Summary of the FCC-ee Workshop on Tracking Detectors and Software

Christoph Paus, Carl Haber
May 20, 2025, FCC Week, Vienna

What was the point?

Context

- Feasibility study is in the books
- Projected FCC-ee start in 2040+, Proto-collaborations ~2028
- Planning for 4 detectors: LEP had 4, with different emphases
  - Too early to lock into any too specific design, a few more years of “blue skying”
  - ... but general design guidelines are important to tackle
- Funding is still very limited
- Some very relevant study cases: ALICE, ePIC …

Overall goal

- “… Discussions from the low-level readout architectures to addressing larger scale system integration issues with a goal of creating a workplan that helps to understand and quantify the design choices as a function of cost, performance and flexibility as well as study the advantage of specific design choices to physics. …” → **physics drives all designs**

Substantial agenda and robust discussions

Overview: The State of the Field — *Hucheng Chen*
Physics Large Seminar Room, Physics Building 510A — 08:30 - 10:15

Coffee Break
Physics Large Seminar Room, Physics Building 510A — 10:15 - 10:35

Overview: Brainstorming: Physics Driven Tracker Concepts — *Christoph Paus*
Physics Large Seminar Room, Physics Building 510A — 10:35 - 12:30

Lunch (provided by host)
Physics Large Seminar Room, Physics Building 510A — 12:30 - 13:30

Session:: Constraints from MDI — *Manuela Boscolo*
Physics Large Seminar Room, Physics Building 510A — 13:30 - 14:50

Coffee
Physics Large Seminar Room, Physics Building 510A — 14:50 - 15:10

Session:: Semiconductor Tracker 1 — *Didier Claude Contardo*
Physics Large Seminar Room, Physics Building 510A — 15:10 - 18:00

Session:: Semiconductor Tracker 2 — *Fabrizio Palla, Fabrizio Palla*
Physics Large Seminar Room, Physics Building 510A — 08:30 - 10:10

Coffee
Physics Large Seminar Room, Physics Building 510A — 10:10 - 10:30

Session:: Gaseous Tracker — *George Iakovidis, Mogens Dam*
Physics Large Seminar Room, Physics Building 510A — 10:30 - 12:30

Lunch (provided by host)
Physics Large Seminar Room, Physics Building 510A — 12:30 - 13:30

Session:: Mechanics and Services — *Carl Haber*
Physics Large Seminar Room, Physics Building 510A — 13:30 - 15:30

Coffee
Physics Large Seminar Room, Physics Building 510A — 15:30 - 15:50

Session:: Brainstorming: Integrated Tracker Designs — *Charlie Young*
Physics Large Seminar Room, Physics Building 510A — 15:50 - 18:00

Session:: Simulation — *Brieuc Francois, Michele Selvaggi*
Physics Large Seminar Room, Physics Building 510A — 08:05 - 10:20

Coffee
Physics Large Seminar Room, Physics Building 510A — 10:20 - 10:40

Session:: Reconstruction — *Brieuc Francois, Michele Selvaggi*
Physics Large Seminar Room, Physics Building 510A — 10:40 - 13:00

Lunch (on your own)
Physics Large Seminar Room, Physics Building 510A — 13:00 - 14:00

Planning — *Carl Haber, Christoph Paus*
Physics Large Seminar Room, Physics Building 510A — 14:00 - 15:30

End of Workshop
Physics Large Seminar Room, Physics Building 510A — 15:30 - 15:50

Conclusions
here

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Overview: The State of the Field — *Hucheng Chen*

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Session:: Simulation — *Brieuc Francois, Michele Selvaggi*

The workshop was smaller but very good to have discussions with everybody in the room and participating. Nothing entirely new emerged but **communication about what we know and think was very positive and has sharpened our minds and goals**.

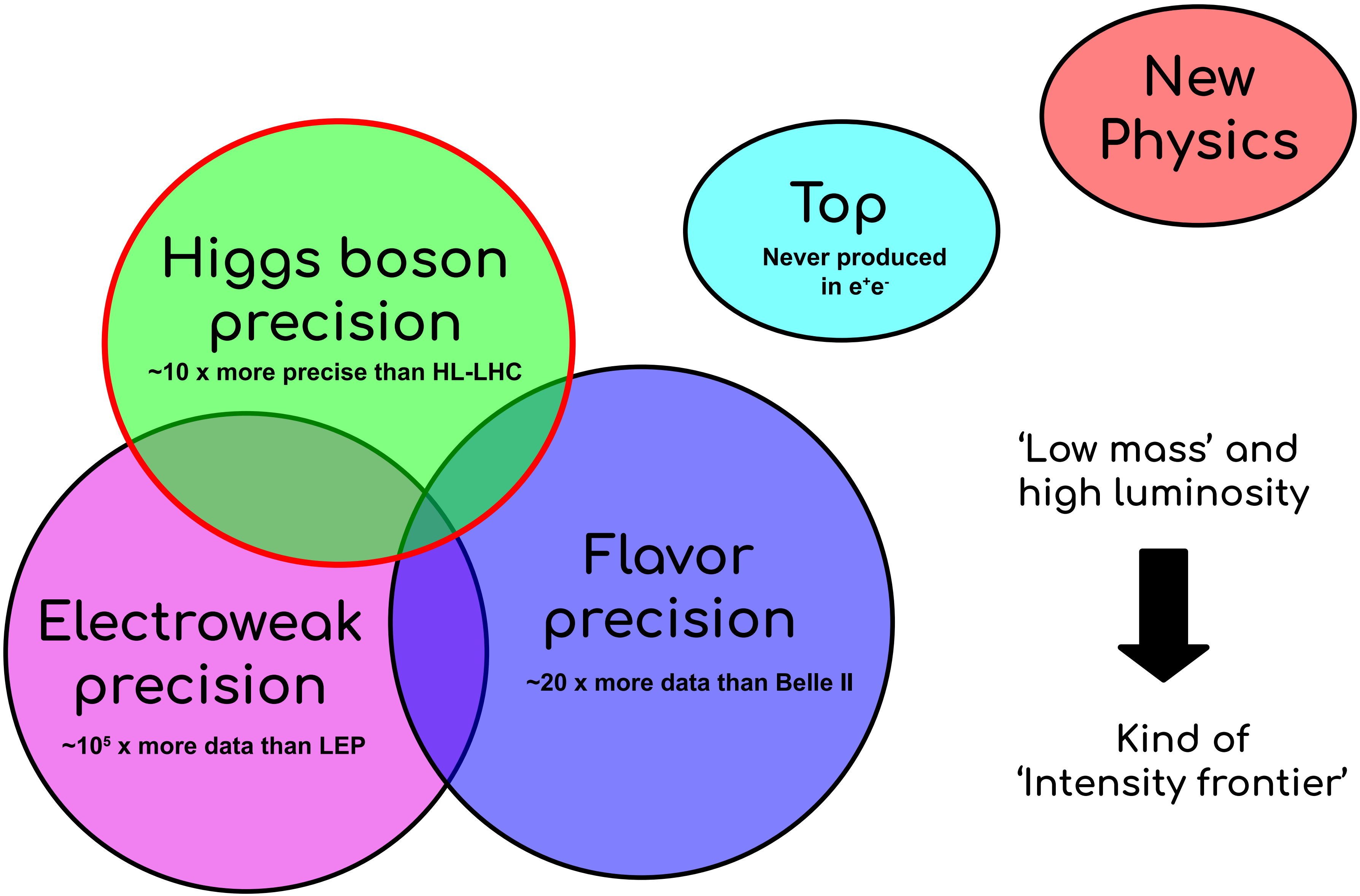
Hopefully the beginning of a community discussion of a coherent effort.

Conclusions here

Physics Large Seminar Room, Physics Building 510A 15:10 - 18:00

Physics Large Seminar Room, Physics Building 510A 15:50 - 18:00

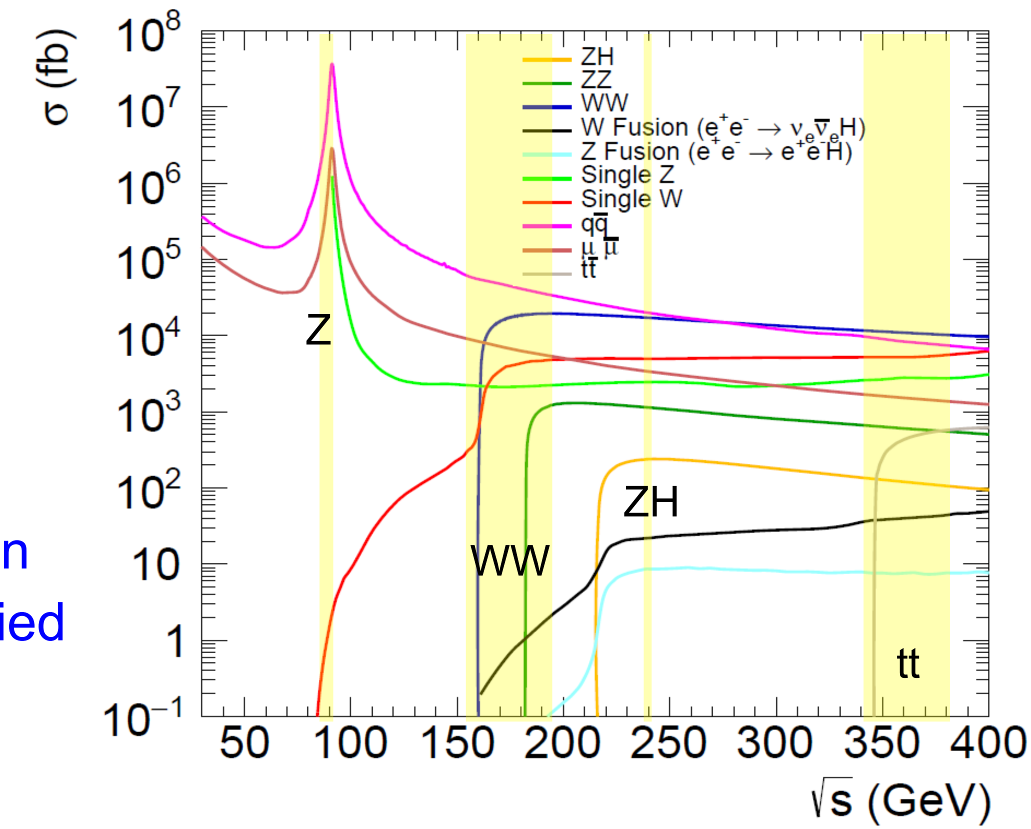
Physics Goals of the FCC-ee



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: $1/\text{sqrt}(10^{12}) = 10^{-6}$
  - WW: $1/\text{sqrt}(10^{8}) = 10^{-4}$
  - ZH/tt: $1/\text{sqrt}(10^{6}) = 10^{-3}$
- O(10^6) Higgs bosons, ultra clean
- Top quark has never been studied at 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} cm^{-2}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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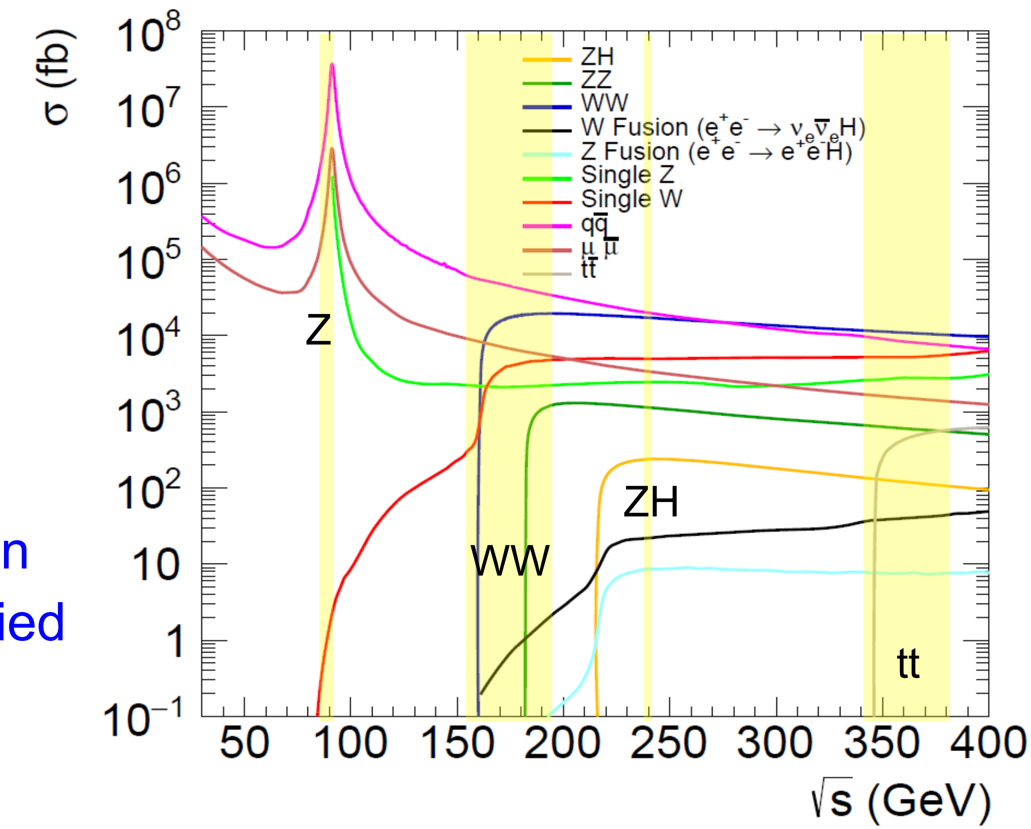

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Lower momentum, high intensity

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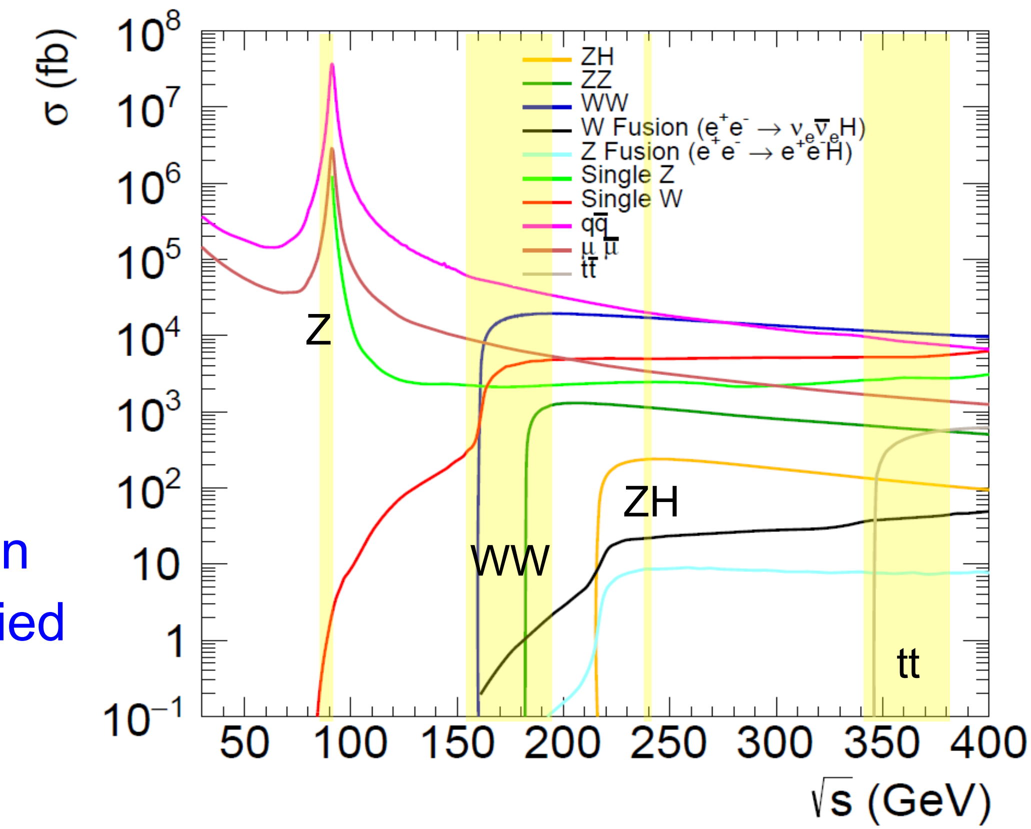

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higher momentum, low intensity

Requirements

Taken from Feasibility Study report (Vol. 1)

- Vertex
  - FSR: $H_{bb/cc}$, Flavor: $B \rightarrow K^*$ tau tau, R_b, R_c with exclusive decay, 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 $B \rightarrow K^*\nu\nu$, $B_s \rightarrow \nu\nu$, $B_s \rightarrow D_s K$, V_{ts} ...

LEP Trackers

History is good to study

- ALEPH: reasonably new technologies, homogeneous detector, granularity more than energy resolution.
- DELPHI: very new technologies, larger variety of techniques
- L3: measure leptons (and photons) with high 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**

Tracker Options

Wide range of E_{CM} and number of events

- Build just one tracker? 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 rs	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	Promising
TOF	30-100 ps		–	all	OK
RICH	Higher momenta		–	all	difficult, material?

Magnetic Field

General considerations

- Detector magnetic field needs to compensated to not perturb the accelerator magnets
- Larger magnetic fields lead to lower instantaneous luminosity
- Larger magnetic fields make momentum more precise
- At 2 T tracks do not reach the outer tracker below ~0.70 GeV
  - Is that a good thing? (1 T → ~0.35 GeV, 3T → ~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

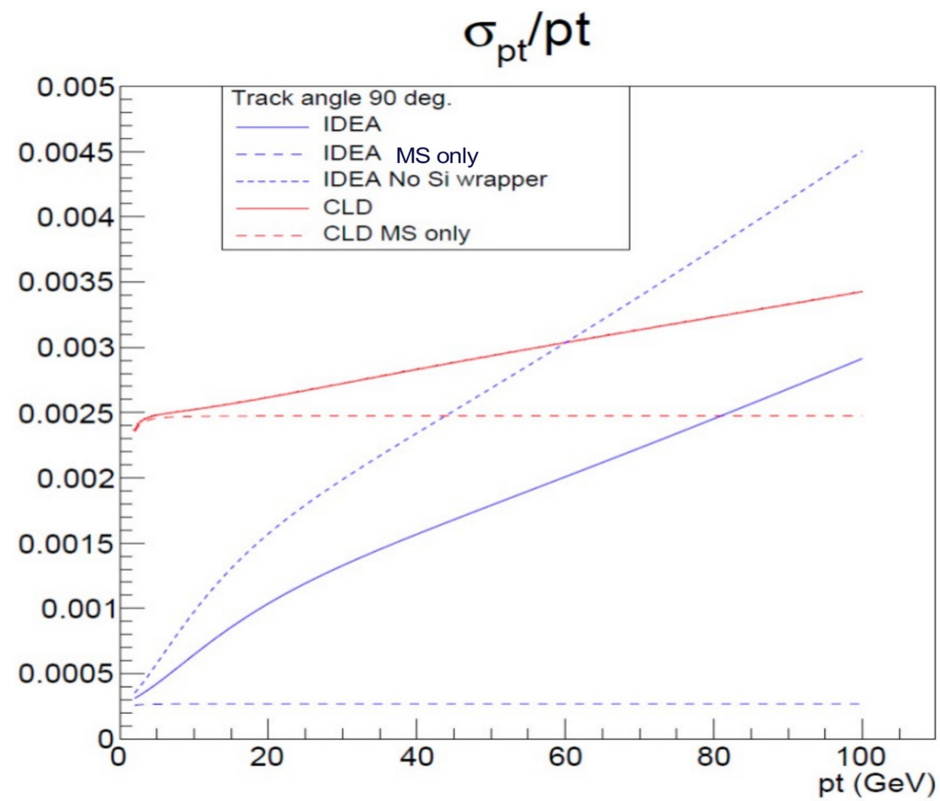
Resolutions and beyond

Asymptotic resolution

- Not the driver due to lower particle momentum

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 condition is crucial for simulation



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

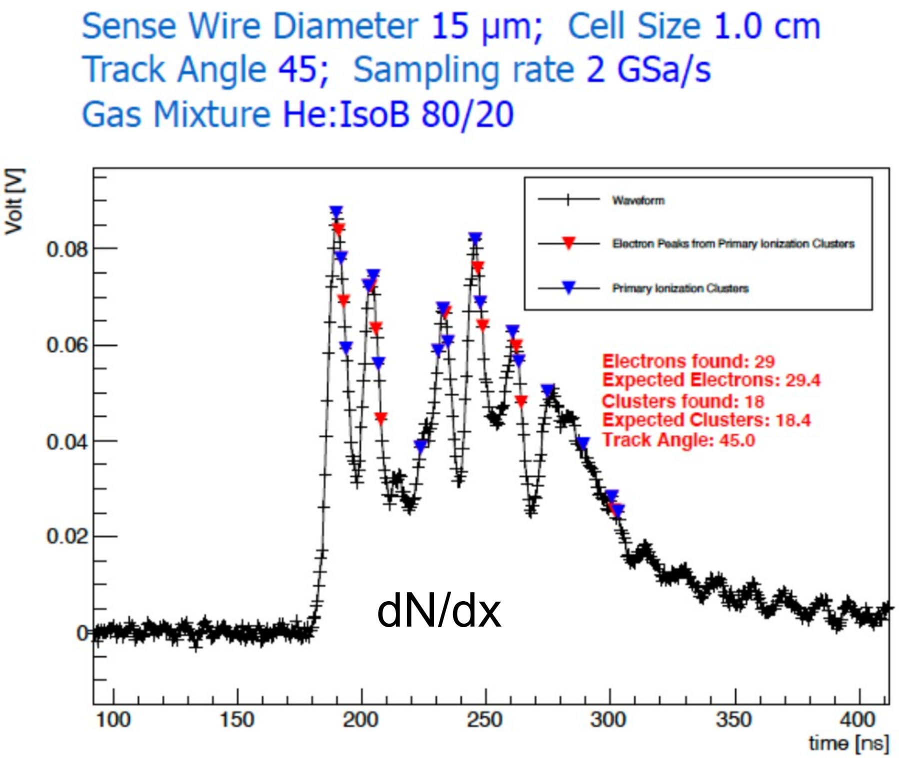
$\sigma_{r\phi}$ is the hit resolution

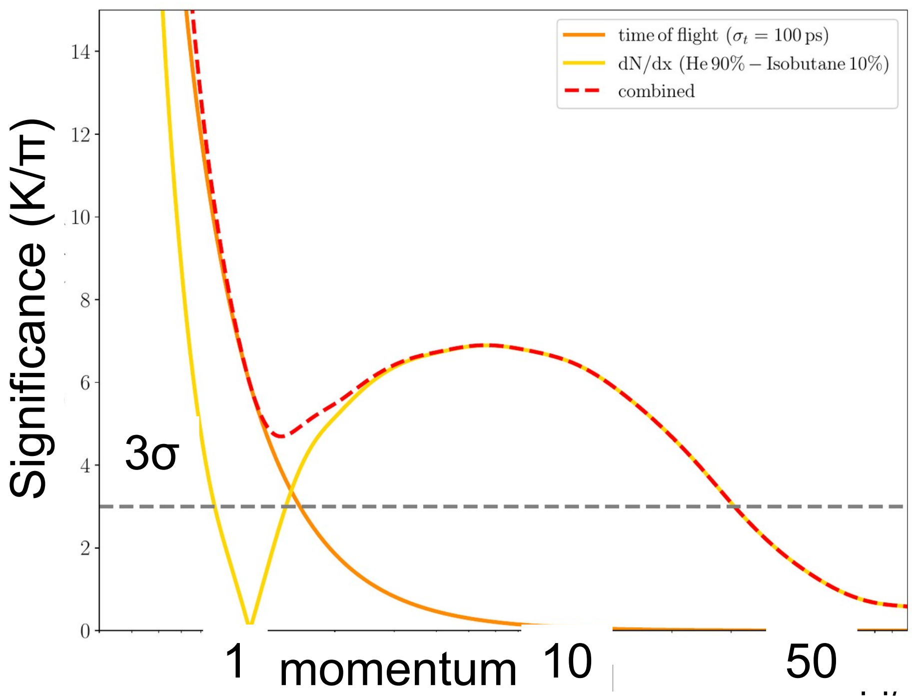
d_{tot} is the total thickness

Particle ID

The challenge is resolved ...

- Drift chamber (dN/dx) combined with ~100 ps TOF (10-30 ps at 0.35 m)
- … or all silicon tracker + RICH and TOF at ~100 ps
- Detailed simulations missing: ex. low momentum particles curl





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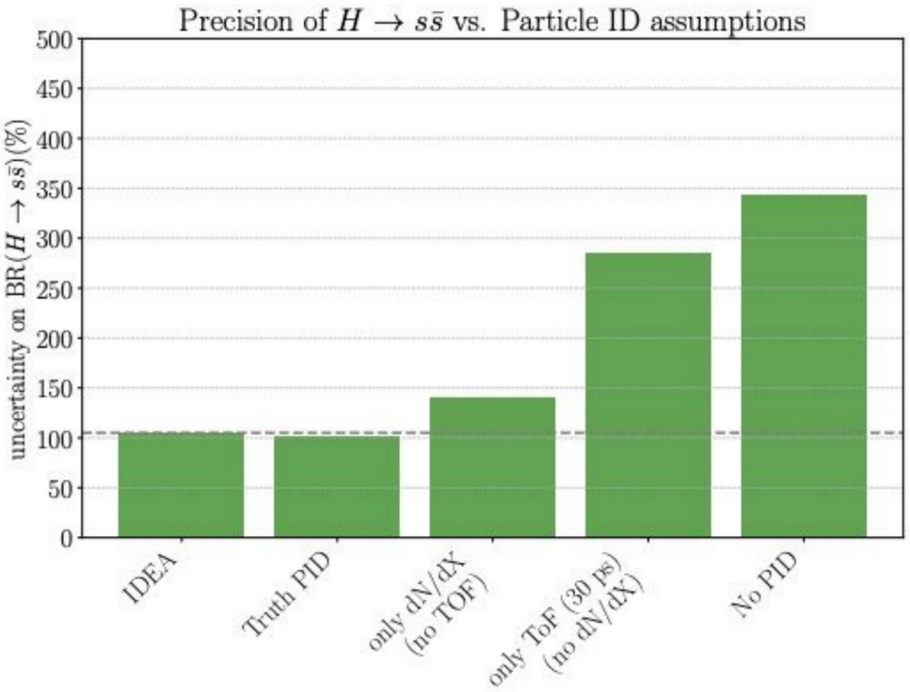

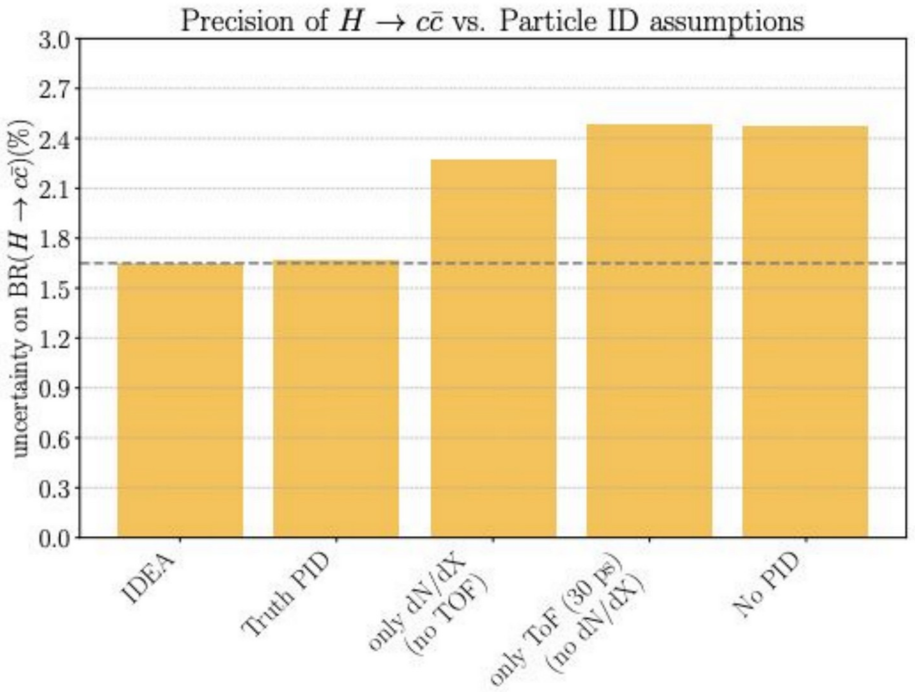

Our "To do" list

Forming a community

- Meeting has shown
  - Integrated tracker has various pieces that have to fit together
  - Community is for now working mostly on isolated topics
- 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
- 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

- Vertex as lightweight is clear (very likely MAPS)
  - Do we want timing in vertex layer?
  - Maybe inside beampipe like LHCb?
- Drift chamber à la CDF or Strawtube have strong case
  - dN/dx essential for Particle ID, many detailed full sim. studies lined up
  - Can one build dN/dx in analog electronics to limit power?
  - IDEA drift chamber is risky due to wire tangles, even if it is lowest mass
  - Pixel TPC at lower intensity is interesting, but unclear what advantage?
- RICH + all silicon: best multi-track resolution (taus?)
- Magnetic field question remains open
  - Detailed studies might reveal new conclusions on what is best
  - Competing effects: luminosity versus tracking precision versus acceptance
  - Z and WW phase and ZH and tt phase might have different requirements

Questions

Tracking at different E_{cm}?

- Different physics at different E_{cm}?
- Should the magnetic field be the same? Lower E_{cm} → 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?
- TOF close and far?
- RICH for high momenta: what is the trade-off with removing lever arm for momentum measurements?