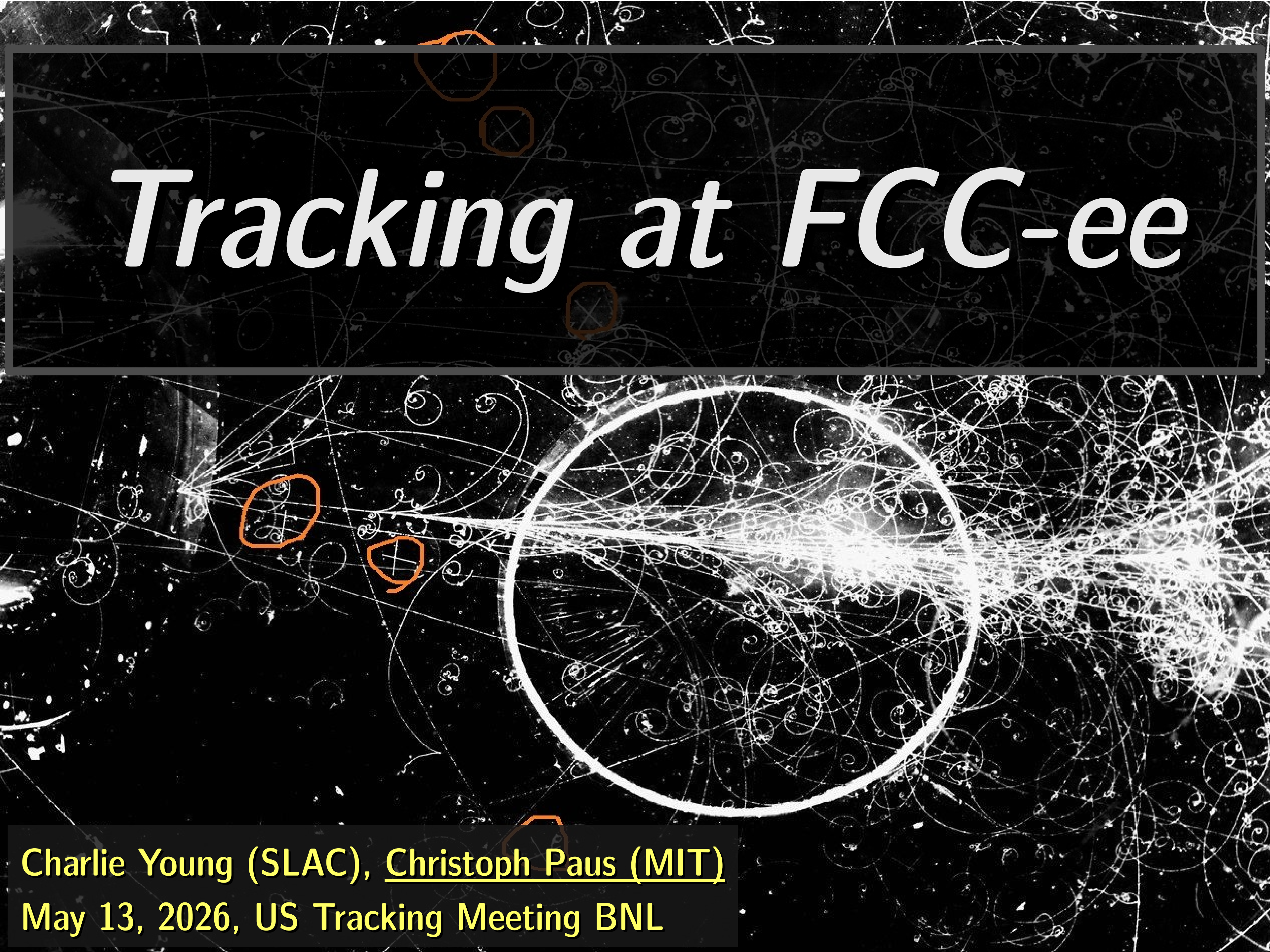


Tracking at FCC-ee

Charlie Young (SLAC), Christoph Paus (MIT)

May 13, 2026, US Tracking Meeting BNL

Workshop Motivation

Get US FCC Tracker community together

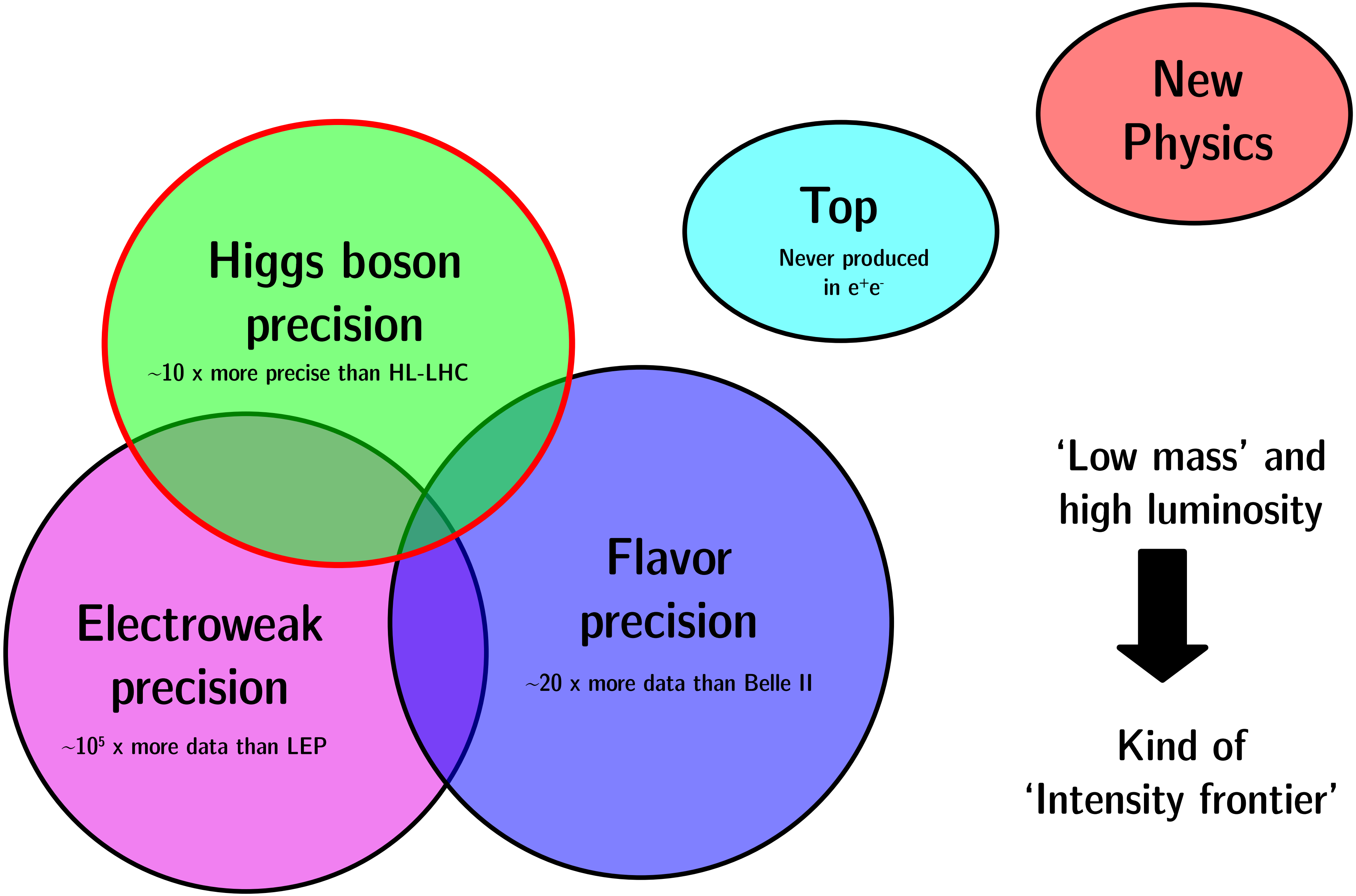
- Funding is remaining very limited, in particular in the U.S.
- Some very relevant study cases: ALICE, ePIC, ...

'Synergize' with EIC (ePIC tracker) activities

- EIC is working with ALICE
- EIC environment is similar but not the same: estimates say that power requirements for FCC will be more stringent
  - A new design is needed
  - Good work but much to leanr from the first production MAPS detector
- Other tracking might also inspire: particle Id and gaseous tracking (MPGDs)? MicroMegas, μRWELL?

To indicate US opportunities in the following → US Opp.

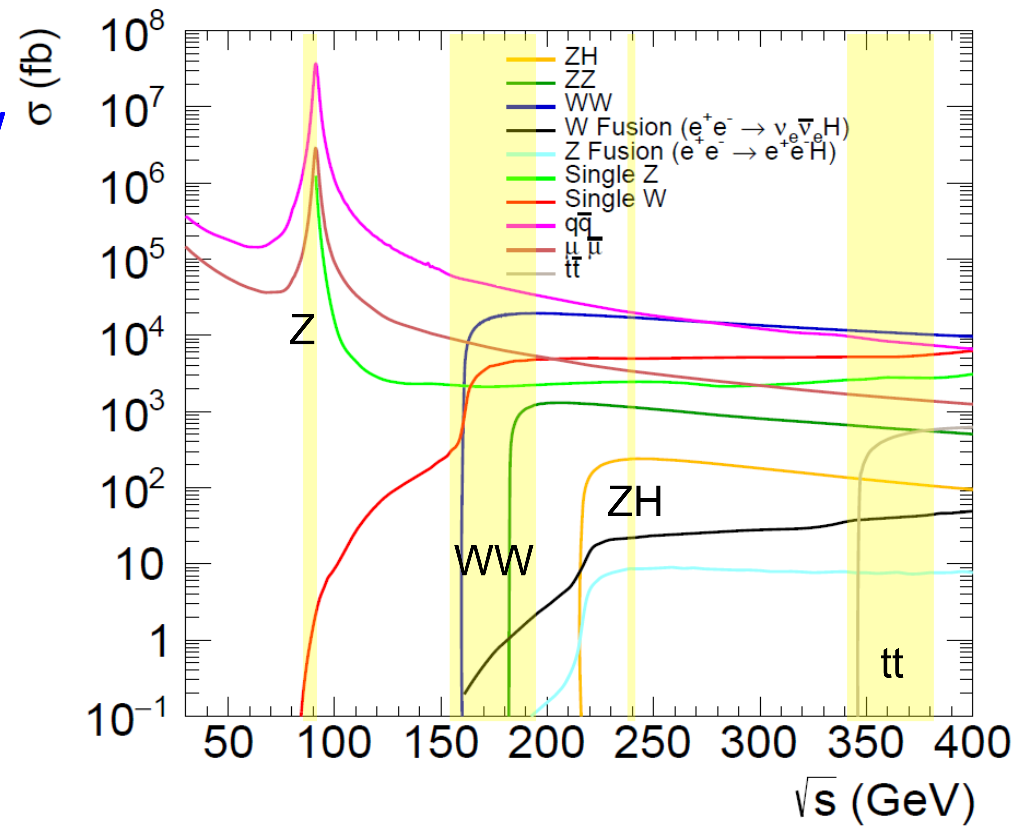
Physics Goals of the FCC-ee



FCC-ee Run Plan

Baseline run plan for FCC-ee

- Z run has most events followed by WW run
- The precision expected is extraordinary
  - Z: $1/\mathrm{sqrt}(10^{12}) = 10^{-6}$
  - WW: $1/\mathrm{sqrt}(10^{8}) = 10^{-4}$
  - ZH/tt: $1/\mathrm{sqrt}(10^{6}) = 10^{-3}$
- O(10^6) Higgs bosons, ultra clean
- Top quark has never been studied at a lepton collider



Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	0	3	1	4
Number of events	$6\,10^{12}$ Z		$2.4\,10^{8}$ WW		$1.45\,10^{6}$ HZ + 45k WW → H	$1.9\,10^{6}$ $t\bar{t}$ +330k HZ +80k WW → H	

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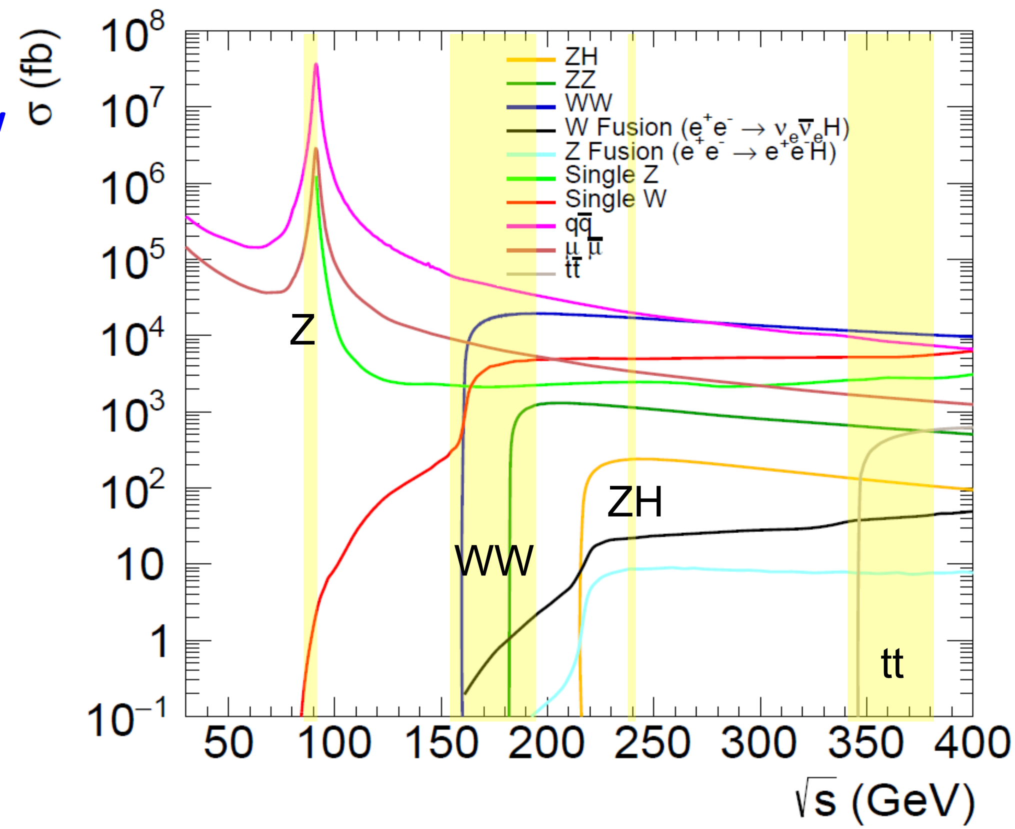

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Lower momentum, high intensity

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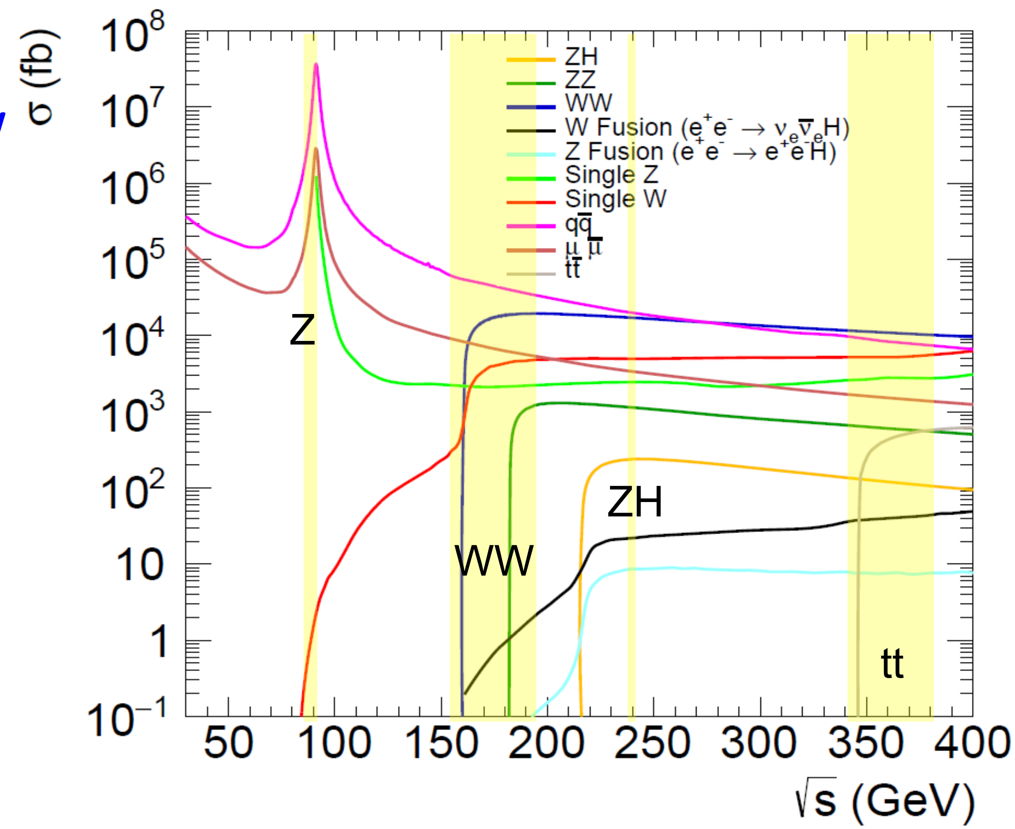

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higher momentum, low intensity

Requirements

Taken from Feasibility Study Report (Vol. 1)

- Vertex
  - Higgs: $H_{bb/cc}$, Flavor: $B \to K^* \tau+\tau-$, R_b, R_c with exclusive decays, but all is in fast simulation (Delphes)
  - Now: Full Simulation all the $R_{b/c}$, AFB $_{b/c}$ huge samples, re-study systematics
- Momentum
  - Higgs mass, point-to-point $\sqrt{s}$ calibration (for all lineshape measurements)
- PiD
  - H_{ss}, we do not have a full simulation PiD implementation
  - AFB_{ss}, R_s (never done, neither at LEP nor in our feasibility report)
  - Non-perturbative QCD strange fragmentation, strange hadron content of collision
  - Flavor $B \to K^*\nu\nu$, $B_s \to \nu\nu$, $B_s \to D_s K$, V_{ts} ...

LEP Trackers

Looking at the past is a good idea:

- **ALEPH:** reasonably new technologies, homogeneous detector, granularity more than energy resolution.
- **DELPHI:** very new technologies, larger variety of techniques
- **L3:** measure electrons, muons and photons with highest resolution
- **OPAL:** only proven and reliable technologies, to be sure at least one of these huge detectors would be ready in time

Detector	B field	Vertex	Momentum/PiD	Radius
ALEPH	1.5 T	2 layers	TPC	1.70 m
DELPHI	1.2 T	2 → 3 layers	TPC+RICH	2.10 m
L3	0.5 T	2 layers	TECH	0.45 m
OPAL	0.4 T	2 layers	Drift cham.	1.86 m
SLD	0.6 T	Pixel, 3 layers	Drift chamb.+RICH	1.00 m
FCC-ee generic	2.0 T	MAPS, 4 layers	Drift chamb.+LGADs	2.00 m

Note: get ∼6 orders of magnitude more events → need better detectors

Tracker Options

Wide range of E_{CM} and number of events

- Build just one tracker/experiment? Or maybe 4, one for each period? Or one for Z and WW and one for ZH and tt?

Tracker Option	MS ($\Delta p_T/P_T$)	@100 GeV	multi-track res.	rate	operations/risk
MAPS				all	OK
Silicon strips tracker	0.0025	0.0035	~100 μm	all	OK
IDEA type drift ch.	0.0003	0.0030	n x 100 μm	all	loose wires?
CDF type drift ch,	~0.0015	~0.0030	ok	all	OK, SuperCell
Strawtube tracker	0.0015	0.0040	n x 100 μm	all	OK
Pixel TPC	0.0009	0.0030	2 mm	$<10^9$	difficult, space charge
Scint. Fiber Tracker	?	?	?	all	OK
dN/dx (dE/dx)			n x 100 μm	all	very promising
TOF	30-100 ps		–	all	OK
RICH	Higher momenta		–	all	difficult, material?

Resolutions and beyond

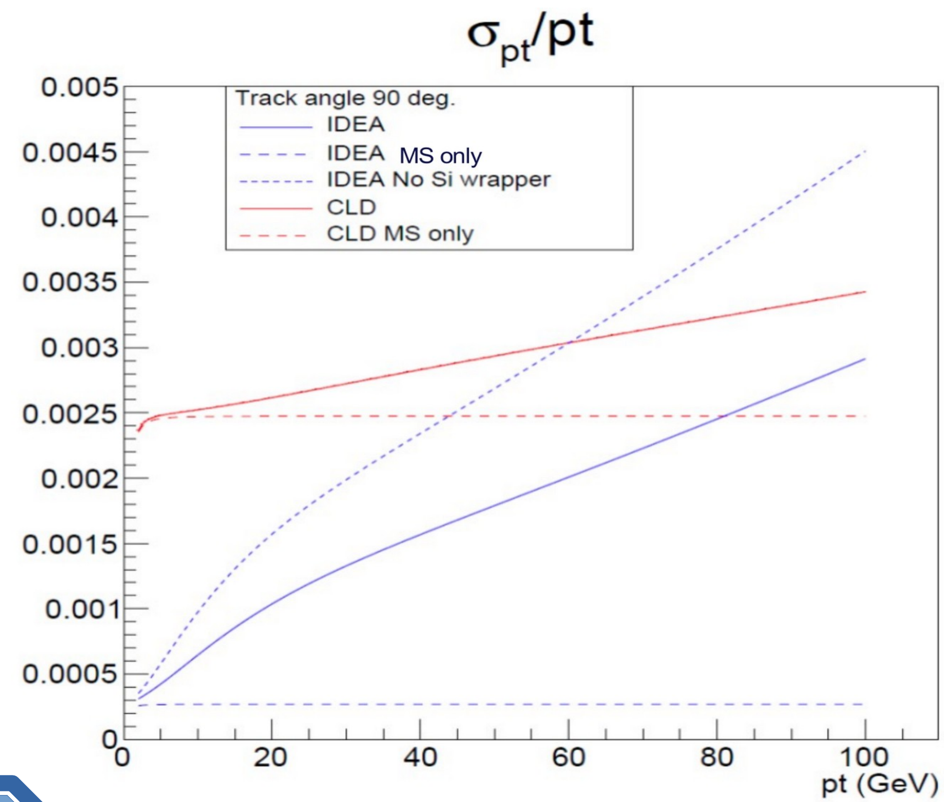
Asymptotic resolution

- Not the driver due to lower particle momentum (CLD)
- Minimize material

Systematic uncertainty

- Knowledge of acceptance is crucial O(10 μm) → requires a silicon wrapper, including endcap disks
- Drift chamber alone is not precise enough
- Reliable operation conditions are crucial for simulation

US Opp.



$$\frac{\sigma(p_T)}{p_T} \approx \frac{12\sigma_{r\phi}\, p_T}{0.3BL^2}\sqrt{\frac{5}{N+5}} \oplus \frac{14\ MeV}{0.3BL}\sqrt{\frac{d_{tot}}{X_0 \sin\theta}}$$

$\sigma_{r\phi}$ is the hit resolution
d_{tot} is the total thickness

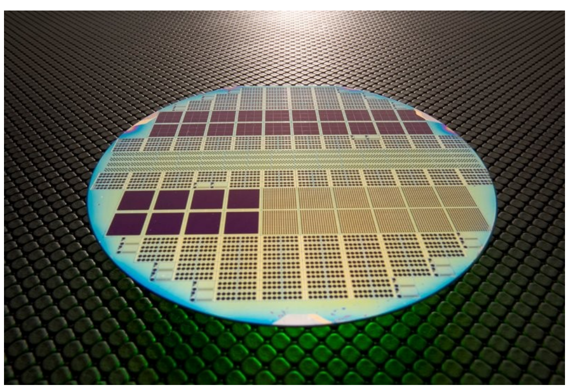
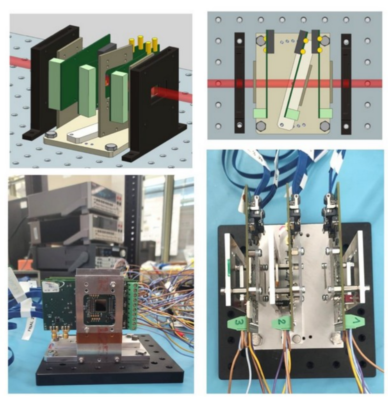
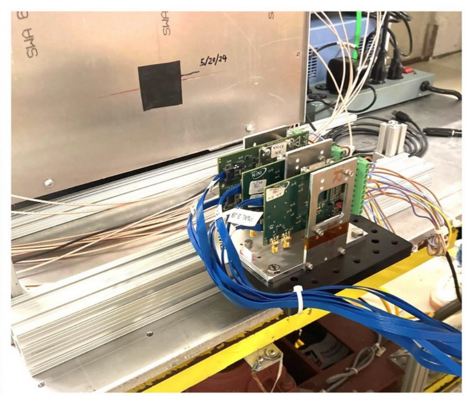
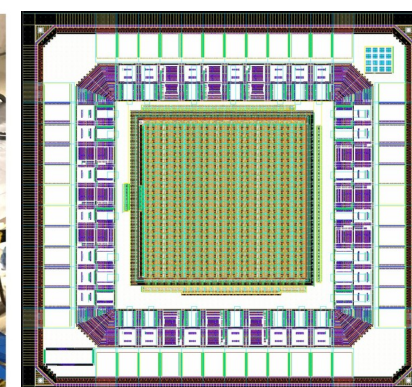
Solid state tracking

US R&D Focus: Development of MAPS, LGADs, readout electronics

MAPS Development

US Opp.

- SLAC-led effort
  - Napa-p2 characterization in FY26
  - Part of Versatile MAPS (DRD3.1); needs ASIC designer continuity to investigate: sub-ns TDC: power/timing trade-offs, wafer stacking, sub 65 nm CMOS
- FNAL-led (ARCADIA + SkyWater):
  - MAPS prototype testing, TCAD simulation, test structures, infrastructure upgrades

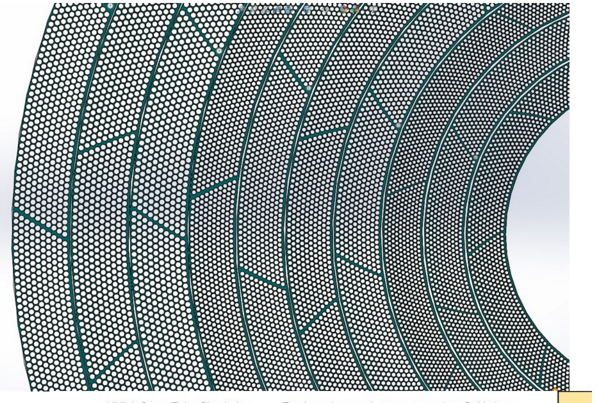





Gaseous Tracking

U.S. has deep, detailed expertise in drift chambers

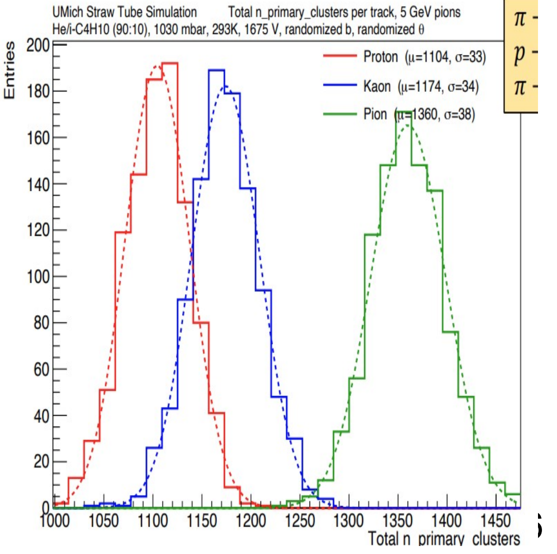
US Opp.

- CDF, DO, ATLAS and many other earlier experiments
- Open drift chamber design and jet chamber
- Muon detection systems provide synergy
- Carbonfiber wire – could further reduce material



U.S. is straw tube powerhouse

- Detailed knowledge about Straw tubes
- Study of gas mixtures very relevant in particular for particle Id
- Straw tubes are safe against wire snaps... remains just an isolated failure
- Material of the tubes reduces other performance



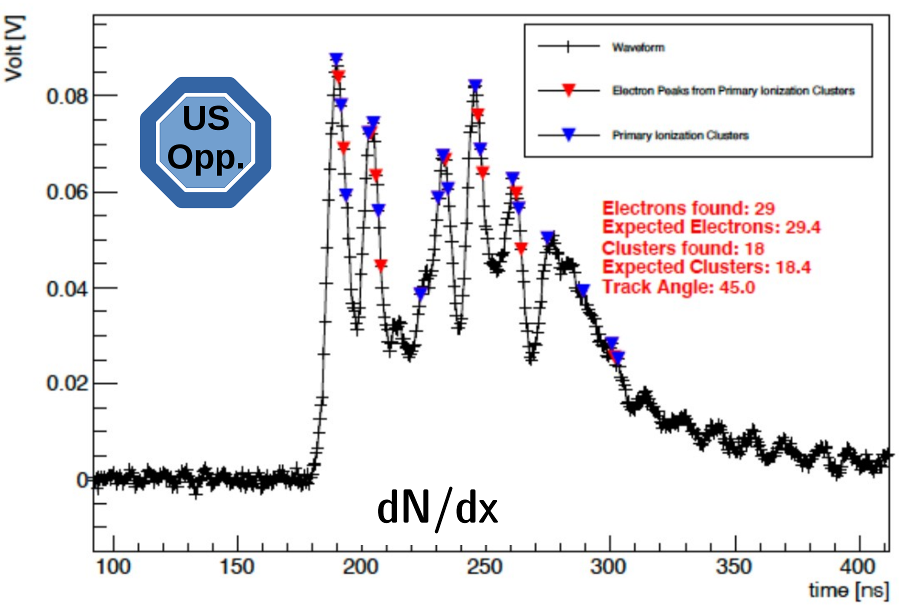
Particle ID

The fundamental requirement seems clear

- Drift chamber (dN/dx) combined with TOF (<100 ps @ r=2m, <30 ps @ r=0.35 m)
- ... or all silicon tracker + RICH and TOF at <100 ps
- Detailed simulations missing: ex. low momentum particles curl

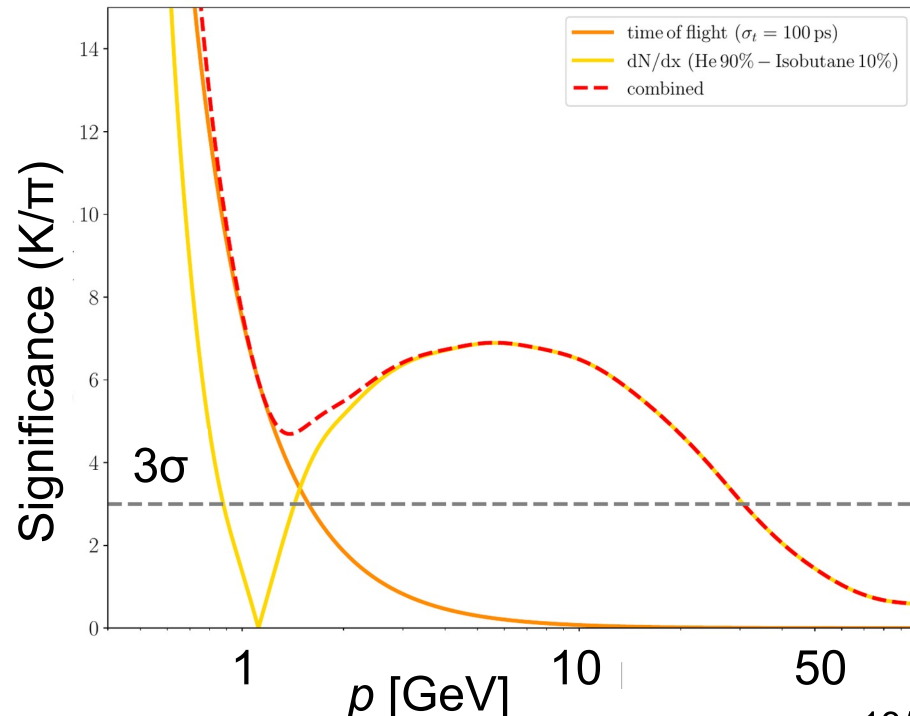
US Opp.

Sense Wire Diameter 15 μm; Cell Size 1.0 cm
Track Angle 45; Sampling rate 2 GSa/s
Gas Mixture He:IsoB 80/20



Project: dN/dx in analog electronics

Project: Study of gas mixtures essential

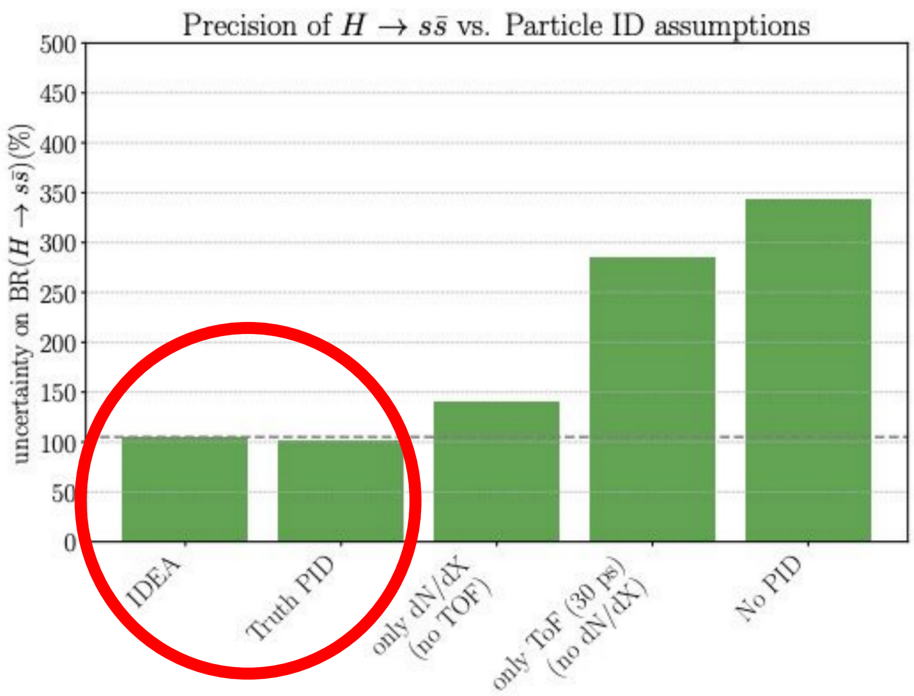


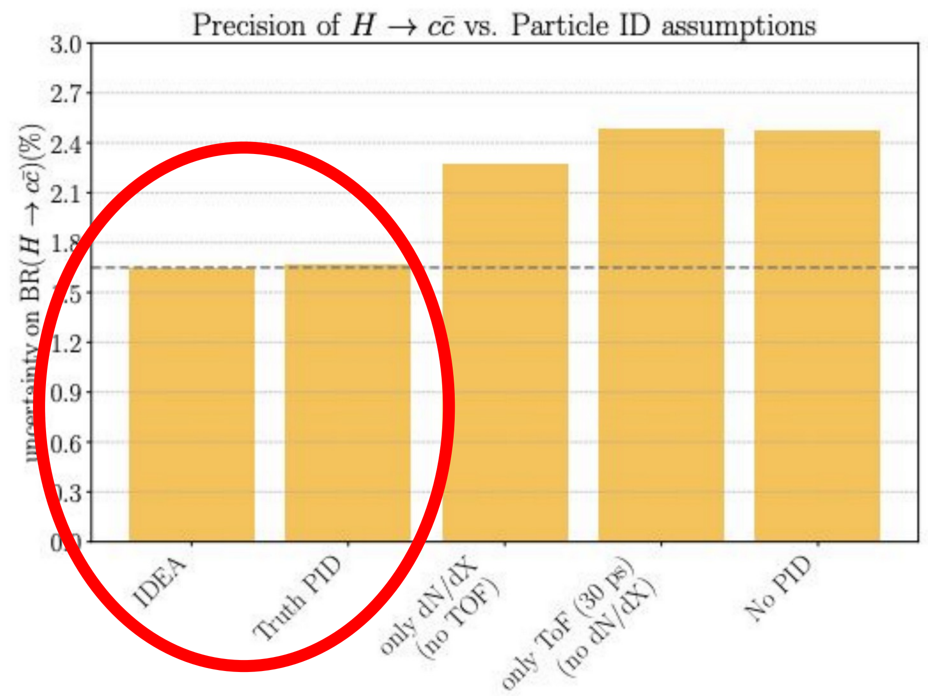
PiD challenge in theory 'solved'

Combination of known methods close to MC truth

- Version 1: Drift chamber (dN/dx) combined with <100 ps TOF
- Version 2: all silicon tracker + RICH and TOF at <100 ps
- Detailed simulations missing: ex. low momentum particles curl

US Opp.





In the plots dN/dx + TOF at 30 ps resolution was used

Mechanical Support/Cooling

U.S. institutes technological leaders in small/large composite support mechanics

Expertise in thermal interfaces, cooling aspects and novel materials

Support mechanics and/or cooling add significantly to the material budget

Work in context of RDC10 (US) and DRD8 (CERN)

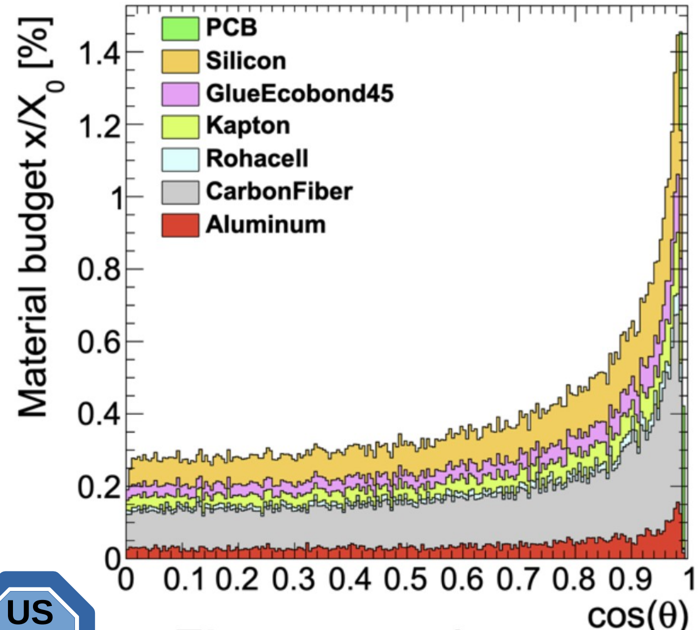
Three RDC10 WPs focusing on strength of US institutes

- RDC10-WP1: Detector cooling
- RDC10-WP2: Low-mass mechanics and thermal management
- RDC10-WP3: System Design, Integration, and Qualification tools

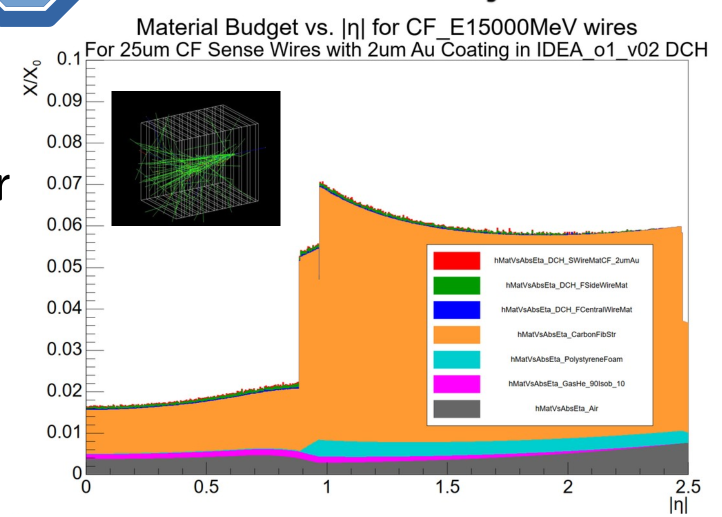
Carbon Fiber as active sensing for FCC Drift Chamber

- Saves factors of 5-8 in material, challenges: coating, tensioning, readout, etc.
- Simulation work, Delphes, Geant – wires are not consistently implemented in "official packages"

US Opp.



First vertex layer



Early tracker simulation is essential

Is the tracker safe to operate?

- Particle rates and occupancy in particular close to the beam are critical
- Standard e+e- collisions not sufficient, beam induced background (BIB) important
- Implementation of generators still being worked on, not fully matched to experiment, remember: LEP did not do this (lower instantaneous luminosity)

Overall tracking design

- Simulation is key to test many integrated tracking designs to find the best
- What tracker configuration is best, and which magnetic field to choose ...
- Accurate fast simulation (Delphes) essential for first impressions, iterative studies
- Full simulation required to confirm many important details

Weekly meetings in US on these topics

- Are you interested to join? Ask Jan Eysermans (jaeyserm@mit.edu) or Anja Beck (anbeck@mit.edu) to put you on the email list and join

US Opp.

Magnetic field discussion

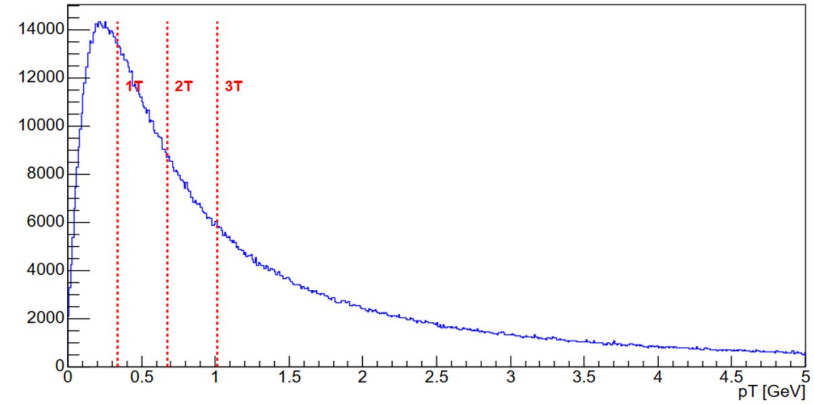
General considerations

- Detector magnetic field needs compensation to not perturb the accelerator magnets
- Larger magnetic fields B
  - Lower instantaneous luminosity (accelerator people are working on this)
  - Measured momenta more precise
- At 2 T tracks do not reach the outer tracker below $\sim$0.70 GeV
  - Is that a good thing? (1 T $\rightarrow$ $\sim$0.35 GeV, 3 T $\rightarrow$ $\sim$1.05 GeV)
  - Can we still measure those tracks precisely?
  - Do these tracks lead to higher energy depositions due to the ‘curling’ effect?
  - Is TOF measurement still possible? Second, inner layer of TOF?
- Do we need long barrel or short barrel and endcap (disks)?
- No systematic studies with full simulation exist
  - Lower magnetic field might be better for some physics cases involving jets

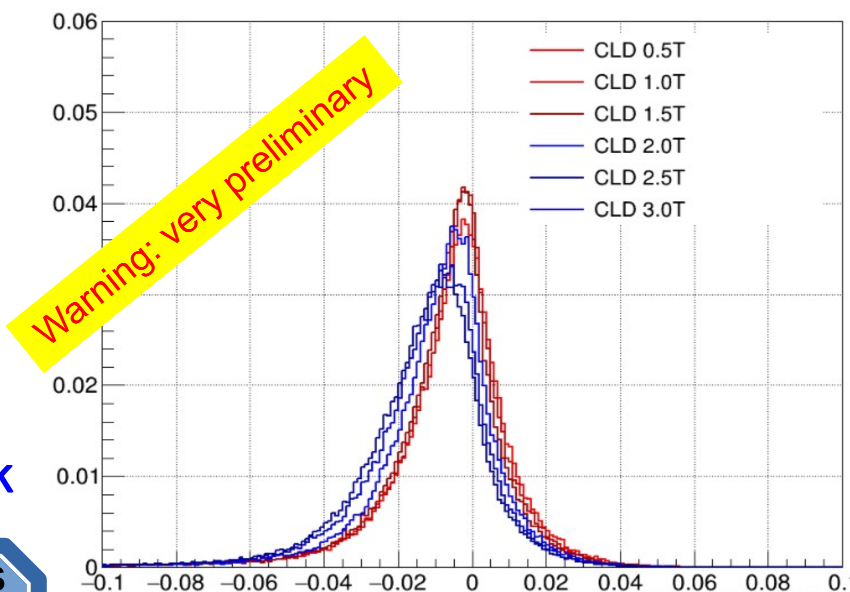
Magnetic field discussion

Some charge tracks will not reach the 'gaseous trackers' to measure momentum precisely

- Not an issue for dimuon events of course, but hadronic decays at all energy points will be affected, lost tracks are equivalent to an irreducible noise floor
- Hadronic decays are dominant and will be essential
- A full study is not trivial, because it needs to include a reasonably complete calibration process for hadronic decays
- Likely not an issue … but good to check in more detail



Hadronic Energy Resolution (qq) for CLD



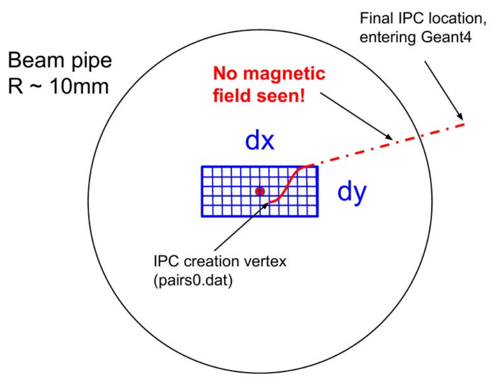
US Opp.

$(E_{measured} - E_{CMS}) / E_{CMS}$

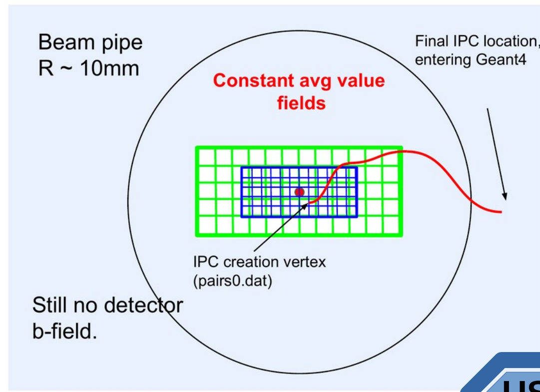
BIB: Guinea Pig simulates

How does Guinea Pig work?

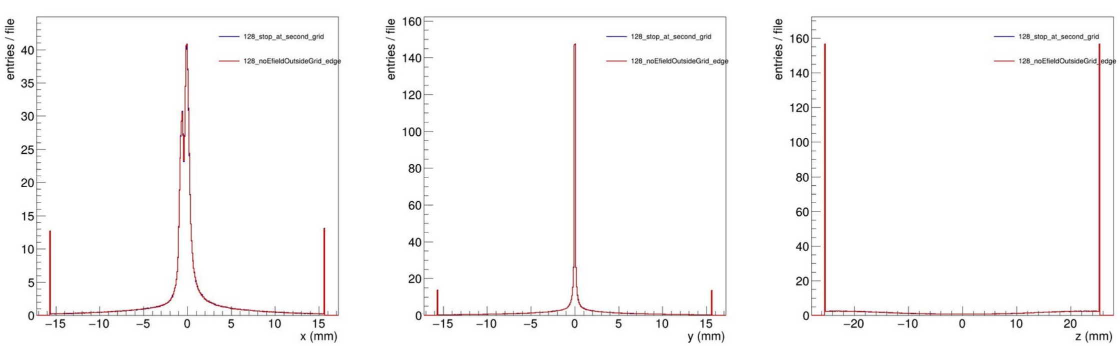
What we originally thought:



What we learned from experiment & Ciarma:



Results



Mapping these particles back and stopping them within Guinea Pig finally result in the same physics → We understand how Guinea Pig works.

BIB simulation

- ee, e-beam and beam-beam interactions → grid calculations needed
- Very different generator from all other MC
- Takes very long

Summer project

- Initially no detailed understanding of how this works …. now we do
- Main issues addressed and first samples available
- Available for all of FCC

Beyond summer

- Can we use WarpX? Faster!

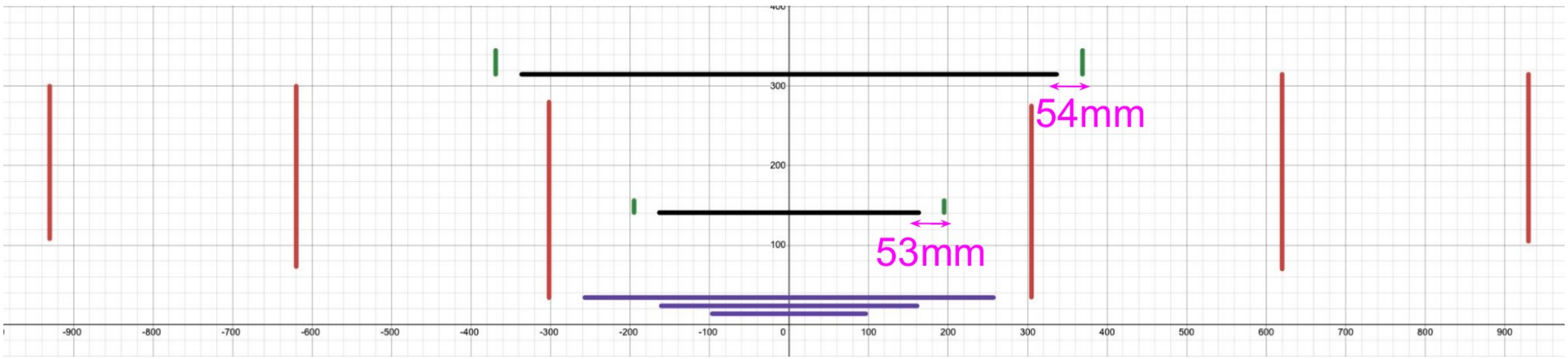
https://arxiv.org/abs/2405.09583

Tuning Delphes

Fast simulation (Delphes) work this summer

- Ideal for fast turnaround tracker design studies, including BIB
- ... but geometries need to be reasonably correct to arrive at correct conclusions
- Various geometries tested and major issues identified and corrected, implementation of active and passive material *etc.*
- This work is fed back to the FCC software base and available to everyone

IDEA_base25: Filler visualization



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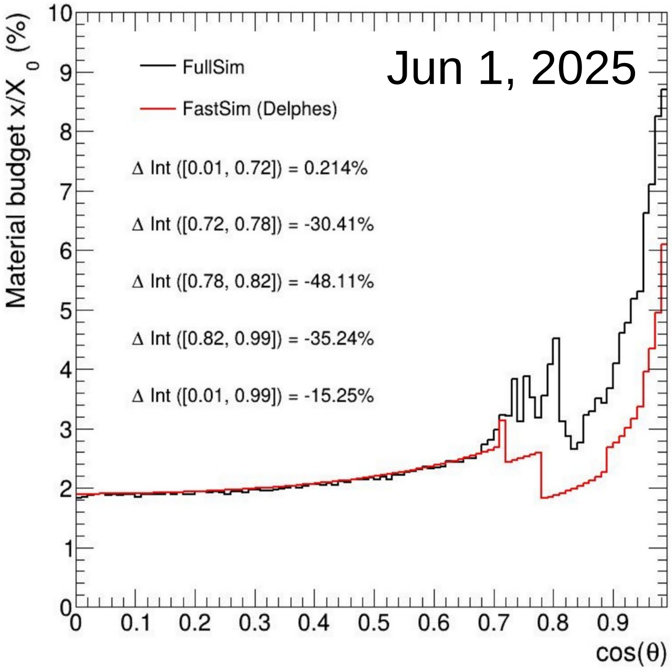

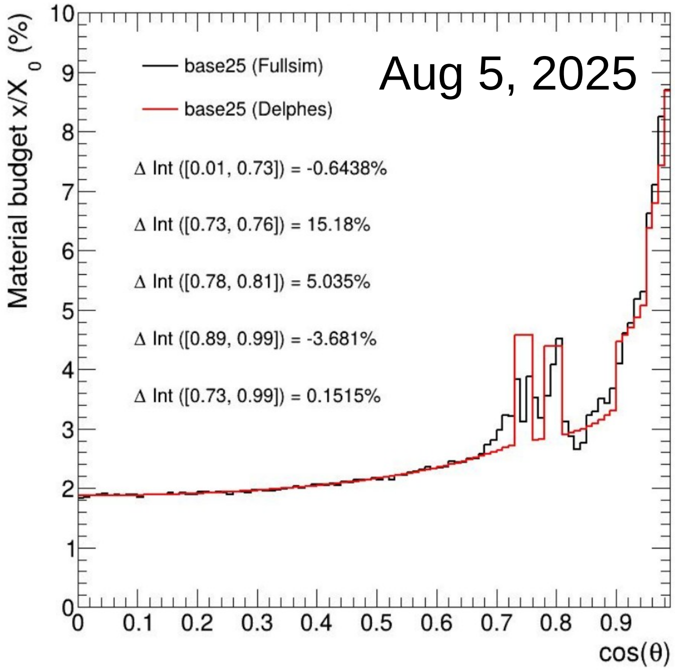

Our "To do" list

Forming a community

- Single efforts need to expand to multi institute collaborations
- Coherent and complete detector concepts need to emerge
- Need a series of follow-up meetings

Feasibility study submitted, questions remain

- Full Simulation study of most of everything
  - Particle ID: dN/dx and TOF and RICH
  - Can we do analog cluster counting (onboard)?
  - What gas mixtures will deliver best dN/dx at FCC conditions?
  - What is the cost of an inner precise wrapper for TOF, is it needed?
- Magnetic field: what is the right field for what period?
  - Loopers and their impact, endcap tracker design, ...

Conclusion

Tracker design should converge in ~5 years

- Lightweight Vertex, very likely MAPS
  - Do we want timing in vertex layer? Maybe inside beampipe like LHCb?
  - U.S. is running behind but has potential and lots of interest
  - Detailed simulation studies essential due to backgrounds
- Drift chamber à la CDF or Strawtube have strong cases
  - dN/dx essential for Particle ID, many detailed full simulation studies lined up
  - Do we know the right gas mixtures $\rightarrow$ key issue: synergy between drift, straws, muons
  - Can one build dN/dx in analog electronics to limit power? $\rightarrow$ studies started
  - IDEA drift chamber risky due to wire tangles, do we need a jet chamber proposal?
  - Pixel TPC at lower intensity is interesting, but unclear what advantage?
  - Straw tubes are a US strong hold, but more material
- RICH + all silicon: best multi-track resolution (taus?)
- Magnetic field question remains interesting
  - Detailed studies might reveal new conclusions on what is best
  - Competing effectys: luminosity vs tracking precision vs acceptance vs reproducibility
  - Z and WW phase and ZH and tt phase will have different requirements

Additional material

Questions

Tracking at different E_{cm}?

- Different physics at different E_{cm}?
- Should the magnetic field be the same? Lower E_{cm} $\rightarrow$ lower B?
- Can we do 3 T? Does it work for accelerator?
- Curlers: How useful are low momentum particles? Can they get in the way?

Tracking technologies, which ones to use?

- Silicon tracking for vertex is obvious and a must (?)
- Does all silicon make sense for the momentum measurement?
- Is densest environment (taus, jets) a challenge for gas trackers?
- Role of Tracking efficiency/purity in PF reconstruction, and flavor tagging?

Simulation versus reality, do we understand this well enough?

- Are we expecting any significant differences?
- What full simulation campaigns do we need?
- Is incoherent pair production nailed down and tied to reality?

Questions

Cost analysis and optimization

- Do we have a cost model for each detector type that is reliable?
- Can/should we perform a real optimization with fixed budget and requirements?

Particle Id: what momentum range do we need to cover and why?

- Core benchmarks are all on Fast simulation (Delphes), what are the key questions that need verification?
- Tracker Wrapper: TOF close and far?
- RICH for high momenta: what is the trade-off with removing lever arm for momentum measurements?