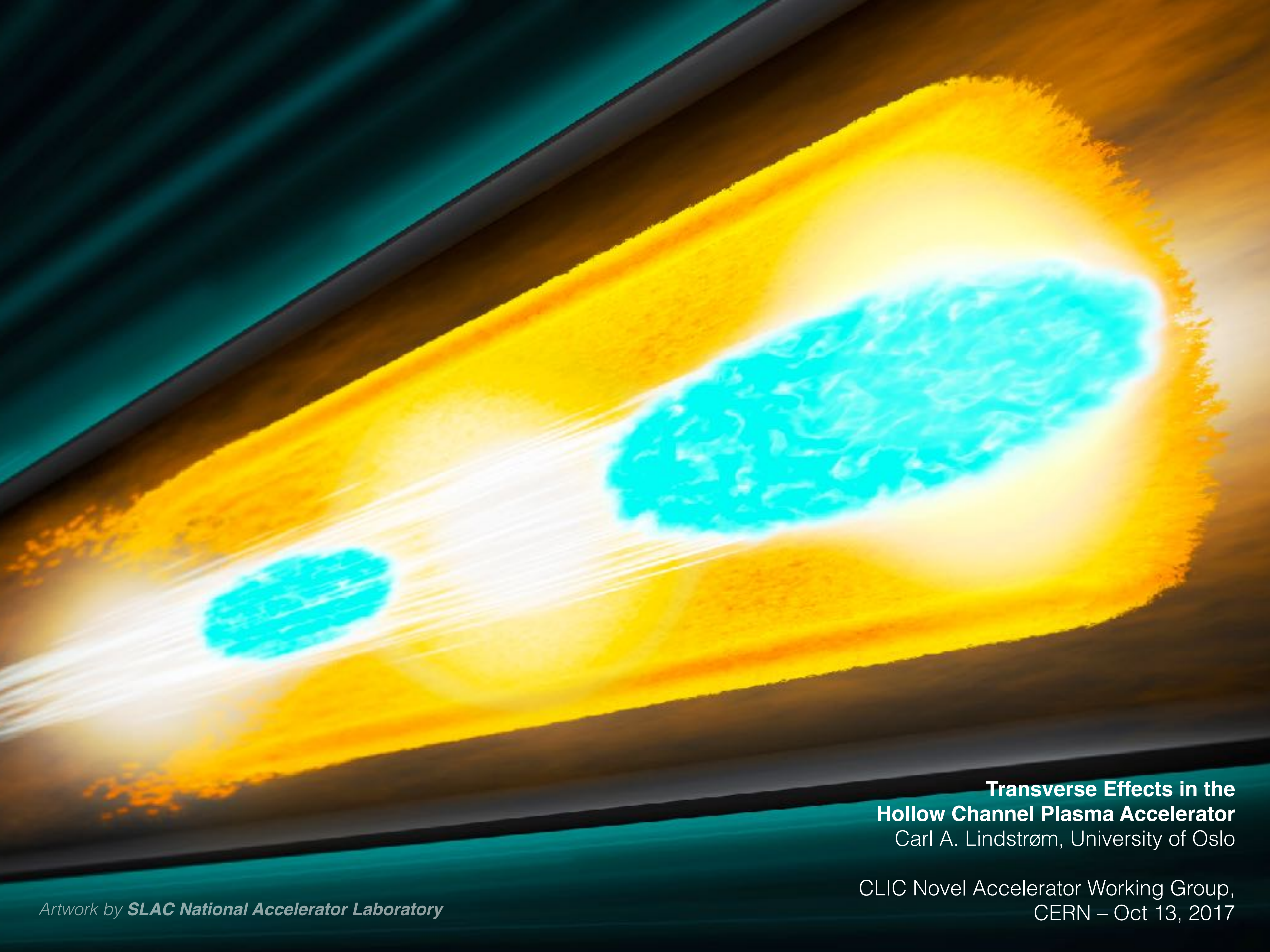

Transverse Effects in the Hollow Channel Plasma Accelerator

Carl A. Lindstrøm, University of Oslo

CLIC Novel Accelerator Working Group,
CERN – Oct 13, 2017

Artwork by ***SLAC National Accelerator Laboratory***

Transverse Effects in the Hollow Channel Plasma Accelerator

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Why use a hollow channel?

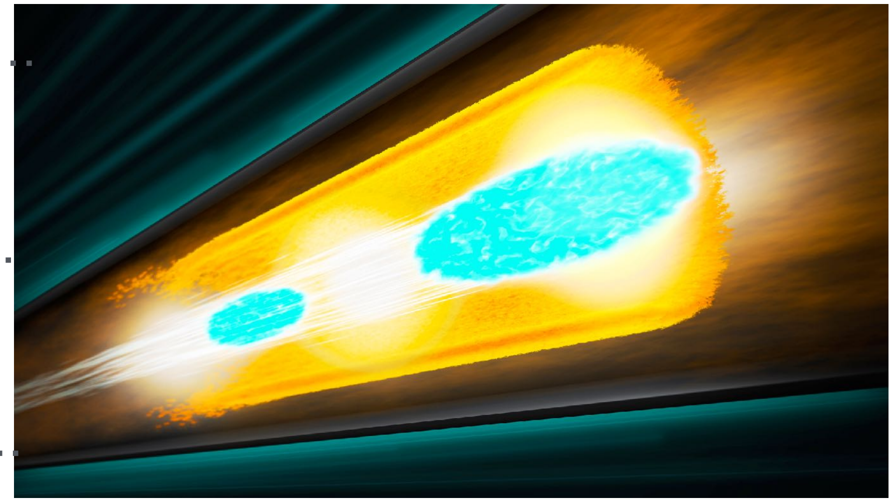
- Bigger picture:
  - If you want an **electron-positron collider**, you need **positron acceleration** (!)
  - You therefore need to charge-symmetrize your technology
    (or make another different, but equally good technology)

- Main reasons for using a hollow plasma channel are

charge symmetry
(works also positrons)

no focusing fields
(no tight beam matching)

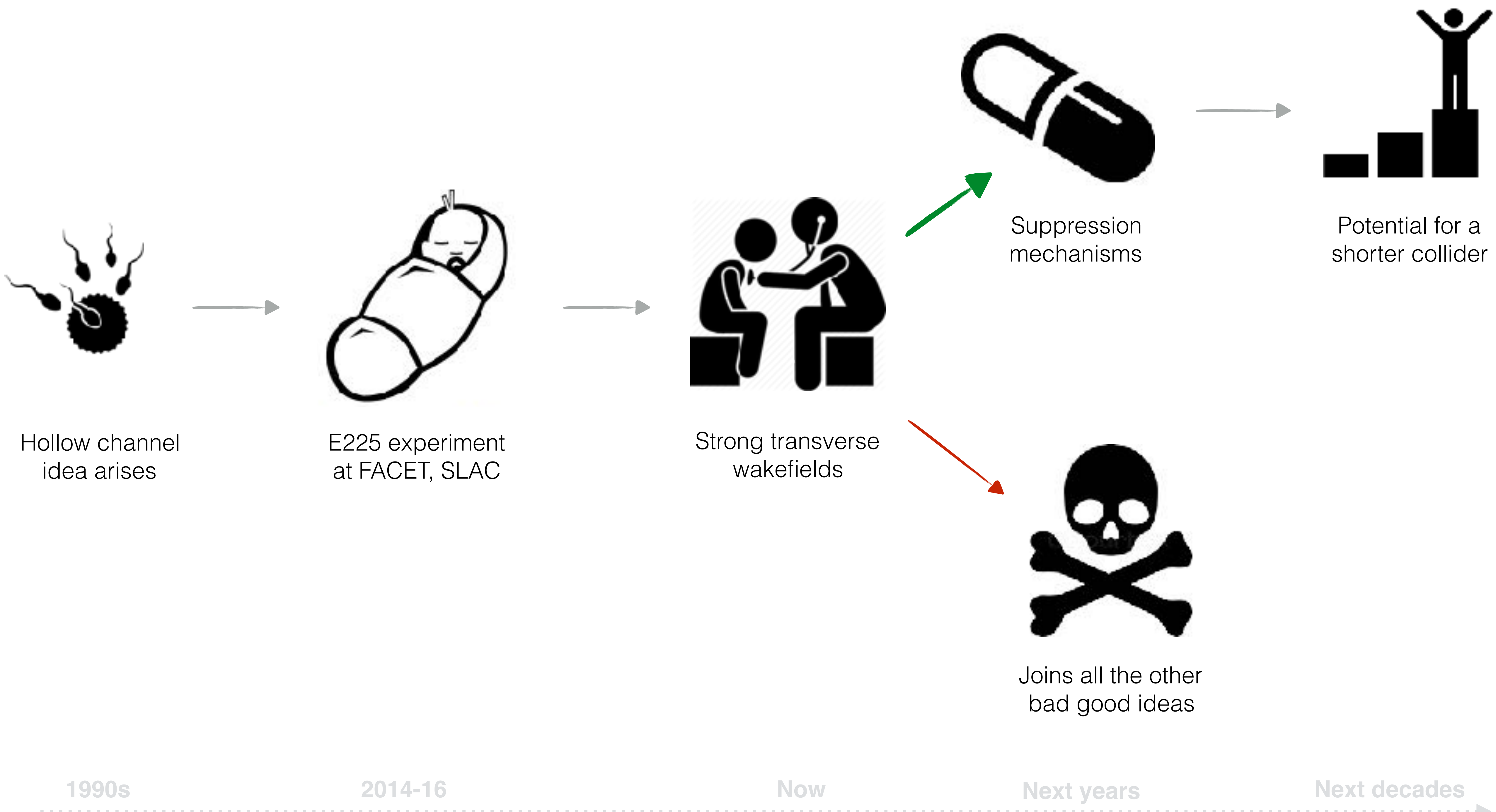
no structure failure
(new channel every time)



- **However**, we soon discover that unless you are perfectly aligned, there is a **strong transverse wakefield**.

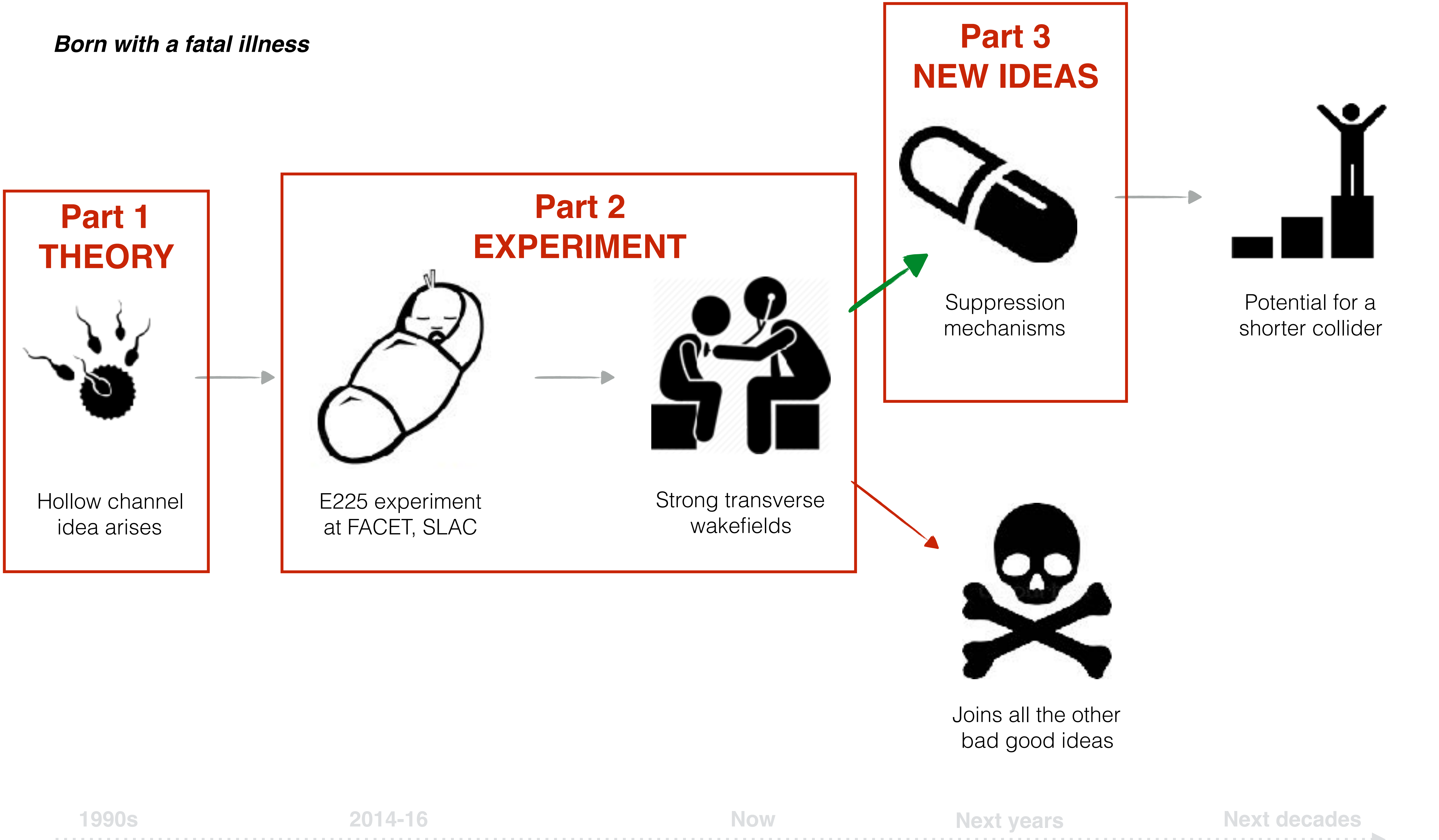
A useful analogy

Born with a fatal illness



A useful analogy

Born with a fatal illness



PART 1:
Conception

Hollow plasma channel
transverse wakefield theory

Linear model

- Assume:
  – plasma electrons are not moving (just slightly perturbed)
  – that the plasma behaves as a dielectric medium

- The most significant longitudinal wakefield (for acceleration):

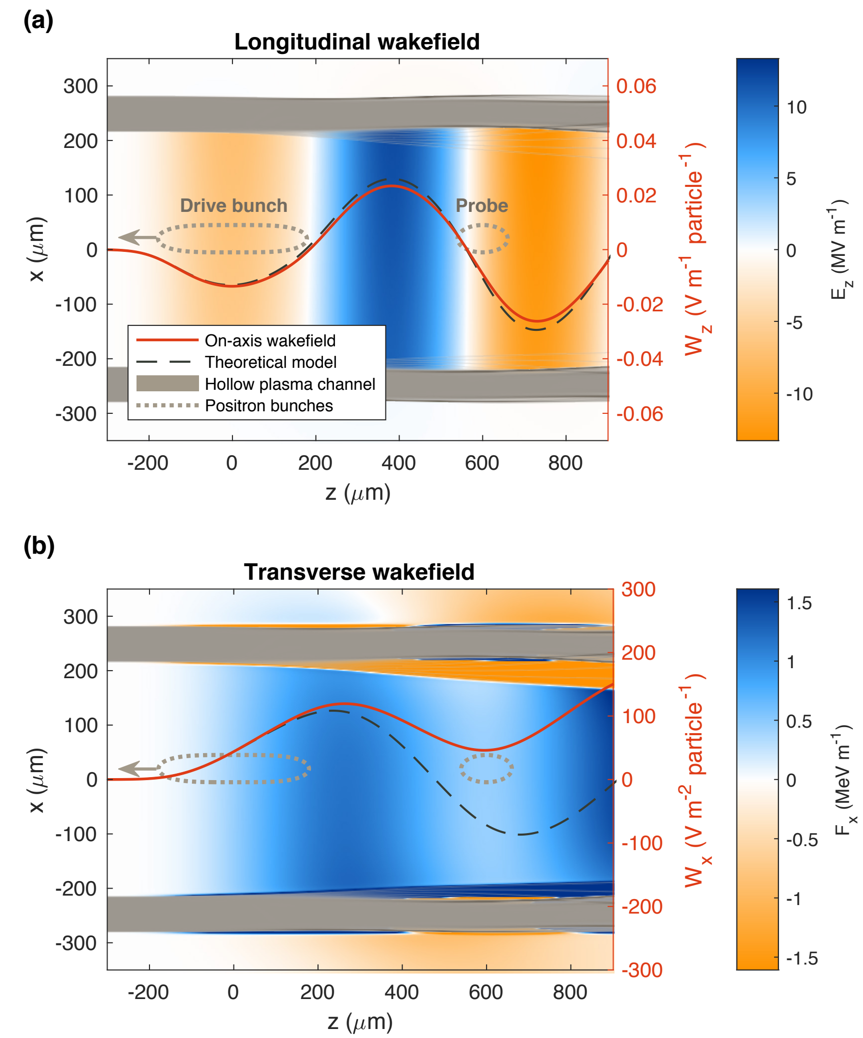
$$W_{z0}(z) = \frac{e k_p \chi_\parallel^2}{2\pi\epsilon_0 a} \frac{B_{00}(a,b)}{B_{10}(a,b)} \cos(\chi_\parallel k_p z)\Theta(z)$$

- The most significant transverse wakefield is a dipole mode:

$$W_{x1}(z) = -\frac{e \Delta x \chi_\perp}{\pi\epsilon_0 a^3} \frac{B_{11}(a,b)}{B_{21}(a,b)} \sin(\chi_\perp k_p z)\Theta(z)$$

- When the response is non-linear, we turn to particle-in-cell (PIC) simulations.

QuickPIC simulation:



$$\chi_\parallel = \sqrt{\frac{2B_{10}(a,b)}{2B_{10}(a,b) - k_p a B_{00}(a,b)}}$$

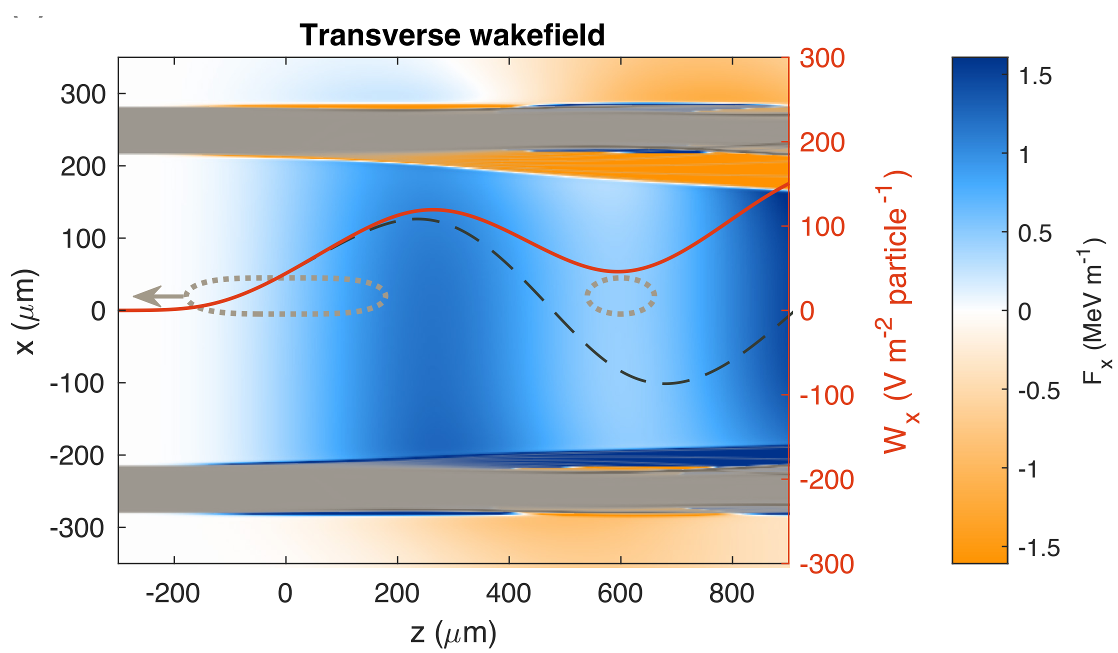
$$\chi_\perp = \sqrt{\frac{2B_{21}(a,b)}{4B_{21}(a,b) - k_p a B_{11}(a,b)}}$$

$$B_{ij}(a,b) = I_i(k_p a)K_j(k_p b) + (-1)^{i-j+1} I_j(k_p b)K_i(k_p a)$$

Comparing numbers to conventional wakefields

- Typical CLIC transverse wakefields per offset in structures:
  ~1-100 V/pC/m/mm

- Hollow channel (500 μm diameter at 3 x 10^{15} cm^{-3}):
  ~150 V/m^2/particle = ~1 000 000 V/pC/m/mm



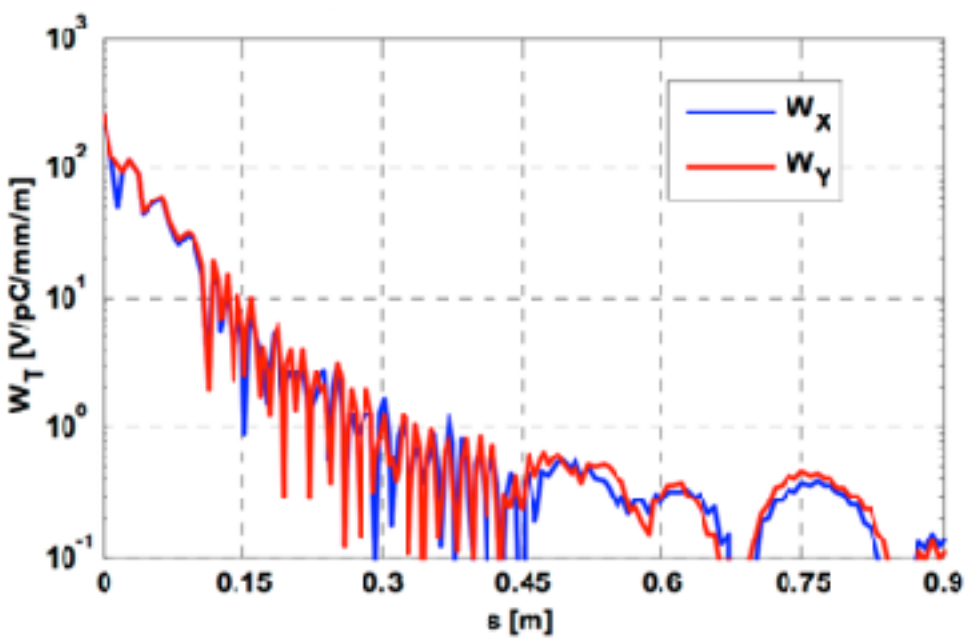


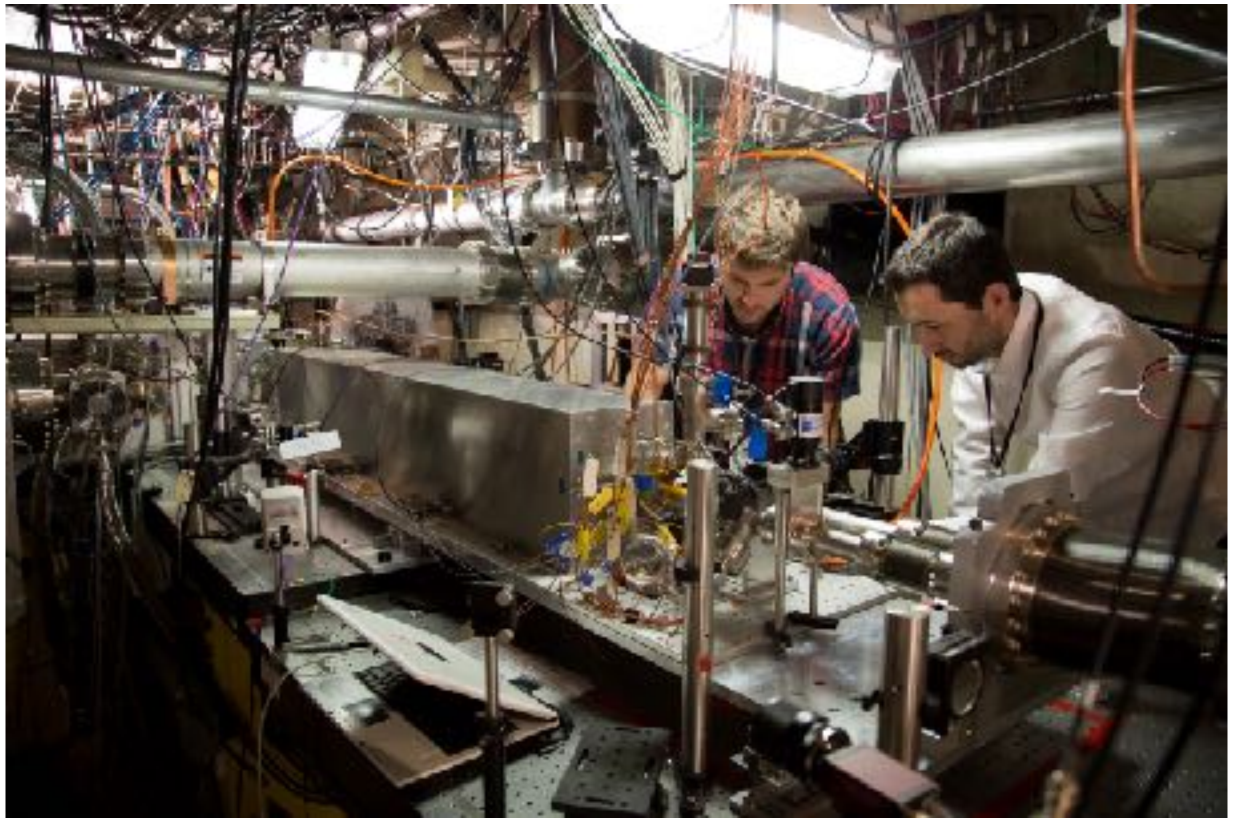
Figure 8: The envelope of the transverse wakefields for both planes is shown. The CLIC bunch spacing is 0.15 m.

PART 2:
Diagnosis

Experiments at FACET, SLAC

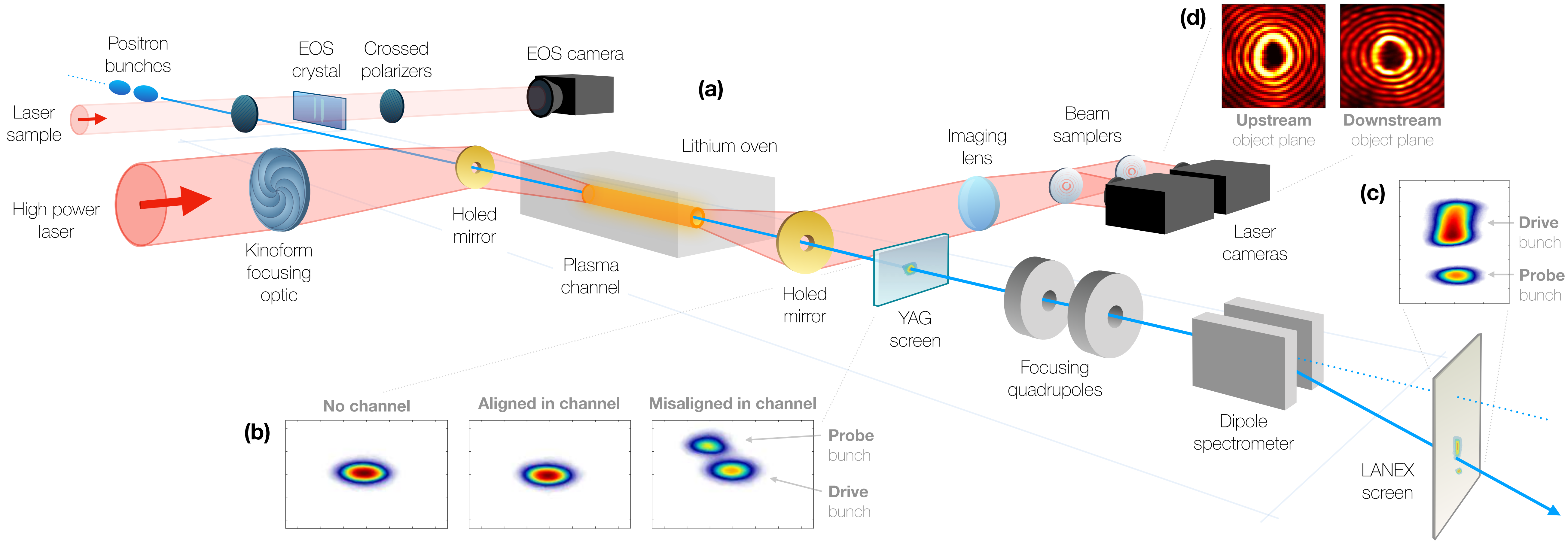
The E225 experiment

- One of these experiments was the E225 Hollow Channel experiment, **lead by Spencer Gessner**.
- **E225 successfully demonstrated acceleration** of a trailing positron bunch in a positron driven hollow plasma channel.
- Transverse wakefields were also measured in the E225 experiment.



Spencer Gessner (left) and Sebastien Corde (right) at FACET tunnel, SLAC.
Image source: SLAC National Accelerator Laboratory

E225 – Experimental setup



- The SLAC linac provided **two 20 GeV bunches**, made from one bunch using a beam notching device.
- The FACET laser (up to 10 TW, 60 fs pulses) was adjusted down to ensure **no ionisation in the channel**.
- A lithium oven was set to give a neutral gas density of $3\text{x}10^{16}$ cm^{-3} (but was necessarily fully ionized).

The experiment

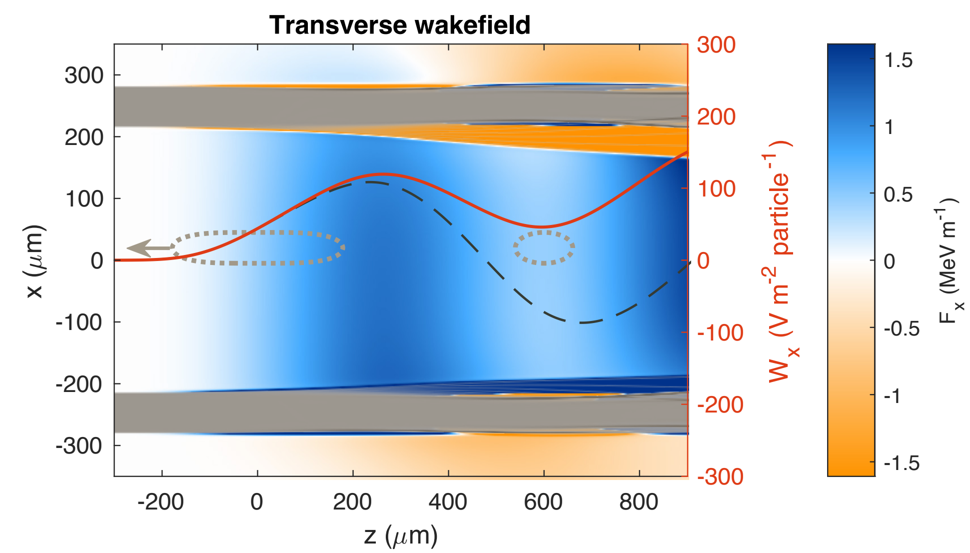
- Our **goal** was to **measure the how the transverse wakefield varied longitudinally**.

- The probe bunch observing the wakefield is deflected angularly (kicked) when the channel and the drive bunch are relatively offset.

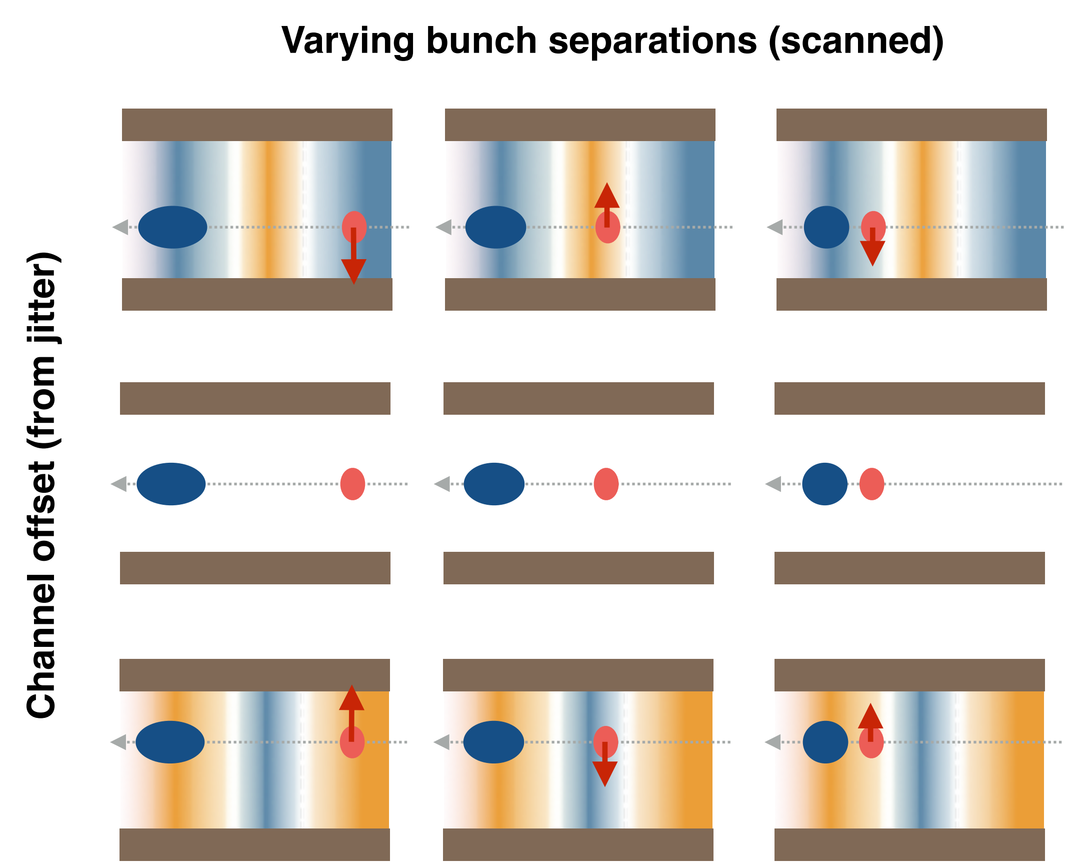
- The experiment performed was:
  Transverse channel offsets for various bunch separations
  – The channel (250 µm radius) was offset by transverse laser jitter (20-40 µm rms)
  – The bunch separation was varied by stretching the bunch and adjusting the notching device.

- Diagnostics:
  – Laser offset imaged downstream (**laser cameras**).
  – Probe kick measured on a **spectrometer** (in the non-dispersed plane).
  – Bunch separation measured using an **electro-optical sampler**.

Prediction:



Experiment (2D "scan"):



Another independent measurement

- An independent measurement is beneficial (due to high complexity).
- It is possible to estimate the transverse wakefield per offset from the measured longitudinal wakefield, via the Panofsky-Wenzel theorem and the linear model.

Panofsky-Wenzel theorem:

$$\frac{\partial W_x}{\partial z} = \frac{\partial W_z}{\partial x}$$

Integrate (++) →

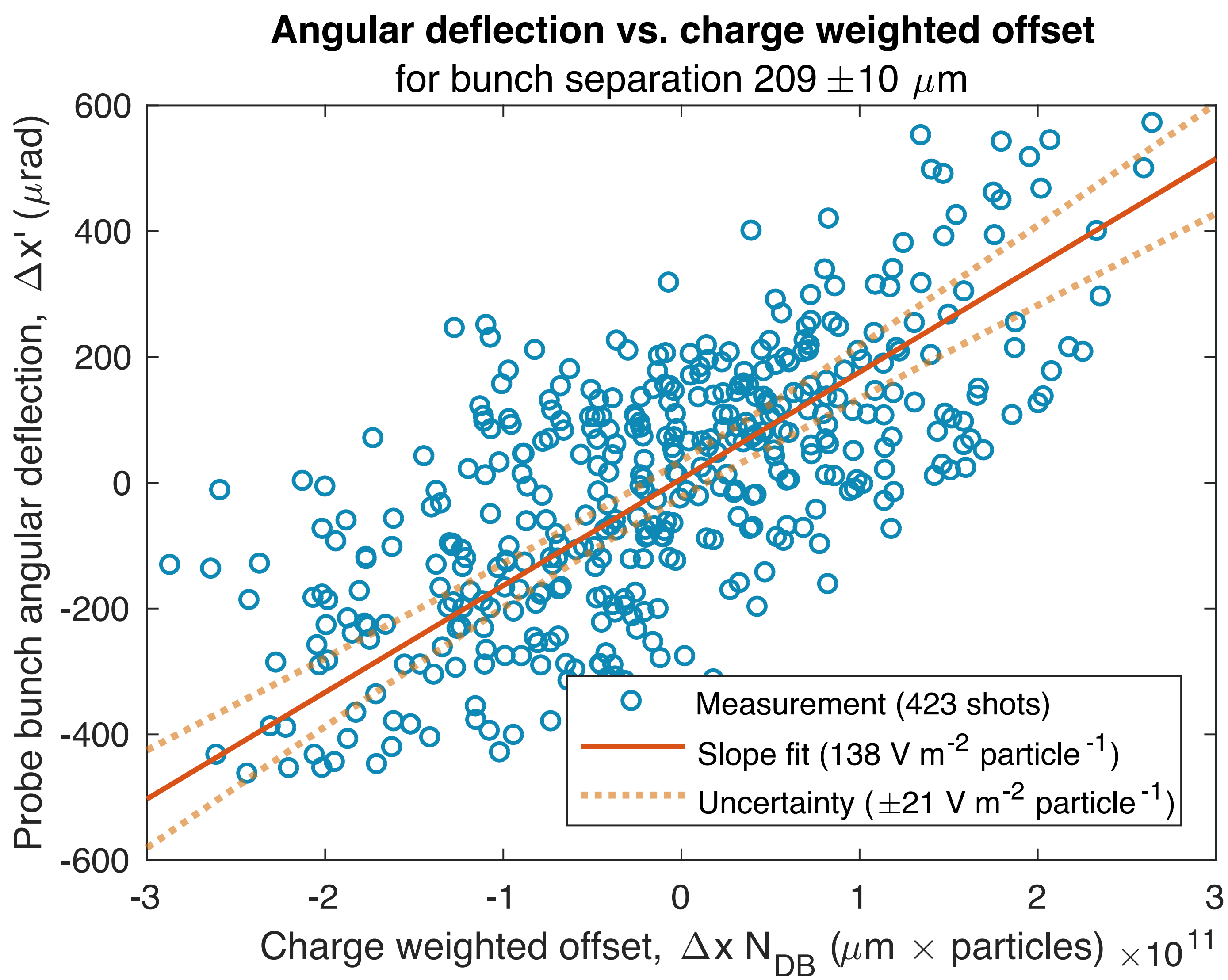
Estimate of transverse from longitudinal wakefield:

$$\frac{W_x(z)}{\Delta x} \approx -\frac{\kappa(a,b)}{a^2} \int_0^z W_z(z') dz'$$

where $\kappa(a,b) = \frac{4\chi_{\perp}^2 - 2}{\chi_{\parallel}^2 - 1}$

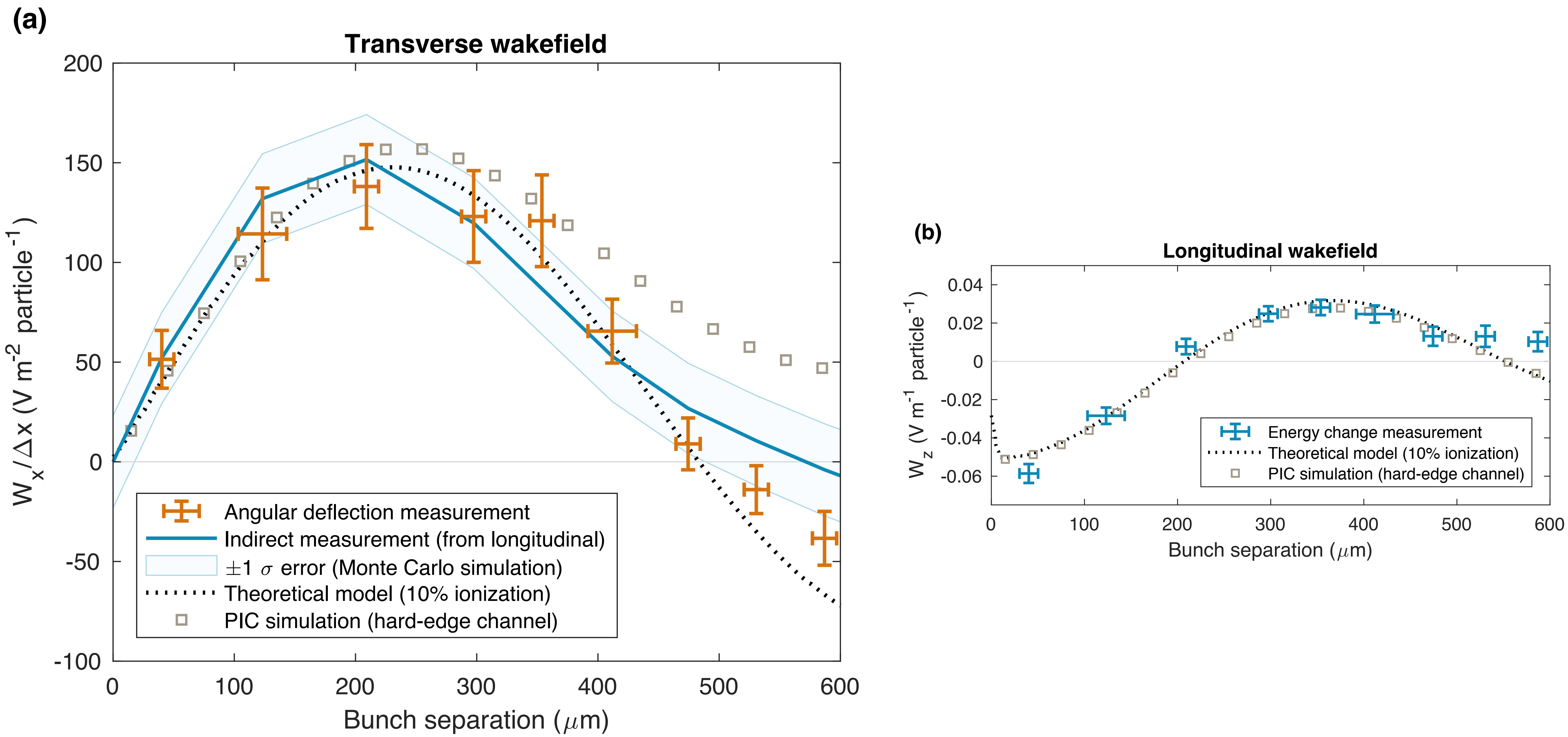
- Not perfect: Assumes linear model, breaks down far behind the drive bunch.
- Provides verification of numerical calibrations, etc.
- The longitudinal wakefield was measured by the energy change of the probe bunch (on a spectrometer).

Observed data (deflection vs. channel offset)



- For each bunch separation, a correlation between channel offset and probe bunch angular deflection was observed.
- The **slope of this correlation is proportional to the transverse wakefield per offset** at the z-location of the probe bunch.

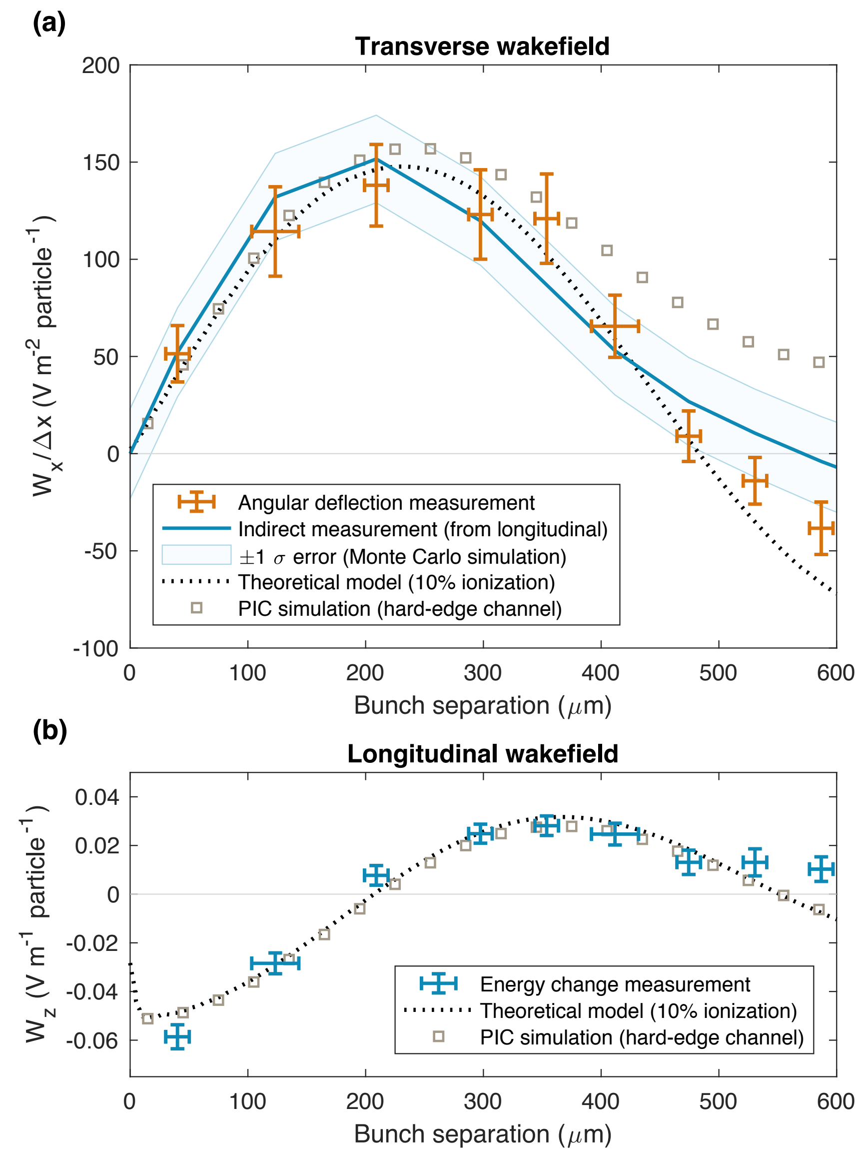
Final experimental results



- Plasma density determined by a wavelength fit (10% ionization = $3\text{x}10^{15}$ cm^{-3})
- Good fit, largely consistent with theory. Some discrepancy at larger separations.

Implications

- **Overall, the measurement agrees with the theoretical models.**
- Simulation-based parameter scans indicate that the discrepancy at large separations can possibly be explained by using a more complex radial plasma shape (not possible to exclude with our diagnostics).
- Implication: There is indeed a strong transverse wakefield.
- Submitting these results to Physical Review Letter.



PART 3:
Finding a cure

New ideas
for fixing the hollow channel

Fundamental problem:
transverse wakefields

Ideas for transverse wakefield suppression

- Conventional BNS damping
  => Requires very large energy spreads

- External focusing
  => Requires very strong focusing
  => Solenoids do not scale well with ene… (1/γ^2, but kick scales with 1/γ)
  => Does not help unless perfectly aligne… …l center

- Near hollow channels (low density plas…
  => Breaks the ch… symmetry

- Tailoring … locally c…

Clarification on what needs to be damped

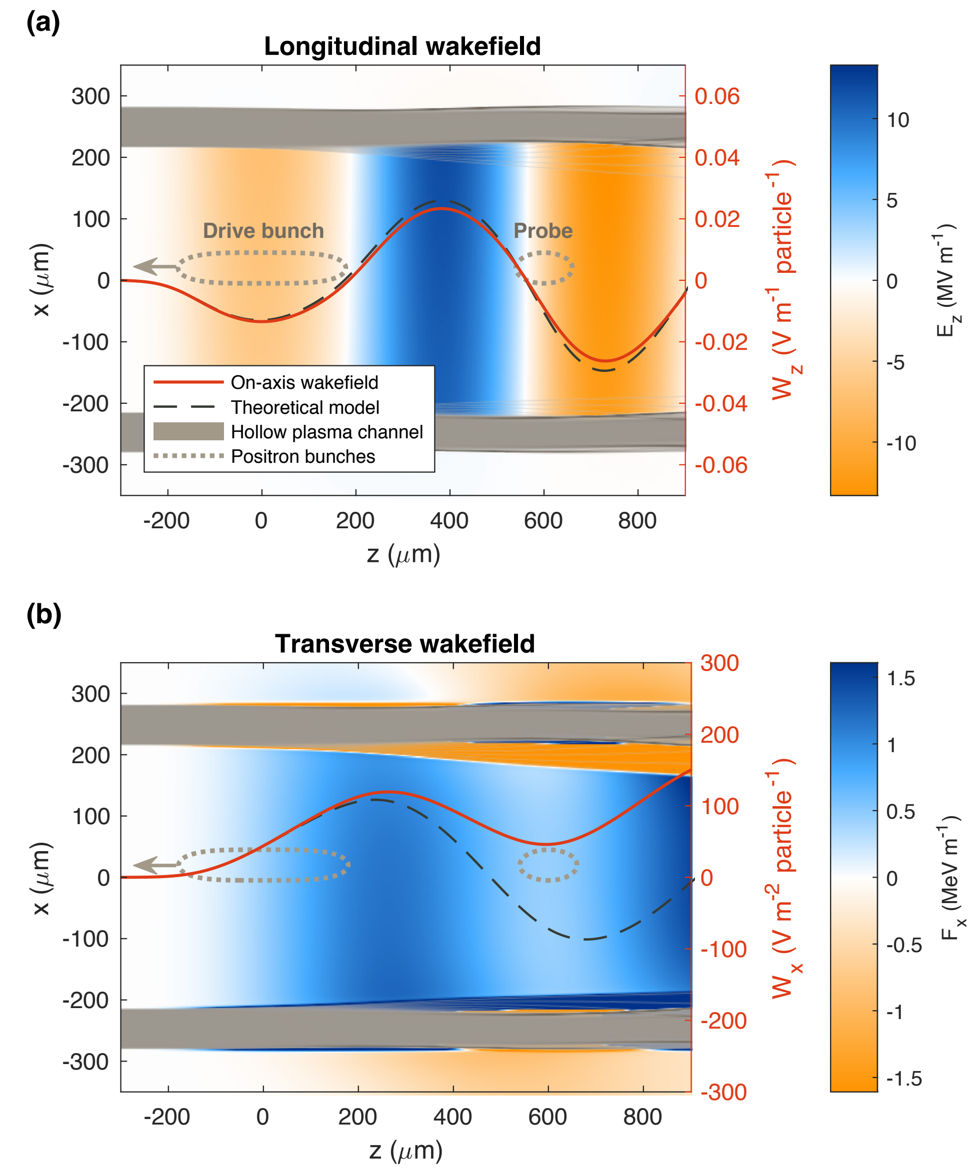
- Two different problems
  – Transverse instability of the drive beam (feedback loop)
  – Transverse deflection of accelerated beam caused by drive beam wakefield
  – Transverse instability of the accelerated beam (from its own transverse wakefield)

- The drive beam only needs to **survive one stage**. It does not need to preserve its emittance.

- The accelerated beam can in principle be placed on the **zero crossing** of the transverse wakefield from the driver.

- The self-wakefield can in principle be used to transversely **beam load** the transverse wakefield of the driver (at the zero crossing).

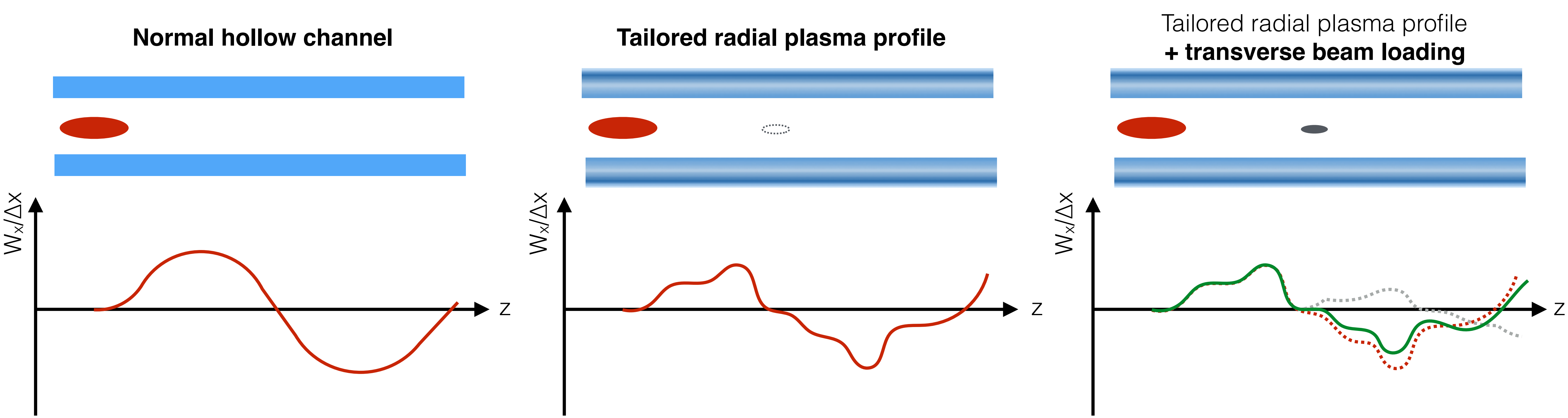
- Now we just need to make a hollow channel with all the above + high accelerating gradient + high efficiency



EASY PEASY!

Tailored radial plasma profiles

- Currently just at the speculative stage: Hollow plasmas are naturally not high-Q cavities: can we use this to our advantage?
- A strength of plasma channels compared to structure-based channels:
  Many degrees of freedom to play with (radial distribution of plasma density)
- This work will benefit from a theoretical model for arbitrary radial plasma profiles **n(r)** – *(as an alternatively a brute force PIC simulation search)*
- If it actually works, the next step is to somehow make this plasma profile (with the kinoform of all kinoforms?)



Only works for channel offsets
(same offset for both bunches)

Can maybe be combined with weak solenoid focusing and BNS damping for the drive bunch?

Conclusions

- Strong wakefields is a big challenge for the hollow channel
- We did an experiment at FACET to diagnose the problem
- Experiments correspond well with theory (but still some discrepancies)
- We have ideas on how to fix it (with radially tailored plasma profiles?)
- Will be pursued at FACET-II

A Haiku of Hope

We do not de-clare

the ho-llow cha-nnel dead yet.

First try all id-eas.

Thank you for your attention!