Limiting soft particle production and QCD

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Multi-hadron production at high energies

a) initiated by hard sub-processes (pQCD, EW,...)
at short distances
emerging quarks and gluons (partons)
initiate parton cascade (perturbative QCD)

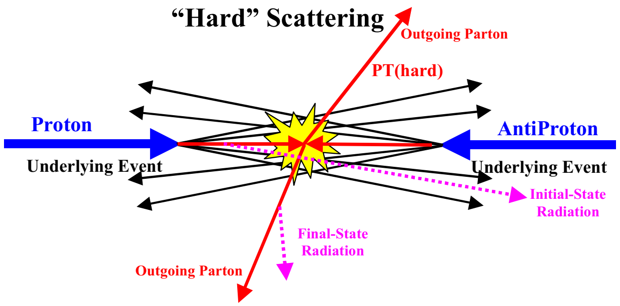
b) formation of mesons $(q\bar{q})$ and baryons (qqq)
at large distances
(non-perturbative mechanism)

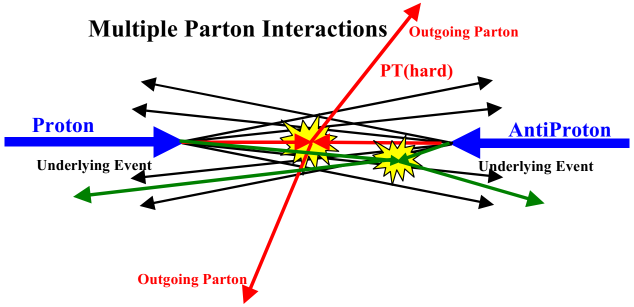
- e^+e^- annihilation: $e^+e^- \to q\bar{q}$;

  development of q and $\bar{q}$ quark gluon cascade
  transition of partons to hadrons: hadronic jets

- pp collisions: $p \to q(qq), \ \to q, g, (qq), \ldots$

  hard subprocesses: $qq \to qq, \ \ gg \to q\bar{q}, \ldots$
  formation of sidewise jets from scattered q, g
  spectator jets from beam remnants;





R.D. Field

multiple interactions at TeV energies
soft particles form “underlying event”

untriggered events: “minimum bias events”
small angle parton parton scattering

- AA collisions: $A \rightarrow$ nucleons, nucleons $\rightarrow q, g$

  hard parton parton interactions as in pp collisions

  in addition:

  - parton rescattering in nuclei
  - multiple interactions:
    large number of nucleons participating in the interaction
  - collective phenomena, flow effects, plasma formation

Limiting soft particle emission

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

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

because of Born term dominance:
universal features in the soft limit for all processes:

1. inclusive spectra become energy independent (near $y \sim 0$)
2. relative normalisation of spectra in different processes given by relevant colour factors

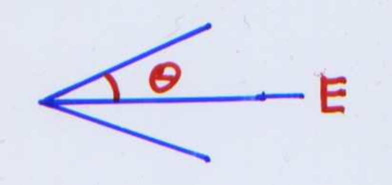
This holds for QCD partons, we assume the same is true for hadrons qualitative picture:

- coherent emission of soft gluons from parton cascade
- gluons of large wavelength do not resolve any detailed intrinsic jet structure
- 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

parton jet with energy E: particles inside opening angle Θ



$Q = E\Theta$ virtuality (max. p_T in jet)

global observables

mean multiplicity: $\bar{n} \ = \ \sum_n nP_n, \quad \bar{n} = \frac{\partial Z(Q,u)}{\partial u}|_{u=1}$

factorial moments: $f_q \ = \ \sum_n n(n-1)...(n-q+1)P_n, \quad f_q = \frac{\partial^n Z(Q,u)}{\partial u}|_{u=1}$

multiplicity generating function

$Z(Q,u) = \sum_{n=1}^{\infty} P_n(Q)u^n$

inclusive distributions:

$D(x) \equiv \frac{dn}{dx}$ (No of particles in interval $(x, x+dx)$)

generating functional and probing function $u(k)$:

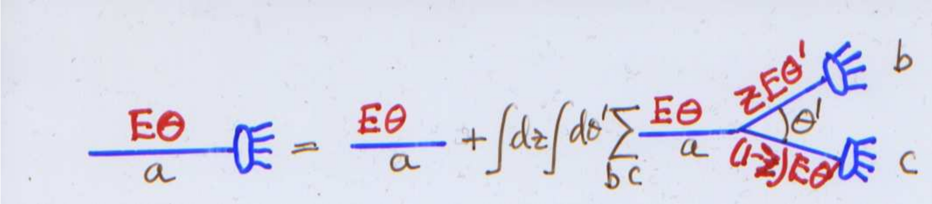
$Z(\{u\}) = \sum \int d^3k_1 \ldots d^3k_n P_n(k_1 \ldots k_n)u(k_1) \ldots u(k_n)$

inclusive distribution: $D^{(1)}(k_1) = \frac{\delta Z(\{u\})}{\delta(u(k_1))}|_{u=1}$

inclusive correlations: $D^{(n)}(k_1 \ldots k_n) = \frac{\delta^n Z(\{u\})}{\delta(u(k_1)...\delta(u(ki_n))}|_{u=1}$

Analytical perturbative QCD predictions

integral evolution equation for generating function in scale $E\Theta$



Bassetto et al., '83

Dokshitzer et al.,'84

differential evolution equation in QCD: splitting of partons $a \to b, c$

$$\frac{d}{dY} Z_a(Y,u) = \sum_{b,c} \int_{z_c}^{1-z_c} dz \frac{\alpha_s(\tilde{k}_T)}{2\pi} P_{bc}(z) \times$$

$$\{Z_b(Y+\ln z, u) Z_c(Y+\ln(1-z), u) - Z_a(Y,u)\}$$

$$Z(0,u) = u$$ initial condition: one parton at threshold

- evolution variable $Y = \ln \frac{E\Theta}{Q_0}$
- non perturbative cut-off $k_T \geq Q_0$
- running coupling $\alpha_s(\tilde{k}_T)$, $\tilde{k}_T = \min(z, 1-z) E\Theta$, 1-loop
- angular ordering: in decays $1 \to 23, 2 \to 45$ keep $\Theta_{45} < \Theta_{23}$

high energy approximations

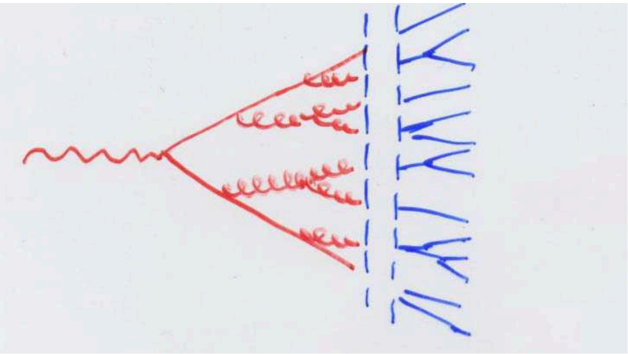
- Double logarithmic approximation (DLA):
  $P_{gg}(z) \sim \frac{1}{z}$ for gluon emission
- Modified leading logarithmic approximation (MLLA):
  include next to leading (single $\log$) terms

full solution

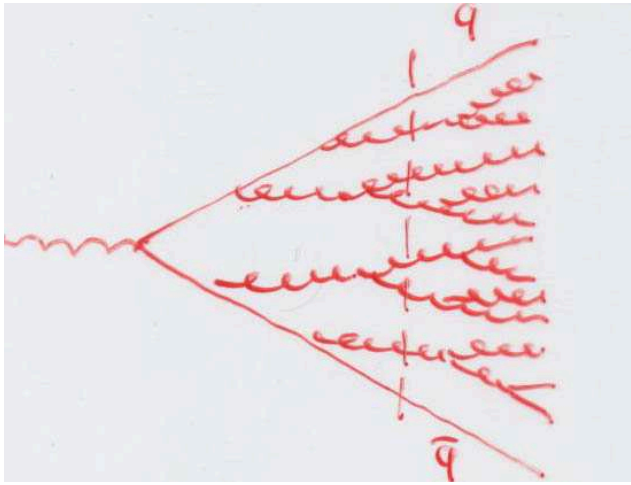
- numerical solution of evolution eqn.
  (Complete up to MLLA)
- Monte Carlo generation of parton cascade
  ARIADNE-D, fitted parameters $\Lambda,\ Q_0$

Hadronization: parton hadron duality

Hadronization model



Parton Hadron Duality



parameter Λ

$Q_0 \sim 1 - 2$ GeV

hadrons, resonances

parameter Λ,

$k_T \geq Q_0 > \Lambda$ (few 100 MeV)

hadrons $\sim$ partons

Duality: QCD cascade evolves towards lower scale
results directly compared to hadron final state

Motivation and early history

- "Preconfinement"

  perturbative preparation of colour singlet $q\bar{q}$ systems

  $\rightarrow$ hadron clusters with mass near cut-off $Q_0 \gtrsim 1$ GeV

  Amati, Veneziano (1979)

- "Local Parton Hadron Duality (LPHD)"

  Simple ansatz for hadronization

  inclusive spectra $D(\xi)|_{\text{hadron}} = K \times D(\xi)|_{\text{parton}}$

  for $\xi = \ln(1/x)$ at cut-off scale $Q_0 \sim \Lambda$

  Azimov, Dokshitzer, Khoze, Troyan (1985)

Analytical and numerical results for many jet observables

particles and subjets of variable resolution

generally a successful approach

Example: Particle Multiplicities in quark and gluon jets

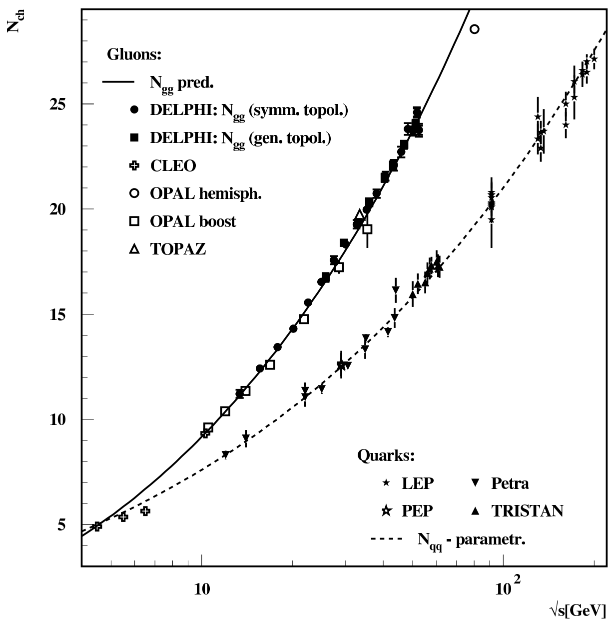
- Leading order (DLA)

$$\bar{N} \sim \exp(c\sqrt{Y}), \quad Y = \ln \frac{E_{jet}\Theta}{\Lambda}$$

- Next to leading order (MLLA)

$$\bar{N} \sim \exp(c1/\sqrt{\alpha_s(Y)} + c2 \ln \alpha_s(Y) + \ldots)$$

$$c_1 = \frac{\sqrt{96\pi}}{b}, \qquad c_2 = \frac{1}{4} + \frac{10N_f}{27b} \qquad b = \frac{11}{3}N_C - \frac{2}{3}N_f$$



DELPHI collaboration (2005):
quark and gluon jets

Furmanski, Petronzio, Pokorski ’79;
Ermolaev, Fadin ’81; Mueller ’81;
Dokshitzer, Fadin, Khoze;
Bassetto, Marchesini, Ciafaloni ’82

Difference between quark and gluon jets

mean multiplicity in quark jets N_q and gluon jets N_g

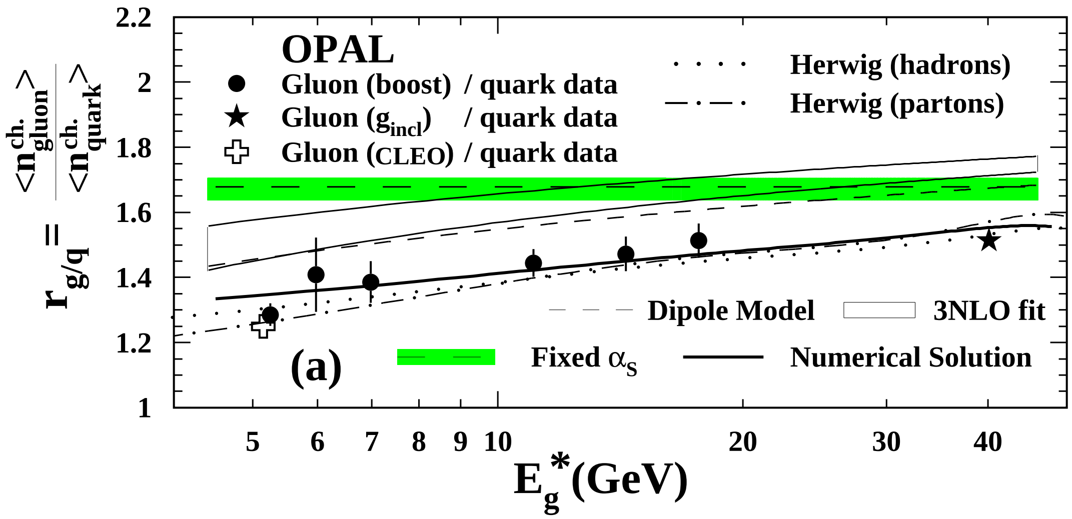
$$r(Y) = \frac{N_g}{N_q} = \frac{C_A}{C_F}(1 - r_1\gamma_0(Y) - r_2\gamma_0^2(Y)) + O(\gamma_0^3), \quad Y = \ln Q/Q_0$$

$$\gamma_0 = \left(\frac{2C_A\alpha_S}{\pi}\right)^{1/2}, \quad \text{Colour factors: } C_A = 3,\ C_F = 4/3$$

$$r_1 = 2\left[h_1 + \frac{n_f}{12N_c}\left(1 - \frac{2C_F}{N_c}\right)\right] - \frac{3}{4}$$

$$r_2 = \frac{r_1}{6}\left(\frac{25}{8} - \frac{3}{4}\cdot\frac{n_f}{N_c} - \frac{C_F}{N_c}\cdot\frac{n_f}{N_c}\right) + \frac{7}{8} - h_2 - \frac{C_F}{N_c}\cdot h_3 + \frac{n_f}{12N_c}\cdot\frac{C_F}{N_c}h_4,$$

$$h_1 = \frac{11}{24},\ h_2 = \frac{67-6\pi^2}{36},\ h_3 = \frac{4\pi^2-15}{24},\ h_4 = \frac{13}{3}.$$



MLLA: $r_{g/q} = \frac{C_A}{C_F} = \frac{9}{4} = 2.25$

OPAL coll. ’04

Gaffney, Mueller ’85;

Dremin et al. ’00

Lupia, Ochs ’98 (Num. Sol.)

Inclusive energy spectrum and soft limit

variables $\xi = \ln(1/x) = \ln(E_{jet}/E)$, particle energy E

fixed jet energy E_{jet} and jet opening Θ, $Y = \ln(\frac{E_{jet}\Theta}{Q_0})$, k_T cut-off Q_0

DLA evolution equation for energy spectrum of parton p:

$$D_p^g(\xi, Y) = \delta_p^g \delta(\xi) + \int_0^\xi d\xi' \int_0^{Y-\xi} dy \frac{C_p}{N_C} \gamma_0^2(y) D_g^g(\xi', y); \quad \gamma_0^2 = \frac{2N_C\alpha_s}{\pi}$$

only most singular terms kept in $g \to gg,\ q \to qg$

For large particle energies $x = E/E_{jet}$ like DGLAP eqn.

fixed α_s: solve by iteration:

$$\begin{aligned} D_p^g(\xi, Y) &= \delta_p^g \delta(\xi) + \frac{C_p}{N_C}\gamma_0^2 (Y-\xi) + \frac{1}{2}\frac{C_p}{N_C}\gamma_0^4 \xi (Y-\xi)^2 + \ldots \\ &= \delta_p^g \delta(\xi) + \frac{C_p}{N_C}\gamma_0 \sqrt{\frac{Y-\xi}{\xi}}\, I_1(2\gamma_0\sqrt{\xi(Y-\xi)}) \end{aligned}$$

coherent emission of soft gluons lead to depletion at small x:

”hump-backed platau”

double differential: $\frac{dN_p}{d\xi dY} = \frac{C_p}{N_C}\gamma_0^2 + \ldots, \qquad \frac{dN_p}{dE d\Theta} = \frac{2C_p}{\pi}\frac{\alpha_s}{E\Theta} + \ldots$

Born term for soft gluon bremsstrahlung:

independent of jet energy, proportional to colour factors $p = F, A$

DLA with running coupling:

first iterations $\gamma_0^2 = \frac{\beta^2}{\ln(k_T/\Lambda)}$, $\beta^2 = \frac{12 N_C}{11 N_C - 2 n_f}$

$$D_p^g(\xi, Y) =$$
$$\delta_p^g \delta(\xi) + \frac{C_p}{N_C}\beta^2 \log\left(1 + \frac{Y-\xi}{\lambda}\right)\left[1 + \frac{\beta^2 \int_0^{Y-\xi} d\tau \log(1+\frac{\tau}{\lambda}) \log(1+\frac{\xi}{\tau+\lambda})}{\log(1+\frac{Y-\xi}{\lambda})}\right] + \dots$$

MLLA:

$$D(\xi, Y) = D(\xi, Y)|_{DLA} \exp\left[-a \int_\xi^Y \gamma_0^2(y)/(4N_C)dy\right]$$

Hadronization:

kinematics at soft limit:

partons: $k_T \geq Q_0$, hadrons: $k_T \geq 0$

compare both at the same energy

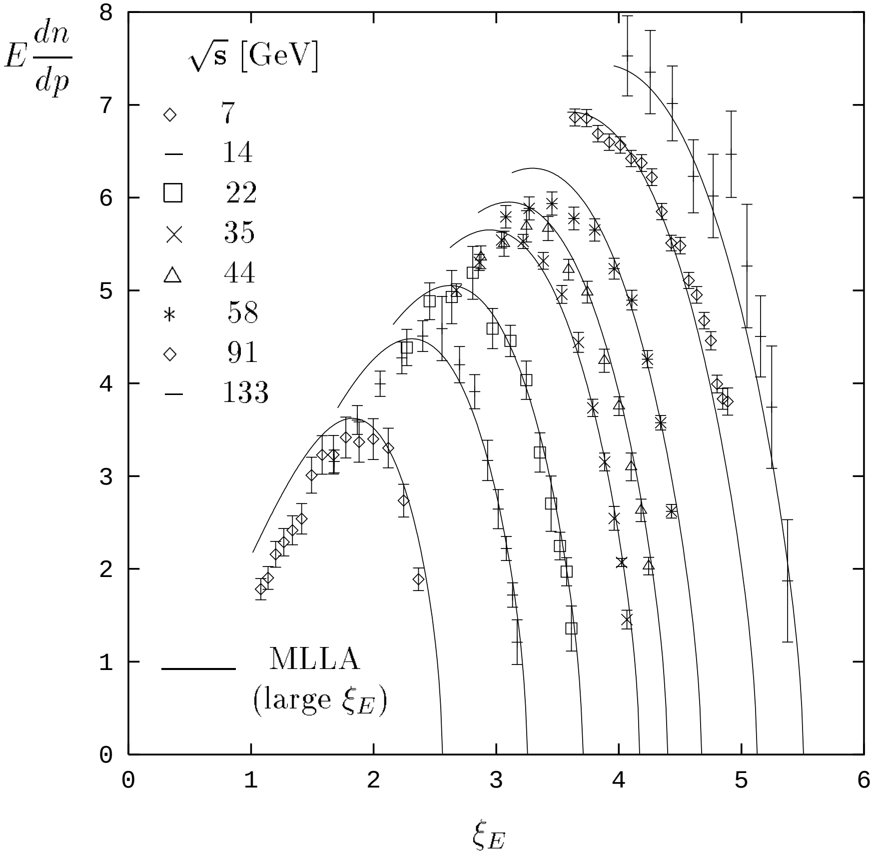
$$E_{hadron} = \sqrt{p_h^2 + Q_0^2} \; = \; E_{parton} \equiv E$$

and

$$E_{hadron}\frac{dn(\xi_E)}{dp_{hadron}} = K_h E_{parton}\frac{dn(\xi_E)}{dp_{parton}}$$

then $E\frac{dn}{d^3p} \to const$ for $p_{hadron} \to 0$.

$D(\xi) \rightarrow E\frac{dn}{dp}$ near $E \rightarrow E_{jet}$

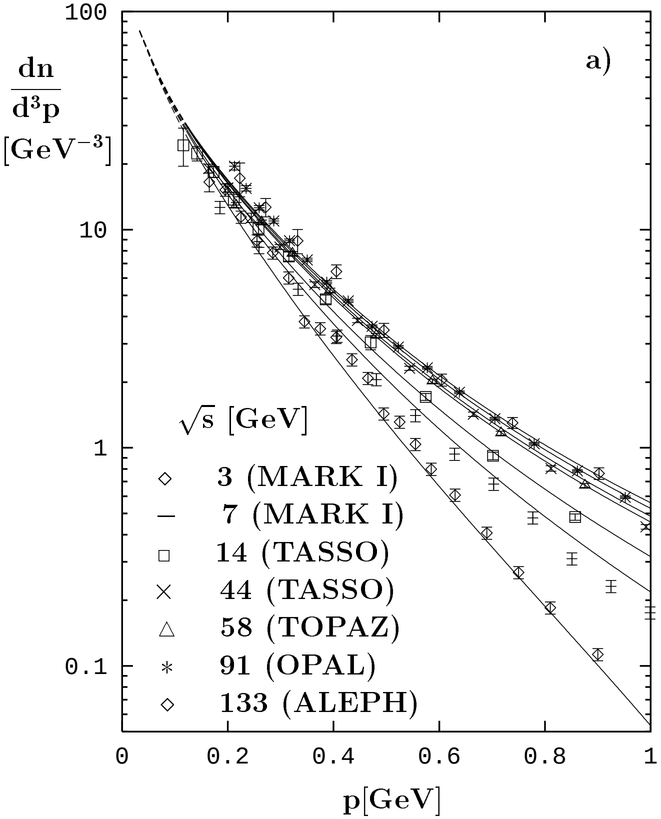


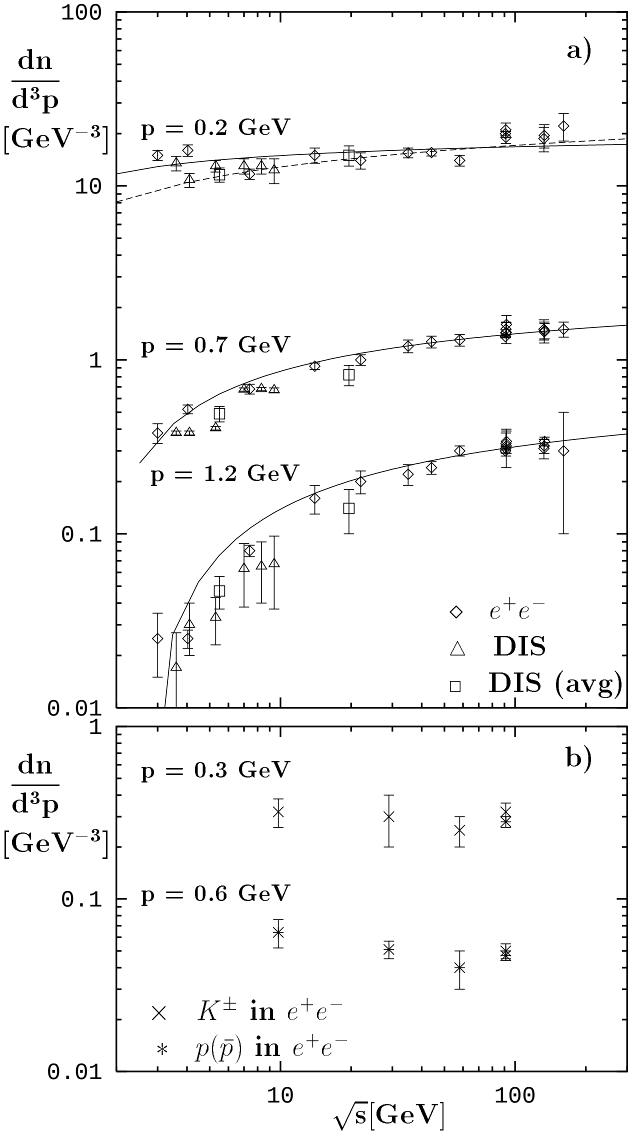
$$\xi_E = \ln(E_{jet}/E)$$

“hump backed plateau”

Inclusive spectra $\frac{dn}{d^3p}$ vs cms energy $\sqrt{s}$

charged particles





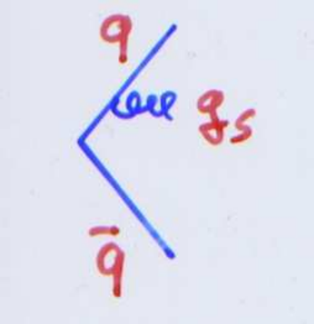
kaons

protons

Colour factors in quark and gluon jets

soft gluon bremsstrahlung from “colour dipole antenna” ($q\bar{q}$ or gg)

Born term (massless quarks)

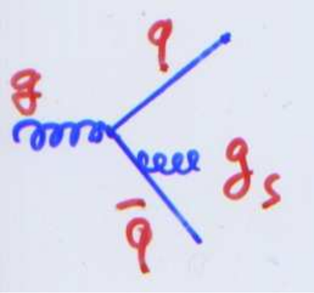


$$\frac{dN_{A,F}}{d\Omega dE} = \frac{\alpha_s}{(2\pi)^2}\frac{1}{E}W_{A,F}(\vec{n}_g), \quad W_{A,F}(\vec{n}_g) = 2C_{A,F}(\widehat{i,j})$$

$$(\widehat{i,j}) = \frac{1-\cos\Theta_{ij}}{(1-\cos\Theta_{is})(1-\cos\Theta_{js})}$$ antenna function

aligned $q\bar{q}$ antenna: $W_F = 4C_F/\sin^2\Theta_{qs}$

soft gluons from $e^+e^- \to q\bar{q}g$



$$W_{q\bar{q}g}(\vec{n}_g) = C_A\left[(\widehat{q,g}) + (\widehat{\bar{q},g}) - \frac{1}{N_C^2}(\widehat{q,\bar{q}})\right]$$

limits: $q\|g$ like $q\bar{q}$ dipole $W = 4C_F/\sin^2\Theta_{qs}$

$q\|\bar{q}$ like $g\bar{g}$ dipole $W = 4C_A/\sin^2\Theta_{gs}$

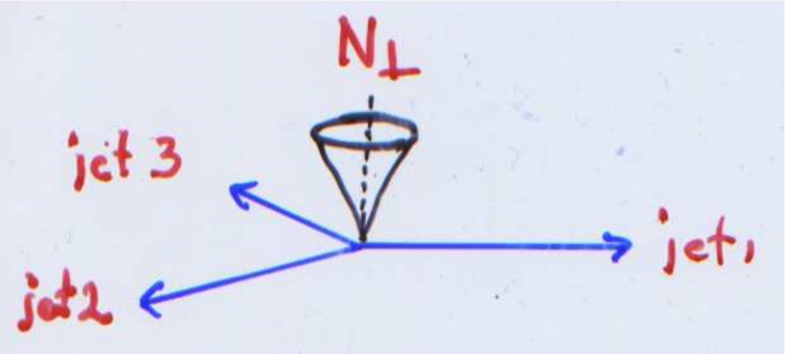
these extreme limits are not accessible experimentally, but ...

Color factors from 3 jet events

study soft radiation perpendicular to event plane $(\cos\Theta_{is}=0)$

measure multiplicity of particles $N_\perp$ in sidewise cone

(p_T distribution independent of angles Θ_{ij} for $p_T<1$ GeV



$$\frac{N_\perp^{q\bar{q}g}}{N_\perp^{q\bar{q}}} = \frac{W_\perp^{q\bar{q}g}}{W_\perp^{q\bar{q}}} \equiv \frac{C_A}{C_F}\, r$$

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

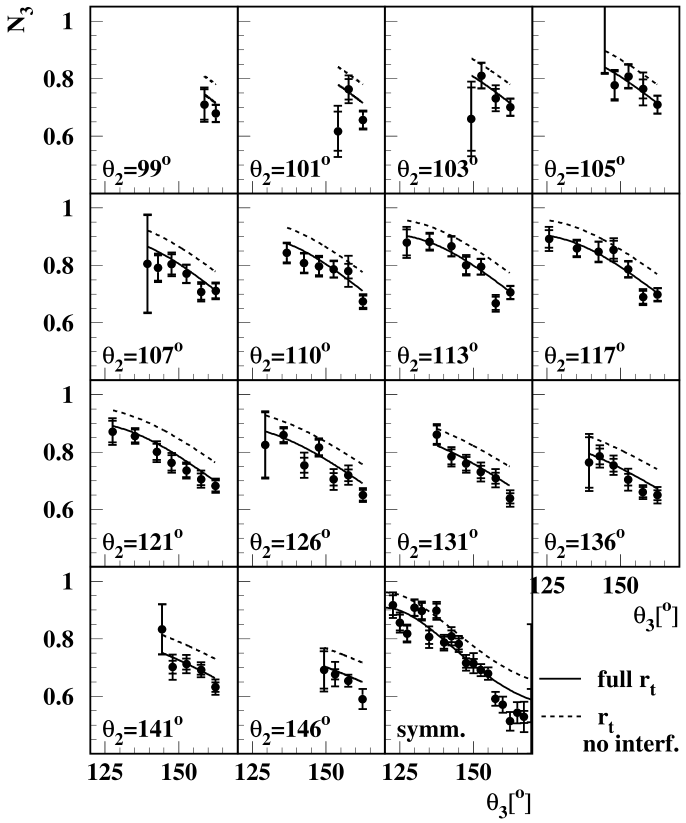
(normalised by 2 jet rate $W_\perp^{q\bar{q}} = 4C_F$)

only 2 angles are independent

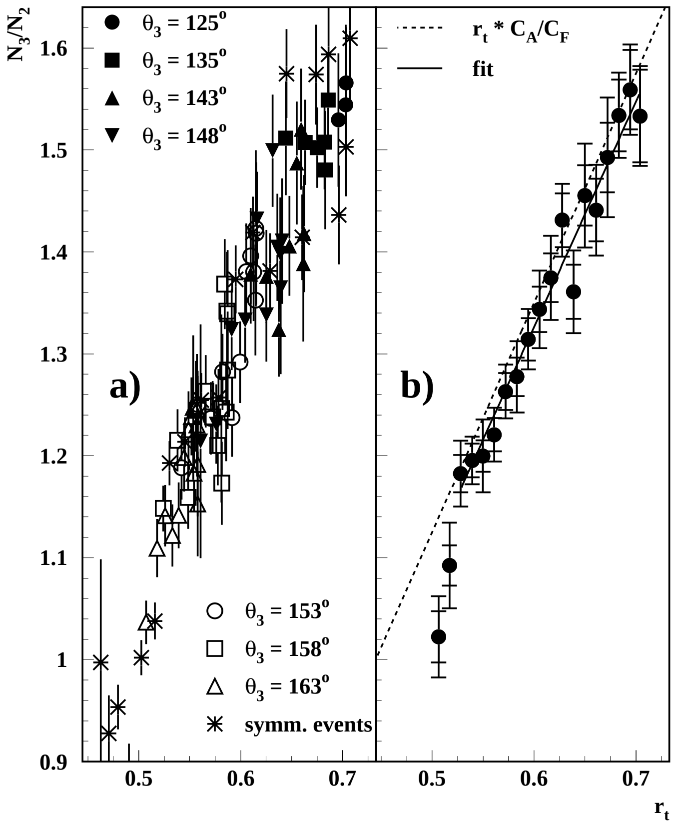
Khoze, Lupia, W.O. '97

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

$N_\perp^{q\bar{q}g}$ vs. Θ_2, Θ_3



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



DELPHI

2005

dashed line: no $1/N^2$ term

full line: QCD

dashed: QCD prediction

full: slope = $C_A/C_F = 2.211 \pm 0.053$

Summary on soft particles in e^+e^- annihilation

soft particle density follows the soft gluon QCD Born terms

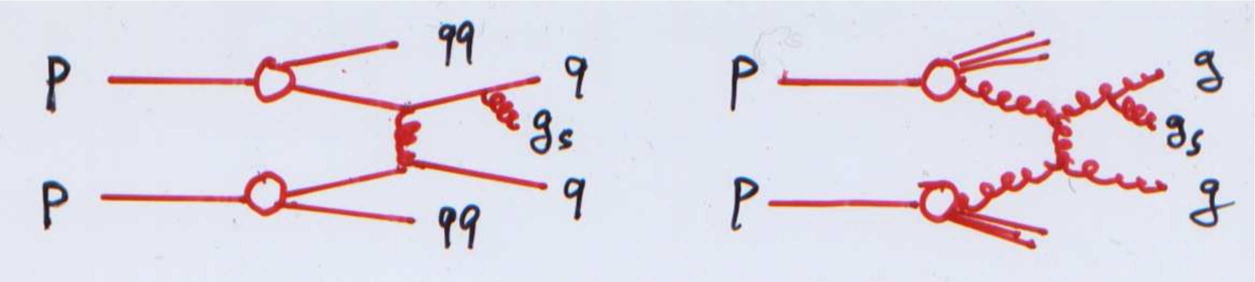
- $E\frac{dn}{d^3p}$ becomes energy independent for $p \to 0$
- soft particle density varies with orientation of colour antenn as predicted
  density in quark and gluon jets proportional to colour factors C_F, C_A
- this limiting behaviour is in contrast to the behaviour of global observables

$pp/p\bar{p}$ scattering

W.O., V.A. Khoze, M.G. Ryskin, EPJC 2010

pp "minimum bias" events

minimal partonic process $2 \rightarrow 2 + g_s$ at small angles (semi-hard process):
soft bremsstrahlung from gluon exchange processes
(asymptotically non-vanishing cross sections Low, Nussinov '75)



soft bremsstrahlung in $qq \rightarrow qqg_s, \quad qg \rightarrow qgg_s, \ldots$
$qq \rightarrow qq$: gluon exchange leads to radiating colour octet dipole,
corresponding to initial and final bremsstrahlung from 2 qq triplet dipoles

more complex processes with the same radiation pattern:
multiple gluon exchanges in qq, ladder diagrams, diquarks in $pp \rightarrow 8 + 8$

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

see also Brodsky, Gunion '76

multiple interactions: $4 \to 4 + g_s, \ldots$

in present calculations added incoherently.

leads to rising cross sections and rising soft densities:

example Pythia:

I_0^{pp} rises by factor 2 or more for $\sqrt{s} = 23$ to 14000 GeV ($p_T < 0.5$ GeV)

physics in e^+e^- and pp very different otherwise

(for example: leading protons in pp collisions)

Energy dependence of the limiting soft spectrum

pp data: Extrapolation to $p_T = 0$:

$E\frac{d\sigma}{d^3p} = A\exp(Bp_T + Cp_T^2 + Dy^2)$ or

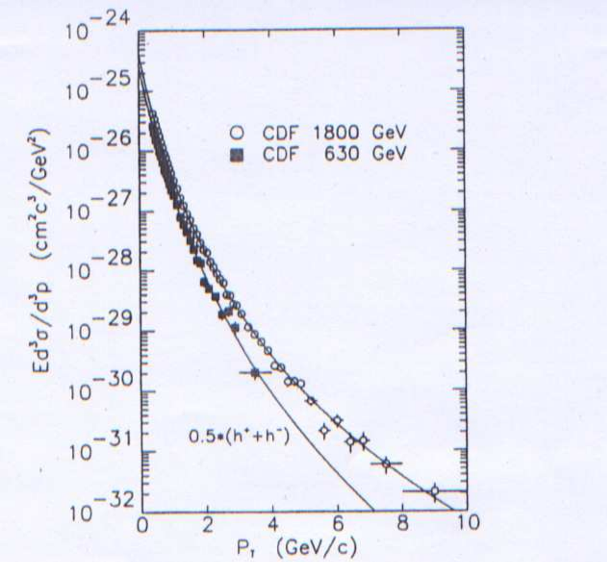
$E\frac{d\sigma}{d^3p} = A(1 + p_T/p_0)^{-n}$

Exp	$\sqrt{s}$ [GeV]	$p_{T,min}$ [GeV]	A [mb/GeV^2]	σ_{tot} [mb]	σ_{el} [mb]	σ_{in} [mb]	$I_0 = A/\sigma_{in}$ [GeV$^{-2)}$]
BS	23	0.1	191 ± 7	39.4	6.8	32.6 ± 0.5	5.9 ± 0.3
BS	45	0.3	238 ± 7	41.9	7.5	34.4 ± 0.7	6.9 ± 0.3
BS	63	0.1	307 ± 20	43.0	7.8	35.2 ± 0.6	8.7 ± 0.7
STAR	200	0.2					7.5 ± 0.8
UA1	200	0.25	286 ± 17	52	9.2	43 ± 4	6.6 ± 0.7
UA1	500	0.25	408 ± 24	62	13	49 ± 2	8.3 ± 0.6
CDF	630	0.4	300 ± 20	63	13	50 ± 2	6.0 ± 0.5
UA1	900	0.25	382 ± 20	68	15	53 ± 4	7.2 ± 0.7
CDF	1800	0.4	450 ± 10	74	17	57 ± 3	7.9 ± 0.5

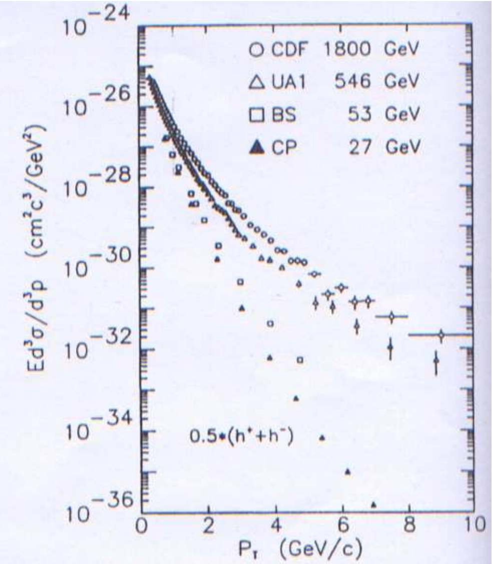
AA data: $E\frac{d\sigma}{d^3p} = \frac{A}{(\exp(m_T/T) - 1)}$; $m_T = \sqrt{m^2 + p_T^2}$ (fits for $p_T \gtrsim 30$ MeV PHOBOS)

spectra of $E\frac{dN}{d^3p}$ in pp collisions

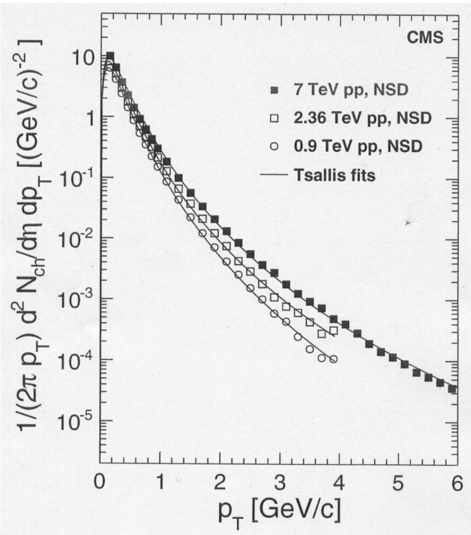
630 - 1800 GeV



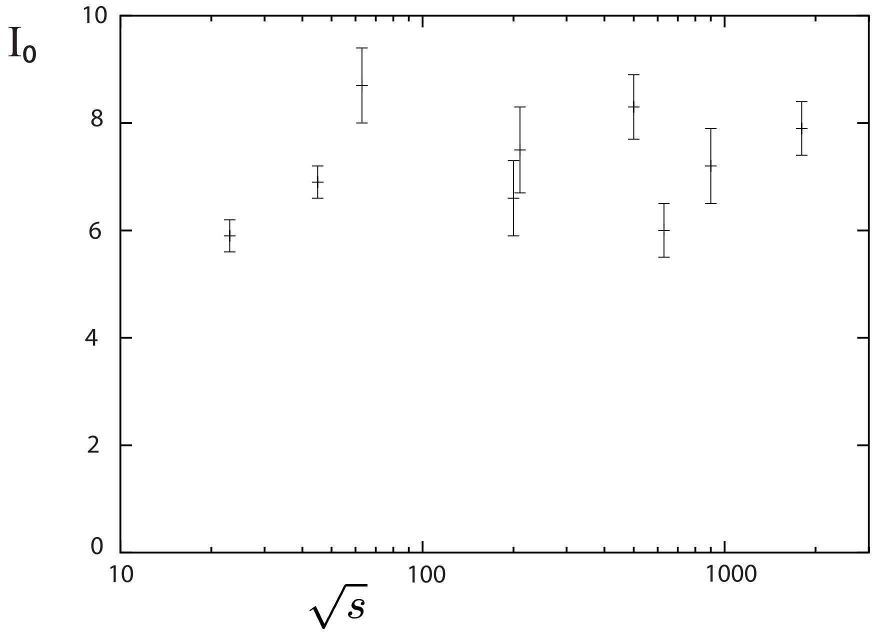
27 - 1800 GeV



900 - 7000 GeV



Soft limit of $E\frac{dN}{d^3p}$ from exponential extrapolation



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

to compare with e^+e^- annihilation:

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

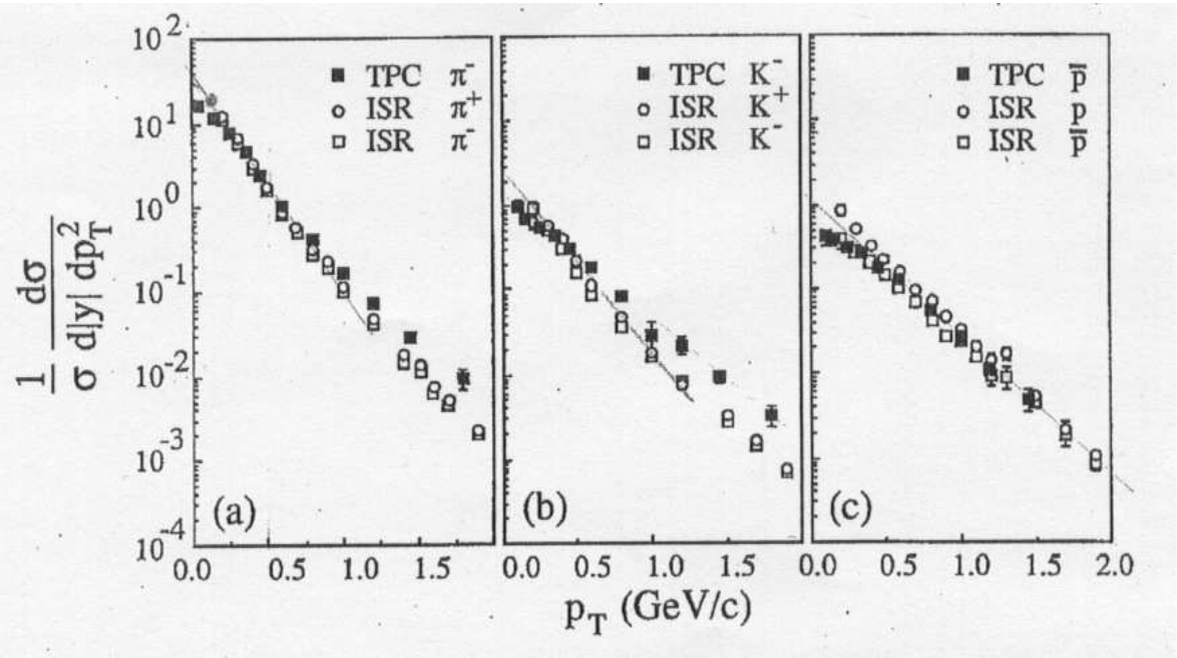
non-diffractive $pp/p\bar{p}$ collisions (therm. fit): $I_0 \approx (6 \pm 1)$ GeV^{-2} (-25%)

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

$\Rightarrow$ consistent with expectations from soft gluon bremsstrahlung

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:
one experiment: TPC at SLAC, Aihara et al., 1987
in comparison with 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.

$r \approx 2.0$ for thermal fit.

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

2. fits to the energy spectra in e^+e^- annihilations

$$\frac{E}{4\pi p^2}\frac{d\sigma}{dp} = \sum_m A_m \exp(-B_m E)$$

Exp	$\sqrt{s}$ [GeV]	p_{min} [GeV]	A_1 [nb/GeV^2]	B_1 [GeV^{-1}]	σ_{tot} [nb]	I_0 [GeV$^{-2)}$]
ARGUS	10	$p > 0.05$				3.0 ± 0.5
TASSO	14	$p > 0.3$	23.9 ± 3.9	5.25 ± 0.43	1.77	3.5 ± 0.6
TASSO	22	$p > 0.3$	8.0 ± 1.2	4.70 ± 0.32	0.72	3.4 ± 0.5
TASSO	34	$p > 0.3$	3.7 ± 0.6	4.97 ± 0.45	0.30	3.4 ± 0.5
TPC/2γ	29	$p_T \sim 0.05$				3.0 ± 0.3

e^+e^- annihilations: $I_0^{e^+e^-} \approx (3.3 \pm 0.5)$ GeV^{-2}

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

thermal exponential extrapolation of pp data.

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

AA scattering

Spectra at low p_T in AA collisions

expect for the particle production in nuclear AB collision naively:

pointlike interactions, like high p_T production

$$\frac{dN_{AB}}{dp_T} = N_{coll}\frac{dN_{pp}}{dp_T} \quad \text{define} \quad R_{AB}^{N_{coll}} = \frac{1}{N_{coll}}\frac{dN_{AB}/dp_T}{dN_{pp}/dp_T}$$ nuclear modification factor

N_{coll} is the number of nucleon nucleon collisions

(can be calculated in the nuclear theory by Glauber).

but: energy loss in medium

Soft particle production:

particles with large wavelength $1/p_T \gtrsim r$ are coherently emitted

from range r: nucleon $R_N \sim 1/m_\pi$ or nucleus $R_A \sim 1/30$ MeV

$\Rightarrow$ expect reduced rate

bulk particle production depends on No of participating nucleons N_{part}

or “wounded nucleons” Bialas, Bleszynski and Czyz ’76

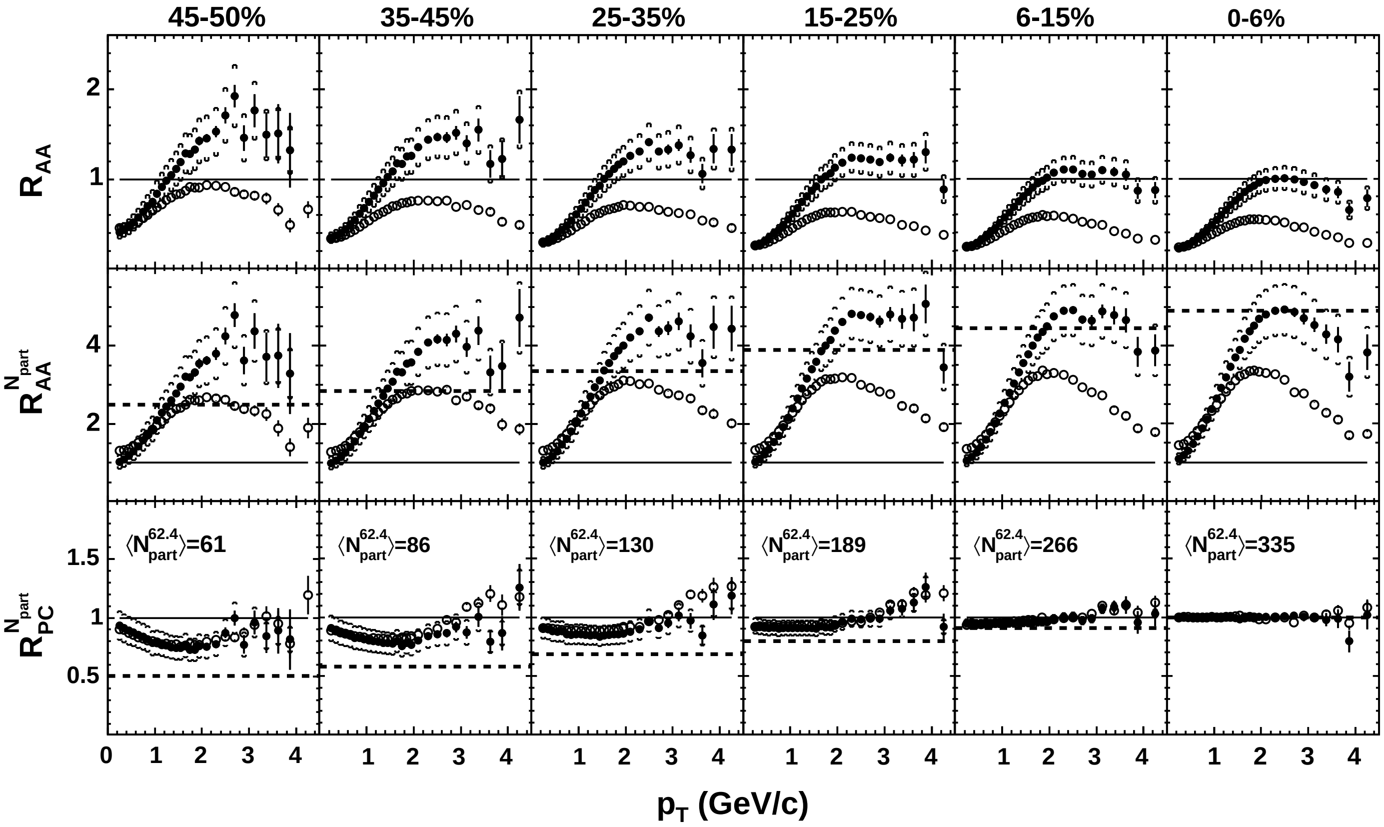
$$\frac{dN_{AB}}{dp_T} = \frac{N_{part}}{2}\frac{dN_{pp}}{dp_T} \quad \text{define} \quad R_{AB}^{N_{part}} = \frac{2}{N_{part}}\frac{dN_{AB}/dp_T}{dN_{pp}dp_T}$$ don’t count rescatterings

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 collaboration ’05



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

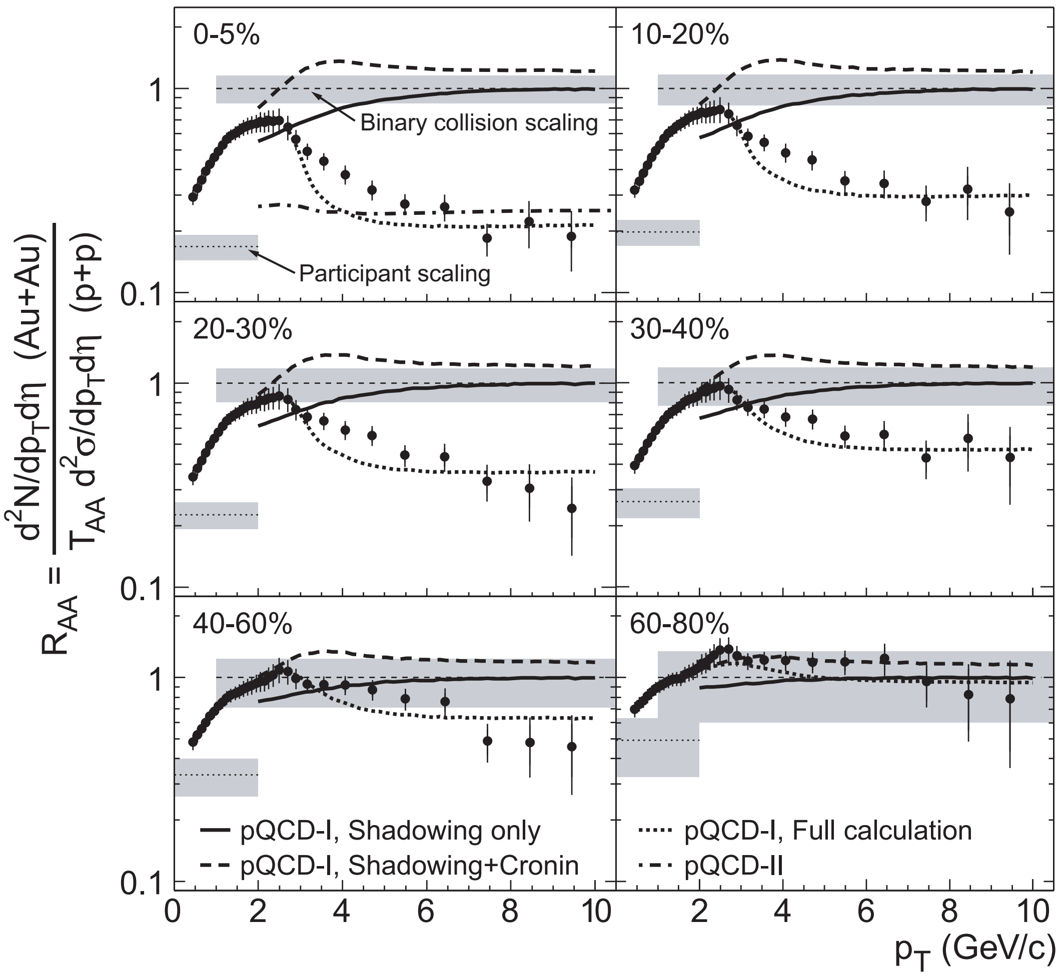
$R_{AA}^{N_{part}}$

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

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

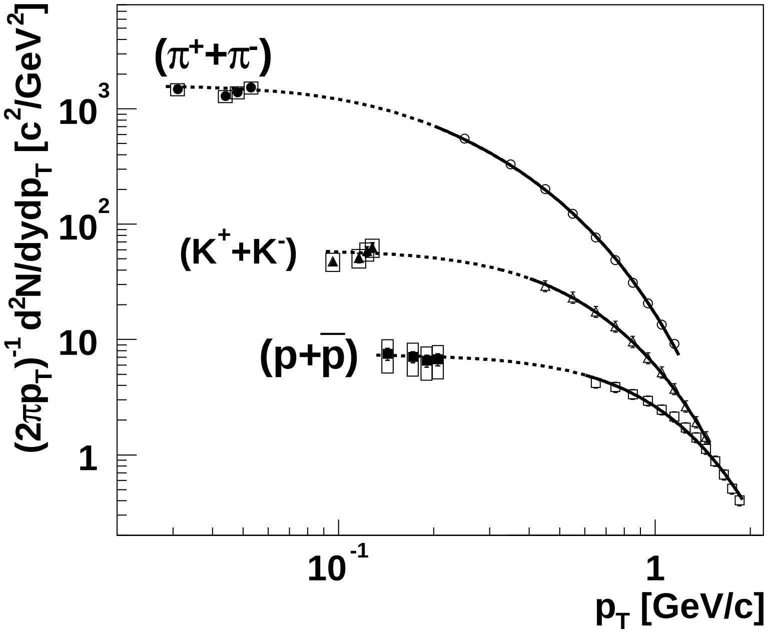
$\Rightarrow$ 2. Normalization for $p_T \to 0$: $R_{AA}^{N_{part}} \to 1$

Normalisation as measured by STAR ’2003



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

Thermal extrapolation of spectra to $p_T = 0$:

pp collisions	$I_0 \simeq 5.9$ GeV^{-2}	T=0.182 GeV	STAR
$AuAu$ central	$I_0 \simeq (950 \pm 100)$ GeV^{-2}	T=0.229 GeV	PHOBOS, STAR

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

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

conclude:

$p_T \to 0:$ $R_{AA}^{N_{part}} \to 1$ and $I_0^{AuAu} \approx \frac{N_{part}}{2}\, I_0^{pp}$

Antenna pattern in nuclear collisions

coherent particle production over nucleon size r_p

(not nuclear size r_A, no structure at $p_T \sim 1/r_A \sim 30$ MeV)

Minimal model for soft particles in nuclear collisions:

exchanged gluons couple to quarks/ diquarks,

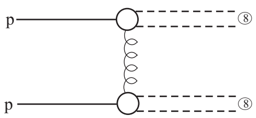
each nucleon after repeated rescatterings produces colour octet state.

soft gluons coherently produced from external colour charges,

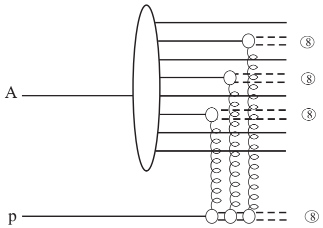
$N_{coll} = 1$

$N_{part}/2 = 1$

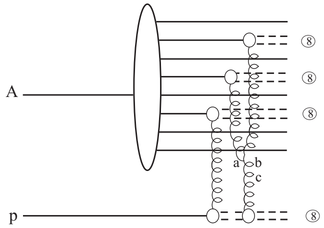
(a)



(b)



(c)



$N_{coll} = 3$

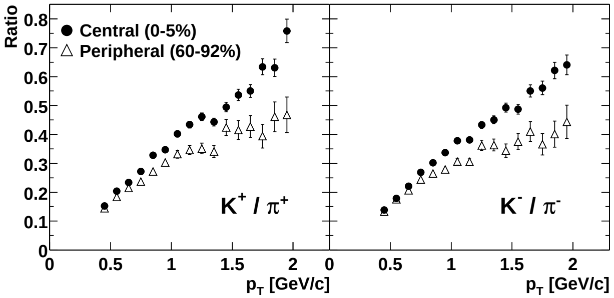
$N_{part}/2 = 2$

This mechanism results in “participant scaling”

Universal composition of soft particles?

for soft qq scattering

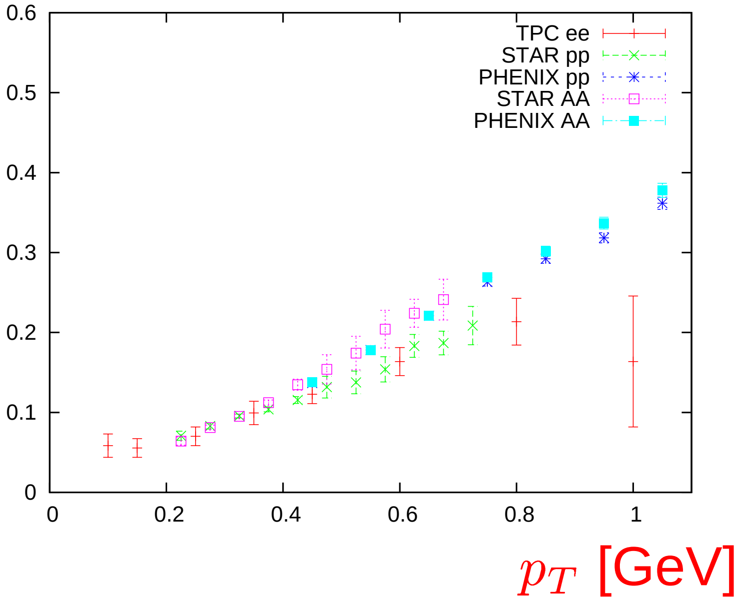
particle ratios reflect quark fragmentation:



K^-/π^- ratios

central > peripheral

Phenix



K^-/π^- ratios

converge

for $p_T \to 0$

in e^+e^-, pp and AA

collisions

very soft particles stay behind expanding plasma, $\Rightarrow$ decouple from thermalisation

Summary

- Universal features of particle production for $p \to 0$
  based on QCD gluon bremsstrahlung
  a) energy independendence
  b) intensity I_0 determined by color factors
  (no universal thermalisation)
  - 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: $I_0(AA)/I_0(pp) = (N_{part}/2)\ C_A$
- particle ratios tend to converge to those from $q\bar{q}$ dipoles
  Soft hadrons in central region produced first,
  they do not participate in equilibration
- LHC:
  New incoherent sources: $I_0(pp)$ rising with energy?