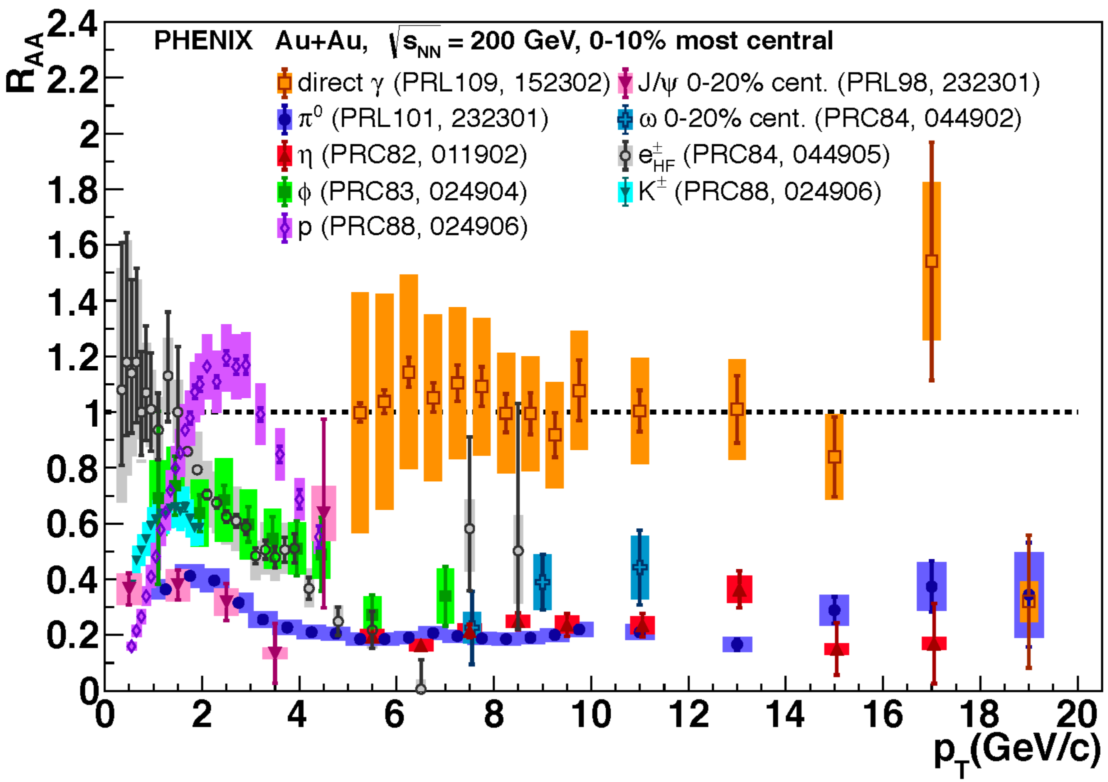
Au+Au: Phys. Rev. Lett. 109, 152302 (2012)

A theory: F. Arleo (JHEP 0609 (2006) 015)?

- **Isospin effect, in addition to jet-quenching(BDMPS) and shadowing.**

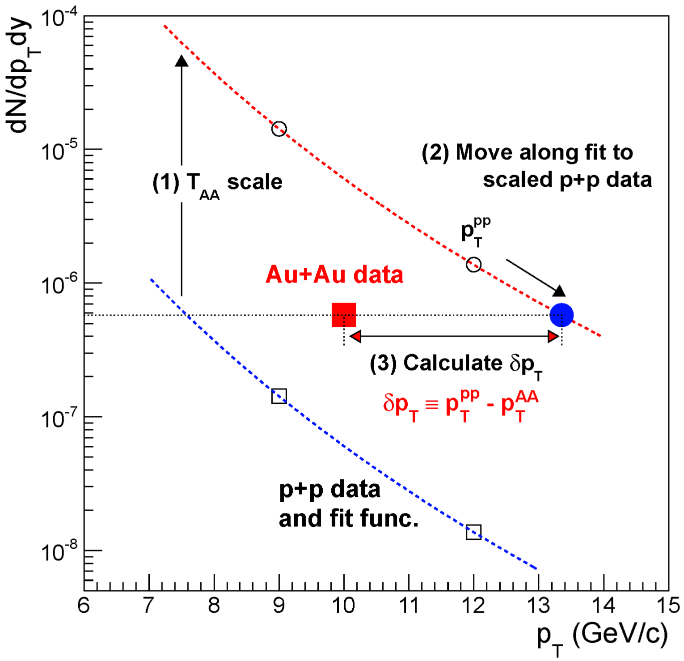
Gluon radiation when energy loss

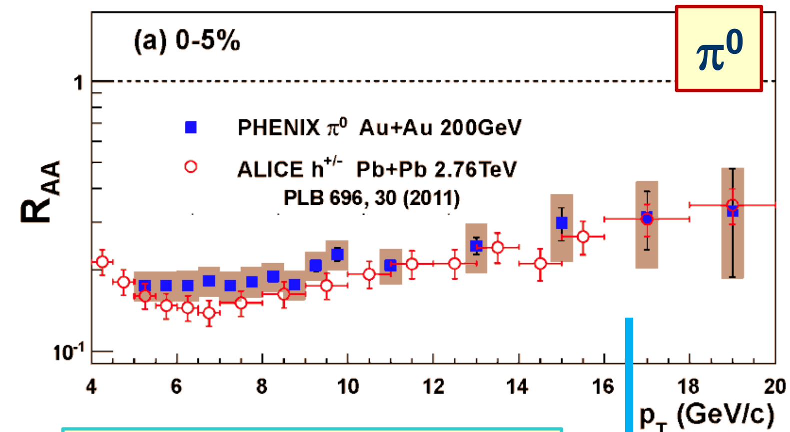
- Energy loss of partons by emitting gluons
- How about photons?



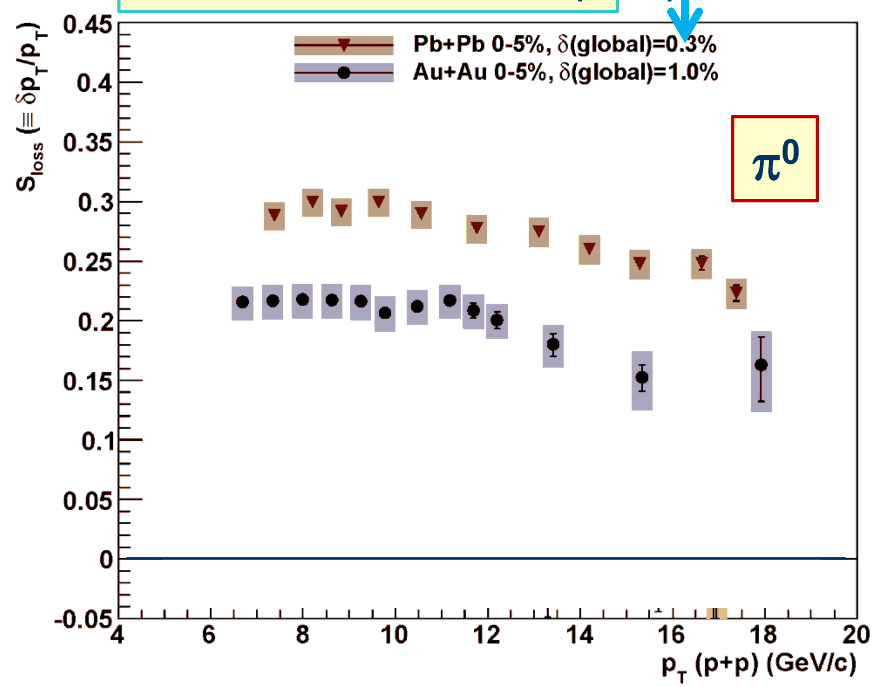
Fractional momentum loss of hadrons

- Yield suppression is the consequence of the momentum shift of the hadrons.
- Fractional momentum loss (S_{loss}) is calculated using spectra in Au+Au and N_{coll} scaled p+p spectra.
  - $S_{loss} = (p_T^{pp} - p_T^{AA})/p_T^{pp}$





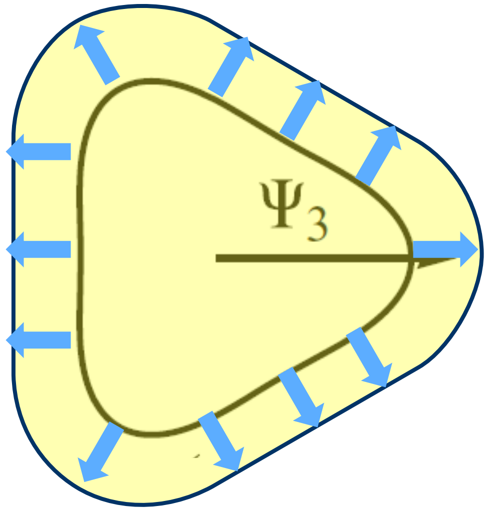
PHENIX, PRC87, 034911 (2013)



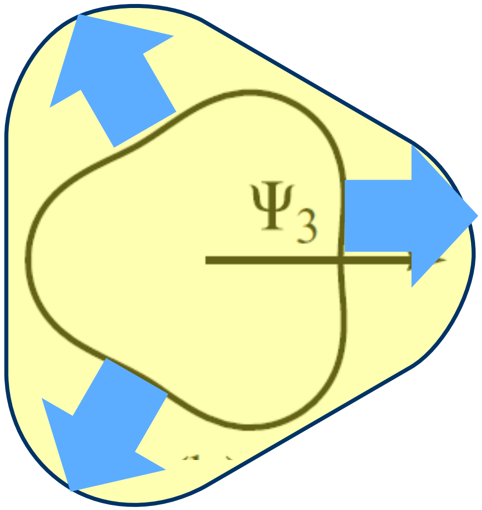
3^{rd} order HBT radii has rich feature

- Simple triangular geometry at the freezeout does not produce 3^{rd} order modulation in HBT radii (not from static source) unlike 2^{nd} order
  - Plumbert, Shen and Heinz, PRC88, 044914 (2013)
  - Either non-zero triangular flow in a spatially isotropic source, or triangular geometry coupled with azimuthally symmetric radial flow or both.
- Coupling of static source with dynamic motion of the system!
  - System dynamics can be observed through HBT

Geometry deform dominant



Flow anisotropy dominant



Emission duration changes

- π+ π+ and K+K show the different HBT radii coming from possible different emission duration
  - STAR has similar result as well
- The difference is also seen in emission angle dependent HBT radii
- Recent result of π+ K correlation from ALICE collaboration attracted me quite a bit, too

PHYSICAL REVIEW C **92**, 034914 (2015)