Exchange of high- and low energy photons in ultraperipheral relativistic heavy ion collisions

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Table of Contents

Ultraperipheral collisions(UPC) at the colliders RHIC(Au-Au, $\gamma = 100$)and LHC(Pb-Pb, $\gamma = 3400$): high flux of photons up to high energies

photon flux $\propto Z^2$, maximum energy $\propto \gamma$

- Theoretical tools to analyse multiphoton processes:

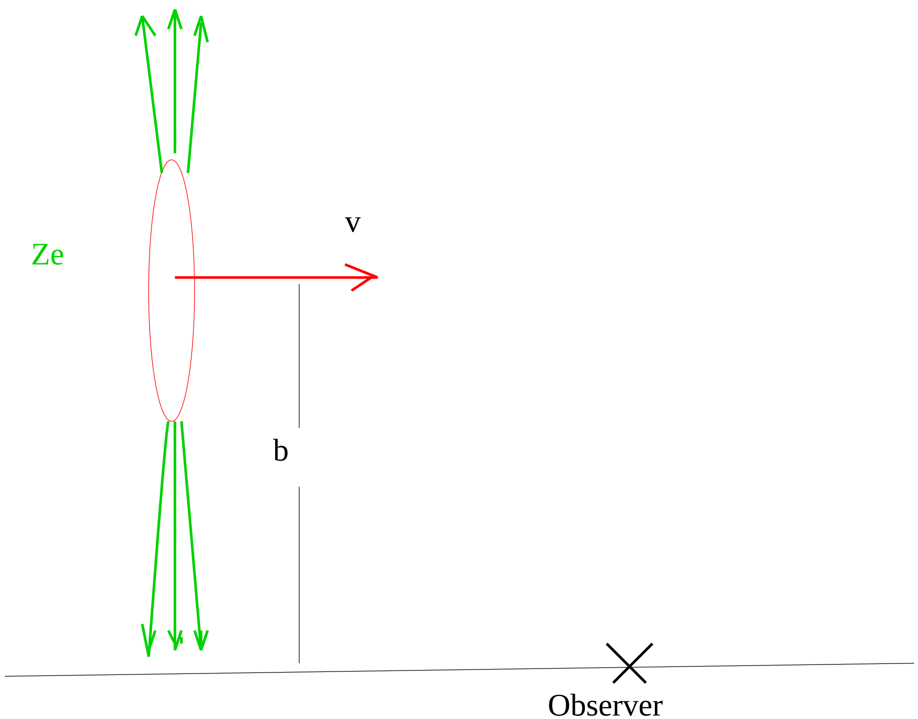
  Semiclassical or Glauber methods
- Photon-hadron collisions
- photons from one or the other ion:

  interference determines $p_\perp$ momentum distribution of produced vector mesons
- Photon-photon collisions:Z^4 enhancement
- a special case: e^+e^- pair production
- strong field effects: multiple pair production
- Conclusion

Ultraperipheral Collisions

UPC: nuclei do not touch each other

$\longrightarrow$ only electromagnetic interaction between the ions



recent reviews

A.J. Baltz et al. Physics Reports 458(2008)1

C.A. Bertulani, S.R. Klein, J.Nystrand, Ann. Rev. Nucl. Part. Sci. 55(2005) 271

G.Baur, K.Hencken, D. Trautmann, S.Sadovsky, Y. Kharlov, Phys. Rep. 364(2002)359

Characteristics of the electromagnetic pulse

Strong electromagnetic field: $E_{max} \sim \frac{Ze}{b^2}\gamma$

short time: $\tau_{\text{collision}} \sim \frac{b}{\gamma v}$ $b > R_{min}$

momentum transfer $\Delta p \sim eE_{max}\tau_{\text{collision}} \sim \frac{Ze^2}{bv}$ independent of γ

Huge cross sections

for soft processes: both useful and a nuisance

excitation of giant dipole resonance (GDR)

e^+e^--pair production:

free pairs: huge, several kb

bound-free pairs: large $\sim$ 100b

the mechanism to produce fast antihydrogen atoms: C.T. Munger, S.J. Brodsky, I.Schmidt, Phys. Rev. D49(1994) 3228; observed at CERN/LEAR (W.Oelert et al. 1996) and Fermilab (1998)

$\rightarrow$ beam loss, local beam pipe heating with danger of quenching of LHC magnets (Spencer Klein)

bound-free pairs measured at RHIC: R.Bruce et al. Phys. Rev. Lett. 99(2007)144801

(Physics News Update October 2007:'The vacuum strikes back')

$\rightarrow$ GDR excitation, followed by neutron emission: signal in Zero Degree Calorimeter: trigger on interesting UPC processes luminosity monitor, at RHIC: M.Chiu et al. PRL 89(2002)012302

Method of equivalent photons

taken from Sebastian White, Erice 2001, Hot Topics in UPC

one-photon process

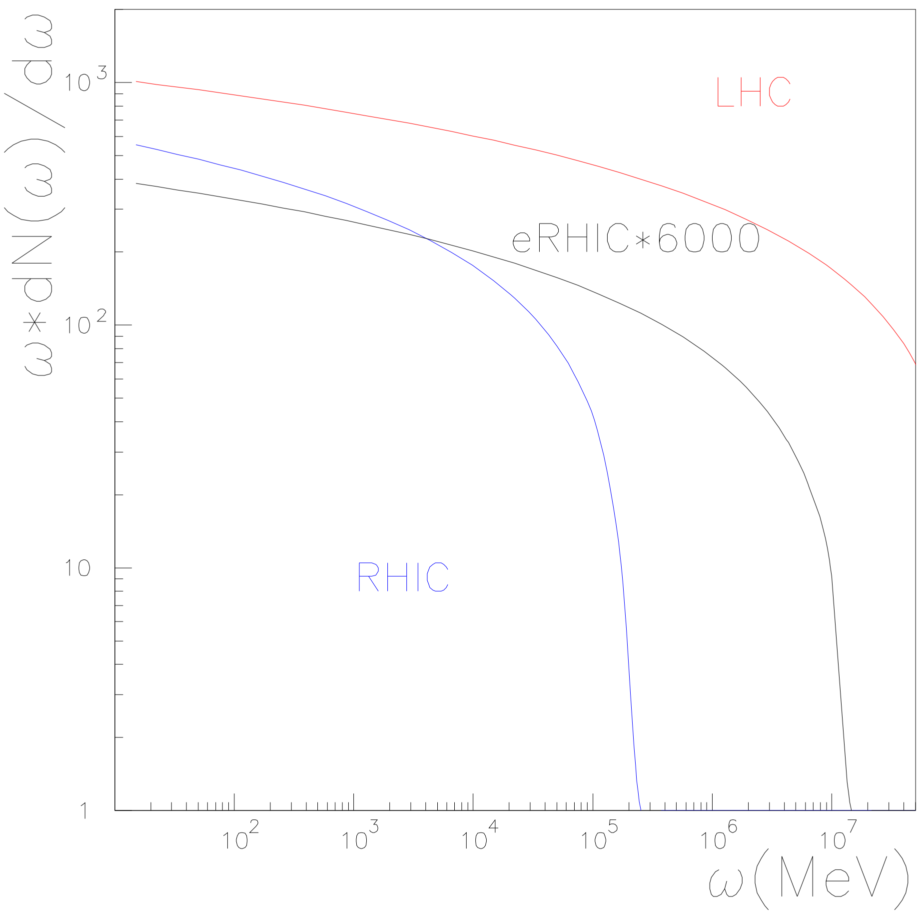
Fermi(1924), Weizsäcker-Williams

factorization:$\sigma = \int \frac{d\omega}{\omega} n(\omega) \sigma_\gamma(\omega)$

soft spectrum

$n(\omega) \sim Z^2 \log \frac{\gamma v}{\omega R_{min}}$

R_{min} is the major uncertainty



Typical maximum equivalent photon energies(in the collider frame!)

$R_{min} \sim 7fm$

for RHIC($\gamma = 100$)$\rightarrow$ $\omega_{max} = 3GeV$

for LHC ($\gamma = 3400$)$\rightarrow$ $\omega_{max} = 100GeV$

now: ω im orbiterframe $n(\omega) \equiv \omega dN/d\omega$

strong fields, for a short time

perturbative treatment

Coulomb parameter $\eta \equiv \frac{Z_1 Z_2 e^2}{\hbar v} \sim \frac{Z_1 Z_2}{137} >> 1$ $\rightarrow$ exchange of many (O(η)) photons in elastic collisions

high photon flux (up to very high energy $\sim \frac{\gamma}{R}$)

For $\eta >> 1$ the ion motion can be treated classically: straight line, with impact parameter b

The ion creates a time-dependent (external) field $A_\mu(b,t)$

time-dependent interaction $V(t) \sim A_\mu \cdot j_\mu$

j_μ ... currents for various (independent) processes, e.g. nuclear GDR excitation, vector meson production, e^+e^- pair production

some simple scaling results, see below

exchange of many photons

in a single fast collision:
many inelastic photon exchanges occur in one collision:

G.Baur, K.Hencken, A. Aste, D.Trautmann und S.R.Klein NPA729(2003)787

matrix-element $< f|e^{i\chi(b)}|i >$

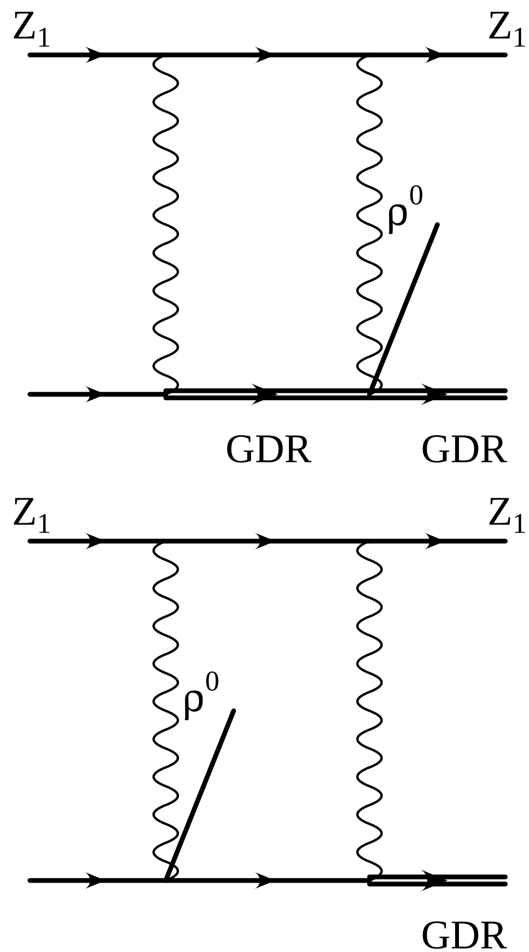
with $\chi(b) = \chi_{GDR} + \chi_{e^+e^-} + \chi_\rho^0 + ...$

Factorization:

probability $P(b) = \prod_i P_i(b)$

where i denotes a specific inelastic channel

Many graphs are summed up in the semiclassical (or eikonal) method

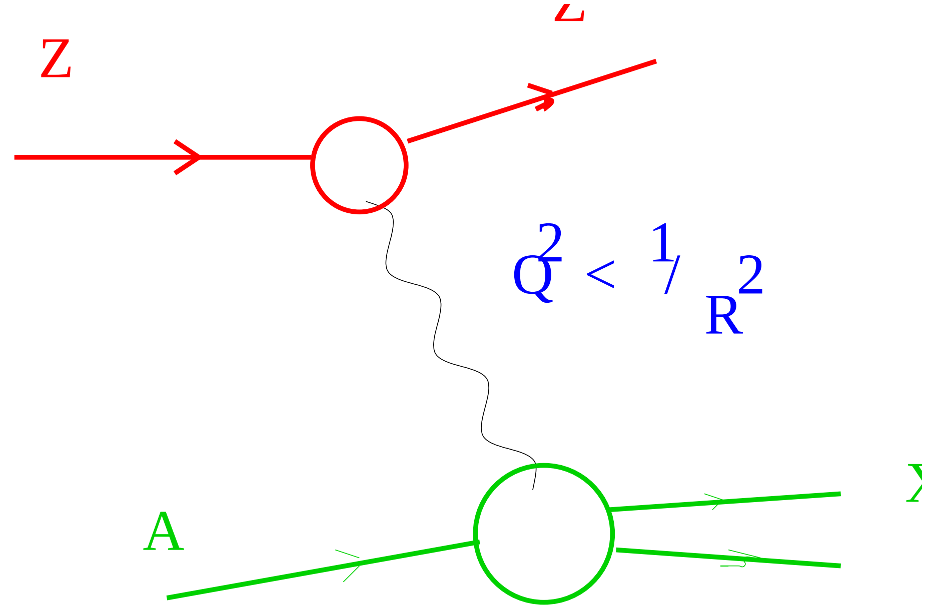


ρ^0 production and GDR excitation in a single collision

Vector meson photoproduction

low-x QCD studies

- Interference and transverse momentum distribution of vector mesons
  S.R. Klein and J.Nystrand PRL 84(2000)2330;
  A.J. Baltz, S.R. Klein, J.Nystrand, PRL 89(2002)012301;
  K.Hencken, G.Baur and D.Trautmann PRL 96(2006)012303
- experimental results for ρ^0 production from STAR: C.Adler et al. PRL 89(2002)272302, B.I. Abelev et al. PRC77(2008)034910
- J/Ψ production at PHENIX



exchange of quasireal photon

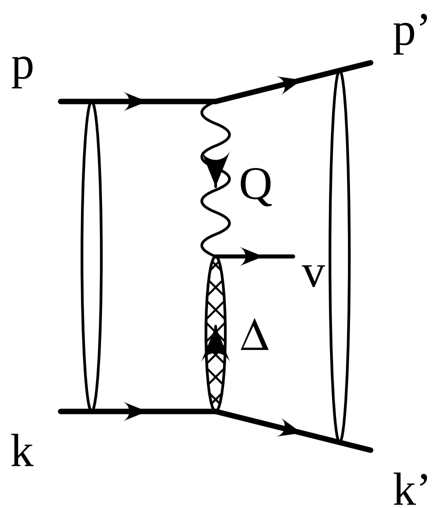
transverse momentum

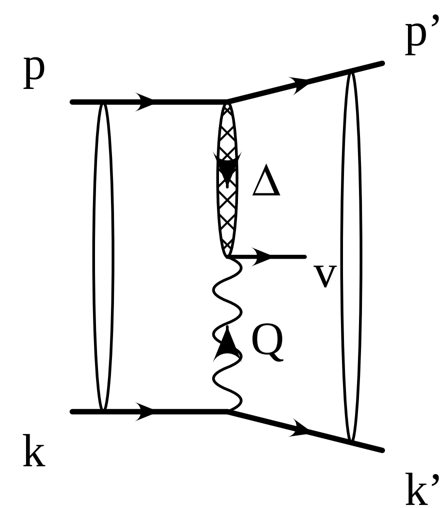
distribution of vector mesons

kinematics:

$p + k \to p^{'} + k^{'} + v$ for reaction $A + A \to A^{(*)} + A^{(*)} + V$ with or without excitation of giant dipole resonance A^*

'direct' process 'exchange' process





factorization of semiclassical excitation amplitudes:

$a_{fi}(b) = a_1(b) a_2(b) a_V(\vec{b}, \vec{v_\perp}, Y)$ ($Q_0 = \frac{m_V}{2} e^Y$)

$P_i(b) = |a_i(b)|^2$ GDR excitation of ion i: $P_i(b) = S/b^2$

with $S = 5.4 \times 10^{-5} Z^3 N A^{-2/3} fm^2$ (TRK-sum rule, $E_{GDR} = 80 A^{-1/3} MeV$)

transverse momentum

distribution of ρ^0 meson production

electromagnetic current (simple model)

$J^\mu(A \rightarrow A+V,Q) = e_V^\mu F_0(Y) exp(-\Delta^2 R_V^2)$

$\vec{\Delta} = \vec{v} - \vec{Q}$

amplitude for vector meson excitation:

$a_V(\vec{b}, \vec{v_\perp}, Y) =$

$= \int d^4Q A^\mu_{ext}(b,Q) \cdot J_\mu(Q)$

$= ZeF_0 \int d^2Q_\perp \vec{Q_\perp} \cdot \vec{e_V} \frac{e^{-i\vec{Q_\perp}\cdot\vec{b}} e^{-R_V^2(\vec{v_\perp}-\vec{Q_\perp})^2}}{Q_\perp^2+(\frac{\omega}{\gamma v}{}^2}$

perpendicular momentum of photon (depends on impact parameter b) is taken into account (small effect, however)

Interference: photon can either come from ion 1 or ion 2:

$a_V^{\mathrm{total}}(\vec{b}, \vec{v}_\perp, Y) = a_V(\vec{b}, \vec{v}_\perp, Y) + \exp(-i\vec{v_\perp}\cdot\vec{b}) a_V(-\vec{b}, \vec{v_\perp}, Y)$

$P(b) = |a_V^{total}|^2 \sim N(\omega,b)\sigma_\gamma$ +interference term

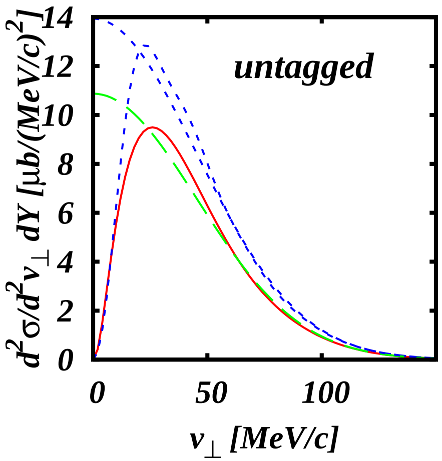
b-dependent equivalent photon number: $N(\omega,b) \sim \frac{Z^2\alpha}{b^2}$ for $0 < \omega < \frac{\gamma v}{b}$

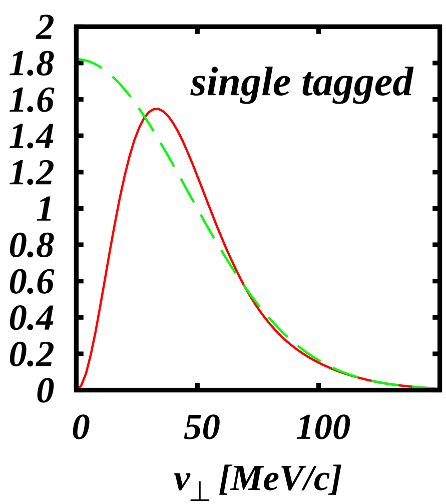
note that $b > b_{min}$

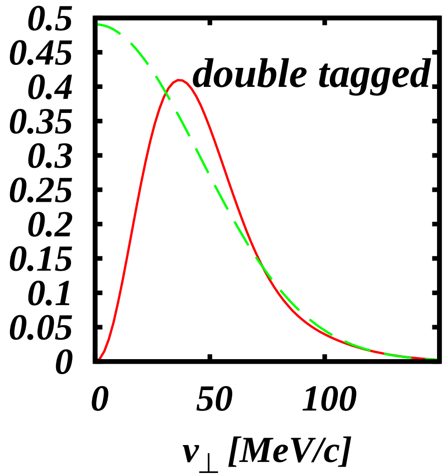
$N(\omega,b) \sim |\int d^2Q_\perp \frac{\vec{Q}_\perp e^{-i\vec{Q}_\perp\cdot\vec{b}}}{Q_\perp^2+(\frac{\omega}{\gamma v})^2}|^2$

numerical results

ρ-production, Y=0, RHIC, Au-Au







with interference

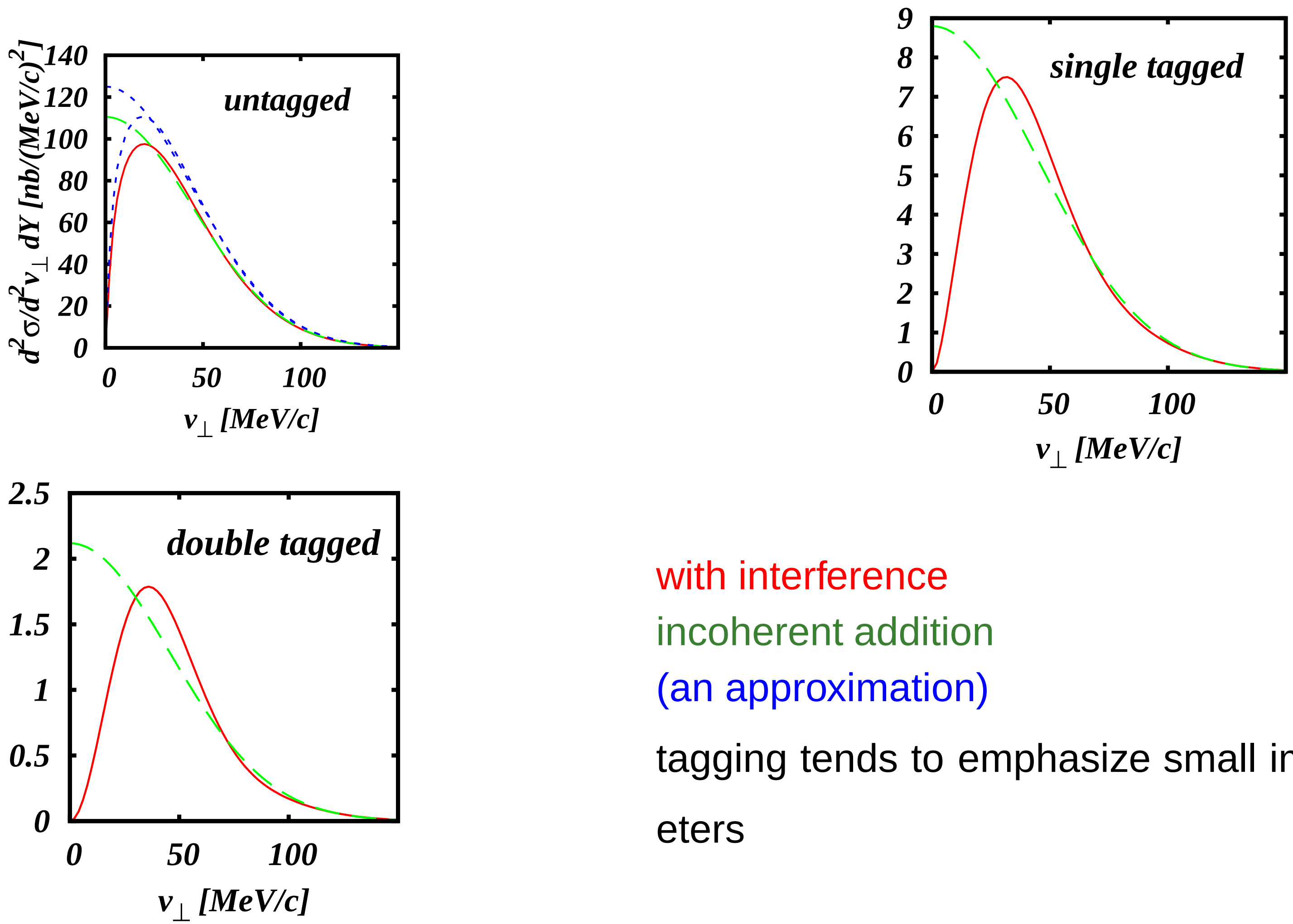
incoherent addition

(an approximation)

tagging tends to emphasize small impact parameters

transverse momentum

J/Ψ meson production, Y=0,LHC, Pb-Pb



with interference

incoherent addition

(an approximation)

tagging tends to emphasize small impact parameters

Lepton (electron) pair production

$Z_1 + Z_2 \rightarrow e^+e^- + Z_1 + Z_2$

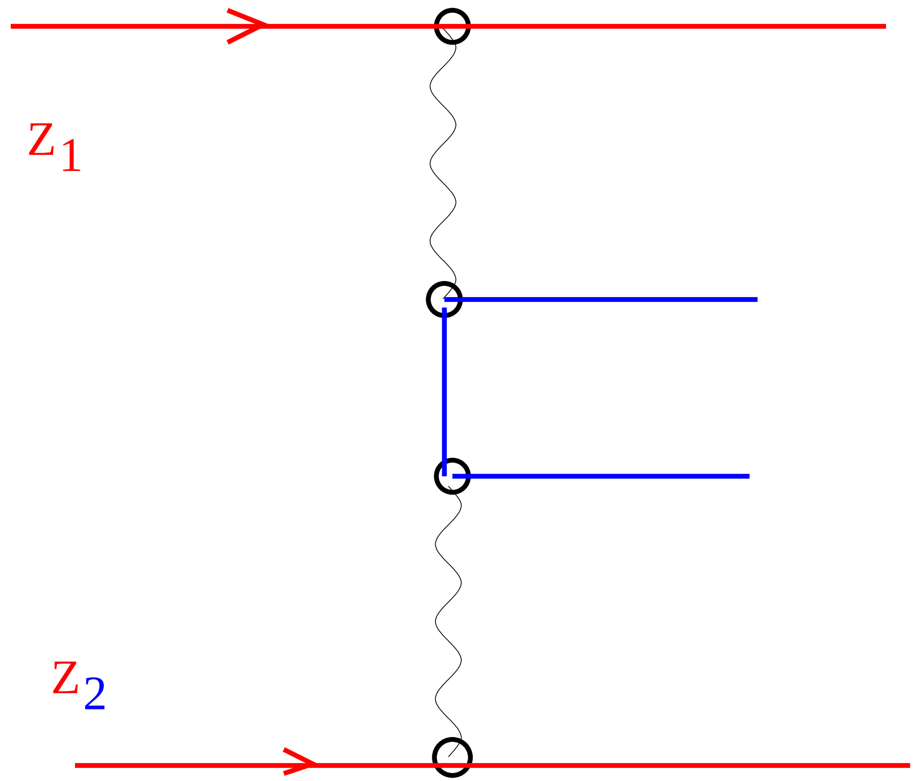
lowest order: 2-photon mechanism:

Serbo et al.:

probability P(b) $\sim \frac{(Z_1 Z_2 \alpha^2)^2}{(m_e b)^2} \times$

$\times \ln\gamma$ ($1 < m_e b < \gamma$)

$\times (ln\gamma)^2$ ($\gamma < m_e b < \gamma^2$)



Lowest order contribution

(bremsstrahlung- mechanism

amplitude $\sim Z_1^2 Z_2 e^4$ is suppressed)

review: G.Baur, K.Hencken and D.Trautmann Physics Reports 457(2007)1

higher order effects

- 'Bethe-Maximon' type of corrections (cf. $\gamma + Z \to e^+e^- + Z$
  $\sigma_{\mathrm{Bethe-Heitler-Maximon}} = \frac{28Z^2\alpha^2}{9m_e^2}(\ln\frac{2\omega}{m_e} - \frac{109}{42} - f(Z\alpha))$ with
  $f(Z\alpha) = \gamma_E + Re\Psi(1 + iZ\alpha)$
- Bound-free pair production:$Z_1 + Z_2 \to (Z_1 + e^-)_{\mathrm{K,L,...-shell}} + Z_2 + e^+$
  bound state wave function contains the higher order effects
  limit of Pb-Pb luminosity at LHC
- $Z_1 + Z_2 \to n(e^+e^-) - +Z_1 + Z_2$
  multiple pairs $n > 1$

Bound-free pair production

$Z_1 + Z_2 \rightarrow (Z_1 + e^-)_{nlj} + e^+ + Z_2$

approximate scaling: $\sigma \propto Z_2^2 Z_1^5 \frac{\delta_{l0}}{n^3} \log\gamma$

H.Meier et al. Phys. Rev. A63(2001)032713

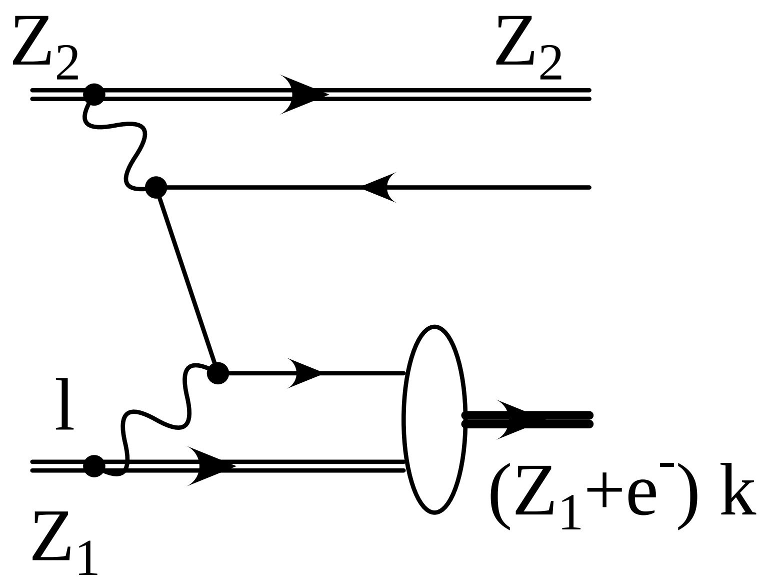
argument for scaling: $l \sim O(m_e)$

relative momentum of bound state wave function $k_{rel} \sim O(Z_1 \alpha m_e)$

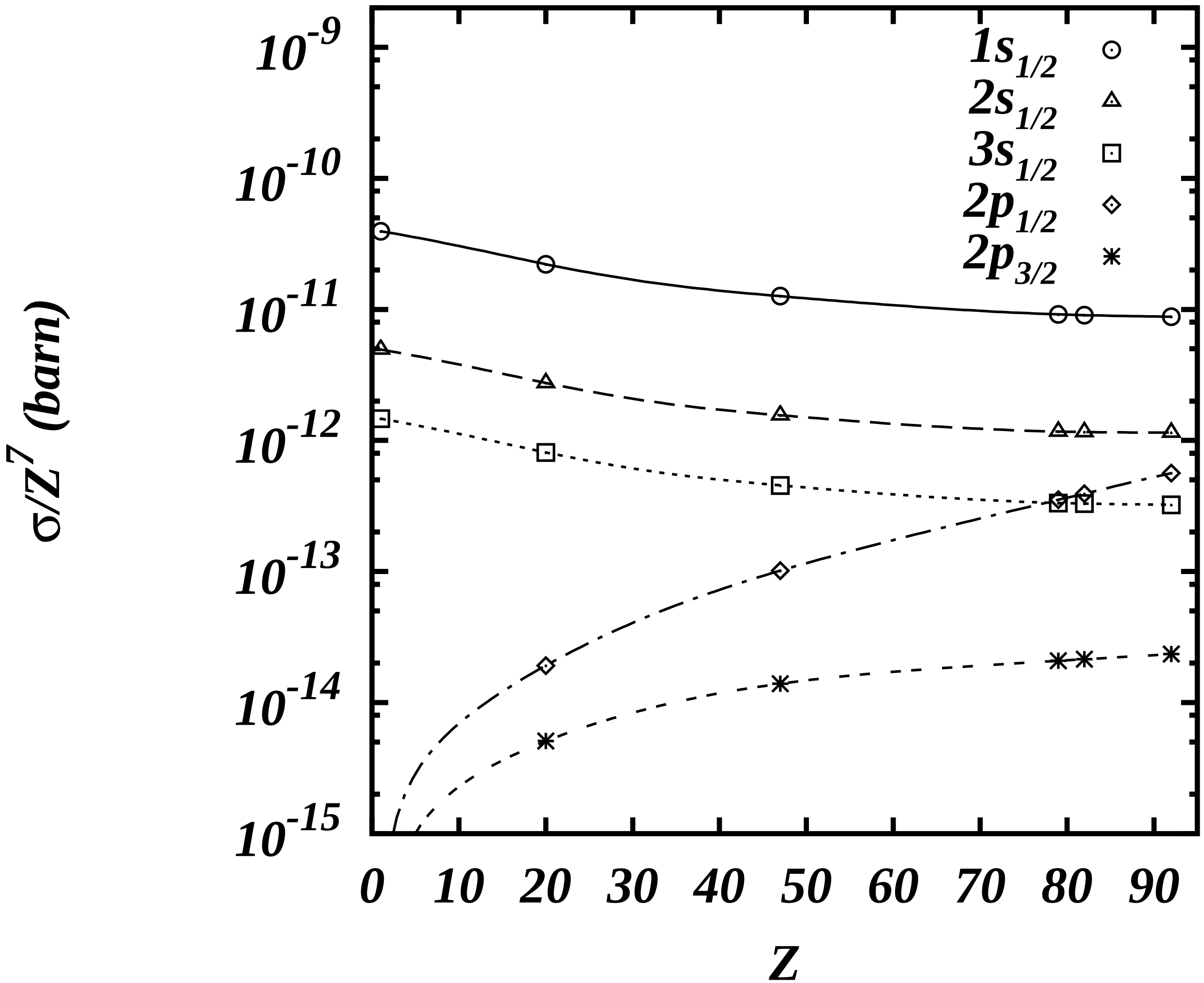
loop integration...$\rightarrow \Psi(0) \propto Z^{3/2}$

and deviations from scaling: for heavy nuclei $Z_1\alpha$ is not $<< 1$,

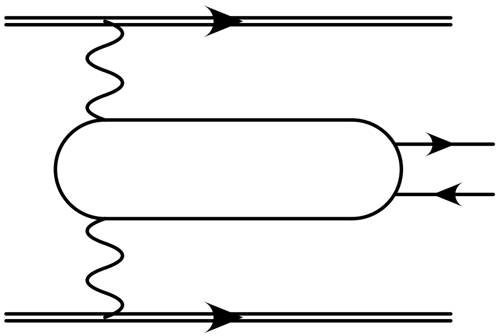
s-wave character of $p_{1/2}$ -Dirac wave function



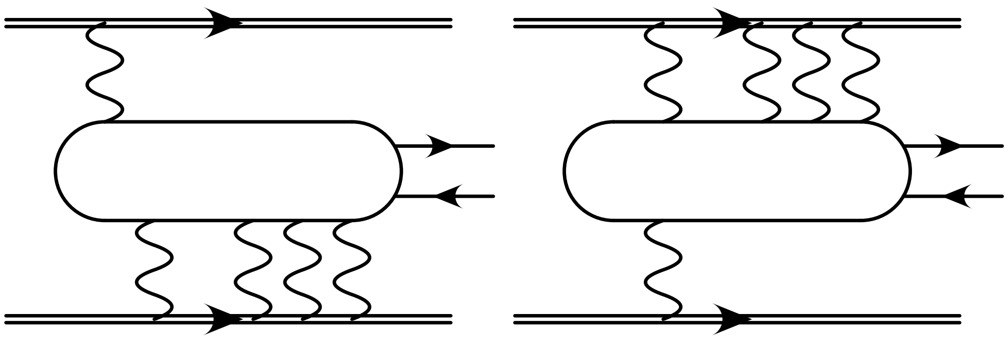
Numerical Results



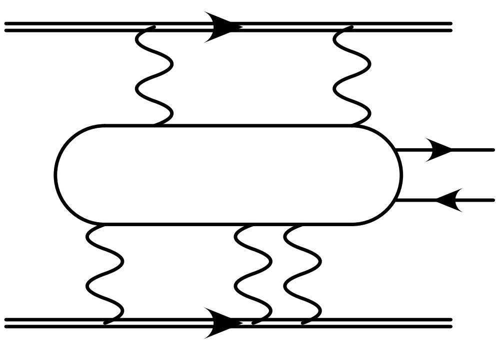
Classes of diagrams



Born approximation $\sigma \propto (ln\gamma)^3$ (Landau, Lifshitz)



Bethe-Maximon type of corrections, $\sigma \propto (ln\gamma)^2$



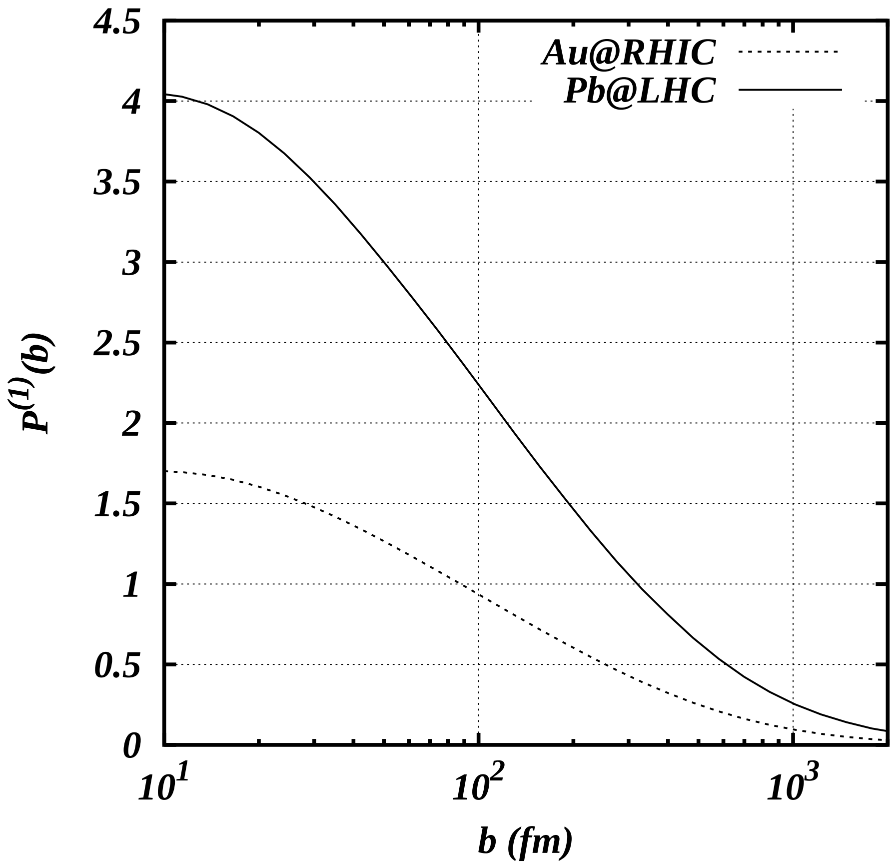
genuine type for heavy ions : small for $\ln\gamma >> 1$ (Ivanov, Serbo, Schiller,1999);difficult problem

Multiple pair production

A strong field effect

An early observation (C.A.Bertulani and G.Baur Phys. Rep. 163(1988)299):

lowest order pair production amplitude $P^{(1)}(b)$ exceeds unitarity limit



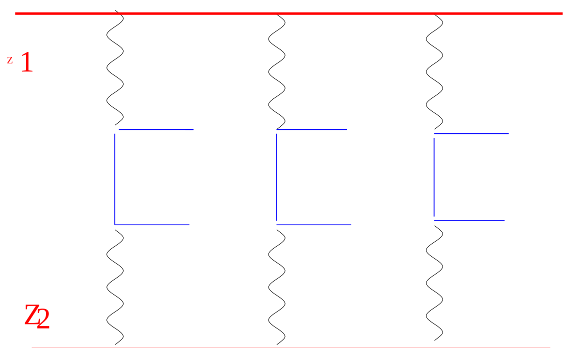
(from K.Hencken, D.Trautmann, and G.Baur Phys. Rev. A51(1995)1874)

emission of multiple pairs

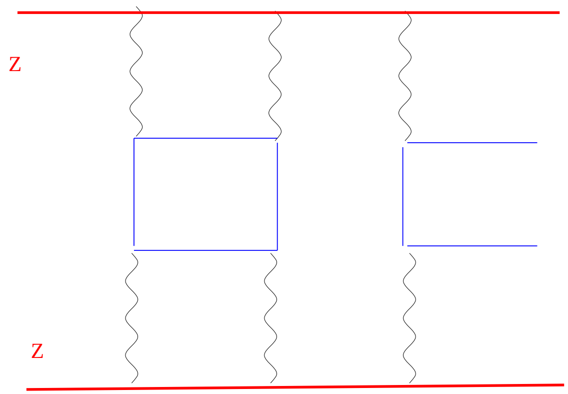
in a single collision: G.Baur Phys. Rev. A42(1990)5736

Poisson distribution $P_n(b) = \frac{(P^{(1)})^n}{n!} \exp\left(-P^{(1)}\right)$

$P^1(b)$: lowest order pair production probability, can be > 1.



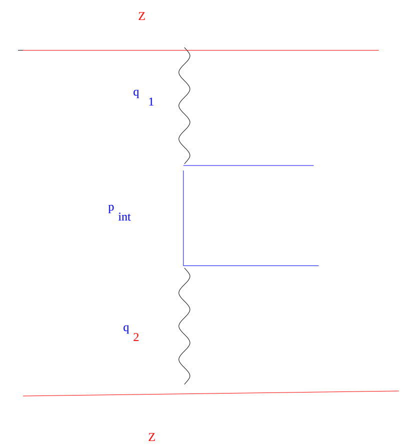
3-pair-production



higher order correction to one-pair-production

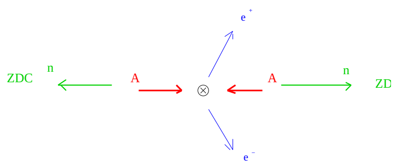
cf. infrared catastrophe: emission of many soft photons,

STAR @ RHIC



Production of e^+e^-pairs accompanied by nuclear dissociation in ultraperipheral heavy ion collisions

J.Adams et al. Phys. Rev. C70(2004) 031902(R)



neutrons from GDR decay: UPC

$p_\perp^\pm > 65$ MeV/c, pseudorapidity $|\eta| = |-\log\tan\theta/2| < 1.15$ neutrons in ZDC(Zero Degree Calorimeter)

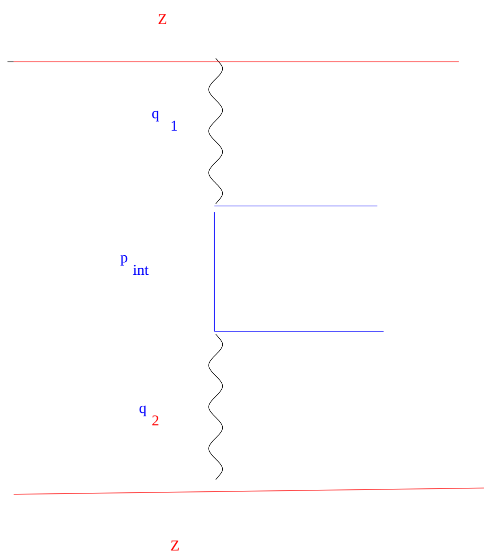
cross section for e^+e^- pair production and giant dipole resonance excitation in both nuclei

$$\frac{d^3\sigma}{d^3p_+d^3p_-} = 2\pi\int_{b_{min}}^{\infty} bdbP^2_{GDR}(b)\frac{d^6P(b)}{d^3p_+d^3p_-}$$

STAR @RHIC

comparison of experiment to theory
EPA: equivalent photon approximation
QED: lowest order (=two-photon pair production)

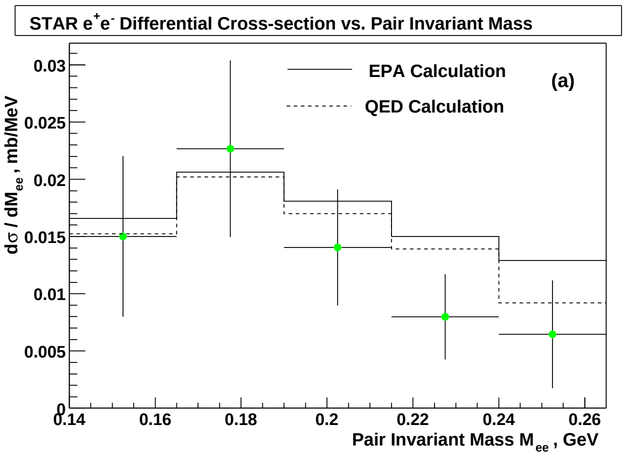
K.Hencken, G.Baur and D.Trautmann, Phys. Rev. C69(2004)054902

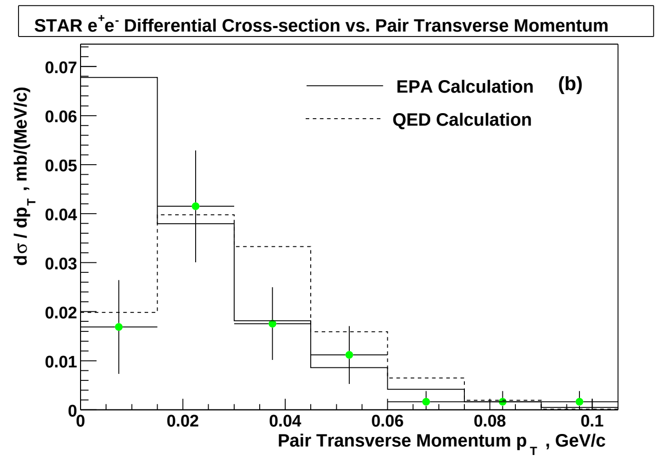


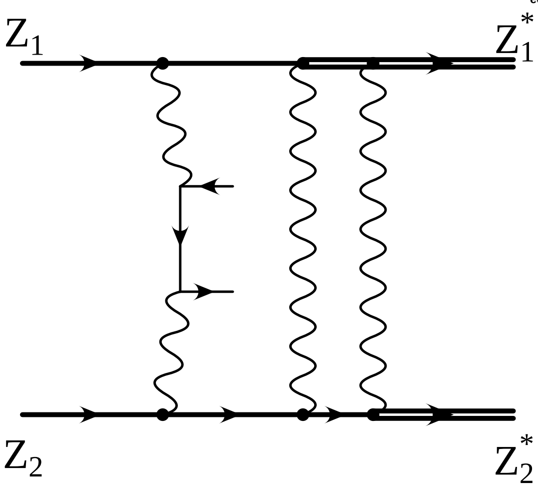
EPA favours $q_{1\perp}, q_{2\perp} \sim 0 \rightarrow p_\perp$ is small in EPA
QED favours in addition: $p_{int}^2 \sim m_e^2$: 'equivalent electron approximation': intermediate electron almost 'on-shell'
electron pair with large $p_\perp$

results from STAR/RHIC

comparison of QED and EPA calculations to experiment







another analysis by A.J. Baltz Phys. Rev. Lett. 100(2008)062302 : inclusion of higher order electromagnetic effects : consistent with data

Conclusion

- the power of coherence
- high flux of quasireal photons up to unprecedented energies

- photon-nucleus collisions at very high energies:
- coherent vector meson production, transverse momentum distribution depends on interference effect
- strong field effects: multiphoton exchange, can be treated perturbatively