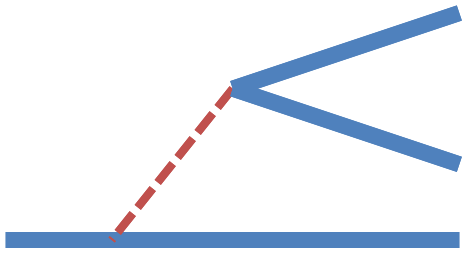
Trident process *)

B. Kämpfer

Helmholtz-Zentrum Dresden-Rossendorf
Technische Universität Dresden

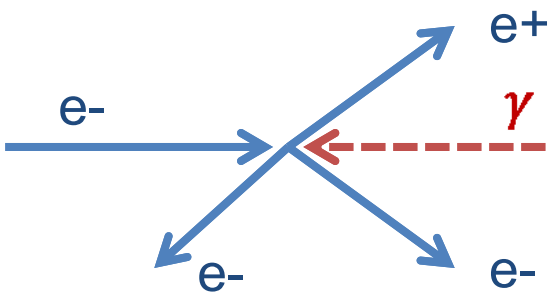
(strong) laser pulses: trident = Compton x Breit-Wheeler,
first step in seeded cascades,
F QED vs. pQED

*) U. Hernandez Acosta



Furry picture

= laser dressed e+-



e- + gamma → e+ + e- + e-

pulses of
laser, XFEL, MeV-GeV photons

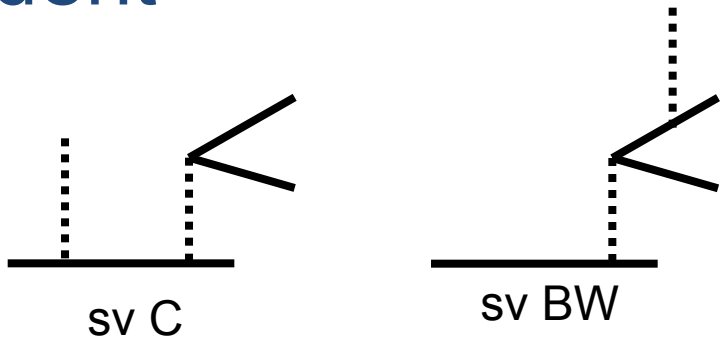
former exps. E-144 [Burke et al., PRL 79 (1997) 1526]
[Bamber et al., PRD 60 (1999) 092004]
theory [Hu, Muller, Keitel, PRL 105 (2010) 020404]
[Ilderton, PRL 106 (2011) 020404]
[King, Ruhl, PRD 88 (2013) 013005]
[King, Fedotov, PRD 98 (2018) 016005]
[Dinu, Torgrimsson, PRD 97 (2018) 036021]
[Mackenroth, Di Piazza, 1805.01731]

pQED exclusive
2 → 3 process

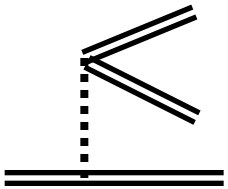
[Borsellino, Phys. Rev. 89 (1953) 1023]
[Suh, Bethe, PR 115 (1959) 674]
[Mork, Phys. Rev. 160 (1967)1065]
[Jarp, Mork, PRD 8 (1973) 159]
[Haug, Z. Naturf. A30 (1973) 159]
[Enod, Kobayashi, NIM A328 (1993) 517]
[Gakh et al., 1711.01770]

Triple Facet of Trident

pQED: triplet (trident)

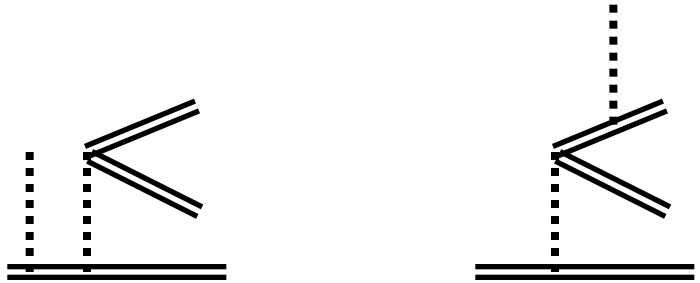


F QED: strong-field trident



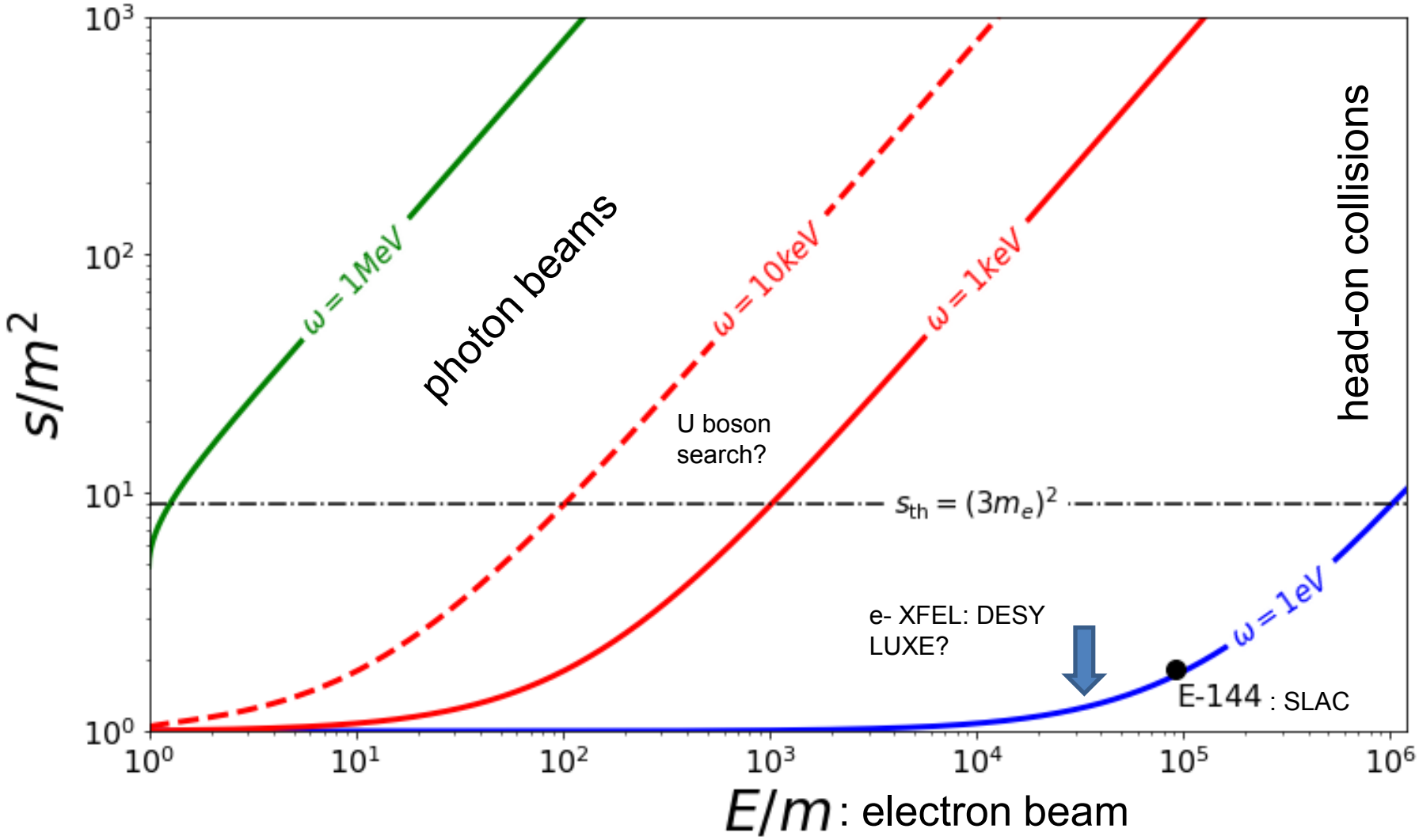
= C x BW

pF QED: assisted trident

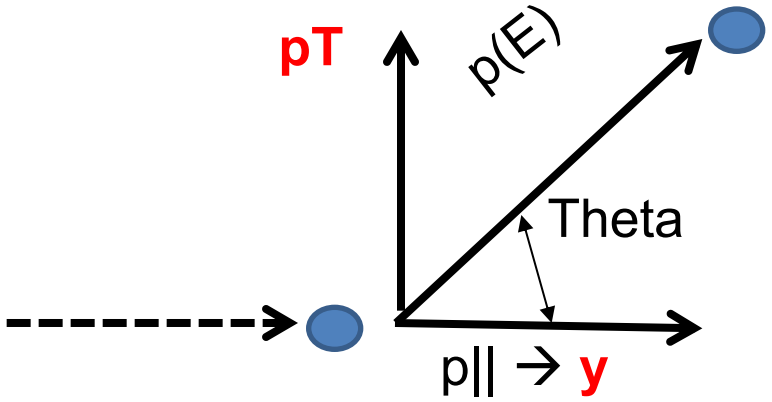


WF in any A(phi)

s = [k + p(e-)]^2


10^3
10^2
10^1
10^0
s/m^2
$\omega = 1MeV$
photon beams
$\omega = 10keV$
$\omega = 1keV$
U boson
search?
head-on collisions
$s_{th} = (3m_e)^2$
e- XFEL: DESY
LUXE?
$\omega = 1eV$
E-144 : SLAC
10^0
10^1
10^2
10^3
10^4
10^5
10^6
E/m : electron beam

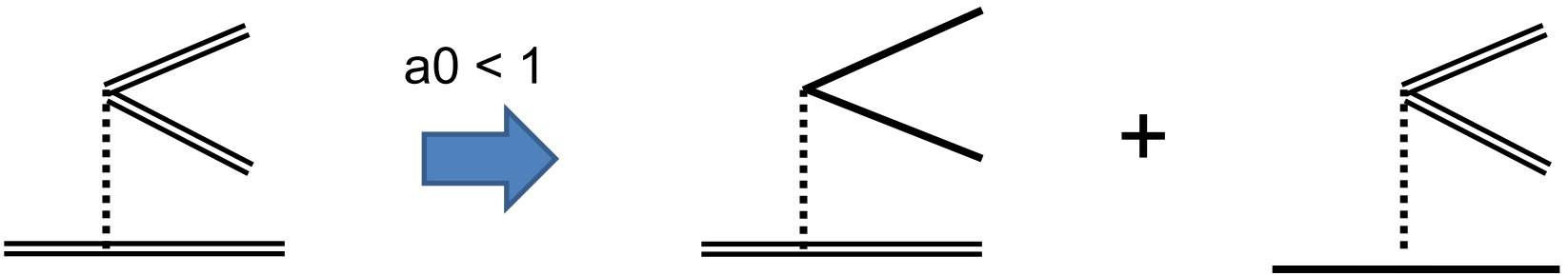
phase space distributions



E = mT cosh y
p|| = mT sinh y
= p cos Theta
mT = sqrt{m^2 + pT^2}
p = sqrt{E^2 – m^2}

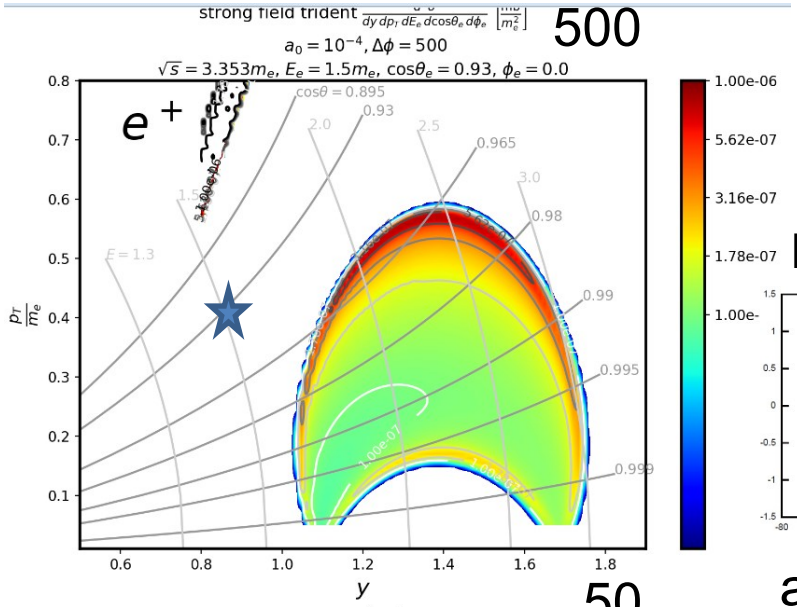
→ invariant distribution w.r.t. long. Lorentz boosts

F QED

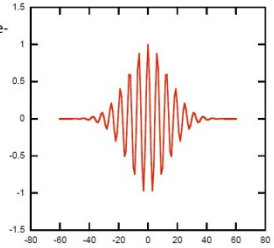


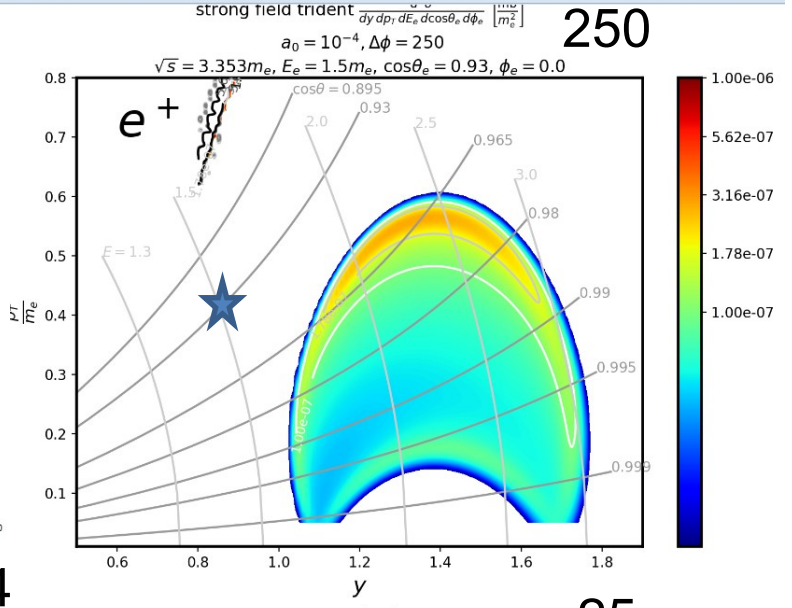
includes multi-photon & pulse shape effects

(i) impact of the pulse width: blowing up the phase space

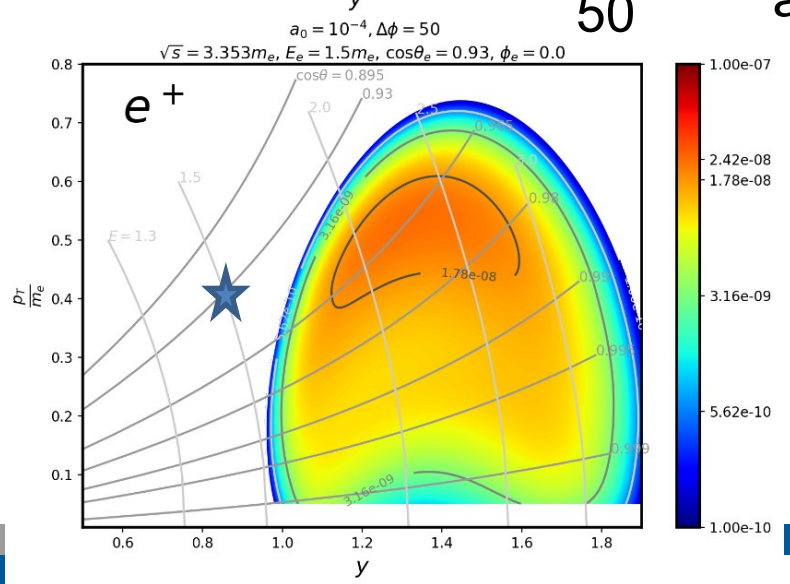


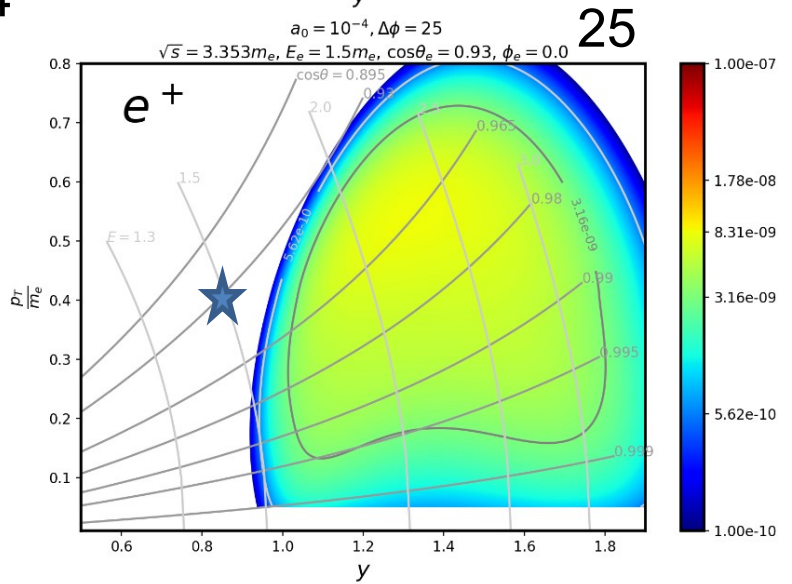
N = # / 2pi



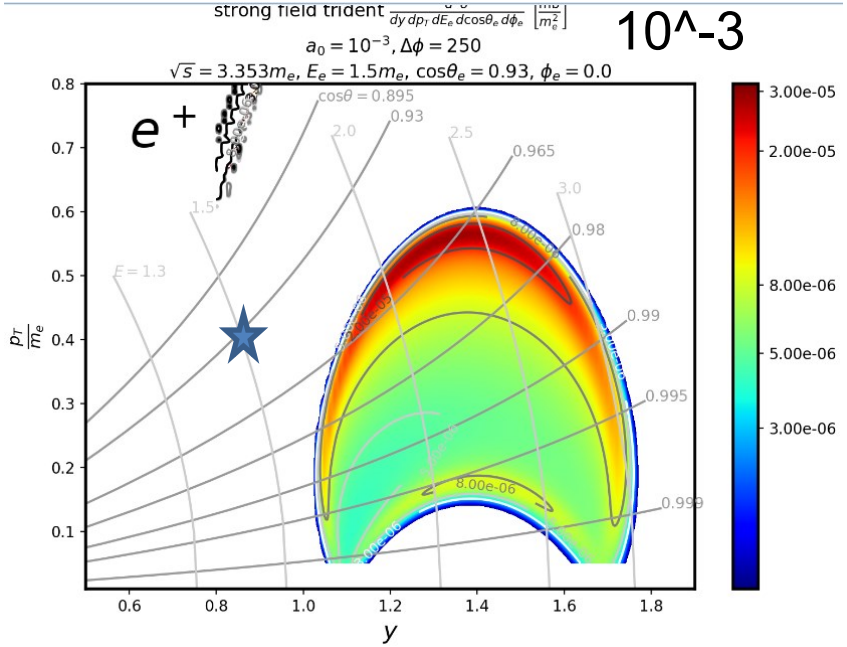


a0 = 10^-4

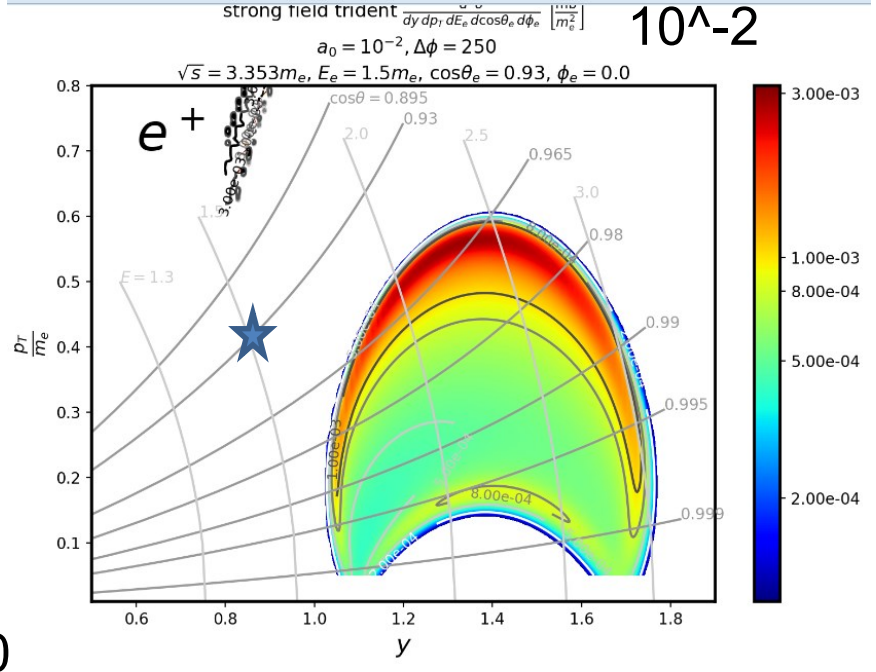




(ii) impact of the intensity a0: sigma vs. W normalization

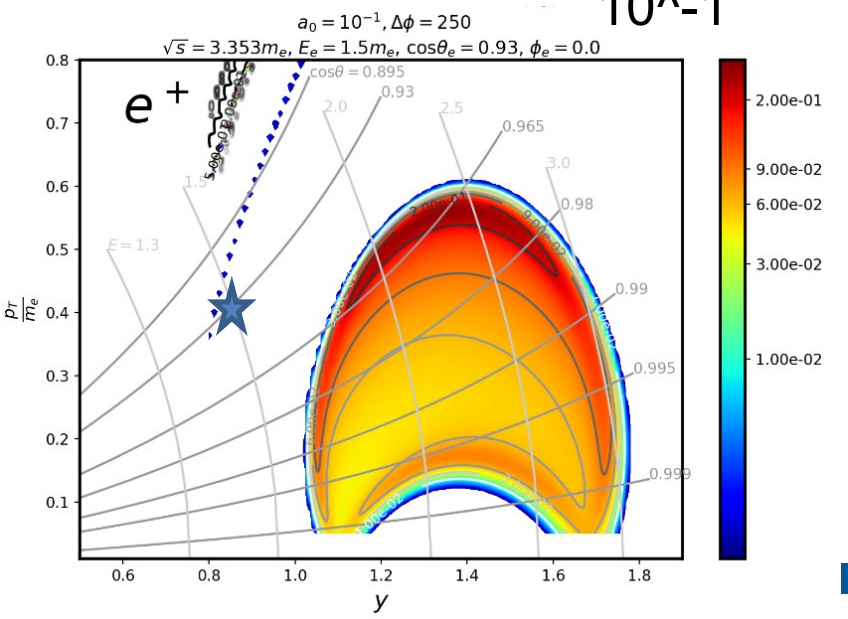


10^-3



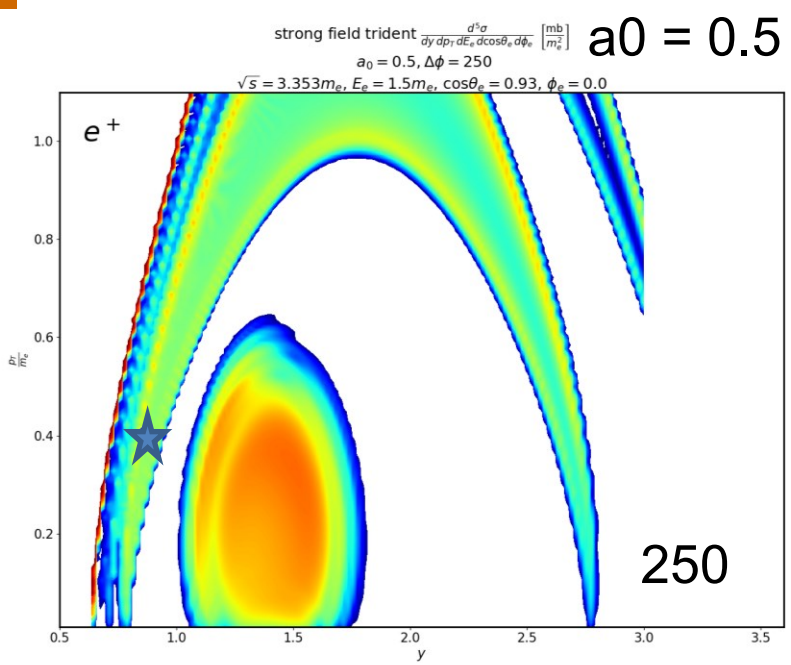
10^-2

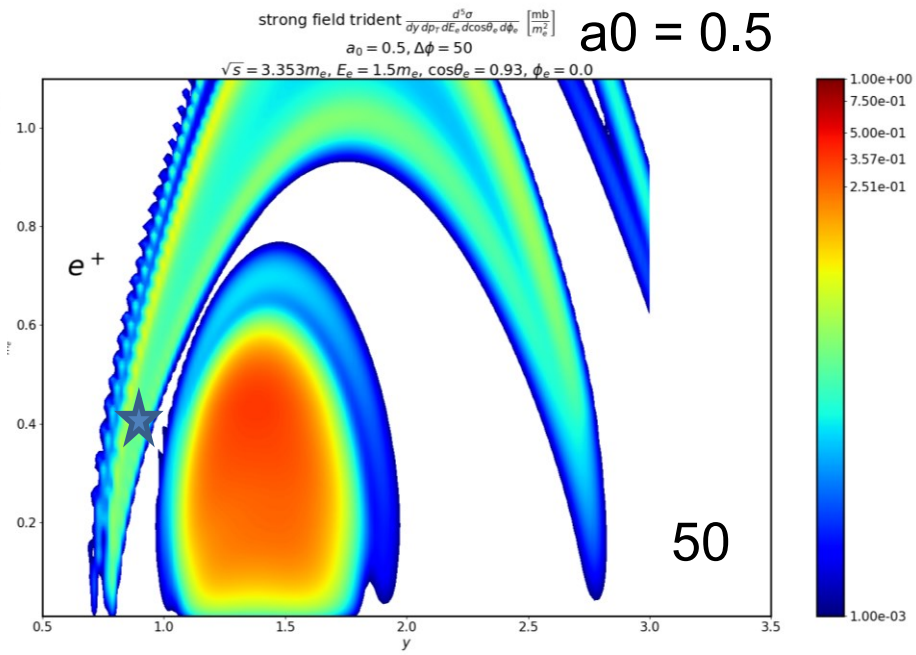
250

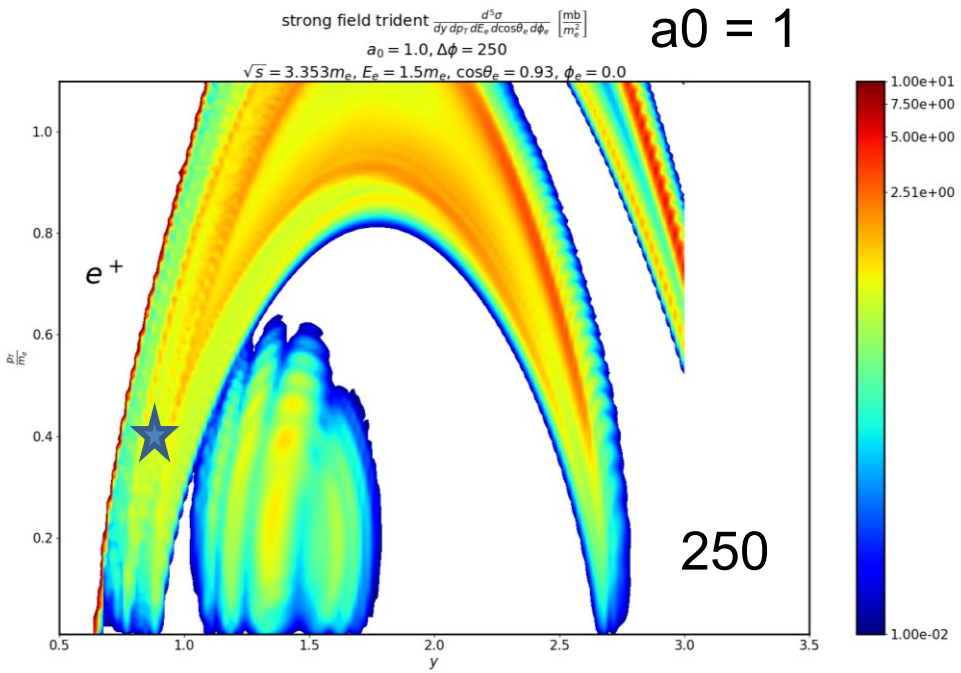


10^-1

larger a0:
multi-photon/harmonics?

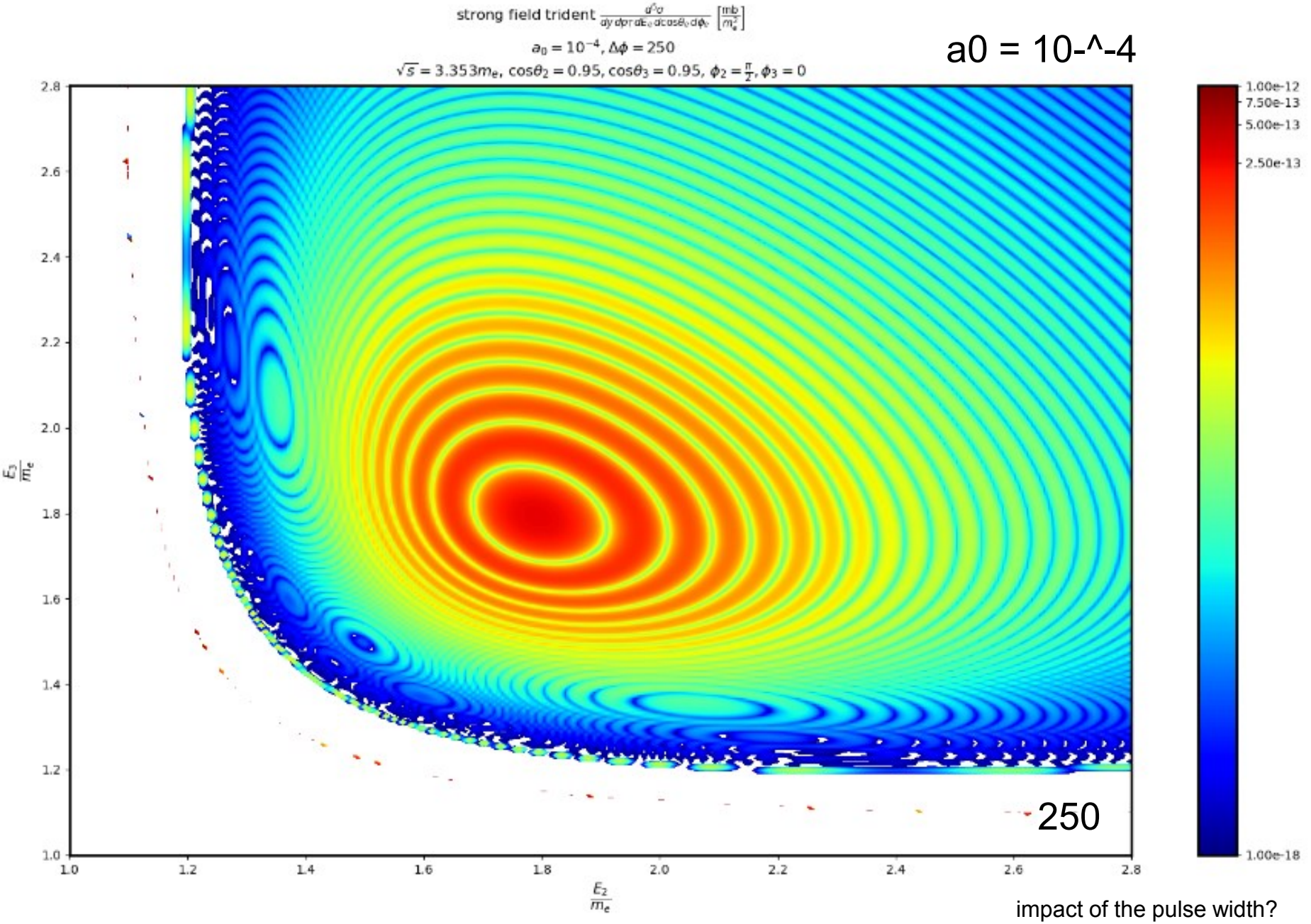






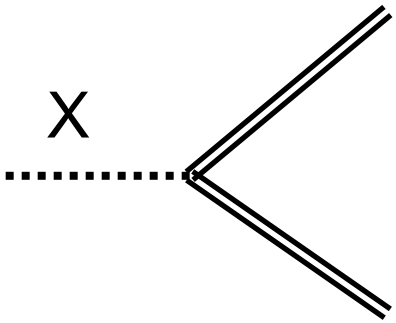
warning:
further terms needed
at these a0?

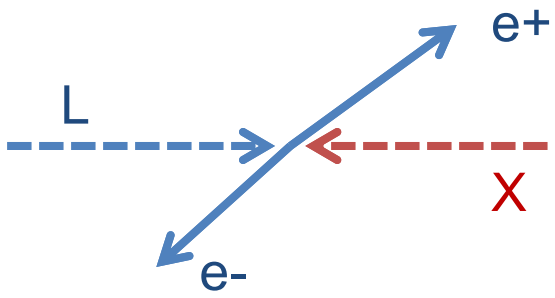
(iii) Dalitz plot as E1 – E2 distribution



impact of the pulse width?

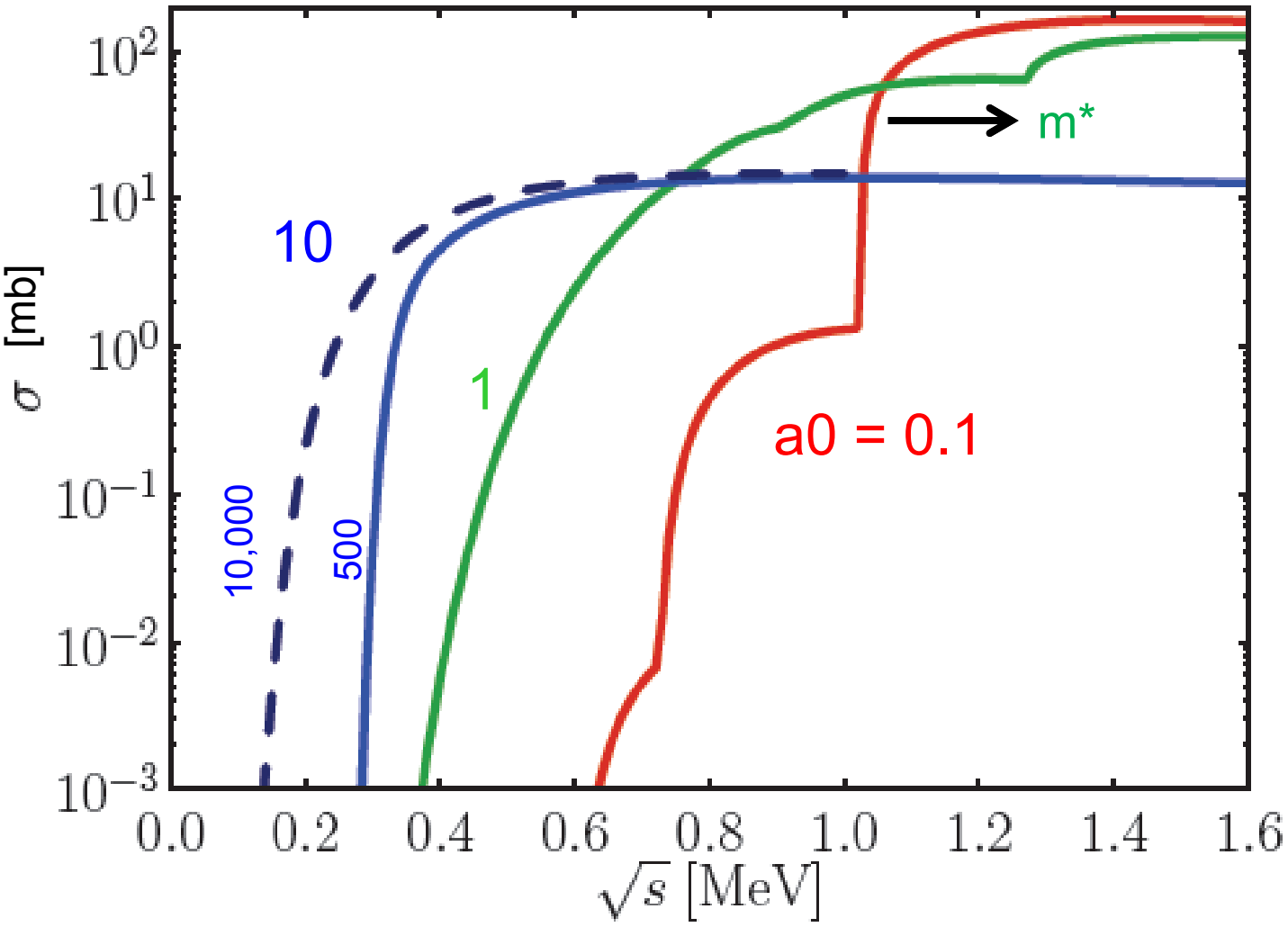
Aside: Breit-Wheeler below threshold





[Hartin, Ringwald, Tapia 1807.10670]
LUXE

measure Ec by BW in Ritus corner
X = e- XFEL bremsstrahlung



s = (kX + kL)^2

Ritus: kappa = s a0 /2m^2
a0 = m E / wL Es

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

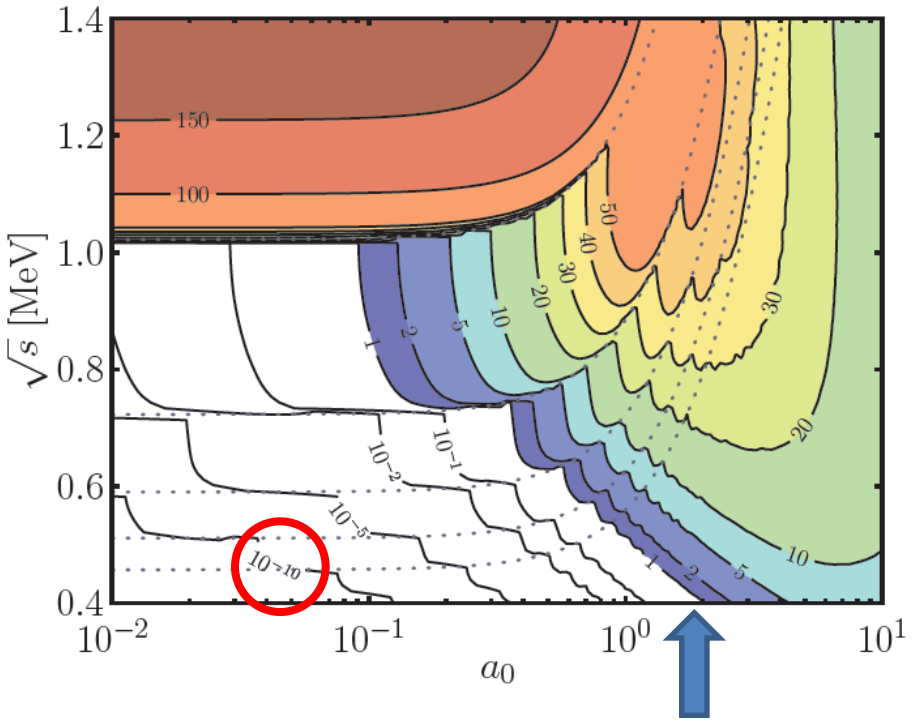
Pair Production in Ultra-Short Laser Pulses

lin. polarization, sigma [mb]

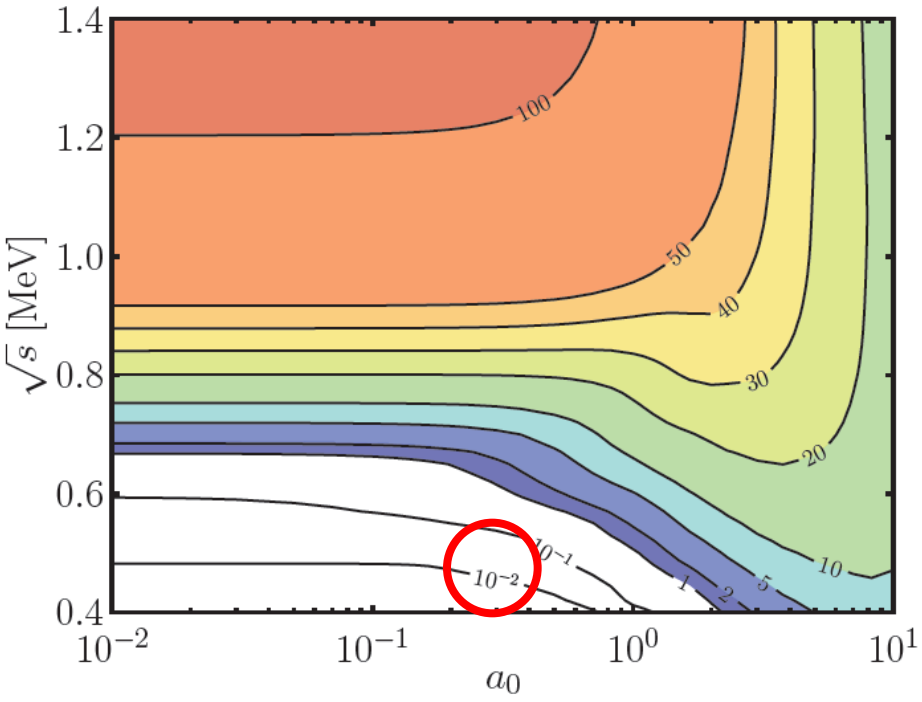
[Nousch, Seipt, BK, Titov PLB (2012)]
[Titov, Takabe, BK, Hosaka PRL (2012)]

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

IPA



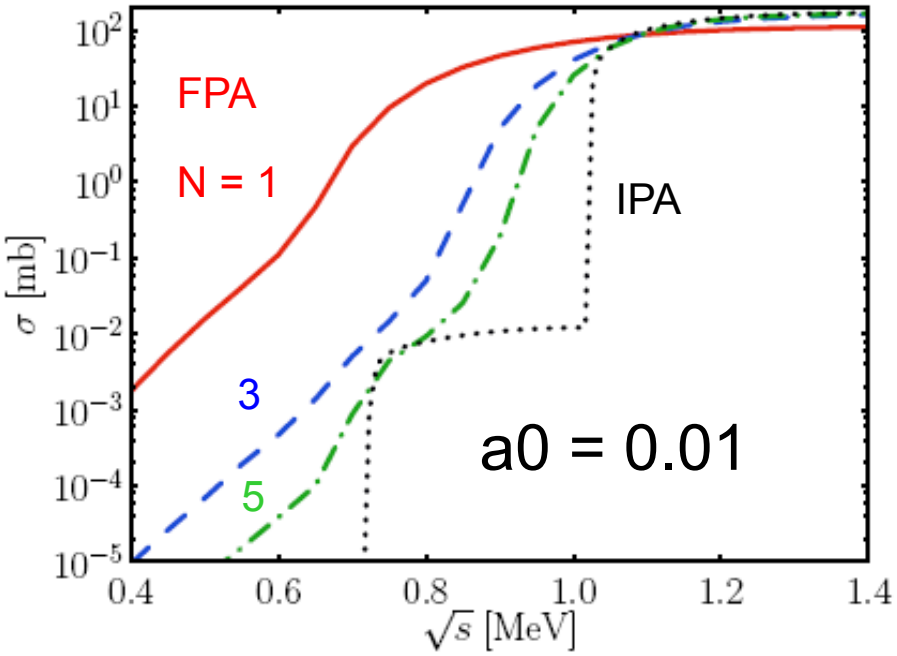
FPA, N = 1

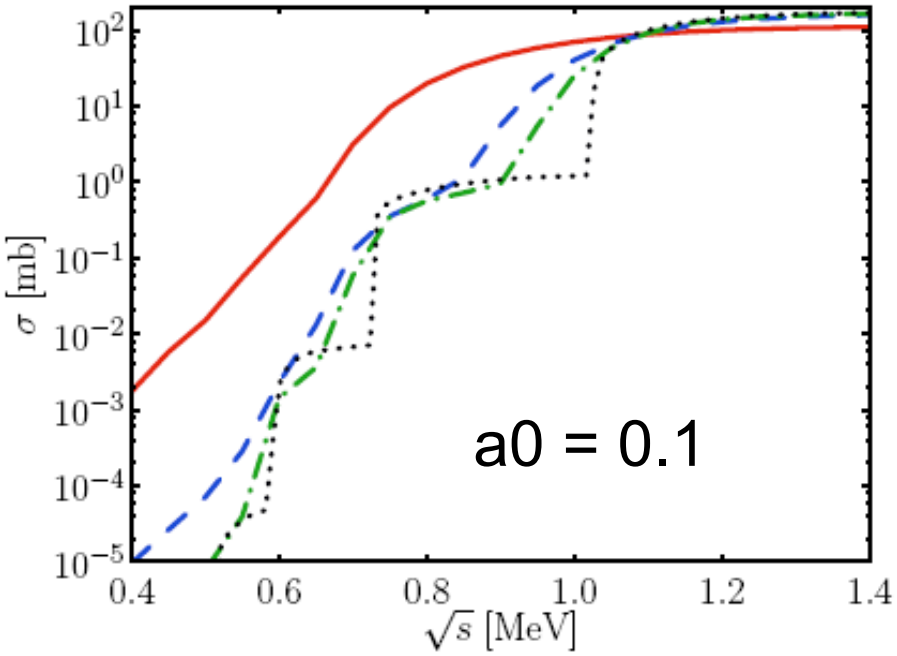


Ritus corner for a0 > 1, kappa < 1: $\propto \exp\{-\frac{8}{3}\frac{E_c}{E}\frac{m}{\omega_X}\}$

similar to Sauter-Schwinger: $\propto \exp\{-\pi\frac{E_c}{E}\}$

N dependence





harmonics & finite bandwidth effects →

laser enabled subthreshold production

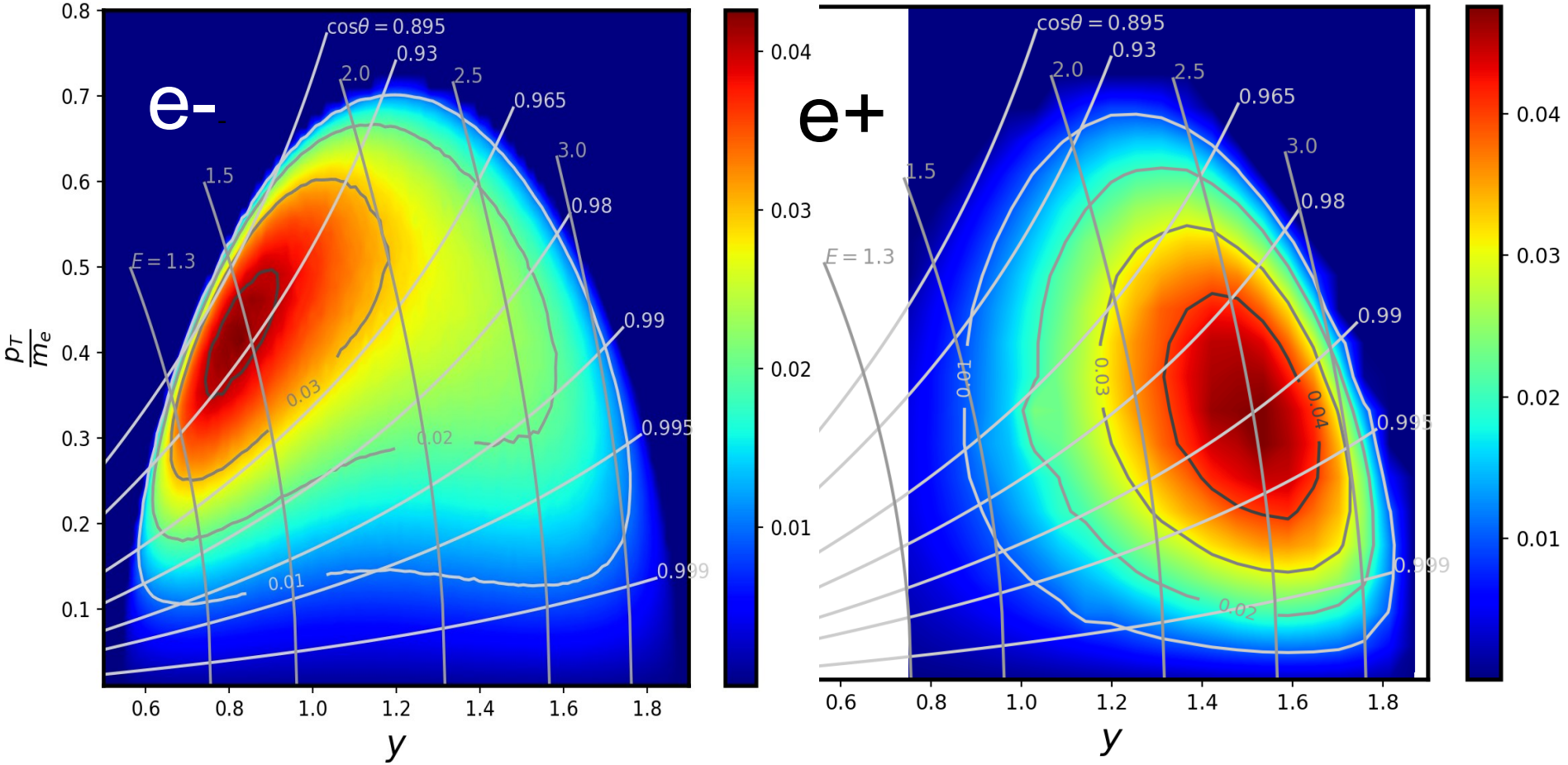
Seipt, BK, PLB 2012: folding model(s) - intensity vs. frequency variation → spectrum

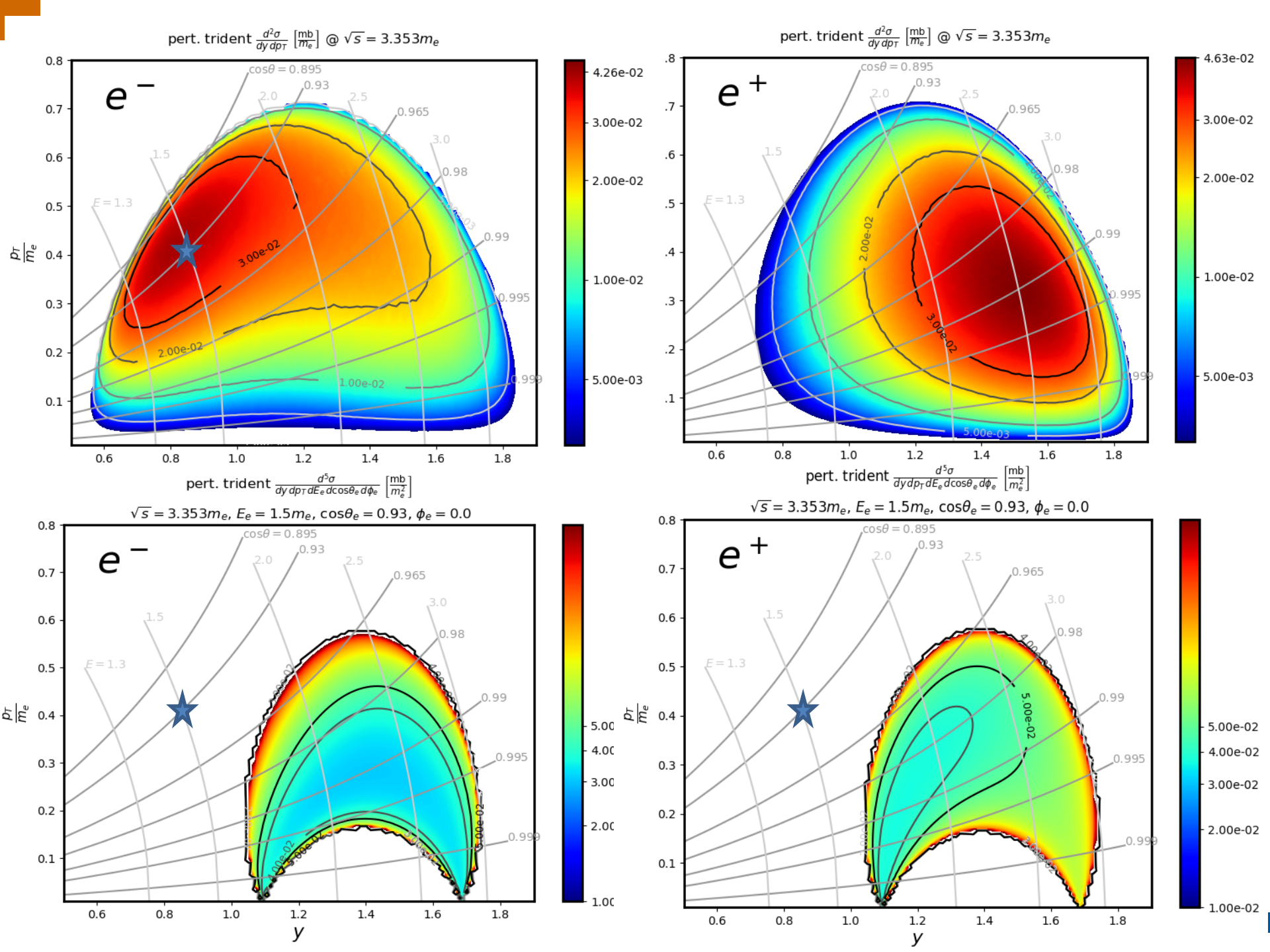
[Titov et al., PRA 87 (2013) 042106]

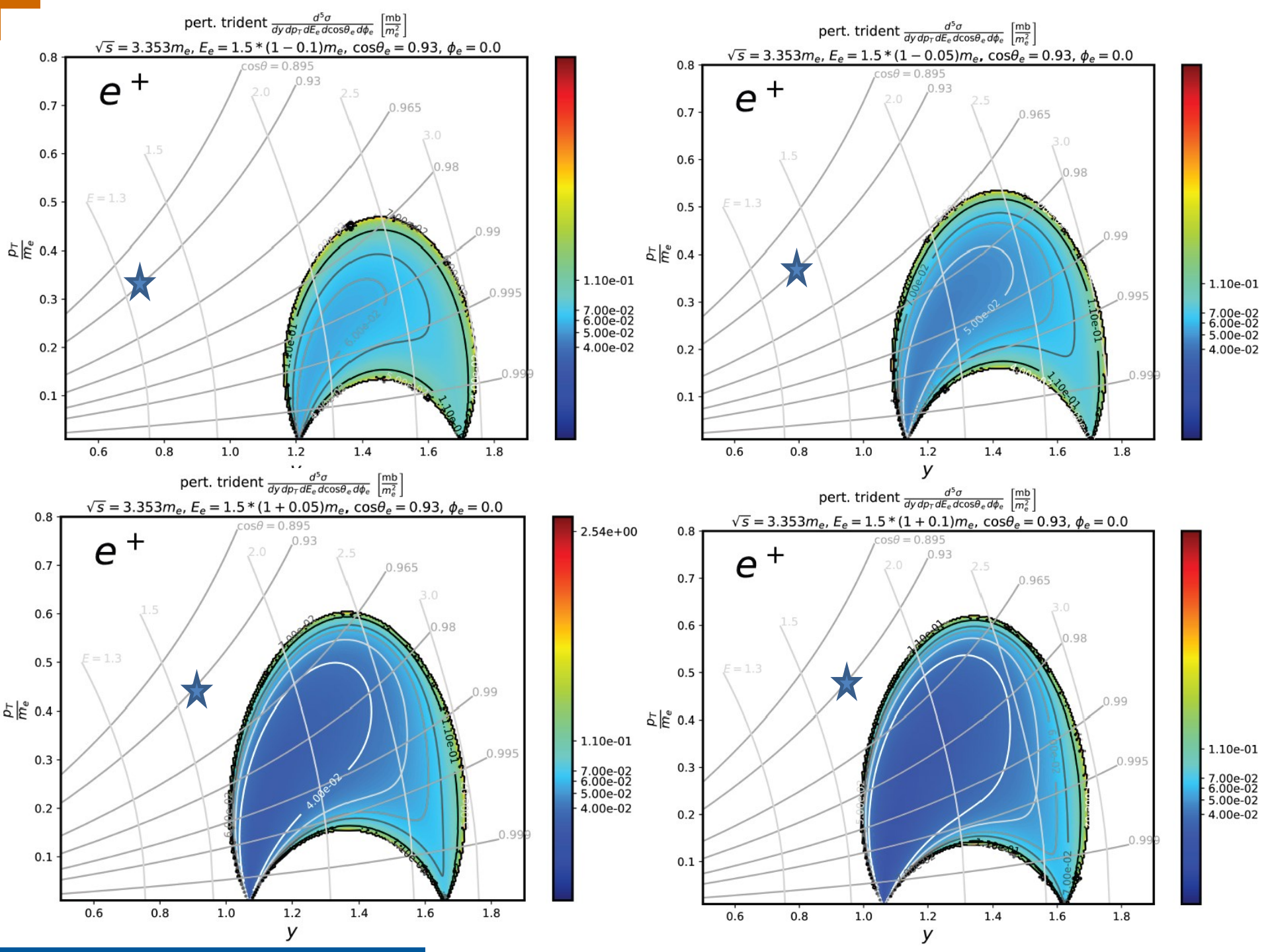
lessons from pQED trident

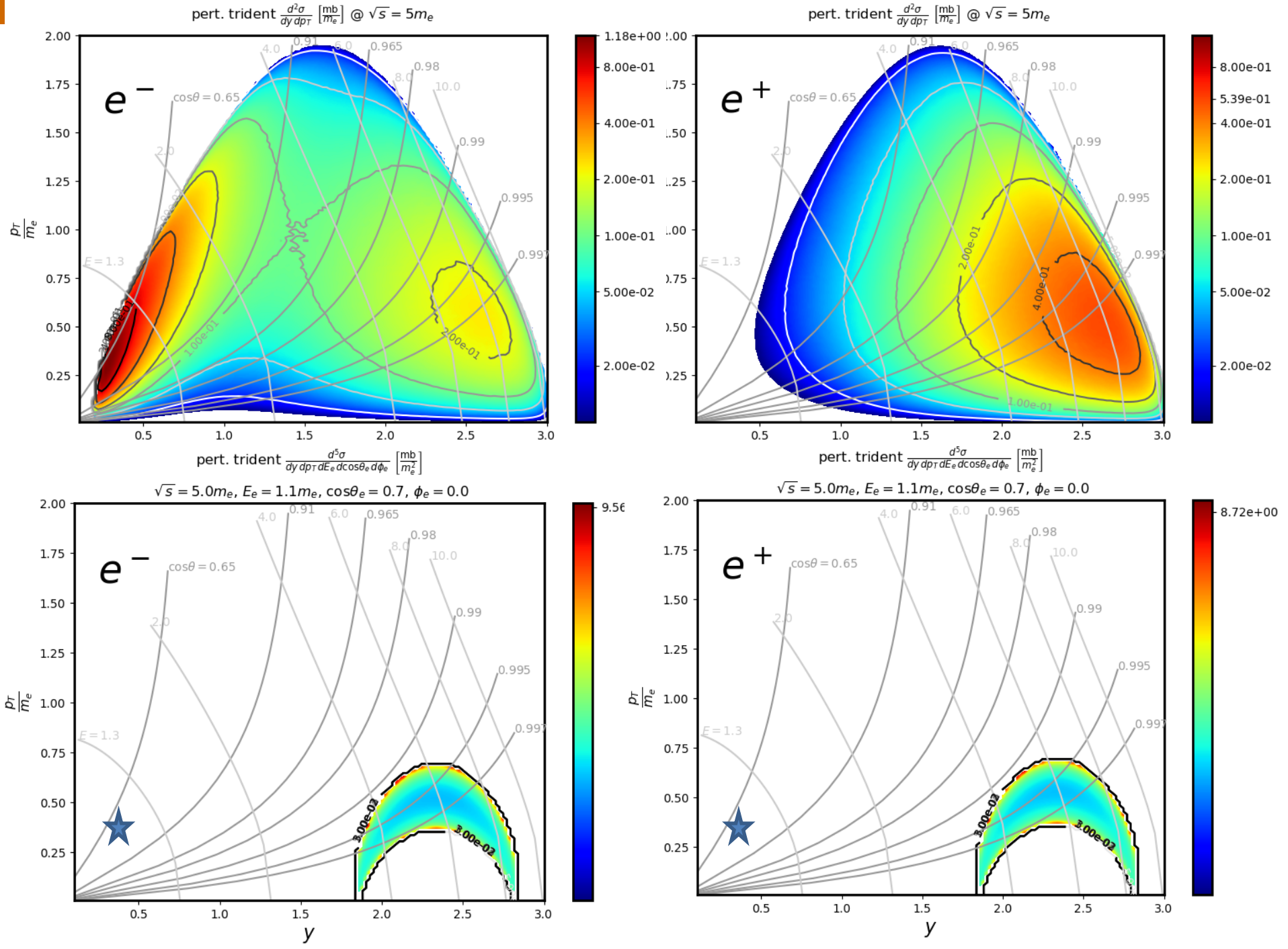
e- init. at rest (pT = 0, y = 0)
omega = 5.12 m

d sigma / dy dpT [mb/m]

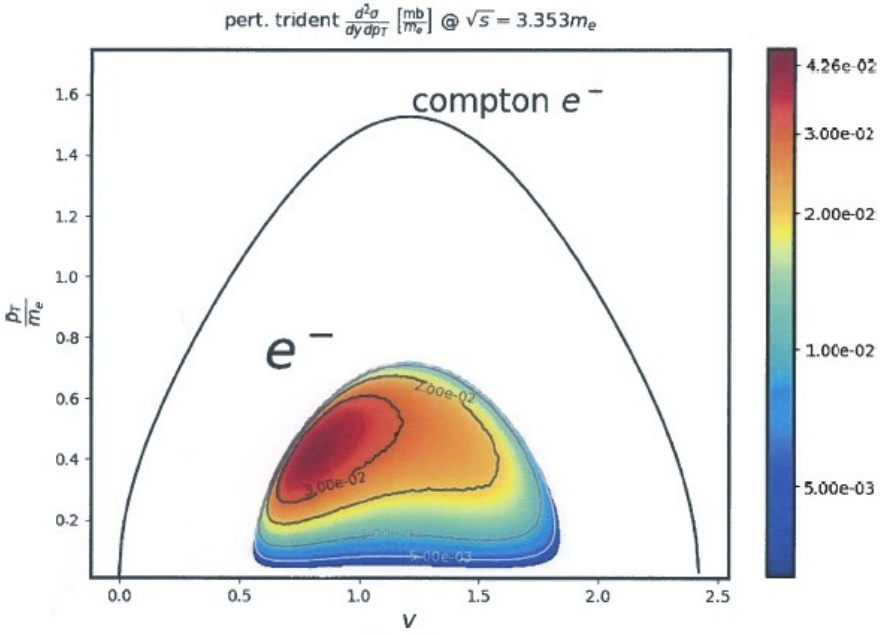


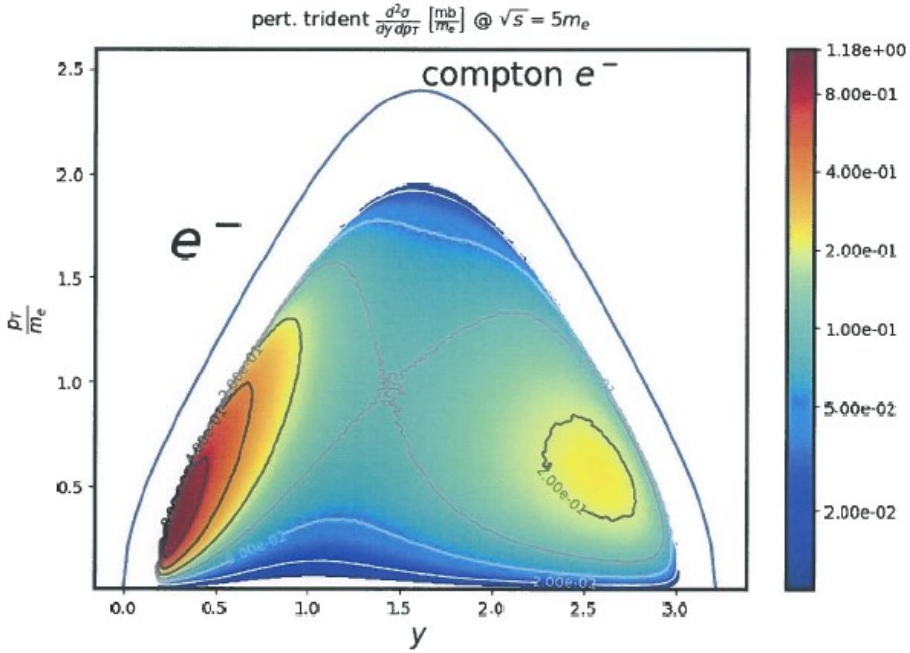

pert. trident $\frac{d^2\sigma}{dy\,dp_T}$ $\left[\frac{\text{mb}}{m_e}\right]$ @ $\sqrt{s} = 3.353m_e$
e^-
e^+
$\cos\theta = 0.895$
0.93
0.965
0.98
0.99
0.995
0.999
$E = 1.3$
1.5
2.0
2.5
3.0
3.00e-02
2.00e-02
1.00e-02
5.00e-03
4.26e-02
4.63e-02
$\frac{p_T}{m_e}$
pert. trident $\frac{d^5\sigma}{dy\,dp_T\,dE_e\,d\cos\theta_e\,d\phi_e}$ $\left[\frac{\text{mb}}{m_e^2}\right]$
$\sqrt{s} = 3.353m_e$, $E_e = 1.5m_e$, $\cos\theta_e = 0.93$, $\phi_e = 0.0$
5.00e-02
4.00e-02
y

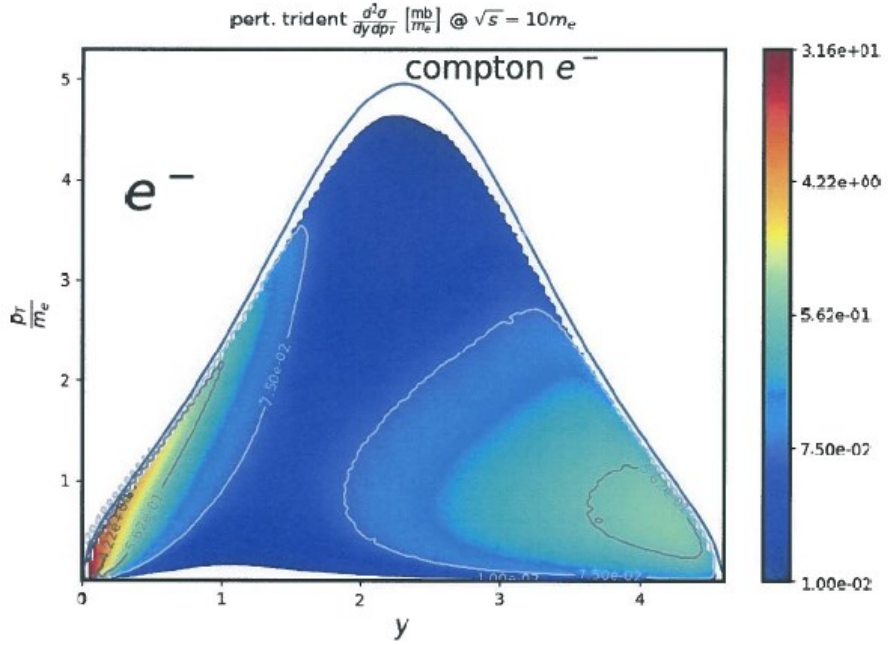

pert. trident $\frac{d^5\sigma}{dy\,dp_T\,dE_e\,d\cos\theta_e\,d\phi_e}\left[\frac{\text{mb}}{m_e^2}\right]$
$\sqrt{s} = 3.353m_e$, $E_e = 1.5*(1-0.1)m_e$, $\cos\theta_e = 0.93$, $\phi_e = 0.0$
e^+
$\frac{p_T}{m_e}$
y
pert. trident $\frac{d^5\sigma}{dy\,dp_T\,dE_e\,d\cos\theta_e\,d\phi_e}\left[\frac{\text{mb}}{m_e^2}\right]$
$\sqrt{s} = 3.353m_e$, $E_e = 1.5*(1-0.05)m_e$, $\cos\theta_e = 0.93$, $\phi_e = 0.0$
e^+
$\frac{p_T}{m_e}$
y
pert. trident $\frac{d^5\sigma}{dy\,dp_T\,dE_e\,d\cos\theta_e\,d\phi_e}\left[\frac{\text{mb}}{m_e^2}\right]$
$\sqrt{s} = 3.353m_e$, $E_e = 1.5*(1+0.05)m_e$, $\cos\theta_e = 0.93$, $\phi_e = 0.0$
e^+
$\frac{p_T}{m_e}$
y
pert. trident $\frac{d^5\sigma}{dy\,dp_T\,dE_e\,d\cos\theta_e\,d\phi_e}\left[\frac{\text{mb}}{m_e^2}\right]$
$\sqrt{s} = 3.353m_e$, $E_e = 1.5*(1+0.1)m_e$, $\cos\theta_e = 0.93$, $\phi_e = 0.0$
e^+
$\frac{p_T}{m_e}$
y


pert. trident $\frac{d^2\sigma}{dy\,dp_T}$ $\left[\frac{\text{mb}}{m_e}\right]$ @ $\sqrt{s} = 5m_e$
e^-
e^+
$\cos\theta = 0.65$
$E = 1.3$
0.91
0.965
0.98
0.99
0.995
0.997
2.0
4.0
6.0
8.0
10.0
1.00e-01
2.00e-01
4.00e-01
pert. trident $\frac{d^5\sigma}{dy\,dp_T\,dE_e\,d\cos\theta_e\,d\phi_e}$ $\left[\frac{\text{mb}}{m_e^2}\right]$
$\sqrt{s} = 5.0m_e$, $E_e = 1.1m_e$, $\cos\theta_e = 0.7$, $\phi_e = 0.0$
3.00e-02
$\frac{p_T}{m_e}$
y

Trident vs. Compton background

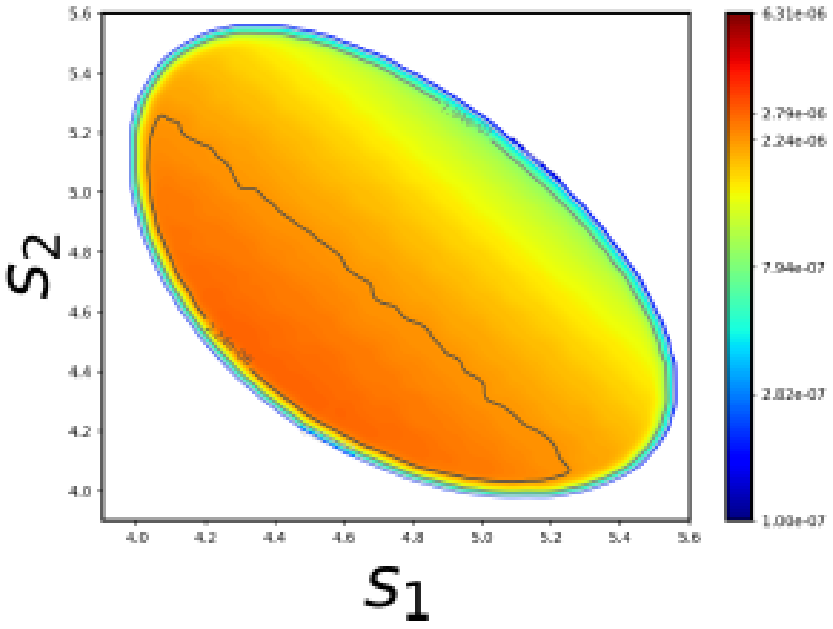


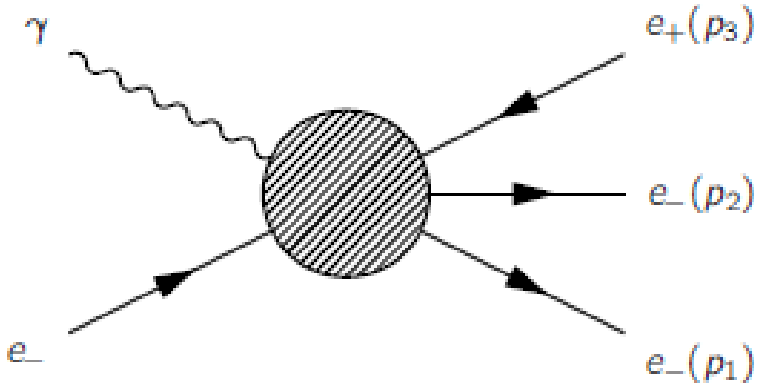




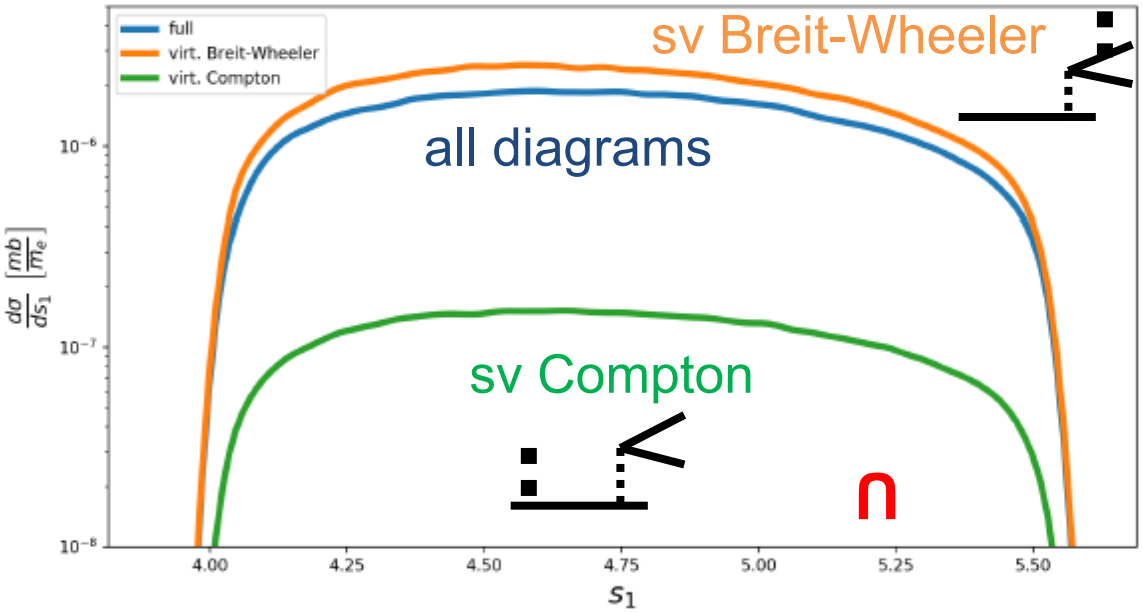
cos Theta = const

Dalitz plot





$$s_1 = (p_1 + p_3)^2$$
$$s_2 = (p_2 + p_3)^2$$

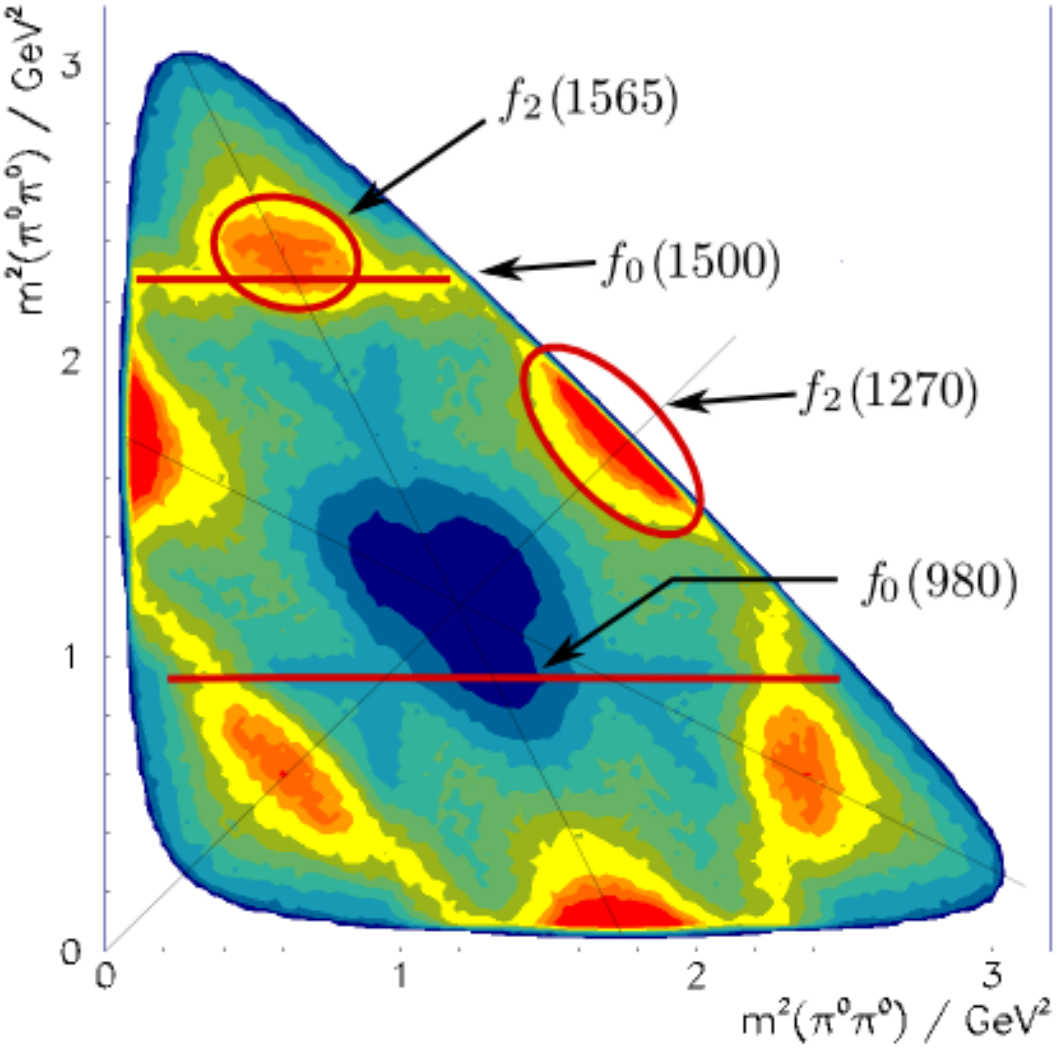


$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{8M}\,\overline{|\mathscr{M}|^2}\,dE_1\,dE_3$$

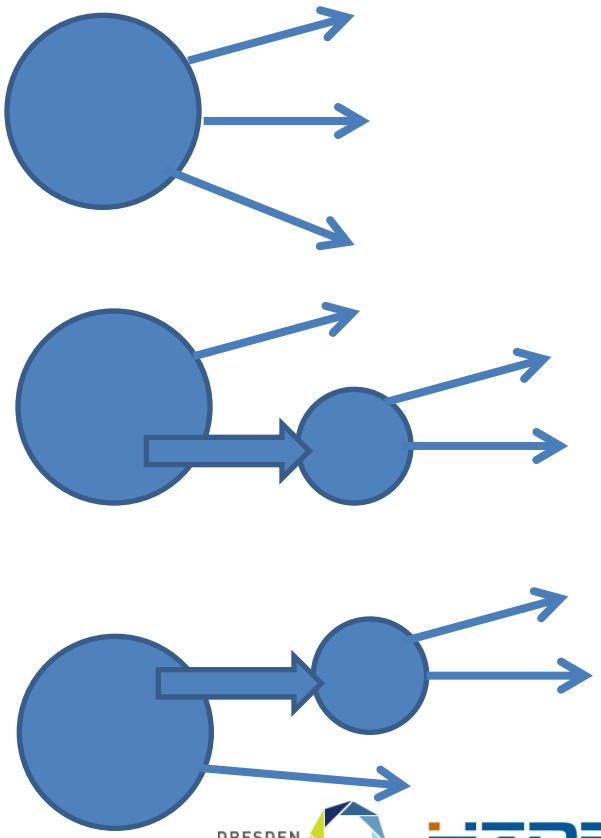
$$= \frac{1}{(2\pi)^3}\frac{1}{32M^3}\,\overline{|\mathscr{M}|^2}\,dm_{12}^2\,dm_{23}^2$$

M = mass of parent particle

recall: Dalitz plot in particle physics → access to intermediate resonances



P → pi0 pi0 pi0



Trident Summary

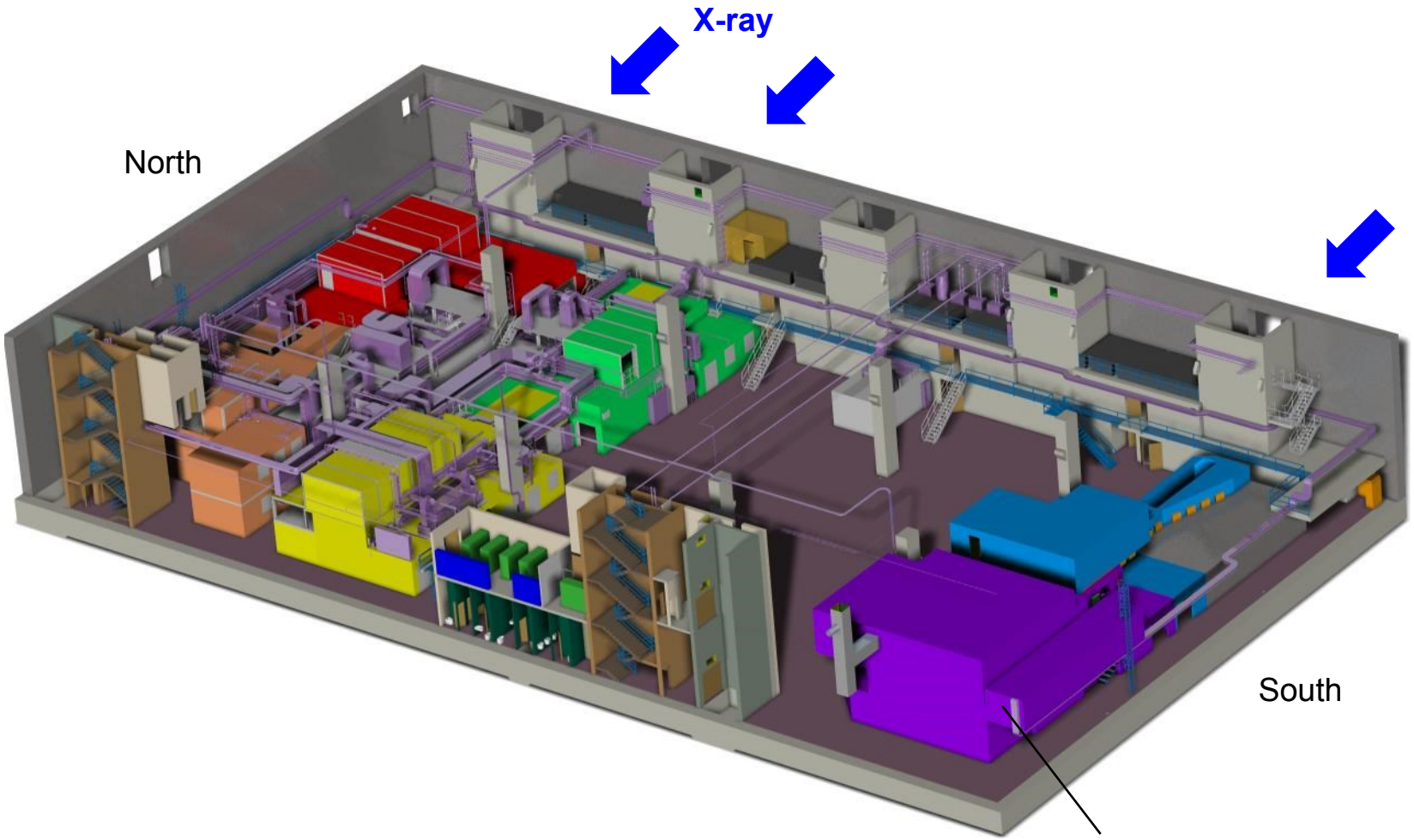
Furry picture vs. pert. QED background

Focus on weak (XFEL) pulses

To do: subthreshold a la E-144

Potential of Dark Photon detection/exclusion?

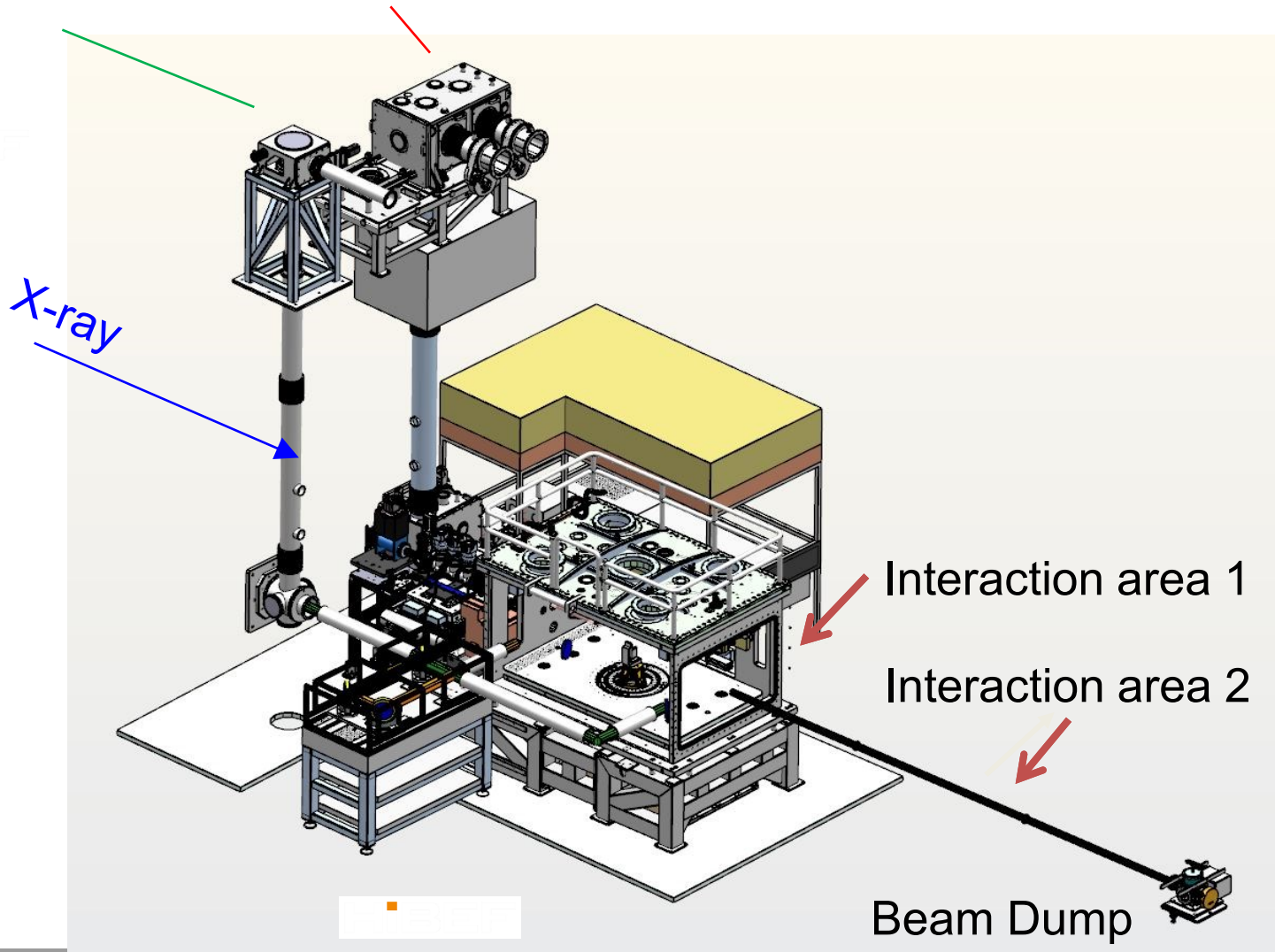
Experiment hall: SASE2 (HED, MID)



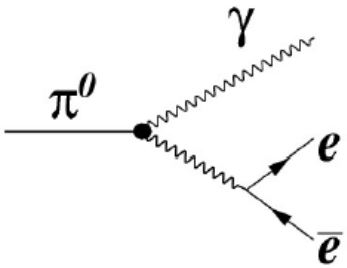
Schenefeld Campus

Helmholtz International Beamline for Extreme Fields

High-energy (HE) and high-intensity (HI) optical lasers

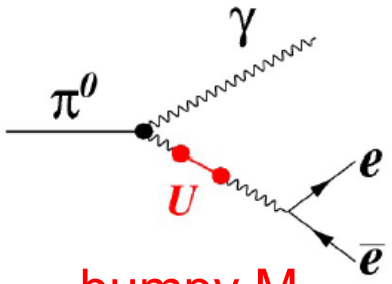


beyond SM $\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} + \frac{m_V^2}{2}V_\mu V^\mu + eJ_{\rm em}^\mu A_\mu,$



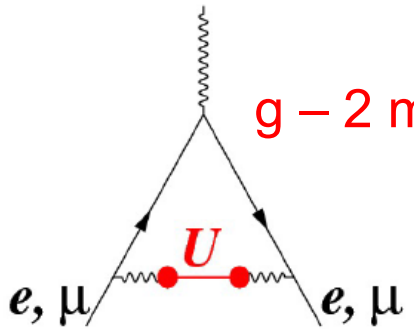
smooth M

b)



bumpy M

c)



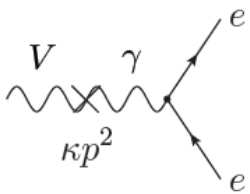
g – 2 modification

inv. mass → M^2 = [p(e-) + p(e+)]^2

U = V = A‘ = gamma‘
kappa = epsilon

Two ways to think about $-\frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu}$

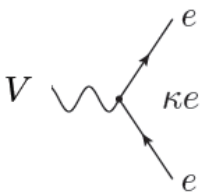
Keep the mixing:



$eA_\mu J_{EM}^\mu$

Photon-Dark Photon mixing manifest

Or diagonalize kinetic term:

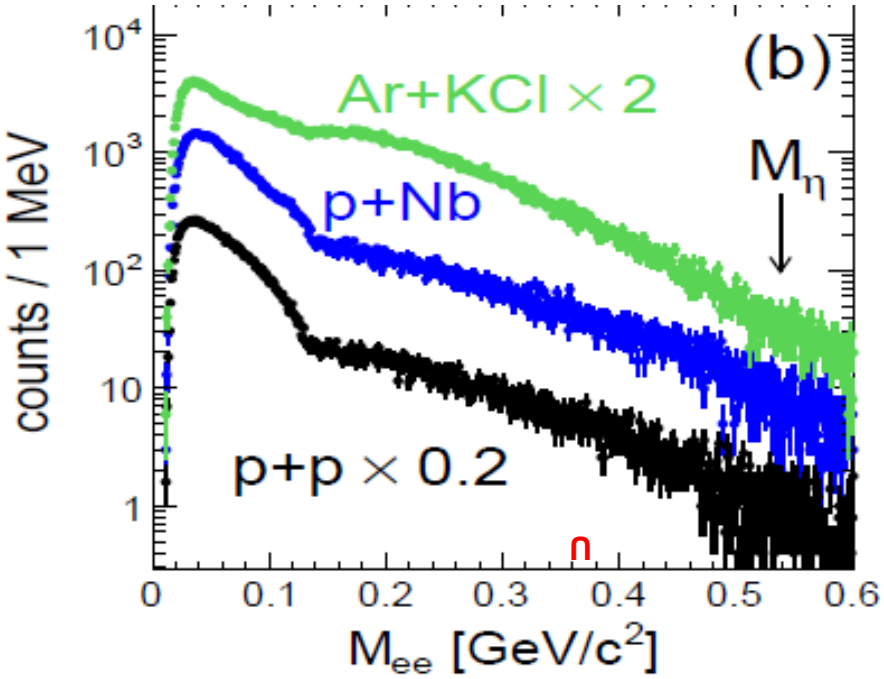


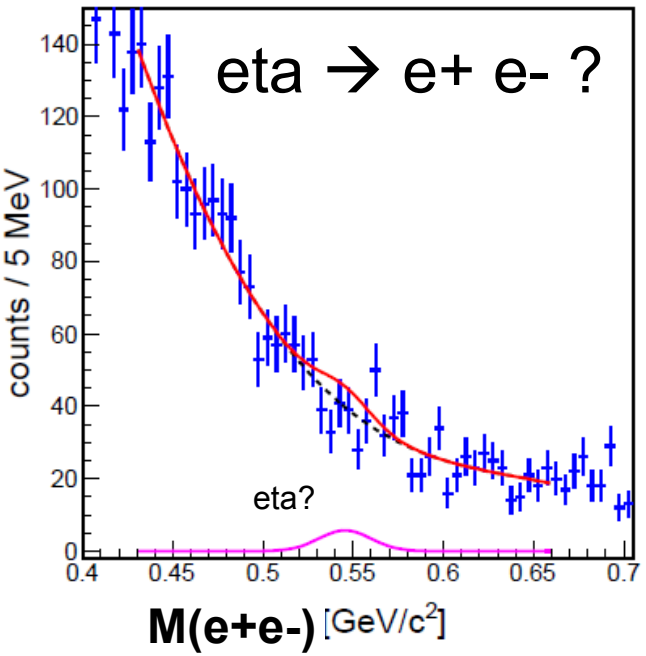
$eA'_\mu J_{EM}^\mu - \kappa e V'_\mu J_{EM}^\mu$

Ordinary matter has milli-charge under new force

[Ahlers, Gies, Jeackel, Rendono, Ringwald, PRD 77 (2008) 095001]

searching a signal in background, e.g. HADES data

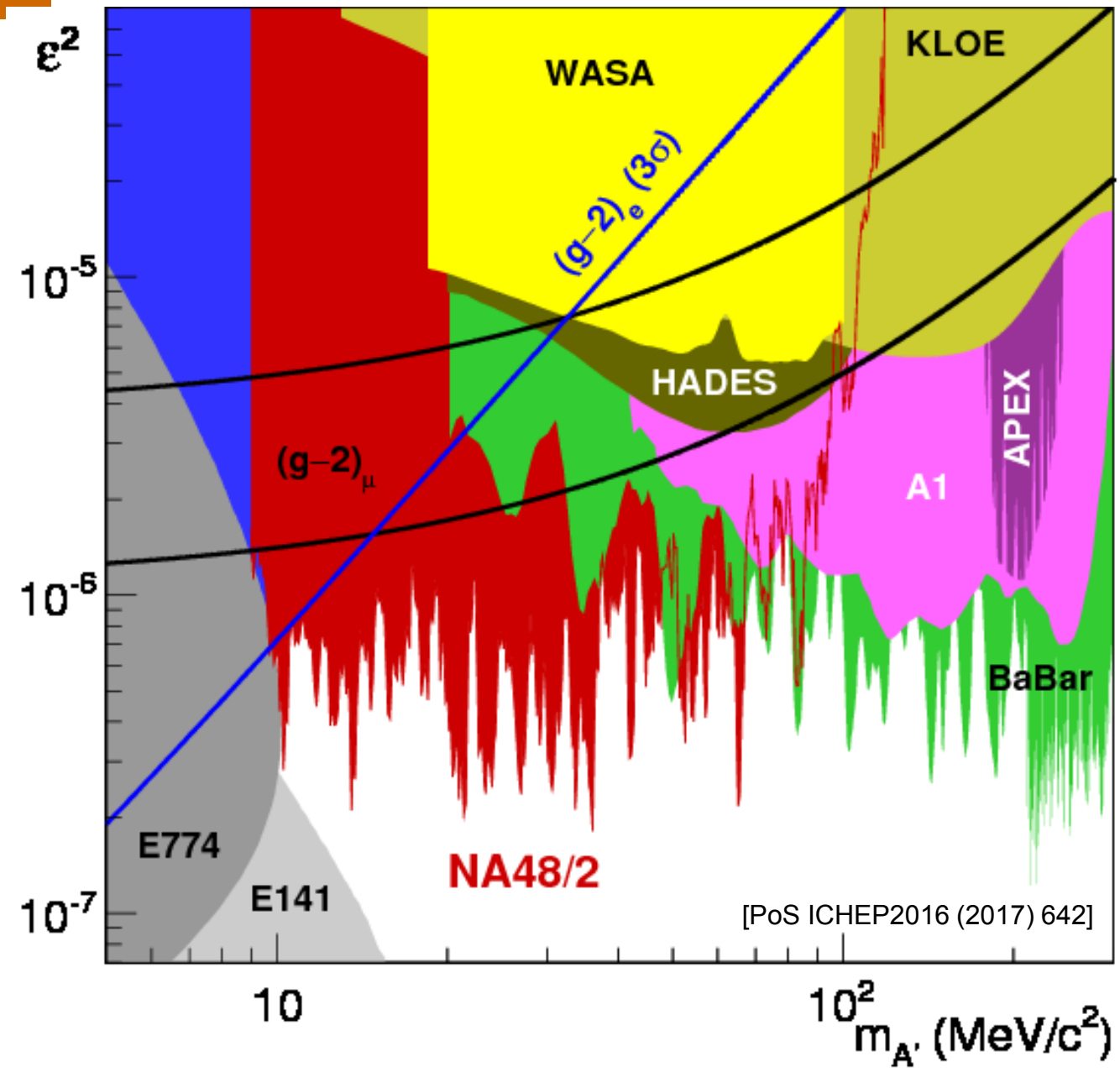




$$\frac{-g^{\alpha\beta} + q'^{\alpha} q'^{\beta}/m_{\gamma'}^2}{q'^2 - m_{\gamma'}^2 + i\, m_{\gamma'}\, \Gamma_{\gamma'}}$$

$$\Gamma_{\gamma' \to l^+ l^-} = \frac{\alpha \varepsilon^2}{3 m_{\gamma'}^2} \sqrt{m_{\gamma'}^2 - 4 m_l^2}\, (m_{\gamma'}^2 + 2 m_l^2),$$

Kolomogorov-Smirnov test,
Cousins-Feldman method



exp. signature:
peak in e+e- distrib.
→ **bump hunting**

e.g. [HADES, PLB 731 (2014) 265]

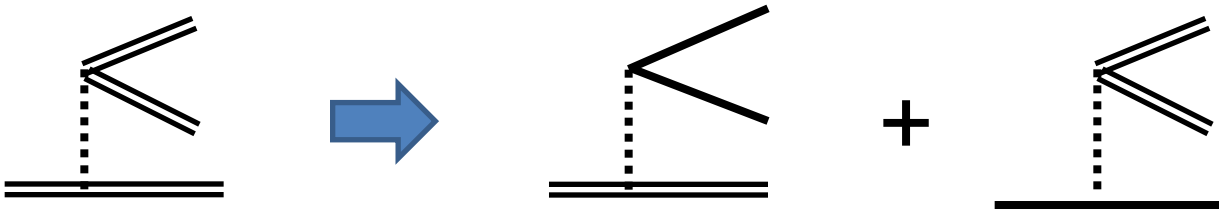
colored region:
exp. excluded
(90% CL)

View on HADES (rear side)

No Dark Photons seen in HADES

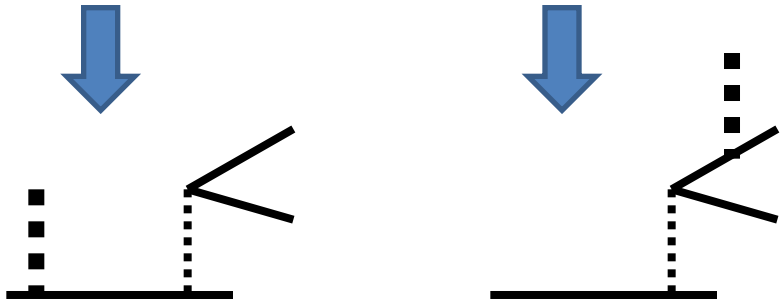
Hades/Serapis with Cerberus

in preparation: Dalitz plots
impact of the energy
impact of the pulse shape
larger a0
sub-threshold energies
e+ as trigger particle



2 Fermion lines

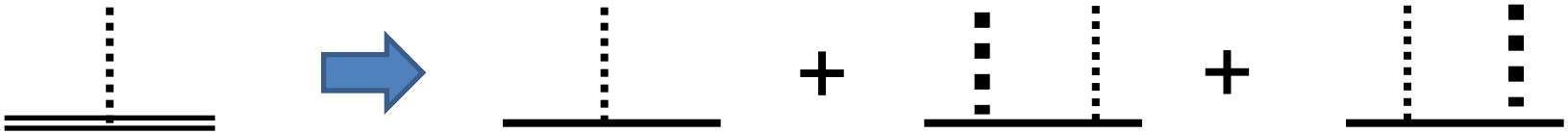
F QED



pQED

virt. Compton

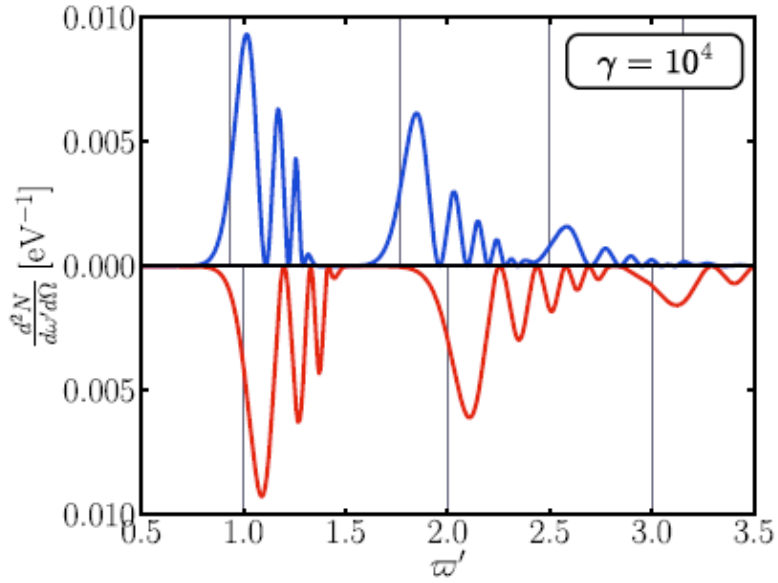
virt. Breit-Wheeler

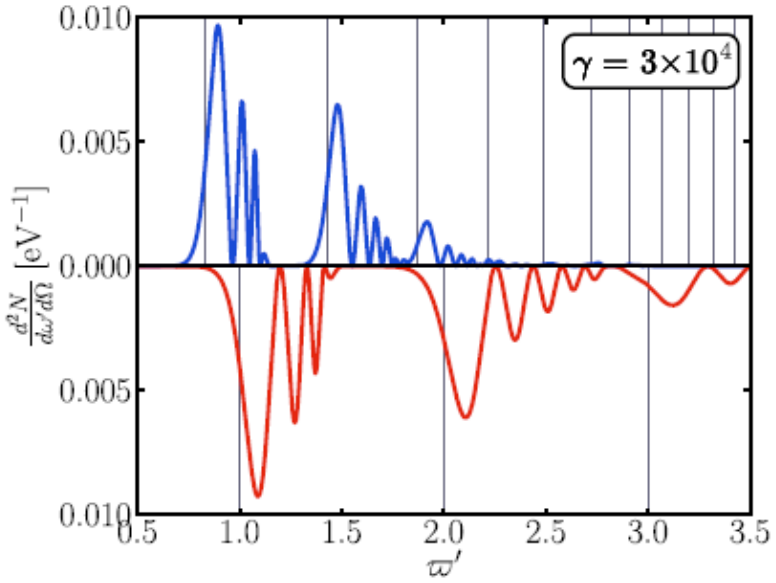


1 Fermion line

F Compton

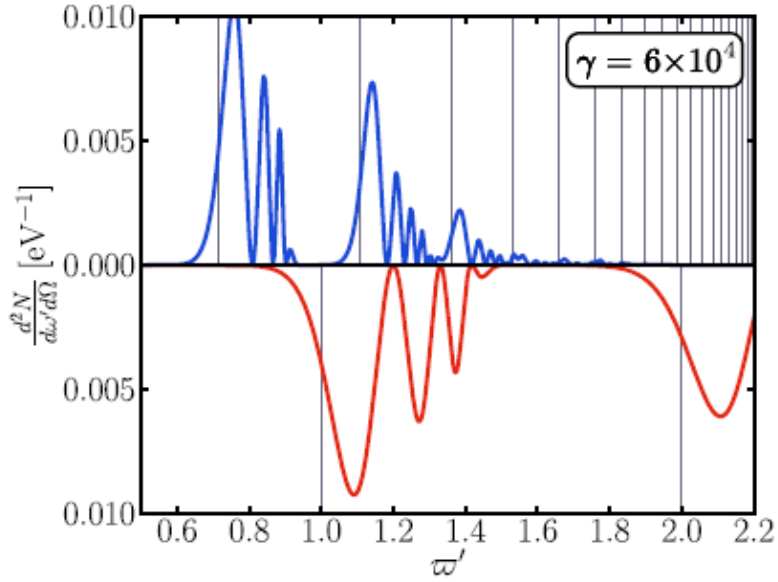
F Breit-Wheeler

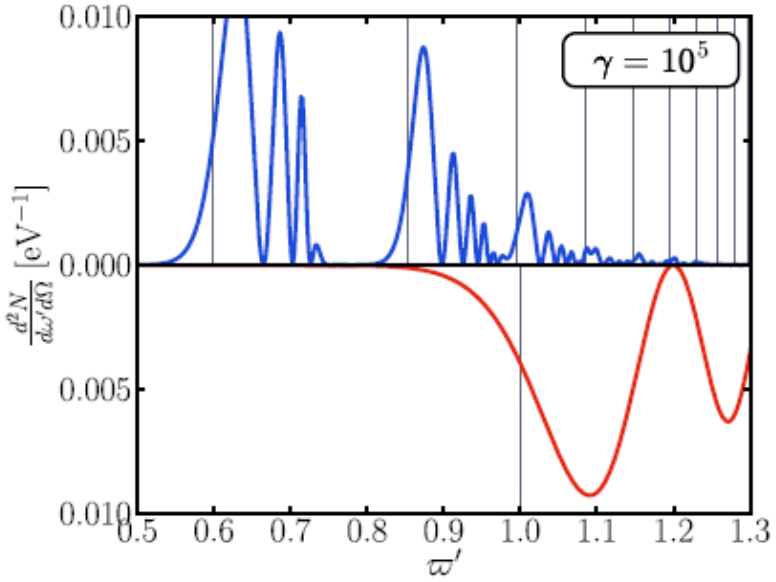




Compton (QED)

Thomson (clas.rad.)





Compton (QED)

Thomson (clas.rad.)

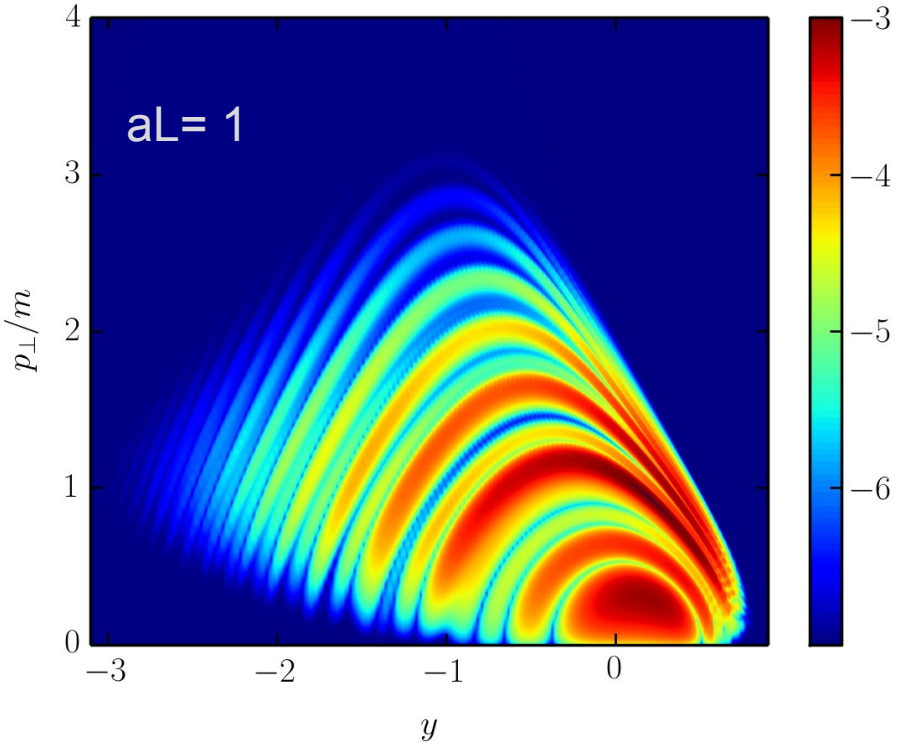
cosh laser pulse, a0 = 1, lin. pol.

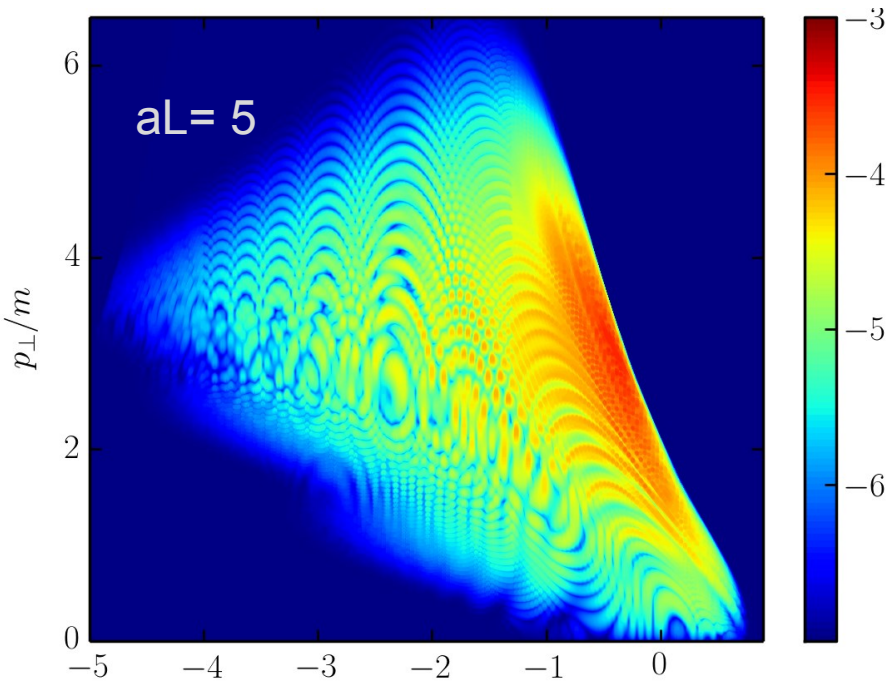
[Seipt, BK, Phys. Rev. A83 (2011) 022101]

Breit-Wheeler processes

(i) probe photon + laser pulse

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



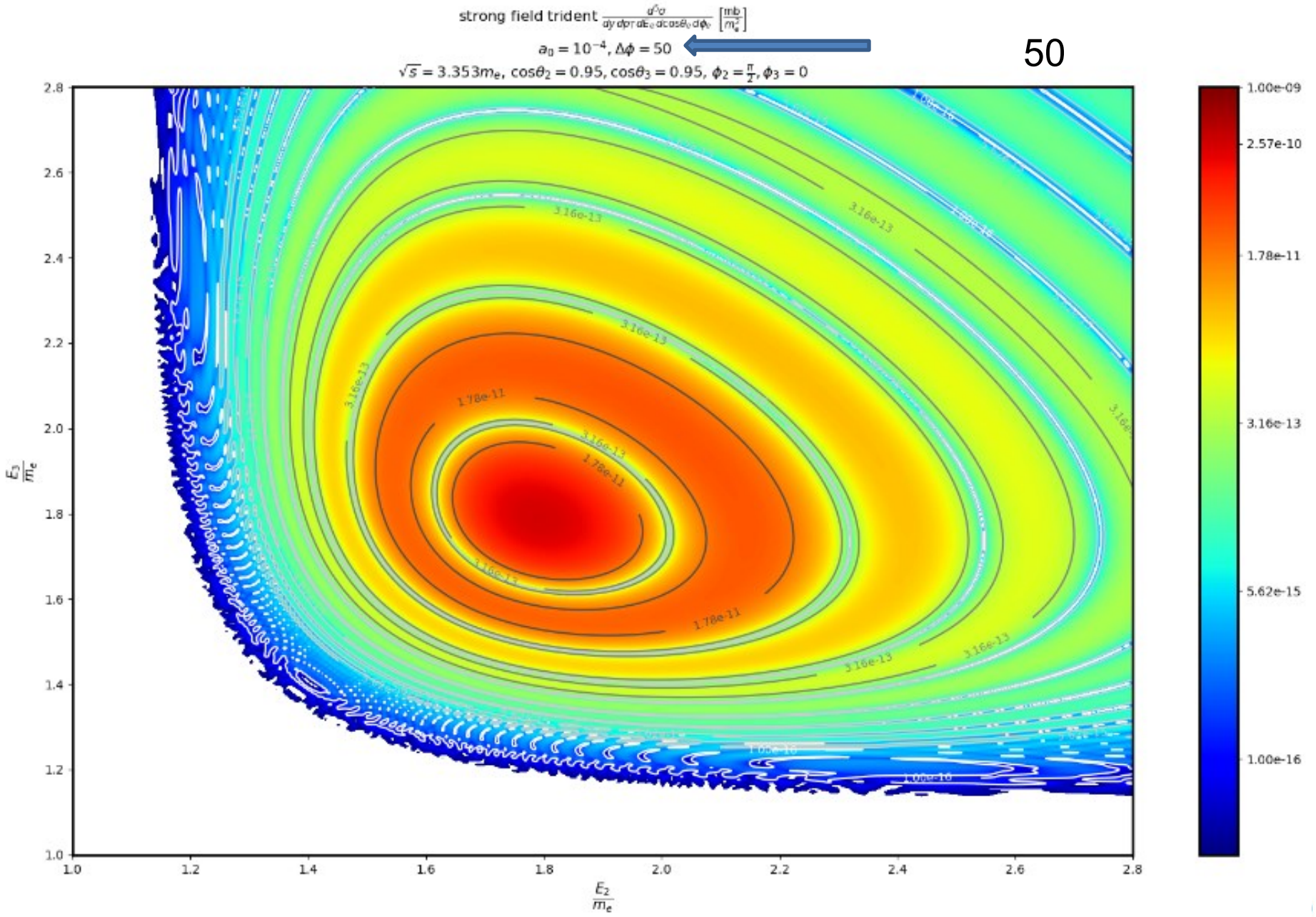


sqrt(s) = 1.2 MeV, N = 8
envelope: cos^2 (phi/2N)
circ. pol.

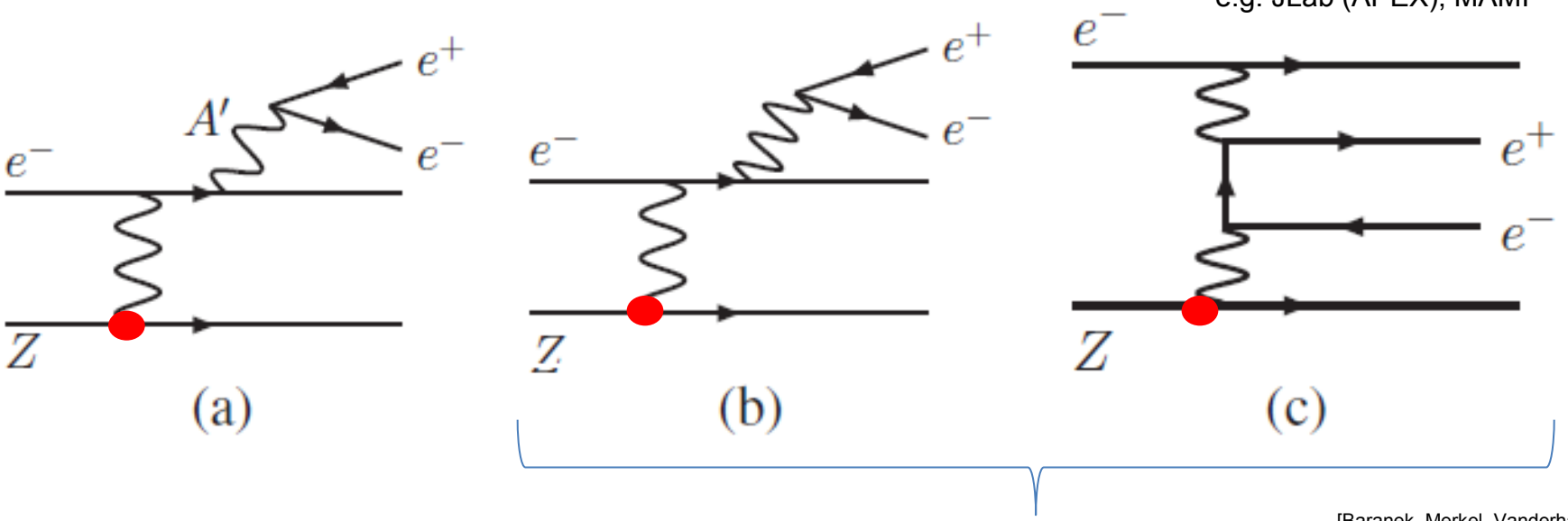
"pair production in a plane wave is a diffractive process with interference pattern and rich substructure"
[Heinzl, Ilderton, Marklund, PLB 692 (2010) 250]

(ii) probe photon + bi-frequent laser pulse (XFEL + laser: HIBEF)

[Nousch et al., PLB 755 (2016) 162] [Jansen, Muller, PLB 766 (2017) 71]


strong field trident $\frac{d^5\sigma}{dy\,dp_T\,dE_e\,d\cos\theta_e\,d\phi_e}\left[\frac{mb}{m_e^2}\right]$
$a_0 = 10^{-4}, \Delta\phi = 50$
$\sqrt{s} = 3.353 m_e,\ \cos\theta_2 = 0.95,\ \cos\theta_3 = 0.95,\ \phi_2 = \frac{\pi}{2}, \phi_3 = 0$
50
$\frac{E_3}{m_e}$
$\frac{E_2}{m_e}$
1.00e-09
2.57e-10
1.78e-11
3.16e-13
5.62e-15
1.00e-16

e.g. JLab (APEX), MAMI



QED background

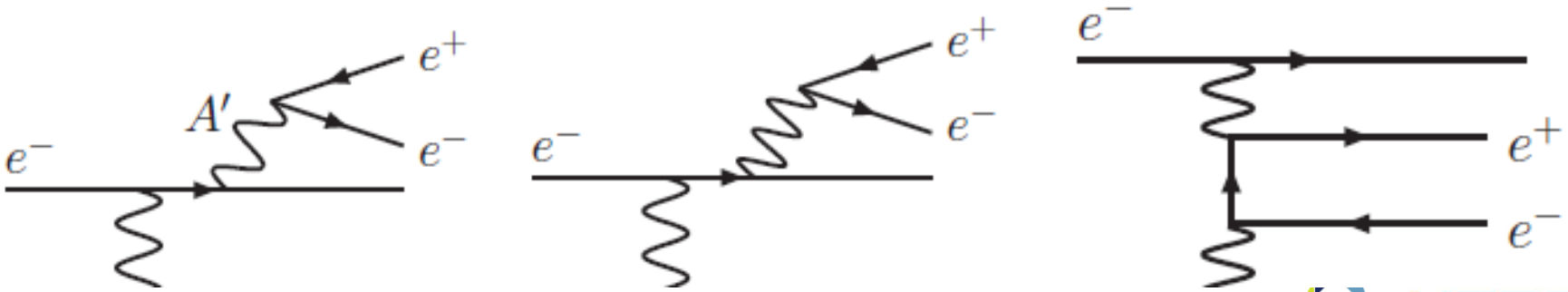
[Baranek, Merkel, Vanderhaeghen, PRD 88 (2013) 015032]
[Baranek, Vanderhaeghen, PRD 89 (2014) 055006]

Z = nucleus, proton → formfactors ● but proton charge radius puzzle

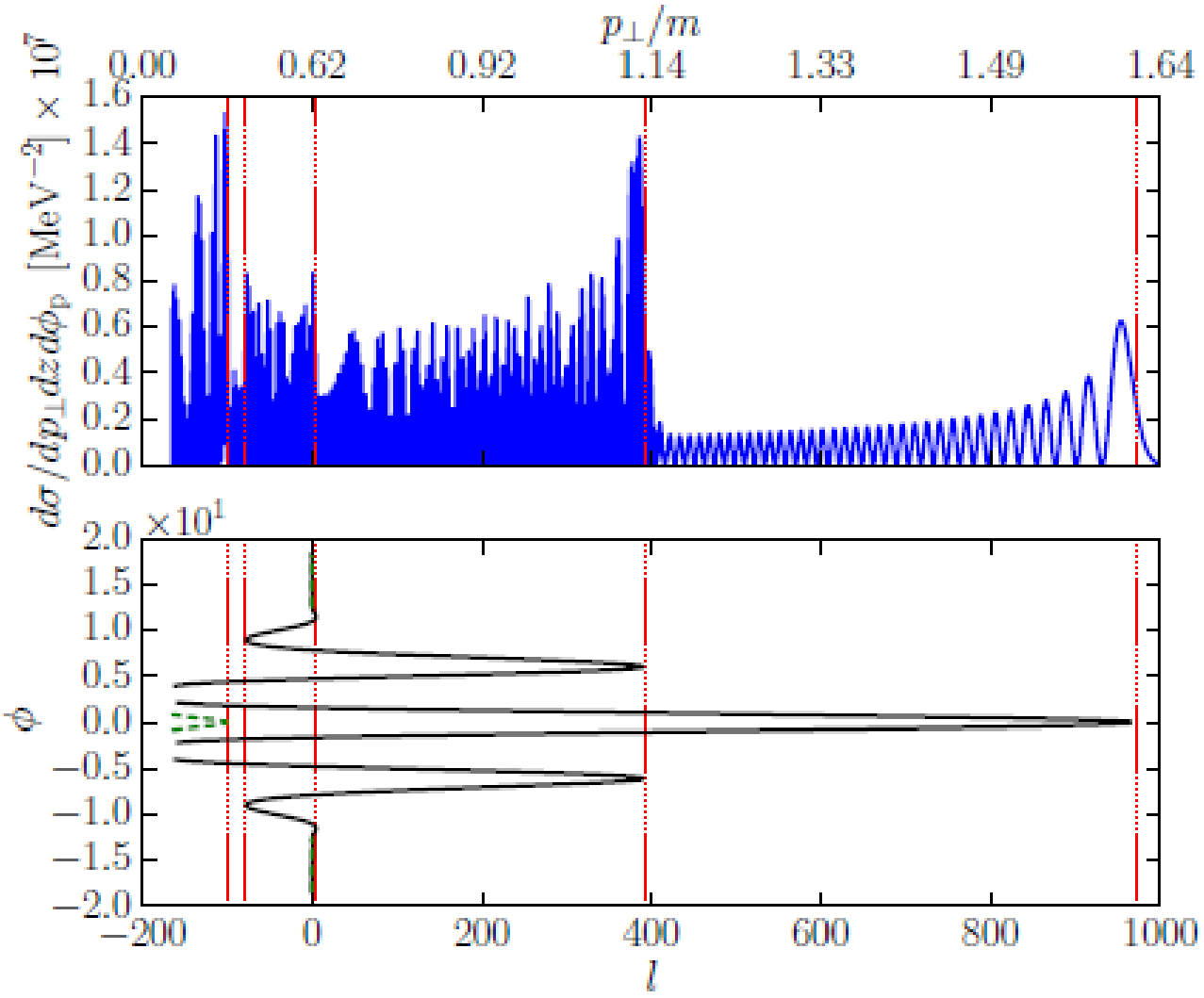
→ replace Z by e+ or e-: clean QED processes

e.g. BESS III

→ simplify further: trident process



Caustics in laser assisted Breit-Wheeler process



$$k^\mu_{X'} + k^\mu_X + \ell k^\mu_L = p^\mu_p + p^\mu_e \,.$$

Figure 1: $a_{0L} = 1$, $a_{0X} = 10^{-5}$, $\sqrt{s} = 1.2$ MeV, $\omega_{ph} = \omega_X = 0.6$ MeV, $\omega_L = 1$ keV, $\tau_L = 4\pi$, $\tau_X = 5.1/\kappa$, $\kappa = \omega_L/\omega_X \simeq 1.67 \times 10^{-3}$, $g_L = \cos^2$, $g_X =$ Gauss, lineare Polarisation, $\phi_{pos} = \pi$, $z = 0$

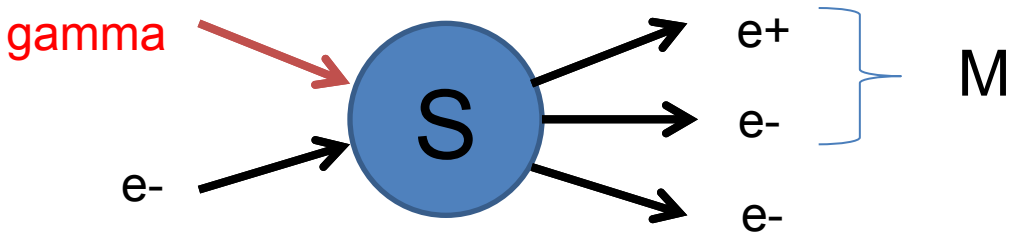
A growing idea

At IRIDE we can search for U boson via the lepton triplet production process in the electron-photon collision. The main QED process of the lepton triplet production is through u channel exchange ("BH diagram") and the t channel exchange ("VCS diagram"), see Fig. 9.5. [1307.7967]

B. Kampfer, talk at ExHILP, Lisboa 2017

The triplet photoproduction on a free electron as a possible way to search for a dark photon

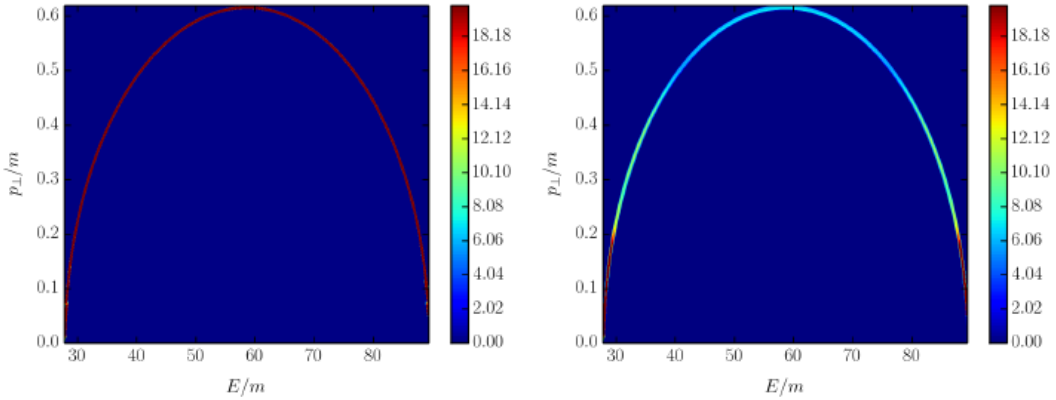
[Gakh et al., 1711.01770]



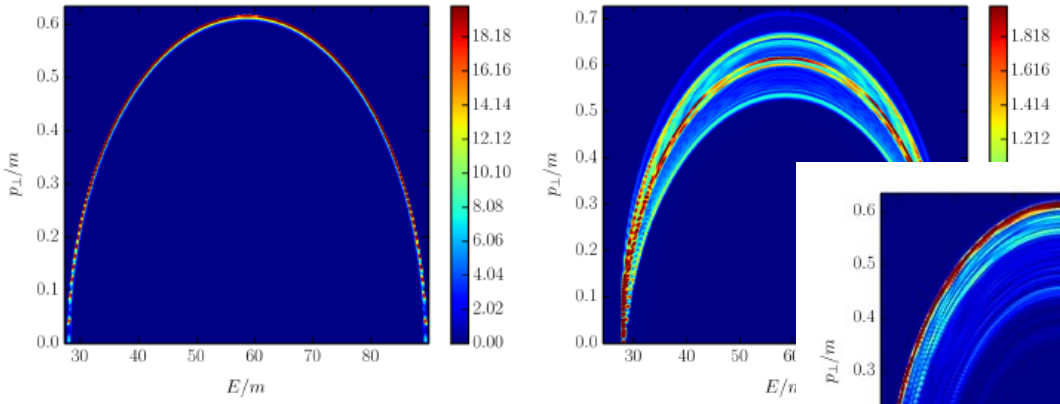
spectral caustics

left panels: phi = pi/2
right panels: phi = pi

a0(L) = 0.01

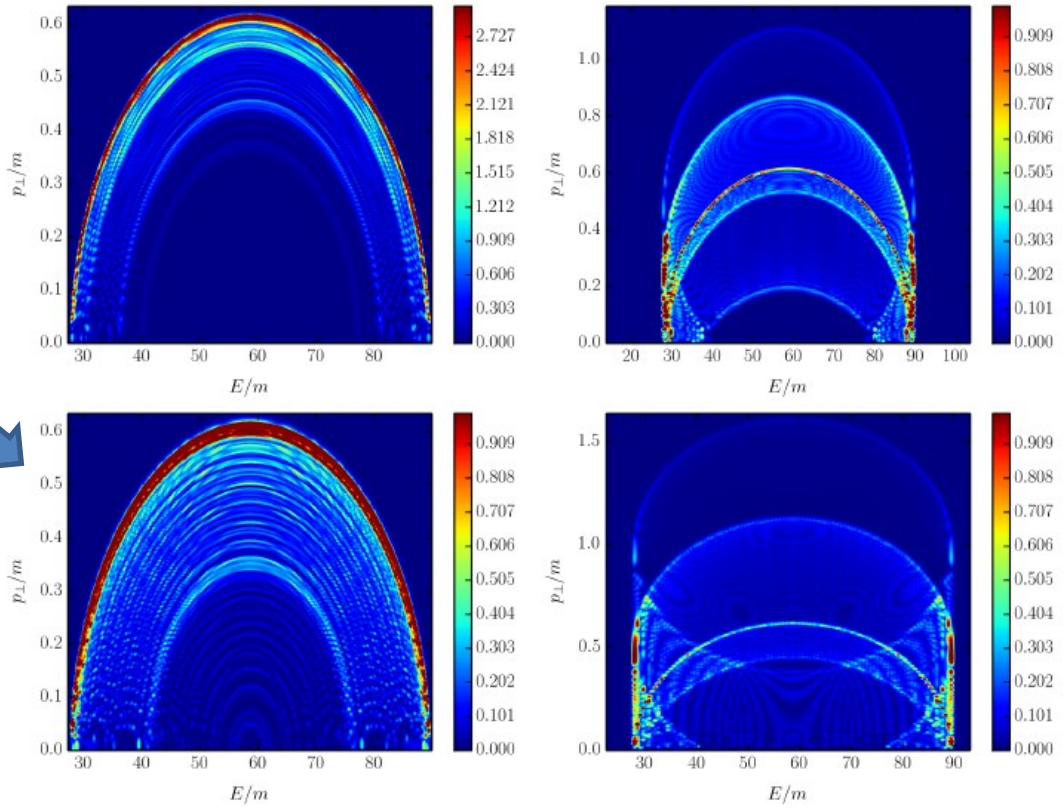


a0(L) = 0.1



lin. pol.
envelopes:
cos^2(pi phi/2 tau_L)
exp{- phi^2/ 2 tau_X}

a0(L) = 0.5
a0(L) = 1

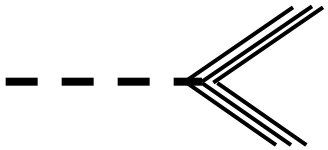


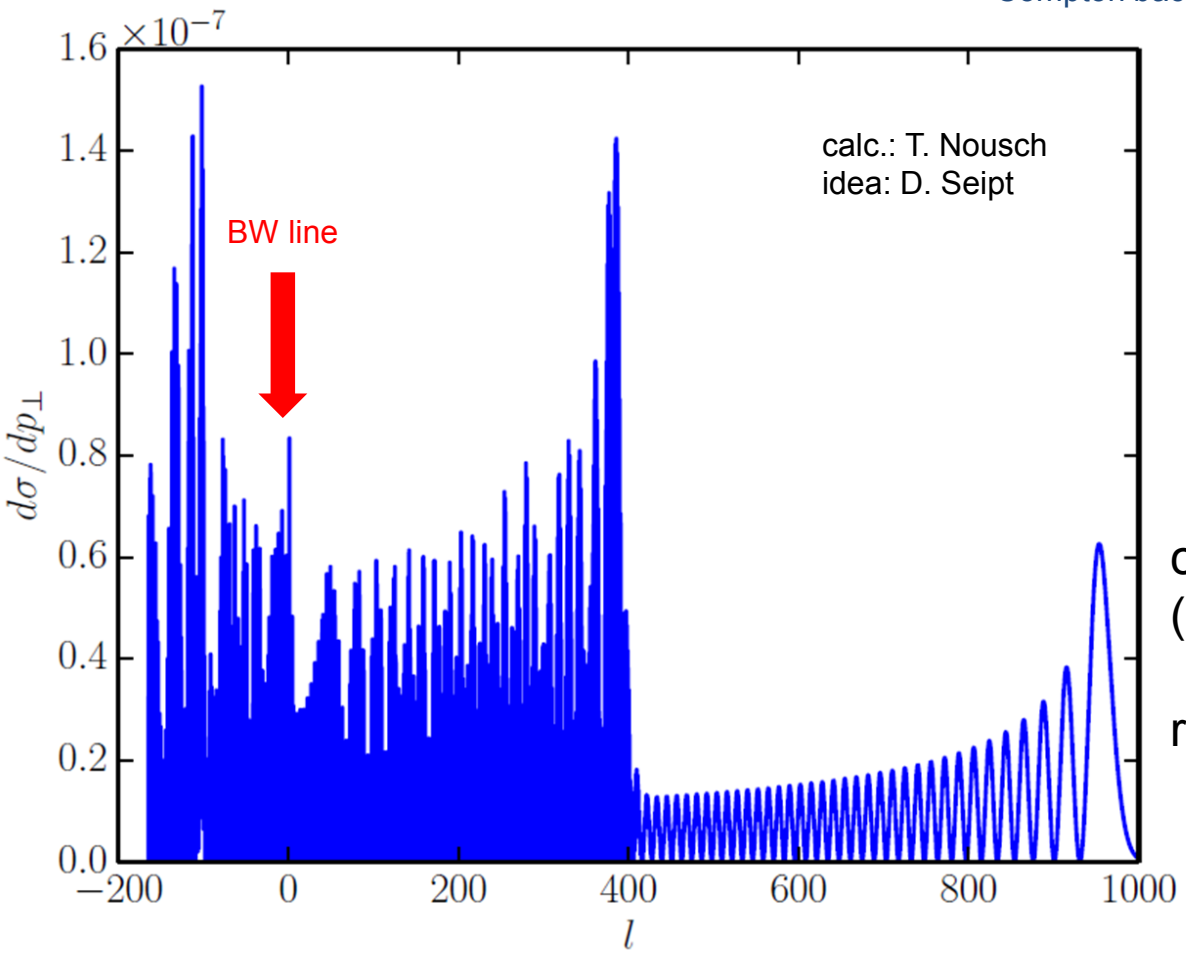
Interpretation:
(i) XFEL: plain BW
(ii) Laser: redistribution
in phase space
bad news for PIC:
quantum interferences!

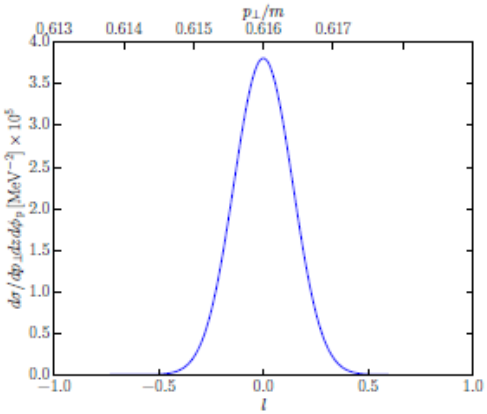
Laser assisted Breit-Wheeler process

IPA-FPA & mono/bi-frequent fields:
C. Müller (2013 - 2016), Wu, Xue (2014)

Furry picture QED:





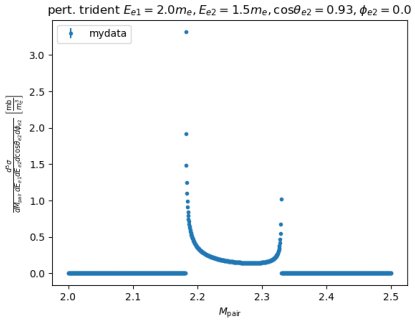


w/o laser

caustics = stat. phase points
(quasi-class. motion after creation with interferences)
redistribution in phase space

(analog to Meuren et al. 2015)

Numeric Games



$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}E_+\mathrm{d}E_-}(E_0,\varepsilon_0,s,E_+,E_-)$$

$$= \frac{\alpha_f\, r_0^2}{4\pi^2 s} p_+ p_- \int_{x_{\min}}^{1} \mathrm{d}x \int_{y_{\min}(x)}^{y_{\max}(x)} \mathrm{d}y [a_1(y_{\max}-y)(y-y_{\min})]^{-1/2} \int_0^{2\pi} X \,\mathrm{d}\phi_+,$$

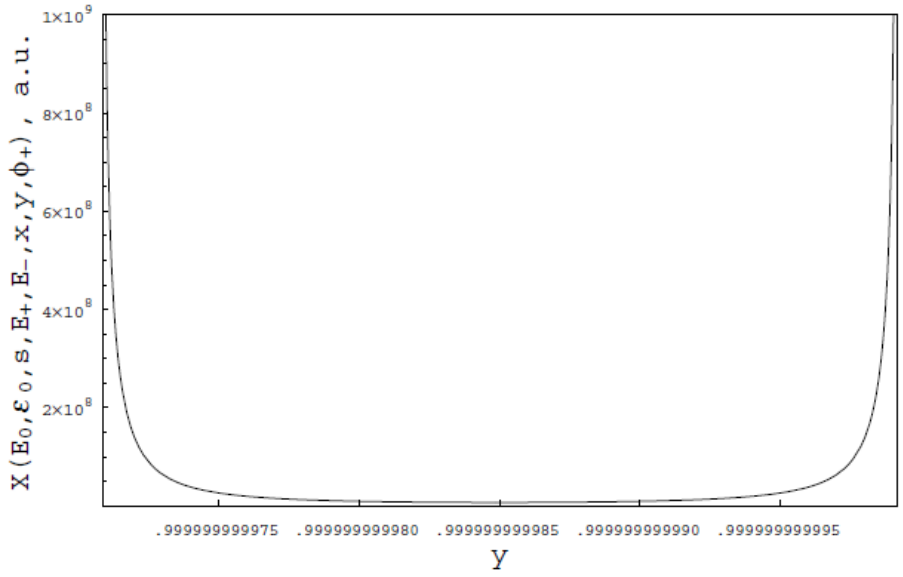


Figure 1. Integrand function $X(E_0,\varepsilon_0,s,E_+,E_-,x,y,\phi_+)[a_1(y_{\max}-y)(y-y_{\min})]^{-1/2}$ in arbitrary units (before change of variables) versus the polar-angle cosine $y=\cos\theta_-$ at $E_0=10^8$, $\varepsilon_0=10^{-3}$, $s=10^5$, $E_+=4.999925000425\times10^7$, $E_-=2.500037499837\times10^7$, $x=\cos\theta_+=0.999999999995$, $\phi_+=\pi$.

[astro-ph/0001252]

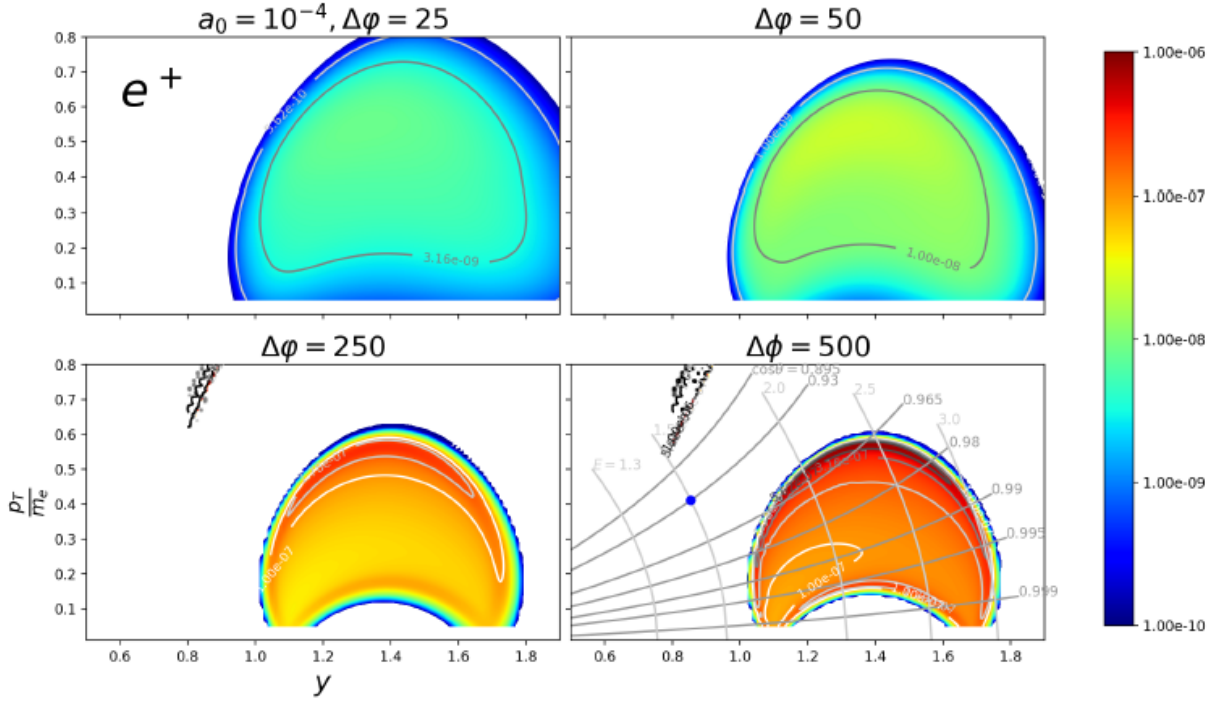
talk.pdf - Adobe Reader

Datei Bearbeiten Anzeige Fenster Hilfe

8 (9 von 17) 154% Werkzeuge Kommentar

Weak-field limit

Partial diagrams: $\sqrt{s} = 3.353\, m_e$ (e^-_{init} at rest, p_1 fix)



$$y = \frac{1}{2} \ln\left(\frac{E + p_z}{E - p_z}\right) \qquad p_T = \sqrt{E^2 - m_e^2} \cos\theta$$

HZDR

Page 8/15

Member of the Helmholtz Association

U. H. Acosta | HZDR | u.hernandez@hzdr.de

DRESDEN concept HZDR