

# **Schwinger, Breit-Wheeler, Compton (Short & Strong Laser Pulses)**

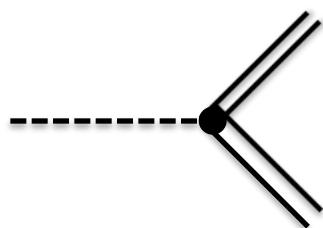
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Technische Universität Dresden

with A.I. Titov, H. Takabe, A. Hosaka,  
D. Blaschke, S. Smolyansky, S. Schmidt et al.  
D. Seipt, T. Nousch, A. Otto



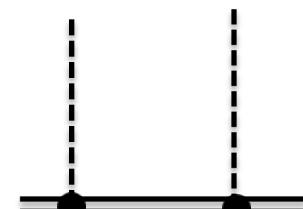
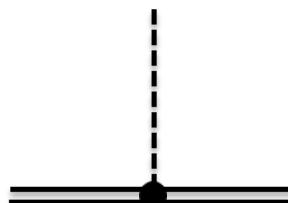
# Schwinger   Breit-Wheeler



$E_1(vt) + E_2(Nvt)$

kinetic eqs.  
(Bogolyubov transf.)

# Compton



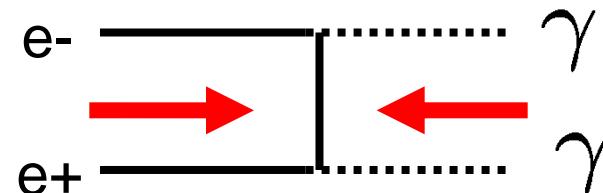
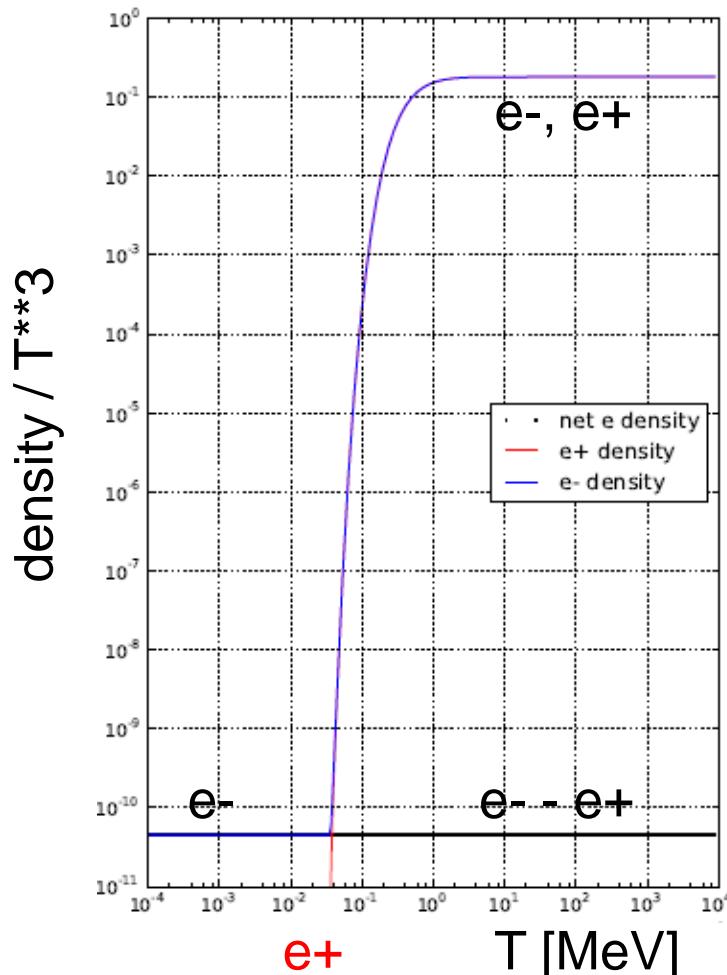
$A_1(kx) + A_2(Nkx)$

probe photons (pert.) + sQED  
(Furry: Volkov)

periodic  
finite duration  
pulse shape

# Disappearance of Anti-Matter in the Universe

- (i)  $T \sim 40$  MeV: annihilation of anti-nucleons
- (ii)  $T \sim 0.5$  MeV: annihilation of positrons



$t \sim 15$  s,  $T \sim 3 \times 10^9$  K

from  $\eta = 10^{-10}$   
and charge neutrality

mystery: high-energy  $e^+$  from AMS

# 1. Dynamically Assisted Schwinger Process (Pair Production from „Vacuum“)

Schutzhold, Dunne, Gies (2008):  
tunneling + multi-photon

$$\dot{f}(\mathbf{p}, t) = Q(\mathbf{p}, t) \int_{t_0}^t dt' Q(\mathbf{p}, t') [1 - \eta f(\mathbf{p}, t')] \cos 2[\Theta(\mathbf{p}, t) - \Theta(\mathbf{p}, t')]$$

$$\Theta(\mathbf{p}, t) = \int_{t_0}^t dt' \omega(\mathbf{p}, t') ,$$

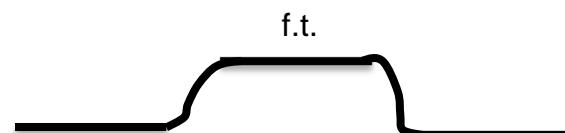
$$\omega(\mathbf{p}, t) = \sqrt{\epsilon_{\perp}^2 + (p_{\parallel} - eA(t))^2}$$

$$Q(\mathbf{p}, t) = \frac{eE(t)\epsilon_{\perp}}{\omega^2(\mathbf{p}, t)} ,$$

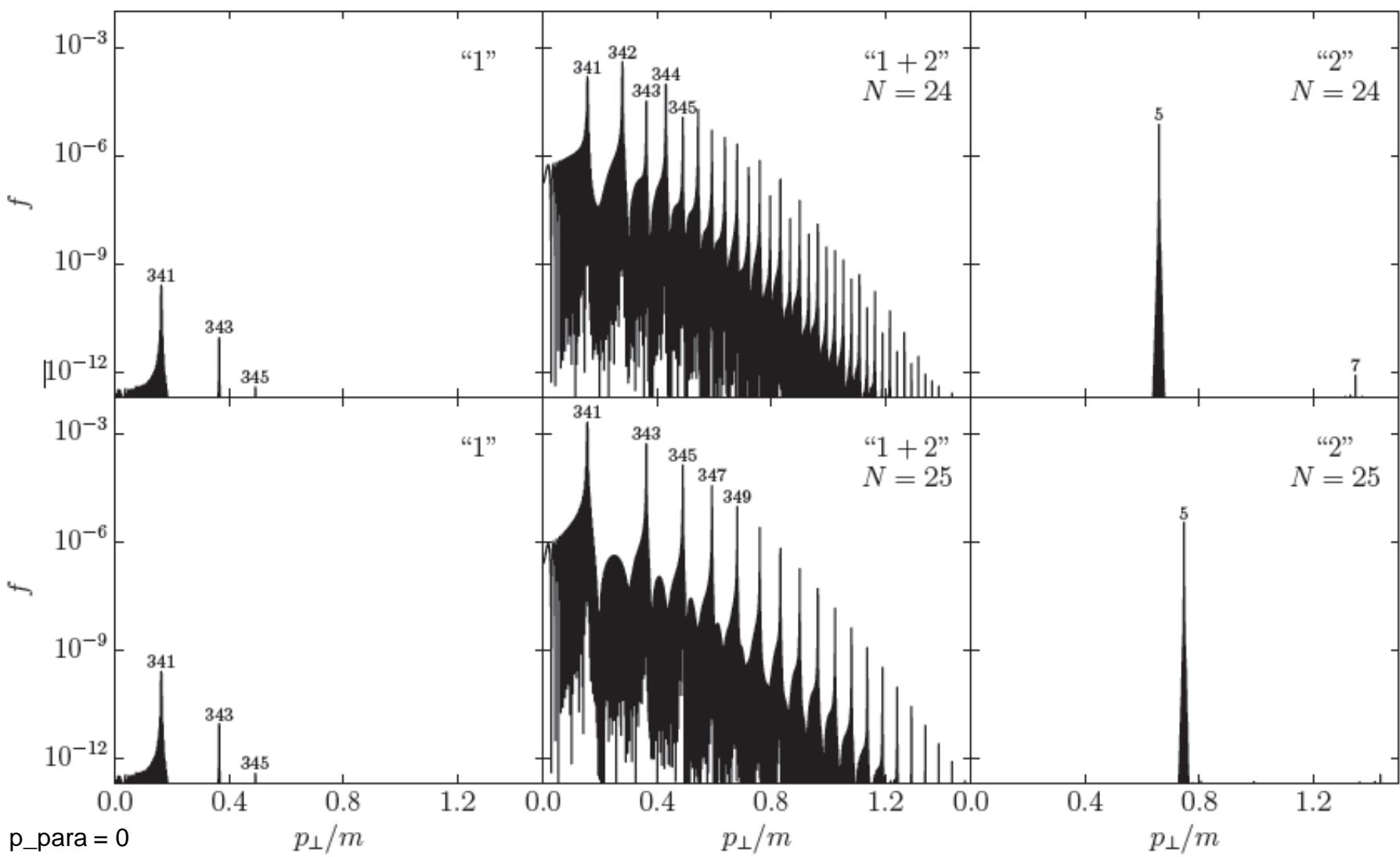
e.g. Grib, Mamaev, Mostepanenko (1988)  
Eq. (9.73)

specific to our work (Laser + XFEL):

$$A(t) = \left( \frac{E_1}{\nu} \cos(\nu t) + \frac{E_2}{N\nu} \cos(N\nu t) \right) K(\nu t)$$



$$K(\tau) = \begin{cases} 0 & \text{for } \tau < 0 \\ & \text{smooth transition} \\ 1 & \text{for } \tau_{\text{ramp}} < \tau < \tau_{\text{ramp}} + \tau_{\text{f.t.}} \\ & \text{smooth transition} \\ 0 & \text{for } \tau_{\text{pulse}} < \tau \end{cases} \quad C^{\infty}$$



slow strong field „1“  
 $E_1 = 0.1 E_c$   
 $v = 0.02 m$   
 $g_1 = 0.2 \rightarrow$  tunnel.

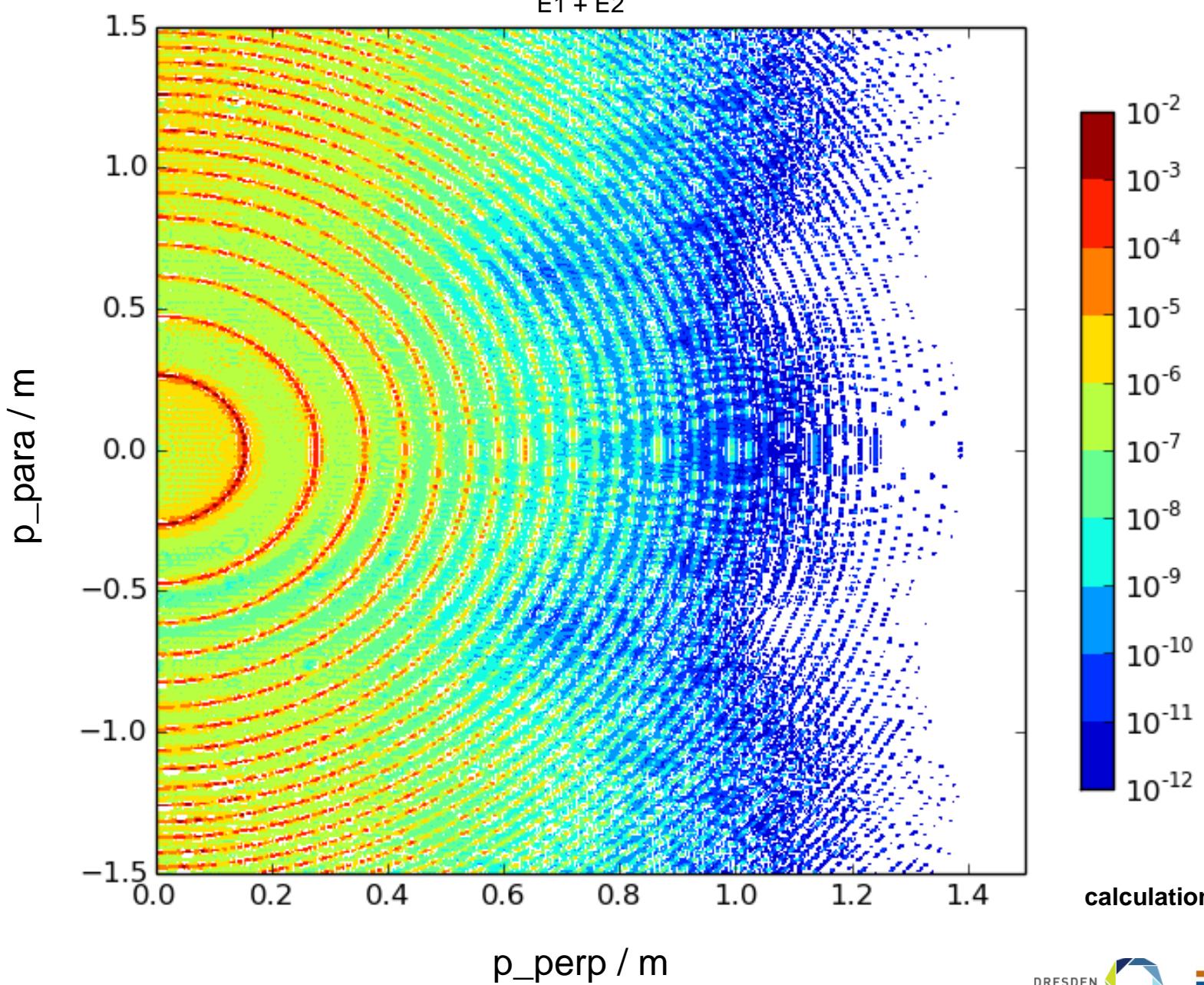
flat top: 50 T  
ramping: 5 T  
 $g = (E_c/E)(v/m)$

fast weak field „2“  
 $E_2 = 0.05 E_c$   
 $g_2 \sim 10 \rightarrow$  m.p.



**HZDR**

E1 + E2



low-density approximation  
( = w/o Pauli blocking)

$$f(\mathbf{p}, t) = \frac{1}{2} |I(\mathbf{p}, t)|^2 ,$$

$$I(\mathbf{p}, t) = \int_0^t dt' \frac{eE(t')\epsilon_{\perp}}{\omega(\mathbf{p}, t')^2} e^{2i\Theta(\mathbf{p}, t')}$$

$N$  = integer: Fourier + Fourier

$$I(\mathbf{p}, t) = \sum_{\ell} iF_{\ell}(\mathbf{p}) \frac{e^{-i(\ell\nu - 2\Omega(\mathbf{p}))t} - 1}{\ell\nu - 2\Omega(\mathbf{p})}$$
shell width shrinking

shell occupation kinematics, shell structure

$$F_{\ell}(\mathbf{p}) = \frac{1}{T} \int_0^T dt F(\mathbf{p}, t) e^{i\ell\nu t} \quad \Omega(\mathbf{p}) = \frac{1}{T} \int_0^T dt \omega(\mathbf{p}, t) = \text{Fourier zero mode}$$

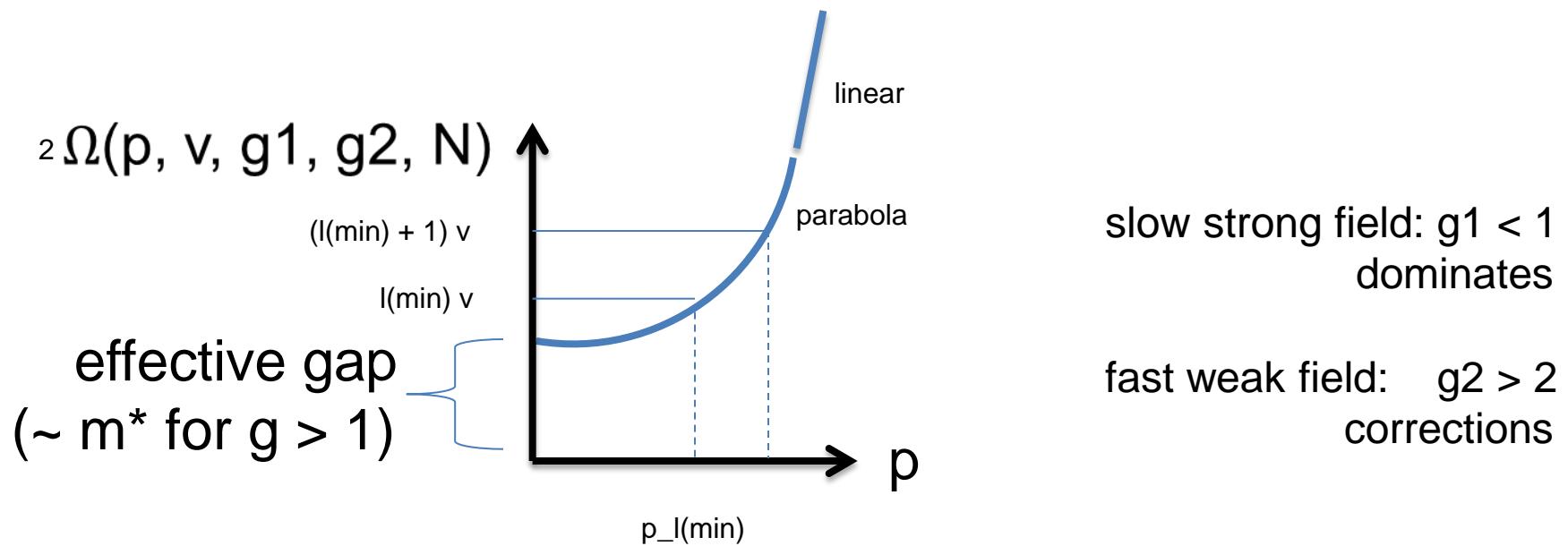
$$\begin{aligned} f(\mathbf{p}^{(\ell)}, t) &= \frac{1}{2} \left| iF_l(\mathbf{p}^{(\ell)})t + \sum_{k \neq \ell} iF_k(\mathbf{p}^{(\ell)}) \frac{e^{i(k\nu - 2\Omega(\mathbf{p}^{(\ell)}))t} - 1}{k\nu - 2\Omega(\mathbf{p}^{(\ell)})} \right|^2 \\ &= \frac{1}{2} \left| F_{\ell}(\mathbf{p}^{(\ell)}) \right|^2 t^2 + G(\mathbf{p}^{(\ell)}, t)t + H(\mathbf{p}^{(\ell)}, t), \end{aligned}$$

flat-top time  transient



## kinematics (shell positions)

$\Omega = \text{Fourier zero mode of } \omega$

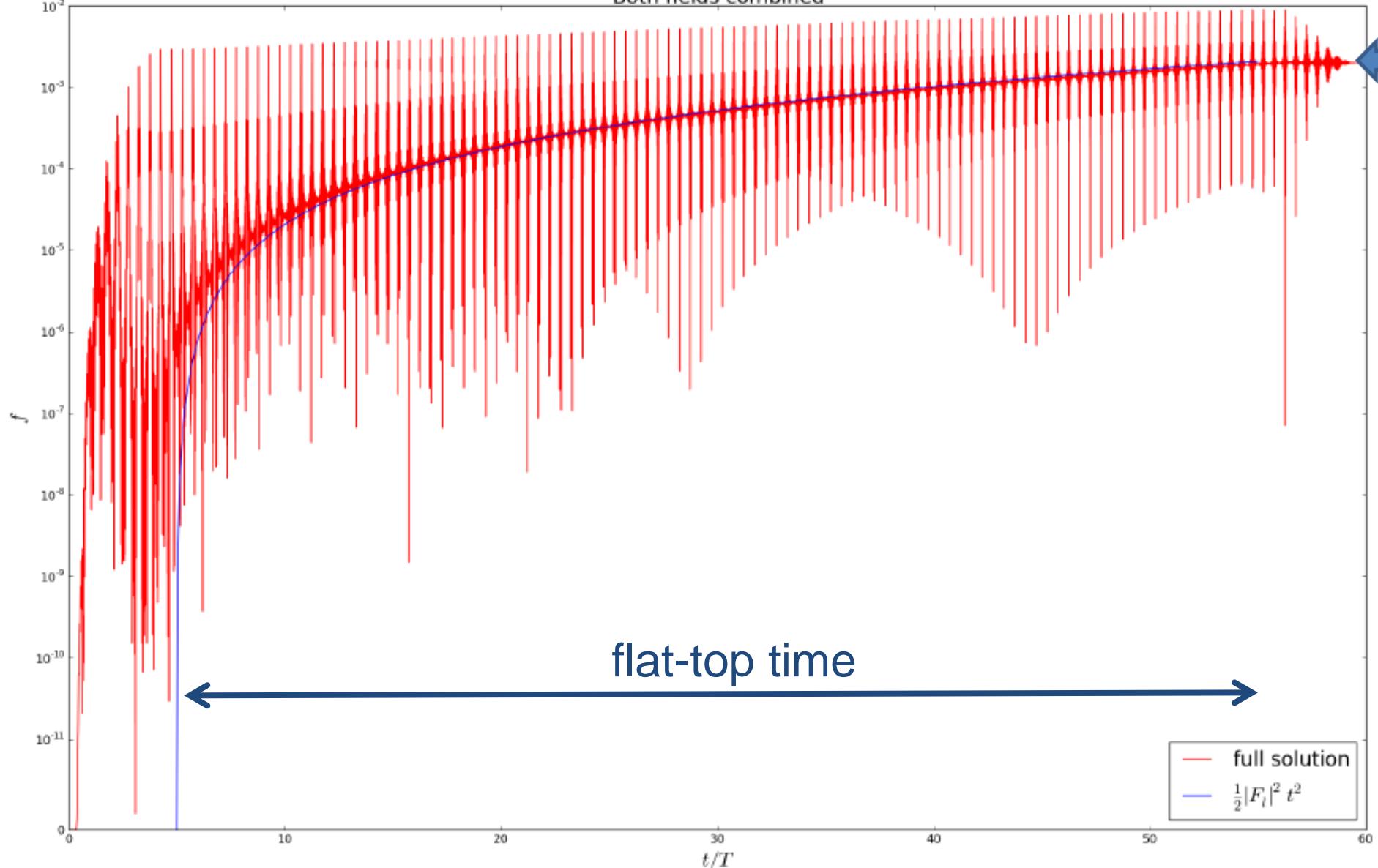


analog to channel closing in ATI

Popov (1973, 1974): 1 periodic field

# „dynamics“

$E_1 = 0.1E_c$   $\nu = 0.02m$   $E_2 = 0.05E_c$   $N = 25$   
 $k = 341$   $p_\perp = 0.155325m$   
Both fields combined



analog to “quark number” in chiral mass model with  $m(t)$  (C. Greiner, Michel)



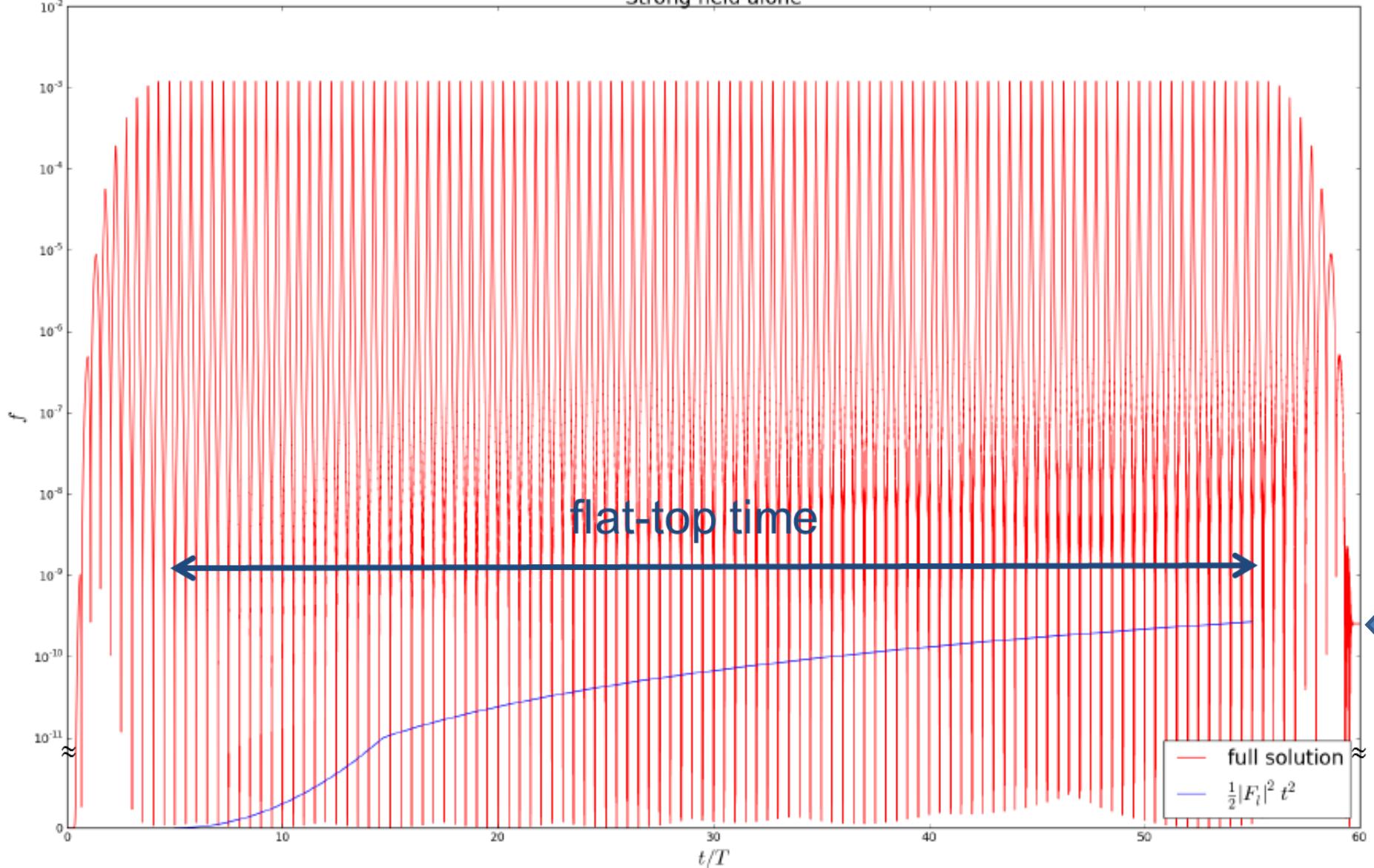
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$$E_1 = 0.1E_c \quad \nu = 0.02m \quad E_2 = 0.05E_c \quad N = 25$$

$$k = 341 \quad p_{\perp} = 0.155325m$$

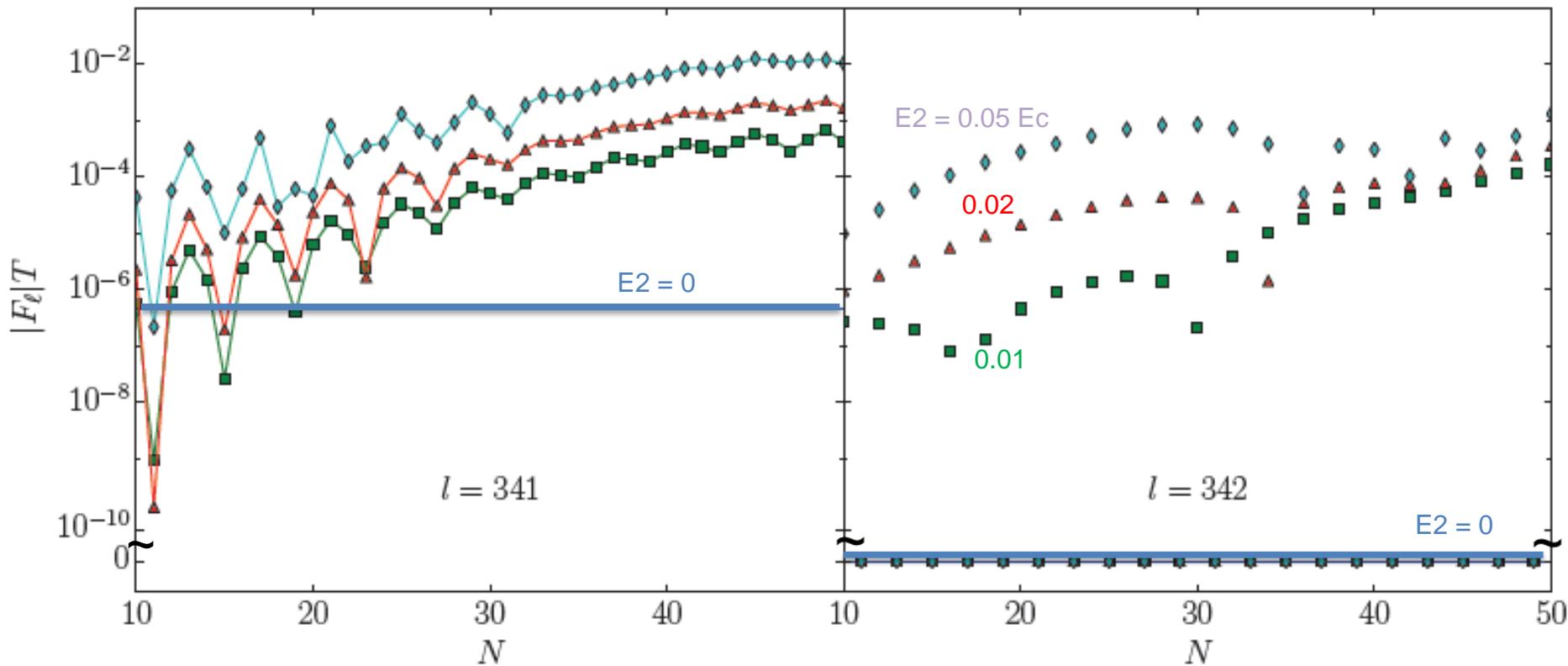
Strong field alone



Dabrowski, Dunne (2014): transient  $f(t)$  depends on basis

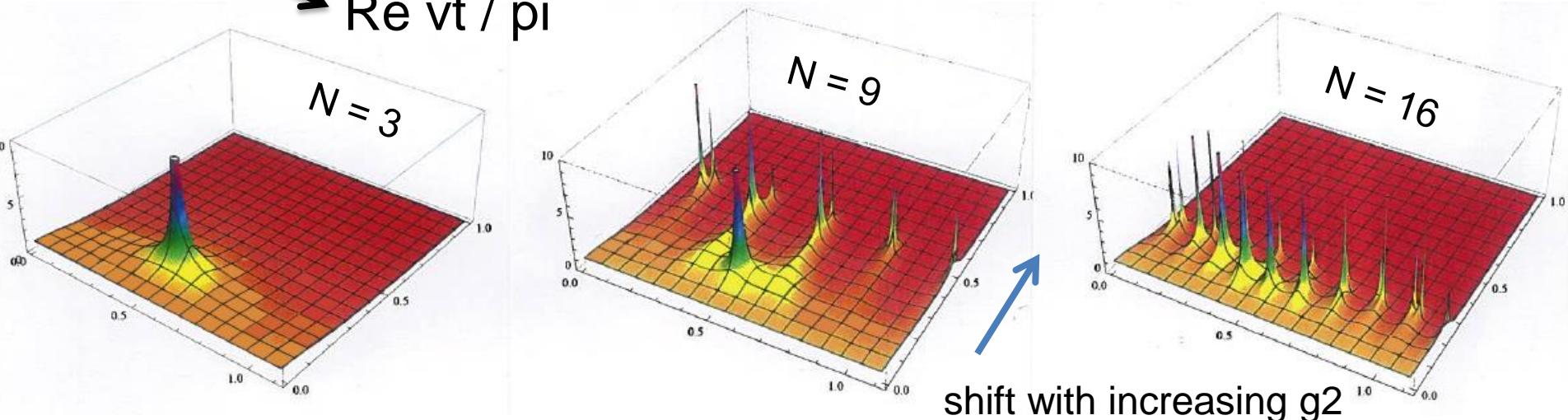
$$n \approx 2\pi^2 \sum_{\ell=\ell_{\min}}^{\infty} p_{\perp}^{(\ell)2} / |\Omega'(p_{\perp}^{(\ell)}, 0)| |F_{\ell}(p_{\perp}^{(\ell)}, 0)|^2 t_{\text{f.t.}}$$

linear due to  
shell shrinking



$|\omega^{-2}|$   
 $\text{Im } vt$   
 $\text{Re } vt / \pi$

$$\begin{aligned} g_1 &= 0.2 \\ g_2 &= 20 \end{aligned}$$



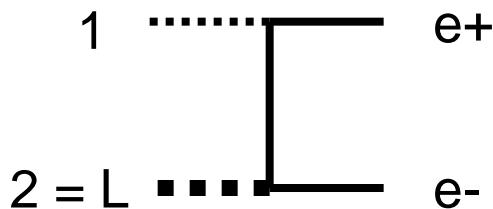
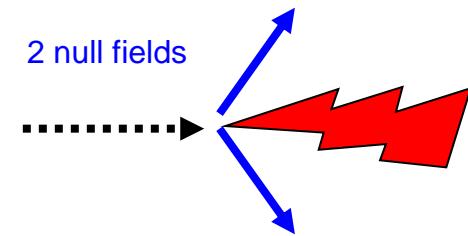
Brezin, Itzykson (1970): 1 periodic field (stat. phase, steepest desc.)  
 $\rightarrow$  1 pole with  $\text{Re } vt = \pi/2$ ,  $\text{Im } vt = \text{arsh } g$

under construction: lifting function



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## 2. Breit-Wheeler and Beyond

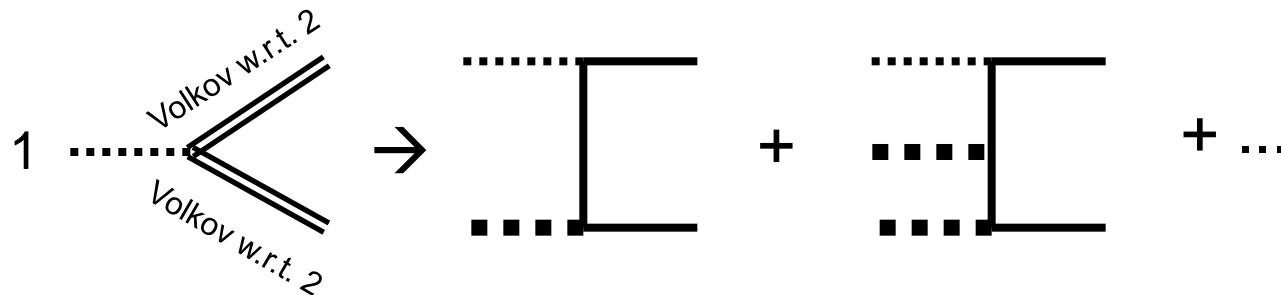


$2 \rightarrow 2$ : s, t  
crossing of Compton  
time reversed annihilation

Mandelstam:  $s = 2\omega_1\omega_L(1 - \cos\Theta_{\vec{k}_1\vec{k}_L})$

threshold:  $s_{th} = 4 m^2 \rightarrow \sigma_{BW}(s < s_{th}) = 0$

sub-threshold pair production: non-linear BW (multi-photon)

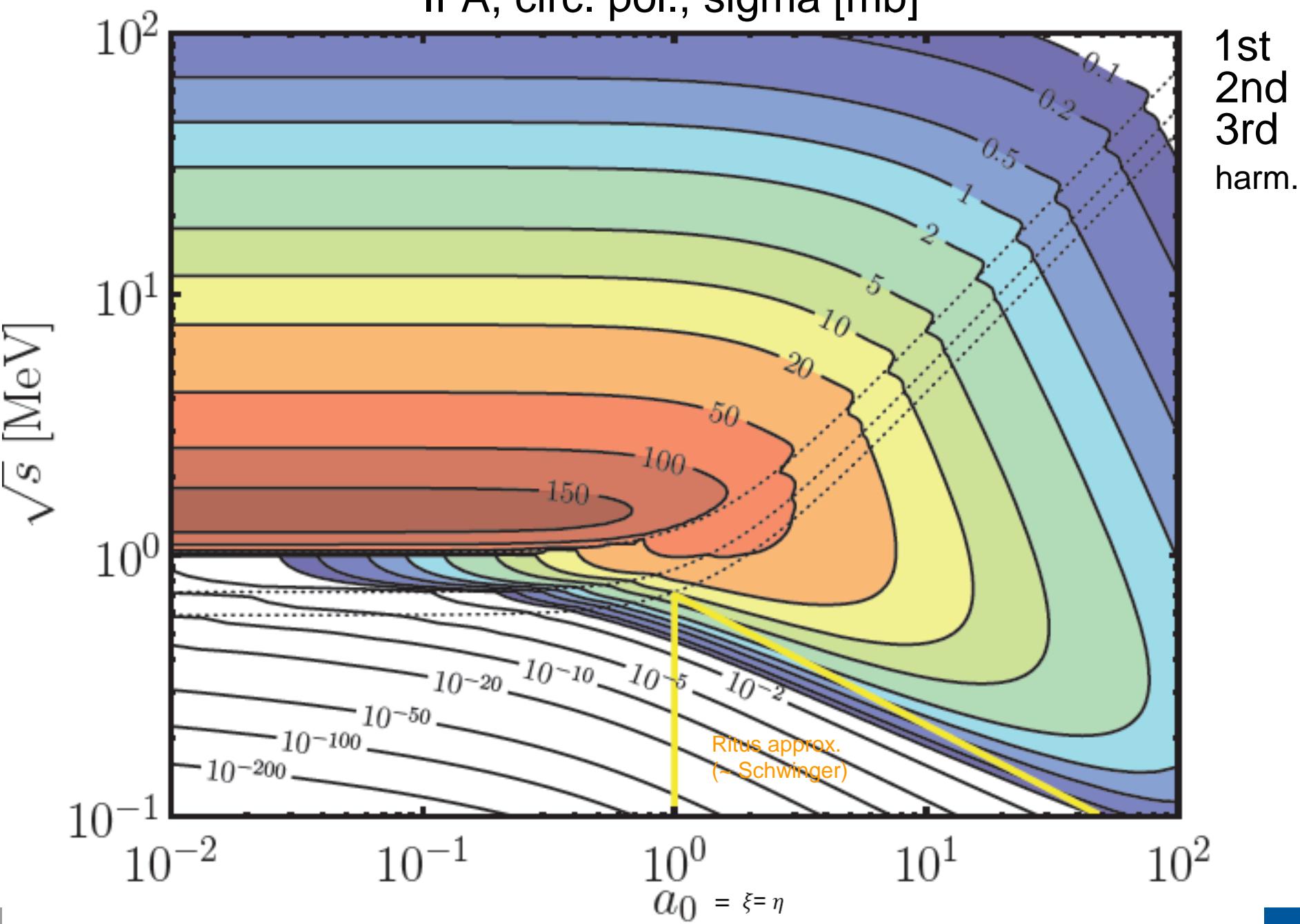


Breit-Wheeler    n.l. Breit-Wheeler

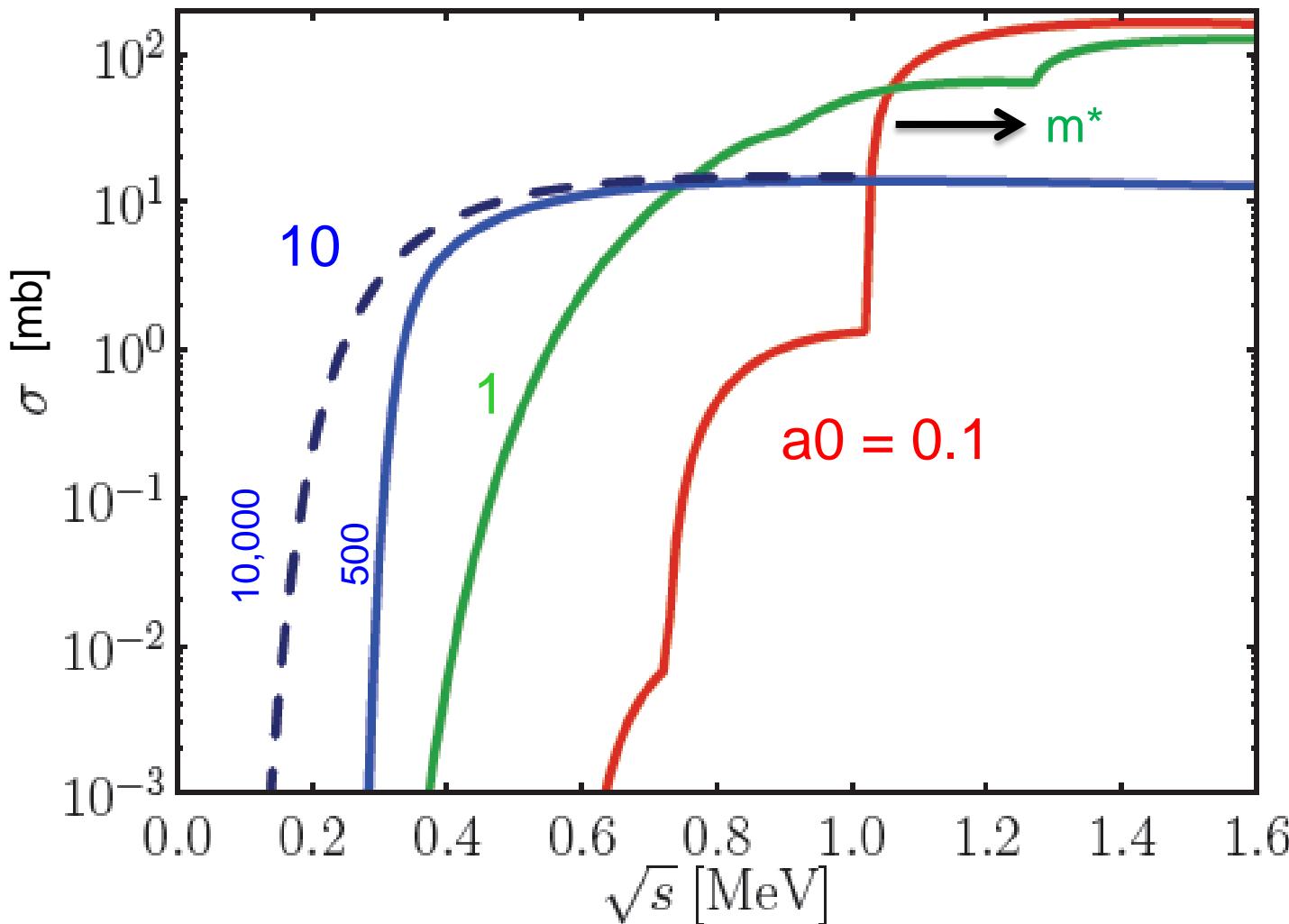
emphasis on short pulses & intensity effects:

Nousch, Seipt, BK, Titov PLB (2012), Titov, Takabe, BK, Hosaka PRL (2012), PRA (2013)

# IPA, circ. pol., sigma [mb]



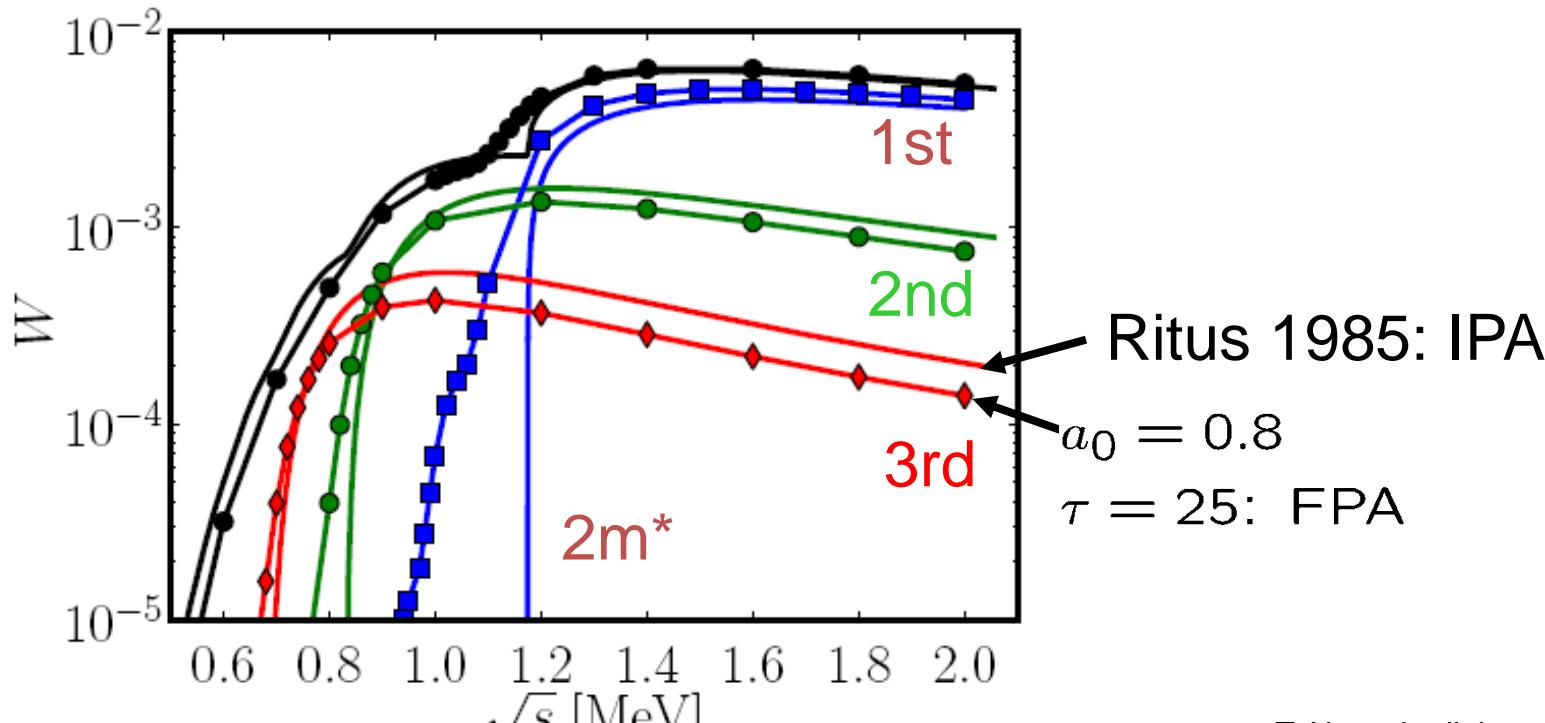
# IPA



IPA: infinitely-long pulse approx. (plane wave)

# Pair Production in Short Laser Pulses

FPA: finite pulse approx. (plane wave)



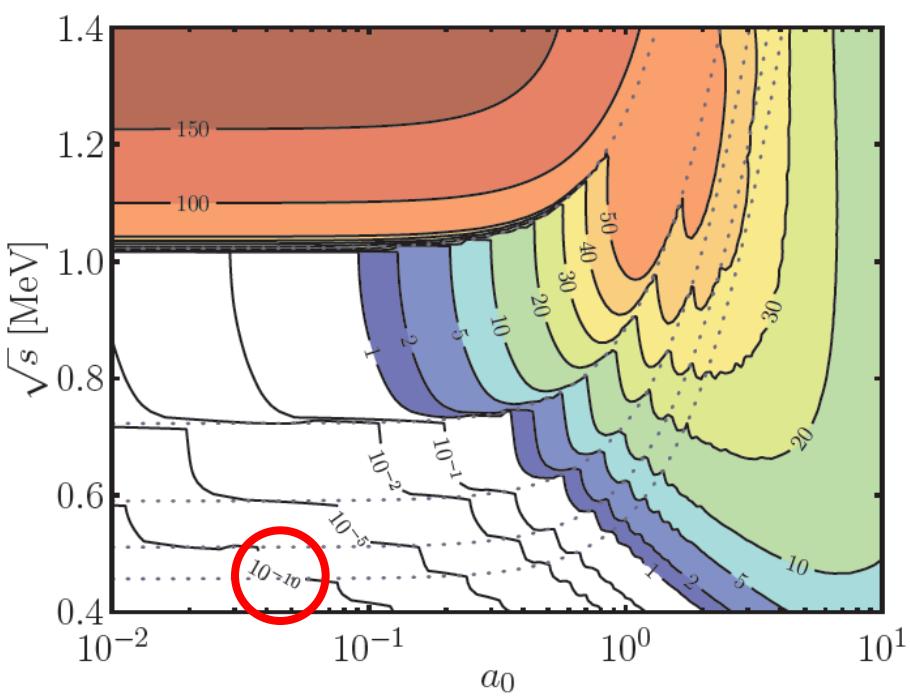
T. Nousch, diploma thesis, Dresden 2011  
supervision: D. Seipt

# Pair Production in Ultra-Short Laser Pulses

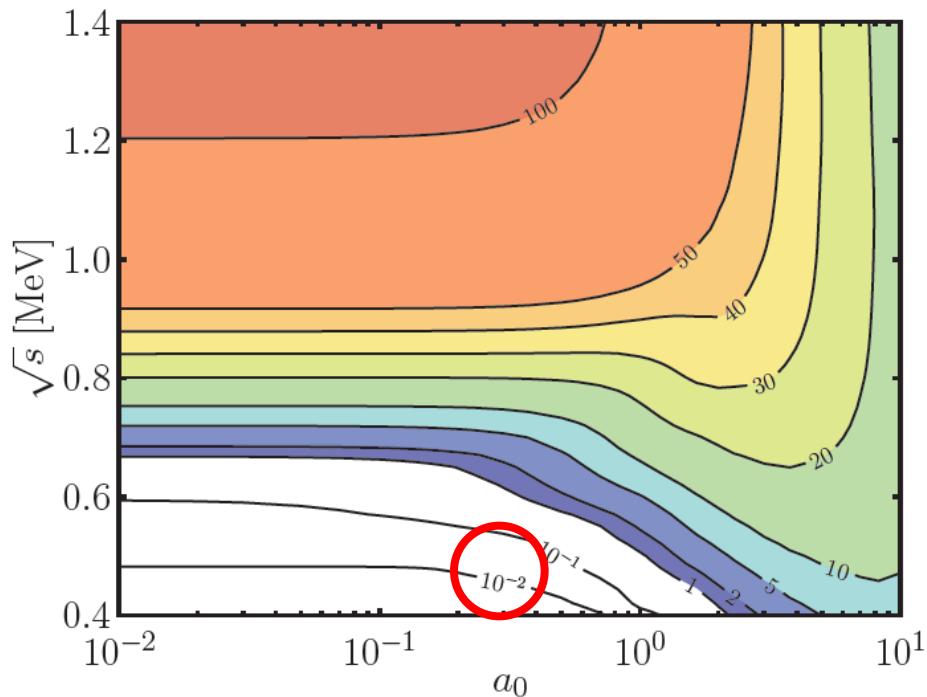
lin. polarization, sigma [mb]

pulse shape:  $g(\varphi) = \cos^2(\varphi/2 N)$

IPA

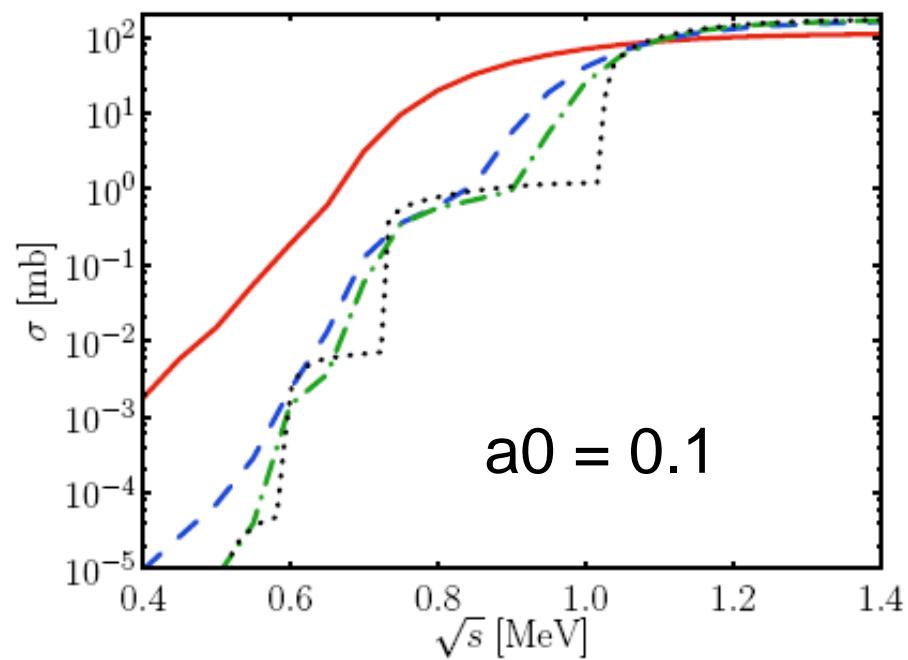
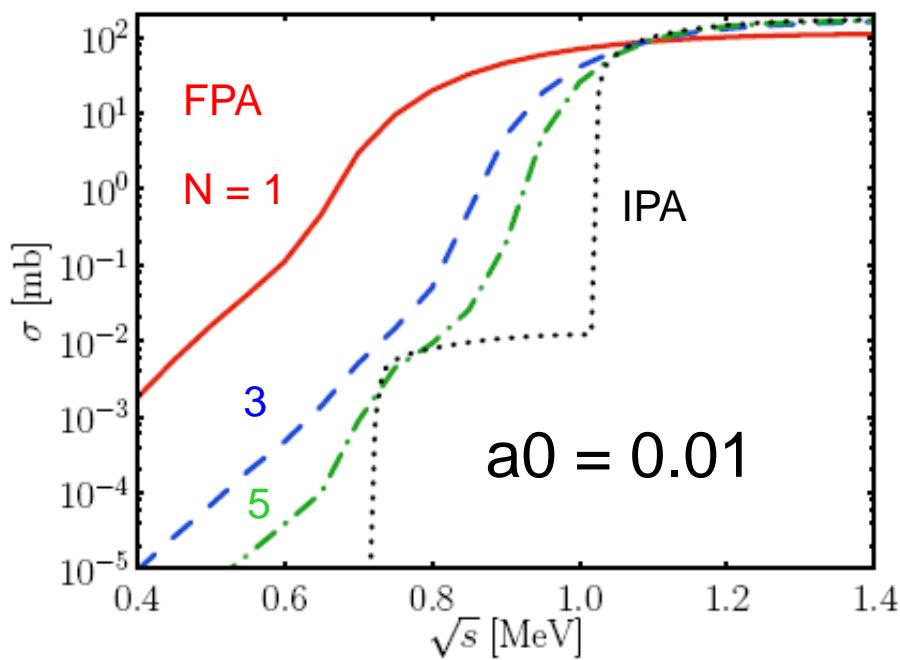


FPA,  $N = 1$



Nousch, Seipt, BK, Titov PLB (2012), Titov, Takabe, BK, Hosaka PRL (2012)

# N dependence

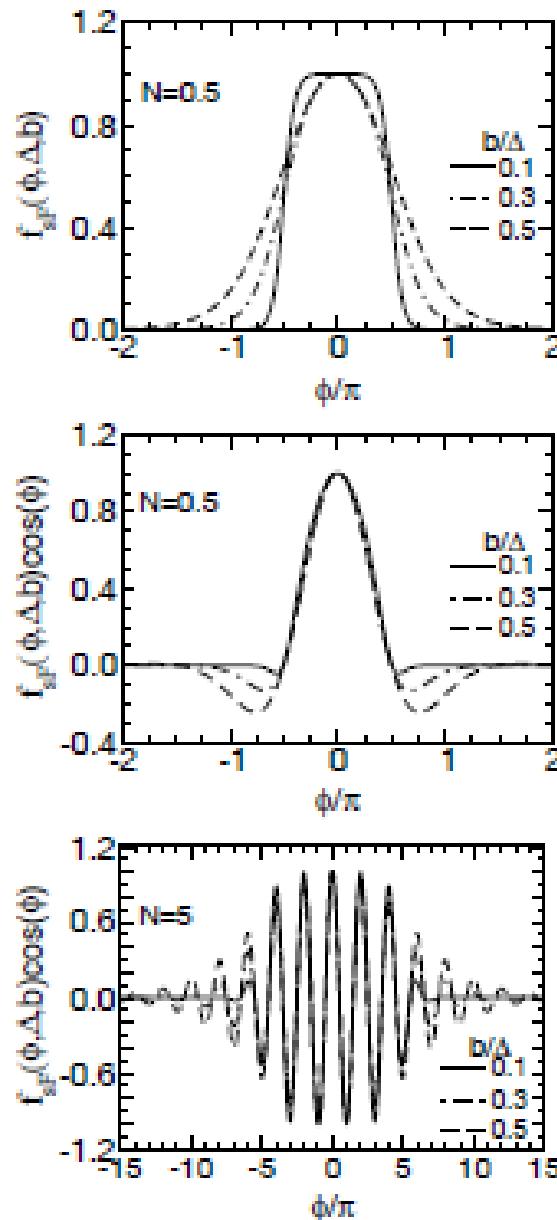
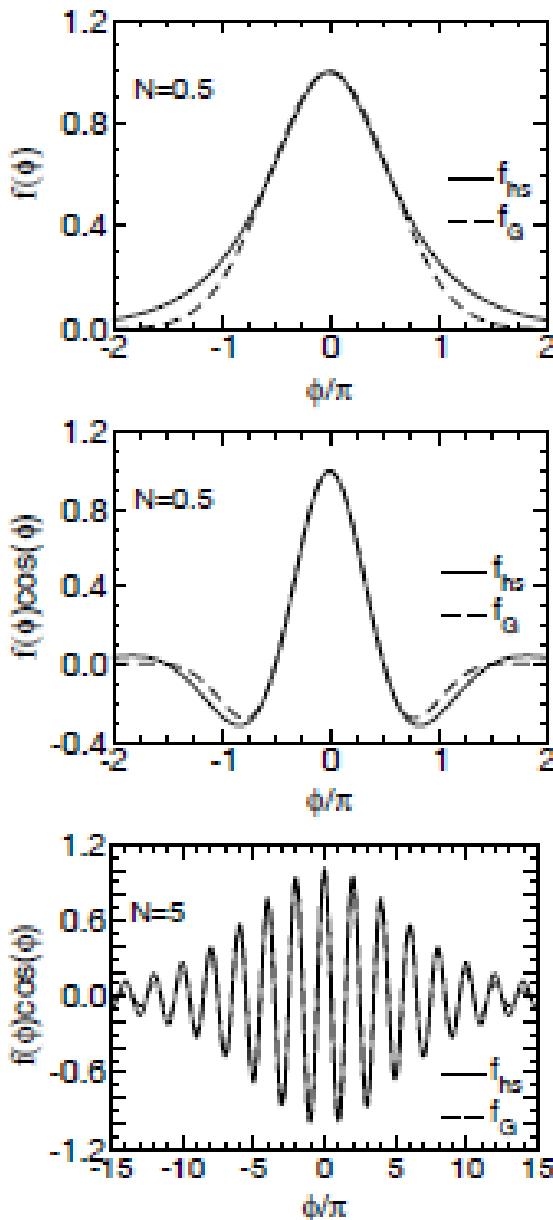


harmonics & finite bandwidth effects →

laser enabled subthreshold production

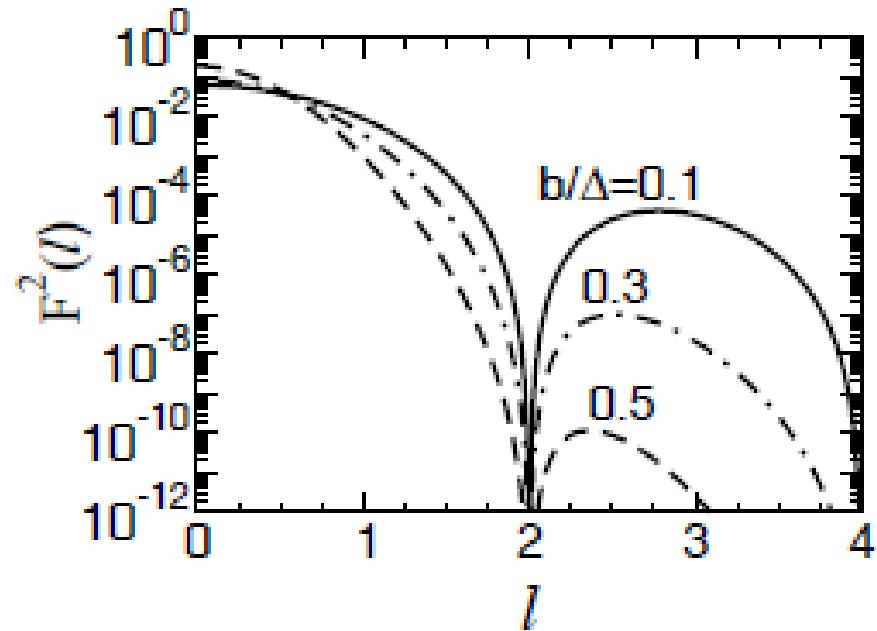
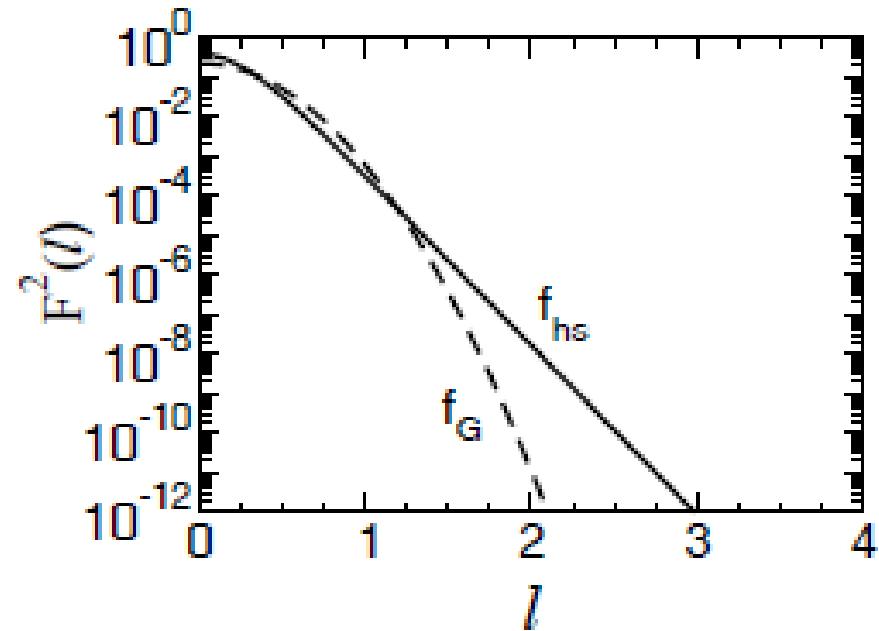
Seipt, BK, PLB 2012: folding model(s) - intensity vs. frequency variation → spectrum

# Pulse Shapes



Titov, BK, Takabe, Hosaka  
PRA (2013)

# Fourier Transforms



$$F_{hs}(l) = \frac{\Delta}{2 \cosh \frac{1}{2}\pi\Delta l} ,$$

$$F_G(l) = \frac{\tau_G}{\sqrt{2\pi}} \exp \left[ -\frac{1}{2}\tau_G^2 l^2 \right] ,$$

$$F_{sF}(l) = \frac{1 + \exp \left[ -\frac{\Delta}{b} \right]}{1 - \exp \left[ -\frac{\Delta}{b} \right]} \frac{b \sin \Delta l}{\sinh \pi b l} .$$

}

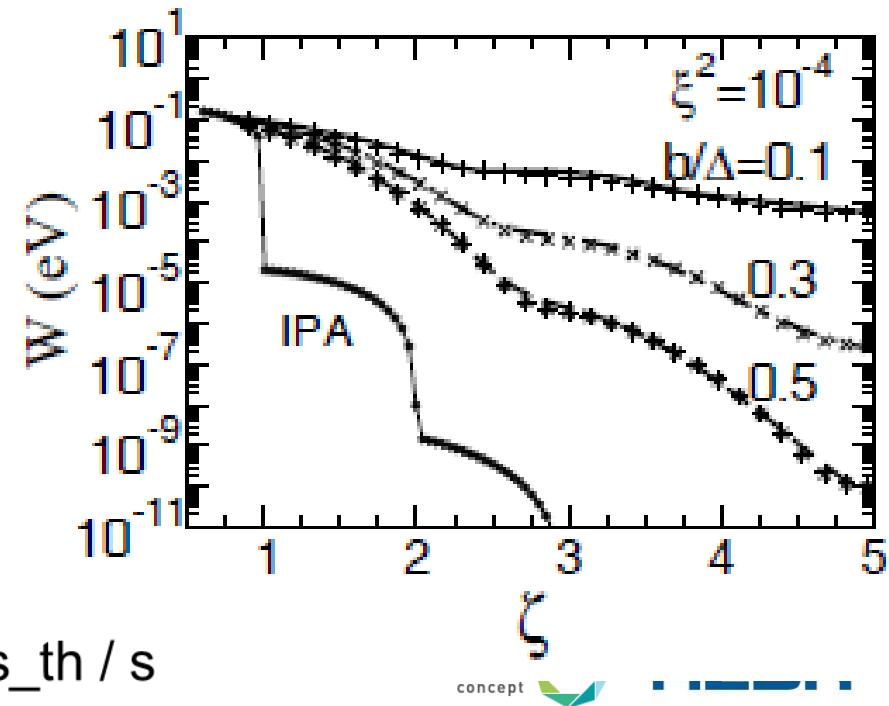
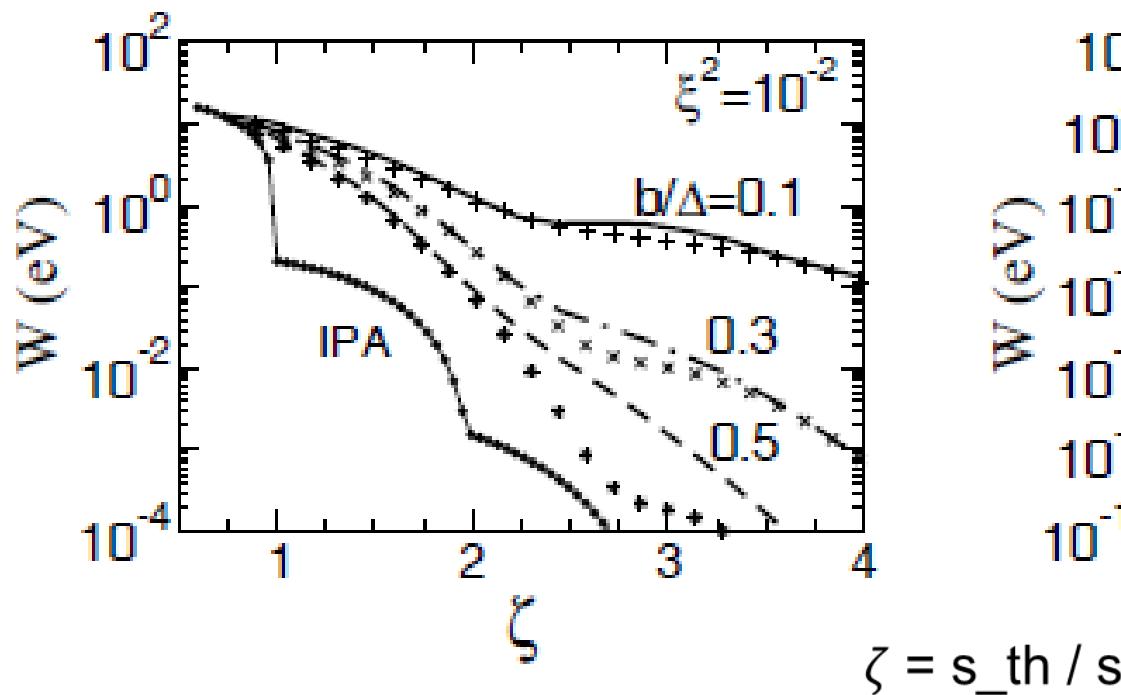
1 parameter: width

2 parameters:  
flat-top section + ramping

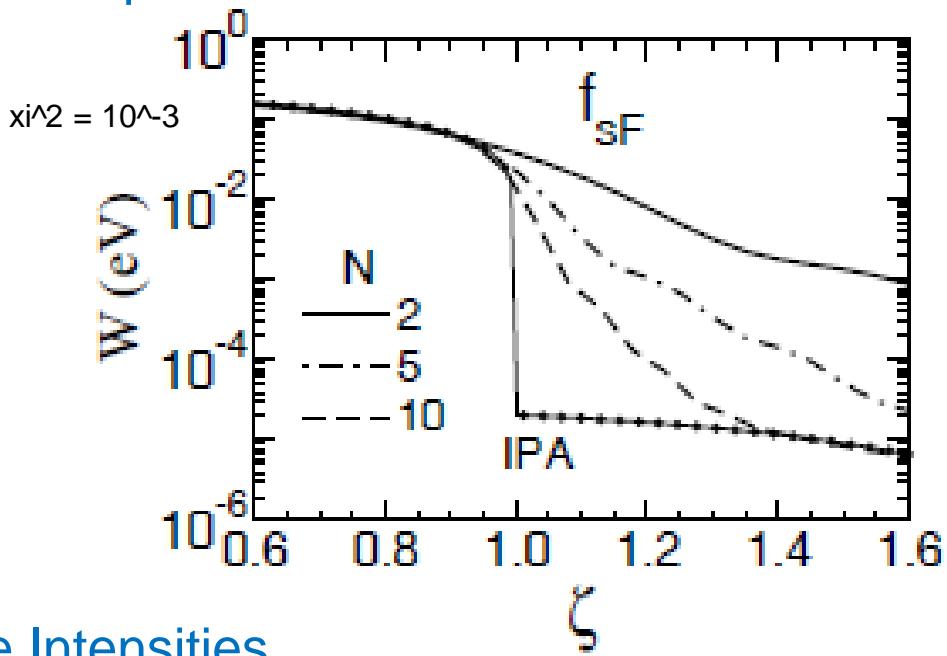
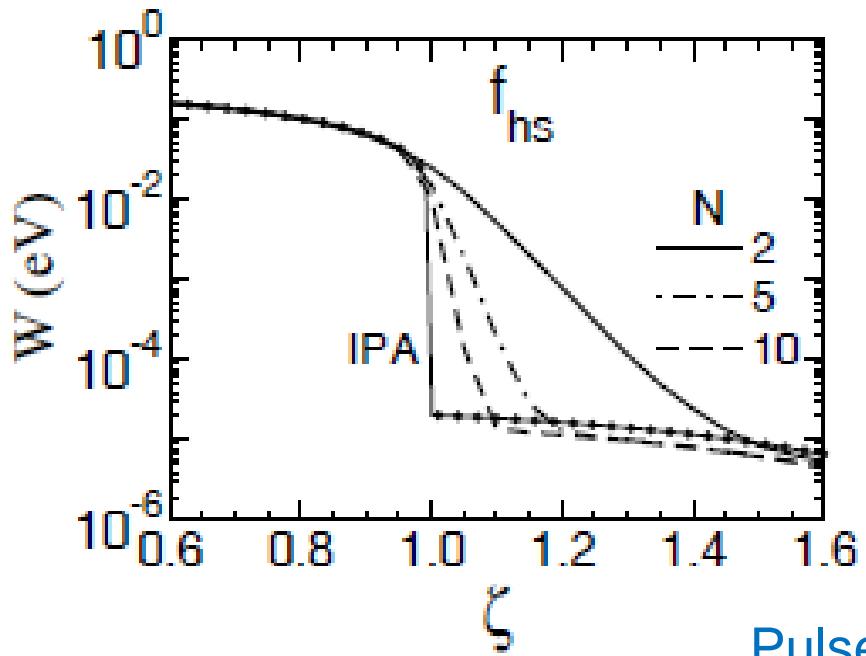
$$dW = \frac{\alpha \zeta^{1/2}}{2\pi N_0 M_e} \int_{\zeta}^{\infty} dl |M_{fi}(l)|^2 \frac{d\vec{p}}{2p_0} \frac{d\vec{p}'}{2p'_0} \delta^4(k' + lk - p - p') .$$

↑

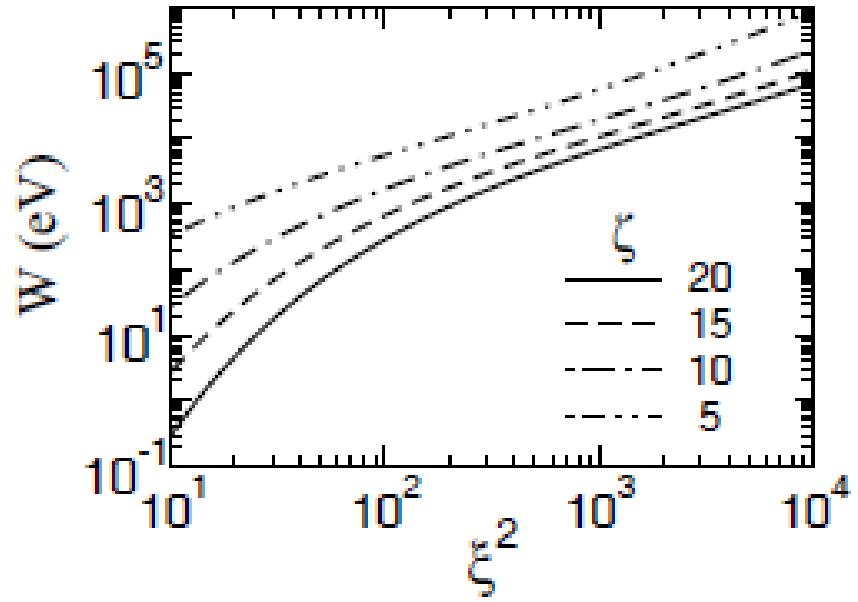
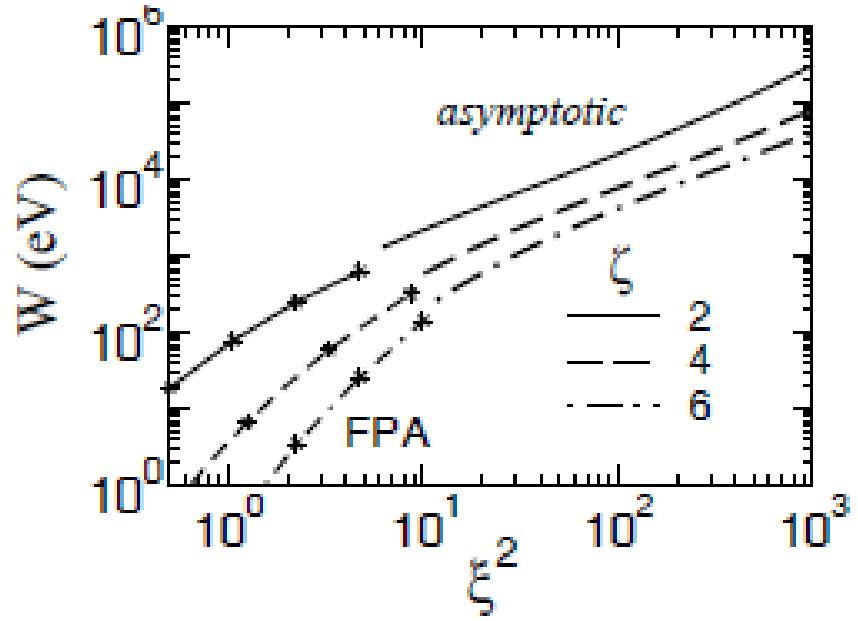
$$N_0 = \frac{\int_{-\infty}^{\infty} S dz (E_{FPA}^2 + B_{FPA}^2)}{\int_0^{\lambda} S dz (E_{IPA}^2 + B_{IPA}^2)} = \frac{1}{2\pi} \int_{-\infty}^{\infty} d\phi (f^2(\phi) + f'^2(\phi)),$$



## Pulse Shapes

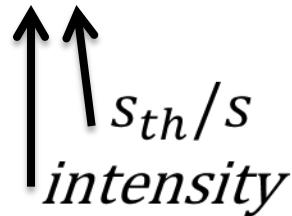


## Pulse Intensities



two regimes:

(i)  $\xi\varsigma \ll 1$



$N < 2$ : *high Fourier components enhance W*

(ii)  $\xi \gg 1$

*pulse shape and duration unimportant  
(dominant contribution from central  
pulse section)*

$FPA \sim IPA$

*complicated interplay of all effects*

(iii)  $\xi \sim 1$

Titov, BK, Takbe, Hoska PRA (2013)

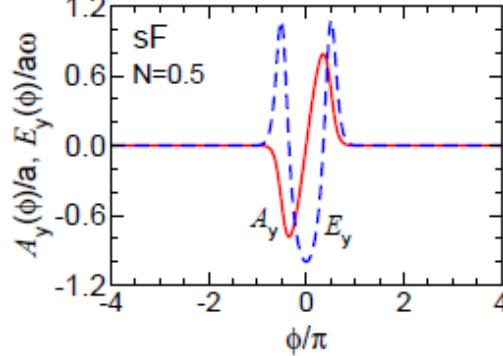
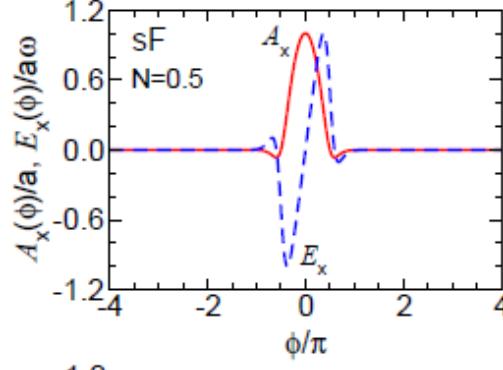
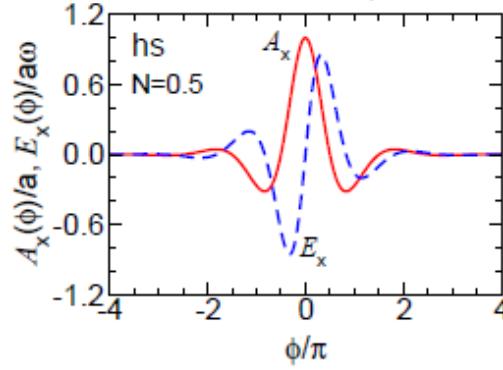
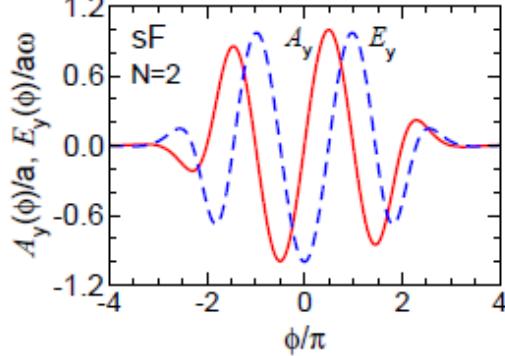
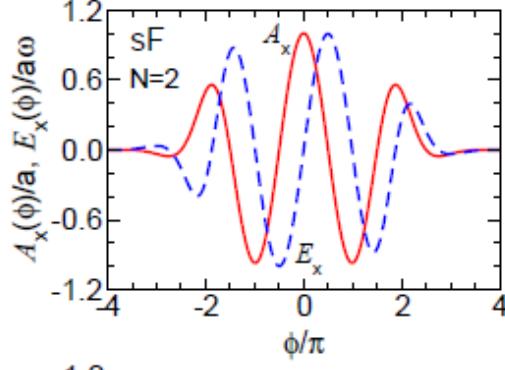
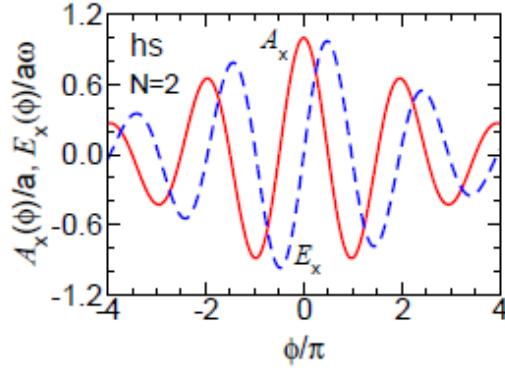
work in progress (T. Nousch):



IPA: Jansen, Muller (2013), Wu, Xue (2014)

### 3. Compton: ultra-short pulses

$$\vec{A}(\phi) = f(\phi) \left( \vec{a}_1 \cos(\phi + \tilde{\phi}) + \vec{a}_2 \sin(\phi + \tilde{\phi}) \right)$$



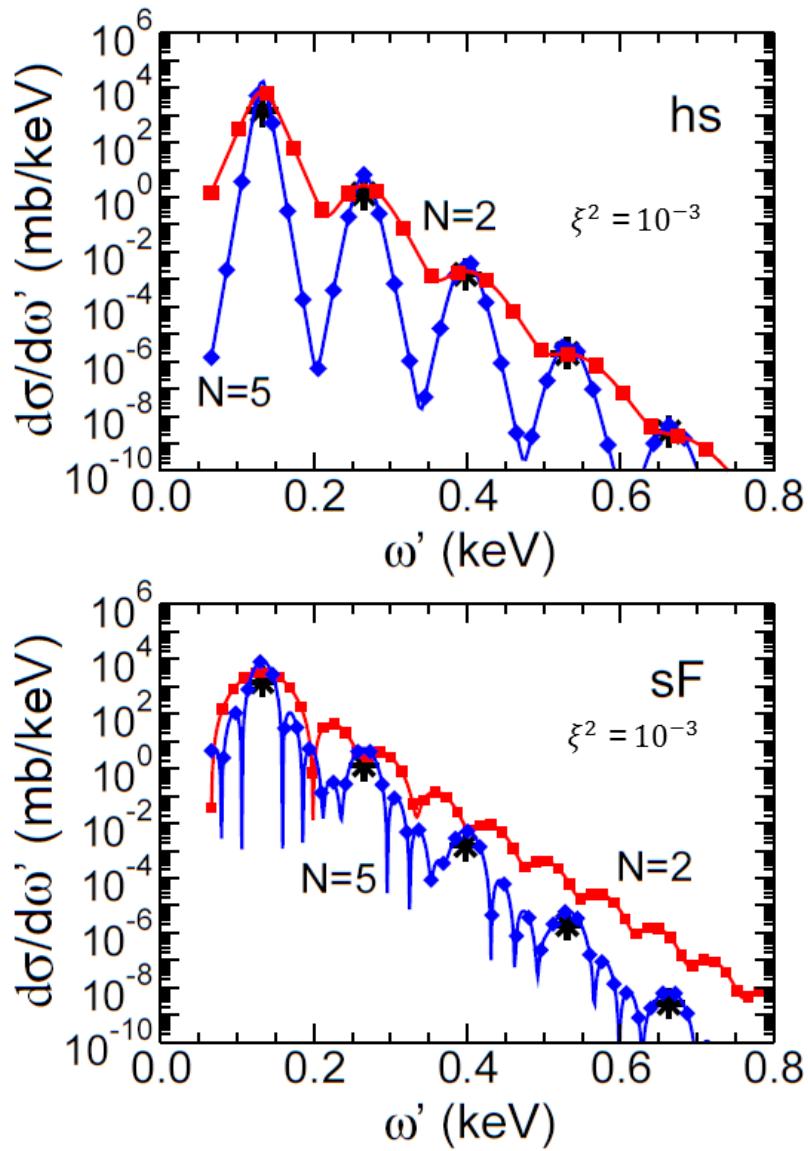
$$f_{\text{hs}}(\phi) = \frac{1}{\cosh \frac{\phi}{\Delta}}$$

$$f_{\text{sF}}(\phi) = \frac{\cosh \frac{\Delta}{b} + 1}{\cosh \frac{\Delta}{b} + \cosh \frac{\phi}{b}}$$

N = Delta/pi

Titov, BK, Shibata, Hosaka, Takabe  
1408.1040

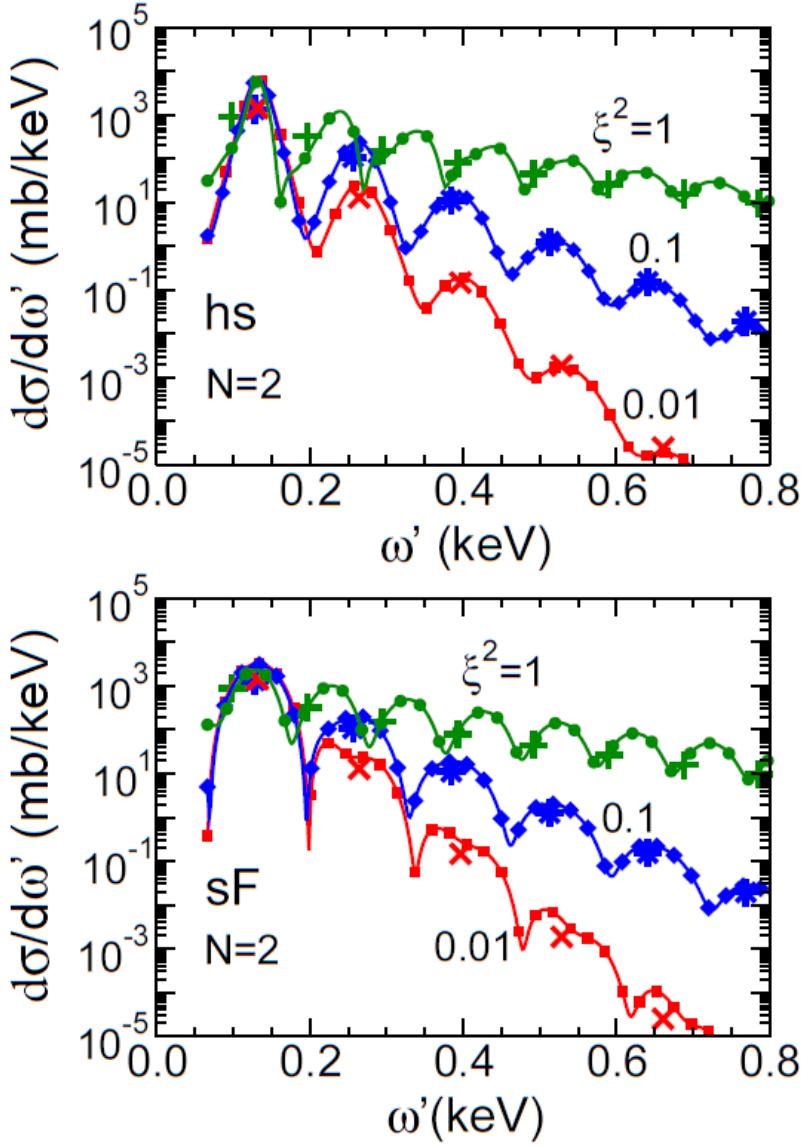
$\omega'$ , 170 degrees



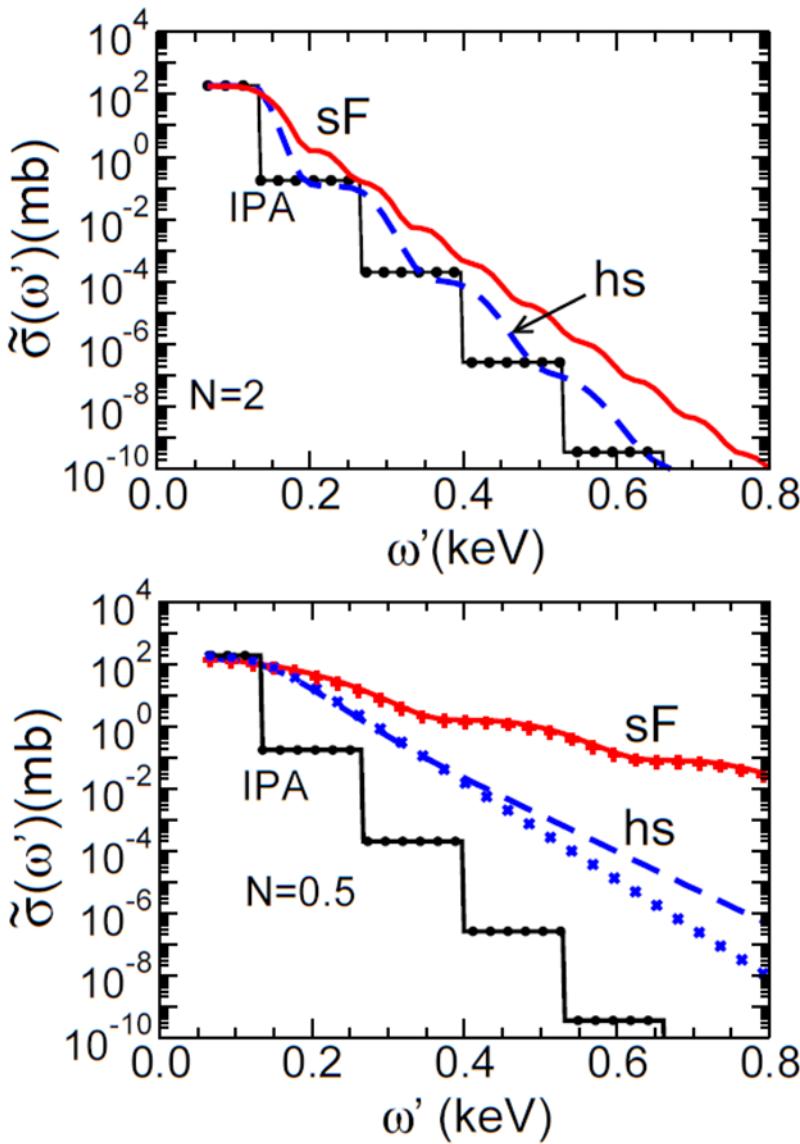
4 MeV



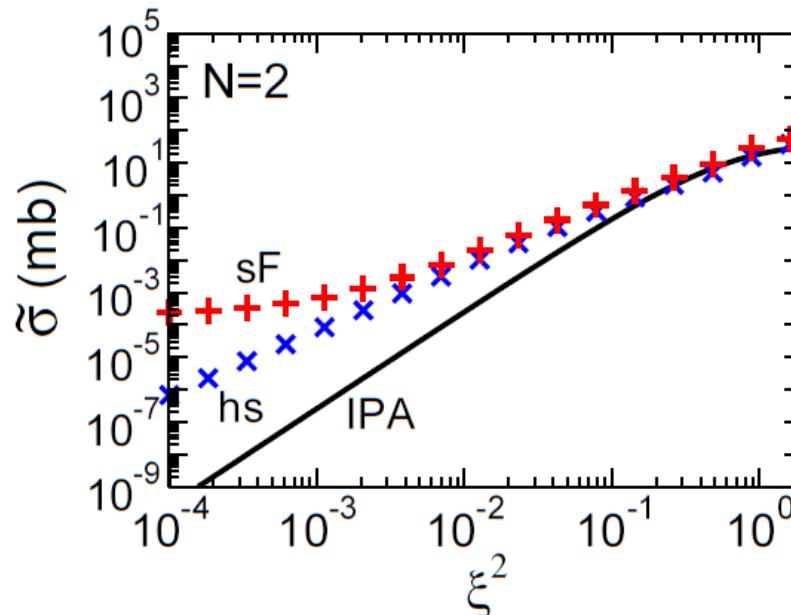
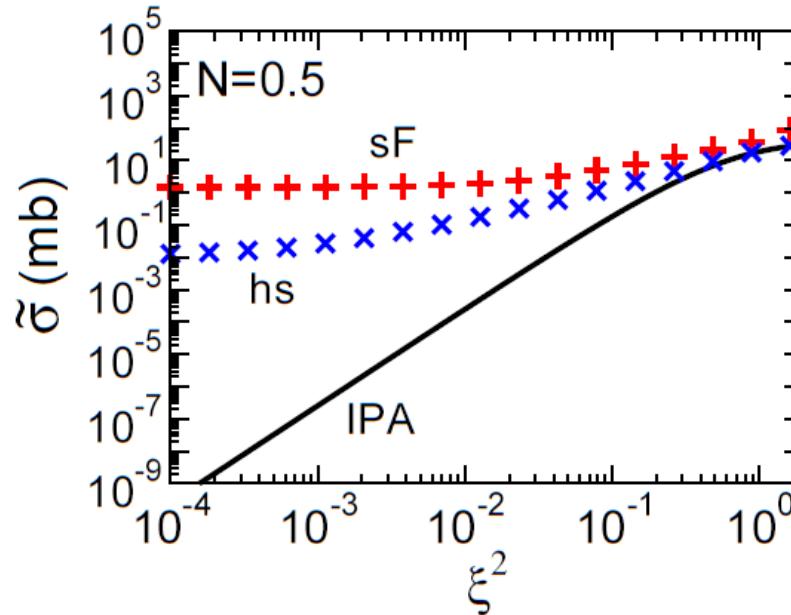
1.55 eV



# highlighting multi-photon effects



$$\tilde{\sigma}(\omega') = \int_{\omega'}^{\infty} d\bar{\omega}' \frac{d\sigma(\bar{\omega}')}{d\bar{\omega}'} = \int_{l'}^{\infty} dl \frac{d\sigma(l)}{dl}$$



# Summary

pairs = particles & anti-particles (anti-matter)

Schwinger: strong assistance by 2nd field

Breit-Wheeler: sub-threshold, pulse length, pulse shape, intensity

elementary processes – prospects for laser matter interaction

Compton: ultra-short pulses, probing multi-photon effects

laser-assisted scattering of x-rays: Seipt, BK PRA (2014)  
entangled 2-photon emission: Seipt, BK PRD (2012)

# Outlook

free electron (positron)

pQED

laser dressed (Volkov)

sQED

laser + Coulomb

spatio-temporal structure

$QED_{light}$ :  $\gamma, e^\pm \rightarrow QED_{heavy}$ :  $\gamma, e^\pm, \mu^\pm, \tau^\pm$

$QED$ :  $\gamma, e^\pm, \mu^\pm, \tau^\pm, hadrons/quarks$

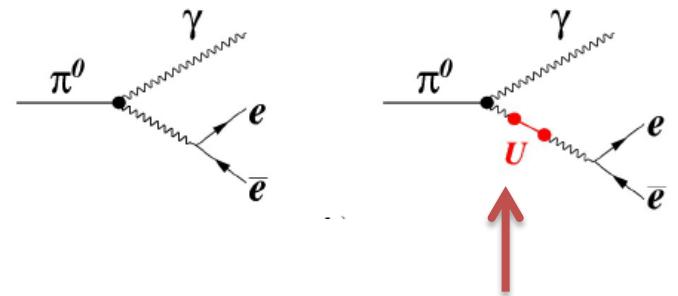
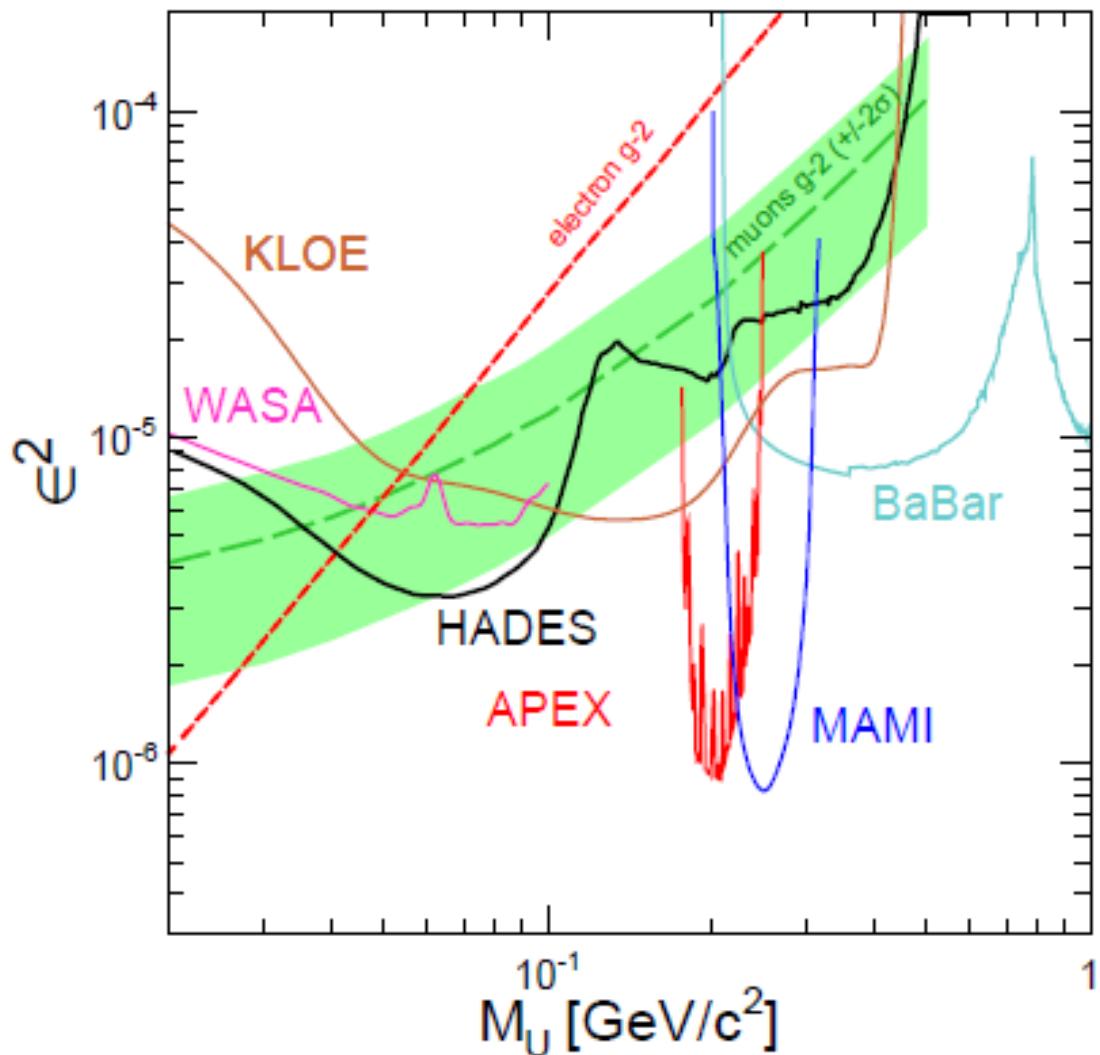
$QED_{e.w.}$ :  $\gamma, Z^0, e^\pm, \mu^\pm, \tau^\pm, hadrons/quarks, W^\pm, \nu$

What is beyond QED?  $\mathcal{L} = -\frac{1}{4}F^2 + j \cdot A + ?, \quad 4D \rightarrow XD$

$U(1) \otimes SU(2) \rightarrow ?, \text{ new couplings, new fields, } \dots$

# Searching a Dark (U) Photon

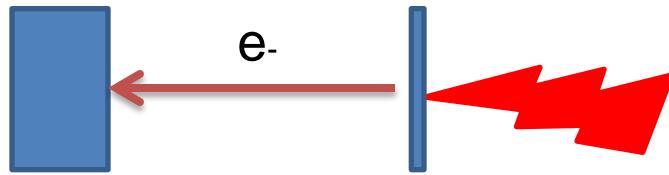
HADES, Phys.Lett. B731 (2014) 265



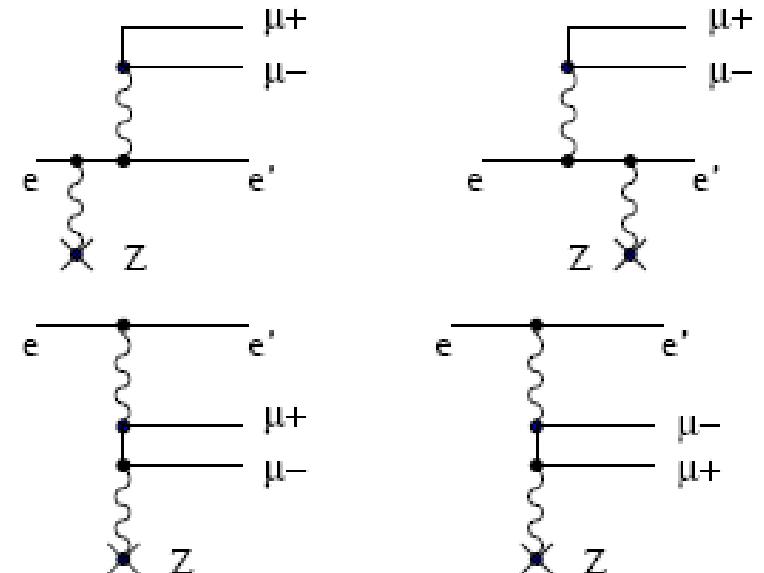
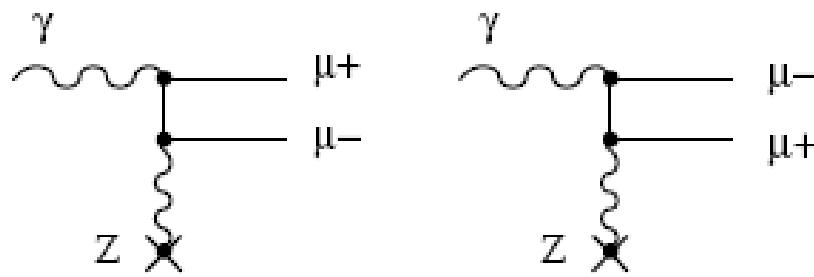
Dark Matter candidate

excluding more and more

# Muon Pair Production

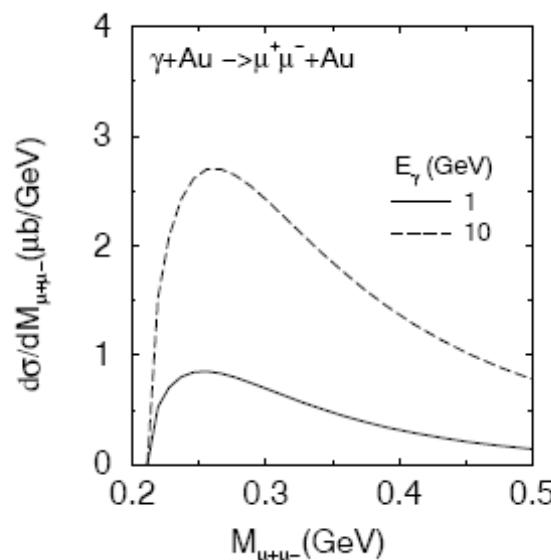
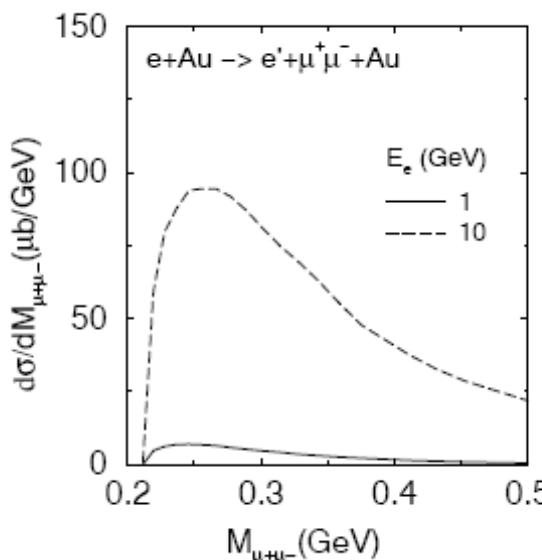


Bethe-Heitler



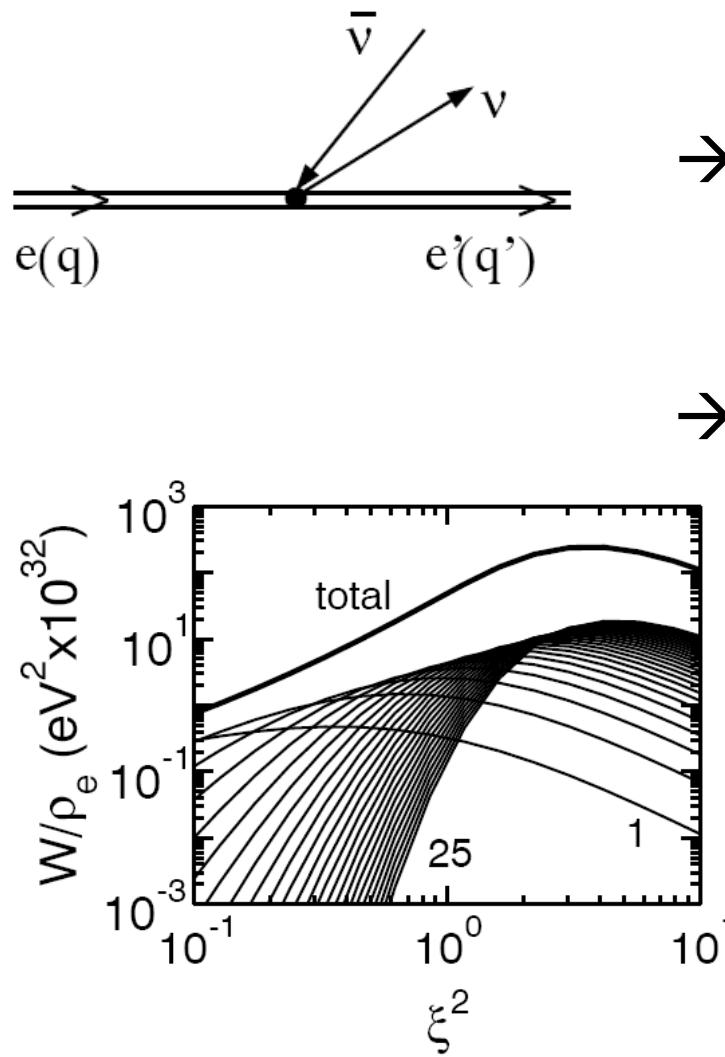
1

2



Titov, BK, PR ST AB 2009

# Neutrino Pair Production

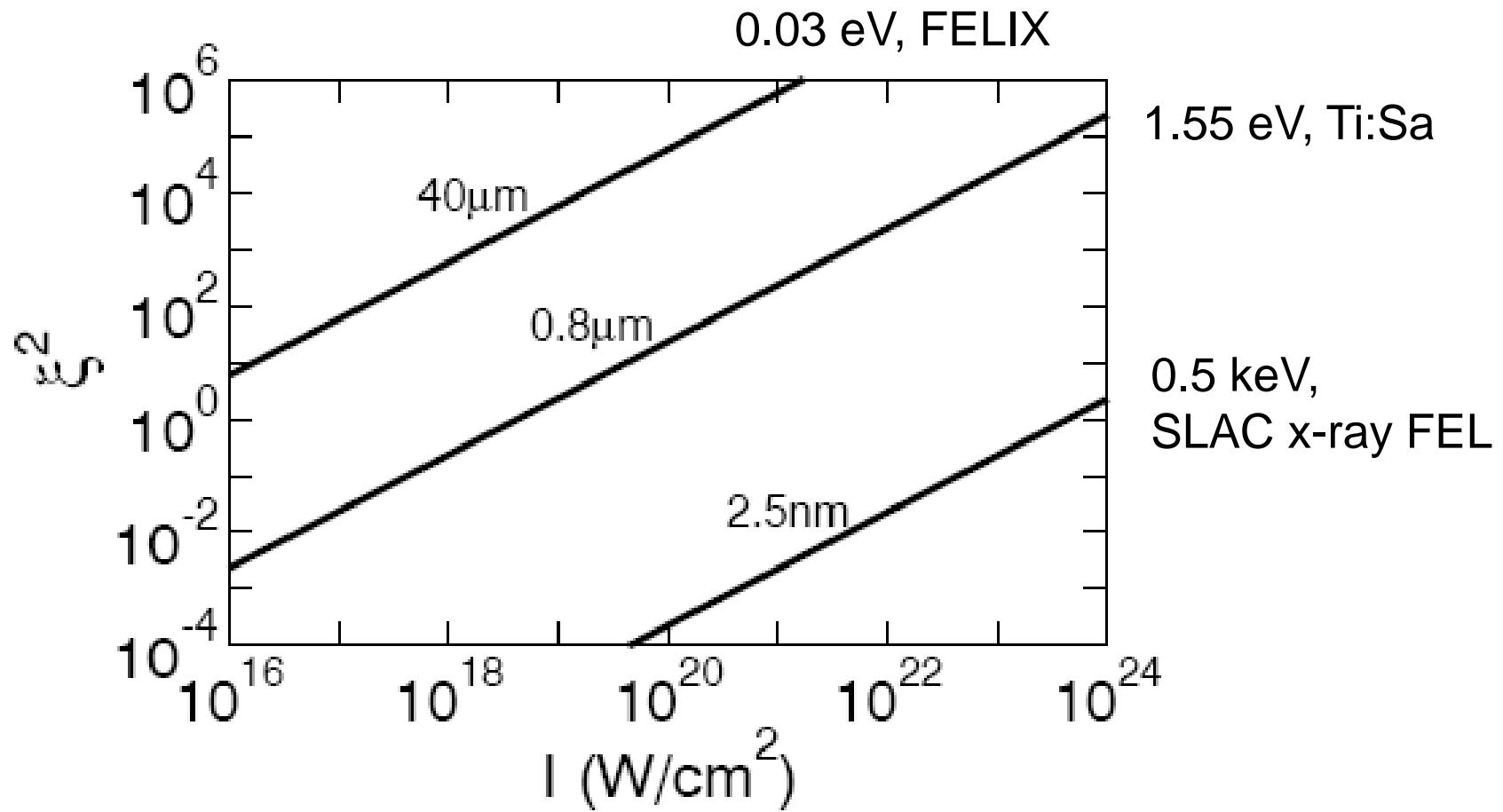


Titov, BK, Hosaka, Takabe, PRD 2011

page 31

$$a_0 = \frac{ea}{m} = \eta/2 = \xi \quad A = ag(\phi)(\epsilon_1 \cos \phi + \epsilon_2 \sin \phi)$$

circ. pol.

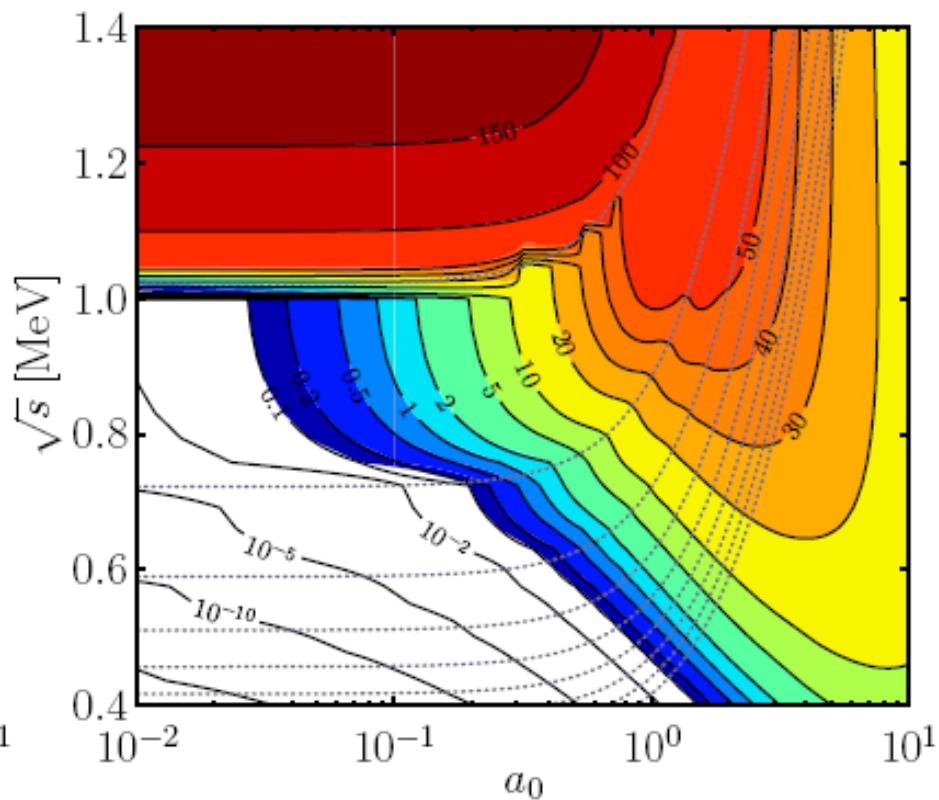
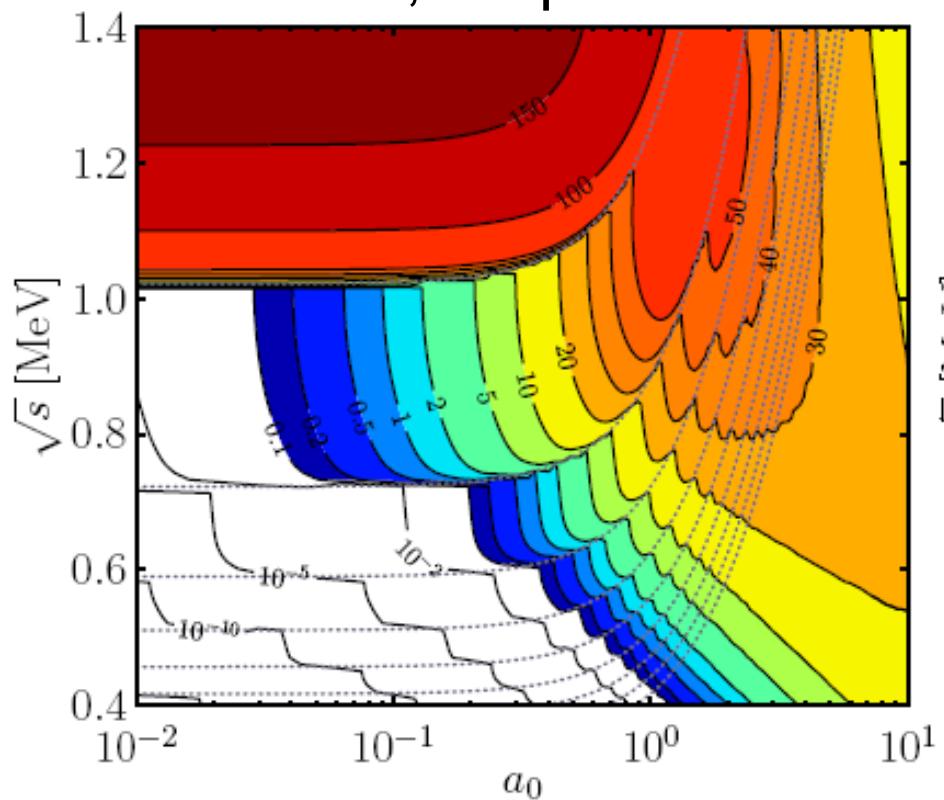


Titov, BK, Takabe, Hosaka PRD 2011

IPA, lin. pol.

$\sigma$  [mb]

IPA, circ. pol.



$$a_0 = 7.5 \sqrt{I_L / 10^{20} \frac{W}{cm^2}} \frac{eV}{\omega_L}$$

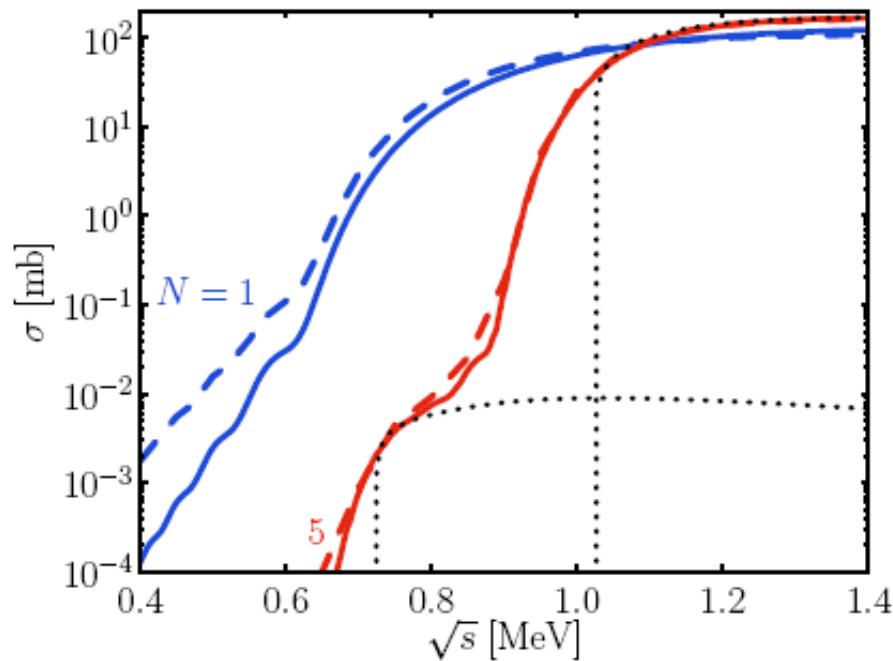
$$\kappa = 6 \cdot 10^{-2} \sqrt{I_L / 10^{20} \frac{W}{cm^2}} \frac{\omega_1}{GeV}$$

## D. Seipt: Folding Model (i)

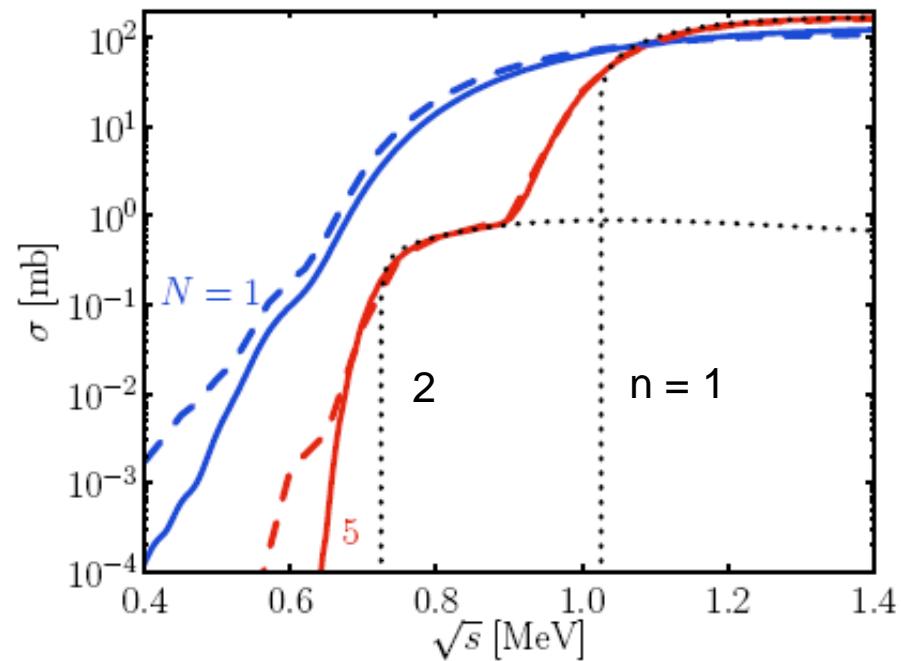
Fourier transform of g  
weak field harmonics

$$\langle \sigma_n \rangle(s) = R_n \frac{\int_0^\infty d\ell G(\ell - 1)^{2n} \sigma_n^{(0)}(\ell s)}{\int_0^\infty d\ell G(\ell - 1)^{2n}}.$$

$a_0 = 0.01$



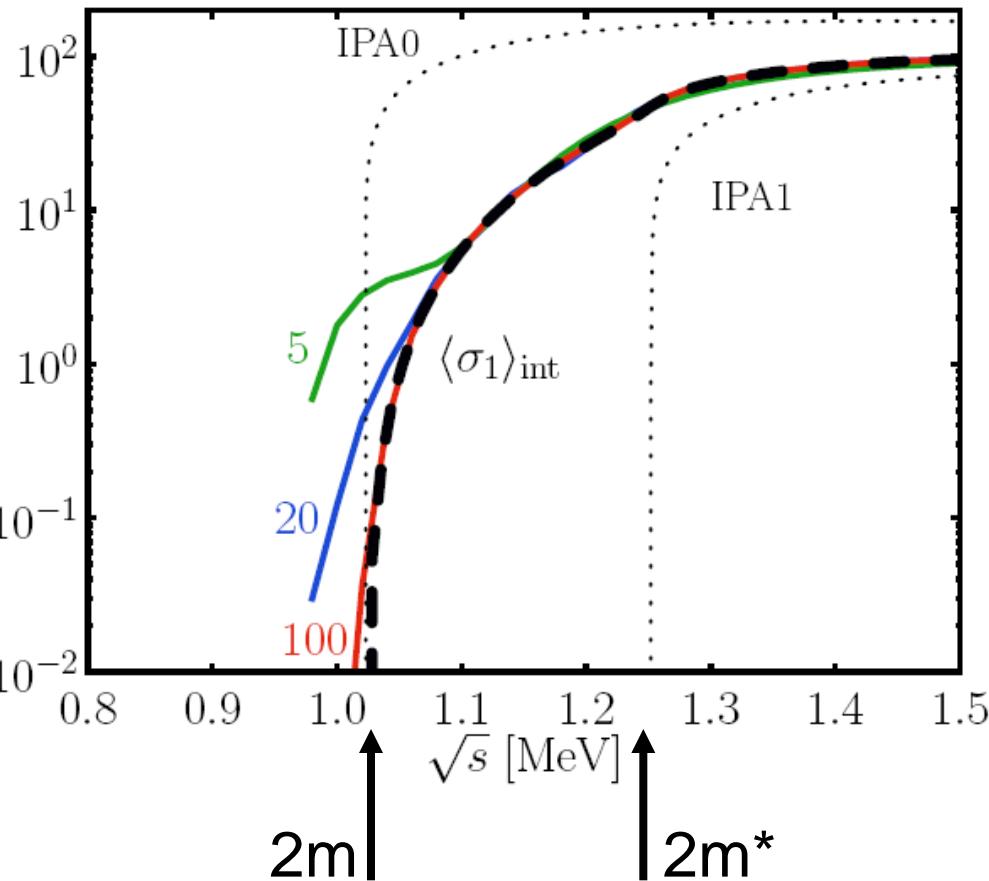
$a_0 = 0.1$



## D. Seipt: Folding Model (ii)

$$\langle \sigma_1 \rangle_{int} = \frac{\int d\phi g^2(\phi) \sigma_1(a, a_0 \rightarrow a_0 g(\phi))}{\int d\phi g^2(\phi)}$$

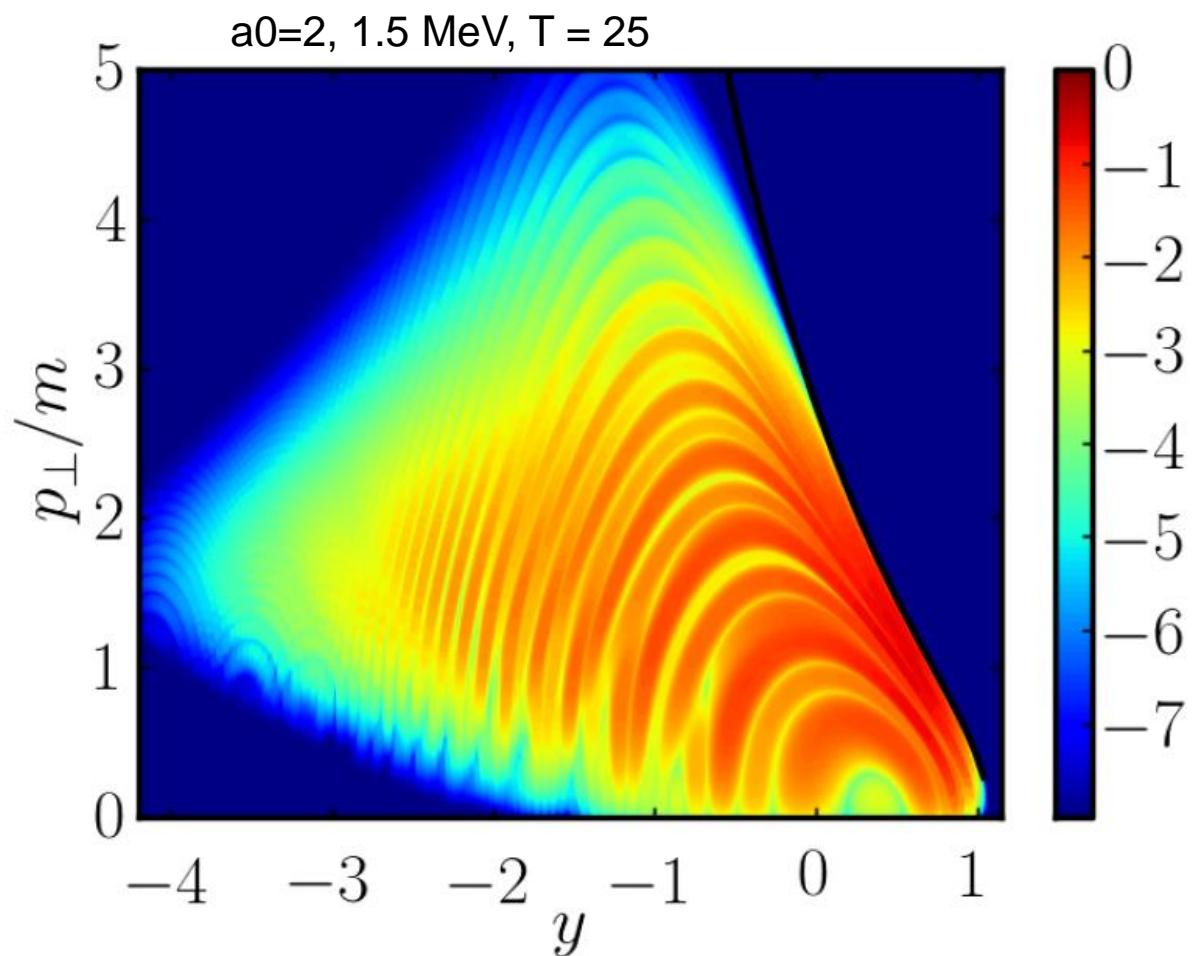
IPA, 1st harmonic



$N^{-1} > a_0^2$ :  
frequency distr.  $\rightarrow$  spectrum

$N^{-1} < a_0^2$ :  
intensity variation  $\rightarrow$  spectrum

# IPA & FPA: Asymmetry in Longitudinal Direction



T. Nousch, diploma thesis Dresden 2011

cf. Heinzl et al., PLB 2011