Limiting soft particle emission

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- lessons from e^+e^-annihilations
- soft particle spectra in pp collisions
- nucleus nucleus interactions

with V.A. Khoze, M.G. Ryskin, EPJC 68, 141, 2010

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Limiting soft particle emission

inclusive production of particles in the limit $p \to 0; \ (p_T \to 0)$

$$I_0 \equiv E \frac{dN}{d^3p}|_{p \to 0}$$

in this limit Born term in perturbative expansion dominates:
$\Rightarrow$ universal features for all processes:

1. inclusive spectra become energy independent
2. relative normalisation of spectra in different processes given by relevant colour factors

This holds for QCD partons,
we assume the same is true for hadrons

qualitative picture:

- gluons of large wavelength do not resolve any detailed intrinsic jet structure
- coherent emission from all final partons
- they “see” only the colour charge of primary partons i.e. they are represented by the Born term for the minimal partonic process

e^+e^- **annihilation**

Quark and gluon jets in e^+e^- annihilations

inclusive spectra in pQCD

particle energy k and production angle Θ

evolution eqn. including angular ordering

Bassetto et al. '83

Dokshitzer et al. '84

most simple example:

Double Logarithmic Approximation (DLA) at fixed α_s

$$\frac{dN_p}{dk d\Theta} = \frac{2}{\pi}\frac{C_p}{k\Theta}\alpha_s + \frac{4N_C}{\pi^2}\frac{C_p}{k\Theta}\alpha_s^2 \ln\frac{E}{k}\ln\frac{k_T}{Q_0} + \ldots$$

$\Rightarrow$ Born term $O(\alpha_s)$ dominates in soft limit ($k_T \to Q_0 \equiv k_T^{cut}$):

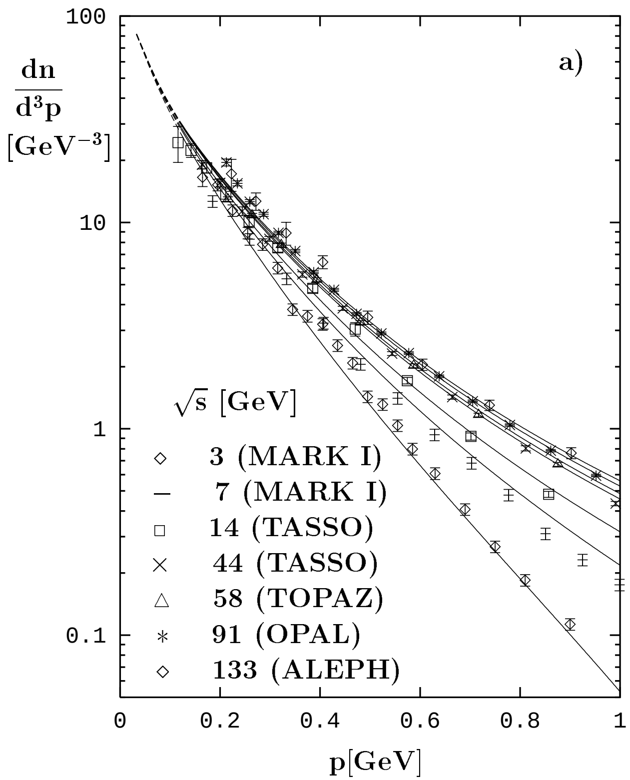
$\Rightarrow$ independent of jet energy E, proportional to colour factors $C_p = C_F, C_A$

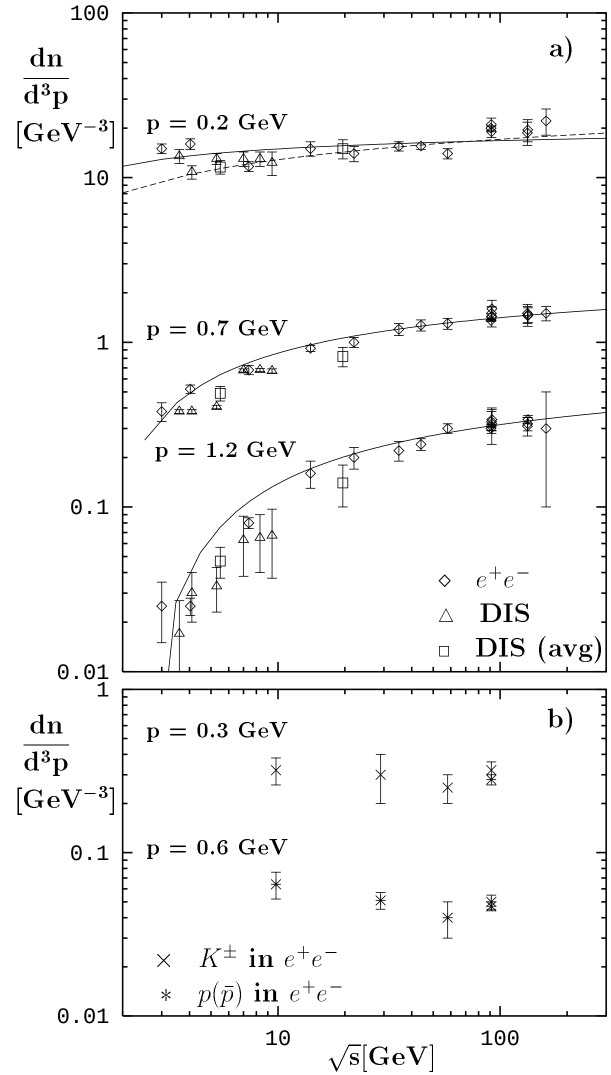
more realistic case:

Modified Leading Logarithmic Approximation (MLLA)

Limiting behaviour of p_T spectra in $\sqrt{s}$

charged particles





kaons

protons

analytic solution $O(\alpha_s^2)$ at $p \lesssim 1$ GeV based on MLLA+LPHD ($Q_0 \sim m_{had}$)

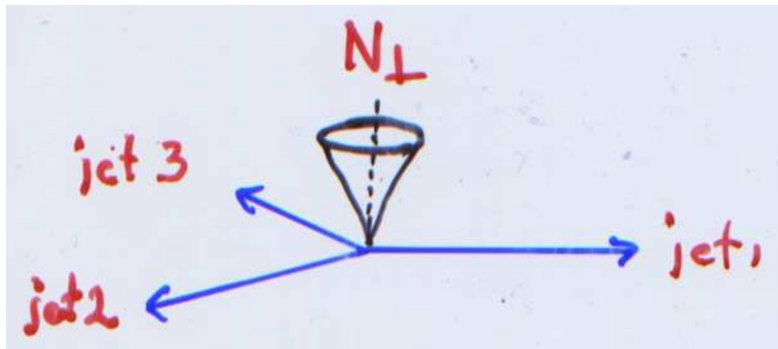
Khoze, Lupia, W.O. '97

$\Rightarrow$ spectra become energy $\sqrt{s}$ independent for $p \to 0$

Colour factors in quark and gluon jets

For soft radiation

study particles $N_\perp$ perpendicular to event plane in 2 and 3 jet events



aligned jets:

$qg \longleftrightarrow \bar{q}$ like $q \longleftrightarrow \bar{q}$ color factor $C_p = C_F$

$q\bar{q} \longleftrightarrow g$ like $g \longleftrightarrow g$ color factor $C_p = C_A$

perpendicular radiation in $q\bar{q}g$ events

for general angles interpolate:

$$\frac{N_\perp^{q\bar{q}g}}{N_\perp^{q\bar{q}}} \equiv \frac{C_A}{C_F}\, r_t$$

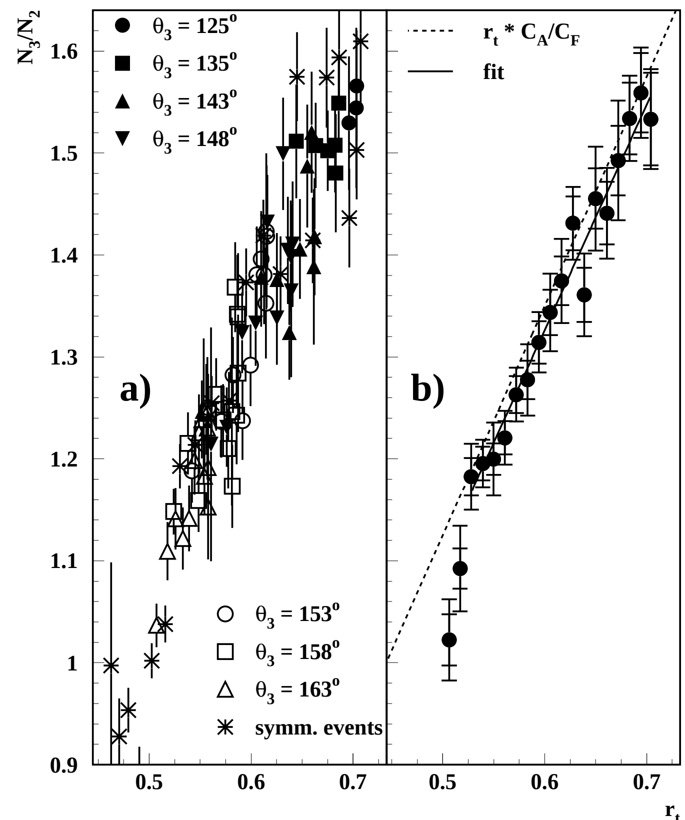
$$r_t(\Theta_{ij}) =$$

$$= \frac{1}{4}[(1-\cos\Theta_{qg}) + (1-\cos\Theta_{\bar{q}g}) - \frac{1}{N_C^2}(1-\cos\Theta_{q\bar{q}})]$$

only 2 angles are independent

Khoze, Lupia, W.O.'97

$N_\perp^{q\bar{q}g}/N_\perp^{q\bar{q}}$ vs. $r_t(\Theta_{ij})$



DELPHI 2005

dashed: QCD prediction

full: fit with slope

$$C_A/C_F = 2.211 \pm 0.053$$

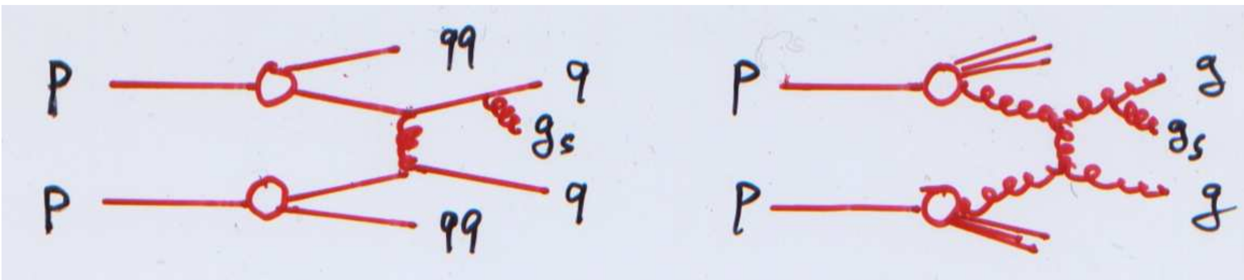
$pp/p\bar{p}$ scattering

Soft limit in pp "minimum bias" events

minimal partonic process resolved : $2 \to 2 + g_s$ at small angles:

gluon exchange (non-vanishing cross sections for large s)

examples:



gluon exchange leads to radiating colour octet dipole, $pp \to 8 + 8$

qq scattering with initial and final bremsstrahlung ($\sim$ two $q\bar{q}$ triplet dipoles)

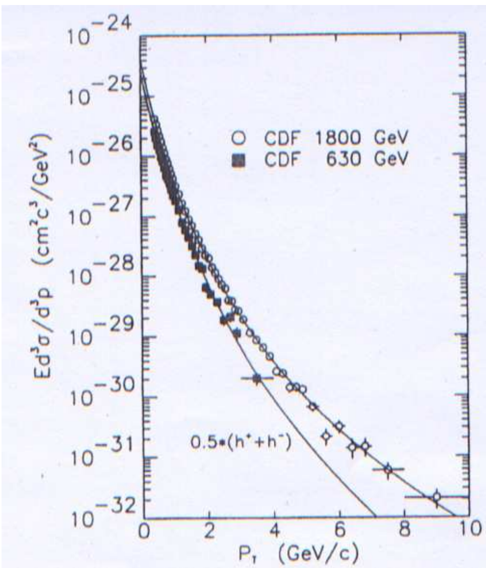
$q - qq$ as color octet

$$\Rightarrow I_0^{pp}/I_0^{e^+e^-} \sim \frac{dN^{pp\to 8+8}}{dEd\eta} \Big/ \frac{dN^{e^+e^-\to \bar{q}q}}{dEd\eta} \to \frac{C_A}{C_F} \quad \text{for} \quad p \to 0$$

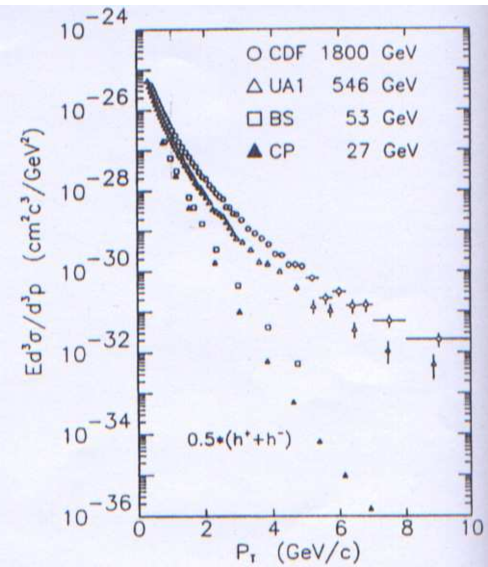
compare with Brodsky, Gunion '76

Energy dependence of $E\frac{dN}{d^3p}$ $vs.$ p_T in pp collisions

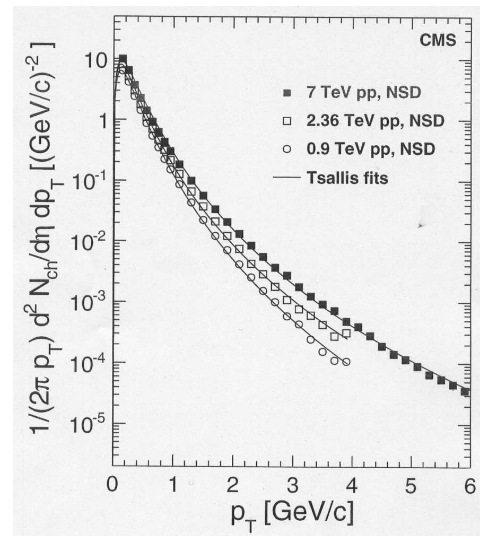
630 - 1800 GeV



27 - 1800 GeV



900 - 7000 GeV

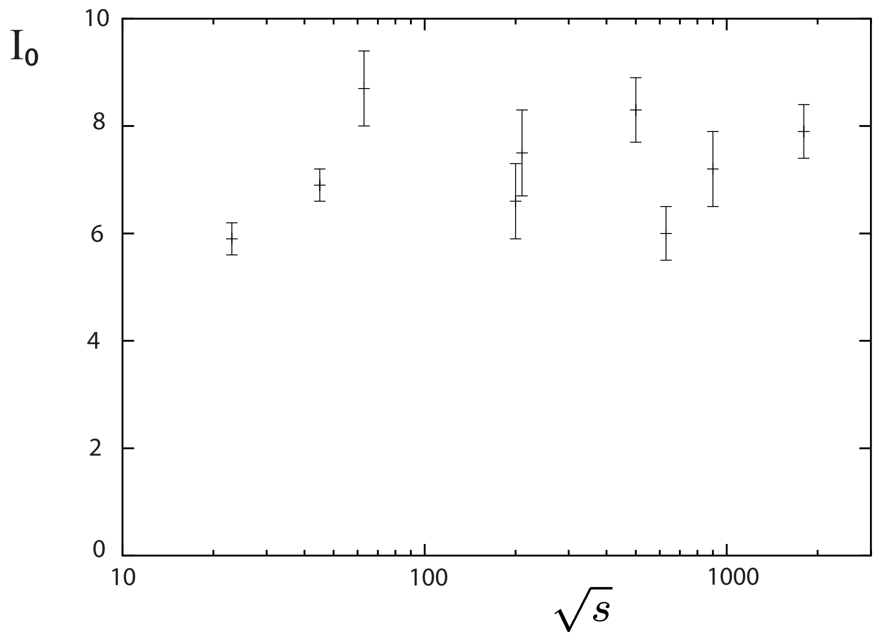


Extrapolation $p_T \to 0$?

pp data: “exponential p_T” fits ($p_T > 0.1$ GeV (BS)) (bad analyticity)

AA data: “thermal” fits in $m_T = \sqrt{m^2 + p_T^2}$ ($p_T \gtrsim 30$ MeV (PHOBOS))

Soft limit $I_0 = E\frac{dN}{d^3p}|_{p_T\to 0}$ in pp collisions



BS, STAR, UA1,CDF

exponential p_T fit

data

normalised by σ_{in}

inelastic $pp/p\bar{p}$ collisions (exp. fit): $I_0 \approx (7 \pm 1)$ GeV^{-2}

Data suggest rather flat energy dependence (contrast: $\frac{dN}{dy}$ rise by factor 2)

to compare with e^+e^- annihilation we use instead:

non-diffractive $pp/p\bar{p}$ collisions (exp. fit): $I_0 \approx (8 \pm 1)$ GeV^{-2}

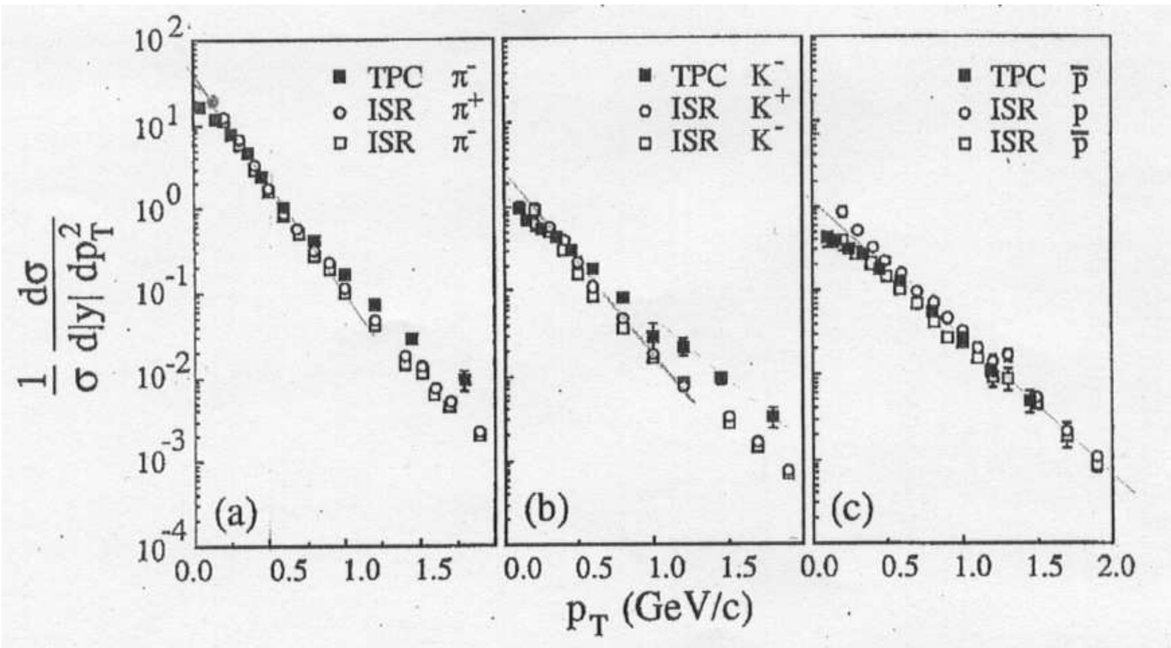
non-diffractive $pp/p\bar{p}$ collisions (therm. fit): $I_0 \approx (6 \pm 1)$ GeV^{-2} (-25%)

Comparison of pp with e^+e^- collisions

1. spectrum $E\frac{dN}{d^3p}$ vs p_T using sphericity-jet axis in e^+e^- annihilations:

e^+e^-: TPC Coll. at SLAC, 1987

pp: British-Scandinavian Coll. at ISR, 1975



spectra are falling more steeply in pp collisions; also different shapes

for pions: $r \approx I_0^{pp}/I_0^{e^+e^-} \approx 2.7$ for exp. extrapol. of pp

$r \approx 2.0$ for thermal fit.

for kaons: $r \approx I_0^{pp}/I_0^{e^+e^-} \approx 2.0$ for exp. extrap.

2. fits to the momentum spectra (p, not p_T) in e^+e^- annihilations

fits exponential in energy, $\sqrt{s}$ = 10-34 GeV ARGUS, TASSO, TPC/2γ

$$I_0^{e^+e^-} \approx (3.3 \pm 0.5) \text{ GeV}^{-2} \qquad (p \gtrsim 0.05 \text{ GeV} \quad \text{ARGUS,TPC/2}\gamma)$$

$$\Rightarrow \boxed{I_0^{pp}/I_0^{e^+e^-} \approx (1.8 \pm 0.4) \div (2.4 \pm 0.5)}$$

thermal exponential p_T extrapolation of pp data.

expect $I_0^{pp}/I_0^{e^+e^-} = C_A/C_F = 2.25$

(thermal fit is more realistic from theoretical standpoint)

$\Rightarrow$ existing data are consistent with expectations from soft bremsstrahlung: independence of I_0 on energy, color factors

$\Rightarrow$ What will happen at LHC? Incoherent multiple scattering? Rising I_0?

AA scattering

Spectra at low p_T in AA collisions

limiting cases:

- pointlike interactions, $R_{AA}^{N_{coll}} = 1$

  $$R_{AA}^{N_{coll}} = \frac{1}{N_{coll}} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$ nuclear modification factor

  N_{coll} No of nucleon nucleon collisions (Glauber)

- Soft particle production:
  expect reduced rate for coherent production over range $R \sim 1/p_T$

  Phenomenology: normalization by
  No of participating nucleons N_{part} or “wounded nucleons”
  Bialas, Bleszynski and Czyz ’76

  $$R_{AA}^{N_{part}} = \frac{1}{N_{part}/2} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$ $\Leftrightarrow$ don’t count nucleon rescatterings

p_T distributions in $AuAu$ collisions

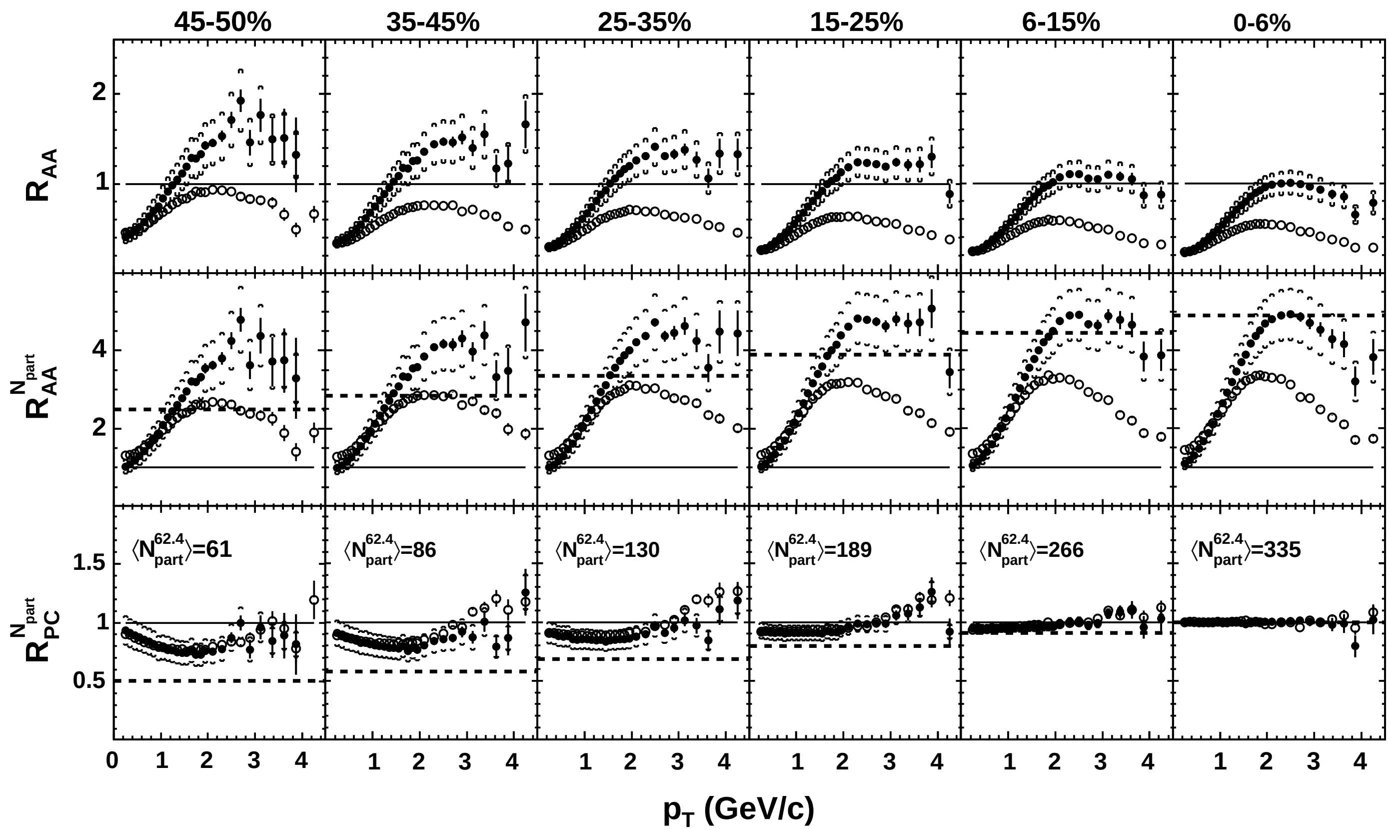
upper data points: $\sqrt{s} = 62.4$ GeV; lower data points: $\sqrt{s} = 200$ GeV

centralities: peripheral $\Longleftrightarrow$ central Phobos ’05

$R_{AA}^{N_{coll}}$

$R_{AA}^{N_{part}}$

$R_{PC}^{N_{part}}$



normalized to STAR pp data

$\Rightarrow$ 1. R has weak energy dependence for $p_T \to 0$ (AA behaves like pp)

$\Rightarrow$ 2. Normalization for $p_T \to 0$: $R_{AA}^{N_{part}} \to 1$

Comparison of AA and pp collisions

Thermal extrapolation of pp and $AuAu$ spectra to $p_T = 0$ at 200 GeV:

pp collisions	$I_0 \simeq 5.9$ GeV^{-2}	$p_T > 0.4$ GeV	STAR
$AuAu$ central	$I_0 \simeq (950 \pm 100)$ GeV^{-2}	$p_T > 0.03$ GeV	PHOBOS, STAR

$$\Rightarrow \boxed{I_0^{AA}/I_0^{pp} \approx 160 \pm 17}$$

compare with

$N_{coll} = 1040$ and $N_{part}/2 = 172\ (\pm 15\%)$ (Glauber model calculation)

conclude:

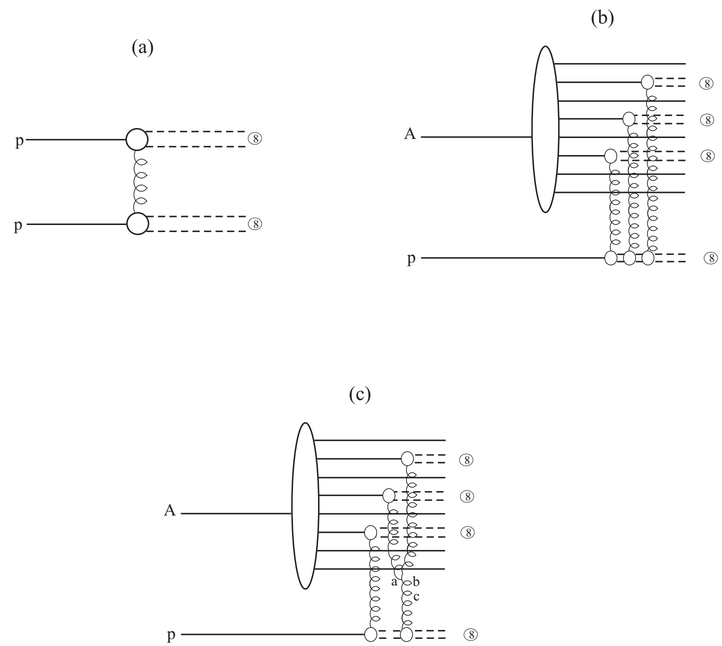
$$\Rightarrow \boxed{I_0^{AuAu} \approx \frac{N_{part}}{2}\ I_0^{pp}}$$ works very well, but only for $p_T \to 0$

Color antenna pattern in nuclear collisions

each nucleon after repeated rescatterings produces colour octet state.

$N_{coll} = 1$

$N_{part}/2 = 1$



$N_{coll} = 3$

$N_{part}/2 = 2$

simple example: gluon exchange between quarks & diquarks ($p \to q$-qq)

compare Bialas and Bzdak

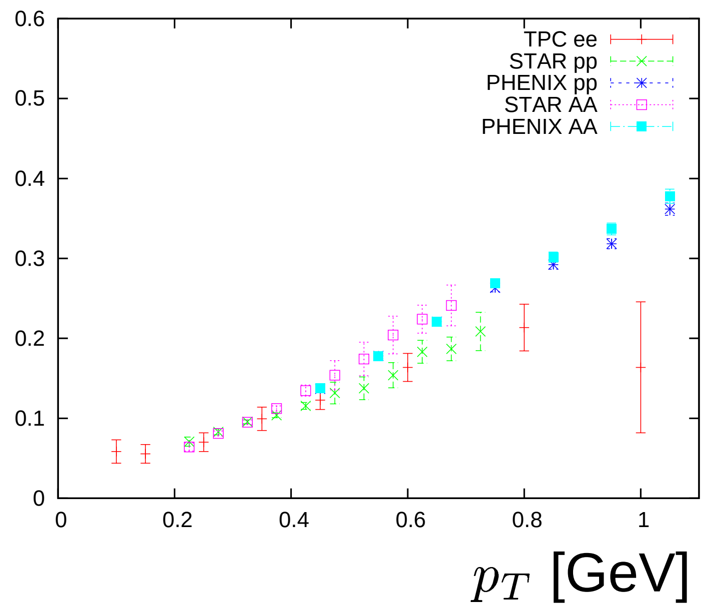
BFKL at large s: color 8 exchange dominates over color 12, 27 . . . Bronzan

This mechanism results in "participant scaling"

Universal composition of soft particles?

K^-/π^- ratios converge for $p_T \to 0$

in e^+e^-, pp and in peripheral and central AA collisions



very soft particles emitted as from quarks

stay behind expanding plasma and decouple from thermalisation

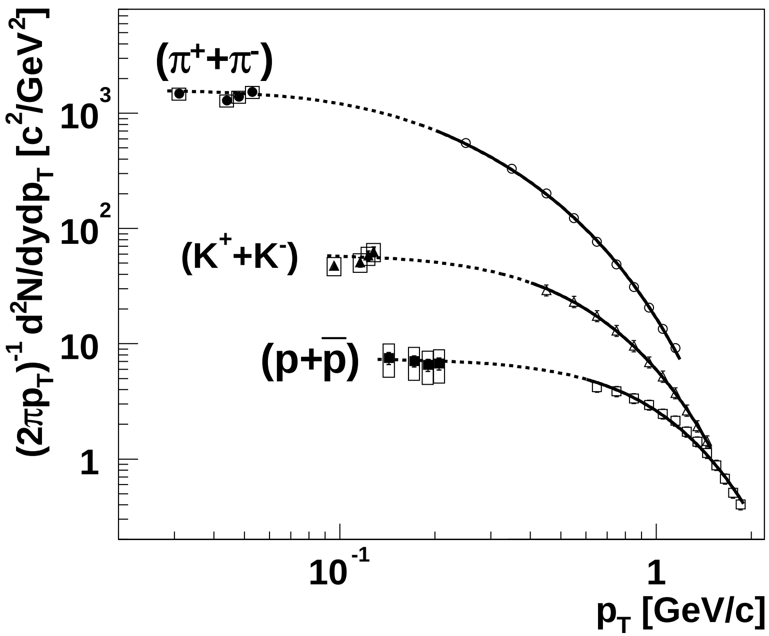
Summary on limiting soft particle emission

- Universal features of particle production for $p, p_T \to 0$
  (dominance of QCD gluon bremsstrahlung)
  a) energy independence of I_0
  b) intensity I_0 determined by color factors
  - e^+e^- annihilation: I_0(gluon jet)/I_0(quark jet) = C_A/C_F
  - pp scattering: $I_0(pp)/I_0(e^+e^-) = C_A/C_F$
  - AA scattering: $I_0(AA)/I_0(pp) = (N_{part}/2)C_A/C_A$
- all particle ratios vs. p_T converge to those from quark jets
  Soft hadrons decouple from equilibration
- LHC:
  New incoherent sources: $I_0(pp)$ rising with energy?

Back up

Extrapolated I_0 in AA collisions

π spectra at very low $p_T \gtrsim 30$ MeV measured by PHOBOS ’04
common fit with data from PHENIX ’04 at $p_T \gtrsim 300$ MeV

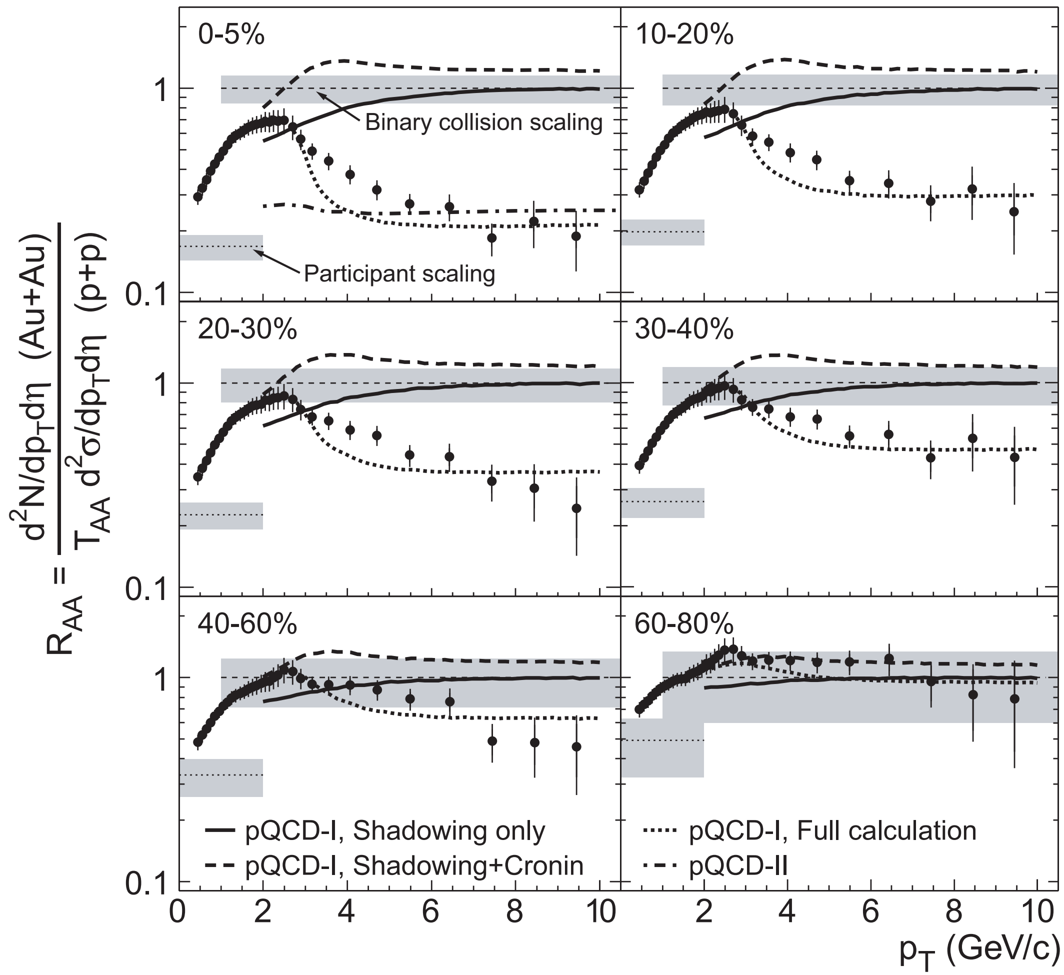


“thermal fit” to spectrum in central $AuAu$ collisions

$$E\frac{dN}{d^3p} = \frac{A}{(\exp(m_T/T) - 1)}; \quad m_T = \sqrt{m^2 + p_T^2}$$

with T=0.229 GeV

Normalisation as measured by STAR '2003 for $\sqrt{s} = 200$ GeV



smooth extrapolation from $p_T > 0.4$ GeV to $R_{AA} = N_{part}/2$ for $p_T \rightarrow 0$