Strong electromagnetic fields in ultraperipheral heavy ion collisions:

multiphoton processes

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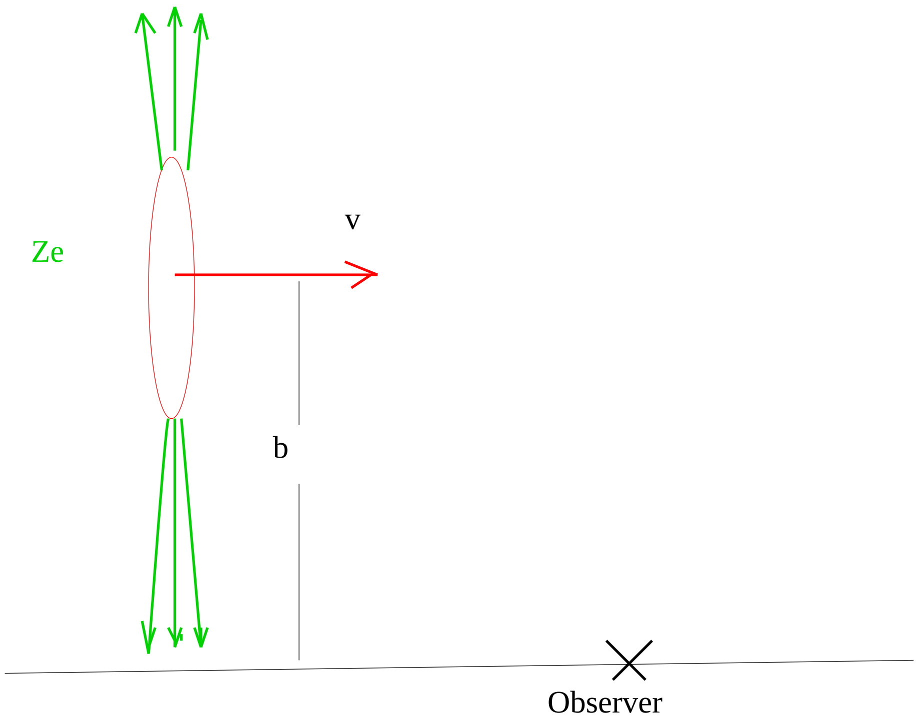
Ultraperipheral collisions(UPC) at the colliders RHIC(Au-Au, $\gamma = 100$)and LHC(Pb-Pb, $\gamma = 3400$): high flux of photons up to high energies

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

- Semiclassical or Glauber method: impact-parameter-dependent probabilities P(b) for various processes
- 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 but: effects usually small as compared to γ -hadron reactions
- a special case: e^+e^- pair production
- strong field effects: multiple pair production
- Conclusion

Ultraperipheral Collisions

UPC: nuclei do not touch each other
$\rightarrow$ only electromagnetic interaction between the ions



reviews

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

F.Krauss, M.Greiner, G.Soff, Prog. Part. Nucl. Phys.39(1997)503

Characteristics of the electromagnetic pulse

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

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

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

(cf. production of fast antihydrogen atoms: C.T. Munger, S.J. Brodsky, I.Schmidt, Phys. Rev. D49(1994) 3228; observed at LEAR and Fermilab)

$\rightarrow$ beam loss, local beam pipe heating with danger of quenching of LHC magnets (Spencer Klein)
This processes has not been studied at RHIC (?)
$\rightarrow$ 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

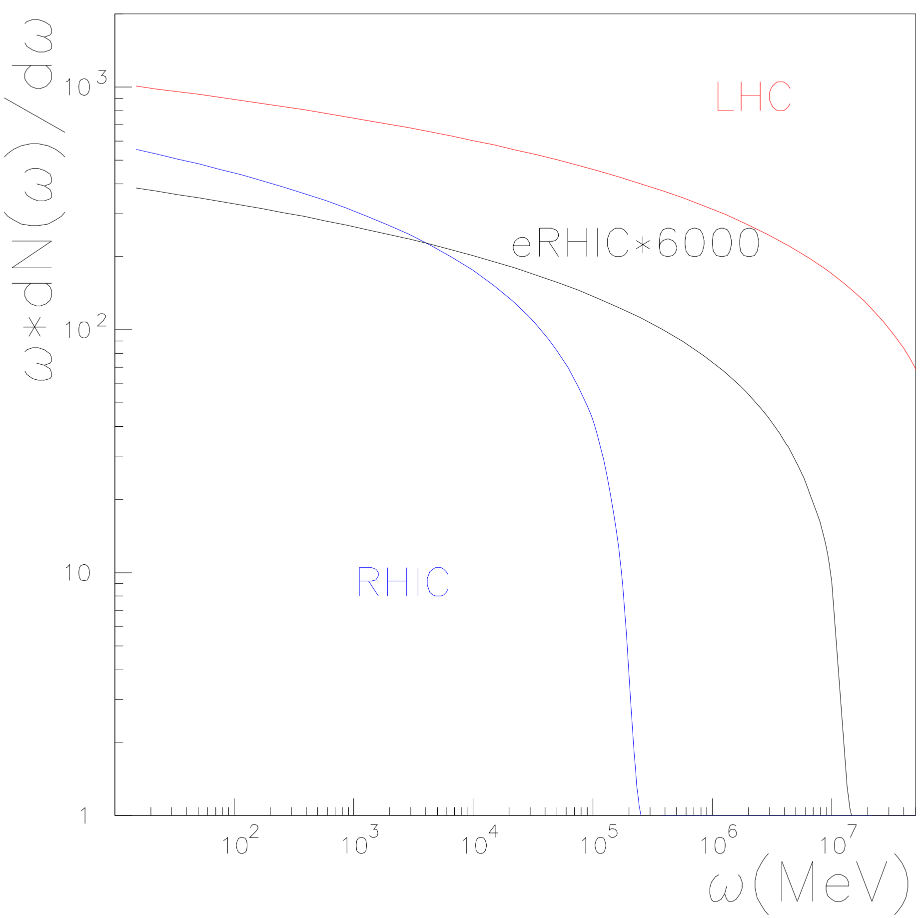
$n(\omega) \sim Z^2 \log \frac{\gamma v}{\omega R_{min}}$

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

$R_{min} \sim 7fm$

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

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



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 $A_\mu(b,t)$

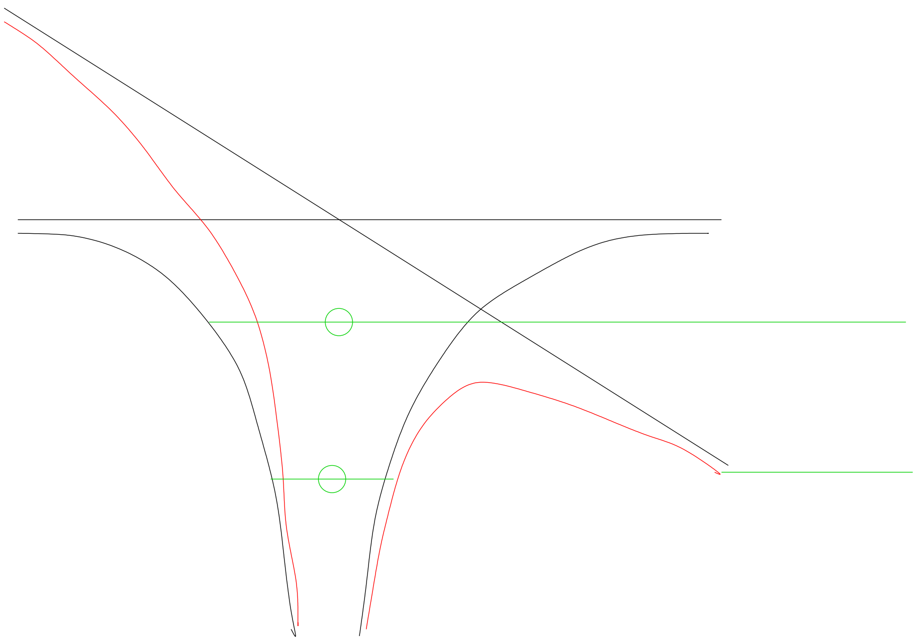
time-dependent interaction $V(t) \sim A_\mu \cdot j_\mu$

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

A digression

strong fields, for a long time



Field ionization of atoms

classical

tunneling

Schwinger mechanism

$eE_c\lambda_e = m_e c^2$ Compton-wavelength $\lambda_e = \frac{\hbar}{m_e c}$

critical field $E_c = \frac{m^2 c^3}{e\hbar} = 1.3 * 10^{16} \frac{V}{cm}$

Production of e^+e^- pairs per unit volume and time:

$\frac{d^4 n_{e^+e^-}}{d^3x dt} \sim c/(4\pi^3 \lambda_e) \exp(-\pi \frac{E_C}{E})$

field strength E: non-perturbative effect

exchange of many photons

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

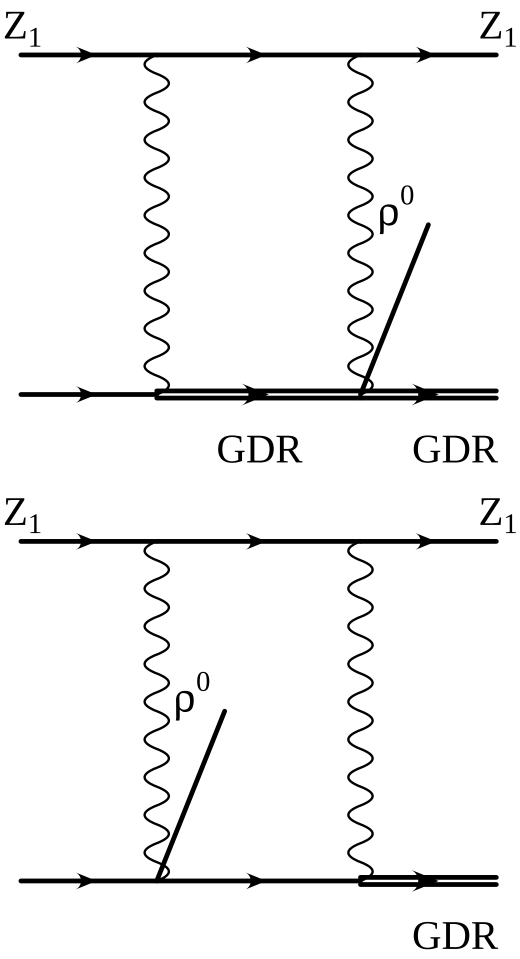
G.Baur, K.Hencken, A. Aste, D.Trautmann und S.R.Klein NPA729(2003)787

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

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

Factorization:

probability $P(b) = \Pi_i P_i(b)$
where i denotes a specific inelastic channel
Many grafs are summed up in the semiclassical
(or eikonal) method



ρ^0 production and GDR excitation in a single collision

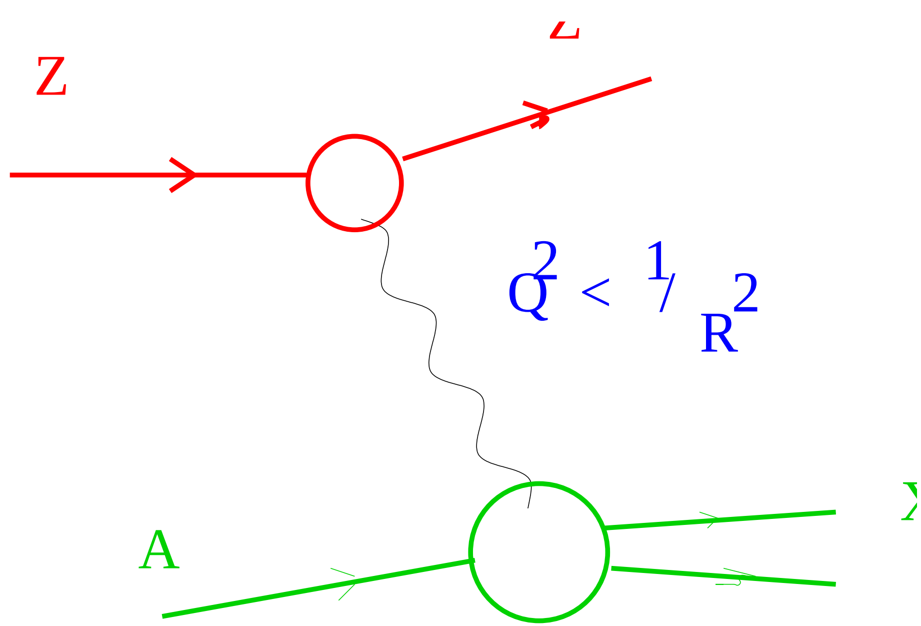
Vector meson photoproduction

vital for low-x QCD studies, see M.Strikman etal.

- 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 from STAR: C.Adler et al. PRL 89(2002)272302 production of ρ^0 in UPC



exchange of quasireal photon

- J/Ψ production at PHENIX

transverse momentum

distribution of vector mesons

kinematics:

$p + k \rightarrow p^{'} + k^{'} + v$ for reaction $A + A \rightarrow A^{(*)} + A^{(*)} + V$ 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, $E_{GDR} = 80A^{-1/3}MeV$)

transverse momentum

distribution of ρ^0 meson production

electromagnetic current (simple model)

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

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

amplitude for vector meson excitation:

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

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

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

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

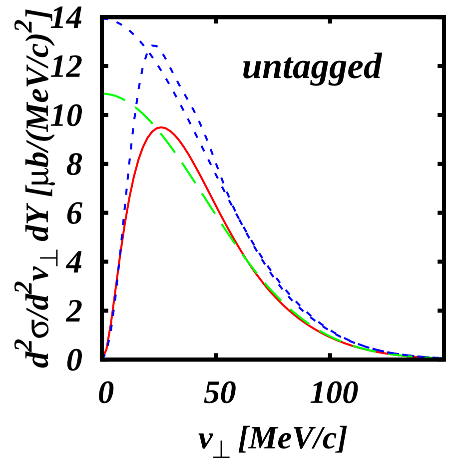
$P(b) = |a_V^{total}|^2 \sim N(\omega,b)\sigma_\gamma$ +int. term

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

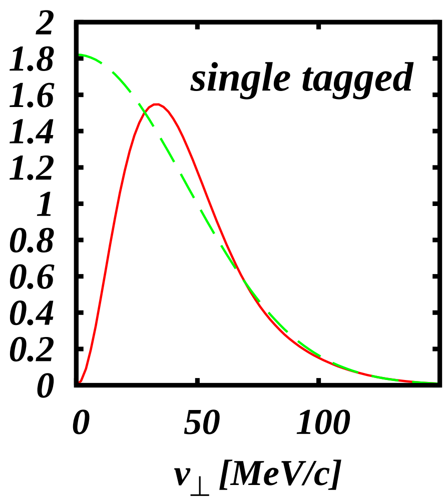
note that $b > b_{min}$

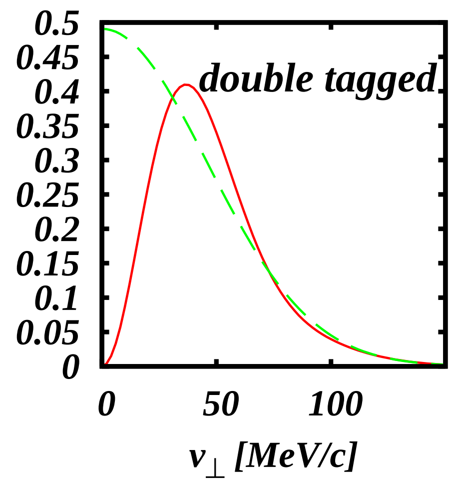
$N(\omega,b) \sim |\int d^2Q_\perp \frac{\vec{Q}_\perp e^{-i\vec{Q}_\perp\cdot\vec{b}}}{Q_\perp^2+(\frac{\omega}{\gamma v})^2}|^2$

numerical results



ρ-production, Y=0, RHIC, Au-Au





with interference

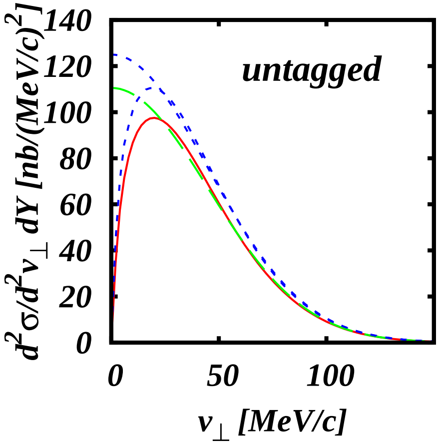
incoherent addition

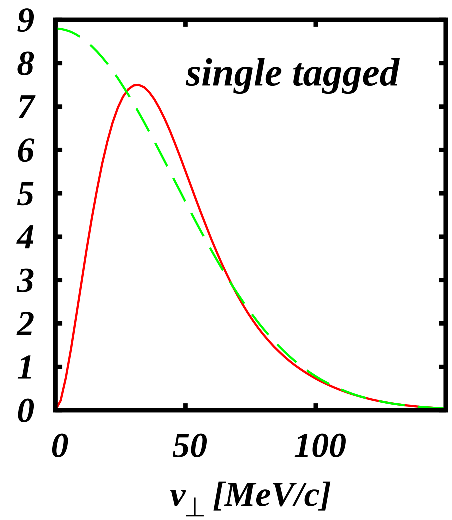
(an approximation)

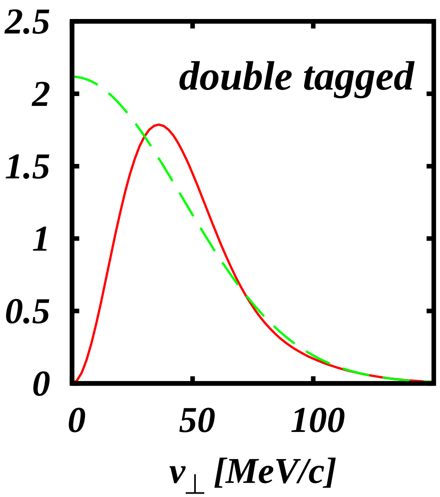
tagging tends to emphasize small impact parameters

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

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

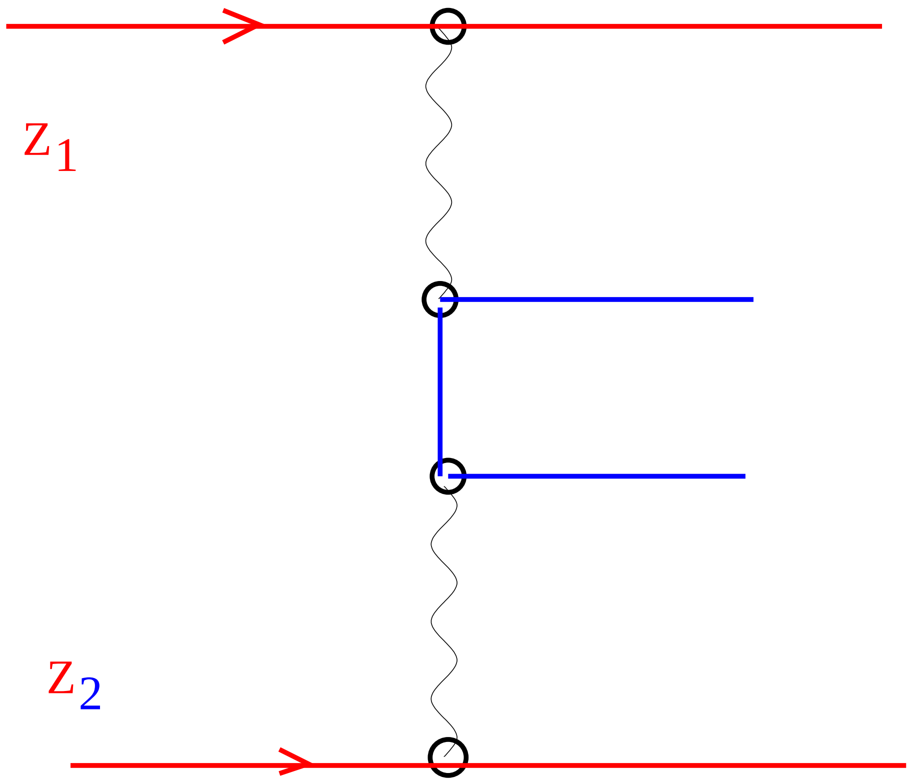
It,s just QED.... lowest order: 2-photon mechanism:

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)

higher order effects

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

Bound-free pair production

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

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

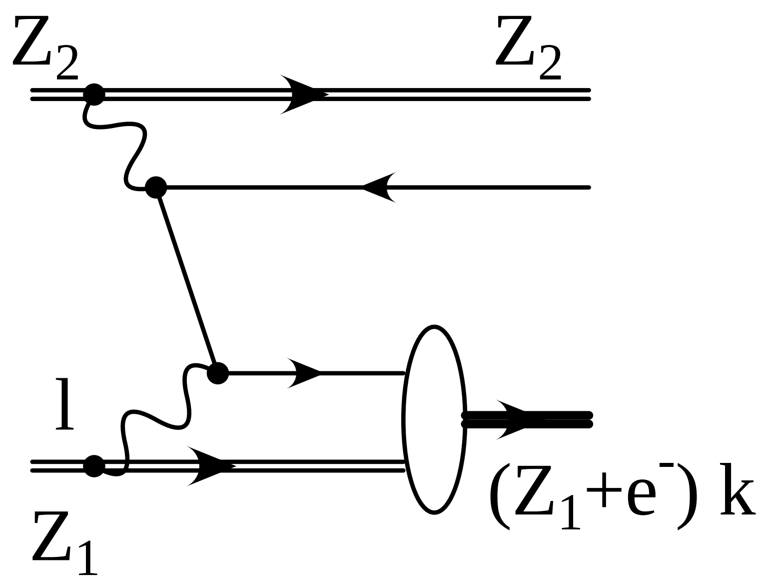
argument for scaling: $l \sim O(m_e)$

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

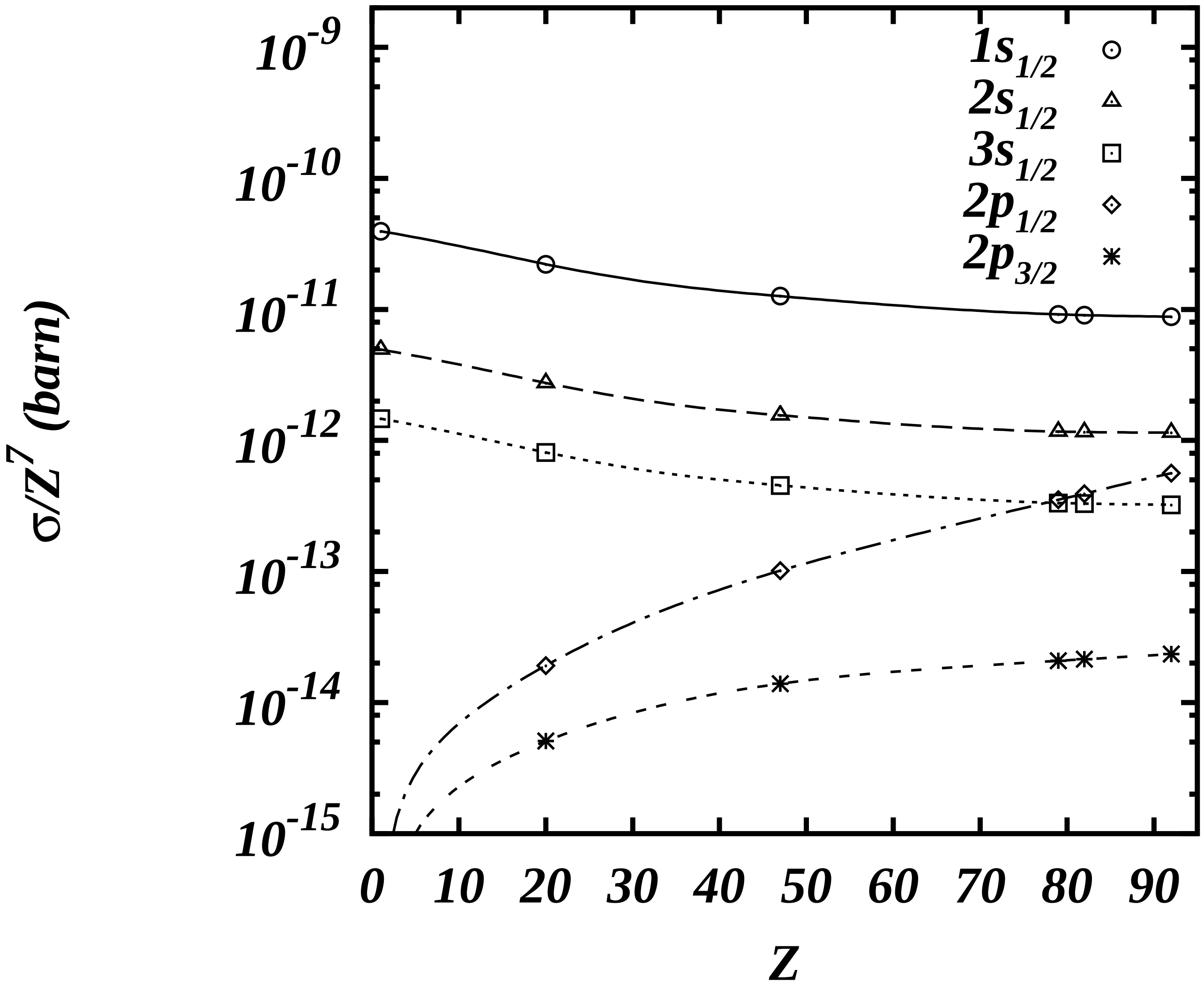
loop integration...$\to \Psi(0) \propto Z^{3/2}$

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

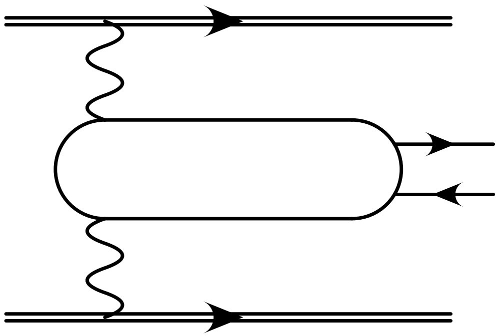
s-wave character of $p_{1/2}$ -Dirac wave function



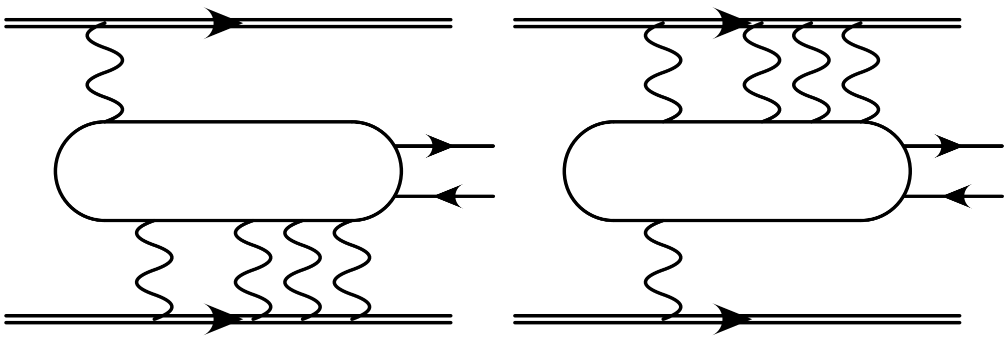
Numerical Results



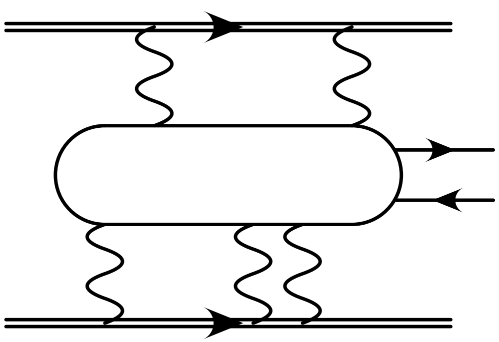
Classes of diagrams



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



Bethe-Maximon type of corrections, $\sigma \propto (ln\gamma)^2$ A. Baltz, this workshop



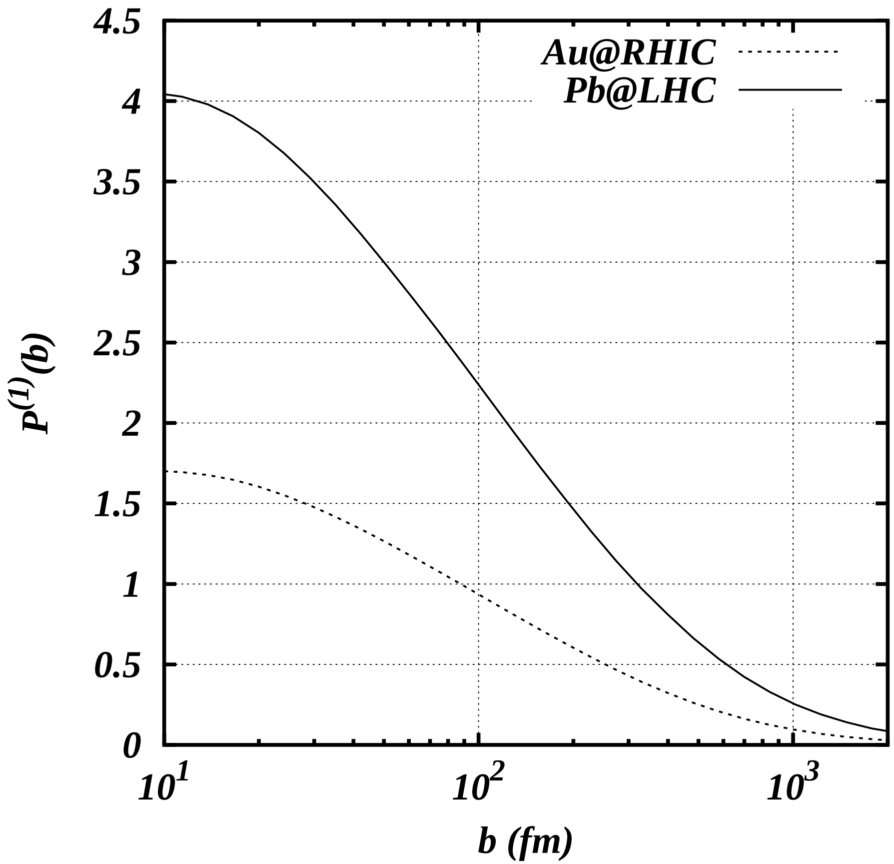
genuine type for heavy ions : small for $\ln\gamma >> 1$ (Ivanov, Serbo, Schiller,1999);difficult problem

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



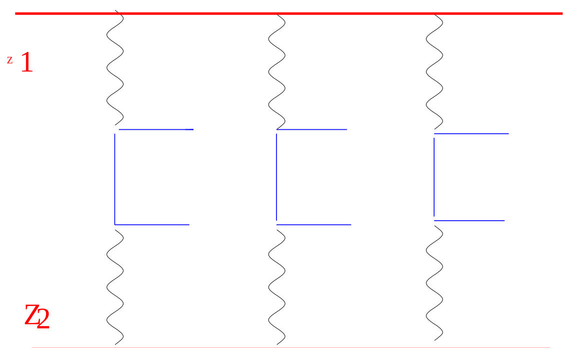
(from K.Hencken, D.Trautmann, and G.Baur Phys. Rev. A51(1995)1874)

emission of multiple pairs

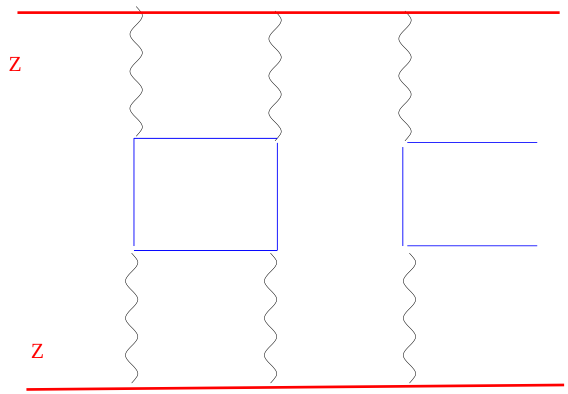
in a single collision: G.Baur Phys. Rev. A42(1990)5736

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



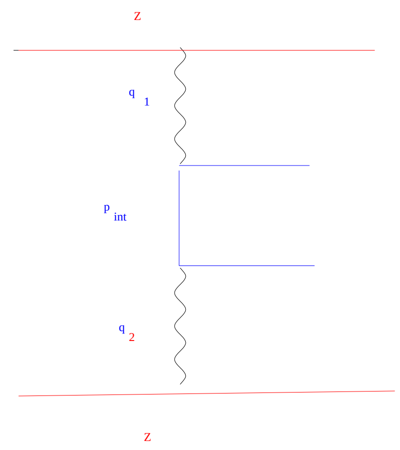
higher order correction to one-pair-production

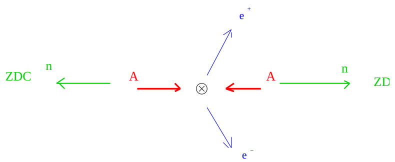
cf. infrared catastrophe: emission of many soft photons,

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)

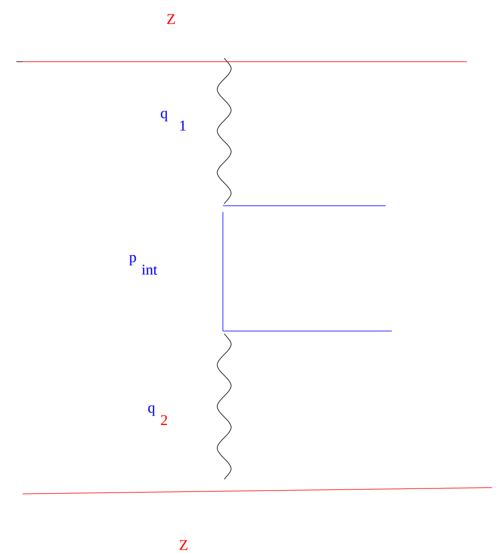
cross section for e^+e^- pair production and giant dipole resonance excitation in both nuclei

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

STAR @RHIC

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

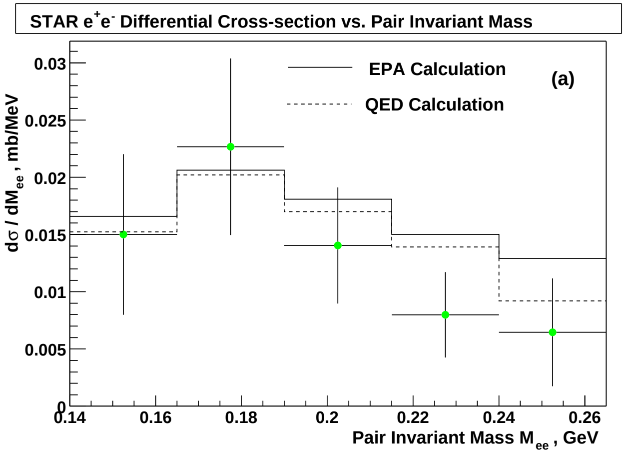
K.Hencken, G.Baur and D.Trautmann, Phys. Rev. C69(2004)054902

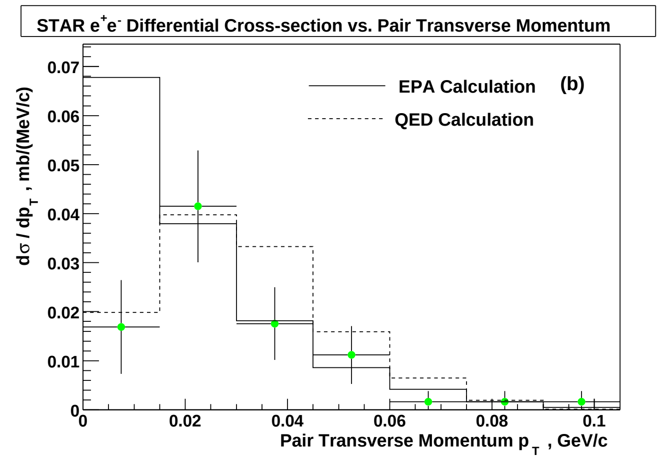


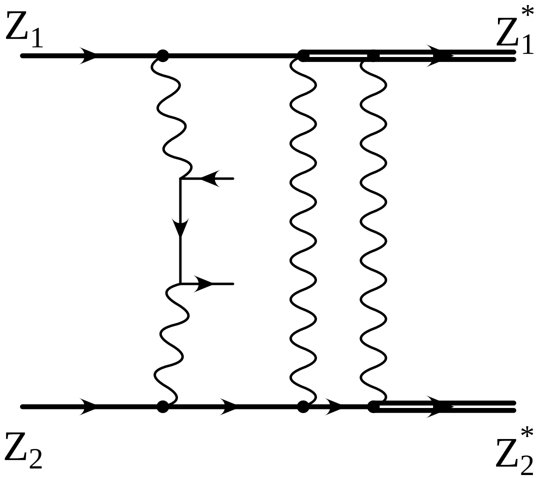
EPA favours $q_{1\perp}, q_{2\perp} \sim 0 \rightarrow p_\perp$ is small in EPA
QED favours in addition: $p_{int}^2 \sim m_e^2$: 'equivalent electron approximation': intermediate electron almost 'on-shell'
electron pair with large $p_\perp$

results from STAR/RHIC

comparison of QED and EPA calculations to experiment







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
- experiments at RHIC :gain experience for LHC
- next ECT* workshop: results from LHC