RHIC Physics with the Parton Cascade Model

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- The PCM: fundamentals & implementation
- Applications: stopping @ RHIC and direct photons
- Outlook & plans for the future

The PCM Model: current status

results since QM'02:

•*Parton Rescattering and Screening in Au+Au at RHIC*
- Phys. Lett. **B551** (2003) 277

•*Light from cascading partons in relativistic heavy-ion collisions*
- Phys. Rev. Lett. **90** (2003) 082301

•*Semi-hard scattering of partons at SPS and RHIC : a study in contrast*
- Phys. Rev. **C66** (2002) 061902 Rapid Communication

• *Net baryon density in Au+Au collisions at the Relativistic Heavy Ion Collider*
- Phys. Rev. Lett. **91** (2003) 052302

• *Transverse momentum distribution of net baryon number at RHIC*
- Journal of Physics **G29** (2003) L51-L58

Basic Principles of the PCM

- degrees of freedom: quarks and gluons
- classical trajectories in phase space (with relativistic kinematics)
- initial state constructed from experimentally measured nucleon structure functions and elastic form factors
- an interaction takes place if at the time of closest approach d_{min} of two partons

$$d_{\min} \leq \sqrt{\frac{\sigma_{tot}}{\pi}} \quad \text{with} \quad \sigma_{tot} = \sum_{p_3,p_4} \int \frac{d\sigma\left(\sqrt{\hat{s}}; p_1, p_2, p_3, p_4\right)}{d\hat{t}} d\hat{t}$$

- system evolves through a sequence of binary ($2\rightarrow 2$) elastic and inelastic scatterings of partons and initial and final state radiations within a leading-logarithmic approximation ($2\rightarrow N$)
- binary cross sections are calculated in leading order pQCD with either a momentum cut-off or Debye screening to regularize IR behaviour
- guiding scales: initialization scale Q_0, p_T cut-off p_0 / Debye-mass μ_D, intrinsic k_T, virtuality > μ_0

Limitations of the PCM Approach

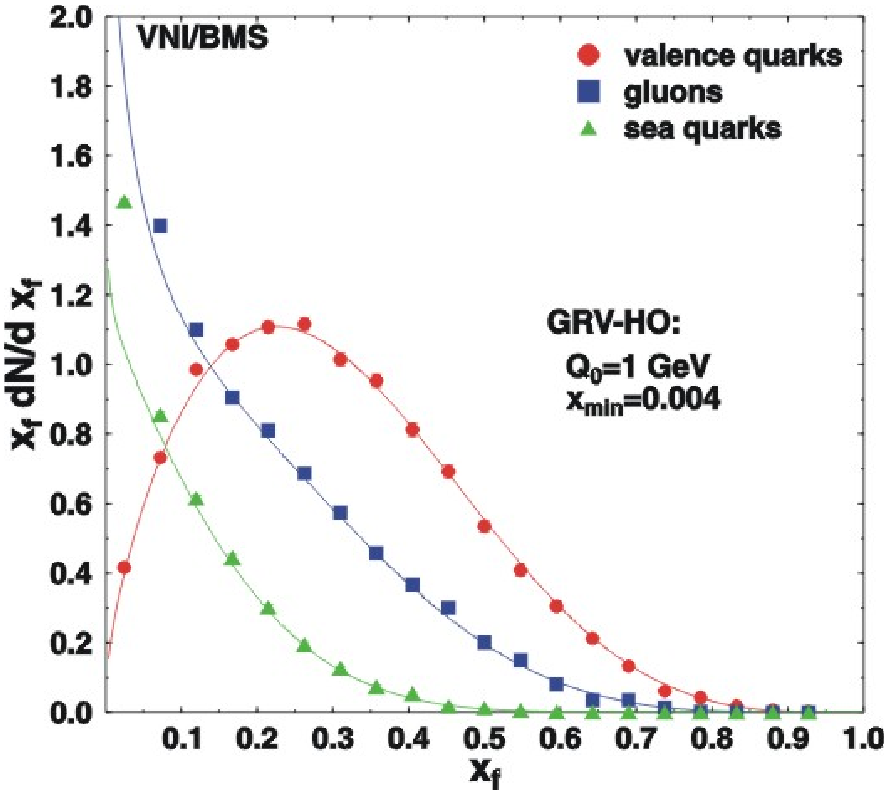
Fundamental Limitations:

- lack of coherence of initial state
- range of validity of the Boltzmann Equation
- interference effects are included only schematically
- hadronization has to be modeled in an ad-hoc fashion
- restriction to perturbative physics!

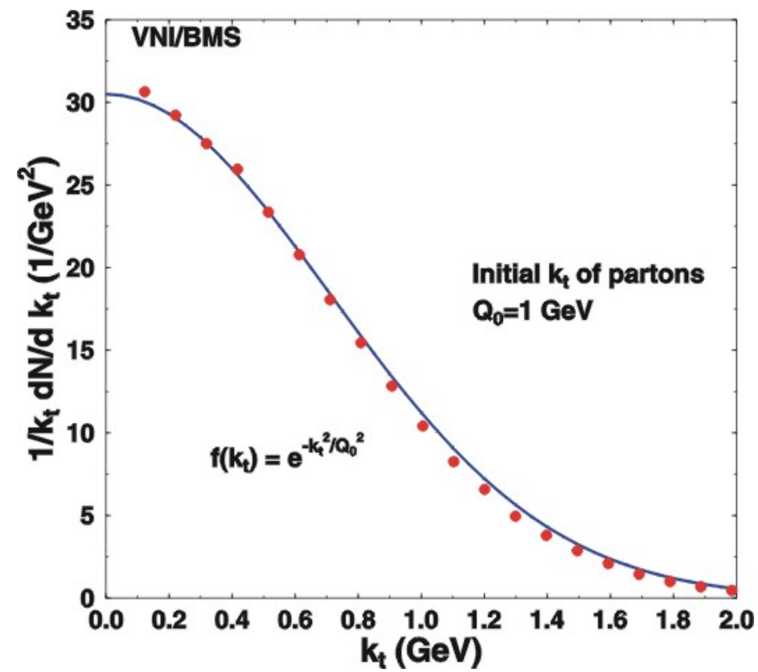
Limitations of present implementation (as of Dec 2003)

- lack of detailed balance: (no N $\rightarrow$ 2 processes)
- lack of selfconsistent medium corrections (screening)
- heavy quarks?

Initial State: Parton Momenta



- flavor and x are sampled from PDFs at an initial scale Q_0 and low x cut-off x_{min}
- initial k_t is sampled from a Gaussian of width Q_0 in case of no initial state radiation



- virtualities are determined by:

$$\left(\sum_i E^i\right)^2 - \left(\sum_i p_x^i\right)^2 - \left(\sum_i p_y^i\right)^2 - \left(\sum_i p_z^i\right)^2 = M_N^2$$

with $p_z^i = x^i P_z^N$ and $E^i = \beta_N^{-1} p_z^i$

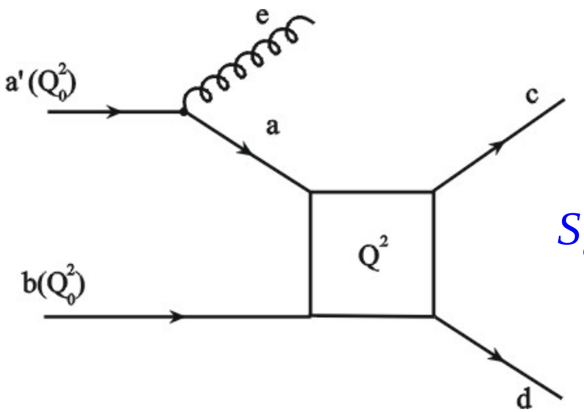
Parton-Parton Scattering Cross-Sections

$g\,g \to g\,g$	$\frac{9}{2}\left(3-\frac{tu}{s^2}-\frac{su}{t^2}-\frac{st}{u^2}\right)$	$q\,q' \to q\,q'$	$\frac{4}{9}\frac{s^2+u^2}{t^2}$
$q\,g \to q\,g$	$-\frac{4}{9}\left(\frac{s}{u}+\frac{u}{s}\right)+\frac{s^2+u^2}{t^2}$	$q\,\bar{q} \to q'\,\bar{q}'$	$\frac{4}{9}\frac{t^2+u^2}{s^2}$
$g\,g \to q\,\bar{q}$	$\frac{1}{6}\left(\frac{t}{u}+\frac{u}{t}\right)-\frac{3}{8}\frac{t^2+u^2}{s^2}$	$q\,g \to q\,\gamma$	$-\frac{e_q^2}{3}\left(\frac{u}{s}+\frac{s}{u}\right)$
$q\,q \to q\,q$	$\frac{4}{9}\left(\frac{s^2+u^2}{t^2}+\frac{s^2+t^2}{u^2}\right)-\frac{8}{27}\frac{s^2}{tu}$	$q\,\bar{q} \to g\,\gamma$	$\frac{8}{9}e_q^2\left(\frac{u}{t}+\frac{t}{u}\right)$
$q\,\bar{q} \to q\,\bar{q}$	$\frac{4}{9}\left(\frac{s^2+u^2}{t^2}+\frac{u^2+t^2}{s^2}\right)-\frac{8}{27}\frac{u^2}{st}$	$q\,\bar{q} \to \gamma\,\gamma$	$\frac{2}{3}e_q^4\left(\frac{u}{t}+\frac{t}{u}\right)$
$q\,\bar{q} \to g\,g$	$\frac{32}{27}\left(\frac{t}{u}+\frac{u}{t}\right)-\frac{8}{3}\frac{t^2+u^2}{s^2}$		

- a common factor of $\pi\alpha_s^2(Q^2)/s^2$ etc.
- further decomposition according to color flow

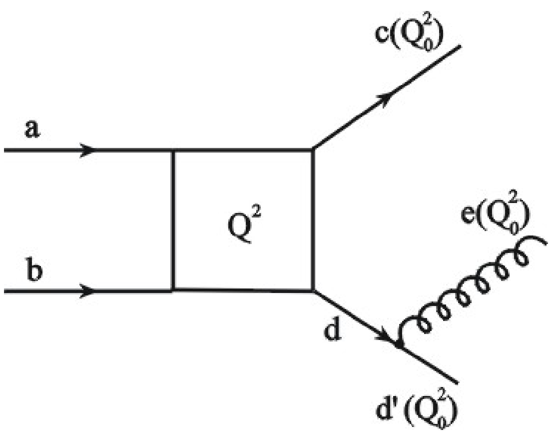
Initial and final state radiation

Probability for a branching is given in terms of the Sudakov form factors:



space-like branchings:

$$S_a\left(x_a, t_{\max}, t\right) = \exp\left\{ -\int_t^{t_{\max}} dt' \frac{\alpha_s\left(t'\right)}{2\pi} \sum_{a'} \int dz\, P_{a' \to ae}\left(z\right) \frac{x_{a'} f_{a'}\left(x_{a'}, t'\right)}{x_a f_a\left(x_a, t'\right)} \right\}$$

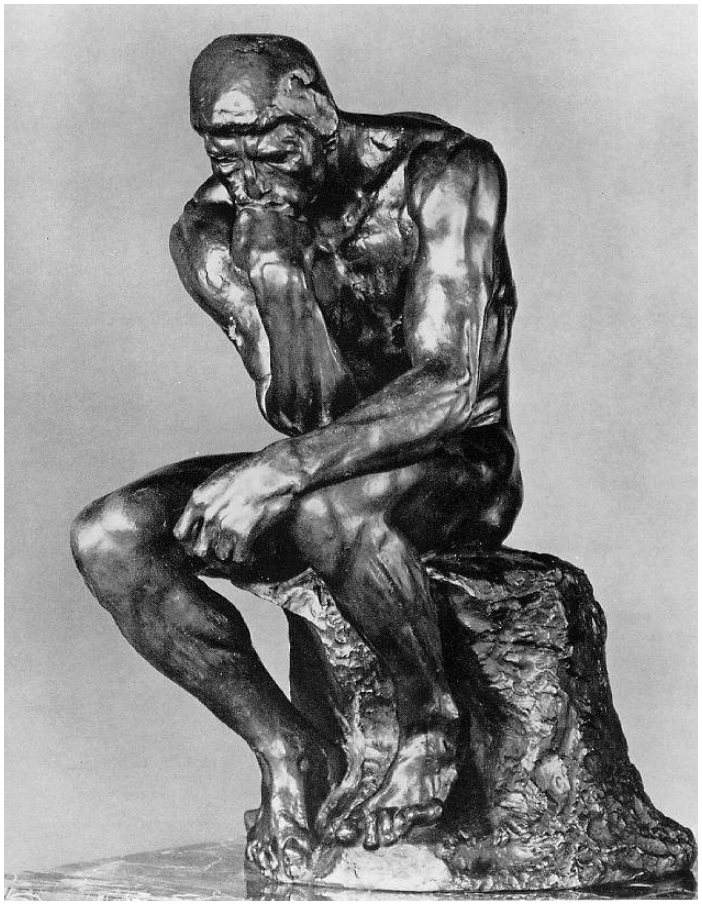


time-like branchings:

$$T_d\left(x_d, t_{\max}, t\right) = \exp\left\{ -\int_t^{t_{\max}} dt' \frac{\alpha_s\left(t'\right)}{2\pi} \sum_{a'} \int dz\, P_{d \to d'e}\left(z\right) \right\}$$

- Altarelli-Parisi splitting functions included: $P_{q\to qg}$, $P_{g\to gg}$, $P_{g\to qqbar}$ & $P_{q\to q\gamma}$

Hadronization



- requires modeling & parameters beyond the PCM pQCD framework
- microscopic theory of hadronization needs yet to be established
- phenomenological recombination + fragmentation approach may provide insight into hadronization dynamics
- avoid hadronization by focusing on:
  - direct photons
  - net-baryons

Model Parameters

- momentum cut-off p_0

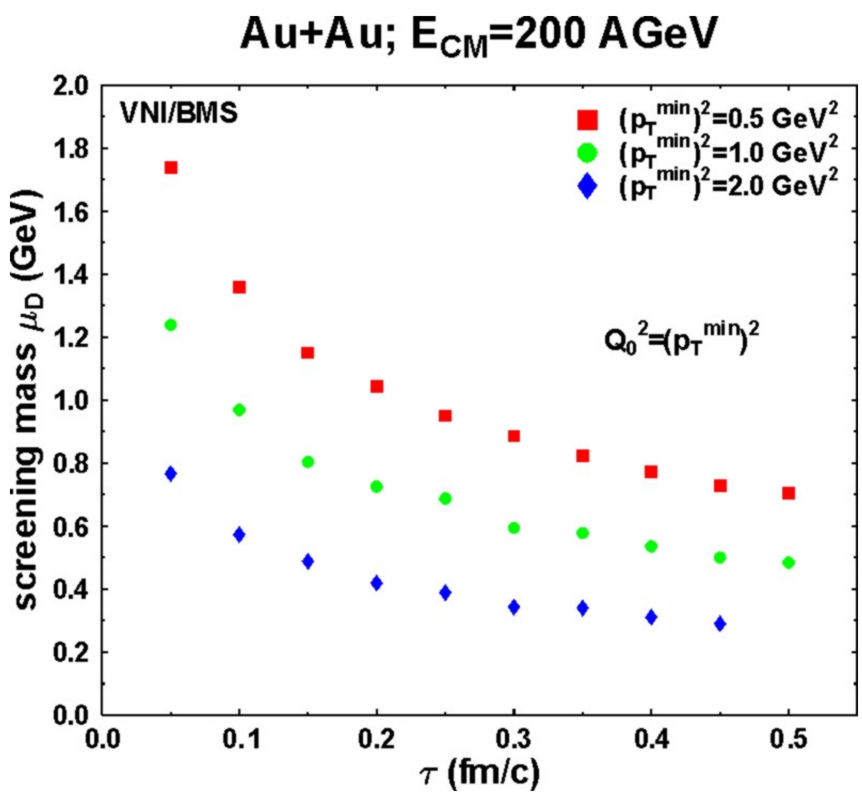
Debye Screening in the PCM

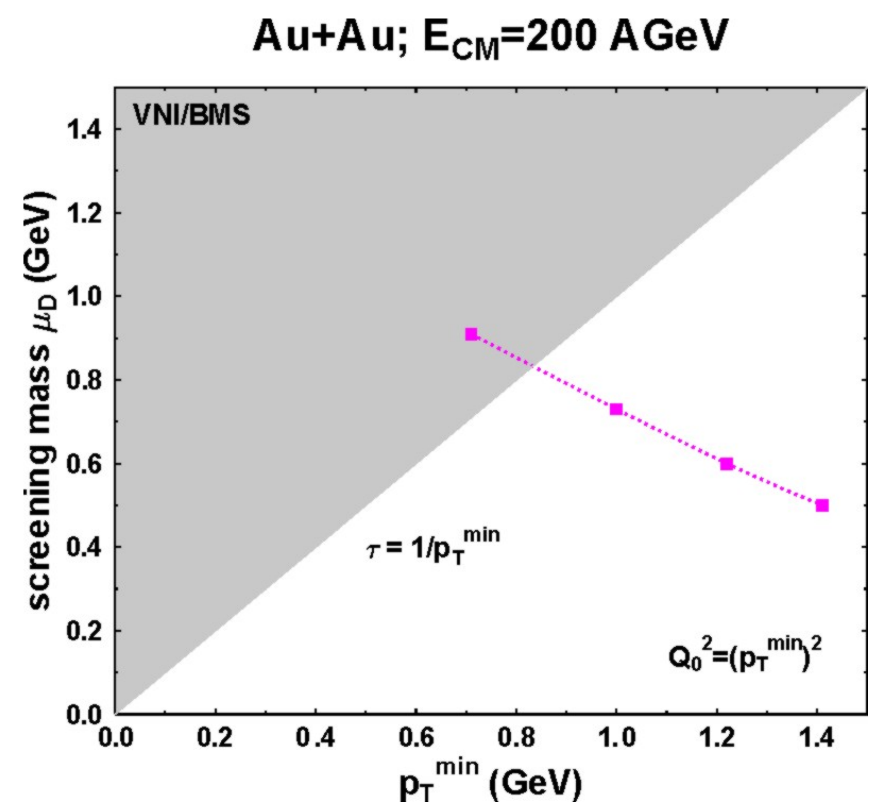
- the Debye screening mass μ_D can be calculated in the one-loop approximation [Biro, Mueller & Wang: PLB **283** (1992) 171]:

$$\mu_D^2 = \frac{3\alpha_s}{\pi^2} \lim_{|\vec{q}|\to 0} \int d^3p \, \frac{|\vec{p}|}{\vec{q}\cdot\vec{p}} \, \vec{q}\cdot\nabla_{\vec{p}} \left[F_g(\vec{p}) + \frac{1}{6}\sum_q \left\{ F_q(\vec{p}) + F_{\bar{q}}(\vec{p}) \right\} \right]$$

- PCM input are the (time-dependent) parton phase-space distributions F(p)
- Note: ideally a local and time-dependent μ_D should be used to self-consistently calculate the parton scattering cross sections
  - ➢currently beyond the scope of the numerical implementation of the PCM

Choice of p_T^{min}: Screening Mass as Indicator



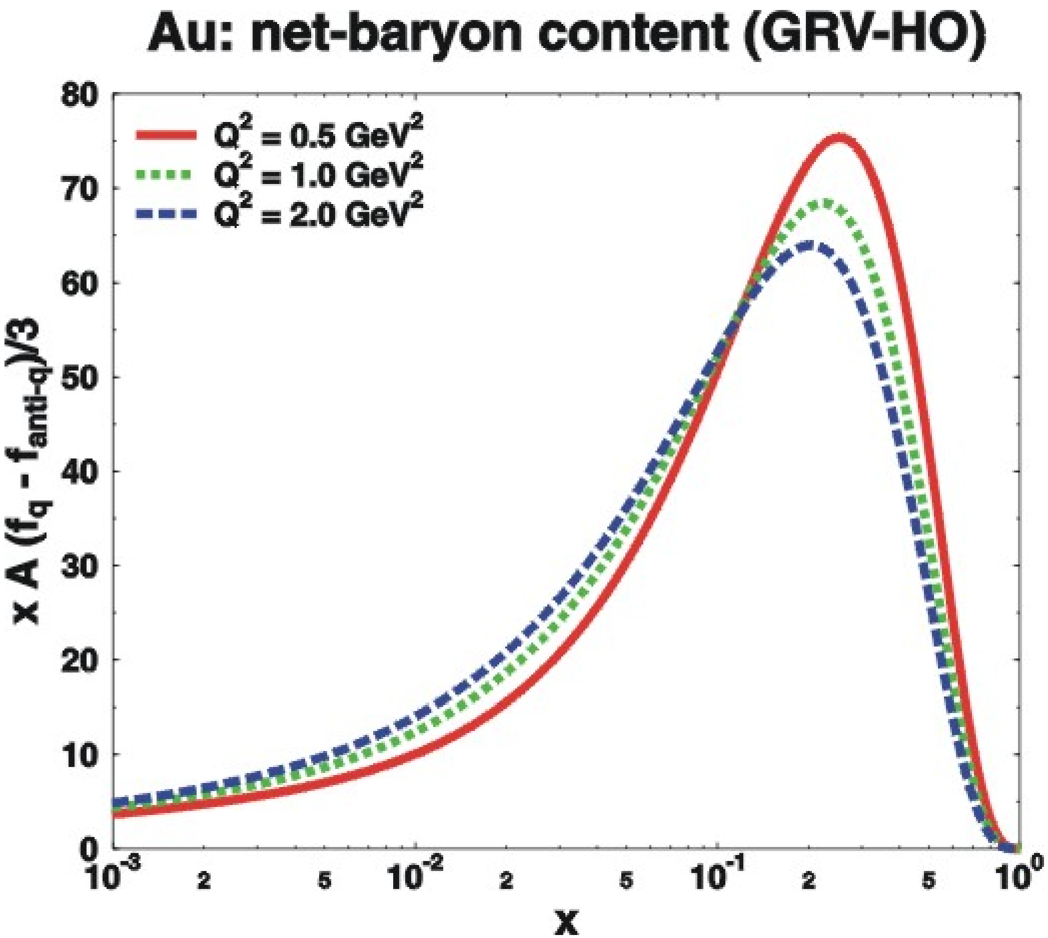


- screening mass μ_D is calculated in one-loop approximation
- time-evolution of μ_D reflects dynamics of collision: varies by factor of 2!
- model self-consistency demands $p_T^{min} > \mu_D$:
  - ➢lower boundary for p_T^{min} : approx. 0.8 GeV

Baryon stopping at RHIC

- influence of initial state
- parton rescattering
- temporal evolution

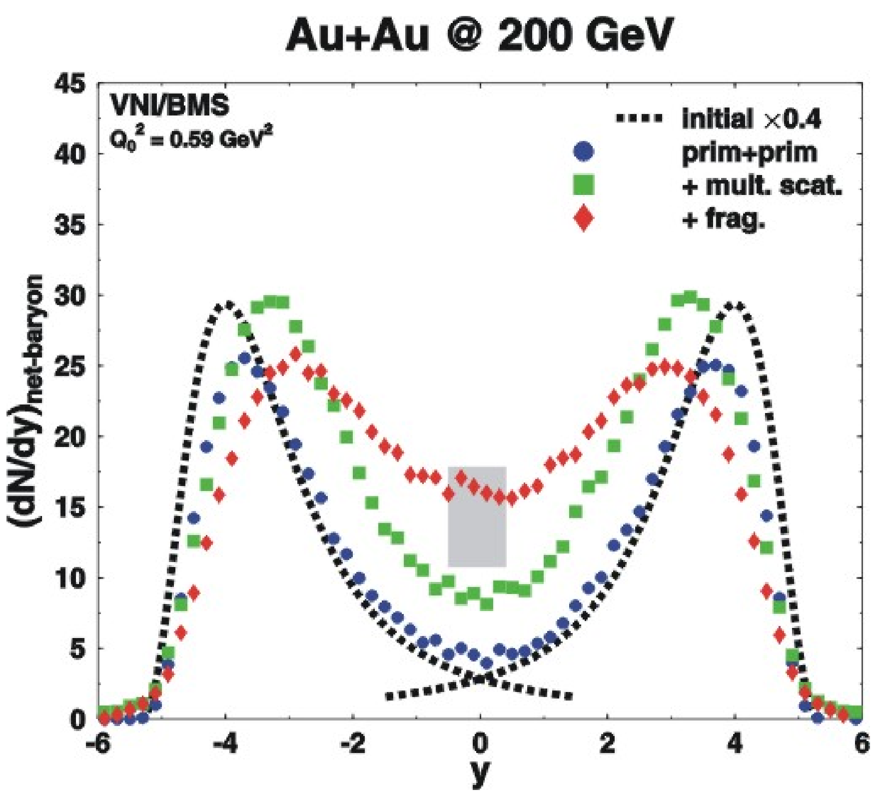
Baryon stopping at RHIC: Initial or Final State Effect?

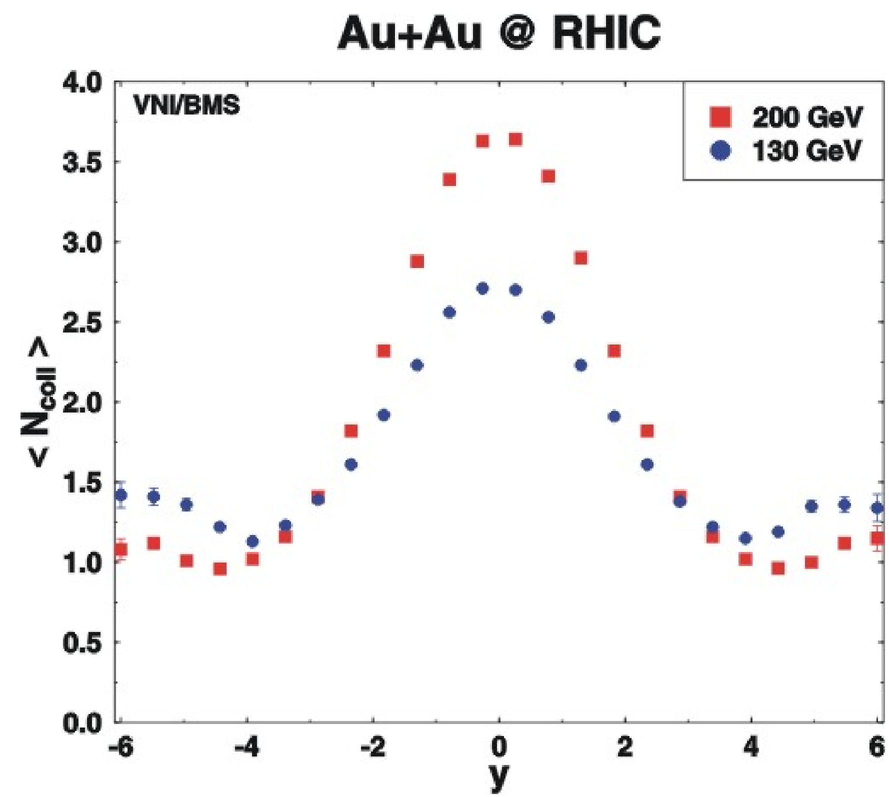


- net-baryon contribution from initial state (structure functions) is non-zero, even at mid-rapidity!
  - ➢initial state alone accounts for $dN_{net\text{-}baryon}/dy \approx 5$

- is the PCM capable of filling up mid-rapidity region?
- is the baryon number transported or released at similar x?

Baryon stopping at RHIC: PCM Results

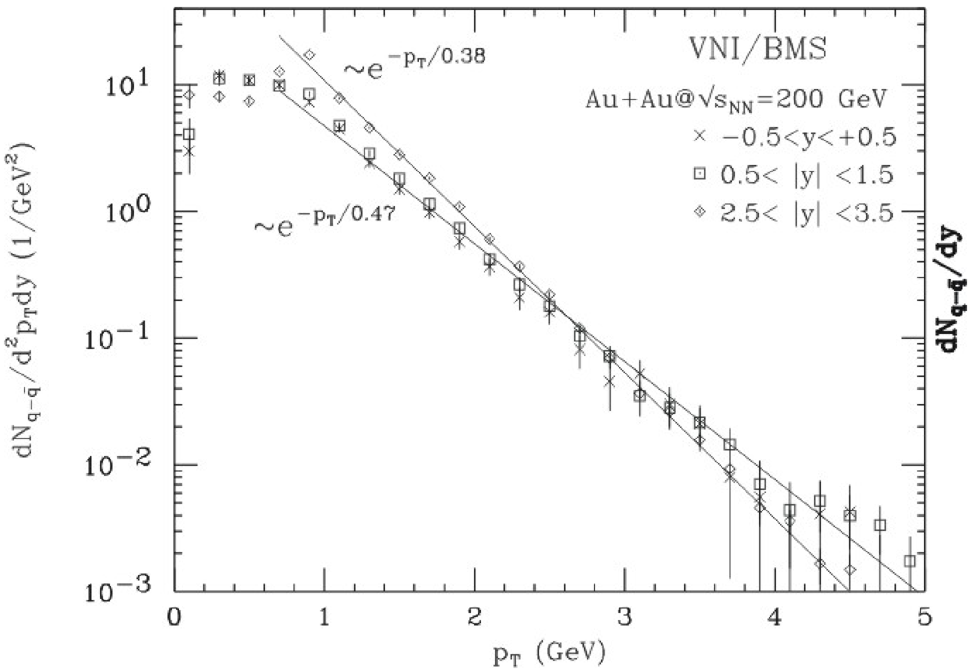


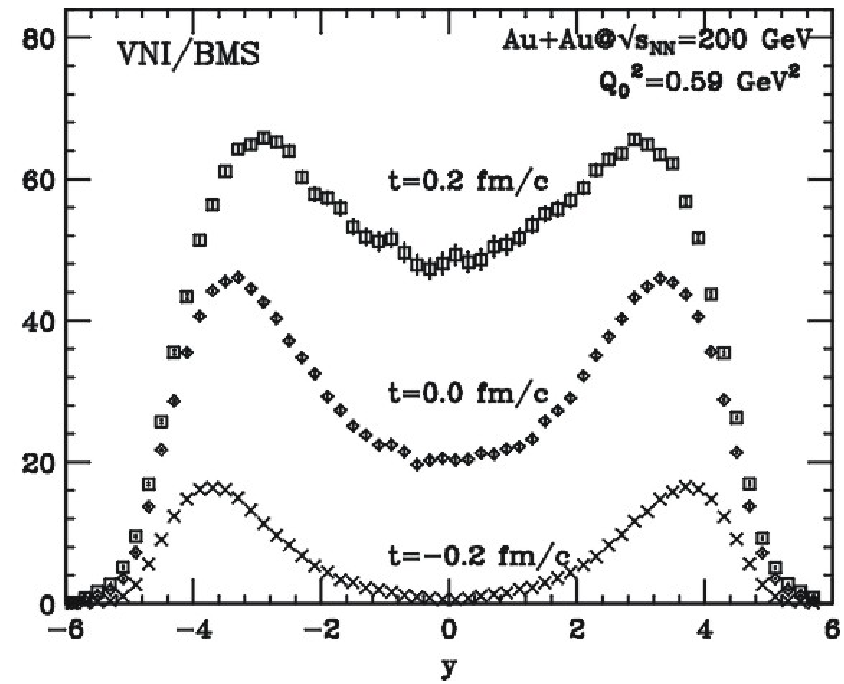


- primary-primary scattering releases baryon-number at corresponding y
- multiple rescattering & fragmentation fill up mid-rapidity domain

➢ initial state & parton cascading can fully account for data!

p_t dependence of net-quark dynamics





- slope of net-quark p_t distribution shows rapidity dependence
- net-quark distributions freeze out earlier in the fragmentation regions than at y_{CM}

➢ forward/backward rapidities sensitive to initial state / CGC?

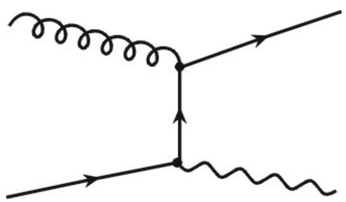
Direct Photons

- spectra and mass dependence
- production times & dynamics
- comparision: RHIC vs. SPS

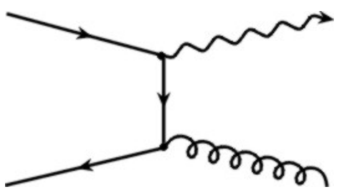
Photon Production in the PCM

relevant processes:

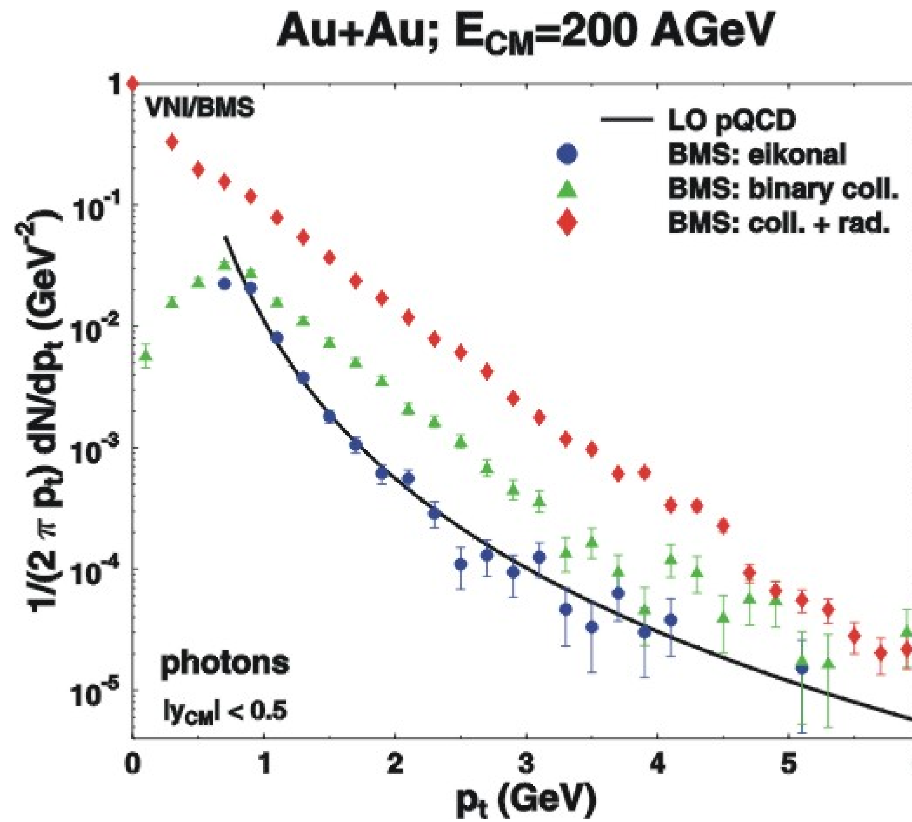
- Compton: **q g →q γ**



- annihilation: **q qbar → g γ**

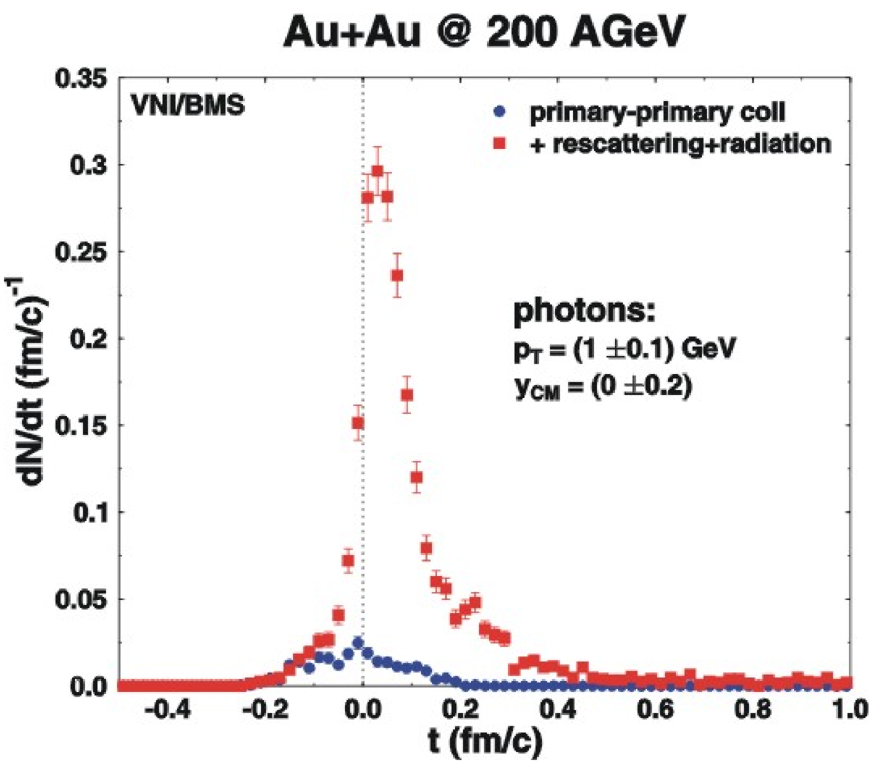


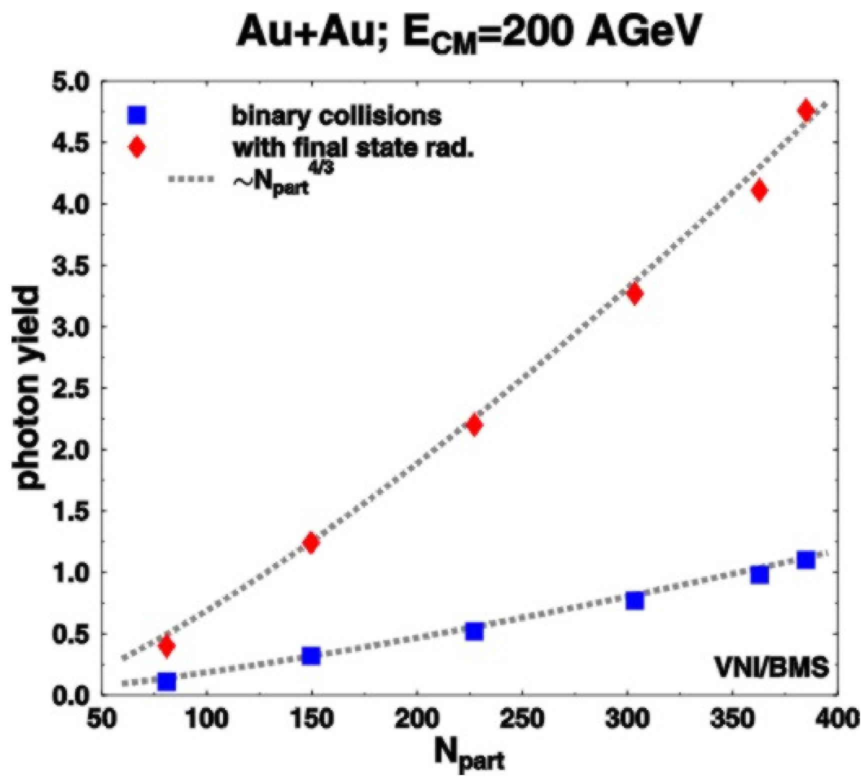
- bremsstrahlung: **q* →q γ**



➢ photon yield very sensitive to parton-parton rescattering

What can we learn from photons?

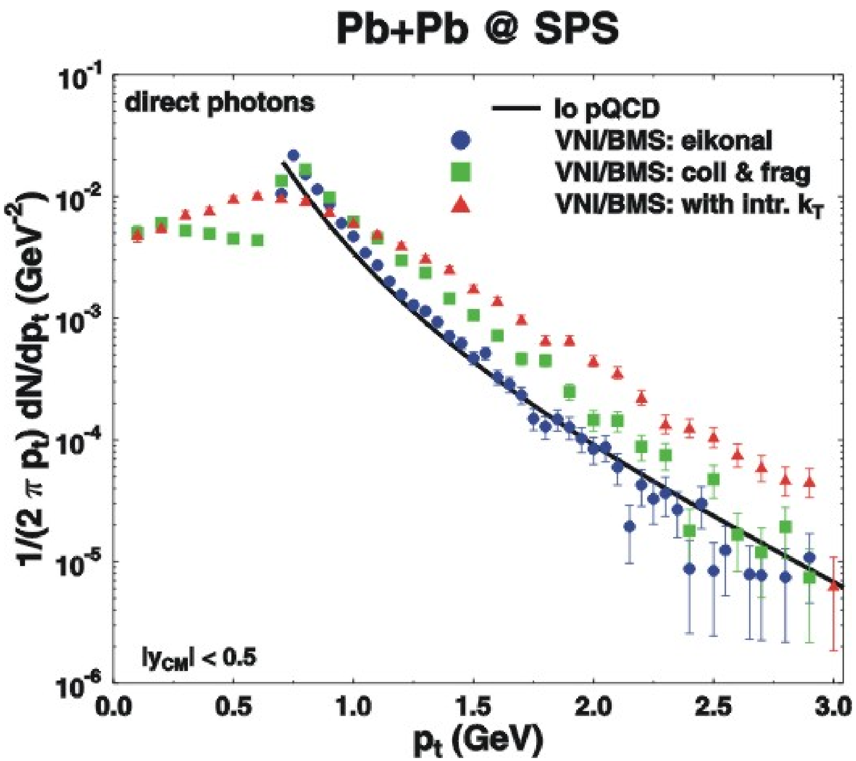


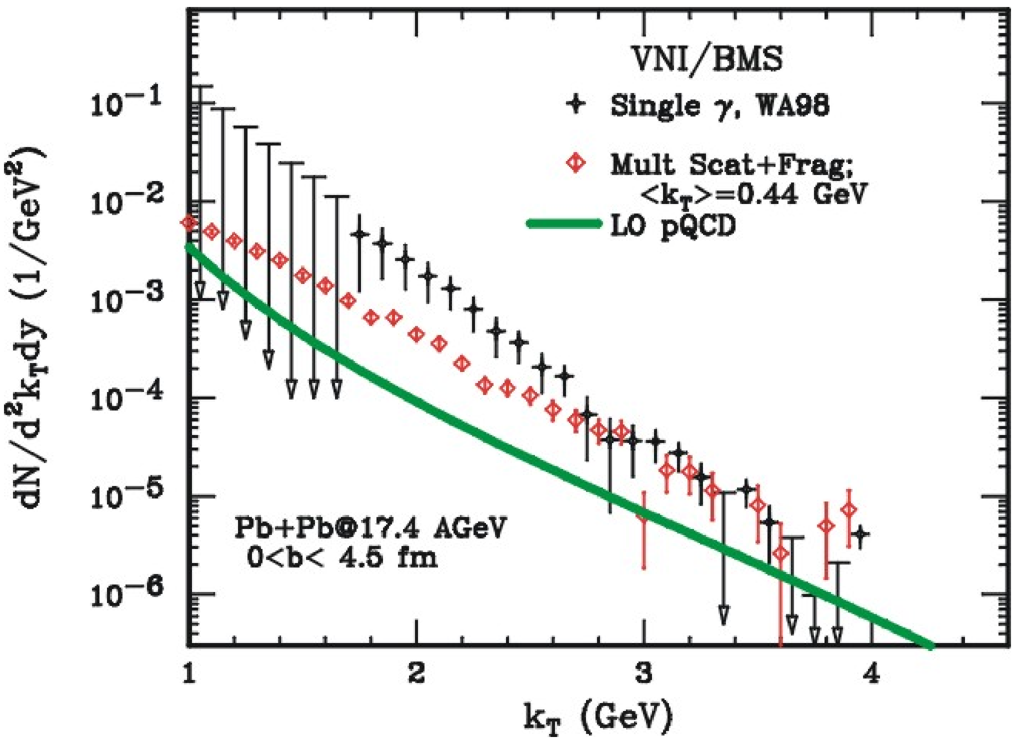


- primary-primary collision contribution to yield is < 10%
- emission duration of pre-equilibrium phase: ~ 0.5 fm/c

- photon yield directly proportional to the # of hard collisions
- ➢ photon yield scales with $N_{part}^{4/3}$

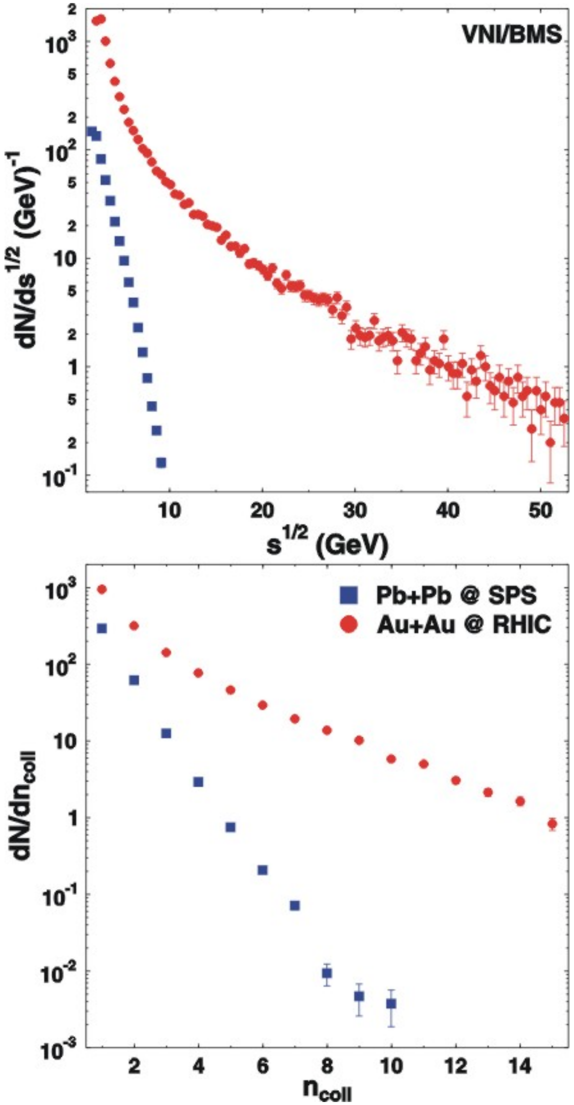
Photon Production at SPS





- at SPS, effects of parton rescattering can be observed via direct photons
  - including intrinsic k_T, the PCM can account for measured photon yield

SPS vs. RHIC: a study in contrast



	SPS	RHIC
cut-off p_t^{min} (GeV)	0.7	1.0
# of hard collisions	255.0	3618.0
# of fragmentations	17.0	2229.0
av. Q^2 (GeV^2)	0.8	1.7
av. $\sqrt{s}$ (GeV)	2.6	4.7

- perturbative processes at SPS are negligible for overall reaction dynamics
- sizable contribution at RHIC, factor 14 increase compared to SPS

Summary and Outlook

Baryon Stopping:

- initial state + PCM are compatible with the measured net-baryon density
- no need for exotic and/or non-perturbative mechanisms
- initial state contributes 30%, parton scattering 70% to dN/dy
- forward/backward rapidities may be sensitive to initial parton distribution

Direct Photons:

- strong sensitivity to parton rescattering
- short emission duration in pre-equilibrium phase

Outlook:

- inclusion of gluon-fusion processes: analysis of thermalization
- investigation of the microscopic dynamics of jet-quenching
- heavy quark production: predictions for charm and bottom
- hadronization: develop concepts and implementation

The End