Detector Considerations for a multi-TeV Plasma Wakefield Collider

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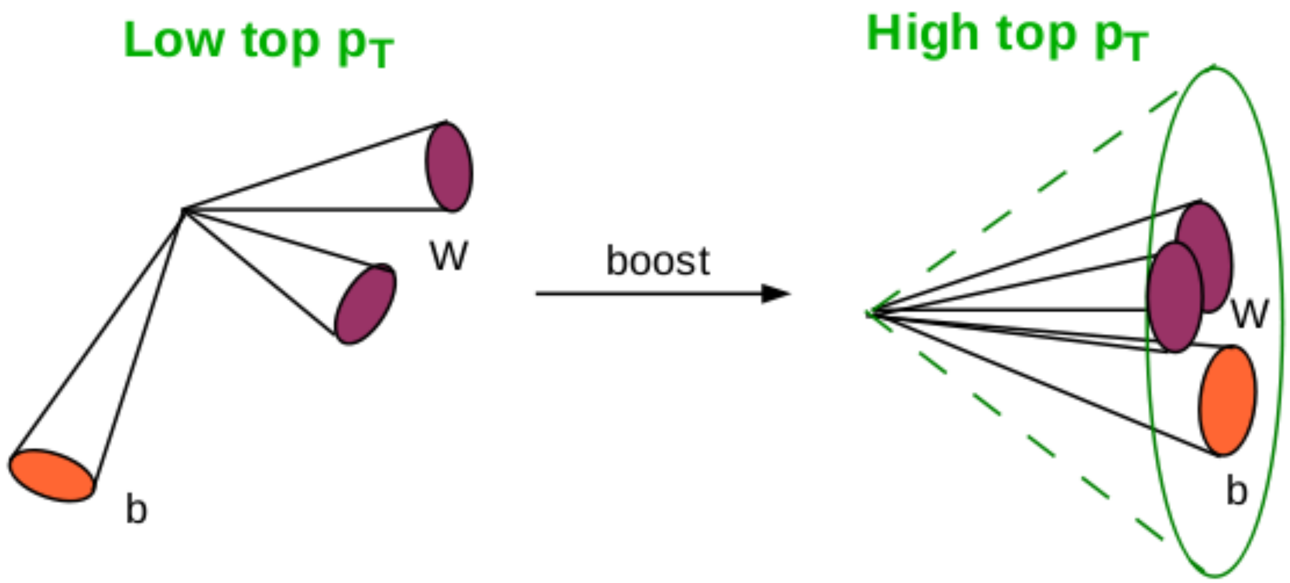
TRIUMF

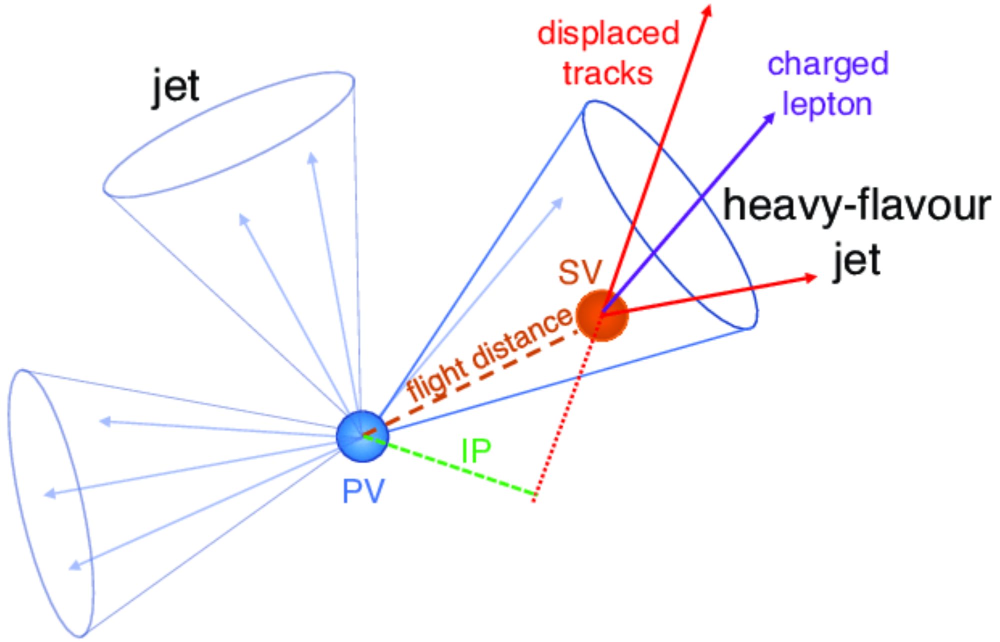
Disclaimer

- Spencer asked me to give a **speculative** talk about building detectors for extremely high energy future facilities
    - Consider $\sqrt{s} = 15\ \mathrm{TeV}$ (or beyond?), luminosity $5 \times 10^{35}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
- This assumes using plasma wakefield for acceleration, and a plasma *focus* for luminosity
    - What are the challenges that these devices provide?
- This is all *extremely* speculative: no actual work done (yet?)
    - So speculative that the list of topics here is inherently incomplete
- Many thanks to Michael Peskin, Caterina Vernieri, Lindsey Gray for brainstorming ideas!
    - See also this talk, and this one, from Michael
    - Many technical accelerator details available in the advanced concepts paper
- Please suggest other areas to consider!

Physics at 15 TeV (or higher?)

E. Thompson



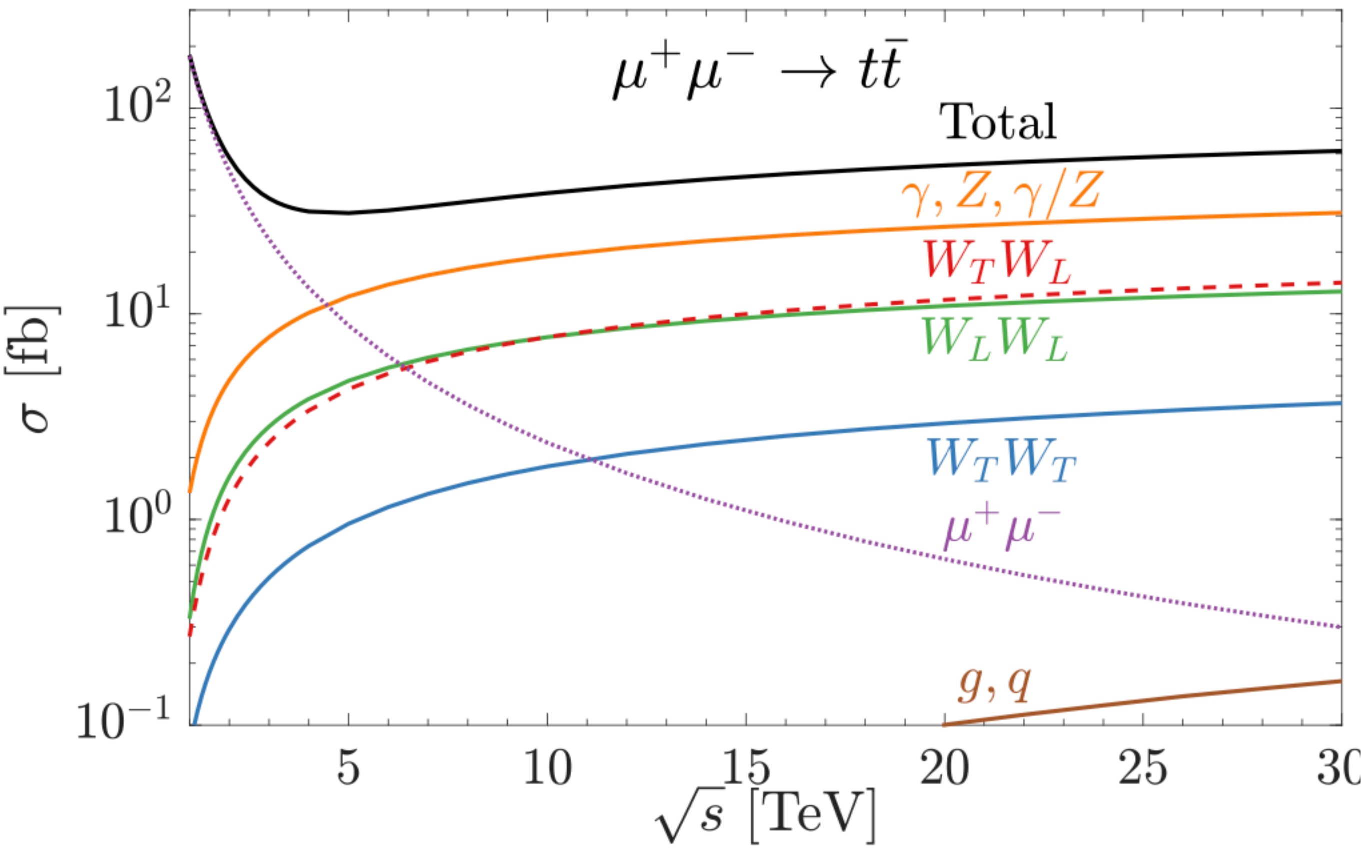


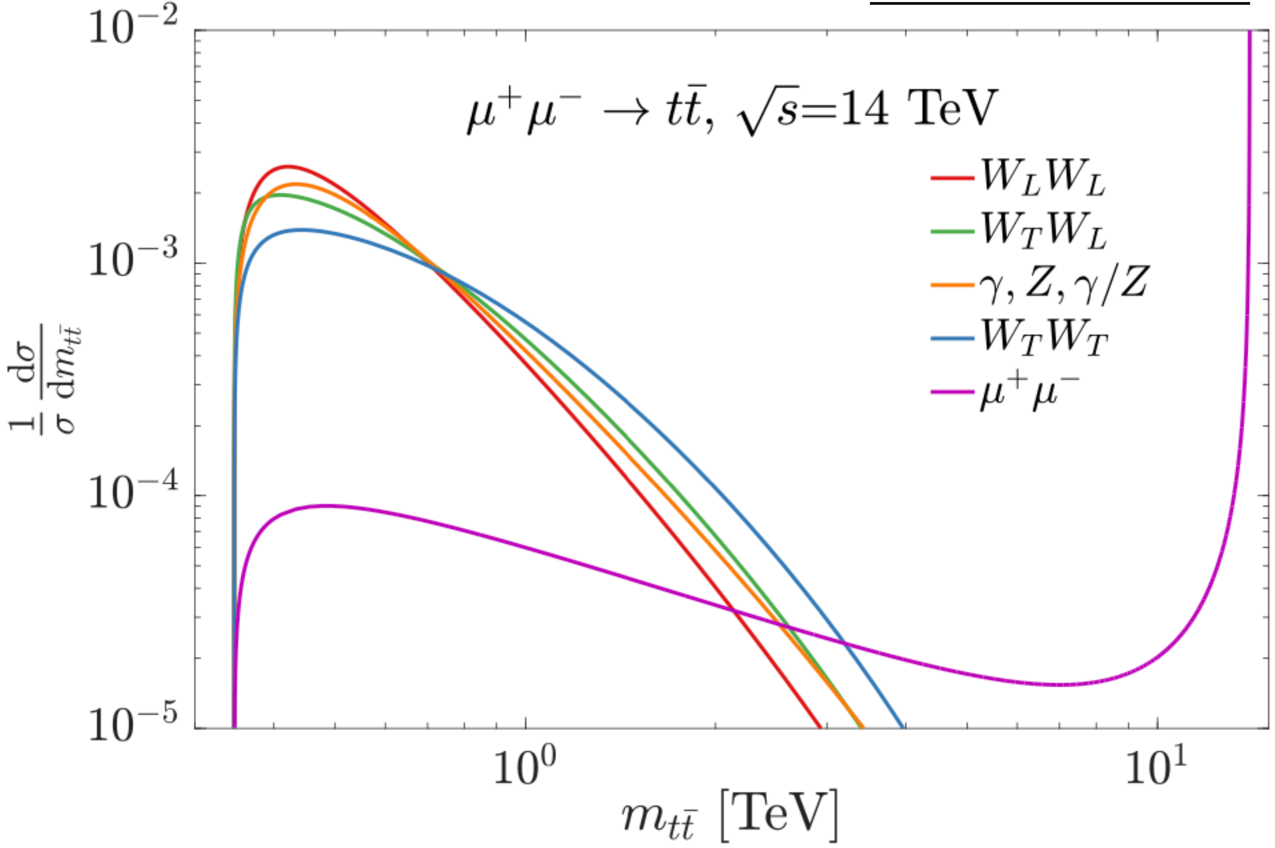
arXiv:1712.07158

arXiv:2103.14043

- In high energy collisions, get extremely high energy outgoing particles
- Even heavy particles— typically well separated in current detectors— are super-collimated
- Lifetimes (due to time dilation) are huge: B-hadron travels ~20 cm (compared to ~1 cm at LHC)
  - Identifying B-hadrons critical for Higgs, top quark, new physics: motivates "vertex" detectors that measure secondary vertex

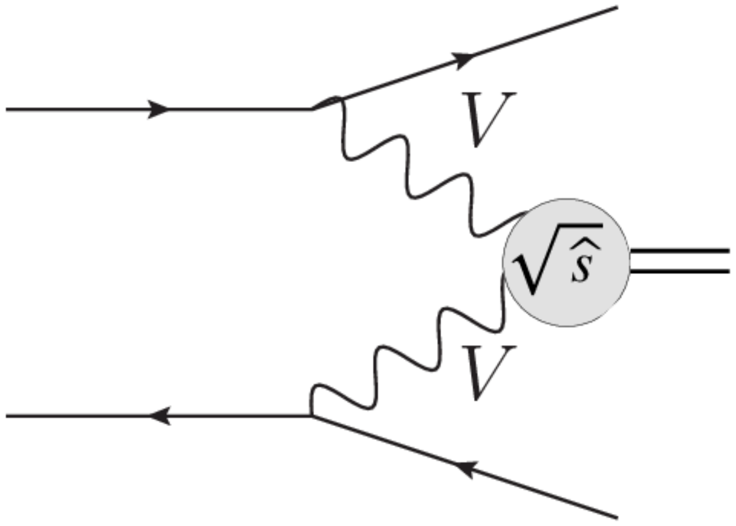
More on EWK-strahlung





arXiv:2007.14300

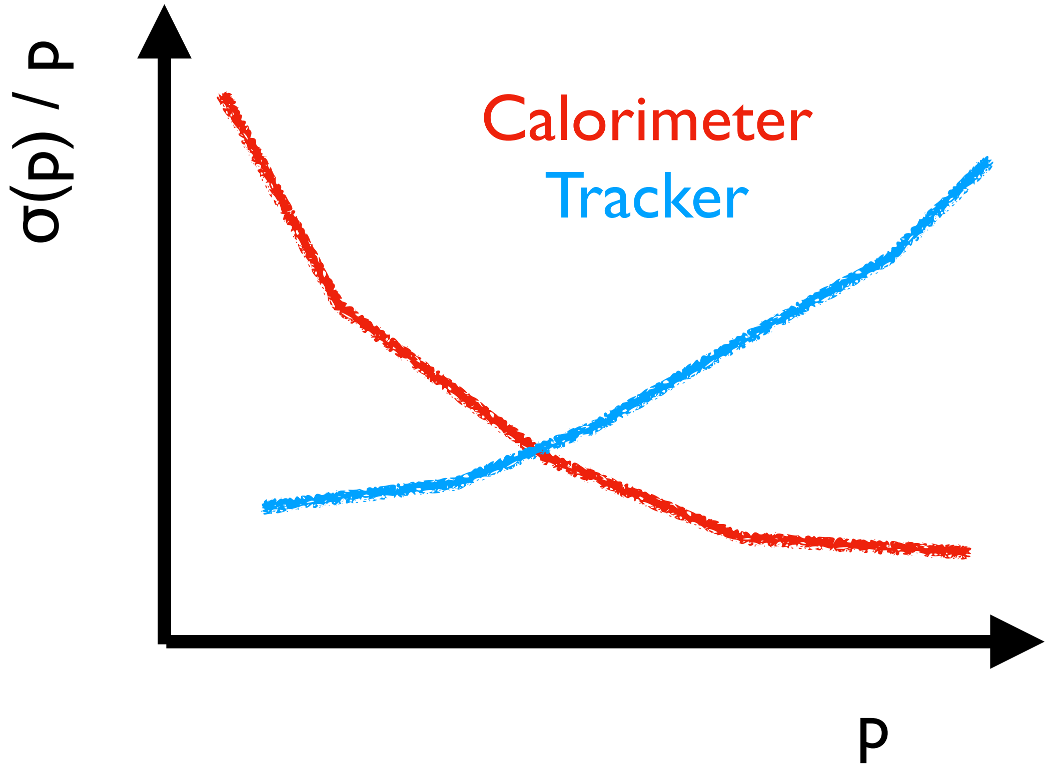
- At extremely high energy, production mechanisms can be dominated by radiation: EWK-Fusion processes
  - If you want to study Higgs physics: most of your Higgs are being produced at much lower energy than your beam!
  - But if you are focusing on discovery physics: plenty of events also at the highest masses

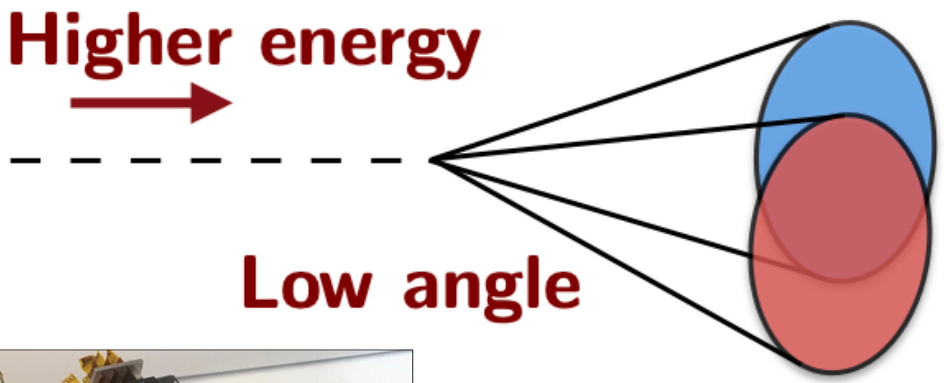


arXiv:2203.07256

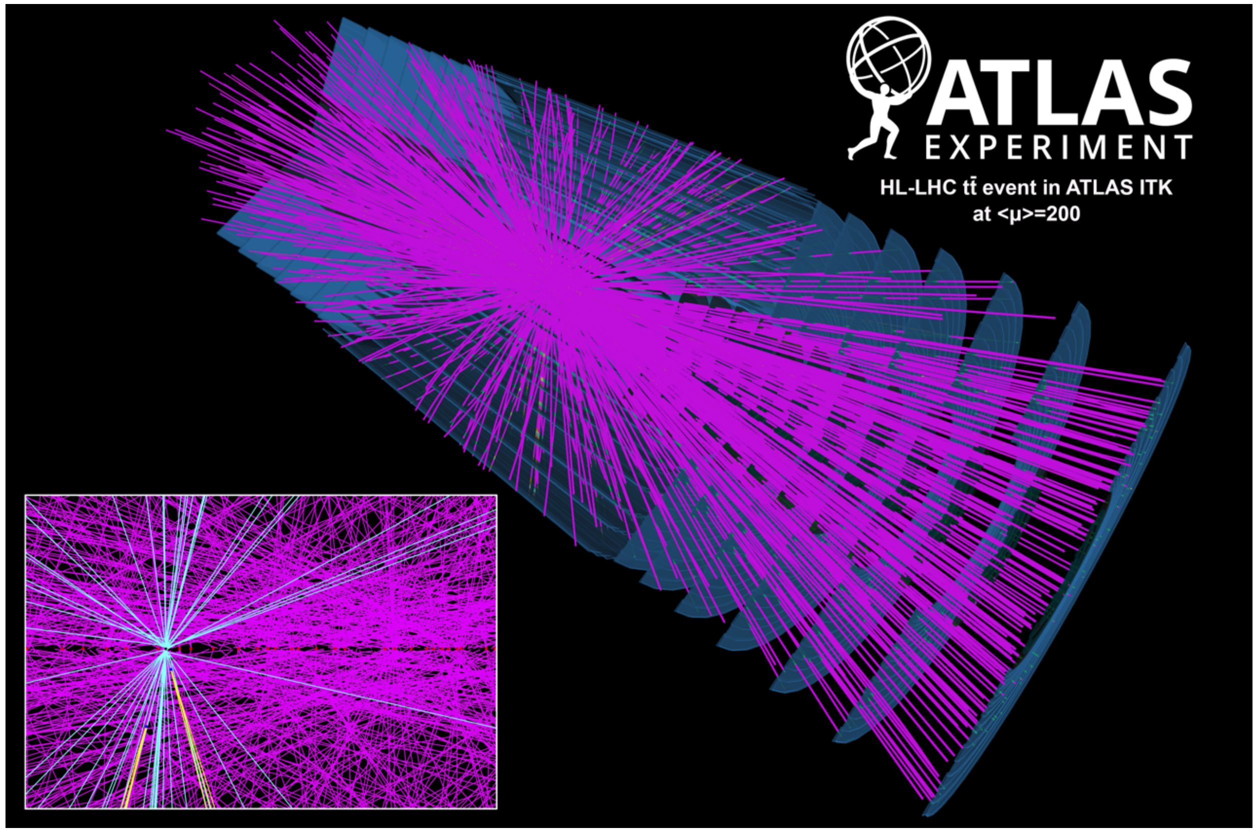
Impact on Detector Design

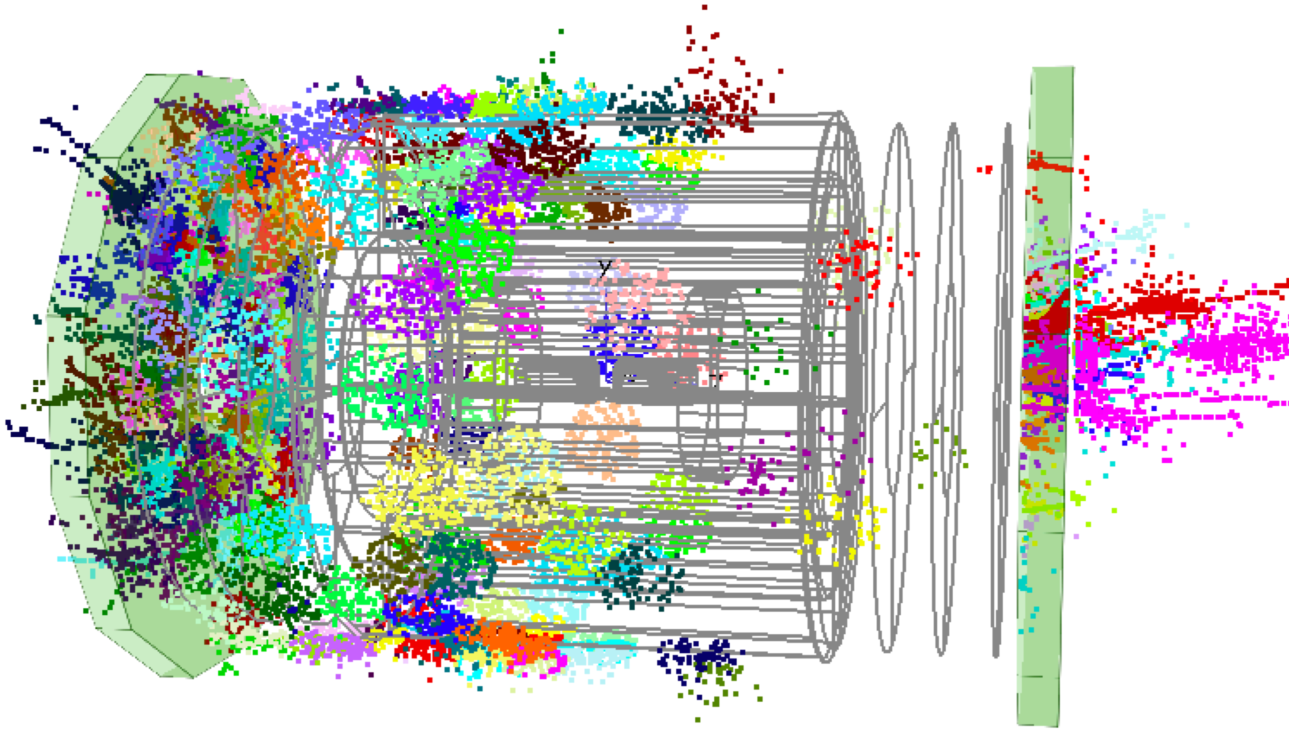
- Tracker potentially less useful for momentum: focus on calo?
  - Tracker could still help resolve structure, 'tag' jets
- Calorimeter probably requires high granularity (or use tracker for granularity?)
- "Vertex" detector required much further out?
  - Reduces susceptibility to radiation





The Context of Discovery Machines

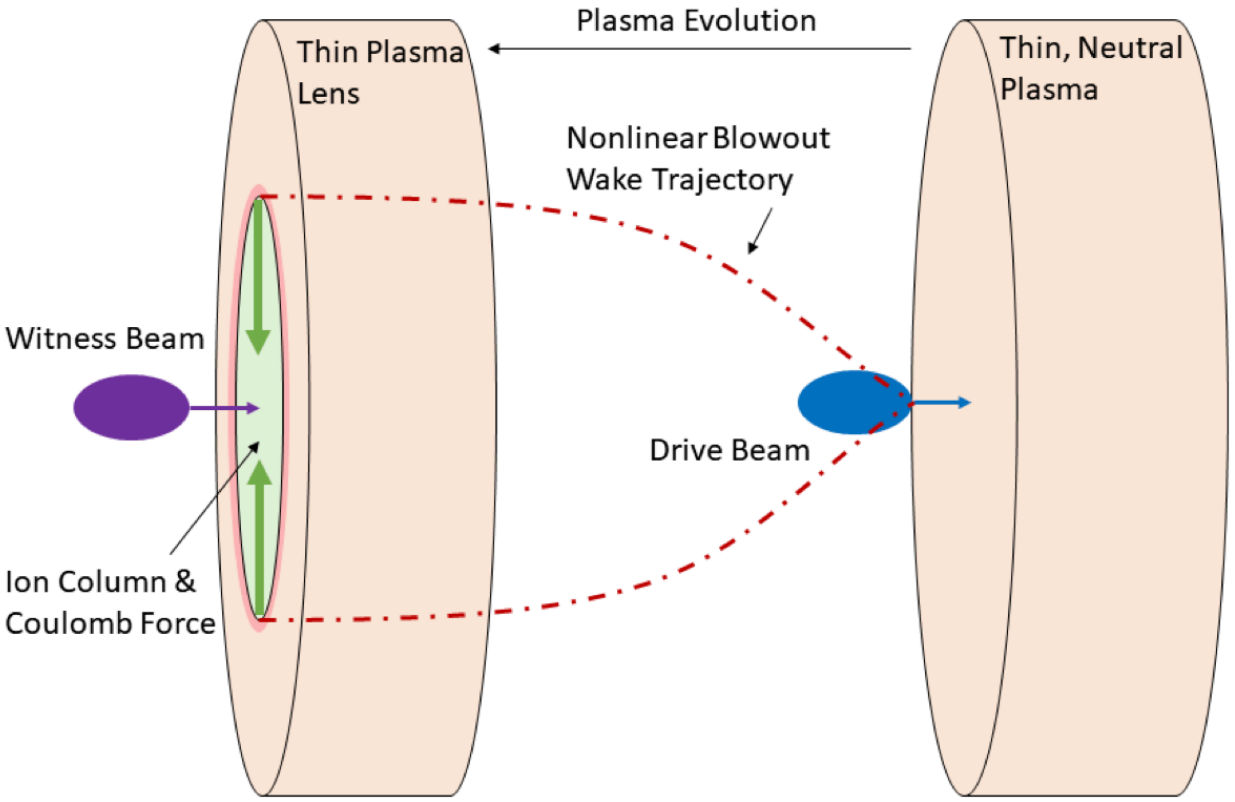


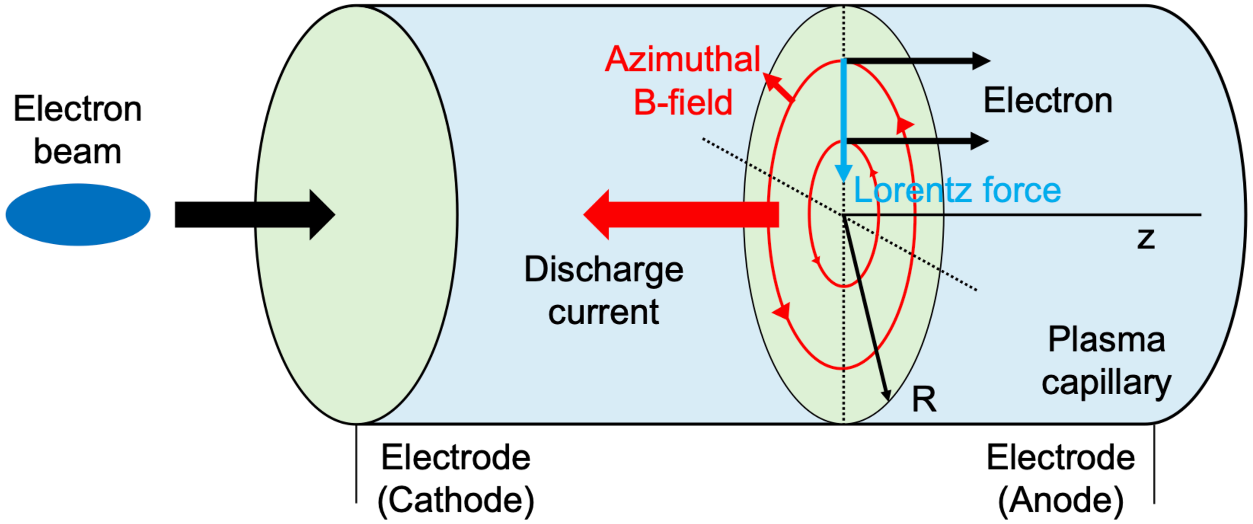


$\mu\mu \to H\nu\nu \to bb\nu\nu$ + 0.03% BIB

- Discovery machines don't have to be precision machines
- Every other discovery-class machine (FCC-hh, µC…) has extreme backgrounds
- We shouldn't be (completely) afraid of backgrounds!

Plasma Lenses





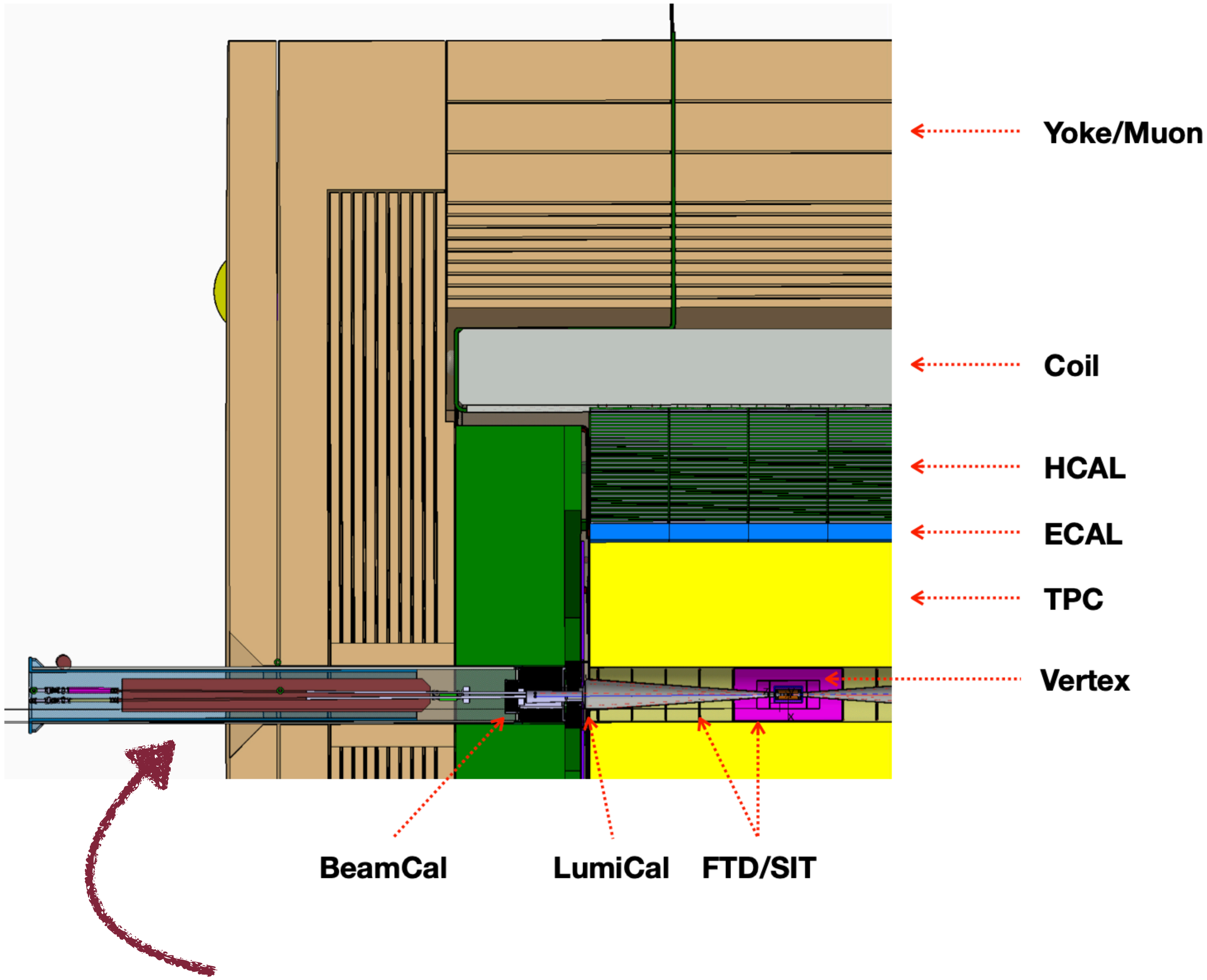
Passive Lens

- Typical drive + witness setup

Active Lens

- Current applied across plasma to create field

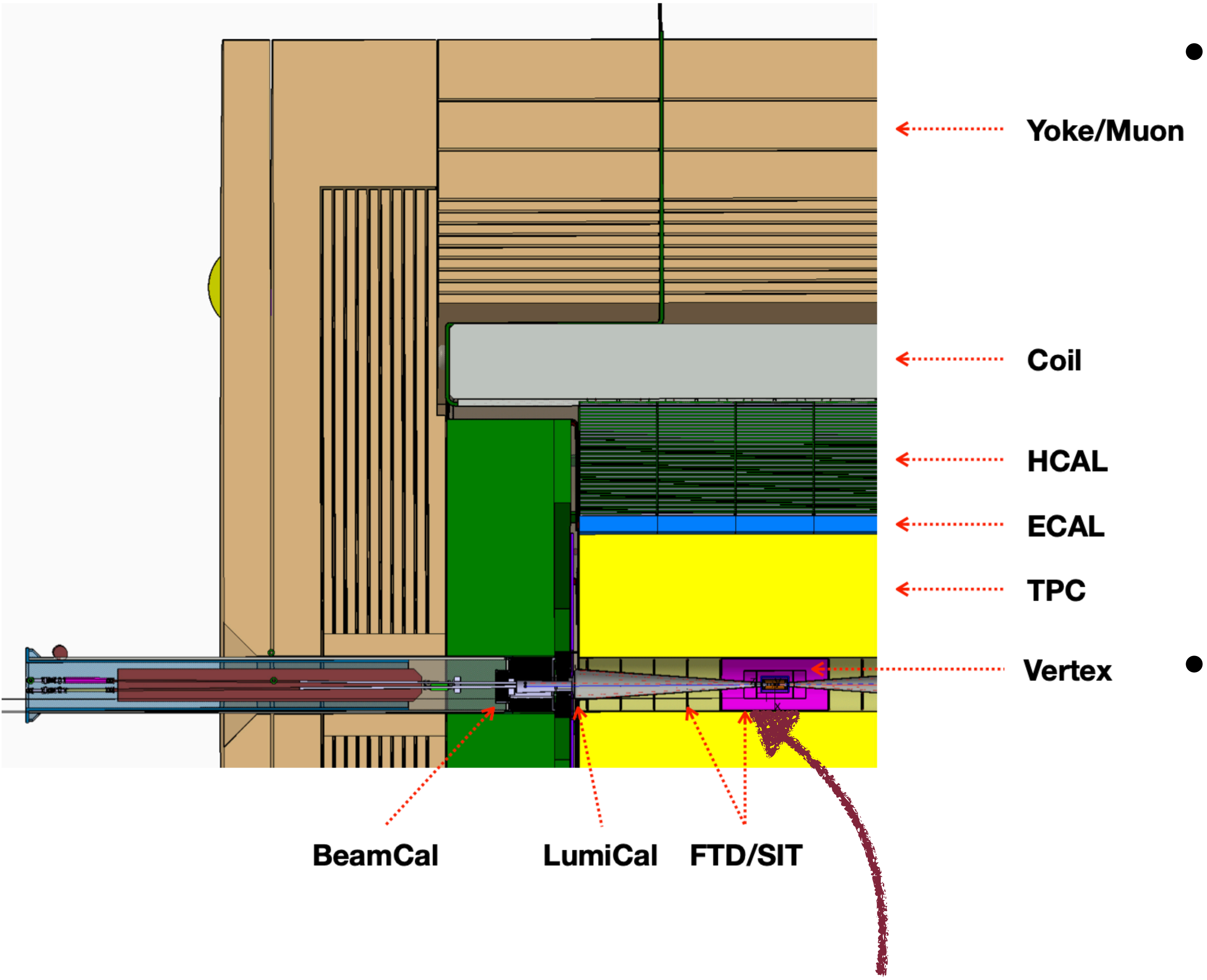
Plasma Lens Locations



Nominal QD0 location?

- First location to consider would be near the nominal $L^* \approx 4\ \mathrm{m}$
- Over here, probably not so much impact?
- Beamstrahlung will be a large background…
- Beam-plasma interactions could introduce additional backgrounds
  - (Mostly very far forward: larger concern from upstream plasma acceleration cells?)
- Generally seems pretty straightforward…?

Plasma Lens Locations



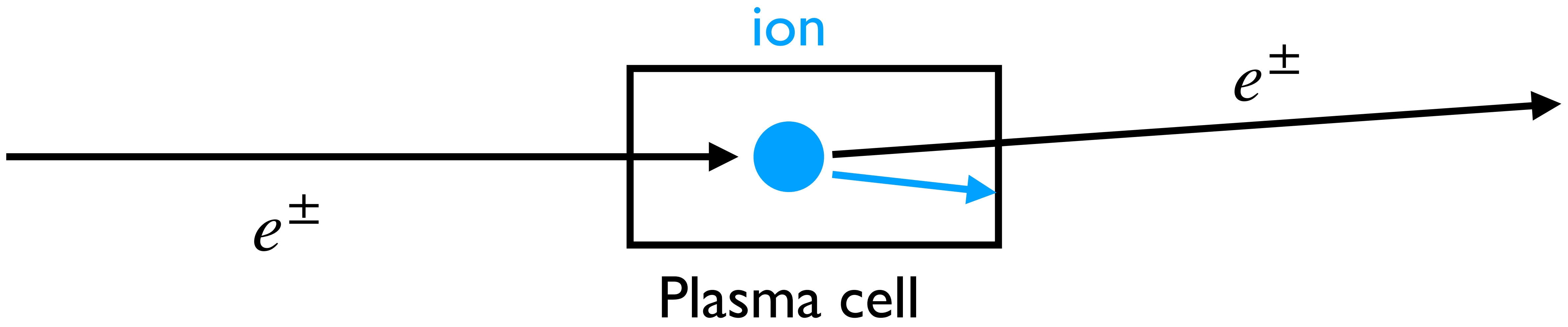
Focusing at the IP?

- Another provocative idea: what about a lens extremely close (or on top of??) the IP: $L^* \approx 0\ \mathrm{m}$
  - Extremely powerful focusing might "over focus" with a longer L^*
  - "Oide limit" might mean you won't be exactly on top of the IP, but very close
- What are the physics consequences of something this aggressive?
  - Consequences will likely be smaller for anything less aggressive: treat this as a "worst case" thought experiment

Considerations

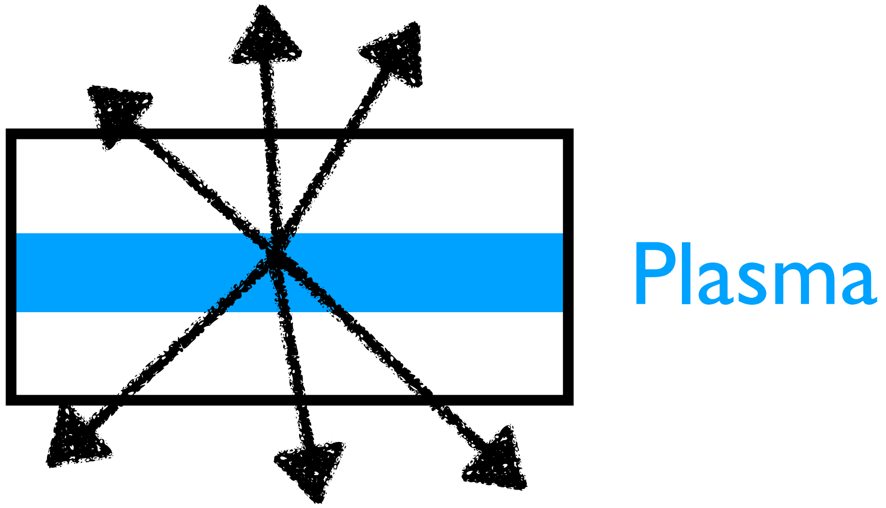
- Beam-plasma interactions
- Outgoing particle-plasma interactions
- Plasma magnetic fields
- Beam-plasma photoproduction
- “Plasmapipe” material
- Anything else I’ve missed!?
- At each slide, I list what I consider the “need to know:” information that will impact detector design/physics

Beam-Plasma Interactions



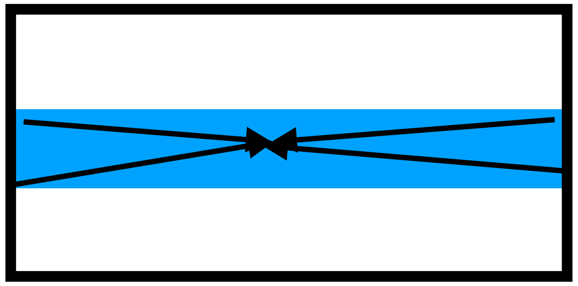
- First active concern: beam interactions with plasma in the collision region
    - Typical operation of plasma cell: 1 atmosphere
    - Beam-gas operations usually require **significantly** lower pressures to avoid overwhelming detectors with background
- Is this really so bad though?
    - Usually a largest concern from *upstream* since (most) scattering is extremely forward
    - And our detector will be placed > 20 cm out…
    - **Doesn't seem like a showstopper?** What about for the collider?
- Need to know: pressure, plasma composition, plasma charge

Outgoing Particle-Plasma Interactions



- Outgoing particles could also interact with the plasma cell!
  - Scattering could induce early showers, deflect particles, etc.
  - However: plasma at ~1 atm is not a lot of material
  - And plasma cells are only a ~few mm transversely
  - **Number of radiation lengths should be minimal**
    - Probably a significant difference between charged and neutral plasmas?
- Need to know: pressure, plasma composition, plasma charge

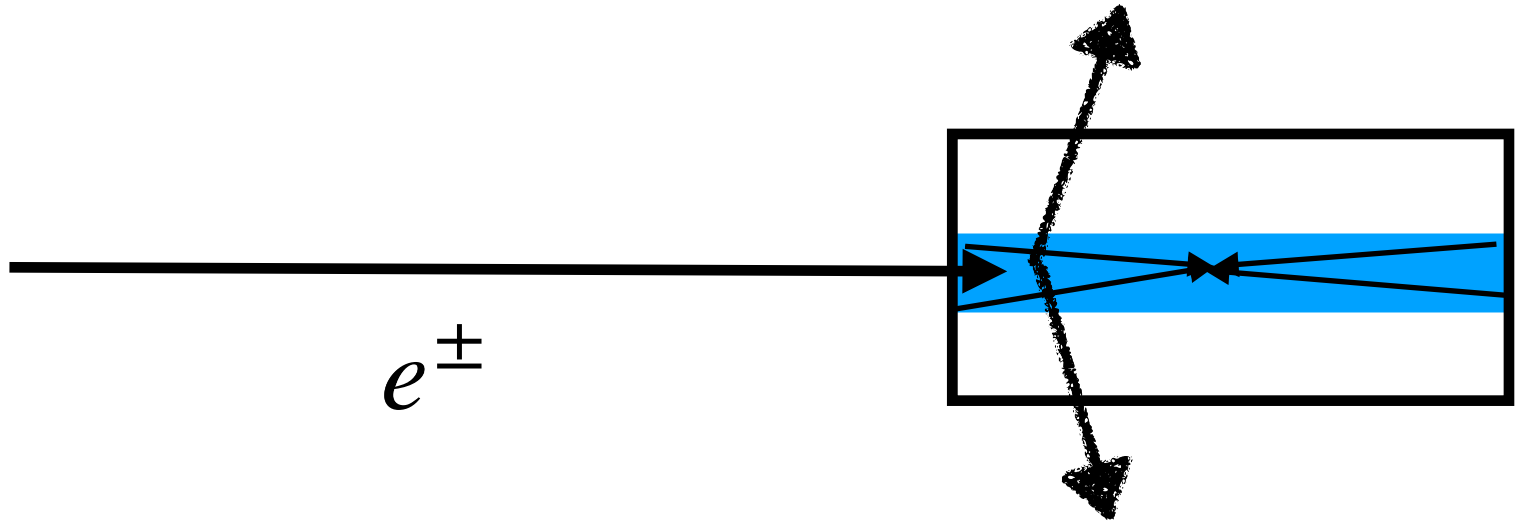
Plasma Magnetic Fields



(Bad sketch of extremely strong magnetic forces)

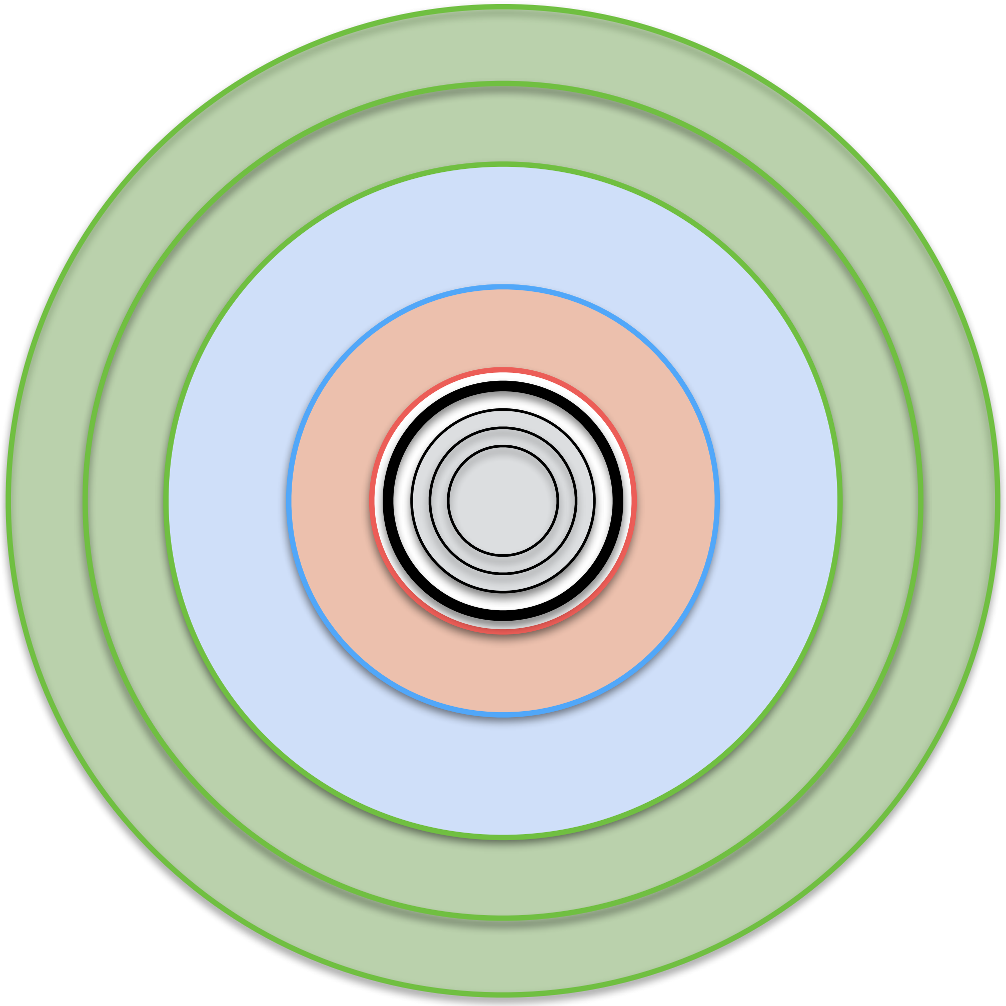
- Plasma lens by definition contains extremely strong magnetic forces to focus beams
  - These forces are hard to predict: time-varying (in passive configuration only?), complicated radial profile, etc.
  - Outgoing particles will also interact with this, but:
    - Outgoing particles are extremely high energy (stiff to fields)
    - Plasma only has a ~few mm of lever arm
- Bending and deflection from magnetic fields should be minimal: might introduce smearing to detector measurements, but naively seems acceptable
- Need to know: "worst case" magnetic field model? Ideas on how much time variation (on what time scale, etc.)

Photoproduction/Beamstrahlung



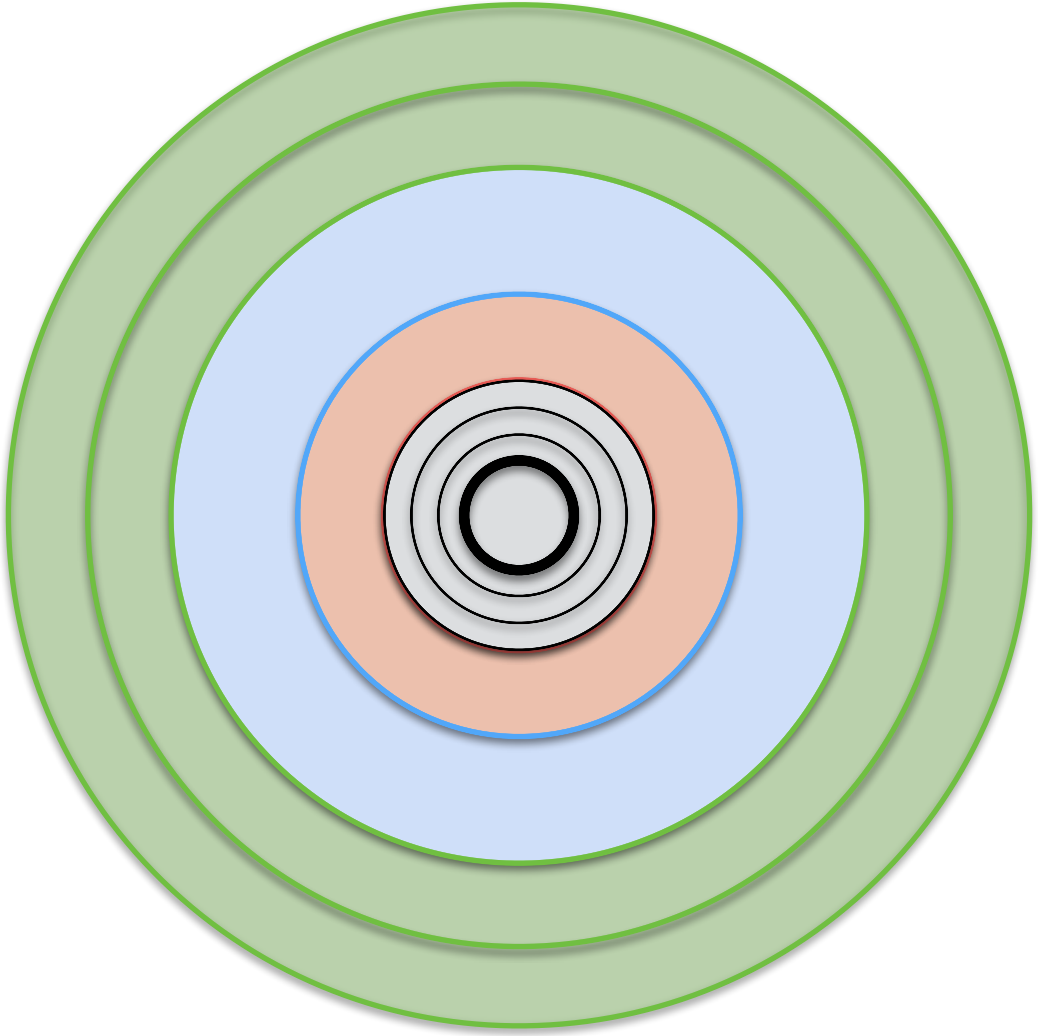
- Extreme focusing of beams will create large beamstrahlung effects
  - But "flat beam" configurations may potentially alleviate this at least partly
  - Could harness this radiation: make a γγ collider without Compton laser scattering?
- Extreme presence of magnetic fields (and beam interactions) will also create photoproduction
- Certainly expect large presence of backgrounds from these processes— especially at high angles
  - But most particles will be "low" energy and forward
- Extremely limited knowledge of extreme QED at this scale…! Improved simulations to GuineaPig (WarpX, OSIRIS) under development (see talk from Marina)
- Need to know: photoproduction and beamstrahlung particle energies, angular distributions

Detector Cleaning?



Typical HEP Detector

- **Solenoid** around (at least) inner detector



Advanced Detector?

- Solenoid (or other magnet) *inside* other detectors, to sweep away backgrounds?
  - Use return flux to bend in tracker?
- Something like anti-DID

“Plasmapipe”

- Previous sketches was not exactly accurate— my understanding is that current plasma cells have ~cm scale containment walls
  - Typically made of sapphire (or some similar material)
  - ~cm of material is probably not the end of the world for our very energetic particles
  - But still probably prefer to reduce this as much as possible
    - Beampipes tend to be made from extremely thin beryllium to reduce particle-material interaction: how thin can you go?
- Need to know: materials and size of beampipe

What Else?

- What have I missed?

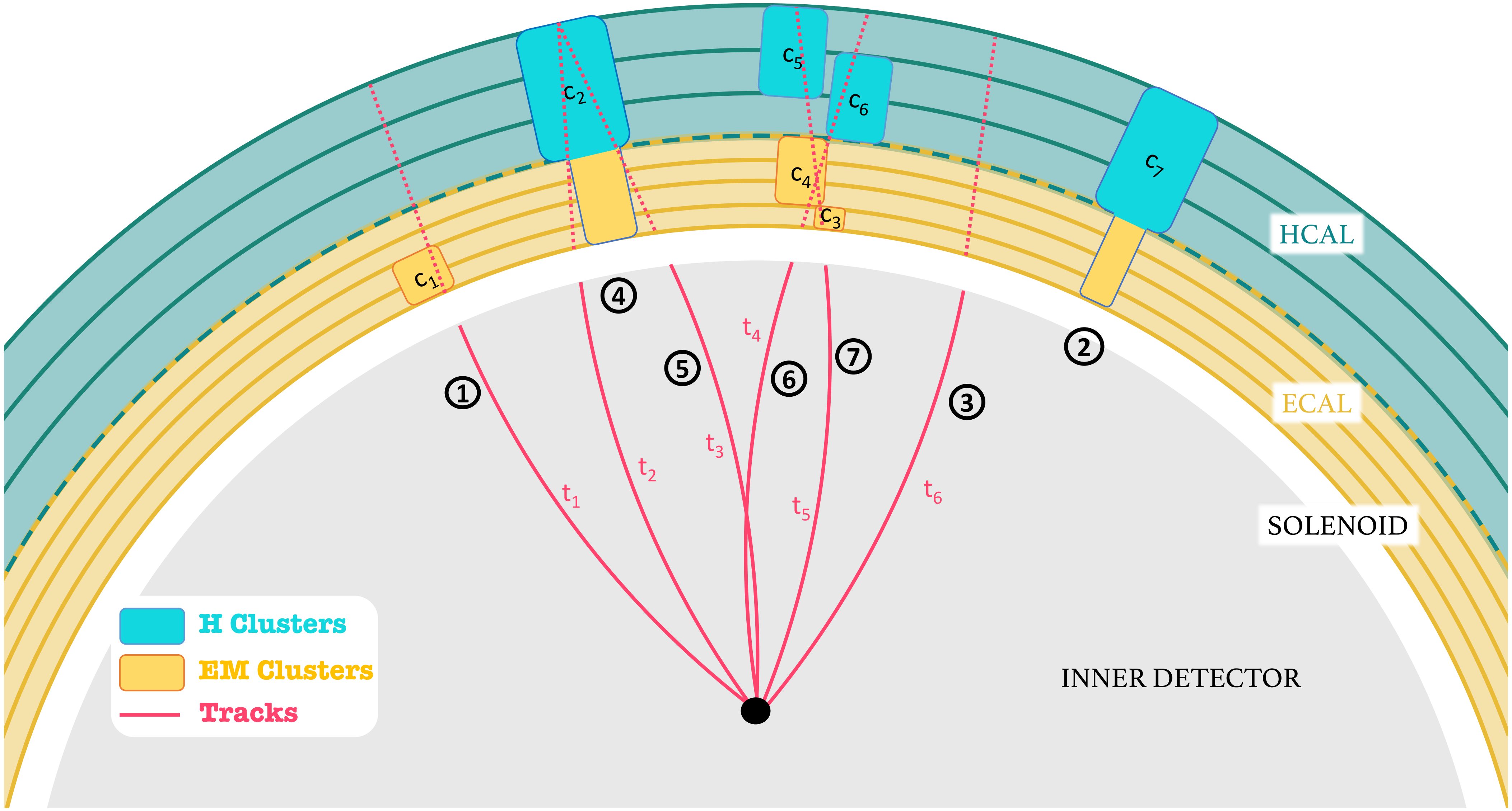
Conclusions

- Physics and detector considerations are quite special at the "extreme energies" and luminosities being considered here
    - Detector design could potentially be quite different: might actually reduce some stress on backgrounds, etc.
- Tried to flag the main questions/requests needed to actually design a detector
    - For a more complete design with very different backgrounds, see designs from FCC-hh
- Many apologies to Tim Barklow— not enough time to include material on XCC-like $\gamma\gamma$ interactions!

Thank you!

Again, many thanks to Spencer Gessner, Michael Peskin, Lindsey Gray, Caterina Vernieri for brainstorming with me

Track-Calo-Clusters



- Use spatial locations from Inner Tracker
- Split energy locations of matched calorimeter cells to locations specified by tracks
  - Use granularity of tracker, energy resolution of calorimeter

Calorimeter Design

- ClicDet 3 TeV has outer radius for HCal at 1.6m, 7.5λ
- Need a logarithmically larger detector: $\ln(15/3) \approx 1.6$
    - 2.6m outer radius for HCal: still plausible
- Objects are extremely boosted: but instrumenting at high granularity this large a calorimeter is $$$
    - Consider hybrid design: high-granularity in earlier stages, less granularity deeper?