PHOTONS, DILEPTONS AT LHC

P. Aurenche

- $\gamma, \ell^+\ell^-$ non interacting probes → history of hot matter / quark-gluon plasma

e.g. : if QGP thermalised :

$$\frac{dN}{dE} \sim e^{-E/T}$$

⇒ large E, P_T $\gamma/\ell^+\ell^-$ produced when T largest ⇒ early in collision.

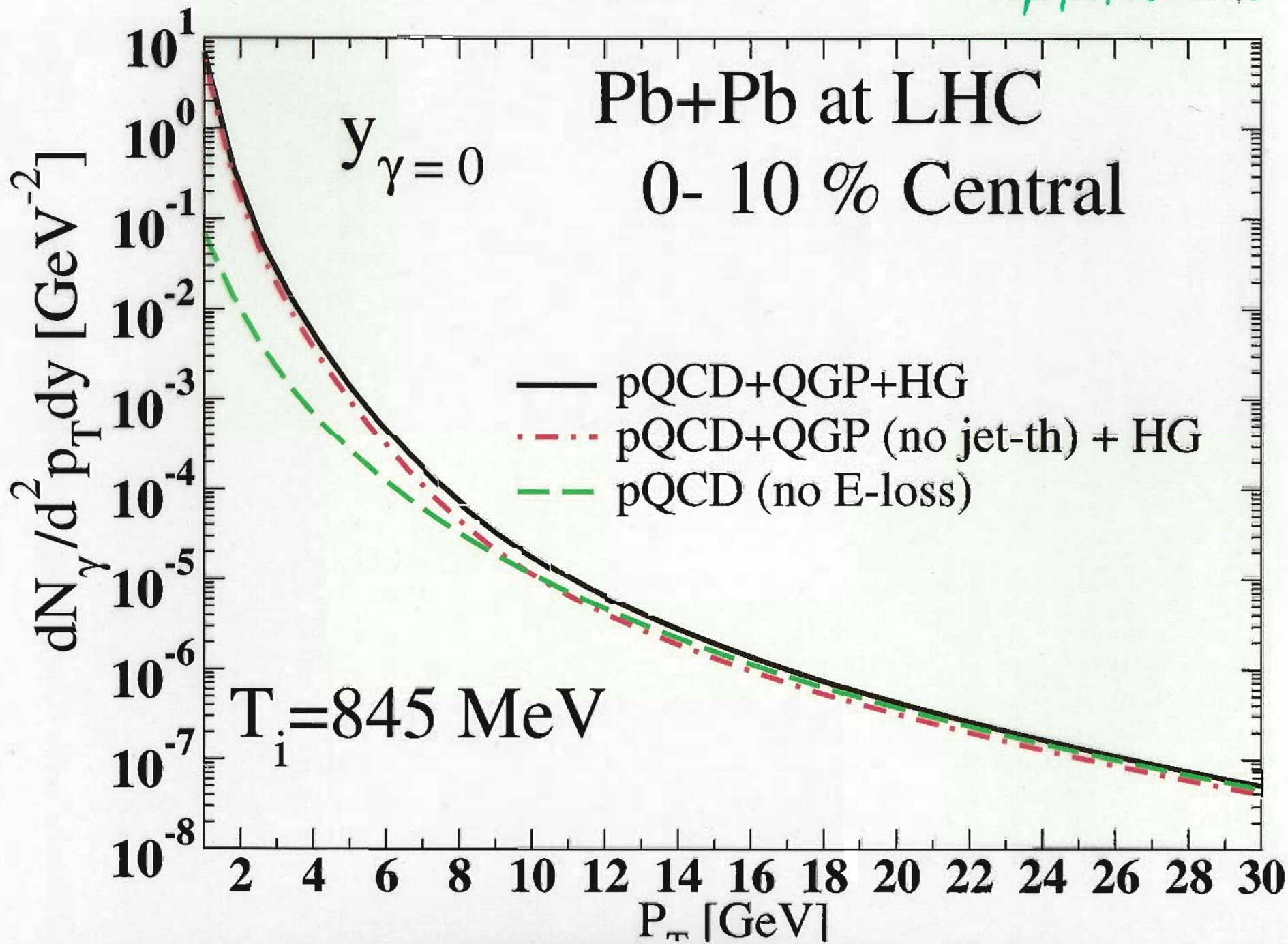
- Compared to pp collisions, expect in AA collisions an excess of $\gamma/\ell^+\ell^-$. FIG : Turbide et al.

BUT !

- one expects a very large background :
radiative decays of hadrons : $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$, ...
specially at lower P_T.

$\pi^0 \to \gamma\gamma$ ~ 90% bckgd.,
avoided when looking at $\ell^+\ell^-$: $m_{\ell^+\ell^-} > m_{\pi^0}$

Turbide et al
hep-ph/0502248



If one considers

$m_{\gamma^*}/p_T \ll 1$: same dynamics as real γ, background smaller
⇒ explore lower p_T (Phenix)

γ^* useful at low p_T ($m_{\gamma^*}/p_T \ll 1$)

γ large p_T (rate larger)

γ, γ^* production mechanisms, increasingly refined:

4 classes :

1] p-p like processes : prompt photons
early in collisions, calculable in NLO p-QCD, sensitive to final state interac.

$\frac{dN}{dp_T} \sim \frac{1}{p_T^n}$, dominate at large p_T

2] produced in hot matter : thermal photons

QGP at temperature T

$\frac{dN}{dp_T} \sim e^{-E/T}$ $\qquad p_T^2 = E^2 - p_{\parallel}^2$

calculated at leading order
important at lower p_T.

3) jet-photon conversion : thermal photons

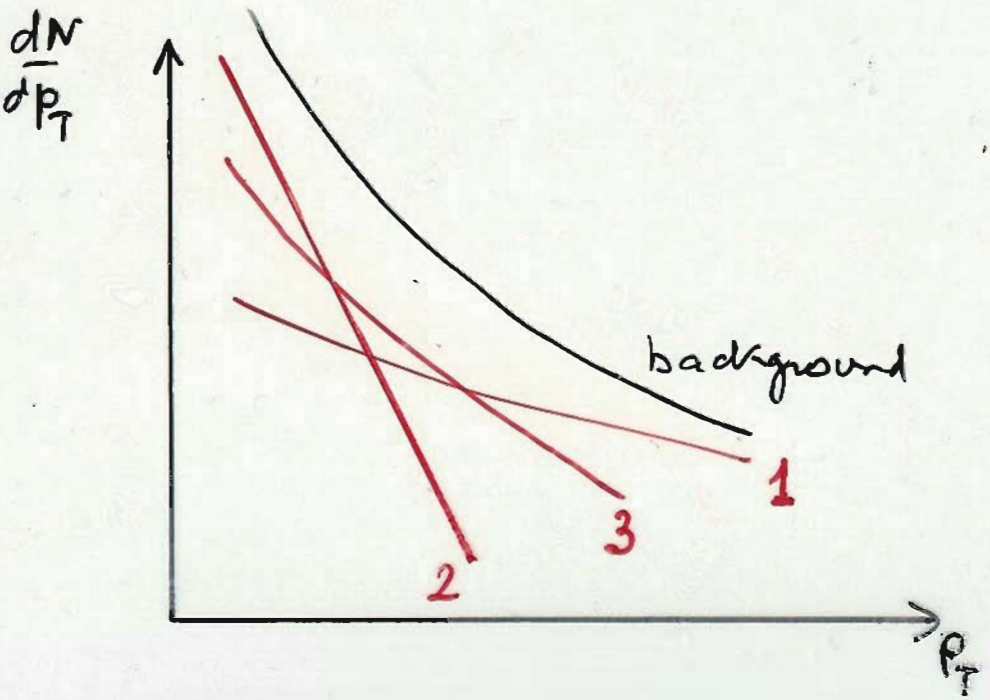
$$\frac{dN}{dp_T} \sim \frac{1}{p_T^p} \quad , \quad \text{intermediate } p_T$$

leading order calcul., model dependence

4) Decay from hadrons : background

Signal : 1 + 2 + 3 [2 + 3 → excess wrt pp coll.]

= direct photons



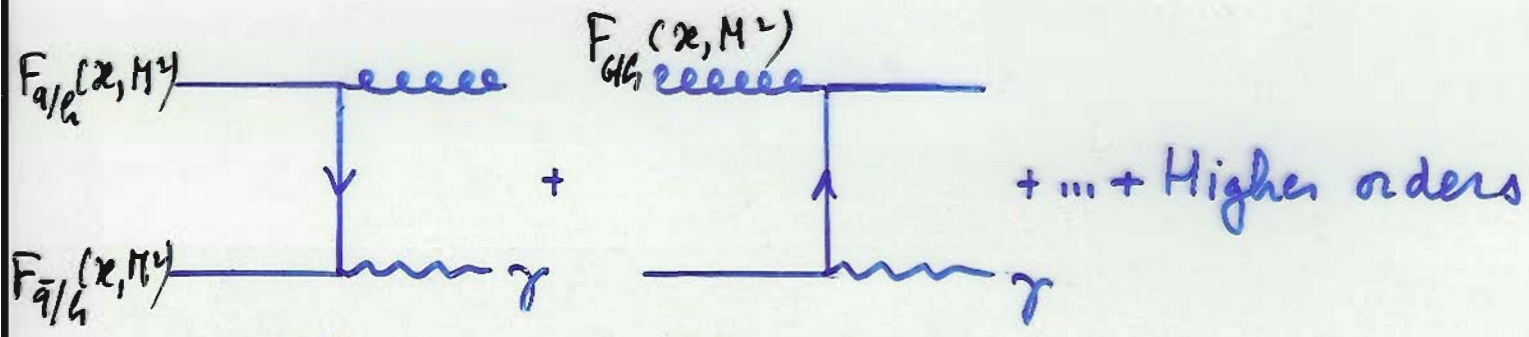
In following:

- Inclusive γ / γ^* production: $\frac{S}{B}$ more favorable than in pp.
- γ-hadron, γ-γ correlations : perturbative γ vs recoiling jet.

INCLUSIVE PRODUCTION

1) Prompt γ production

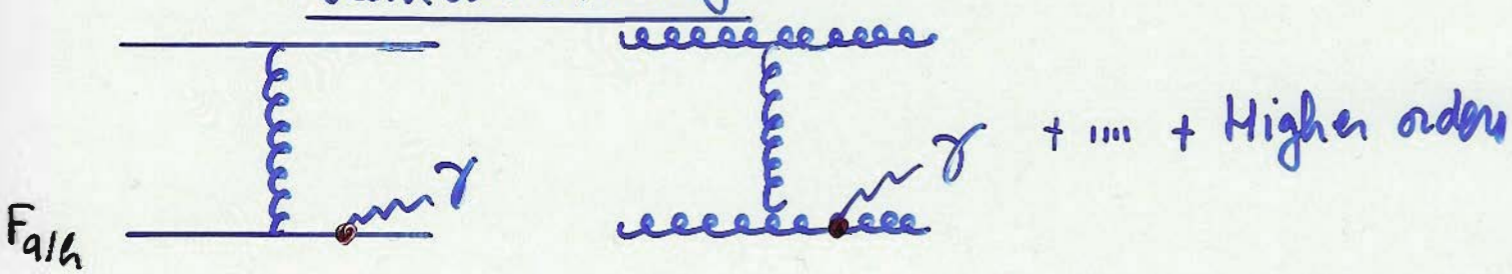
a) In pp collisions, 2 types :



Annihil. Compton

$F_{q/h}$, $F_{G/h}$ well known at NLO : MRS, CTEQ, ...

Bremsstahlung



$D_{\gamma/q}(z,M_F^2)$ $D_{\gamma/G}(z,M_F^2)$

$D_{\gamma/q}$, $D_{\gamma/G}$, at NLO (BFG param.) from $e^+e^- \to \gamma X$
$pp \to \gamma X$

At LHC, bremß. dominates at low $P_T/\sqrt{s}$, but

$D_{\gamma/G}$ not really constrained by data :

isolation criteria at Tevatron cut off $D_{\gamma/G}$, $D_{\gamma/q}$

FIG : data vs NLO Theory : $23\ GeV < \sqrt{s} < 2\ TeV$

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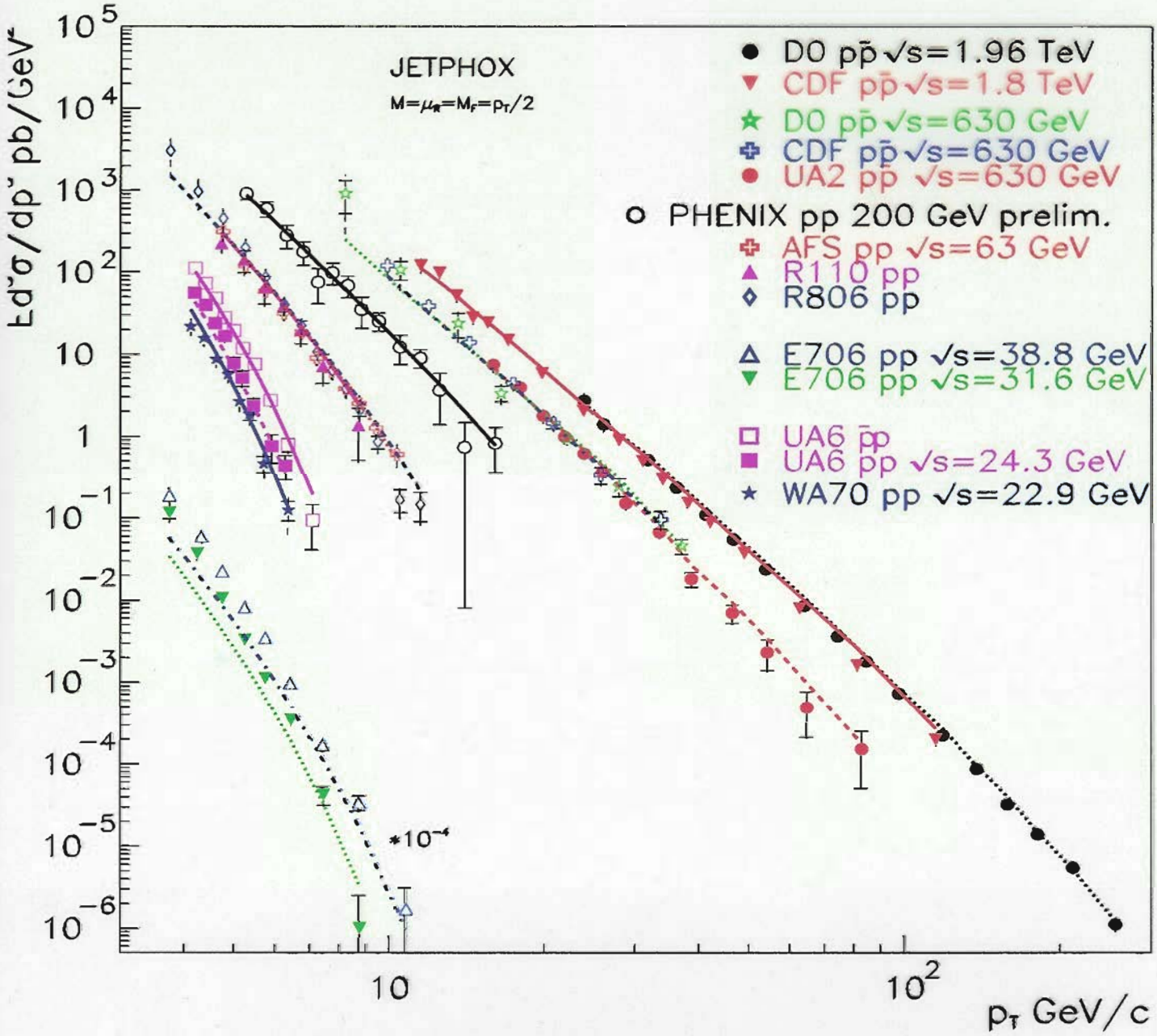
hep-ph/0602133



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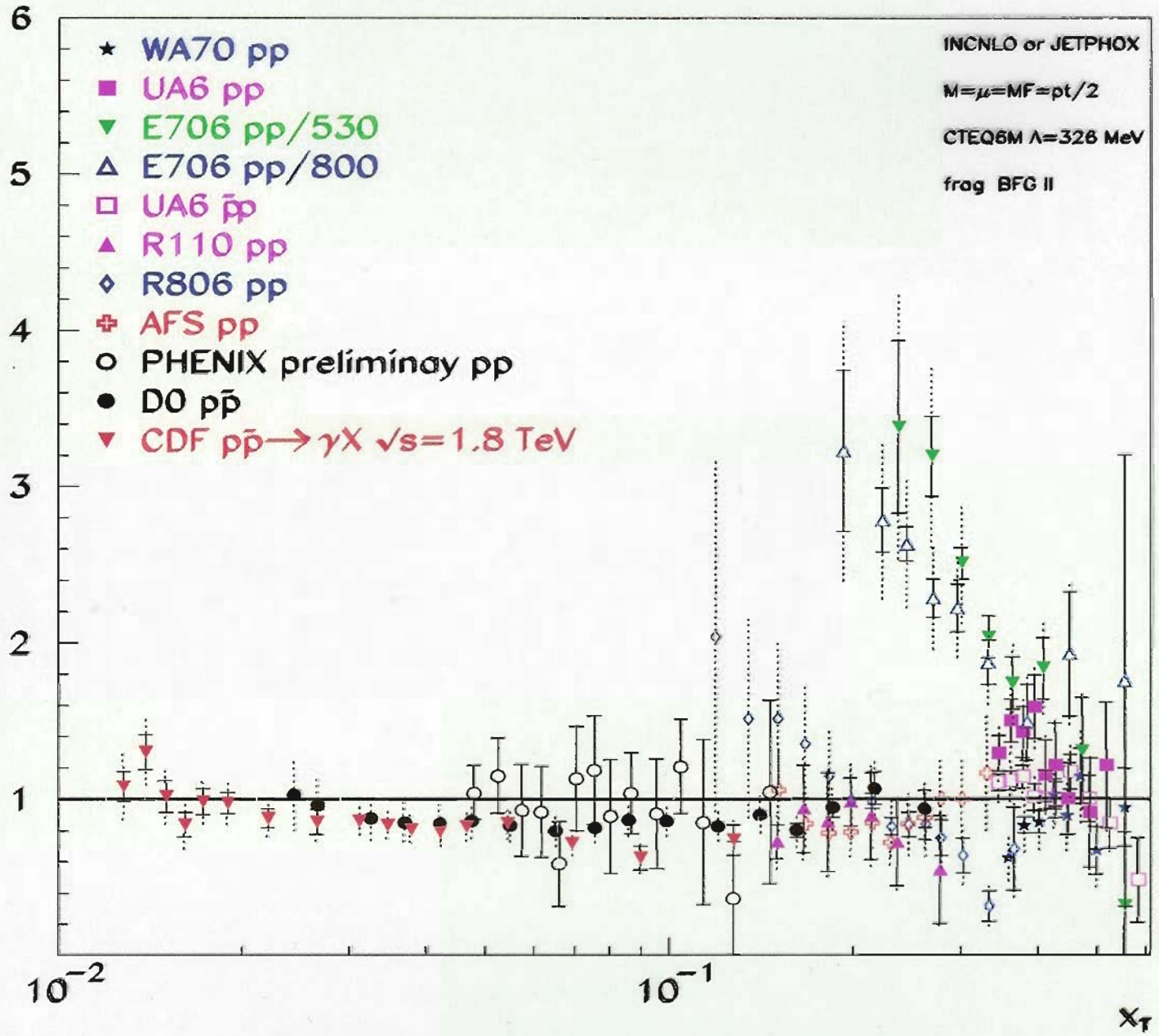

good agreement data vs theory, no primordial "k_T" needed (E706 ?),
scale uncertainties : p_T better at high energy.

At LHC :

$p_T > 20$ Gev , scales, SF uncertainties : OK. (±20%)

lower $p_T \Rightarrow$ lower $x_T = \frac{2p_T}{\sqrt{s}}$

$p_T = 3$ Gev/c $\quad x_T = 7.\,10^{-4}$
$= 10$ Gev/c $\quad = 3.6\,10^{-3}$

} not explored yet
$D_{\gamma/G}$ important (±50%)

Is pQCD reliable ?
Resummation : Laenen, Stavenga, Vogelsang

$\Rightarrow$ Important to measure γ, γ^* in pp

Note : $\frac{d\sigma}{d\vec{p}_T}^{ee} = C \alpha \frac{d\sigma}{d\vec{p}_T}^{\gamma}$

$C = .3 \quad .2 < m_{\gamma^*}$ [Gev] $< .6$
$= .2 \quad 1. < m_{\gamma^*}$ [Gev] $< 3.$

for $p_T > 5$ Gev/c

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b) A-A collisions

- Initial state nuclear effects:
shadowing / antishadowing, several parametrisations :
EKS, rather strong gluon suppression

at small x $\Rightarrow$ suppression of γ at $p_T < 20$ GeV/c

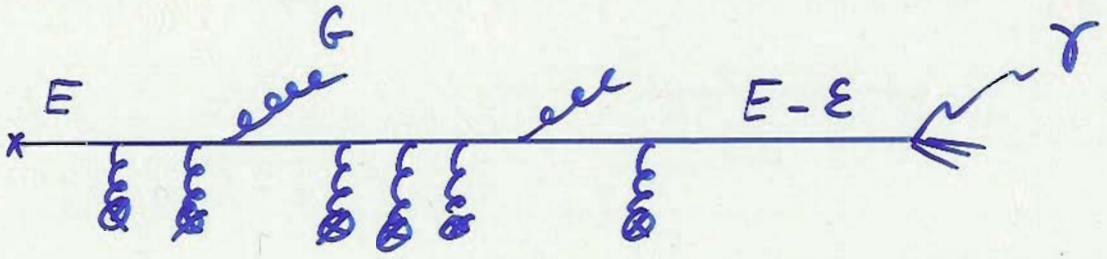
Hirai - Kumano - Migama
de Florian - Sassot

less suppression

- Final state effects

Only on bremβ photons, important for lower p_T values

Energy loss or BDMPS effet or LPM effect



ε parton energy loss

$\Rightarrow$ Fragmentation function modified (as for had)

$$z D^{med}_{\partial/p}(z, E, M^2) = \int_0^{(1-z)E} dz \; P(\varepsilon, E) \; z^* D^{vac}_{\partial/p}(z^*, M^2)$$

Huang, Wong

$$z = \frac{E^\gamma}{E} \qquad z^* = \frac{E^\gamma}{E - \varepsilon} > z$$

$P(\varepsilon, E)$: probab parton of Energy E loses ε.

Model : . assume Poisson distrib. of gluon emission
. use medium induced gluon spectrum of BDMPS:

$$\omega \frac{dI}{d\omega} \sim \alpha \sqrt{\frac{\omega_c}{\omega}} \qquad \omega \ll \omega_c$$

$$\sim \alpha \left(\frac{\omega_c}{\omega}\right)^2 \qquad \omega \gg \omega_c$$

$$\boxed{\omega_c = \frac{1}{2} \hat{q} L^2}$$

$\hat{q}$: transport coef.

L : path length.

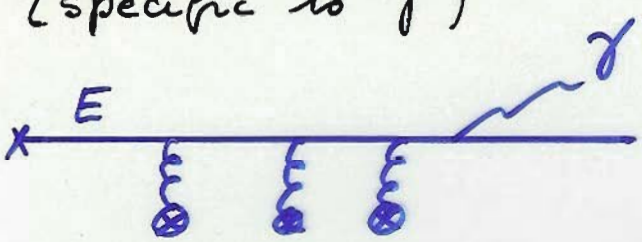
Constraints from energy loss at RHIC

At LHC : $\omega_c \sim 50$ GeV. FIG R_{AA}

Large effect at lower p_T : importance of brem.

- **Final state effects (cont'd).**

Photon can be emitted in medium: enhanced γ prod (specific to γ)



Zakharov

He writes :

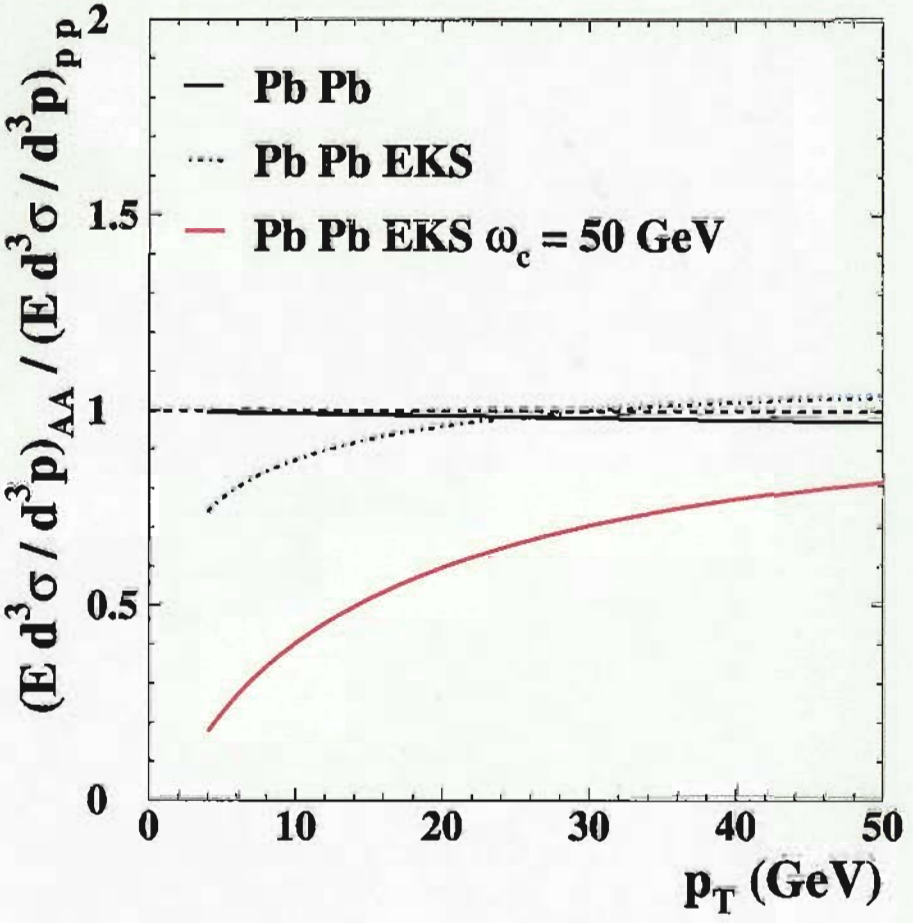
$$D^{med}_{\partial/q}(z,E) = D^{rac}_{\partial/q}(z,E) + D^{ind}_{\partial/q}(z,E) \qquad z = \frac{E_\gamma}{E}$$

γ quenching at LHC

F. Arleo

ntroduction
Single inclusive production
Proton – proton
Nucleus – nucleus
- Ingredients
- Model
- Probability distribution
- Medium-modified fragmentation functions
- π quenching
- γ quenching
- γ / π
- γ quenching at LHC
- Limits

Correlations
Results
Summary



- Shadowing corrections below $p_\perp \lesssim 20$ GeV
- Pronounced energy loss effects

Using "light-cone path integral" formalism (of energy loss)

$$D^{ind}_{\gamma/q}(z,E) \sim \alpha\alpha_s \frac{z^2+(1-z)^2}{E\,(1-z)} \quad L^2 \,, \quad \frac{E(1-z)}{m_q^2} > L$$

$1/z$ of bremsb. $\rightarrow$ $1/(1-z)$ $\rightarrow$ large enhancement

"from suppression of emission at small z due to finite size effects"

FIGS: Zakharov $R_{AA} = \frac{dN^{\gamma}_{AA}}{dN^{\gamma}_{pp}}$ w and w/o. gluon emission

$\Rightarrow$ induced emission and energy loss ~ compensate

- Final state effects (cont'd)

Recently (Turbide, Gale, Jeon, Moore) considered γ emission by fast partons in QGP in Field Theoretic approach $\Rightarrow$ several advantages:

- do not assume fixed scatt. centers in medium
- for quark-gluon plasma at T, all is known:

  f_q, f_G known,

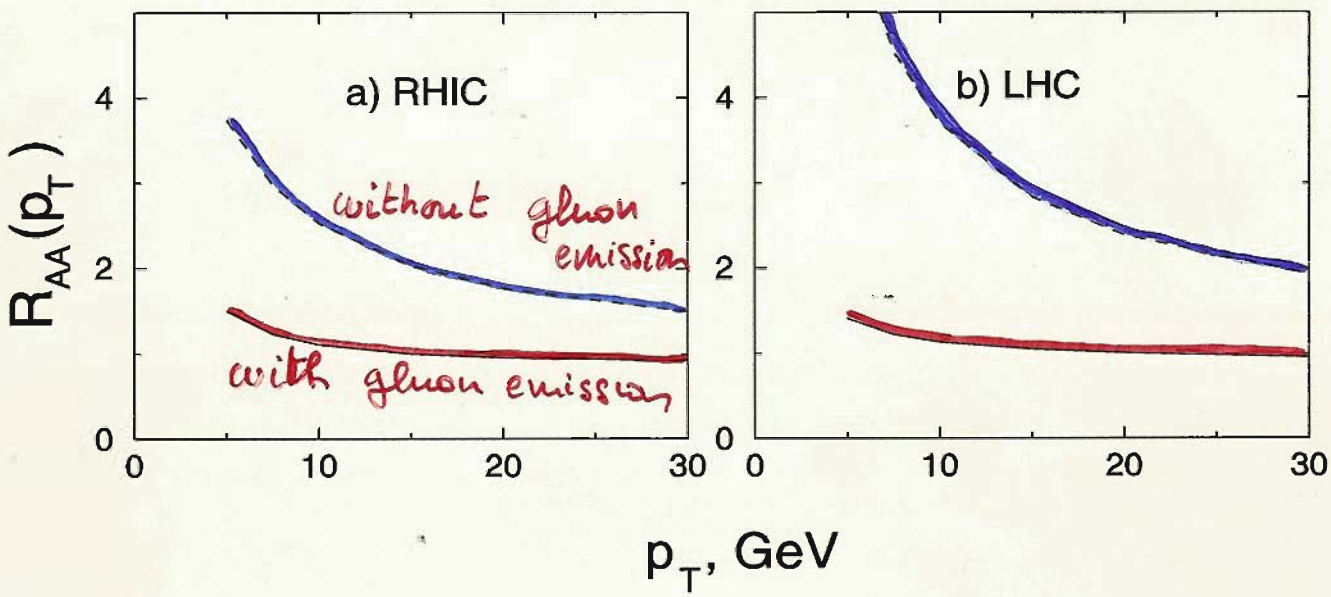
  scattering X-sections, screening masses calculable
- gluon emission and gluon absorption

FIGS: Turbide et al

More later!

(14) (31)

$$R_{AA} = \frac{dN^{\gamma}_{AA}/d\vec{q}_T\,dy}{dN^{\gamma}_{pp}/d\vec{q}_T\,dy}$$



Zakharov 2004
hep-ph/0405101

Note : Rate of γ prod in above processes is

$$\propto \frac{dN^{jet}}{d\vec{p}_T},$$

In pp coll. $\frac{dN^{jet}}{d\vec{p}_T}$ calc. at NLO

- In AA coll. $\frac{dN^{jet}}{d\vec{p}_T} \sim \frac{dN^{parton}}{d\vec{p}_T}$, LO + K factors
- Modifs of $D_{\gamma/p}(z, M_F^2)$ blurs scale compensation between LO ⊕ HO ⇒ scale choice M_F

⇒ AA predictions : L.O. accuracy.

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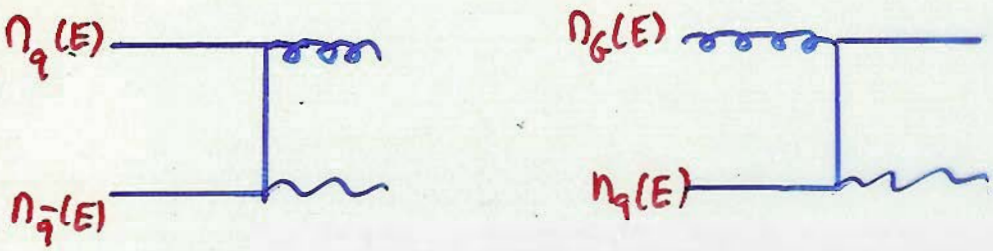
2) Thermal processes

Basic processes same as in prompt γ but ....



Kajantie - Nieminen Shuryak (1981)

$$n_{q,G}(E) = \frac{1}{e^{E/T} \pm 1}$$

unlike in pQCD, integrate over all angles → divergences

$$\frac{E\,dN}{d\vec{p}} \sim \alpha\,\alpha_s \frac{1}{e^{E/T} - 1} T^2 \ln \frac{T^2}{m_q^2}$$

long-distance effects

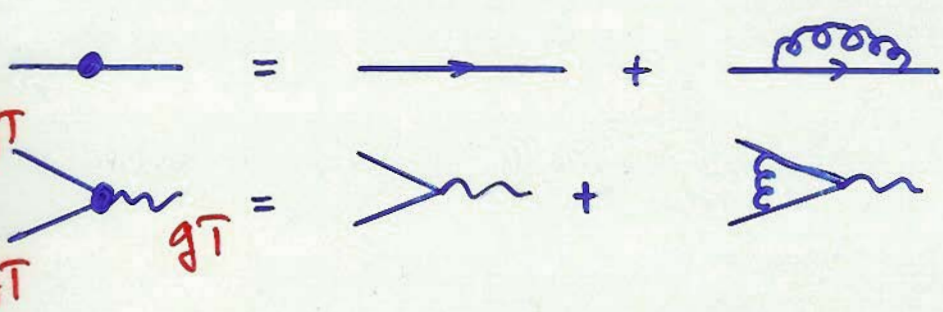
Use Hard Thermal loops resummation (HTL):

(Braaten. Pisarski, Frenkel-Taylor):

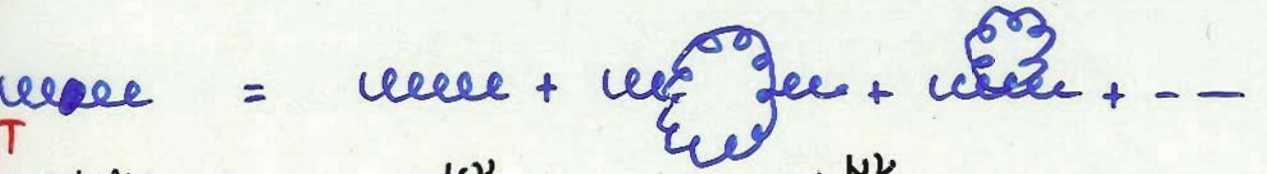
- hard regime : all energy scales $E > T$
- soft regime : $E \sim gT \ll T$, $g \ll 1$.

$\alpha_s = \frac{g^2}{4\pi}$

HTL modify soft propag./vertices



$$m_q^2 = g^2 \frac{T^2}{3}$$



$$\frac{L^{\mu\nu}}{L^2} = \frac{L_T^{\mu\nu}}{L^2 - \Pi_T} + \frac{L_L^{\mu\nu}}{L^2 - \Pi_L}$$

$$\mathrm{Re}\,\Pi_{T,L} = m_D^2 \, f_{T,L}(l_0/l)$$

$$\mathrm{Im}\,\Pi_{T,L} = m_D^2 \, g_{T,L}(l_0/l)$$

$$m_D^2 = \frac{g^2 T^2}{3}\left(N_c + \frac{N_F}{2}\right)$$

Construct pert. expansion in effective theory:

- 1 loop :

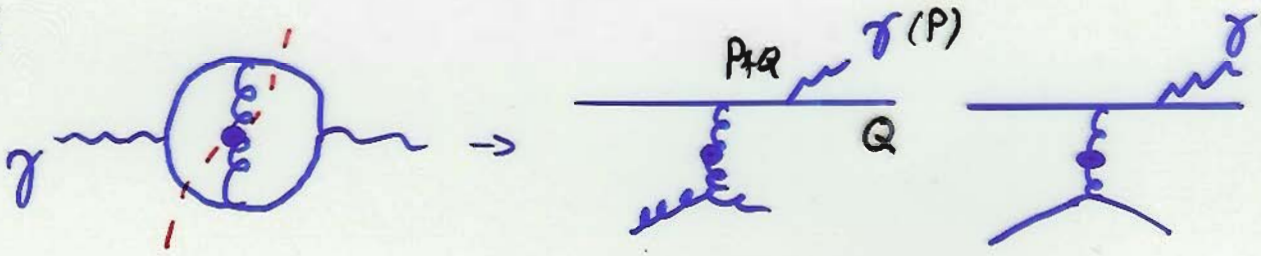
⇒ Compton + Annihilation

Baier et al
Kapusta et al

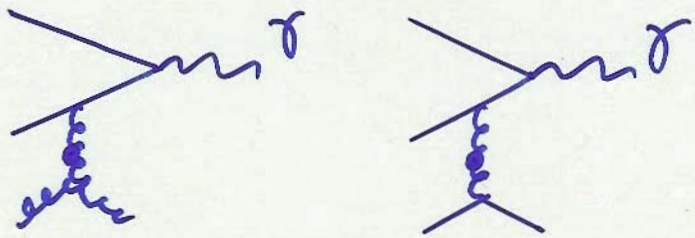
$$\frac{E\,dN}{d\vec{p}} \sim \alpha\,\alpha_s T^2 \left[\ln \frac{ET}{m_q^2} + \text{const} \right] \frac{1}{e^{E/T}-1}$$

($\ln \frac{ET}{m_q^2}$: collinear enhanc.; const: calculated)

- 2 loop :



Bremsstrahlung



Annihil. w. scattering

$$\frac{E\,dN}{d\vec{p}} \sim \alpha\,\alpha_s \left[\frac{T^3}{E} + \frac{1}{\pi^2} ET \right] \frac{1}{e^{E/T}-1}$$

same order as 1. loop : collinear enhanc. $\alpha_s \frac{T^2}{m_q^2} \sim 1$

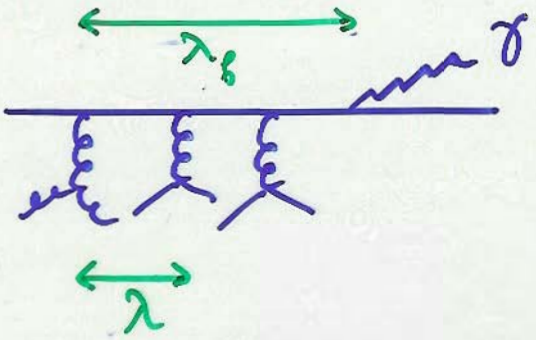
- higher loop :

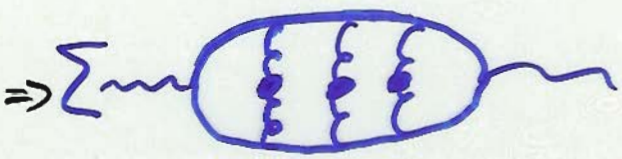
Photon formation length:

$$\lambda_f \sim \frac{1}{\sqrt{(P+Q)^2}} \frac{E+q_0}{\sqrt{(P+Q)\sim}} = \frac{E(E+q_0)}{E(p_T^2+m_q^2)} \sim \frac{T}{m_q^2} \sim \frac{1}{g^2 T}$$

λ_f comparable to $\lambda \sim \frac{1}{n\sigma}$ mean free path

⇒ need to calculate

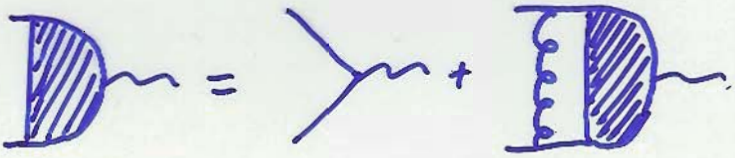




Arnold, Moore, Yaffe

Solve integral equation:

$$E\frac{dN}{d\vec{p}} \sim$$



$$\frac{i}{\lambda_\beta} f(\vec{p}_T) = 2\,\vec{p}_T + 4\pi d_s C_F T \int \frac{d^2 l_T}{(2\pi)^2} C(\vec{l}_T)\left[f(\vec{p}_T+\vec{l}_T) - f(\vec{p}_T)\right]$$

collision kernel : $C(\vec{l}_T) = \dfrac{m_D^2}{l_T^2\,(l_T^2 + m_D^2)}$

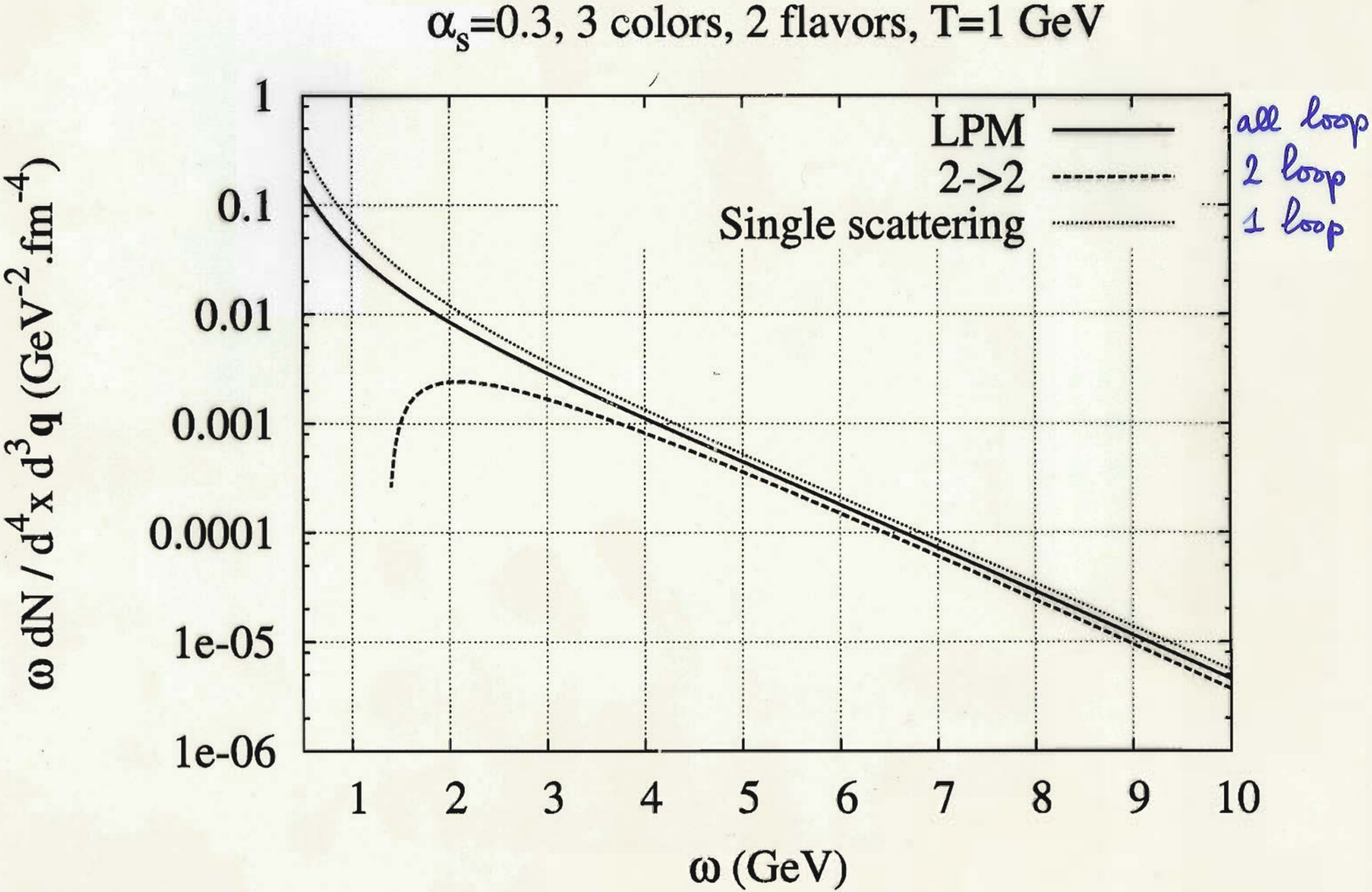
$$\frac{E\,dN}{dp^3} \sim \alpha \frac{1}{e^{E/T}-1} \int_{-\infty}^{\infty} dp_0 \left(n_F(p_0+E) - n_F(p_0)\right) \frac{p_0^2 + r_0^2}{(p_0 r_0)^2}\, \mathrm{Re} \int \frac{d^2 p_T}{(2\pi)^2}\, \vec{p}_T \cdot f(\vec{p}_T)$$

Limits :

$$E\frac{dN}{dp^3} \sim \alpha d_s T^2 \sqrt{\frac{T}{E}} \qquad E \ll T \qquad \text{brem}\beta$$

$$\sim \alpha d_s T^2 \sqrt{\frac{E}{T}} \qquad E \gg T \qquad \text{annihil } 3\to 2$$

Landau-Pomeranchuk-Migdal effect : $\lesssim 20\%$ at LHC


α_s=0.3, 3 colors, 2 flavors, T=1 GeV
LPM
2->2
Single scattering
all loop
2 loop
1 loop
$\omega\, dN / d^4x\, d^3q$ (GeV^{-2}.fm^{-4})
1
0.1
0.01
0.001
0.0001
1e-05
1e-06
1
2
3
4
5
6
7
8
9
10
ω (GeV)

(22) FIG : 1, 2, n loop : $E\frac{dN}{dp^3}$ spectrum $T = 1$ GeV

Note : lepton pair produc. at large energy can be treated in same way :

1. loop : Traxler, Thoma

2. loop, n. loop

FIG : $\frac{dN}{dp^4}$ spectrum vs m_{γ^*} at $E_{\gamma^*} = 5$ GeV

Phenomenology :

A A collisions : • "prompt" γ produc includ. e-loss

• thermal photons :

CERN Yellow_report hep-ph/0311131

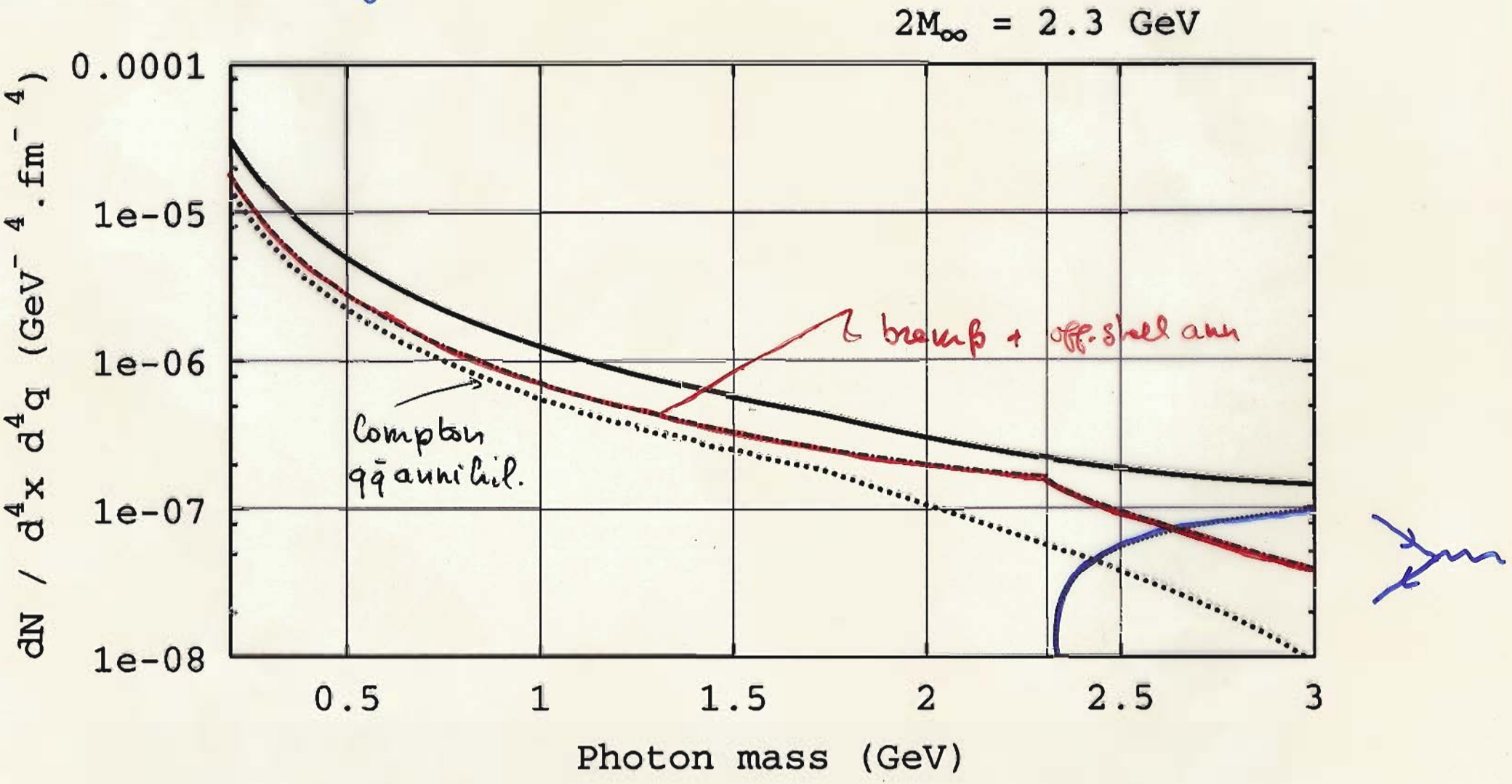
Rate calc. included in hydrodyn. code of Eskola, Niemi, Räsänen, Renk

FIG. . $E\frac{dN^\gamma}{d\vec{p}}$ at RHIC vs PHENIX direct γ

. Phenix γ^* data

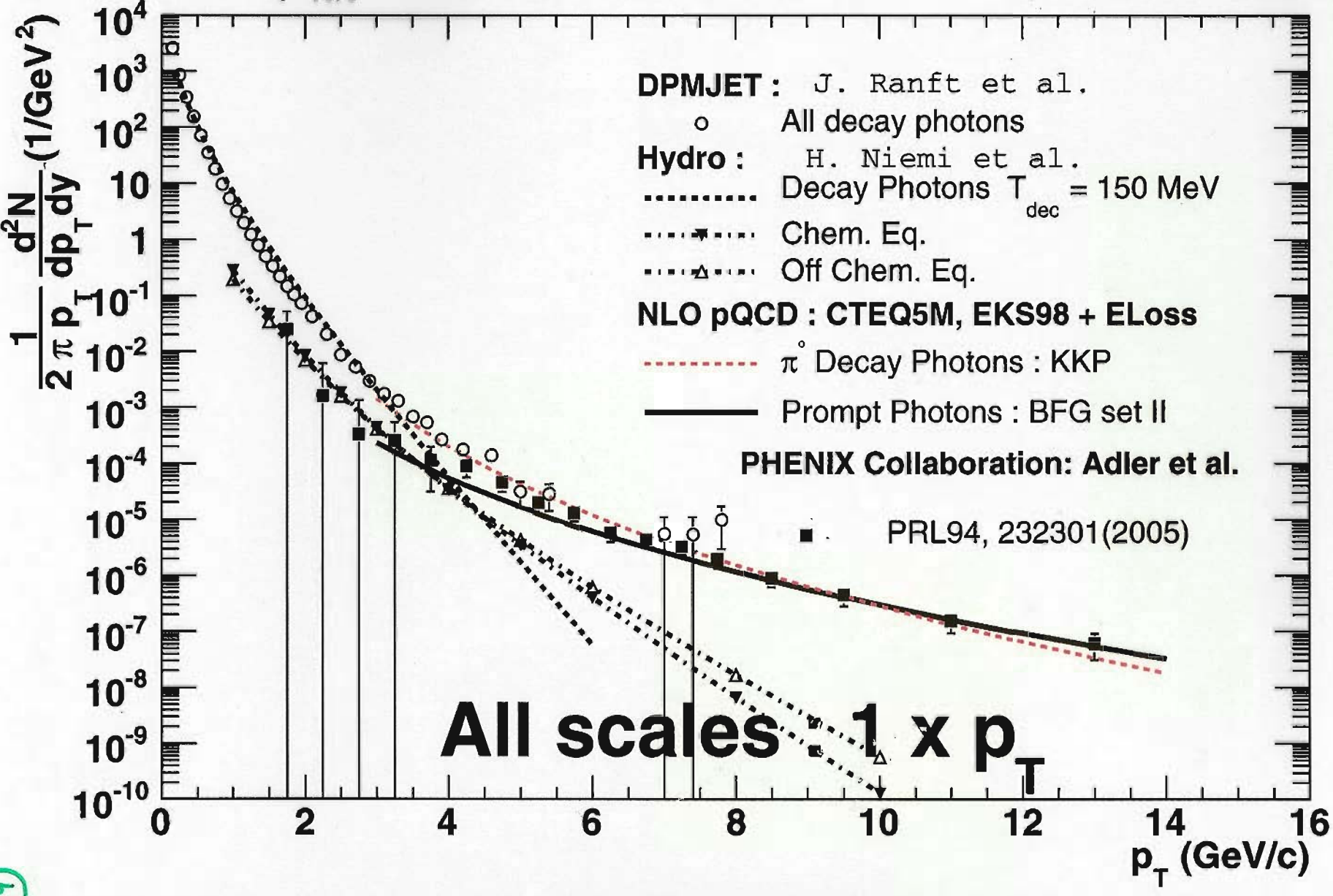
• $\gamma_{all}/\gamma_{background}$

$E_{\gamma^*} = 5$ GeV

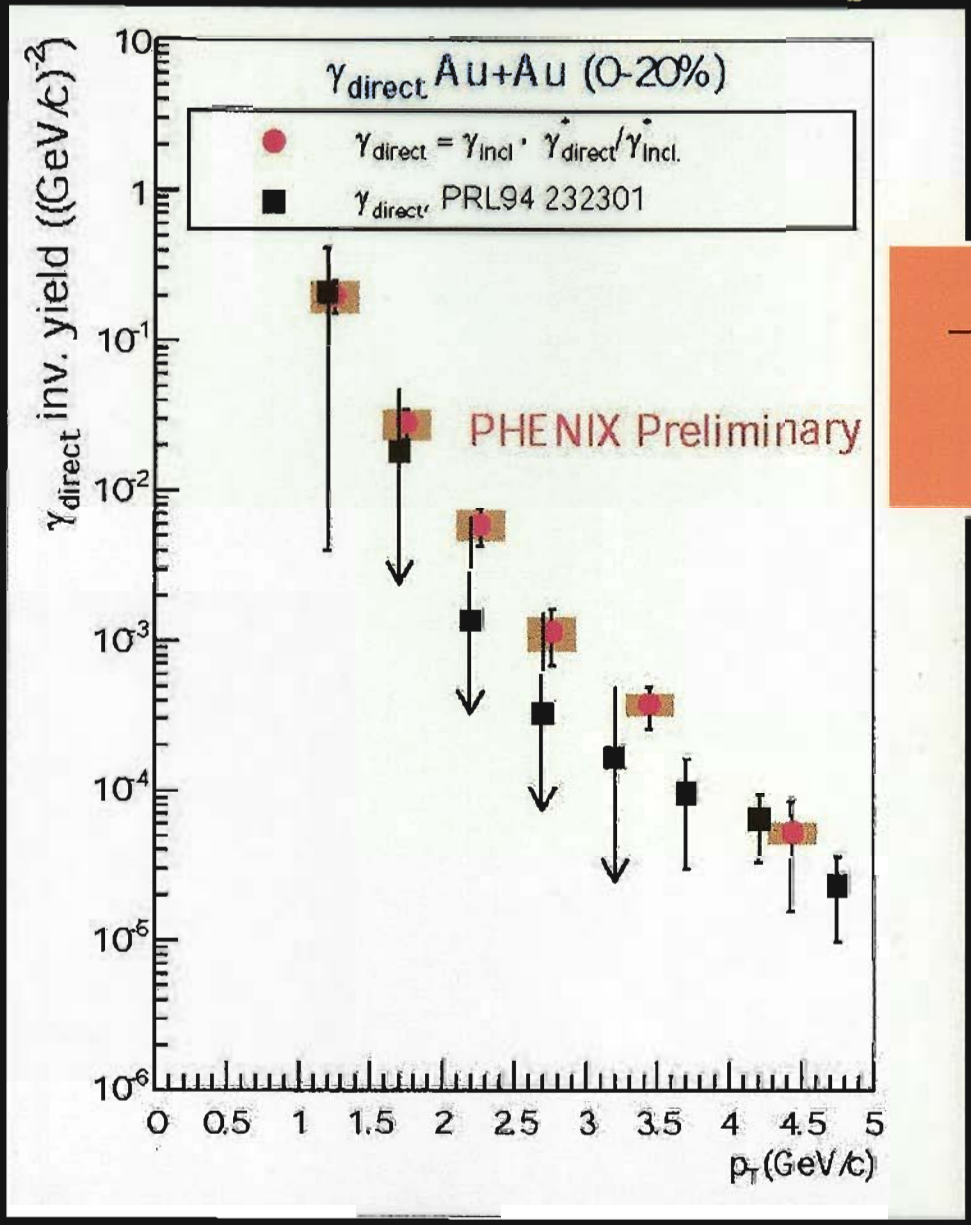

$2M_\infty = 2.3$ GeV
0.0001
1e-05
1e-06
1e-07
1e-08
dN / d^4x d^4q (GeV^{-4}.fm^{-4})
0.5
1
1.5
2
2.5
3
Photon mass (GeV)
brems + off-shell ann
Compton
$q\bar{q}$ annihil.
Born term
rescattering corrections
2->2 processes
Total

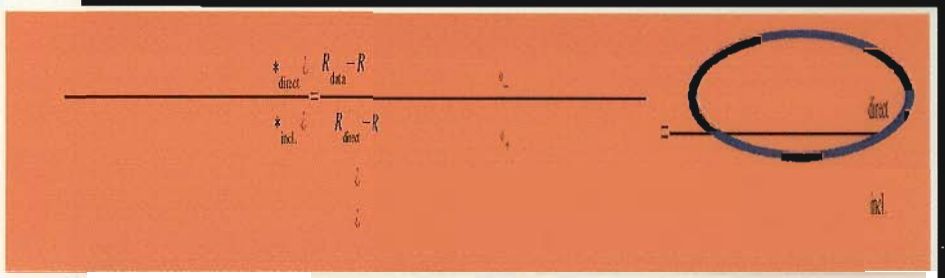
hep-ph/0311131
H. Delagrange

Photons - $\sqrt{s_{NN}}$ = 200 GeV - Au + Au Collisions (0-10 % Central)



The Spectrum



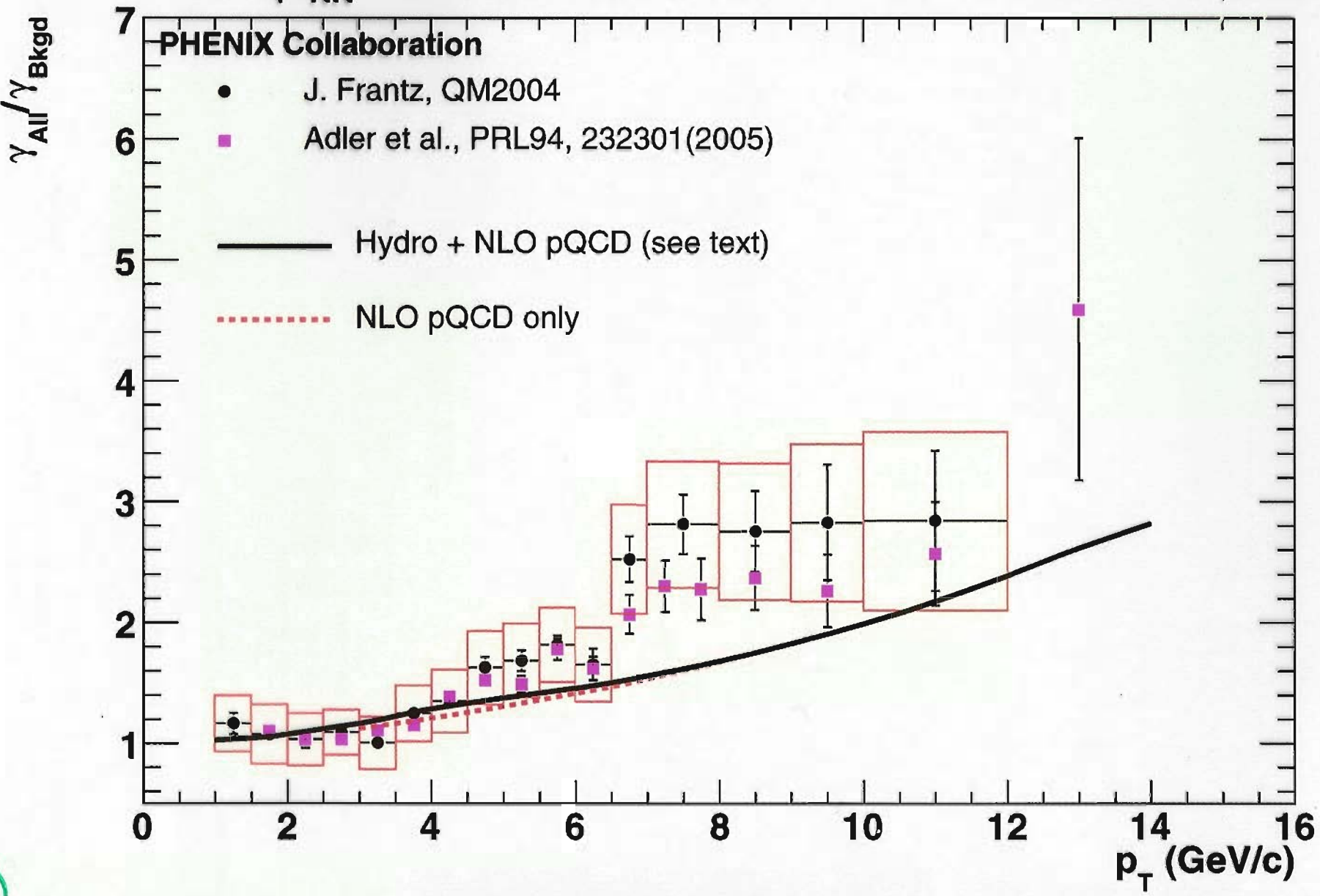


Compare to published Run2 result: PRL94 232301

Y. Akiba
S. Bathe
QM 2005

hep-ph/0311131
H. Delagrange

Photons - $\sqrt{s_{NN}}$ = 200 GeV Au + Au 10 % Most Central Collisions



(17)

For LHC : Hydro init. cond. : $\tau_0 = .1$ fm, $\frac{dN_{ch}}{dy} = 2300$

FIG : $\frac{E\,dN}{d\vec{p}^{\,3}}$ vs p_T : $\gamma^{\text{thermal}} > \gamma^{\text{prompt}}$ for $p_T < 7$ GeV

Large background

Note : insensitivity of thermal photons to chemical equilibrium.

FIG : Dilepton pairs $.2 < M_{ll^*}\,[\text{GeV}] < .6$ vs p_T

At 3 GeV/c : $\gamma^{\text{thermal}} \sim \gamma^{\text{backgd}}$

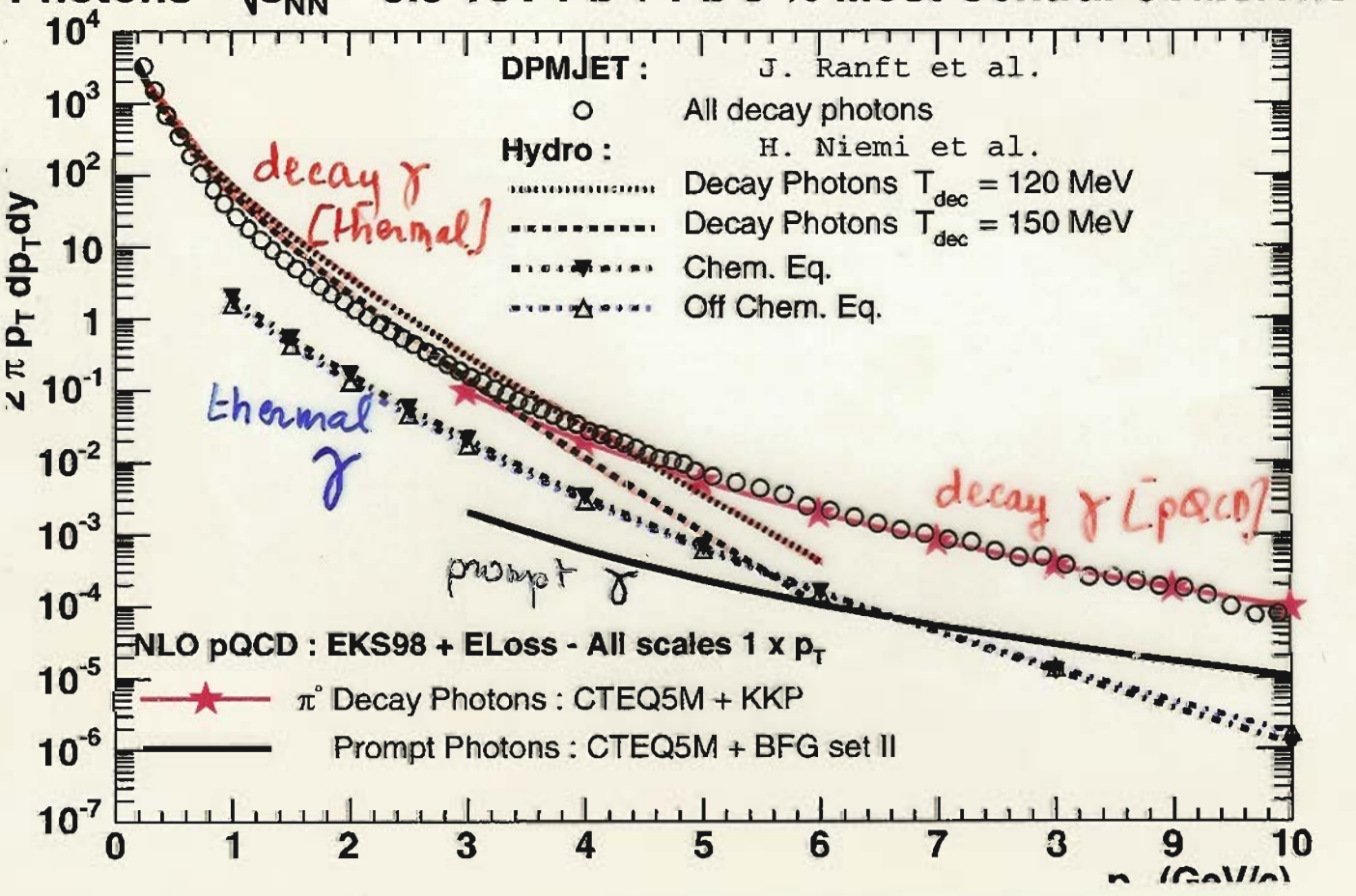
more favorable than real γ.

Pb + Pb → γ [LHC]

decay γ dominates both at low and hi p_T.

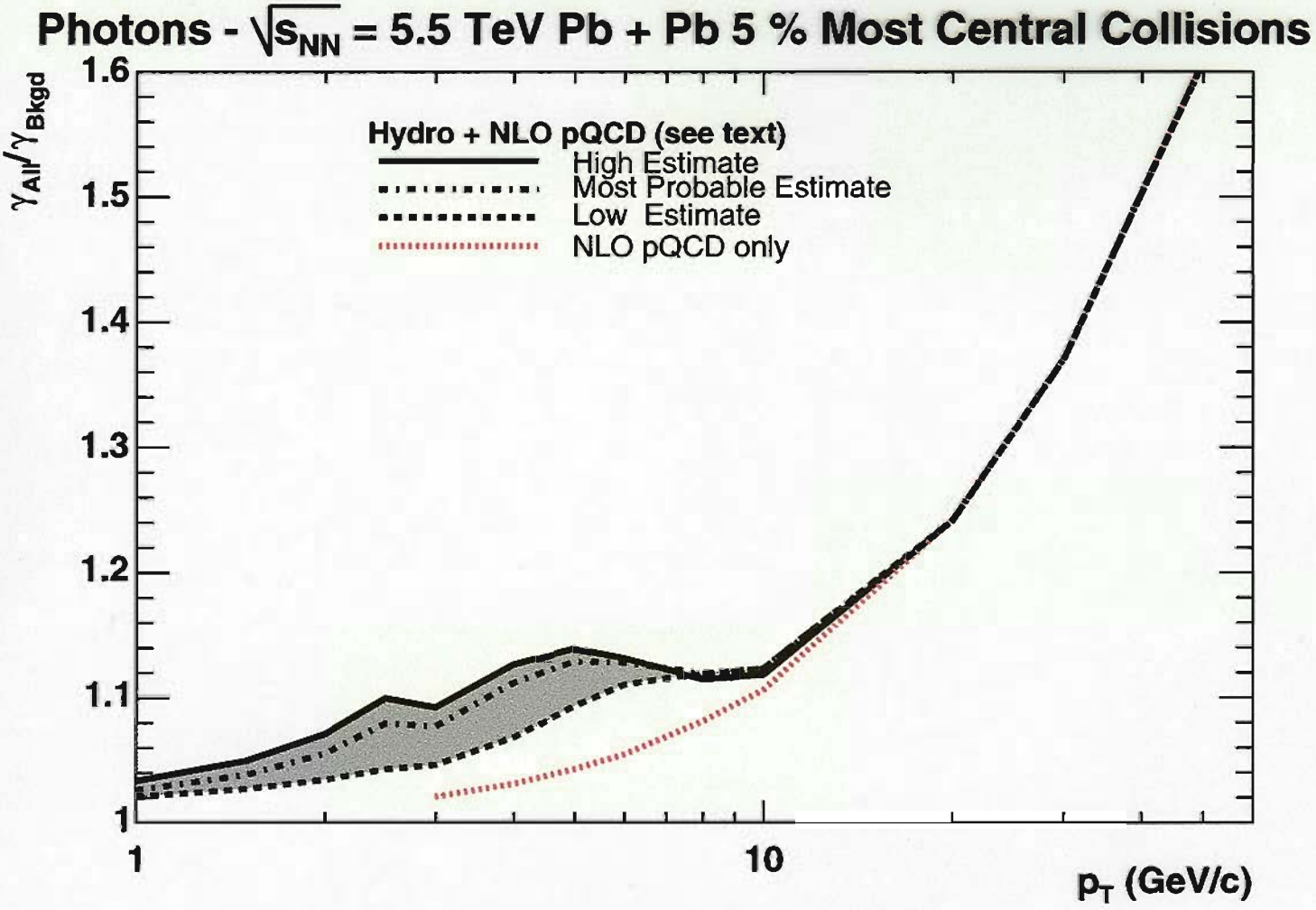
thermal γ prod. > prompt γ prod.
for p_T < 6.7 GeV/c

$\frac{d^2N}{dy\,d\vec{p}_T}$



PHENOMENOLOGY : PHOTONS AT LHC

Arleo et al., hep-ph/0311131, Cern yellow report



Thermal photons gives a 10% excess in "all/decay" ratio at $p_T < 10$ GeV/c.

Is it measurable?

PHENOMENOLOGY : LEPTON PAIRS AT LHC

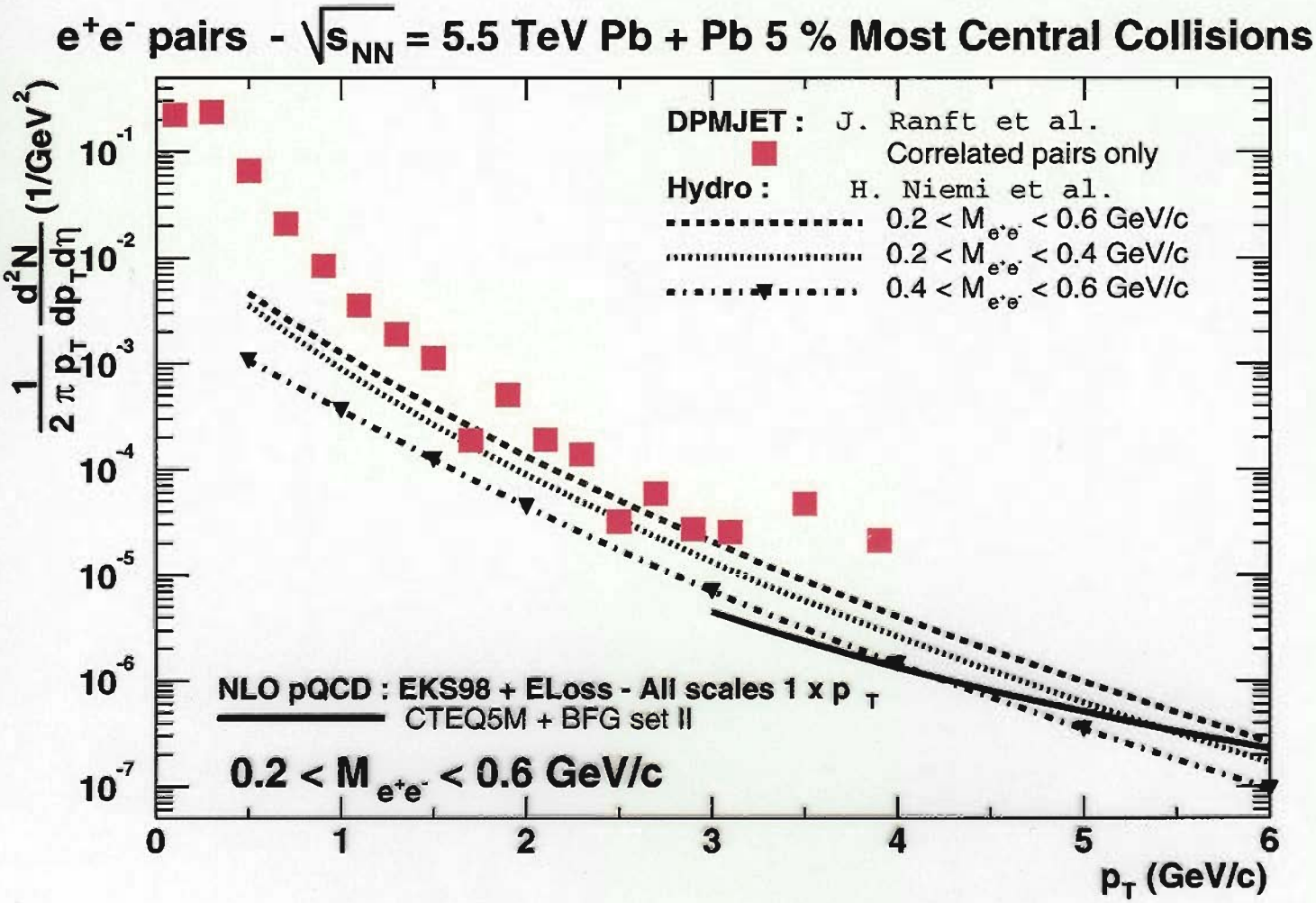
Signal : as for real photons, including photon mass effects

Backgrounds :

At low pair mass : Dalitz decays of π^0, η, $\eta' \to e^+e^-\gamma$, $\omega \to e^+e^-\pi^0$, vector meson decays;

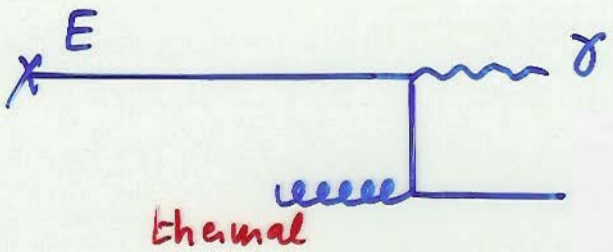
At higher masses : leptons from charm, bottom decays.

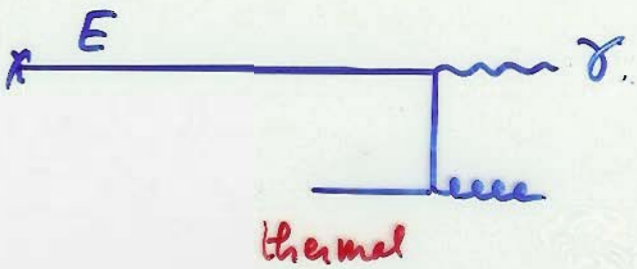
Arleo et al., hep-ph/0311131, Cern yellow report



3] Jet conversion

Fries, Müller, Srivastava





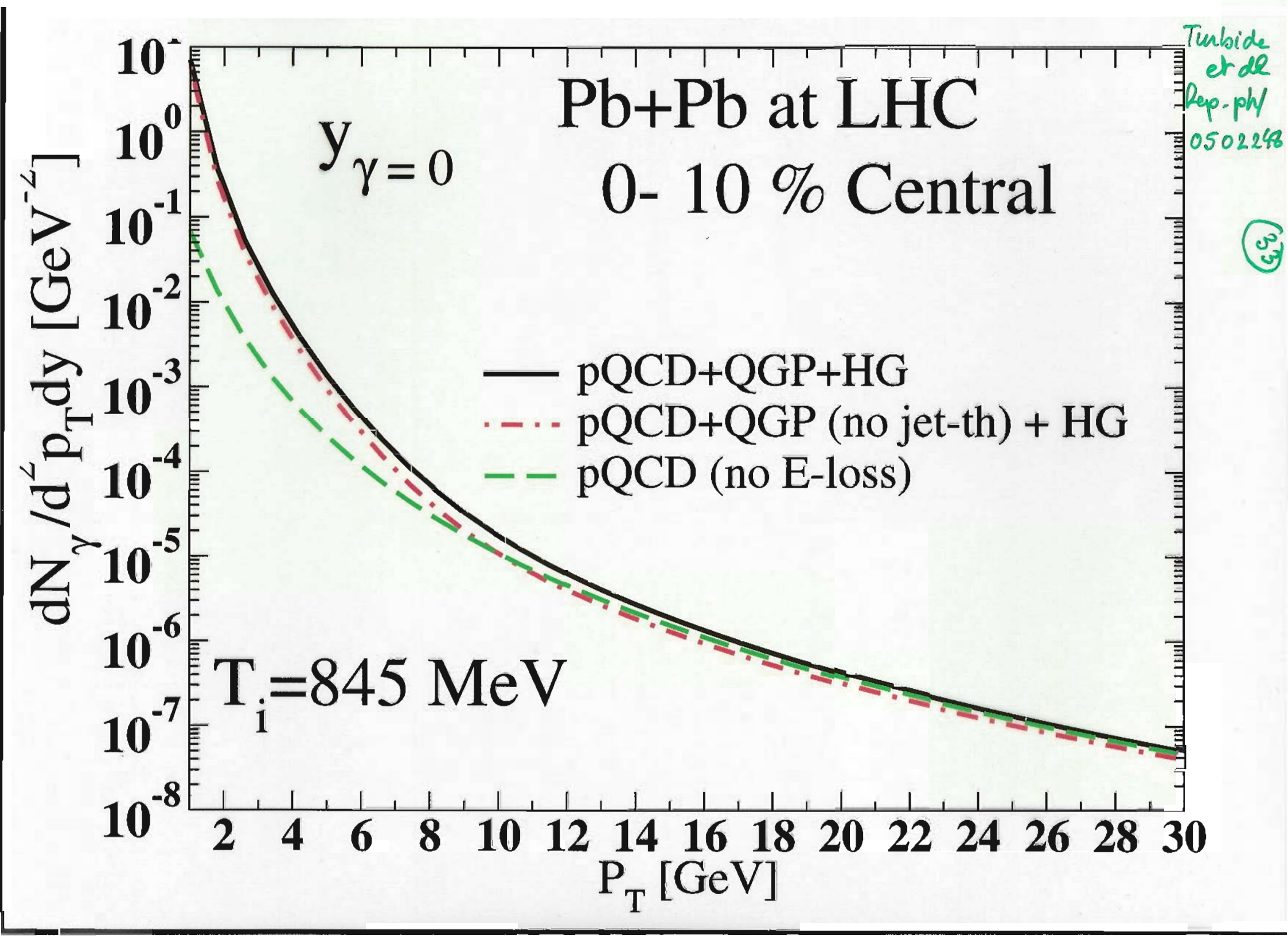
Efficient to produce hard γ : $E \sim E_\gamma$

$$E\frac{dN}{dp^3} \sim \alpha\alpha_s T^2 \left[\ln\frac{ET}{m_q^2} + \text{const}\right]\left[f_q(\vec{p}) + f_{\bar{q}}(\vec{p})\right]$$

⇒ power behaved spectrum

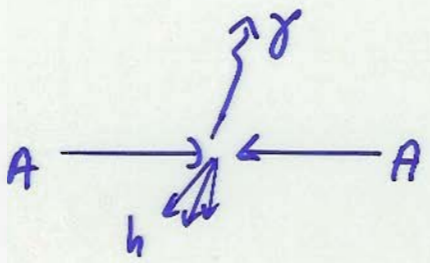
see Ch. Gale talk : dileptons
see S. Jeon talks : γ

FIG


Pb+Pb at LHC
0- 10 % Central
$y_{\gamma=0}$
pQCD+QGP+HG
pQCD+QGP (no jet-th) + HG
pQCD (no E-loss)
T_i=845 MeV
$dN_\gamma/d^2p_T dy$ [GeV^{-2}]
P_T [GeV]
Turbide et al hep-ph/0502248
(33)

PHOTON-HADRON, PHOTON-PHOTON CORRELATIONS

(34) Old idea : use photon to tag opposite side jet



$$p_T^{\gamma} = - p_T^{jet}$$

$$z_h = - \frac{\vec{p}_T^{\,\gamma} \cdot p_T^{had}}{|\vec{p}_T^{\,\gamma}|} \Rightarrow z_{frag} = \frac{p_T^{had}}{p_T^{jet}}$$

Valid at lowest order, collinear fragm. of jet ⇒

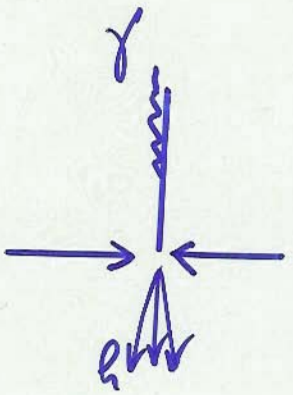
reconstruct $D_{h/p}(z_{frag}, M^2)$, compare p.p and A A

Complication:

. NLO

. Bremsb prod. of γ

} ⇒ $z_h \neq z_{frag}$



Phenomenology :

Take large p_T γ : $p_T^{\gamma} > 25$ GeV/c or 50 GeV/c

look at fragment hadrons opposite : $p_T^h > 5$ GeV/c

Calculate $\frac{d\sigma}{dz_h}$

Compare p p and Pb. Pb at 5.5 TeV.

⇒ Can one distinguish $D_{h/p}^{vac}(z, \pi^2)$ from $D_{h/p}^{med}(z, M^2)$?

(35) FIG : Model fragm. functions (Arleo): suppr ↑ with z.

FIG : $\frac{d\sigma}{dz}$ for $p_T^\gamma > 25$ GeV/c ; 50 GeV/c

and ratio for γ-π^0 correl:

ratio is flat $z > .2$

Reason : 2 production mechanisms

at small z : 1 f γ produced directly $z_h = z_{frag}$

at large z : 2 f γ prod. by brem β $z_h \neq z_{frag}$

FIG : Production mechanisms and ratios.

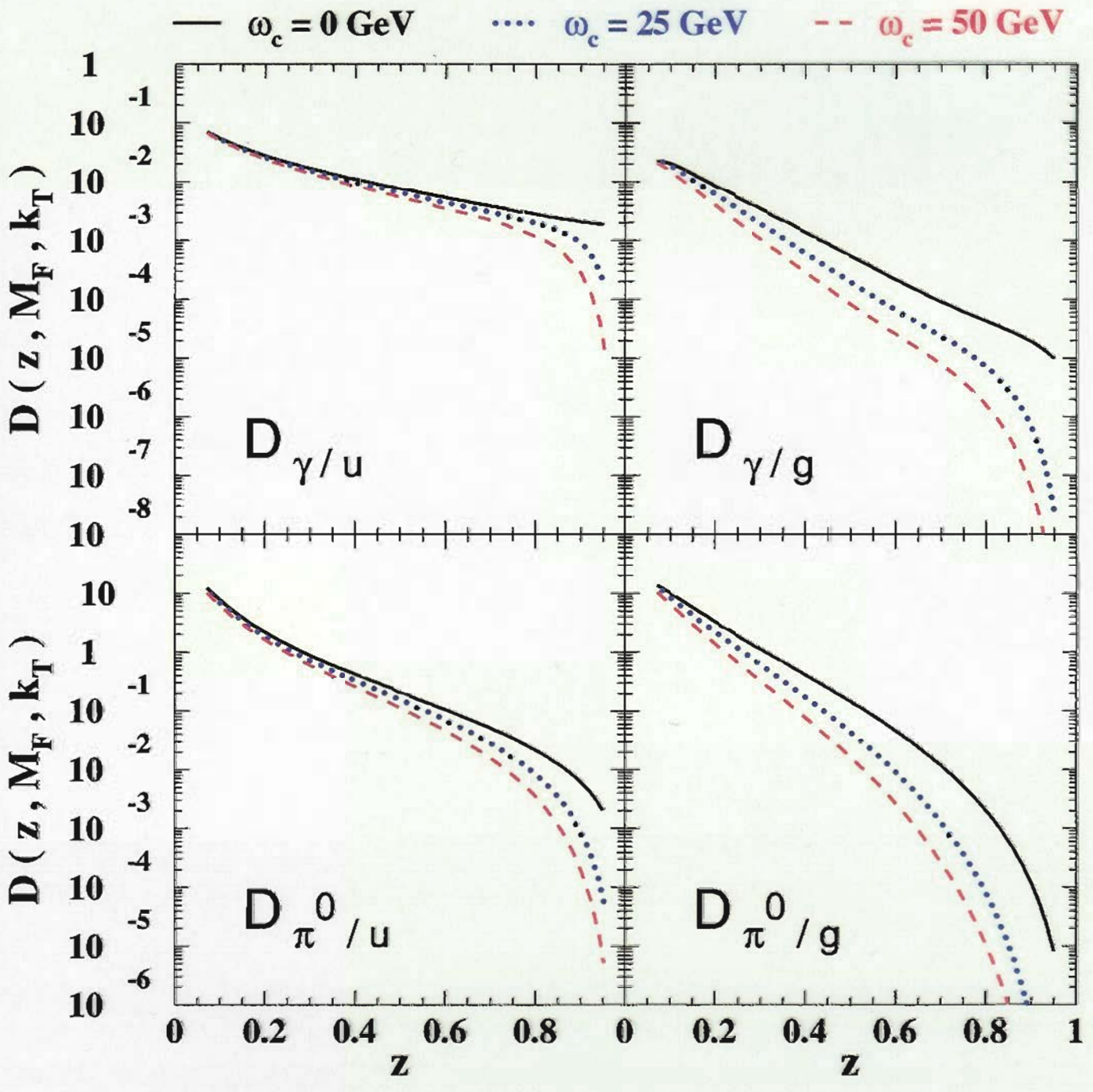
FIG : γ-γ correlations : $\frac{d\sigma}{dz}$, $p_T > 25$ GeV/c ; 50 GeV/c

FIG : Comparison $\frac{d\sigma}{dz}^{\gamma\gamma}$ and $D_{\gamma/q}(z, \pi^2)$

Note : NLO corrections modify $\frac{d\sigma}{dz}$ $z \sim 0$
~ 1

Energy loss model Arleo JHEP 11, 044 (2002)

$k_T = 50$ GeV/c , $\omega_c = \frac{1}{2}\hat{q}L^2$ controls energy loss in medium



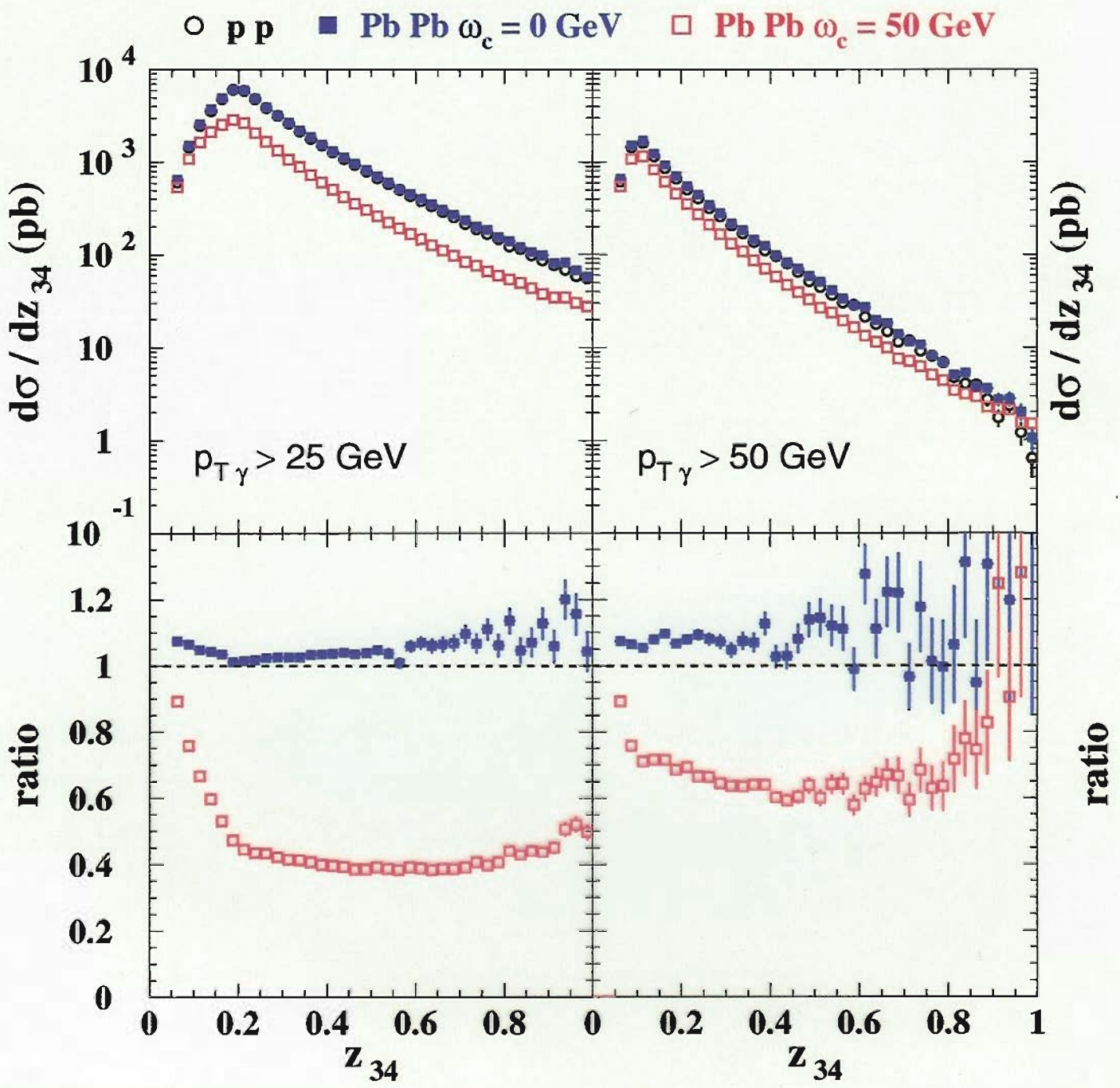
γ - π° correlations

JET RECOILING FROM THE PHOTON

Trigger on a photon (lepton pair) at high p_T on one side and study jet decay properties on the opposite side :

define the scaling variable :

$$z_{34} = -\frac{p_{T\gamma} \cdot p_{T\pi}}{p^2_{T\gamma}} \sim z_{frag}$$



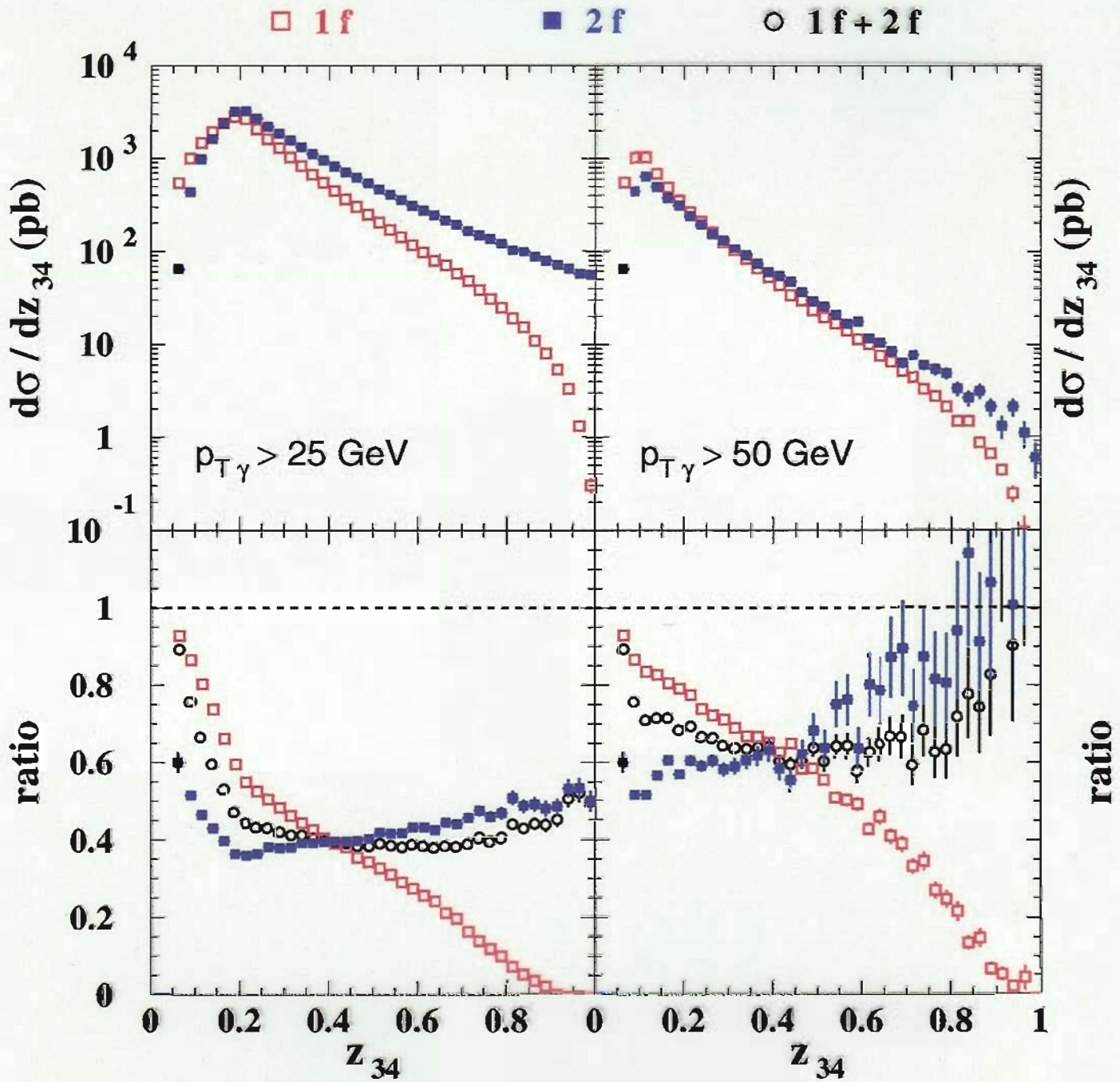
Arleo et al., JHEP 11 (2004) 009

γ - π° correlations

production mechanisms

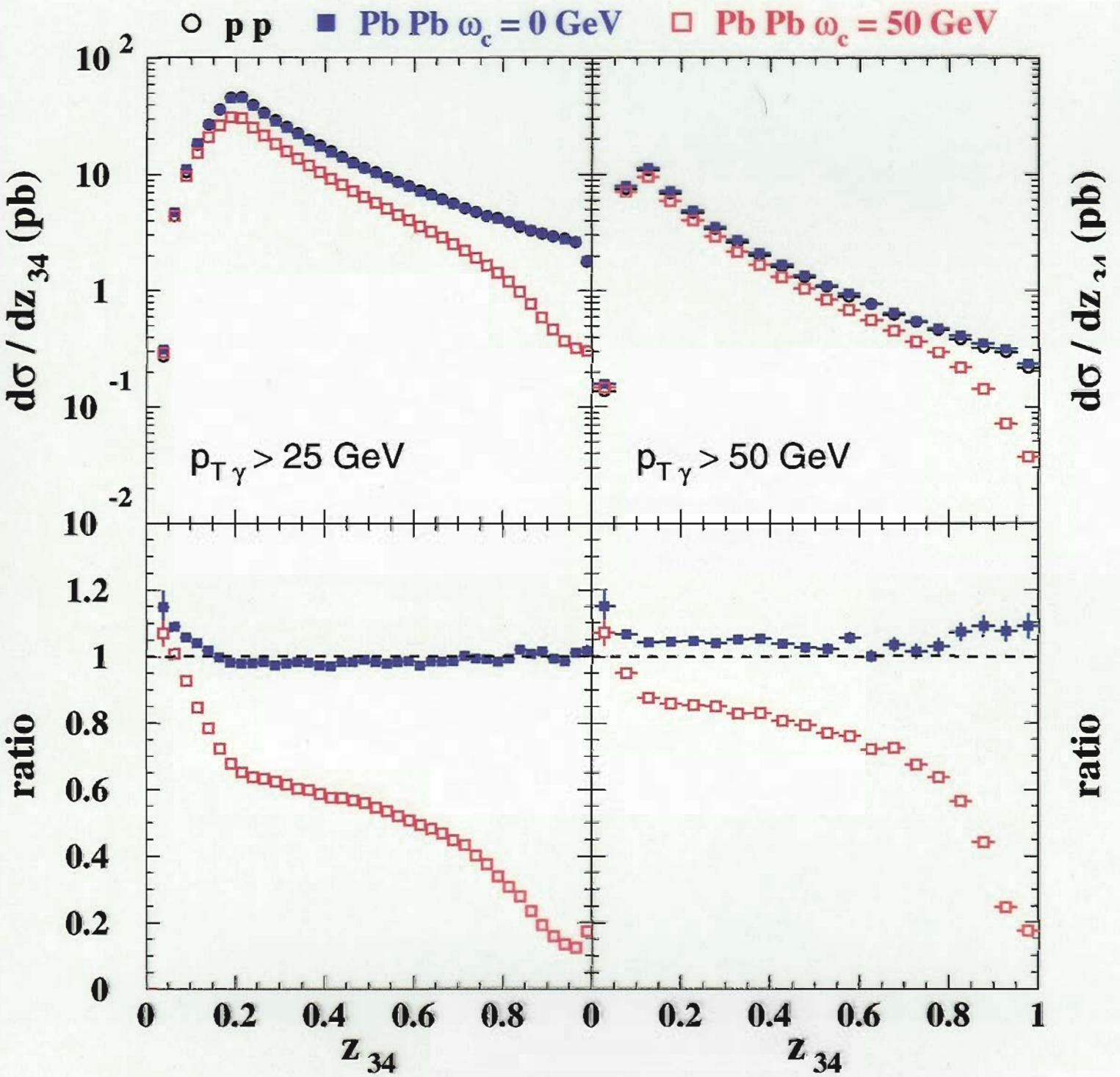
1 f direct γ

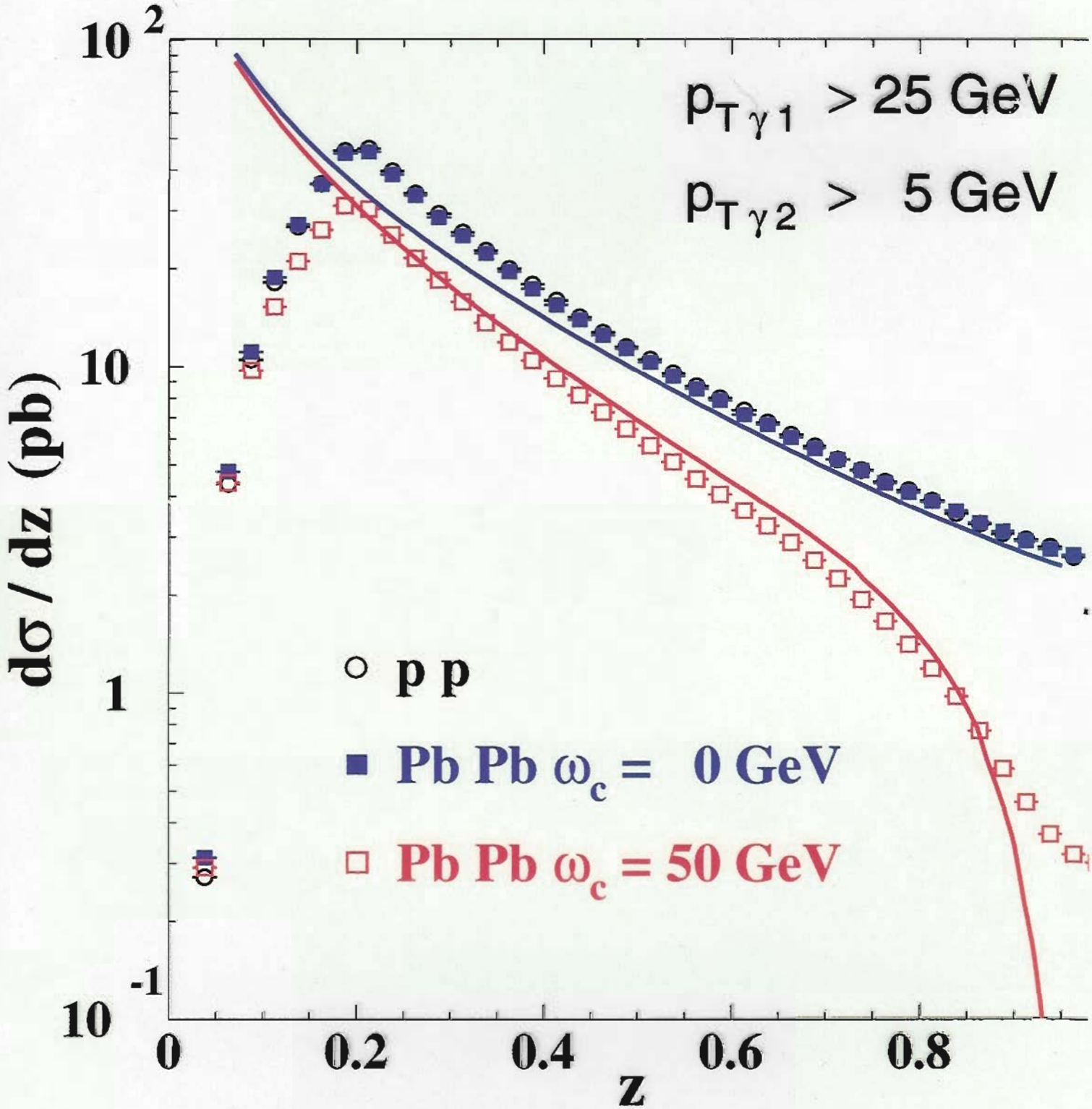
2 f bremsp γ



Arleo et al., JHEP 11 (2004) 009

γ - γ correlation and ratio



Arleo

γ - γ correlations