

# **Direct photon & charged hadron spectra in Pb-Pb at 5.5 TeV: hydro+pQCD predictions**

**Heavy-ions at the LHC – Last Call for Predictions**

**CERN, June 1<sup>st</sup>, 2007**

**Francois Arleo (CERN)**

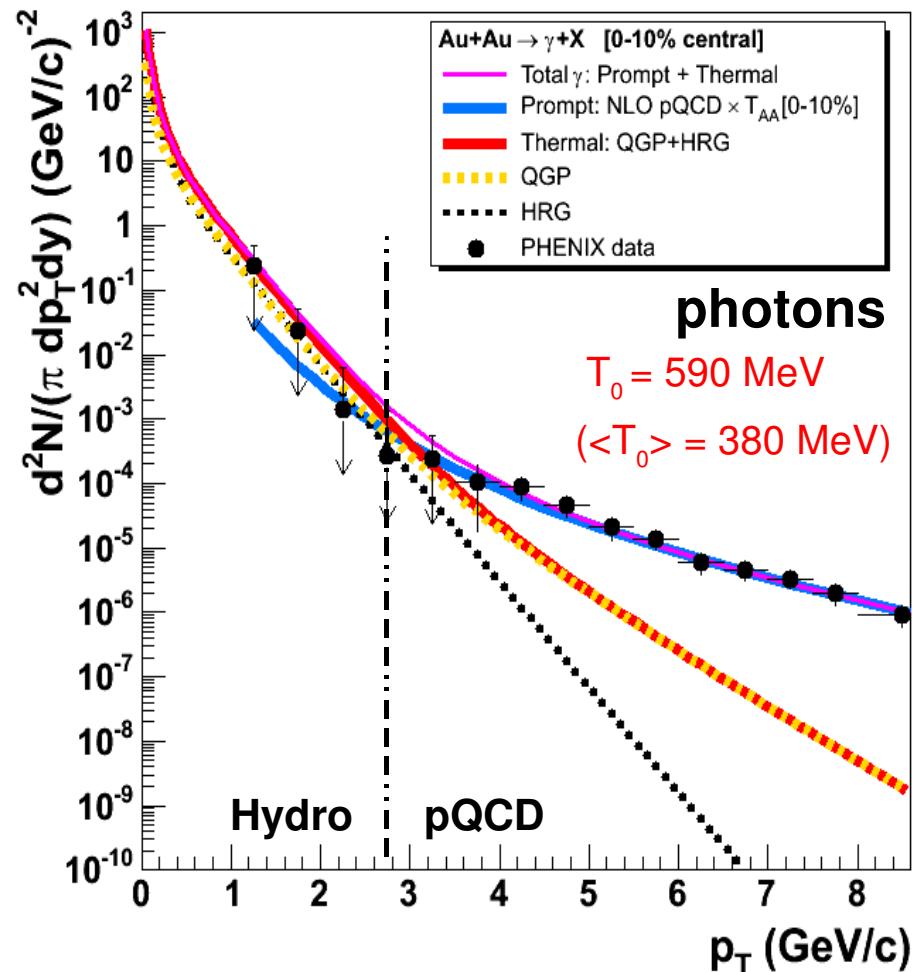
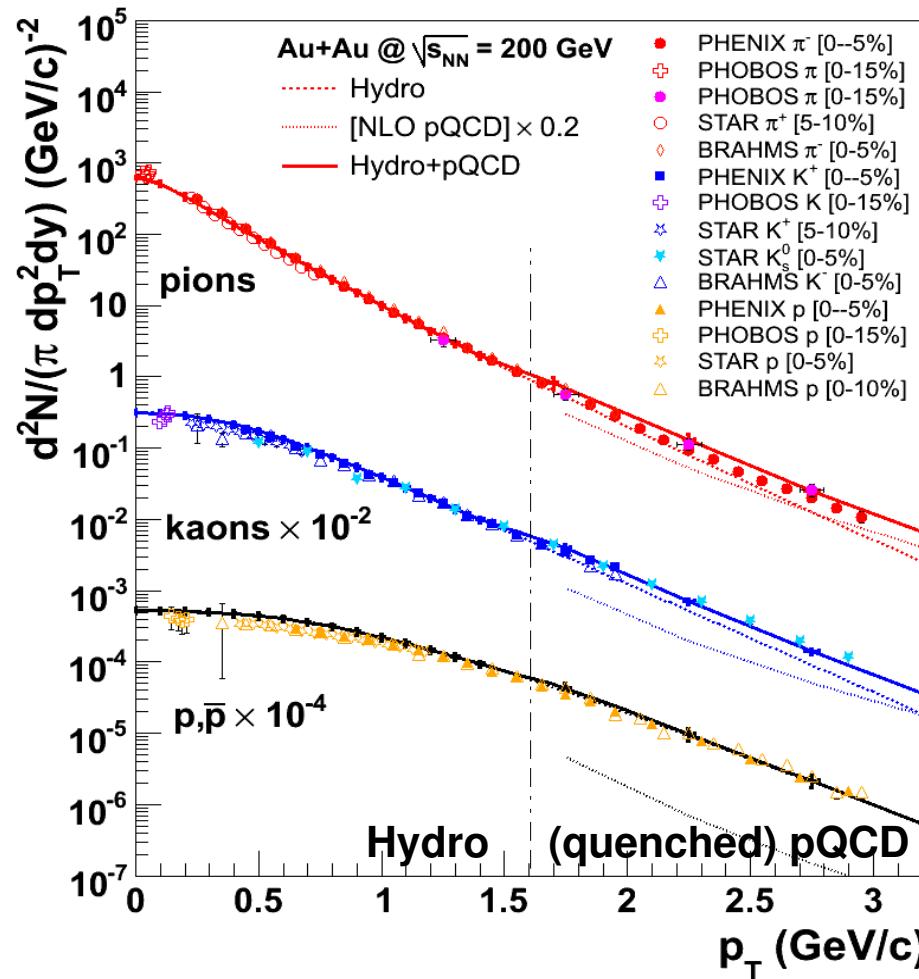
**David d'Enterria (CERN)**

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# Successful pQCD+hydro in Au-Au @ $\sqrt{s}_{NN} = 200$ GeV

Dd'E, D.Peressounko EPJ-C 46, 451 (2006), nucl-th/0503054

Hadron and direct photon spectra in Au-Au @ 200 GeV well reproduced by hydro (soft) + (quenched) pQCD (hard,  $p_T > 3$  GeV/c) production.



Goal: Predict similar spectra for Pb-Pb at LHC within same (validated) approach.

# Hydrodynamical evolution

Peressounko & Pokrovsky, hep-ph/9704386, hep-ph/9906325, hep-ph/0009025

- Relativistic hydro eqs. (local conservation of energy-momentum & any charge)

$$\begin{aligned}\partial_\mu T^{\mu\nu} &= 0 \\ \partial_\mu N_i^\mu &= 0, \quad i = B, S, \dots\end{aligned}$$

$T^{\mu\nu}$  is energy-momentum tensor (10 independ. vars.)

$N_i^\mu$  is charge 4-current (4 independ. vars.)

(5 equations with 14 unknowns)

- (Usual) approximations:

- Ideal (non-viscous) fluid:

$$\begin{aligned}T^{\mu\nu} &= (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu} \\ N^\mu &= n u^\mu\end{aligned}$$

} (6 unknowns)  
 $\epsilon, P, n, u^\mu$

- Cylindrical symmetry in transverse direction.

- Lorentz boost invariant in longitudinal dir. (Bjorken scaling).

}  $\rightarrow$  2D+1:  $(z, r, t)$

$$u^\mu = \gamma_r \left( \frac{t}{\tau}, v_r, 0, \frac{z}{\tau} \right) = \gamma_r (\cosh \eta, v_r, 0, \sinh \eta)$$

Hydro results independent  
of rapidity: valid for  $|y| < 2$

- Equation-of-State (relation between thermodyn. vars. of system):

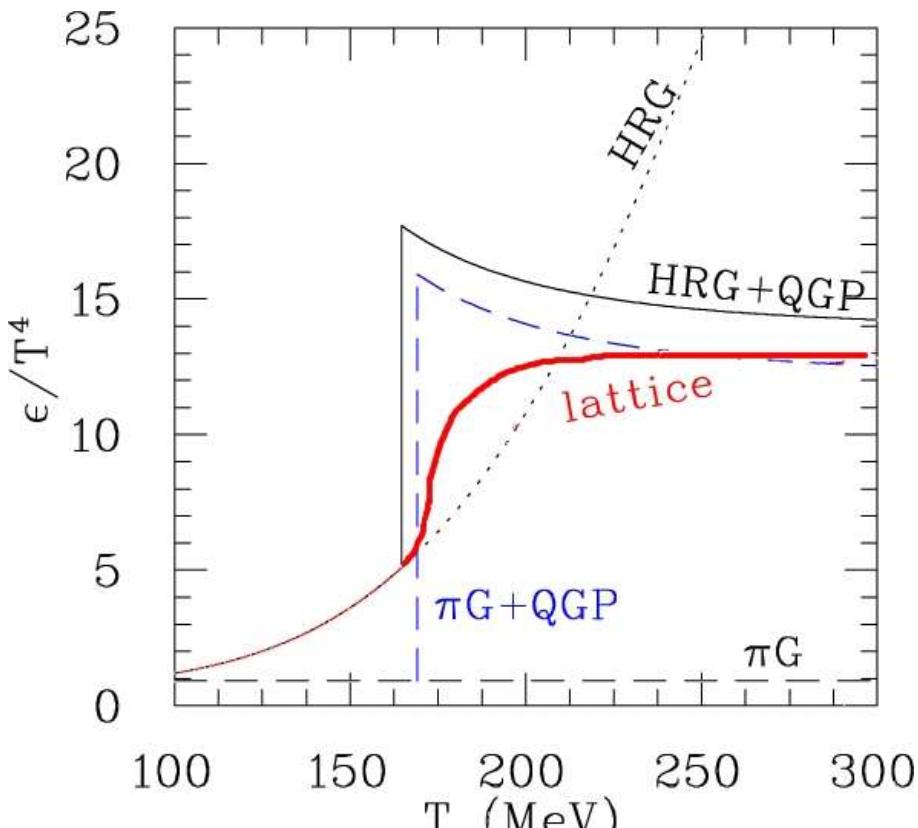
$$P = P(\epsilon, n)$$

“closes” the system of eqs. (given initial conditions)

- [Numerical solution via MacCormack method]

# Hydrodynamics: EoS

- Equation-of-State:



- QGP:**

New result: Lattice parametrization

Default: Ideal (massless) parton gas + MIT bag

$$\epsilon_{QGP} = \frac{3g_{QGP}}{\pi^2} T^4 + B \quad [2+1 \text{ flavors, 16 gluons}]$$

$$g_{QGP} = 42.5$$

$$P_{QGP} = \frac{1}{3}(\epsilon_{QGP} - 4B) \quad B = 0.38 \text{ GeV/fm}^3$$

- HRG:** Hadron resonance gas including  $\sim 400$  hadrons & resonances up to  $m \sim 2 \text{ GeV}/c^2$ .  
Chem. equilibrium (hadron ratios) fixed at  $T_c$

$$\begin{aligned} P(T, \mu) &= \sum_i g_i \int \frac{d^3k}{(2\pi)^3} \frac{k^2}{3E} \frac{1}{e^{(E-\mu_i)/T} \pm 1} \\ &= \sum_i \frac{g_i}{2\pi^2} T^2 m_i^2 \sum_{n=1}^{\infty} \frac{(\mp 1)^{n+1}}{n^2} e^{n \frac{\mu_i}{T}} K_2 \left( n \frac{m_i}{T} \right) \end{aligned}$$

- Maxwell construction** for 1<sup>st</sup> order phase transition at  $T_c = 165 \text{ MeV}$ :

$$P_{QGP}(T_c) = P_{HRG}(T_c) \Rightarrow T_c = \left( \frac{\pi^2}{g_{QGP} - g_\pi} \right)^{\frac{1}{4}} B^{\frac{1}{4}} \quad , \quad LH \sim 1.2 \text{ GeV/fm}^3$$

# Hydrodynamics: Input parameters (RHIC)

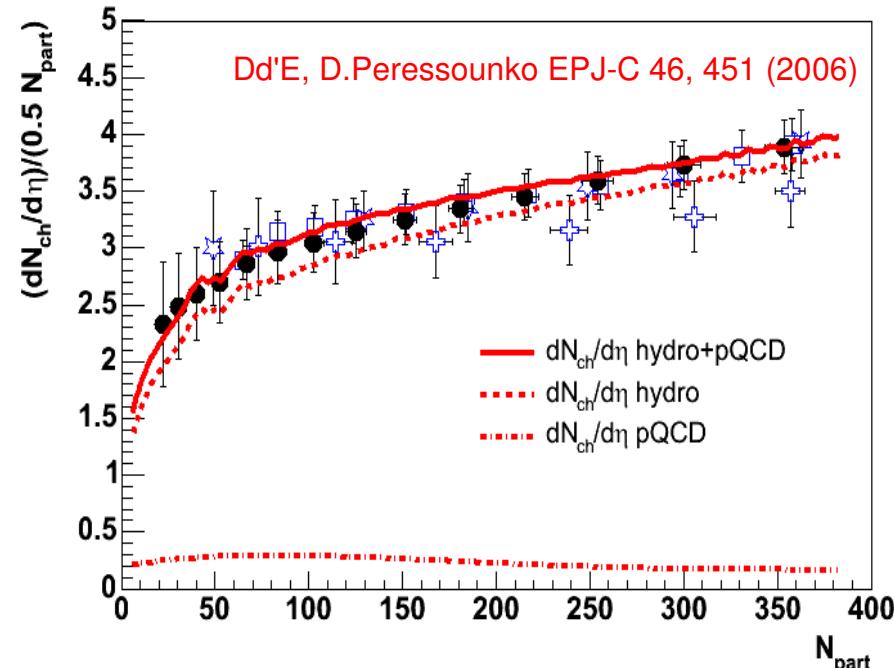
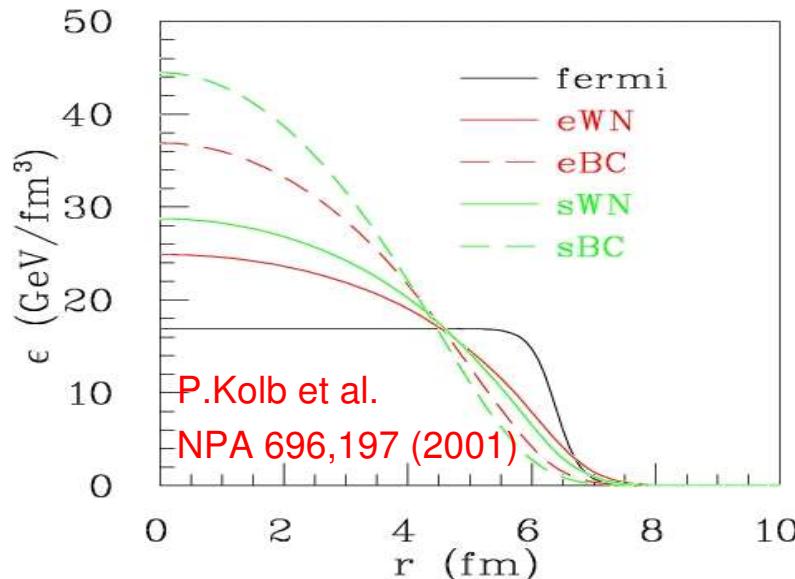
- Initial conditions for head-on ( $b=0$  fm) Au-Au @ 200 GeV:

$$\begin{aligned}\tau_0 &= 2R/\gamma = 0.15 \text{ fm/c} \\ s_0 &\sim 500 \text{ fm}^{-3} \\ \mu_B &= 25 \text{ MeV}\end{aligned}$$

(transit time Au-Au: time scale for secondary parton-parton colls.)  
 (consistent w/  $dN_{ch}/d\eta$ )  $\Rightarrow \epsilon_0 \propto s_0^{4/3} = 220 \text{ GeV/fm}^3$  (source center)  
 (consistent w/ exp. hadron ratios at  $y=0$ )

- Centrality-dependence: Kolb-Heinz-Huovinen-Eskola-Tuominen (Glauber) prescription:

$$s_0(b) = s_0(b=0) \times [0.75 N_{part}(b) + 0.25 N_{coll}(b)]$$



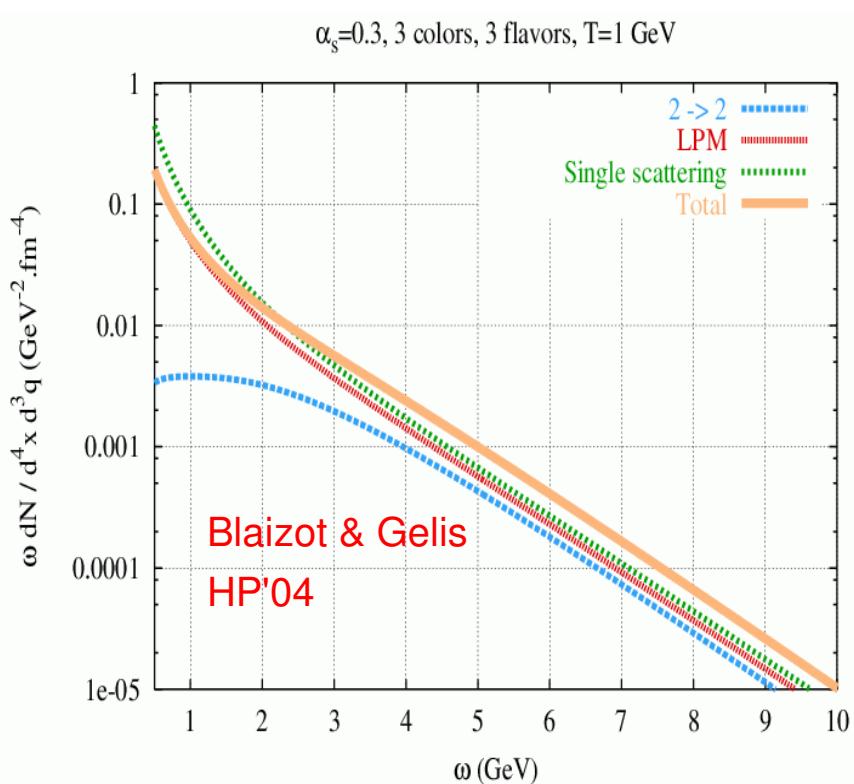
- Chemical freeze-out at:  $T_{chem} = 155 \text{ MeV}$

- End of evolution: Cooper-Frye freeze-out prescription at  $T_{fo} = 120 \text{ MeV}$

# Hydrodynamics: Direct photon production

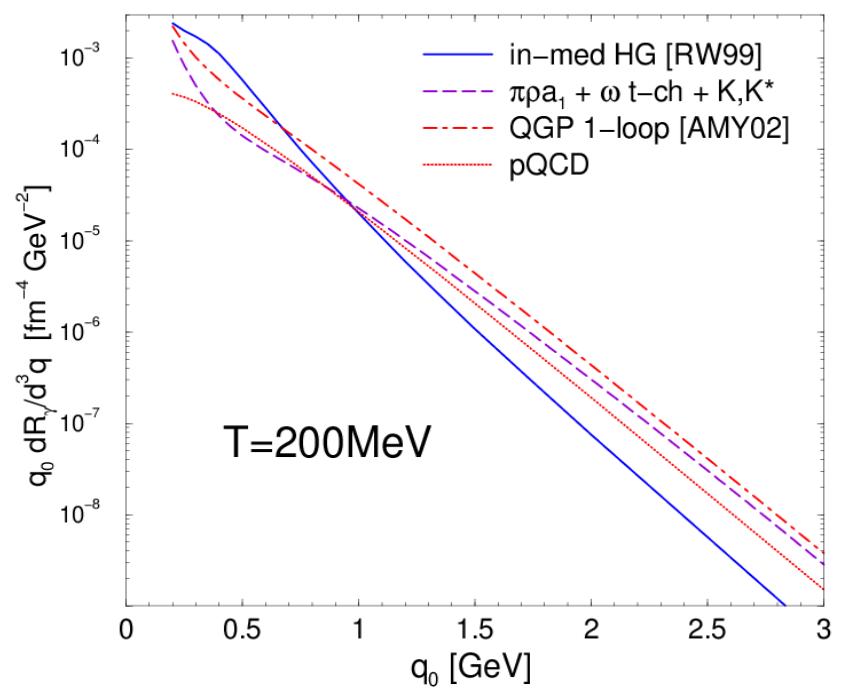
- QGP thermal photon rates by AMY:  
Complete Leading-Log+ LPM suppression

Arnold, Moore, Yaffe JHEP 0112 (2001) 009



- HRG thermal photon rates by Turbide et al.: Most recent parametrization, includes channels not accounted for before

Turbide, Rapp, Gale, PRC 69, 014903 (2004)



- Latt. T-dependent  $\alpha_s$  parametrization:

Kaczmarek, Karsch, Zantow, Peterky, PRD 70, 074505 (2004)

$$\alpha_s(T) = 2.095 / \left\{ \frac{11}{2\pi} \ln(Q/\Lambda_{MS}) + \frac{51}{22\pi} \ln[2 \ln(Q/\Lambda_{MS})] \right\} \text{ with } Q = 2\pi T$$

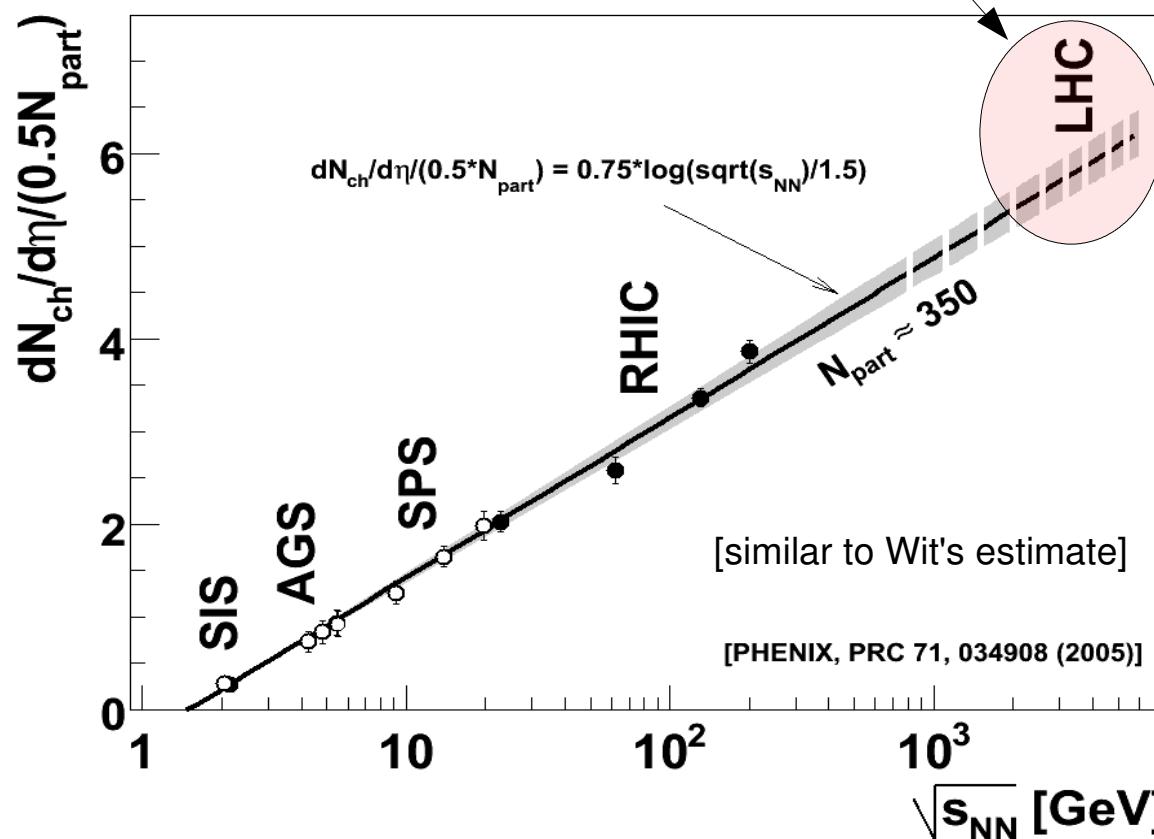
# LHC predictions

# Hydrodynamics: Input parameters (LHC)

- Hydro input parameters for head-on ( $b=0$  fm) Pb-Pb @ 5.5 TeV:

$\tau_0 = 1/Q_s \sim 0.1 \text{ fm}/c$	(time-scale for secondary parton-parton collisions)
$s_0 = 1120 \text{ fm}^{-3}$	$(dN_{\text{tot}}/dy \sim 2200 \text{ extrapolation}) \Rightarrow \epsilon_0 \propto s_0^{4/3} \sim 650 \text{ GeV}/\text{fm}^3$
$\mu_B = 5 \text{ MeV}$	( $\sim$ baryon-free)

$$T_0 = 770 \text{ MeV} (\langle T_0 \rangle = 470 \text{ MeV})$$



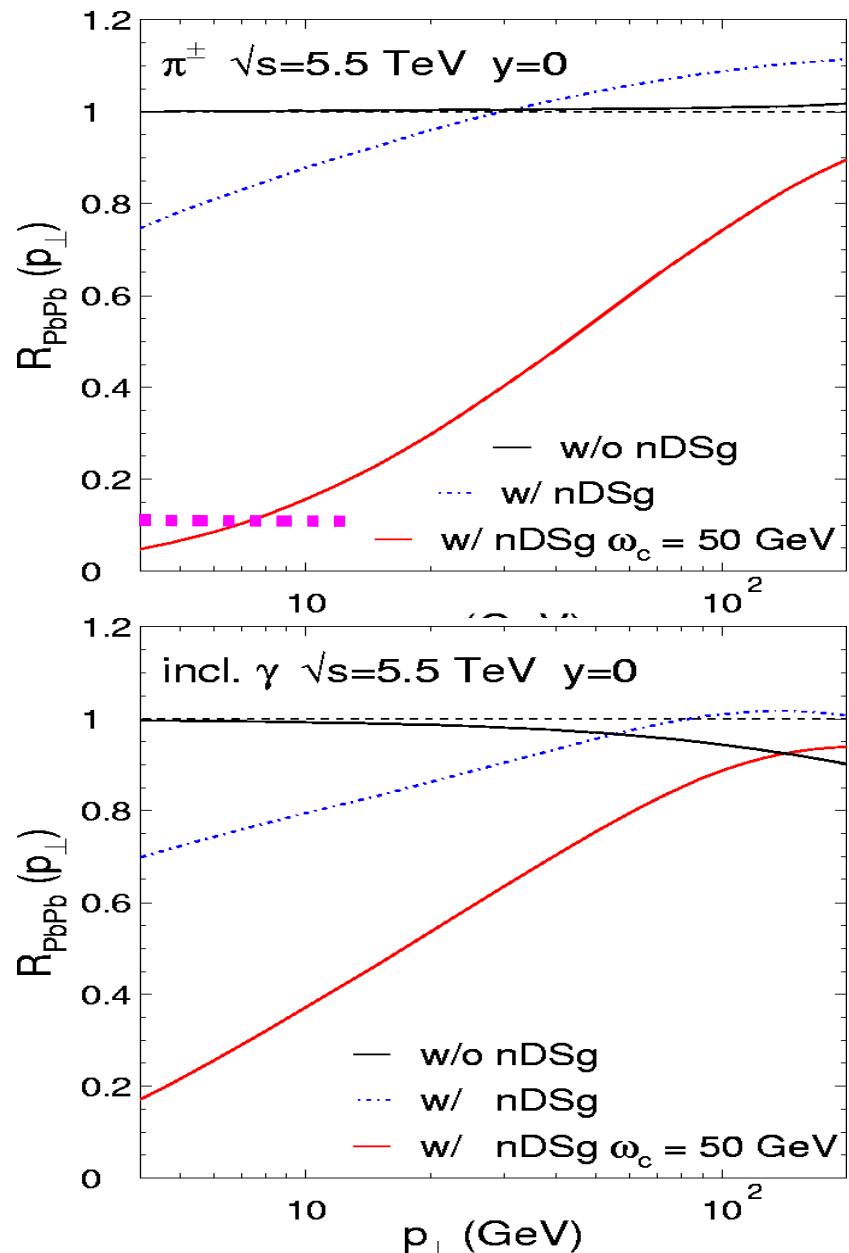
$$\begin{aligned} dN/dy &= N_{\text{tot}}/N_{\text{ch}} * d\eta/dy * dN_{\text{ch}}/d\eta = \\ &= 3/2 * 1.2 * 1300 \sim 2200 \end{aligned}$$

- Rest as of RHIC:  $b$ -dependence, freeze-out ( $T_{\text{chem}} = 155 \text{ MeV}$ ,  $T_{\text{fo}} = 120 \text{ MeV}$ )

# pQCD + parton energy loss (LHC)

See F. Arleo, JHEP 0609:015 (2006), and talk later

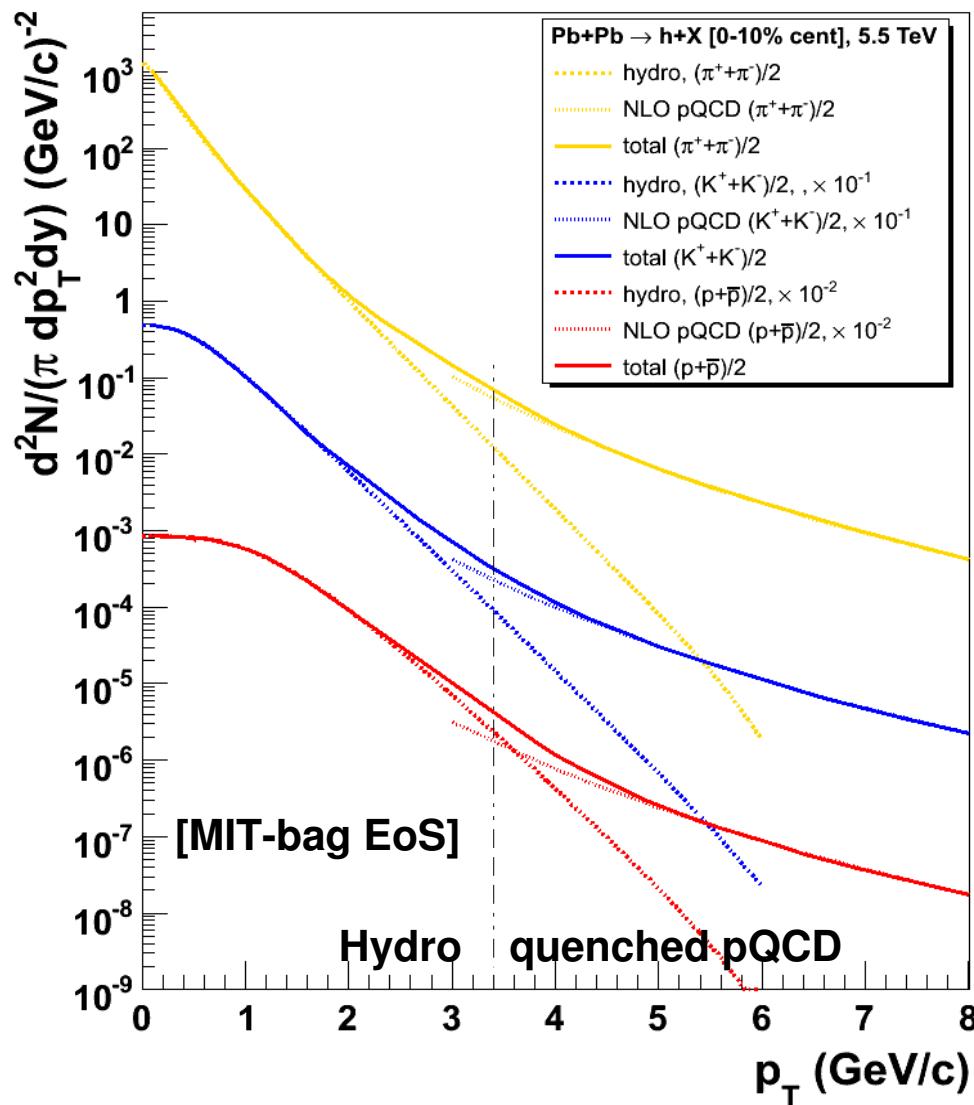
- NLO pQCD (PHOX code). Scales:  $\mu = p_T$
- Parton Distrib. Functions: CTEQ6M + nDSg  
(DeFlorian-Sassot “strong” shadowing)
- Fragmentation functions:  
AKK (newest set for kaons, protons)
- Final-state parton energy loss:  
Medium-modified FFs.  
BDMPS quenching weights:  $P(\varepsilon, E)$   
 $\omega_c = \hat{q} \cdot L^2, \quad dN/dy \sim \alpha_s(Q_s^2) Q_s^{-2}$   
 $\omega_c(\text{LHC}) = \omega_c(\text{RHIC})^*(5500/200)^{\lambda=0.3}$   
 $\omega_c(\text{LHC}) \sim 50 \text{ GeV}$  (for  $dN_{\text{ch}}/dy \sim 1700$ )
- Max. quenching (“corona emission”):  
 $R_{AA} (b=0 \text{ fm}) = N_{\text{part}}/N_{\text{coll}} \sim 400/2200 \sim 0.18$
- Fragment.  $\gamma$  (dominant at low  $p_T$ ) also suppressed



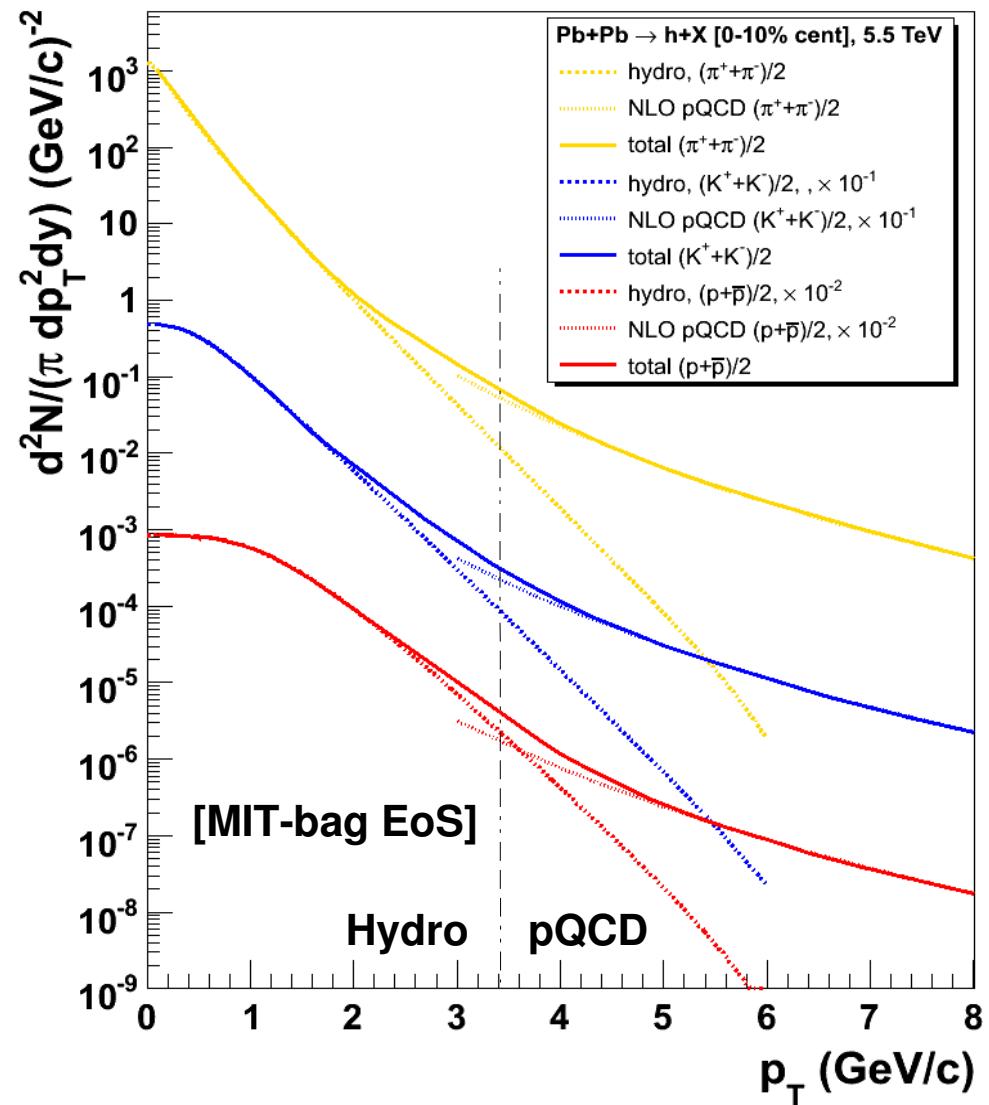
# Hadron spectra: hydro+pQCD prediction (LHC)

- $\pi^\pm, K^\pm, p(\bar{p})$  spectra: hydro + quenched NLO pQCD:

Pb-Pb 0-10% central ( $\langle b \rangle \sim 3$  fm)



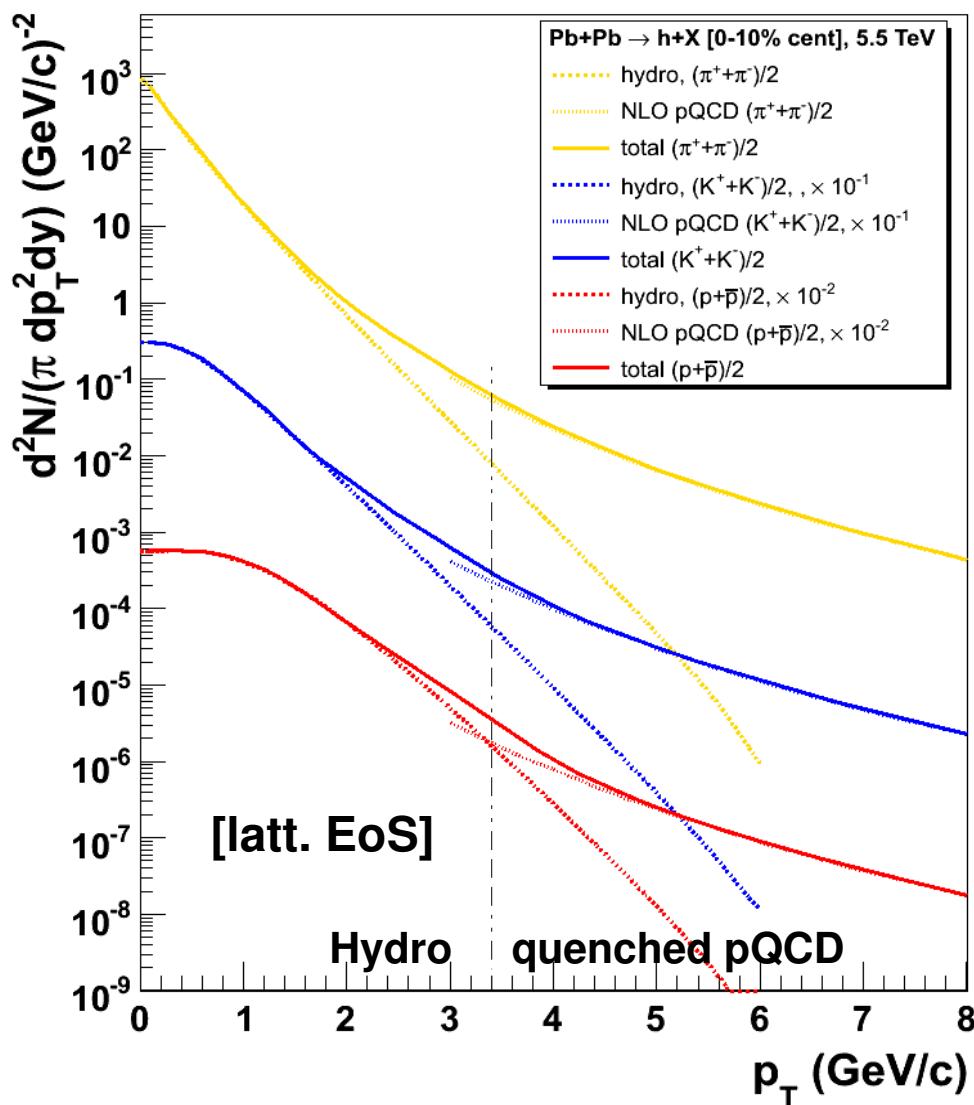
Pb-Pb 70-90% periph. ( $\langle b \rangle \sim 14$  fm)



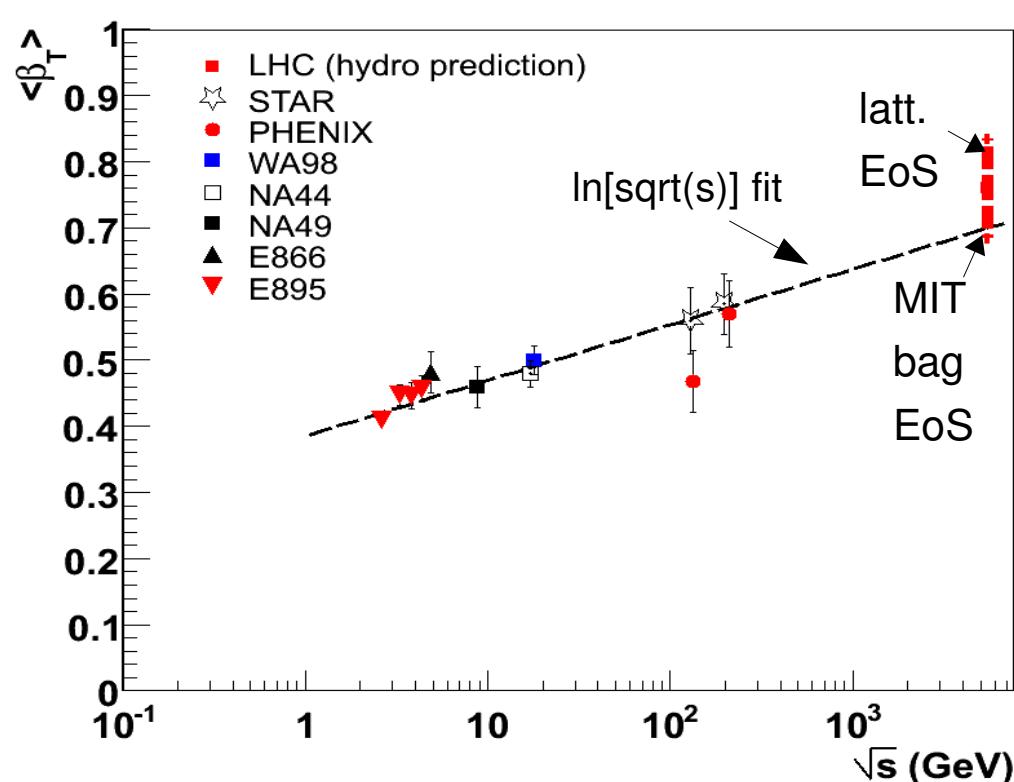
# Hadron spectra: hydro+pQCD prediction (LHC)

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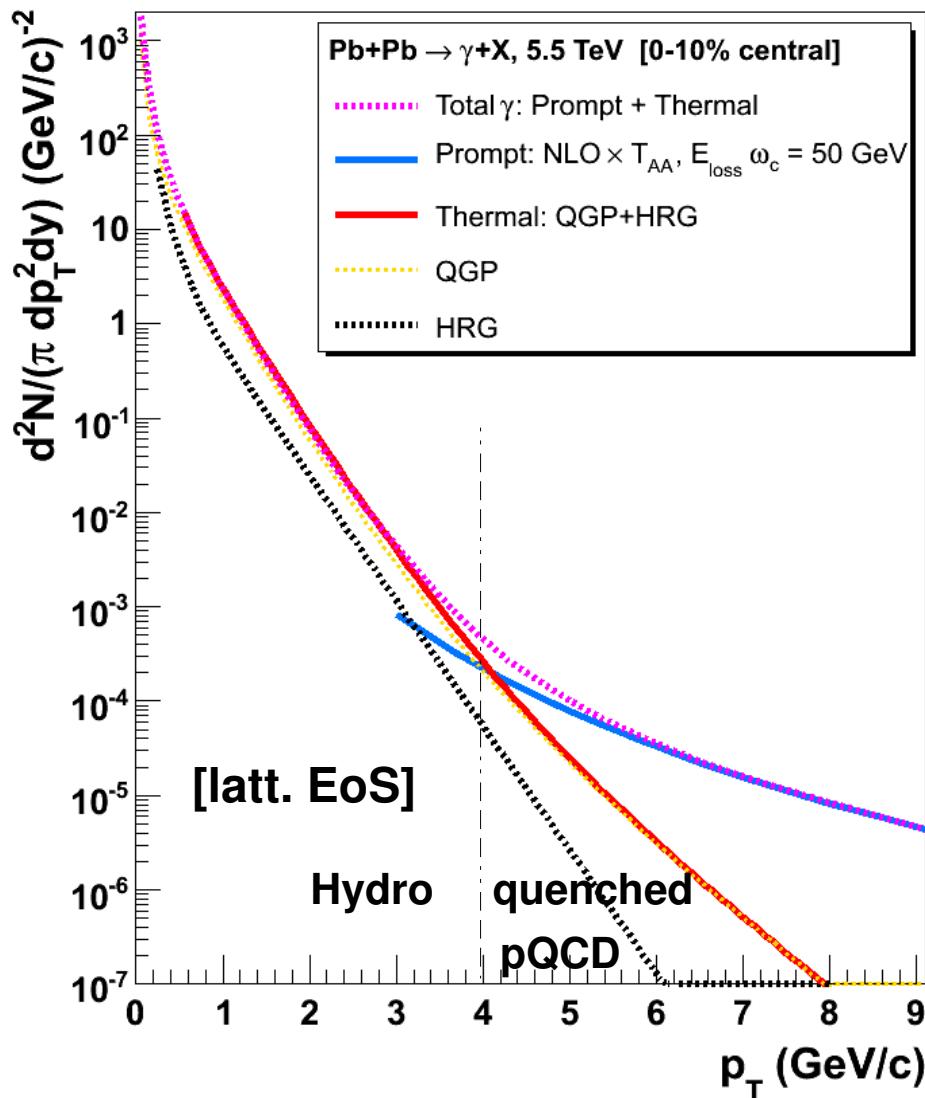
- Hadron collective transverse flow:



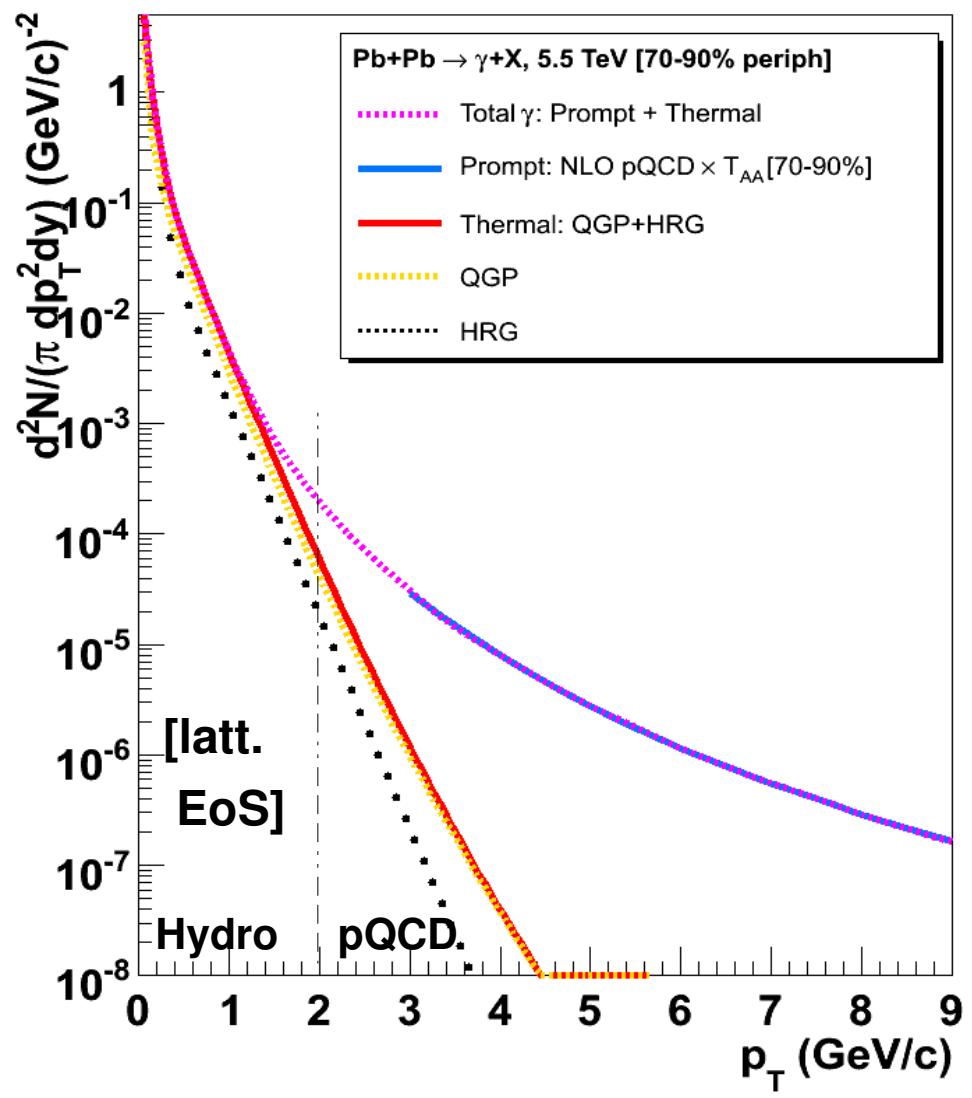
# Direct $\gamma$ spectra: hydro+pQCD prediction (LHC)

Photon spectra: hydro + (quenched) NLO pQCD:

Pb-Pb 0-10% central ( $\langle b \rangle \sim 3$  fm)



Pb-Pb 70-90% periph. ( $\langle b \rangle \sim 14$  fm)



# Summary

## 0. Hadron & direct photon production in high-energy A-A collisions:

- **Prompt** (pQCD):  $T_{AA}$ -scaled p-p (NLO) + parton energy loss
- **Hydrodynamics**: thermal emission from hot expanding medium (i.c., EoS)

## 1. Hydrodynamics:

- 2D+1 ideal fluid, longitud. boost-invariant, cylindrical symm.
- **EoS**: QGP (ideal gas w/ MIT bag or latt. parametrization) + HRG  
+ 1<sup>st</sup> order phase transition ( $T_c=165$  MeV)
- **Initial conditions**:  $\epsilon_0 \sim 650$  GeV/fm<sup>3</sup> (dN/dy~2200 RHIC extrapolation),  $T_0 \sim 770$  MeV,  
 $\tau_0 \sim 1/Q_s = 0.1$  fm/c,  $\mu_B \sim 5$  MeV
- **Freeze-out**:  $T_{chem} = 155$  MeV, Cooper-Frye at  $T_{fo} = 120$  MeV
- **Photon rates parametrizations**: AMY (QGP), Turbide-et-al (HRG)

## 2. pQCD:

- NLO (scale  $\mu=p_T$ ). PDF: CTEQ6M + nDSg shadowing. FF: AKK
- Final-state suppr.: BDMPS parton energy-loss ( $\omega_c \sim 50$  GeV) for hadrons &  $\gamma$ -fragm.

## 3. LHC predictions (validated in Au-Au @ RHIC):

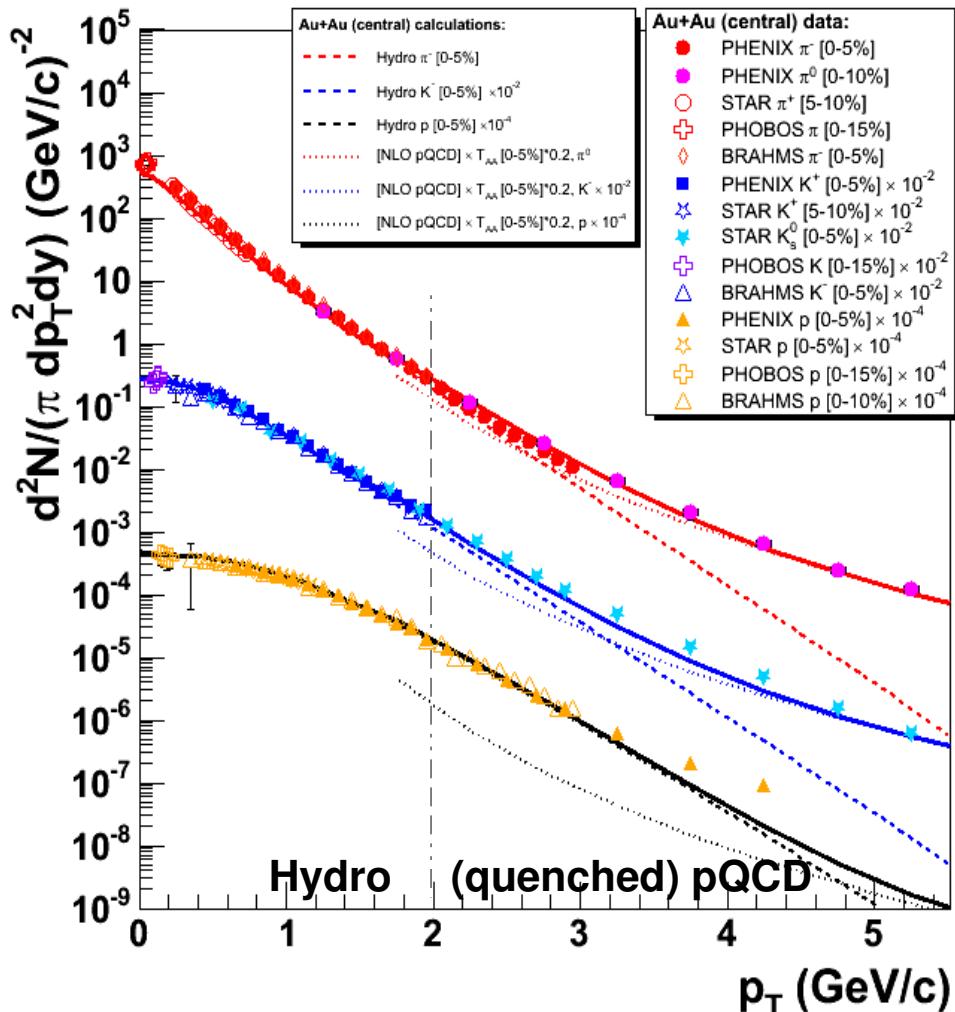
- Hydro-pQCD crossing line at  $p_T \sim 3 - 4$  GeV/c for hadrons & photons.

# Backup slides

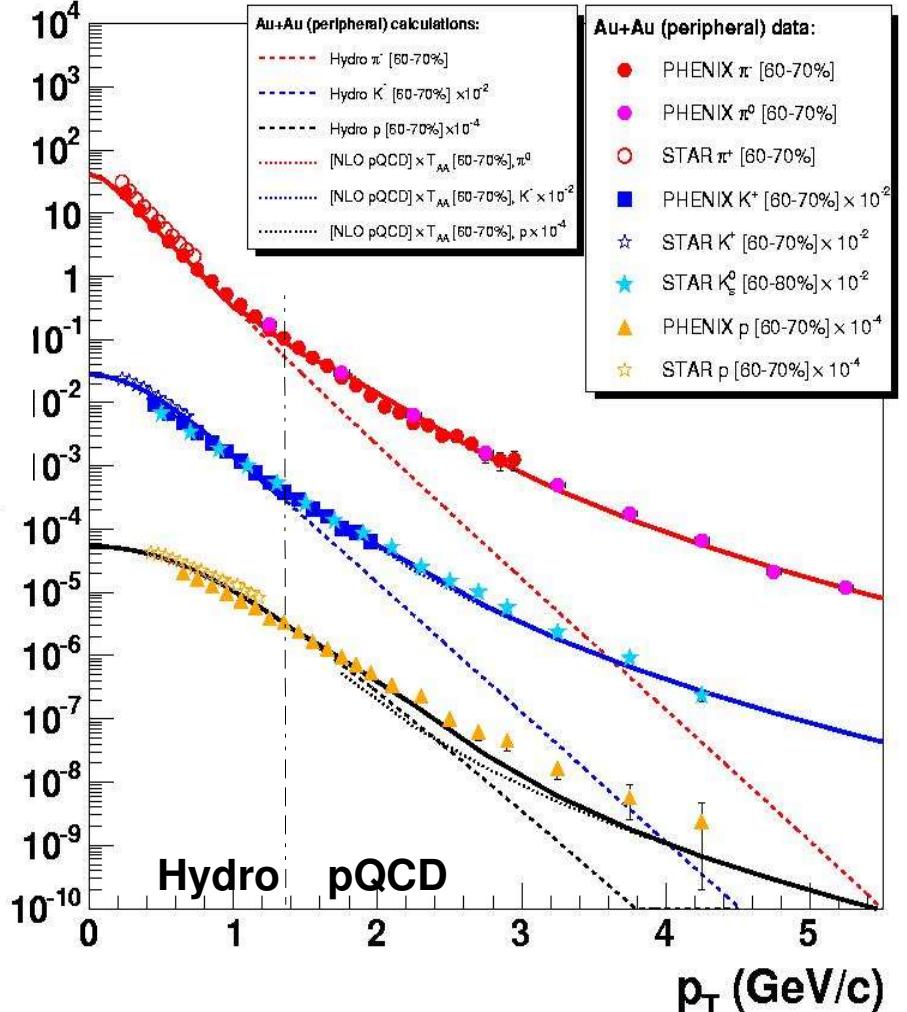
# Hadron spectra: hydro+pQCD vs Au-Au data (RHIC)

- $\pi^\pm, K^\pm, p(\bar{p})$  spectra **very well reproduced** by hydro + (quenched) NLO pQCD:

Au-Au 0-10% central ( $\langle b \rangle = 3.2 fm)$



Au-Au 60-70% periph. ( $\langle b \rangle = 11.2 fm)$

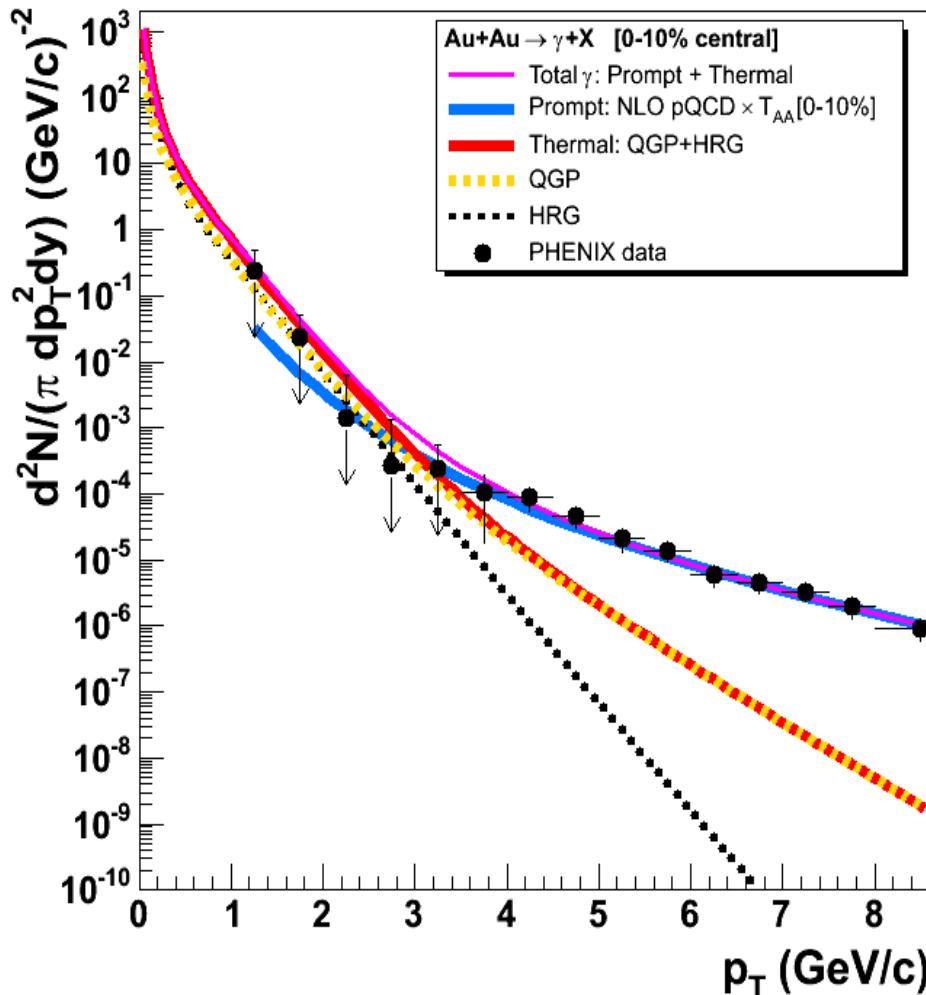


- Quenched pQCD: NLO (W. Vogelsang), CTEQ6 PDFs, KKP FFs,  $R_{AA} = 0.2(0.8)$

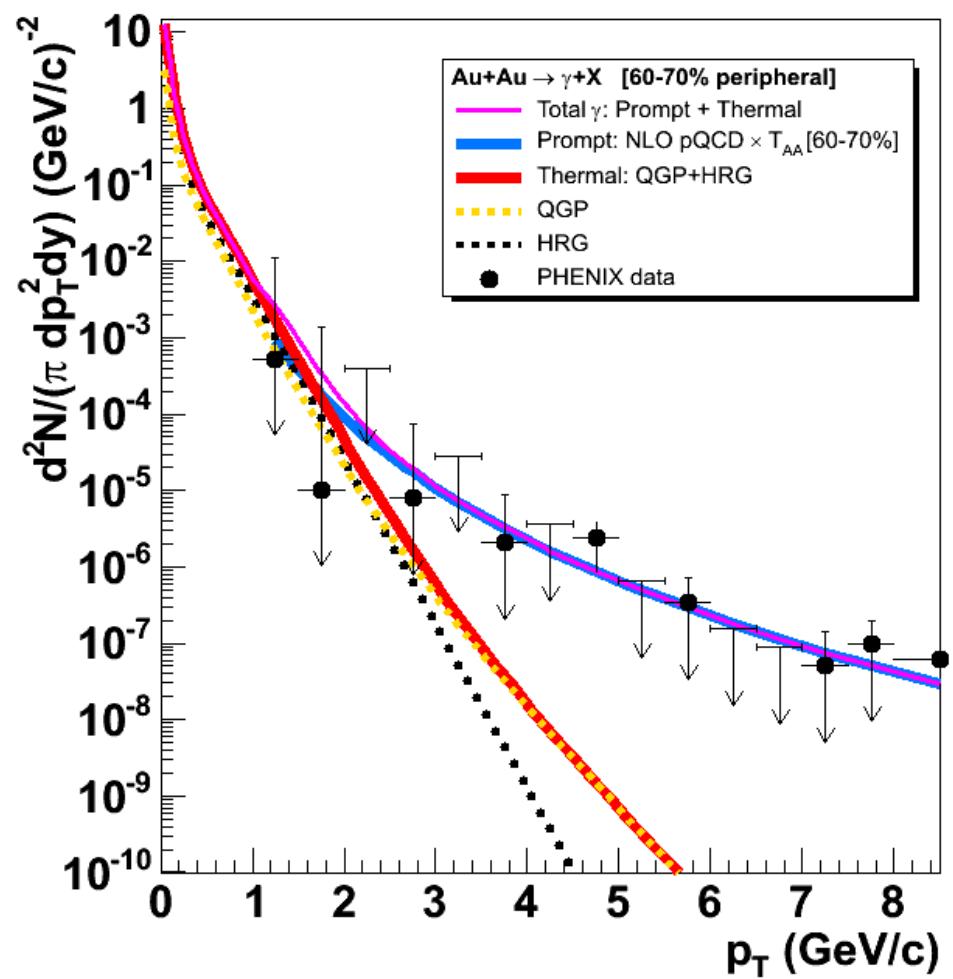
# Direct photon spectra: hydro+pQCD vs Au-Au data (RHIC)

Photon spectra **well reproduced** for all centralities by hydro +  $T_{\text{AuAu}}(b)$ -scaled p-p NLO pQCD [W. Vogelsang]:

Au-Au 0-10% central ( $\langle b \rangle = 3.2 \text{ fm}$ )



Au-Au 60-70% periph. ( $\langle b \rangle = 11.2 \text{ fm}$ )



# Prompt (pQCD) photon in p+p @ $\sqrt{s} = 5.5$ TeV

Photon production in p+p @ 200 GeV:

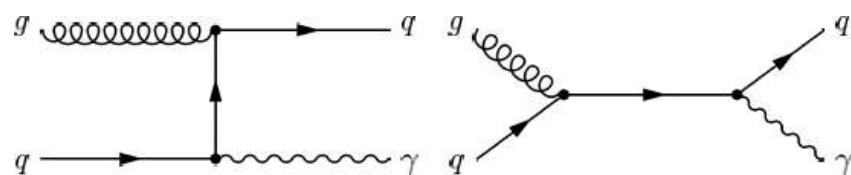


Figure 2.1: Compton diagrams.

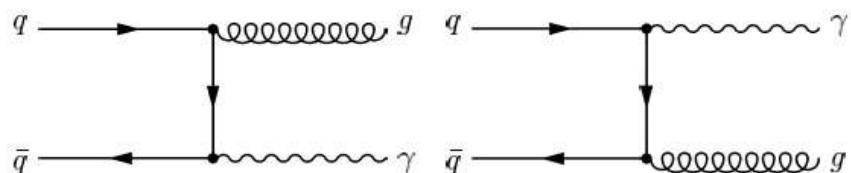


Figure 2.2: Annihilation diagrams.

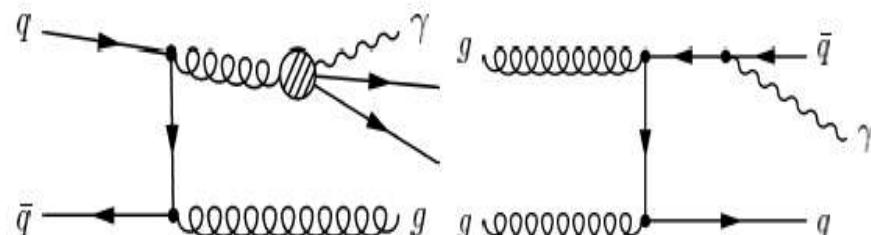
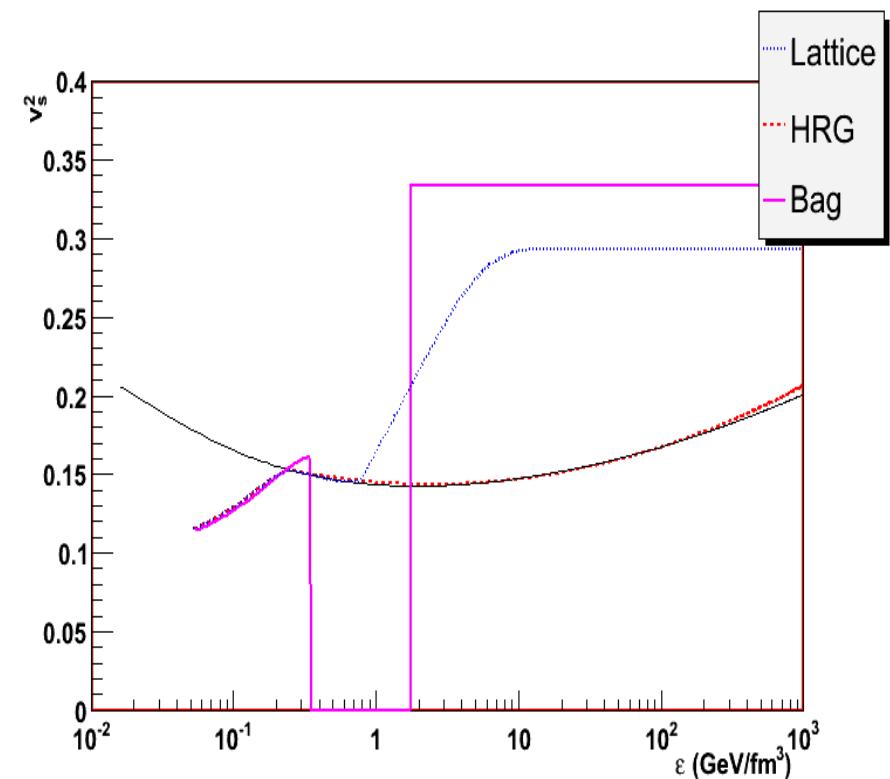
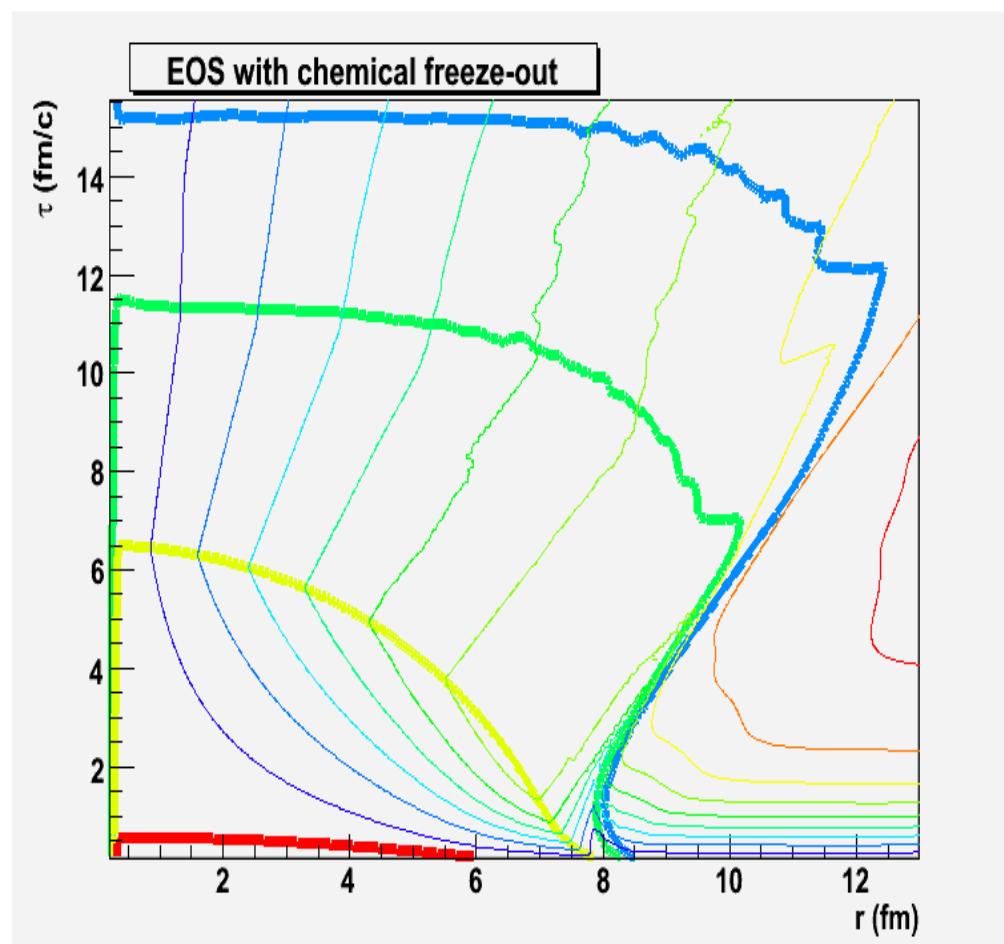


Figure 2.3: Bremsstrahlung diagrams.

# Hydro details



# Thermal photons from other hydros

- Our predictions are very similar to those of Jyvaskyla group :

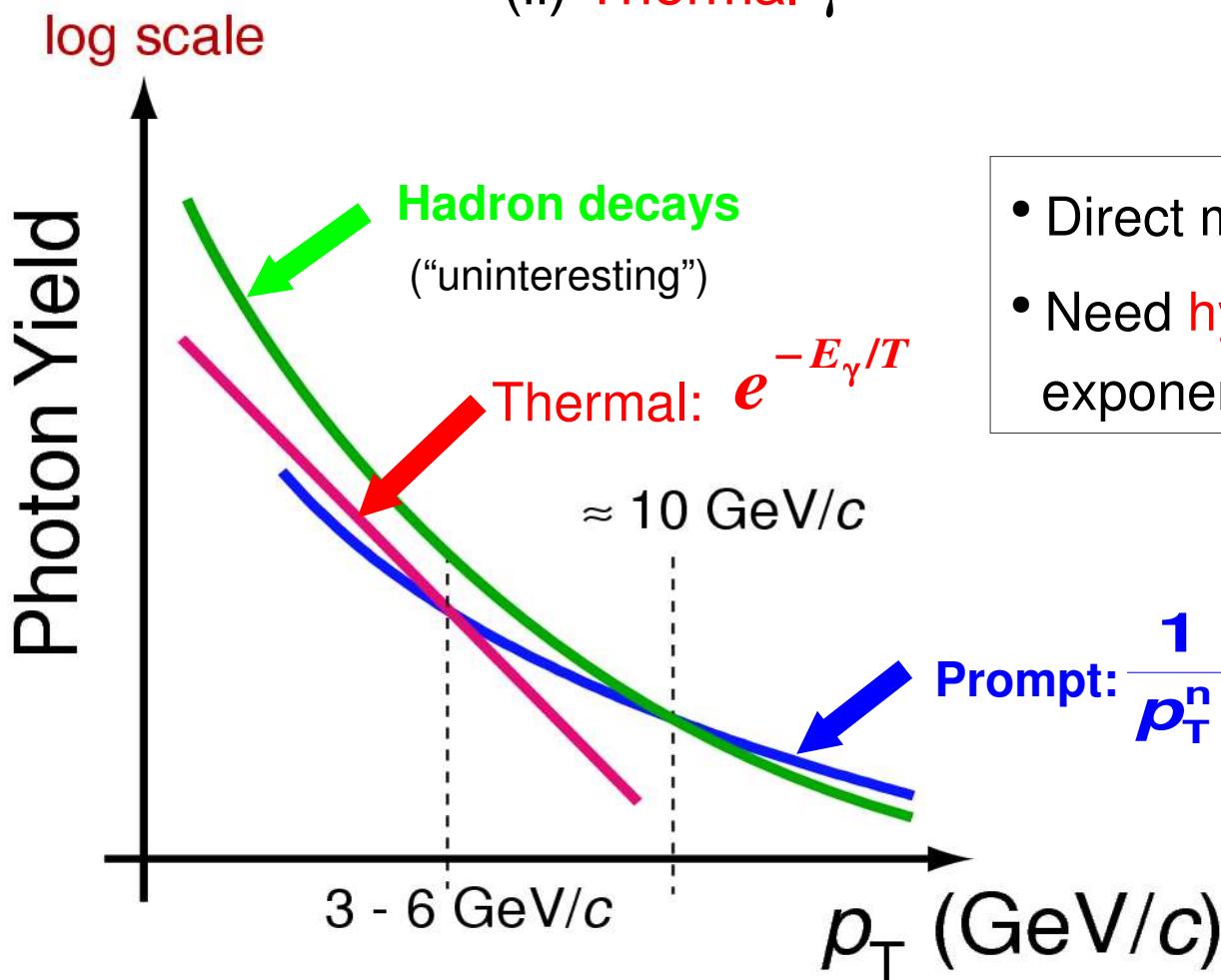
In Arleo et al.  
CERN Yellow Report  
HI @ LHC Photon Physics

hep-ph/0311131

# Photon production mechanisms in A+A collisions

- Three sources:
  - (i) Hadron decay  $\gamma \rightarrow \text{Background}$
  - (ii) Prompt  $\gamma$
  - (iii) Thermal  $\gamma$

→ Direct photon signal



- Direct measure of the medium T.
- Need hydro model to relate exponential slope to temperature.

- Pre-equilibrium component
- Needs to be measured in p+p reference collisions (or calculated via pQCD), scaled by  $T_{AB}$  & subtracted from total direct  $\gamma$  spectrum.