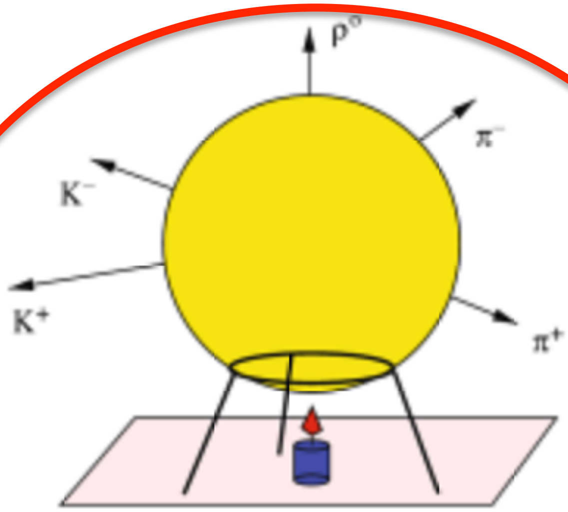
Heavy Ion Physics
Lecture 3: Particle Production

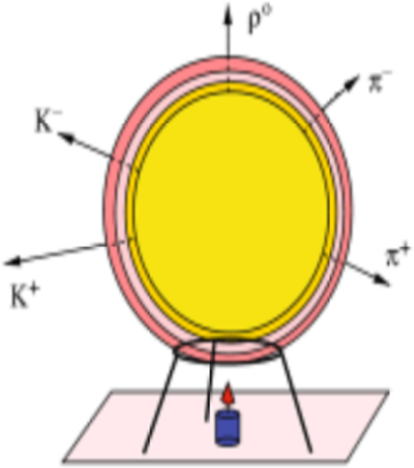
HUGS 2015

Bolek Wyslouch

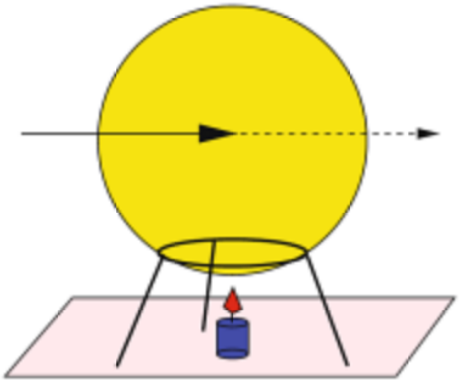
Techniques to study the plasma



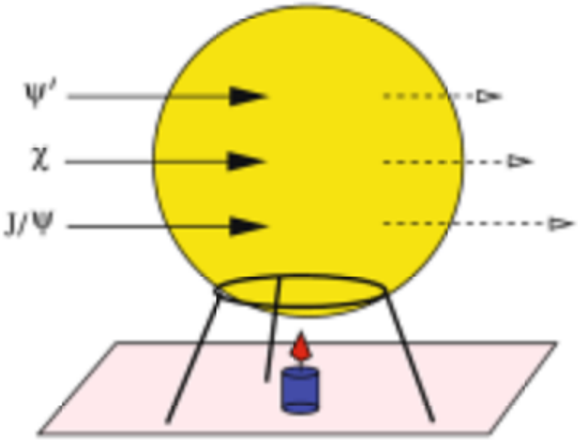
Radiation of hadrons



Azimuthal asymmetry and radial expansion



Energy loss by quarks, gluons and other particles



Suppression of quarkonia

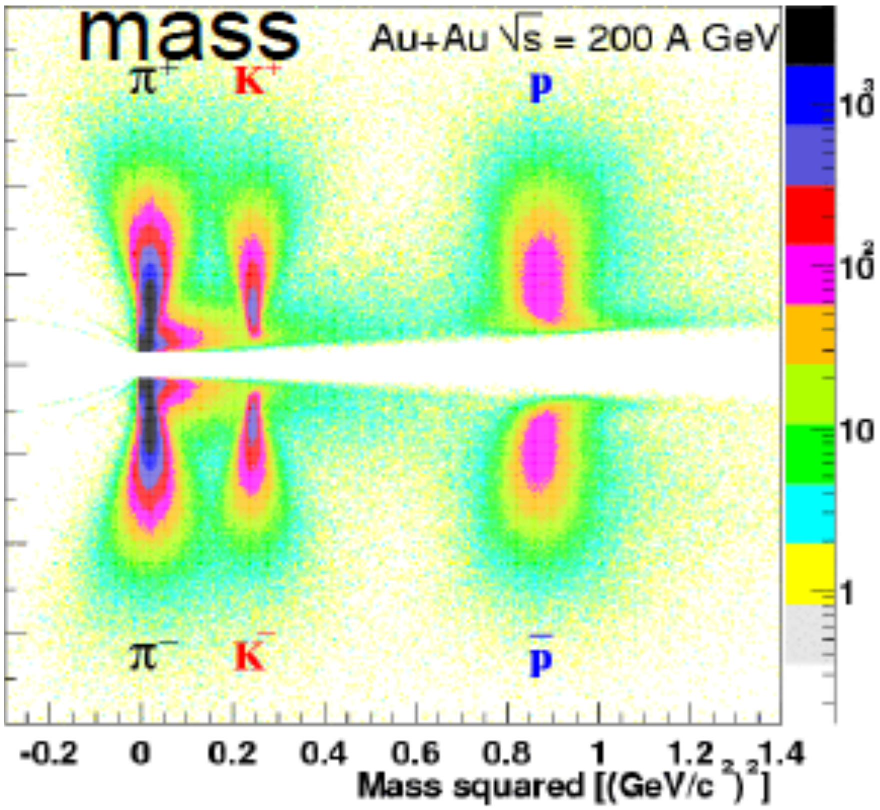
Radiation of hadrons and photons

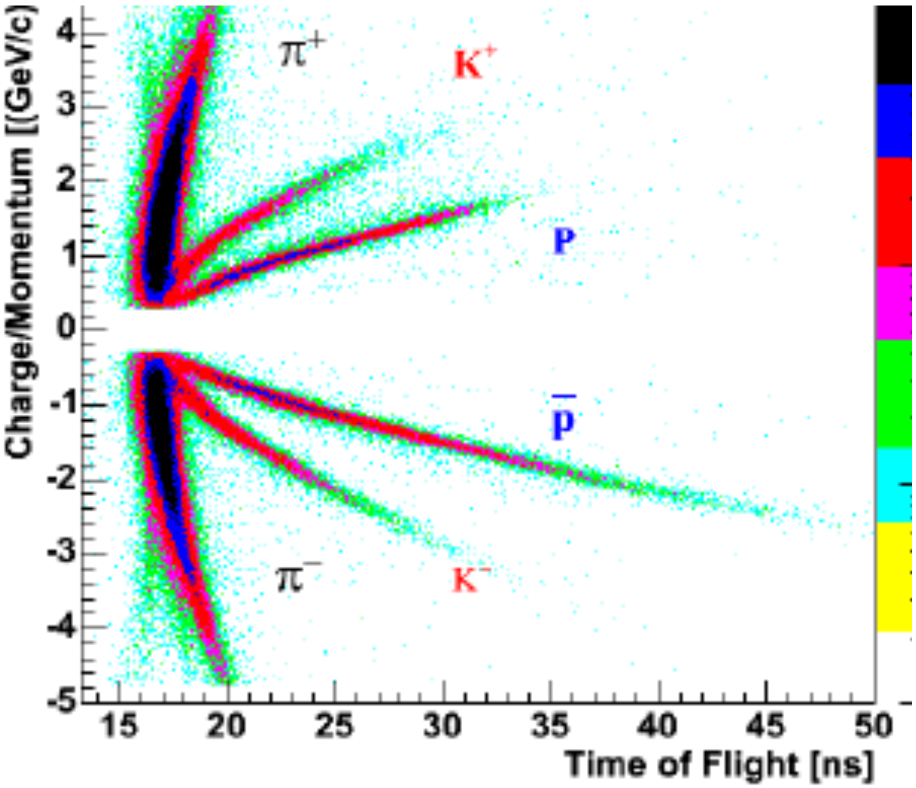
- Effects dependent on energy density
  - Charged multiplicity
  - Energy distribution
- Measuring the “chemistry” of collision, quark content of the plasma, temperature, speed of expansion
  - Momentum spectrum
  - Particle composition: π, K, p, γ
  - Comparison of particle content in nuclear and proton-proton collisions

How do we measure particle yields?

- Identify the particle (by its mass and charge)
- Measure the transverse momentum spectrum
- Integrate it to get the total number of particles
- In fixed target experiment –everything goes forward (due to cm motion) –easy to measure total (4π) yield
- In collider experiment: measure the yield in a slice of rapidity : dN/dy
- Apply corrections for acceptance and decays

Time of flight measurements:PHENIX





Time of Flight

- π/K separation ~ 3 GeV/c
- K/p separation ~ 5 GeV/c

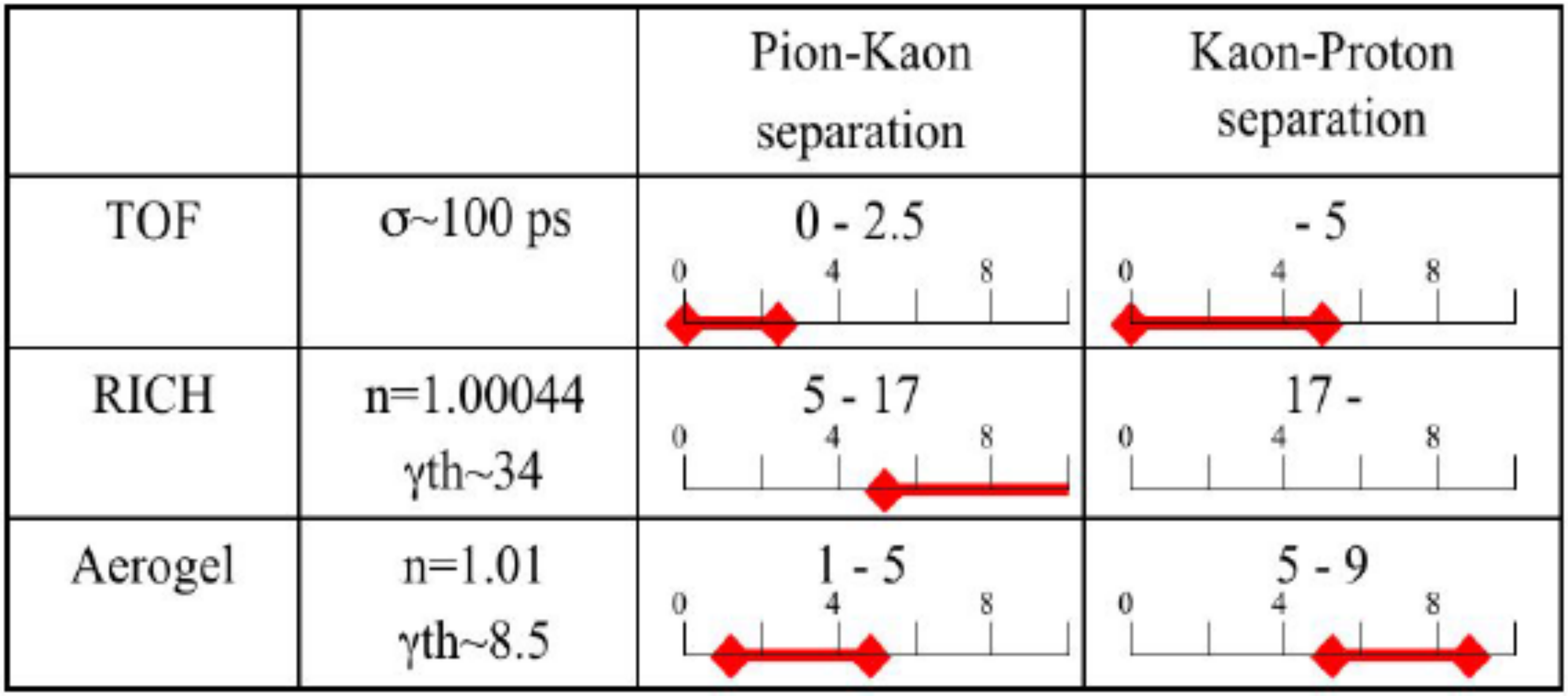
σ_t ~115 ps

Electromagnetic Calorimeter

- π/K separation ~ 1 GeV/c
- K/p separation ~ 2 GeV/c

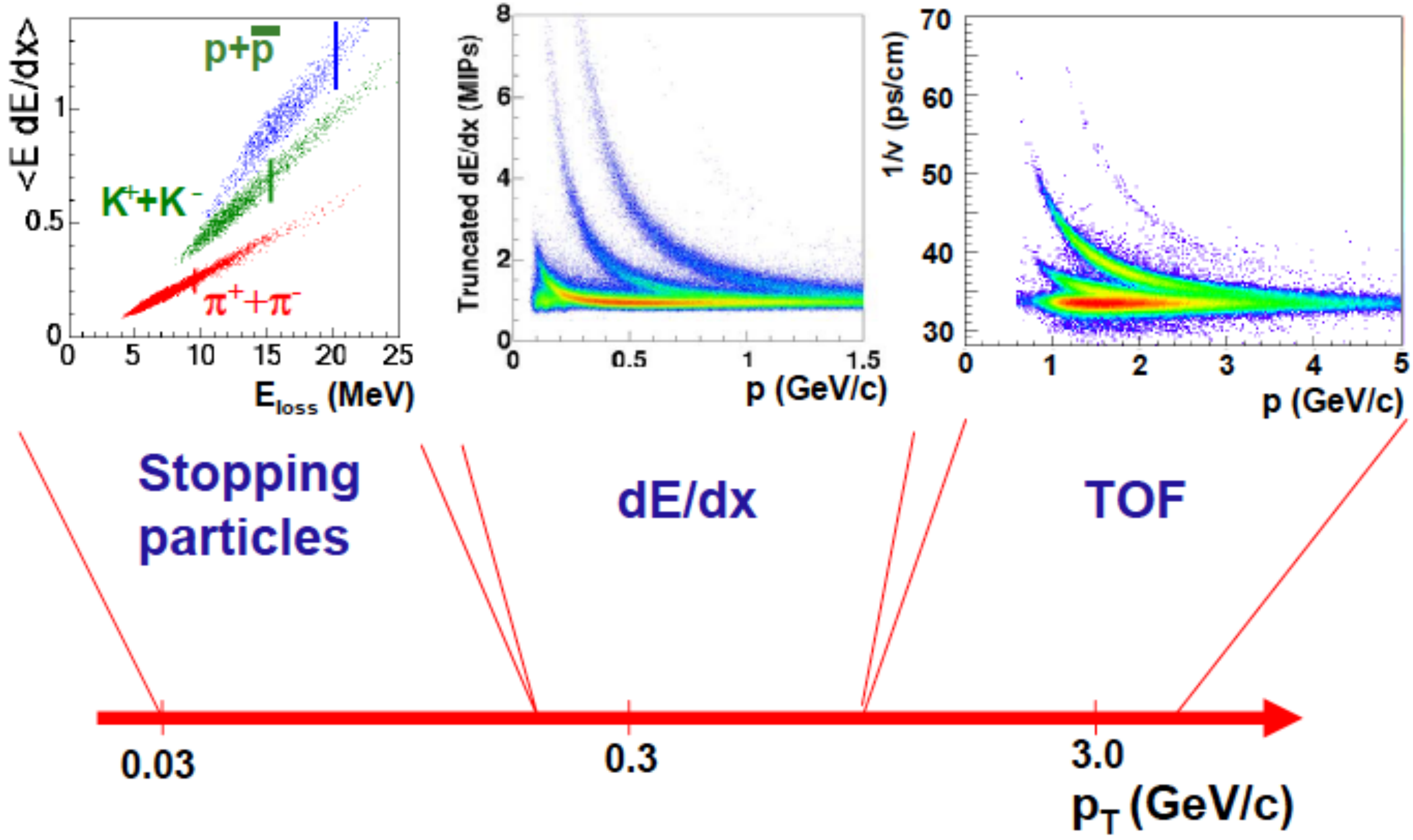
σ_t ~400 ps

Combine multiple detectors: PHENIX



		Pion-Kaon separation	Kaon-Proton separation
TOF	σ~100 ps	0 - 2.5	- 5
RICH	n=1.00044 γth~34	5 - 17	17 -
Aerogel	n=1.01 γth~8.5	1 - 5	5 - 9

PHOBOS



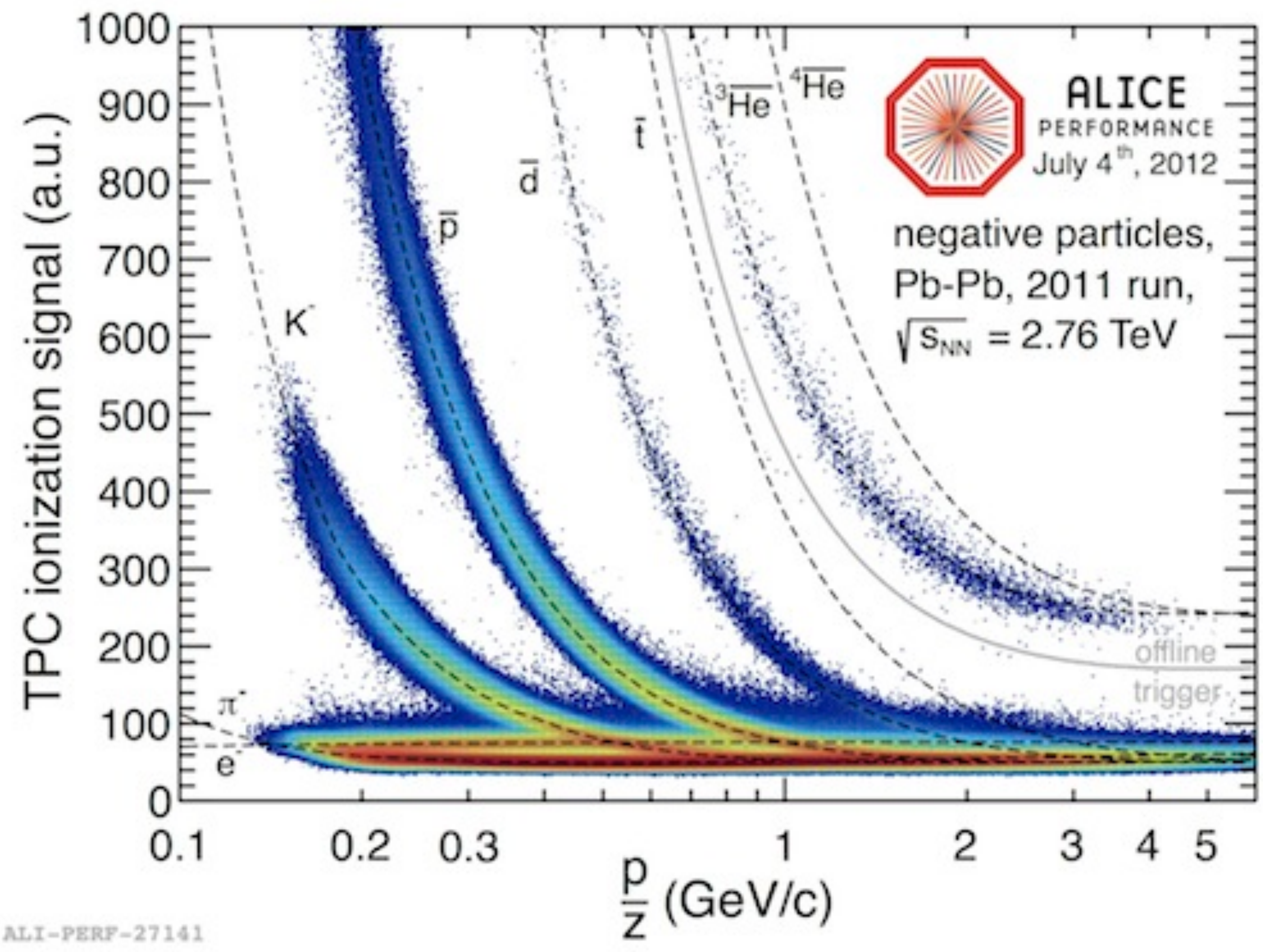
Stopping particles

dE/dx

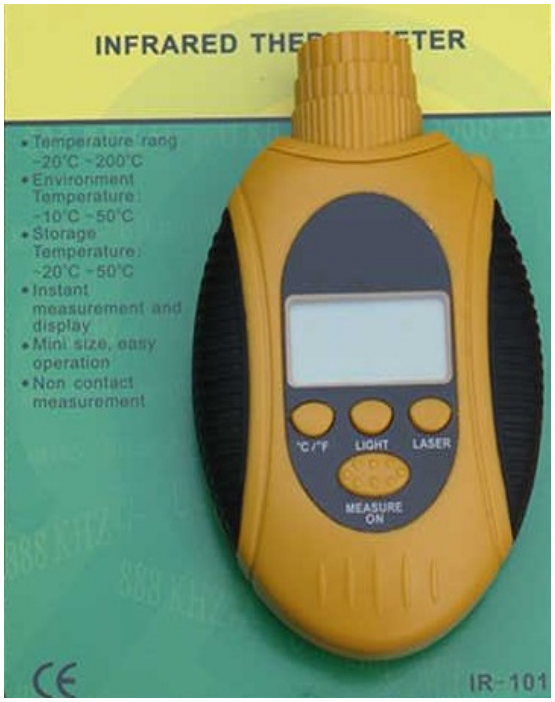
TOF

Particle ID from low to high p_T

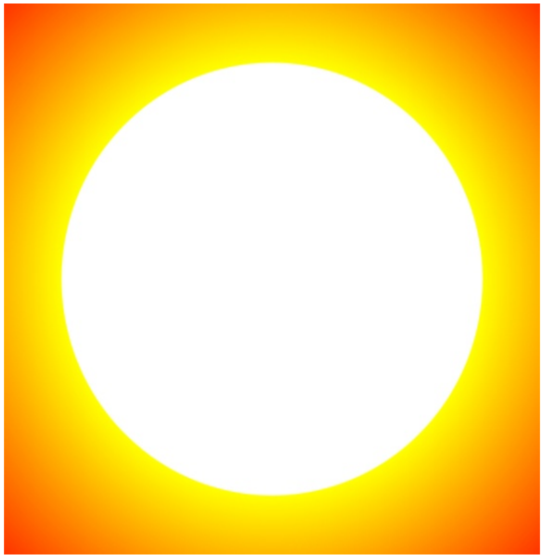
ALICE particle ID in Time Projection Chamber



Remote Temperature Sensing



Red Hot



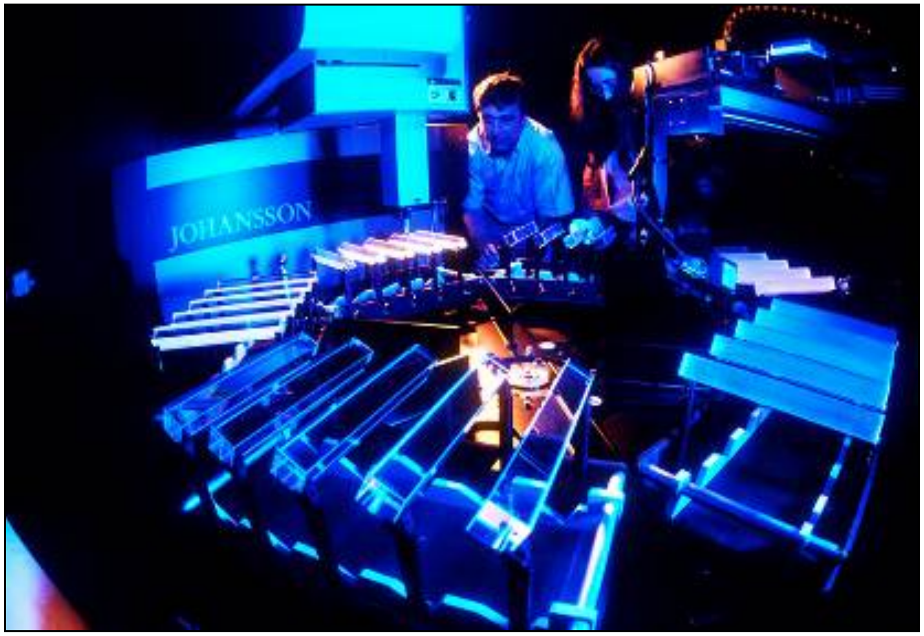
White Hot

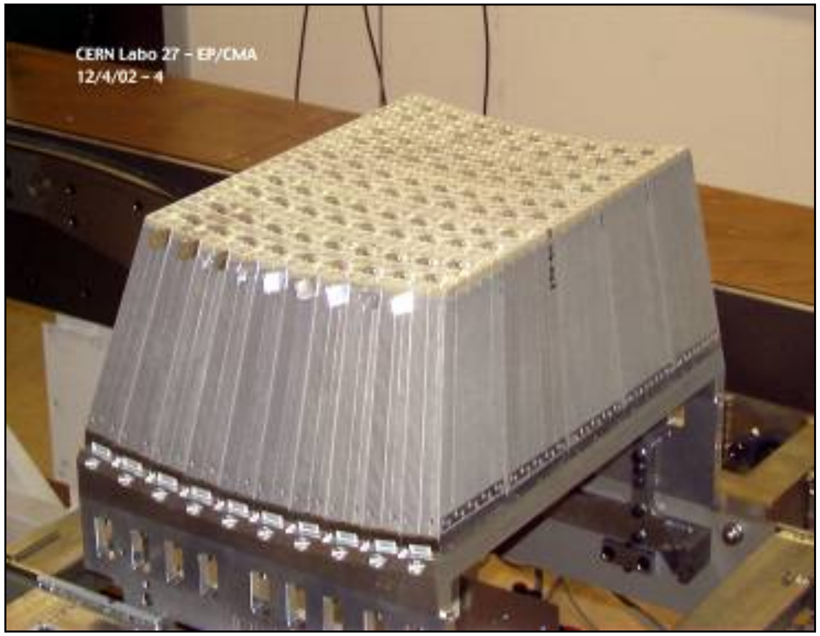
- Hot Objects produce thermal spectrum of EM radiation.
- Red clothes are NOT red hot, reflected light is not thermal.

Photon measurements must distinguish thermal radiation from other sources: HADRONS!!!

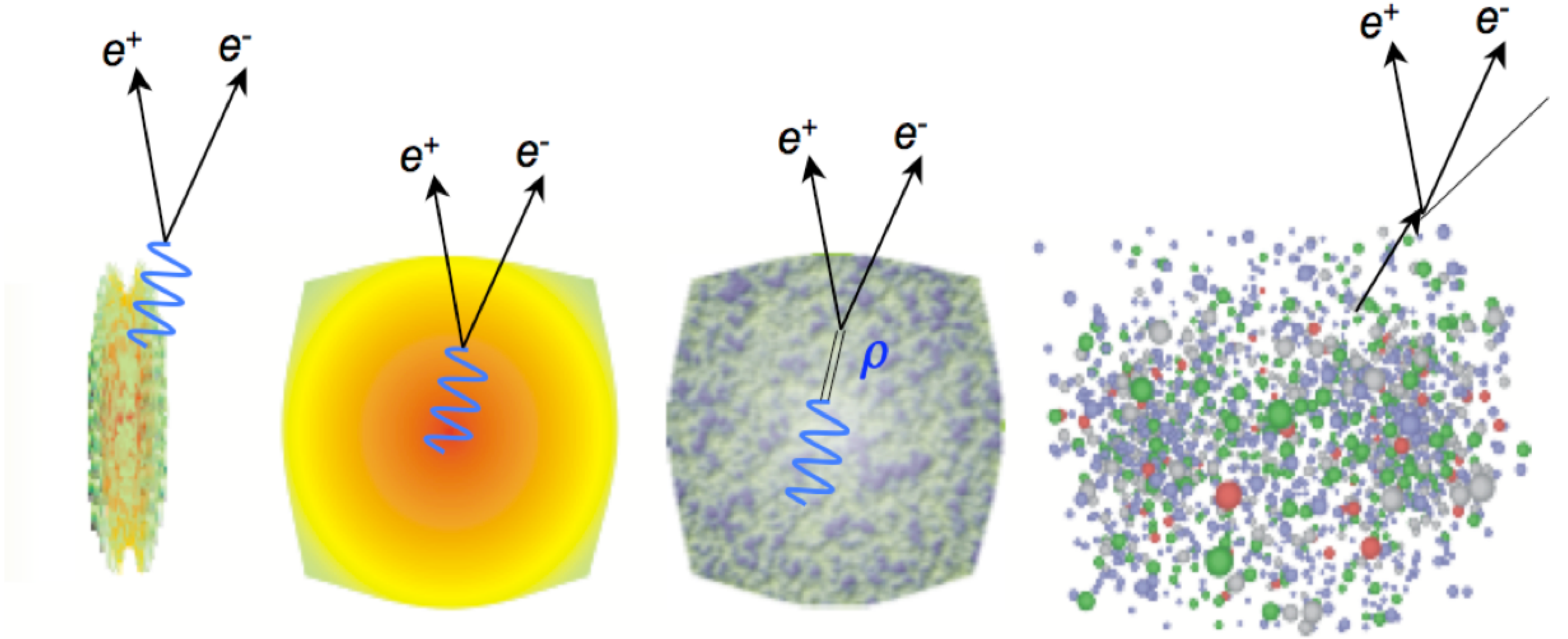
Not Red Hot!

CMS Sub-detectors: ECAL





Direct and virtual photons



Hard scattering
Bremsstrahlung

QGP phase
QGP radiation

Hadron phase
Resonance (ρ) decay

Freeze-out
Long-lived particle (π,η) decay

Direct photon and virtual photon:

- Created throughout evolution of system.
- Very low cross-section with QCD medium.
- Kinetic range reveals source of productions
  - High p_T (>5 GeV/c) --- from initial hard scattering.
  - Low p_T (1-5 GeV/c) --- from QGP.

Real vs. Virtual Photons

Direct photons $\gamma_{\mathbf{direct}}/\gamma_{\mathbf{decay}}$ ~ 0.1 at low p_T, and thus systematics dominate.

Number of virtual photons per real photon:

$$\frac{1}{N_\gamma}\frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}\sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)S$$

Hadron decay:

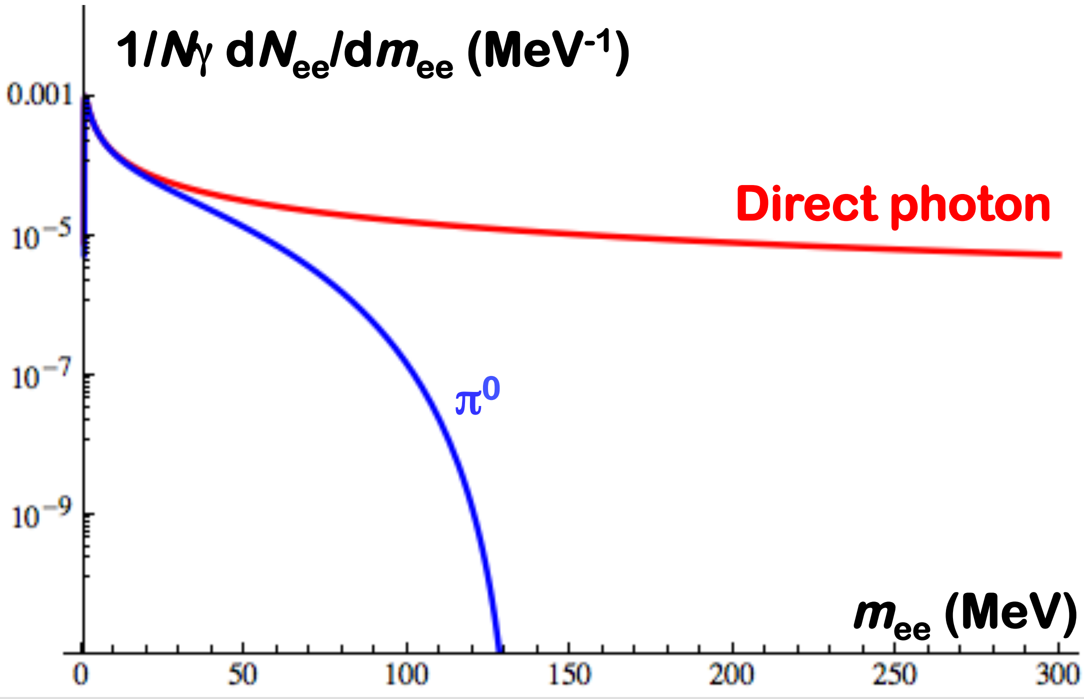
$$S = |F(m_{ee}^2)|^2(1-\frac{m_{ee}^2}{M_h^2})^3$$

form factor

Point-like process:

$$S \approx 1$$

$$(\text{for } p_T^{ee} \gg m_{ee})$$



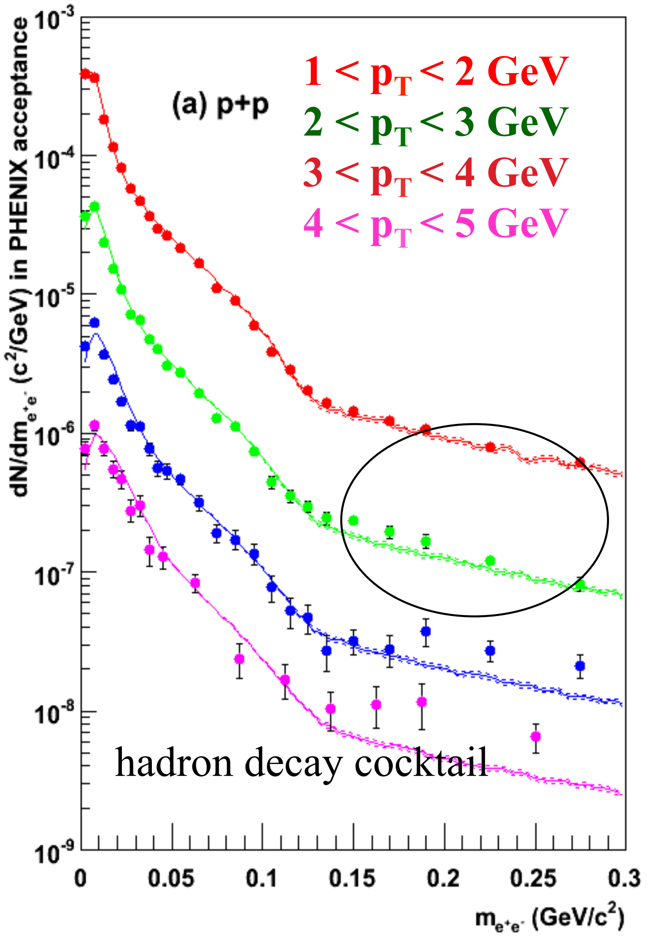
About 0.001 virtual photons with $m_{ee} > M_\pi$ for every real photon

Avoid the π^0 background at the expense of a factor 1000 in statistics

Direct (pQCD) Radiation

- **Measuring direct photons via virtual photons:**
  - any process that radiates γ will also radiate $\gamma*$
  - for $m<<p_T$ $\gamma*$ is "almost real"
  - extrapolate $\gamma* \rightarrow e+e-$ yield to $m = 0$ → direct γ yield
  - $m > m_\pi$ removes 90% of hadron decay background
  - S/B improves by factor 10: 10% direct γ → 100% direct $\gamma*$

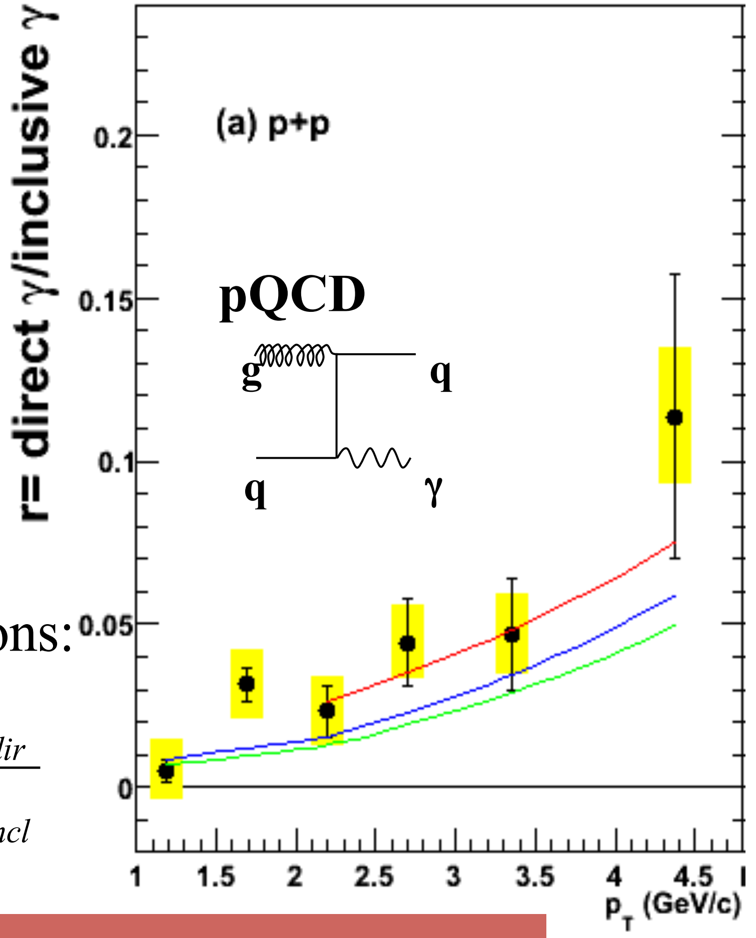
arXiv:0804.4168



access above cocktail

fraction or direct photons:

$$r = \frac{\gamma^*_{dir}}{\gamma^*_{incl}} = \frac{\gamma_{dir}}{\gamma_{incl}}$$

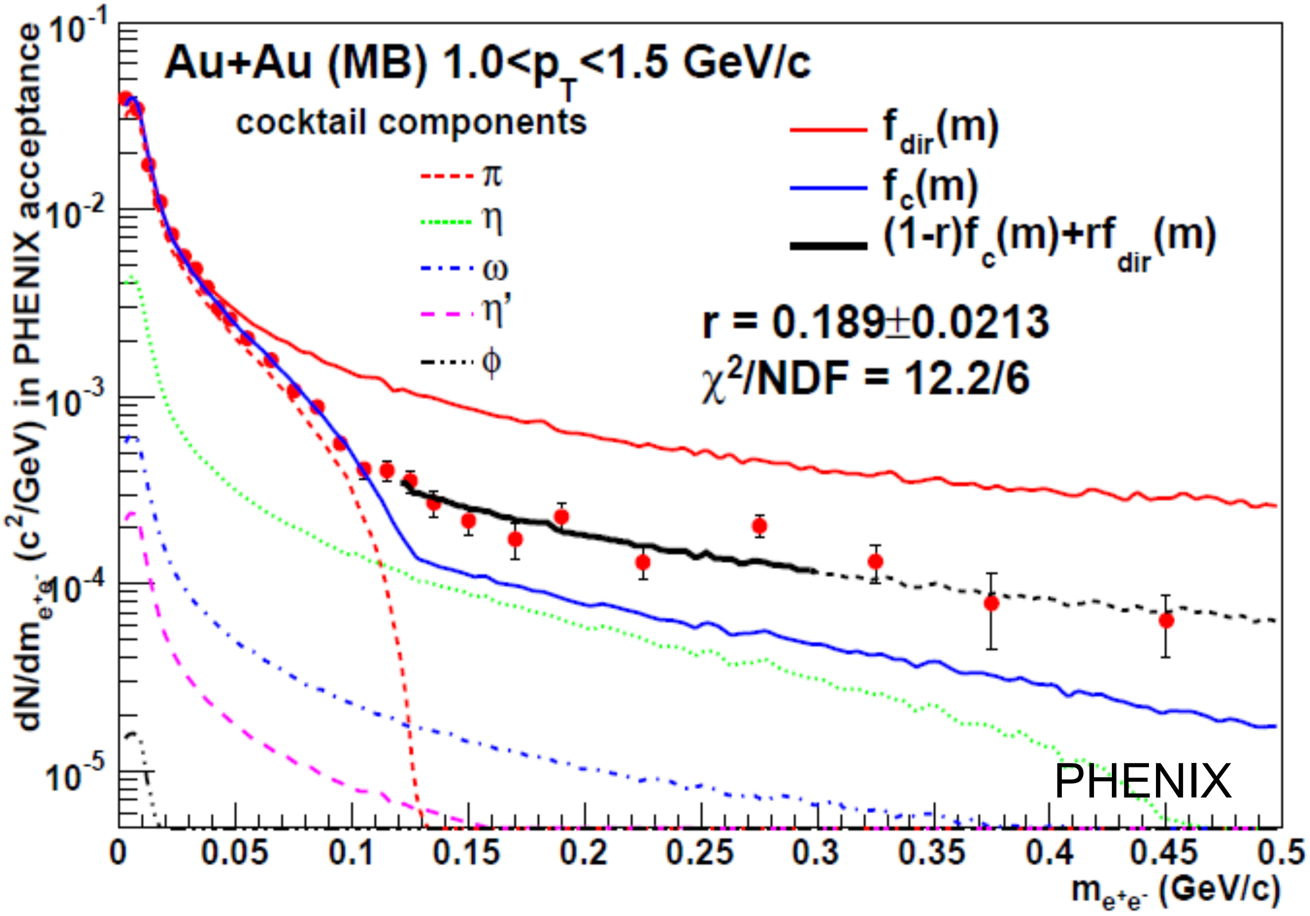


Small excess for $m<< p_T$ consistent with pQCD direct photons

Fit Mass Distribution to Extract the Direct Yield:

- Example: one p_T bin for Au+Au collisions

$$\frac{d^2N_{ee}}{dm_{ee}dp_T} = \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}L(m_{ee})S(m_{ee},p_T)\frac{dN_\gamma}{dp_T},$$



$$L(m_{ee}) = \sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right).$$

$$S_{\mathrm{KW}}(M) = |F_P(M^2)|^2\left(1-\frac{M^2}{m_P^2}\right)^3$$

Yield truncated at parent mass

$f_c(m_{ee})$ and $f_{dir}(m_{ee})$ normalized to data for $m_{ee} < 30\,MeV$

c cocktail
dir direct

Direct γ* yield fitted in range 120 to 300 MeV
Insensitive to π^0 yield

Interpretation as Direct Photon

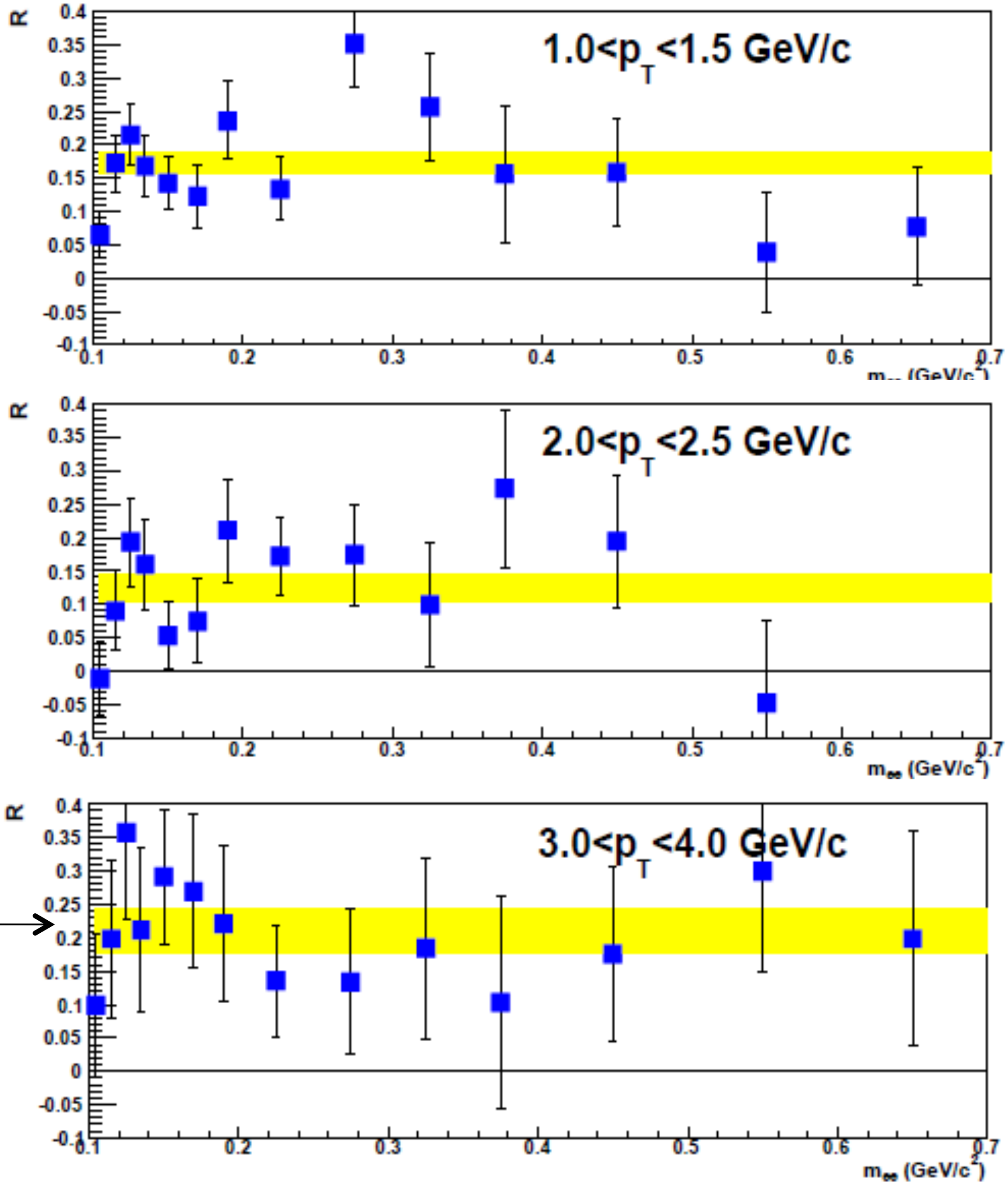
Relation between real and virtual photons:

$$\frac{d\sigma_{ee}}{dM^2\,dp_T^2\,dy} \cong \frac{\alpha}{3\pi}\frac{1}{M^2}L(M)\frac{d\sigma_\gamma}{dp_T^2\,dy}$$

Extrapolate real γ yield from dileptons:

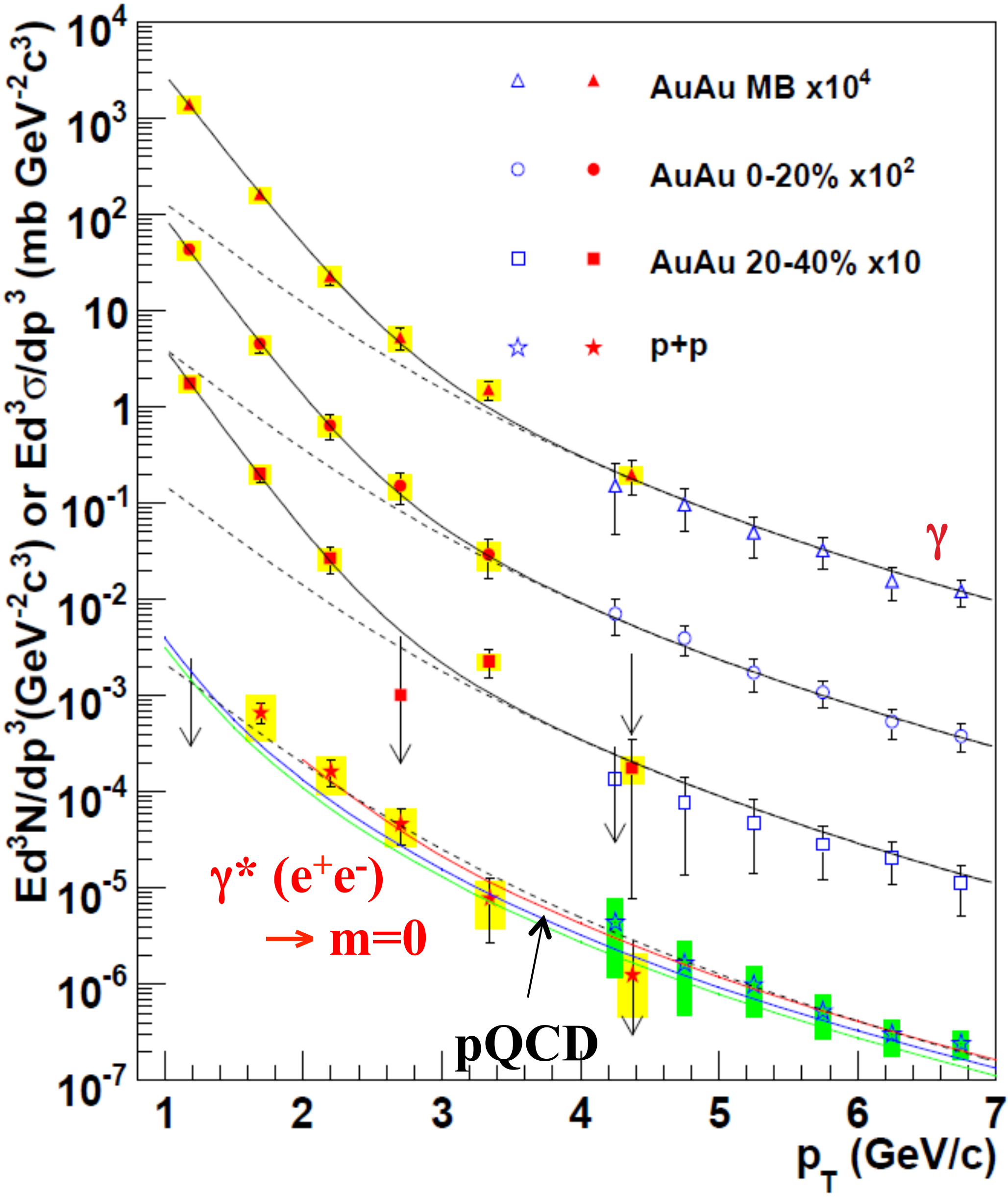
$$M\times\frac{dN_{ee}}{dM} \to \frac{dN_\gamma}{dM} \quad \text{for} \quad M \to 0$$

Virtual Photon excess
At small mass and high p_T
Can be interpreted as
real photon excess

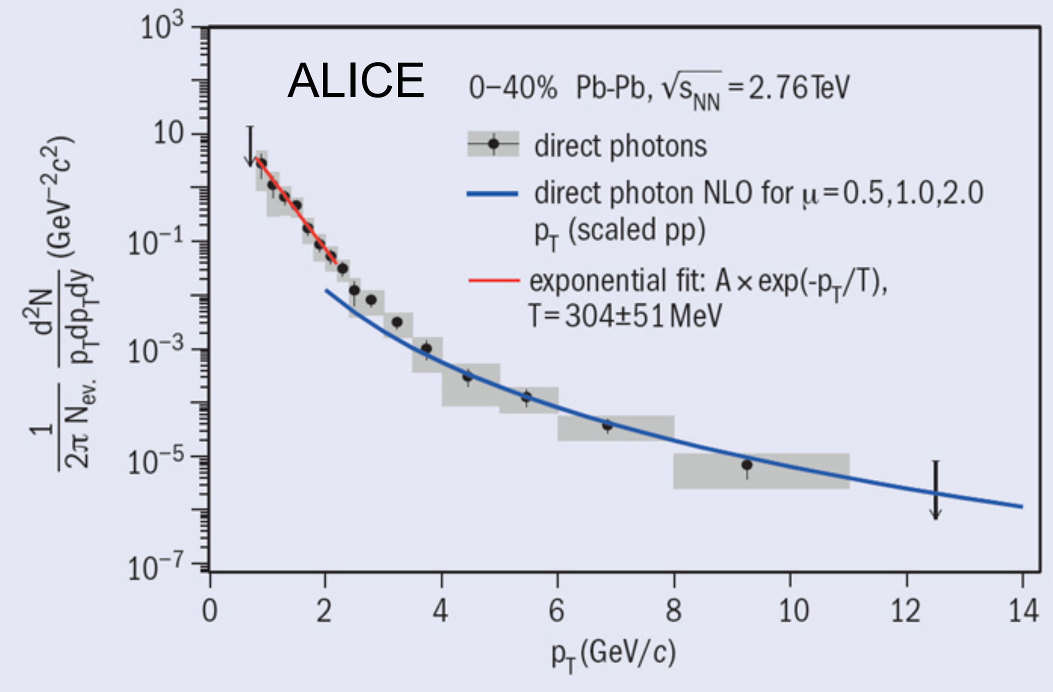


no change in shape
can be extrapolated
to m=0

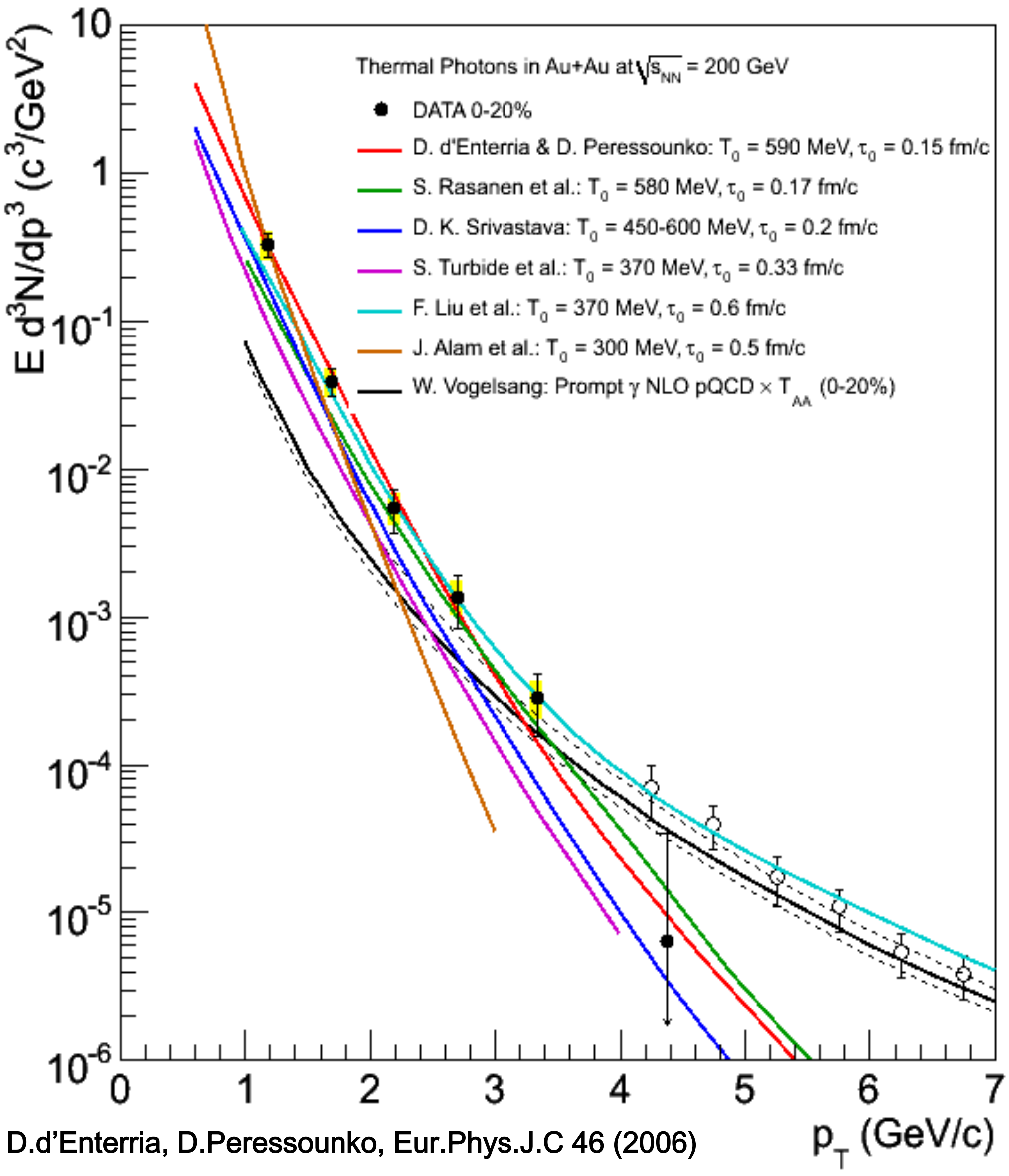
Thermal Radiation at RHIC



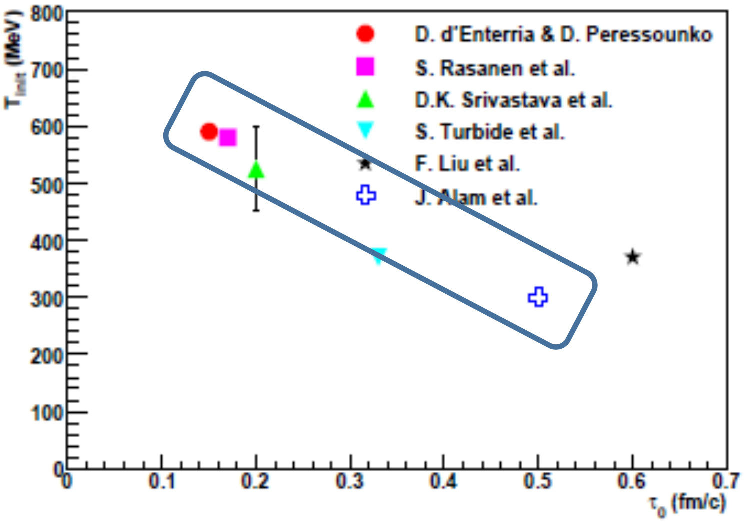
- Direct photons from real photons:
  - Measure inclusive photons
  - Subtract π^0 and η decay photons at S/B < 1:10 for p_T<3 GeV
- Direct photons from virtual photons:
  - Measure e^+e^- pairs at $m_\pi < m << p_T$
  - Subtract η decays at S/B ~ 1:1
  - Extrapolate to mass 0



Calculation of Thermal Photons



D.d’Enterria, D.Peressounko, Eur.Phys.J.C 46 (2006)

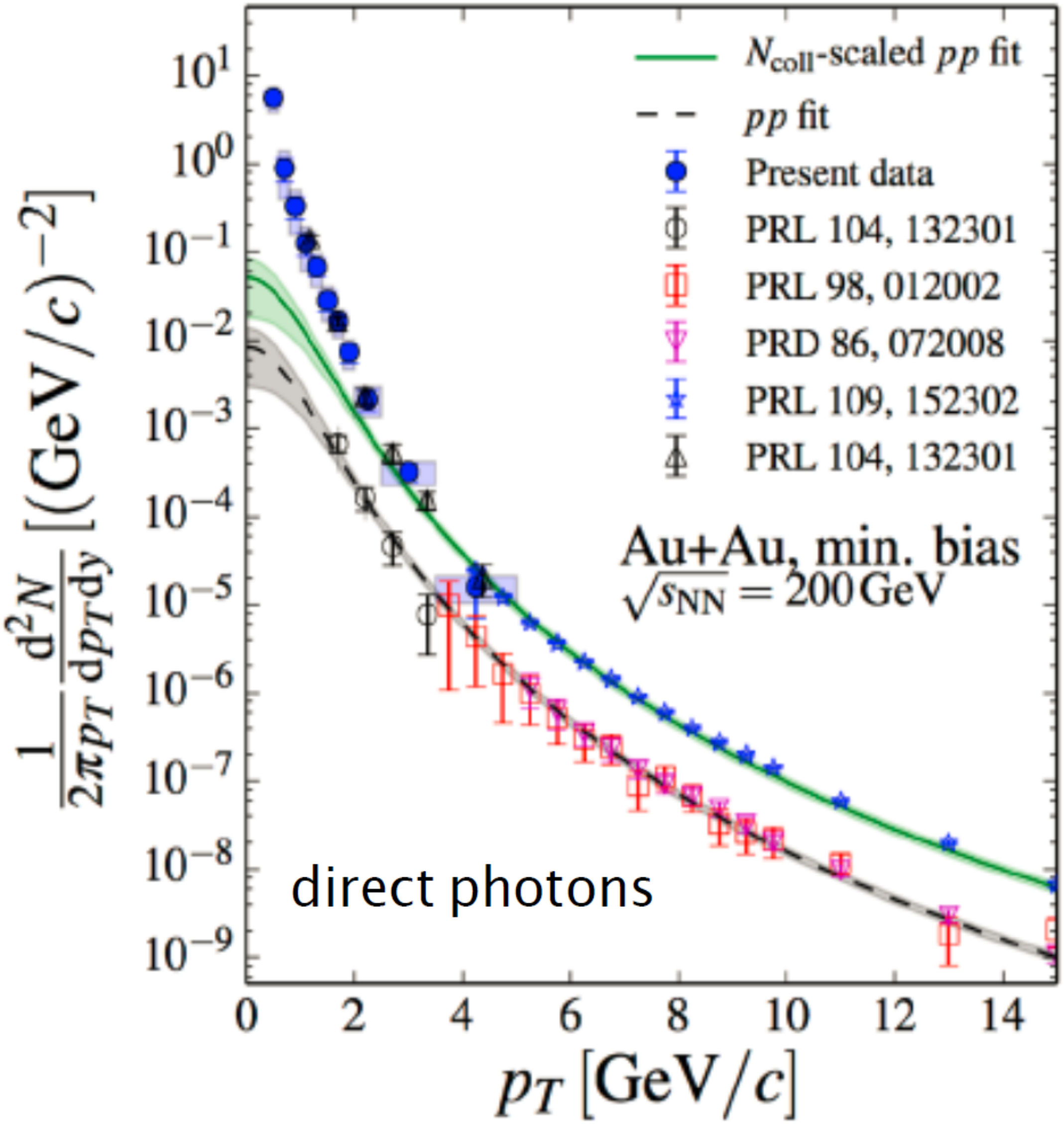


- Initial temperatures and times from theoretical model fits to data:
  - 0.15 fm/c, 590 MeV (d’Enterria et al.)
  - 0.2 fm/c, 450-660 MeV (Srivastava et al.)
  - 0.5 fm/c, 300 MeV (Alam et al.)
  - 0.17 fm/c, 580 MeV (Rasanen et al.)
  - 0.33 fm/c, 370 MeV (Turbide et al.

T_{ini} = 300 to 600 MeV
τ_0 = 0.15 to 0.5 fm/c

Now with Real γ !

arXiv:1405.3940



New analysis using external conversion of real photons

Agreement with virtual photon method publication (earlier discovery of thermal photon radiation)

Extended p_T range, centrality, precision

- Real gamma from photon conversions….

Chemical Equilibrium

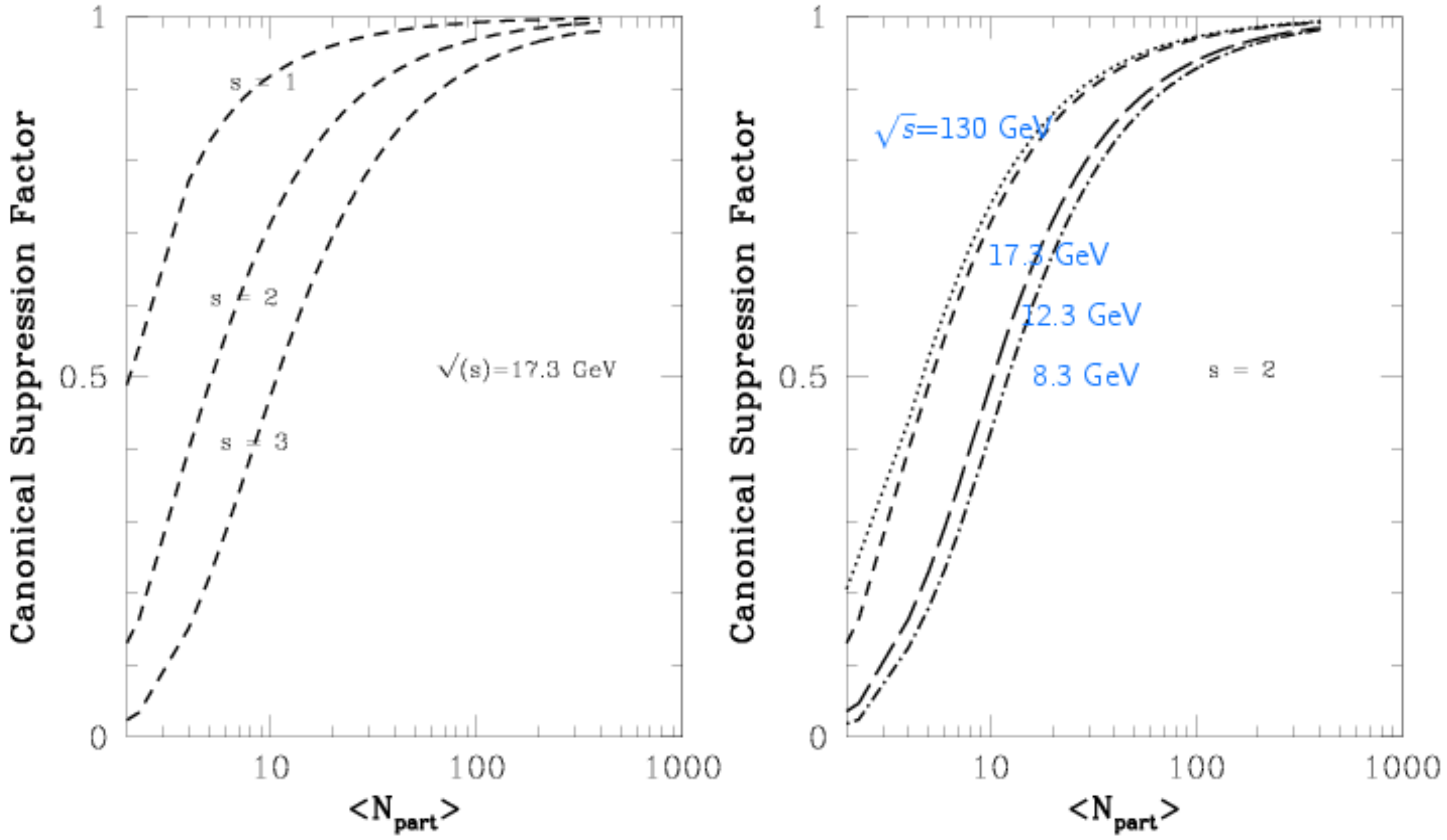
- In a HI collision there is cornucopia of produced particles, seemingly a nightmare.
- However, if the system has exhibited thermalization, then the particle production might be understood through simple considerations.
- We'll consider two aspects of thermal predictions:
  - Chemical Equilibrium
    - Are all the various particle species produced at the right relative rates and abundances?
  - Kinetic Equilibrium
    - Is the particle production consistent with a single underlying temperature plus common flow velocities?

Statistical Ensemble

- We must choose an appropriate statistical ensemble. This choice in itself is instructive to the physics:
  - Grand Canonical Ensemble: In a large system with many produced particles we can implement conservation laws in an averaged sense via appropriate chemical potentials.
  - Canonical Ensemble: in a small system, conservation laws must be implemented on an EVENT-BY-EVENT basis. This makes for a severe restriction of available phase space resulting in the so-called “Canonical Suppression.”
  - Where is canonical required:
    - low energy HI collisions.
    - high energy e+e- or hh collisions
    - Peripheral high energy HI collisions.

Canonical Suppression

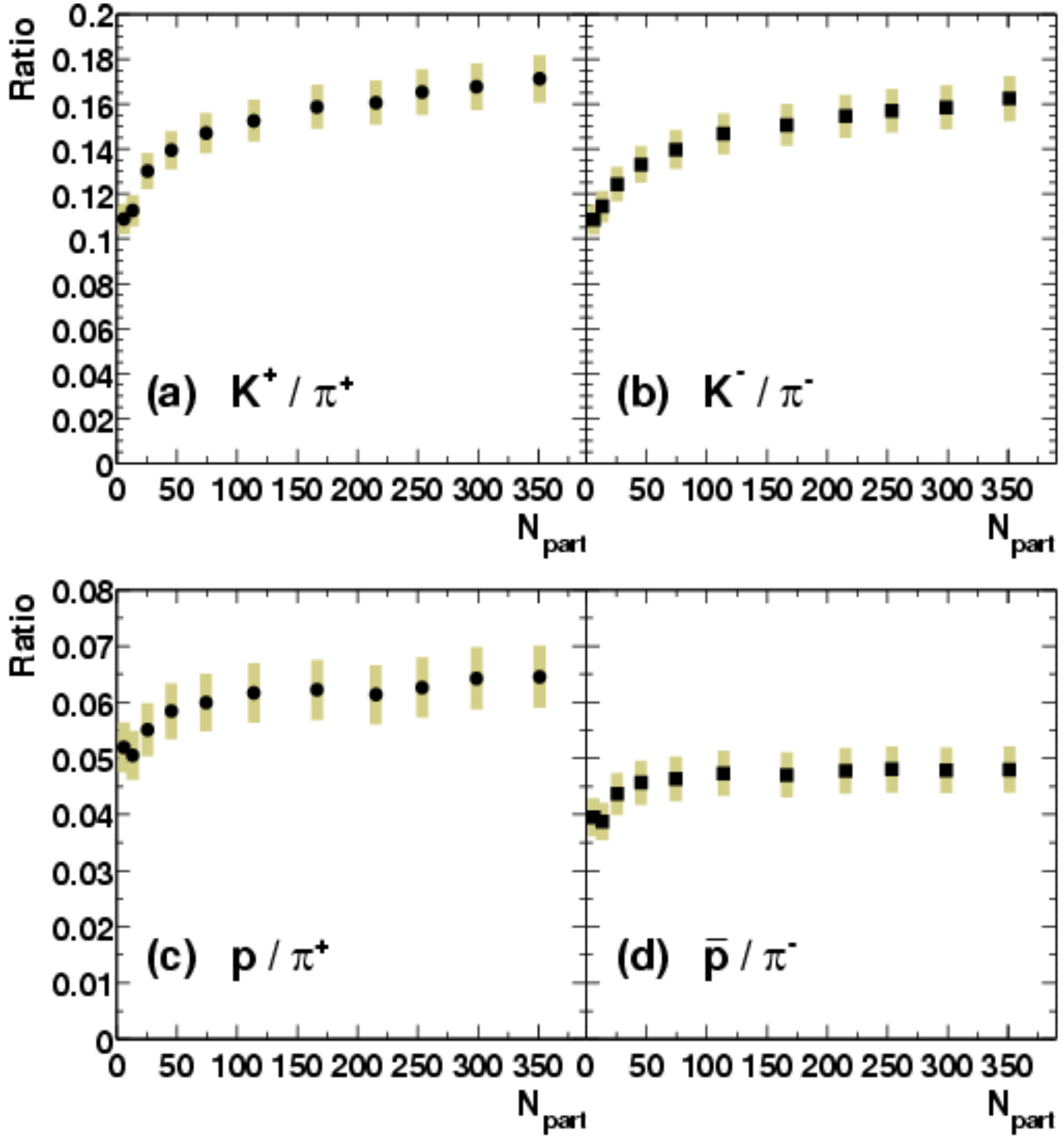
Tounsi and Redlich, hep-ph/0211159



for $\mathrm{N}_{part} \geq 60$ Grand Canonical ok to better 10%

K/p ratios vs. Centrality

- Simple expectation:
  - Particles carrying conserved quantum numbers (strangeness, baryon number) should exhibit loss of canonical suppression with centrality.
- K is strangeness 1
- p is baryon number 1
- Normalized compared to pion, both curves rise rapidly with centrality and then saturate.



Thermal yields

- Begin with the formula for the number density of all species:

$$n_i^0 = \frac{g_i}{2\pi^2}\int \frac{p^2 dp}{e^{\left(E-\mu_B B_i-\mu_s S_i-\mu_3 I^3\right)/T} \pm 1}$$

  here g_i is the degeneracy
  $E^2=p^2+m^2$
  μ_B, μ_S, μ_3 are baryon, strangeness, and isospin chemical potentials respectively
  + for fermions and – for bosons

- Given the temperature and all m, on determines the equilibrium number densities of all various species.
- The ratios of produced particle yields between various species can be fitted to determine T, μ.

Reality check:

- Approximate μ$_B$ assuming a temperature of 170 MeV and that the anti-proton/proton ratio is 0.7 and independent of momentum

$$n_i^0 = \frac{g_i}{2\pi^2}\int \frac{p^2 dp}{e^{\left(E-\mu_B B_i-\mu_s S_i-\mu_3 I^3\right)/T} \pm 1}$$

- All factors in the above equation cancel except the Baryon number (proton=+1, p$_{bar}$=-1). So

$$\frac{\bar{p}}{p} \approx \frac{e^{-\mu_B/T}}{e^{\mu_B/T}} = e^{-2\mu_B/T}; \mu_B \approx 30 MeV$$

- Question: Which has large μ$_B$, high energy or low energy collisions?

Conservation Constraints

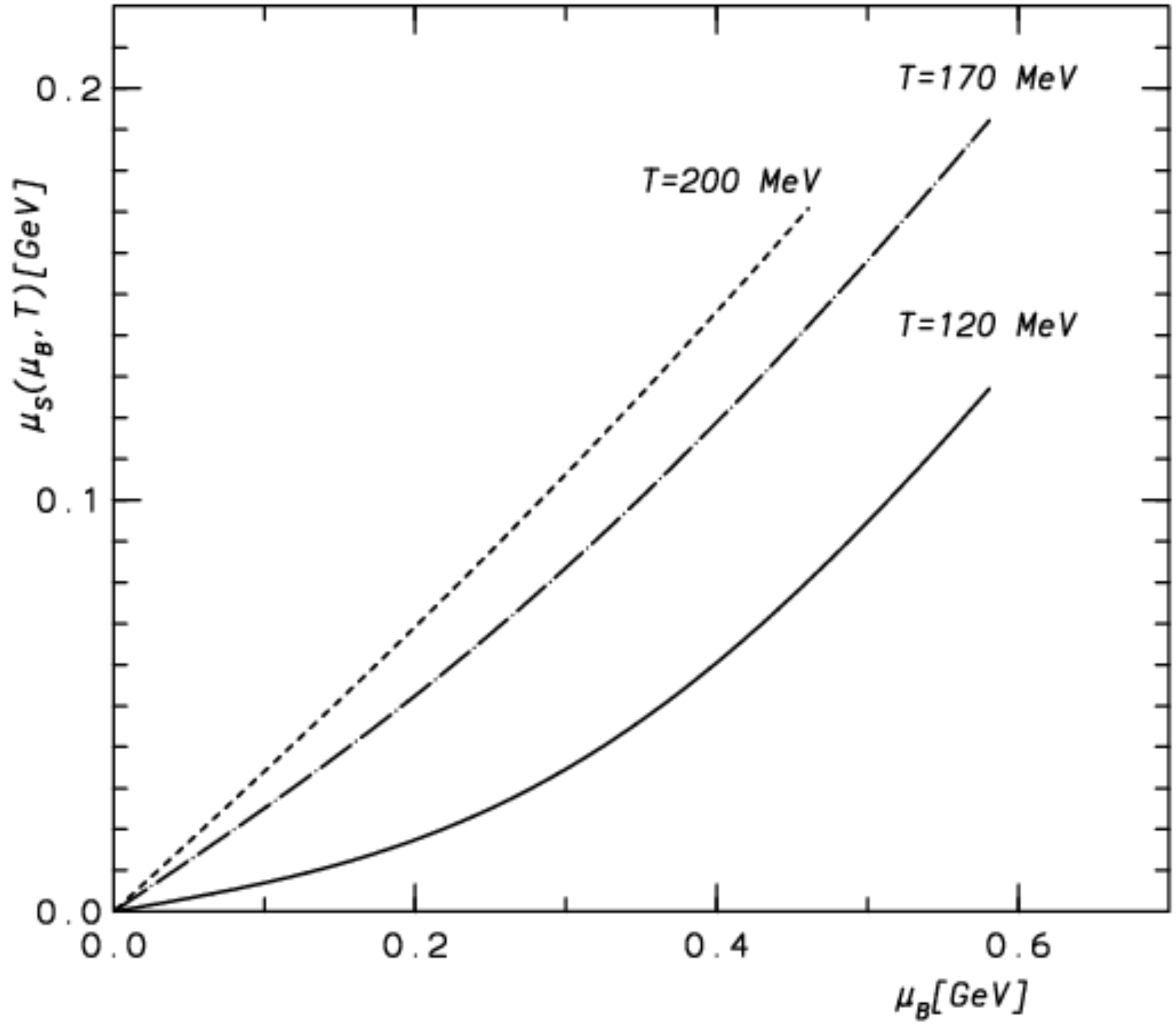
for every conserved quantum number there is a chemical potential μ
but can use conservation laws to constrain:

- Baryon number: $V \sum_i n_i B_i = Z + N \quad \rightarrow V$
- Strangeness: $V \sum_i n_i S_i = 0 \quad \rightarrow \mu_S$
- Charge: $V \sum_i n_i I_i^3 = \frac{Z - N}{2} \quad \rightarrow \mu_{I_3}$

This leaves only μ_b and T as free parameter when 4π considered

Dependence of μ_s on T, μ_B

- At any given T and μ_B, there exists only a single μ_s that makes the final state strangeness neutral.
- Same for I_3.
- Entire model has two free parameters and then makes a prediction for all particle ratios.



Feed-down via decay

Once conservation laws are satisfied:

1. Decay particles according to known branching ratios

   Individual feeddown factors are possible in SHE (most = 1)

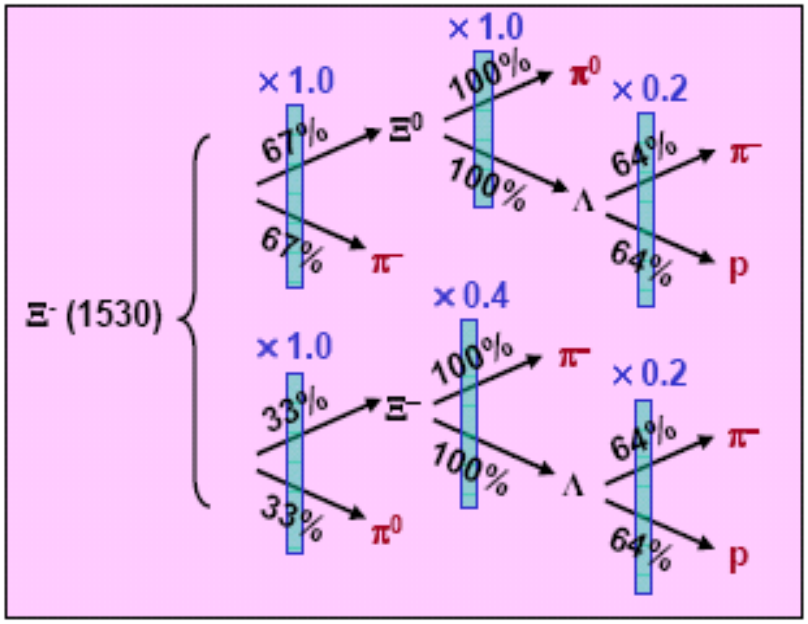
   Factor applies to directly-produced and intermediate particles

   Each particle is decayed recursively until its decay array is empty

   Feeddown correction factors are important here!

Example: STENIX experiment measures 60% Ξ^-, 80% Λ reco efficiency in charged channels

This must be done with care!



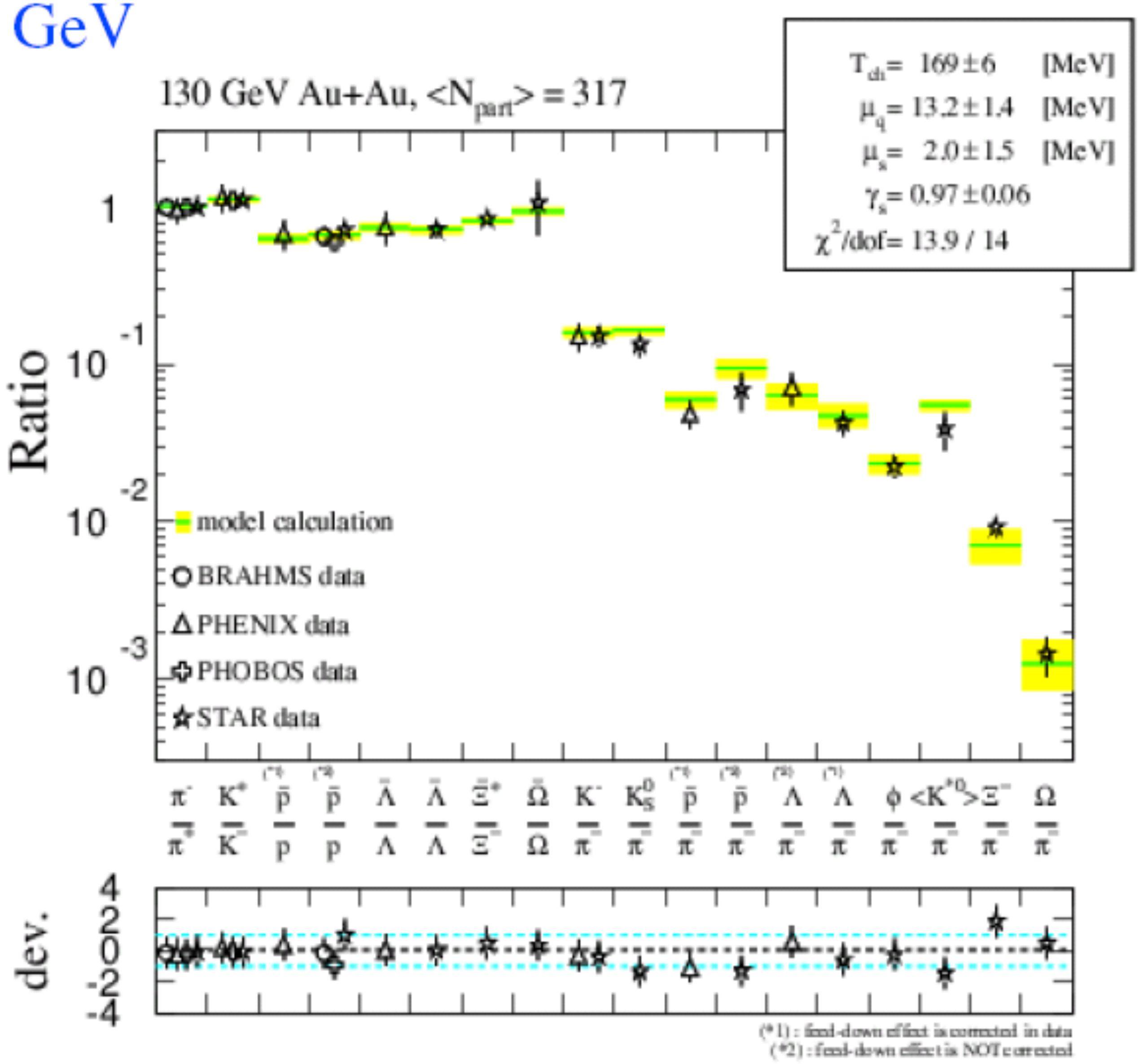
Controversy: γ_s

- Many authors modify the pure thermal ansatz by introducing a strangeness fugacity γ_s as:

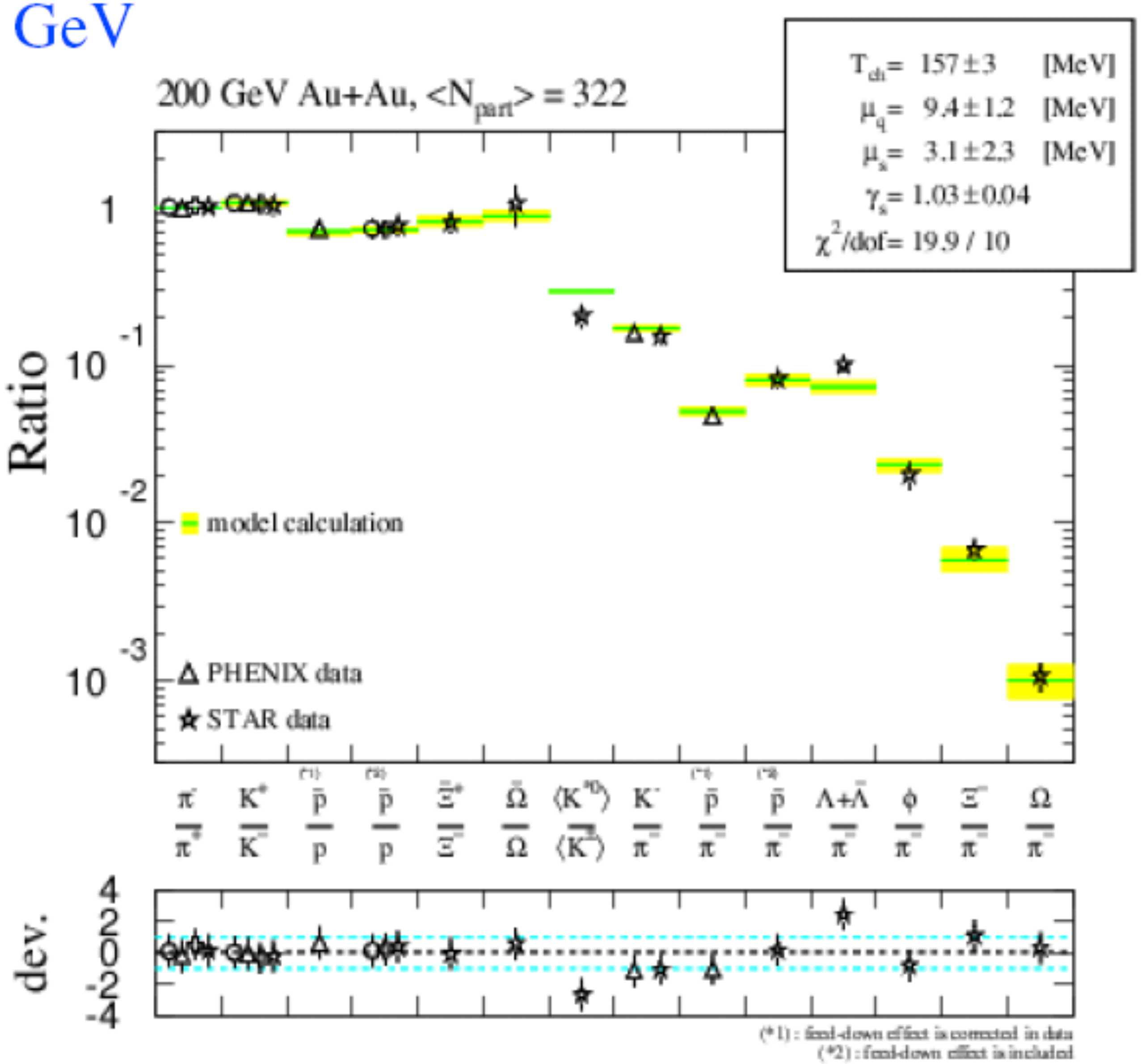
$$n_i^0(strange) = \gamma_s \frac{g_i}{2\pi^2} \int \frac{p^2 dp}{e^{\left(E - \mu_B B_i - \mu_s S_i - \mu_3 I^3\right)/T} \pm 1}$$

- This factor in the range 0-1 determines the level at which strangeness has reached the Grand Canonical level.
- Some authors feel that such a factor violates the thermal ansatz, whereas others like having a measure of the level of equilibrium.

130 GeV


130 GeV Au+Au, <N_part> = 317
T_ch = 169 ± 6 [MeV]
μ_q = 13.2 ± 1.4 [MeV]
μ_s = 2.0 ± 1.5 [MeV]
γ_s = 0.97 ± 0.06
χ²/dof = 13.9 / 14
Ratio
1
10^-1
10^-2
10^-3
model calculation
BRAHMS data
PHENIX data
PHOBOS data
STAR data
π⁻/π⁺
K⁺/K⁻
(*1) p̄/p
(*2) p̄/p
Λ̄/Λ
Λ̄/Λ
Ξ̄⁺/Ξ⁻
Ω̄/Ω
K⁻/π⁻
K⁰_S/π⁻
(*1) p̄/π⁻
(*2) p̄/π⁻
(*2) Λ/π⁻
(*1) Λ/π⁻
φ/π⁻
<K*⁰>/π⁻
Ξ⁻/π⁻
Ω/π⁻
dev.
4
2
0
-2
-4
(*1) : feed-down effect is corrected in data
(*2) : feed-down effect is NOT corrected

200 GeV

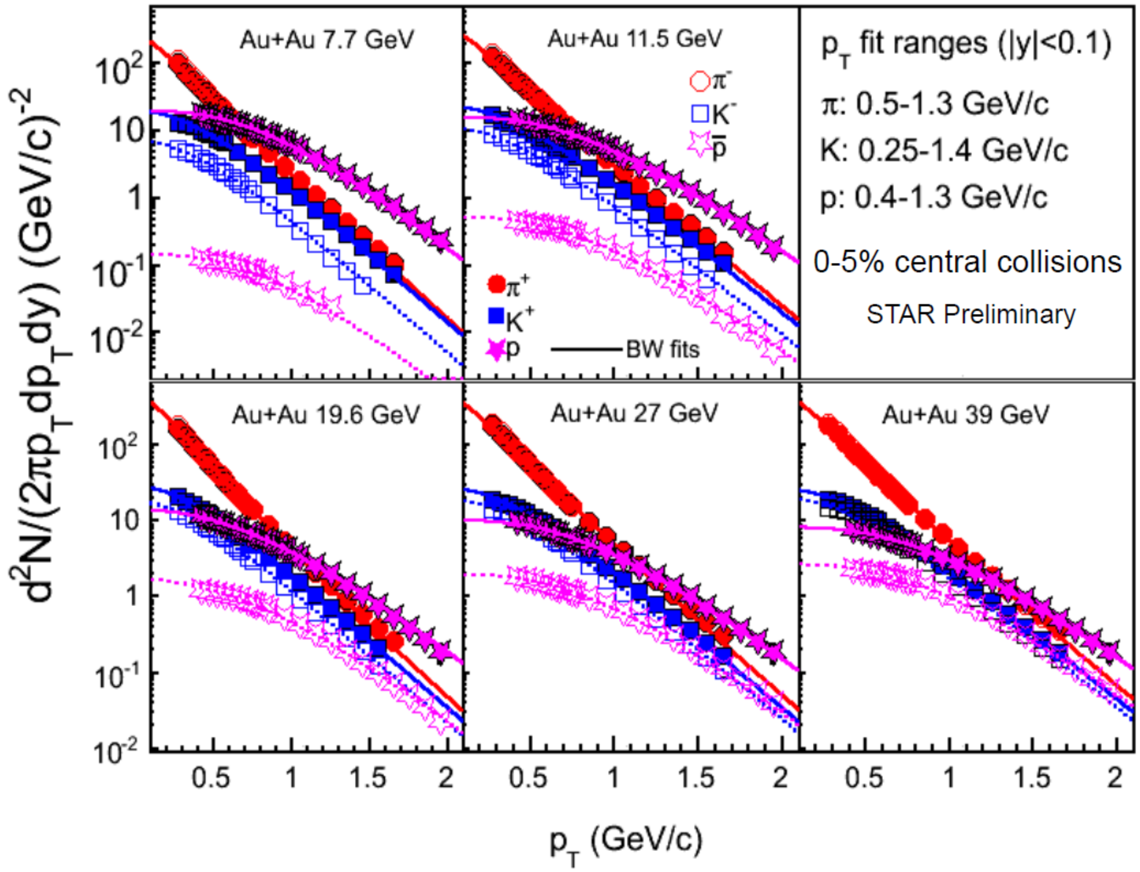

200 GeV Au+Au, <N_part> = 322
T_ch = 157±3 [MeV]
μ_q = 9.4±1.2 [MeV]
μ_s = 3.1±2.3 [MeV]
γ_s = 1.03±0.04
χ²/dof = 19.9 / 10
Ratio
1
10^-1
10^-2
10^-3
model calculation
PHENIX data
STAR data
π⁻/π⁺
K⁺/K⁻
p̄/p (*1)
p̄/p (*2)
Ξ̄⁺/Ξ⁻
Ω̄/Ω
⟨K*0⟩/⟨K⁻⟩
K⁻/π⁻
p̄/π⁻ (*1)
p̄/π⁻ (*2)
Λ+Λ̄/π⁻
φ/π⁻
Ξ⁻/π⁻
Ω/π⁻
dev.
4
2
0
-2
-4
(*1) : feed-down effect is corrected in data
(*2) : feed-down effect is included

Radial Flow

- For any interacting system of particles expanding into vacuum, flow is a natural consequence.
  - During the cascade process, one naturally develops an ordering of particles with the highest common underlying velocity at the outer edge.
- This motion complicates the interpretation of the momentum of particles as compared to their temperature and should be subtracted.
- Hadrons are released in the final stages of the collision and therefore measure “FREEZE-OUT”

Singles Spectra

- Peripheral:
  - Pions are concave due to feeddown.
  - K,p are exponential.
  - Yields are MASS ORDERED.
- Central:
  - Pions still concave.
  - K exponential.
  - p flattened at left
  - Mass ordered wrong (p passes pi !!!)



BW well explains the π, K, p spectra simultaneously

Underlying collective VELOCITIES impart more momentum to heavier species consistent with the basic trends

Blast Wave-I

- Let's consider a Thermal Boltzmann Source:

$$\frac{d^3N}{dp^3} \propto e^{-E/T}$$

$$E\frac{d^3N}{dp^3} = \frac{d^3N}{m_T dm_T d\phi dy} \propto Ee^{-E/T} = m_T \cosh(y) e^{-m_T \cosh(y)/T}$$

- If this source is boosted radially with a velocity β_{boost}, the resulting distribution, evaluated at y=0 and integrated over ϕ is:

$$\frac{1}{m_T}\frac{dN}{dm_T} \propto m_T I_0\left(\frac{p_T \sinh(\rho)}{T}\right) K_1\left(\frac{m_T \cosh(\rho)}{T}\right)$$

where $$\rho = \tanh^{-1}\left(\beta_{boost}\right)$$

Blast Wave-II

- The entire source from the collision may be considered as a superposition of many sources each with a different strength and boost velocity.
- The simplest assumption (and non-physical…) is that the source is a uniform sphere of radius R and that the boost velocity varies linearly to some maximum value. Then:

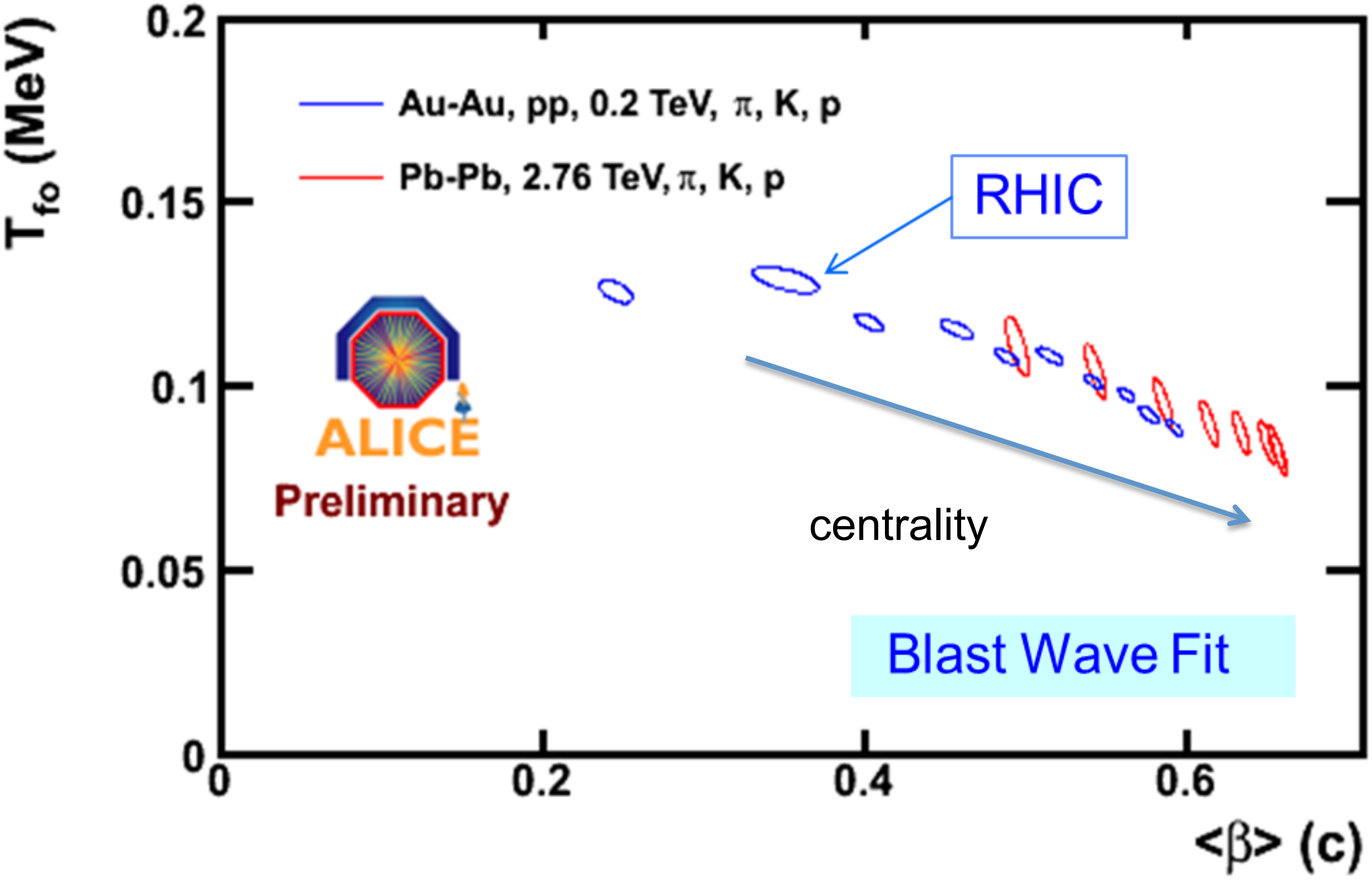
$$\frac{1}{m_T}\frac{dN}{dm_T} \propto \int_0^R r^2 dr m_T I_0\left(\frac{p_T \sinh(\rho)}{T}\right) K_1\left(\frac{m_T \cosh(\rho)}{T}\right)$$

$$\rho(r) = \tanh^{-1}\left(\beta_T^{MAX}\frac{r}{R}\right)$$

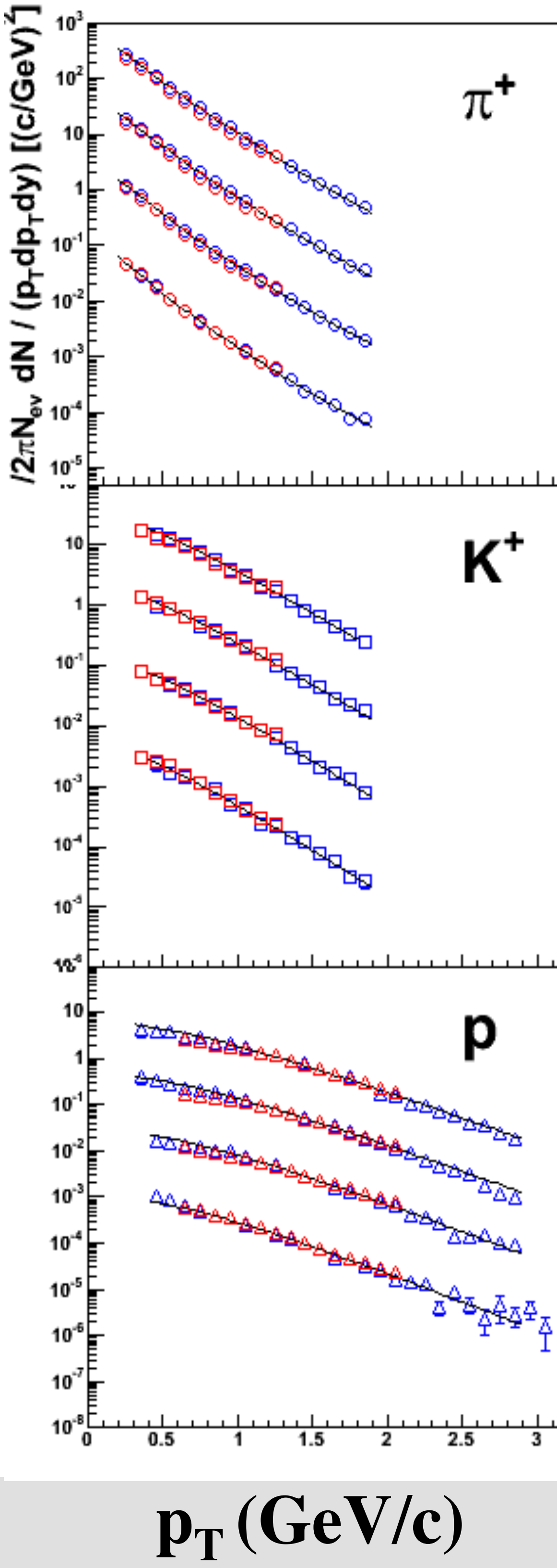
Blast Wave Fits

Fit AuAu spectra to blast wave model:

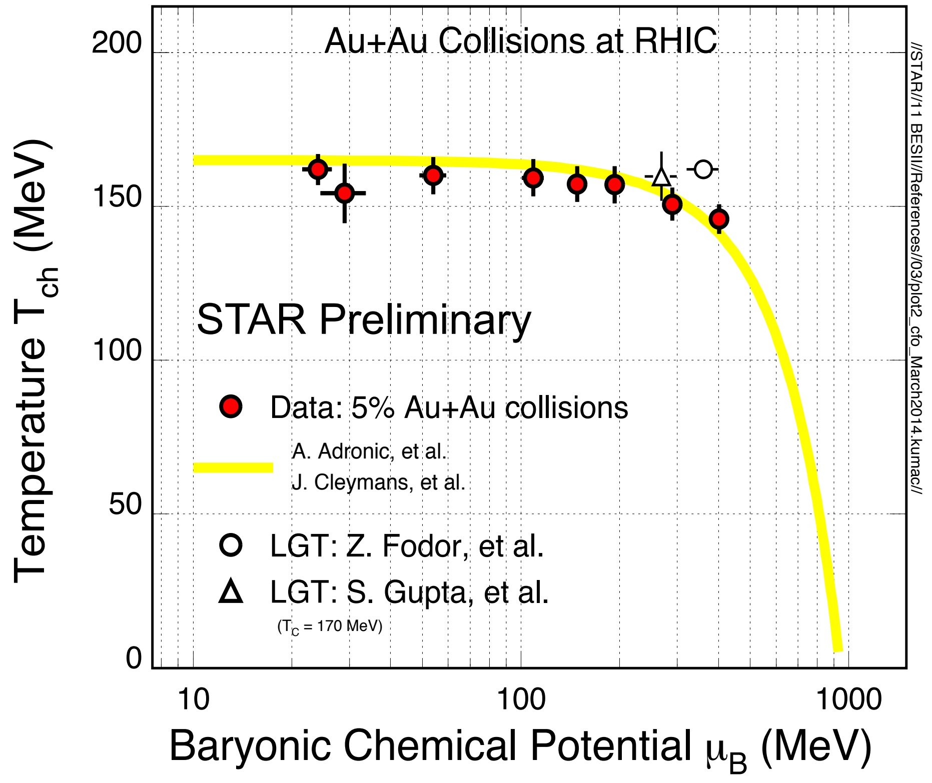
- β_S (surface velocity) drops with dN/dη
- T (temperature) almost constant.

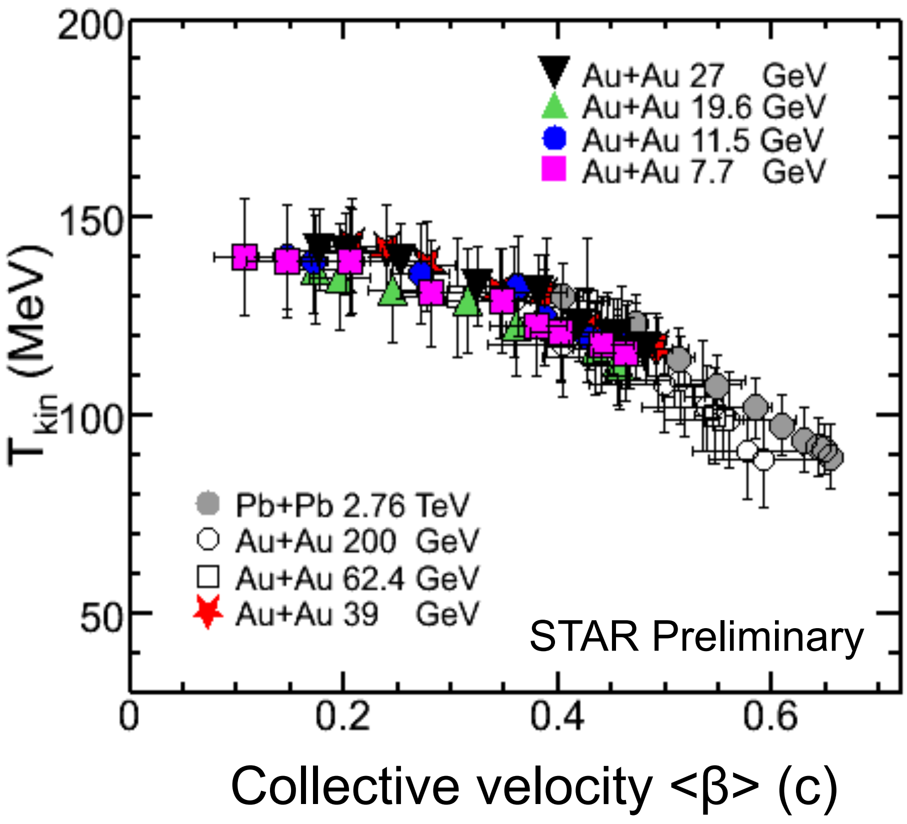


Centrality



Beam Energy Scan shows T Systematics





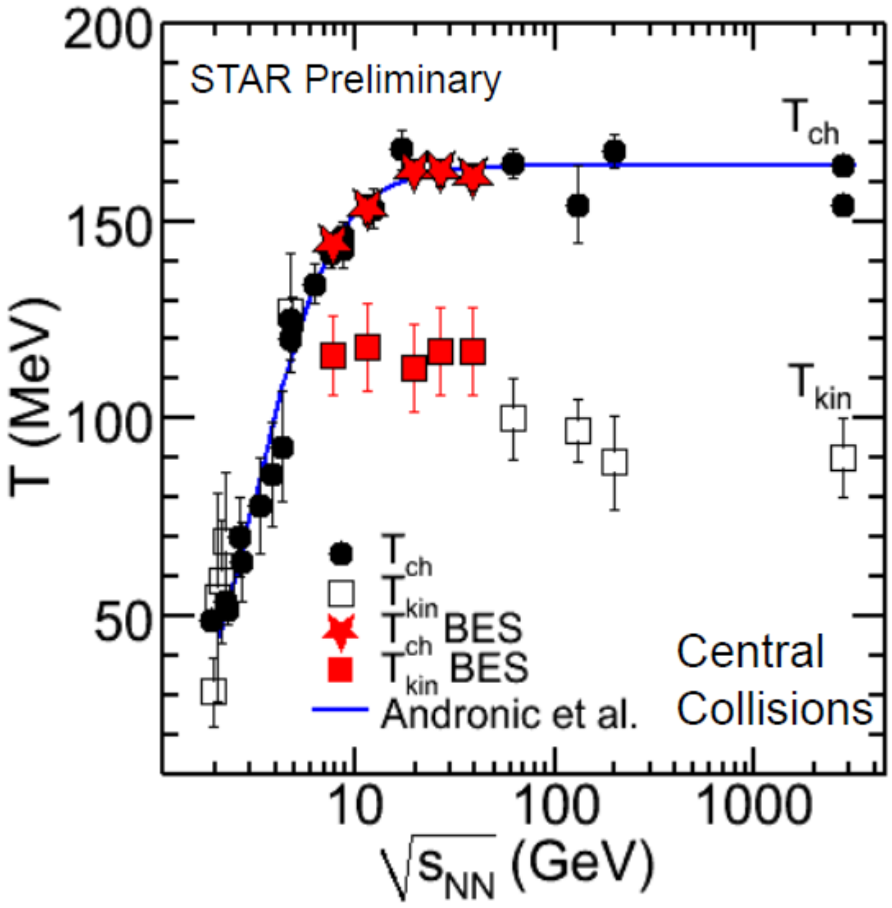
Chemical Freeze-out: (GCE)

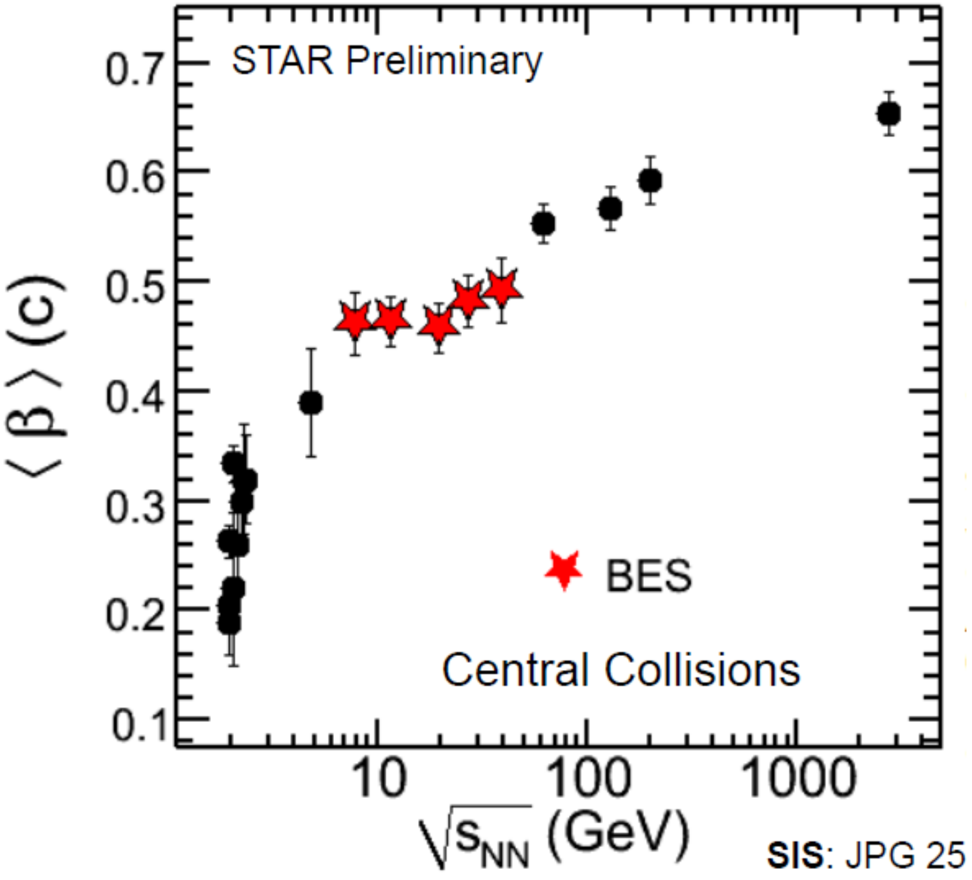
- Central collisions.
- Centrality dependence, not shown, of ***T_{ch}*** and ***μ_B***!

Kinetic Freeze-out:

- Central collisions => lower value of ***T_{kin}*** and larger collectivity ***β***
- Stronger collectivity at higher energy

Temperature/Flow Summary





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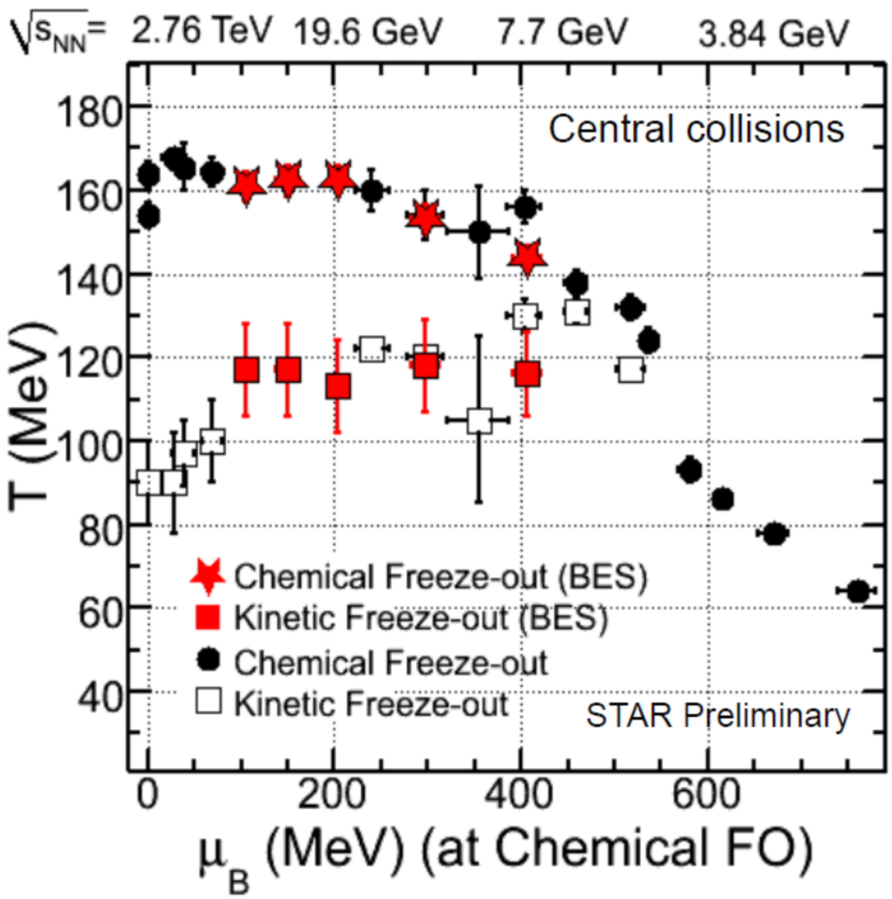
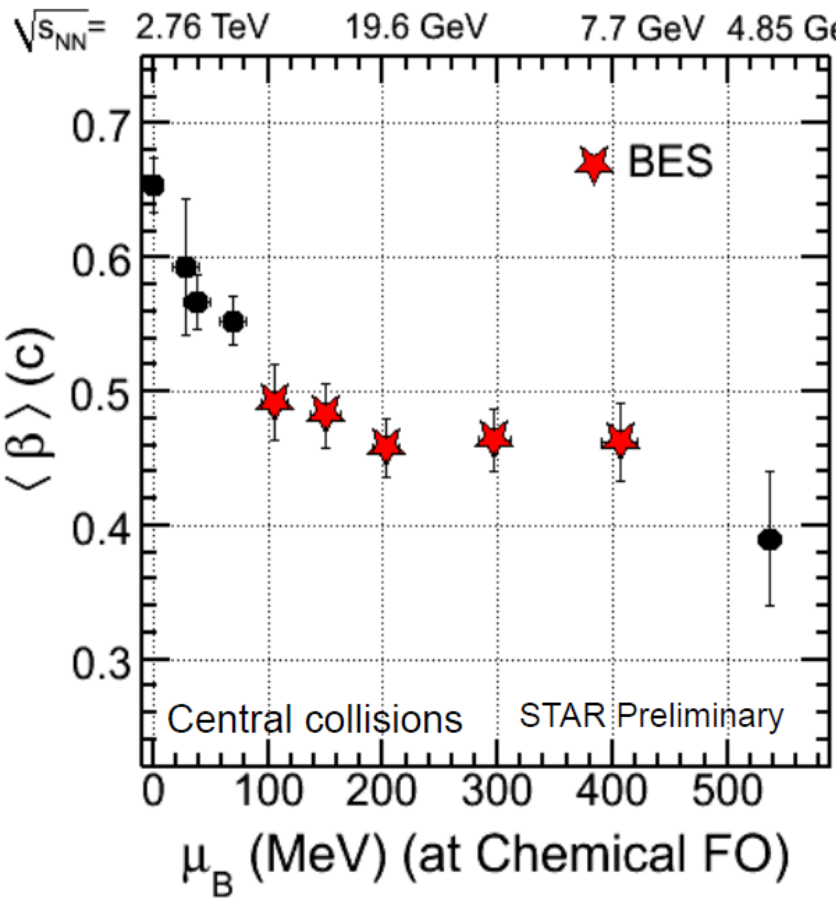
57 3319 (19

- Clear break in behavior ~20 GeV.

Recast Data vs μ_B





- ✧ Covering large portion of QCD phase diagram
- ✧ Difference between T_{kin} and T_{ch} increases for lower μ_B : Effect of hadronic interactions between chemical and kinetic freeze-out
- ✧ <β> is almost similar from μ_B 200-400 MeV

- Lowering RHIC energy requires accelerator upgrades.
- BES-II planned 2018/2019

Summary of particle production measurements

- Statistical treatment of particle production in heavy ion collision describes data pretty well
- The produced particles come from a hot medium with temperatures consistent with expectations for a quark-gluon plasma
- The measurements have to account for rapid expansion of the hot region
- The main “action” is at low energies where one hopes to see effects at the phase boundary