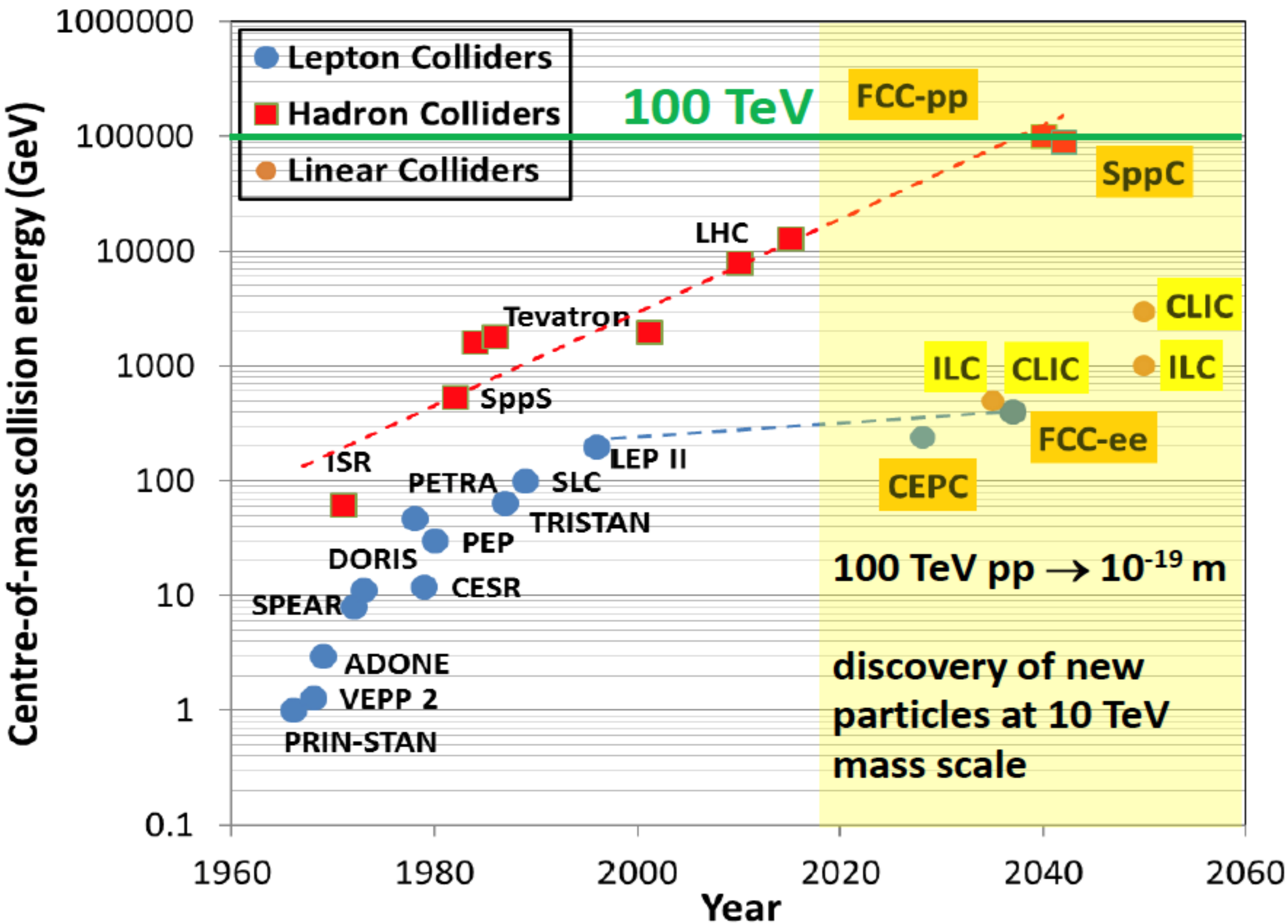
LLP at future colliders

- Overview experimental perspective -

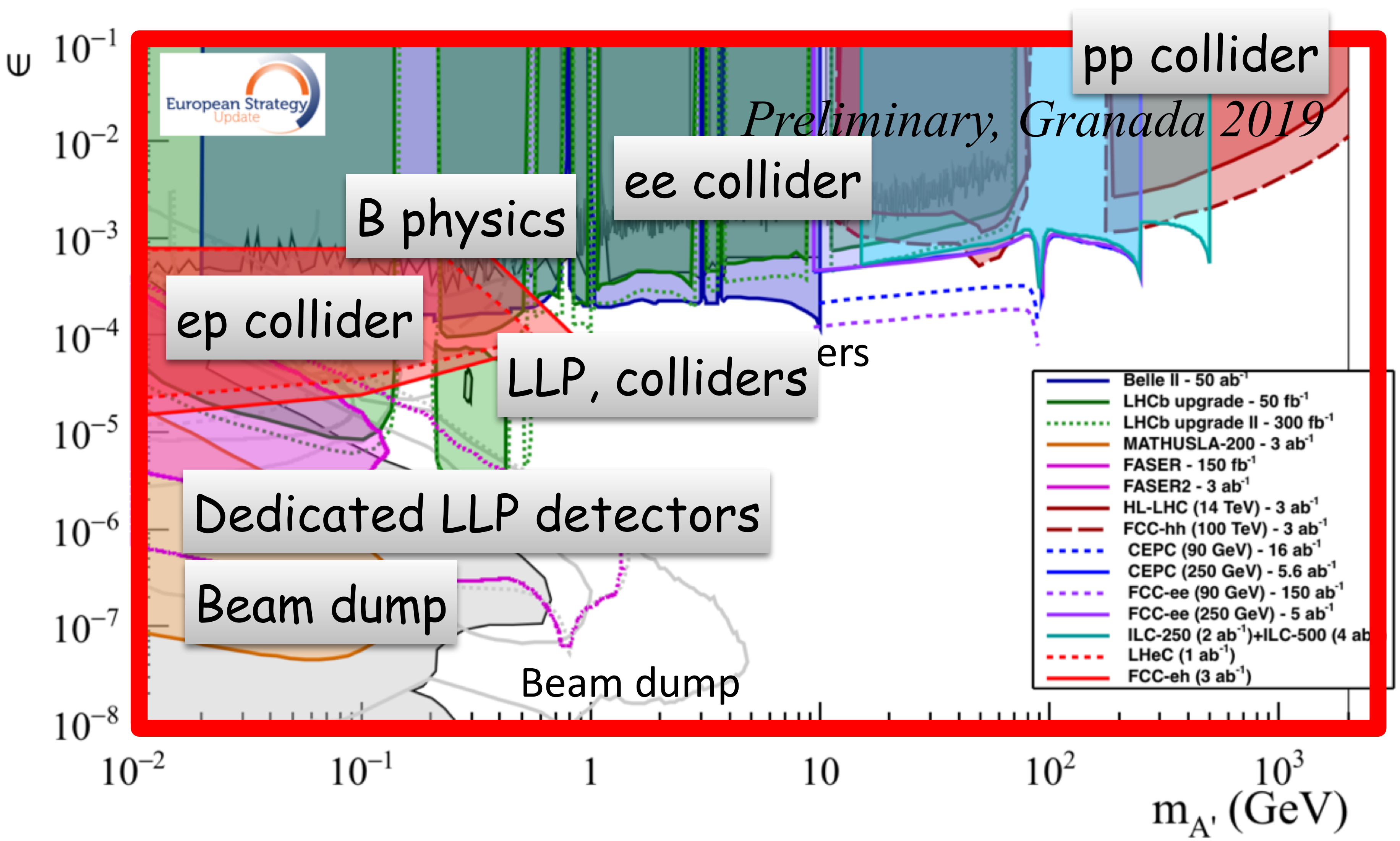
Ryu Sawada
ICEPP, the University of Tokyo
18. Nov. 2020
8th workshop of the LHC LLP community

Future colliders



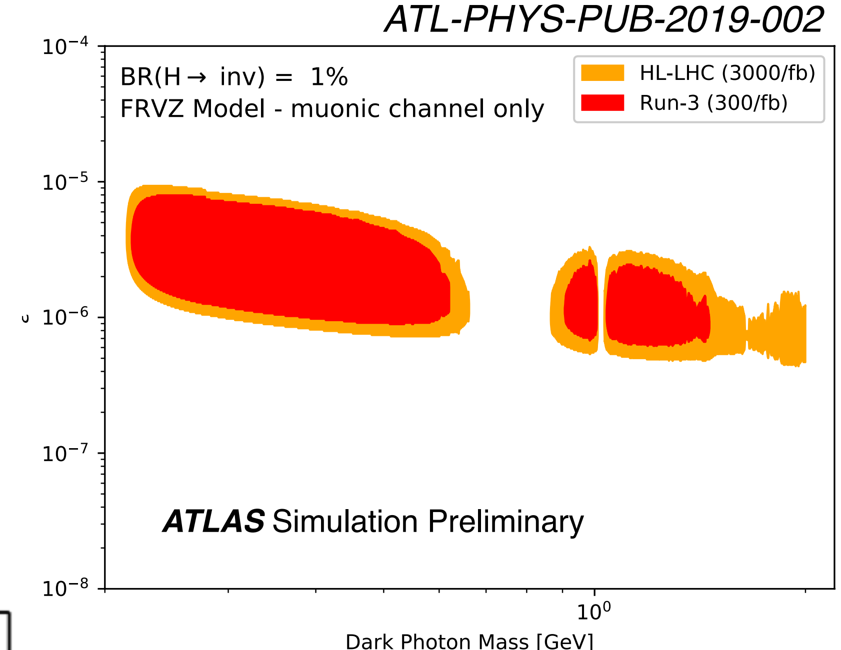
Michael Benedikt, Particle Colliders, 2019

Complementarity:
e.g. dark photon



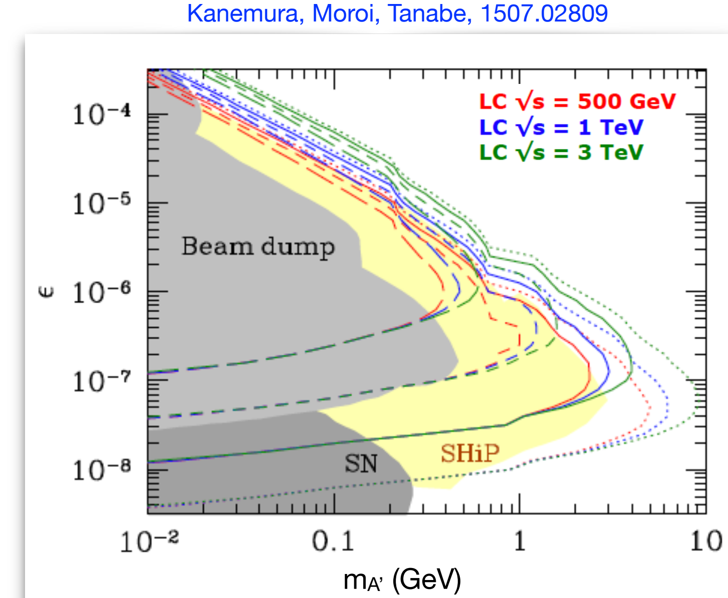
ATLAS upgrade
Displaced muon jets

ATL-PHYS-PUB-2019-002



ILC beam dump

Kanemura, Moroi, Tanabe, 1507.02809



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Gaia Lanfranchi, Granada, 2019

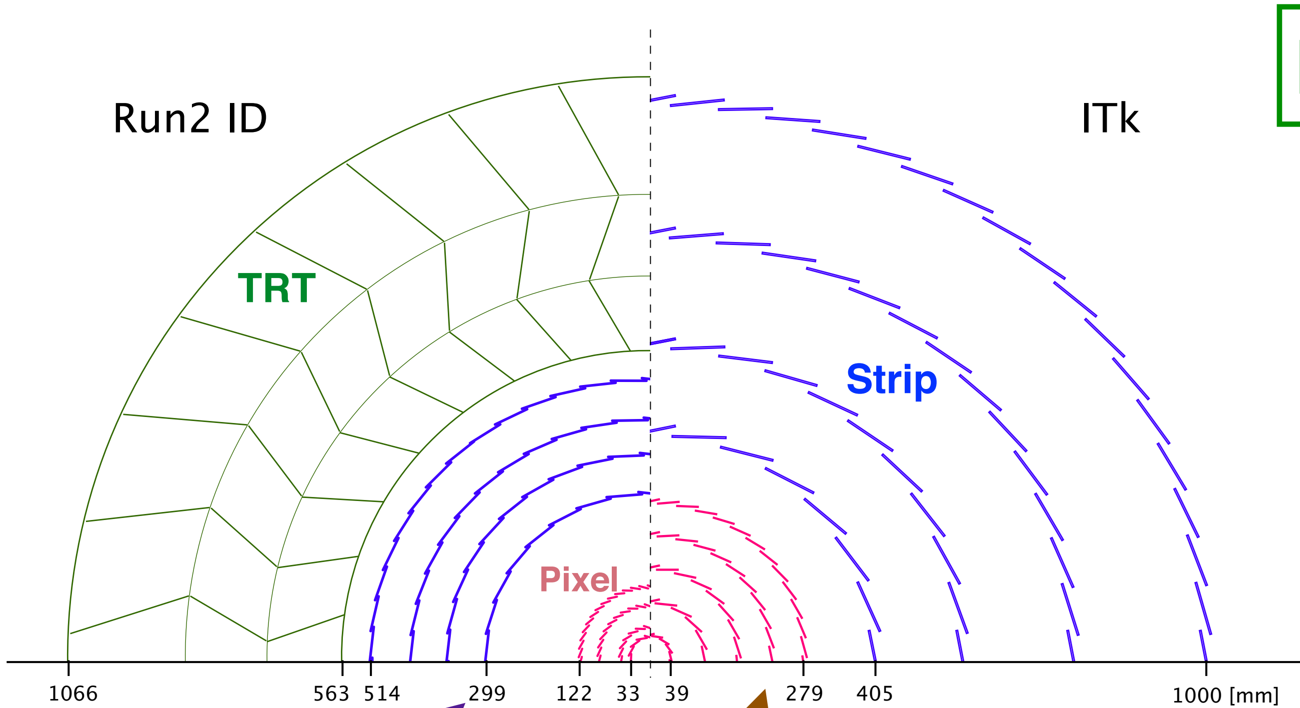
HL-LHC

- Upgrade of the detector and 10× integrated luminosity will give large gain in LLP searches.
  - Higher geometrical acceptance
  - Higher granularity/resolutions of the detector
  - Improved trigger, including tracking
  - Timing detectors

Many results have been presented in this series of workshops

- But there are some negative impact too.
  - High pileup late may increase the BG rate and/or decrease the signal efficiency.
  - For saving CPU and storage, some objects could be dropped (e.g. low-pT tracks?)
  - New detector layout may not be the best for some analyses.

HL-LHC: Tracker layout (ATLAS)

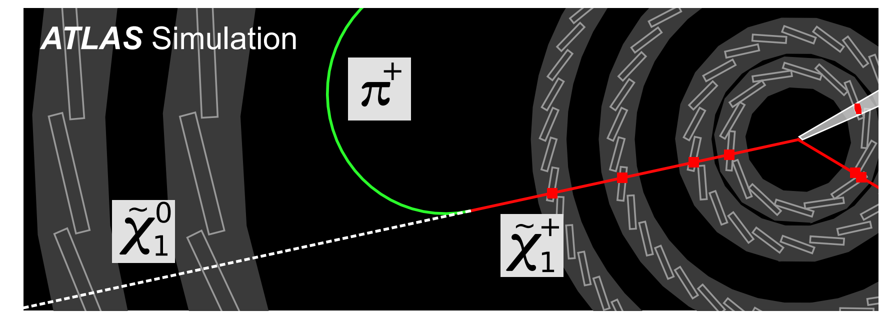


N-4th layer (30 cm)

4th layer (12 → 22 cm)

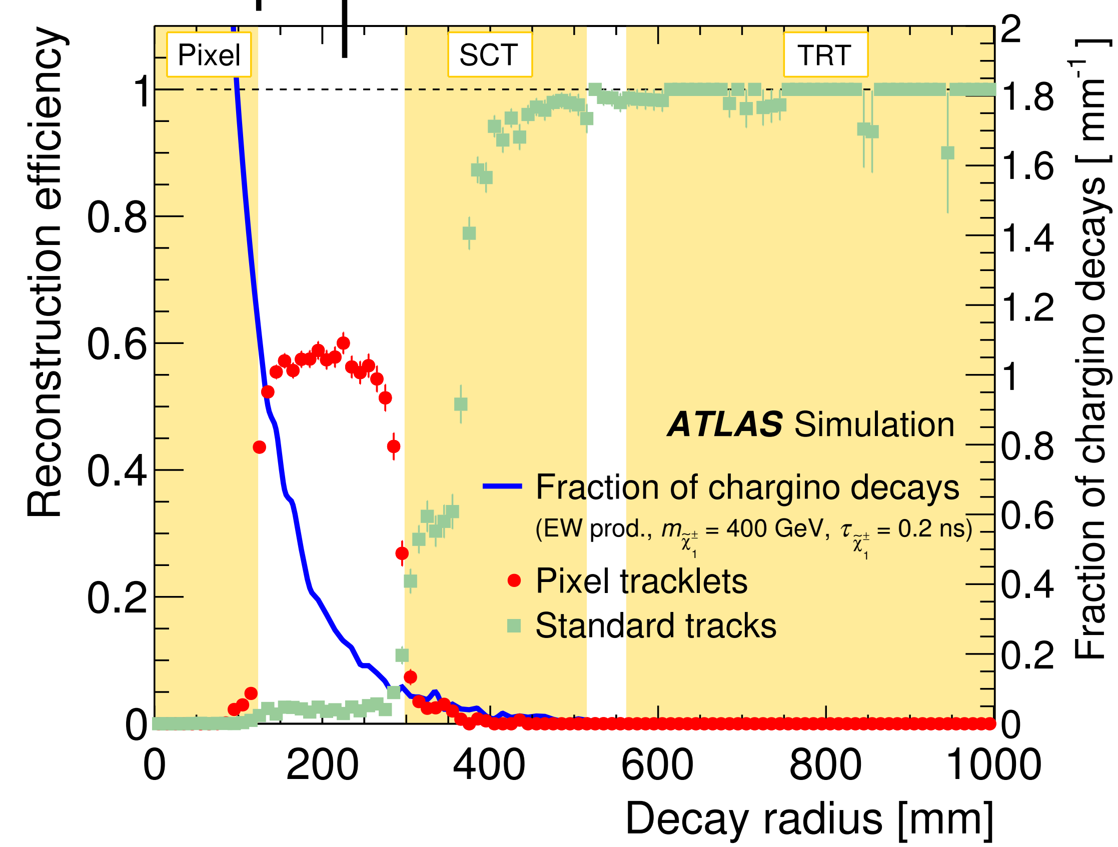
N-4th layer (40 cm)

Disappearing track



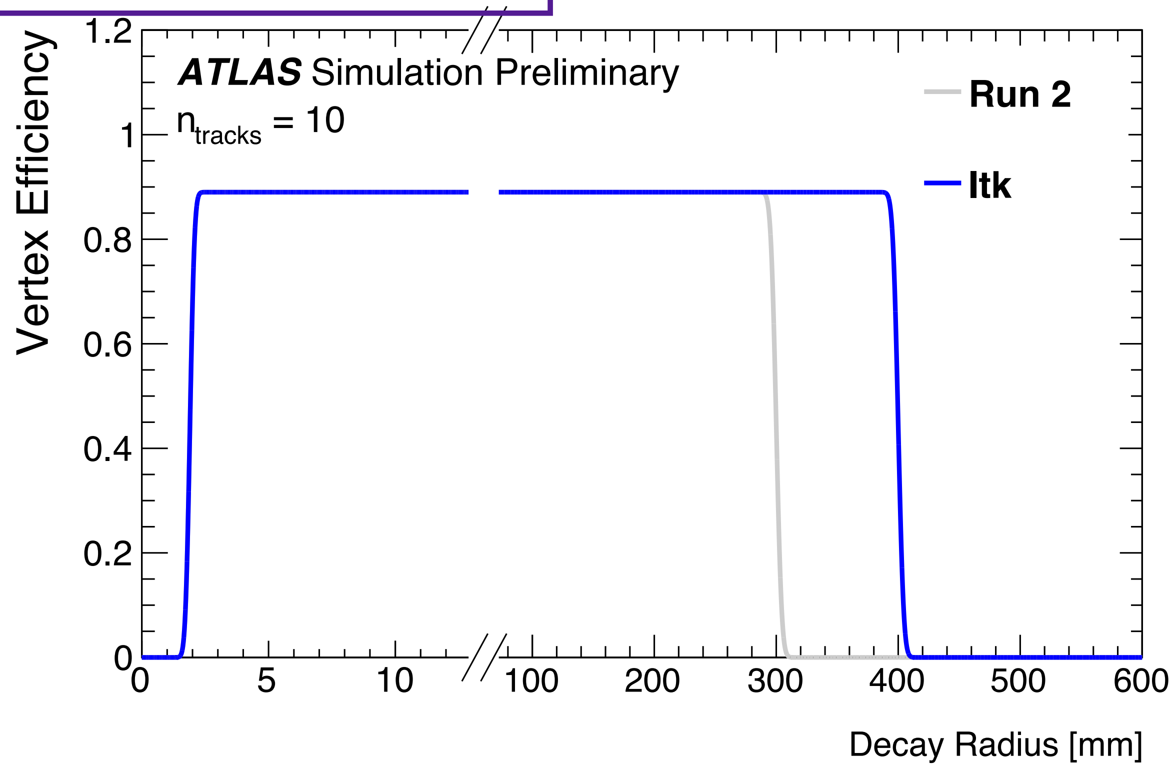
Run2

HL-LHC acceptance

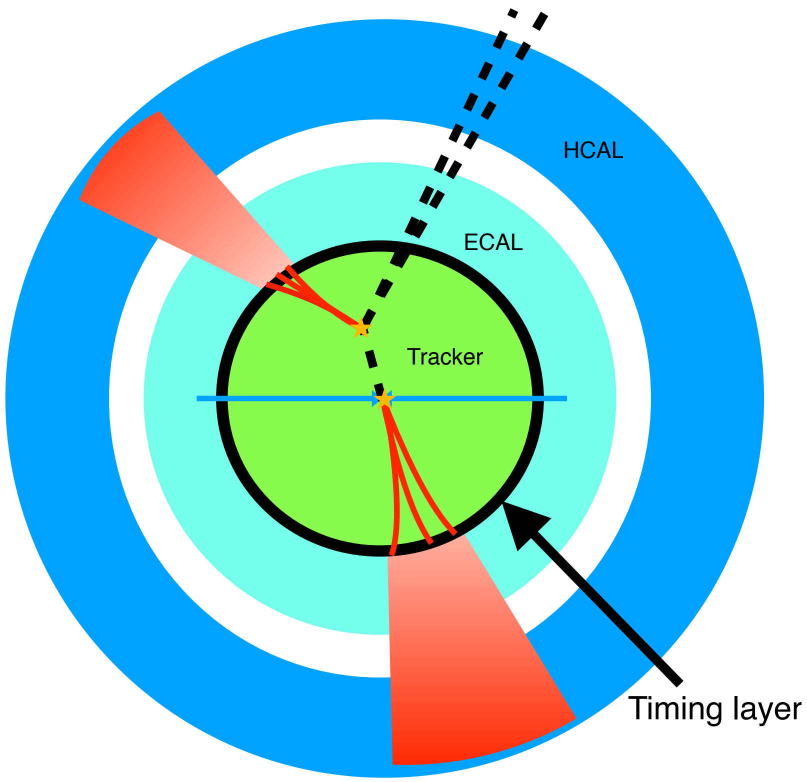


JHEP06(2018)022

Displaced vertex



Timing information @ HL-LHC



$$\boldsymbol{\beta}_{LLP} = \frac{\Delta \boldsymbol{r}_{LLP}}{\Delta t_{\rm ToF}}$$

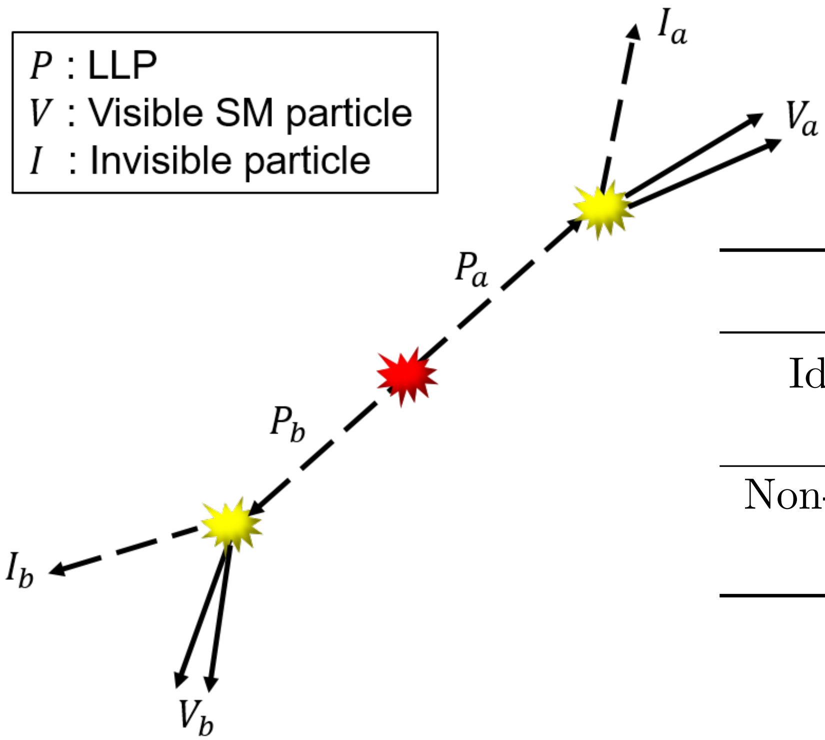
$$\begin{aligned} \boldsymbol{p}^{\rm lab}_{LLP,T} &= \boldsymbol{p}^{\rm lab}_{I,T} + \boldsymbol{p}^{\rm lab}_{V,T} \\ &= E^{\rm lab}_{LLP} \boldsymbol{\beta}^{\rm lab}_{LLP,T} \end{aligned}$$

$$\Rightarrow E^{\rm lab}_{LLP} = \frac{\boldsymbol{\beta}^{\rm lab}_{LLP,T} \cdot \left(\boldsymbol{p}^{\rm lab}_{I,T} + \boldsymbol{p}^{\rm lab}_{V,T}\right)}{|\boldsymbol{\beta}^{\rm lab}_{LLP,T}|^2}$$

$$\boxed{m_{LLP}} = \left(\gamma^{\rm lab}_{LLP}\right)^{-1} E^{\rm lab}_{LLP}$$

$$= \frac{\sqrt{1 - \left(\boldsymbol{\beta}^{\rm lab}_{LLP}\right)^2}}{|\boldsymbol{\beta}^{\rm lab}_{LLP,T}|^2} \boldsymbol{\beta}^{\rm lab}_{LLP,T} \cdot \left(\boldsymbol{p}^{\rm lab}_{I,T} + \boldsymbol{p}^{\rm lab}_{V,T}\right)$$

$$\boxed{m_I} = \sqrt{m^2_{LLP} - 2 m_{LLP} E^{LLP}_V + m^2_V}$$

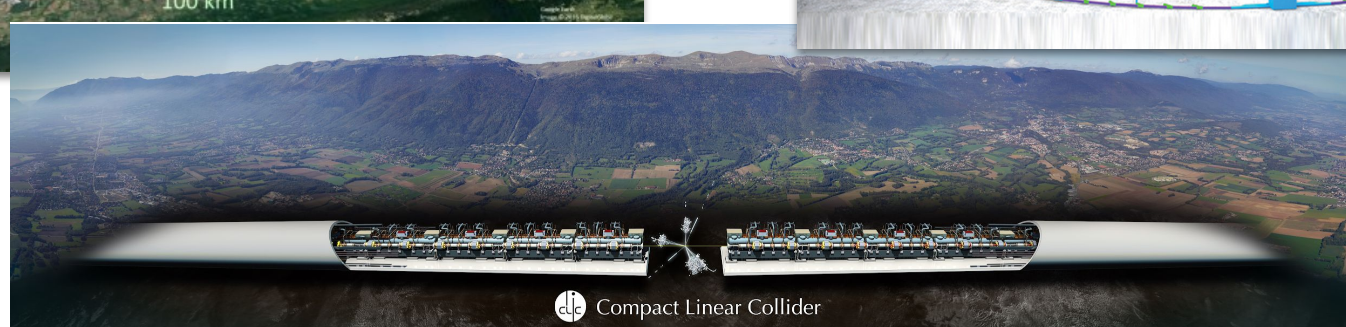


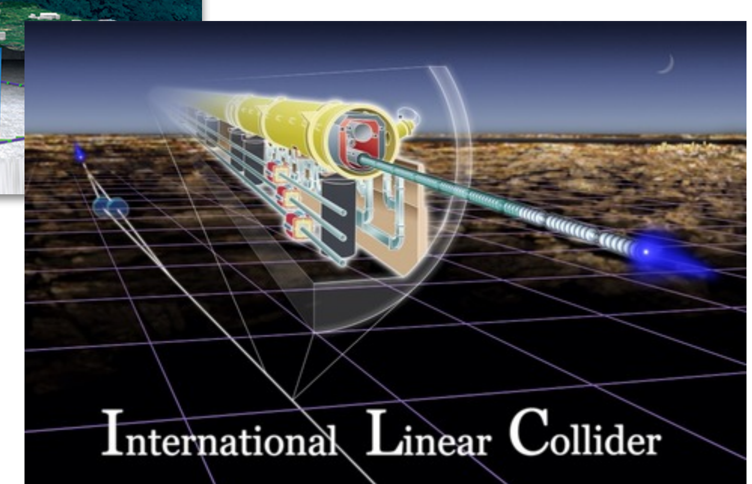
		m_{LLP_a}	m_{LLP_b}	m_{I_a}	m_{I_b}	$\boldsymbol{p}_{LLP_a}$	$\boldsymbol{p}_{LLP_b}$	$\boldsymbol{p}_{I_a}$	$\boldsymbol{p}_{I_b}$
Identical LLPs	w/o timing	△	△	△	△	○	○	○	○
	timing	○	○	○	○	○	○	○	○
Non-identical LLPs	w/o timing	×	×	×	×	○	○	○	○
	timing	○	○	○	○	○	○	○	○

arXiv:1903.05825

Lepton collider

- "***An electron-positron Higgs factory is the highest-priority next collier***" - European strategy
  - (Not so heavy) LLP searches from Higgs decays are natural candidates of the next field to explore.
  - Much cleaner environment than ones in a hadron-machine.
  - Fine-segmented particle-flow oriented detector design.
  - Data and processing-time may not be a big concern (compared to a hadron-machine).
    - More complex trigger- and offline-reconstruction algorithms, which require more CPU and output data, could be used.





Lepton collider: detector performance

	LHC	ILC
Innermost vertex layer to IP	**3.3** cm	**1.4** cm
Layer 4 radius	**12** cm	**4.8** cm
Inner-most pixel size	**50 × 250** μm	**20 × 20** μm
Material in tracker (central)	**0.4–0.5** X_0	~ **0.10–0.15** X_0
$1/p_T$ reresolution	**34 × 10^{-5}** / GeV	**5 × 10^{-5}** / GeV
Impact parameter resolution	**~20** μm	**~5** μm
Low pT tracking	pT > **~0.5** GeV are kept	Efficient down **0.2** GeV
EM calo number of channels	**76k**	**100M**

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LLP from Higgs decays

arXiv:1812.05588

$$Z \to \ell\bar{\ell}$$

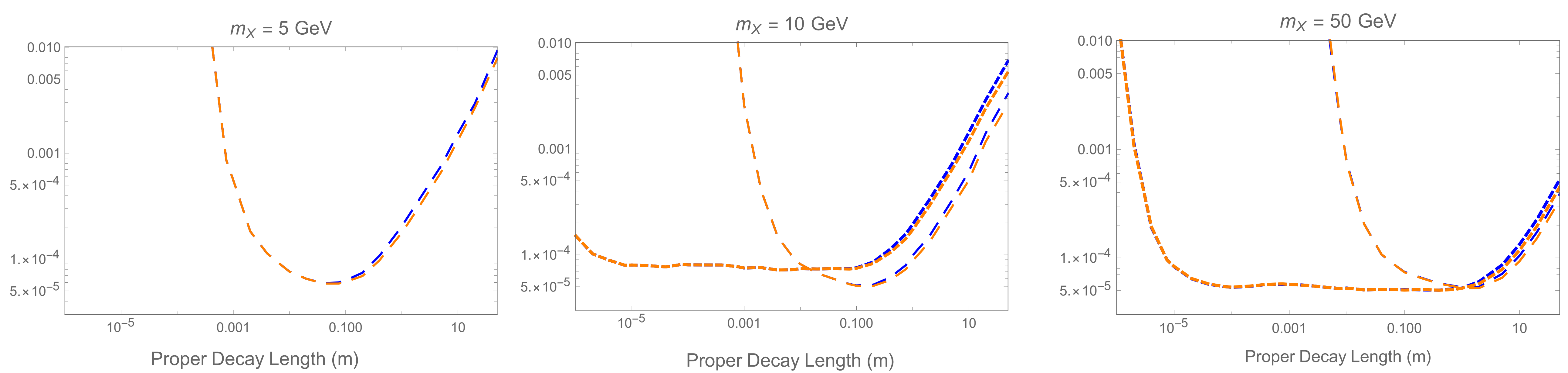
$$e^+e^- \to hZ \text{ followed by } h \to XX$$

LLP

Analysis:

- Clustering particles whose origin is within 7um.
- Impact parameter: average of all particles.

- "long lifetime" analysis: d_{min} = 3 cm, $M_{charged}$ > 2 GeV
- "large mass" analysis: d_{min} = 5 µm, $M_{charged}$ > 6 GeV



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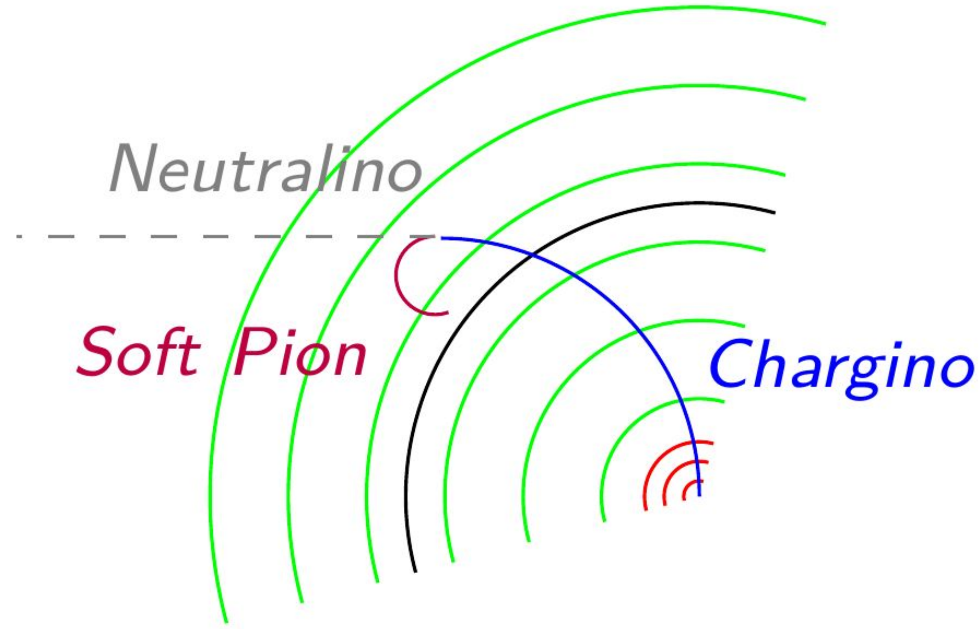
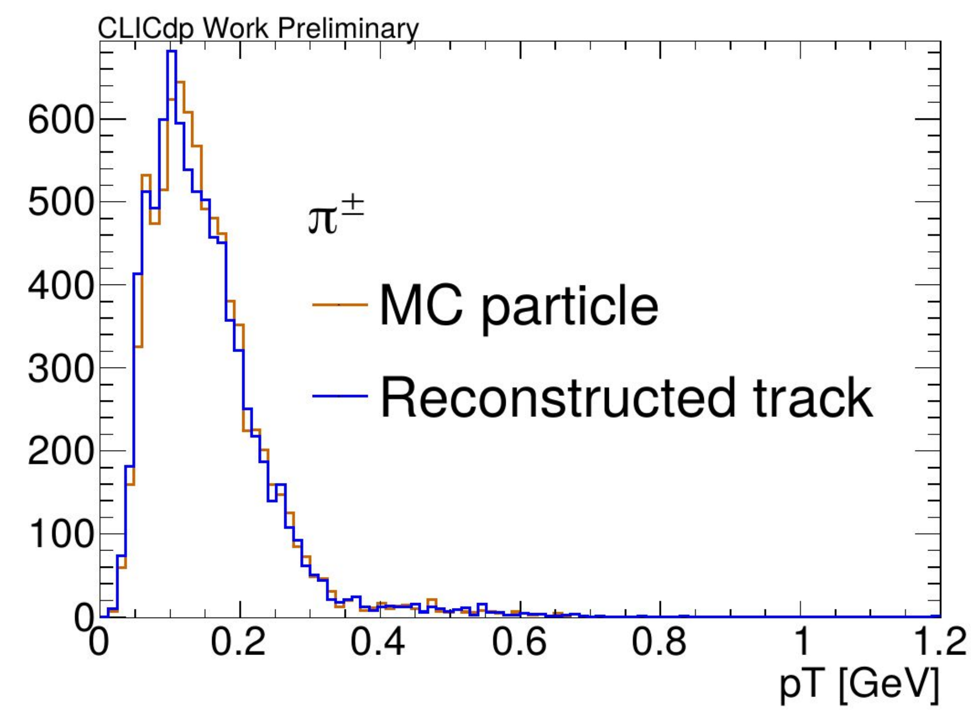
ILC250 limits are ~1.8× worse

Disappearing track at CLIC

- Stub track candidate:
  - At least four hits in the tracking system
  - Prompt, isolated track
  - Minimum transverse momentum
  - **Disappearing** within the tracking syster volume
  - No energy deposition in the calorimeter
  - Additional: dE/dx requirement
- At least one stub candidate per event
- Additional: **soft displaced pion**(s) and additional photons



Soft pion reconstruction

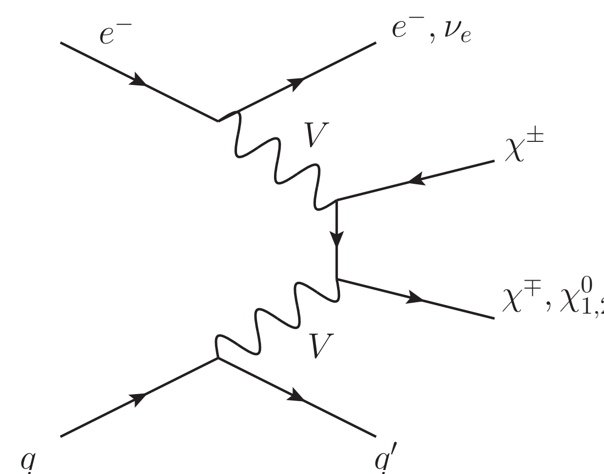


Expected sensitivity by a truth-level study covers the thermal DM mass limit (~1 TeV).

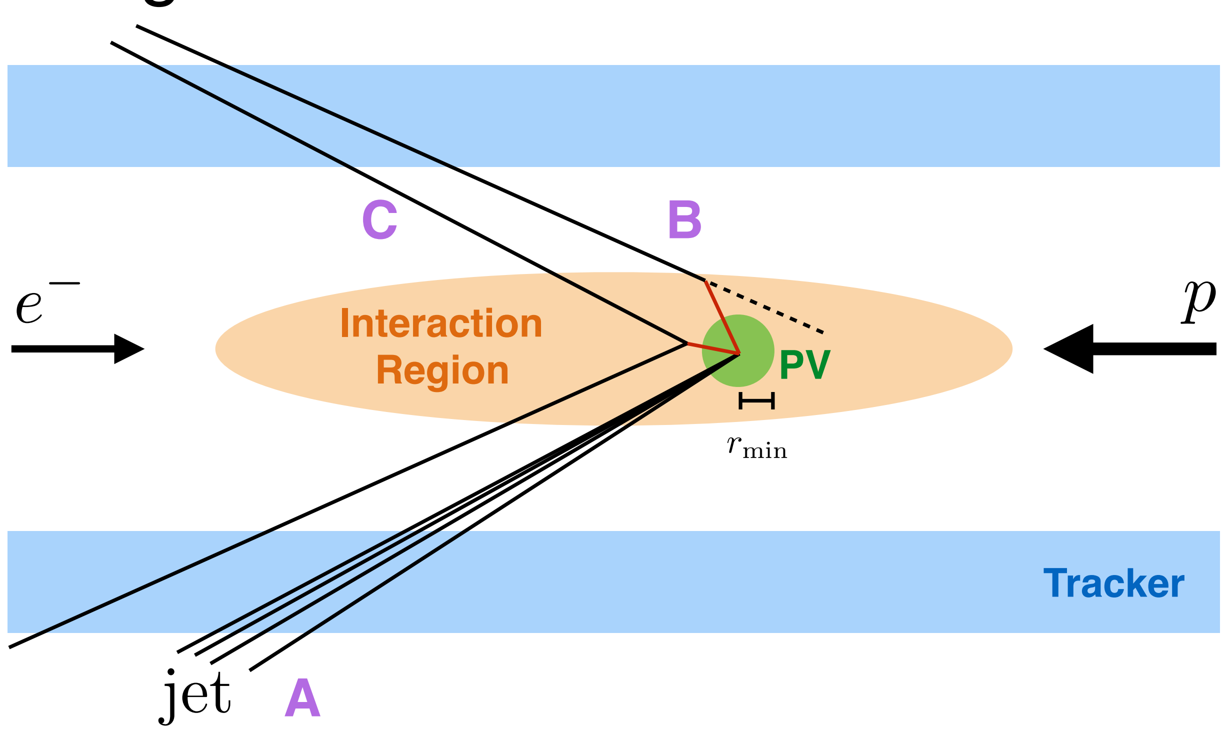
arXiv:1812.02093

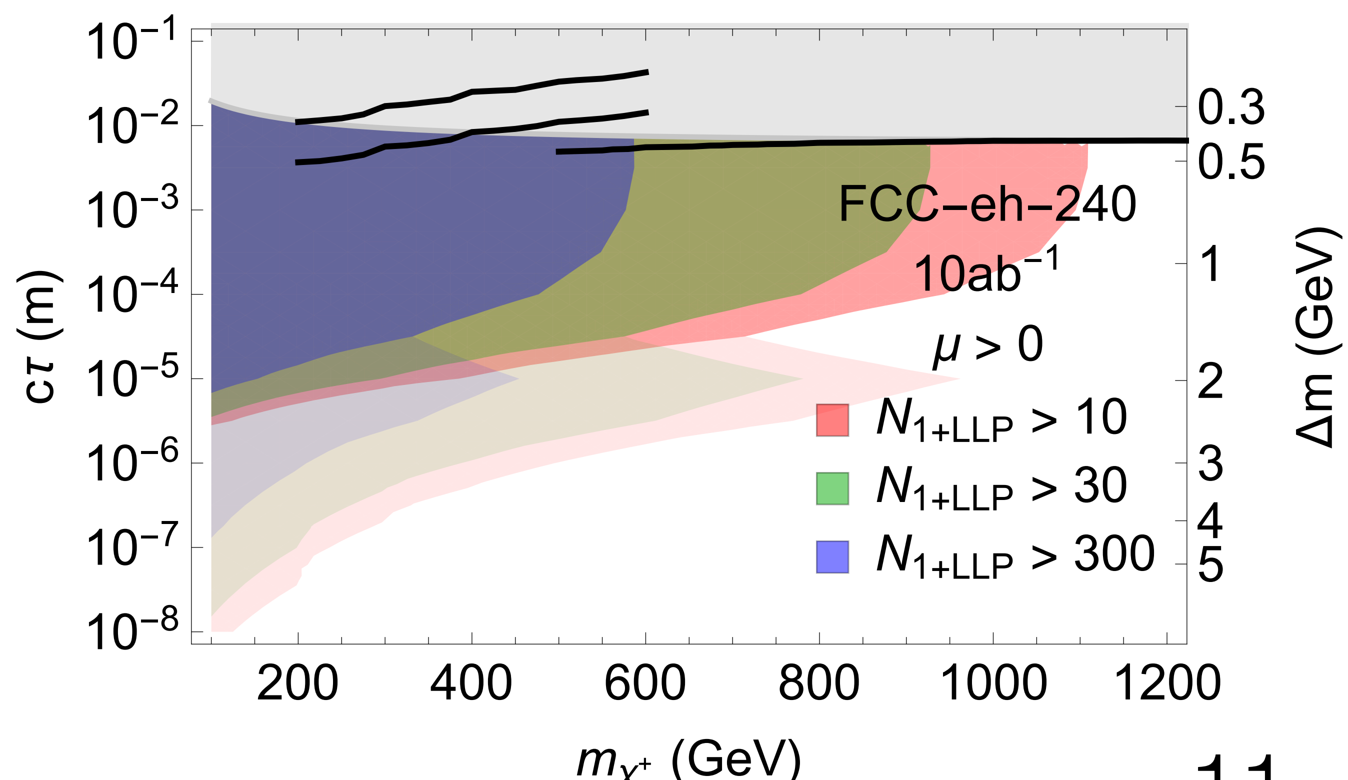
e-p colliders: LL chargino

- e-p collider have “middle” feature between lepton and hadron colliders
  - Higher collision energy than lepton colliders
  - Cleaner environment than hadron colliders. e.g. pileup~1 at FCC-eh (60)



The system is highly boosted by **asymmetric** collision.
Long lifetime in the lab frame.

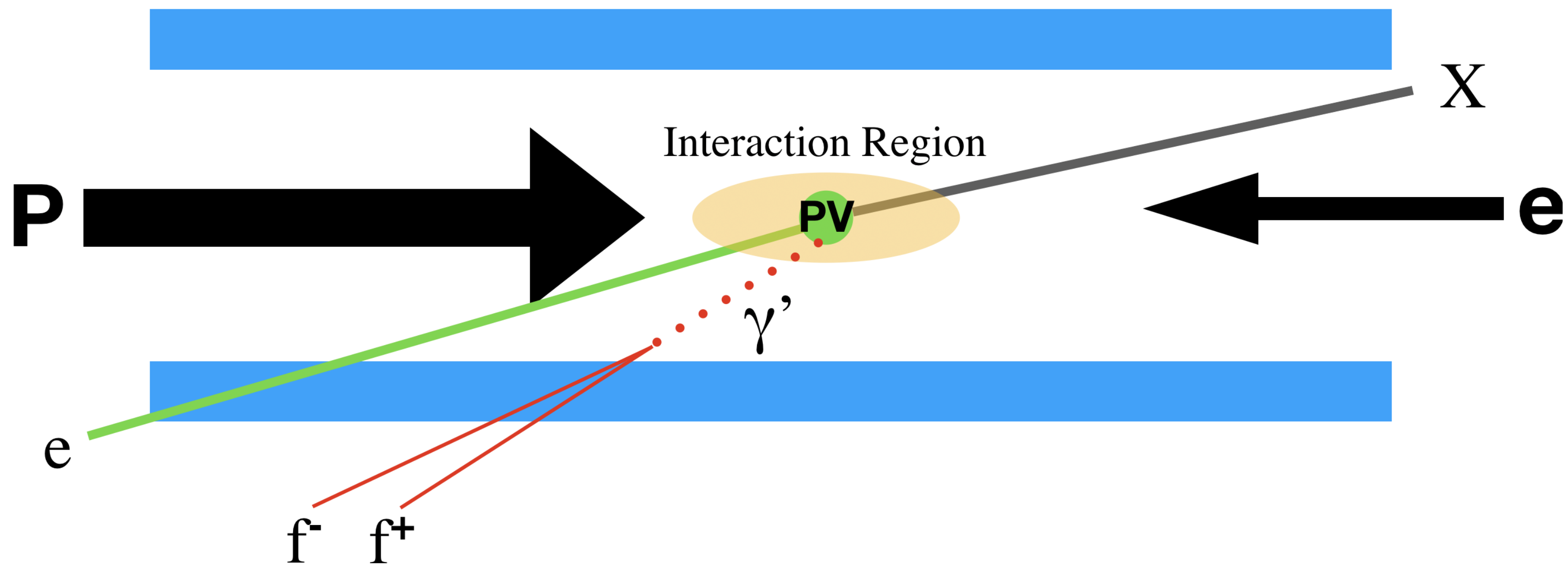


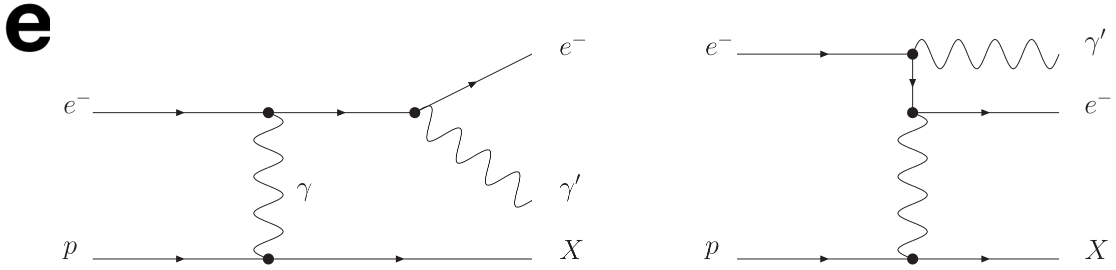


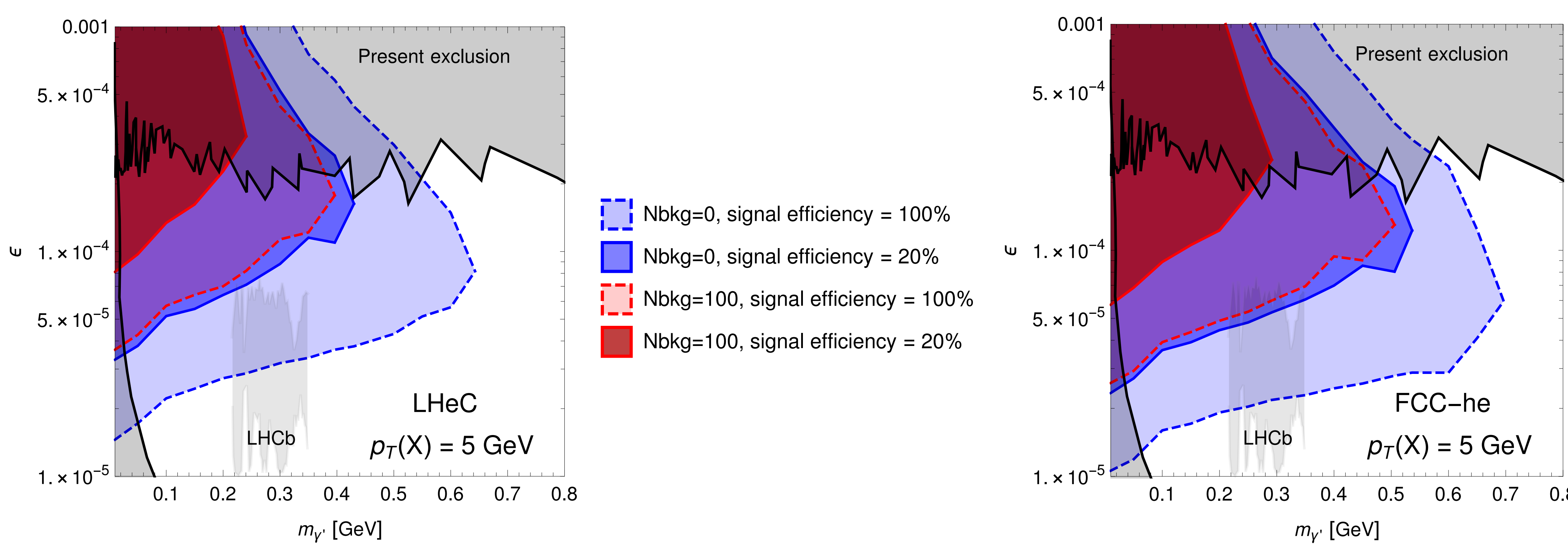
arXiv:1712.07135

e-p colliders: dark photon

arXiv:1909.02312





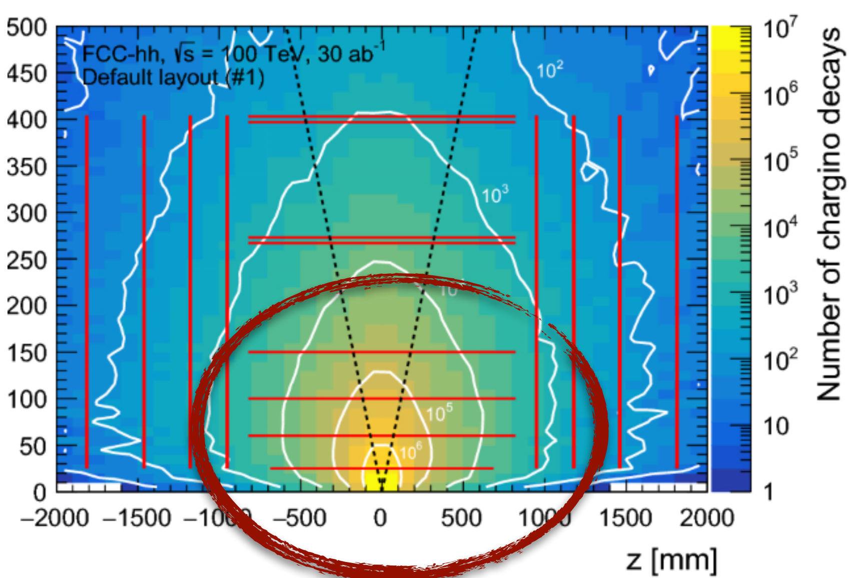


Unique coverage of low mass, intermediate coupling regime, complementary to other present and planned experiments.

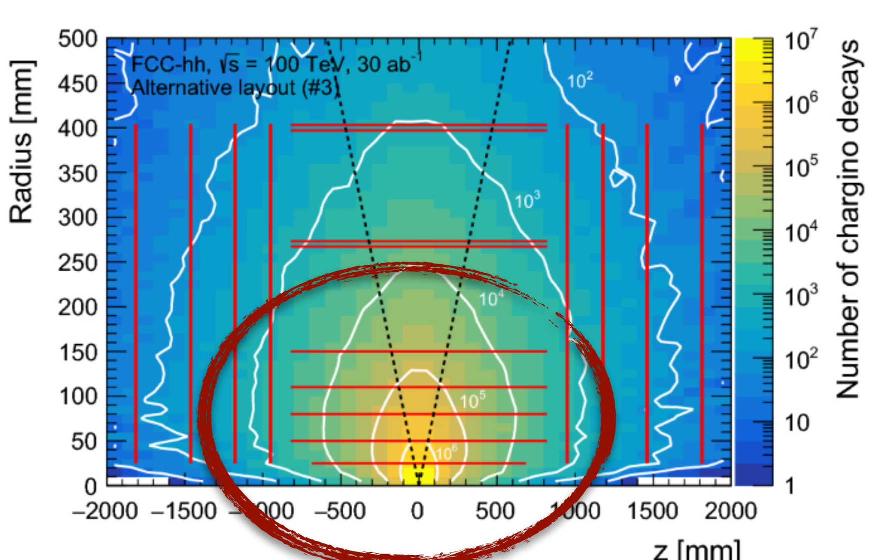
Disappearing track @ FCC-hh

Eur. Phys. J. C (2019) 79:469

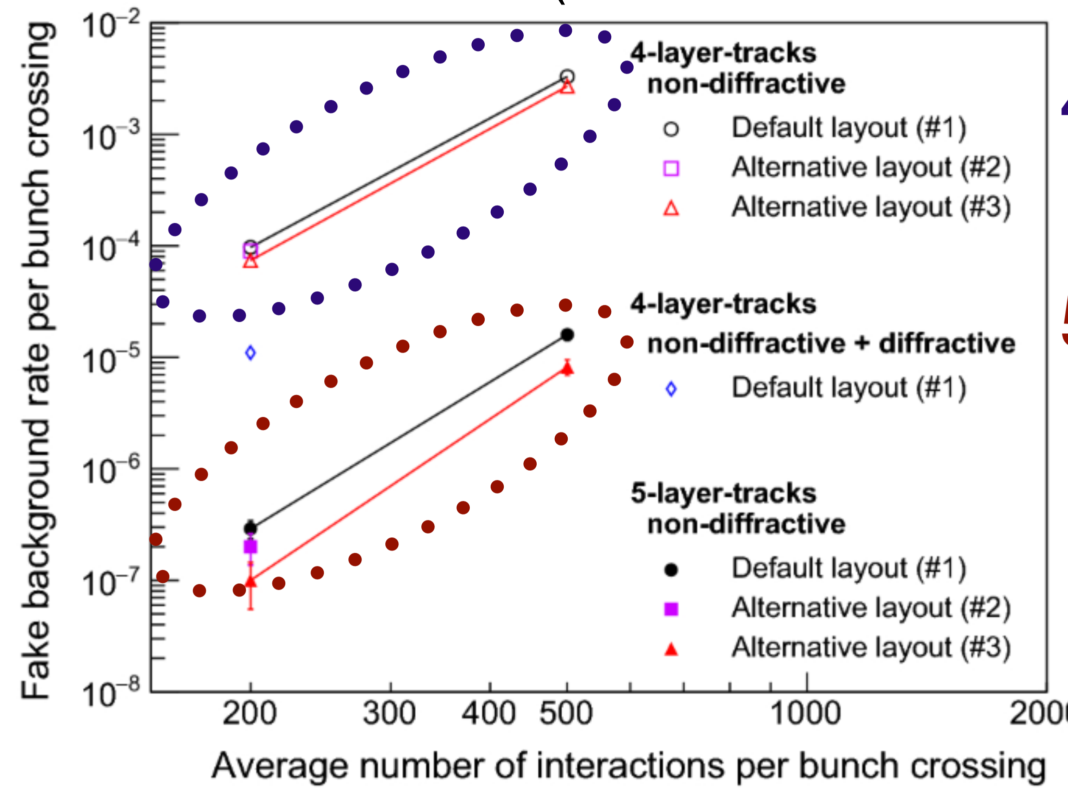
Nominal tracker layout



Better for disappearing track search



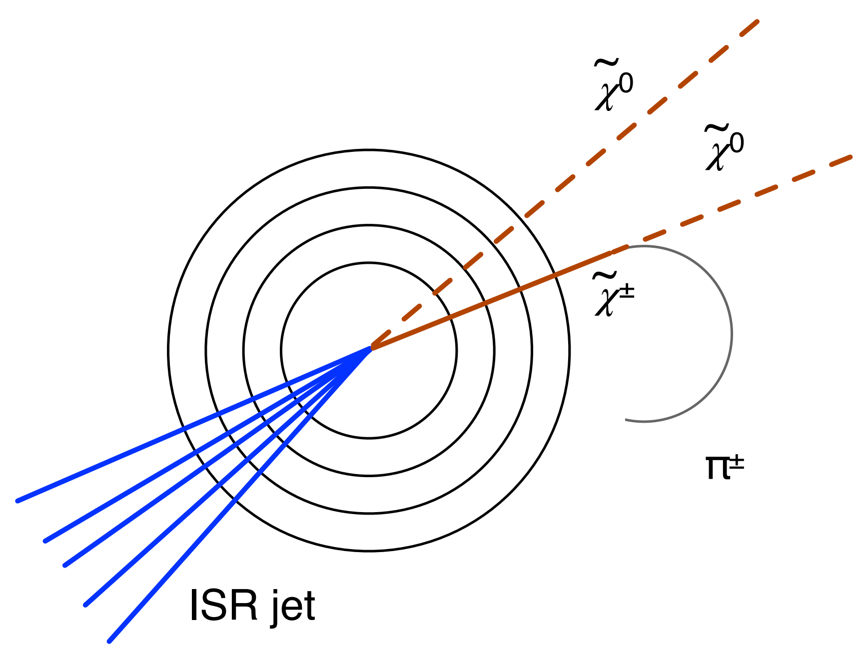
BG track rate (w/o time information)



4 hits required

5 hits required

~3 orders of magnitude BG reduction



Time measurement at each silicon layer.

Further BG reduction (~4%) by requiring consistent hit times as a single particle from IP

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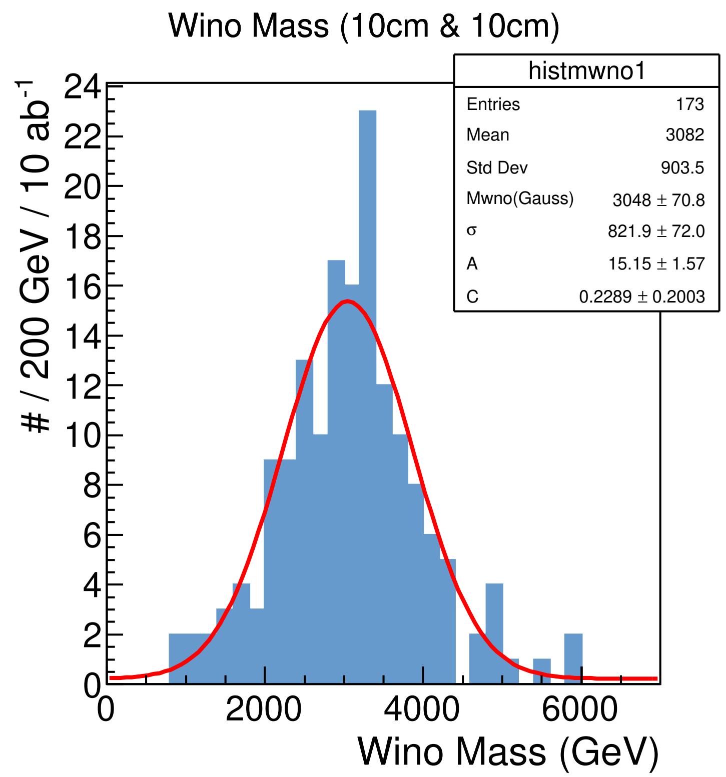
Time information @ FCC

- Hit-time information at each silicon layers can be used for two purposes,
  1. **BG fake tracks** (random-combination) decrease by requiring consistent time of pixel-hits on track.
  2. Measure **the velocity of a particle**.
     - Vertex time can be determined by other objects (e.g. jets)
     - If hit-time resolution is 20 ps, velocity resolution for charginos could be ~6%.

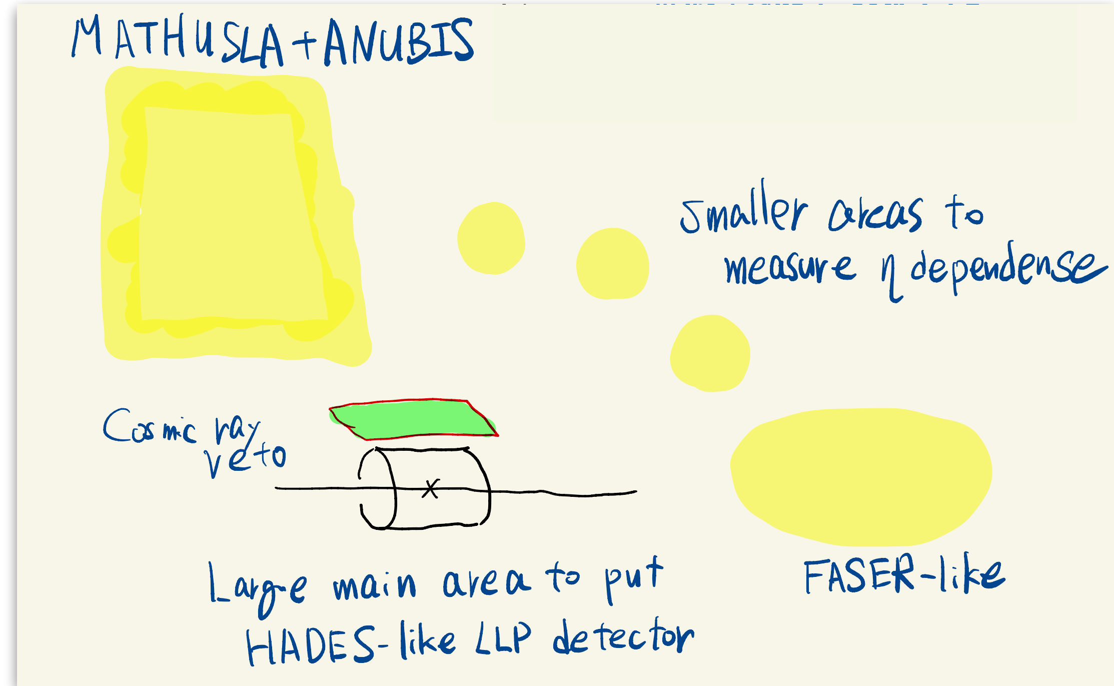
Reconstructed 2.9 TeV wino mass by timing @ FCC-hh 30 ab^{-1}

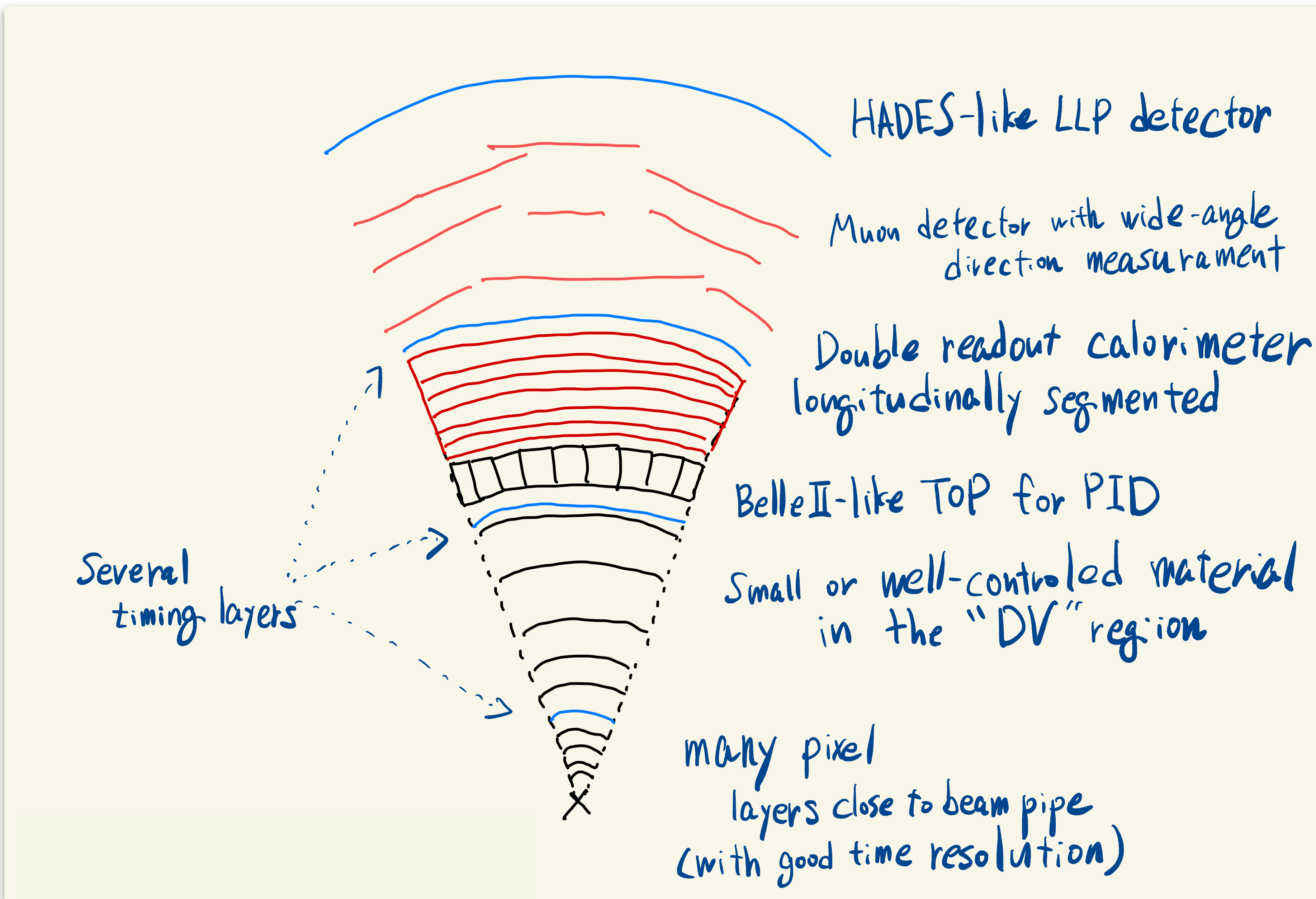


JHEP05(2019)179

- Interesting detector developments (AC-LGAD, Monolithic-LGAD…) are on-going. *Gabriele D'Amen , Snowmass*

A dream LLP detector?





HEPData

- Running experiments usually submit published-paper data to HEPData
  - Numerical values of histograms and graphs
  - Additional material for re-interpretation (efficiency, acceptance etc)
  - Simplified C++/python code to reproduce the analysis.
- Why don't we do also for studies on future colliders ?
  - LLP studies often require significant code development for estimation of efficiency and acceptance.
    - E.g. development of tracking code, special LLP event simulation, massive CPU-time for Geant4 simulation, etc.
  - By sharing data would benefit/accelerate/promote future-collider studies.

- Actually, we put data from our paper (DT@FCC) on HEPData.

doi: 10.17182/hepdata.90451

Conclusion

- There are many proposals in **Snowmass**, which I couldn't cover in this talk, please check them out!
- **What is limiting the current search ?** (Inefficiency of large radius tracks, track-level particle ID, displaced lepton, displaced-vertex resolution, time resolution or DAQ window…)
  - It may be interesting to surveying from analysis experts on detector limitations, then to ask detector experts if we can improve.
  - Such a wish-list may be useful for detector experts to develop new detector technologies.
- **Designing an "LLP-builtin" detector would be fun!**
  - Freely thinking may result an spin-off for nearer-future, i.e. HL-LHC (?)