

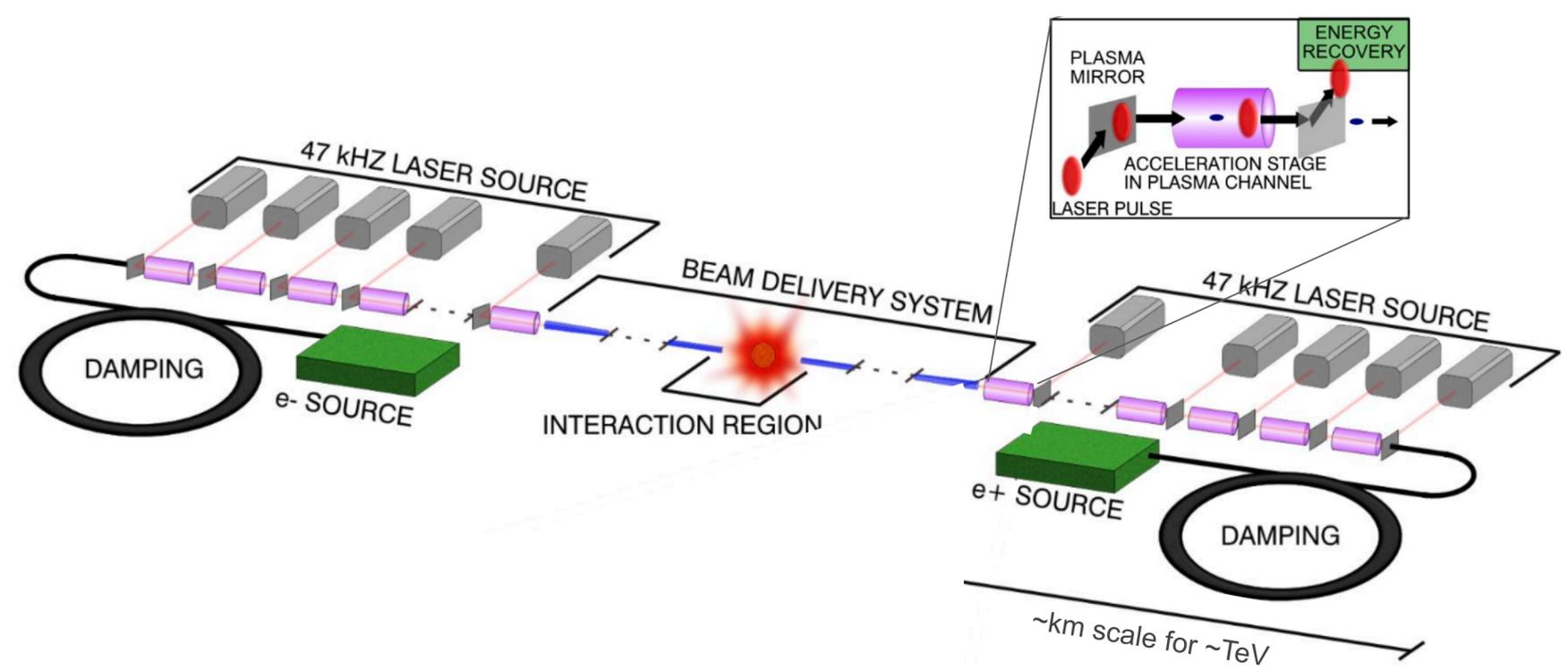
HEP Detectors at 10 TeV $e^+e^- / \gamma\gamma$ colliders

4th Mar 2025
Alegro workshop
SLAC

Nicole Hartman (TUM); Lindsey Gray (FNAL); Max Swiatlowski (TRIUMF)
Dimitris Ntounis, Caterina Vernieri, Ariel Schwartzman (SLAC)
Simone Pagan Griso, Angira Rastogi (LBNL)



**unlock funding for
advanced accelerator R&D**



unlock funding for advanced accelerator R&D

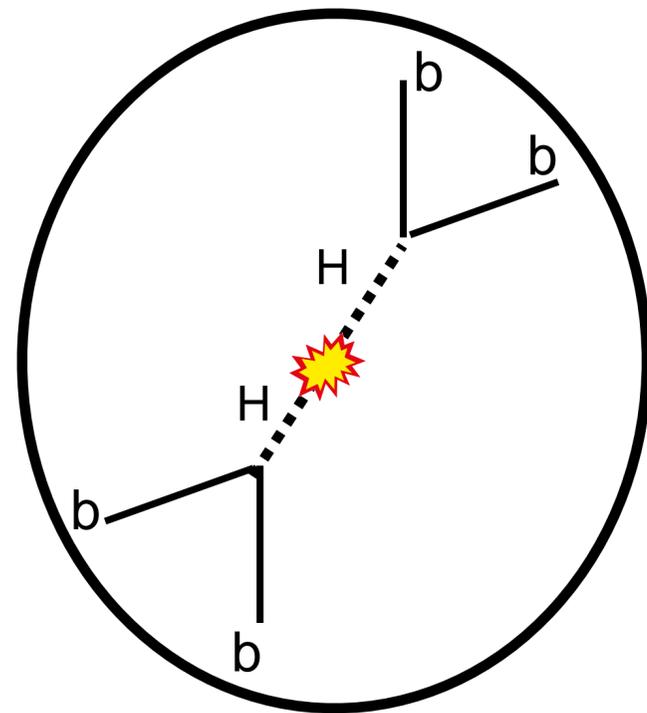
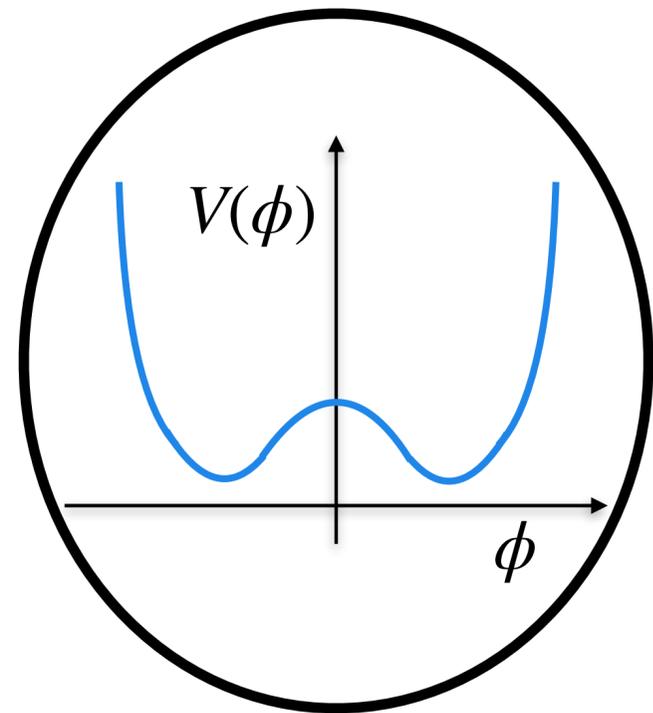
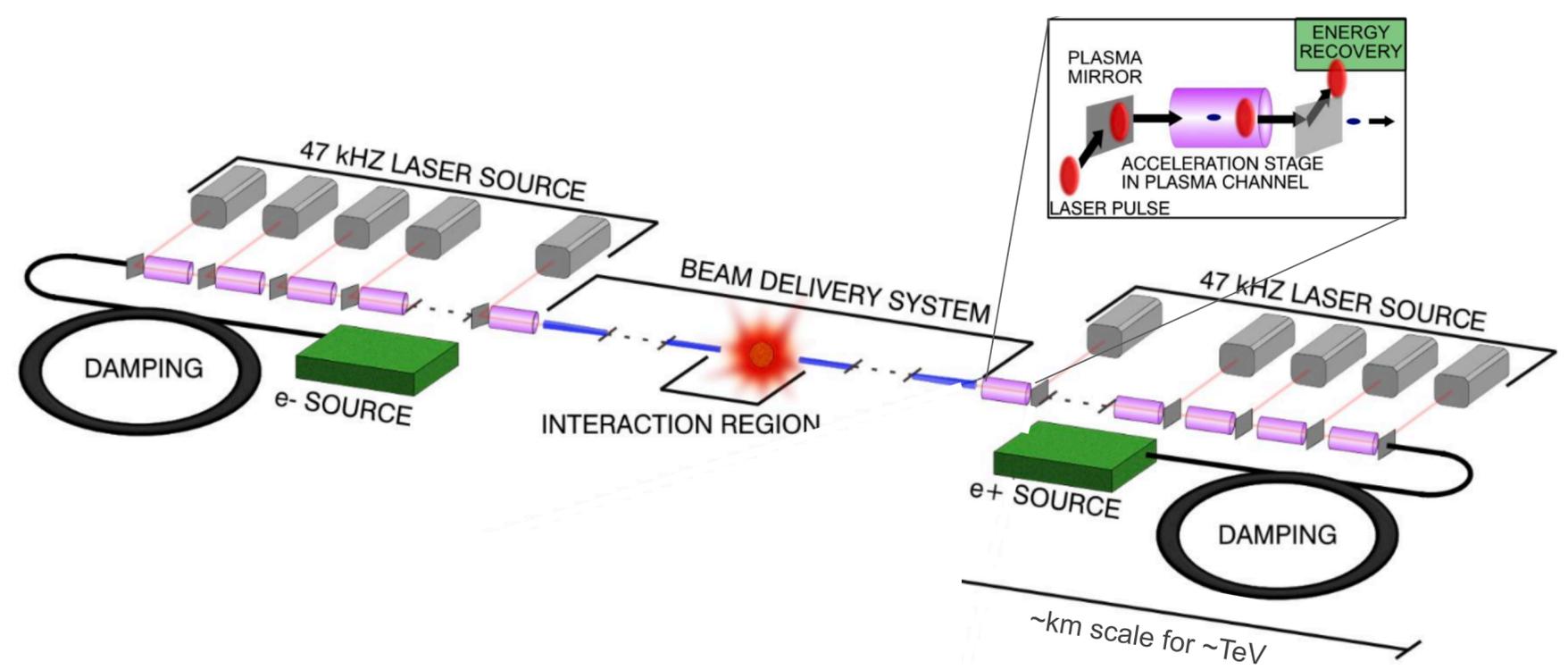
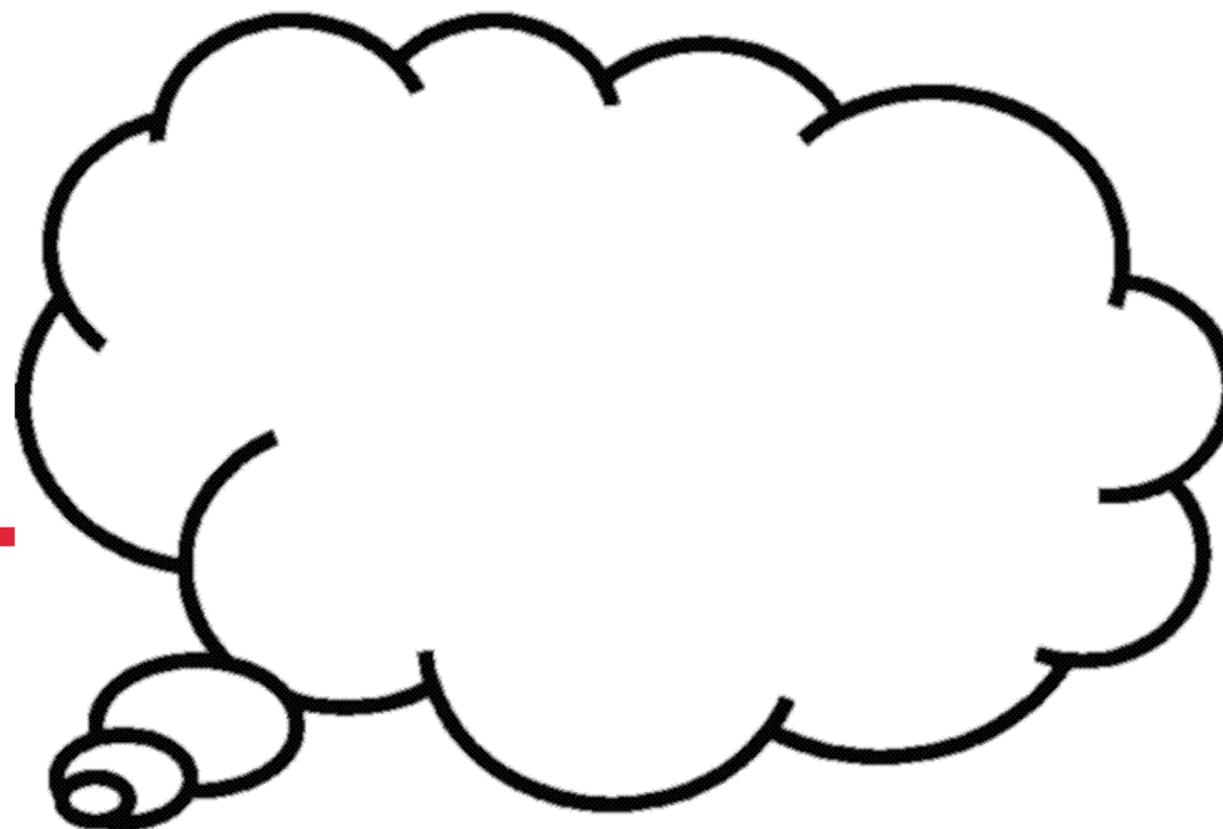
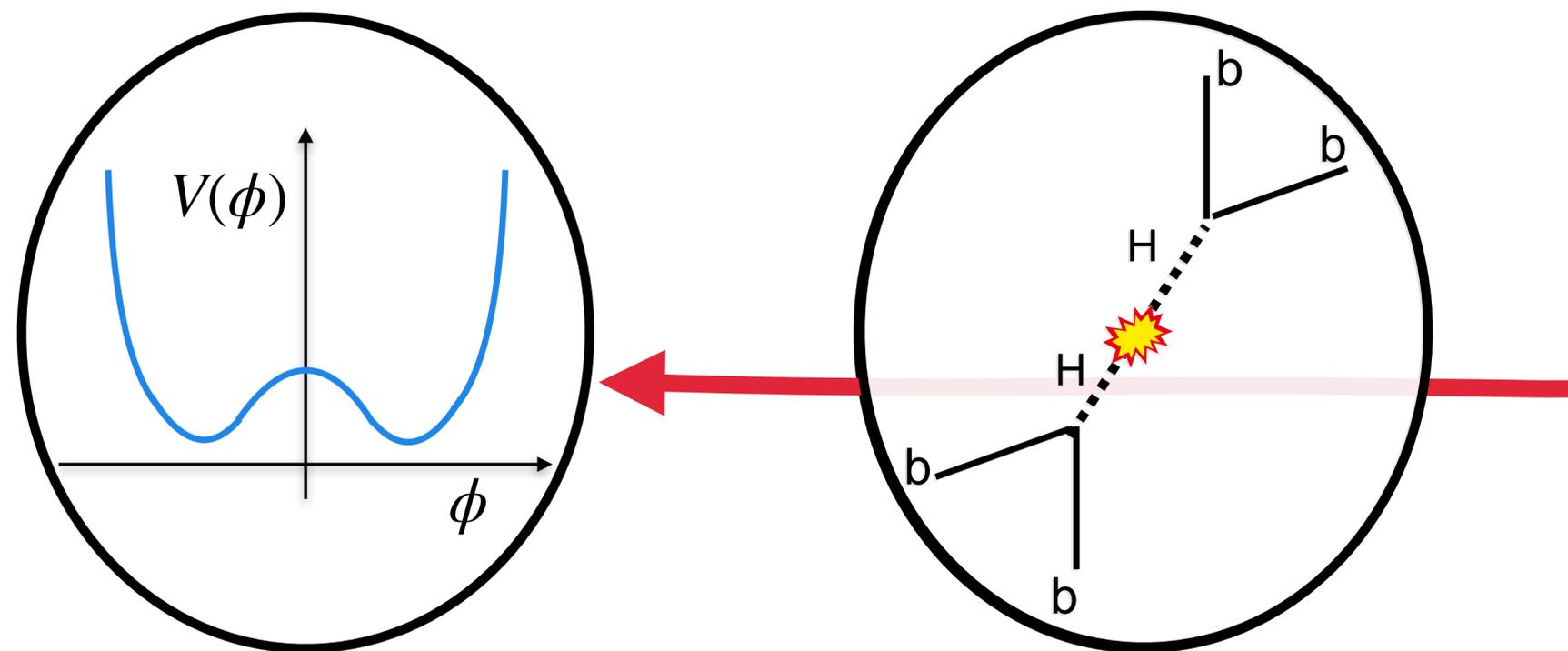
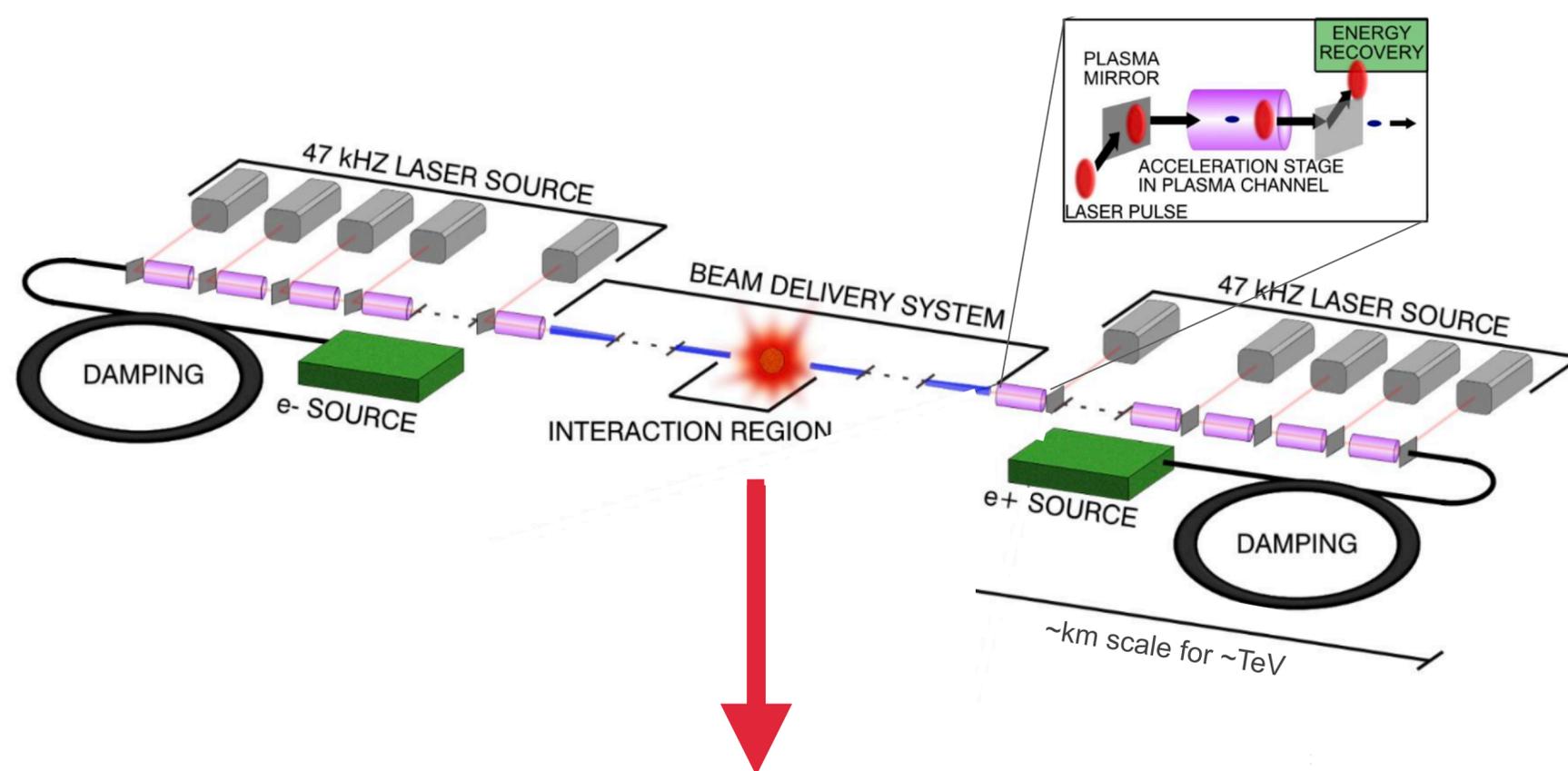
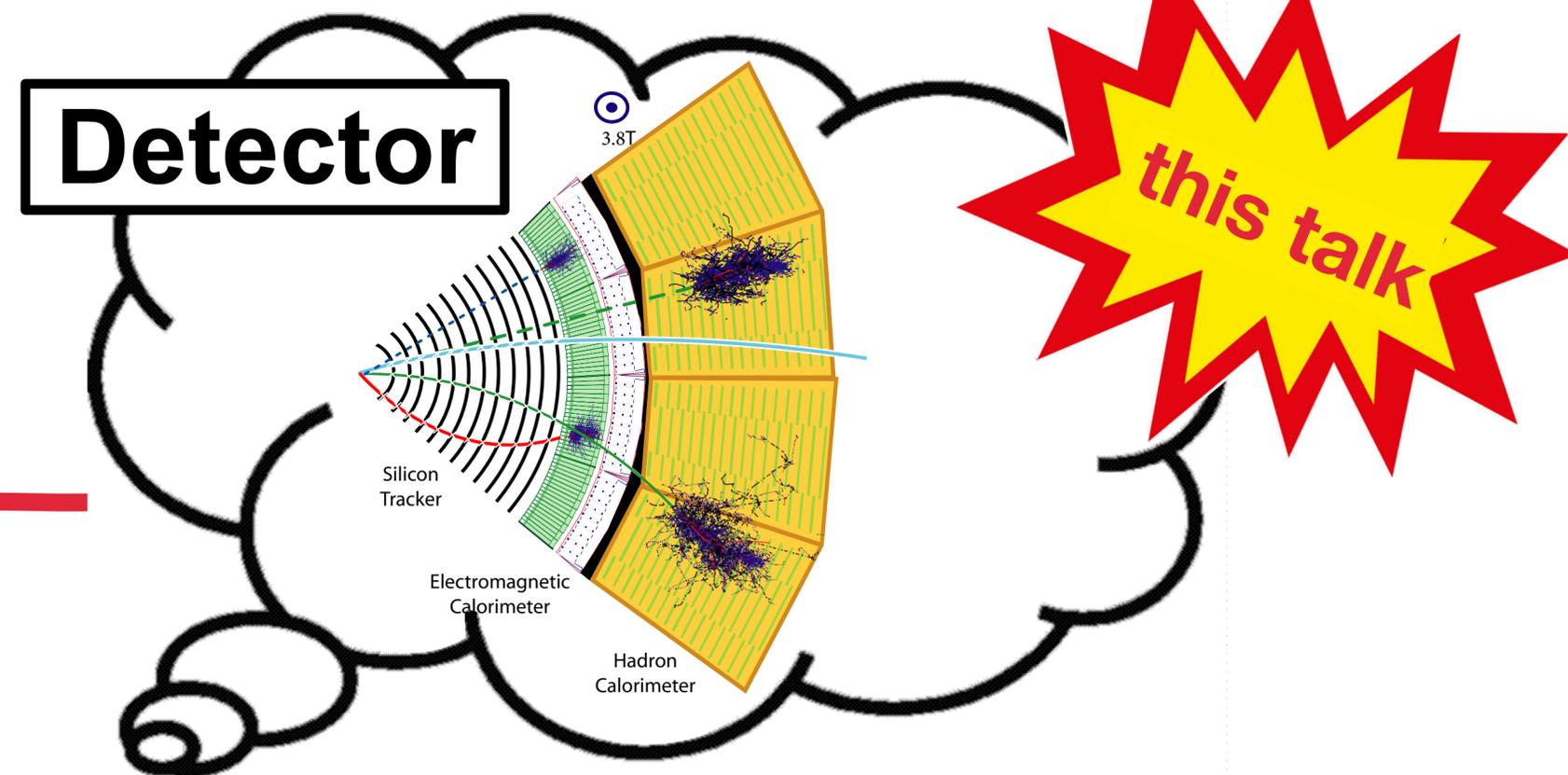
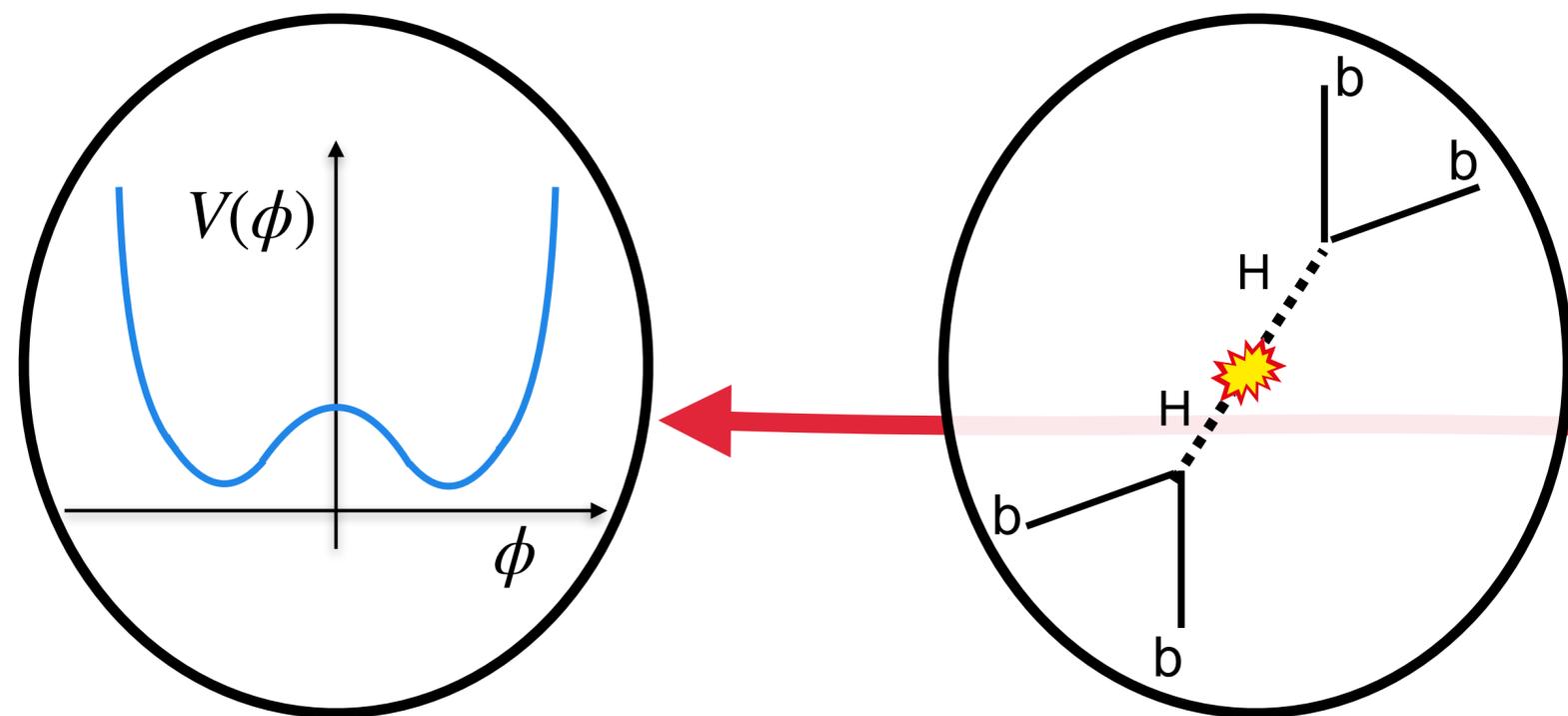
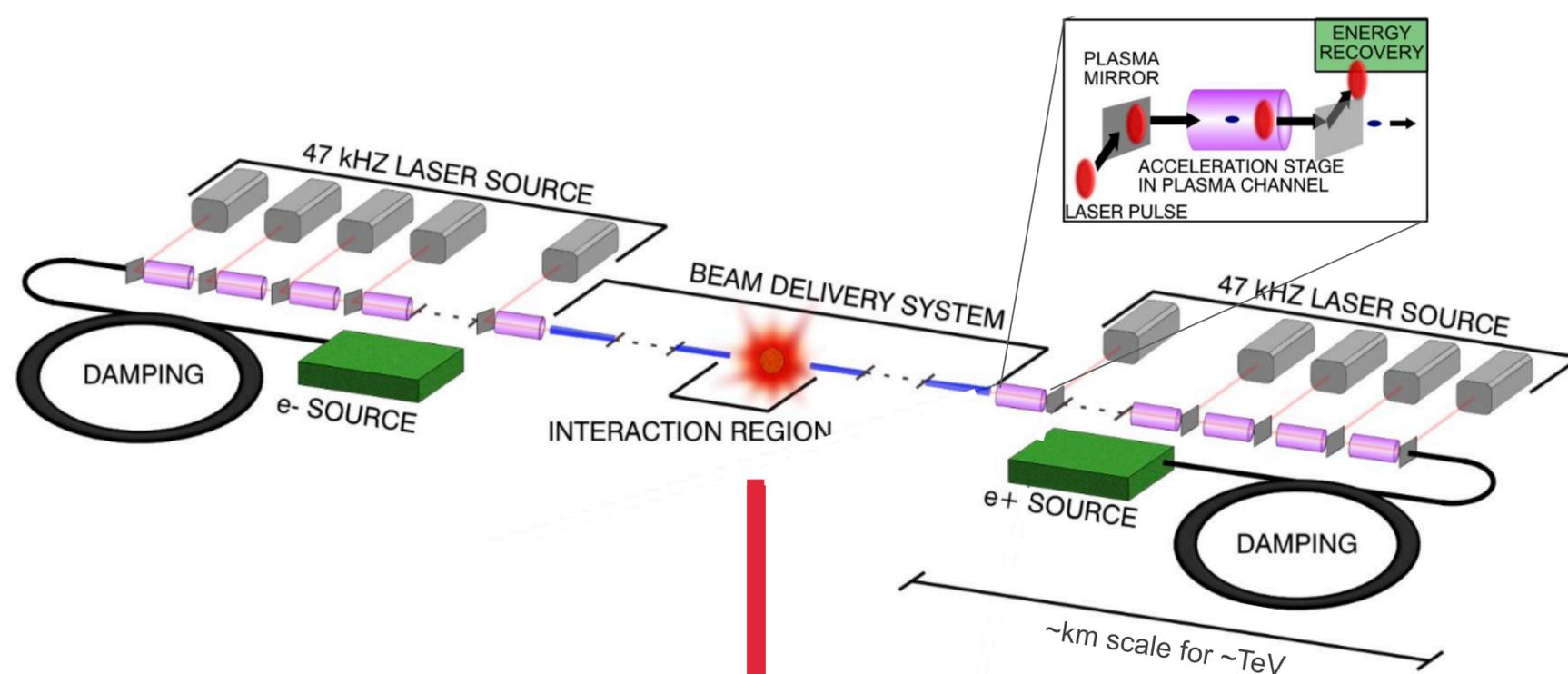


Fig. inspired by K.Cranmer's

Goal: Provide a detector description to “sell” the physics case to **unlock funding for advanced accelerator R&D**

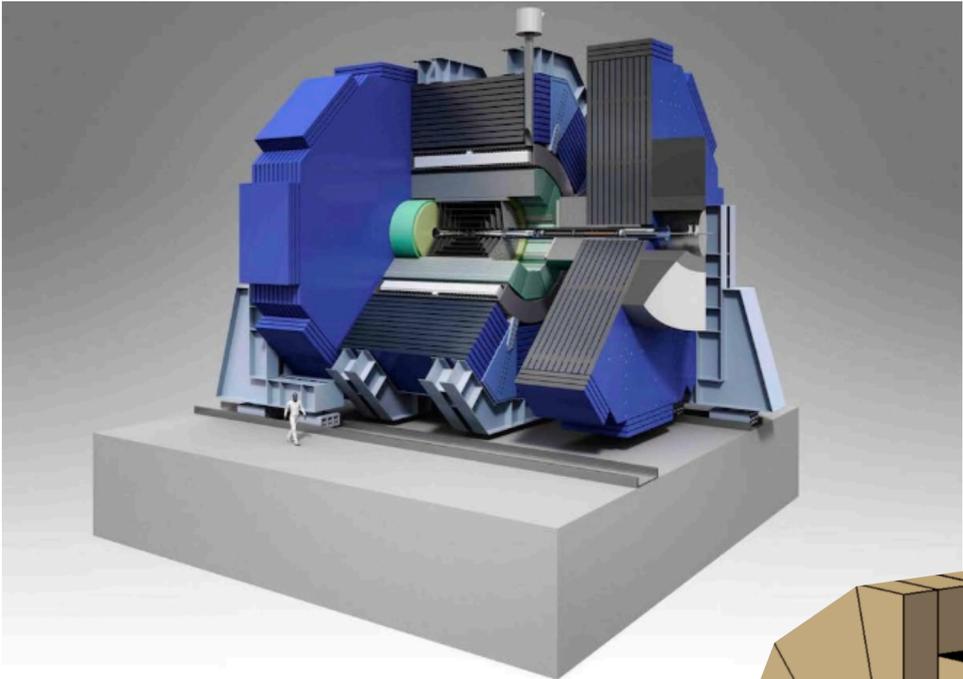


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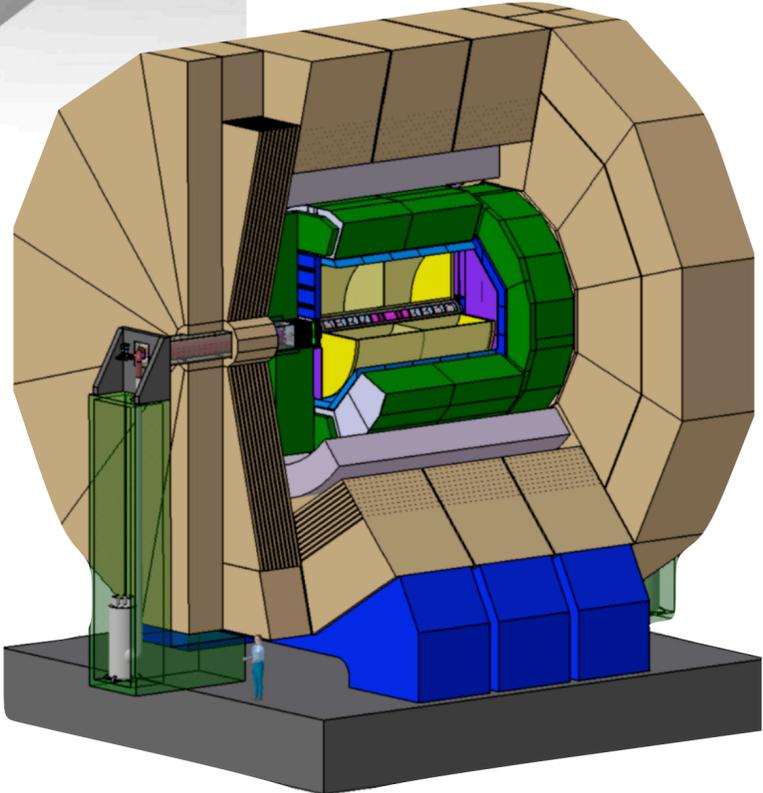
(Selected) detectors “on the market”

SiD Detector



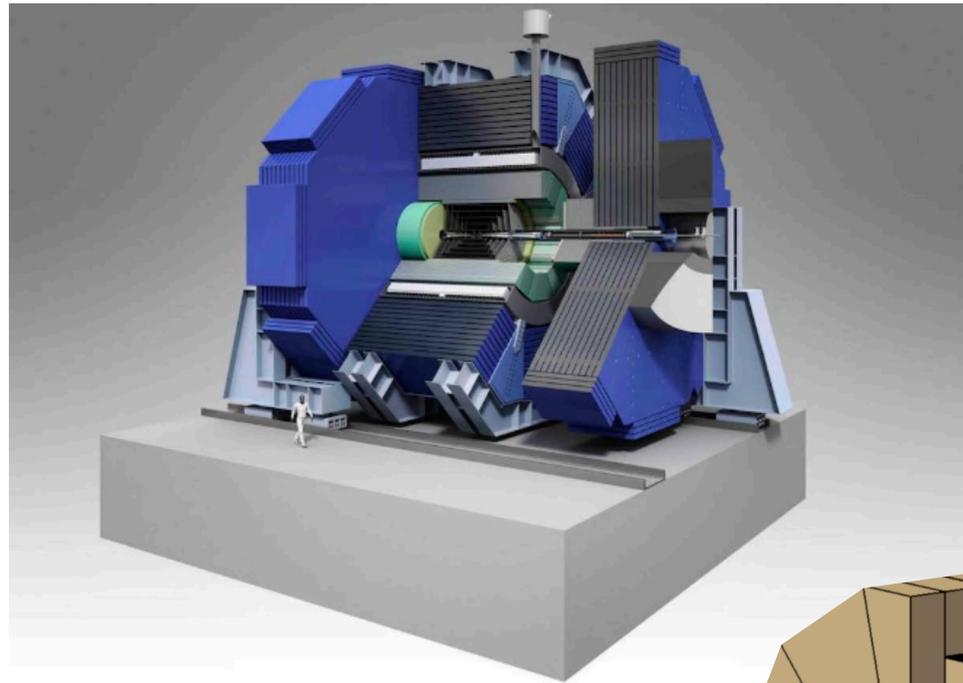
250 GeV; 500 GeV

International Linear Detector



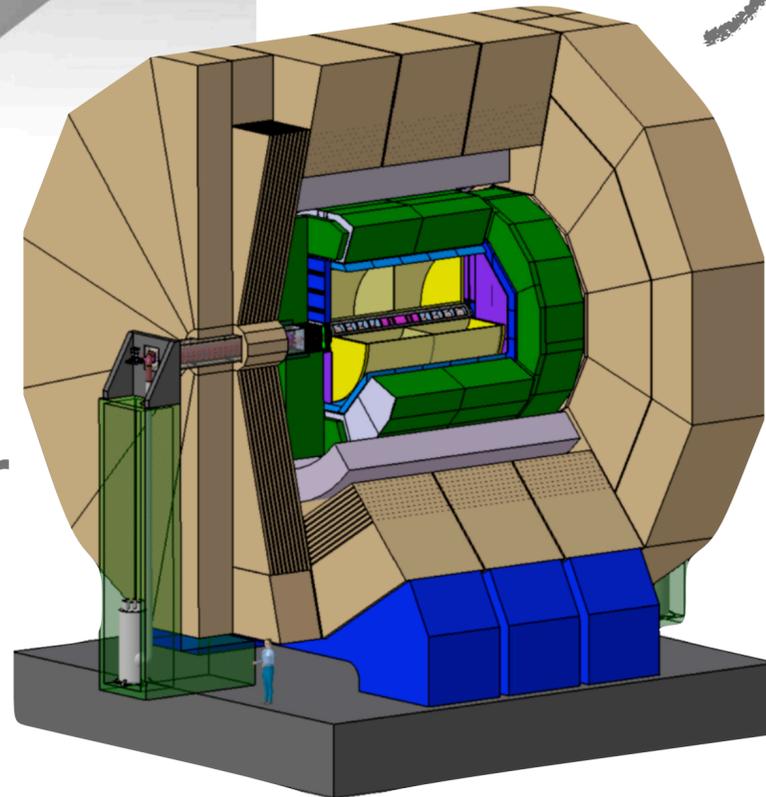
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SiD Detector

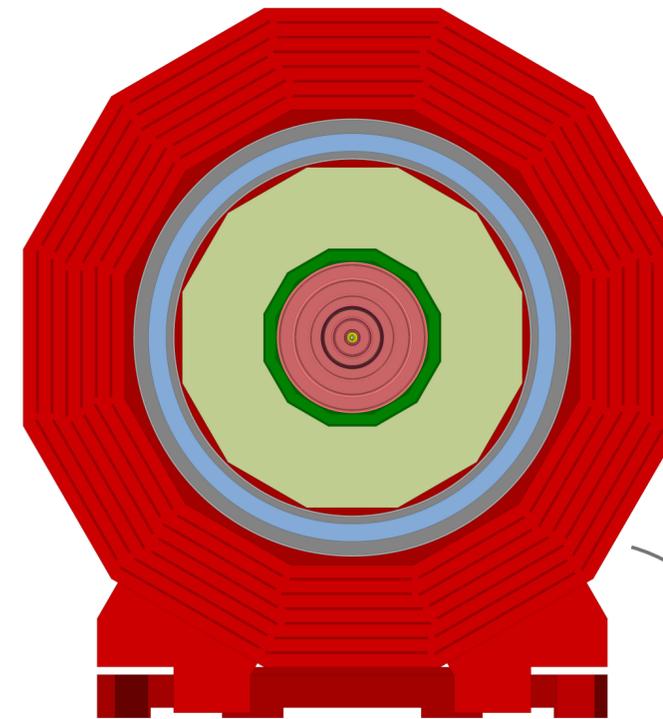


250 GeV; 500 GeV

International Linear Detector



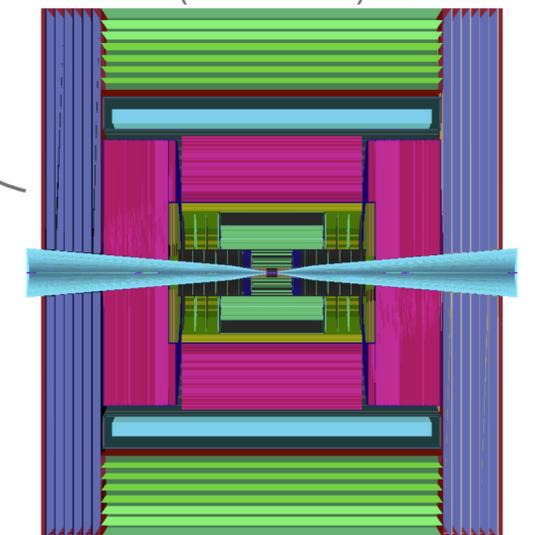
CLICdet

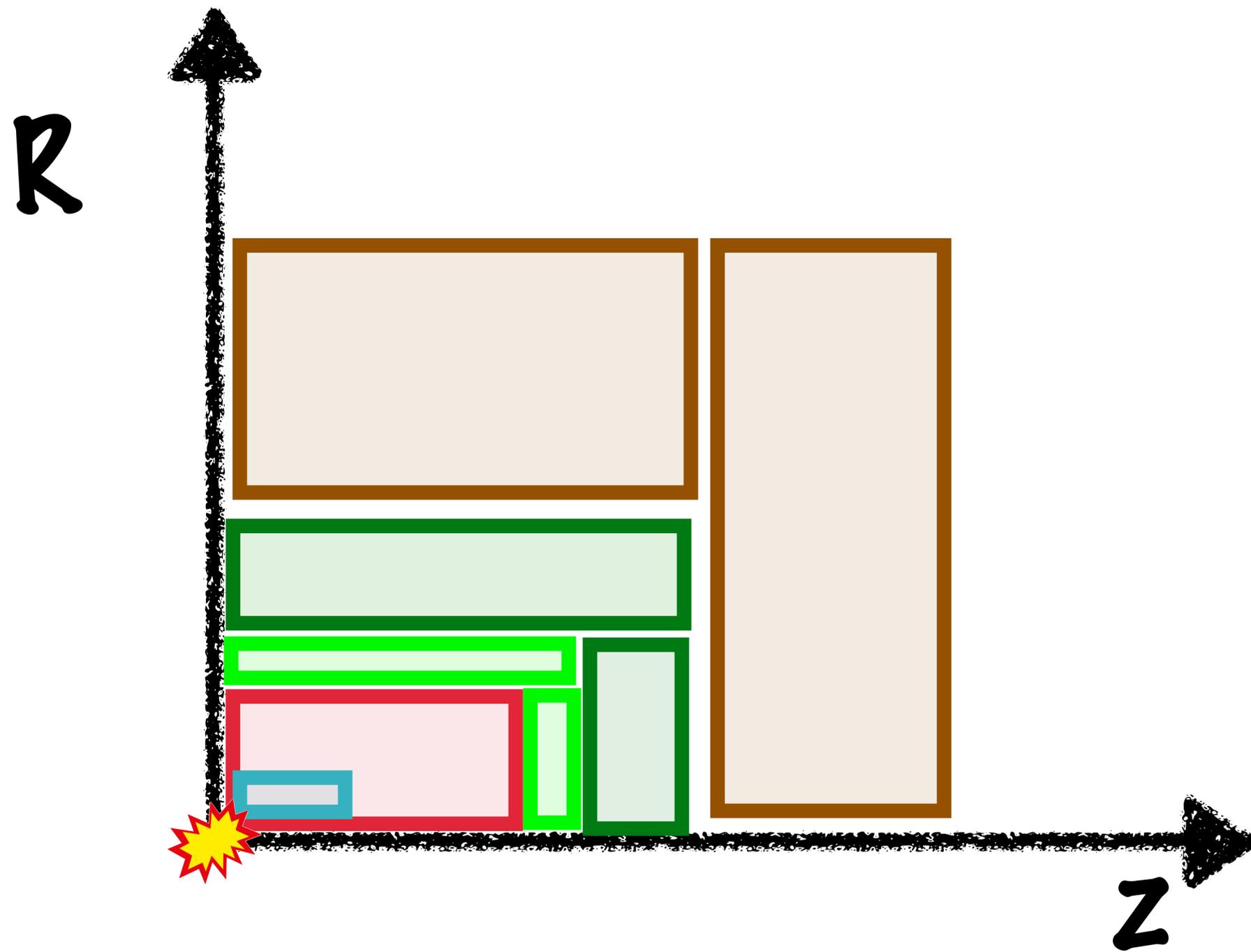


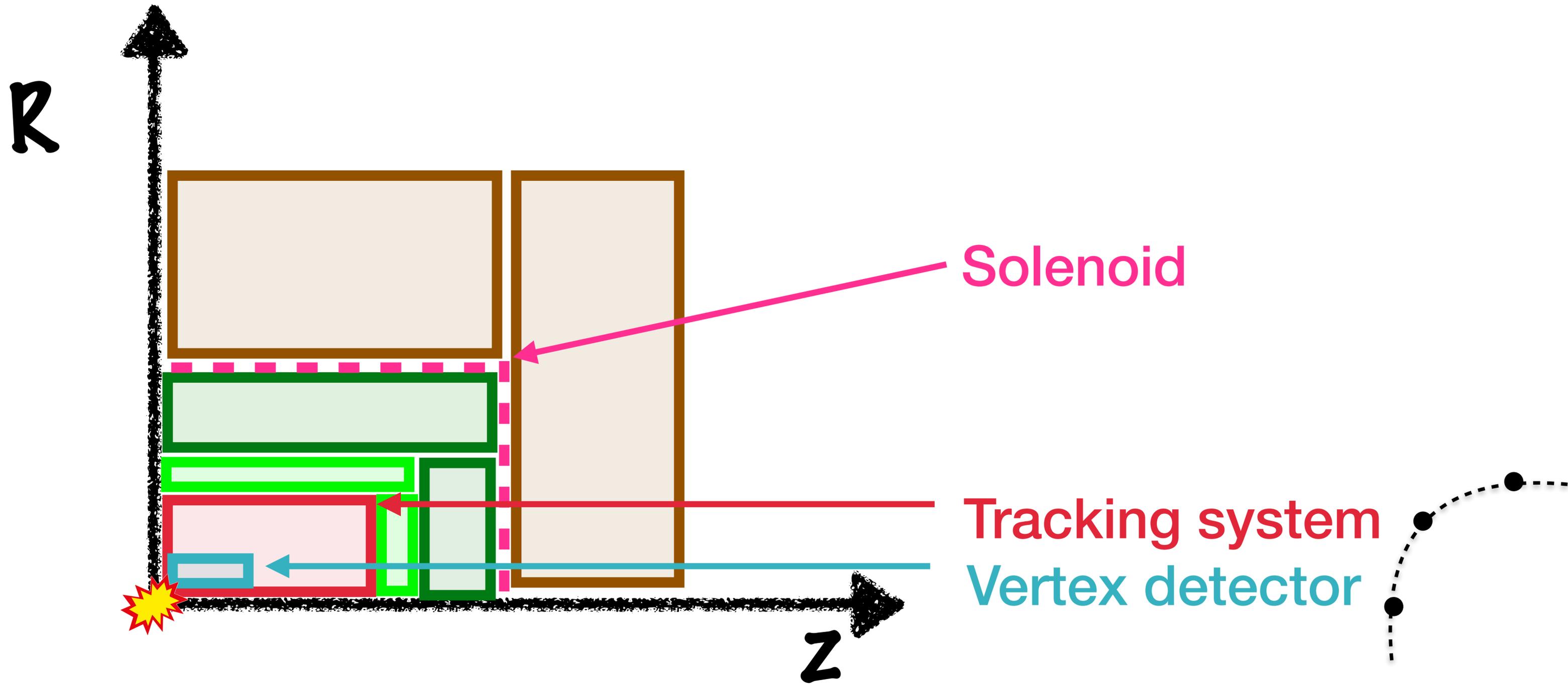
highest e^+e^- collider
formerly considered

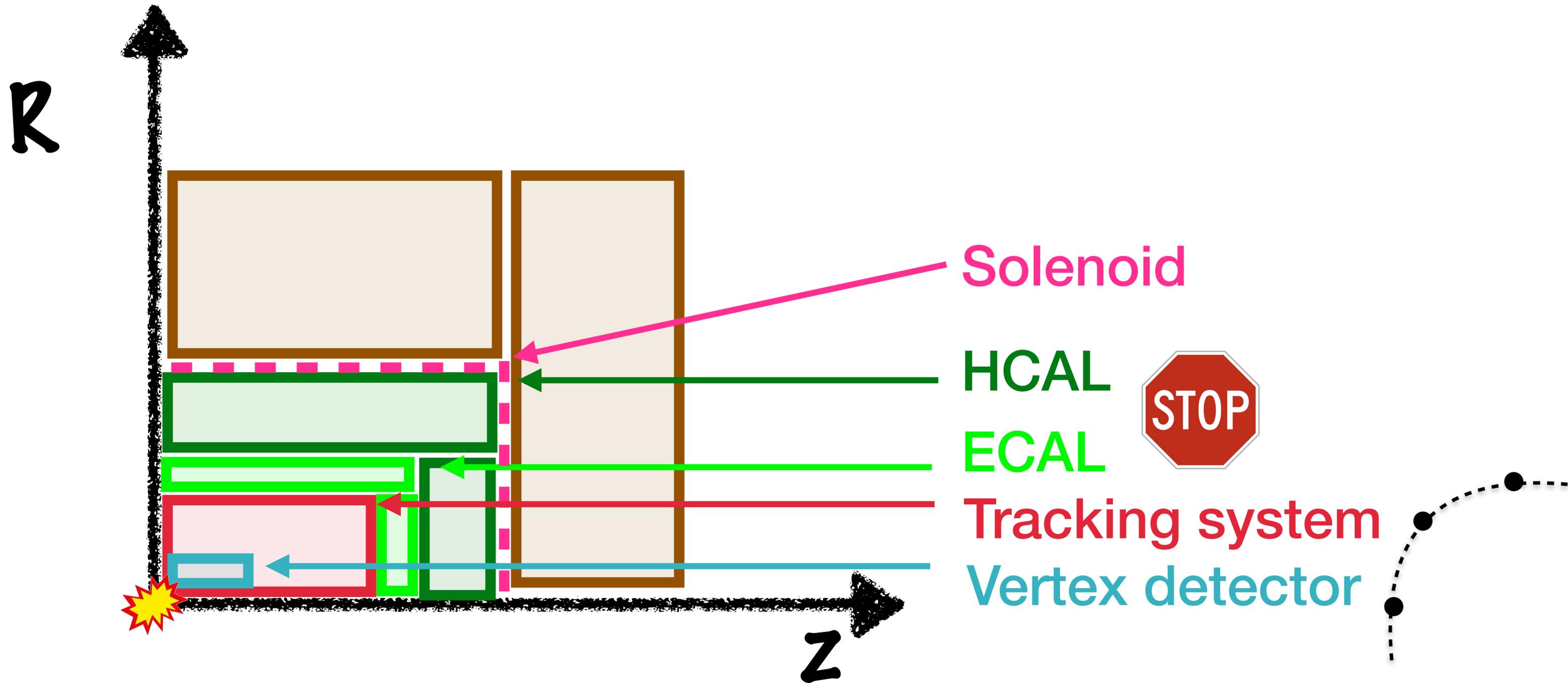
3 TeV; 10 TeV (!)

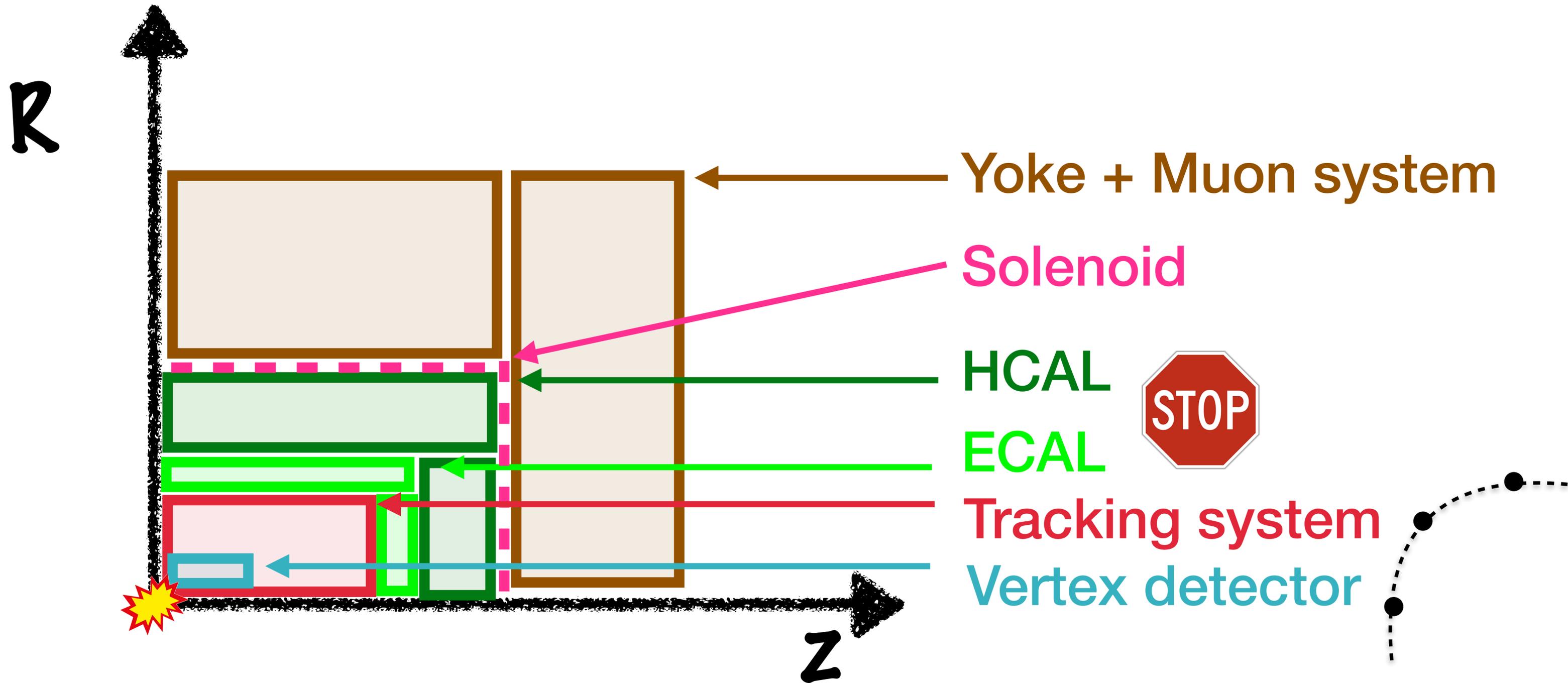
MuColl Det (MUSIC)

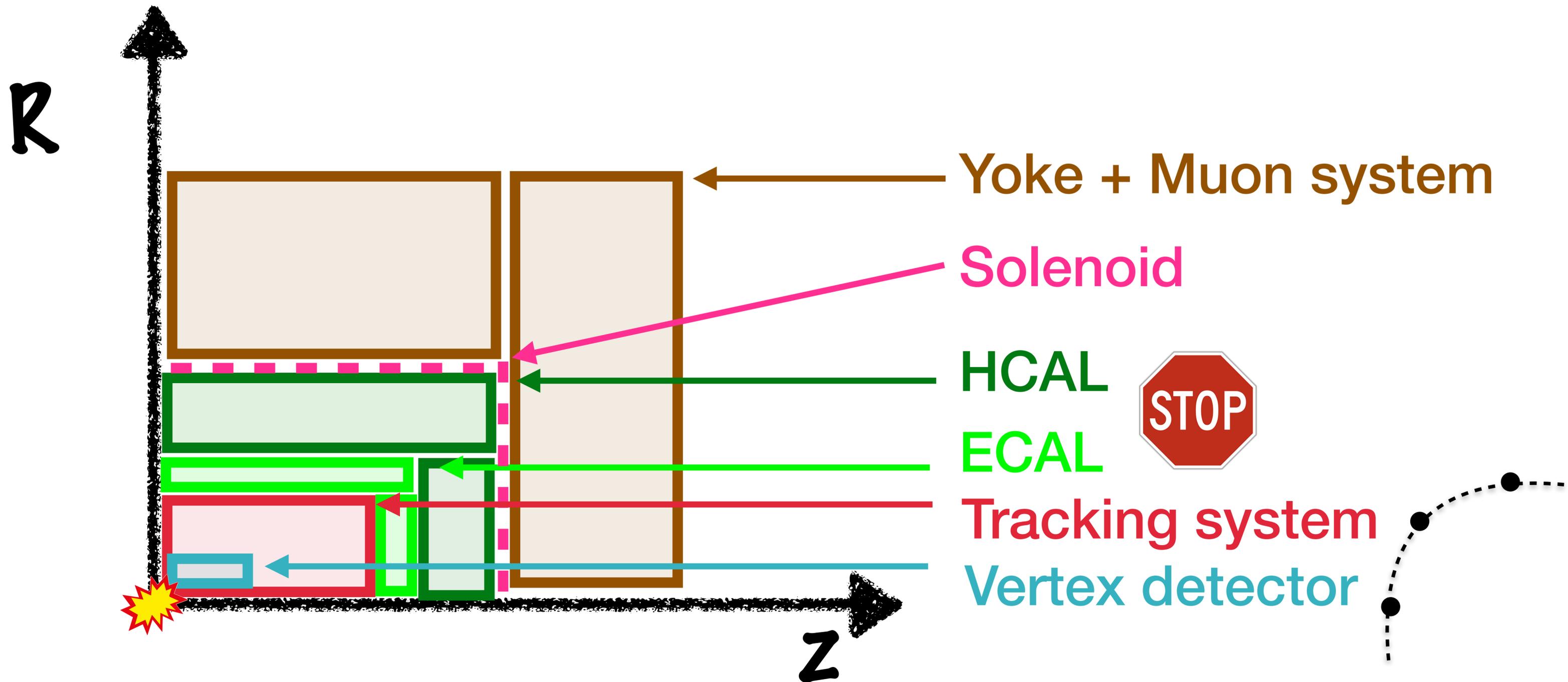




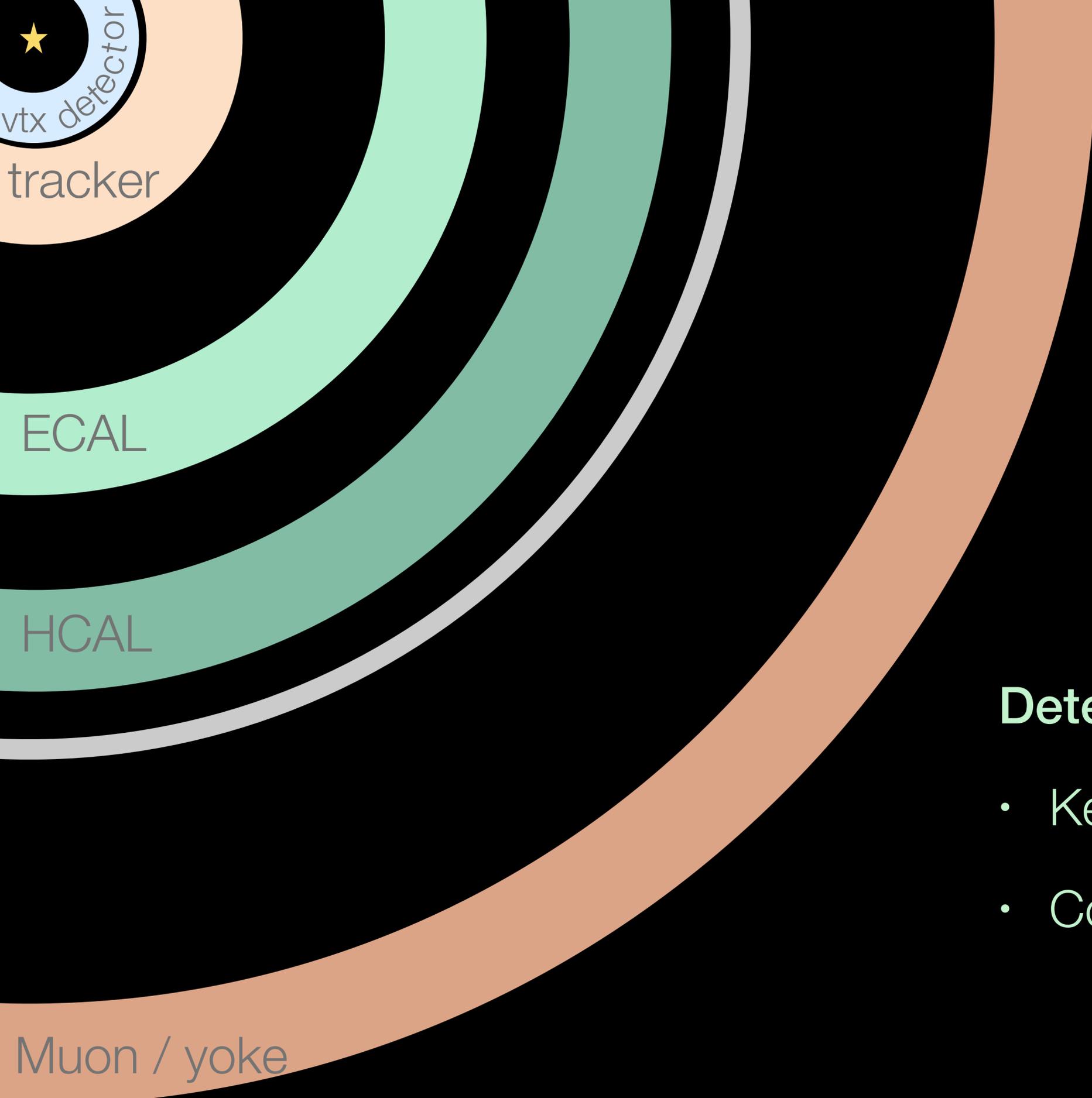








Vertex detector closest to the **interaction point**, and will be most susceptible to the large backgrounds at 10 TeV.

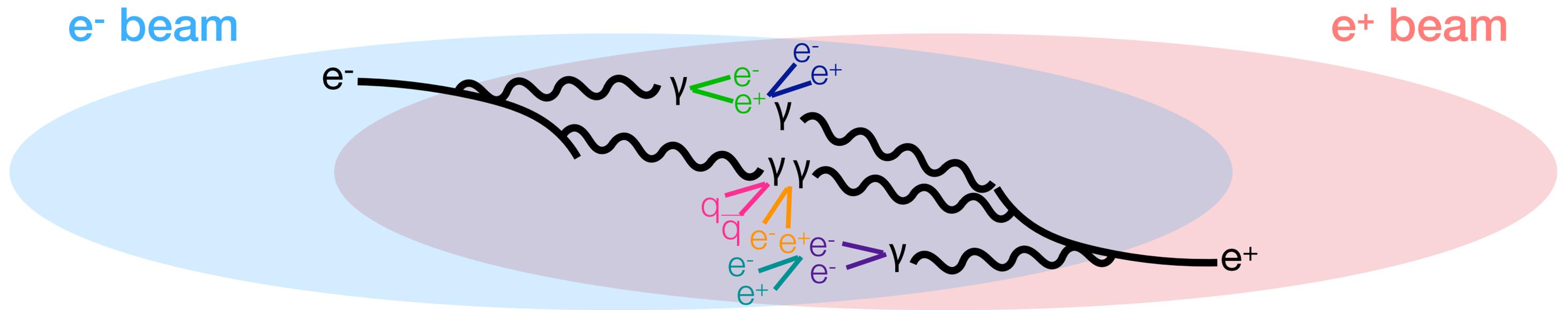


Machine Detector Interface

- Status of existing efforts
- Next plans for the group

Detector design

- Key physics drivers
- Considerations for 10 TeV optimization



Beamstrahlung (or beam-beam) interactions... HUGE background at **10 TeV**.

Goal: Design a robust detector for these backgrounds.

Group goals

Detector configurations

beam-beam codes

Guinea Pig

CAIN

WarpX

OSIRIS

VLPL

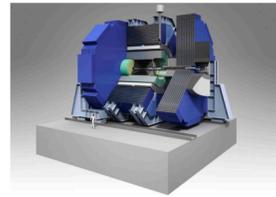
...

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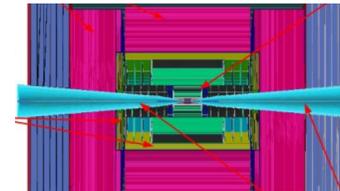
Detector configurations



SiD



MuColl



...

beam-beam codes

Guinea Pig



Dimitris Ntounis
Lindsey Gray; NH

C³ pipeline

CAIN

WarpX



Angira Rastogi
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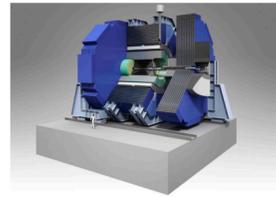
VLPL

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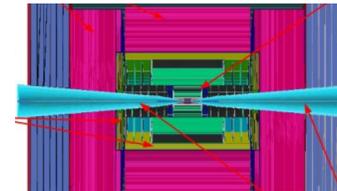
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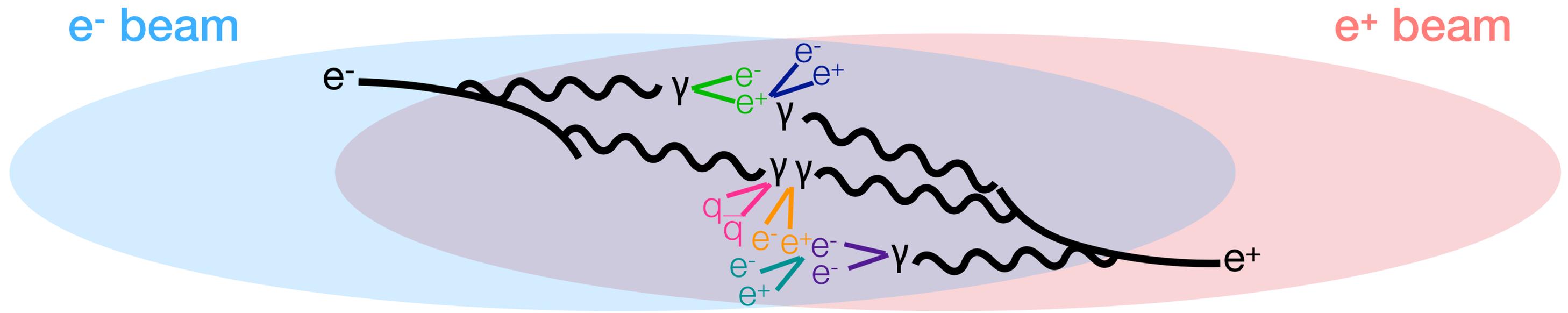
OSIRIS

VLPL



Arianna's meme

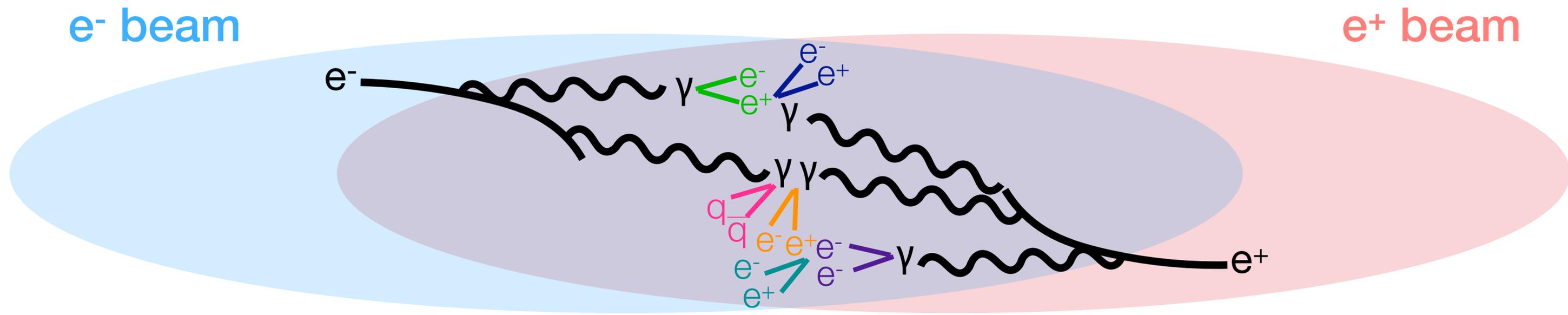
Please interpret these "first pipeline" studies qualitatively.
— Simone Pagan Griso



Forward processes (expected minimal impact on detector design)

Table 1-1.3 Background sources for the nominal 500 GeV beam parameters. [ILC Detailed Baseline Design 1306.6329]

| Source | #particles per bunch | < E > (GeV) |
|--|-----------------------|-------------|
| Disrupted primary beam | 2×10^{10} | 244 |
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| $\gamma\gamma \rightarrow$ hadrons/muons | 0.5 events/1.3 events | - |



Running Guinea Pig for incoherent pairs background.

💕 Ty Arianna Formenti for sharing GP samples and configuration. ✓

Ty Tim Barklow for sharing CAIN $\gamma\gamma$ lumi files ⚠️ with us (might take a bit of time to get off the ground 🛩️)

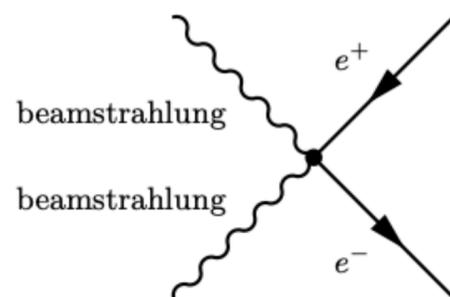
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Incoherent production

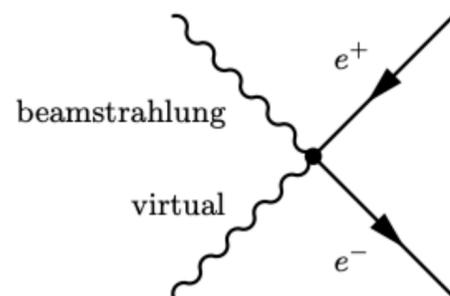
Breit-Wheeler

5%



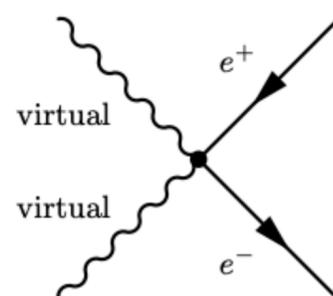
Landau-Lifschitz

35%

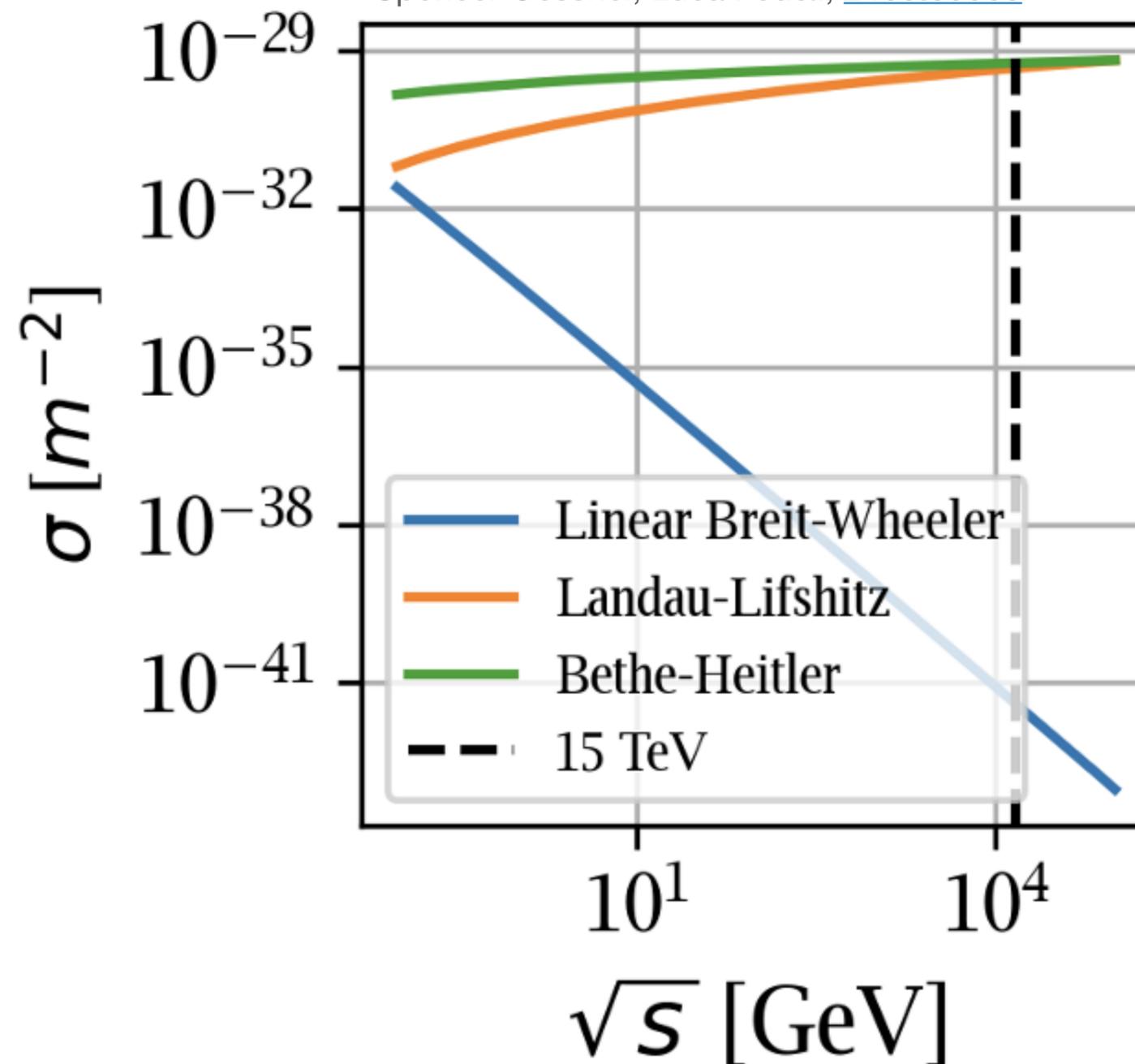


Bethe-Heitler

60%



Bao Nguyen, Arianna Formenti, Remi Lehe, Jean-Luc Vay, Spencer Gessner, Luca Fedeli; [2405.09583](https://arxiv.org/abs/2405.09583)



The percentages from the ILC config run:

Fig 2 from [Phys Rev Accel Beams 27, 061001 \(2024\)](https://arxiv.org/abs/2405.09583);

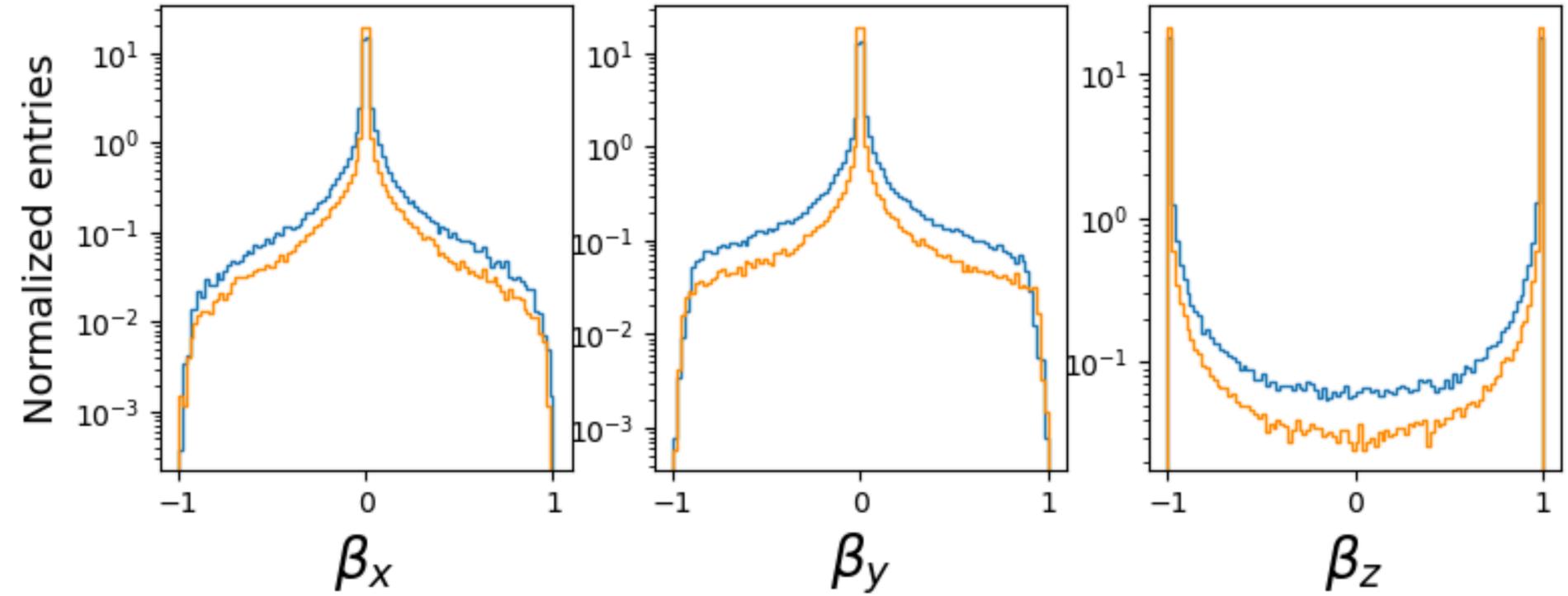
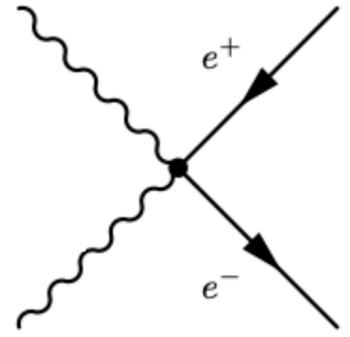
D. Ntounis, E. Nanni, C. Vernieri

Our setup (starting from work)

e+e- collisions

| | ILC | round "ultra-tight" |
|-------------------|------|------------------------|
| E [GeV] / beam | 125 | 5000 |
| ϵ_x [nm] | 5000 | 1E-04 |
| ϵ_y [nm] | 35 | 1E-04 |

Incoherent pair background



^ main differences, more details in the GP configs:

ILC: Jim_pars_Aug2023 in [acc_ILC.dat](#) (from Dimitris)

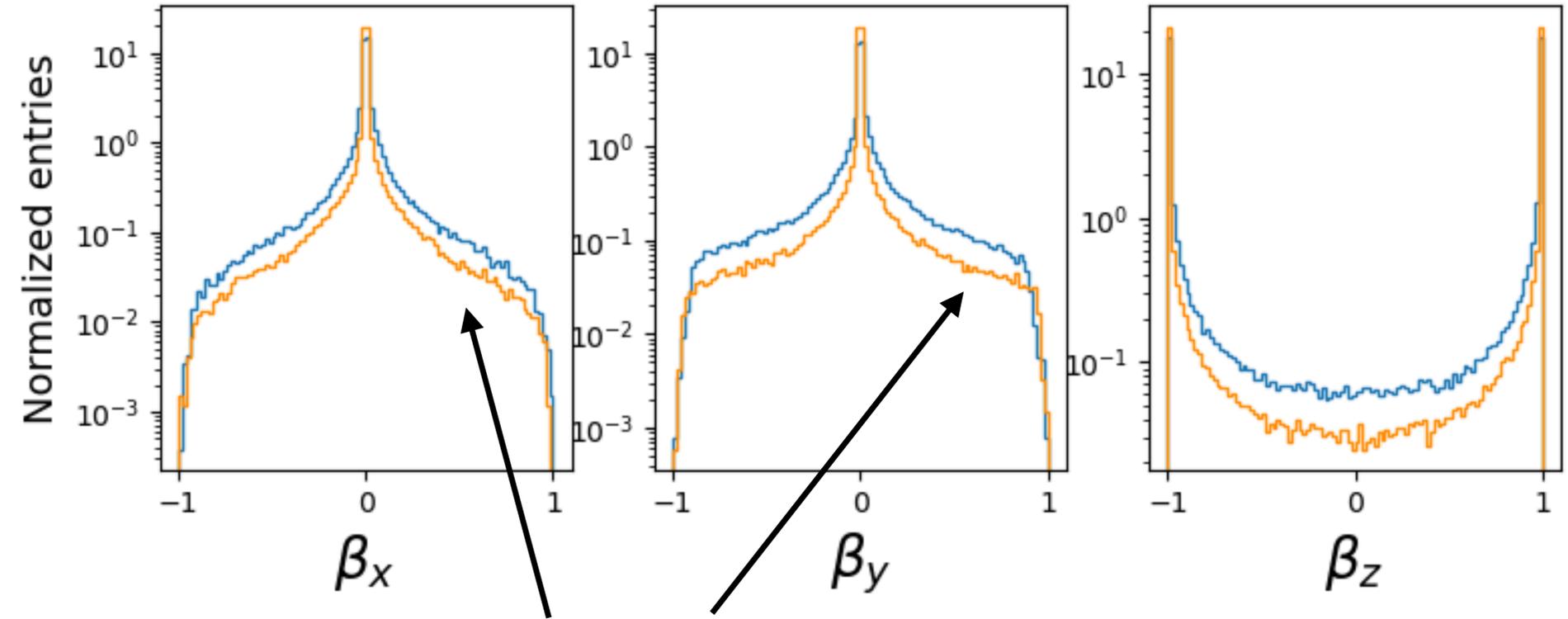
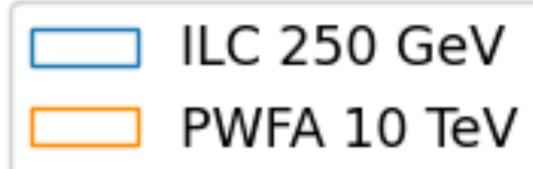
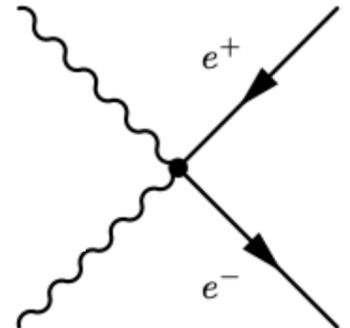
round "ultra-tight": [10TeV](#) (from Arianna)

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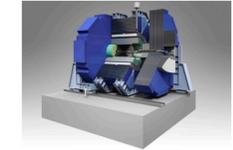
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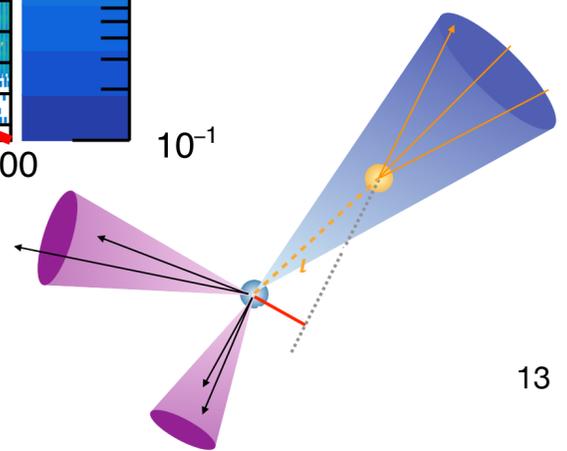
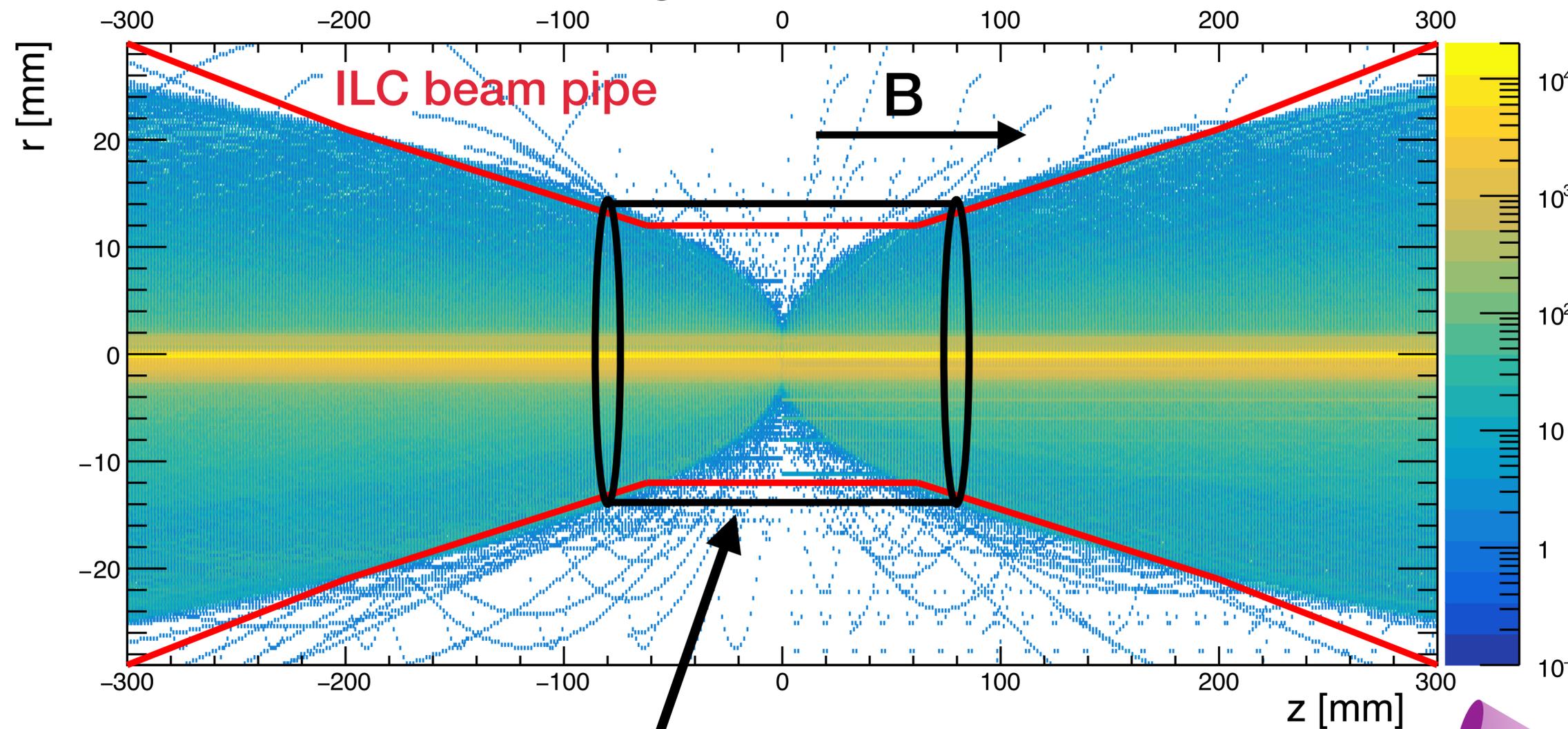
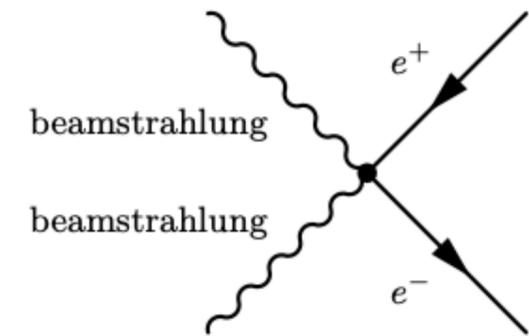
Less momenta in the transverse direction

Impact on detector (envelope plot)

Propagate the incoherent pairs produced by GP through uniform **5 T** B-field (SiD design).



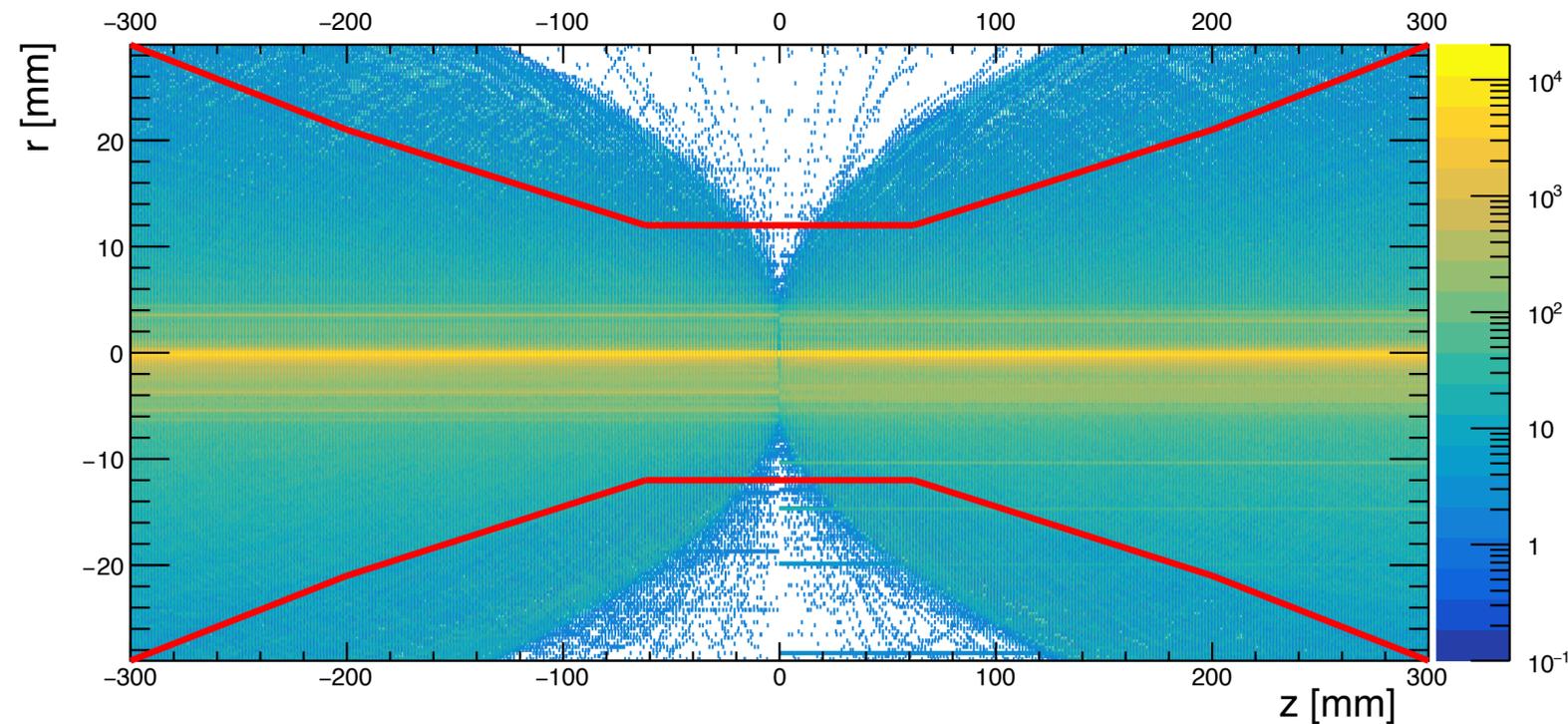
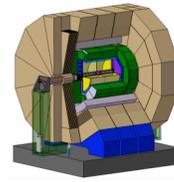
Guinea Pig
pairs.dat



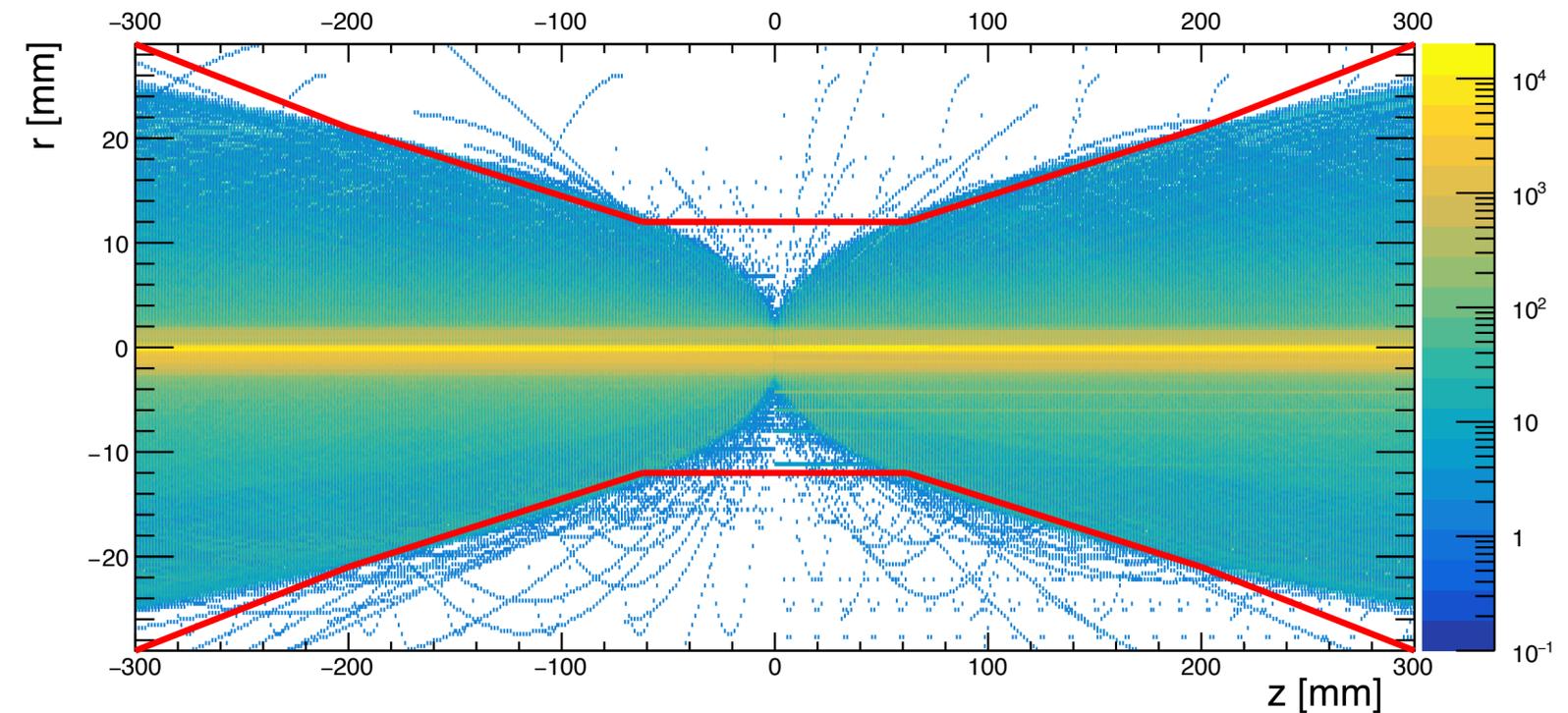
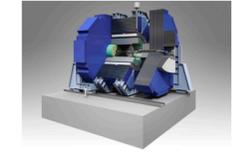
At 10 TeV, so far these incoherent backgrounds are very forward, very few with enough transverse momentum to enter vertex detector.

Varying B-field

2T: ILD design



5T: SiD design

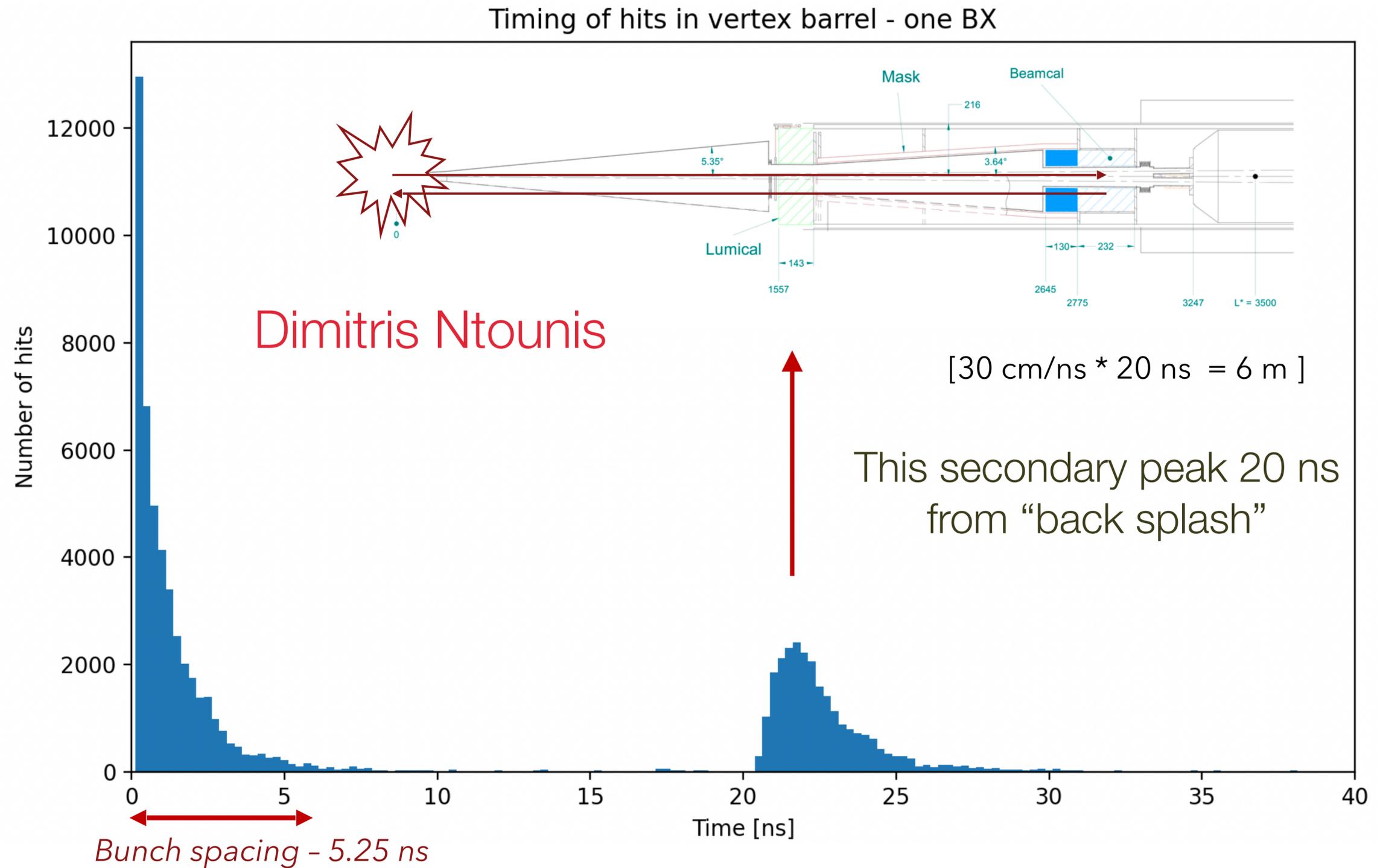
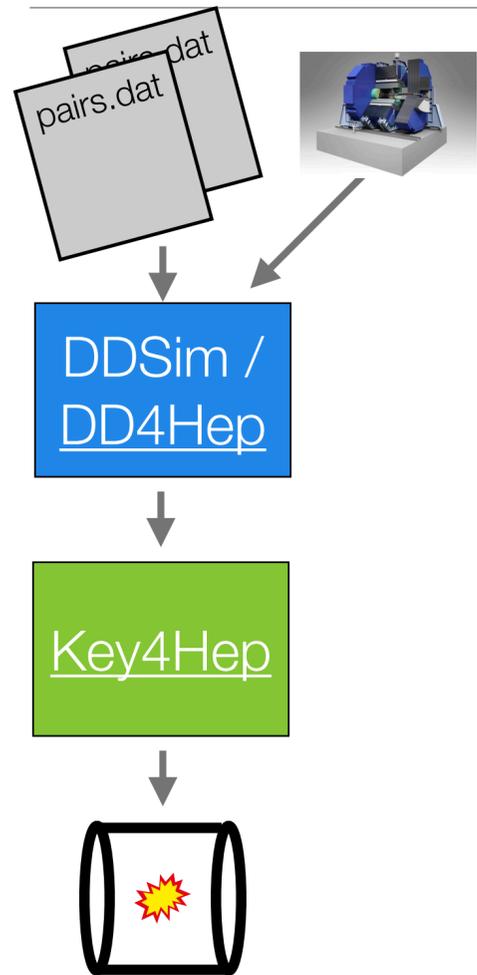


Stronger B-fields necessary to sweep these e^+e^- pairs out of the central region.

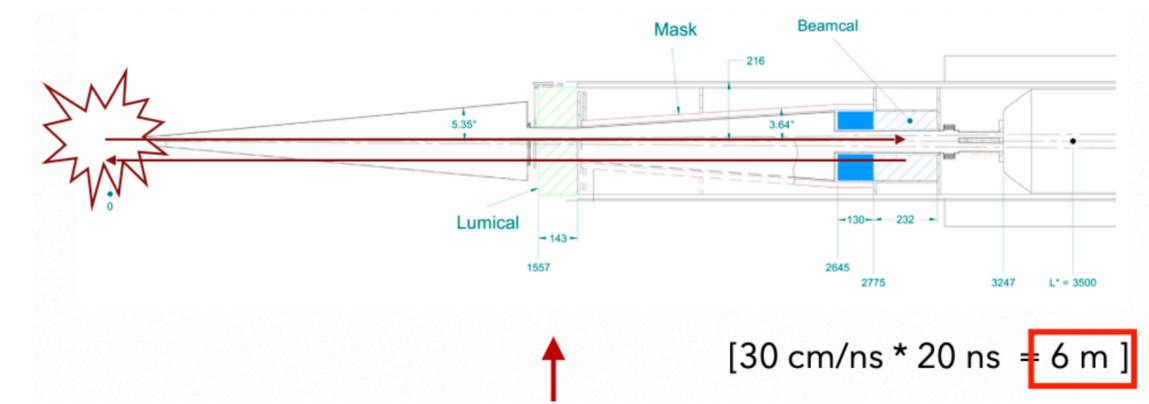
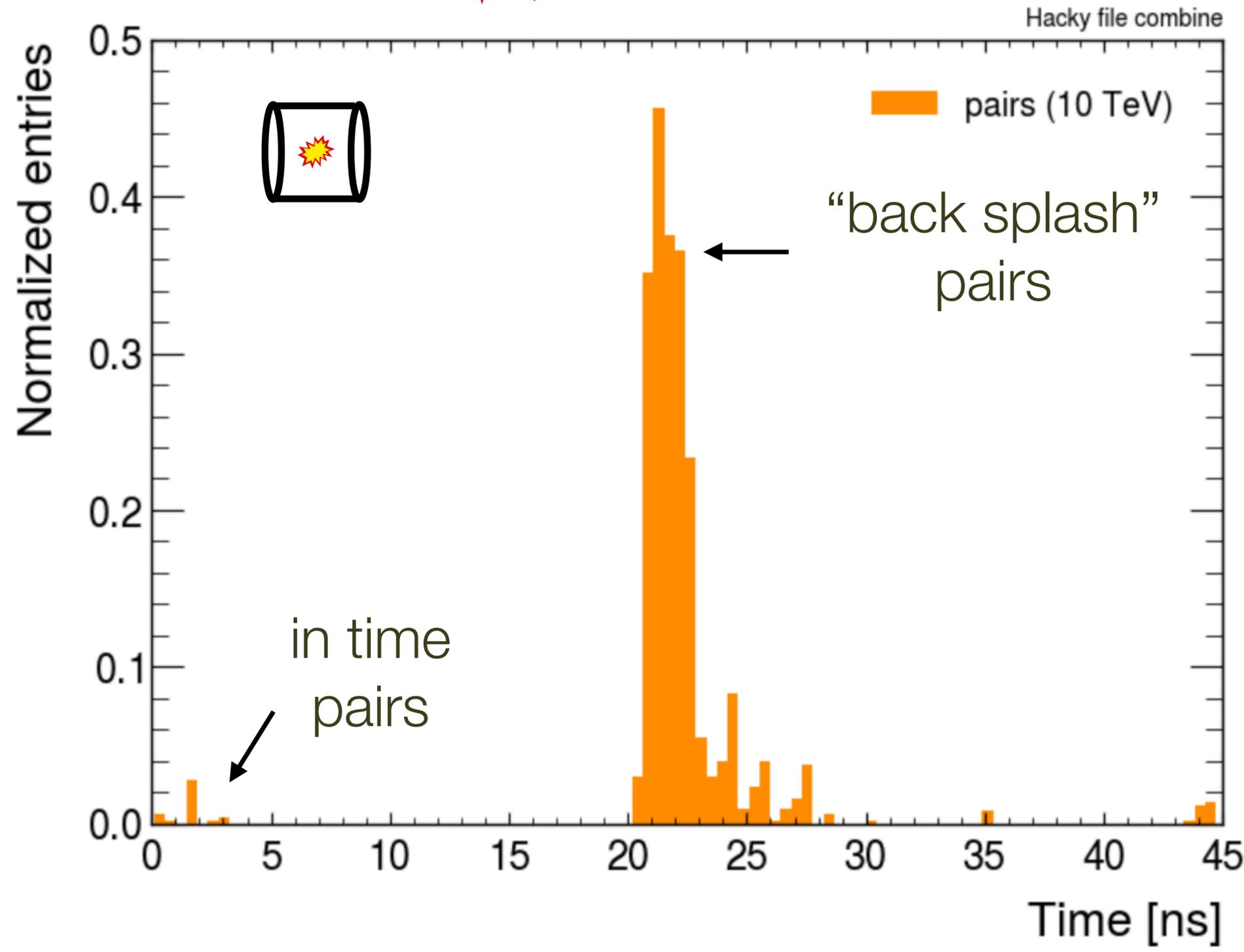
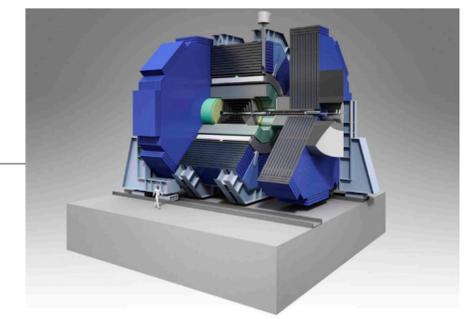
Part of the SiD detector design: ILC Detailed Baseline Design 1306.632

Antoine Laudrain (DESY): need 5 T field for HALF detector as well: [LHCP talk](#)

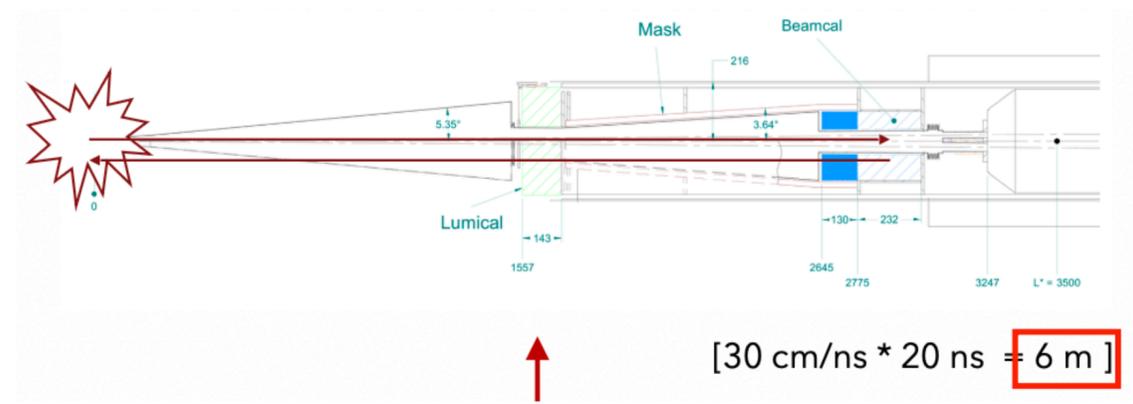
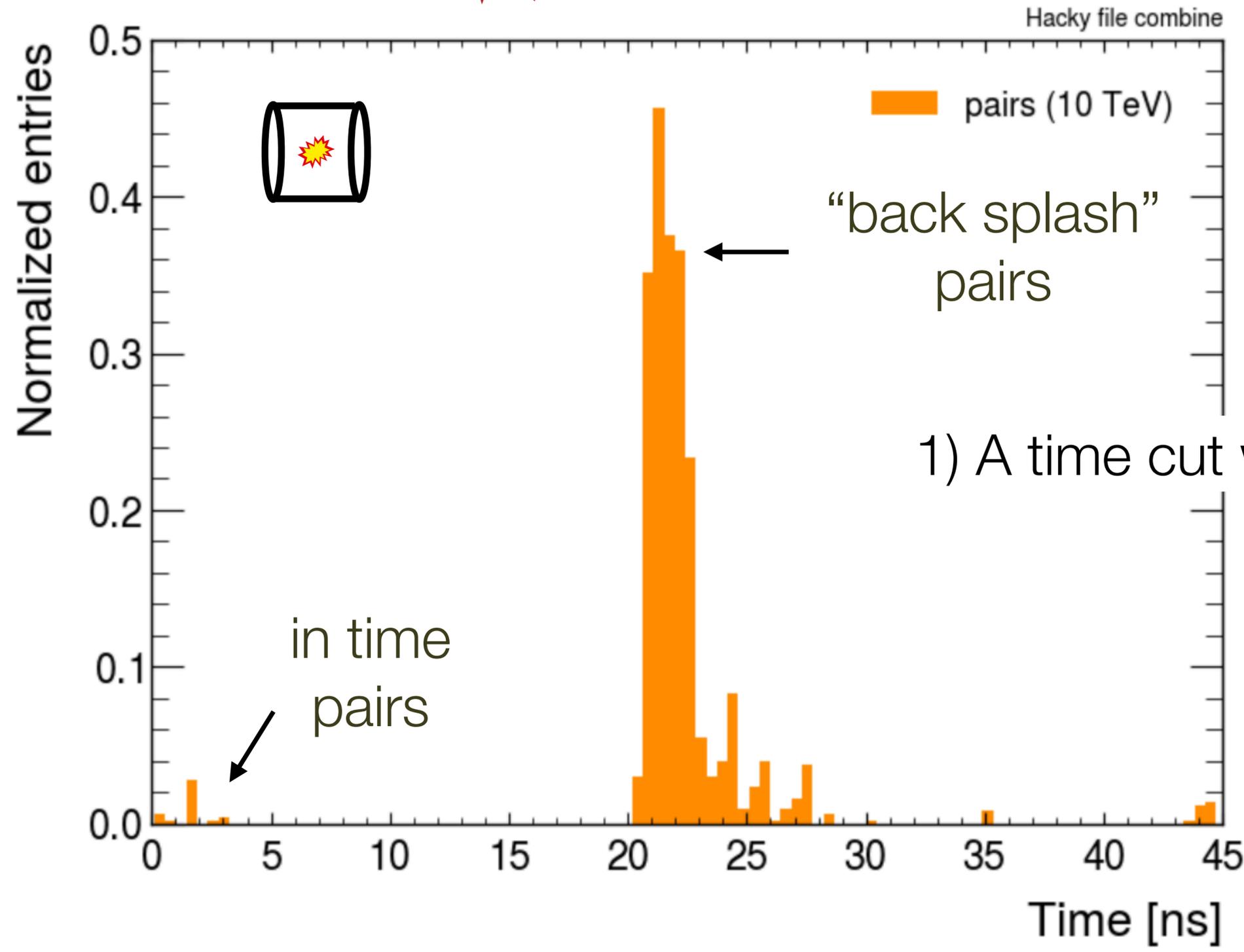
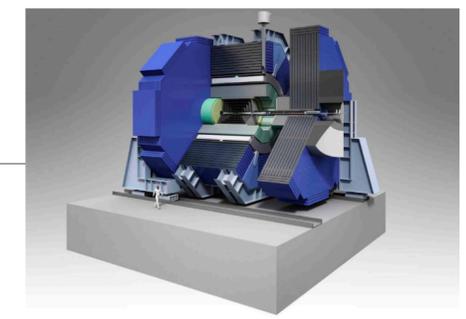
Time arrival



Time arrival

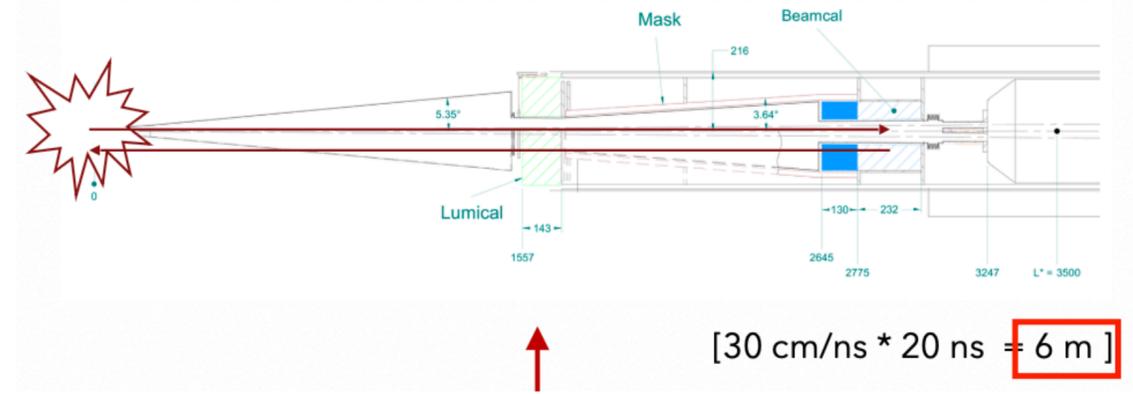
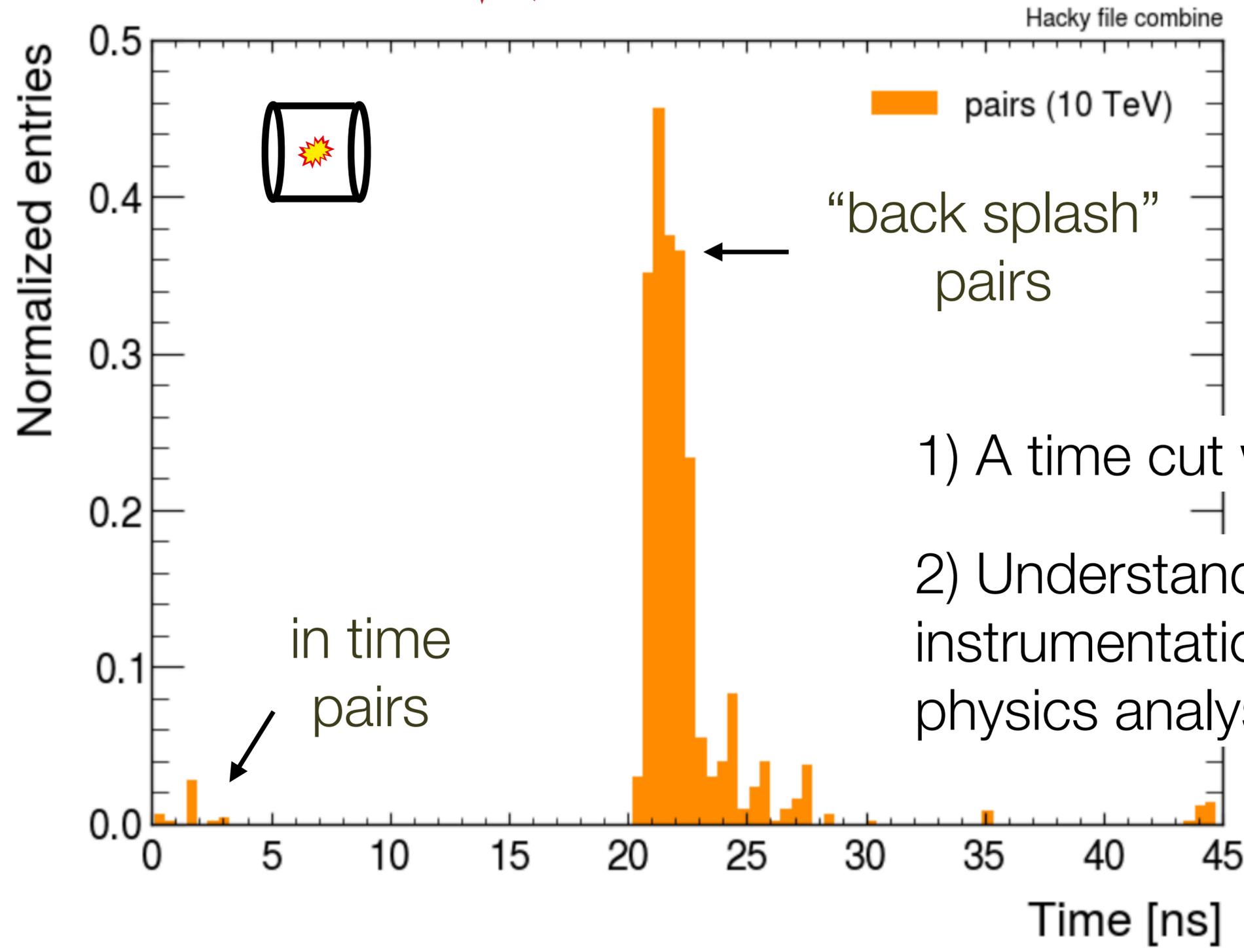
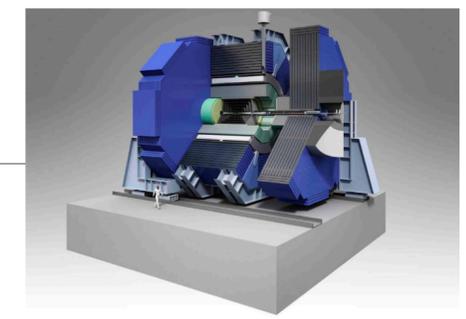


Time arrival



1) A time cut will help suppress this BIB.

Time arrival 10 TeV



- 1) A time cut will help suppress this BIB.
- 2) Understanding the forward instrumentation imperative for impact on physics analysis.

Discussion with the BDS team
Wednesday afternoon.

Hadron photoproduction 250 GeV

| Source | #particles per bunch | < E > (GeV) |
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Developed by Tim Barklow and Lindsey Gray: [ECFA talk](#)

e^+e^- pairs

$\gamma\gamma \rightarrow$ hadrons

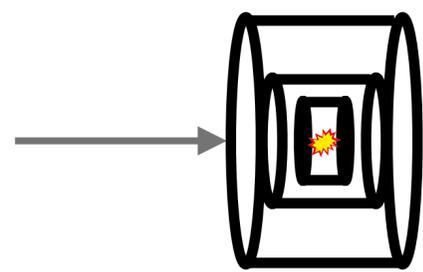
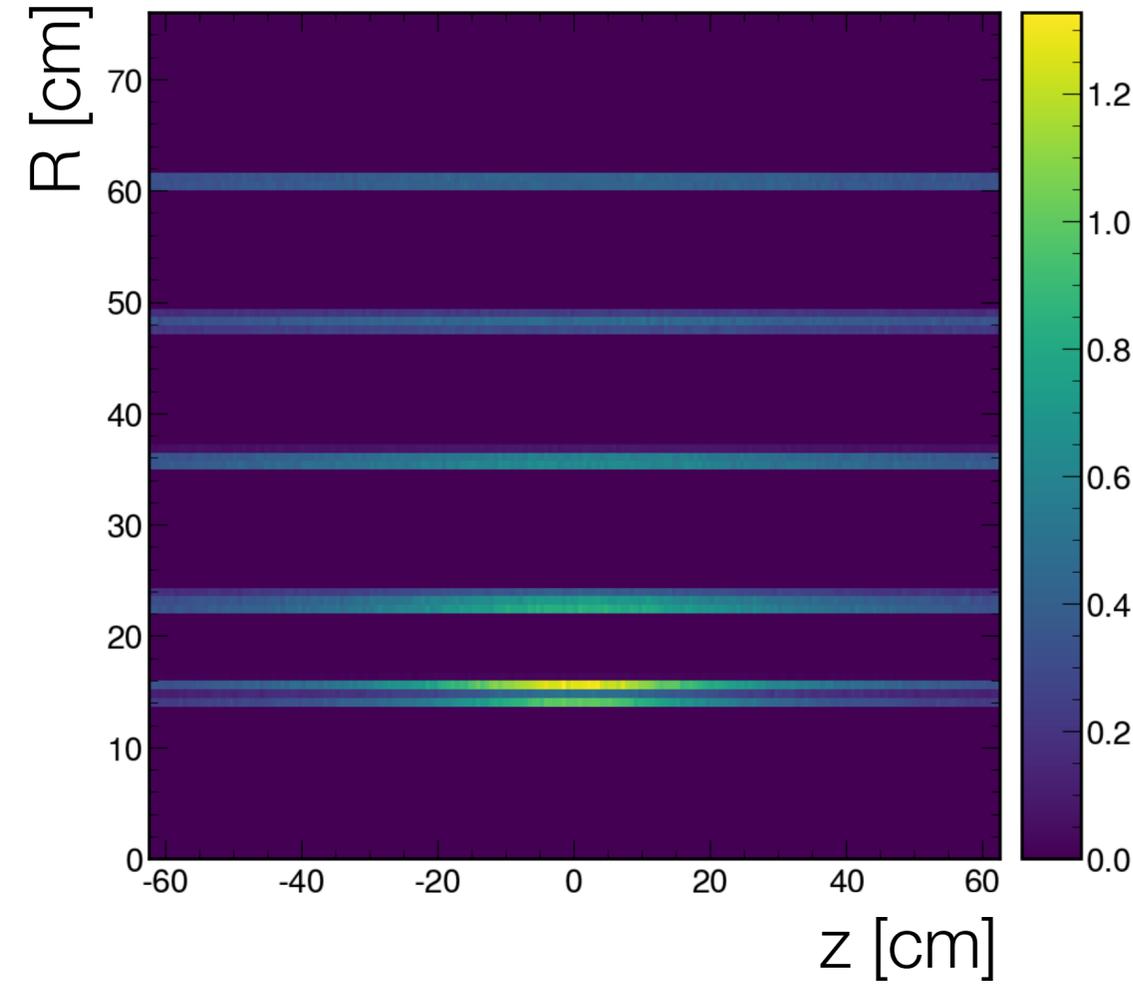
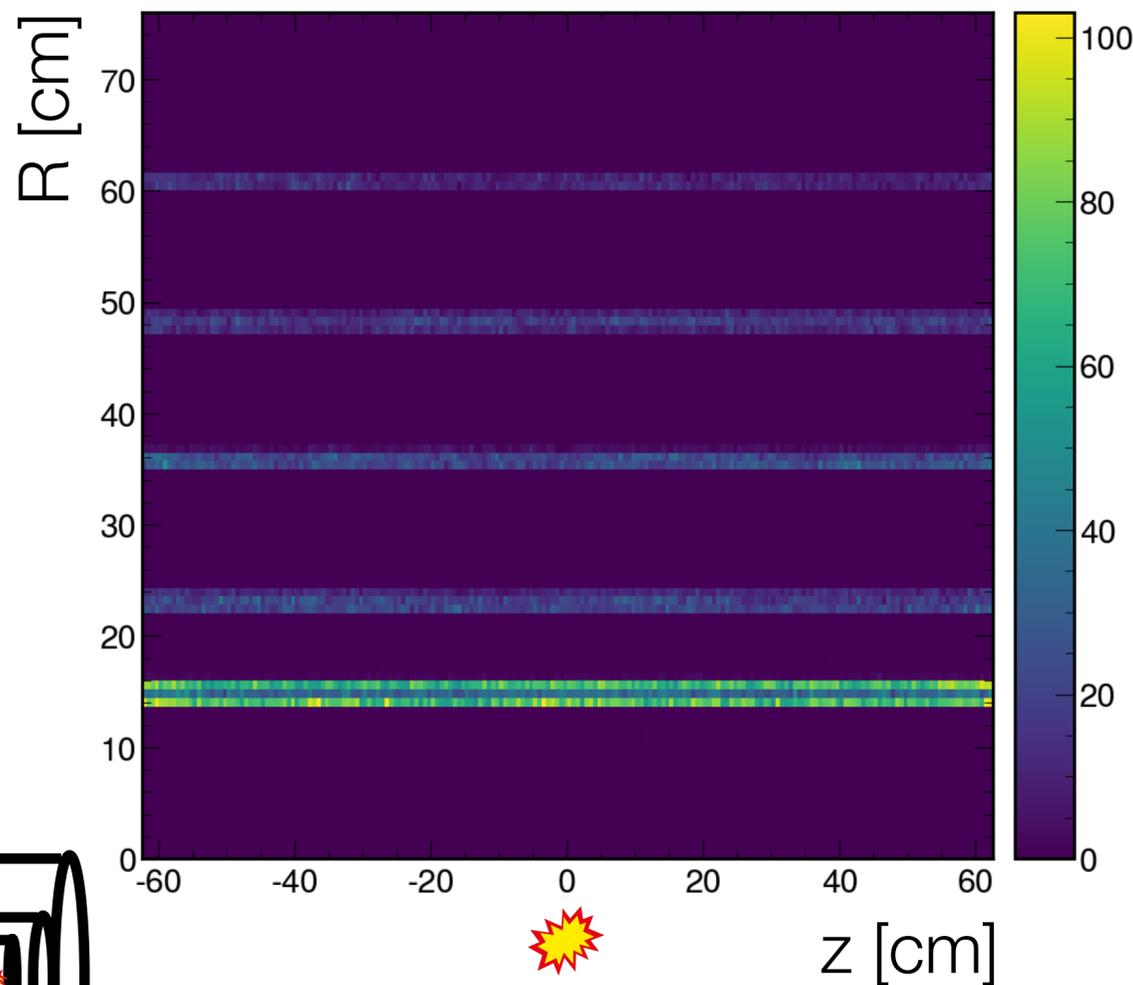
$\mathcal{L}_{\gamma\gamma}$ (GP, CAIN, WarpX ...)

Whizard

Pythia6

DDSim / DD4Hep

Key4Hep



Hadron photoproduction C^3 250 GeV

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Developed by Tim Barklow and Lindsey Gray: [ECFA talk](#)

e^+e^- pairs

$\gamma\gamma \rightarrow$ hadrons

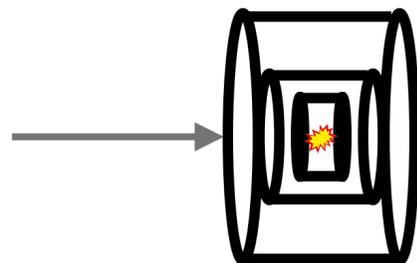
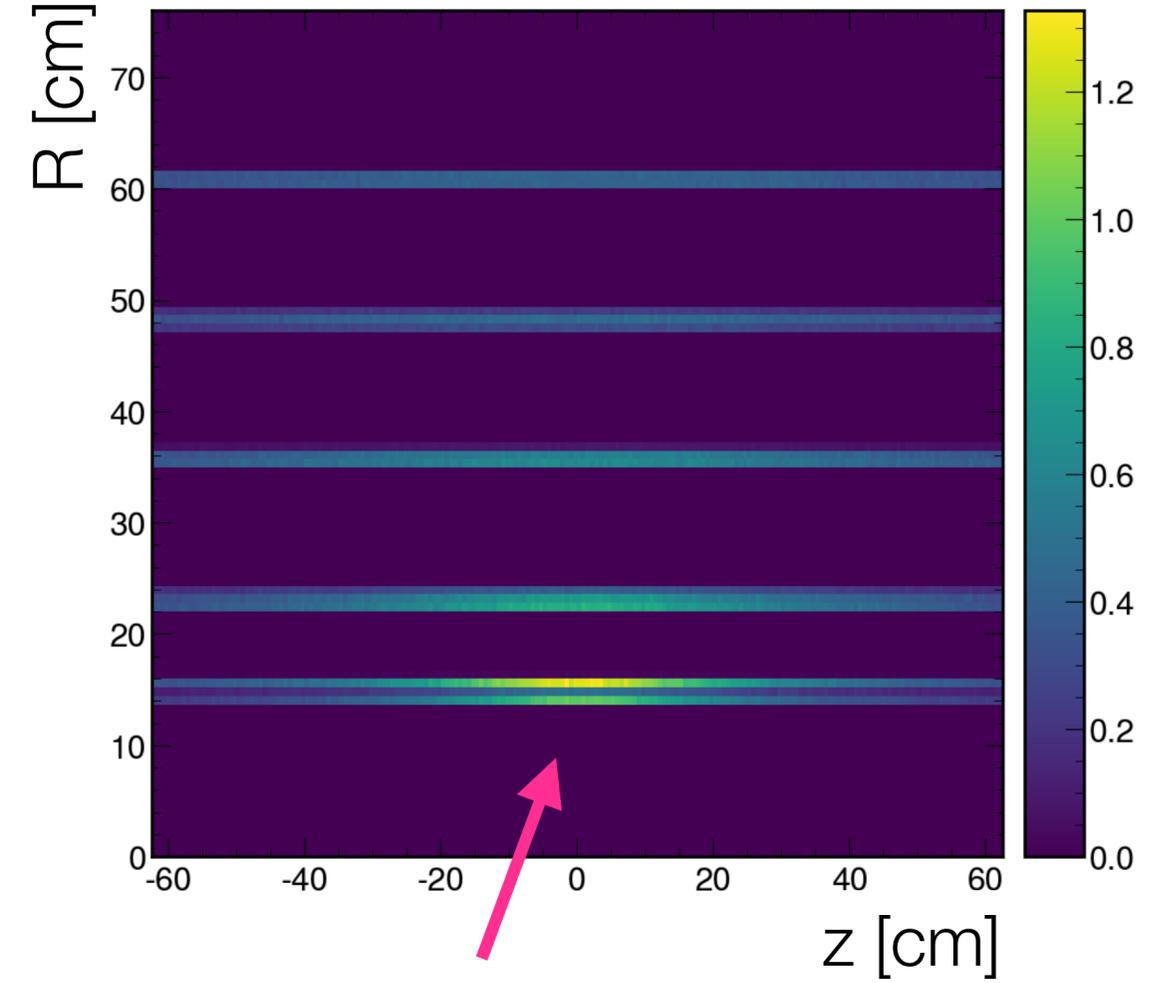
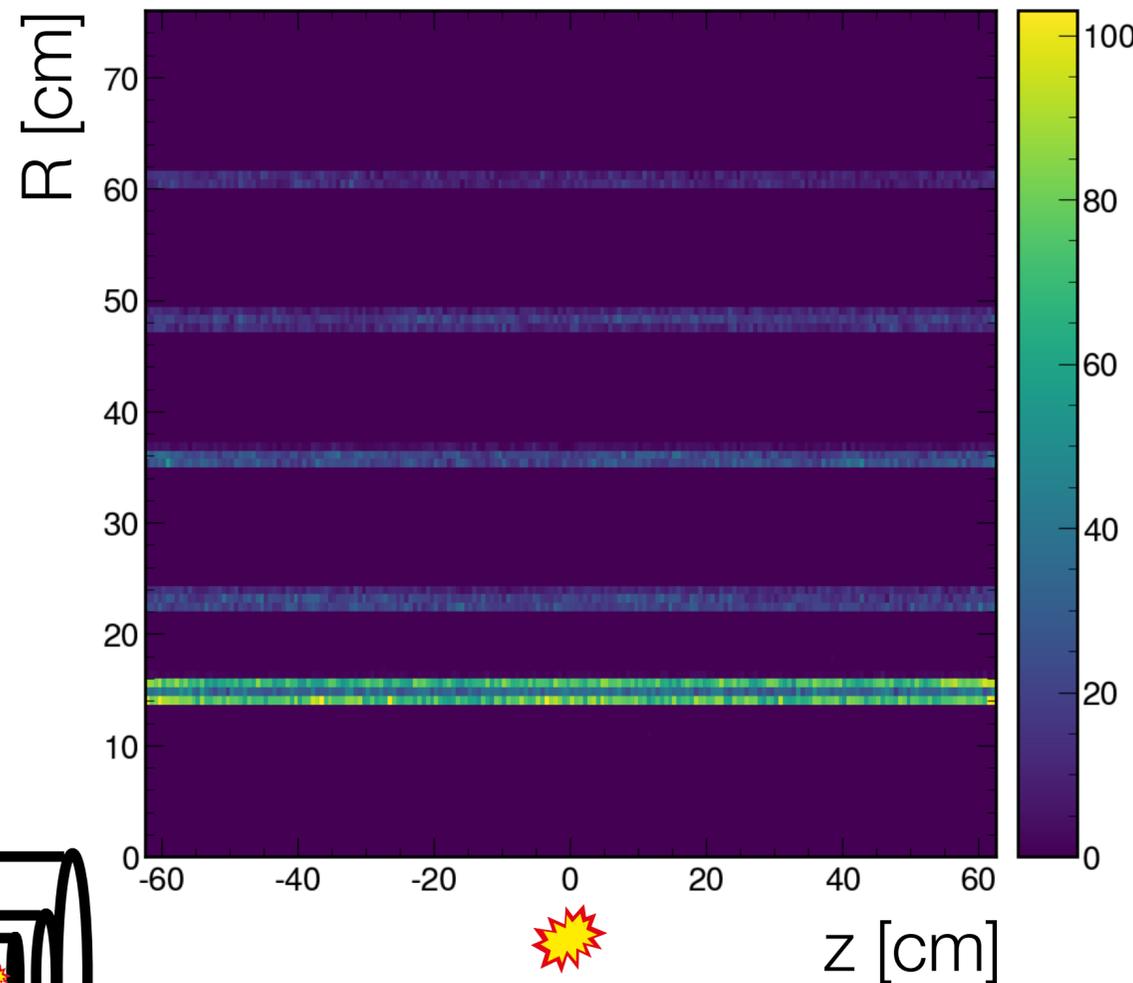
$\mathcal{L}_{\gamma\gamma}$ (GP, CAIN, WarpX ...)

Whizard

Pythia6

DDSim /
DD4Hep

Key4Hep

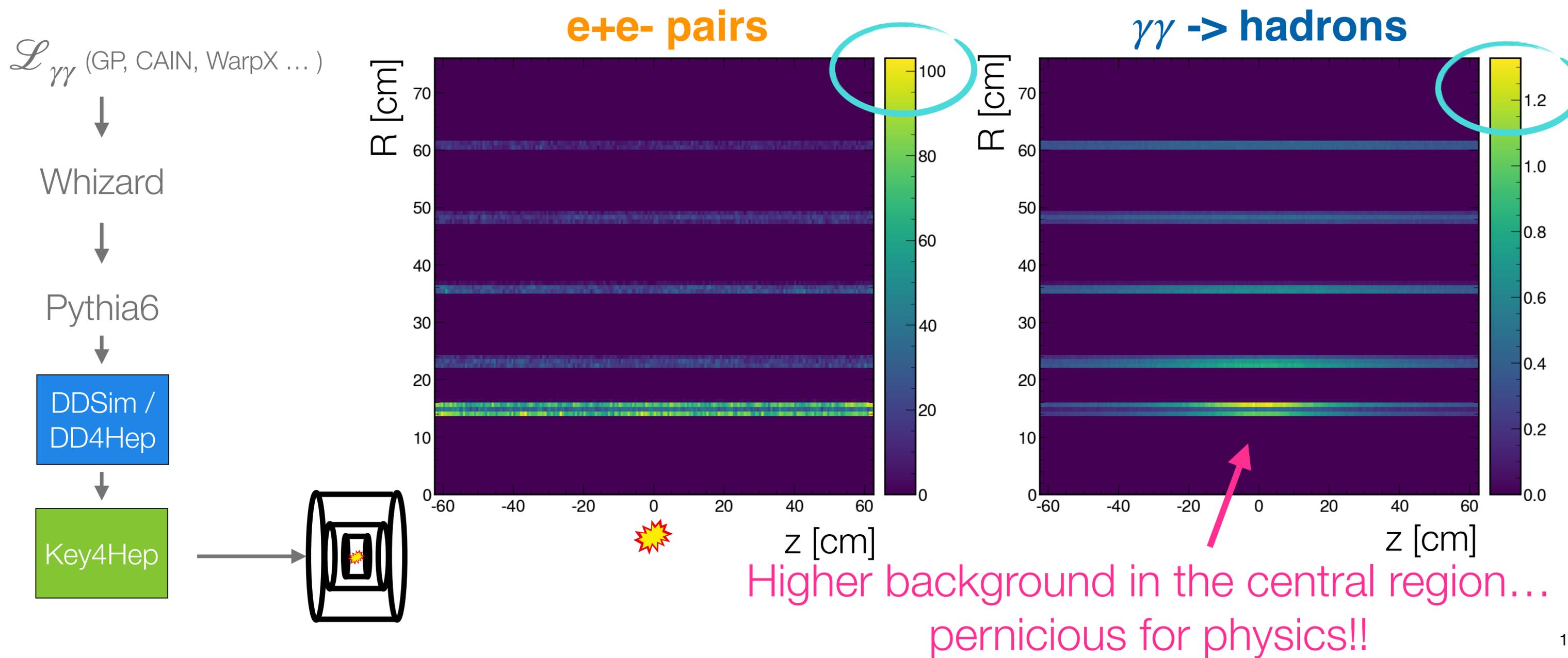


Higher background in the central region...
pernicious for physics!!

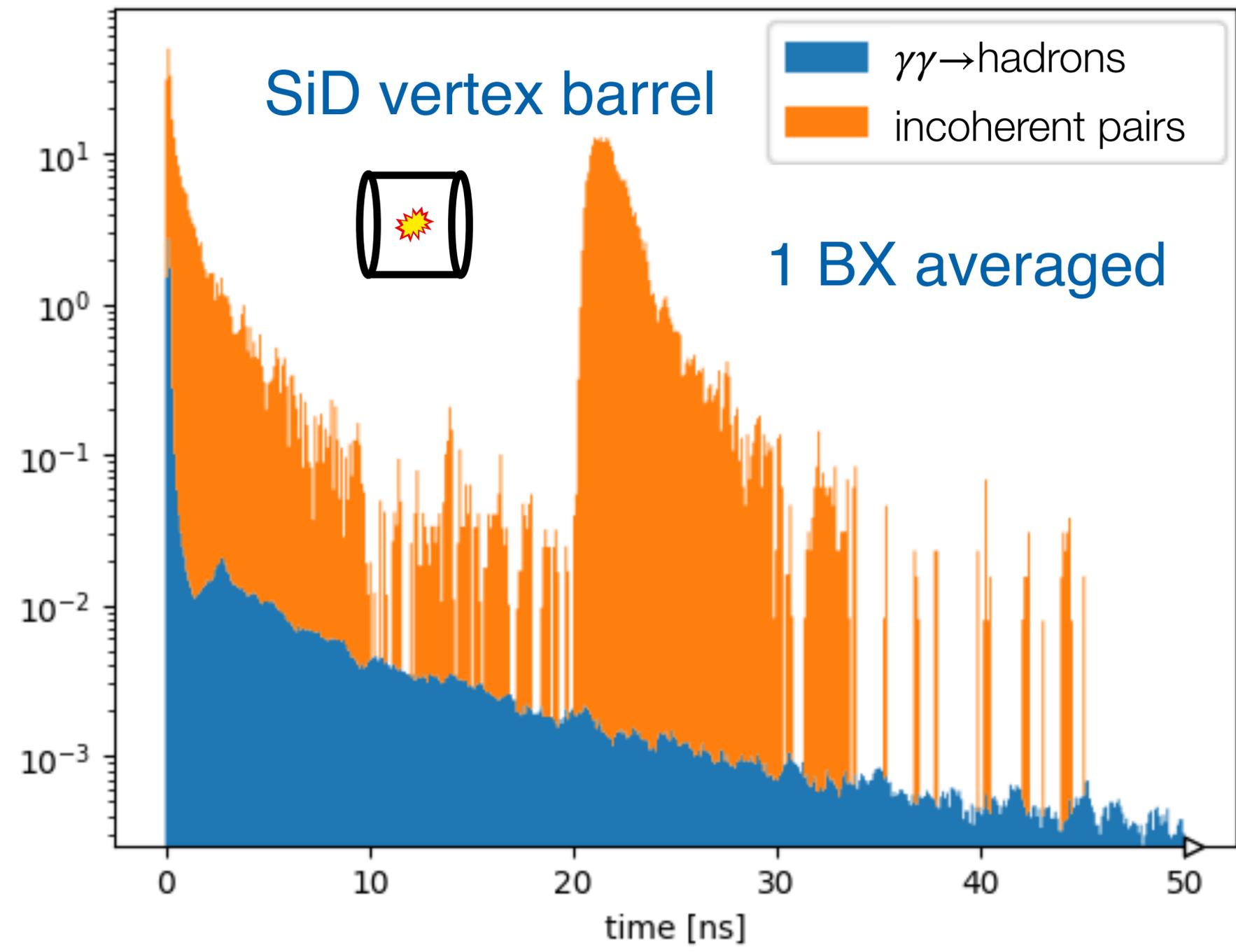
Hadron photoproduction C^3 250 GeV

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| e^+e^- pairs from beam-beam interactions | 75k | 2.5 |
| Radiative Bhabhas | 820k | 133 |
| $\gamma\gamma \rightarrow$ hadrons/muons | 0.5 events/1.3 events | - |

Developed by Tim Barklow and Lindsey Gray: [ECFA talk](#)



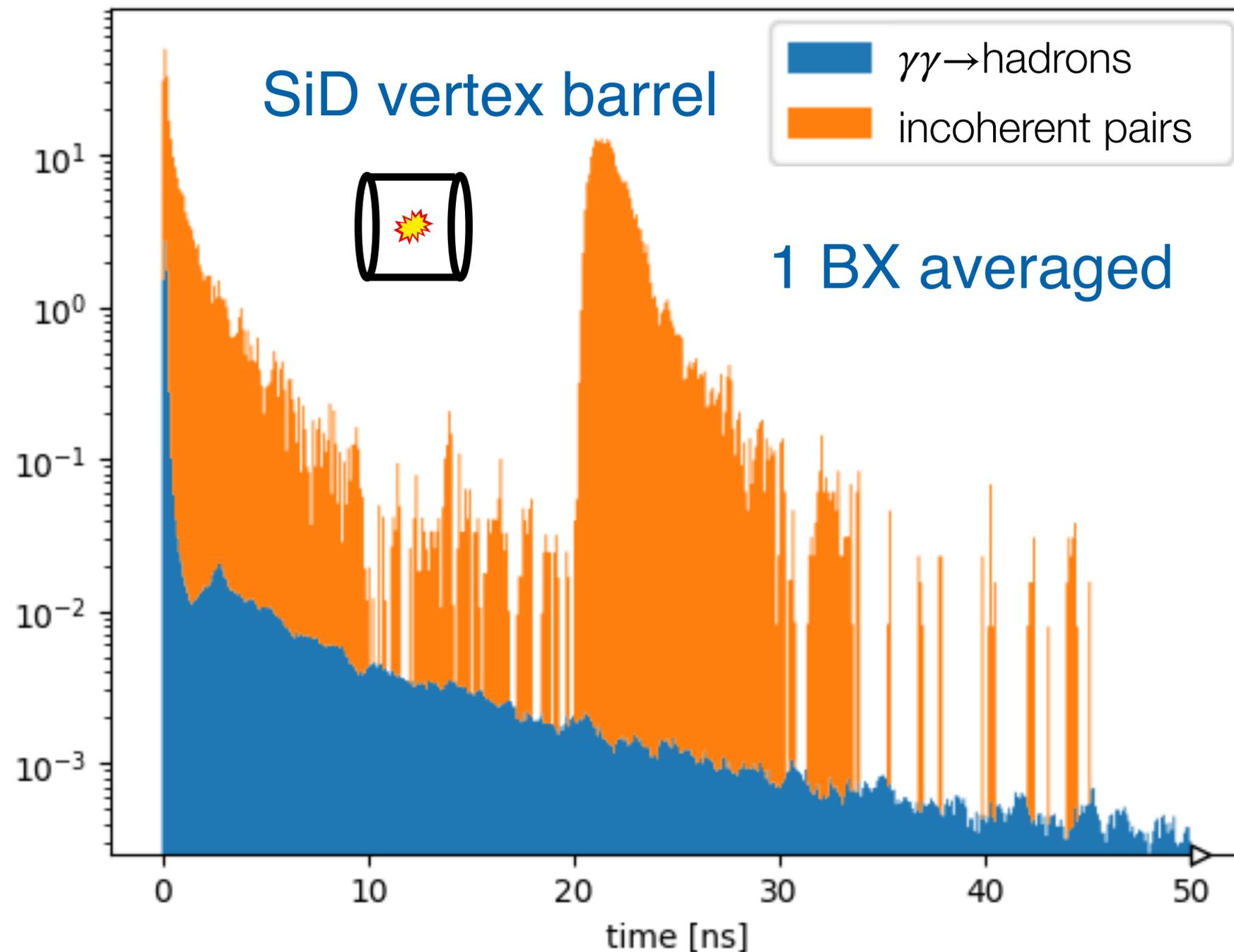
Hadron photoproduction C^3 250 GeV



- Small (1% - 0.1%) impact for C3 backgrounds

Hadron photoproduction C^3 250 GeV

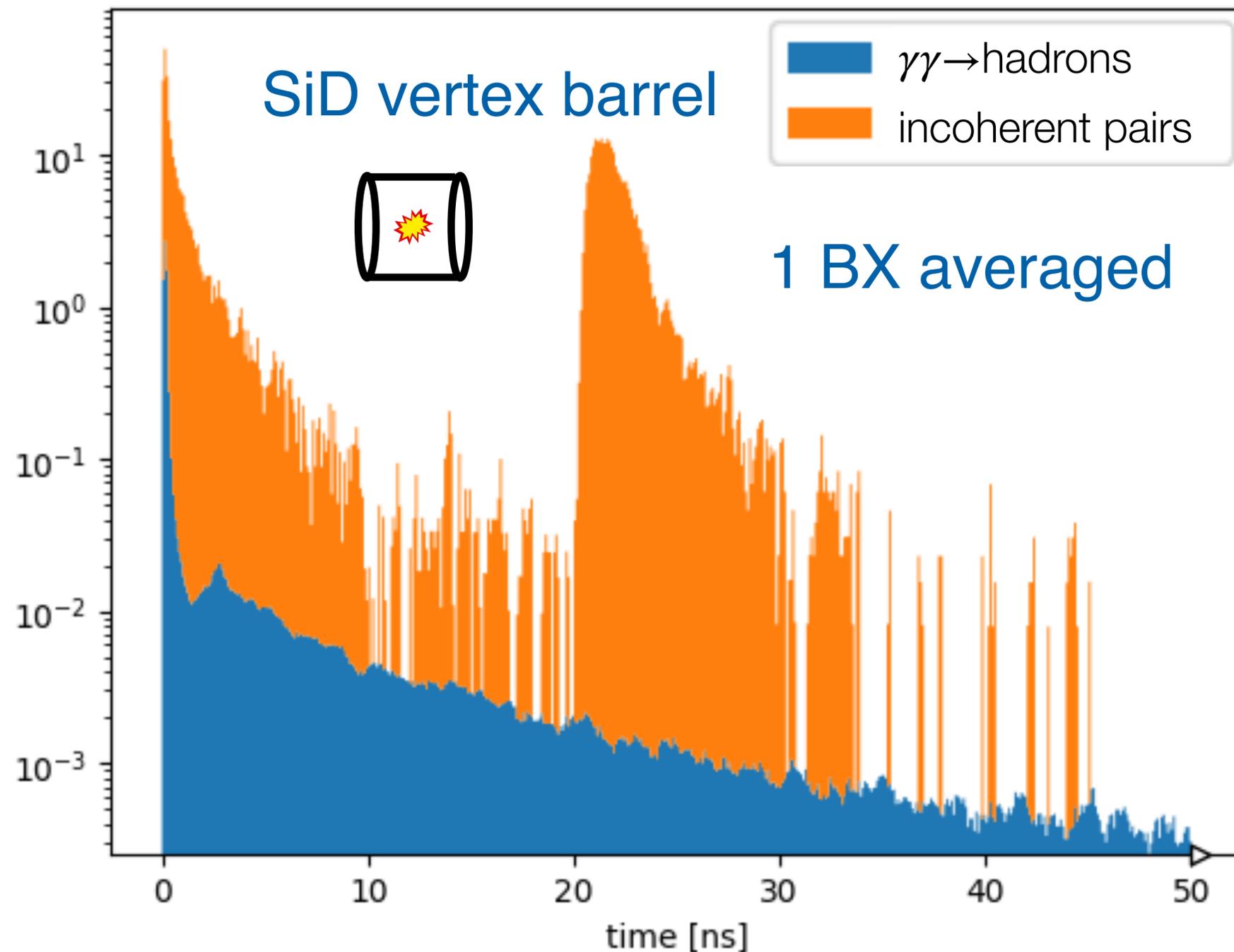
1306.6329 §10.3



- Small (1% - 0.1%) impact for C^3 backgrounds
- Expected larger impact at higher \sqrt{s} (ILC)
 - 500 GeV: $\langle n \rangle = 1.7$
 - 1 TeV: $\langle n \rangle = 4.1$

Hadron photoproduction C^3 250 GeV

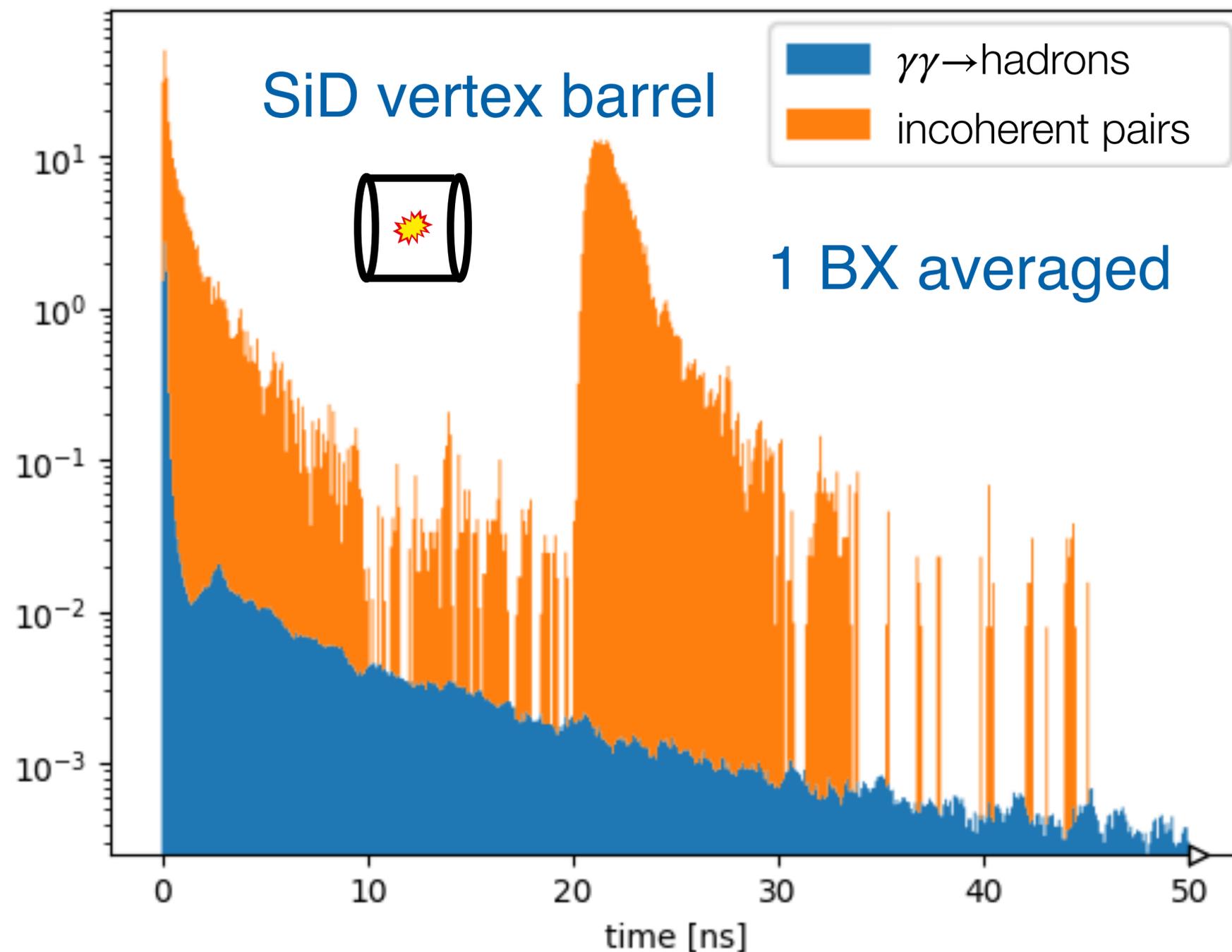
1306.6329 §10.3



- Small (1% - 0.1%) impact for C^3 backgrounds
- Expected larger impact at higher \sqrt{s} (ILC)
 - 500 GeV: $\langle n \rangle = 1.7$
 - 1 TeV: $\langle n \rangle = 4.1$
 - 10 TeV: $\langle n \rangle = ?$

Hadron photoproduction C^3 250 GeV

1306.6329 §10.3



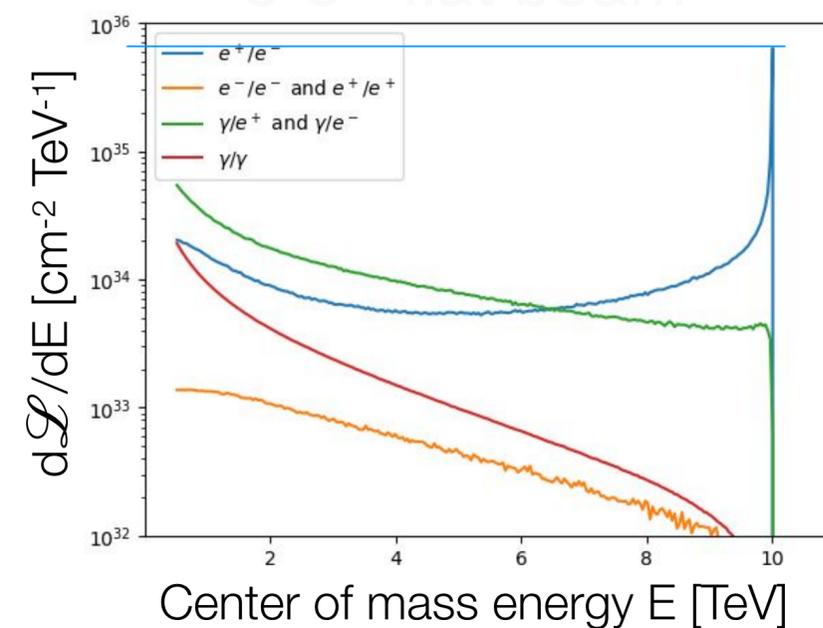
- Small (1% - 0.1%) impact for C^3 backgrounds
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 - 500 GeV: $\langle n \rangle = 1.7$
 - 1 TeV: $\langle n \rangle = 4.1$
 - 10 TeV: $\langle n \rangle = ?$

Next goal for MDI + Detector:
 $\gamma\gamma \rightarrow$ hadron at 10 TeV.

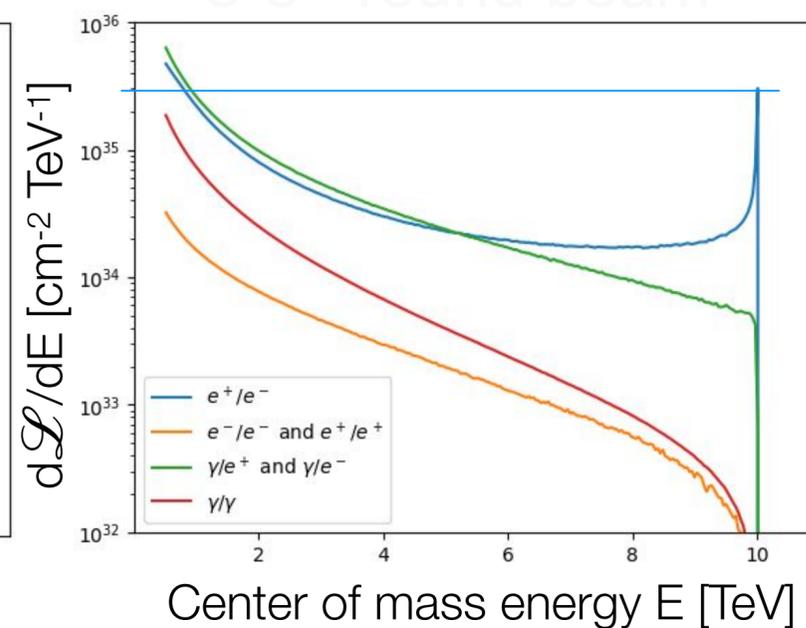
And now... with WarpX

Our lumi spectra induced by these beam-on-beam distortions:

e⁺e⁻ flat beam

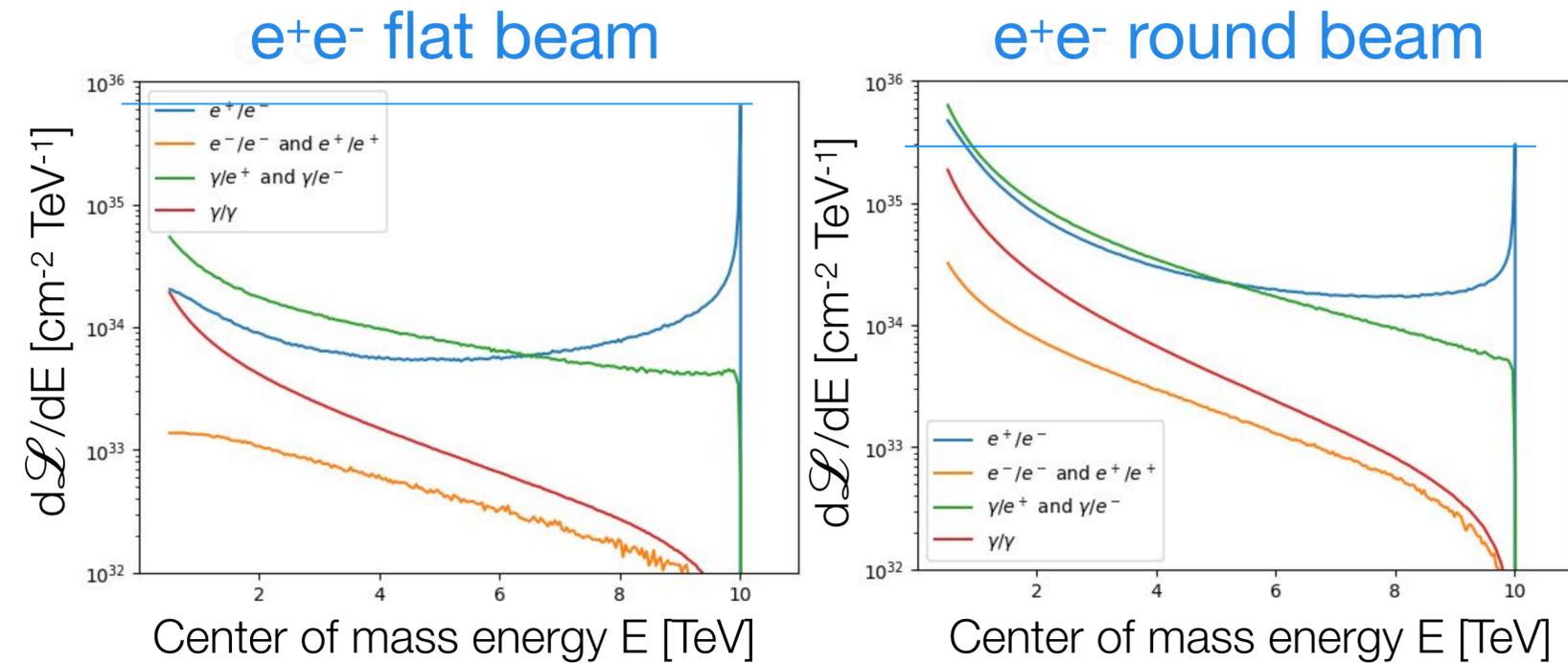


e⁺e⁻ round beam



And now... with WarpX

Our lumi spectra induced by these beam-on-beam distortions:



Decreases the peak e⁺e⁻ lumi by 2x

beamstrahlung parameter

$$\Upsilon = \frac{5}{6} \frac{N_e r_e^2 \gamma}{\alpha (\sigma_x^* + \sigma_y^*) \sigma_z^*} \xrightarrow[\text{beams}]{\text{flat}} \frac{5}{6} \frac{N_e r_e^2 \gamma}{\alpha \sigma_x^* \sigma_z^*}$$

And now... with WarpX

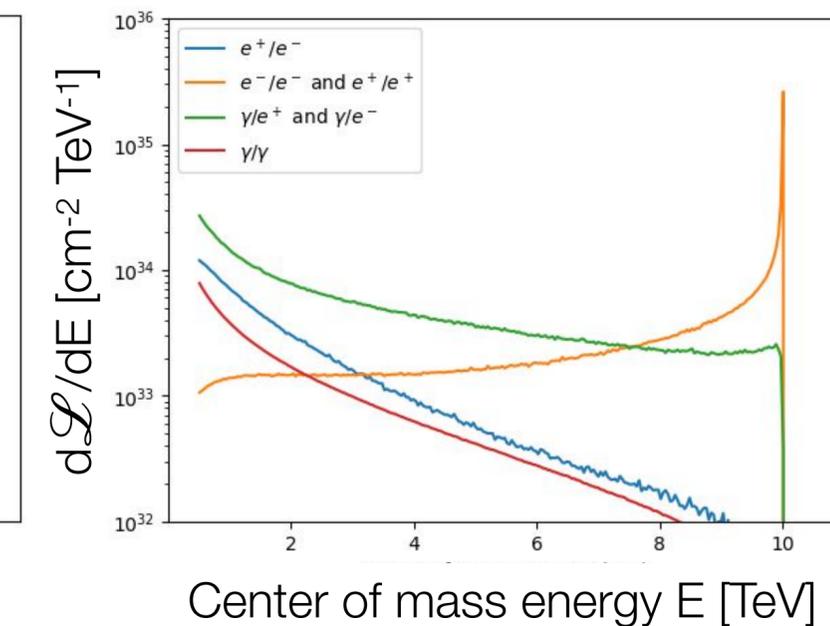
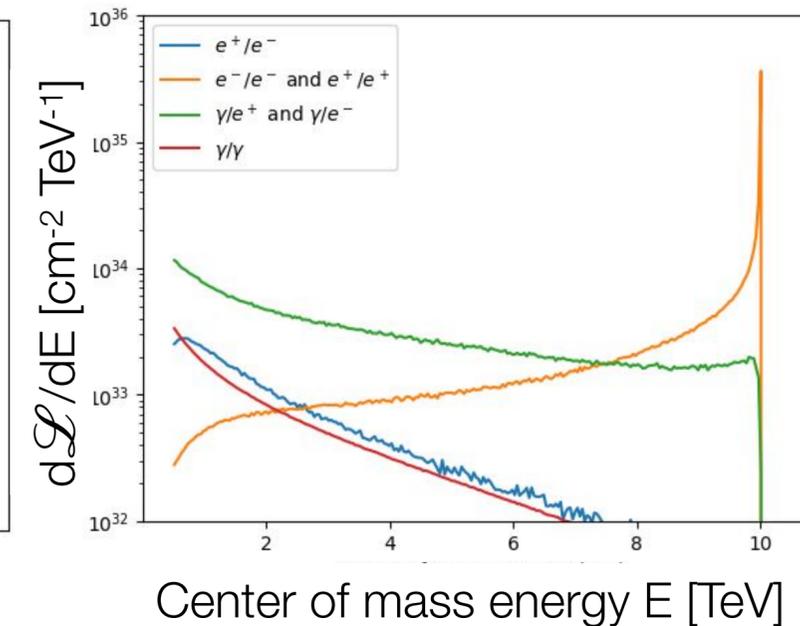
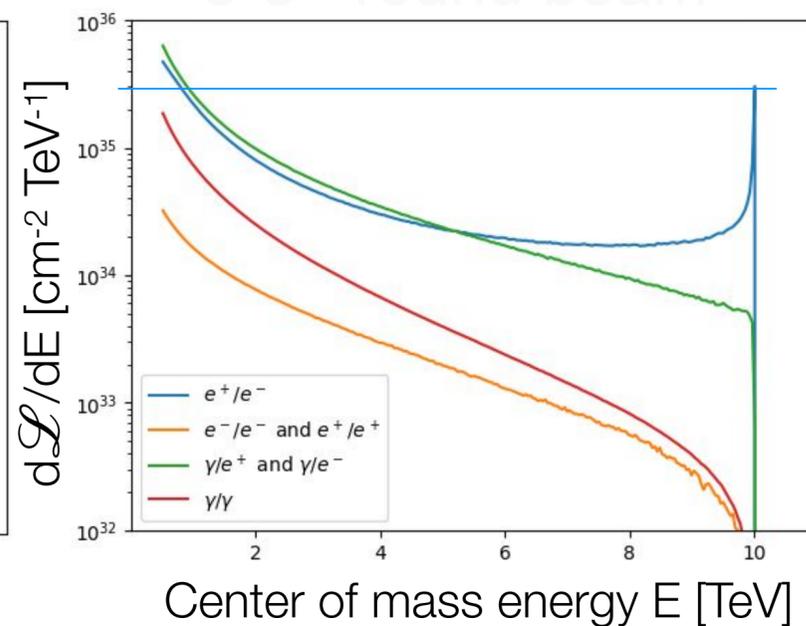
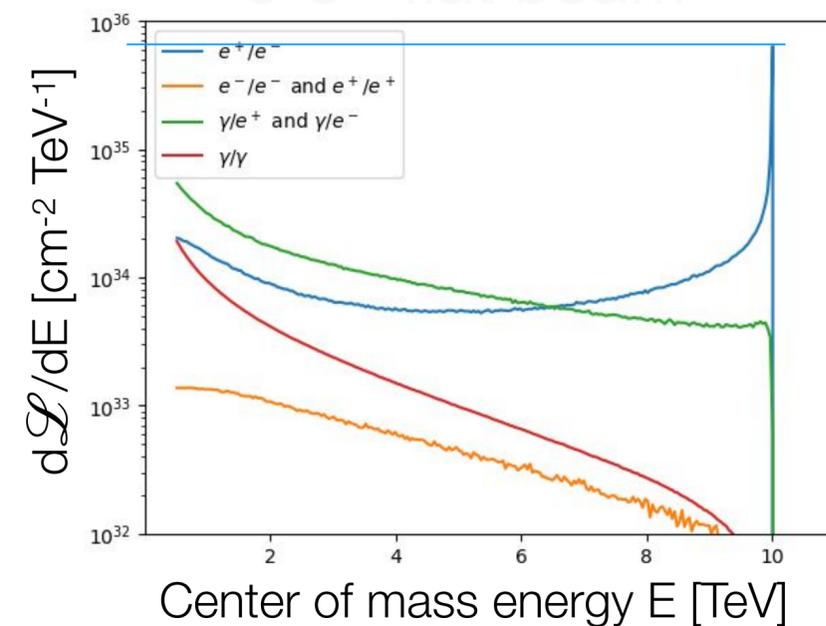
Our lumi spectra induced by these beam-on-beam distortions:

e⁺e⁻ flat beam

e⁺e⁻ round beam

e⁻e⁻ flat beam

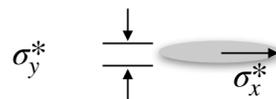
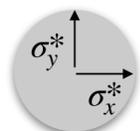
e⁻e⁻ round beam



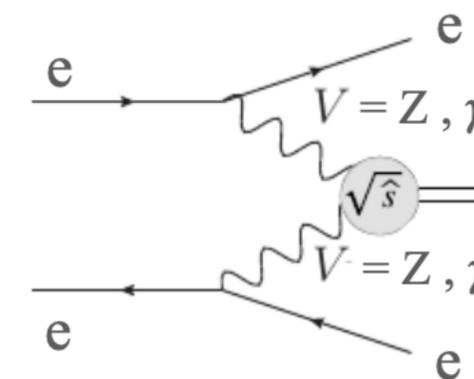
Decreases the peak e⁺e⁻ lumi by 2x

beamstrahlung parameter

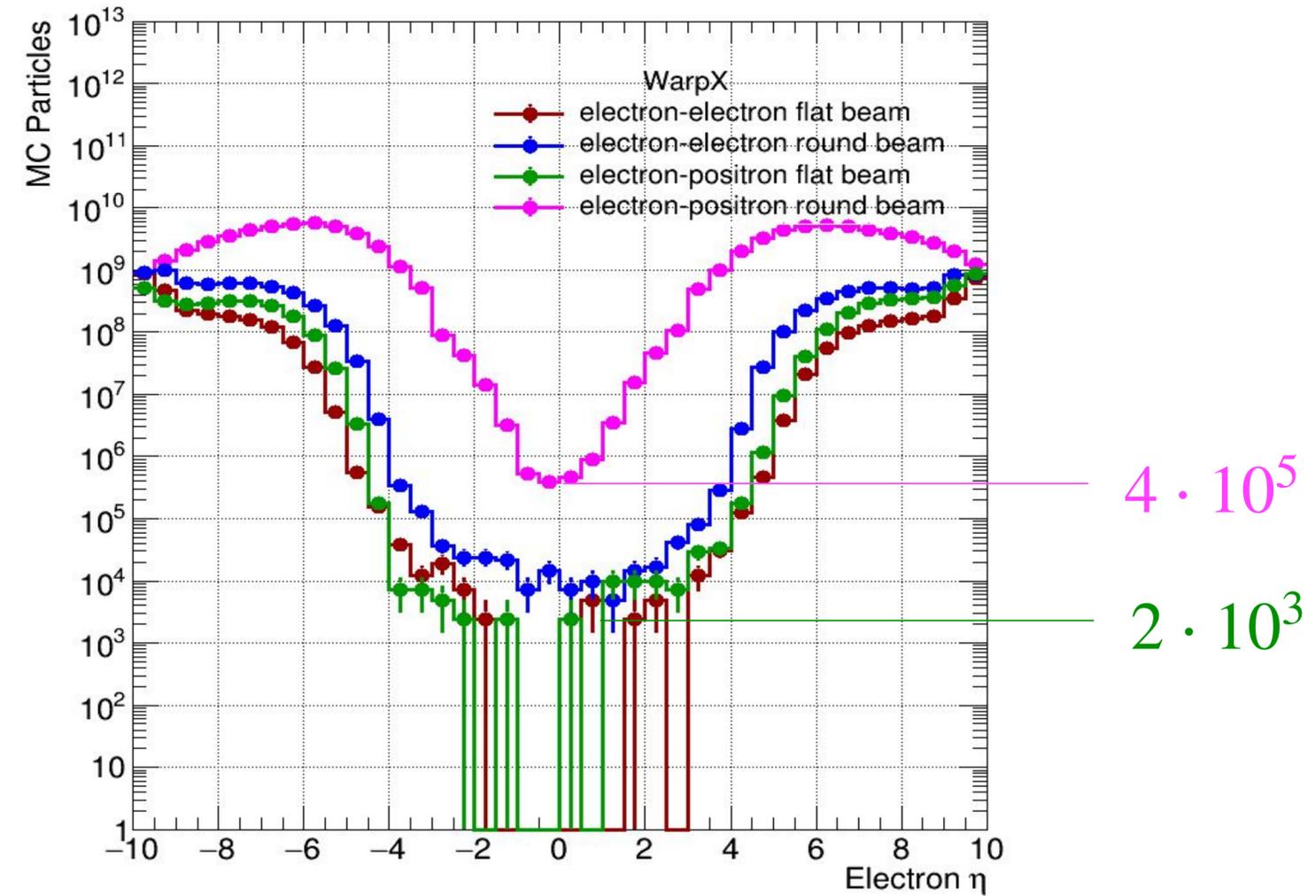
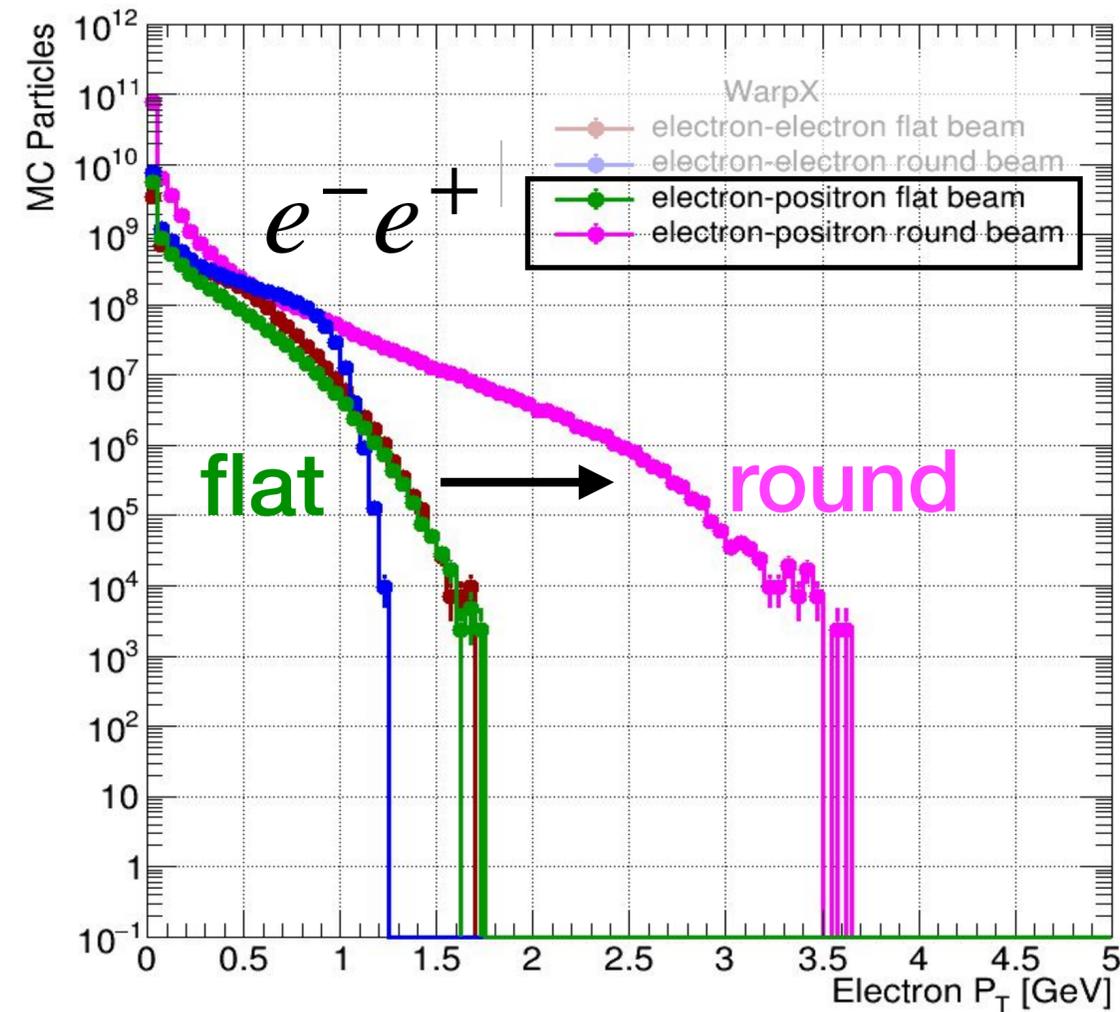
$$\Upsilon = \frac{5 N_e r_e^2 \gamma}{6 \alpha (\sigma_x^* + \sigma_y^*) \sigma_z^*} \xrightarrow{\text{flat beams}} \frac{5 N_e r_e^2 \gamma}{6 \alpha \sigma_x^* \sigma_z^*}$$



Also considering the e⁻e⁻ mode motivated by VBF

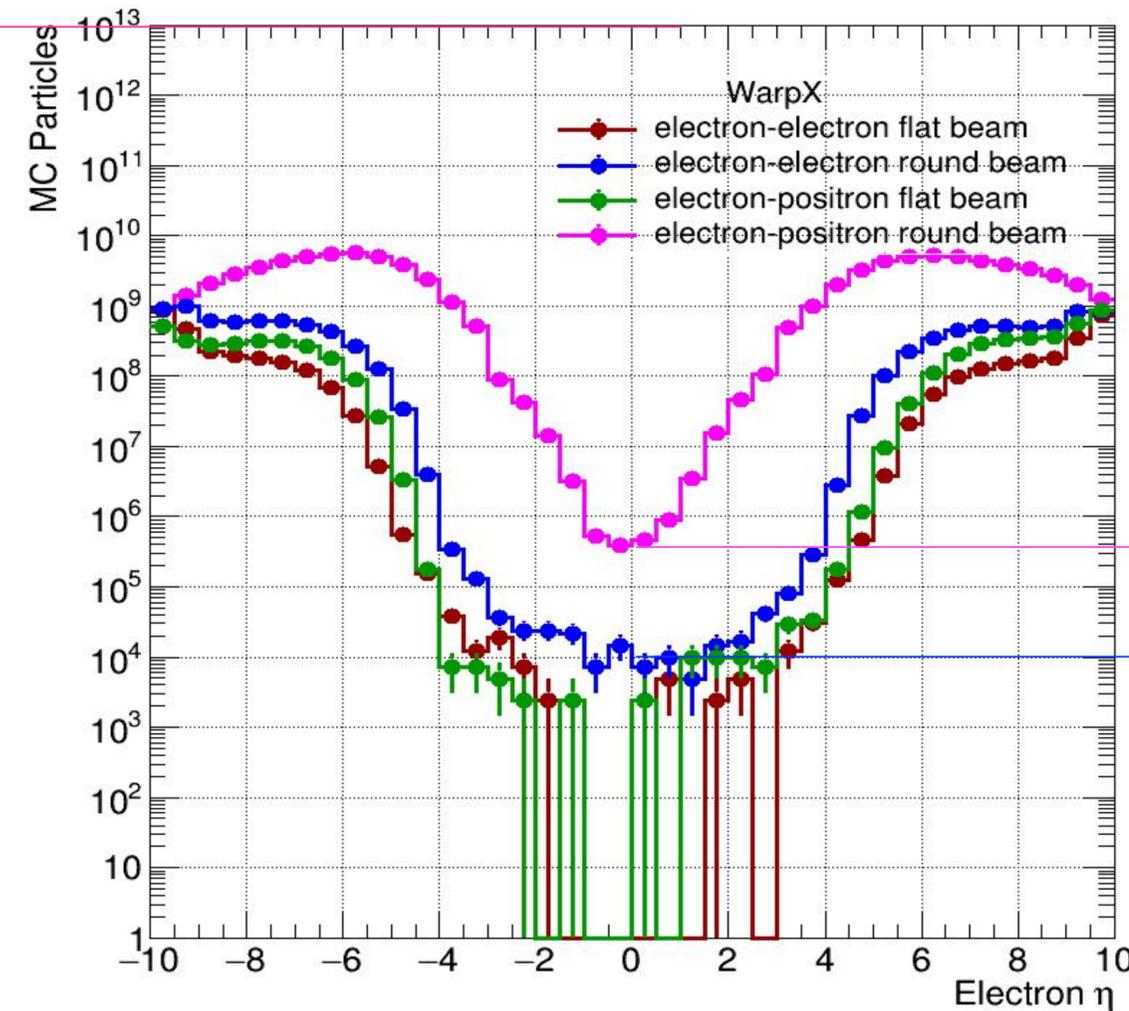
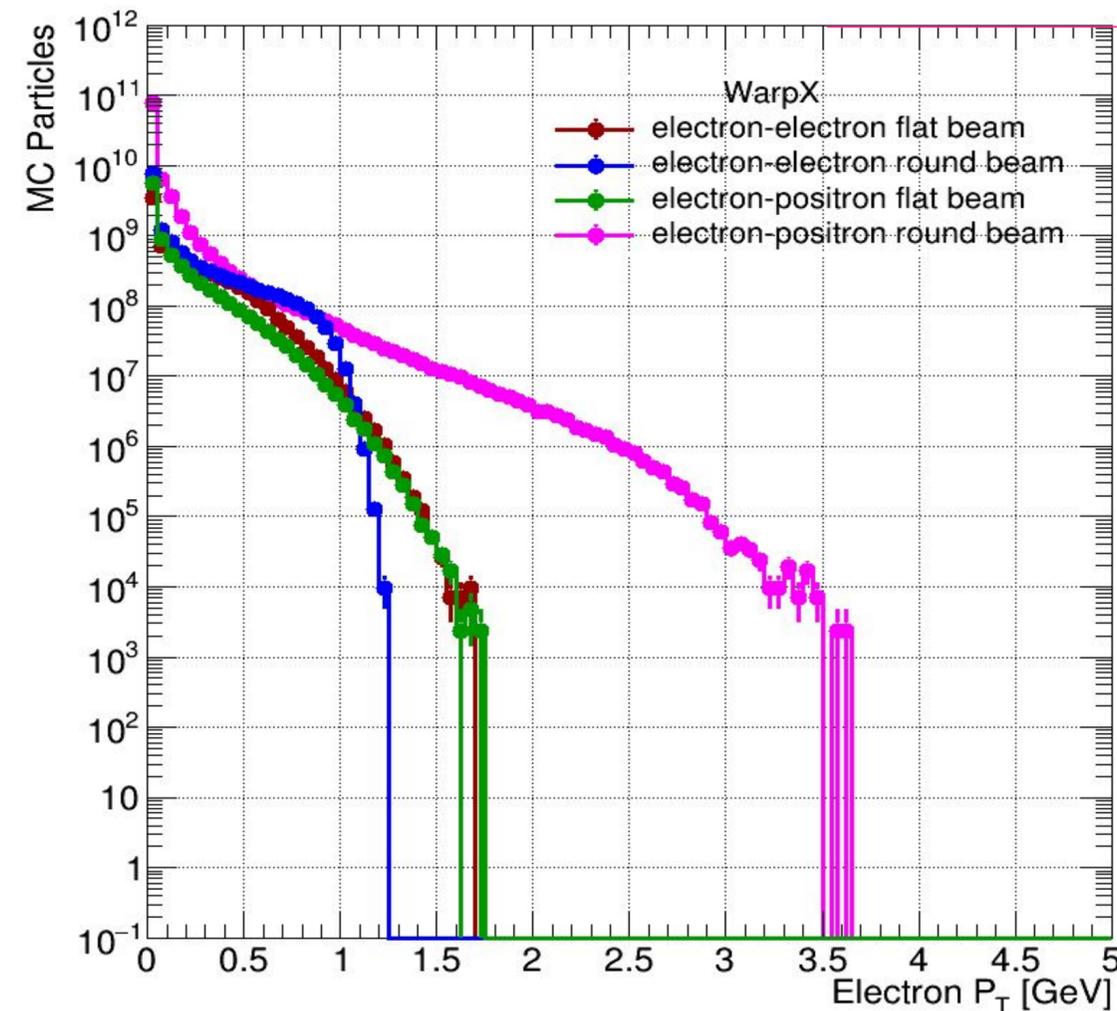


MC particles from WarpX: **electrons**



$e^- e^+$: **round** lots more beamstrahlung (!) ... no surprise 😊

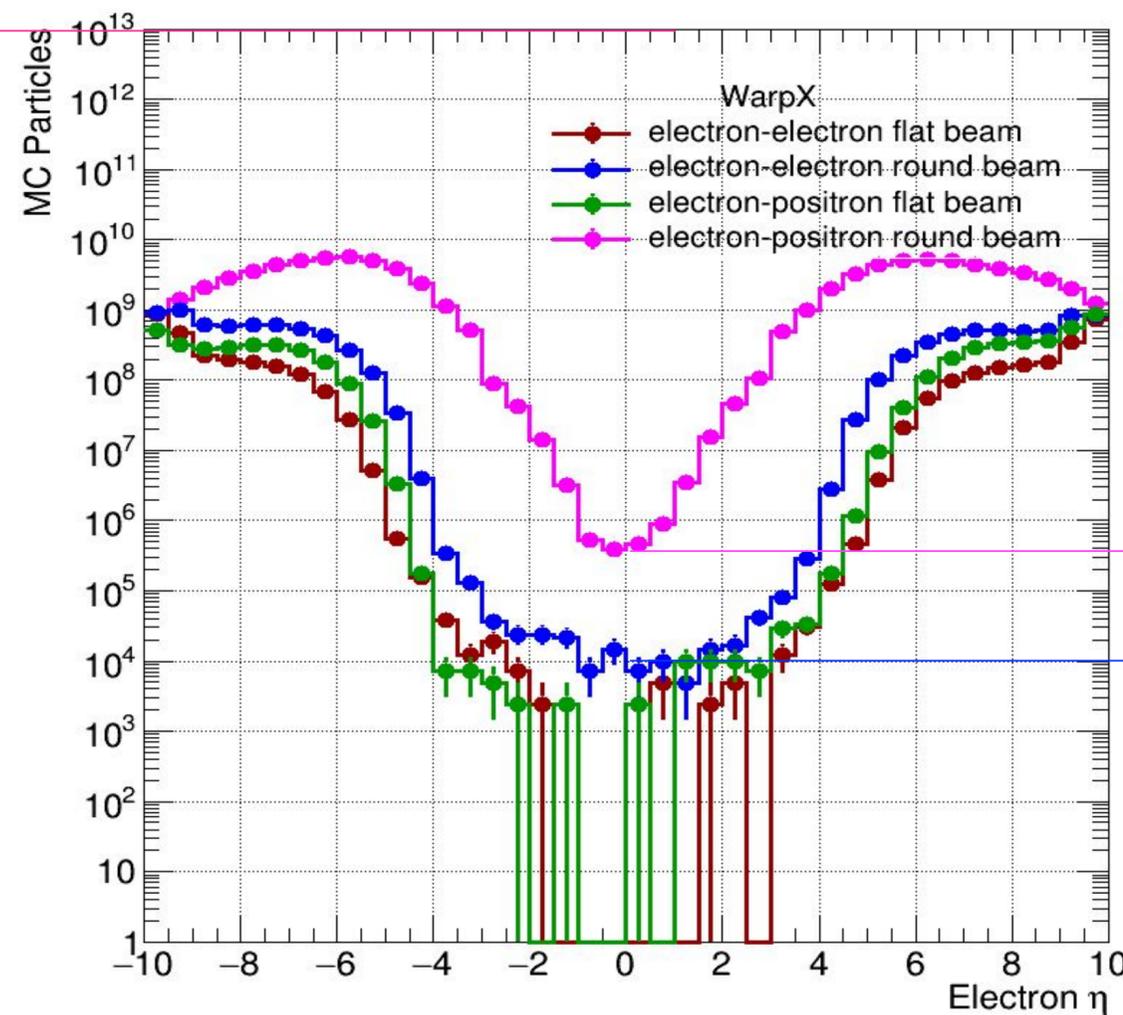
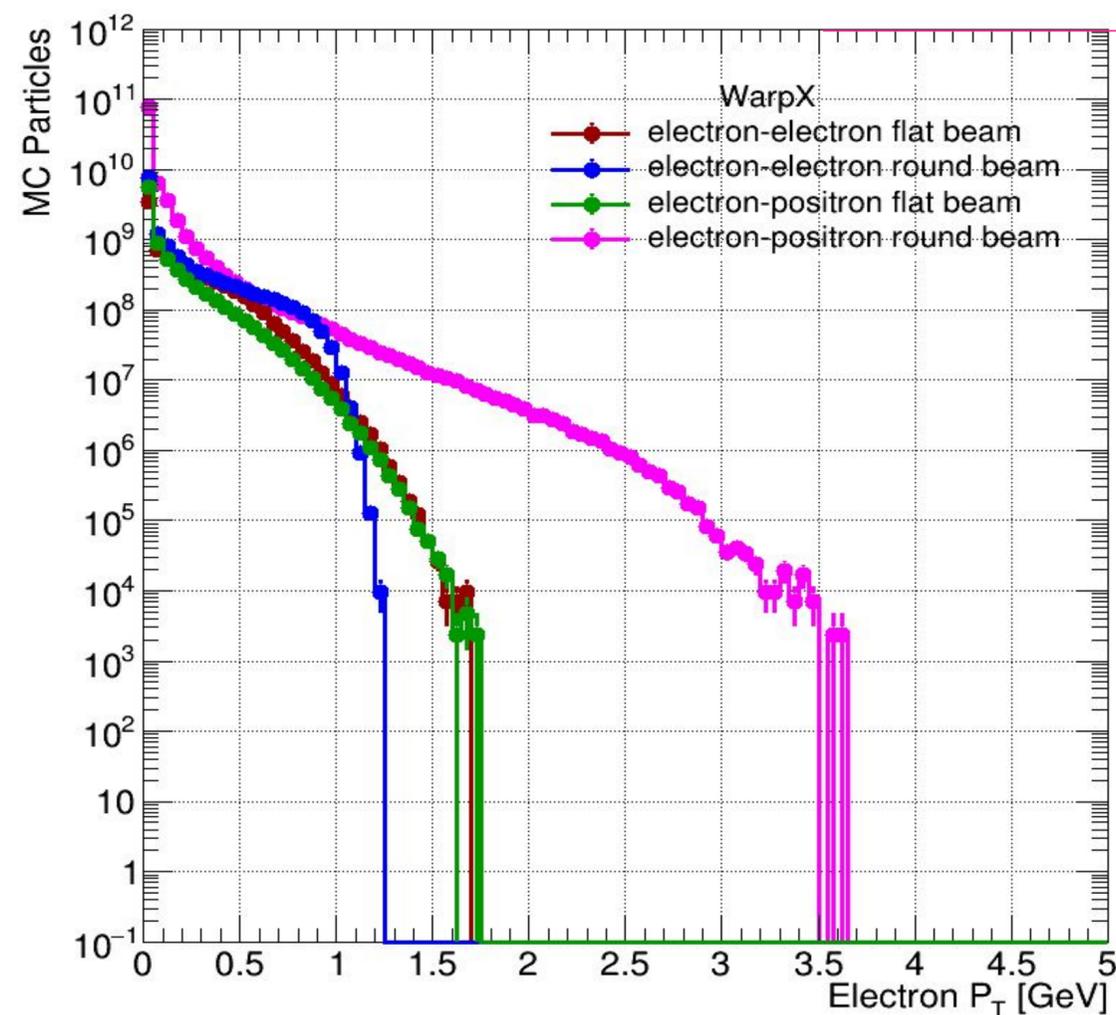
MC particles from WarpX: **electrons**



Round beams: e^-e^- way lower backgrounds than e^+e^-

Signal for e^-e^- is 10x lower (S. Knapen's [slides](#))... so take with 

MC particles from WarpX: **electrons**



$4 \cdot 10^5$

10^4

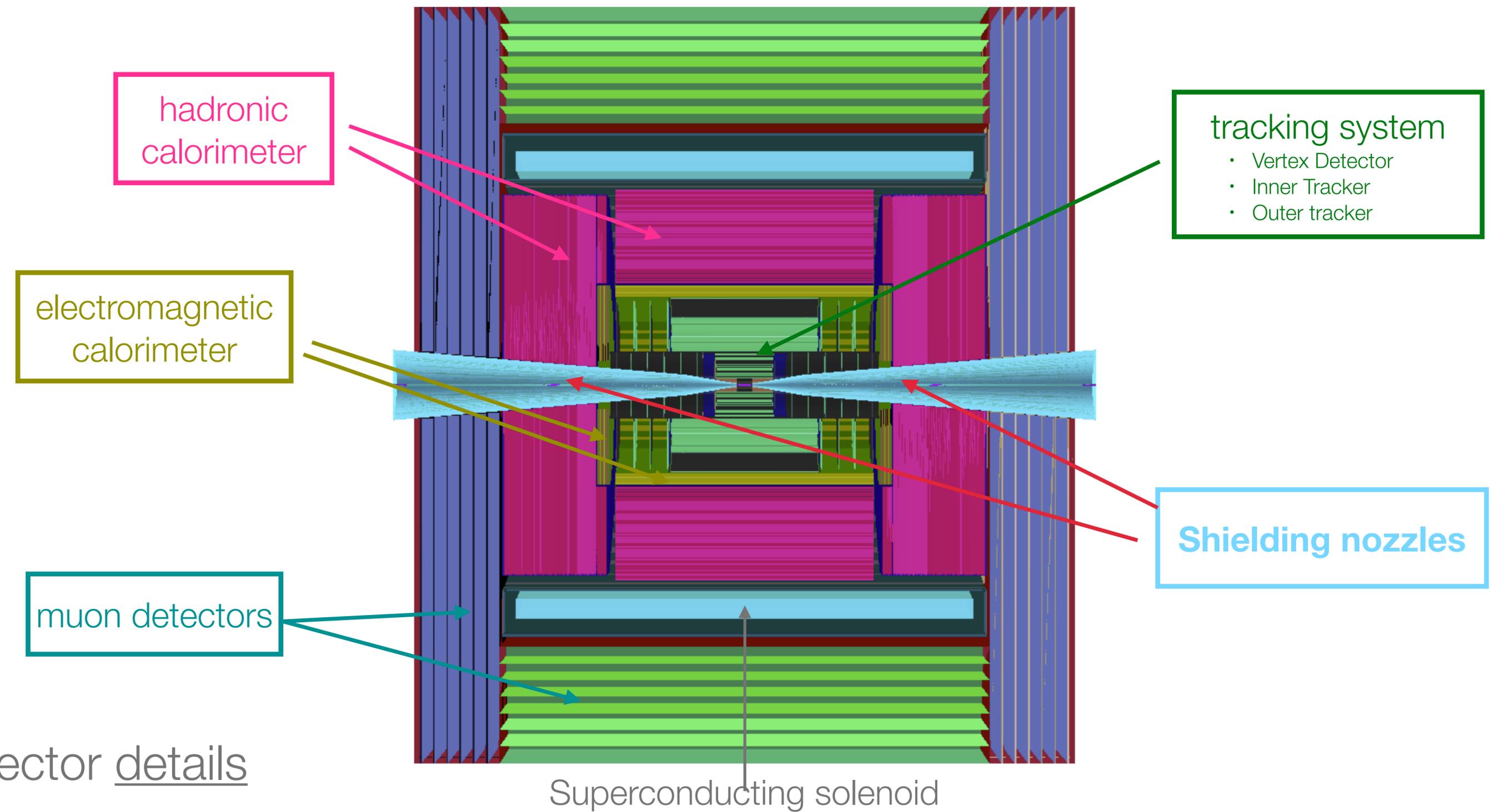
Round beams: e^-e^- way lower backgrounds than e^+e^-

Signal for e^-e^- is 10x lower (S. Knapen's slides)... so take with 

[photons](#) in backup

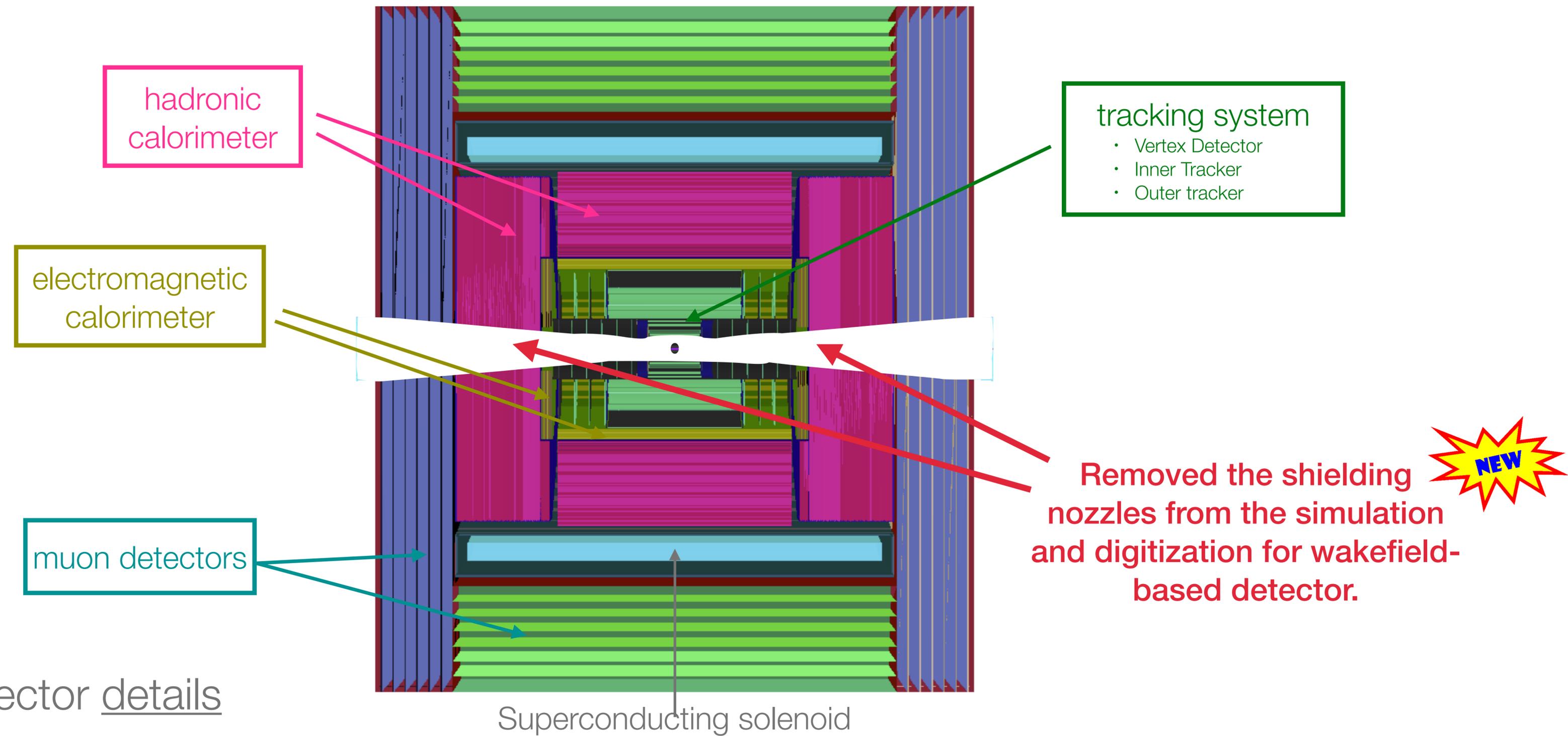


Detector Geometry: MuColl 3 TeV concept



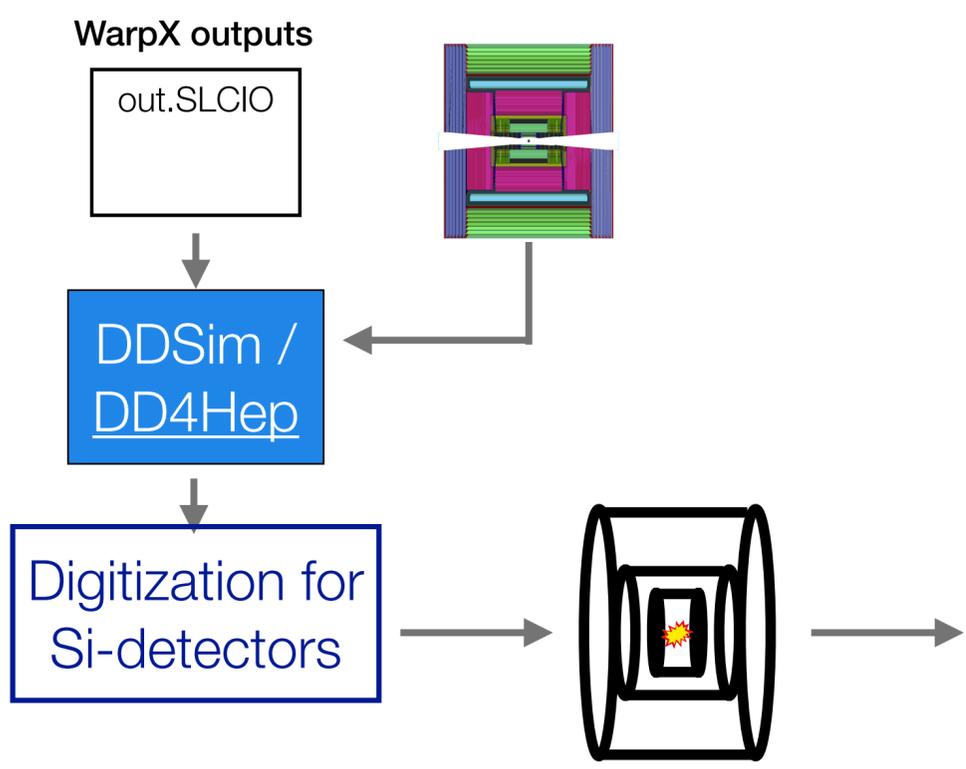
Detector details

Detector Geometry: MuColl 3 TeV concept

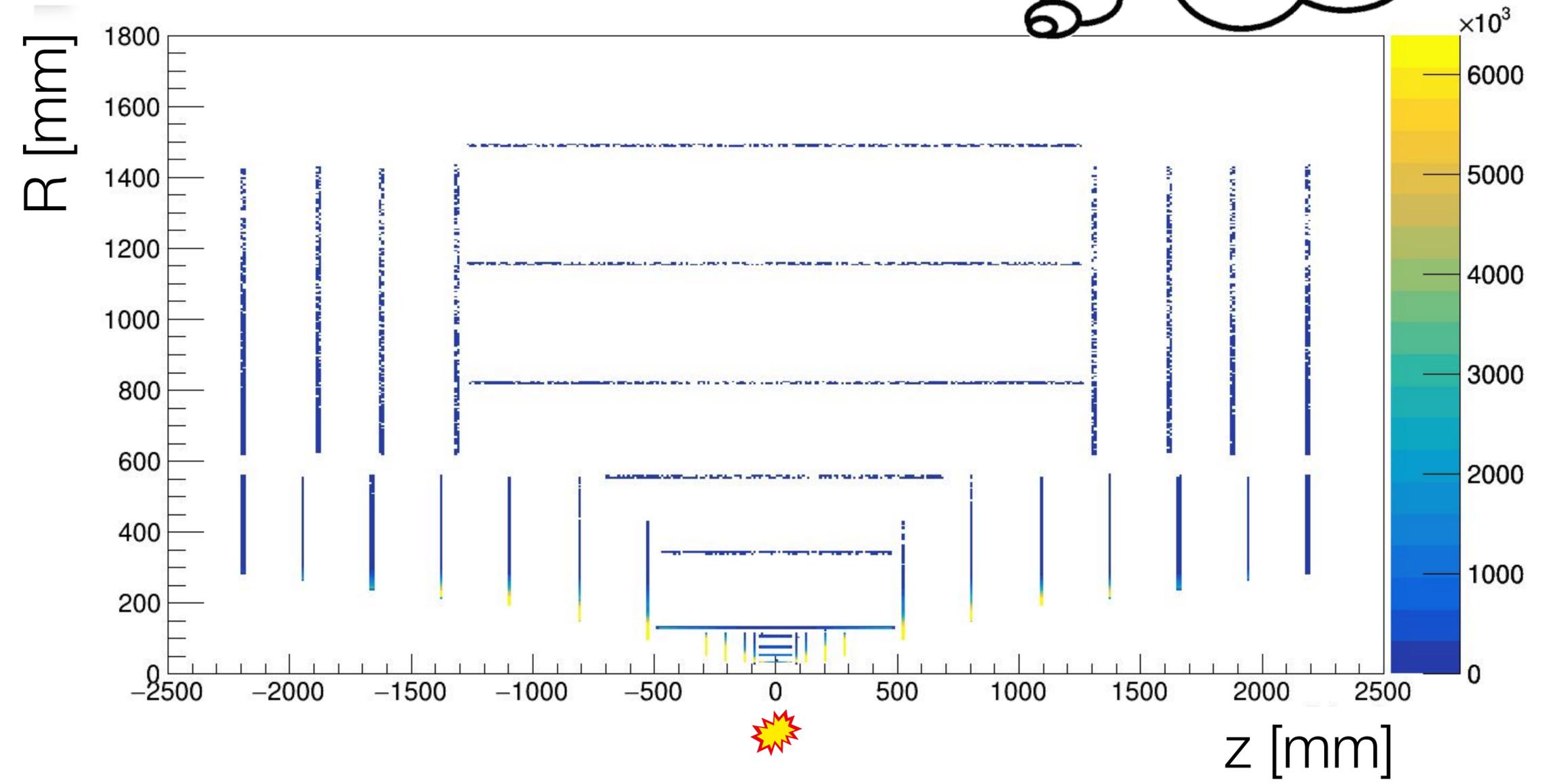


Vertex and tracker configuration

Highest beamstrahlung background of the considered conditions!!



e^+e^- round beams



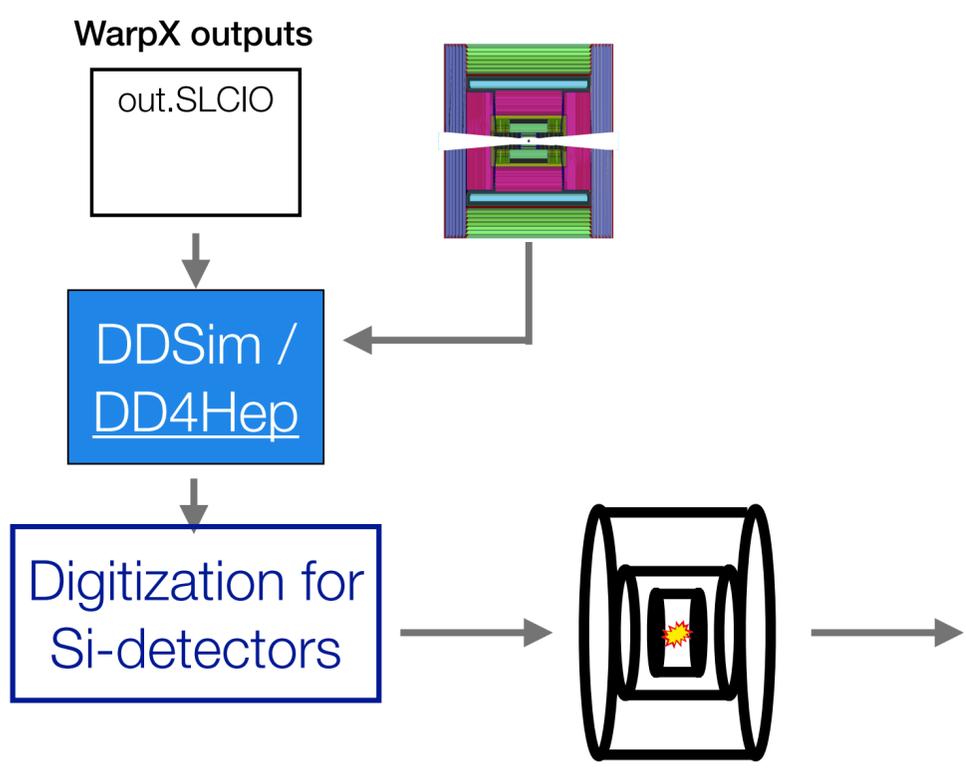
| | Vertex Detector | Inner Tracker | Outer Tracker |
|--------------------|--|---------------------------------------|---------------------------------------|
| Cell type | pixels | macropixels | microstrips |
| Cell Size | 25 $\mu\text{m} \times 25 \mu\text{m}$ | 50 $\mu\text{m} \times 1 \text{mm}$ | 50 $\mu\text{m} \times 10 \text{mm}$ |
| Sensor Thickness | 50 μm | 100 μm | 100 μm |
| Time Resolution | 30 ps | 60 ps | 60 ps |
| Spatial Resolution | 5 $\mu\text{m} \times 5 \mu\text{m}$ | 7 $\mu\text{m} \times 90 \mu\text{m}$ | 7 $\mu\text{m} \times 90 \mu\text{m}$ |

Pixel size and pitch as in detector table above

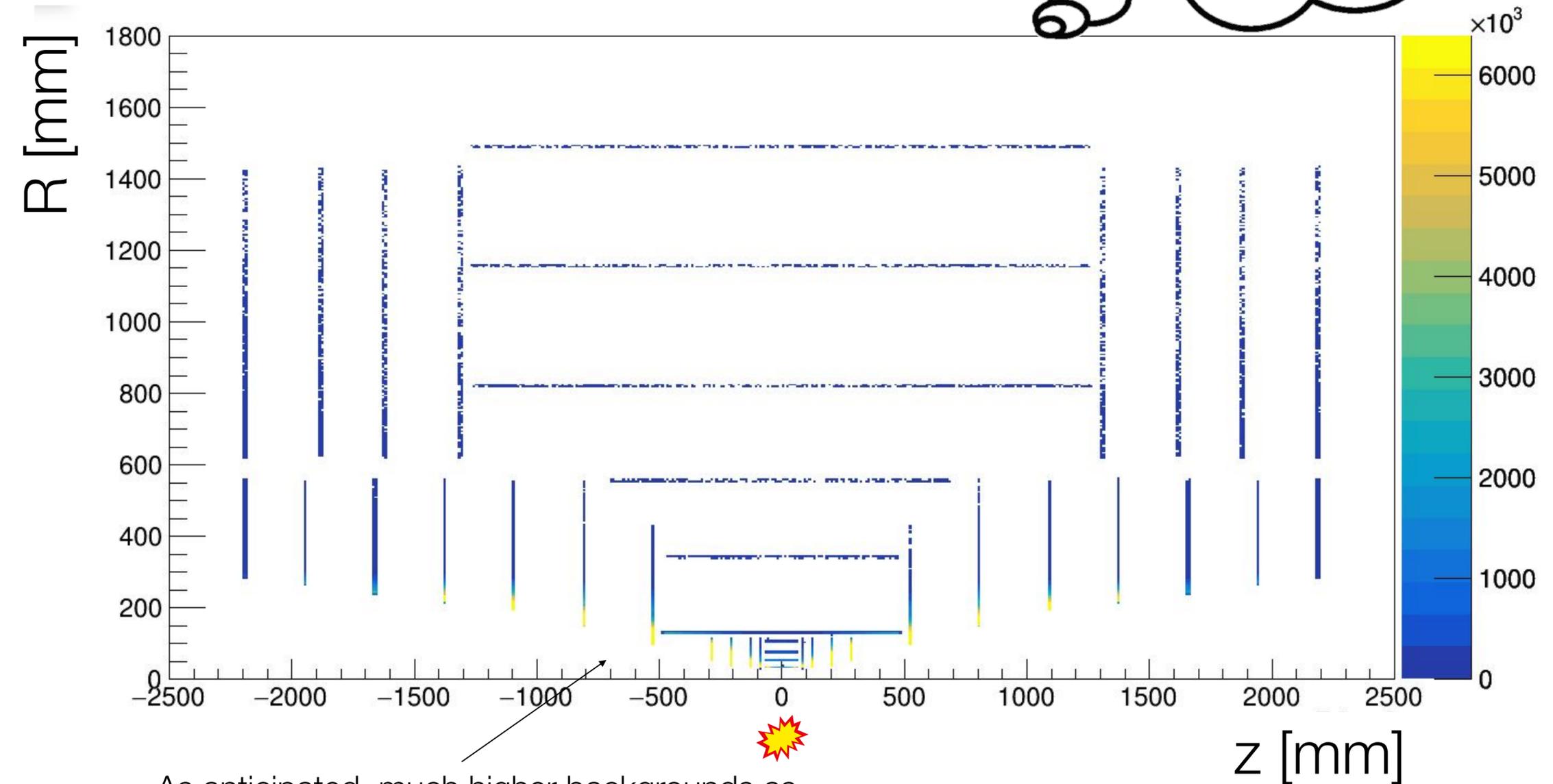
| Sub-Detector | Typical $\langle E \rangle$ loss [e] | Threshold [e] | Threshold variation σ [e] | Noise [e] | #bits for charge | Max charge (overflow) [e] |
|---------------|--------------------------------------|---------------|----------------------------------|-----------|------------------|---------------------------|
| Vertex | 4,000 | 500 | 25 | 80 | 4 | 15,000 |
| Inner Tracker | 8,000 | 1,000 | 25 | 80 | 4 | 60,000 |
| Outer Tracker | 8,000 | 1,000 | 25 | 80 | 4 | 60,000 |

Vertex and tracker configuration

Highest beamstrahlung background of the considered conditions!!



e^+e^- round beams



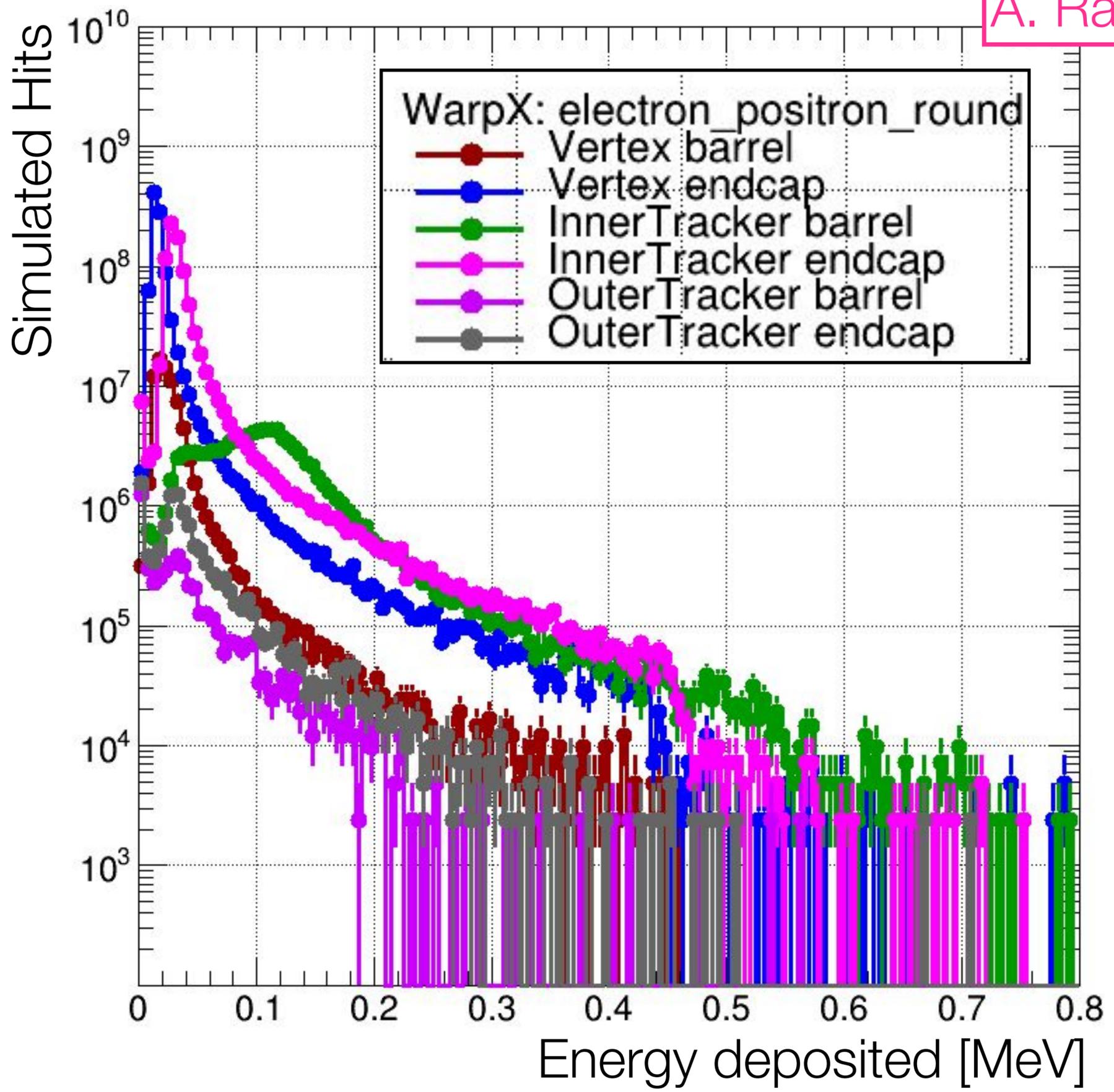
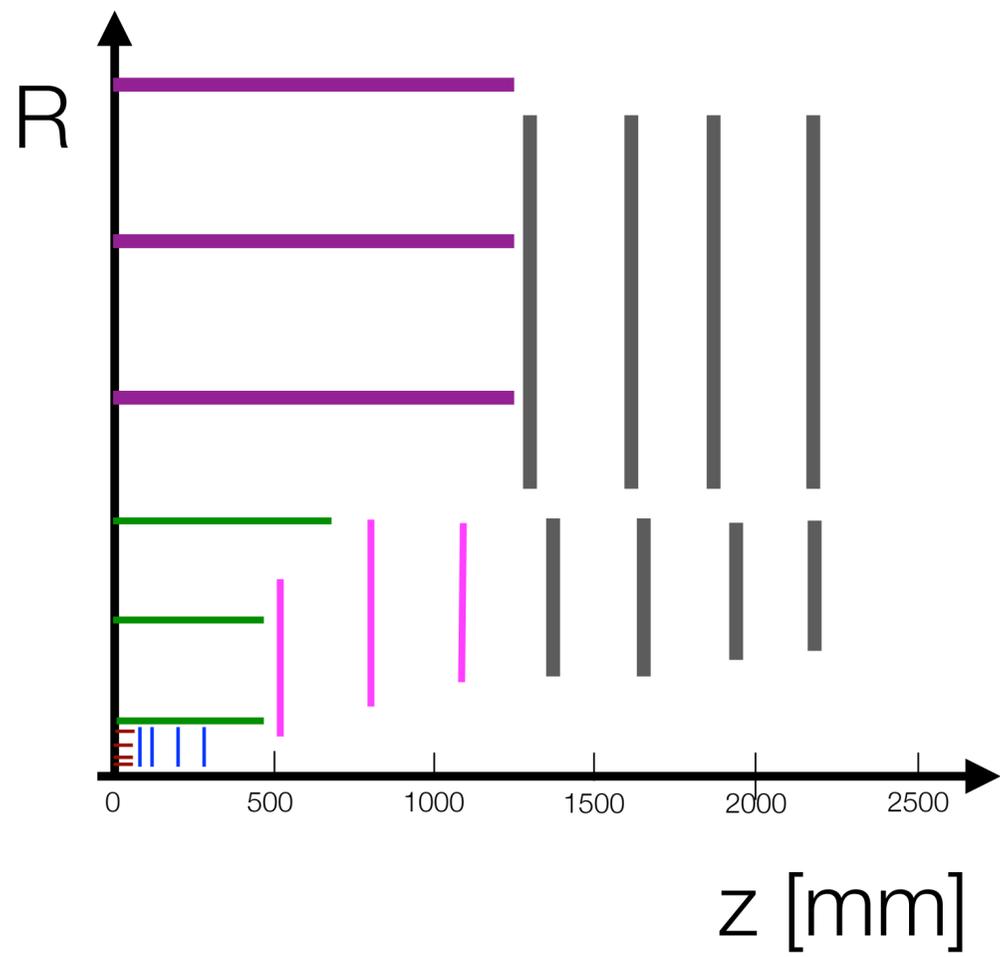
| | Vertex Detector | Inner Tracker | Outer Tracker |
|--------------------|--|---------------------------------------|---------------------------------------|
| Cell type | pixels | macropixels | microstrips |
| Cell Size | 25 $\mu\text{m} \times 25 \mu\text{m}$ | 50 $\mu\text{m} \times 1 \text{mm}$ | 50 $\mu\text{m} \times 10 \text{mm}$ |
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As anticipated, much higher backgrounds as you go into the forward region

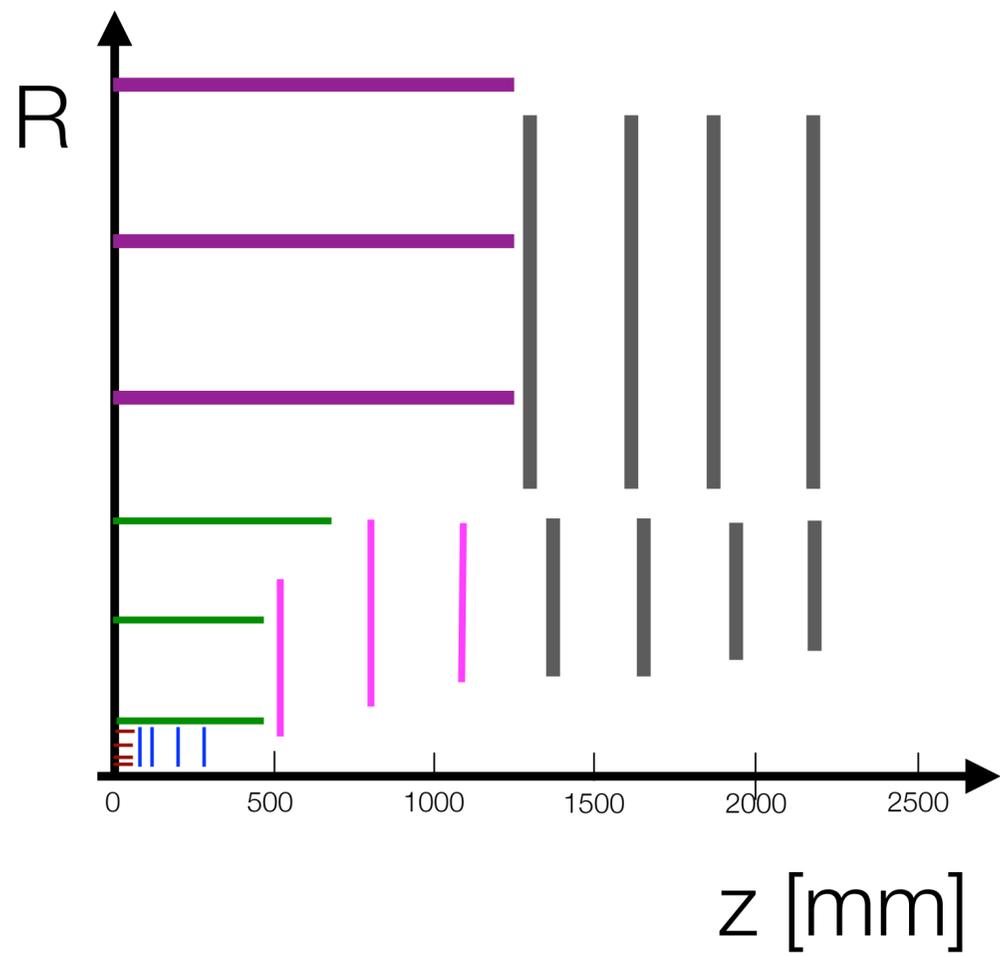
Pixel size and pitch as in detector table above

| Sub-Detector | Typical $\langle E \rangle$ loss [e] | Threshold [e] | Threshold variation σ [e] | Noise [e] | #bits for charge | Max charge (overflow) [e] |
|---------------|--------------------------------------|---------------|----------------------------------|-----------|------------------|---------------------------|
| Vertex | 4,000 | 500 | 25 | 80 | 4 | 15,000 |
| Inner Tracker | 8,000 | 1,000 | 25 | 80 | 4 | 60,000 |
| Outer Tracker | 8,000 | 1,000 | 25 | 80 | 4 | 60,000 |

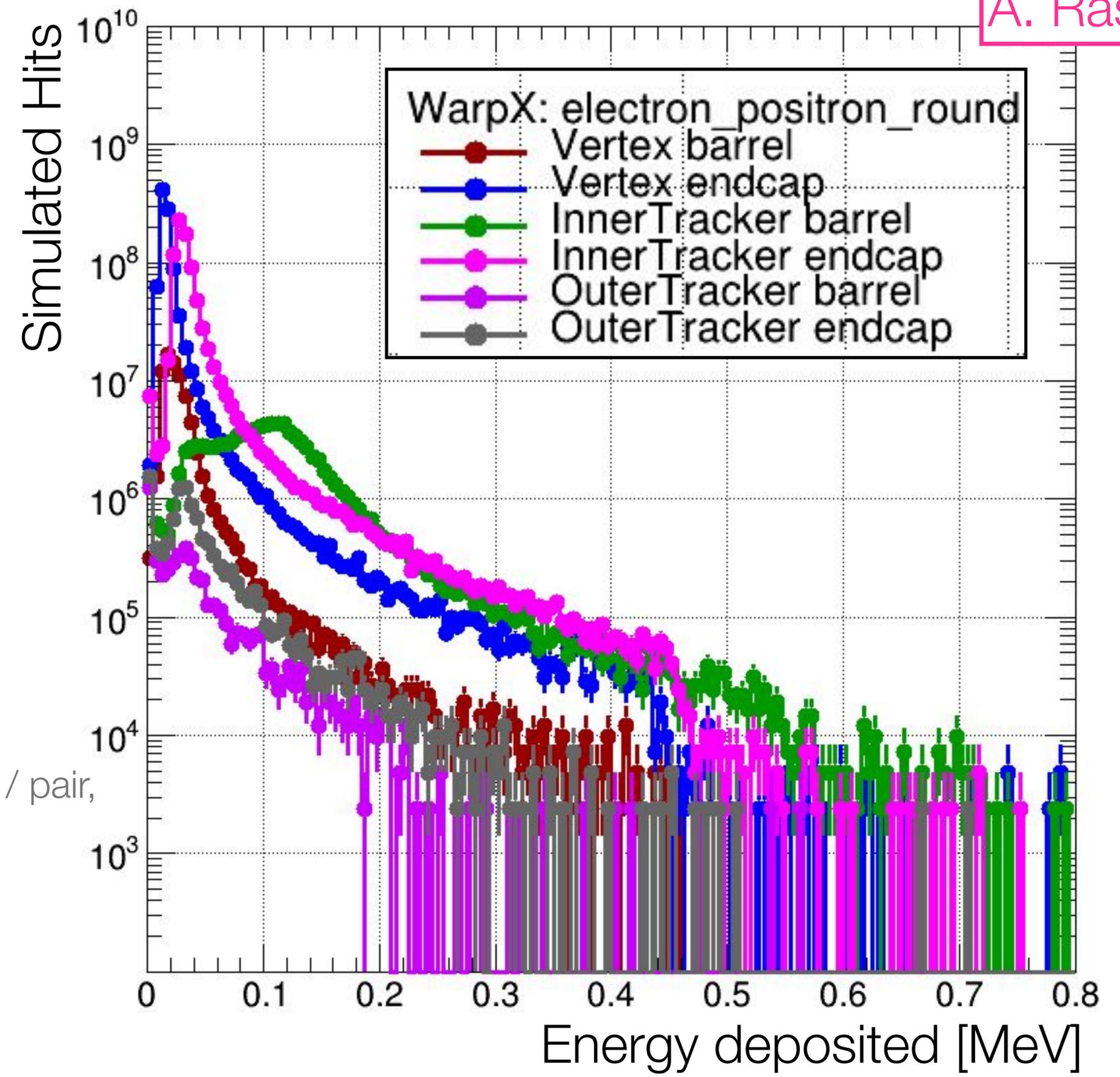
Simulation output



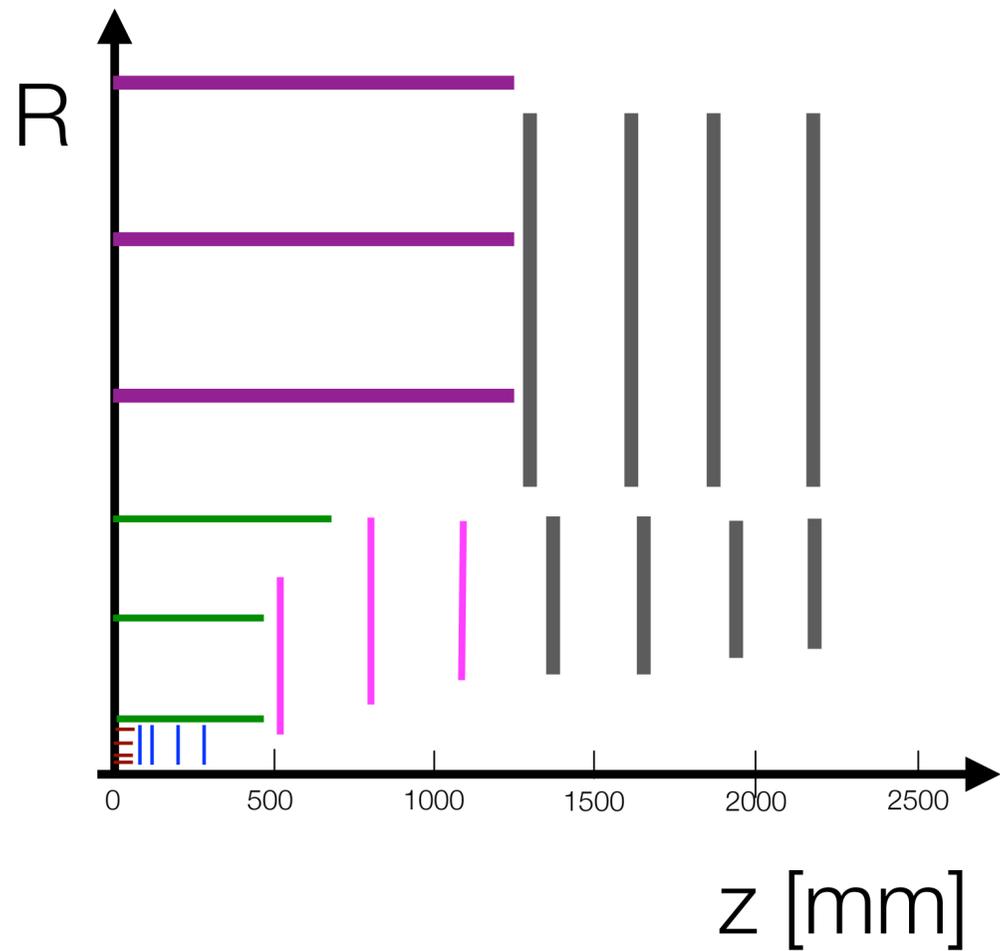
Simulation output



~ 4000 electron-hole pairs, 3.6 eV / pair,
expect $\mathcal{O}(10)$ s keV
➔ Looks reasonable

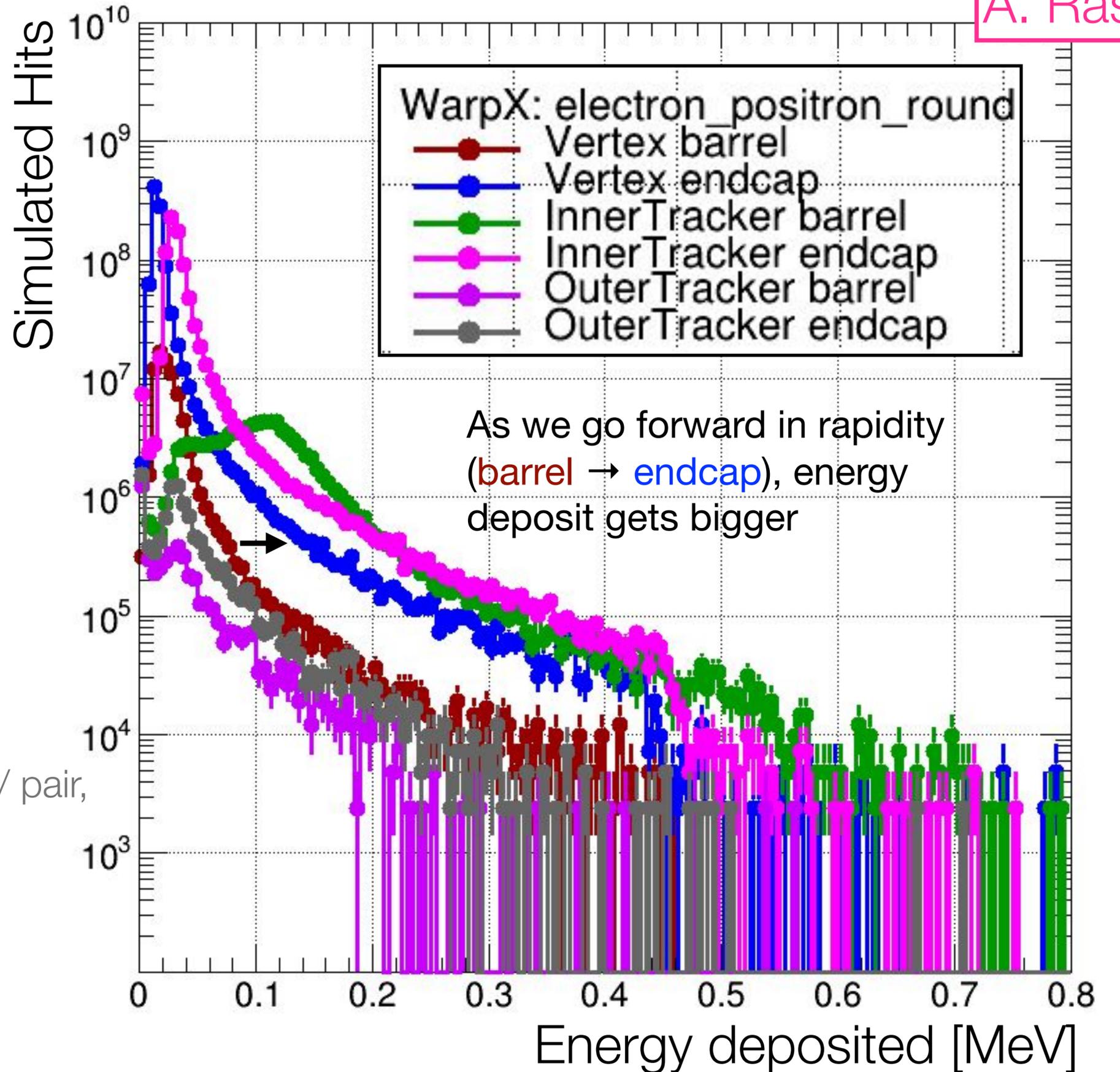


Simulation output

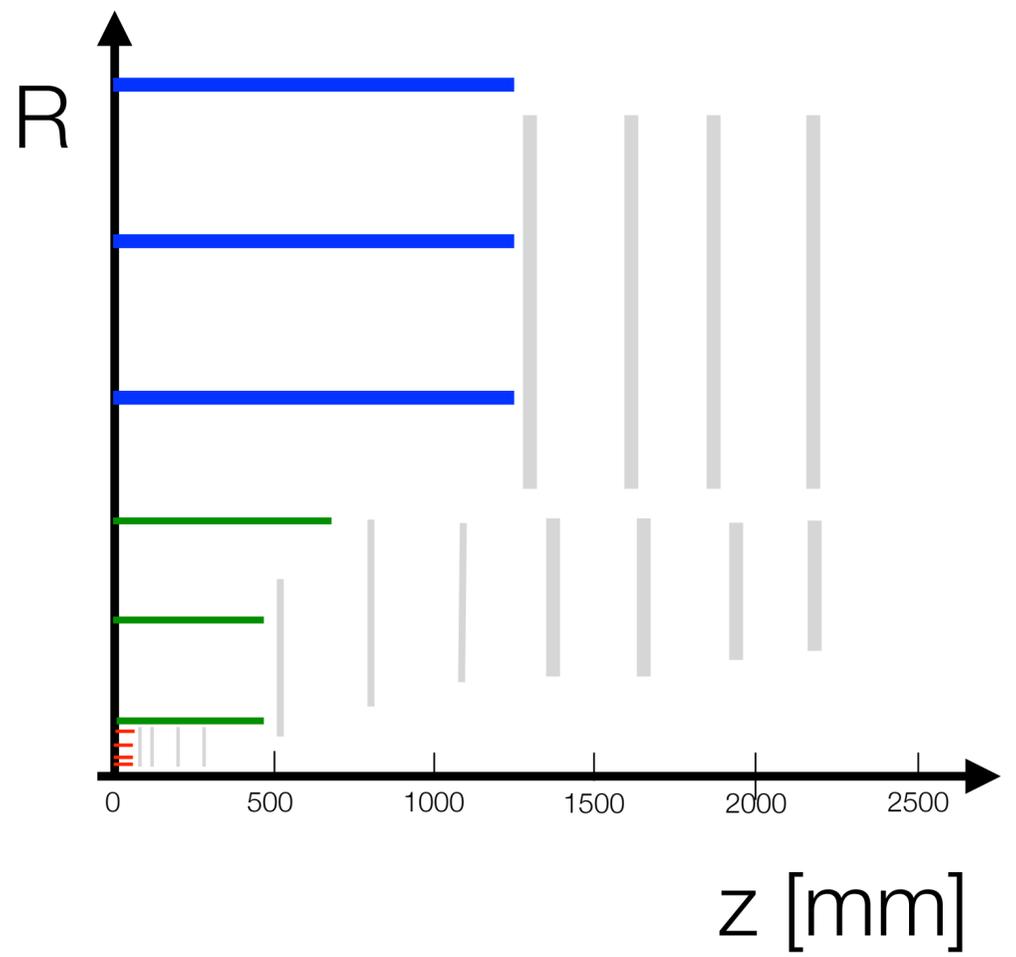


~ 4000 electron-hole pairs, 3.6 eV / pair,
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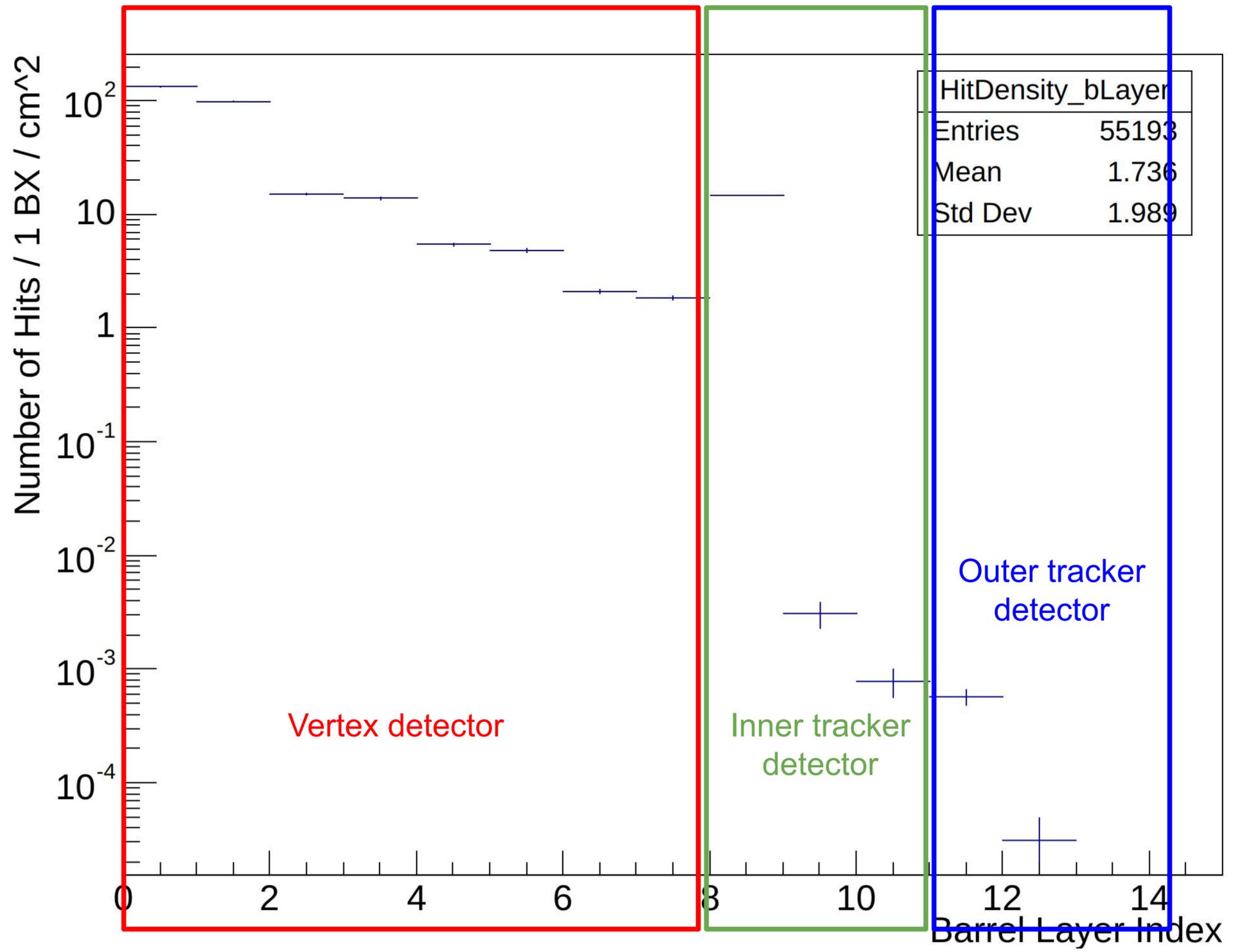
➡ Looks reasonable



Occupancy



As you go farther out from the interaction point, the occupancy gets lower.





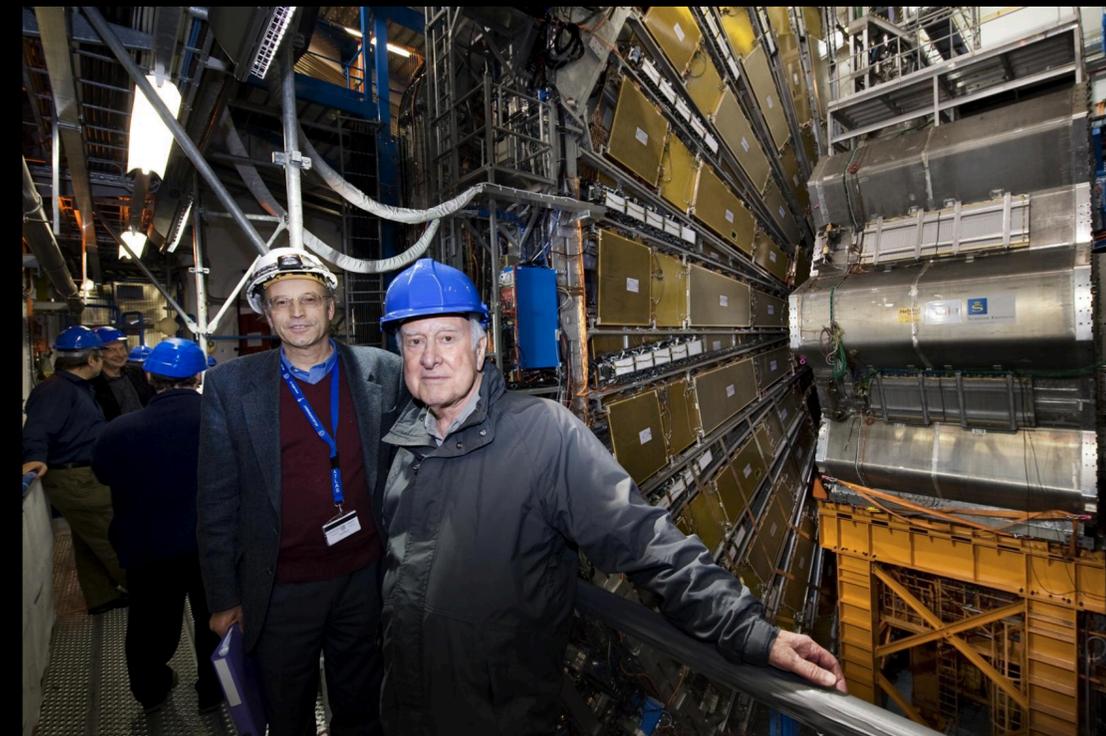


Beyond our wildest imaginations!

BENEFIT OF HINDSIGHT:

[Because of the] granularity of the calorimeters... ATLAS can exploit now with — at the time unforeseen — advanced analysis methods a lot of **physics well beyond the initial dreams.**

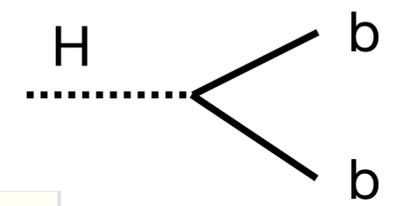
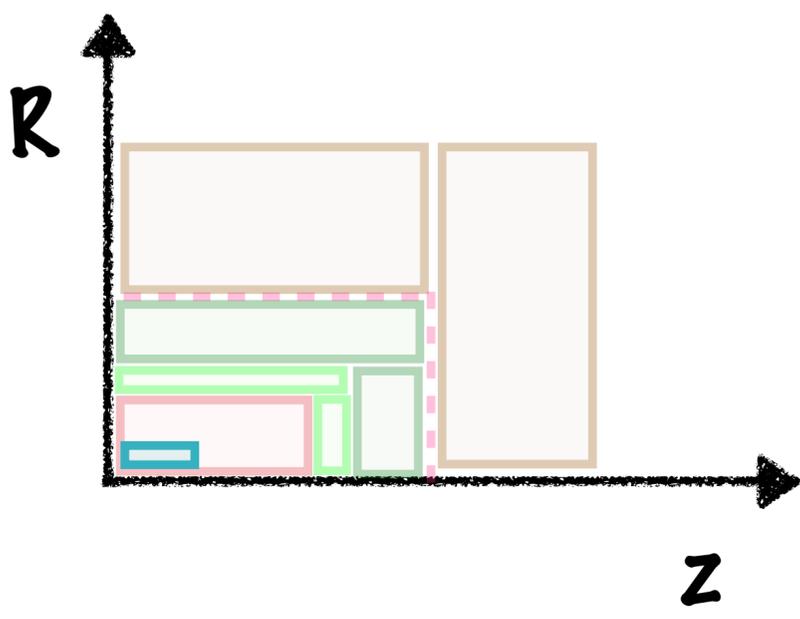
— Peter Jenni, founding spokesperson of ATLAS



Vertex

Vertex detector

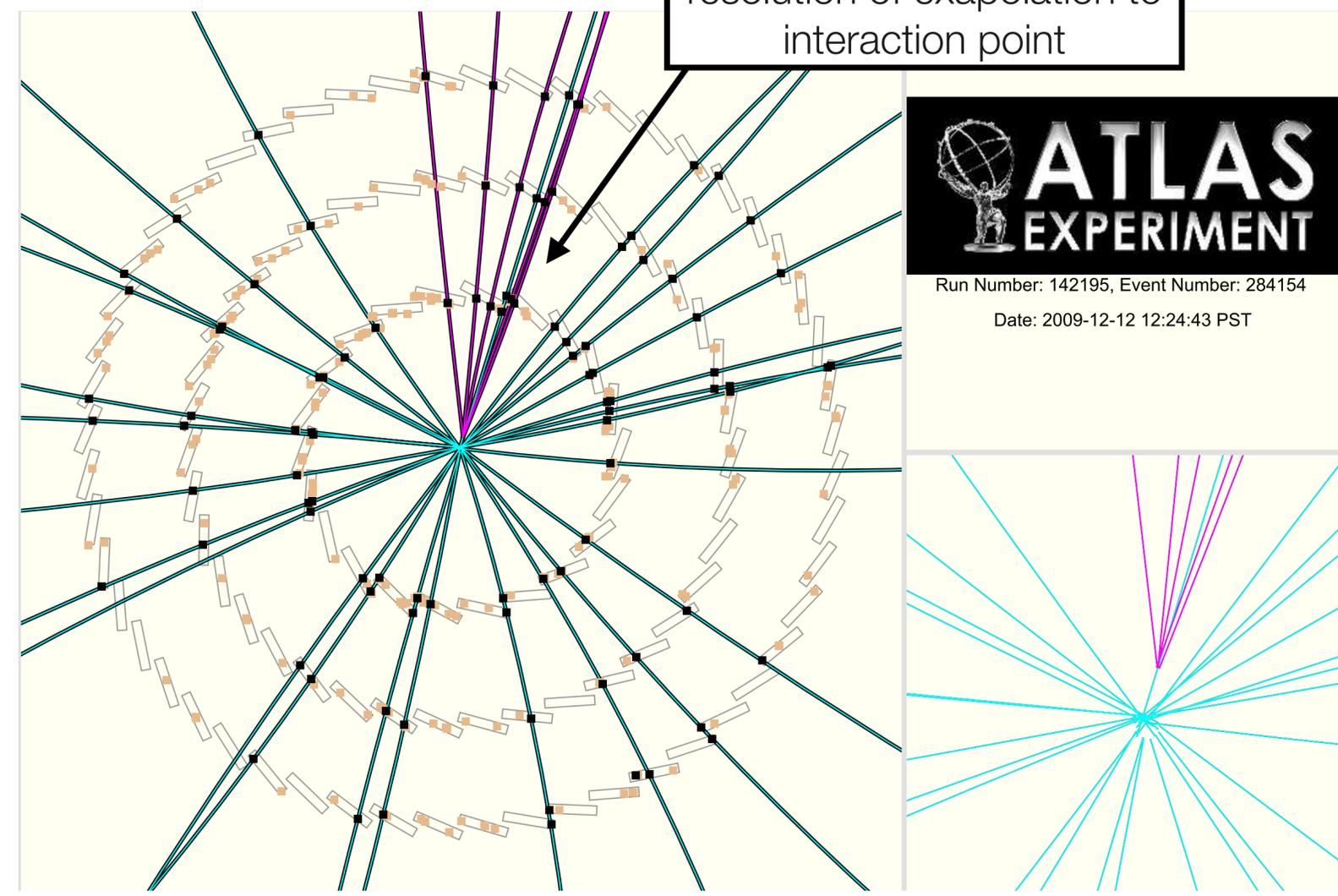
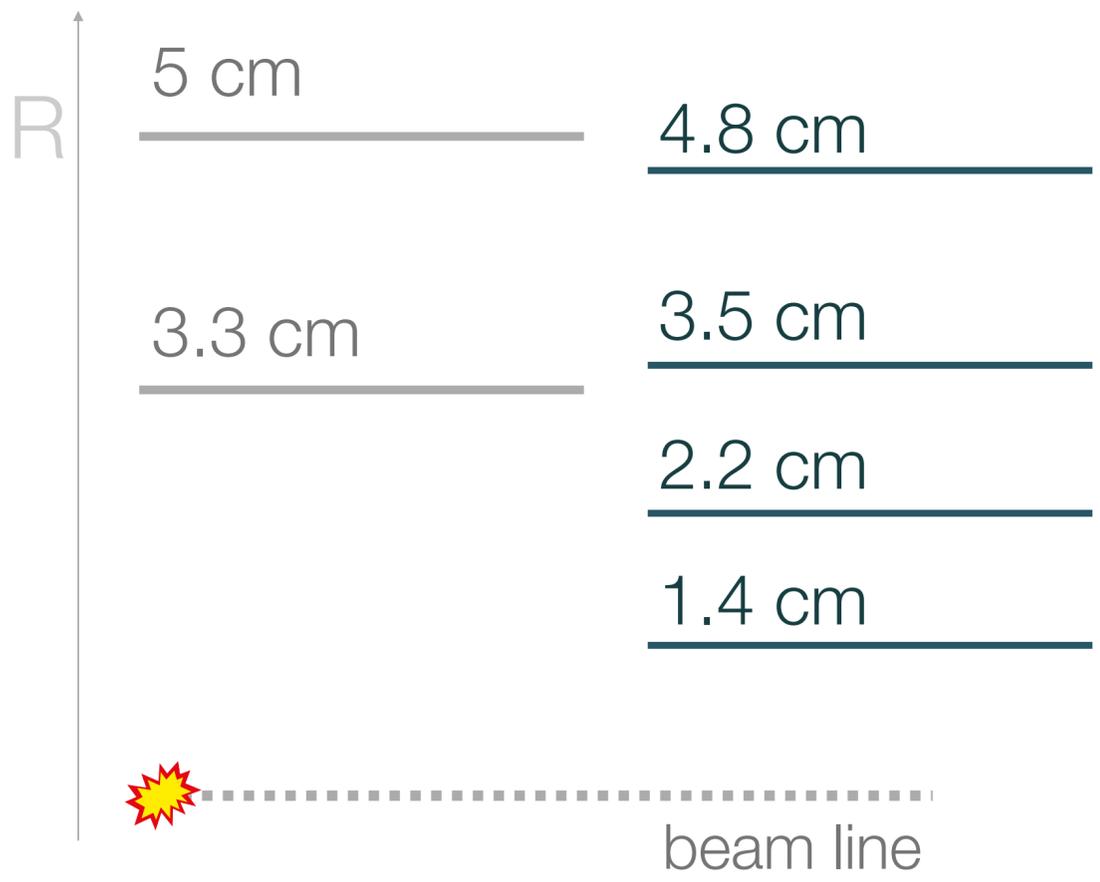
Why close to the interaction point? Crucial for **b/c-tagging**.



Closest hit determines the resolution of extrapolation to interaction point

ATLAS (pp)

SiD (pp)

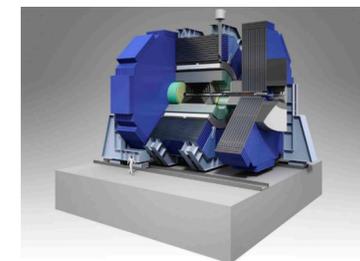


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 Date: 2009-12-12 12:24:43 PST

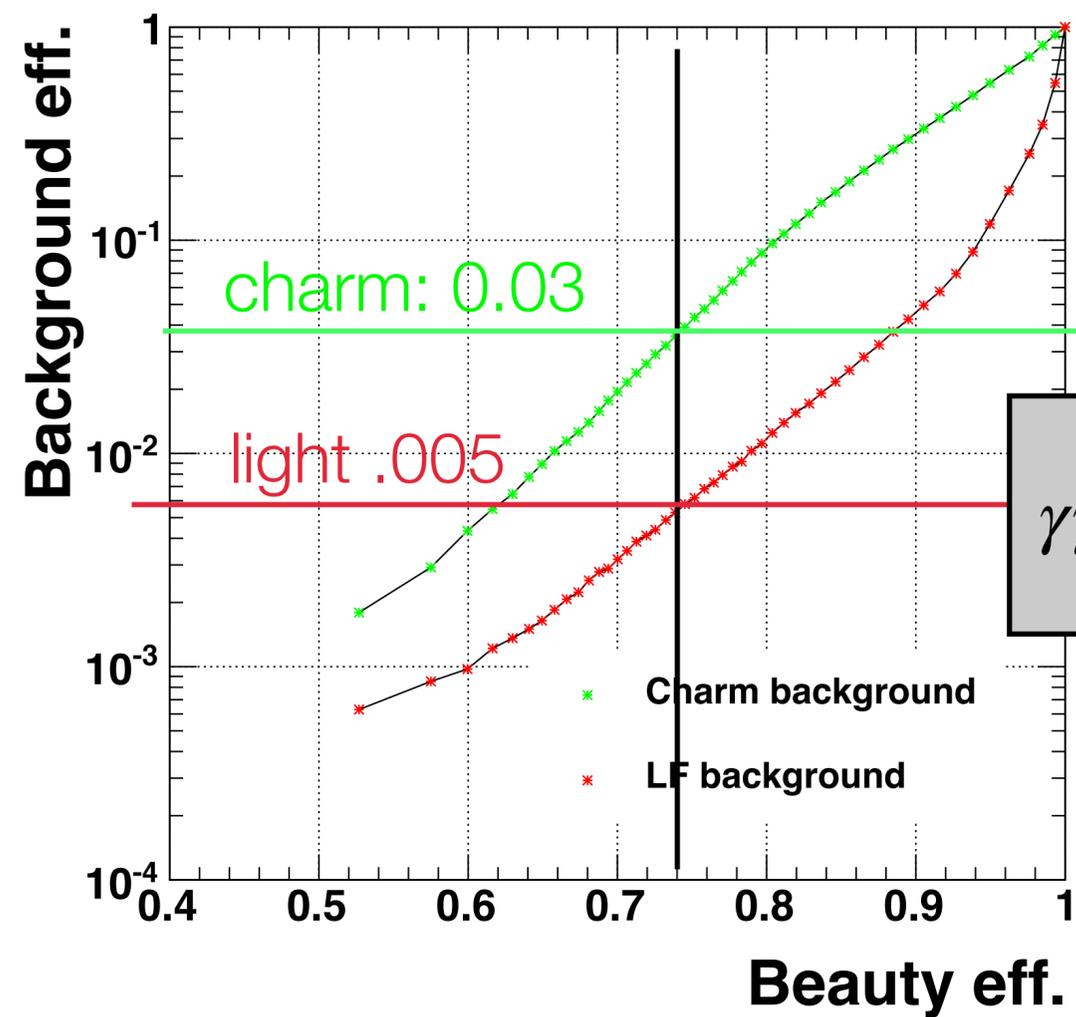
Tracker

Calorimeter

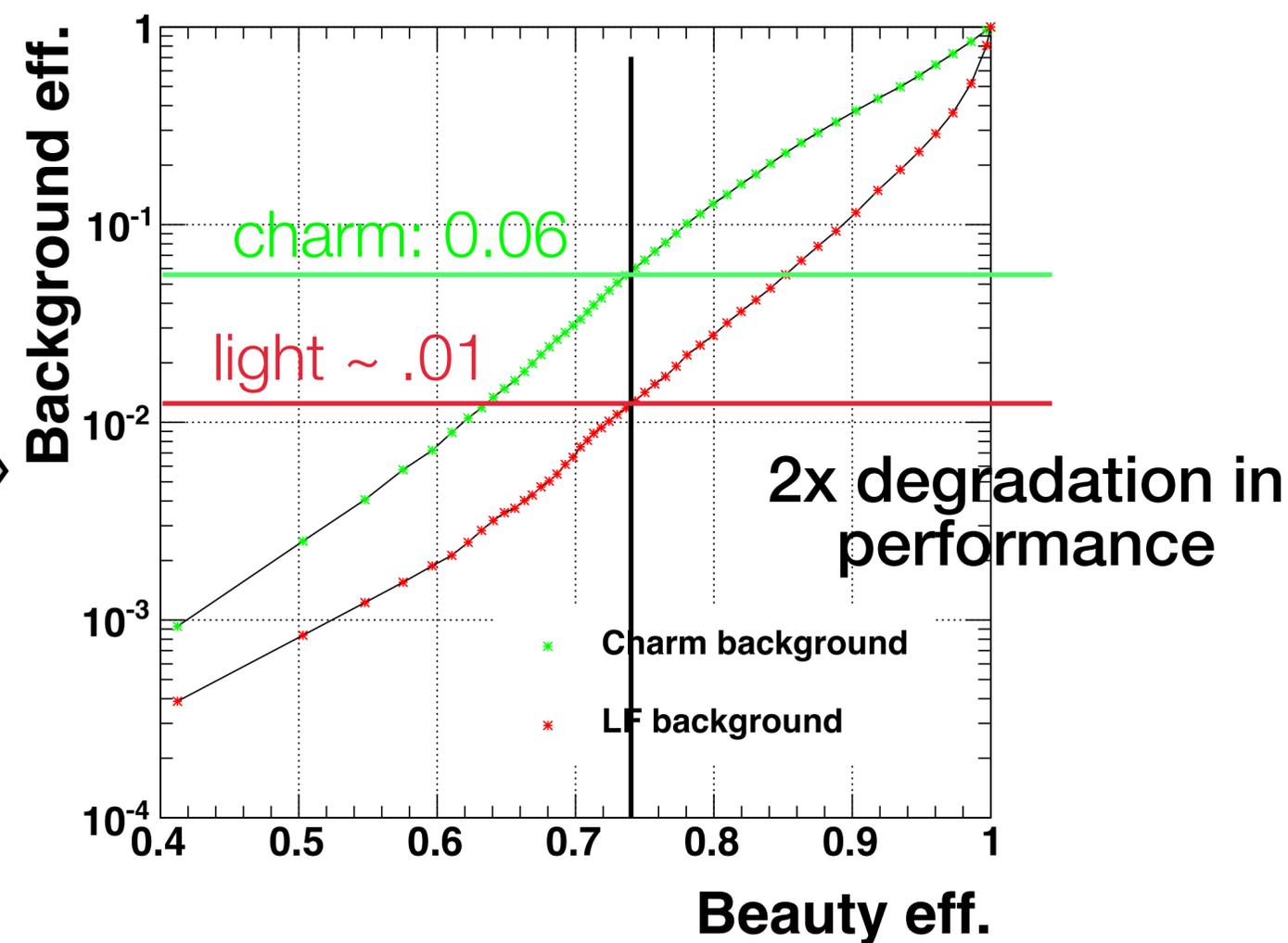
Forward detector

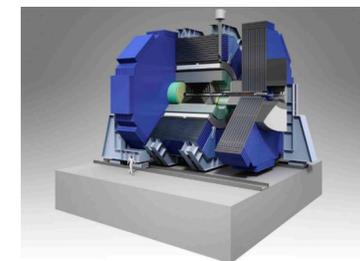


SiD : FTAG

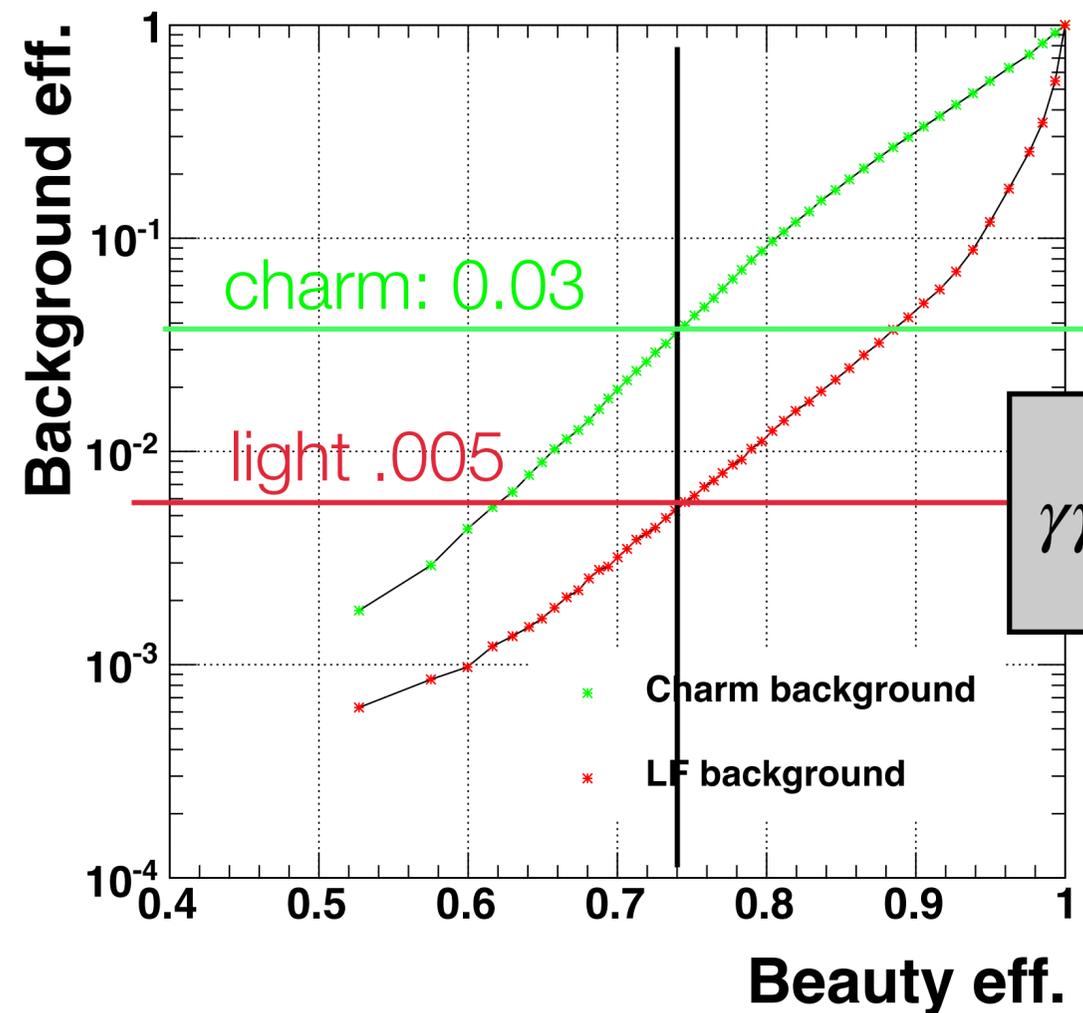


Adding in
 $\gamma\gamma \rightarrow$ hadrons
background

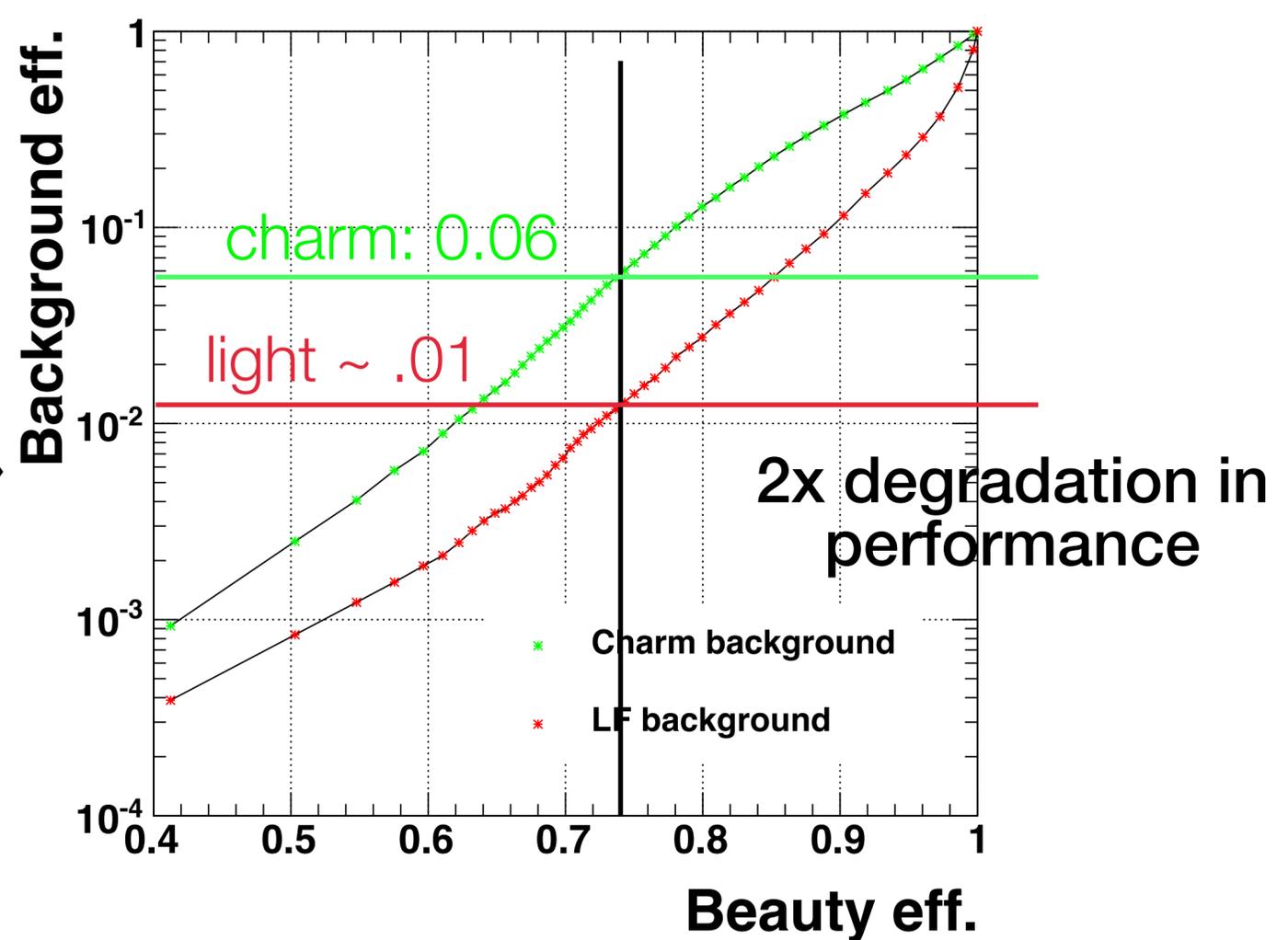




SiD : FTAG

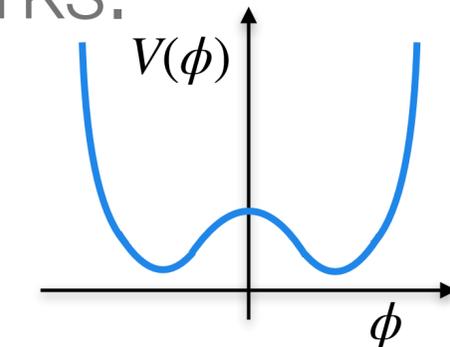
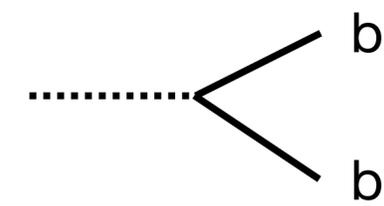


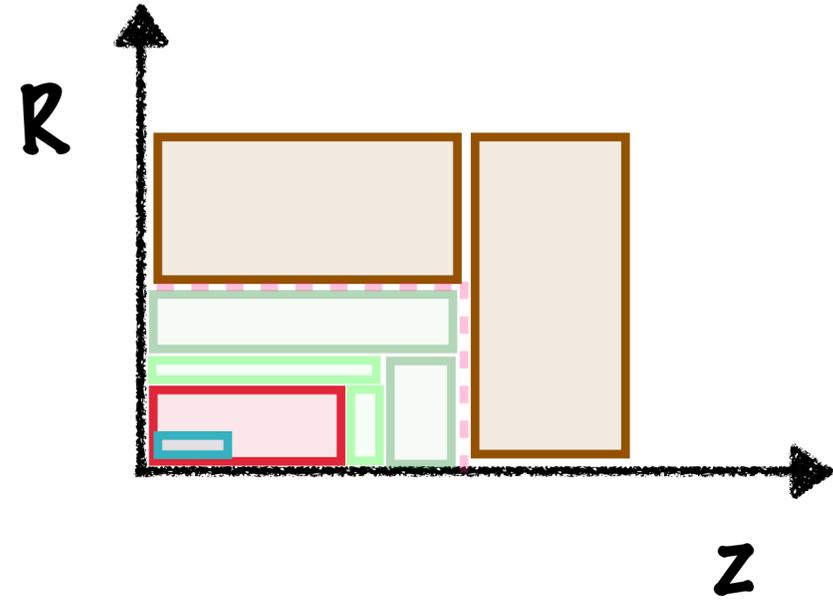
Adding in $\gamma\gamma \rightarrow$ hadrons background



Fun to optimize for our MDI, backgrounds, and physics benchmarks.

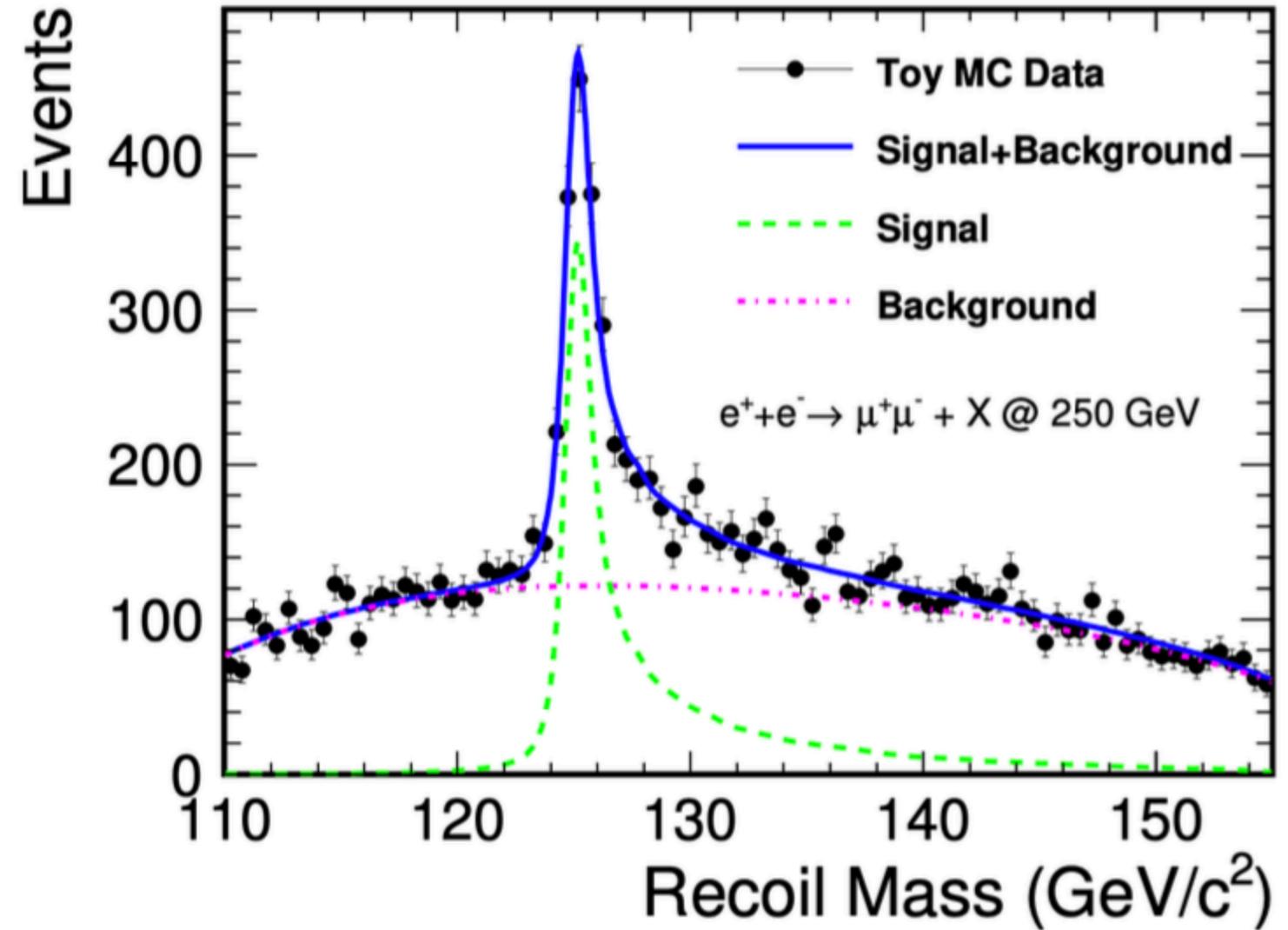
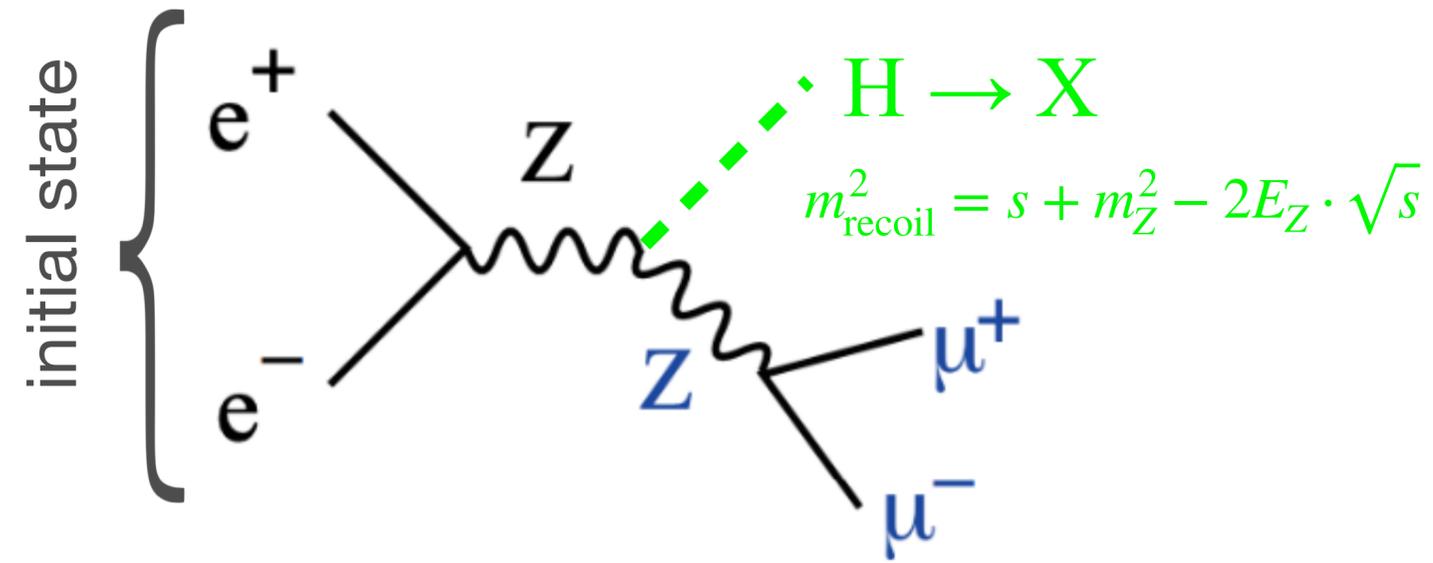
- * Note: Will be WAY better now, ATLAS FTAG already exceeding these SiD performance: **charm mistag = 0.057**; **light mistag = 0.0022**; more details
- * And with dedicated e+e- ftag trainings: 2202.03285; 2406.08590 ; 2501.16584





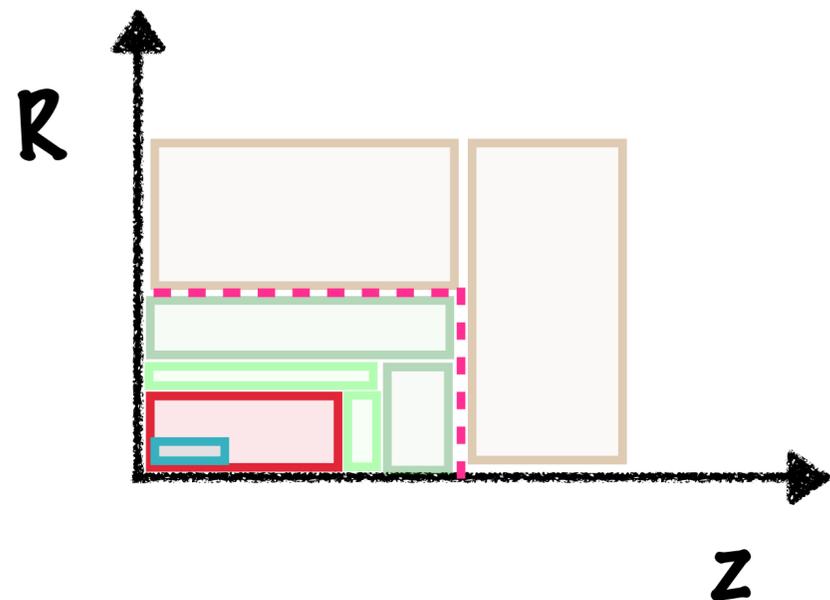
Tracking system

Key process for Higgs physics program is ZH production where we'll "tag" the Z via $\mu^+\mu^-$.



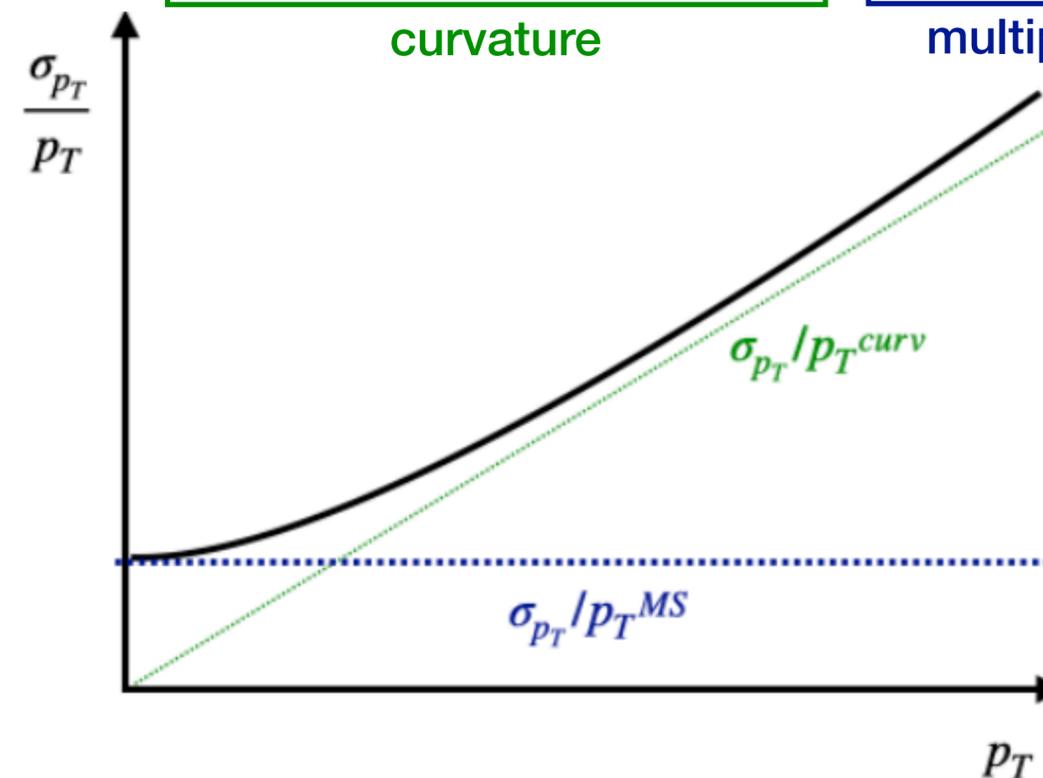
Tracker (+ muon system) defines our momentum desiderata.

Tracking system



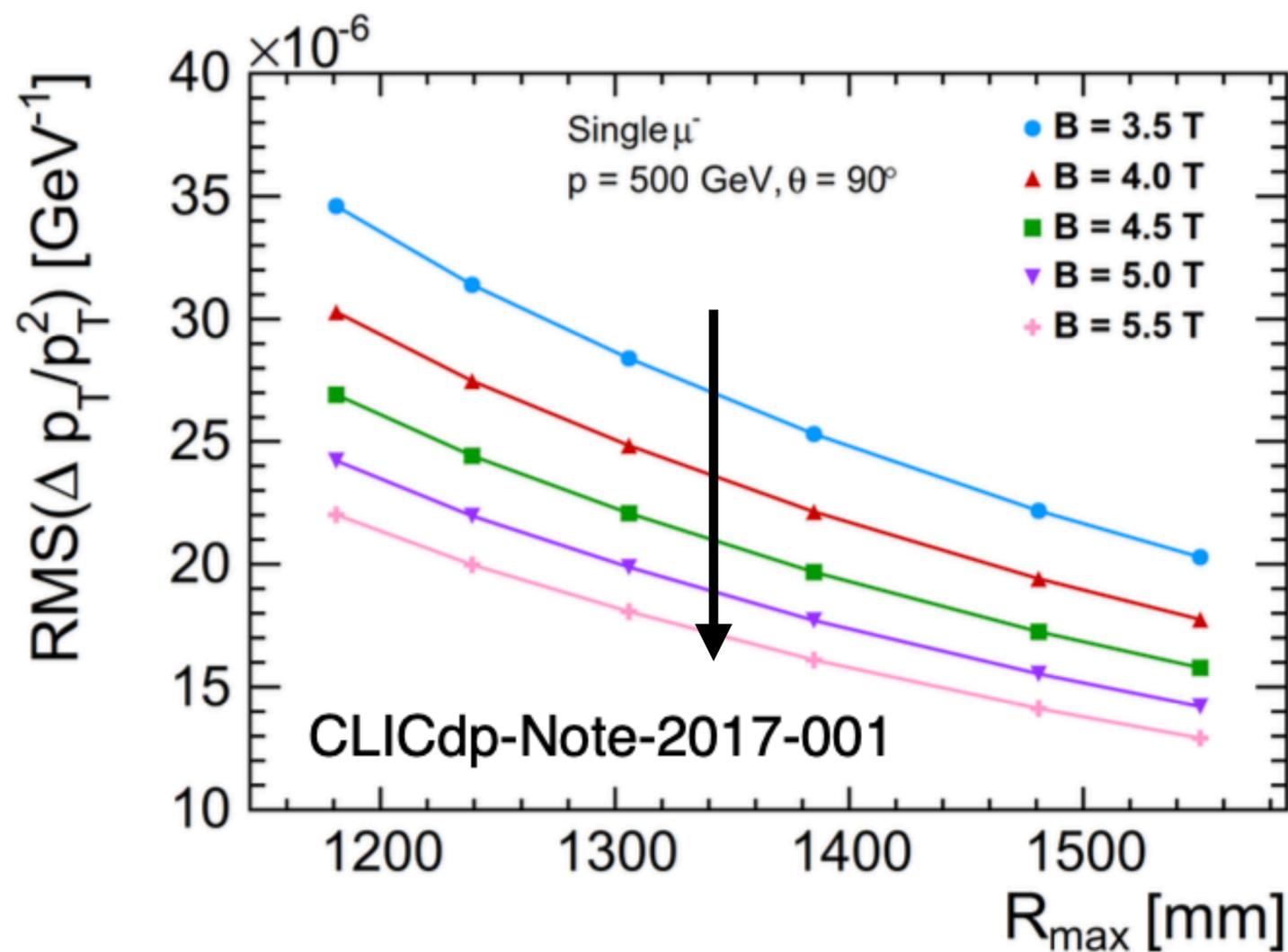
$$\left(\frac{\sigma_{p_T}}{p_T}\right)^2 \propto c_1 \cdot \left(\frac{p_T}{B \cdot R_{\max}^2} \sqrt{\frac{720}{N+4}}\right)^2 + c_2 \cdot \left(\frac{1}{B\sqrt{R_{\max}X_0}}\right)^2$$

curvature
multiple scattering

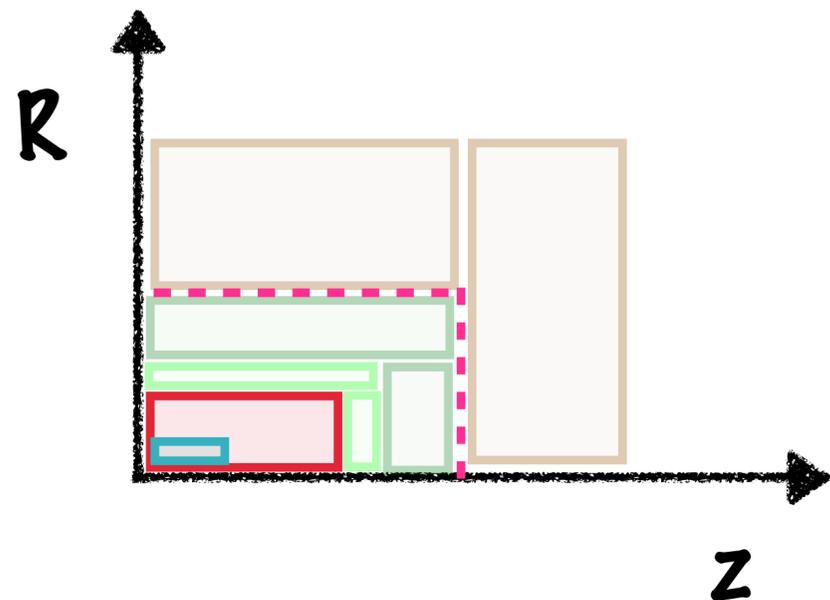


Larger B-field: More curvature

→ better momentum resolution

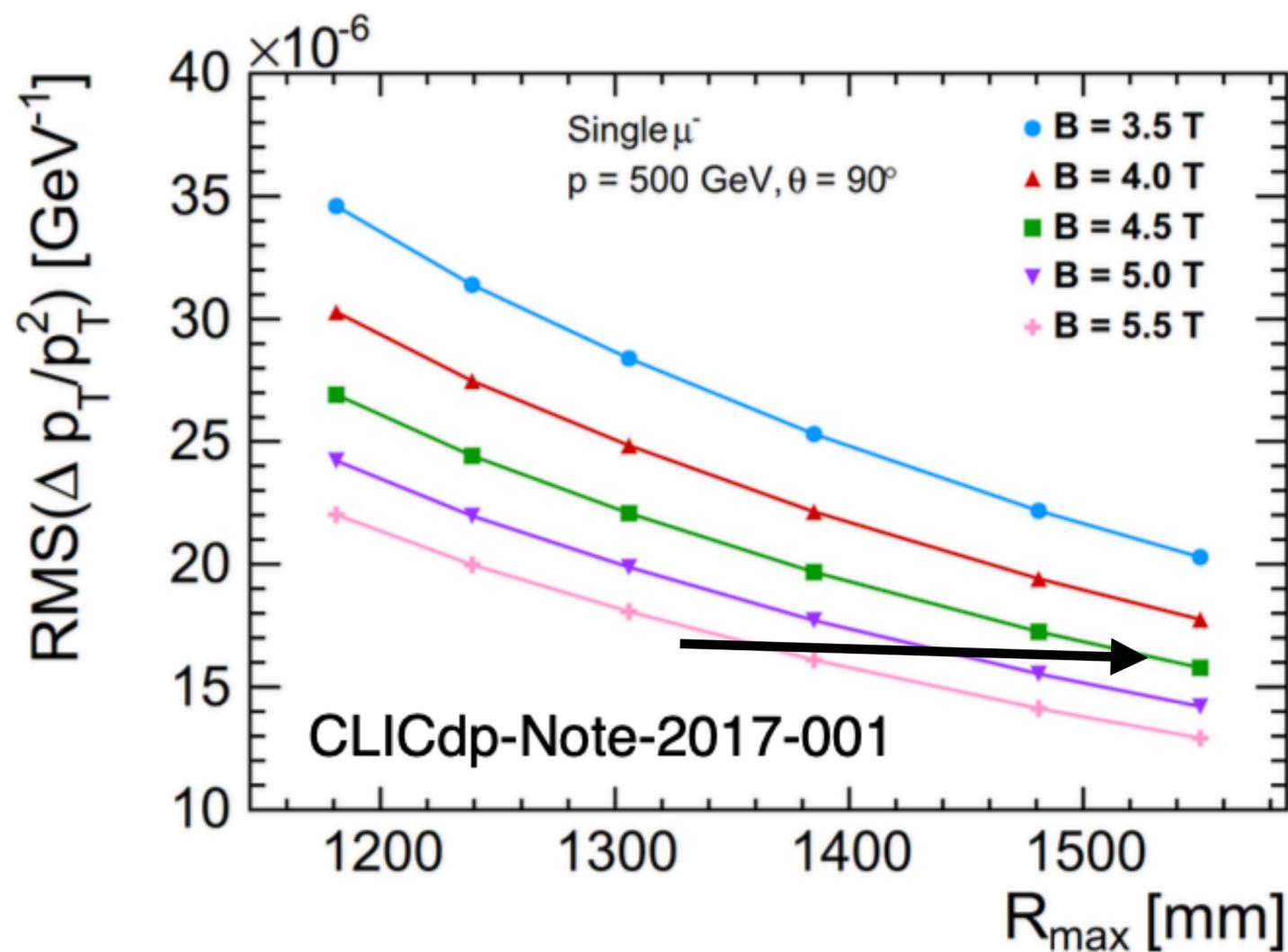
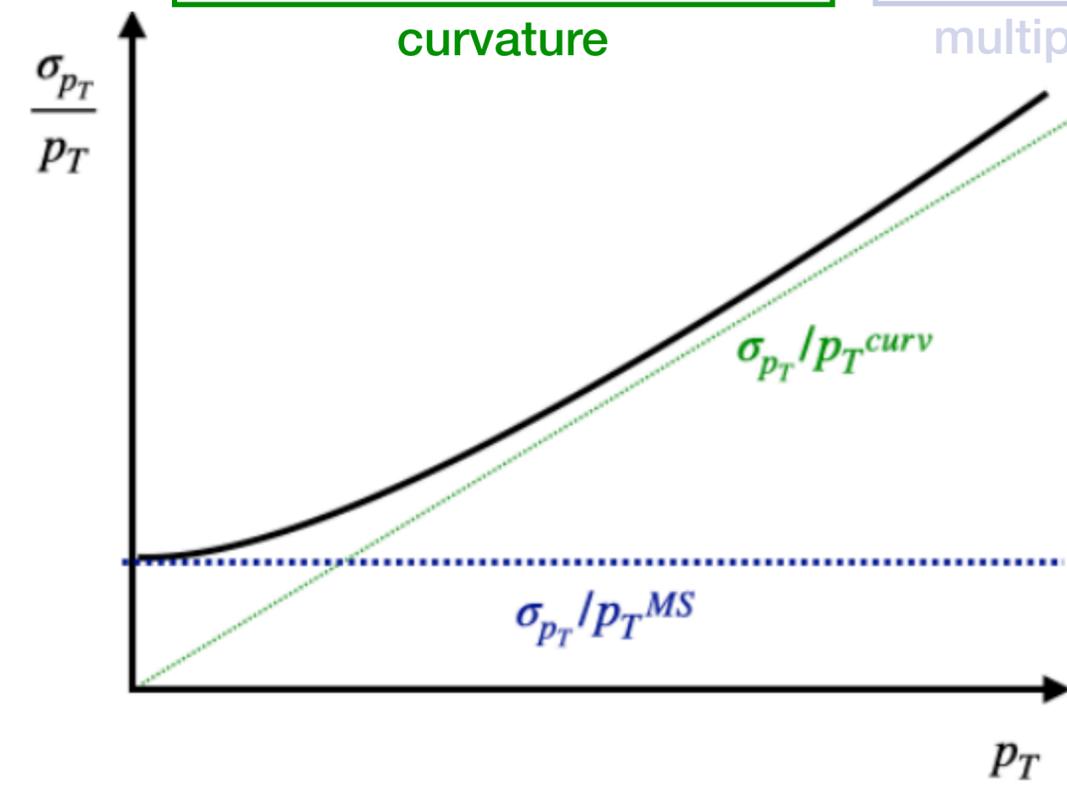


Tracking system



$$\left(\frac{\sigma_{p_T}}{p_T}\right)^2 \propto c_1 \cdot \left(\frac{p_T}{B \cdot R_{\max}^2} \sqrt{\frac{720}{N+4}}\right)^2 + c_2 \cdot \left(\frac{1}{B \sqrt{R_{\max} X_0}}\right)^2$$

curvature
multiple scattering



Larger tracker (increasing R_{\max}), also improves the resolution.

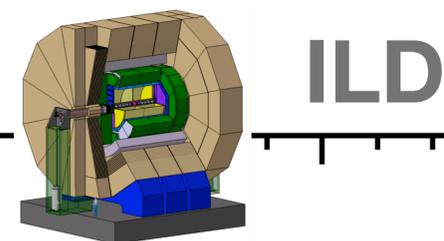
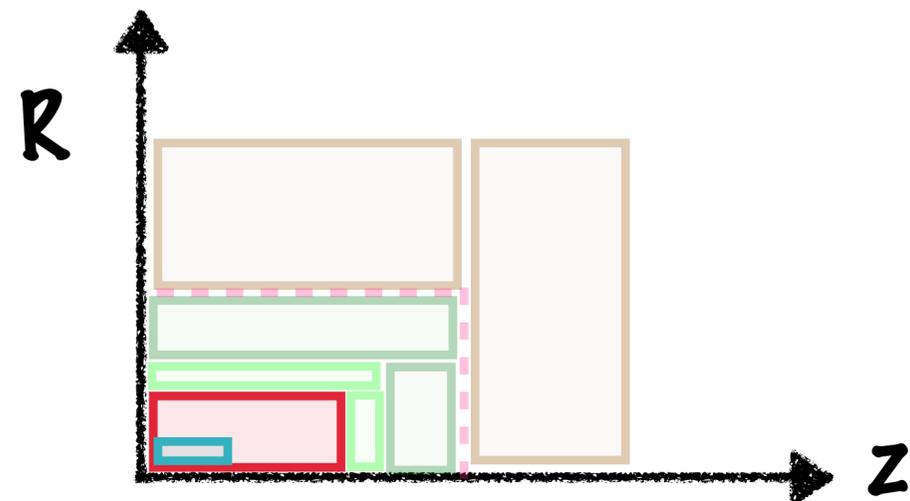
Vertex

Tracker

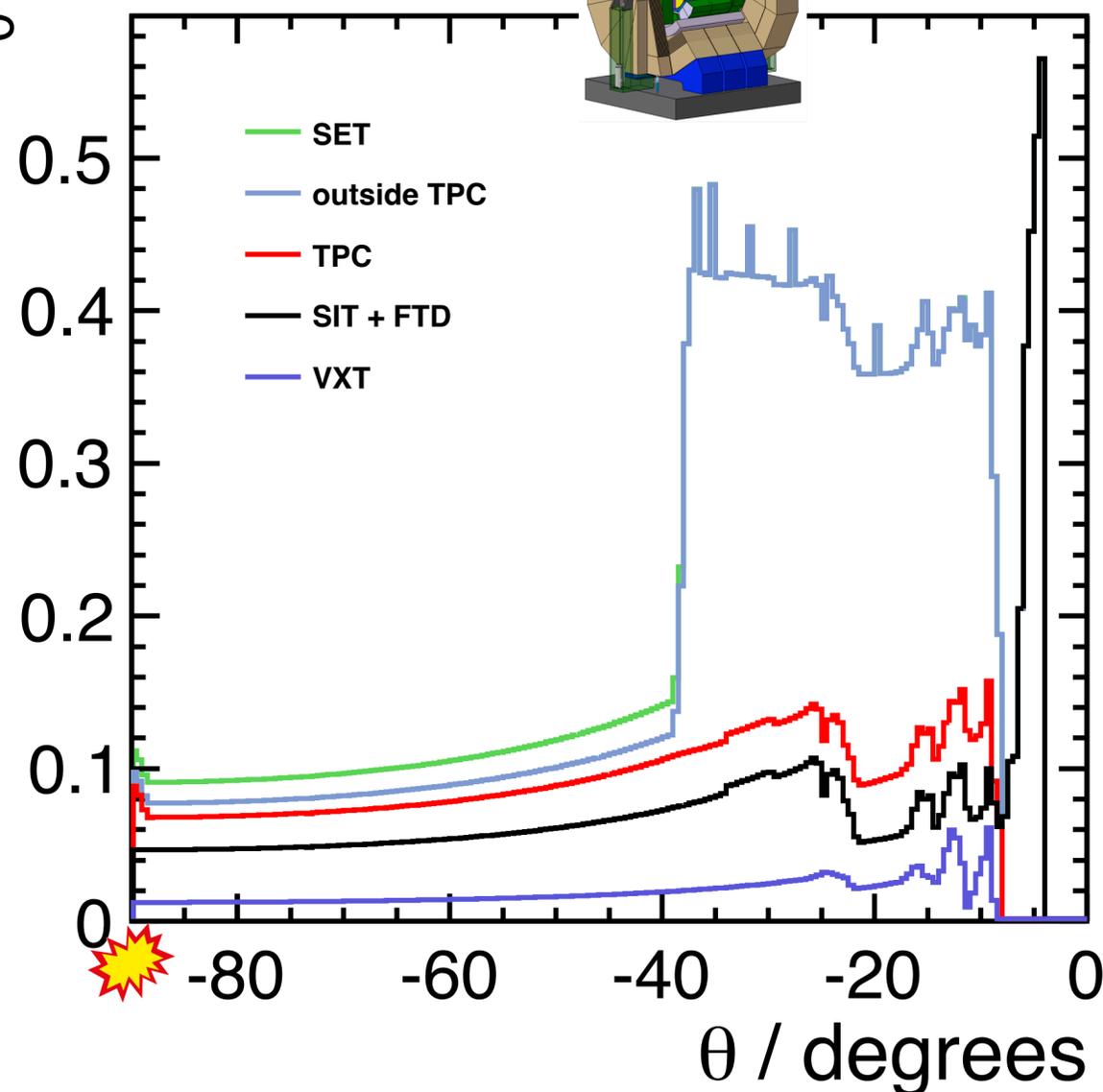
Calorimeter

Forward detector

Tracking system

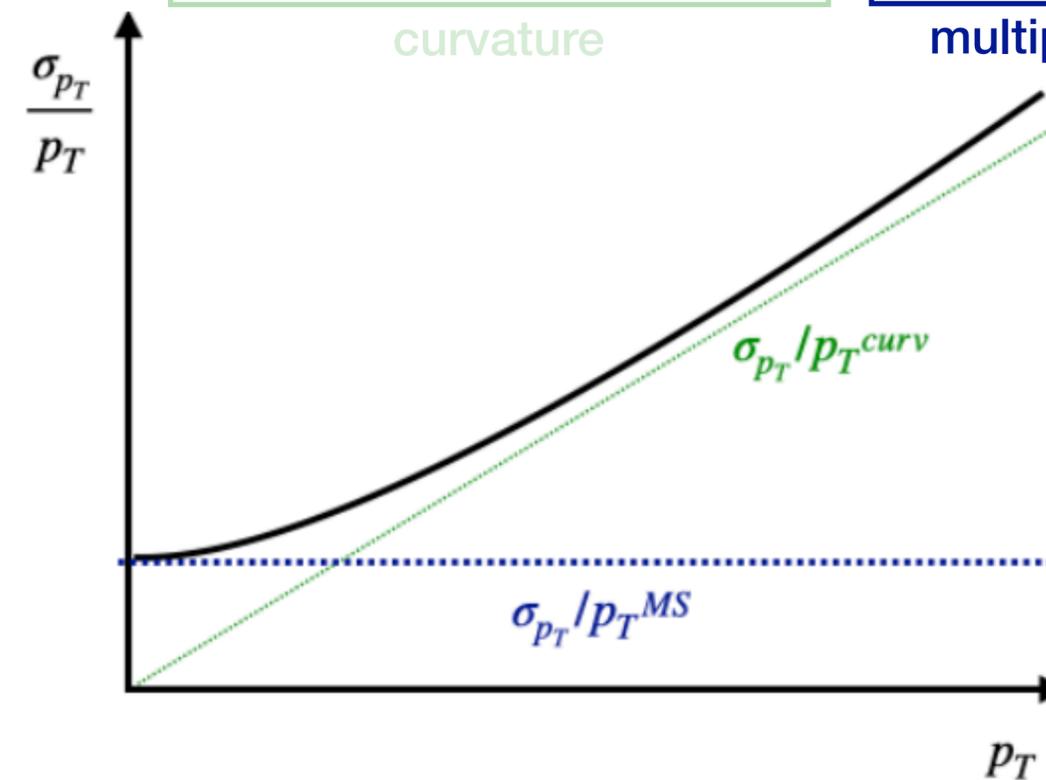


Radiation length
Mean length in material when energy is reduced by 1/e.



$$\left(\frac{\sigma_{p_T}}{p_T}\right)^2 \propto c_1 \cdot \left(\frac{p_T}{B \cdot R_{\max}^2} \sqrt{\frac{720}{N+4}}\right)^2 + c_2 \cdot \left(\frac{1}{B \sqrt{R_{\max} X_0}}\right)^2$$

curvature
multiple scattering



- Minimize multiple scattering \downarrow material
- Drives need to have “light” sensors
- “Power pulsing” key advantage for linear colliders (especially PWFA / $\gamma\gamma$ 😊)

Vertex
Tracker
Calorimeter
Forward detector

Initial state
Final state

Hadron Collider

- High backgrounds
- Higher σ and \mathcal{L}

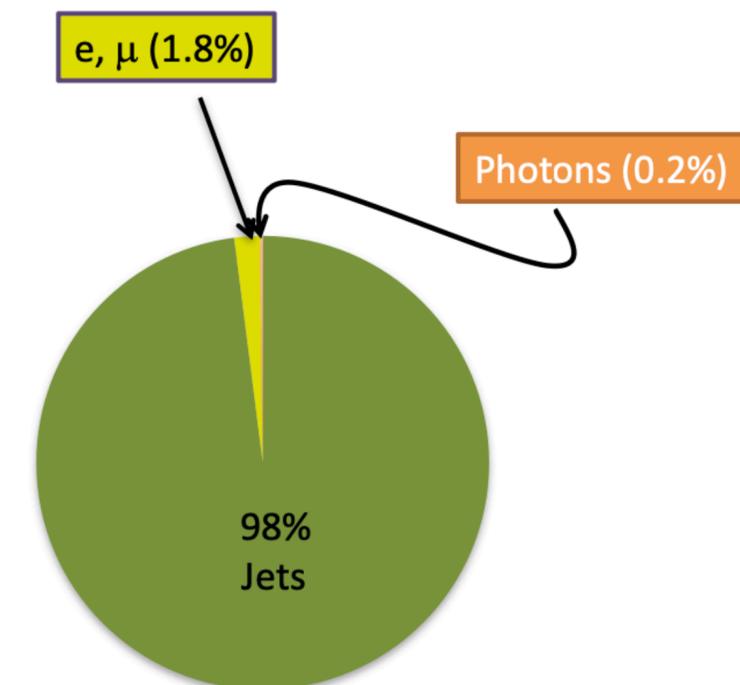
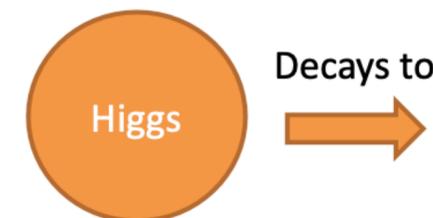
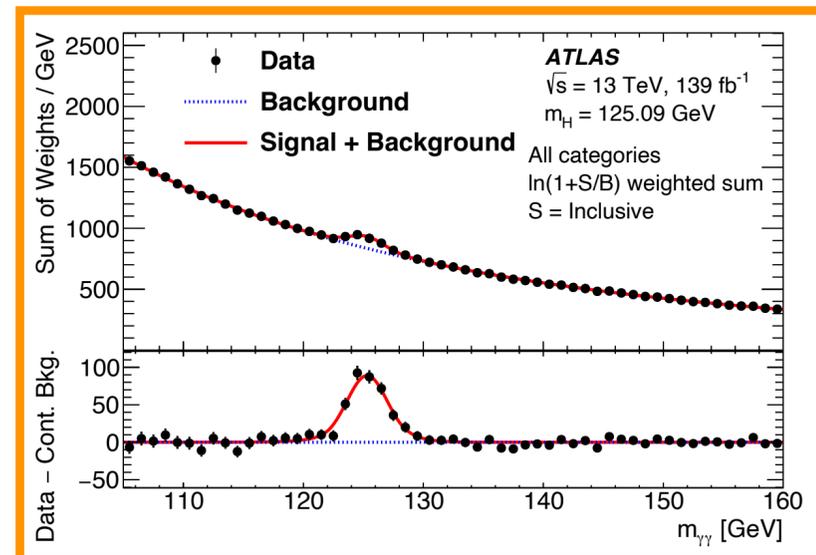
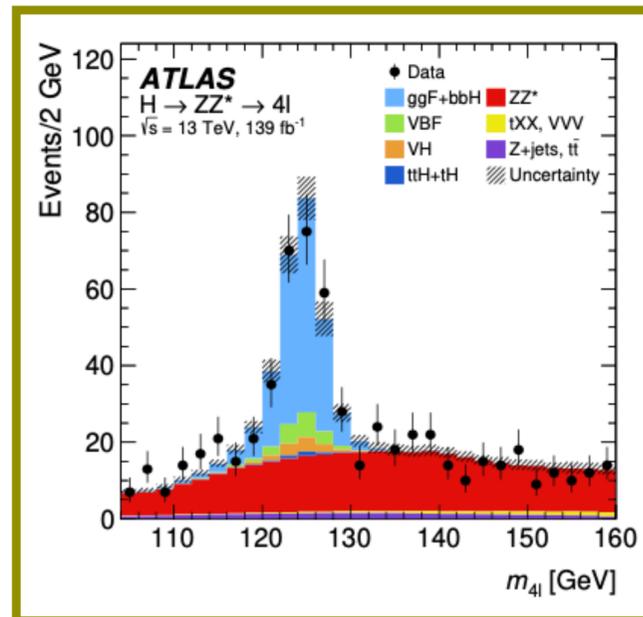
Lepton / $\gamma\gamma$ Collider

- Clean environment
* Our di-jets $\gamma\gamma \rightarrow$ hadrons bkg
- Low cross section

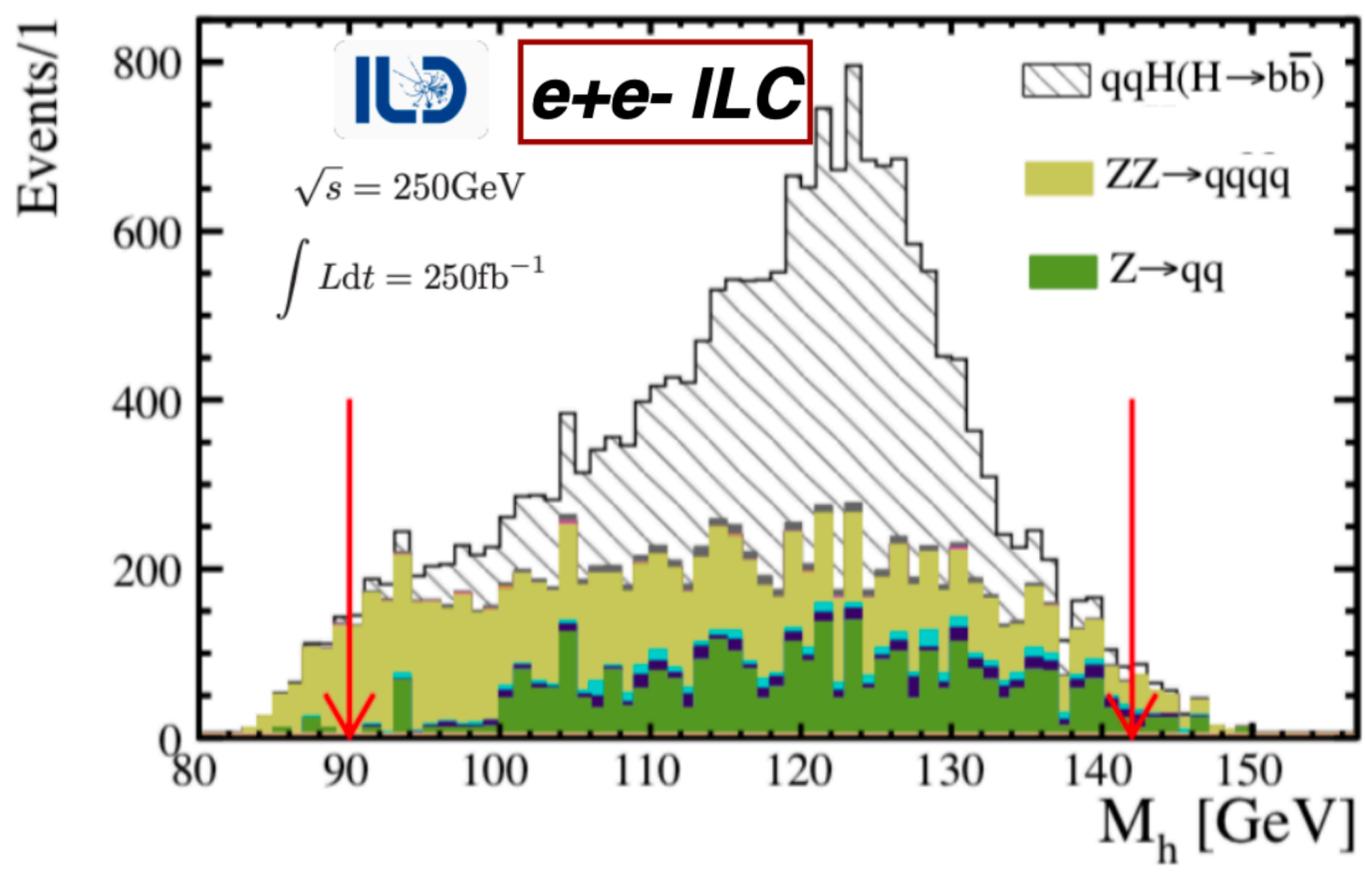
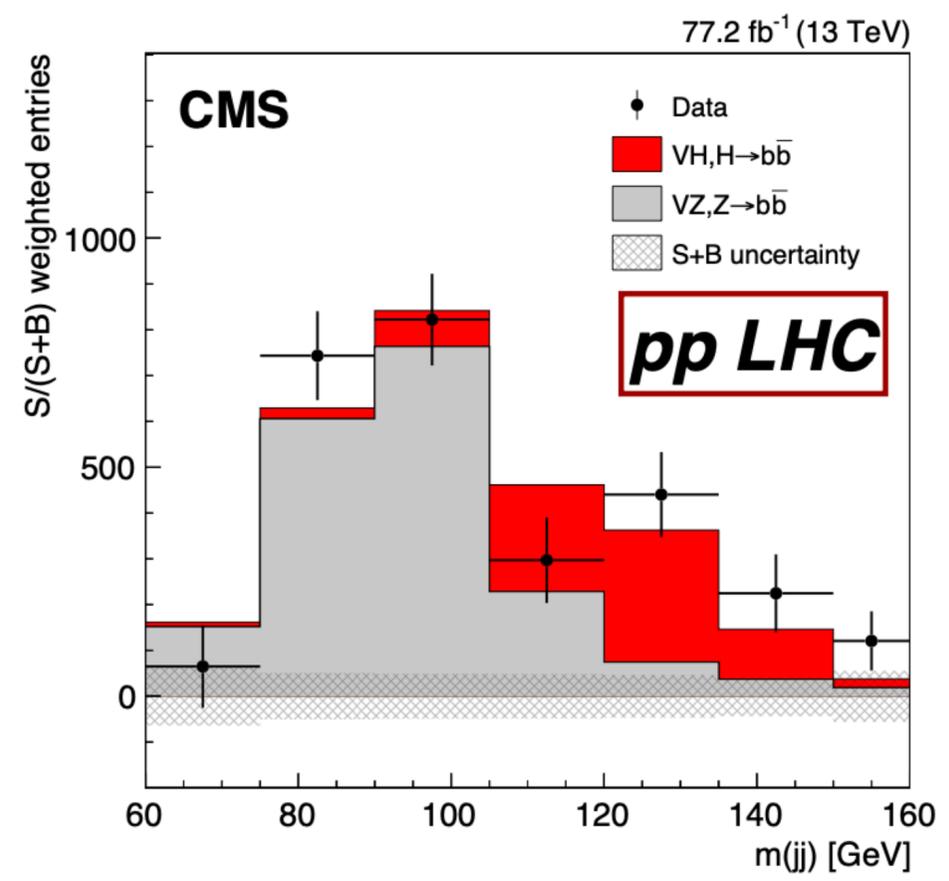


Leptons and photons
in analysis.

Hadronic jets in analysis.



e^+e^- : Branching Ratio *matters*



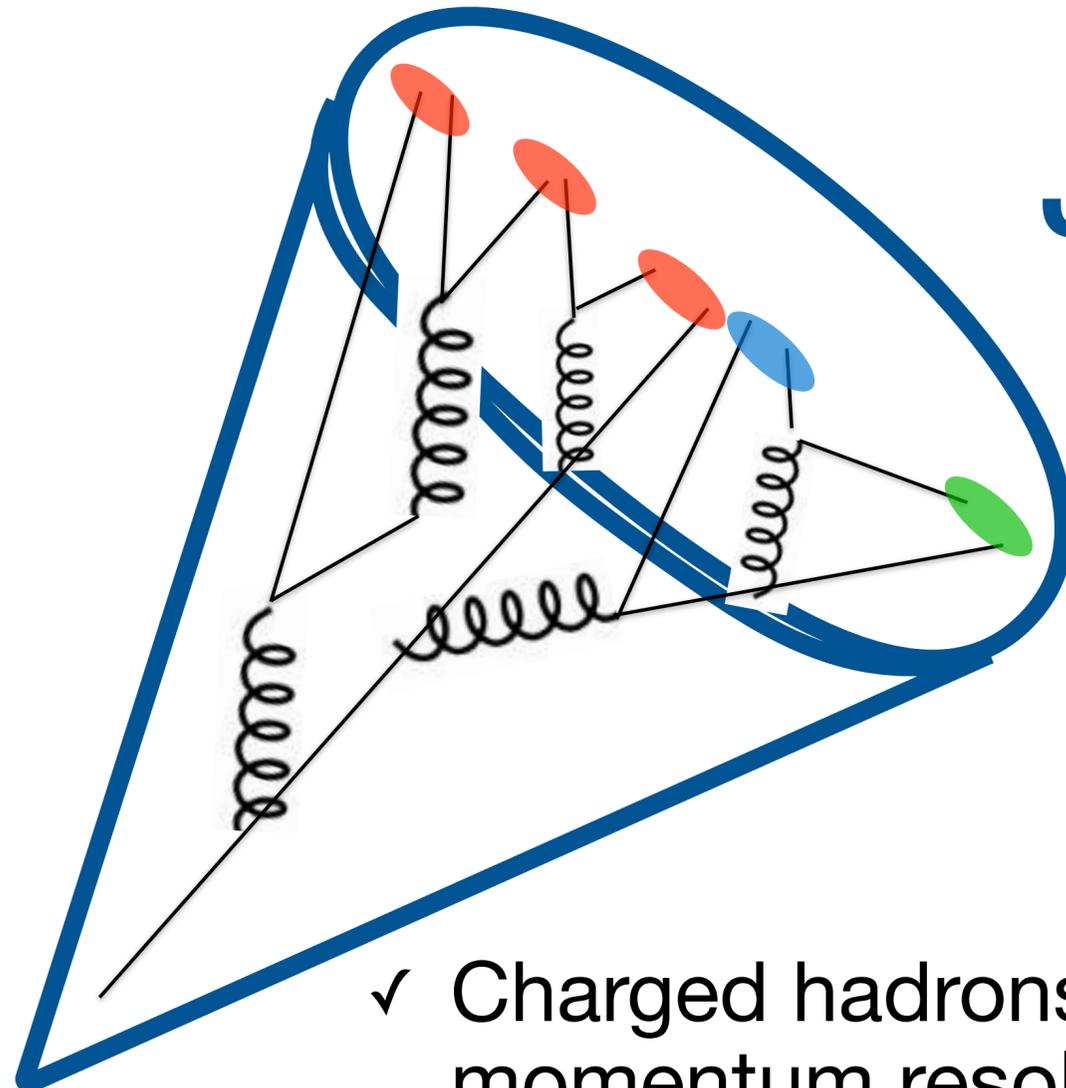
of Higgs produced: ~4M
4.8σ (VH only)

~400
5.2σ

Similar sensitivity ... with 10⁴ fewer Higgs bosons 🐱

Vertex
Tracker
Calorimeter
Forward detector

Jet composition



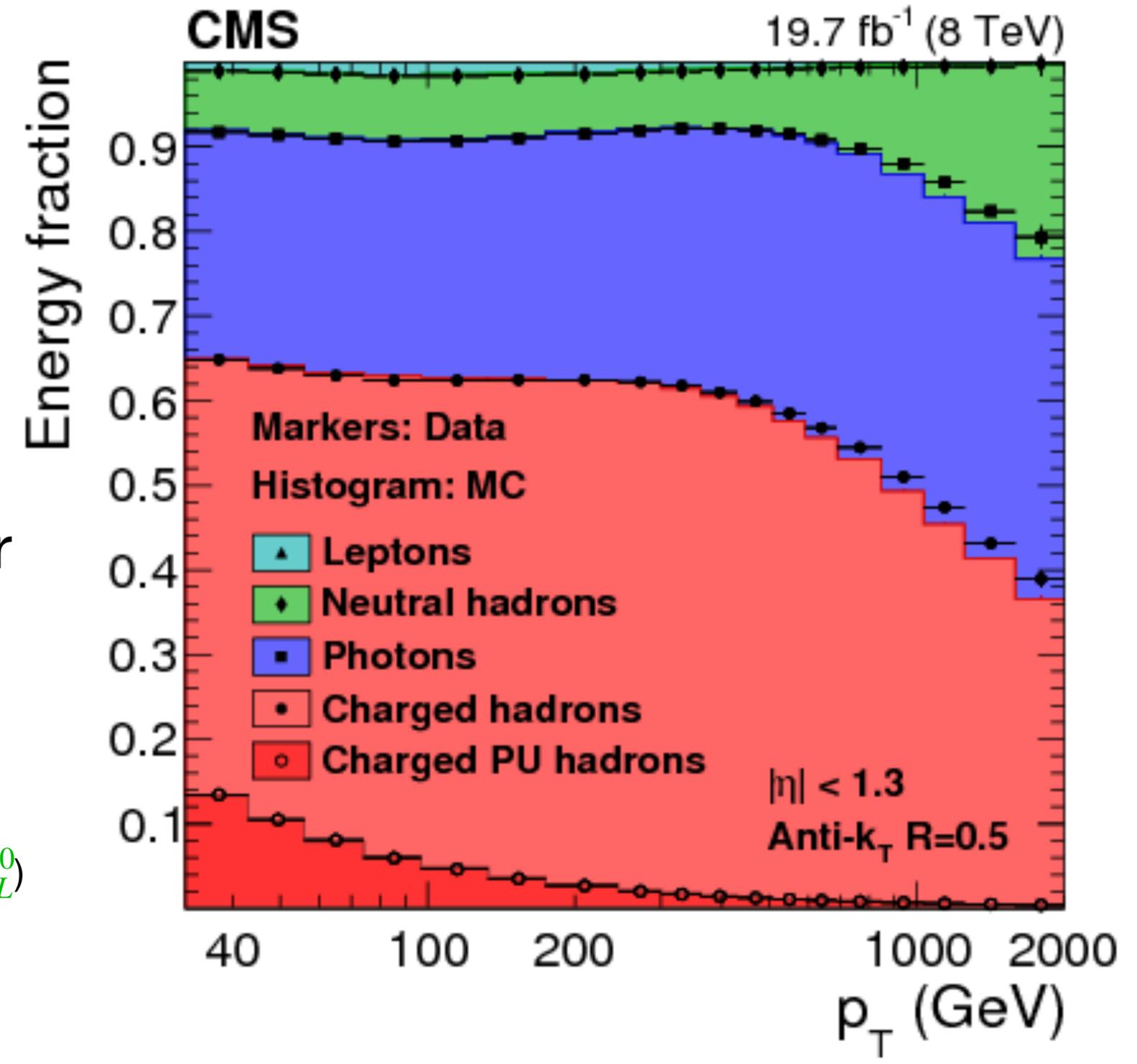
✓ Charged hadrons excellent momentum resolution in tracker

ECAL

30% photons : $\pi^0 \rightarrow \gamma\gamma$

HCAL

10% neutral hadrons (neutrons and K_L^0)



Vertex

Tracker

Calorimeter

Forward detector

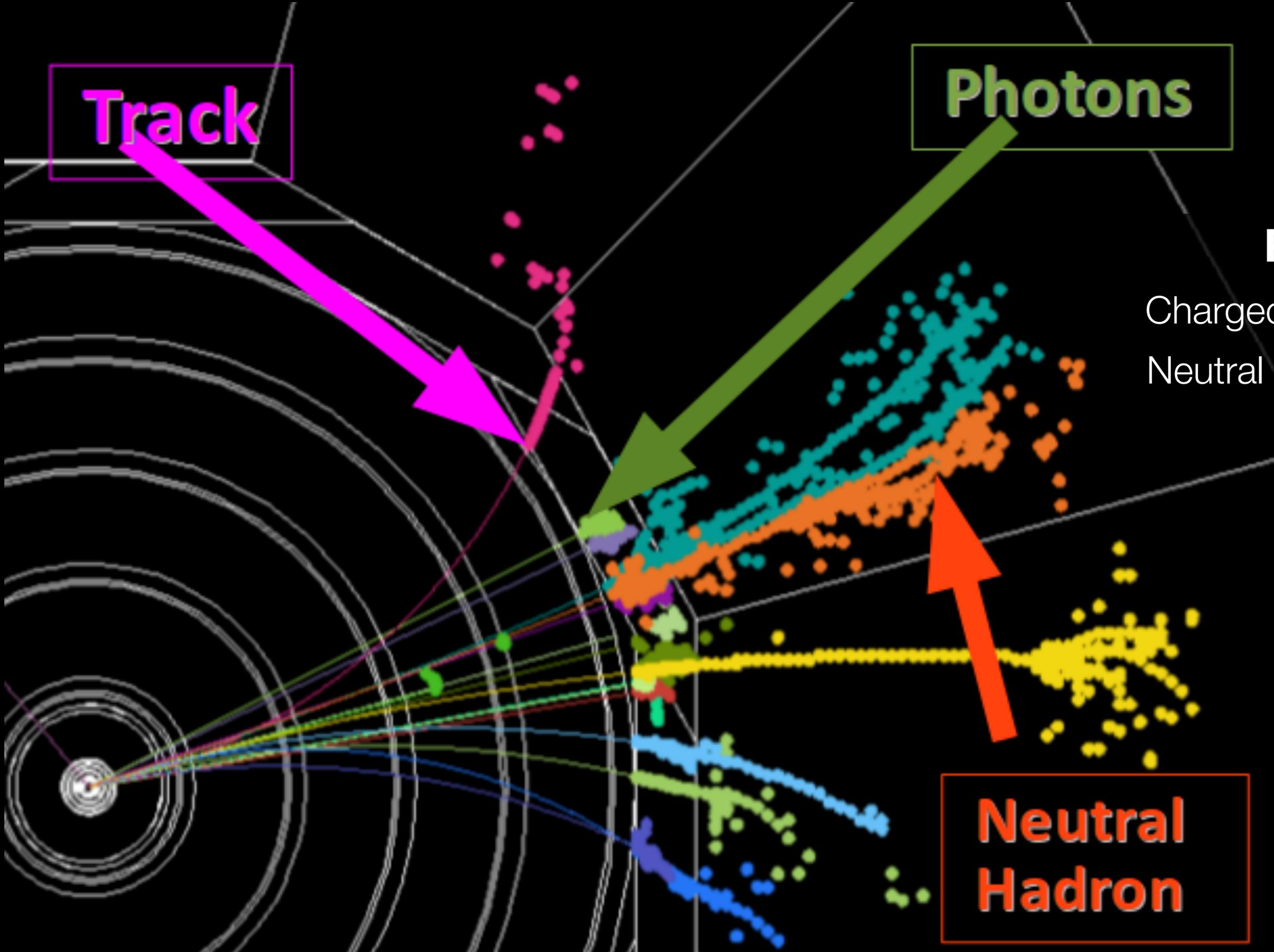
Track

Photons

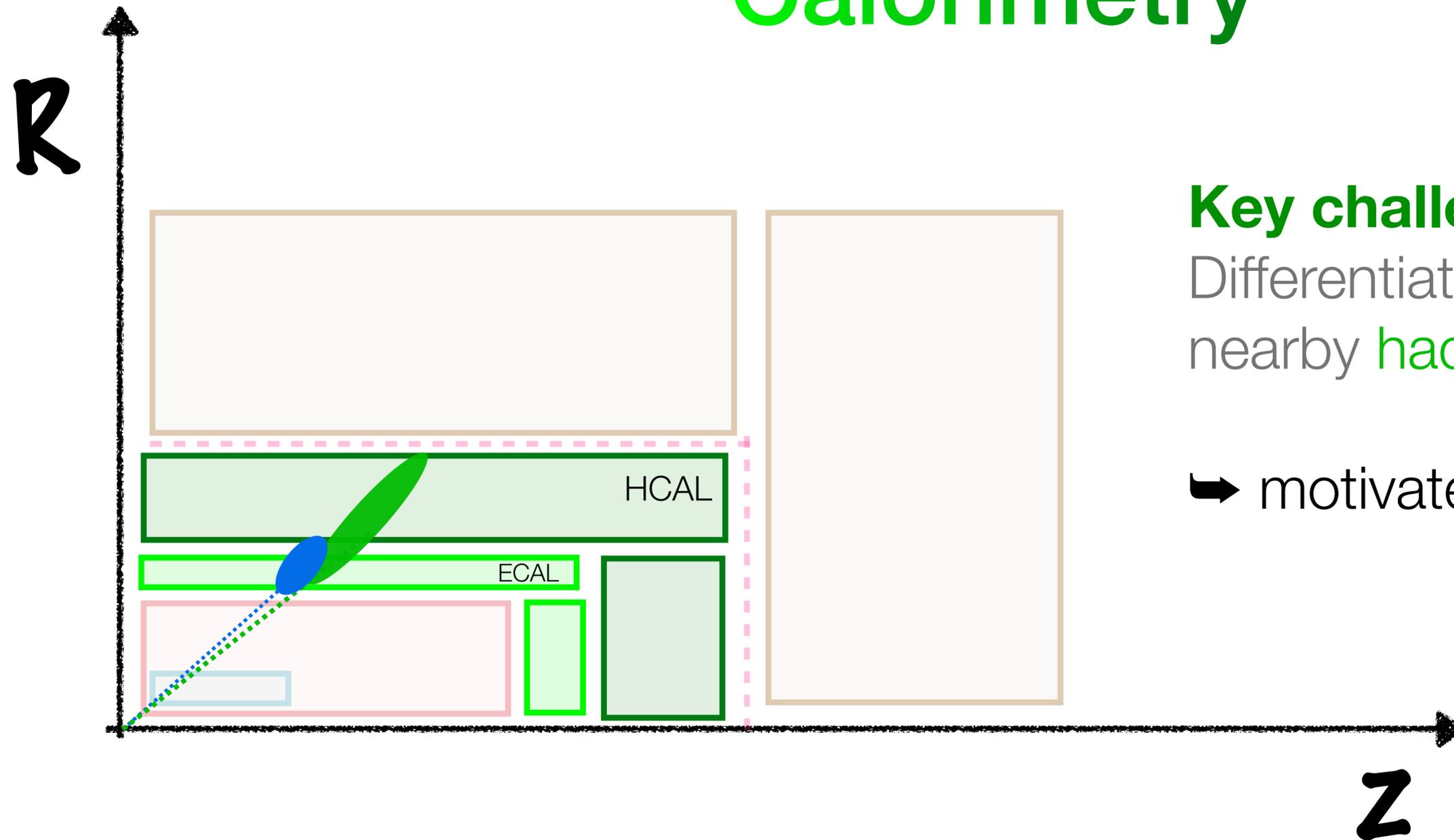
Particle Flow

Charged momentum from track
Neutral energy from calorimeter

Neutral Hadron



Calorimetry



Key challenge for pflow:

Differentiating the **photon** from the nearby **hadron**: “confusion”.

↳ motivates granular calorimeters

If we perfectly separate, the jet energy resolution becomes:
(only using the calorimeter for the neutral hadrons)

$$\frac{\sigma_E}{E} \sim \frac{0.19}{E \text{ [GeV]}}$$

Vertex

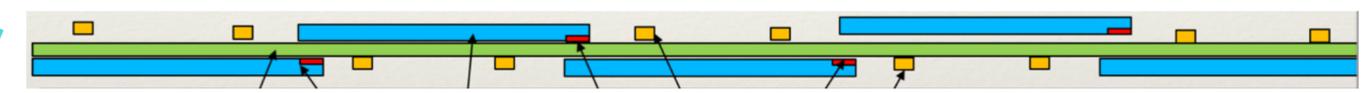
Tracker

Calorimeter

Forward detector

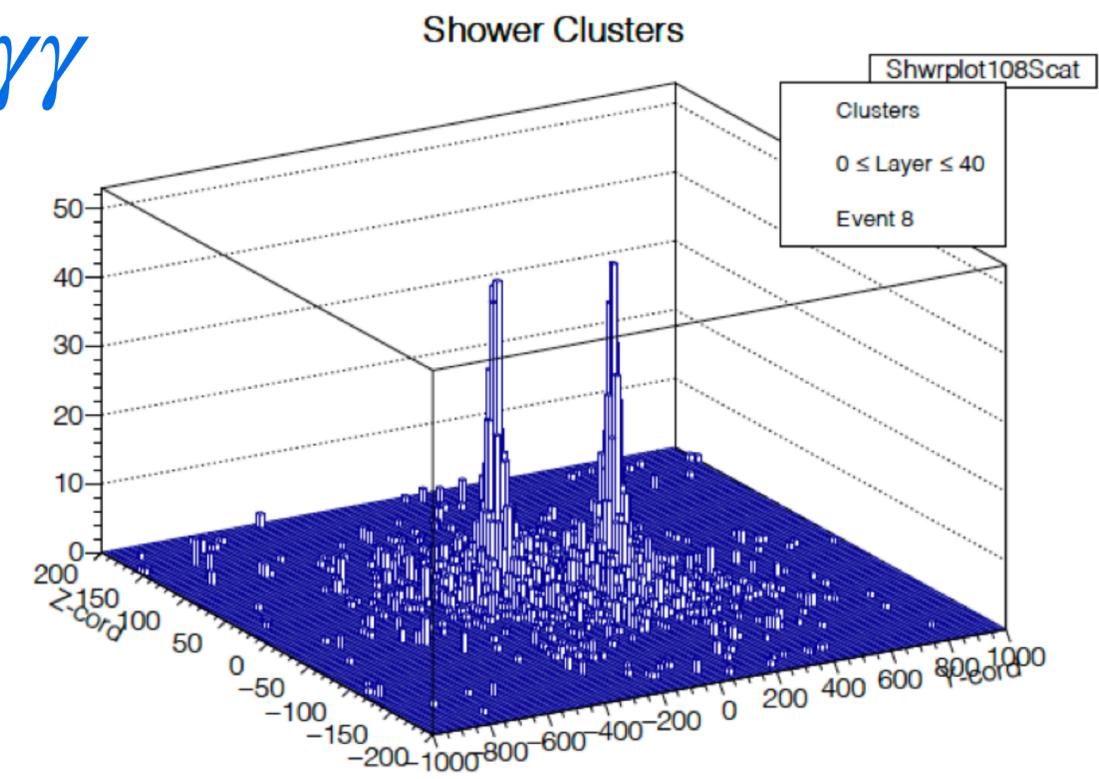
Sampling Calorimeter (ECAL)

What to put in the "active medium"?



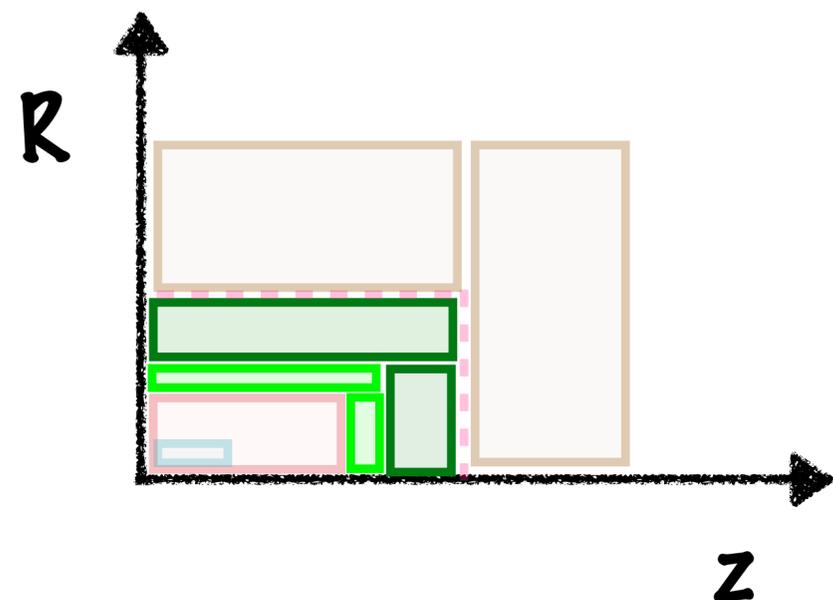
MAPS: Finely tessellate the space
 Monolithic Active Pixel Sensors

$$\pi^0 \rightarrow \gamma\gamma$$



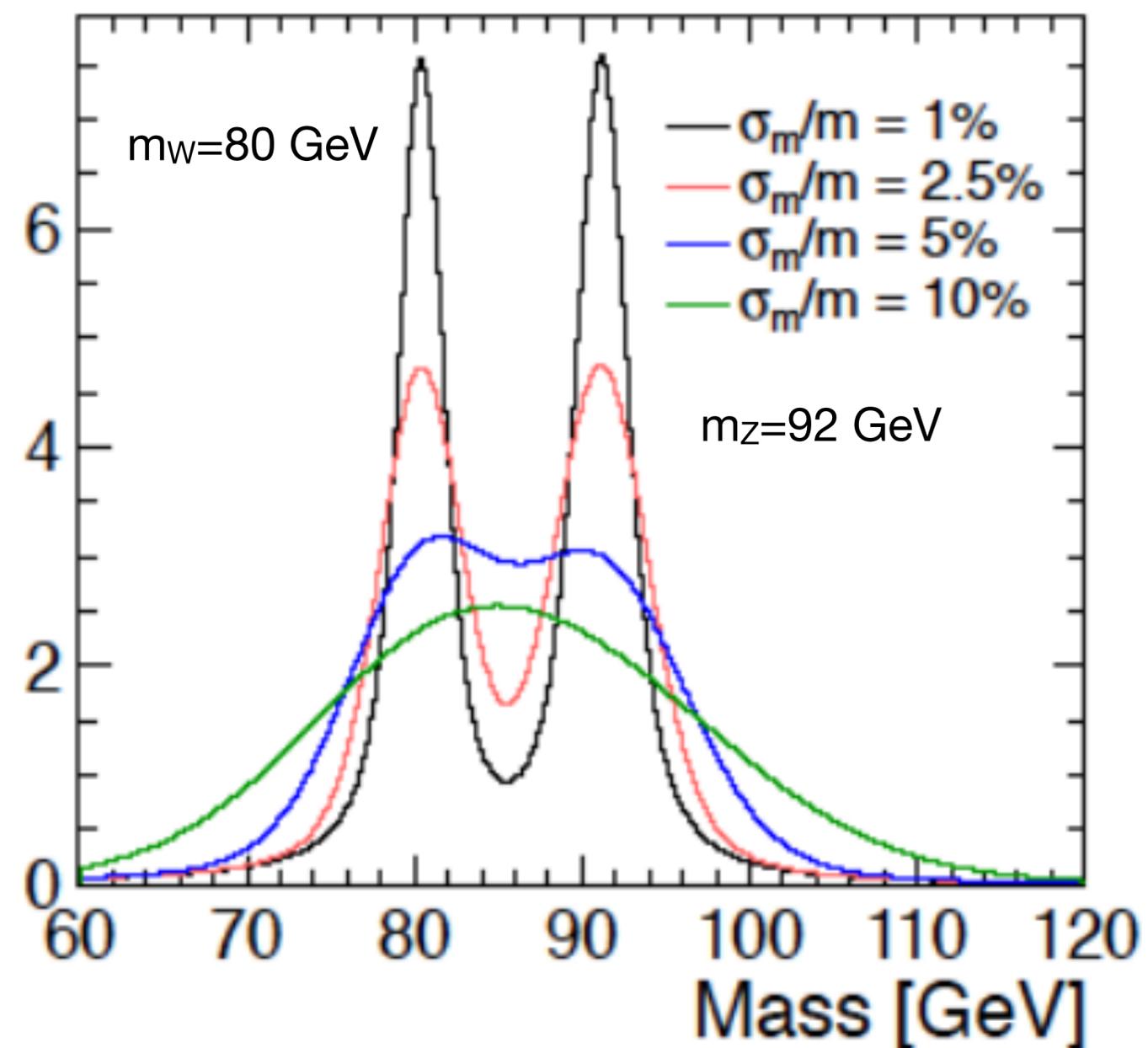
Although other "active materials" under consideration include: Scintillator strips, RPCs (HCAL) ...

Calorimetry



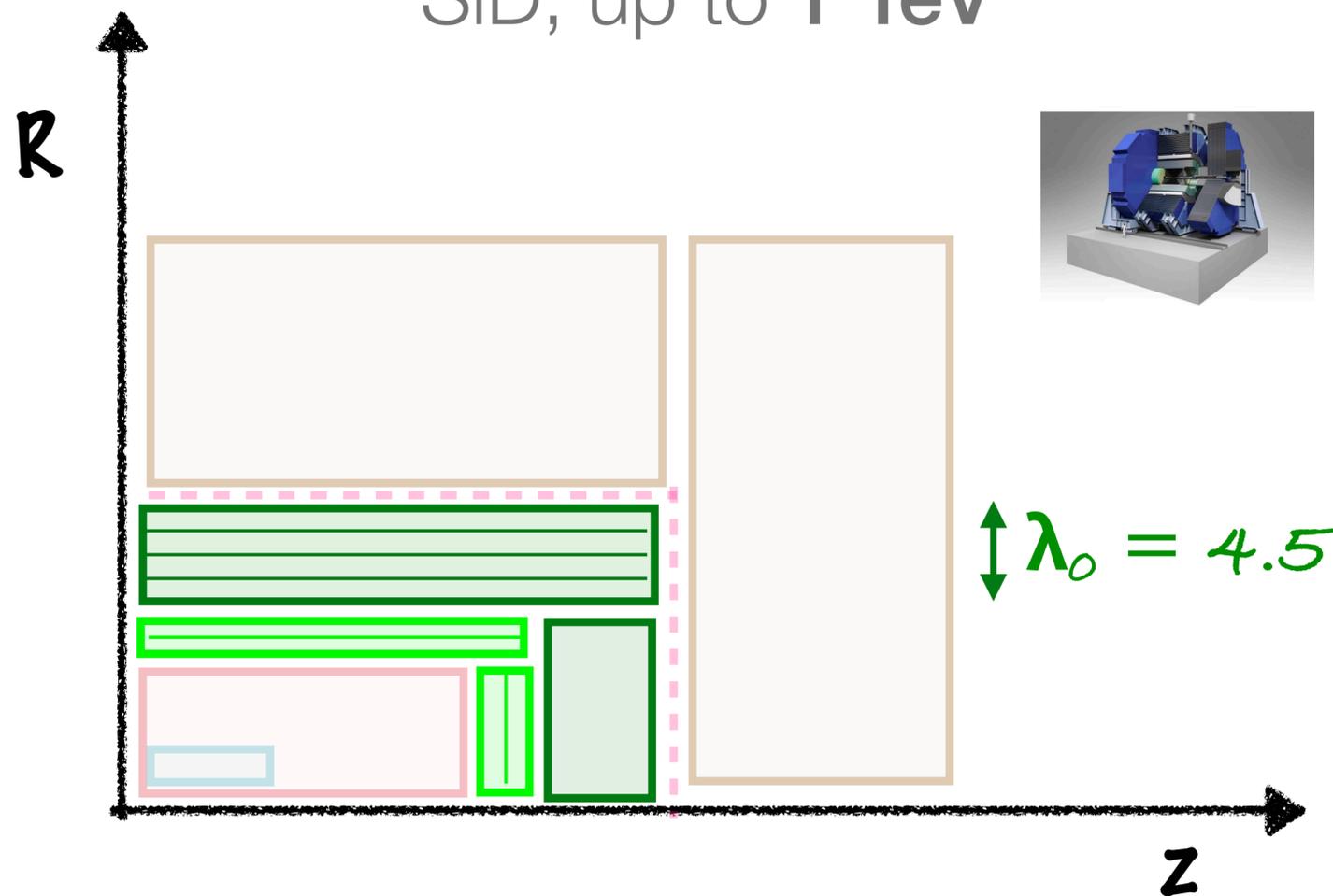
Jet mass resolution: W / Z separation

Key metric: resolution to di-jets pairs

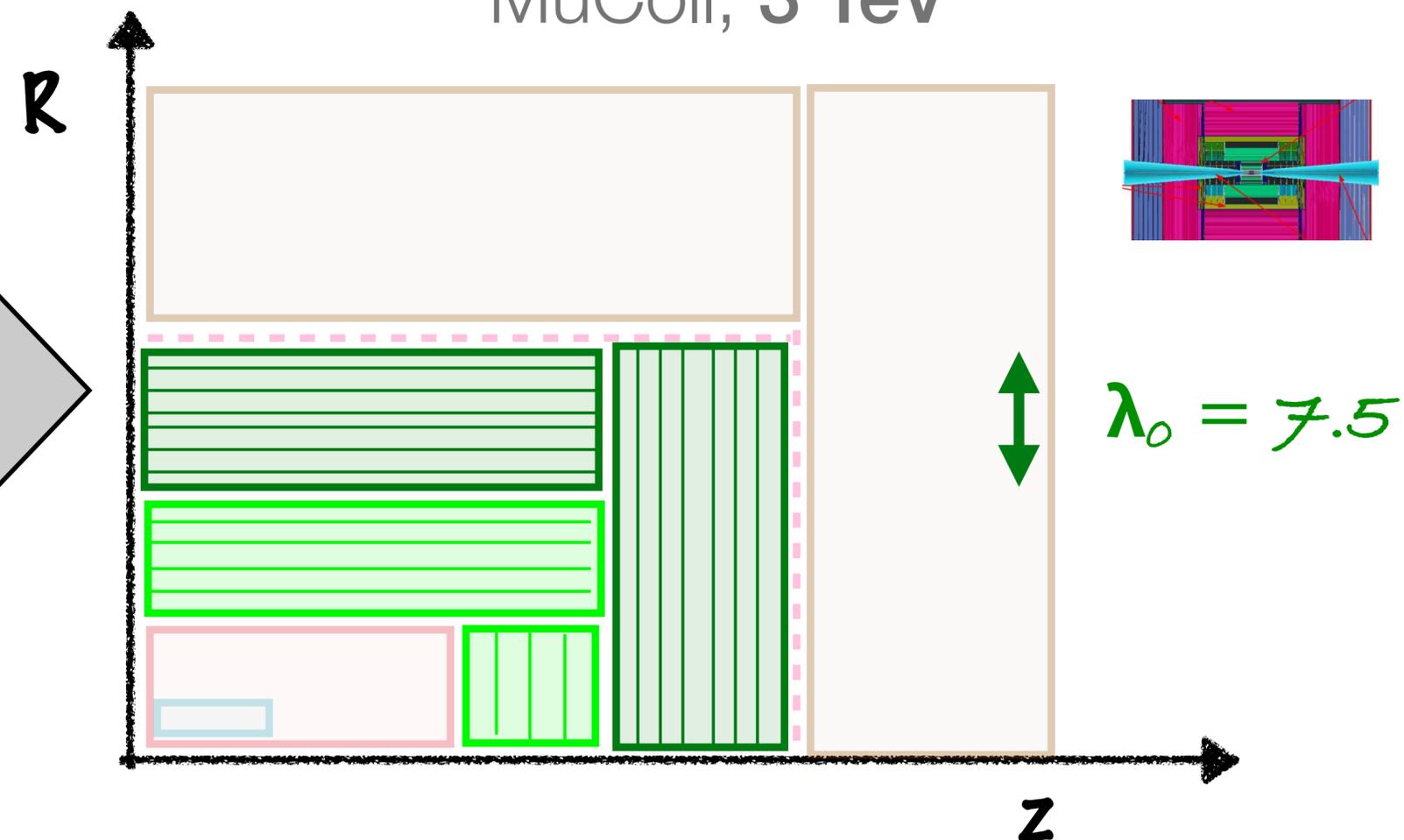


How to extend to 10 TeV ?

SiD, up to 1 TeV

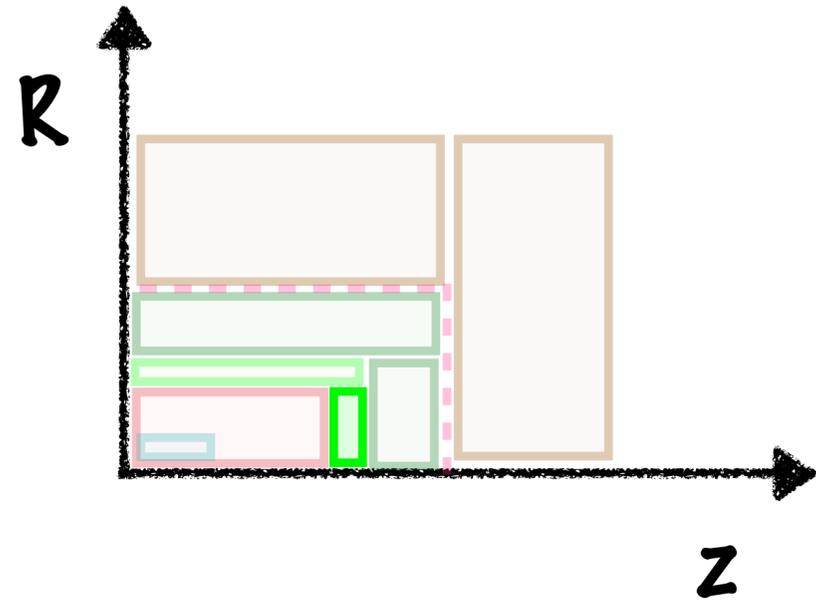


MuColl, 3 TeV



Make calorimeters *deeper*

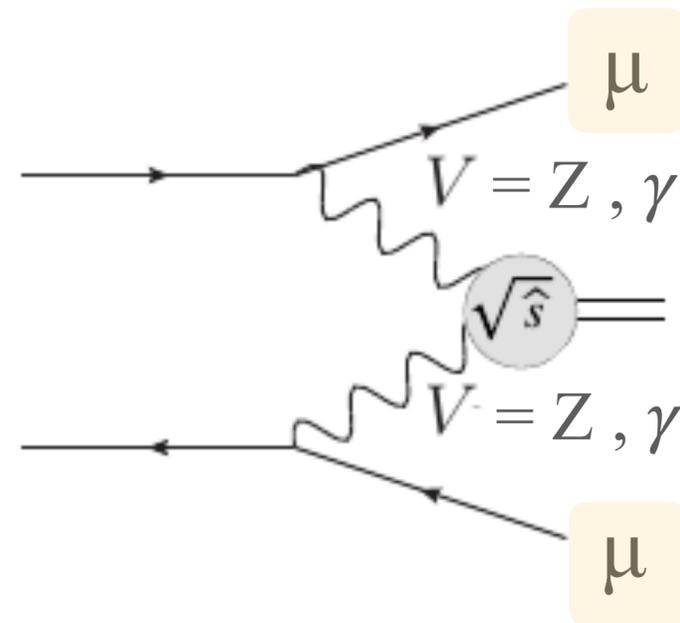
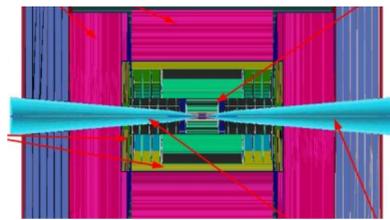
➡ won't need to go too much deeper as penetration depth $\sim \log(E)$



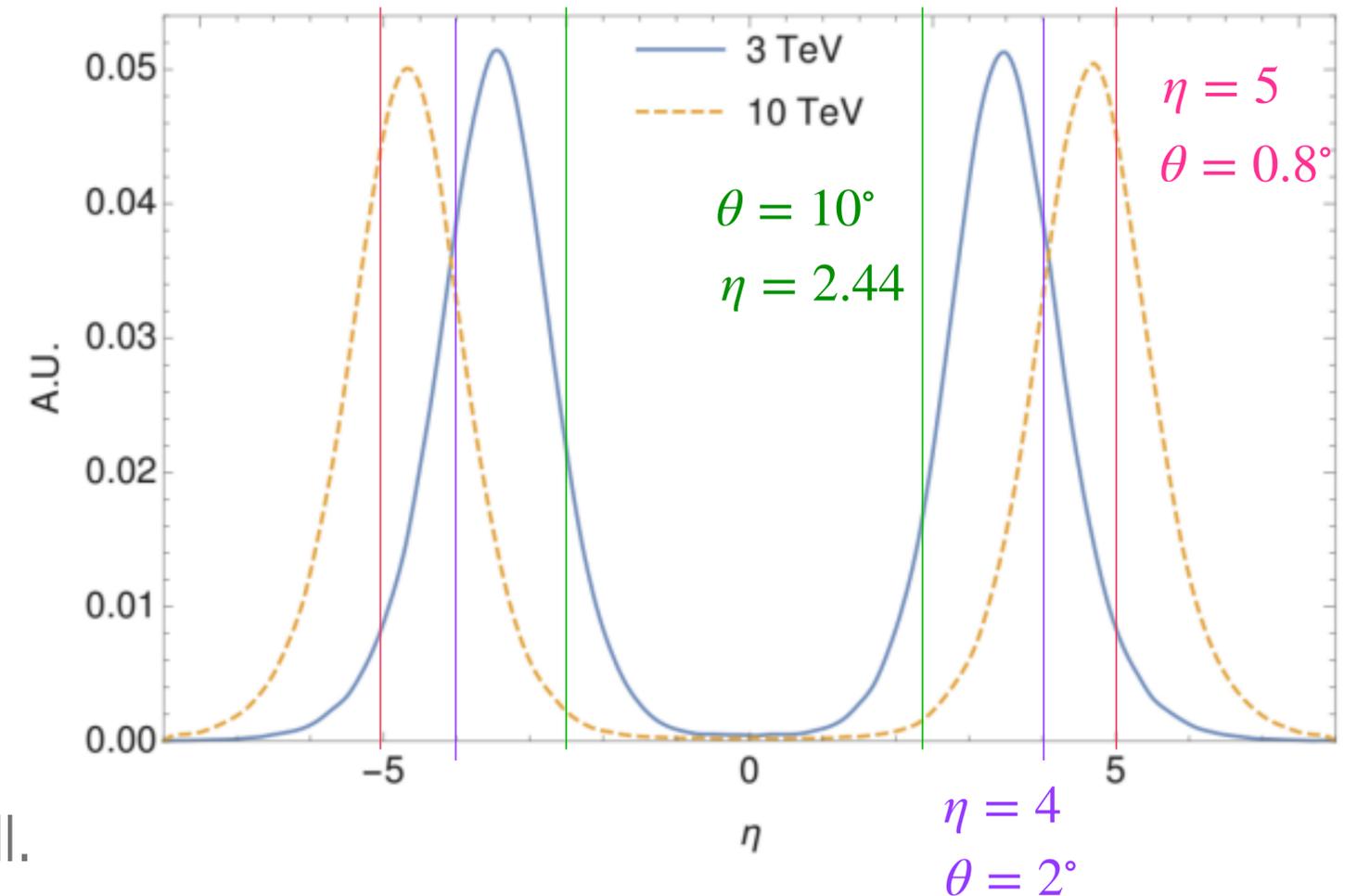
Forward Detectors

Important for VBS physics, identifying the outgoing electron for VBS events.

↪ Distinguishing W and Z initiated VBF production



η_μ for $ZZ \rightarrow h$ fusion



BDS exciting machine & detector interplay, e.g, with focusing magnets.

A. Schwartzman & T. Barklow working on for $\gamma\gamma$ coll.

Conclusion

Ongoing

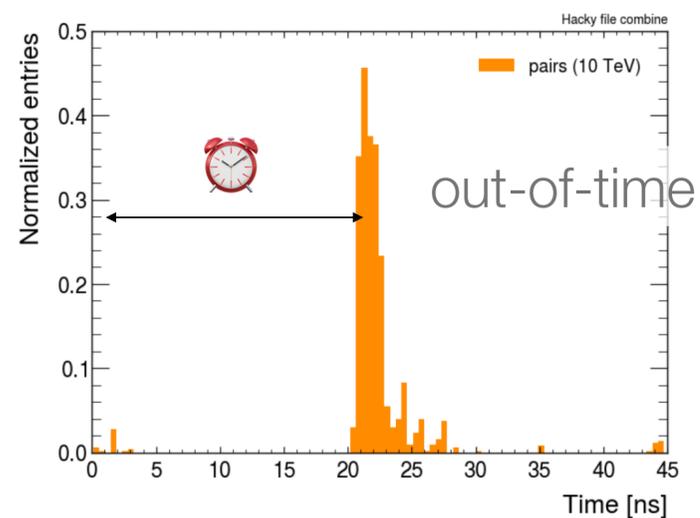
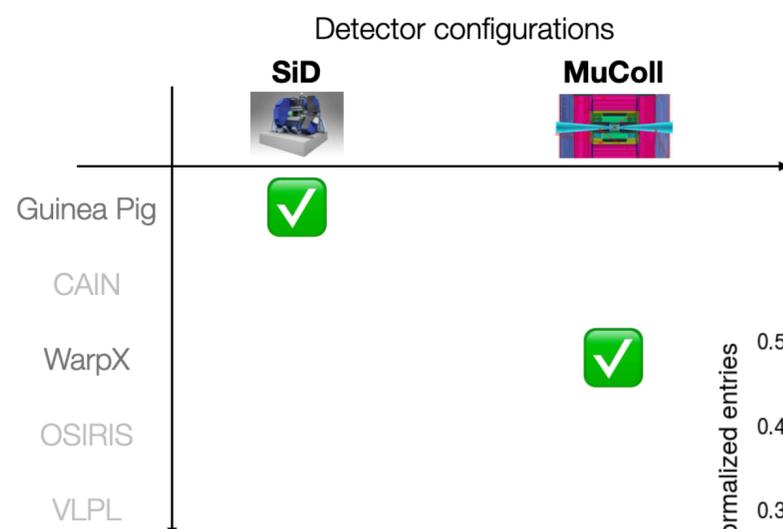
1 year

2 year

3 year

4 year

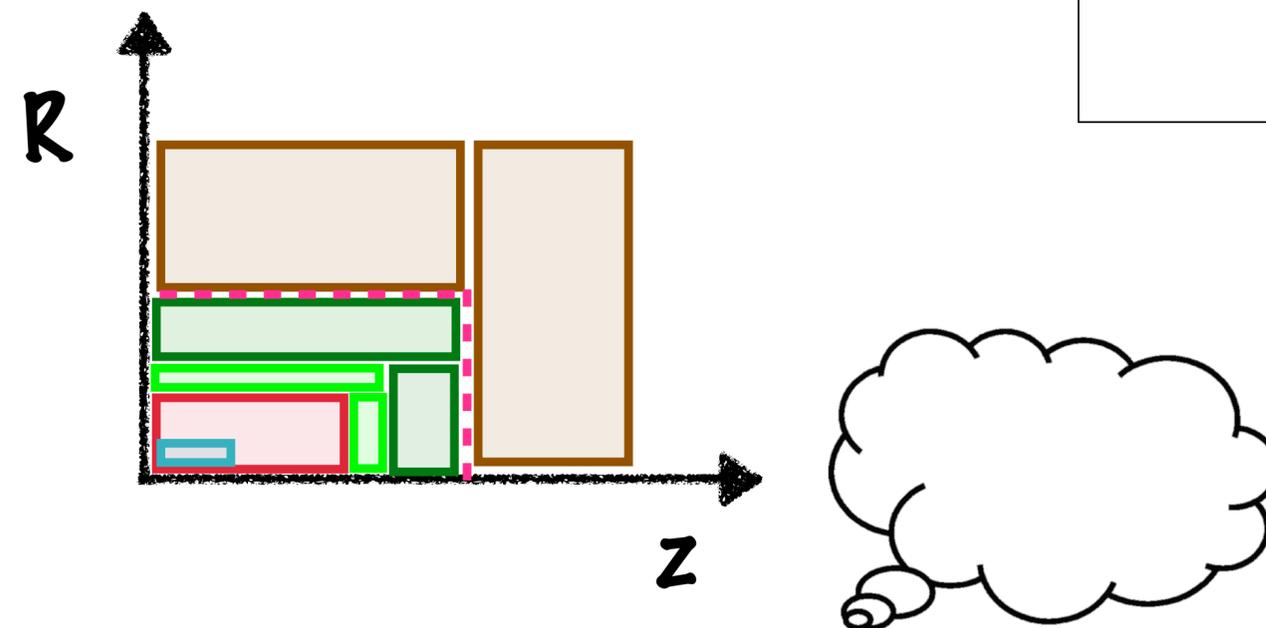
preliminary
Conceptual
Design Report



Arianna's meme



Forward detector: key to our MDI backgrounds

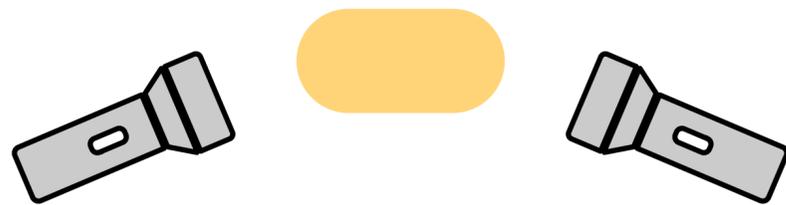


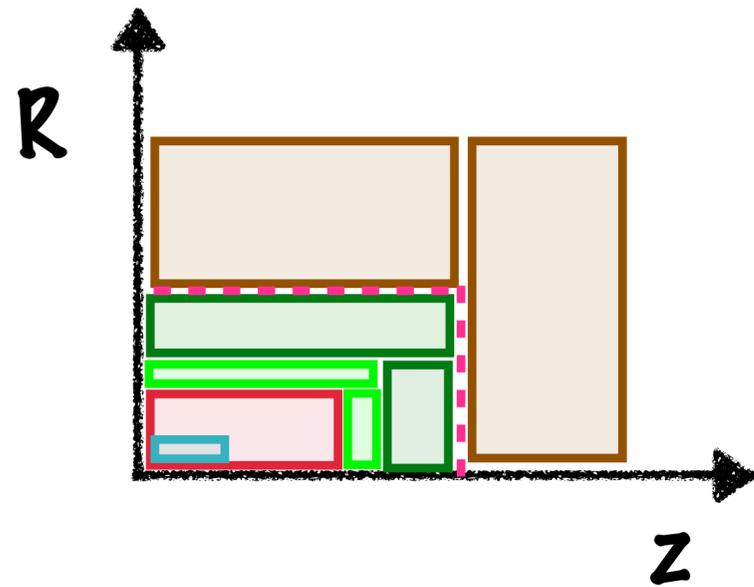
- Tracker acceptance
- Reco for high p_T (s-channel) and low p_T (VBF) jets?
 - B-field; Calo-depth; Muon system
- Best technologies

That's why we're here!! A.k.a, the work in workshop



Backup





More questions than answers ...

A selection of relevant questions from Simone

1) What acceptance should we design our **tracker** for?

2) Need to reco both low- p_T objects (VBF) and high p_T obj (s-channel)... rethinking:

B-field; calorimeters; muon system

3) What technologies are best suited?

That's why we're here!! A.k.a, the **work** in **workshop**



Which physics effects are included

Spencer's [slide](#)

| QED Processes / Numerics | GUINEA-PIG | CAIN | OSIRIS | VLPL | WarpX |
|--------------------------------|------------|------|--------|------|-------|
| Quantum Synchrotron rad. | ✓ | ✓ | ✓ | ✓ | ✓ |
| Nonlinear Breit-Wheeler | ✓ | ✓ | ✓ | ✓ | ✓ |
| Linear Breit-Wheeler | ✓ | ✓ | ✗ | ? | ✓* |
| Bethe-Heitler | ✓ | ✓ | ✓ | ? | ✗ |
| Landau-Lifshitz | ✓ | ✓ | ✗ | ? | ✗ |
| Trident Cascade | ✓ | ✗ | ✗ | ? | ✗ |
| Hadronic Production + Minijets | ✓ | ✗ | ✗ | ? | ✗ |
| Electron-Laser Interaction | ✗ | ✓ | ✓ | ✓ | ✓ |
| Electrostatic (Poisson) | ✓ | ✓ | ✗ | ✗ | ✓ |
| Electromagnetic (Maxwell) | ✗ | ✗ | ✓ | ✓ | ✓ |
| Parallel | ✗ | ✗ | ✓ | ✓ | ✓ |
| GPU support | ✗ | ✗ | ✓ | ✗ | ✓ |

GUINEA-PIG, CAIN: beam-beam PIC codes w/ 2D Poisson solves of beam slices.

OSIRIS, VLPL: Electromagnetic parallel PIC codes w/ 3D Maxwell solver.

WarpX: Electromagnetic parallel PIC codes w/ 3D Maxwell & Poisson solvers + GPUs.

*nearly complete

Please interpret these “first pipeline” studies qualitatively.
— Simone Pagan Griso

Which physics effects are included

Spencer's [slide](#)

| QED Processes / Numerics | GUINEA-PIG | CAIN | OSIRIS | VLPL | WarpX |
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| Hadronic Production + Minijets | ✓ | ✗ | ✗ | ? | ✗ |
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| Electrostatic (Poisson) | ✓ | ✓ | ✗ | ✗ | ✓ |
| Electromagnetic (Maxwell) | ✗ | ✗ | ✓ | ✓ | ✓ |
| Parallel | ✗ | ✗ | ✓ | ✓ | ✓ |
| GPU support | ✗ | ✗ | ✓ | ✗ | ✓ |

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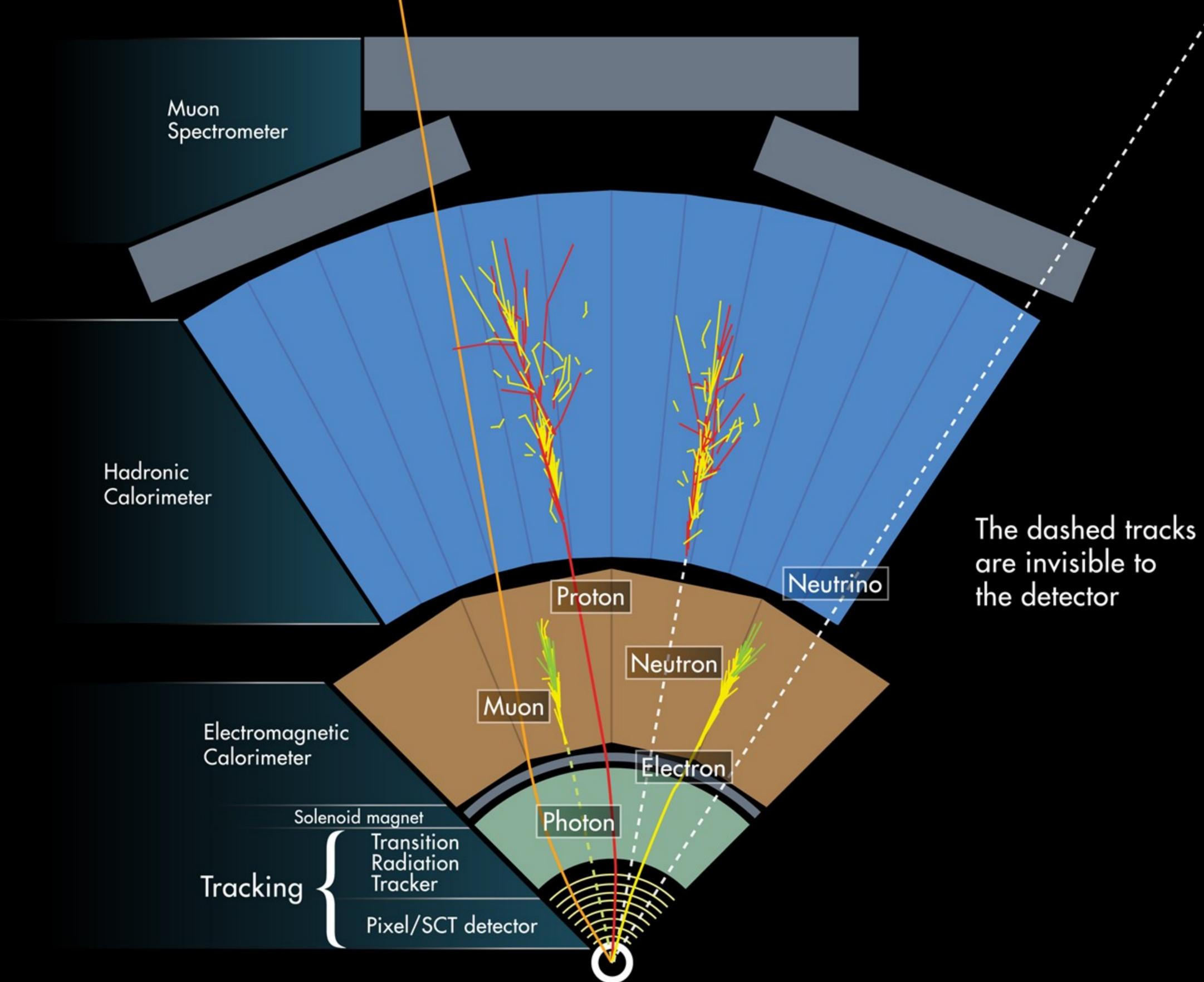
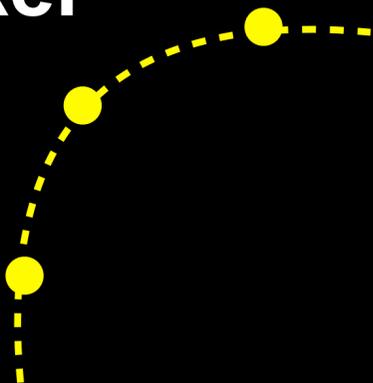
Particle ID

Multi-modal event reconstruction!!

Calorimeter



Tracker



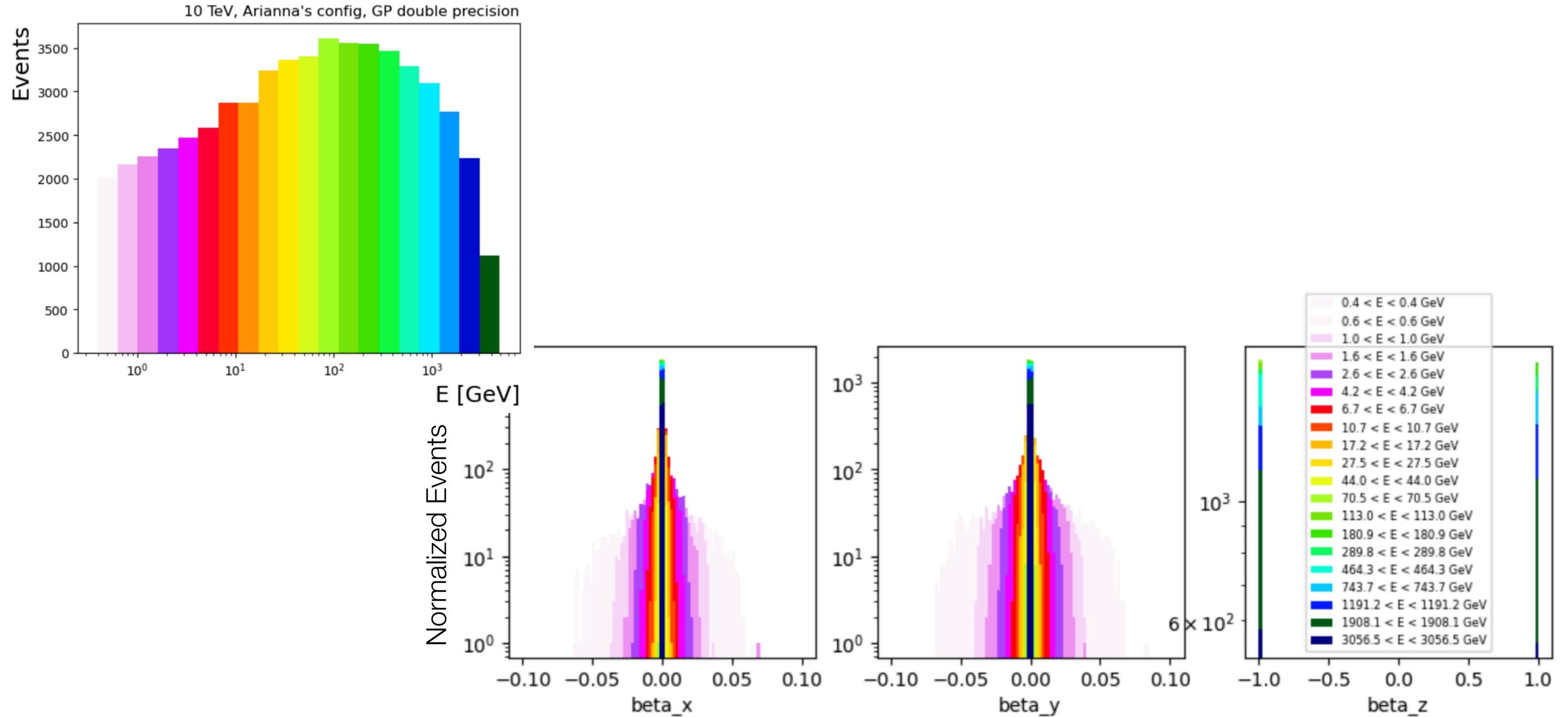
The dashed tracks are invisible to the detector

Main Resources

C3 pipeline:

- Lindsey's ECFA **talk**
- Dimitris's ECFA **talk**

“Rainbow plots”



Accelerator

| Variable | Description | ILC | 10 TeV (Arianna) |
|-------------|---|-------|------------------|
| charge_sign | sign difference between the two beams: -1 means e+e- collisions | -1 | -1 |
| particles | # of p'cles / bunch [units of 10 ¹⁰] | 2 | 0.1 |
| energy | unit GeV | 125 | 5000.0 |
| espread | | 0.001 | 0.0 |
| sigma_x | | | 10 |
| sigma_y | | | 1 |
| sigma_z | | 300.0 | 10 |
| emitt_x | | 5.0 | 1E-07 |
| emitt_y | | 0.035 | 1E-07 |
| waist_x | | | 0 |
| waist_y | | 250.0 | 0 |
| f_rep | | 5 | 1.0 |
| n_b | | 1312 | 1 |
| scale_step | | 1.0 | 1.0 |

Parameters 1/2

| Variable | Description | ILC | 10 TeV (Arianna) |
|----------------|--|--------------|------------------|
| n_x | The number of cells in the horizontal, vertical, and longitudinal directions (respectively) | | 256 |
| n_y | | | 256 |
| n_z | | 25 | 64 |
| n_t | # of time steps used to move a slice to the next slice of the other bund | 6 | 1 |
| n_m | The number of macroparticles used | 100000 | 5E+05 |
| cut_x | The size of the grid in the horizontal and vertical dirs in mm . | 20*sigma_x.1 | 36*sigma_x.1 |
| cut_y | | 20*sigma_x.1 | 36*sigma_y.1 |
| cut_z | Long grid size in microns | | 4*sigma_z.1 |
| do_dump / r | | | 0 |
| rndm_save | If not 0, the status of the random number generator is stored in the file random.save | 0 | 0 |
| rndm_load | | | 0 |
| load_beam | | | 0 |
| store_beam | Save spent beams in beam1.dat and beam2.dat | 1 | 1 |
| electron_ratio | | 1 | 1 |
| do_lumi | If not zero, a file lumi.dat containing the energies for the e+e- scattering is produced... this is the input needed for WIZZARD and circe2/3 that Lindsey was telling me about | | 1 |
| num_lumi | The maximal number of scatters stored in lumi.dat | | 5E+05 |
| ecm_min | | | 0 |

Parameters 2/2

| Variable | Description | IL C | 10 TeV (Arianna) |
|---|-------------|----------|------------------|
| do_photons, photon_ratio, store_photons | | 1 | 1 |
| do_coherent | | 1 | 1 |
| scale_step | | | 1 |
| do_pairs | | 1 | 1 |
| store_pairs | | 1 | 1 |
| track_pairs | | 1 | 1 |
| pair_ecut | | 0 | 0.4 |
| pair_ratio | | | 1.0 |
| pair_q2 | | 1 | 2 |
| grids | | 7 | 7 |
| do_trident | | | 0 |
| do_hadrons | | 1 | 0 |
| do_compt | | | 0 |
| do_eLOSS | | 1 | 1 |
| do_espread | | 1 | 1 |
| do_cross | | | 0 |
| do_jets | | 1 | 0 |
| jet_ratio | | | 0 |
| store_jets | | | 0 |
| beam_size | | 1 | 0 |

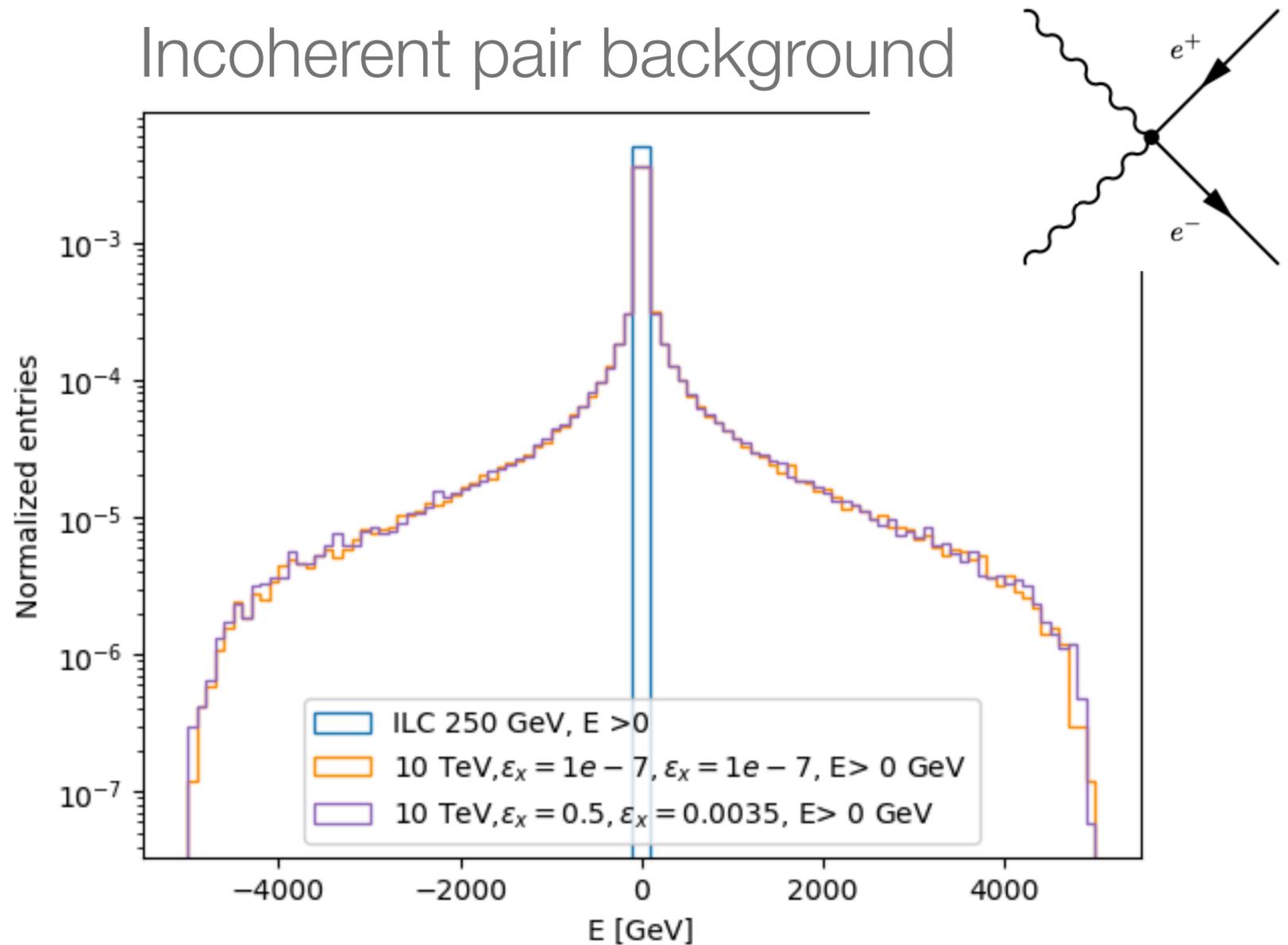
Our setup (starting from  work)

Huge thank you to Arianna Formenti  for sharing GP sample and config 

e+e- collisions

| | ILC | round "ultra-tight" | flat ILC-like |
|-----------------|-------|------------------------|------------------|
| Beam E [GeV] | 125 | 5000 | 5000 |
| ϵ_x | 5 | 1E-07 | 0.5 |
| ϵ_y | 0.035 | 1E-07 | 0.0035 |

Incoherent pair background



^ main differences, more details in the GP configs:

ILC: Jim_pars_Aug2023 in [acc_ILC.dat](#) (from Dimitris)

round "ultra-tight": [10TeV](#) (from Arianna)

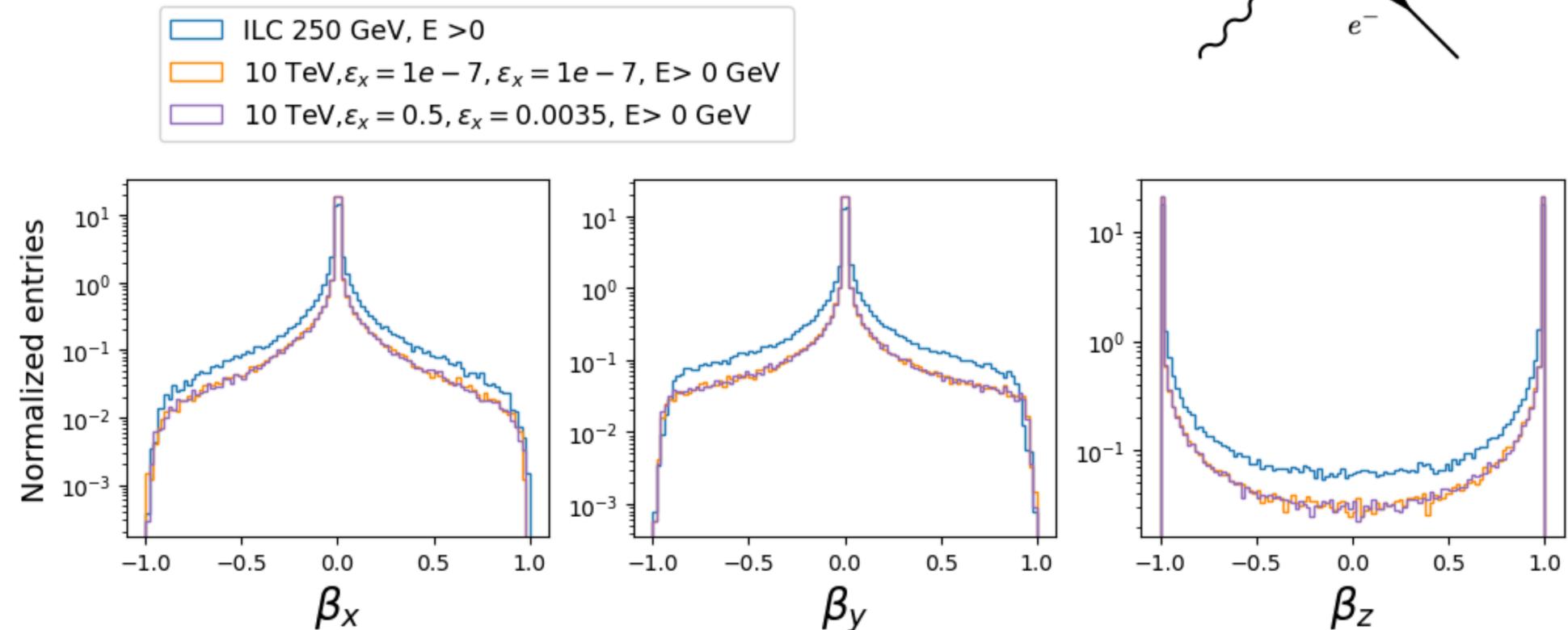
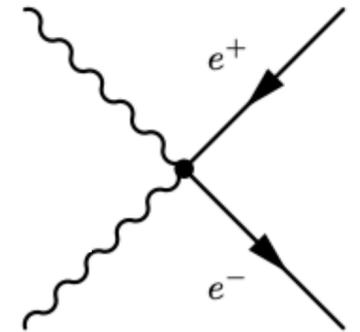
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e+e- collisions

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Incoherent pair background



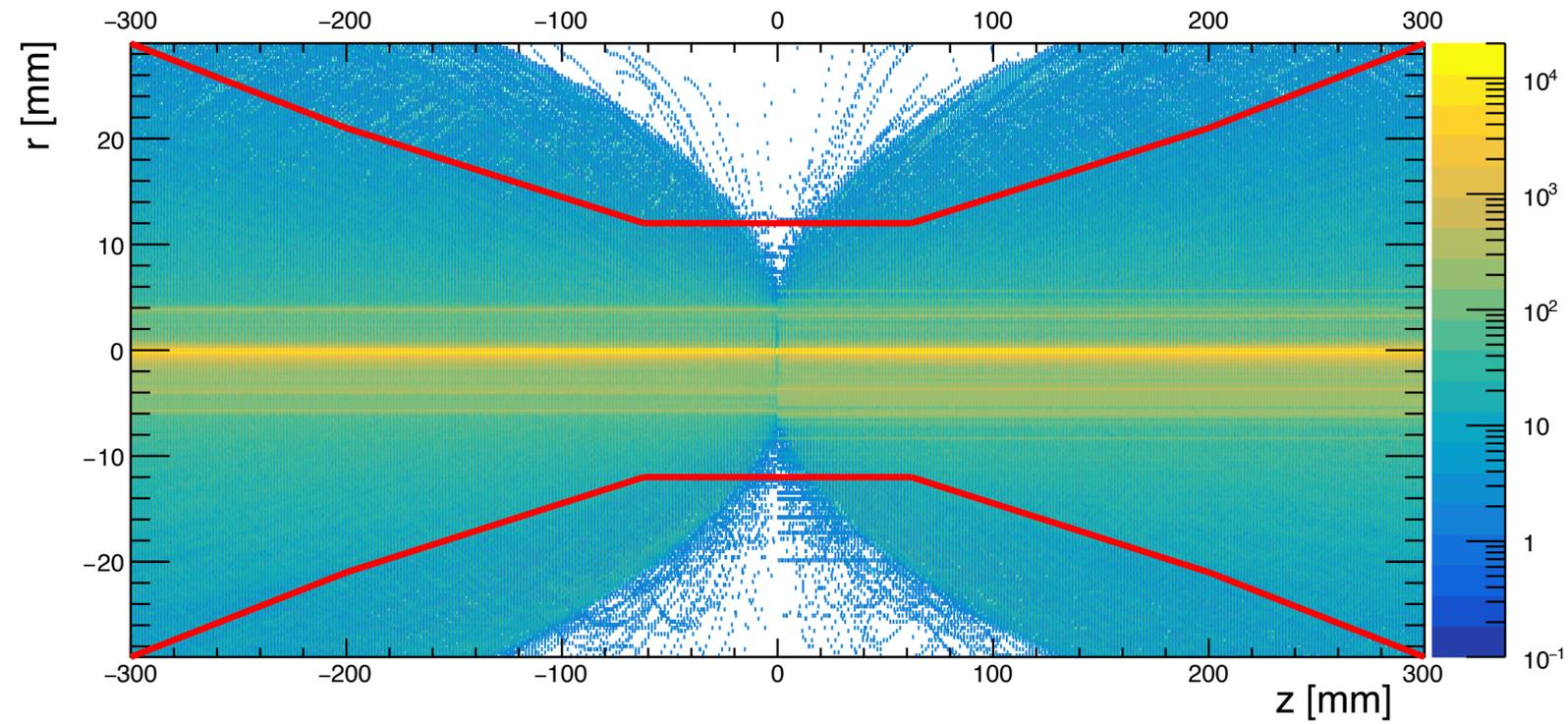
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ILC: Jim_pars_Aug2023 in [acc_ILC.dat](#) (from Dimitris)

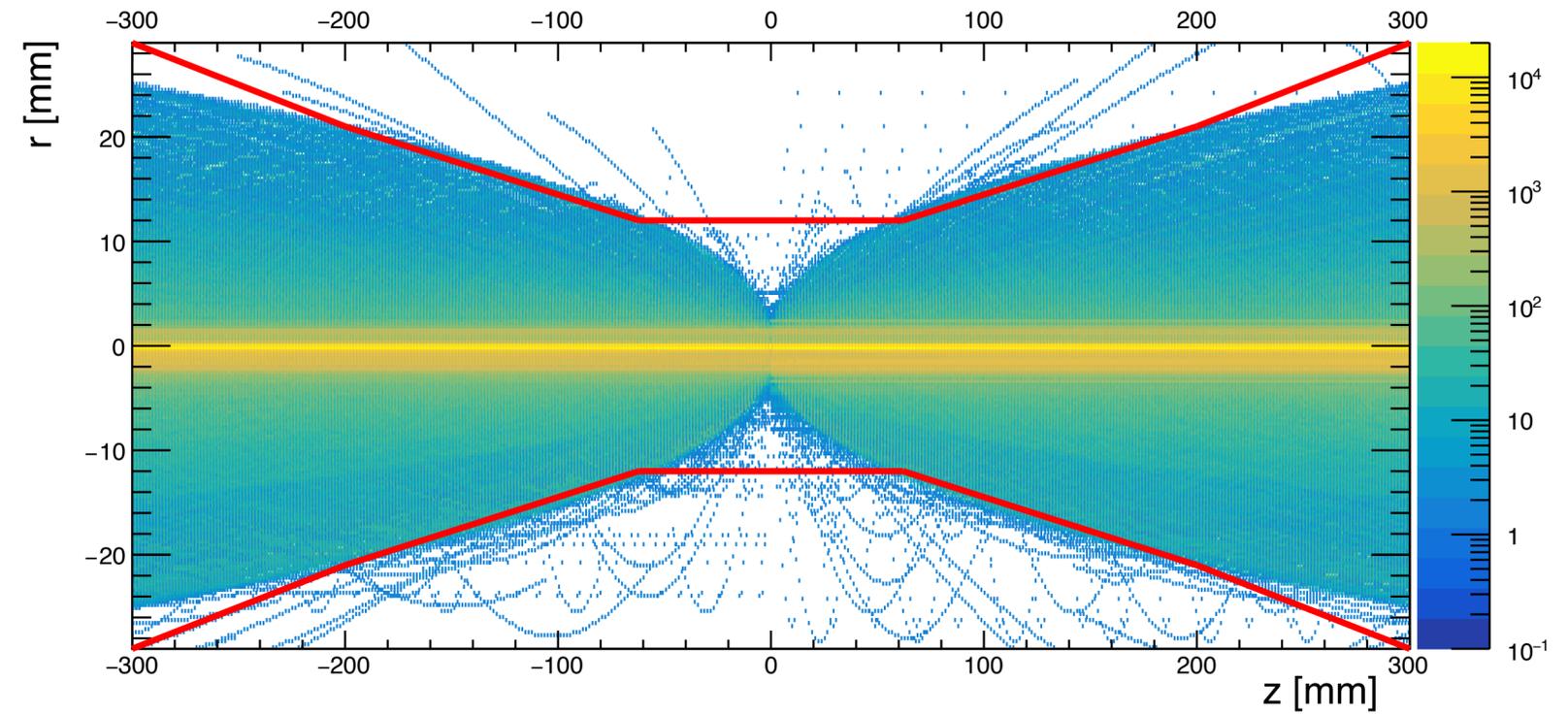
round "ultra-tight": [10TeV](#) (from Arianna)

Varying B-field

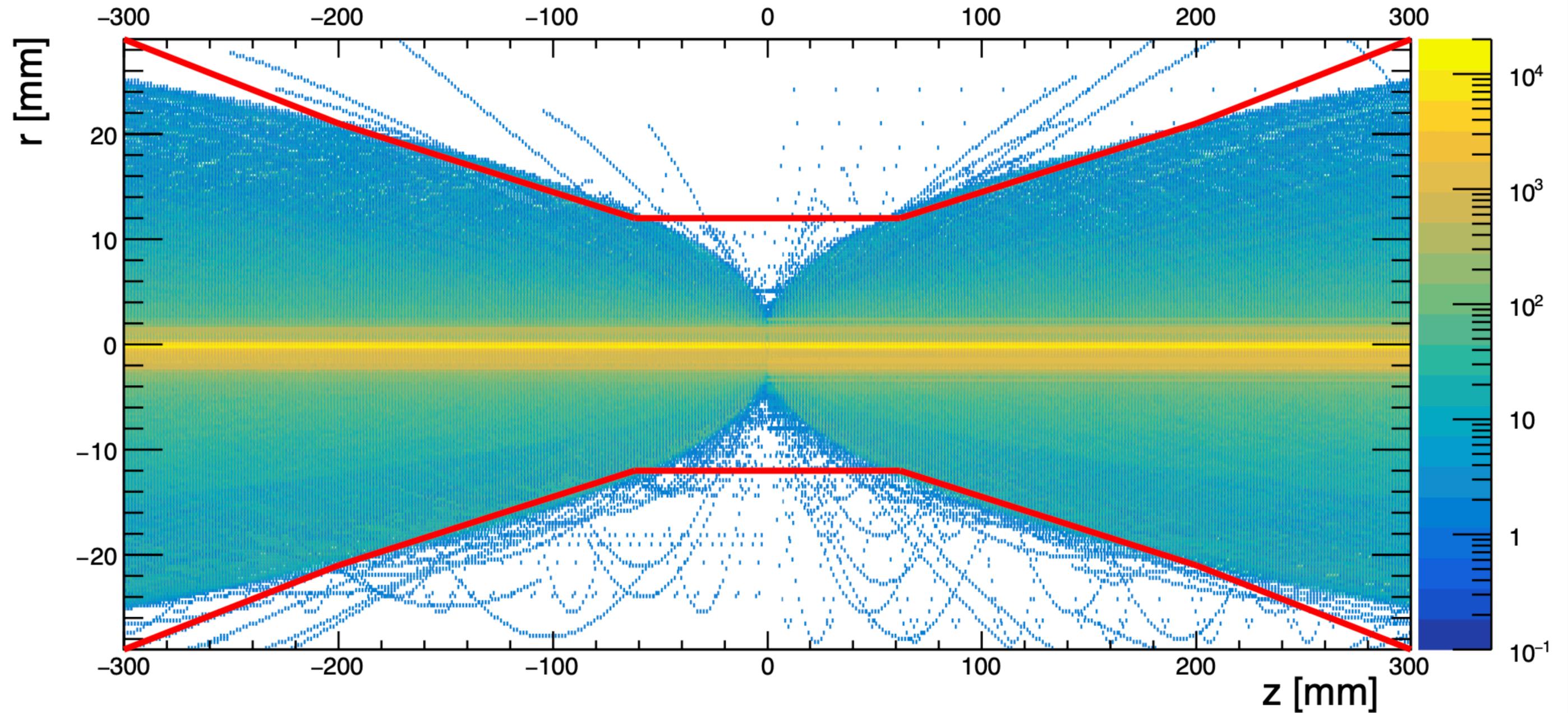
2T: ILD design



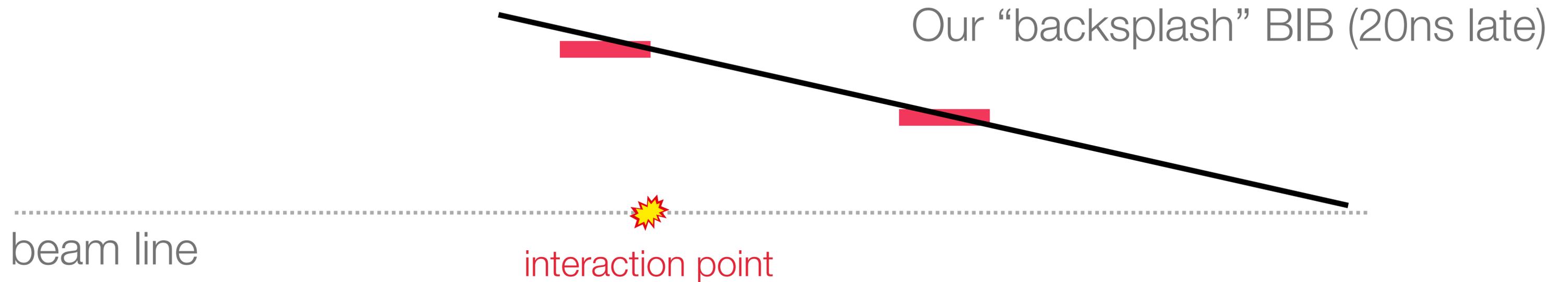
5T: SiD design



Impact on detector (envelope plot)



How to reduce the BIB



Idea: Could play “connect the dots” with the tracks to see if they come from IP or beam cal (same as the “double-layers” idea from muColl)

Detector geometry: MuCol 3 TeV concept

hadronic calorimeter

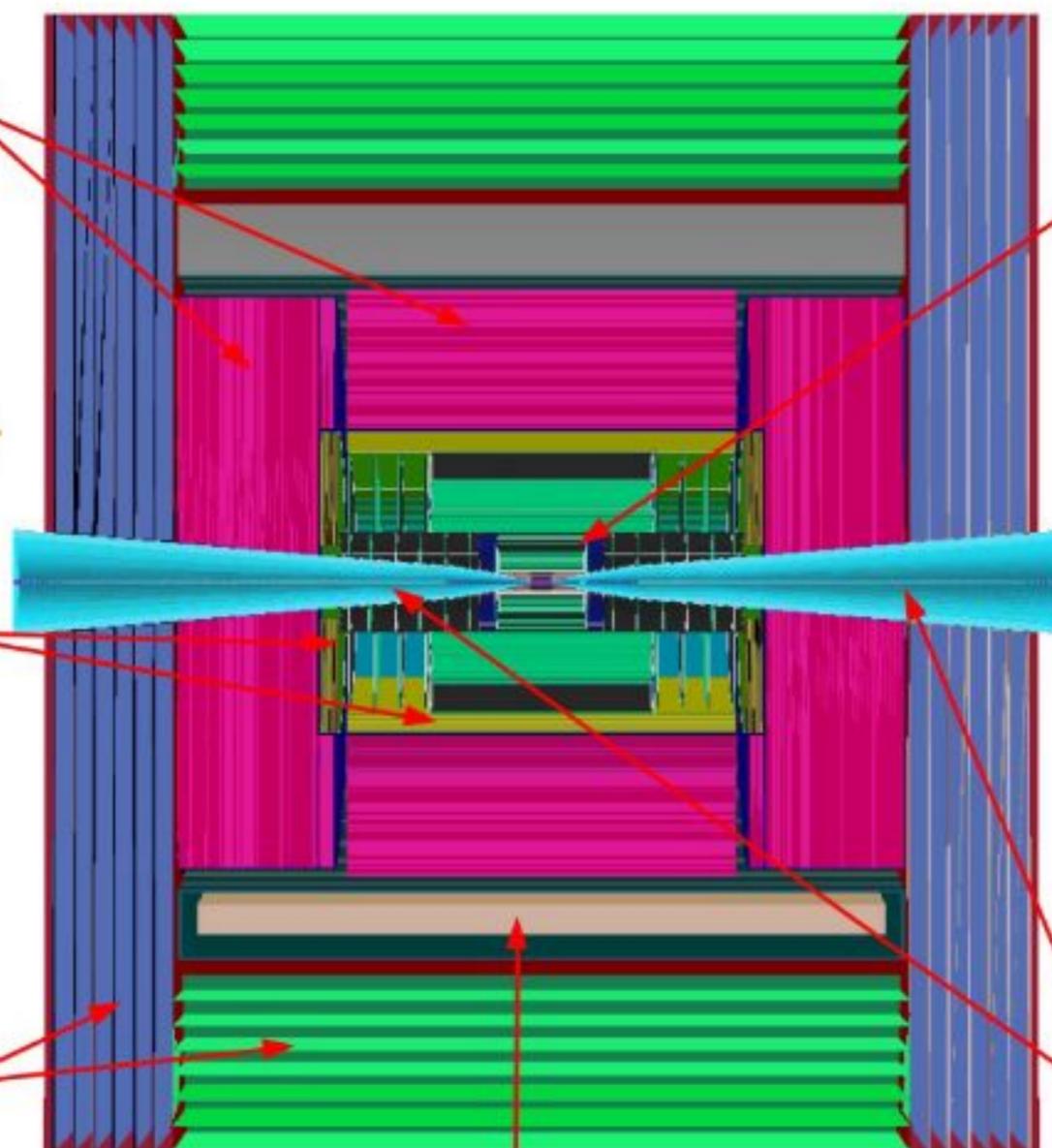
- ◆ 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- ◆ 30x30 mm² cell size;
- ◆ 7.5 λ_I .

electromagnetic calorimeter

- ◆ 40 layers of 1.9-mm W absorber + silicon pad sensors;
- ◆ 5x5 mm² cell granularity;
- ◆ 22 $X_0 + 1 \lambda_I$.

muon detectors

- ◆ 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- ◆ 30x30 mm² cell size.



superconducting solenoid (3.57T)

tracking system

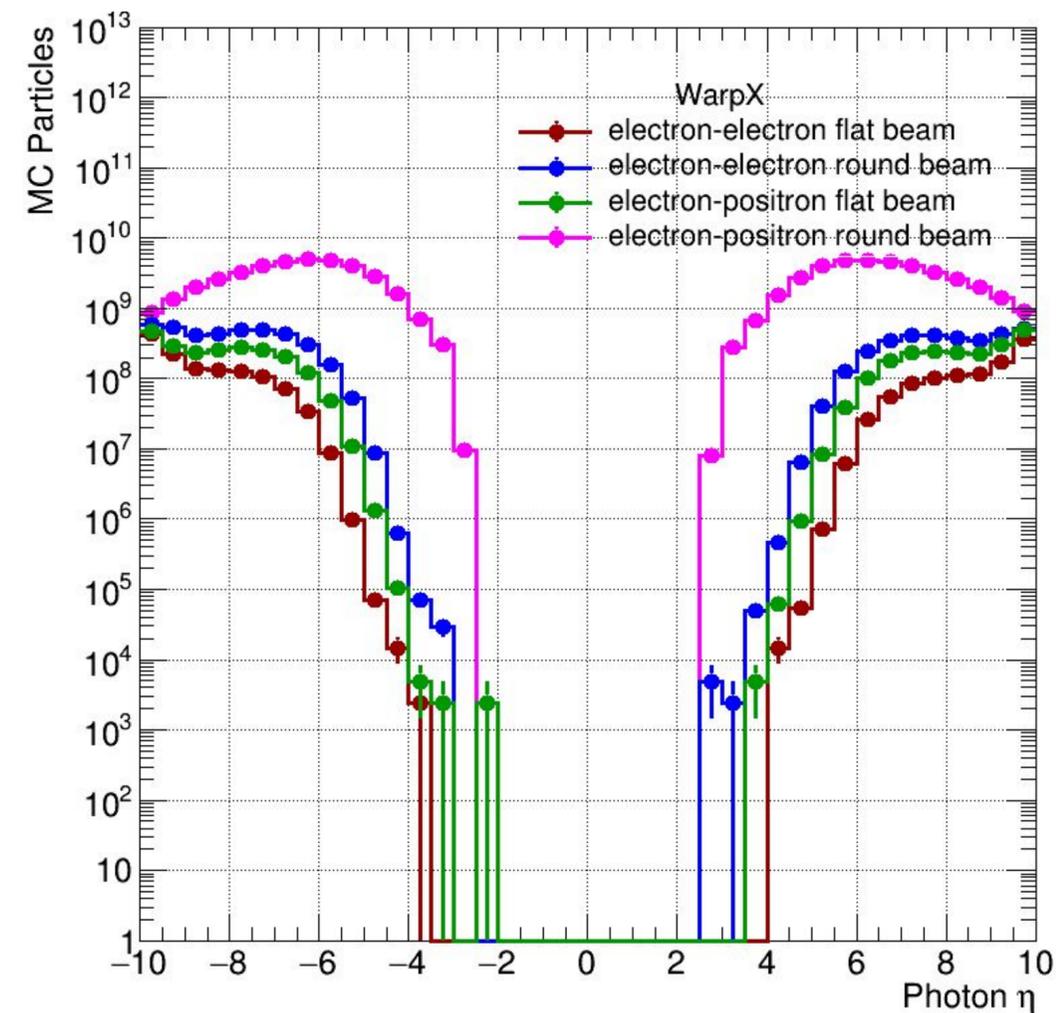
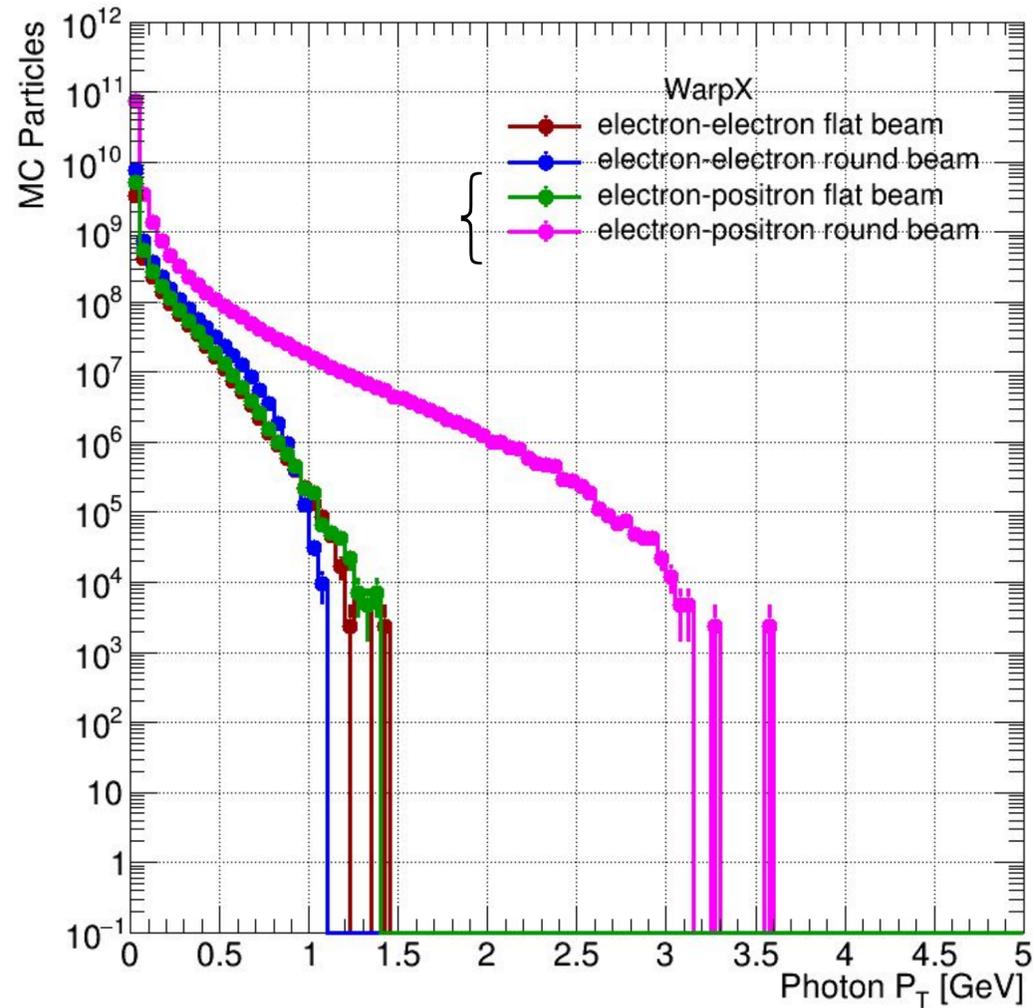
- ◆ **Vertex Detector:**
 - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
 - 25x25 μm^2 pixel Si sensors.
- ◆ **Inner Tracker:**
 - 3 barrel layers and 7+7 endcap disks;
 - 50 μm x 1 mm macro-pixel Si sensors.
- ◆ **Outer Tracker:**
 - 3 barrel layers and 4+4 endcap disks;
 - 50 μm x 10 mm micro-strip Si sensors.

shielding nozzles

- ◆ Tungsten cones + borated polyethylene cladding.

Removed the shielding nozzles from simulation and digitization for wakefield-based detector.

MC particles from WarpX: **photons**



Same high-level messages as we had for electron backgrounds:

- e^+e^- : lower beamstrahlung backgrounds for **flat beams**
- e^-e^- : s lower backgrounds (but crazy lower signal)

Comparison of coherent / incoherent at 10 TeV

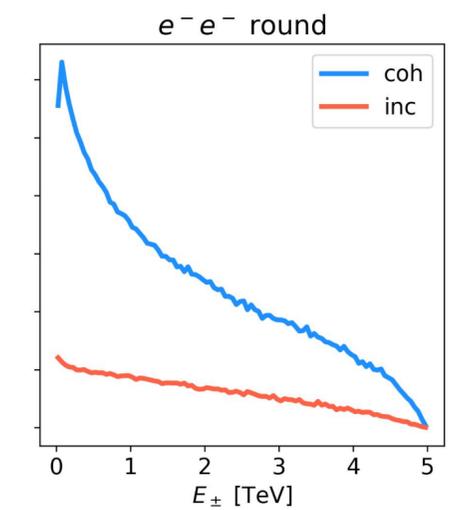
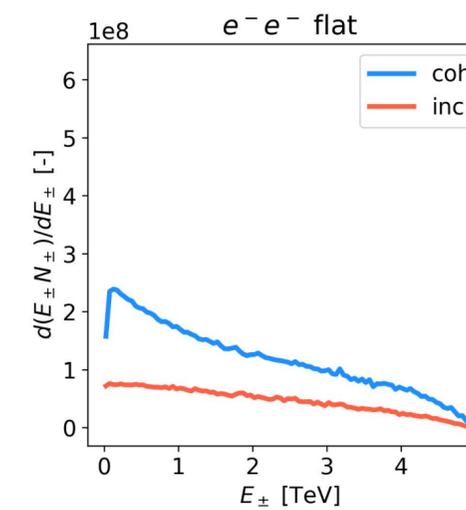
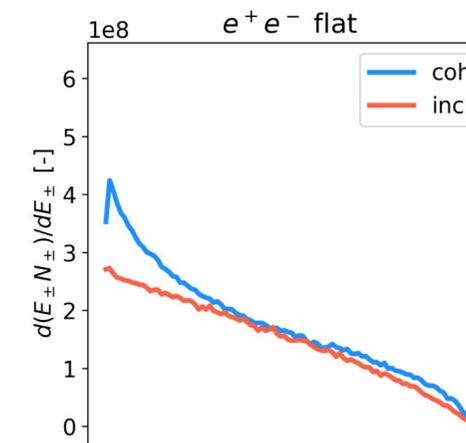
Arianna Formenti's [slide](#)

Simplifications

- local constant field approximation (LCFA)
- collinear emission of photons
- only coherent processes (beamstrahlung & nonlinear Breit-Wheeler)

Physics open questions

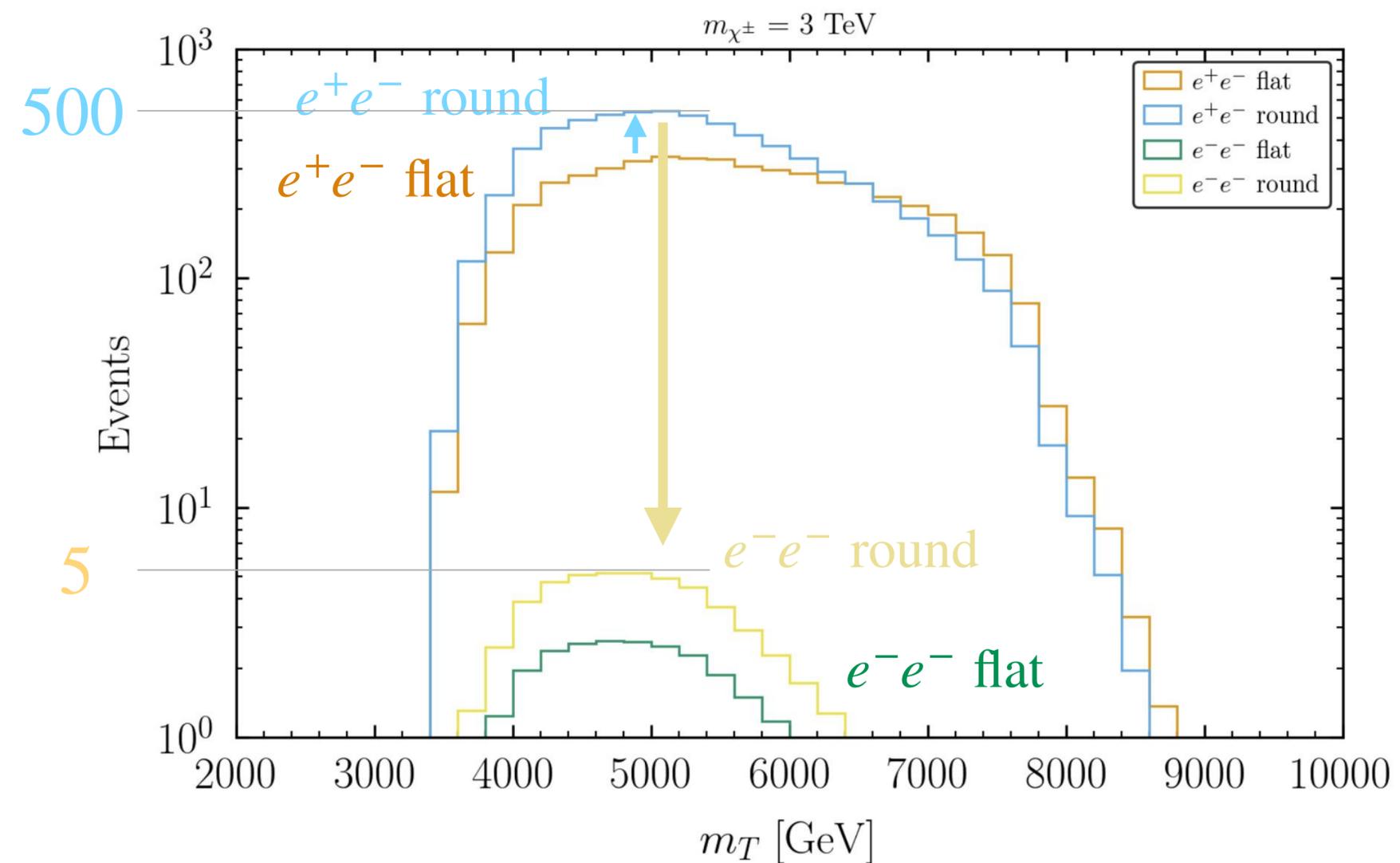
- transition from incoherent to coherent photon emission
- transition from incoherent to coherent pair generation
- emission rates at very high quantum parameters
- validity of LCFA
- circular colliders: couple with other codes
- other processes for muon colliders?
- ...



Physics

Round beams are better for physics (*much* worse for beamstrahlung)

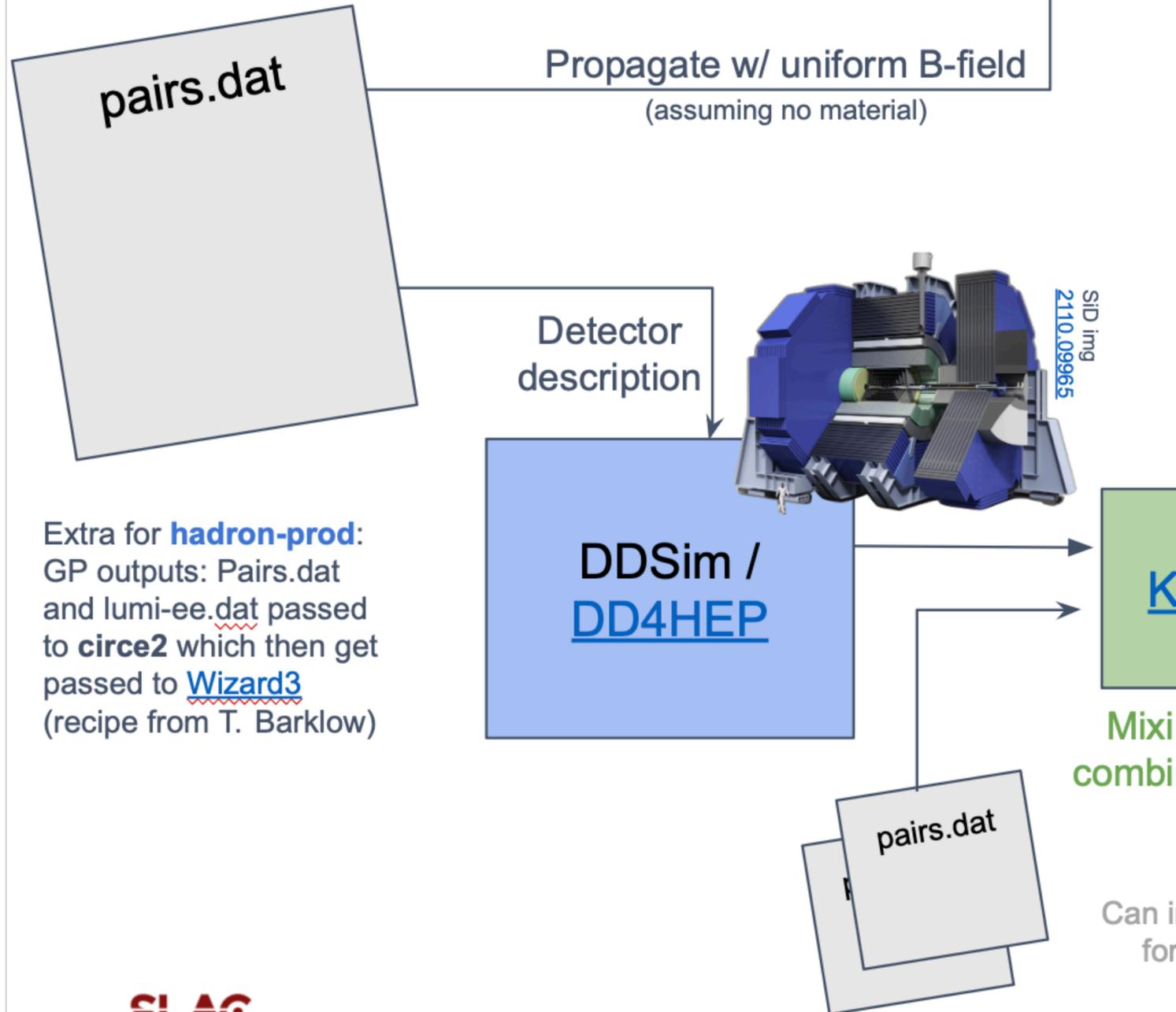
100x reduction in signal from $e^+e^- \rightarrow e^-e^-$



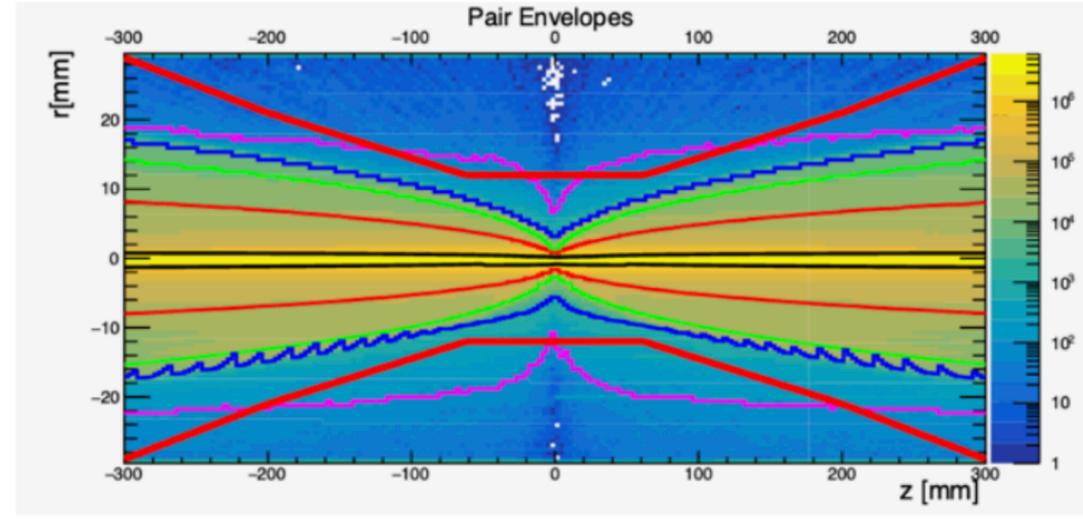
Angira's workflow

- Initial look at the detector-level simulation using DDSIM (DD4Hep) library for full GEANT4-based detector simulation
 - Using SLCIO file produced from WarpX output
- Running realistic digitization for silicon-based detectors to look at the tracking detector occupancy i.e. number of individual pixel hits and clusters.
 - Particle-material interaction is emulated i.e. ionization losses (creation of e-h pairs) with real silicon sensor thickness as well as the response of the front-end electronics for charge collection and timing information
-> to get a feeling of the collision environment for detector design R&D.
- Detector geometry used for these studies is the muon collider detector geometry without the shielding nozzles for the 3 TeV scenario (next slide), just as a starting point.

Pipeline

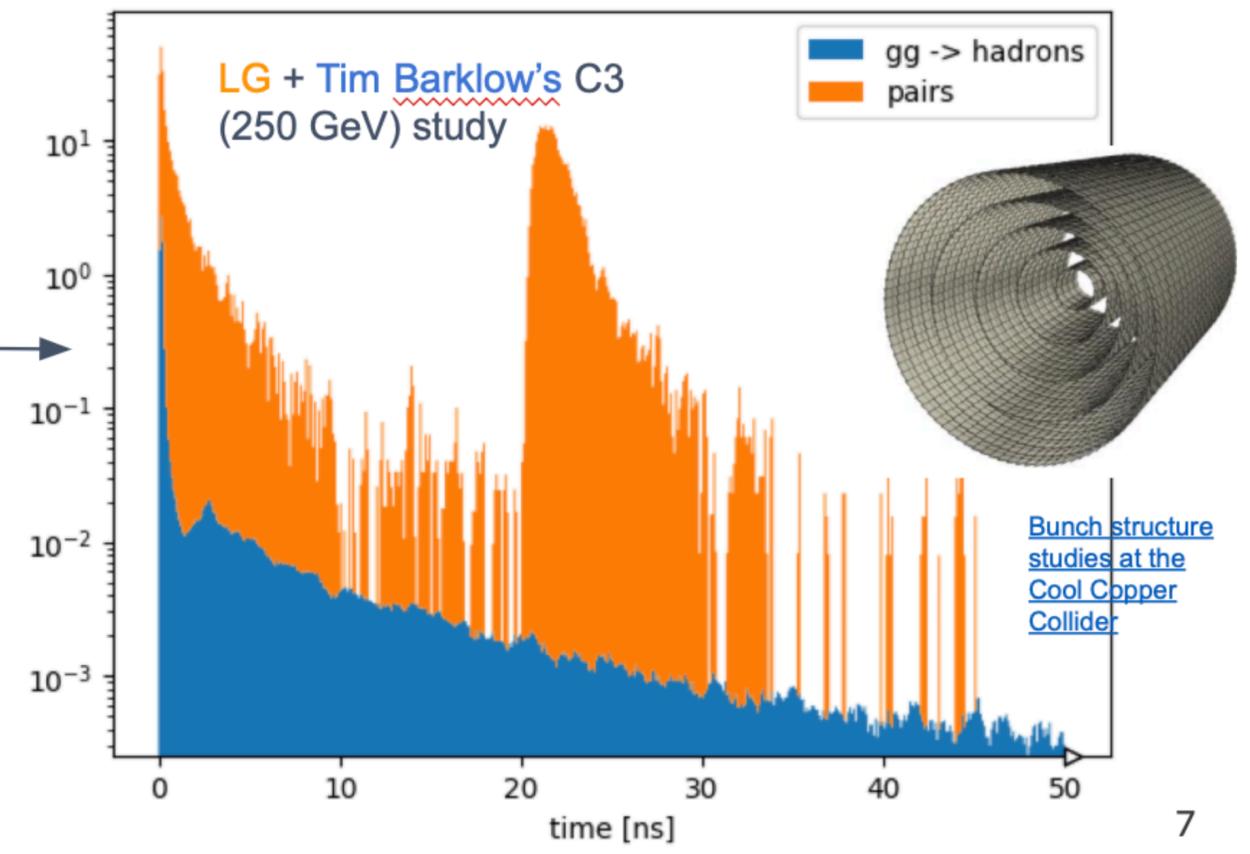


Extra for **hadron-prod**:
 GP outputs: Pairs.dat
 and lumi-ee.dat passed
 to **circe2** which then get
 passed to **Wizard3**
 (recipe from T. Barklow)

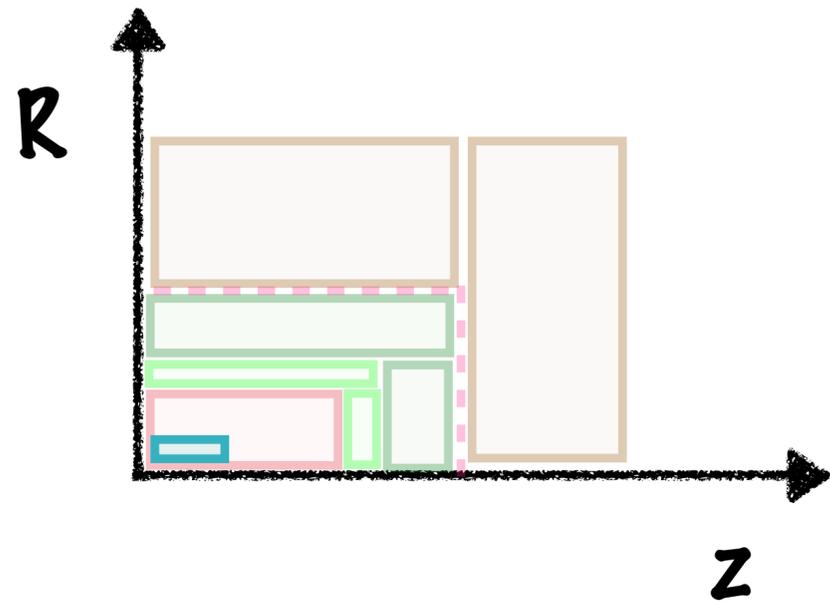


Beam-Induced Background Simulation Studies for the Cool Copper Collider

Inputs normalized to one event

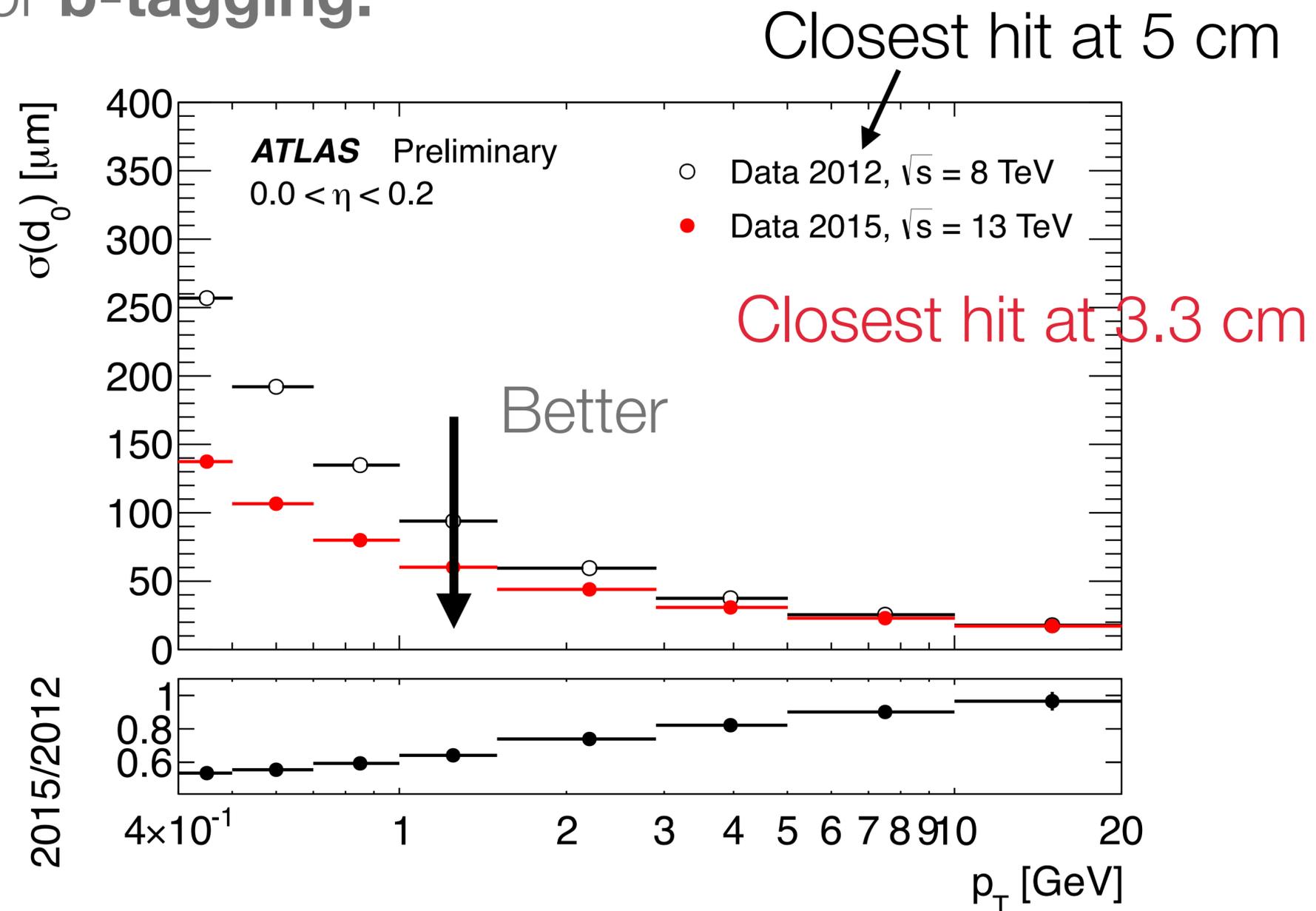
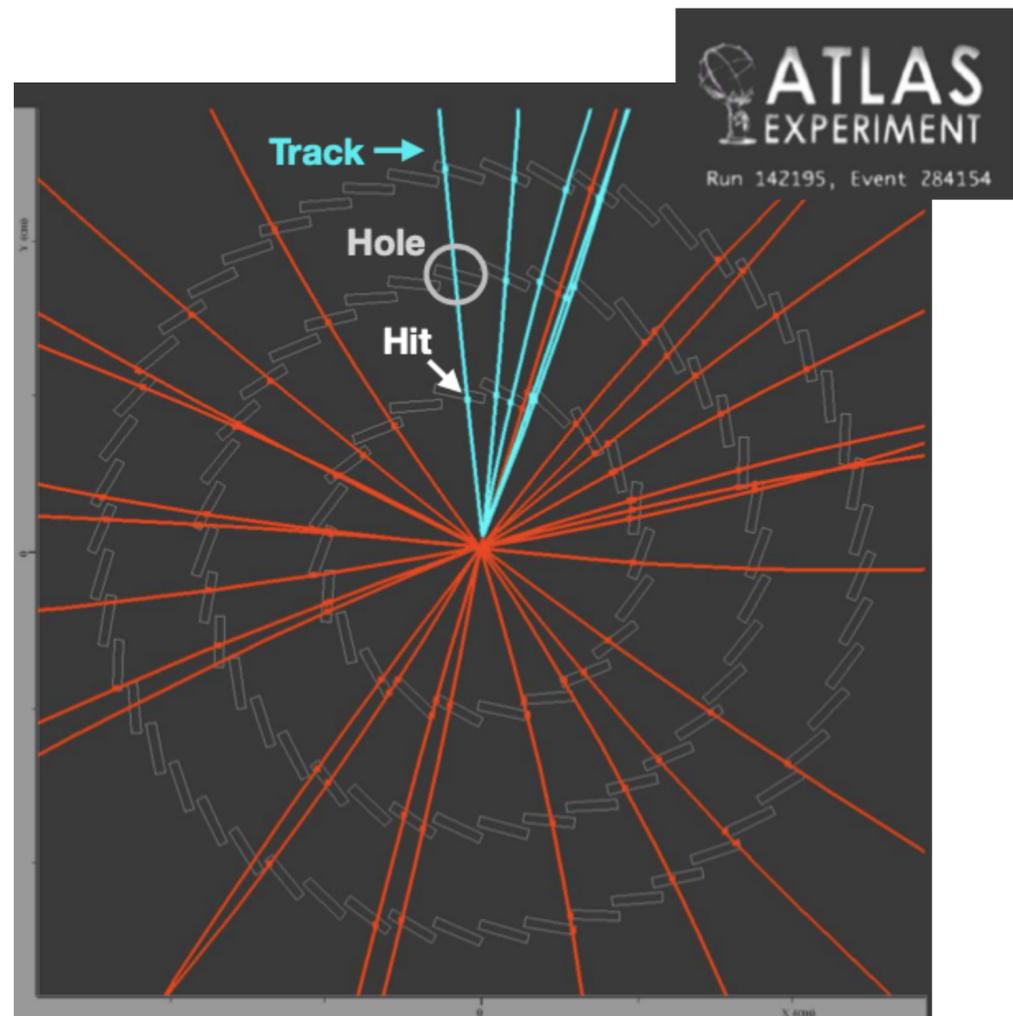


Arrival time at first layer of the vertex detector

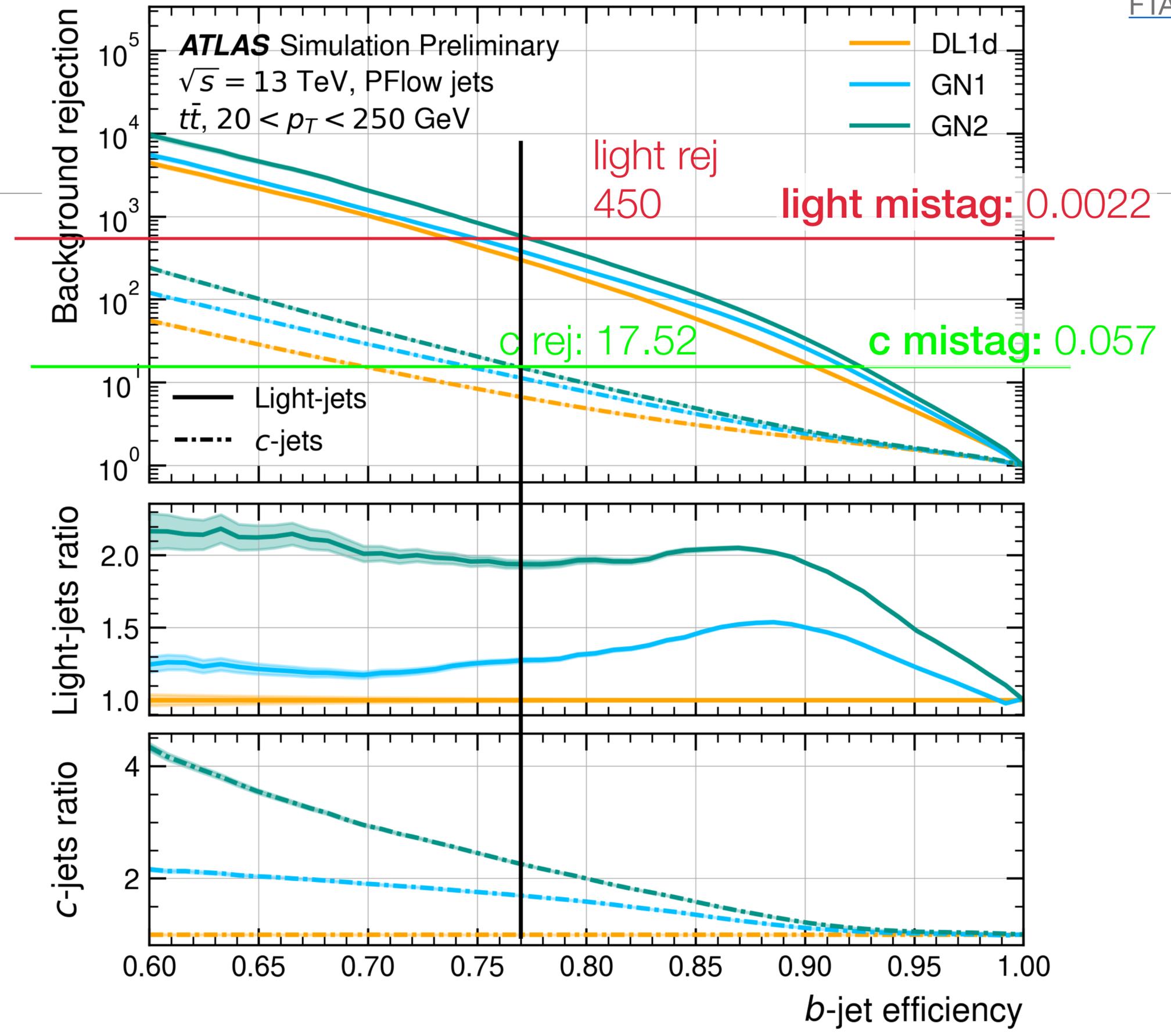


Vertex detector

Why close to the interaction point?
Crucial for **b-tagging**.

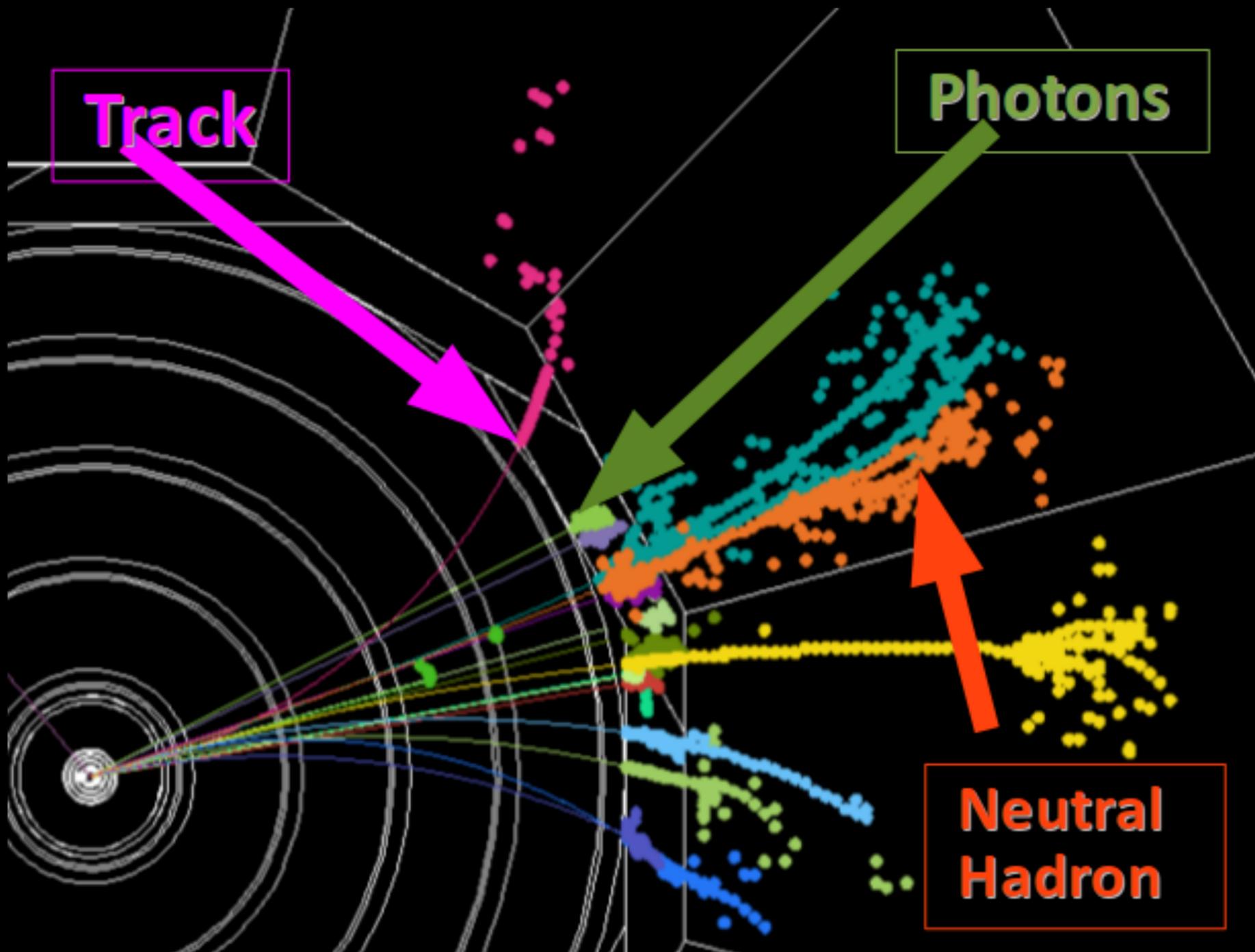


FTAG: ATLAS



Track momentum: $\frac{\sigma(p_T)}{p_T} = 0.036\% \cdot p_T \odot 1.3\%$

Smaller p_T better resolution!



Calorimeter energy

$$\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.7\% \oplus \frac{0.1\%}{E}$$

$$\frac{\sigma(E)}{E} = \frac{50\%}{\sqrt{E}} \oplus 3.4\% \oplus \frac{1\%}{E}$$

Larger energy better resolution!

* exact constants from ATLAS

Particle Flow: Best of both worlds!

Charged momentum from track
Neutral energy from calorimeter

Unpacking the calorimeter error

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

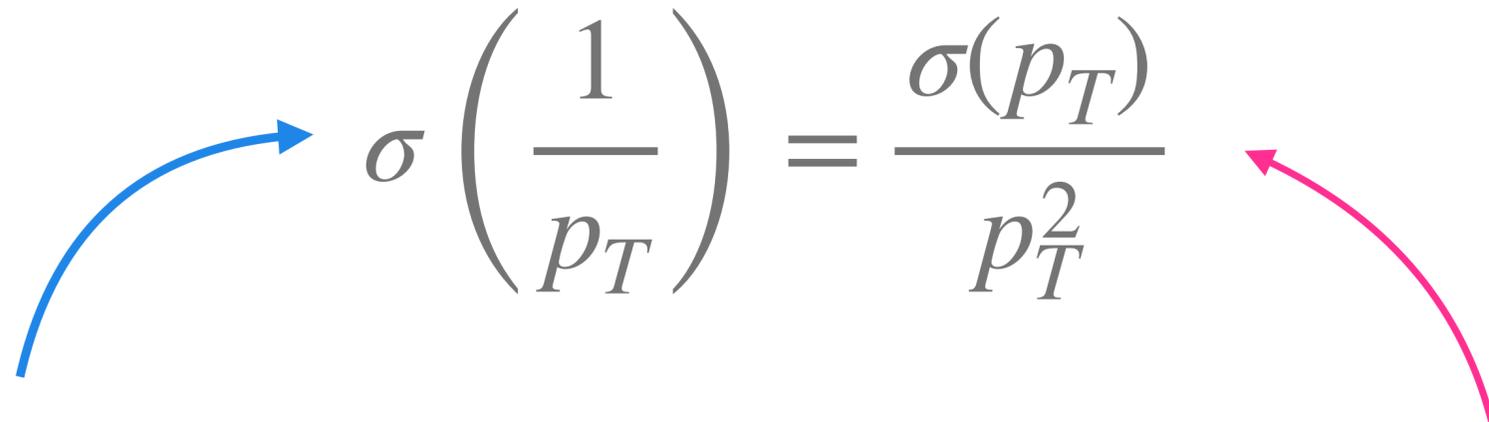
Sampling term
(Poisson fluctuations)

Inactive material,
mis-measured calib

Noise from PU and
electronics

The diagram illustrates the decomposition of the relative calorimeter error $\frac{\sigma(E)}{E}$ into three distinct components. The equation is presented as a sum of three terms, each enclosed in a circle with a plus sign (\oplus). The first term is $\frac{a}{\sqrt{E}}$, where a is blue and \sqrt{E} is also blue. A blue arrow points from the text 'Sampling term (Poisson fluctuations)' to this term. The second term is b , where b is orange. An orange arrow points from the text 'Inactive material, mis-measured calib' to this term. The third term is $\frac{c}{E}$, where c is green and E is also green. A green arrow points from the text 'Noise from PU and electronics' to this term.

Momentum resolution — preliminary thoughts

$$\sigma\left(\frac{1}{p_T}\right) = \frac{\sigma(p_T)}{p_T^2}$$


This is how ATLAS quotes their pT res

MuColl quotes their pT perf this way

In general:

$$\sigma\left(\frac{1}{p_T}\right) \cdot p_T = \boxed{a \cdot p_T} \odot \boxed{b}$$

Grows w/ pT ->
the curvature term

bias = multiple
scattering term

Tracker tensions

Low momentum

- **Low** (enough) B-field to avoid “loopers”
- Low material budget

High momentum

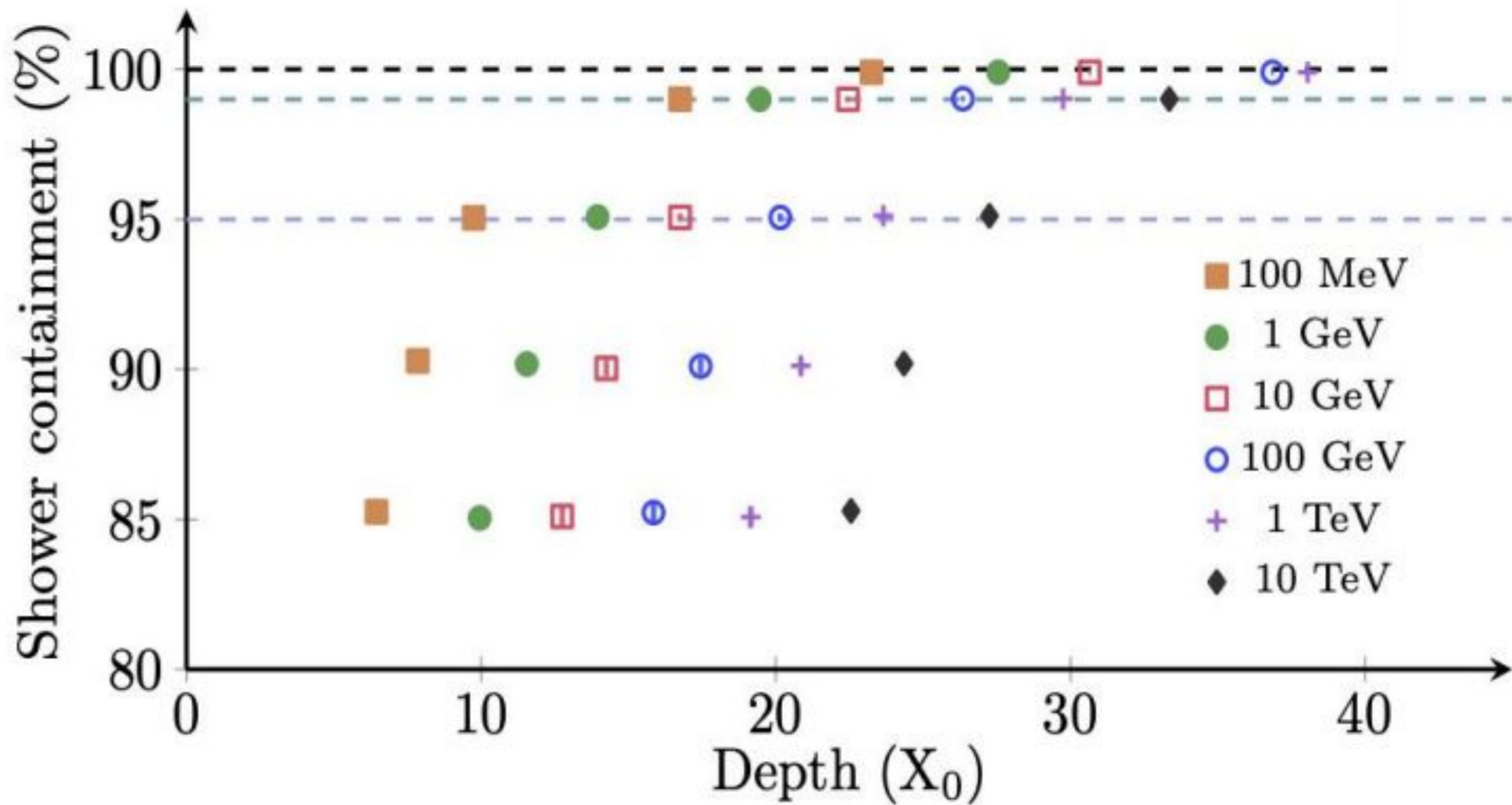
- Want **high** B-field for *strong* curvature (and good momentum resolution)
- **Large** volume (large lever arm)

BIB

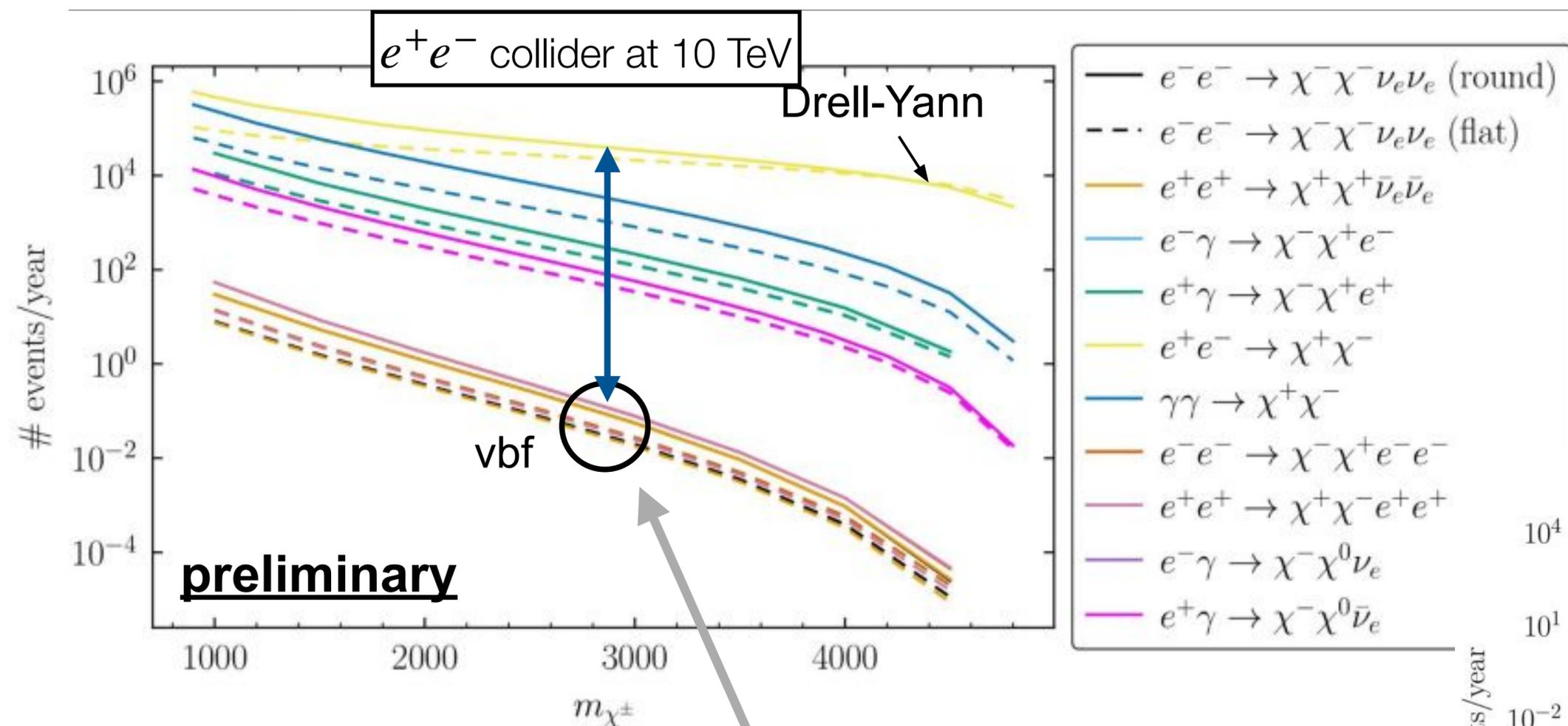
- Want **high** B-field to sweep e⁺e⁻ pairs out of the interaction region
- High granularity to reduce occupancy

Can be in tension!



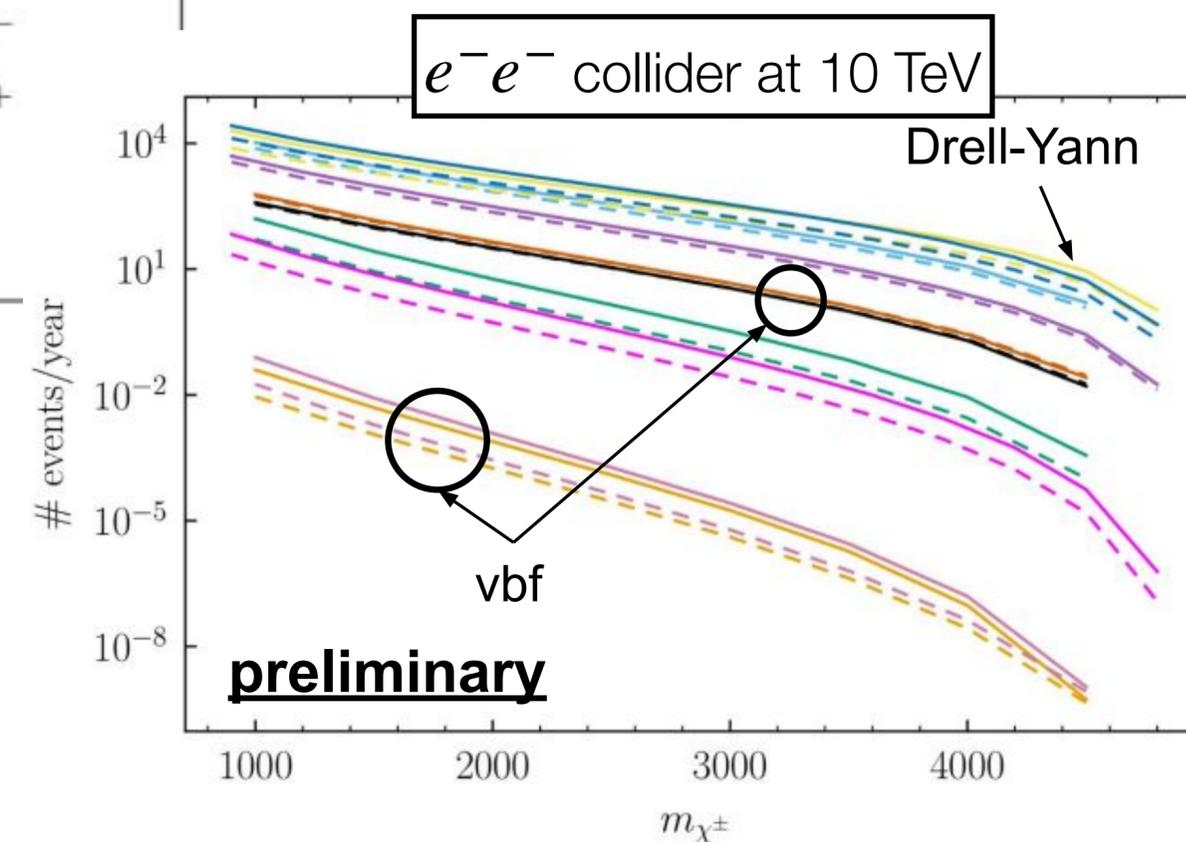


VBF import



Take in xsec is 10^6 c.f. neutrinos in the final state.

These are VBF events where we'd want to tag a forward electron!!

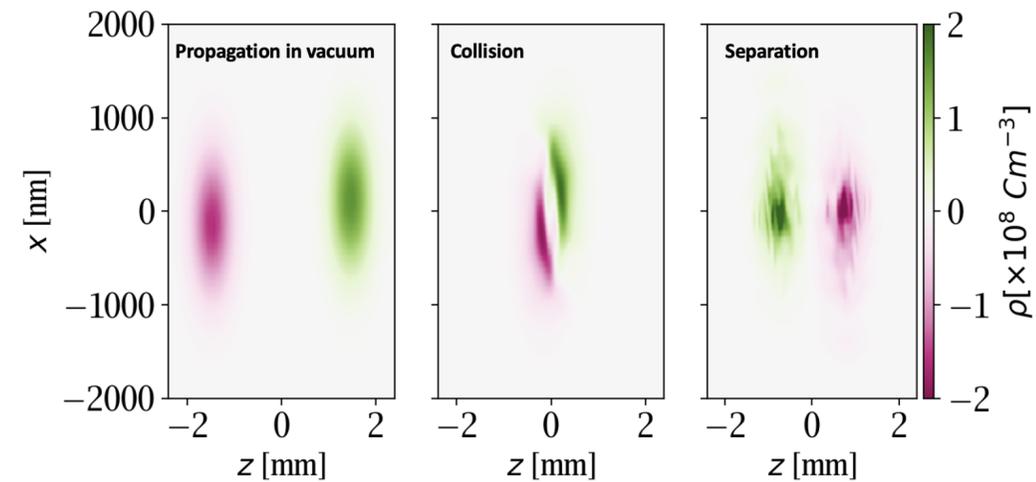


What about the other backgrounds?

Disrupted primary beams

Bao Nguyen, Arianna Formenti, Remi Lehe, Jean-Luc Vay, Spencer Gessner, Luca Fedeli; [2405.09583](#)

Figure 3: Visualization of nominal ILC-250 GeV beam-beam collision in WarpX. Note that the aspect ratio is not correct.



Bremsstrahlung photons

Radiative Bhabhas

| Source | #particles per bunch | $\langle E \rangle$ (GeV) |
|--|-----------------------|---------------------------|
| Disrupted primary beam | 2×10^{10} | 244 |
| Bremstrahlung photons | 2.5×10^{10} | 244 |
| e^+e^- pairs from beam-beam interactions | 75k | 2.5 |
| Radiative Bhabhas | 320k | 195 |
| $\gamma\gamma \rightarrow$ hadrons/muons | 0.5 events/1.3 events | – |

Although these contributions do have the highest $\langle E \rangle$, they are the most forward in the detector, so are not expected to be the most important component for our work

SiD Parameters

Table II-1.1

Key parameters of the baseline SiD design. (All dimension are given in cm).

| SiD Barrel | Technology | Inner radius | Outer radius | z extent |
|-----------------|--------------------|--------------|--------------|--------------|
| Vertex detector | Silicon pixels | 1.4 | 6.0 | \pm 6.25 |
| Tracker | Silicon strips | 21.7 | 122.1 | \pm 152.2 |
| ECAL | Silicon pixels-W | 126.5 | 140.9 | \pm 176.5 |
| HCAL | RPC-steel | 141.7 | 249.3 | \pm 301.8 |
| Solenoid | 5 Tesla SC | 259.1 | 339.2 | \pm 298.3 |
| Flux return | Scintillator-steel | 340.2 | 604.2 | \pm 303.3 |
| SiD Endcap | Technology | Inner z | Outer z | Outer radius |
| Vertex detector | Silicon pixels | 7.3 | 83.4 | 16.6 |
| Tracker | Silicon strips | 77.0 | 164.3 | 125.5 |
| ECAL | Silicon pixel-W | 165.7 | 180.0 | 125.0 |
| HCAL | RPC-steel | 180.5 | 302.8 | 140.2 |
| Flux return | Scintillator/steel | 303.3 | 567.3 | 604.2 |
| LumiCal | Silicon-W | 155.7 | 170.0 | 20.0 |
| BeamCal | Semiconductor-W | 277.5 | 300.7 | 13.5 |

BeamCal: crucial for our
IMDI story... backplash 

SiD : Vertex detector

Table II-2.1

The geometry parameters of the SiD vertex detector (Barrel, Disks and Forward Disks). Units are mm.

| Barrel | R | z_{\max} | |
|--------------|--------------------|--------------------|---------------------|
| Layer 1 | 14 | 63 | |
| Layer 2 | 22 | 63 | |
| Layer 3 | 35 | 63 | |
| Layer 4 | 48 | 63 | |
| Layer 5 | 60 | 63 | |
| Disk | R_{inner} | R_{outer} | z_{center} |
| Disk 1 | 14 | 71 | 72 |
| Disk 2 | 16 | 71 | 92 |
| Disk 3 | 18 | 71 | 123 |
| Disk 4 | 20 | 71 | 172 |
| Forward Disk | R_{inner} | R_{outer} | z_{center} |
| Disk 1 | 28 | 166 | 207 |
| Disk 2 | 76 | 166 | 541 |
| Disk 3 | 117 | 166 | 832 |

SiD : Main Tracker

Table II-3.2

Performance goals for the main tracker.

| Parameter | Design Goal |
|-------------------------------------|---|
| coverage | hermetic above $\theta \sim 10^\circ$ |
| momentum resolution $\delta(1/p_T)$ | $\sim 2 - 5 \times 10^{-5} / \text{GeV}/c$ |
| material budget | $\sim 0.10 - 0.15X_0$ in central region $\sim 0.20 - 0.25X_0$ in endcap region |
| hit efficiency | $> 99\%$ |
| background tolerance | Full efficiency at $10\times$ expected occupancy |

SiD : ECAL

Table II-4.1

Nominal parameters of the silicon-tungsten ECAL for SiD.

| | |
|--|--|
| inner radius of ECAL barrel | 1.27 m |
| maximum z of barrel | 1.76 m |
| longitudinal profile | 20 layers \times 0.64 X_0 10 layers \times 1.30 X_0 |
| EM energy resolution | $0.17/\sqrt{E} \oplus 1\%$ |
| readout gap | 1.25 mm (or less) |
| effective Molière radius (\mathcal{R}) | 14 mm |

Number of channels

Table II-9.2

Overview of read-out details for the various subdetectors. Occupancies and data volumes are for a full bunch train at 1 TeV and include beam-induced background as well as charge sharing between pixels/strips. Safety factors of five and two have been applied to the rates of incoherent pairs and $\gamma\gamma \rightarrow$ hadrons respectively. BeamCal and Lumical are expected to be using the Bean chip with a buffer depth of 2820.

| | cell size (mm ²) | number of channels (10 ⁶) | av. to max. occ. (%) | approx. # bits per hit (bit) | data volume (Mbyte) |
|----------------------------|------------------------------|---------------------------------------|----------------------|------------------------------|---------------------|
| VXD barrel | 0.02×0.02 | 408 | 8 - 60 | 32 | 130 |
| VXD disks inner | 0.02×0.02 | 295 | 4 - 70 | 32 | 50 |
| VXD disks outer | 0.05×0.05 | 980 | 0.5 - 20 | 32 | 20 |
| Main tracker barrel | 0.05×100 | 16 | 33 - 300 | 32 | 20 |
| Main tracker disks | 0.05×100 | 11 | 4 - 500 | 32 | 2 |
| ECAL barrel | 3.5×3.5 | 72 | 2 - 45 | 40 | 7 |
| ECAL endcap | 3.5×3.5 | 22 | 33 - 2300 | 40 | 36 |
| HCAL barrel | 10×10 | 30 | 0.07 - 200 | 40 | 0.1 |
| HCAL endcap | 10×10 | 5 | 96 - 3600 | 40 | 24 |
| LumiCal | 2.5×var. | 0.061 | ≫100 | 16 | 340 |
| BeamCal | 2.5(5.0)×var. | 0.076 | ≫100 | 16 | 430 |

Beamcal

Figure II-8.1
The SiD forward re-
gion.

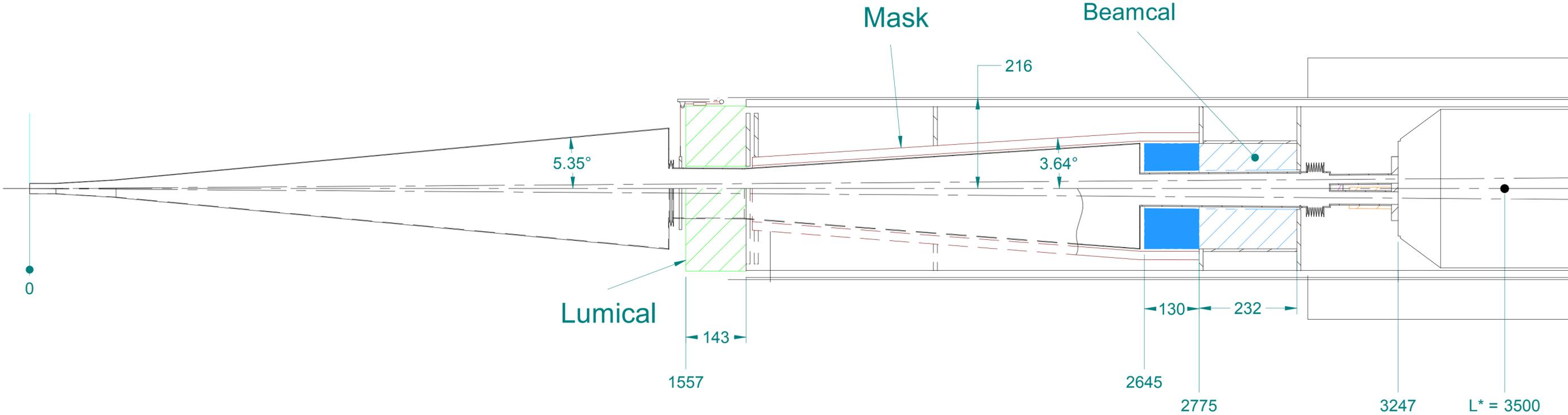
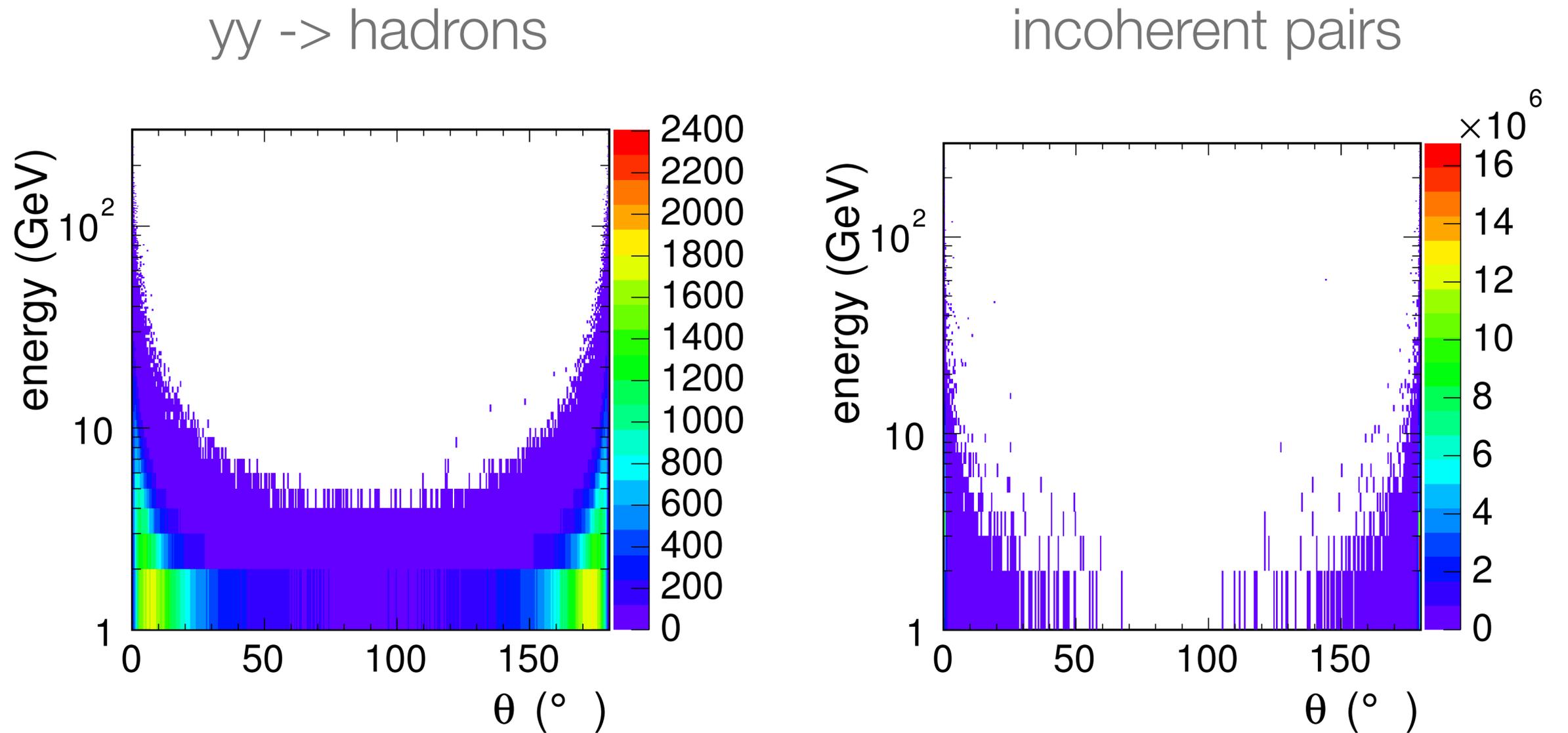


Figure II-10.5
Kinematic properties of the machine-induced backgrounds from $\gamma\gamma \rightarrow$ hadrons processes (left) and from incoherent pairs (right) at 1 TeV.



LHC Detectors optimized for e / γ and muons

Arguing around the mid-1980s of being ambitious and design a general-purpose detector ...

A very simplified summary:

| detector signature | accessible physics process |
|--|---|
| μ^\pm | $H \rightarrow ZZ \rightarrow 4\mu^\pm$ $Z' \rightarrow \mu^+\mu^-$ (σ_m ?) |
| $\mu^\pm, jets, p_T$ | add: $H \rightarrow ZZ \rightarrow \mu^+\mu^-\nu\bar{\nu}$ $W' \rightarrow \mu^\pm\nu$ compositeness \tilde{q}, \tilde{g} (direct decays) jet spectroscopy |
| $e, \mu^\pm, jets, p_T$ (non-)magnetic central part (reduced tracking) | add: $4 \times$ rate $H \rightarrow ZZ \rightarrow 4e^\pm$ $2 \times$ rate $H \rightarrow ZZ \rightarrow e^+e^-\nu\bar{\nu}$ $2 \times$ rate Z', W' \tilde{q}, \tilde{g} (also cascade decays) mass resolution e, μ heavy Q, L $H \rightarrow \gamma\gamma$ |
| $e^\pm, \mu^\pm, \tau^\pm, jets, p_T$ full momentum and tracking | add: more redundancy and cross-checks on above, $H^\pm, SUSY-H,$ heavy flavour tags |

Lepton detection at LHC is crucial. Small rates are expected for many potential signals

\Rightarrow detection of e and μ

Muons are relatively easy to identify but hard to measure well
(precise μ measurements may mean hundreds of MCHF)

Electrons are relatively easy to measure but hard to identify at 10^{34}
(radiation-hard inner detector)

Lepton isolation criteria are also important to reject backgrounds from heavy flavour decays

At a 10 TeV discovery machine, **jets** are now also a discovery channel and get promoted to a first class citizen in the analysis pipeline.

Complementary Approaches in ATLAS and CMS

| | ATLAS \equiv A Toroidal LHC ApparatuS | CMS \equiv Compact Muon Solenoid |
|-------------------|---|---|
| MAGNET (S) | Air-core toroids + solenoid in inner cavity (4 magnets) Calorimeters in field-free region | Solenoid Only 1 magnet Calorimeters inside field |
| TRACKER | Si pixels+ strips TRT \rightarrow particle identification B=2T $\sigma/p_T \sim 3.8 \times 10^{-4} p_T \oplus 0.015$ | Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5 \times 10^{-4} p_T \oplus 0.005$ |
| EM CALO | Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation | PbWO₄ crystals $\sigma/E \sim 2-5\%/\sqrt{E}$ no longitudinal segm. |
| HAD CALO | Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$ | Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$ |
| MUON | Air $\rightarrow \sigma/p_T \sim 10\%$ at 1 TeV standalone ($\sim 7\%$ combined with tracker) | Fe $\rightarrow \sigma/p_T \sim 15-30\%$ at 1 TeV standalone (5% with tracker) |

Detectors on the market

| | ILD | SID | IDEA | CLD | Allegro | MuCol 3TeV |
|--------------------------|-----------------|-----------------------------------|--------------------|-----------------|--------------------|-----------------------------------|
| Vertex Inner Radius (cm) | 1.6 | 1.4 | 1.2 | 1.2 | 1.2 | |
| Tracker technology | TPC + Silicon | Silicon | Si + Drift Chamber | Si | Si + Drift Chamber | Silicon |
| Outer Tracker radius | 1.77 | 1.22 | 2 | 3.3 | 2 | |
| ECAL thickness | 24 X_0 | 26 X_0 | Dual RO | 22 X_0 | 22 X_0 | 22 X_0 |
| HCAL thickness | 5.9 λ_0 | 4.5 λ_0 | 7 λ_0 | 6.5 λ_0 | 9.5 λ_0 | 7.5 λ_0 |
| HCAL Outer Radius [m] | 3.3 | 2.5 | 4.5 | 3.5 | 4.5 | |
| Solenoidal field [T] | 3.5 | 5 | 2 | 2 | 2 | 3.57 |
| Solenoidal length [m] | 7.9 | 6.1 | 6 | 7.4 | 6 | |
| Solenoid Radius | 3.4 | 2.6 | 2.1 | 4 | 2.7 | |

| | | ILD | SID | MuCol 3TeV |
|---------------|-----------------------|-----|-----|-------------------------|
| Vertex | Size | | | 25 x 25 μm^2 |
| | Technology | | | |
| | number of layers | | | 4 barrel, 4+4 endcap |
| Inner Tracker | Size | | | 5 μm x 1 mm |
| | Technology | | | macro pixel Si sensors |
| | number of layers | | | 3 barrel, 7+7 endcap |
| Outer tracker | Size | | | 5 μm x 10 mm |
| | Technology | | | macro strip Si sensors |
| | number of layers | | | 3 barrel, 4+4 endcap |
| ECAL | ECAL absorber | | | |
| | ECAL active material | | | |
| | Cell size | | | 5 x 5 mm^2 |
| | ECAL number of layers | | | |
| HCAL | HCAL absorber | | | 19mm steel |
| | HCAL active material | | | plastic scintillator |
| | Cell size | | | 30 x 30 mm^2 |
| | number of layers | | | 60 |
| Muon | Technology | | | RPC |
| | number of layers | | | 7 barrel, 6 endcap |
| | Cell size | | | 30 x 30 mm^2 |