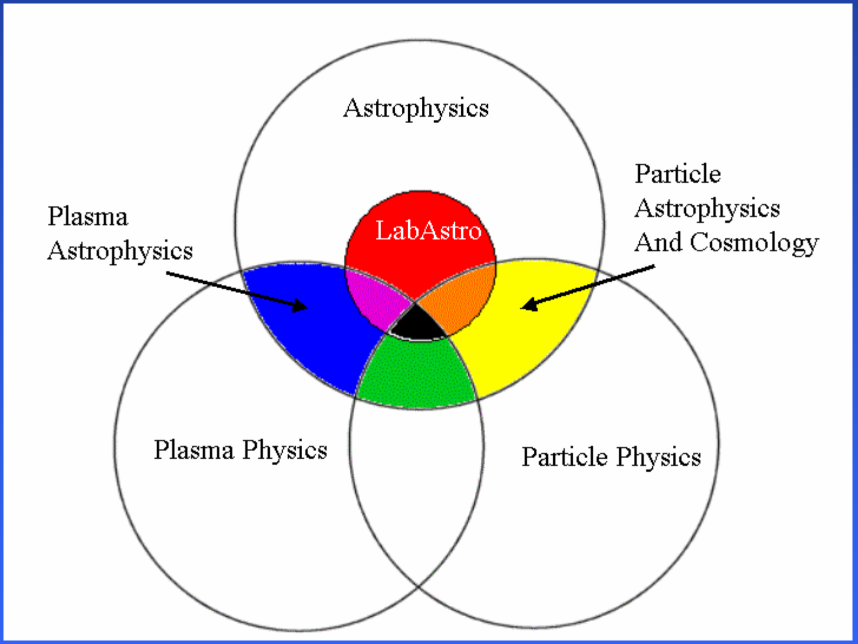
An Astrophysical Plasma Wakefield Accelerator

Alfven Wave Induced

Plasma Wakefield Acceleration

Laboratory Astrophysics at SLAC

- Study in a Laboratory setting:
  - Fundamental physics
  - Astrophysical Dynamics
  - Phenomenon relevant to astrophysics experiments: calibration of techniques, etc

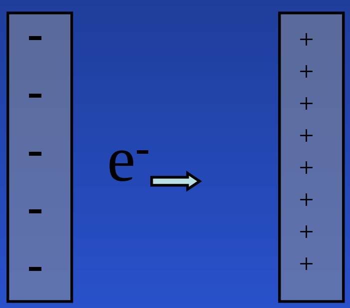


Plasma Wakefield Acceleration

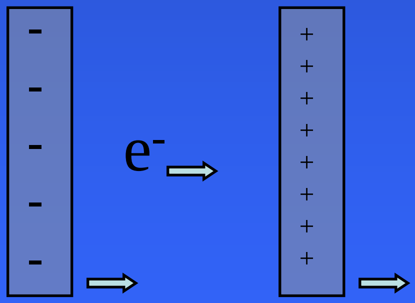
- ARD-B research focus area here at SLAC.
- Laser or beam induced plasma wakefield acceleration.
- At a certain distance behind wake causing disturbance there is a "constant" region of acceleration.

Lake Como

Wake-Field Accelerator

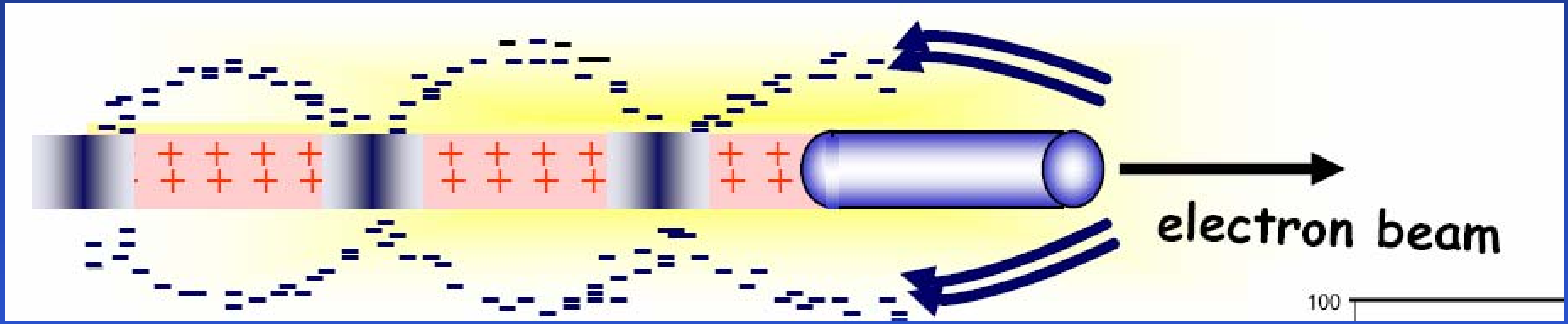


When $v_{grad} \approx c$ the acceleration gradient
Will co-move with the particle ($v_{part} \approx c$)
Providing a great deal of acceleration!



In our case the gradient is provided by an Alfven wave wake-field. The velocity of the gradient is v_{alfven}.

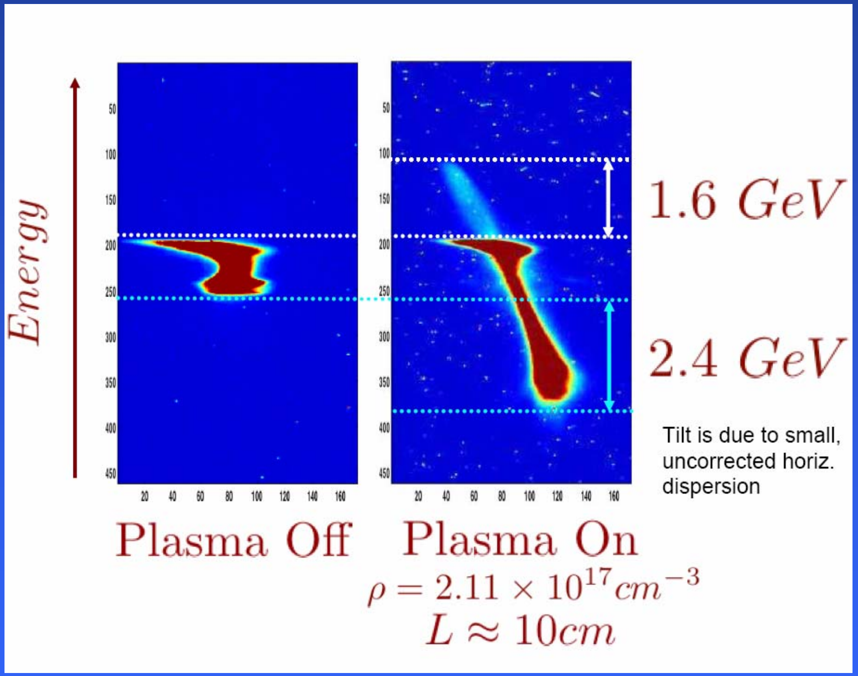
Beam Induced Plasma Wakefield Accelerator



- E164 (X,XX,Y,…)
- Leading edge of beam pulse ionizes ambient plasma and creates wake.
- Portion of trailing edge is inside the acceleration region of the wake.
- (Note: Also a large deceleration region.)

E-164 Results

- Plasma Wakefields generate extremely large scale gradients.
- >10 GeV per meter observed (~2 GeV over 10 cm in E164X.
- Compare to ~10 GeV per km at SLAC.



Working Group 1

http://www-project.slac.stanford.edu/orion/Presentations/SLUO_040706.pdf

WHAT MAKES AN IDEAL ACCELERATOR?

LESSONS FROM TERRISTRIAL ACCELERATORS

- Continuous interaction between the particle and the accelerating longitudinal EM field (Lorentz inv.)
  - Gain energy in macroscopic distance
- Particle-field interaction process non-collisional
  - Avoid energy loss through inelastic scatterings
- To reach ultra high energy, linear acceleration (minimum bending) is the way to go
  - Avoid severe energy loss through synchrotron radiation
- Are these criteria applicable to celestial accelerators?

LINEAR VS. CIRCULAR

SLAC

CERN

A Brief History of Plasma Wakefields

Motivated by the challenge of high energy physics

- Laser driven plasma acceleration

  T. Tajima and J. M. Dawson (1979)

- Particle-beam driven plasma wakefield acceleration

  PC, Dawson et al. (1984)

- Extremely efficient:

$$eE \geq \sqrt{n\,[\mathrm{cm}^{-3}]}\ \ \mathrm{eV/cm}$$

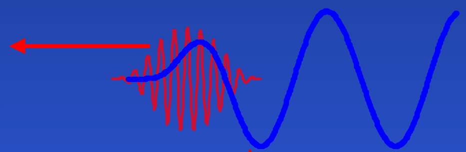
For n=10^{18} cm^{-3}, eE=100 GeV/m → TeV collider in 10 m!

* Plasma wakefield acceleration principle experimentally verified. Actively studied worldwide

Concepts For Plasma-Based Accelerators

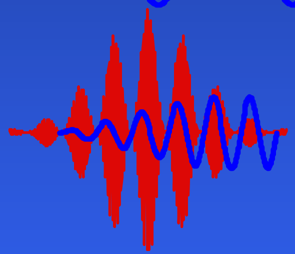
- Laser Wake Field Accelerator(LWFA)

  A single short-pulse of photons



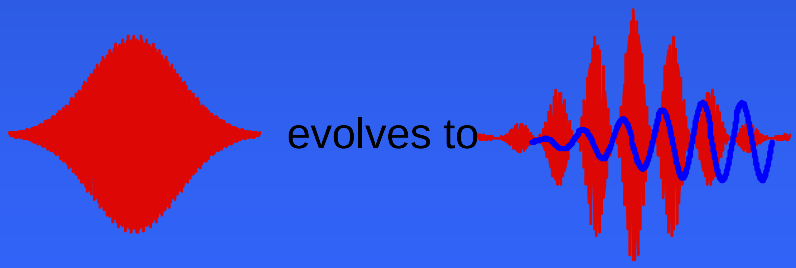
- Plasma Beat Wave Accelerator(PBWA)

  Two-frequencies, i.e., a train of pulses



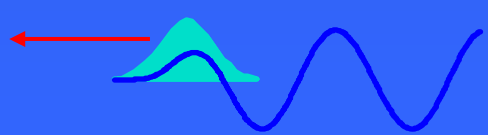
- Self Modulated Laser Wake Field Accelerator(SMLWFA)

  Raman forward scattering instability

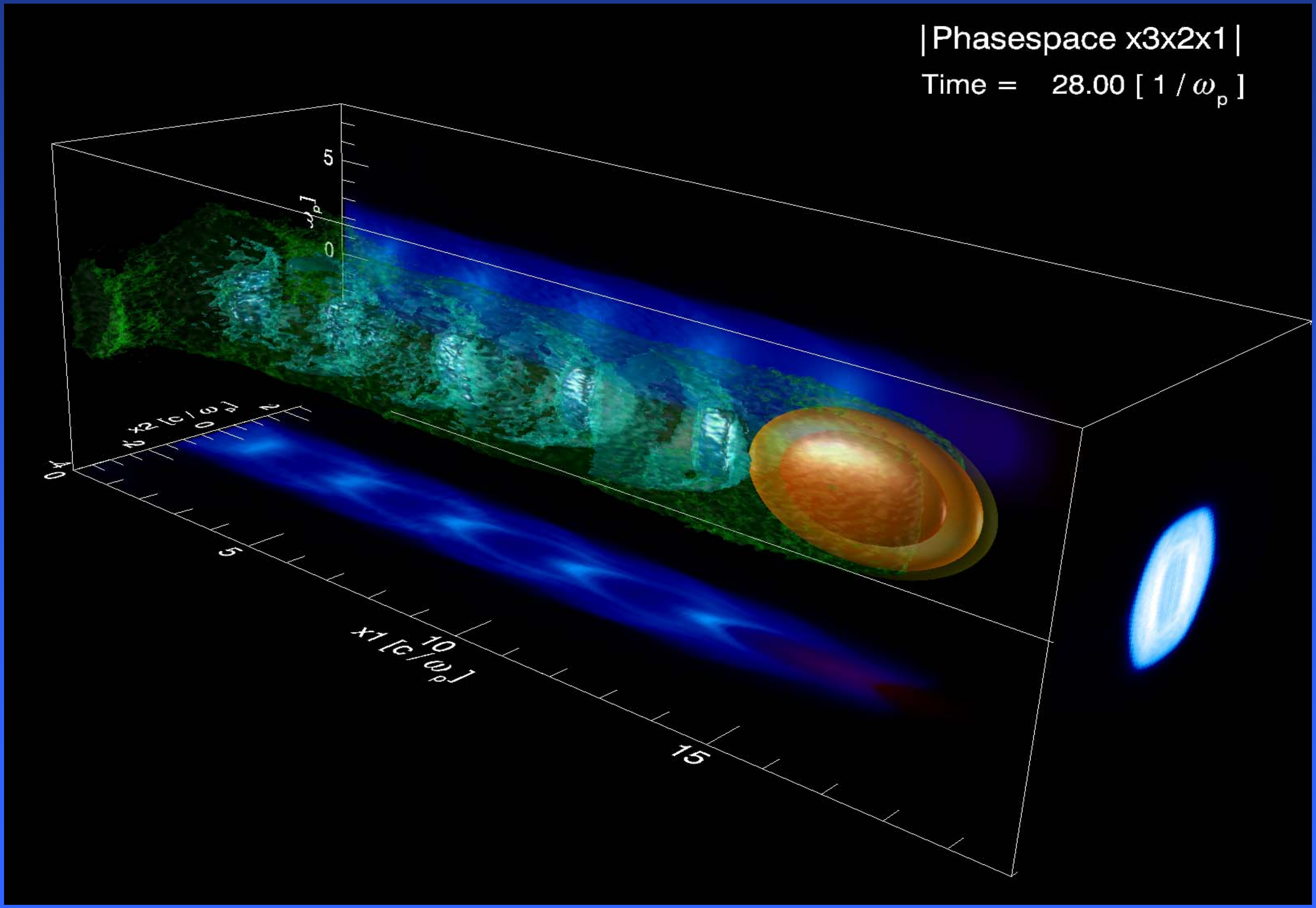


- Plasma Wake Field Accelerator(PWFA)

  A high energy electron (or positron) bunch



Plasma Wakefield Simulation
(SLAC E-157 Collaboration)



Cosmic Accelerators

- 1 of the 11 questions for the new century from Turner Committee:
  - “**How do cosmic accelerators work and what are they accelerating?”**
- 2 of their 7 recommendations:
  - “**Determine the origin of the highest-energy gamma-rays, neutrinos, and cosmic rays.**”
  - “**Discern the physical principles that govern extreme astrophysical environments through the laboratory study of high energy-density physics.** The Committee recommends that the agencies cooperate in bringing together the different scientific communities that can foster this rapidly developing field.”

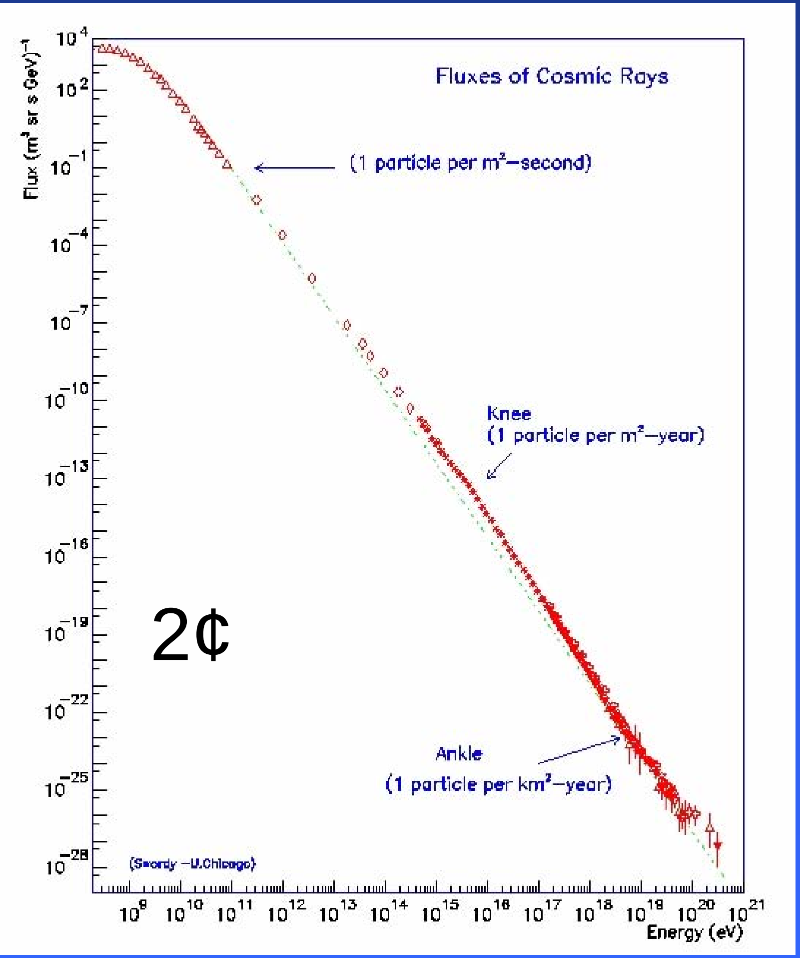
Cosmic Acceleration Mechanisms:

Addressing the Bottom–Up Scenario for Acceleration of Ordinary Particles

- Conventional cosmic acceleration mechanisms encounter limitations:
  - Fermi acceleration (1949) (= stochastic accel. bouncing off B-fields)
  - Diffusive shock acceleration (1970's) (a variant of Fermi mechanism)
    - Limitations for UHE: field strength, diffusive scattering inelastic
  - Eddington acceleration (= acceleration by photon pressure)
    - Limitation: acceleration diminishes as $1/\gamma$
- Examples of new ideas:
  - Zevatron (= unipolar induction acceleration) (R. Blandford, astro-ph/9906026, June 1999)
  - Alfven-wave induced wakefield acceleration in relativistic plasma (Chen, Tajima, Takahashi, Phys. Rev. Lett. 89 , 161101 (2002).
  - Additional ideas by M. Barring, R. Rosner, etc.

Cosmic Acceleration

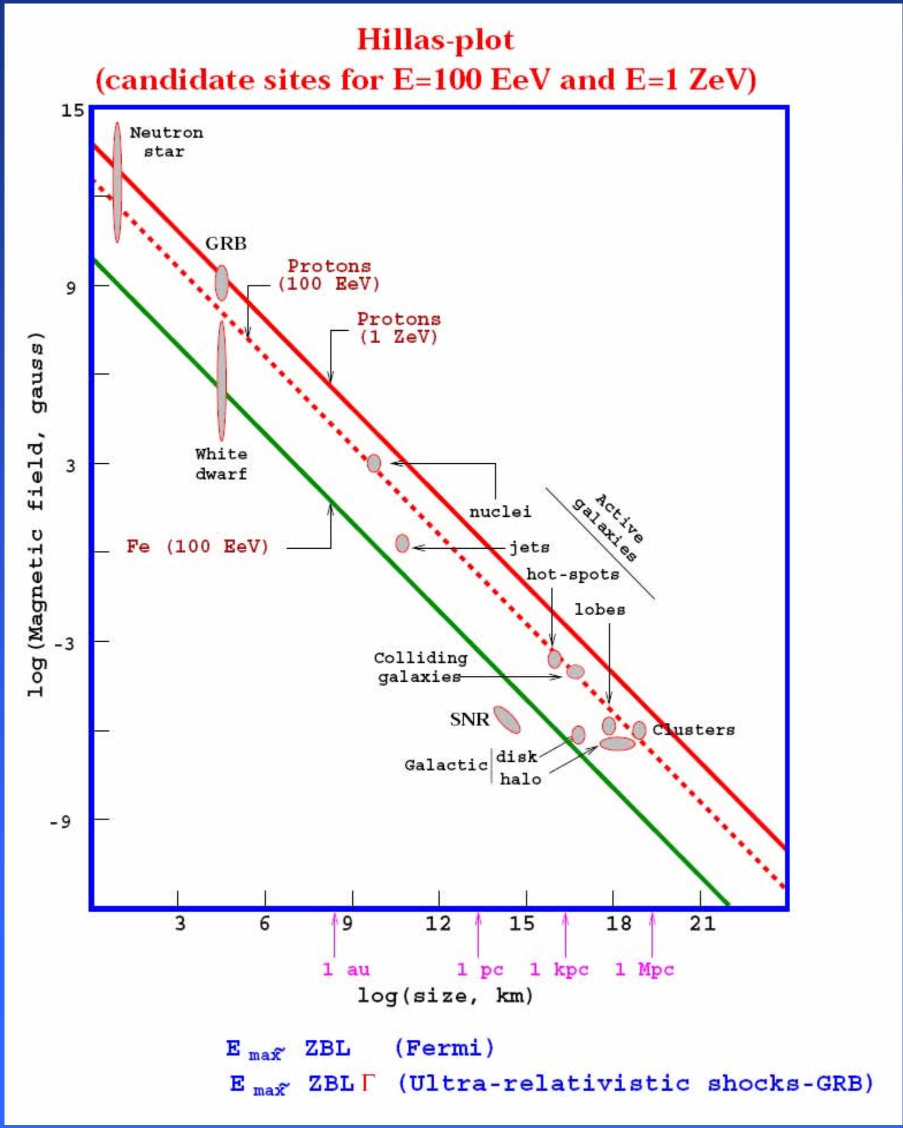
- Need to produce particles with energy in excess of 10^{20} eV.



- 94¢

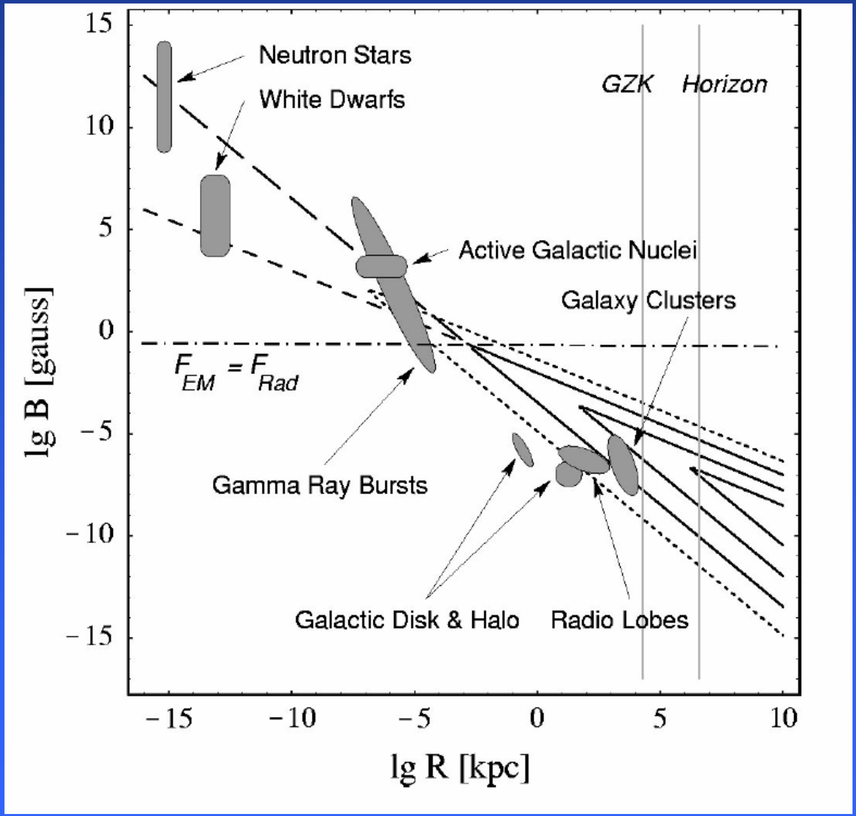
Hillas Diagram

- UHECR created as:
  - Protons receive multiple kicks of energy
  - Protons are confined inside of the acceleration region by magnetic fields.
- In order to achieve UHE:
  - many kicks required.
  - Large field needed to contain the particle for enough kicks to occur.
- Summary:
  - Need large B fields (small acceleration region) OR large acceleration region (small B field)

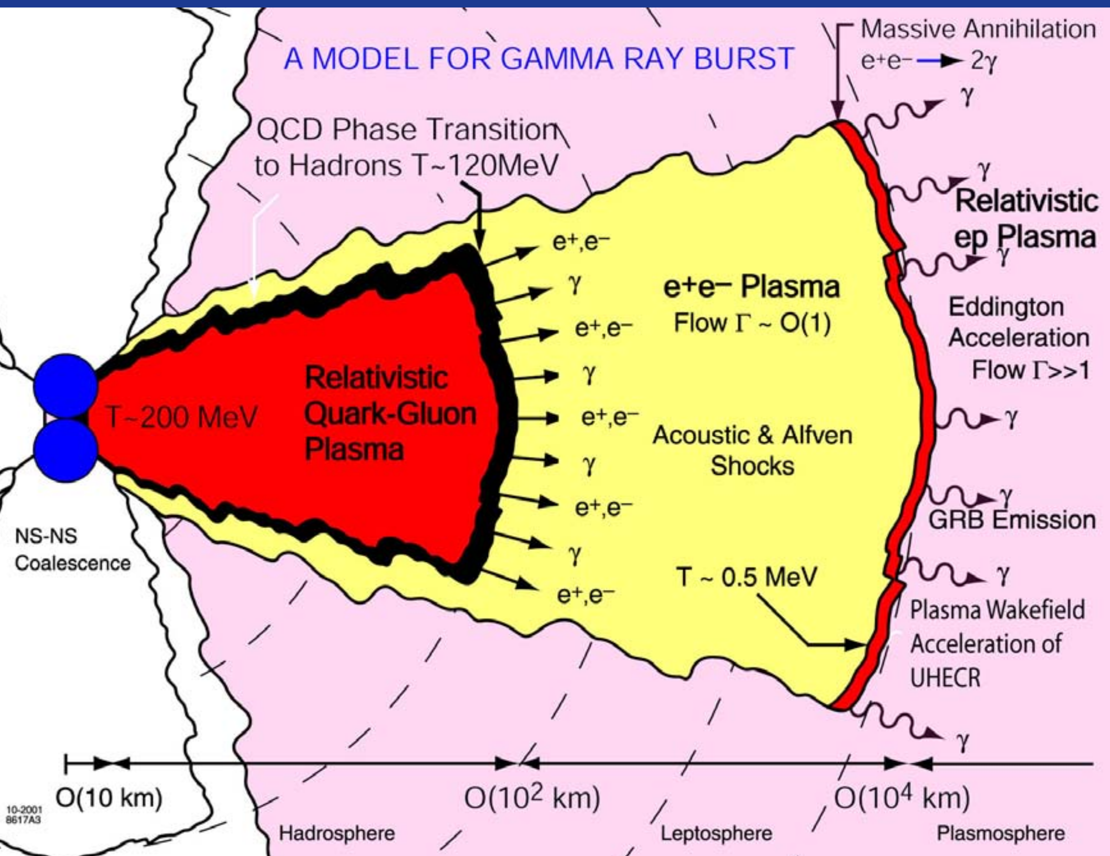


Syncrotron losses!

- **Mikhail V. Medvedev,**
``Constraint on Electromagnetic Acceleration of Highest Energy Cosmic Rays'',
***Physical Review E* 67, 045401 (2003).**
Abstract
- The energetics of electromagnetic **acceleration** of ultra-high-energy cosmic rays (UHECRs) is constrained both by confinement of a particle within an **acceleration** site and by radiative energy losses of the particle in the confining magnetic fields. We demonstrate that the detection of ~3x10^{20} eV events is inconsistent with the hypothesis that compact cosmic accelerators with high magnetic fields can be the sources of UHECRs. **This rules out the most popular candidates, namely spinning neutron stars, active galactic nuclei (AGNs), and γ-ray burst blast waves.** Galaxy clusters and, perhaps, AGN radio lobes remain the only possible (although not very strong) candidates for **UHECR acceleration** sites. Our analysis places no limit on linear accelerators. With the data from the future {\it Auger} experiment one should be able to answer whether a conventional theory works or some new physics is required to explain the origin of UHECRs.
- *PACS nimbers:* 41.60.-m, 96.40.-z



Plasma Wakefields in Astrophysics

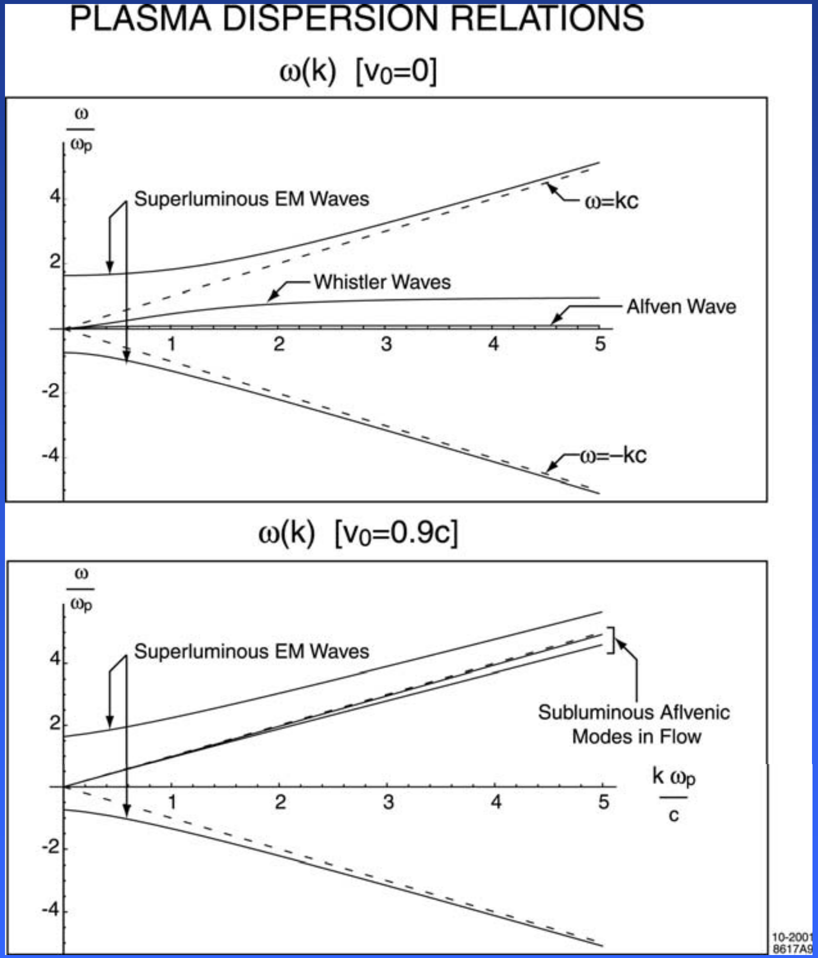


- In accelerator research, great care must be taken to get “entire” bunch accelerated.
- In astrophysics, only a few need to be trapped in the accelerating portion of wakefield.

Chen, **Tajima**, **Takahashi**, Phys. Rev. Lett. 89 , 161101 (2002)

Alfven Shock Induced PWFA!

- In a non-relatistic plasma,
  - $E_A/B_A = v_A/c << 1.$



- In a relativistic plasma,
  - $E_A/B_A = v_A/c \approx 1.$

Alfven Wave Induced Wake Field Simulations

K. Reil (SLAC), PC and R. Sydora (U of Alberta)

Dispersion relation for EM waves in magnetized plasma:

$$\frac{k^2c^2}{\omega^2} = 1 - \frac{2\omega_{pe}^2}{\omega^2-\Omega_e^2}$$

$\omega_{pe}^2 = 4\pi e^2 n/m$
$\Omega_c = eB/mc$

E.M. waves propagate when

(i) $\omega > \sqrt{2\omega_{pe}^2 + \Omega_e^2}$, the high frequency branch

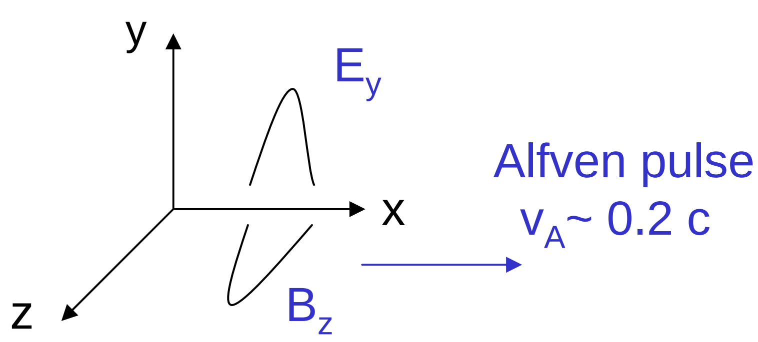
(ii) $\omega < \Omega_e$, the low frequency (or Alfven) branch

$$\omega \simeq kV_A\left(1 - \frac{k^2\omega_{pe}^2 V_A^2}{\Omega_e^4 c^2}\right), \text{ where } V_A = \frac{c}{\sqrt{\left(1+2\frac{\omega_{pe}^2}{\Omega_e^2}\right)}}$$

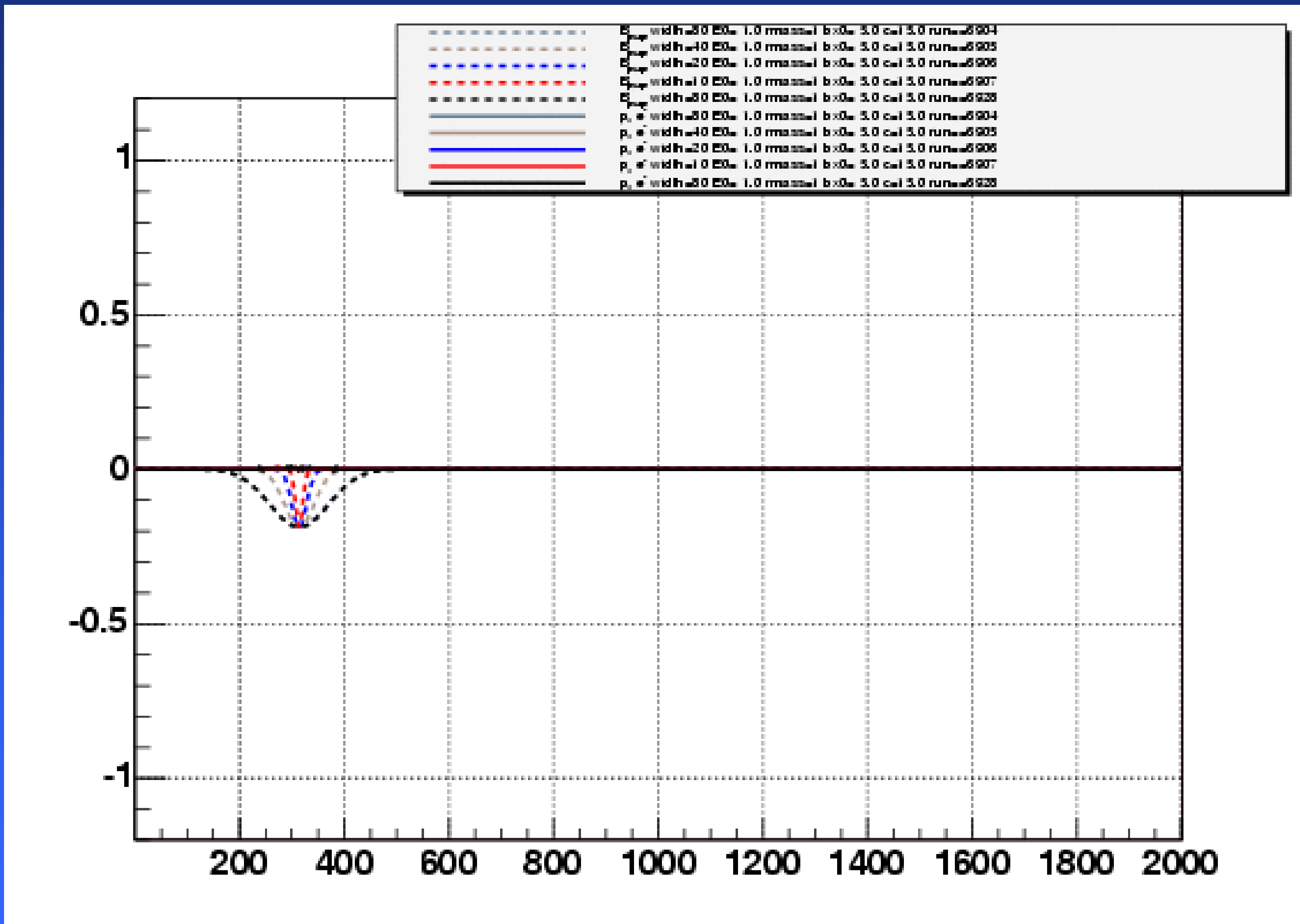
Simulation parameters for plots:

- e+ e- plasma (mi=me)
- Zero temperature (Ti=Te=0)
- Ω_{ce}/ω_{pe} = 1 (normalized magnetic field in the x-direction)
- Normalized electron skin depth c/ω_{pe} is 15 cells long
- Total system length is 273 c/ω_{pe}
- dt=0.1 ω_{pe}^{-1} and total simulation time is 300 ω_{pe}^{-1}
- Aflven pulse width is about 11 c/ω_{pe}
- 10 macroparticles per cell

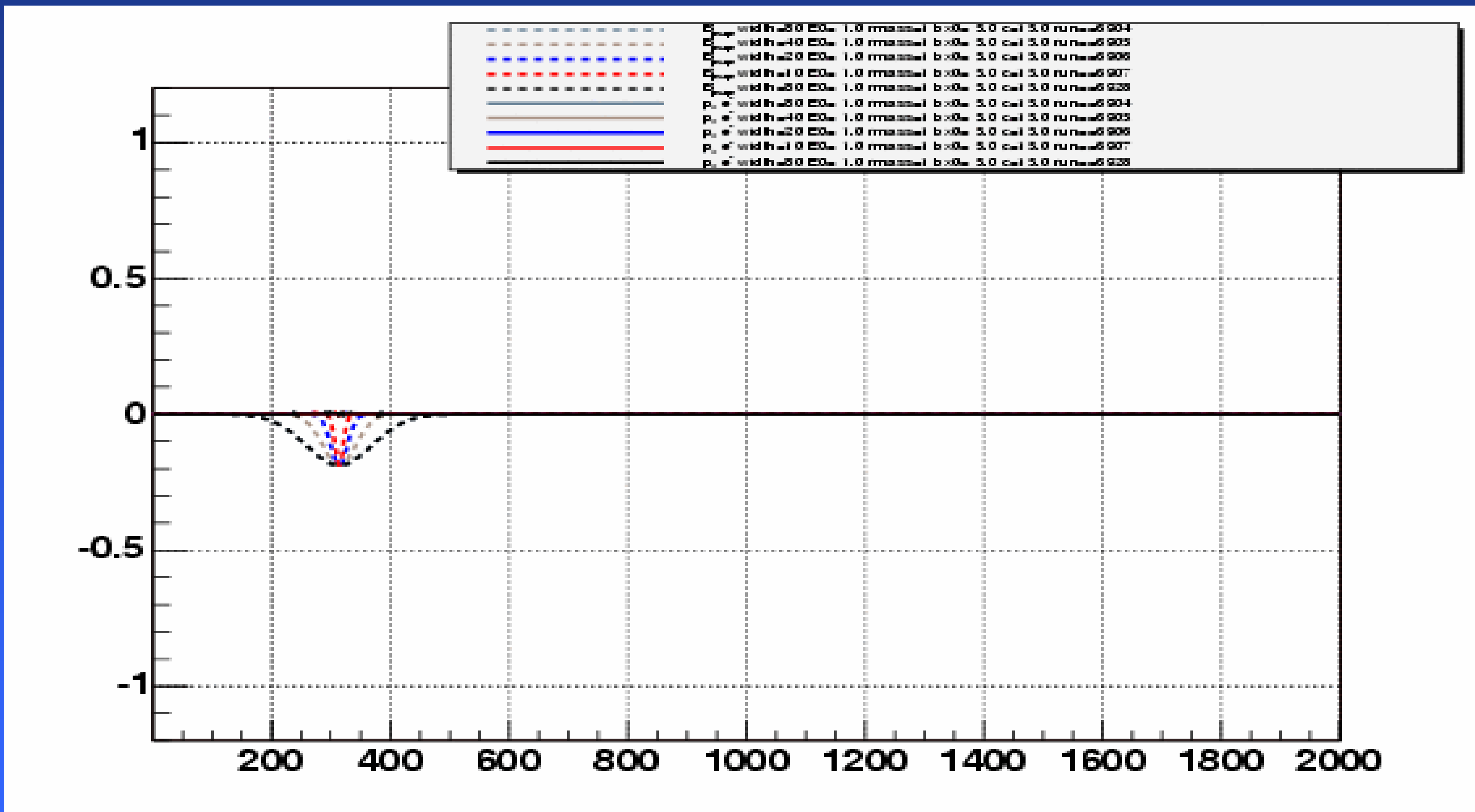
Simulation geometry:



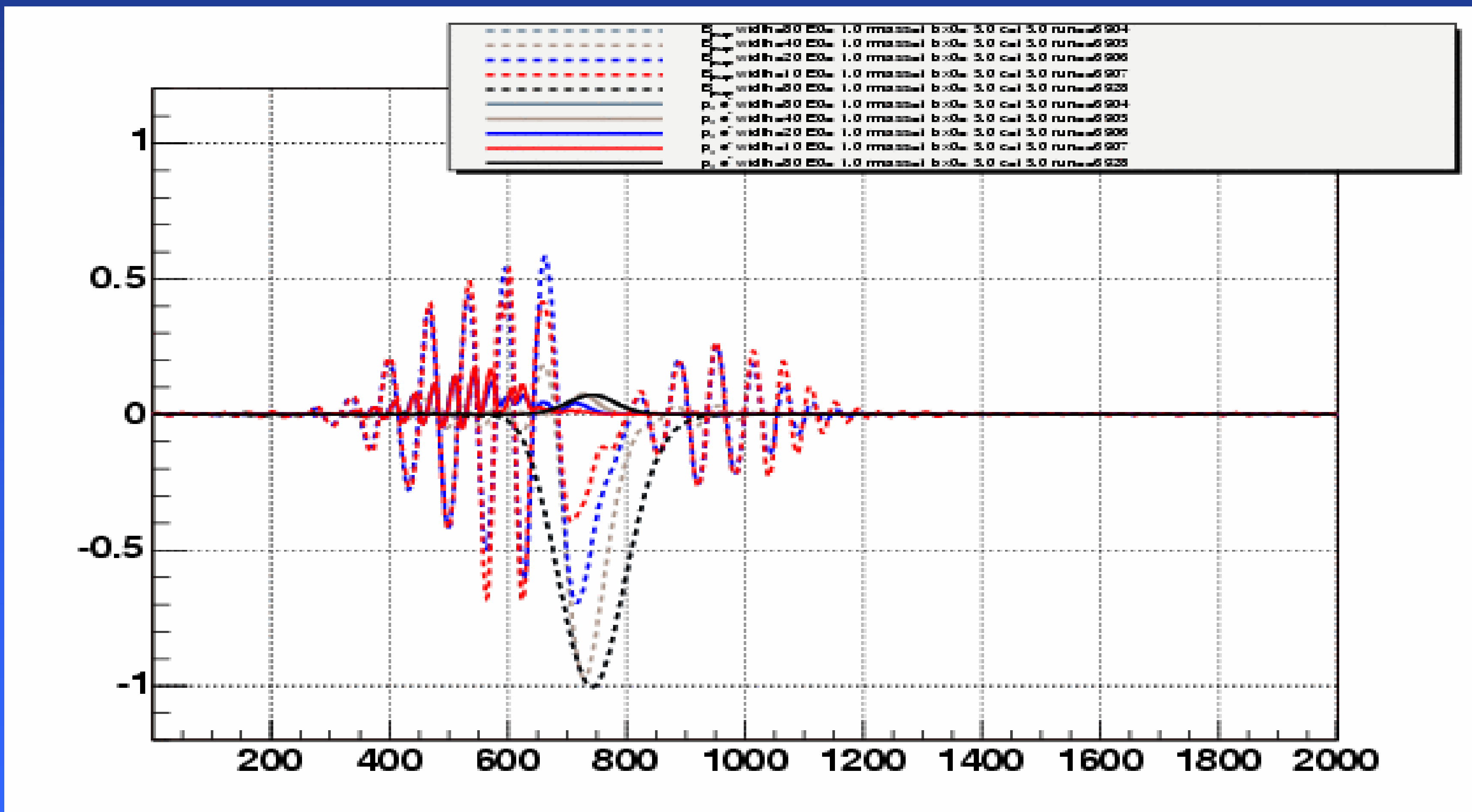
$R_{mass} = 1$



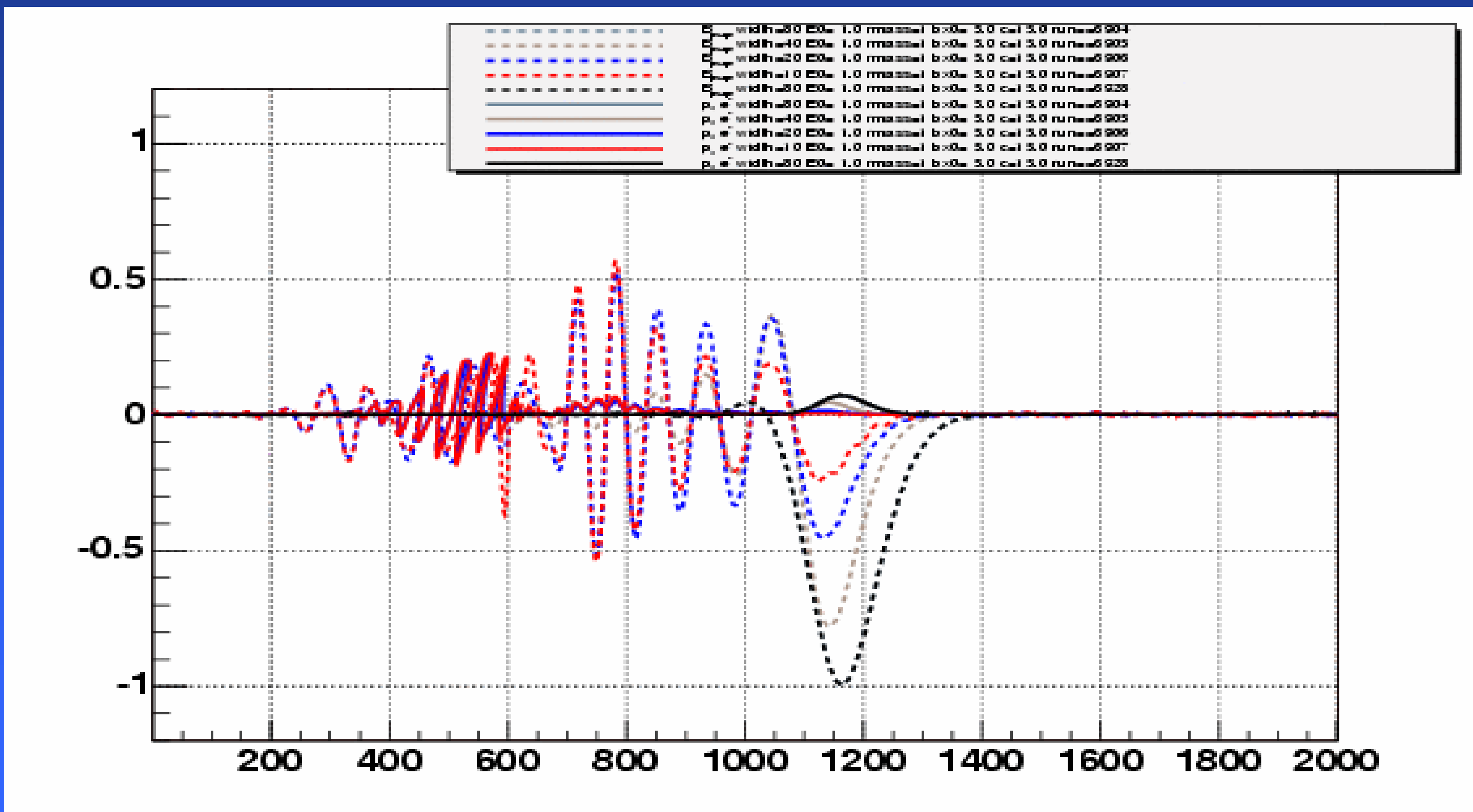
R_{mass}=1 T=25 ω_p^{-1}



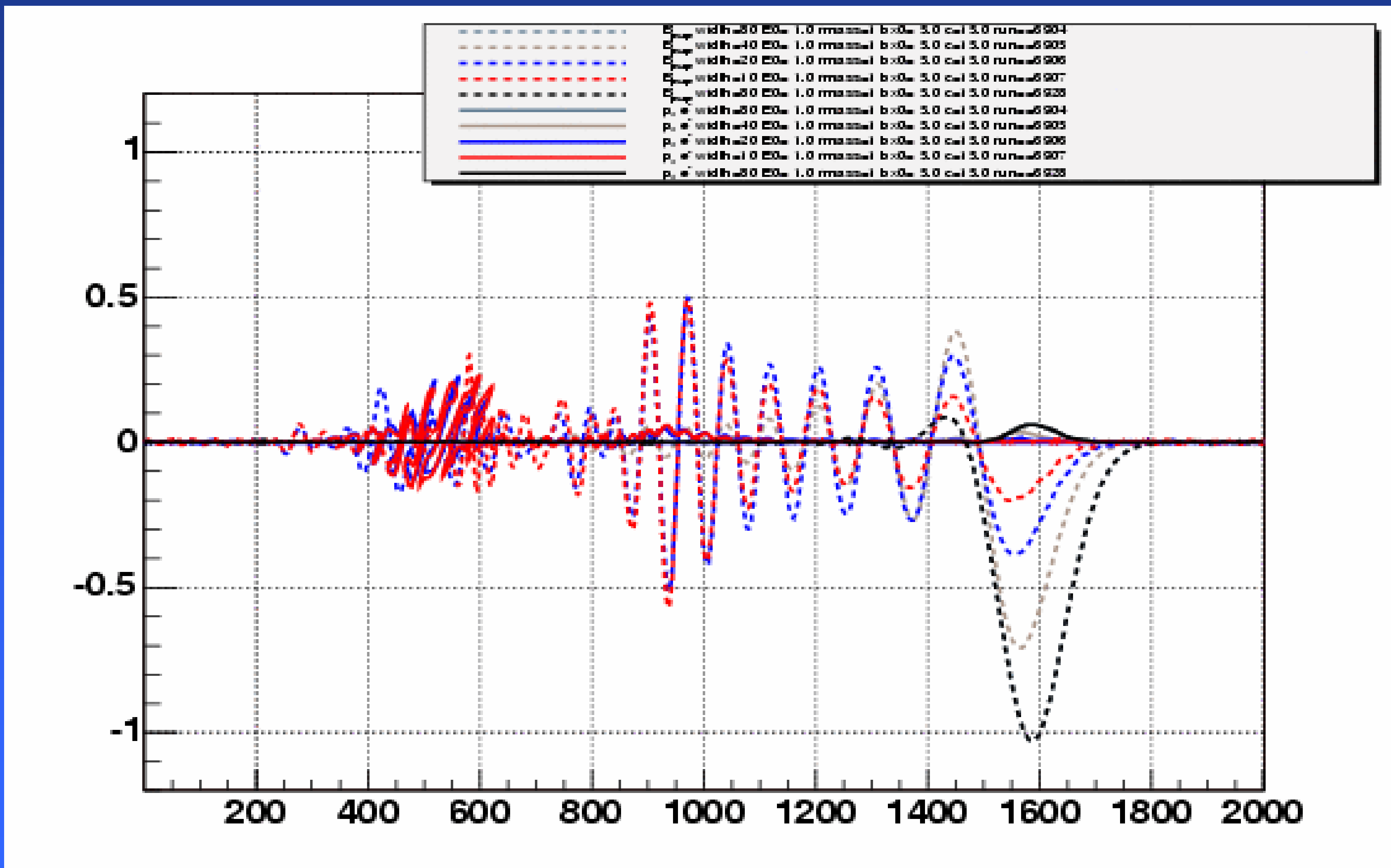
R_{mass}=1 T=150 ω_p^{-1}



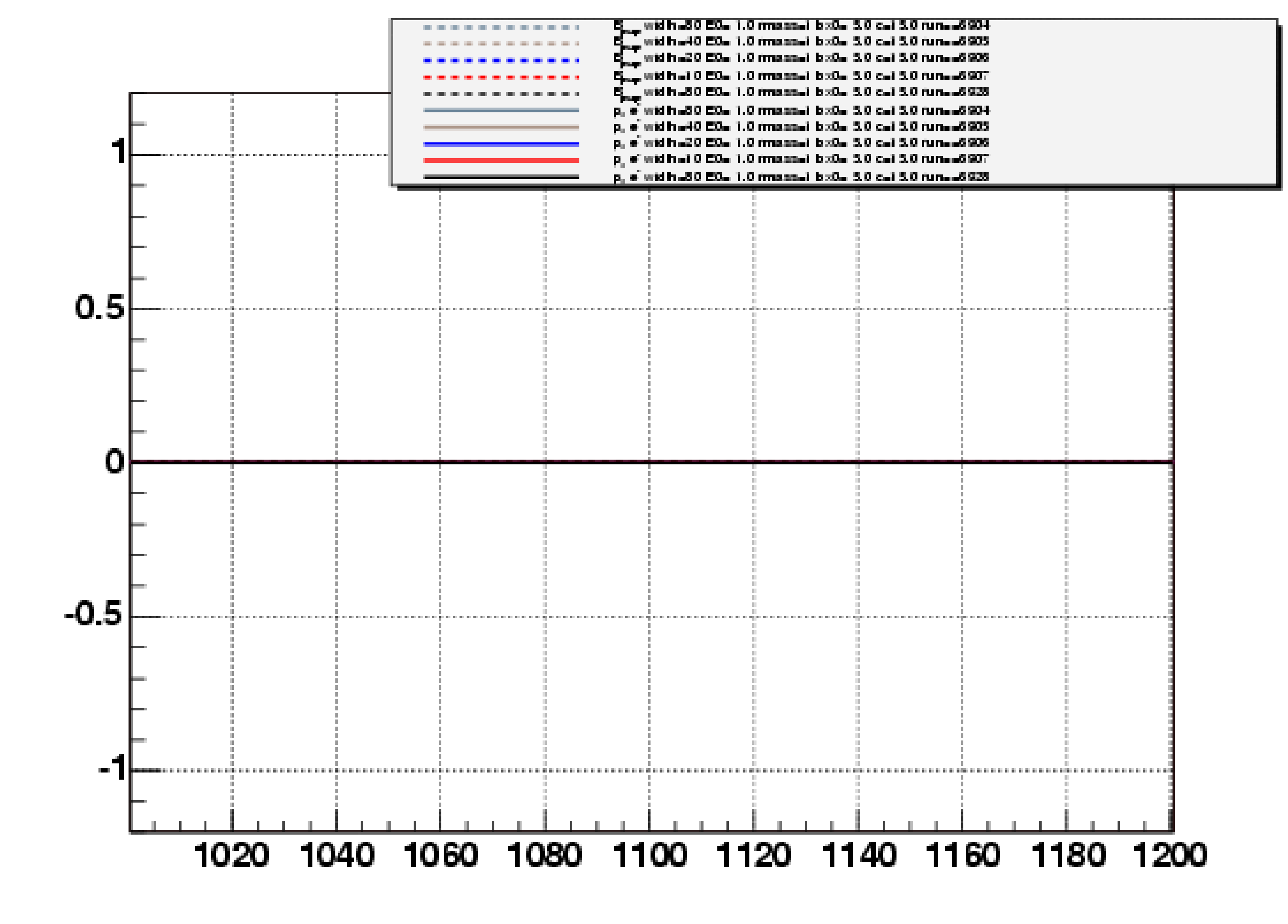
R_{mass}=1 T=275 ω_p^{-1}



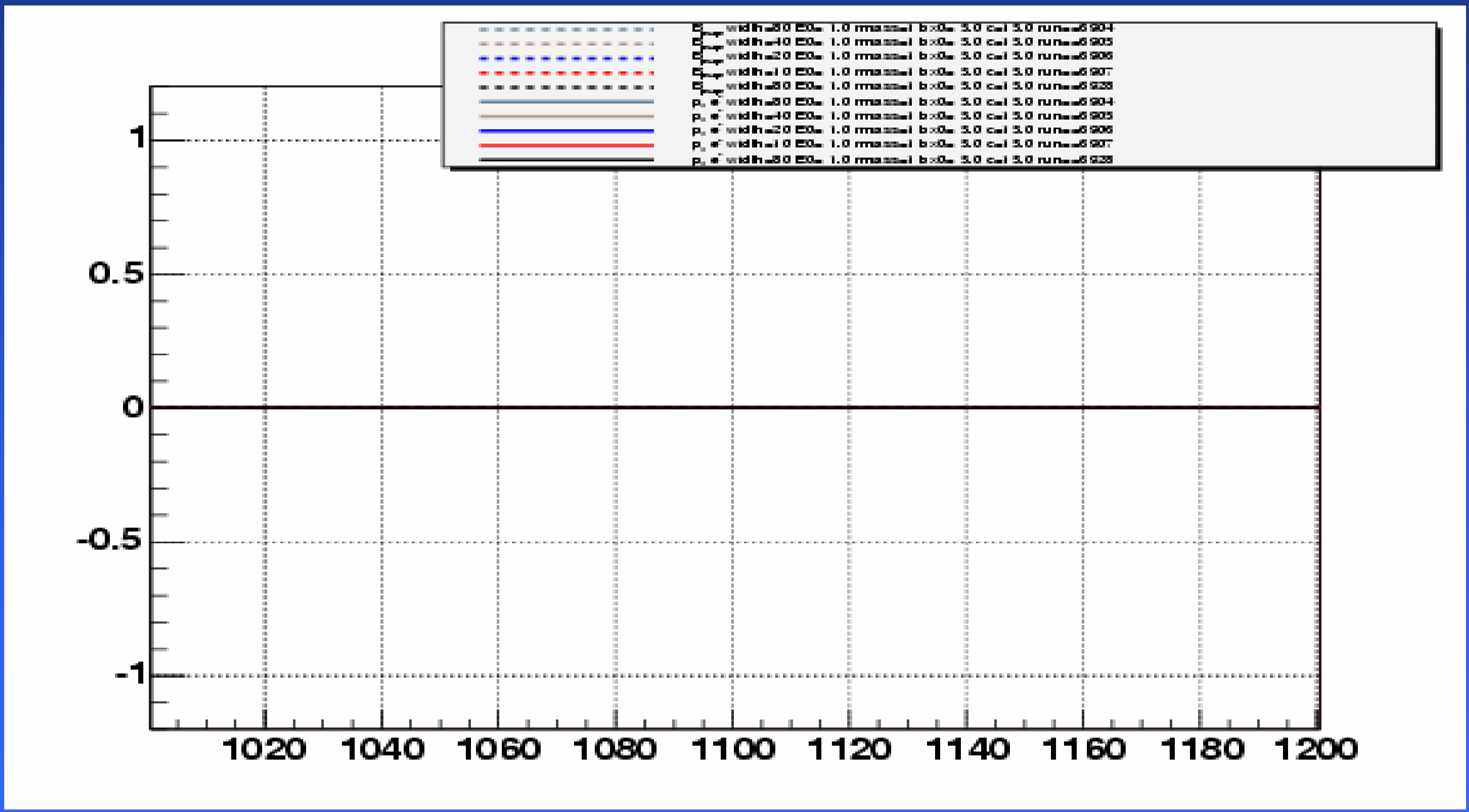
R_{mass}=1 T=400 ω_p^{-1}



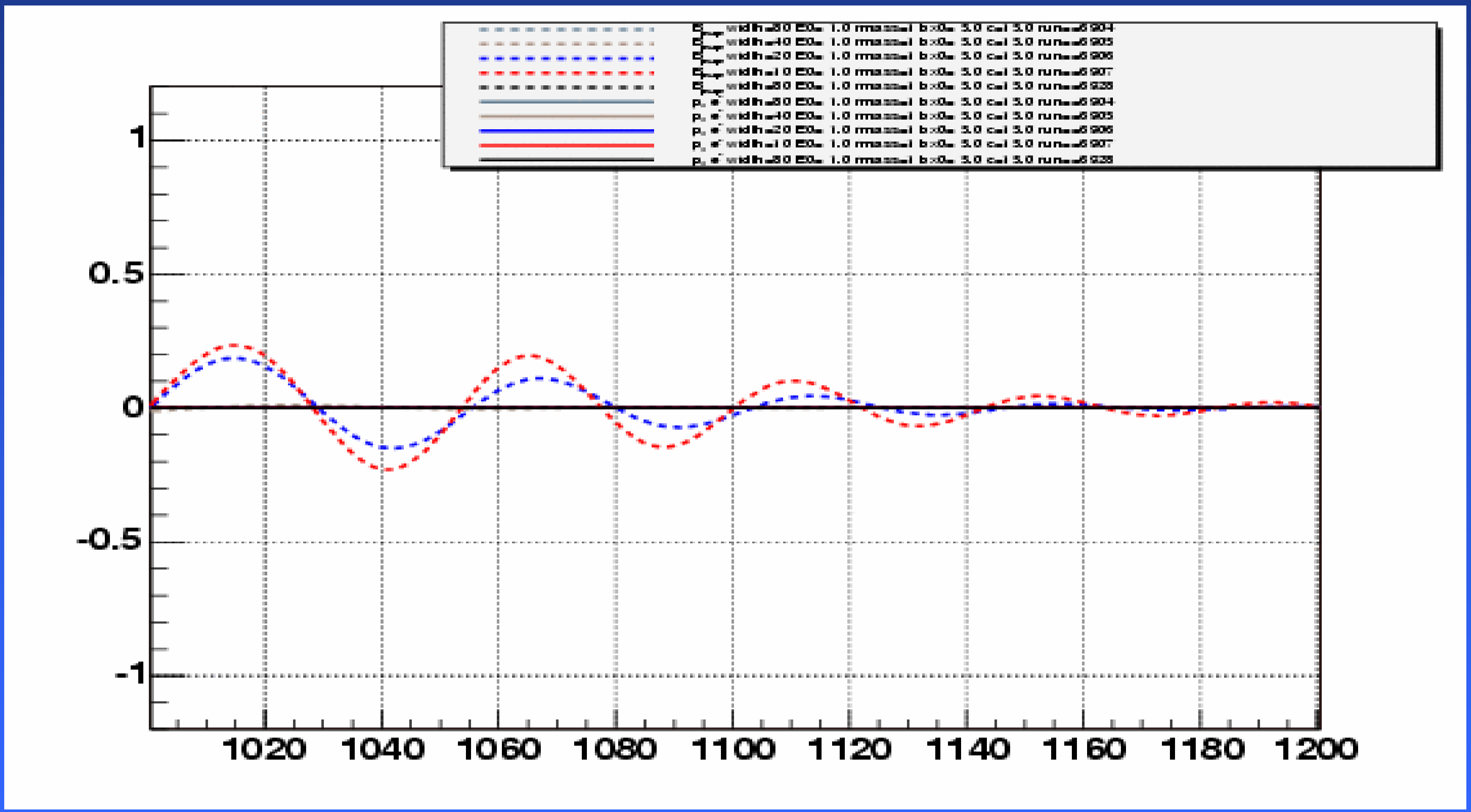
$R_{mass} = 1$



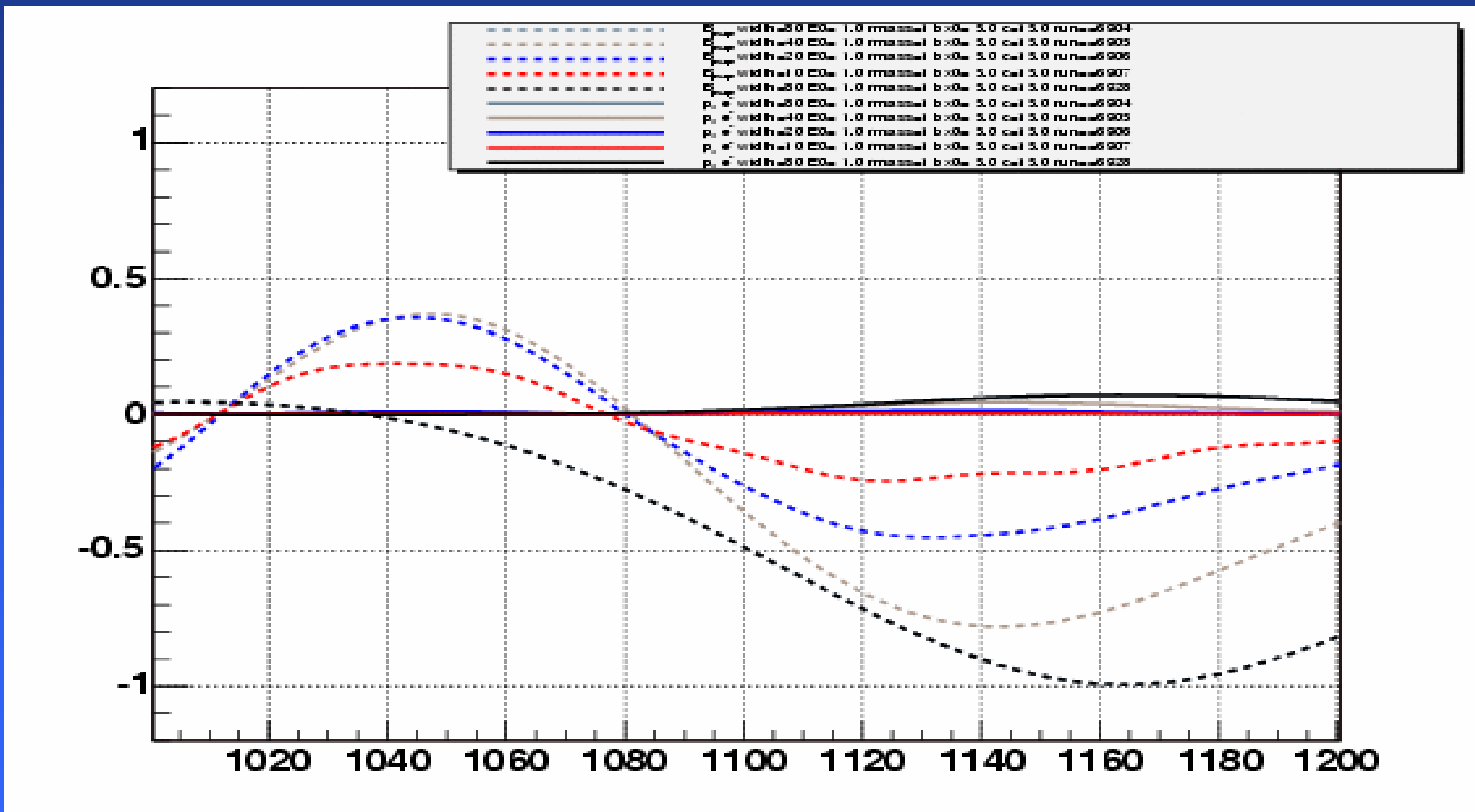
R_{mass}=1 T=25 ω_p^{-1} (Zoomed)



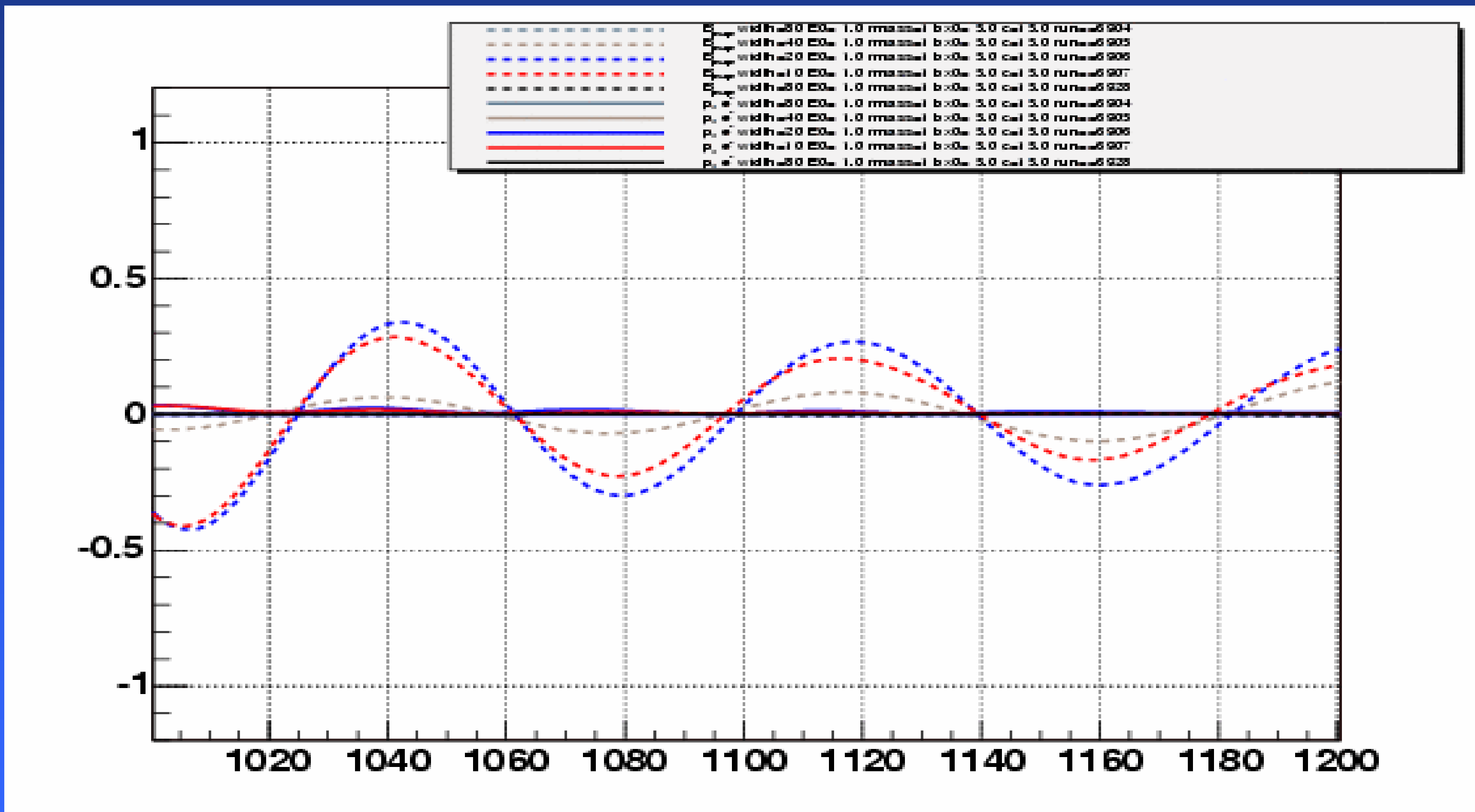
R_{mass}=1 T=150 ω_p^{-1} (Zoomed)



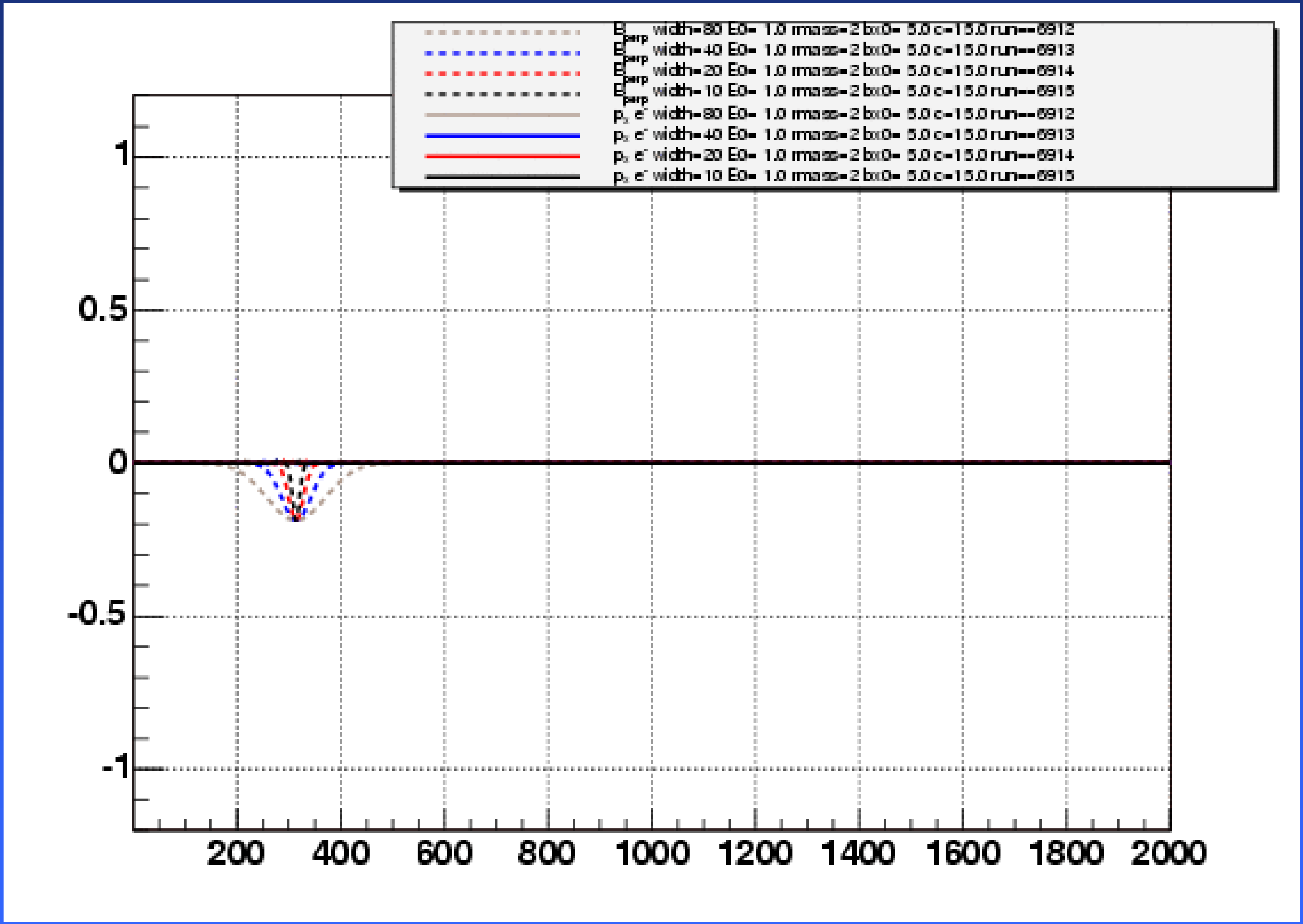
R_{mass}=1 T=275 ω_p^{-1} (Zoomed)



R_{mass}=1 T=400 ω_p^{-1} (Zoomed)

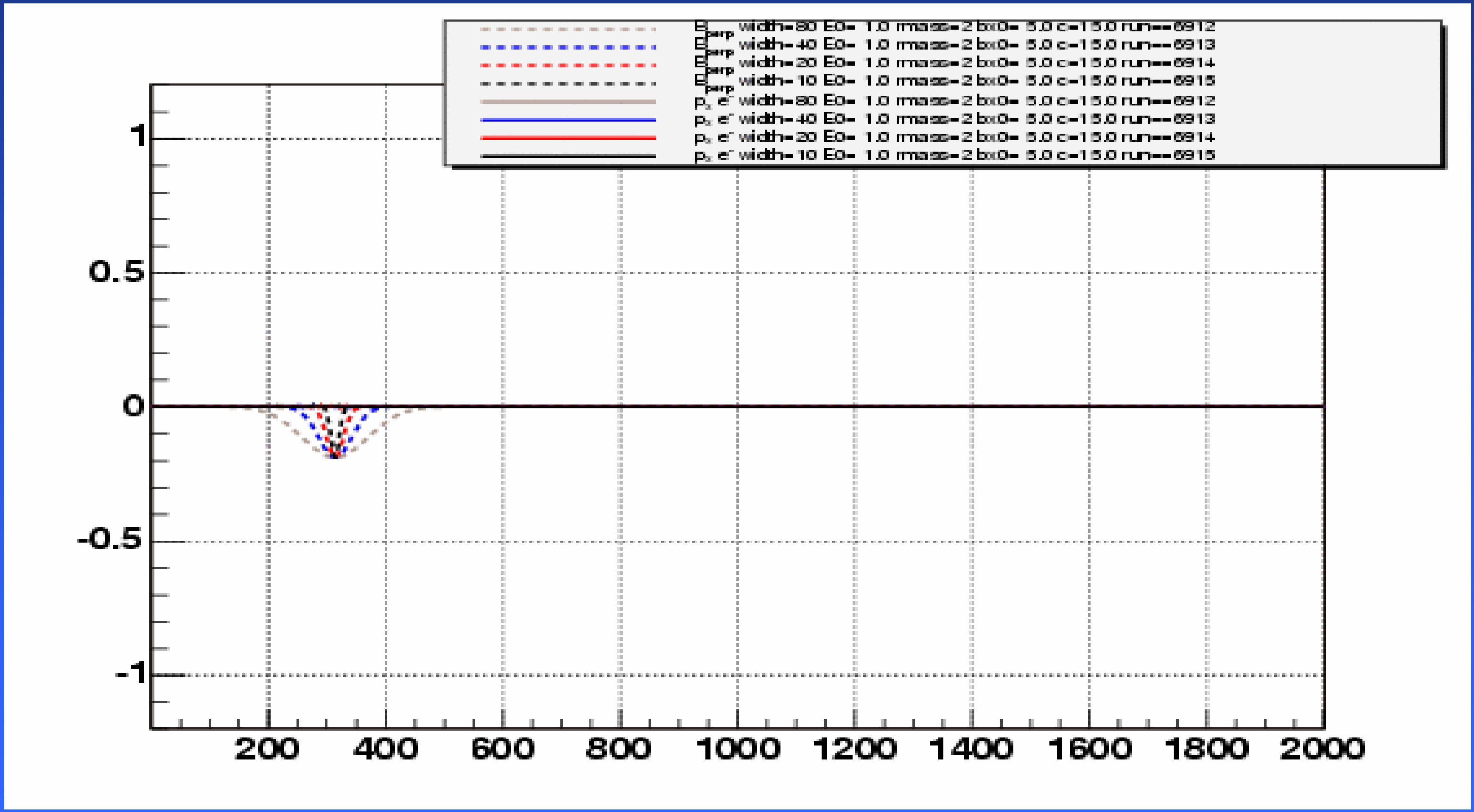


$R_{mass} = 2$

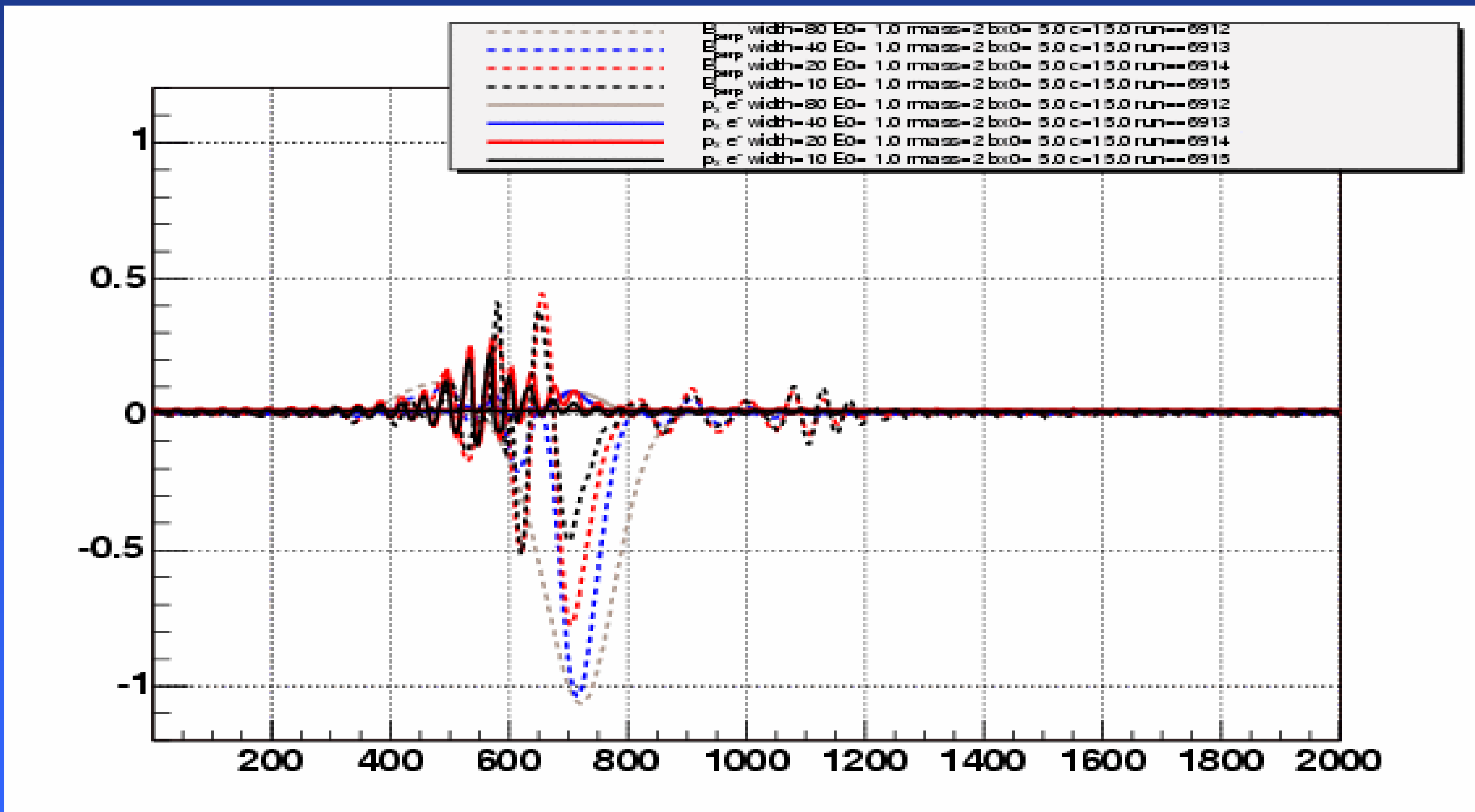


B_perp width=80 E0= 1.0 rmass=2 bx0= 5.0 c=15.0 run==6912
B_perp width=40 E0= 1.0 rmass=2 bx0= 5.0 c=15.0 run==6913
B_perp width=20 E0= 1.0 rmass=2 bx0= 5.0 c=15.0 run==6914
B_perp width=10 E0= 1.0 rmass=2 bx0= 5.0 c=15.0 run==6915
p_x e⁻ width=80 E0= 1.0 rmass=2 bx0= 5.0 c=15.0 run==6912
p_x e⁻ width=40 E0= 1.0 rmass=2 bx0= 5.0 c=15.0 run==6913
p_x e⁻ width=20 E0= 1.0 rmass=2 bx0= 5.0 c=15.0 run==6914
p_x e⁻ width=10 E0= 1.0 rmass=2 bx0= 5.0 c=15.0 run==6915
1
0.5
0
-0.5
-1
200
400
600
800
1000
1200
1400
1600
1800
2000

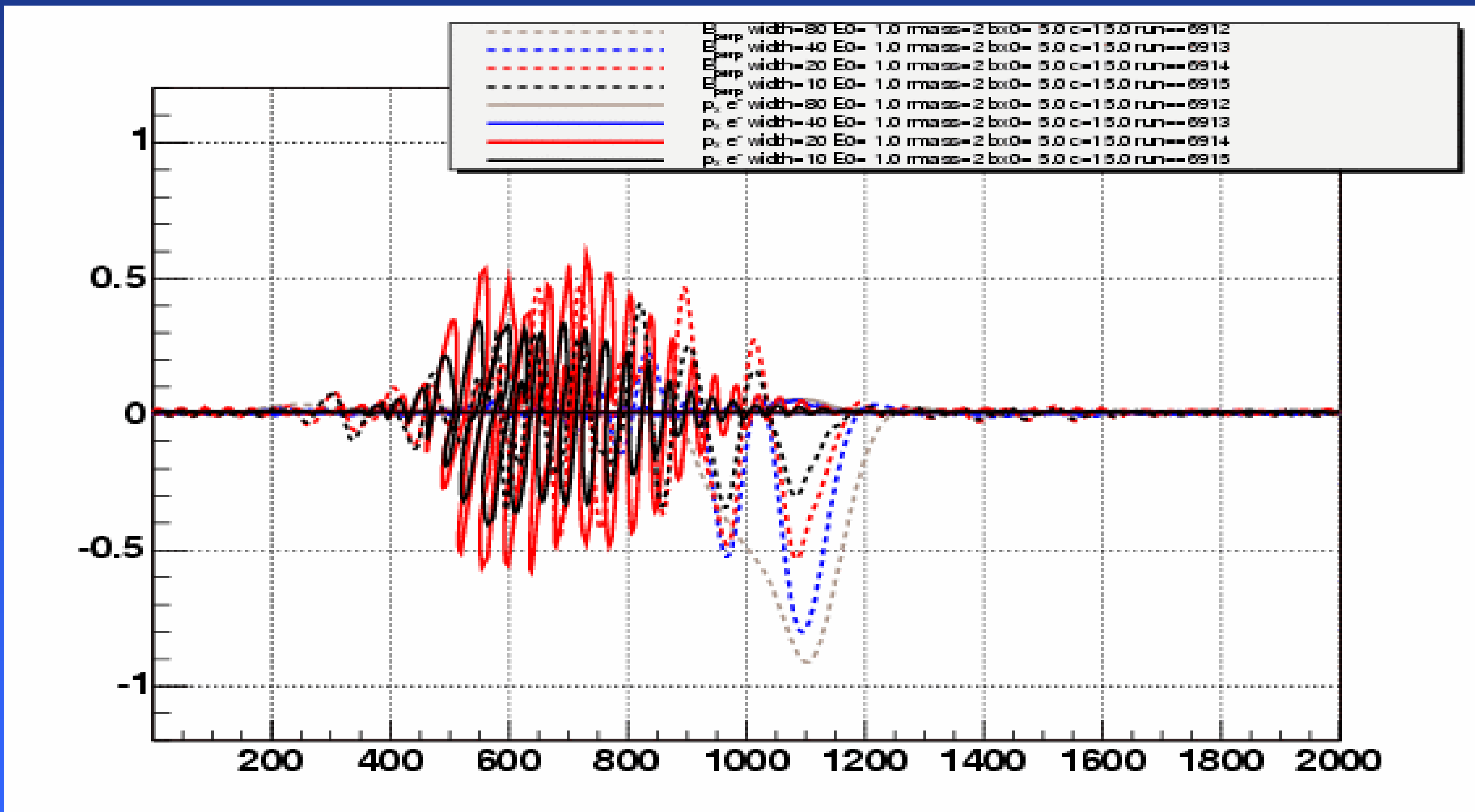
$R_{mass}=2\ T=25\ \omega_p^{-1}$



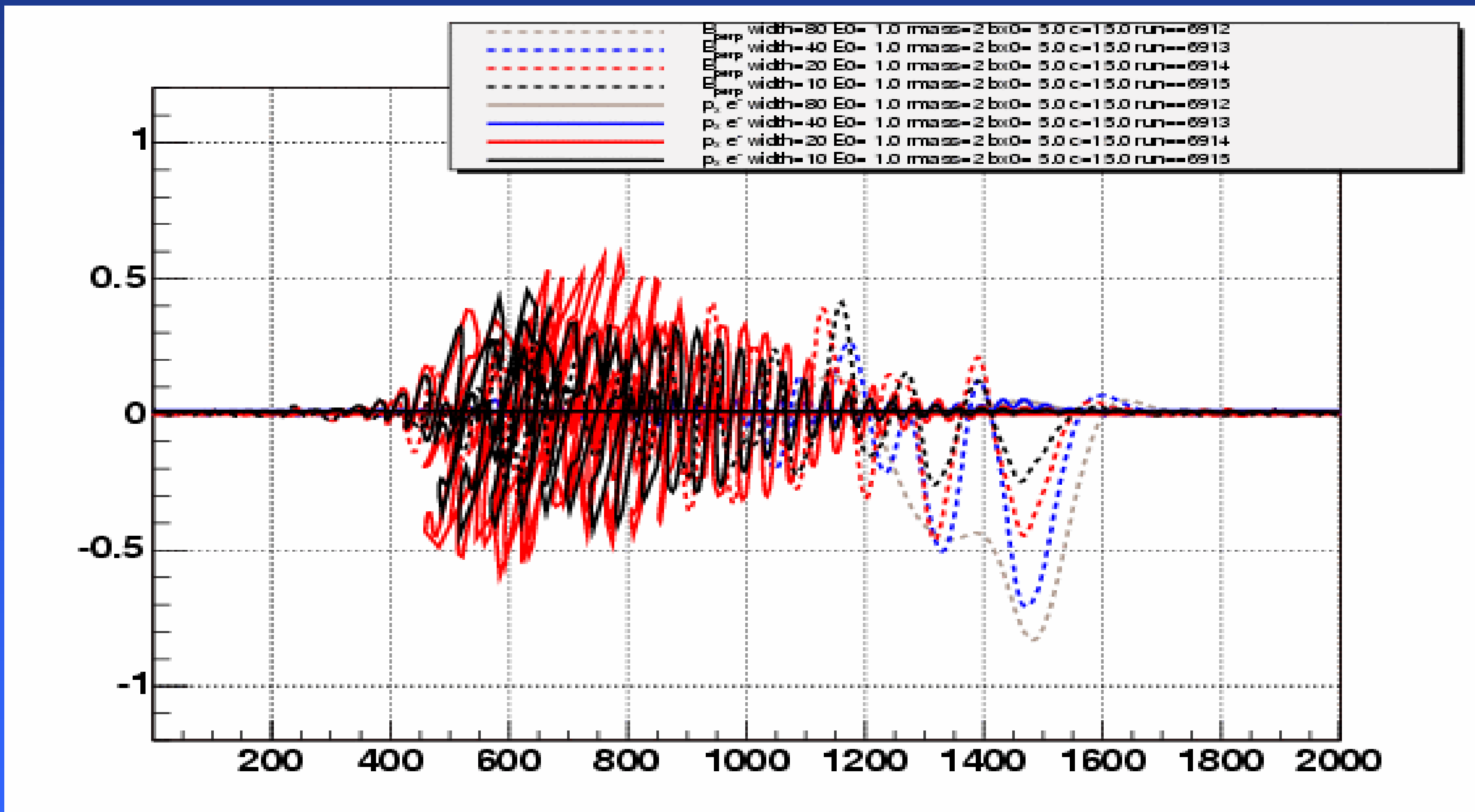
R_{mass}=2 T=150 ω_p^{-1}



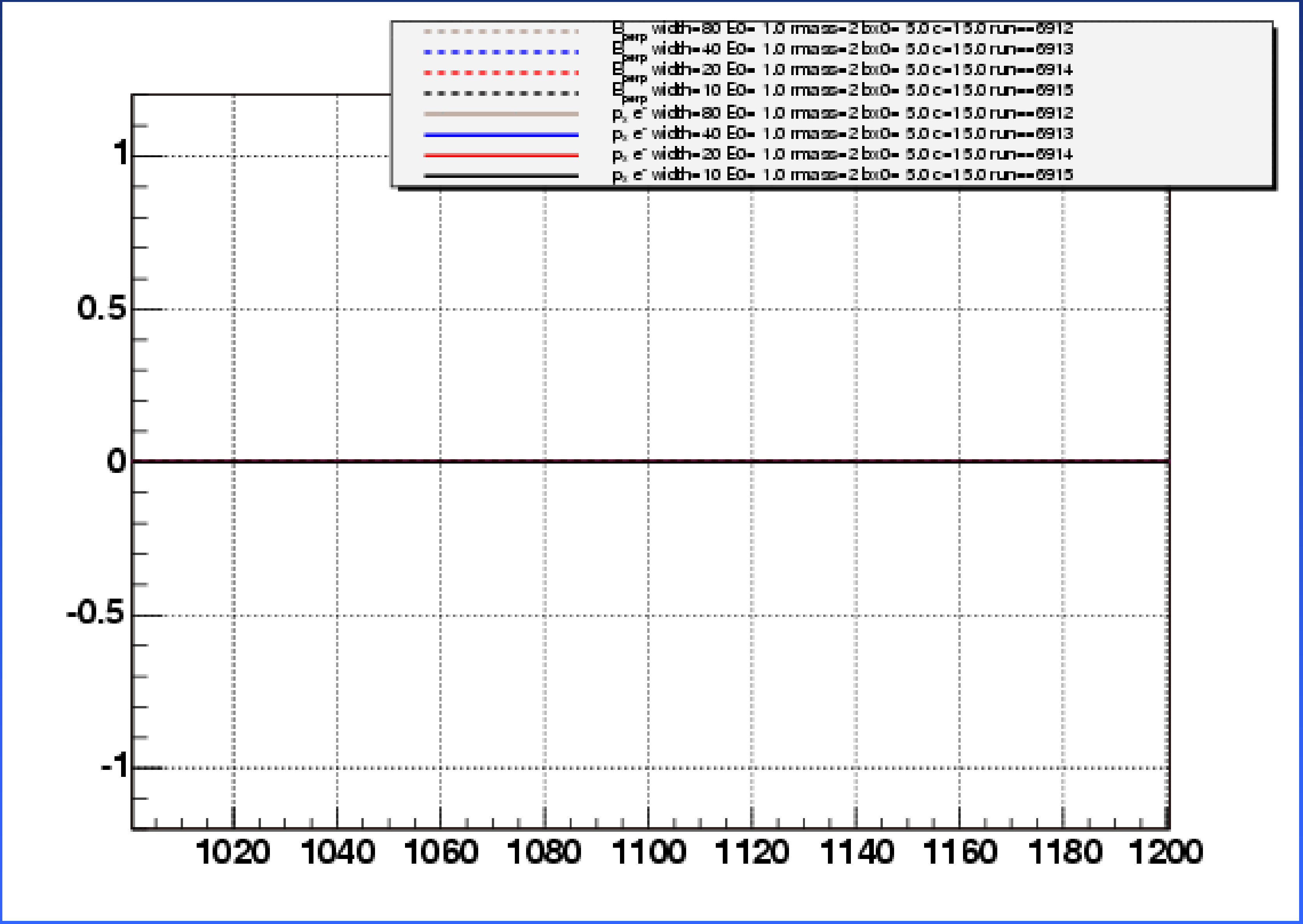
R_{mass}=2 T=275 ω_p^{-1}



R_{mass}=2 T=400 ω_p^{-1}

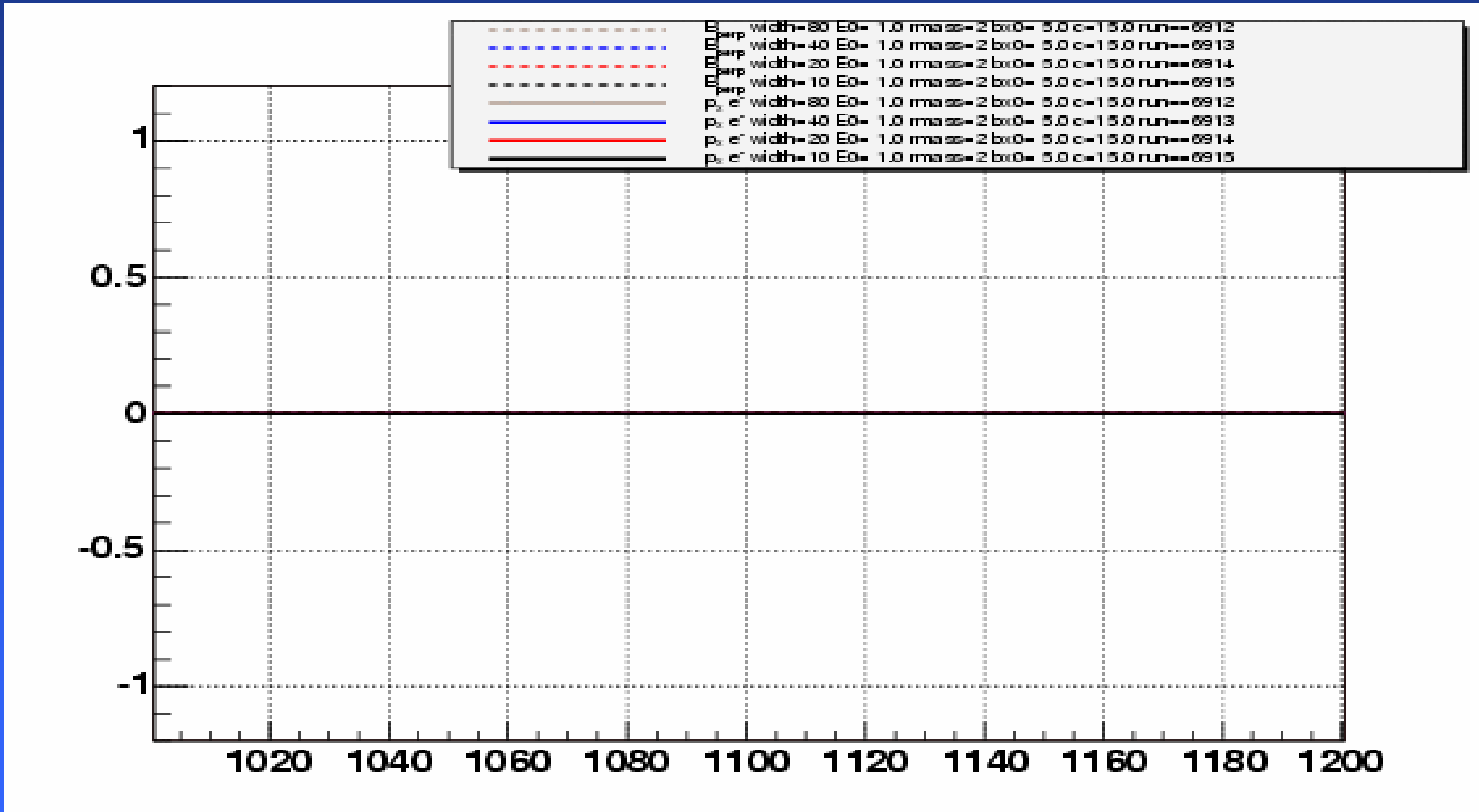


$R_{mass} = 2$

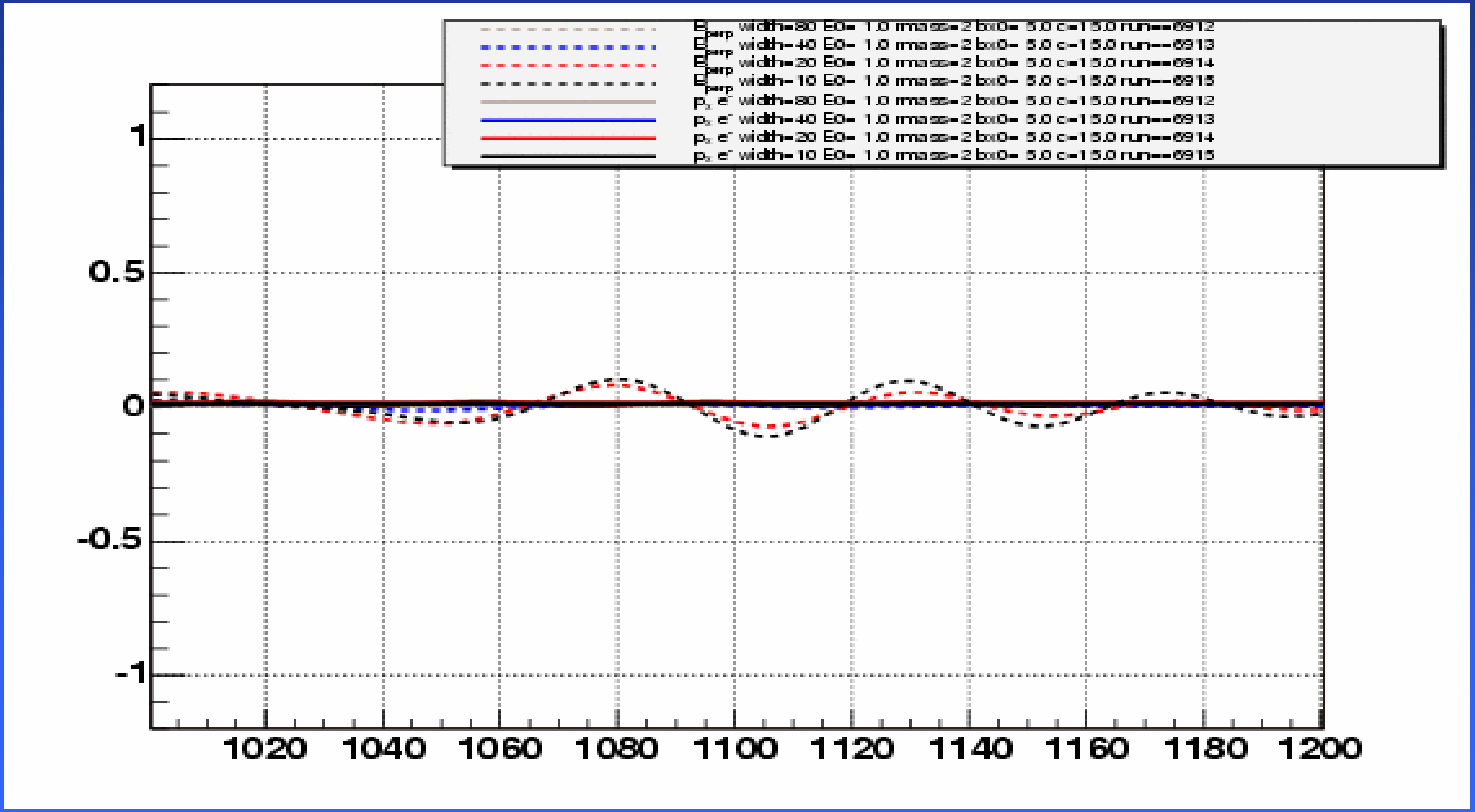


E_perp width=80 E0= 1.0 mass=2 bx0= 5.0 c=15.0 run==6912
E_perp width=40 E0= 1.0 mass=2 bx0= 5.0 c=15.0 run==6913
E_perp width=20 E0= 1.0 mass=2 bx0= 5.0 c=15.0 run==6914
E_perp width=10 E0= 1.0 mass=2 bx0= 5.0 c=15.0 run==6915
p_x e⁻ width=80 E0= 1.0 mass=2 bx0= 5.0 c=15.0 run==6912
p_x e⁻ width=40 E0= 1.0 mass=2 bx0= 5.0 c=15.0 run==6913
p_x e⁻ width=20 E0= 1.0 mass=2 bx0= 5.0 c=15.0 run==6914
p_x e⁻ width=10 E0= 1.0 mass=2 bx0= 5.0 c=15.0 run==6915
1
0.5
0
-0.5
-1
1020
1040
1060
1080
1100
1120
1140
1160
1180
1200

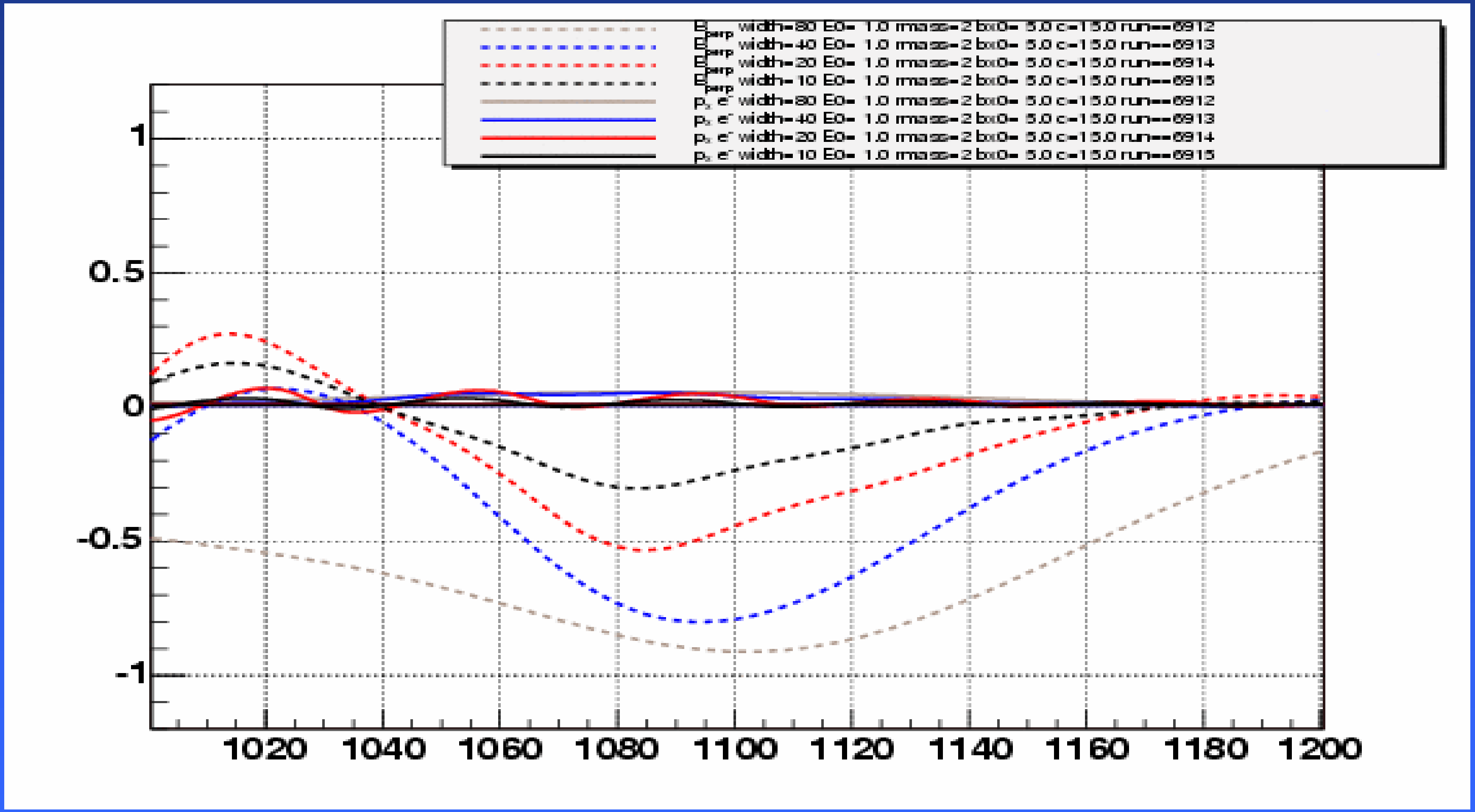
R_{mass}=2 T=25 ω_p^{-1} (Zoomed)



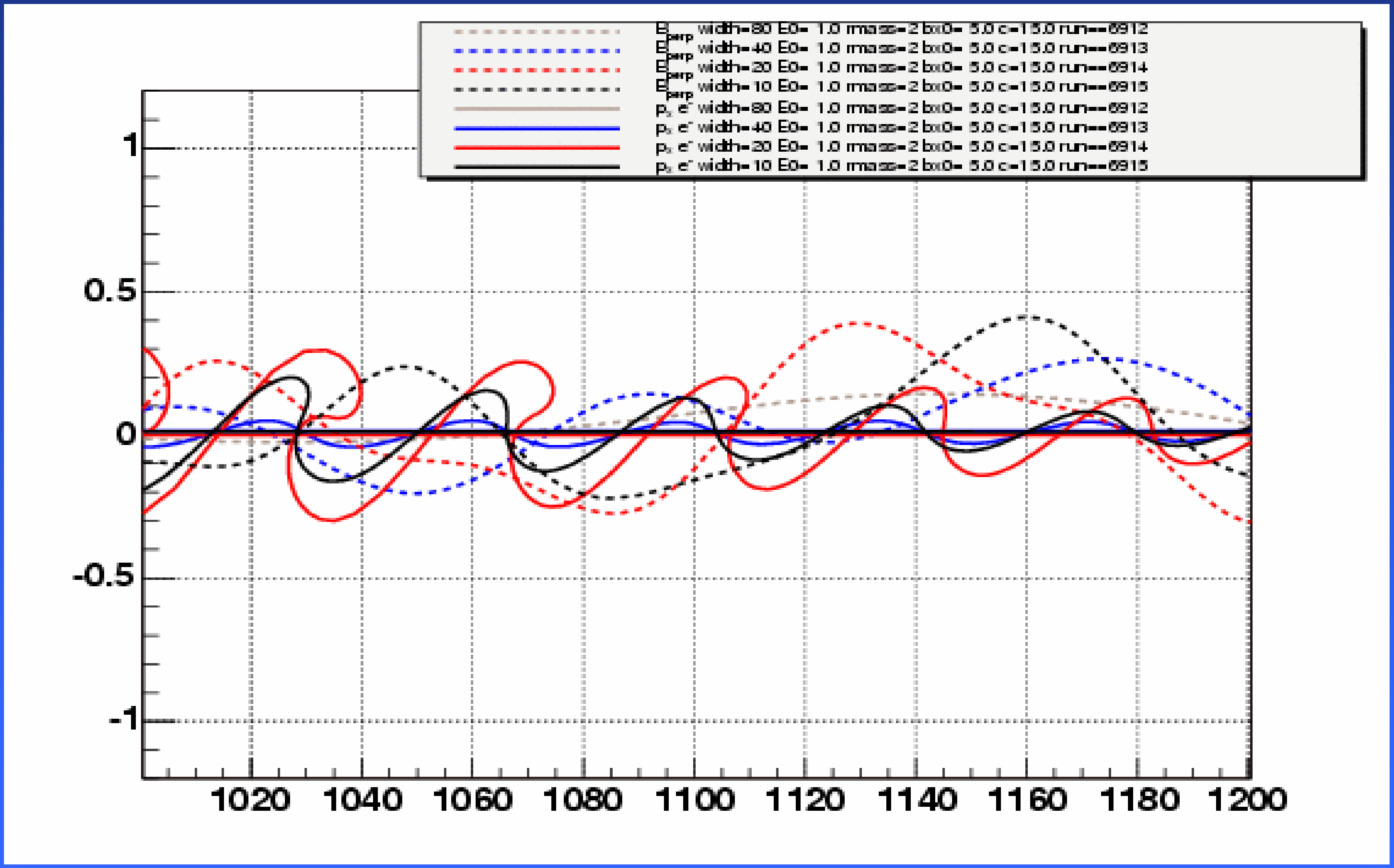
R_{mass}=2 T=150 ω_p^{-1} (Zoomed)



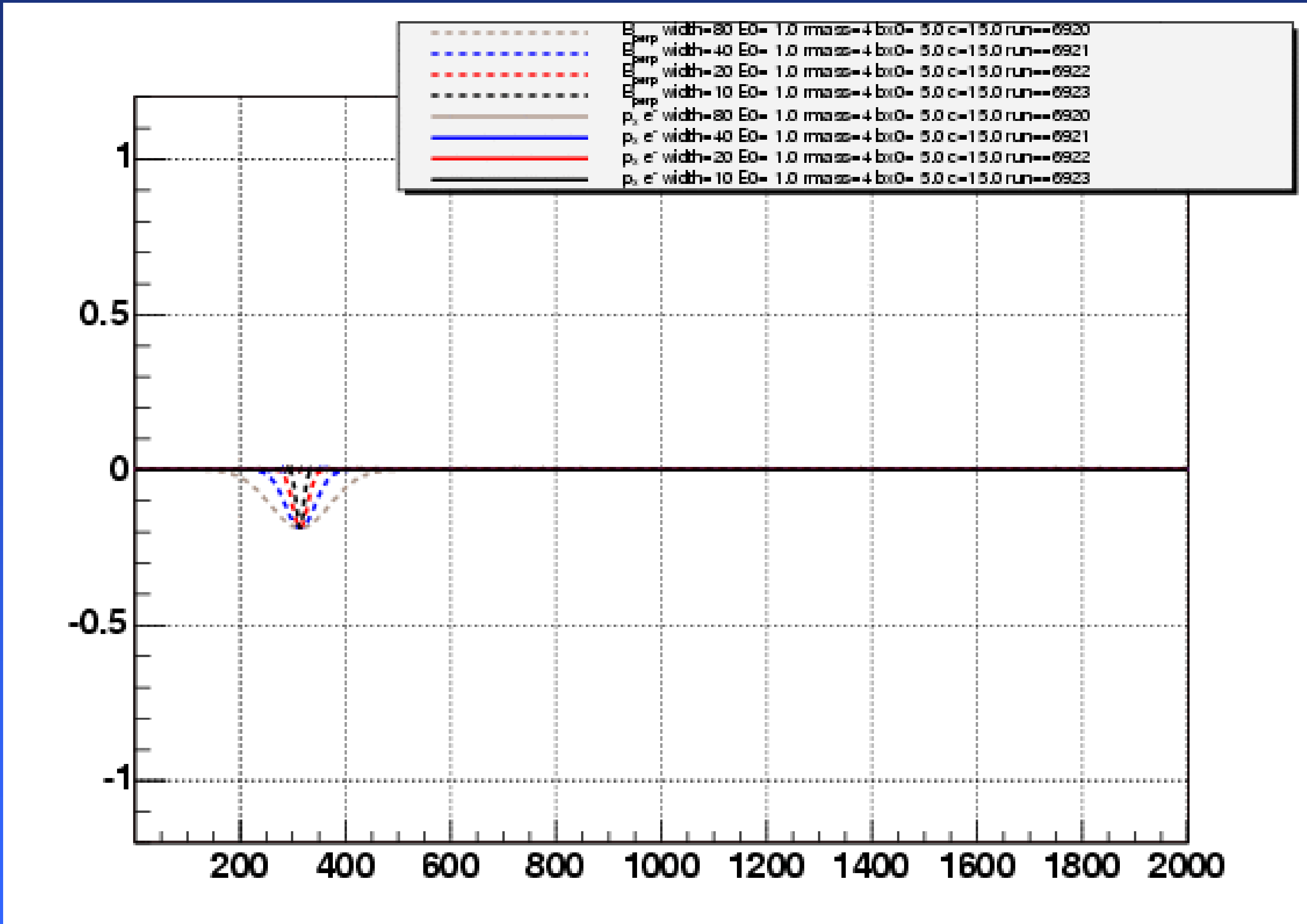
R_{mass}=2 T=275 ω_p^{-1} (Zoomed)



R_{mass}=2 T=400 ω_p^{-1} (Zoomed)

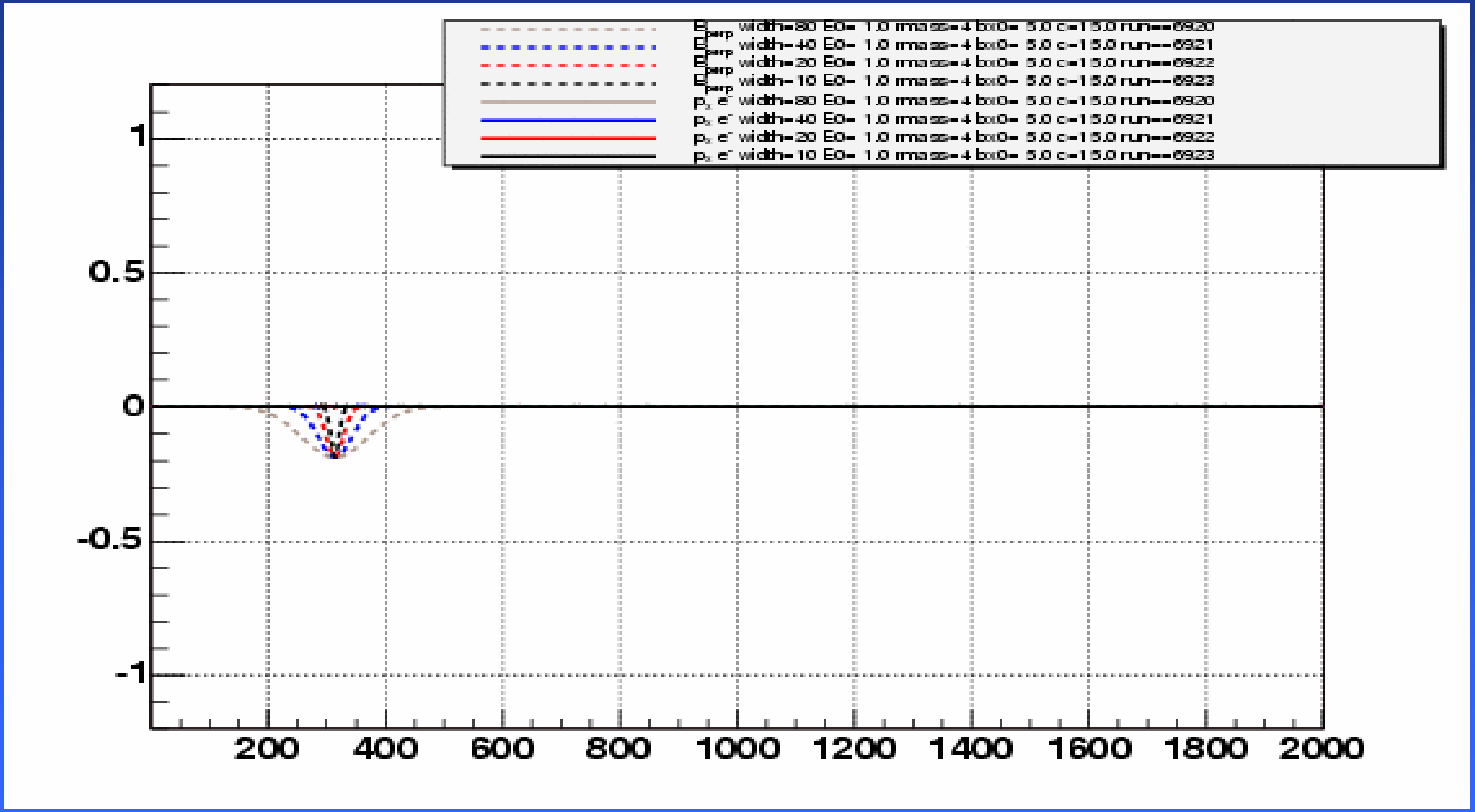


$R_{mass} = 4$

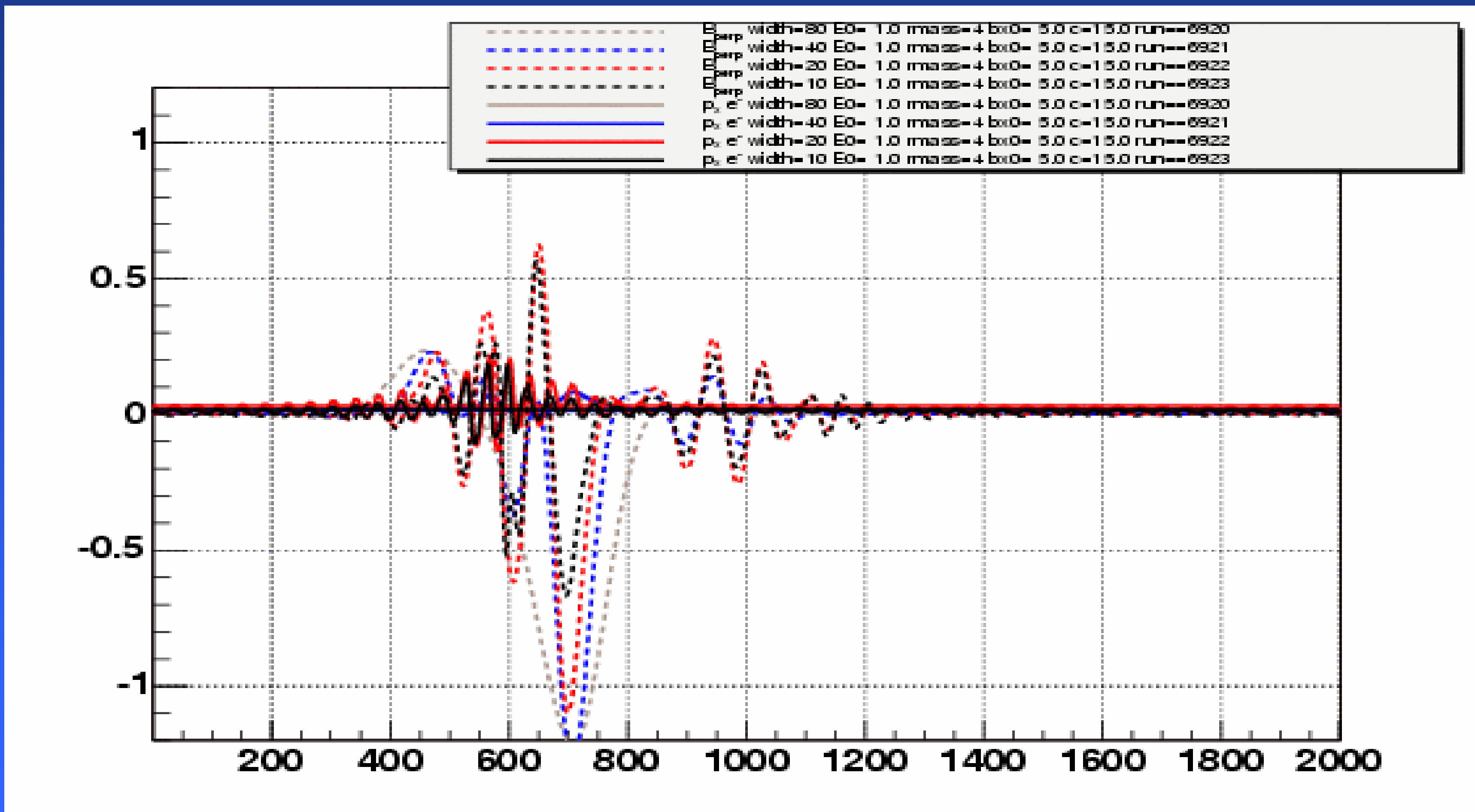


B_perp width=80 E0= 1.0 rmass=4 bx0= 5.0 c=15.0 run==6920
B_perp width=40 E0= 1.0 rmass=4 bx0= 5.0 c=15.0 run==6921
B_perp width=20 E0= 1.0 rmass=4 bx0= 5.0 c=15.0 run==6922
B_perp width=10 E0= 1.0 rmass=4 bx0= 5.0 c=15.0 run==6923
p_z e⁻ width=80 E0= 1.0 rmass=4 bx0= 5.0 c=15.0 run==6920
p_z e⁻ width=40 E0= 1.0 rmass=4 bx0= 5.0 c=15.0 run==6921
p_z e⁻ width=20 E0= 1.0 rmass=4 bx0= 5.0 c=15.0 run==6922
p_z e⁻ width=10 E0= 1.0 rmass=4 bx0= 5.0 c=15.0 run==6923
1
0.5
0
-0.5
-1
200
400
600
800
1000
1200
1400
1600
1800
2000

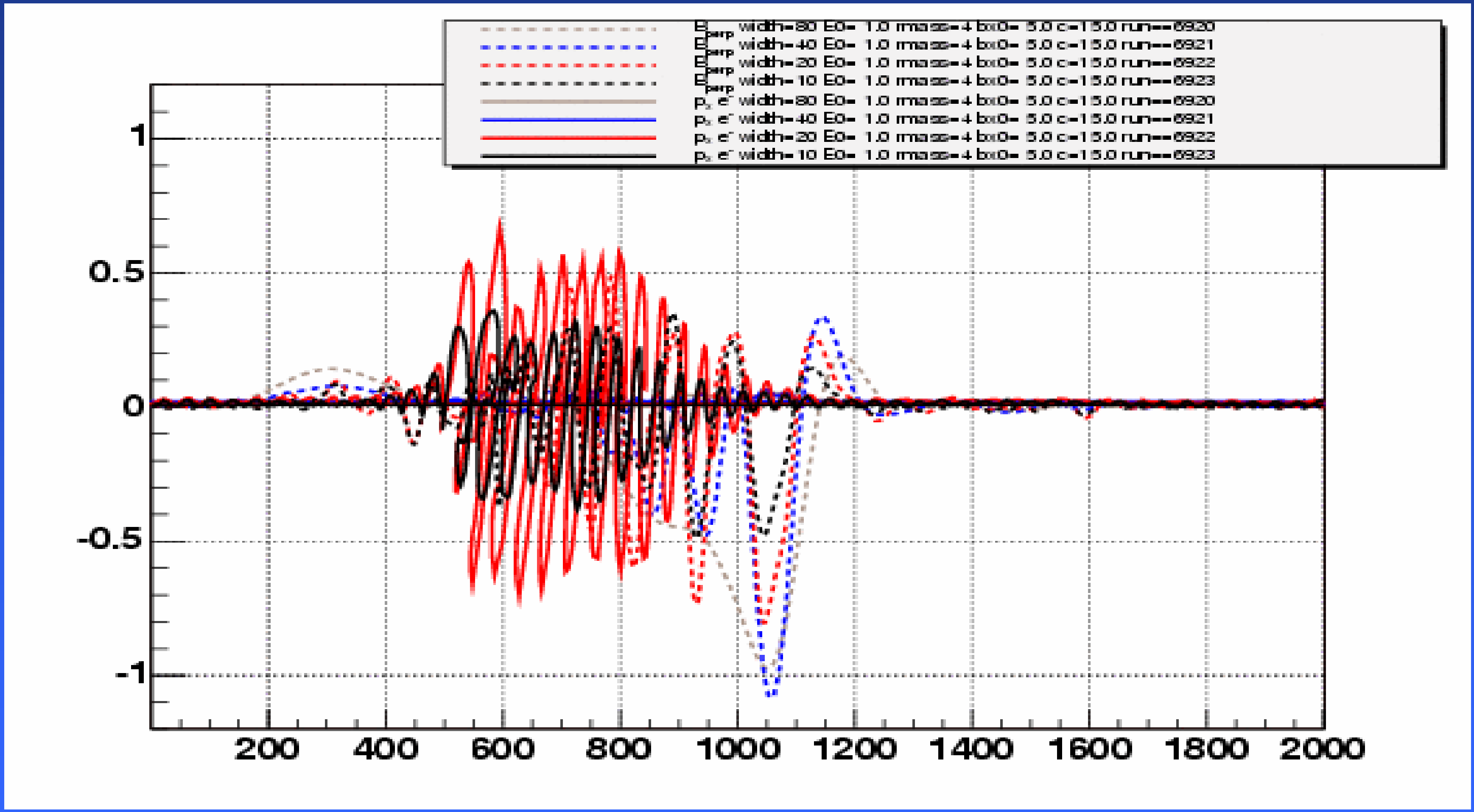
$R_{mass}=4$ $T=25\ \omega_p^{-1}$



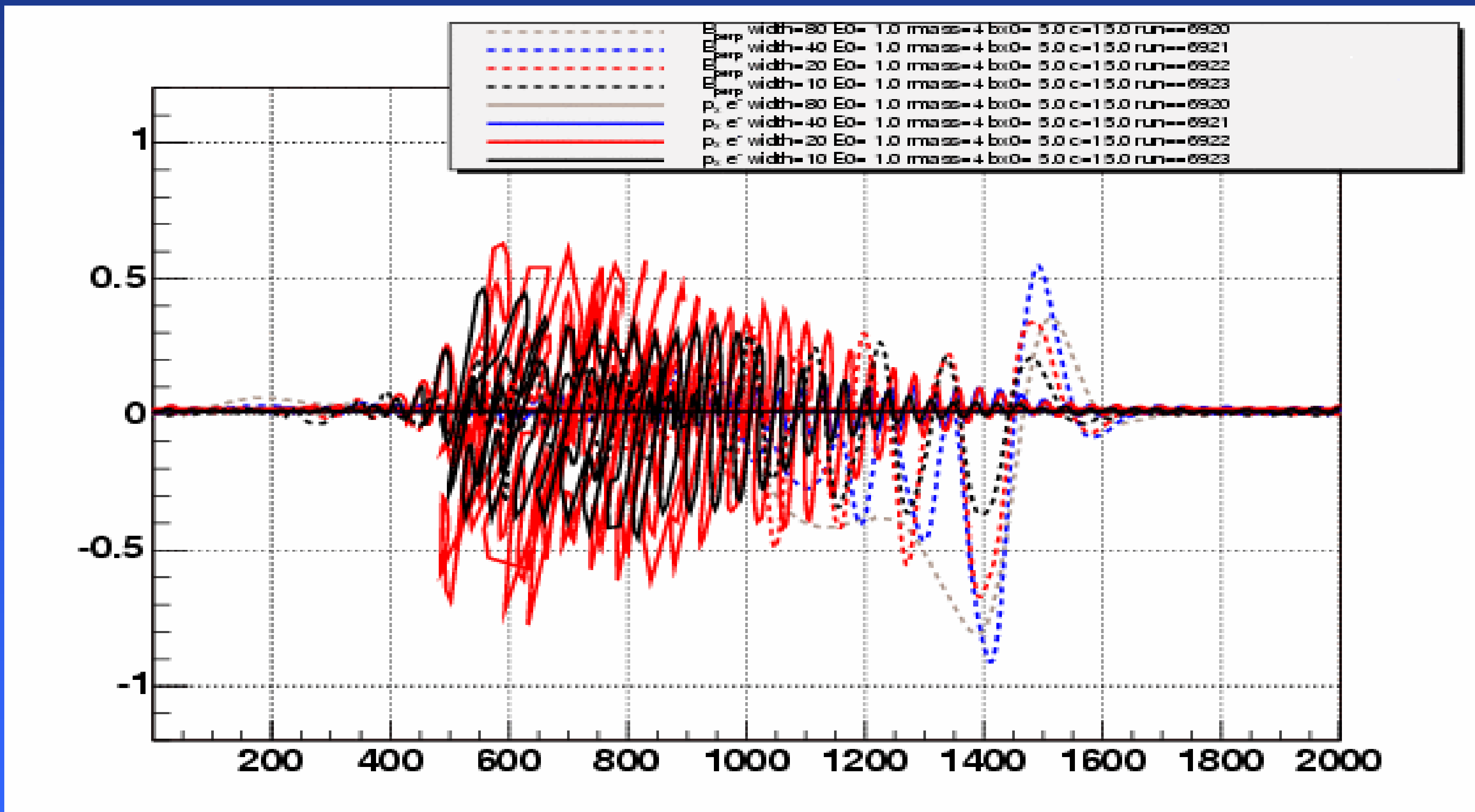
R_{mass}=4 T=150 ω_p^{-1}



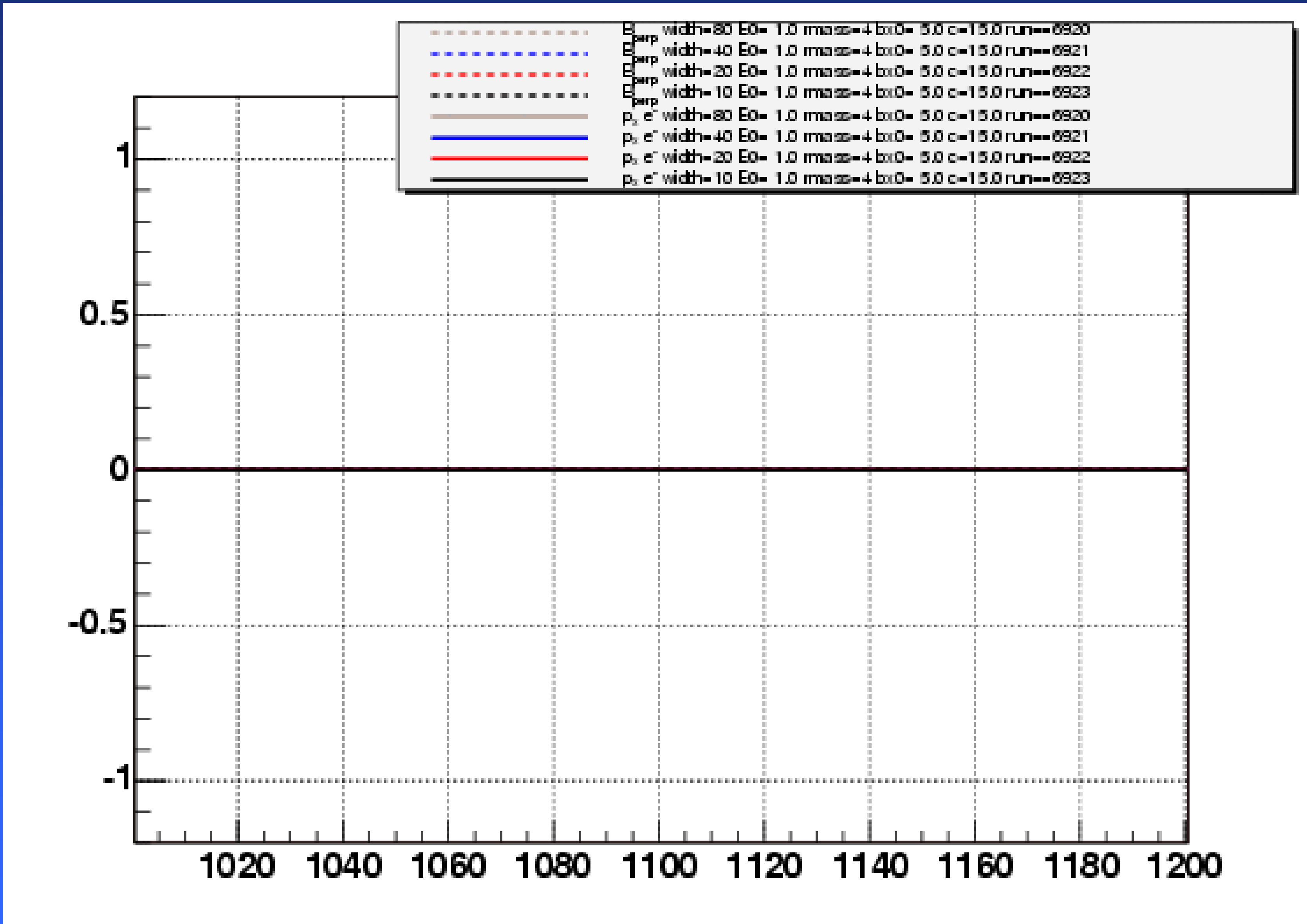
R_{mass}=4 T=275 ω_p^{-1}



R_{mass}=4 T=400 ω_p^{-1}

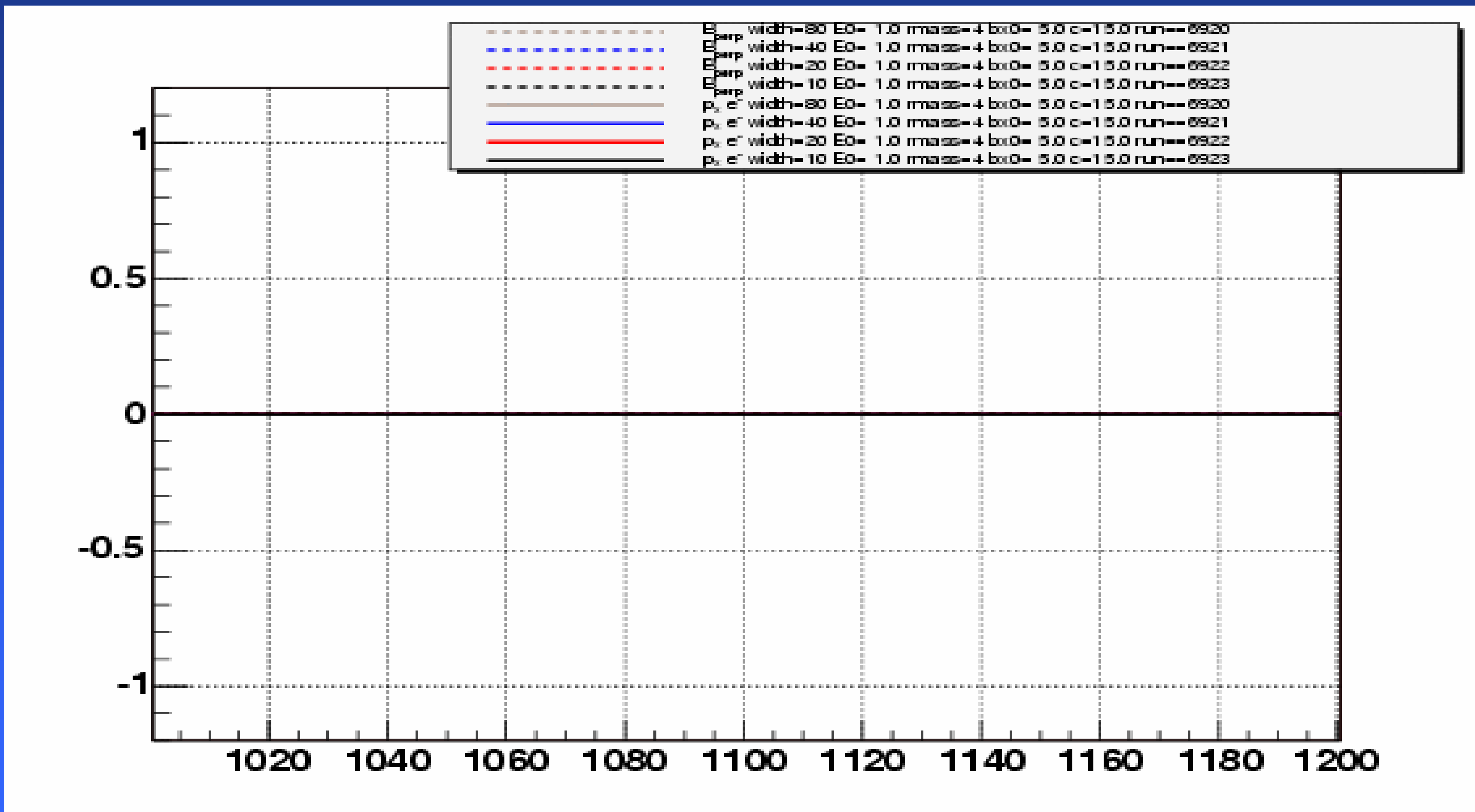


$R_{mass} = 4$

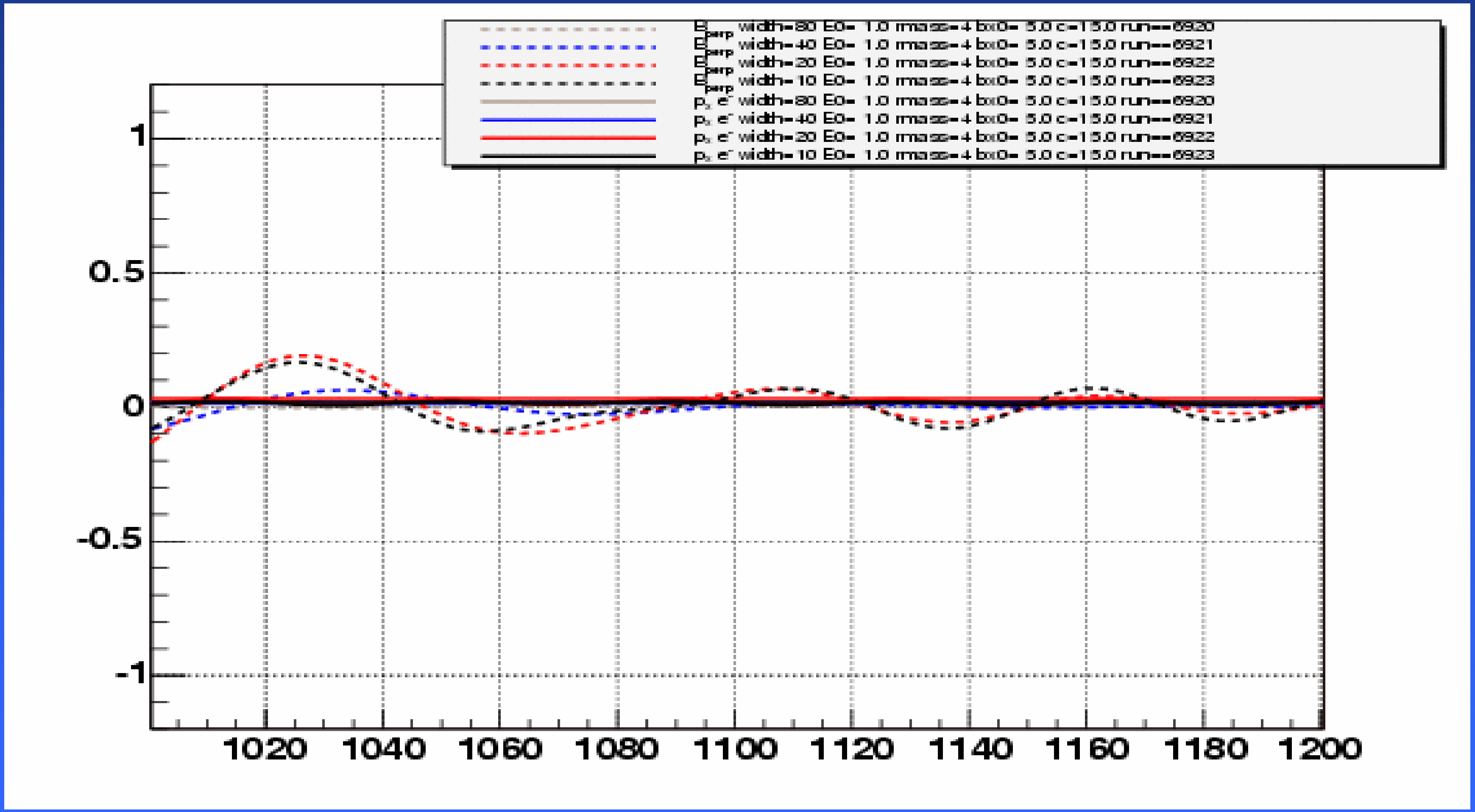


B_perp width=80 E0= 1.0 mass=4 bx0= 5.0 c=15.0 run==6920
B_perp width=40 E0= 1.0 mass=4 bx0= 5.0 c=15.0 run==6921
B_perp width=20 E0= 1.0 mass=4 bx0= 5.0 c=15.0 run==6922
B_perp width=10 E0= 1.0 mass=4 bx0= 5.0 c=15.0 run==6923
p_x e⁻ width=80 E0= 1.0 mass=4 bx0= 5.0 c=15.0 run==6920
p_x e⁻ width=40 E0= 1.0 mass=4 bx0= 5.0 c=15.0 run==6921
p_x e⁻ width=20 E0= 1.0 mass=4 bx0= 5.0 c=15.0 run==6922
p_x e⁻ width=10 E0= 1.0 mass=4 bx0= 5.0 c=15.0 run==6923
1
0.5
0
-0.5
-1
1020
1040
1060
1080
1100
1120
1140
1160
1180
1200

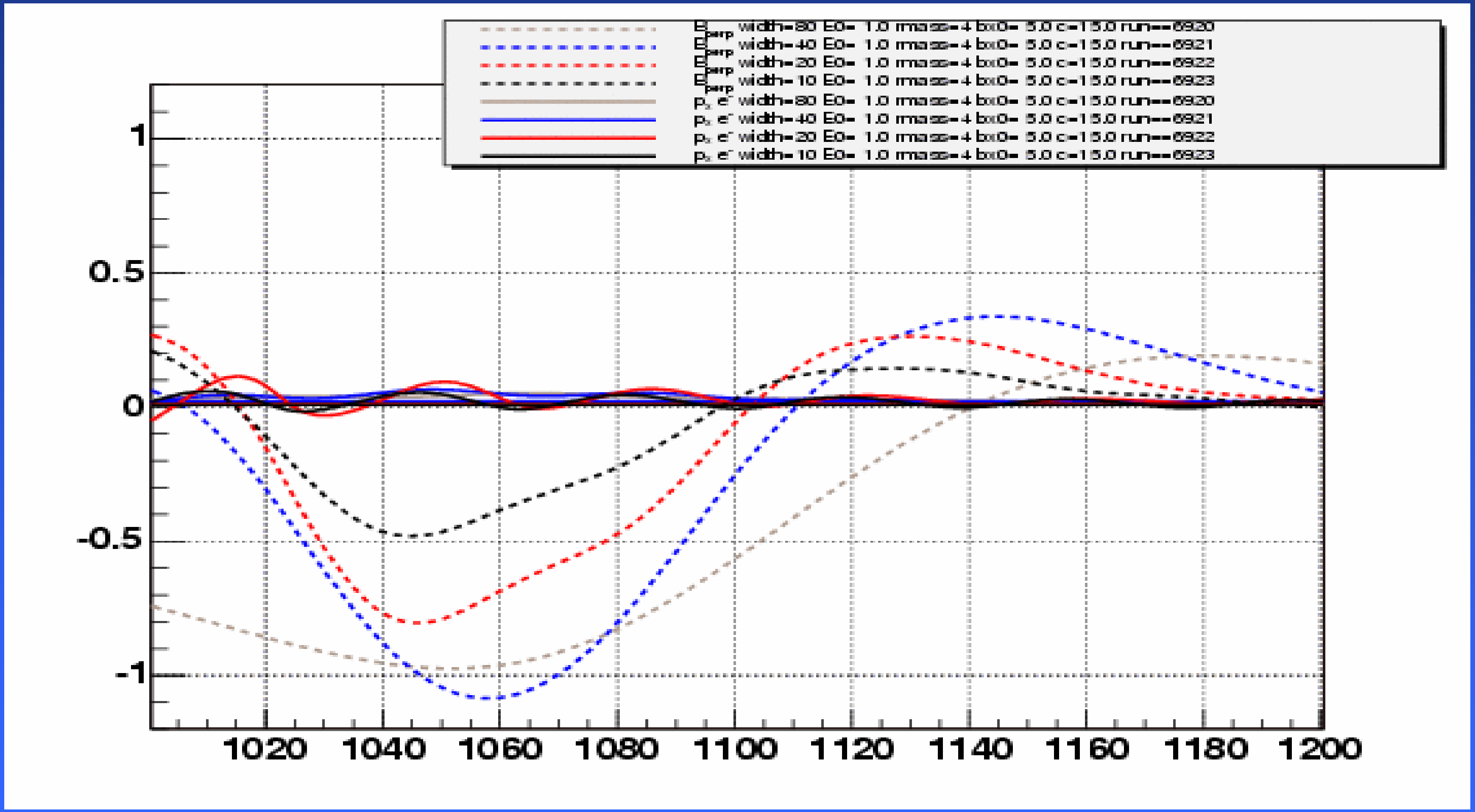
R_{mass}=4 T=25 ω_p^{-1} (Zoomed)



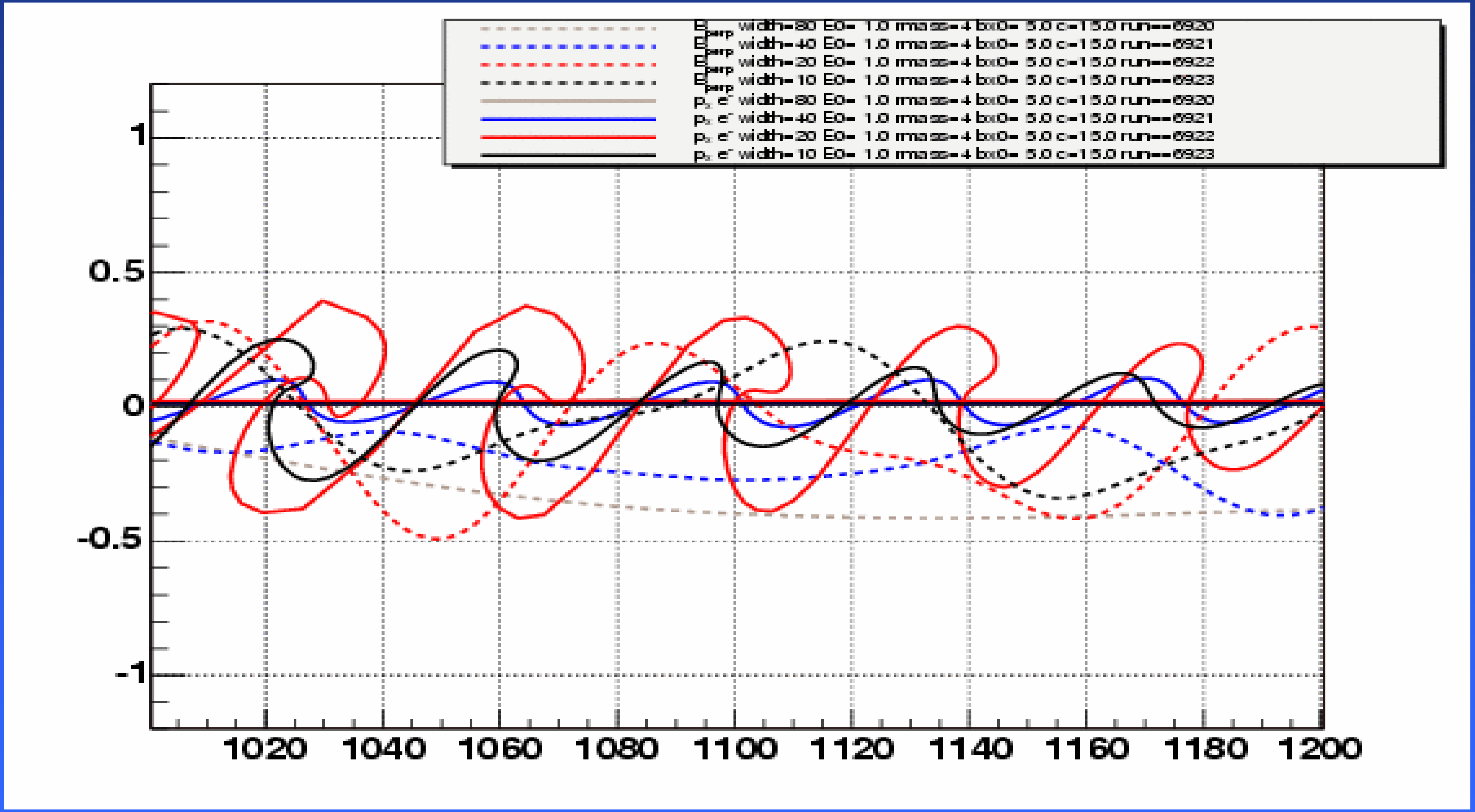
R_{mass}=4 T=150 ω_p^{-1} (Zoomed)



R_{mass}=4 T=275 ω_p^{-1} (Zoomed)

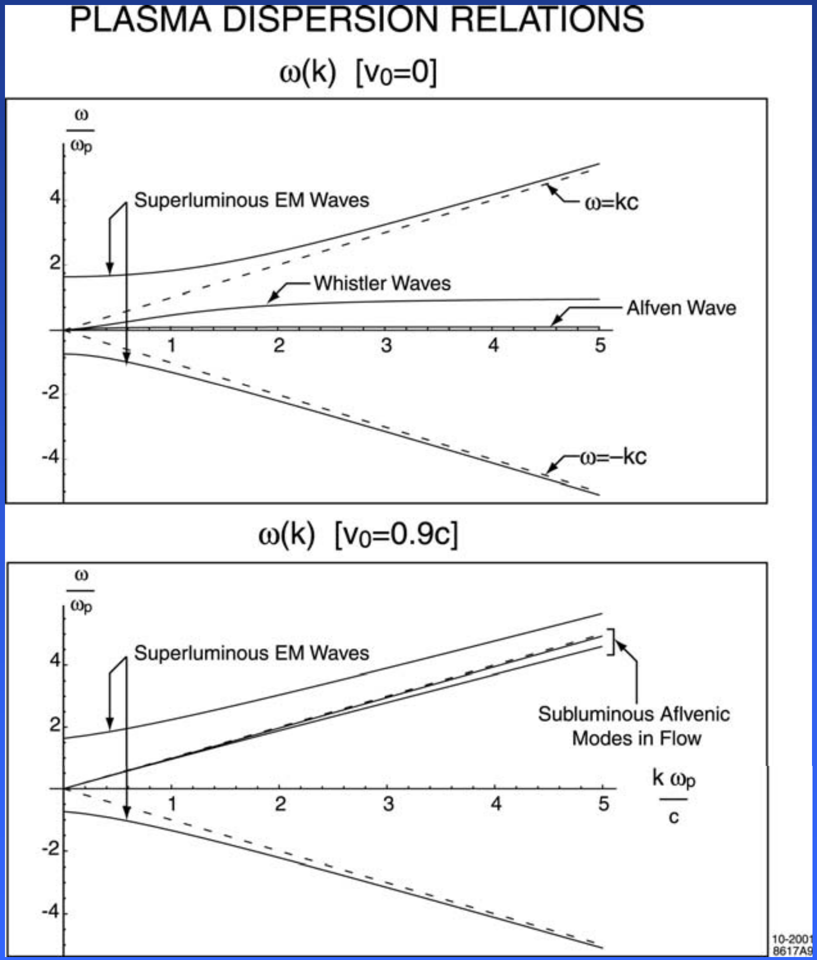


R_{mass}=4 T=400 ω_p^{-1} (Zoomed)

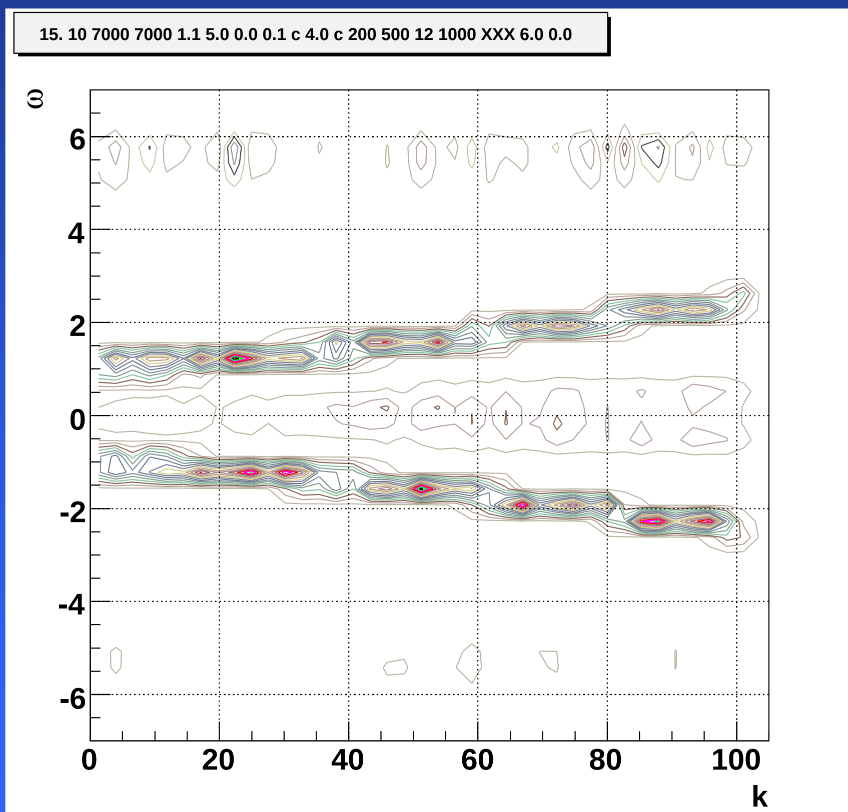


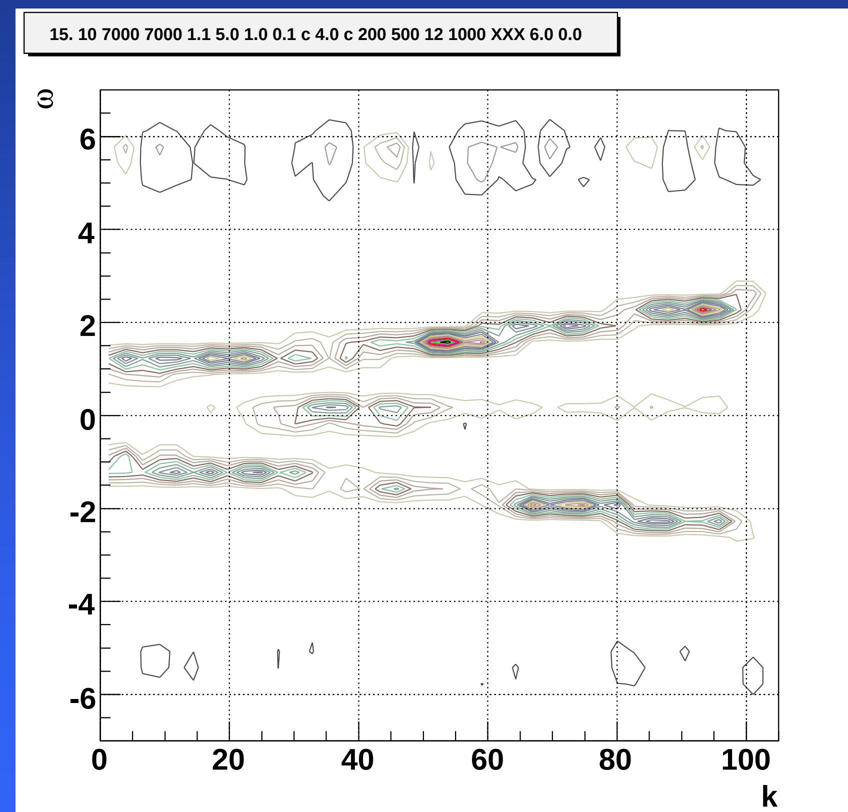
Dispersion Relation

- Study dispersion relation to ensure what we are observing is Alfven branch:
- Excitation increases sharply with shorter pulse width (higher frequency).
- May be Whistler as opposed to Alfven branch.
- Work in progress….

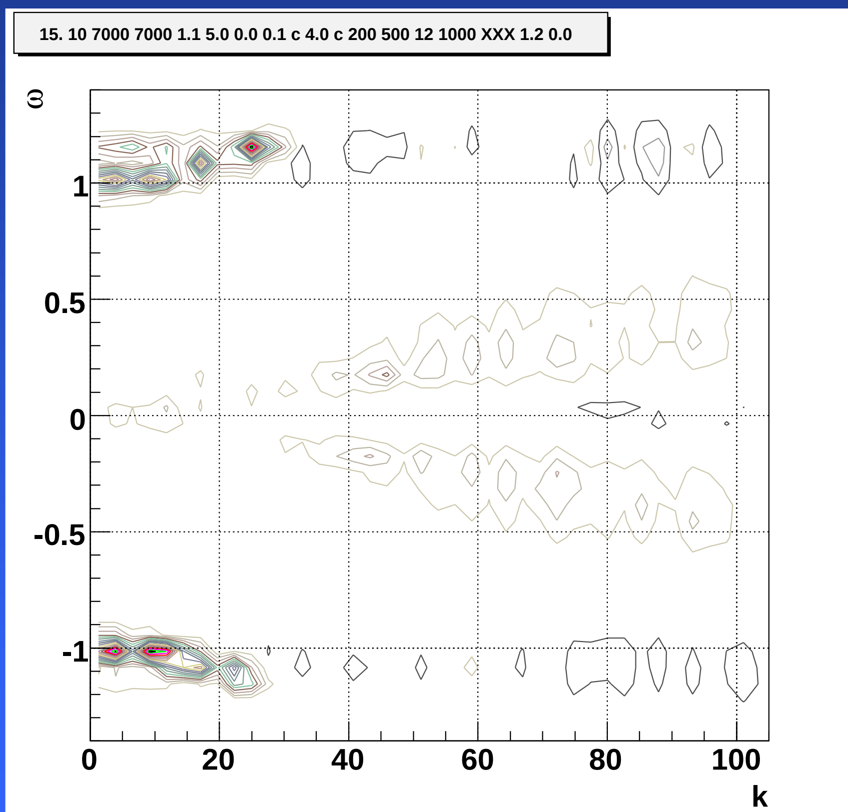


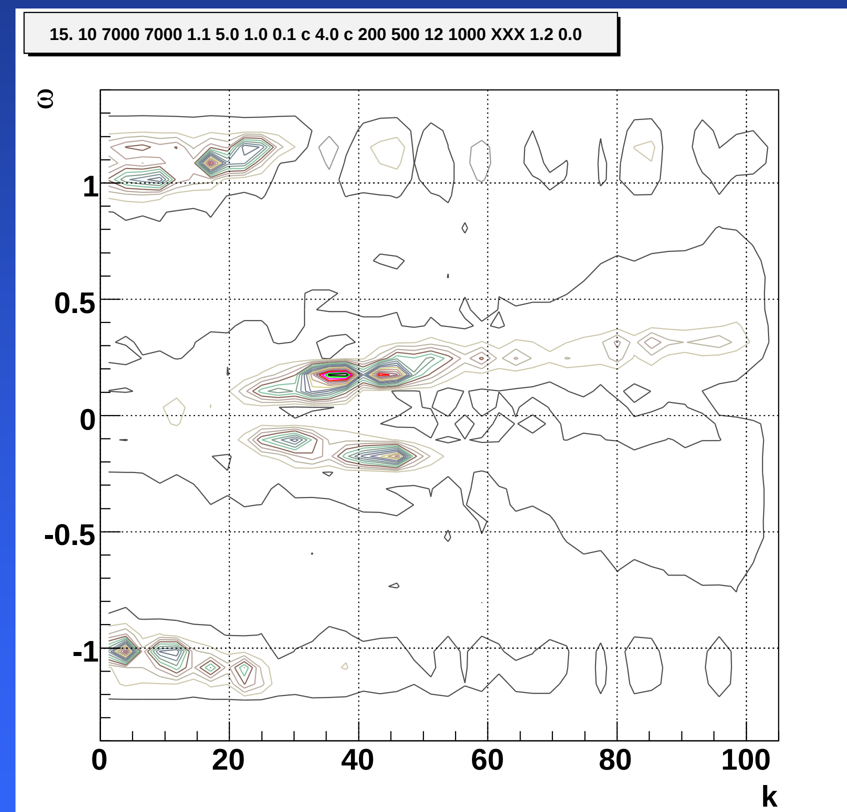
Dispersion Relation



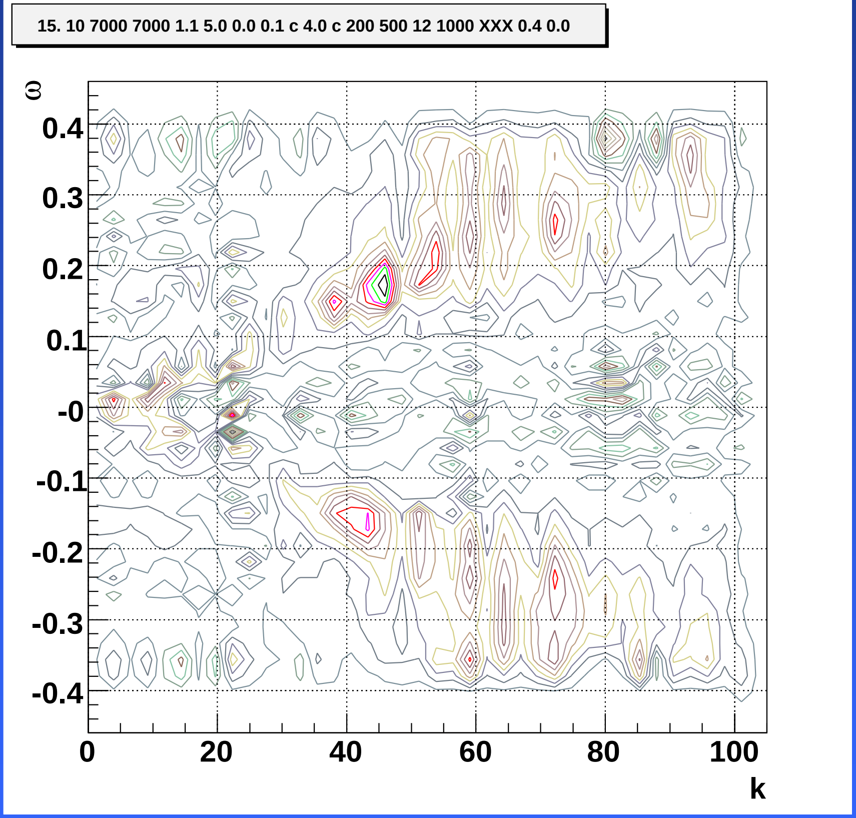


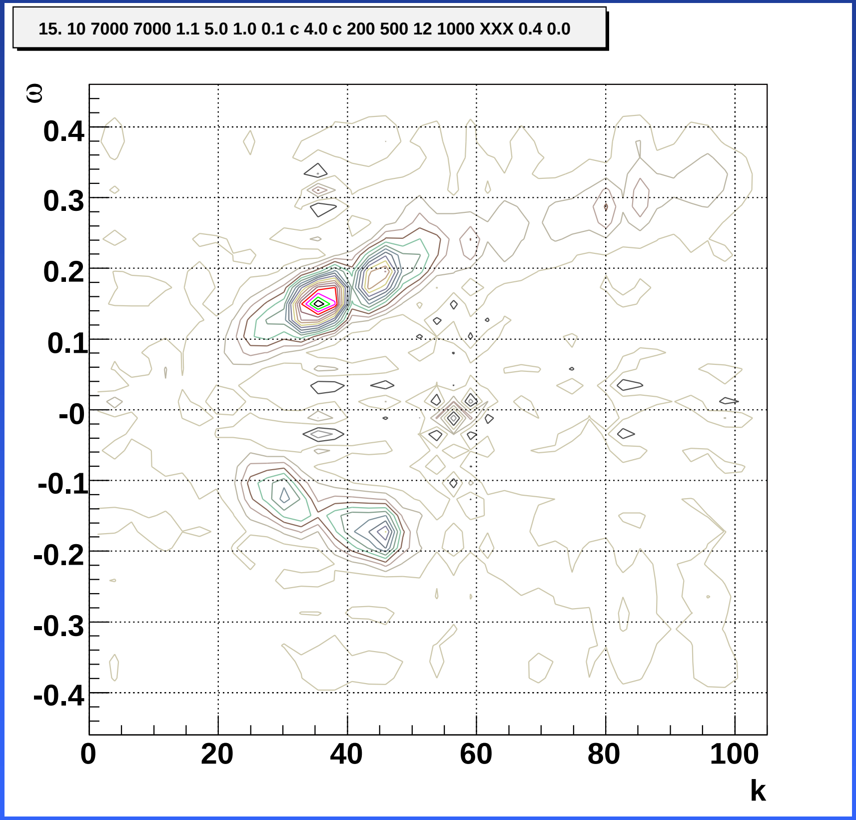
Dispersion Relation





Dispersion Relation





Summary

- Plasma wakefields induced by Alfven shocks can in principle efficiently accelerate UHECR particles.
- Preliminary simulation results support the existence of this mechanism, but more investigation needed.
- In addition to GRB, there exist abundant astrophysical sources that carry relativistic plasma outflows/jets.
- Other electromagnetic sources, for example GRB prompt signals, filamentation of e^+e^- jets, intense neutrino outburst, etc., can also excite plasma wakefields.