Direct photons and thermal dileptons

QM 2001
Quark Matter 2001

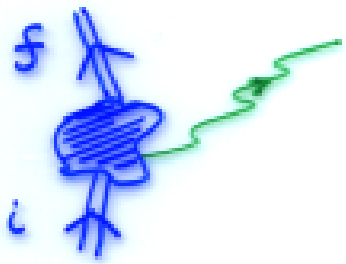
SUNY @ Stony Brook, NY
Jan. 15-20, 2001

Charles Gale
McGill University

Outline

- PHOTONS & DILEPTONS : THE INFORMATION WE CAN ACCESS.
- THE EXPERIMENTAL PROGRAM : RESULTS.
  - LOW-MASS DILEPTONS
  - REAL PHOTONS
  - INTERMEDIATE-MASS DILEPTONS
- THE FUTURE.

The information we can access



$$R_{fi} = \frac{|S_{fi}|^2}{\tau V}$$

$$S_{fi} = \langle f | \int d^4x \, \hat{J}_\mu(x) \, A^\mu(x) | i \rangle \qquad \text{(PHOTONS)}$$

$$S_{fi} = \langle f | \iint d^4x \, d^4y \, \hat{J}_\mu(x) \, D^{\mu\nu}(x-y) \, J_\nu^e(y) | i \rangle$$

(DILEPTONS)

IN A THERMAL ENSEMBLE:

$$dR \sim \sum_i e^{-\beta E_i} \langle f | \hat{J}_\mu | i \rangle \langle i | J_\nu | i \rangle$$

THERMAL AVG. OF CURRENT-CURRENT C.F.

$$\omega \frac{d^3R}{d^3k} = -\frac{g^{\mu\nu}}{(2\pi)^3} \boxed{\mathrm{Im}\, \Pi_{\mu\nu}(k)} \frac{1}{e^{\beta\omega}-1}$$

McLERRAN & TOINET 85
WELDON 83
C.G. & KAPUSTA 91

$$E_+E_- \frac{d^6R}{d^3P_+ \, d^3P_-} = \frac{2e^2}{(2\pi)^6} \frac{1}{k^4} \mathcal{L}^{\mu\nu} \boxed{\mathrm{Im}\, \Pi_{\mu\nu}} \cdot \frac{1}{e^{\beta\omega}-1}$$

Π = IN-MEDIUM γ SELF-ENERGY

A MODEL FOR THE HADRONIC ELECTROMAGNETIC CURRENT: VMD

$$J_\mu = \sum_{i=V} g_i \rho^V_\mu$$

SAKURAI 69

KROLL, LEE, ZUMINO 67

KLINGL et al. 96

$$\langle J_\mu J_\nu \rangle_T \overset{\text{VMD}}{\Longrightarrow} \langle \phi_\mu \phi_\nu \rangle_T$$

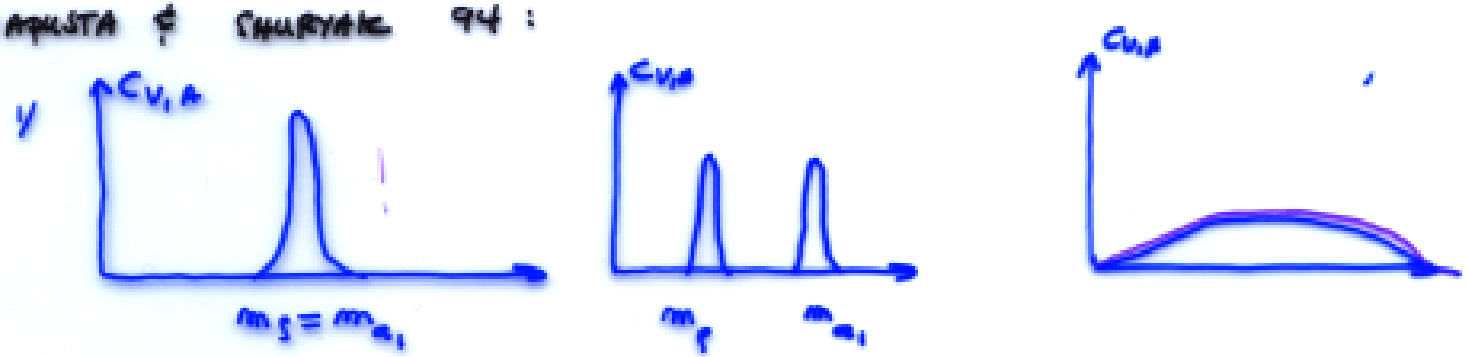
$$R \sim \operatorname{Im} D^T_{\mu\nu} \Rightarrow \text{SPECTRAL DENSITIES}$$

$\therefore$ γ/γ^* TELL US ABOUT <u>IN-MEDIUM</u> VECTOR MESONS.

<u>CHIRAL SYMMETRY</u>:

χ SYMMETRY RESTORATION: NO DIFF. BETWEEN C_V & C_A

KAPUSTA & SHURYAK 94:



DEY, ELETSKY & IOFFE, 1990

The experimental program

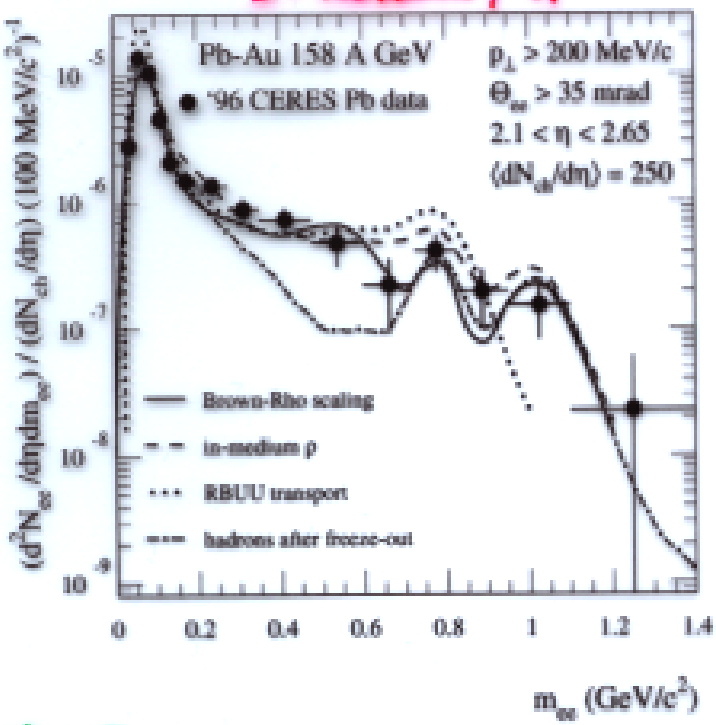
- Low Energy:
  - DLS
  - TAPS
  - HADES

- SpS:
  - HELIOS-1, -2, -3 ($\ell^+\ell^+, \gamma$)
  - CERES ($\ell^+\ell^-, \gamma$)
  - WA80, WA98 (γ)
  - NA38 ($\ell^+\ell^-$)
  - NA50 ($\ell^+\ell^-$)

- RHIC
  - PHENIX ($\gamma, \ell^+\ell^-$)
  - STAR

Dileptons: low mass

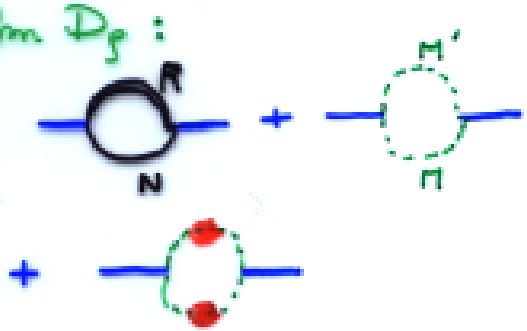
I. TSERRUYA, 99



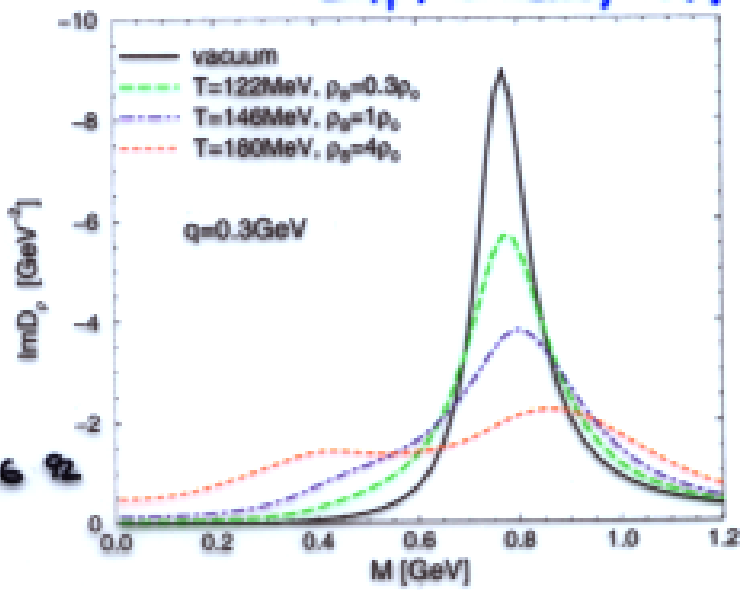
BR: BROWN, RHO, LI 1997

TRANSPORT: V. KOCH, 1999
CASSING & BRATKOVSKAYA 98

dim D_ρ :



RAPP & WAMBACH, 1999



FRIMAN, PIRNER 97
HERMANN, FRIMAN, NÖRENBERG 92
RAPP, CHANFRAY, WAMBACH 97
PETERS et al. 98
SIBIRTSEV, CASSING 98
ELETSKY, JOFFE, KAPUSTA 98
⋮

- γA DATA
- $P_\perp$ DEPENDENCE OF l^+l^- EXCESS

WHAT NEXT ?

- HIGH RESOLUTION MEASUREMENT AROUND THE V PEAKS.

$M \sim m_V$: $\mathrm{Im}\, D_V \sim \dfrac{1}{\mathrm{Im}\,\Sigma_V}$

RAPP & C.G. 1999

CASSING & BRATKOVSKAYA 1998

$M \sim 0$ $\quad \mathrm{Im}\, D_V \sim \mathrm{Im}\,\Sigma_V$

- HIGHLIGHT / EXPLORE THE BARYON CONTRIBUTION :

$\rho_B \uparrow$ = LOW ENERGY RUN ?

BLEICHER, DUTT-MAZUMDER, KO, KOCH, C.G., 2000

HUOVINEN & PRAKASH, 1999

• + • → MIXING

CHIN 1977

WOLF, FRIMAN, SOYEUR 1998

TEODORESCU, DUTT-MAZUMDER, C.G., 2000

(σ-ω, ρ-a_1)

Real photon emission: Considerations

- pQCD contributions
- Intrinsic k_T broadening of the partons J. OWENS 1987 WONG & WANG 1998
- Additional k_T broadening of the incoming partons X.N. WANG, 1998 RAPP, FAI & LEVAI, 1999
- Emission from the QGP phase KAJANTIE, LICHARD & SEIBERT, 1991 AURENCHE, GELIS, et al. 1998
- Emission from the hadron phase KAJANTIE, LICHARD & SEIBERT, 1991 XIONG, SHURYAK & BROWN, 1992 C. SONG, 1993
- Dynamical effects: intrinsic v_T GALLMEISTER et al., 2000 PETRESSOUNKO & POKROVSKY, 2000 ALAM et al., 2001
- In-medium effects:
  - Brown-Rho scaling BROWN, LEE 1991
  - Modifications of the vector spectral densities RAPP, CHANFRAY & WAMBACH, 1997
- Shadowing and energy-loss effects JALILIAN-MARIAN, ORGINOS, SARCEVIC, 2000.
- Pre-equilibrium component SRIVASTAVA & GEIGER, 1997 SEIBERT & ALTHERR, 1993

Photons

OBSERVATIONS: $1.5 < P_\perp < 2.5$ GeV/c WA98

($\tau_0 = 1$ fm/c) HADRON GAS (MESONS) ~ 25-30 %
(Wong, Wang) QCD @ NLO + $k_\perp$ ~ 45-48 %

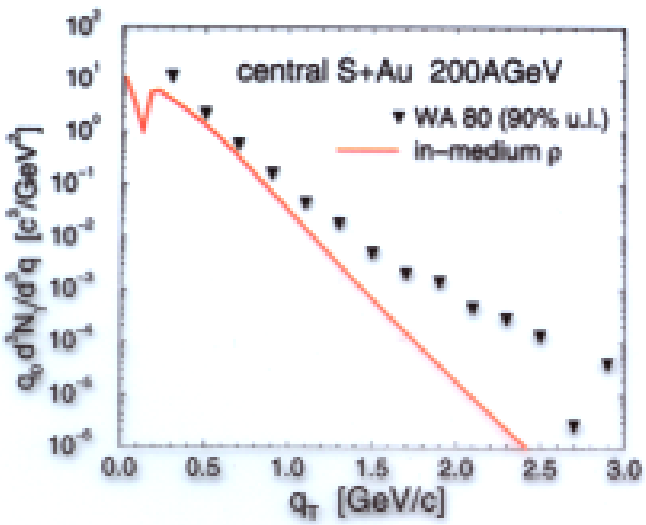
WHAT ABOUT THE BARYONS?

WA80 @ $P_\perp = 1.5$ GeV/c

($\tau_0 = 1$ fm/c) HADRON GAS ~ 22 %

In-medium ρ ~ 16 %

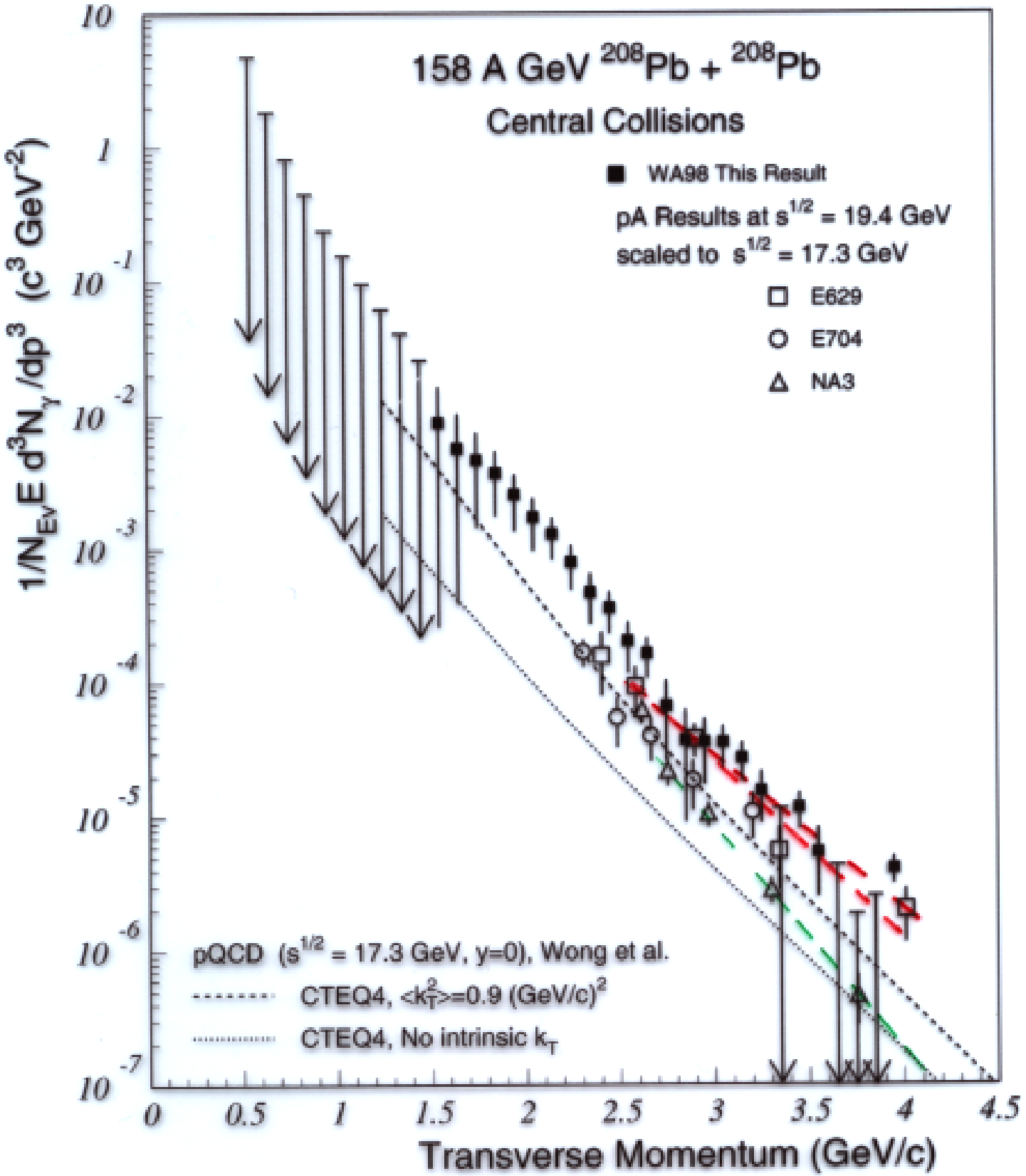
∴ APPLY THE I.M. ρ TO WA98?



Rapp & Wambach
Adv. Nucl. Phys. (in press)
(~ LOWER THAN 5YZ)

∴ ONLY PARTIAL CONCLUSIONS ARE POSSIBLE, UNLESS THE SAME APPROACHES ARE USED FOR γ & γ^*!

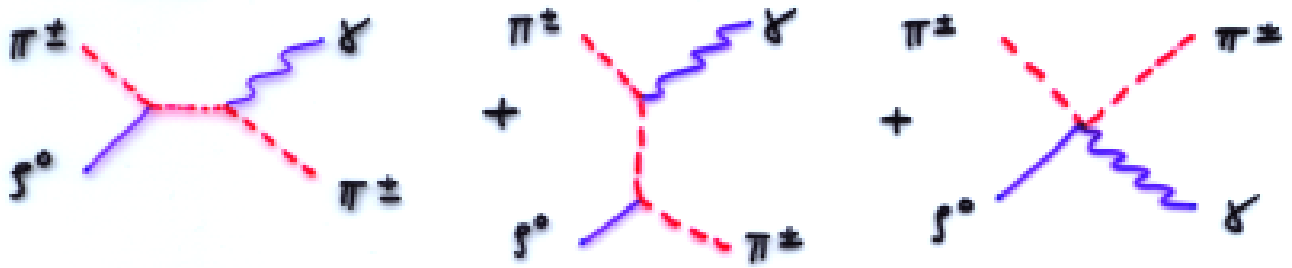
→ CONSISTENCY


158 A GeV ^{208}Pb + ^{208}Pb
Central Collisions
WA98 This Result
pA Results at $s^{1/2}$ = 19.4 GeV
scaled to $s^{1/2}$ = 17.3 GeV
E629
E704
NA3
pQCD ($s^{1/2}$ = 17.3 GeV, y=0), Wong et al.
CTEQ4, $\langle k_T^2 \rangle$=0.9 (GeV/c)^2
CTEQ4, No intrinsic k_T
$1/N_{EV} E\, d^3N_\gamma/dp^3$ (c^3 GeV^{-2})
Transverse Momentum (GeV/c)

Photons: Hadronic rates

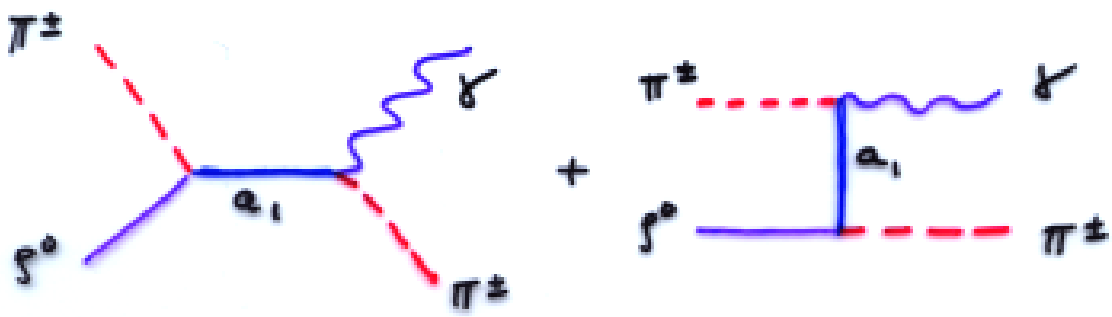
KAGUSTA, LICHARD, SEIBERT 1991, 1993; ALAM et al., 1998
C. SONG, 1993

One finds that the relevant reactions are: $\pi\rho \to \pi\gamma$, $\pi\pi \to \rho\gamma$, $\pi\pi \to \eta\gamma$, $\pi\eta \to \pi\gamma$, and $\rho \to \pi\pi\gamma$, $\omega \to \pi\gamma$.



- Those rates are robust.

The a_1 is found to play an important role:



WIANG, SAURYAKE, BROWN, 1992

Problem: There is no *unique* way to implement a chiral-symmetric model with vector mesons.

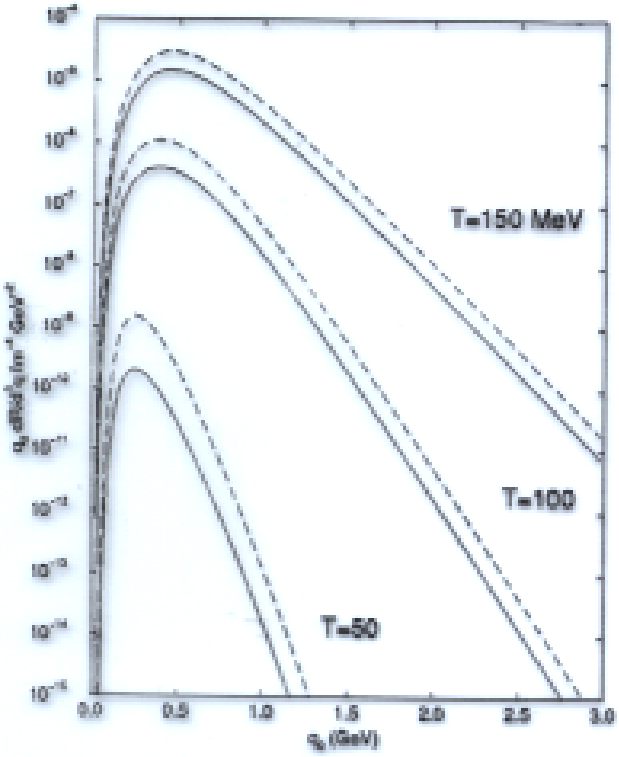
$\mathcal{L}_{a_1 \rho \pi}$

EFFECTIVE HADRONIC LAGRANGIANS WITH THE APPROPRIATE SYMMETRIES CAN BE USED AS USEFUL TOOLS

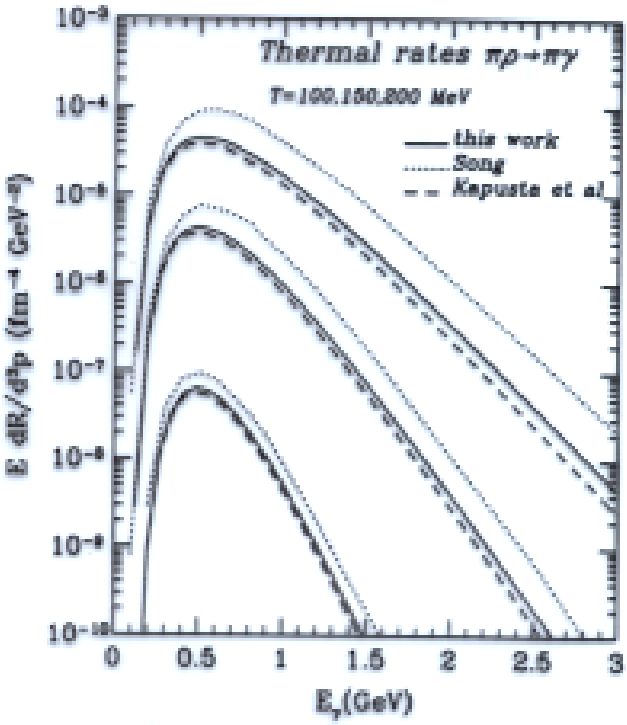
- GAUGING THE NON-LINEAR σ MODEL. Spin 1 FIELDS ARE MASSIVE YANG-MILLS BOSONS.
  SAKURAI 1969, SCHECHTER et al. 1984
- GAUGING THE LINEAR σ MODEL.
  KO & RUDAZ, 1994.
- APPROACHING CHIRAL SYMMETRY RESTORATION VIA THE GEORGI VECTOR LIMIT.
  HALASZ, STEELE, LI & BROWN, 1998
- EFFECTIVE CHIRAL THEORY THROUGH THE BACKGROUND FIELD METHOD D.A. LI, 1995, 1997.
- PHENOMENOLOGICAL APPLICATIONS
  XIONG, SHURYAK, BROWN, 1991
  JANSSEN, HOLINDE & SPETH, 1994.

$\left\{ \begin{array}{l} \text{DIFFERENT CHOICE \& NUMBER OF PARAMETERS} \\ \text{DIFFERENT OFF-SHELL BEHAVIOUR} \end{array} \right.$

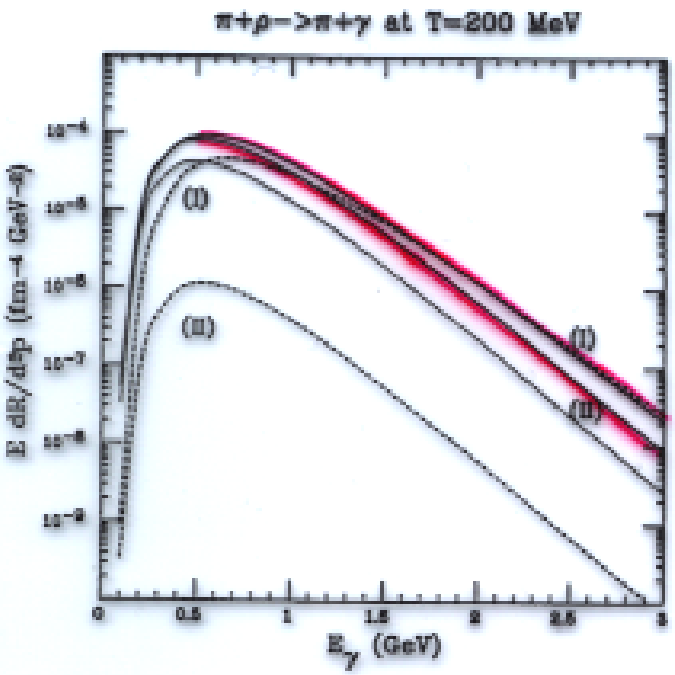
γ HADRONIC RATES:



STEELE, YAMAGISHI, ZAHED 1996



HAGASE, STEELE, LI, BROWN 1998



PRODUCTION RATES CAN DIFFER BY A FACTOR OF ~3

C. SONG, 1998

TABLE I. The phenomenology of the different models

	Ko		GKS	Li	XSB	JHS	DATA
	I	II					
$\Gamma(a_1\rho\pi)$	313.4	579.1	fit	331.7	fit	fit	~ 400 MeV
$\Gamma(a_1\pi\gamma)$	0.572	1.171	0.067	0.331	1.940	0.312	0.640 ± 0.246 MeV
f_D/f_S	0.078	-0.168	-0.099	-0.161	0.185	0.045	-0.09 ± 0.03
χ^2	11.8	9.6	1.8	3.1	37.3	7.3	

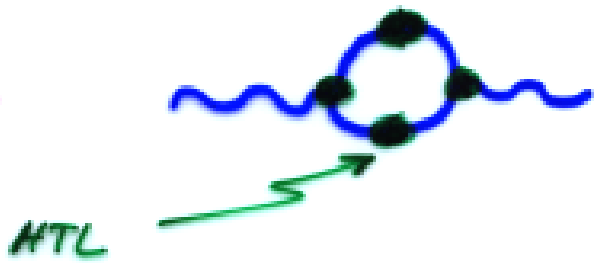
→ $\frac{D}{S}$ RATIO: N. ISGUR et al., 1989.

- EFFECTIVE HADRONIC LAGRANGIANS SHOULD CONFORM TO BASIC HADRONIC PHENOMENOLOGY.

- NARROW THE SPREAD IN γ SPECTRA.

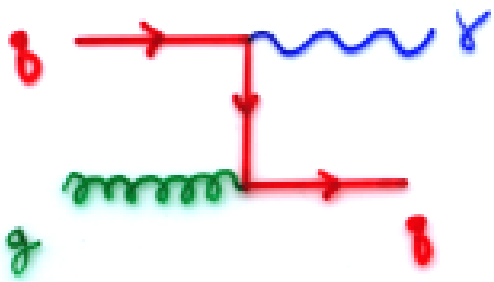
Photons: QCD rates

1ST ORDER: ONE-LOOP

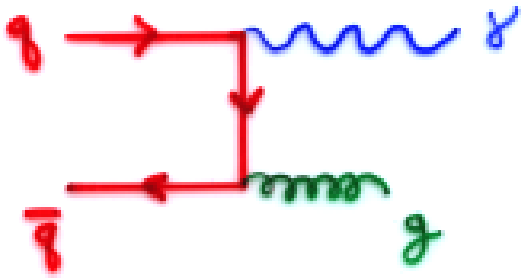


- BRAATEN, PISARSKI & YUAN, 1990.
- BAIER, PEIGNÉ & SCHIFF, 1993.
- AURENCHE, BECHERRAWY, PETITGIRARD, 1993.
- BAIER, NIEGAWA et al., 1993.
- KAPUSTA, LICHARD & SEIBERT, 1993.

THEY CONTAIN:

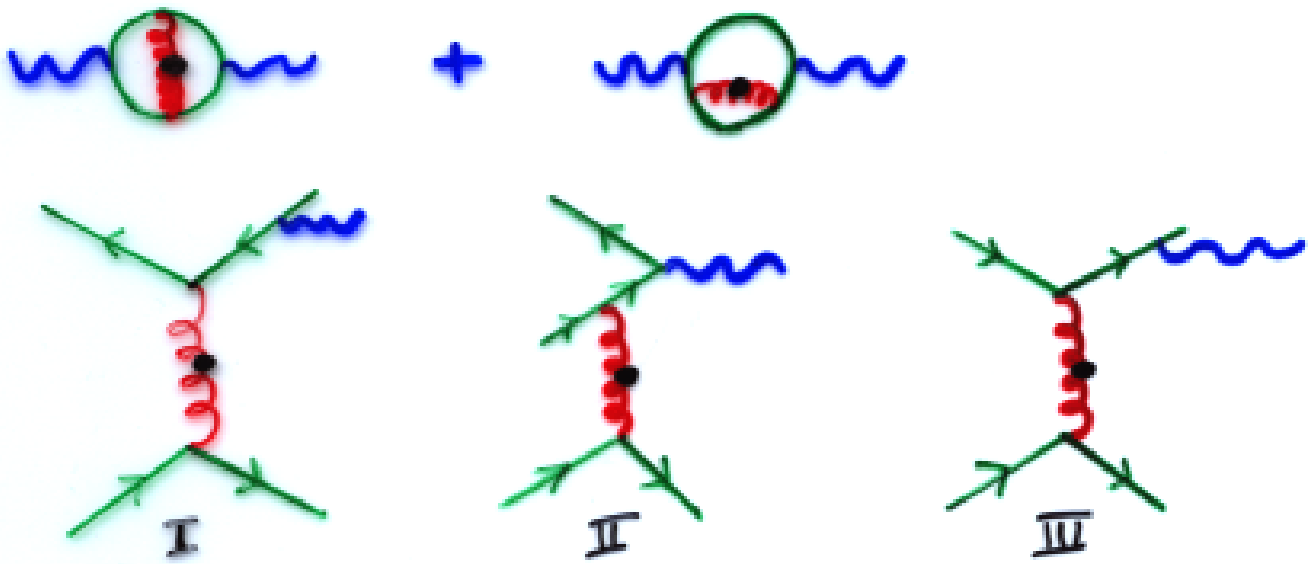


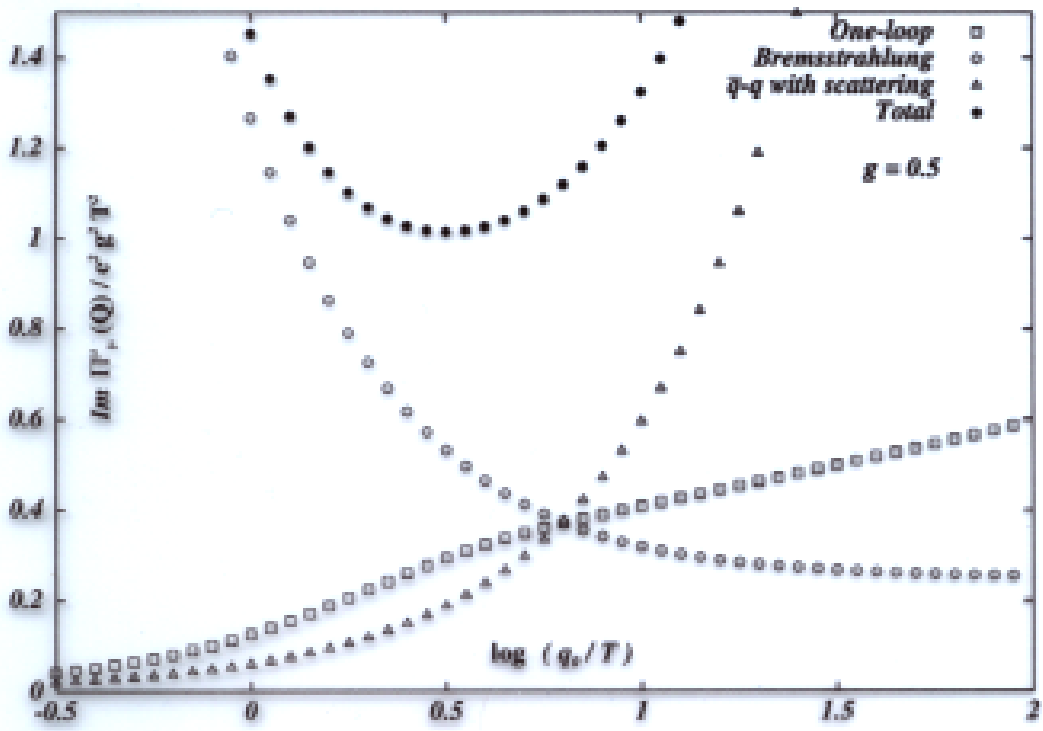
$qg \to q\gamma$



$q\bar{q} \to \gamma g$

Photons: QCD rates (II)





AURENCHE, GÉLIS ET AL. 1998

CONTRIBUTION FROM II DOMINATES.

INTRINSIC $k_\perp$:

$r_H \sim 0.5$ fm , $\sigma \sim \hbar / r_H = 400$ MeV/c

$$\langle k_\perp^2 \rangle = 2\sigma^2 \simeq 0.32 \ (\text{GeV}/c)^2$$

SOFT g EMISSIONS WILL INCREASE THIS.

EARLY ANALYSIS BY OWENS (LO): $\langle k_\perp^2 \rangle = 0.9 \ (\text{GeV}/c)^2$ @ $\sqrt{s} = 20$ GeV

$$K(p_\gamma) = E_\gamma \frac{d^3\sigma}{d^3p_\gamma}(\text{LO}+\text{NLO}) \Big/ E_\gamma \frac{d^3\sigma}{d^3p_\gamma}(\text{LO})$$

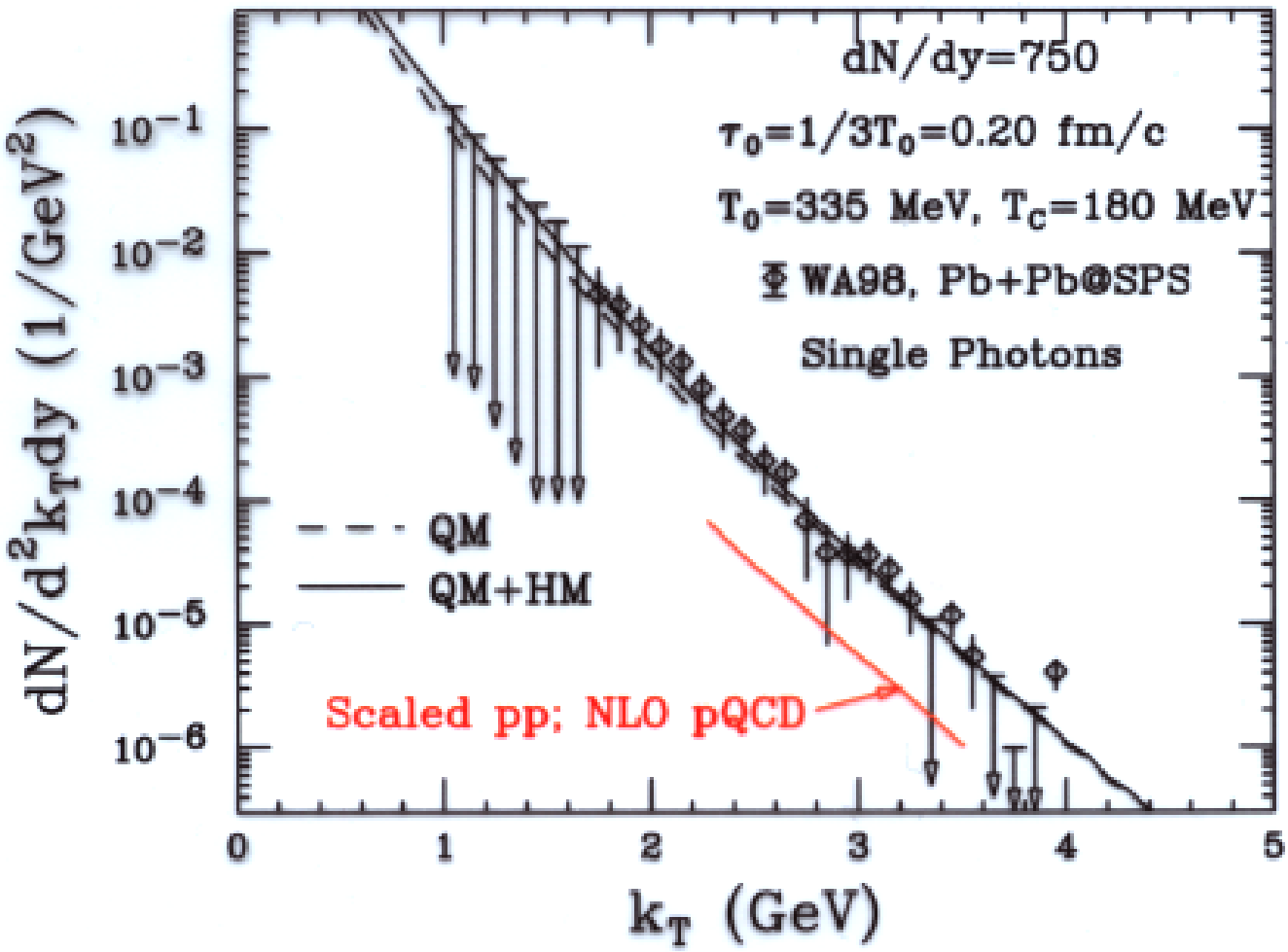
$$E \frac{d^3\sigma}{d^3p_\gamma}(\text{LO}+\text{NLO}+p_\perp) \simeq K(p_\gamma) \ E_\gamma \frac{d^3\sigma}{d^3p_\gamma}(\text{LO}+p_\perp)$$

- SLIGHTLY INCONSISTENT
- ANALYSIS OF DATA <u>NOT</u> CONCLUSIVE:

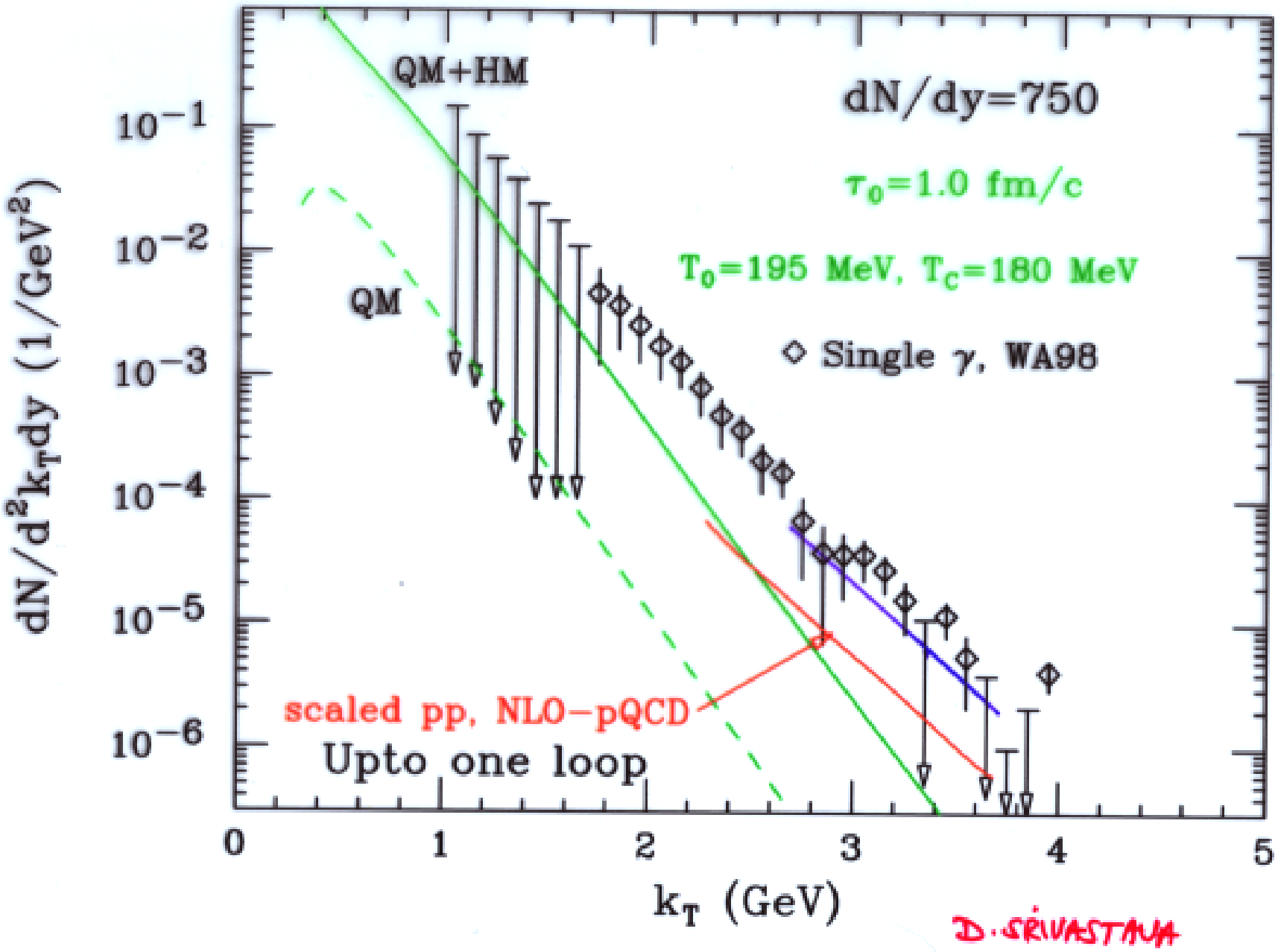
P. AURENCE et al., 1999 :
- NO NEED FOR $k_\perp$
- DATA SETS ARE INCONSISTENT

($\sqrt{s} \geq 23$ GeV)

D.K. SRIVASTAVA & B. SIÓAA, 2000



CONTAINS THE HIGHER ORDER α_s^2
RESULTS OF AURENCHE, GÉLIS ET AL.



D. SRIVASTAVA

HOW CRITICAL ARE THE HIGH T'S ?

HIGH p_T :

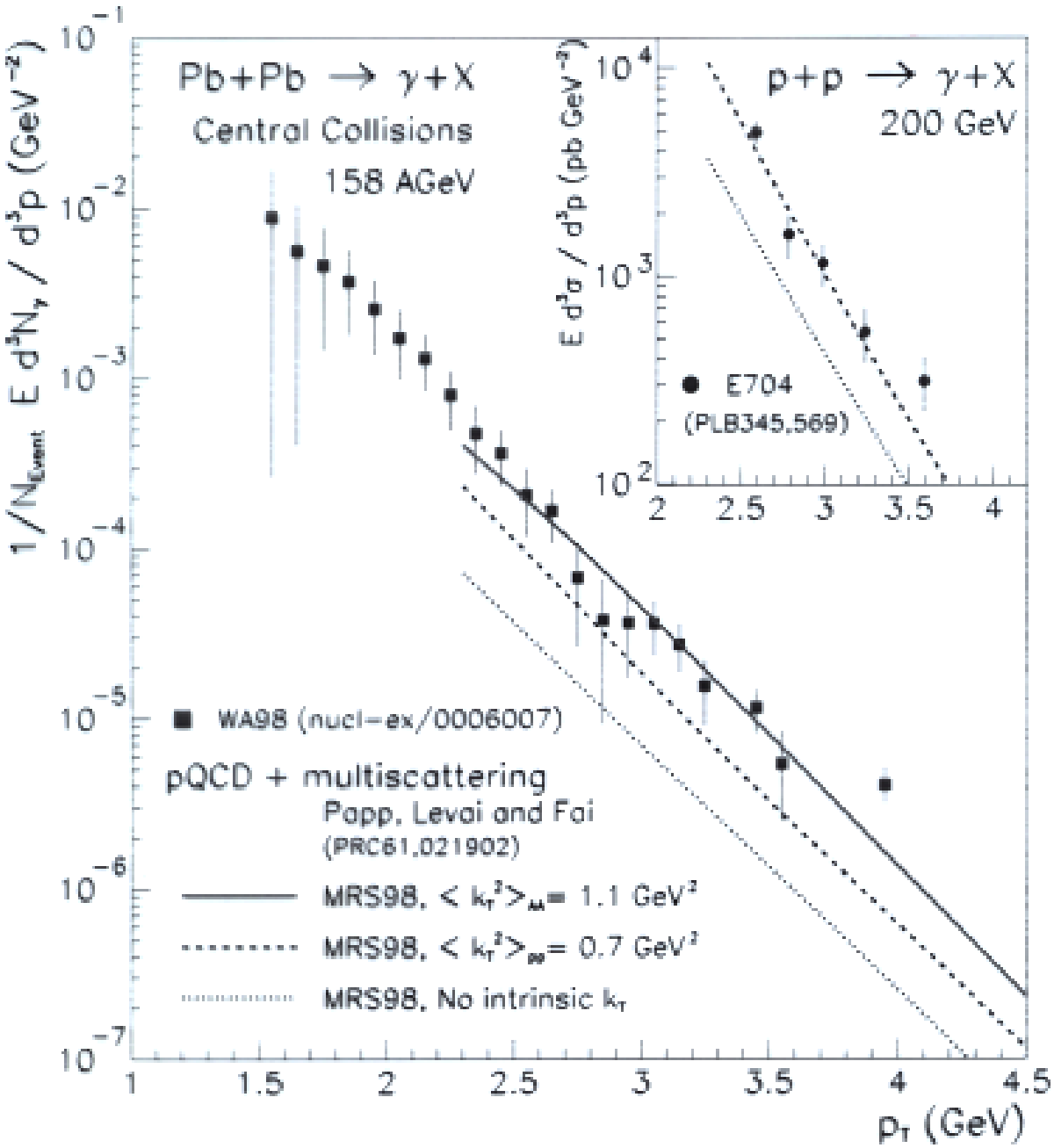
- $k_\perp$ INTRINSIC à la WONG & WANG :

  $k \simeq 2$

- SOFT SCATTERING à la FAI, LEVAI & PAPP :

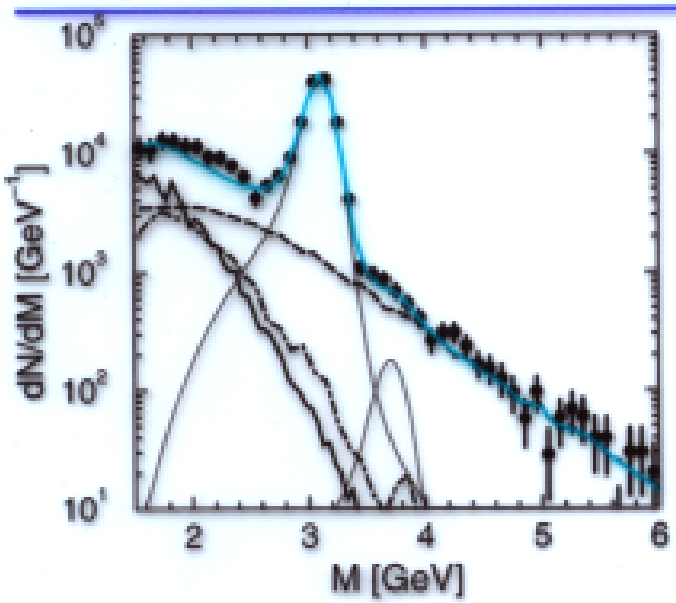
  $k \simeq 2$

(FAI, LEVAI & PAPP, PRC 2000)



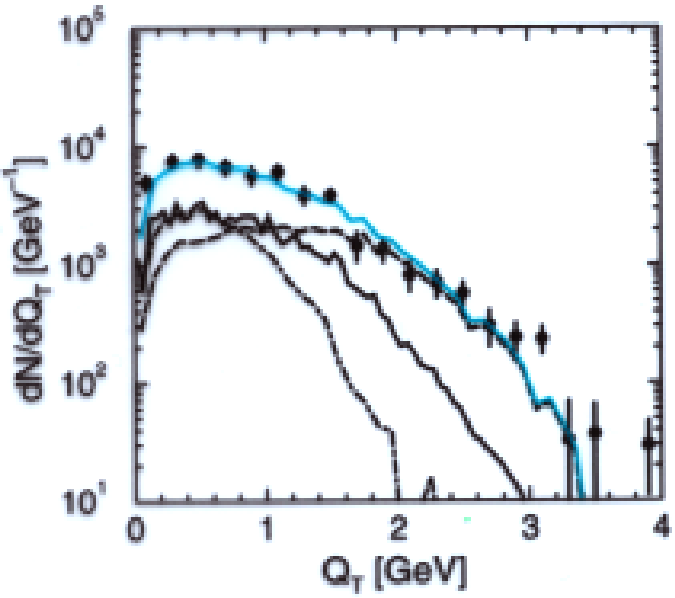
Fai, Levai, Papp, 2001

An attempt at consistency ?

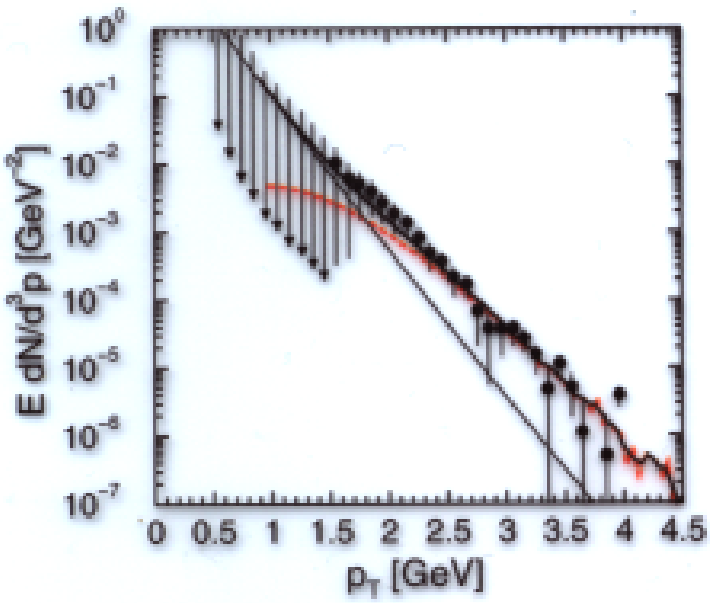


GALLMEISTER et al., 2000.

$$E\frac{d^3N}{d^3p} = V_4\, F(E, T_c, N_0)$$



— THERMAL



$T_c = 170$ MeV $= \langle T \rangle$

- CERES (KLINGL & WEISE, 1998)

SCHNEISER & WEISE, 2000

- SIMPLIFIED DYNAMICS

$T_i > T_c$

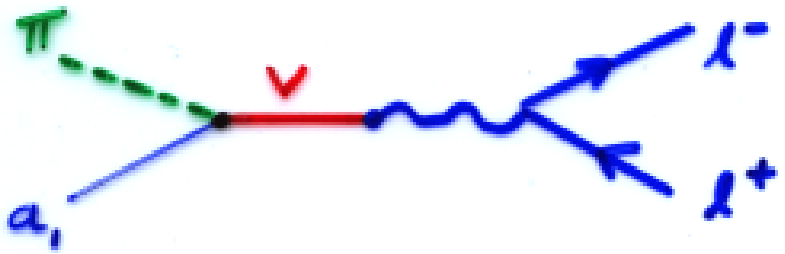
Dileptons: Intermediate mass

- The presence of off-shell effects makes the use of effective hadronic Lagrangians problematic.

$\pi a_1 \to e^+e^- \; (\ell^+\ell^-)$ is <u>IMPORTANT</u>.

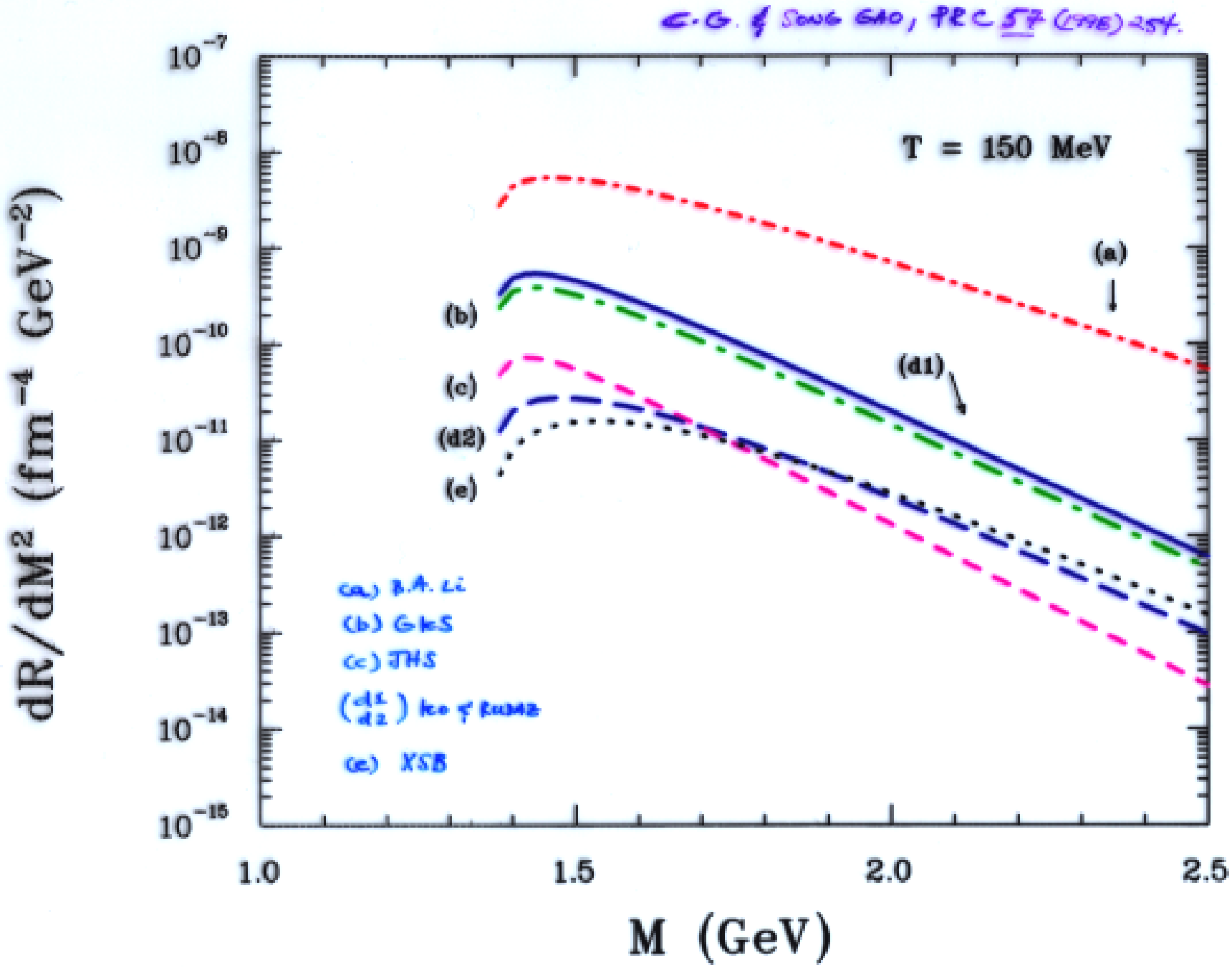
(SONG, KO & C.G., 1994)

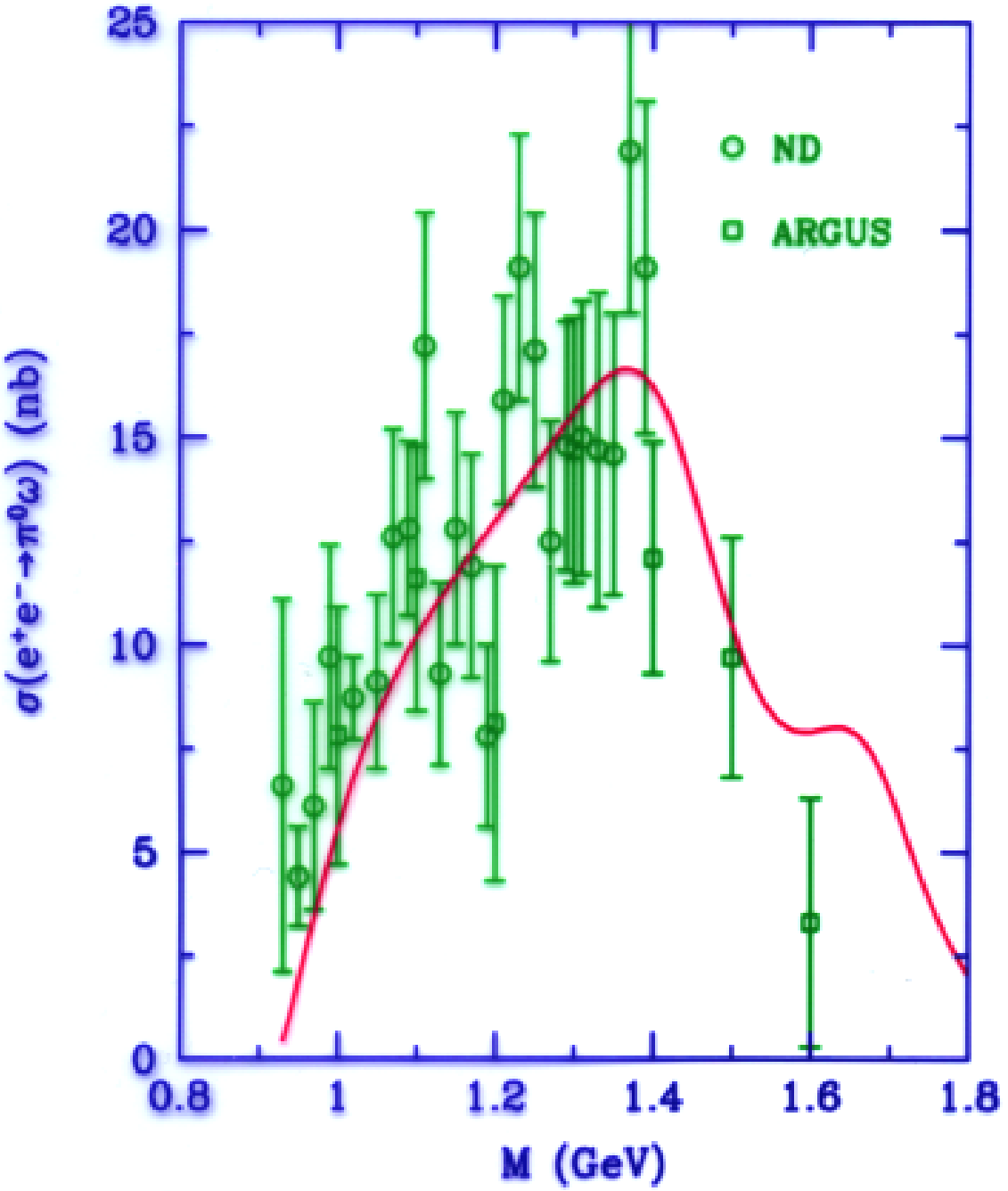
e.g.:



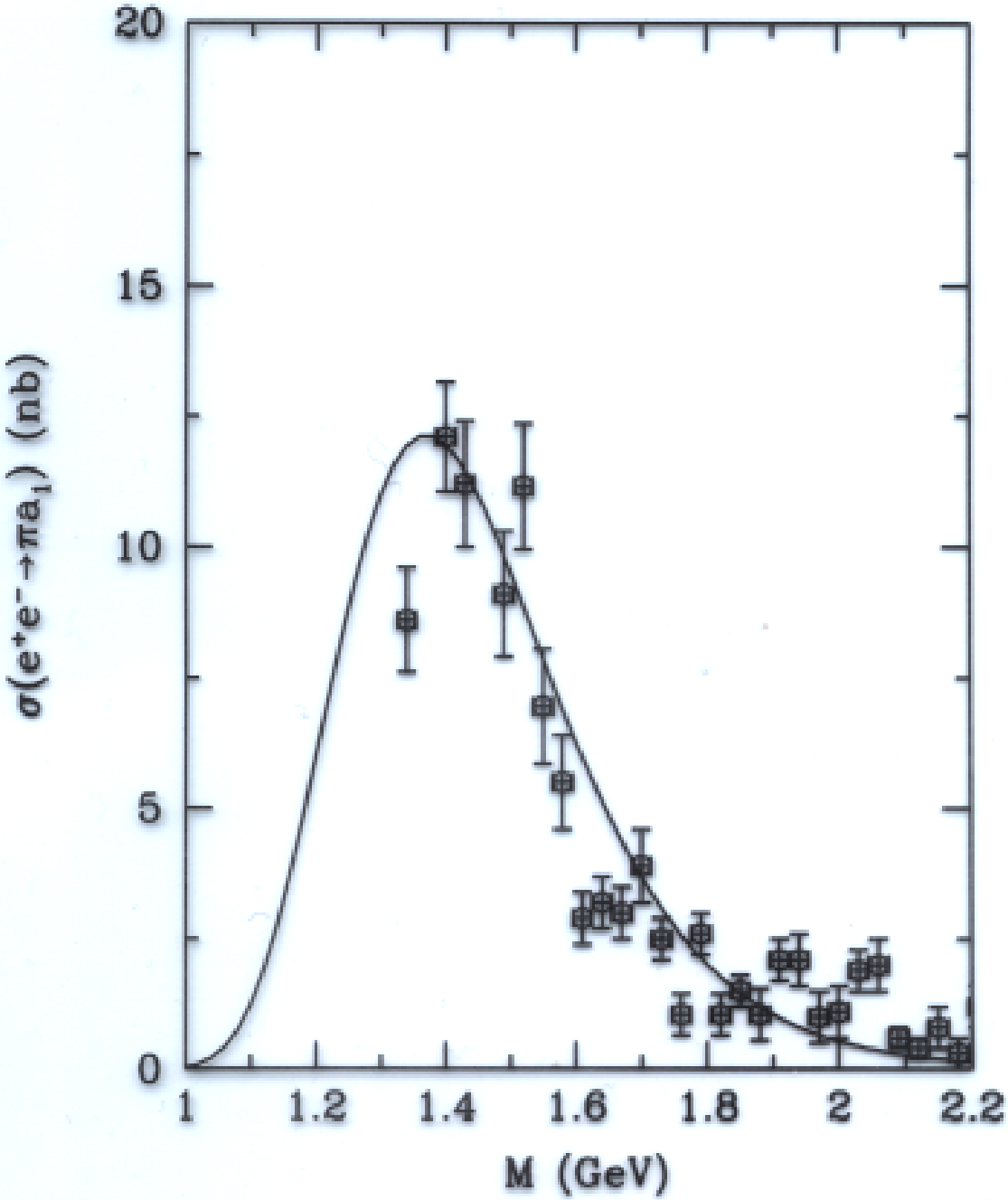
- Fortunately, data exists!

C.G. & Song Gao, PRC 57 (1998) 254.




ND
ARGUS
σ(e⁺e⁻→π⁰ω) (nb)
M (GeV)
0
5
10
15
20
25
0.8
1
1.2
1.4
1.6
1.8

DM2 D. BISELLO et al., 1991

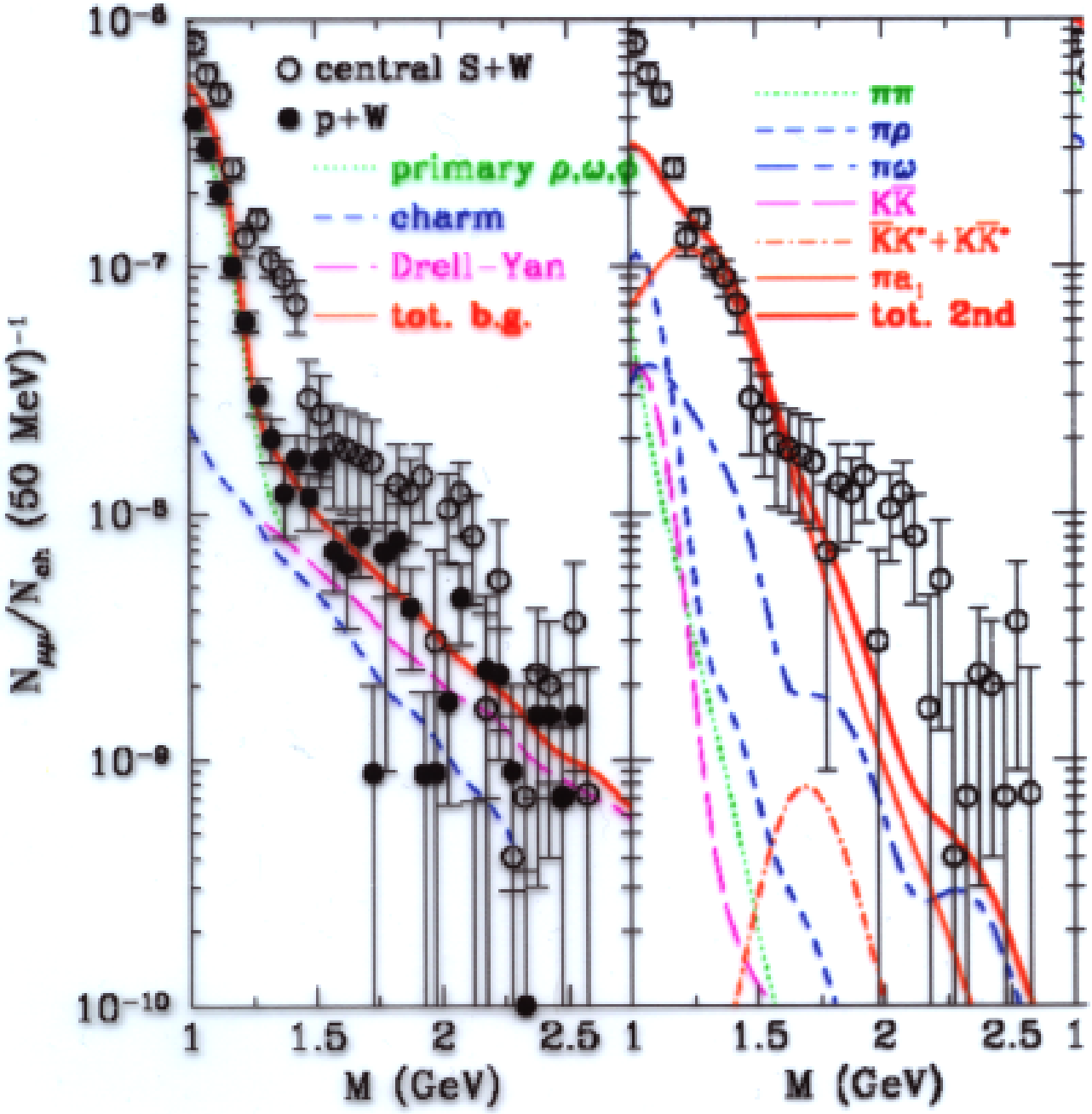


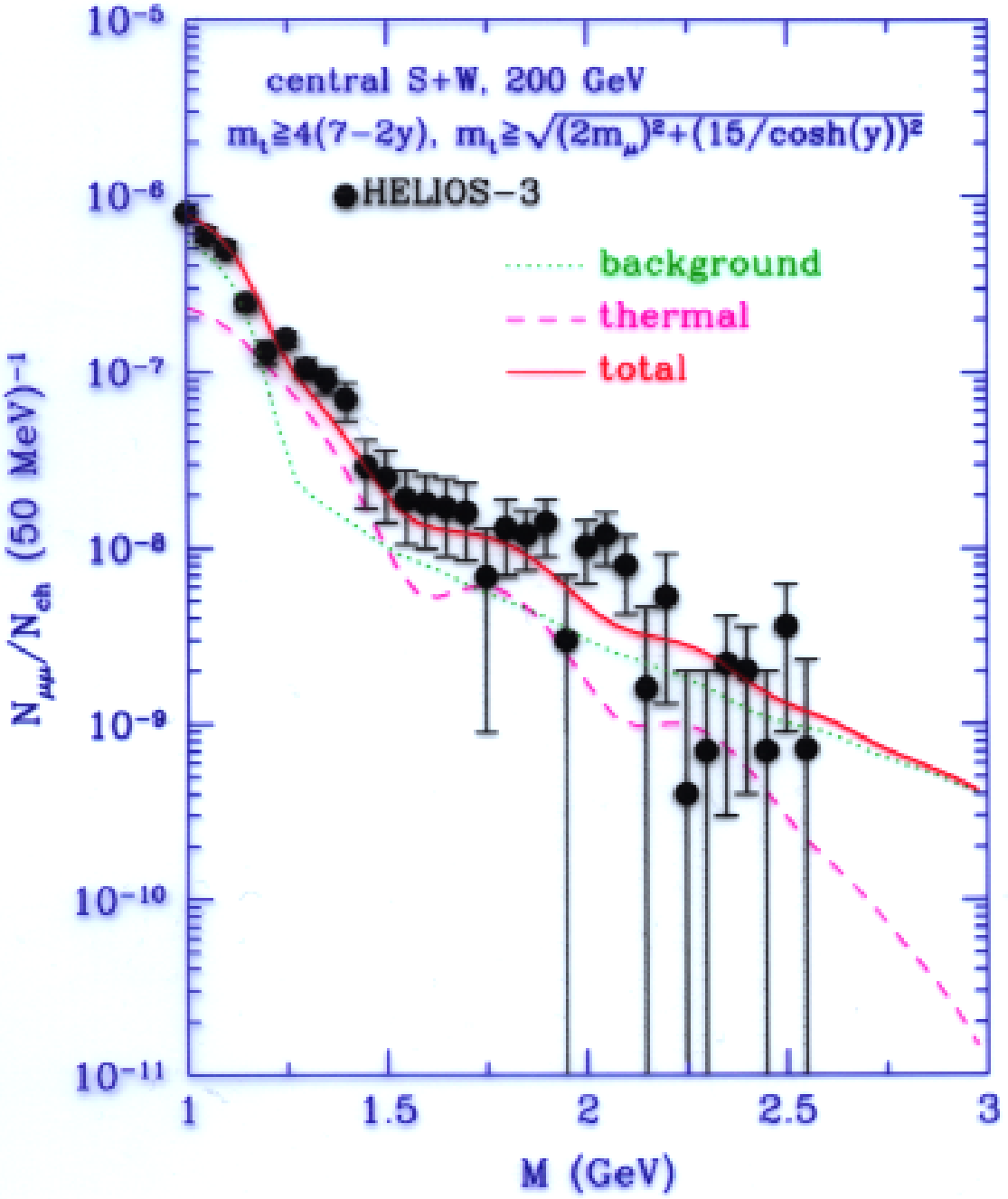
KUASNIKOVA, 2000

INTERMEDIATE - MASS DILEPTONS:

HELIOS/3 $\mu^+\mu^-$ DATA:

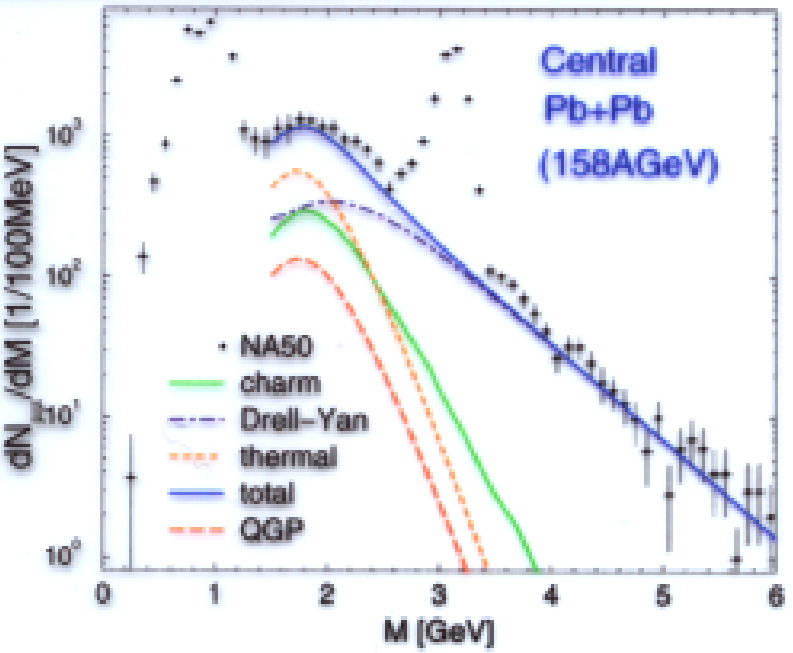
G.Q. Li & C.G., PRC 58, 2914 (1998).



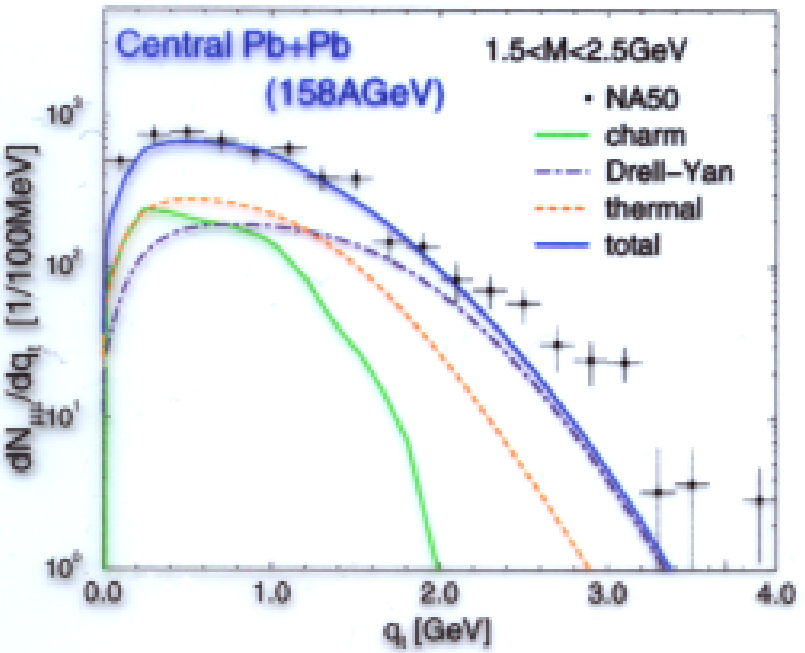

central S+W, 200 GeV
$m_t \geq 4(7-2y)$, $m_t \geq \sqrt{(2m_\mu)^2+(15/\cosh(y))^2}$
HELIOS-3
background
thermal
total
$N_{\mu\mu}/N_{ch}$ (50 MeV)$^{-1}$
M (GeV)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
1
1.5
2
2.5
3

Q.G. Li & C.G., 1998

Intermediate mass dileptons (II)

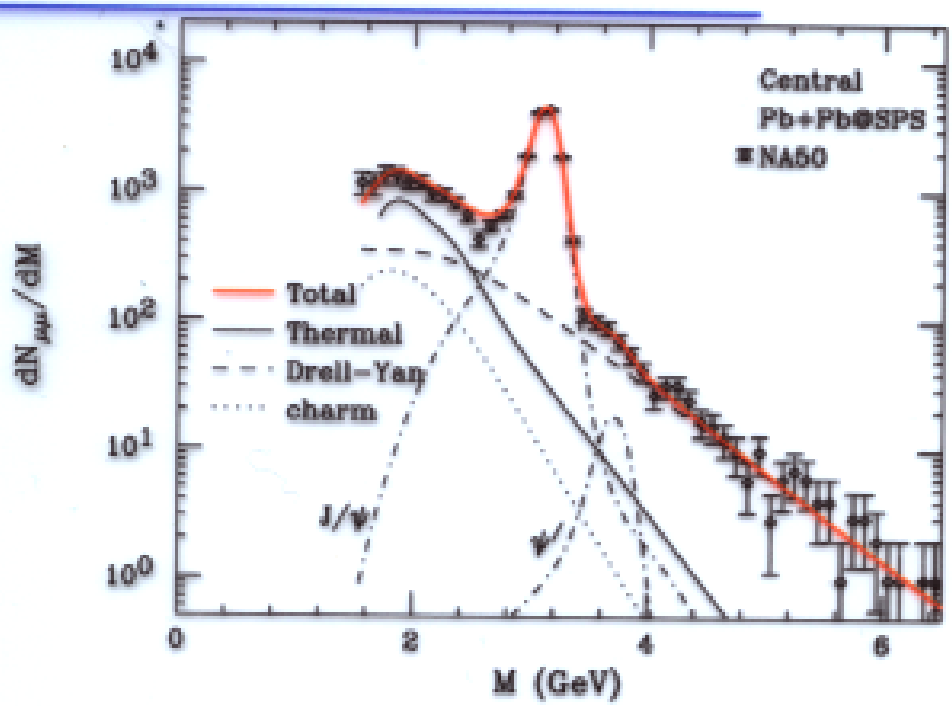


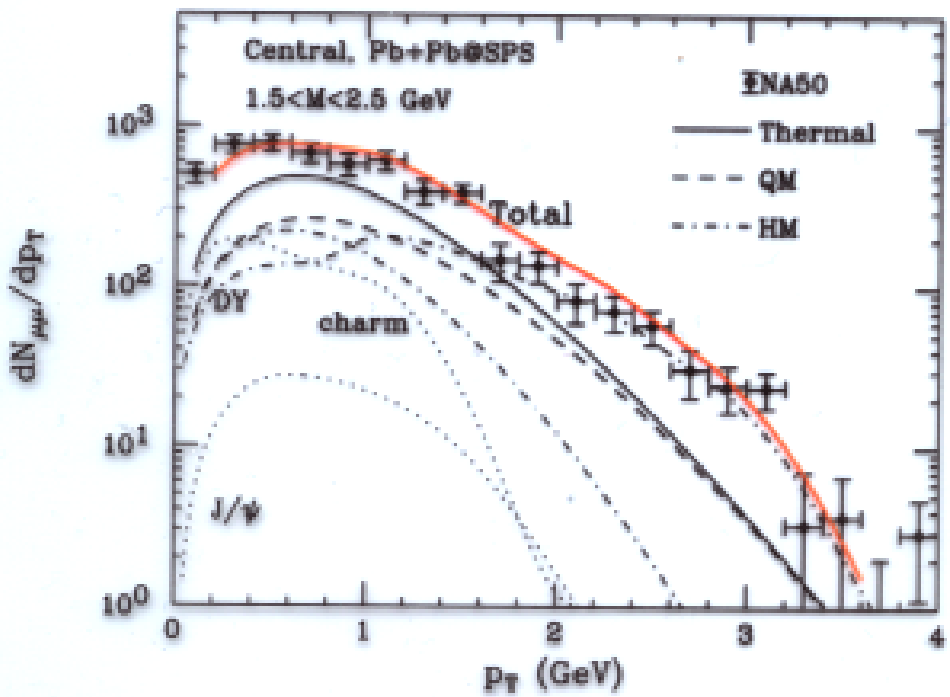
R. RAPP & E. SHURYAK, PHYS. LETT. B473, 13 (2000).



THE INTERMEDIATE-MASS REGION "IS FILLED IN" BY THE "THERMAL" CONTRIBUTION.

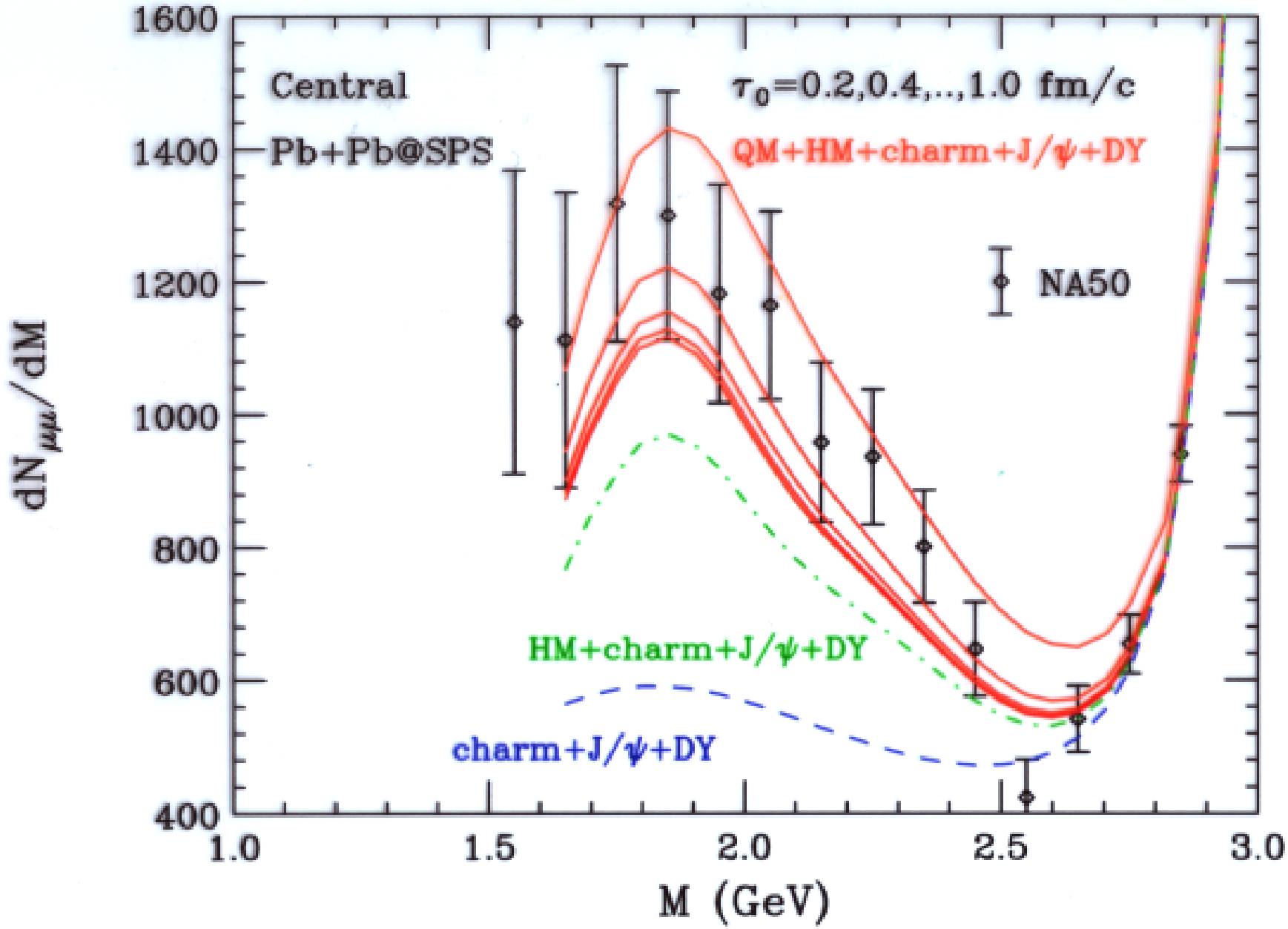
Intermediate mass dileptons





KVASNIKOVA, C. G., and SRIVASTAVA, SINHA
in PREPARATION

SRIVASTAVA, KUVASNIKOVA, C-G.



Conclusions:

LOW MASS l^+l^-:

- LOW ENERGY RUNS RESULTS ANTICIPATED

REAL γ:

- UNCERTAINTIES:
  - QCD SECTOR (RHIC)
  - " HIGH T
  - HADRON RATES: PHENOMENOLOGY
  - COMPLE DYNAMICAL SCENARIOS

$\boxed{\text{WE CAN TAKE PROGRESS}}$

- SPECTRAL DENSITIES (2 loops)

I.M. l^+l^+:

- THERMAL COMPONENT IS PRESENT
- CHARM ENHANCEMENT?
- ACCEPTANCE!

CHIRAL SYMMETRY? • NOT CONCLUSIVE

$\rightarrow \rho_A(\omega, \vec{q}) \Rightarrow a_1$ LMR? NO (RAPP & C.G. 1999, KOCH, 1999)

$\rho_A(\omega, \vec{q}, n, T) \leftarrow$ IMR? MAYBE

γ? MAYBE

RHIC:

SHURYAK 1978

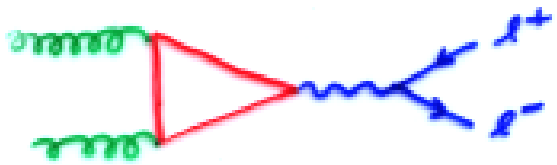
KAJANTIE, KAPUSTA, MCLAREN, MEKJIAN '86

RUUSKANEN 1992

$m_\phi \leq M \leq m_{J/\psi} \rightarrow$ QCD

NEW CONSIDERATIONS: $\rho_g \uparrow (T)$, $\mu_g \neq \mu_{\bar{g}}$

E → FURRY ∴ $gg \rightarrow l^+l^-$



"SQUEEZING DILEPTONS OUT OF BROKEN SYMMETRIES"

Majumder & c.g., 2000

$$\boxed{gg \rightarrow l^+l^- \sim q\bar{q} \rightarrow l^+l^-}$$