Challenges for Vertex detectors at Linear Colliders

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On behalf of the LC Vision Team

with inputs from C. Damerell, Su Dong, L. Gray. D. Ntounis

See also talk from Dominick on vertexing at future lepton colliders

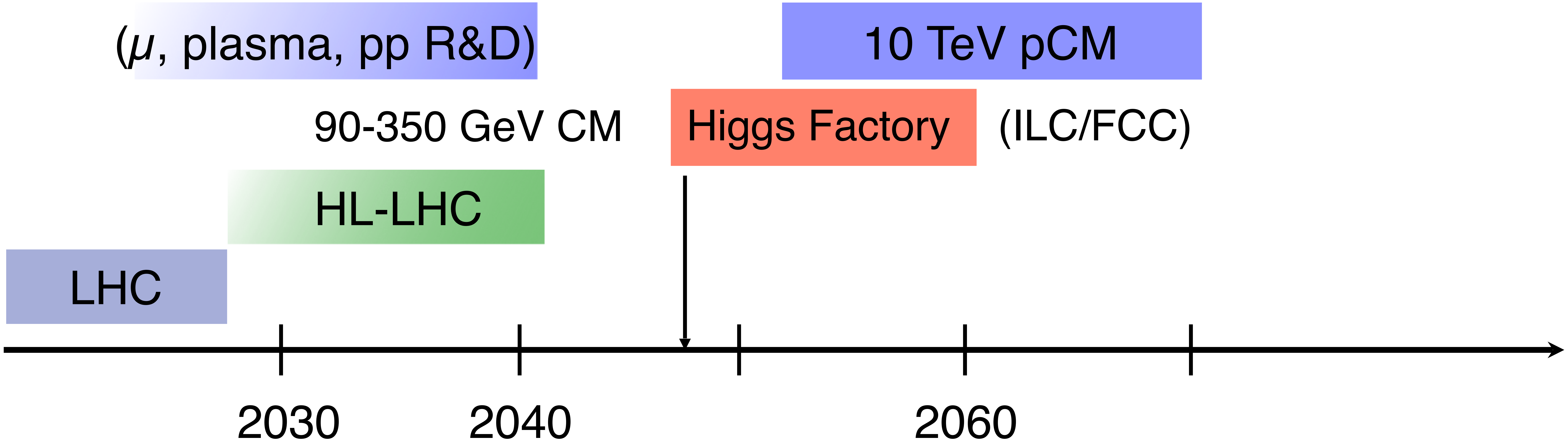
25th – 29th August
VERTEX25
The 33rd International Workshop on Vertex Detectors
Student Union, University of Tennessee Knoxville

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University

U.S. DEPARTMENT OF ENERGY

Collider roadmap (post P5)



(μ, plasma, pp R&D)

10 TeV pCM

90-350 GeV CM

Higgs Factory

(ILC/FCC)

HL-LHC

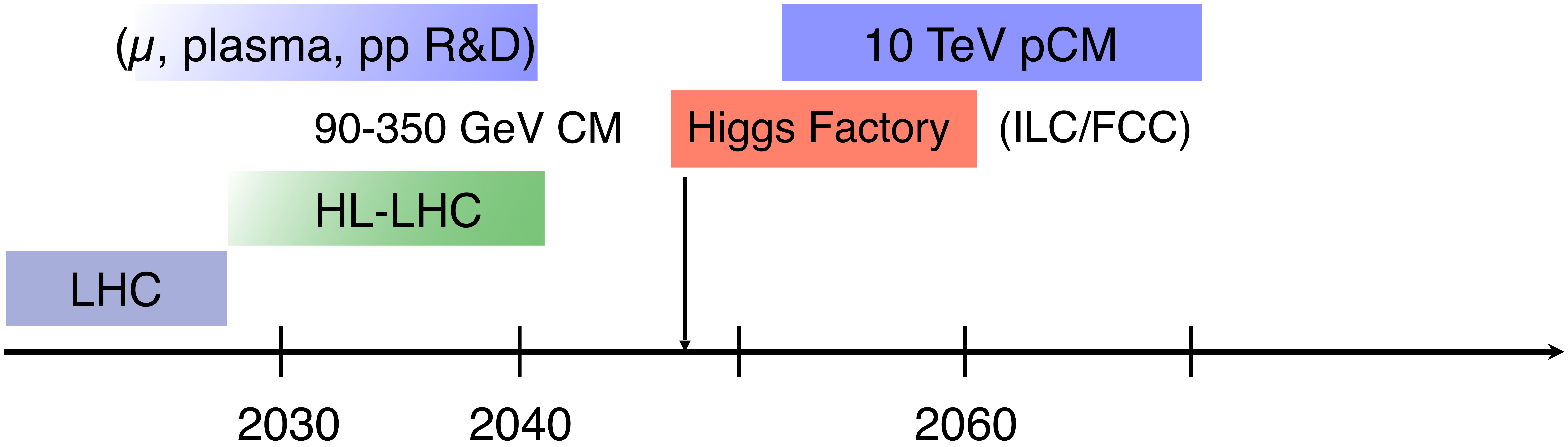
LHC

2030

2040

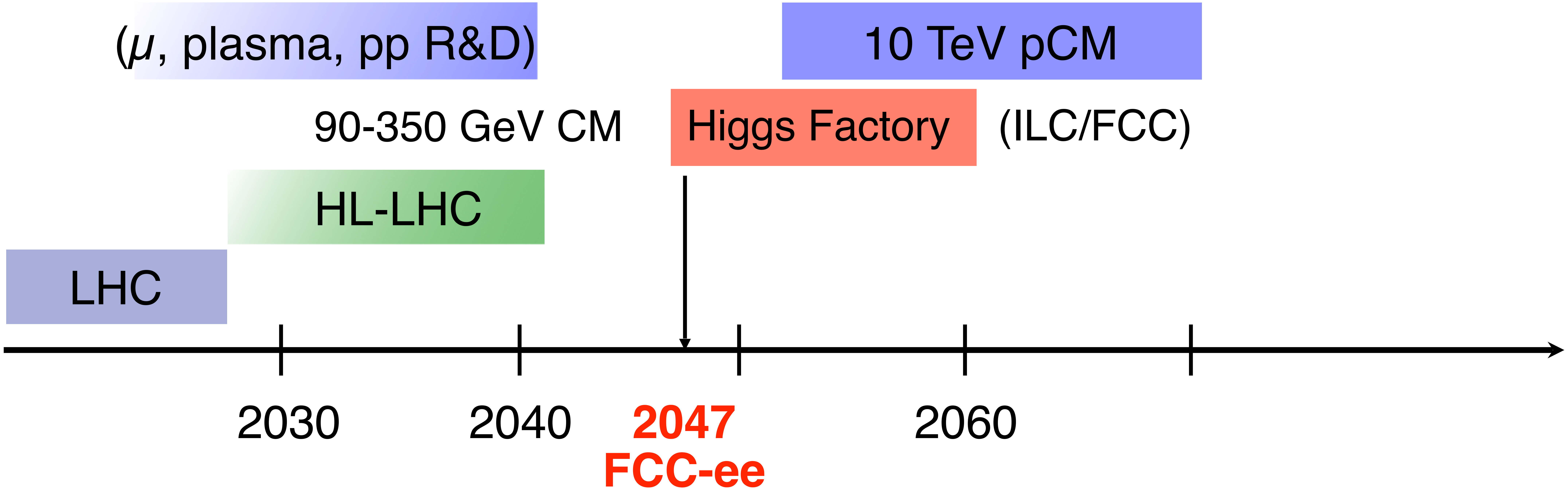
2060

Collider roadmap (post P5)



H couplings to:	**O(5-10)%**	**O(0.1-1)%**
H self-coupling to:	**O(30)%**	**O(1)%**

Collider roadmap (post P5)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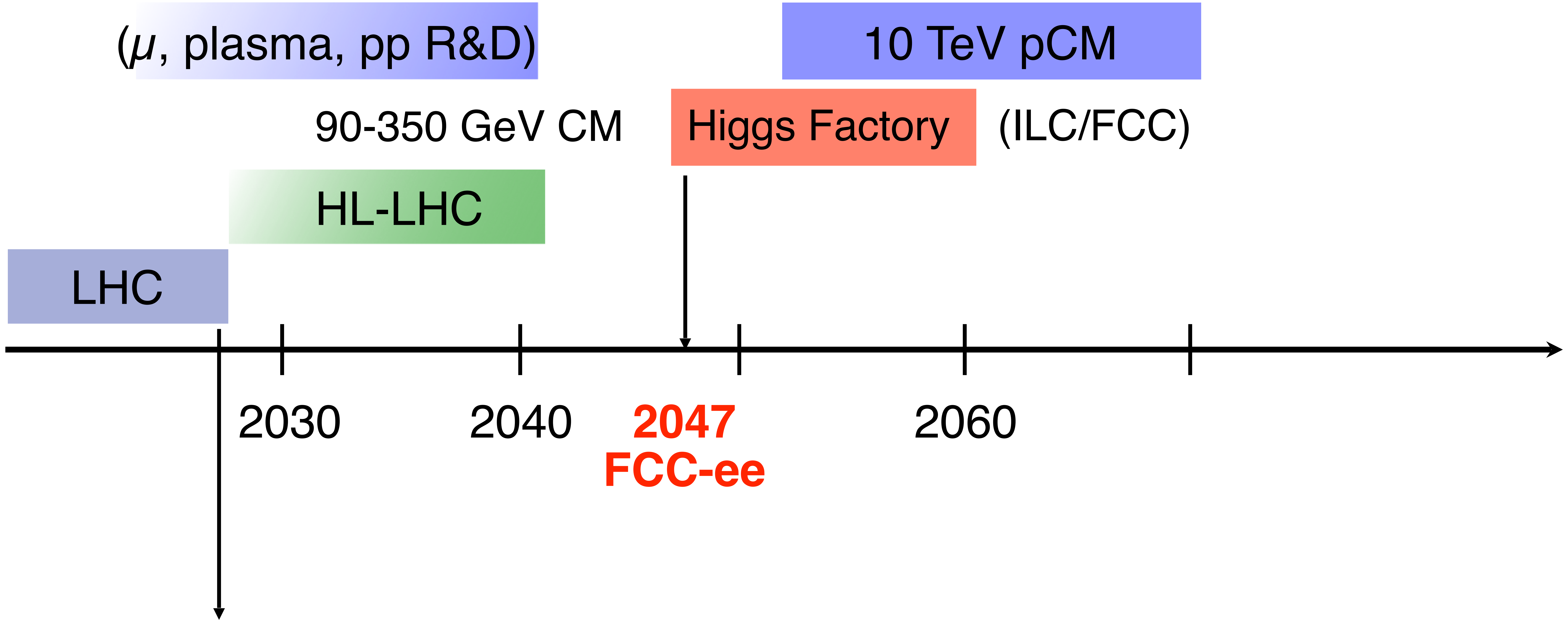
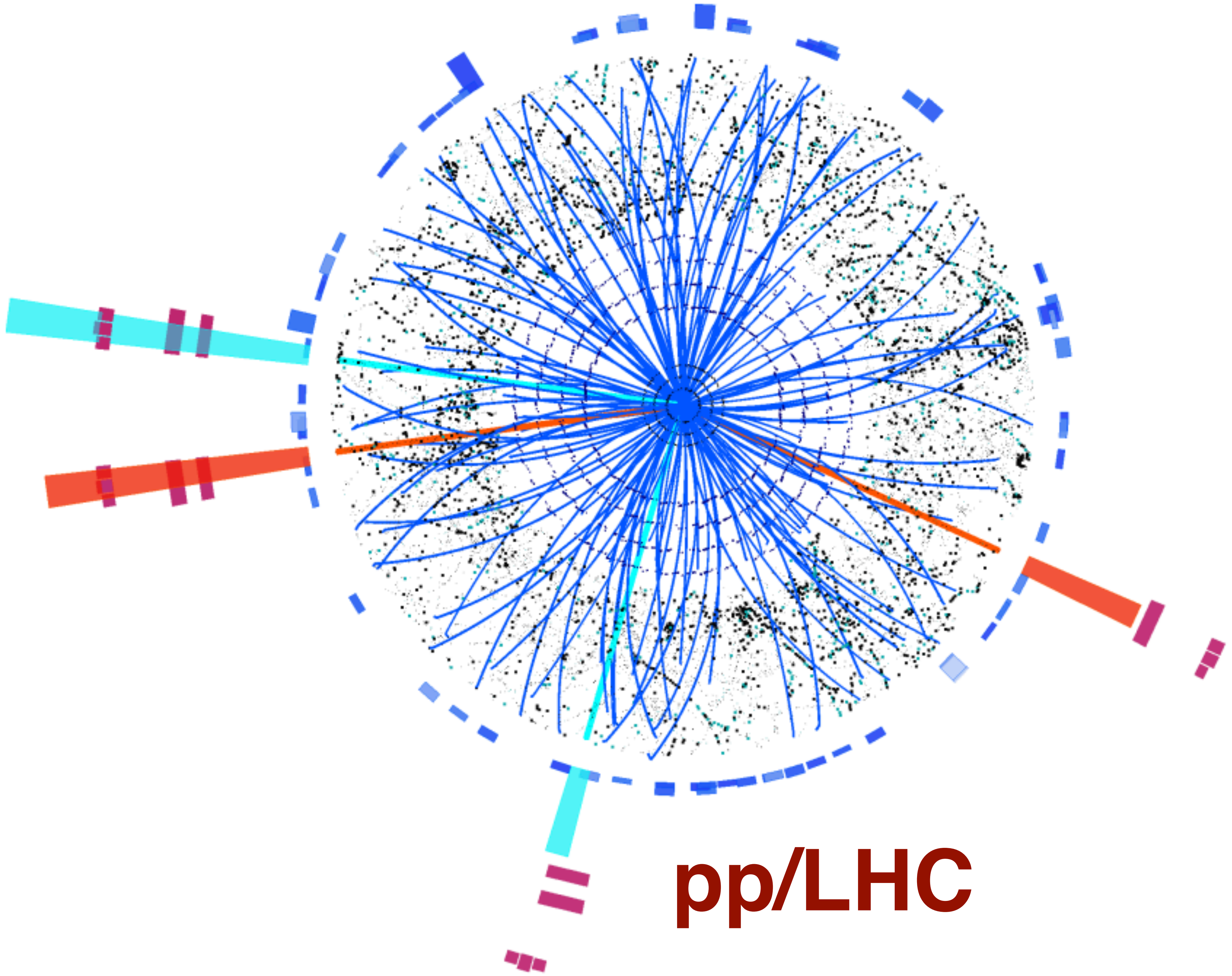


2025/6 European Strategy for Particle Physics Update
FCC feasibility study report

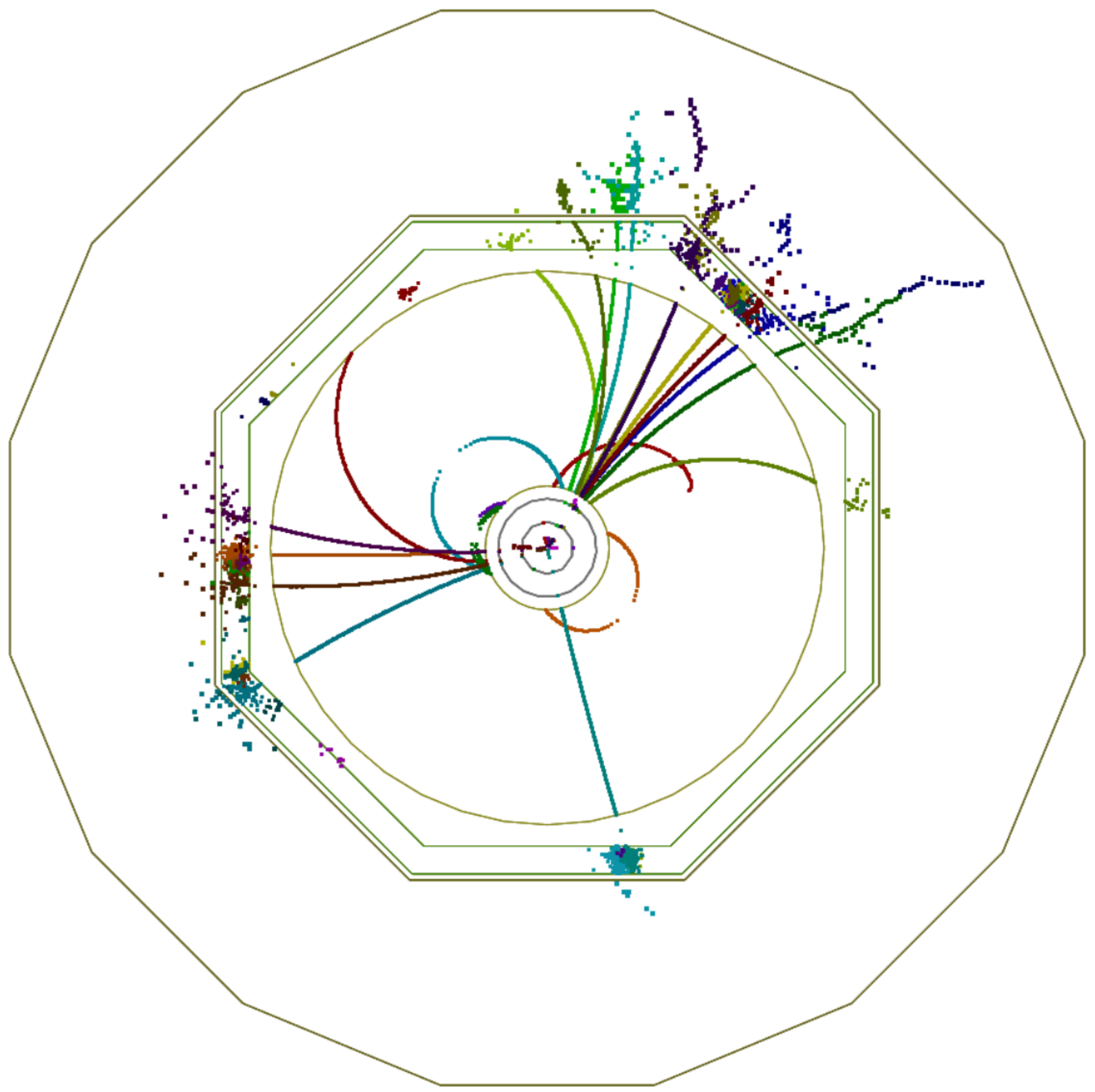
From pp to e^+e^-

Initial state well defined & polarization ⟹ High-precision measurements

Higgs bosons appear in 1 in 100 events ⟹ Clean experimental environment and trigger-less readout



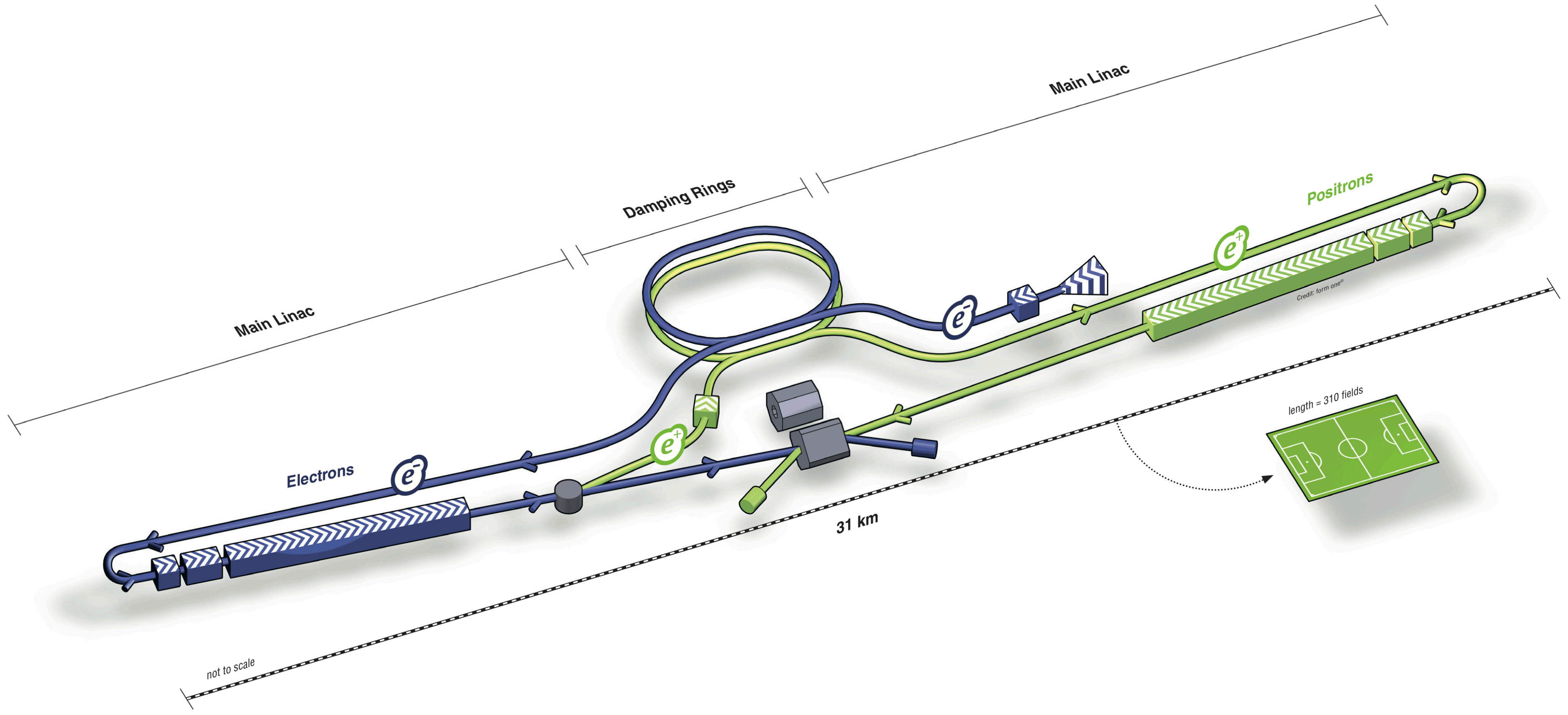
pp/LHC

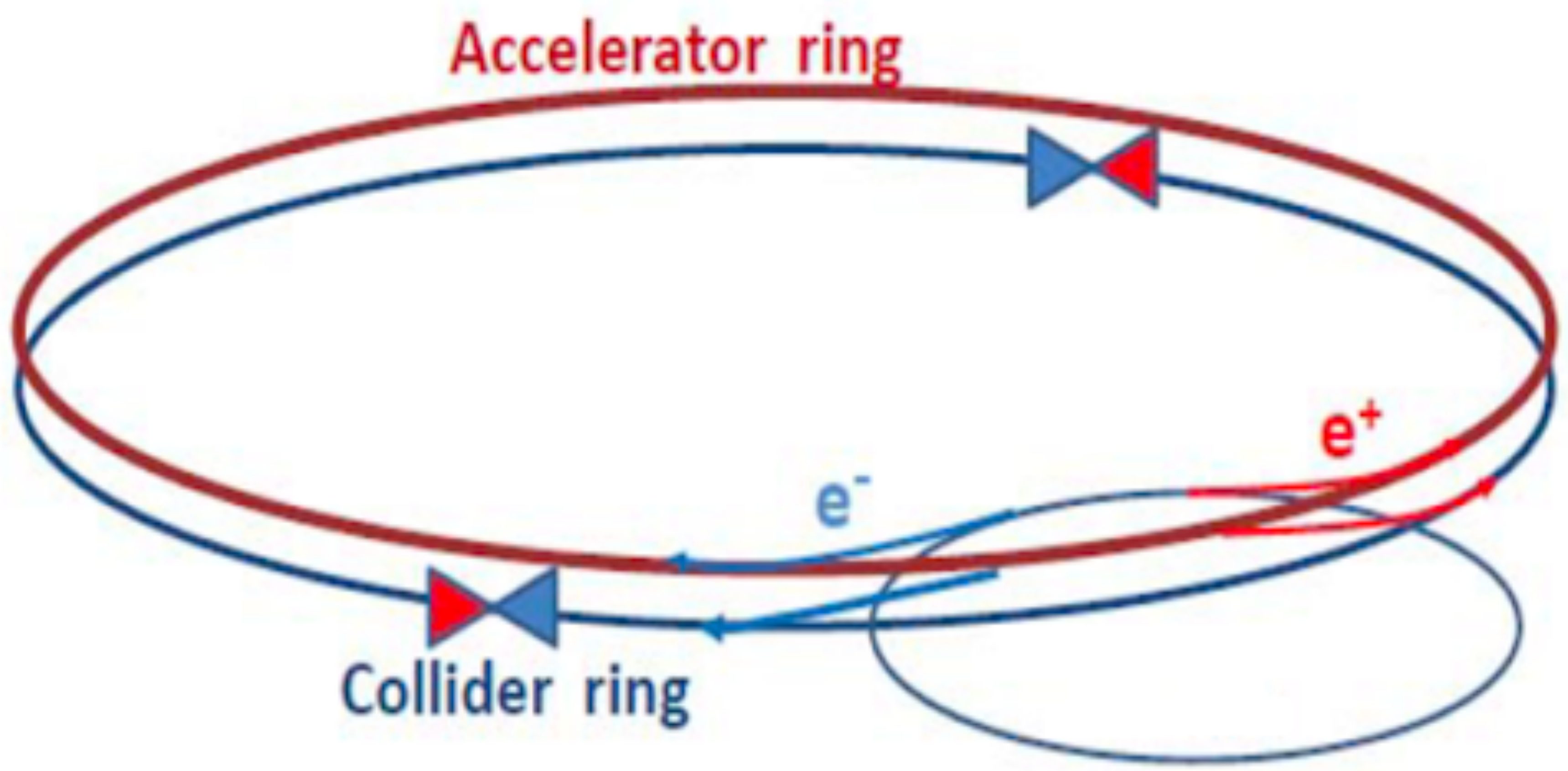


e^+e^-

e^+e^-: Linear and Circular

- **Linear** e^+e^- colliders: **higher energies** (~ TeV)
  - Can use **polarized** beams
  - Collisions in bunch trains (~0.5% duty cycle)
    - **Trigger-less readout**
    - **Power pulsing** → Significant power (& material) saving for detectors
  - **<u>One interaction point</u>**
    - two detectors alternating with push-pull
- **Circular** e^+e^- colliders: **highest luminosity** at Z/WW/Zh
  - Limited by synchrotron radiation above 350/400 GeV
  - Beam continues to circulate after collision
    - Detectors need active cooling (more material)
  - **<u>Multiple interaction points</u>**





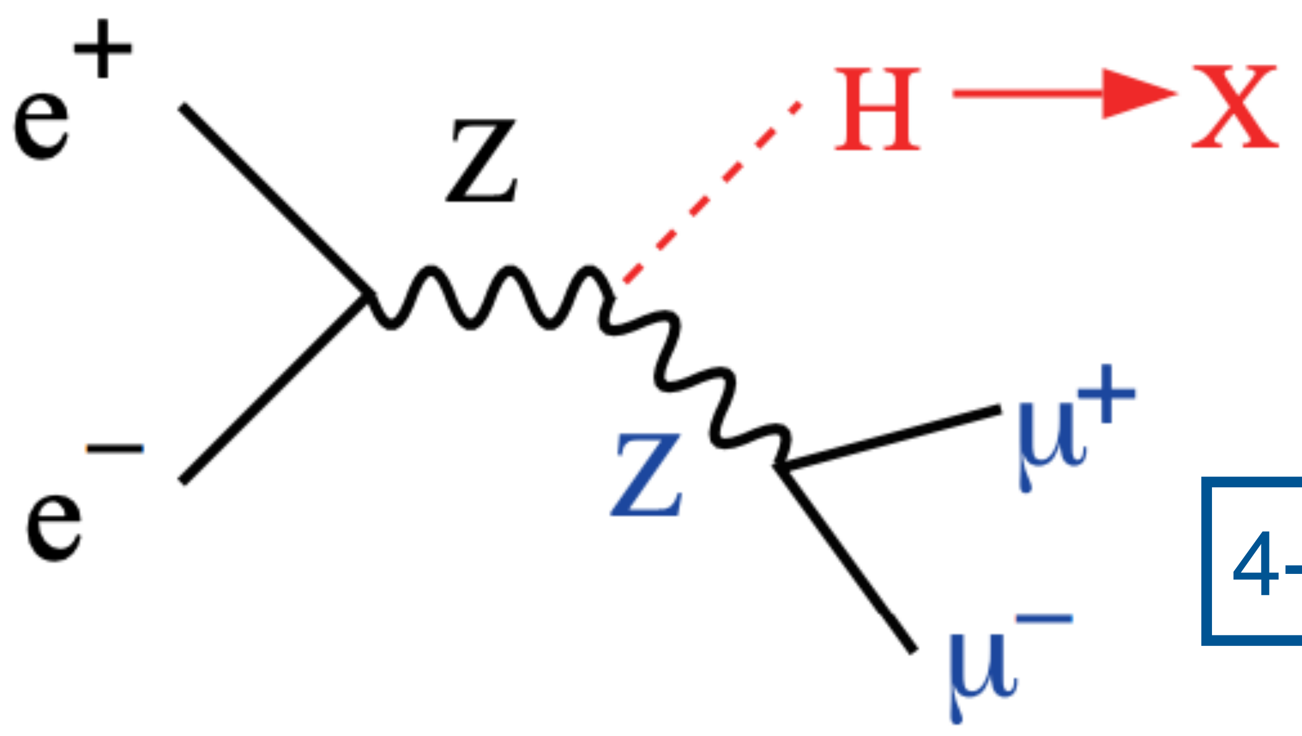
Lots of work in the past decades into ILC/CLIC detectors designs and more recently into first FCC detector concepts

arXiv:1604.07524
arXiv:2203.07622

How physics drives detector requirements

Unprecedented precision unlocked with a well defined initial state

initial 4-momentum
- nominal CM energy +
- beam energy spread [< 0.2%/beam] +
- beamstrahlung energy loss



$$m^2_{recoil} = s + m^2_Z - 2 \cdot E_Z \cdot \sqrt{s}$$

4- momentum measured by detector

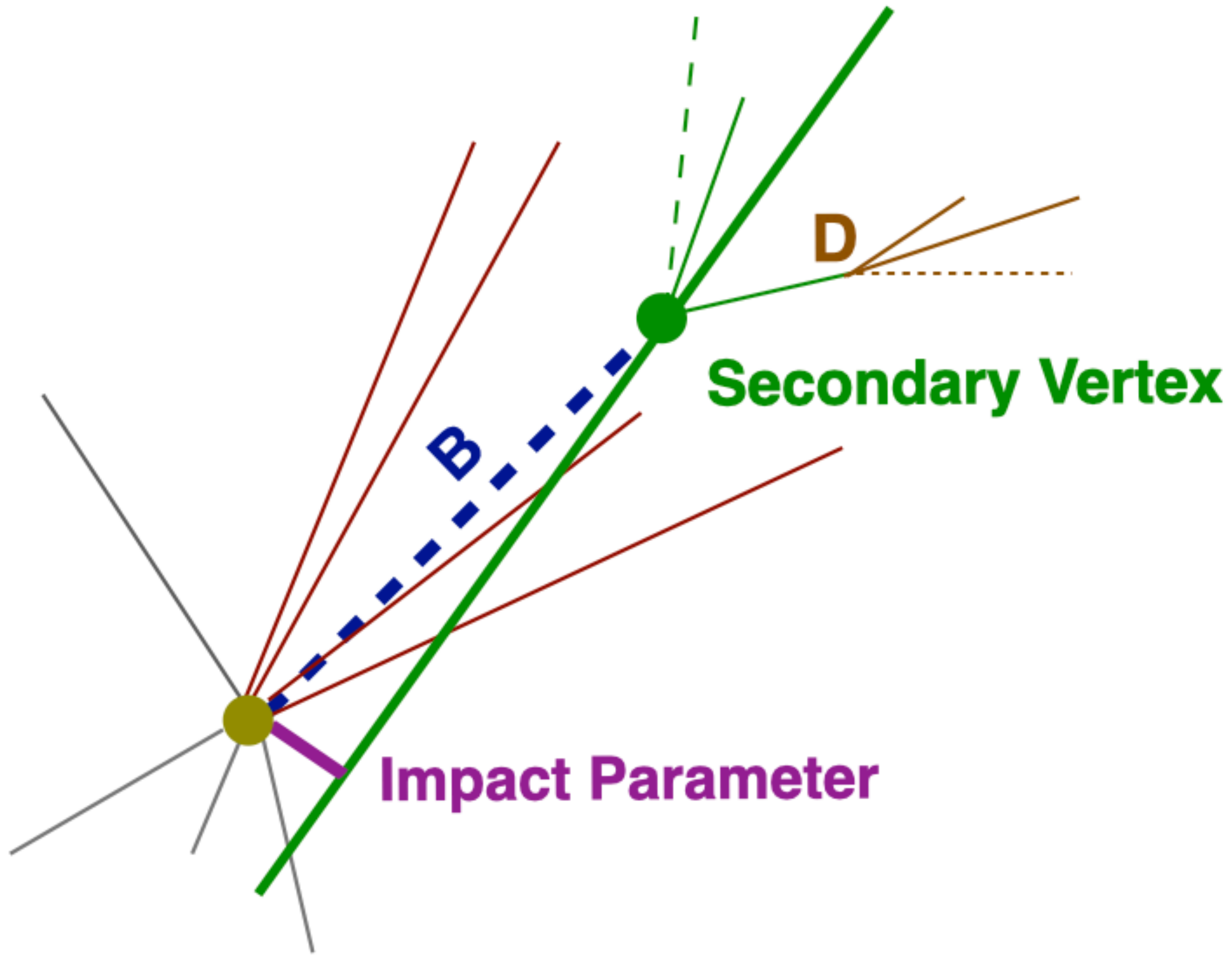
smearing due to Z momentum ~ smearing due to beam energy spread
$dp_T / p_T \sim$ few x 10^{-5} p_T @ high momentum

Flavor tagging requirements

Higgs → bb/cc decays: Flavor tagging tagging at unprecedented level
Drives requirement on charged track **impact parameter resolution**
→ ***low mass trackers near IP***

~1-3% X_0 per layer

For reference, 0.5 X_0 at η ~0 for CMS/ATLAS Phase 2



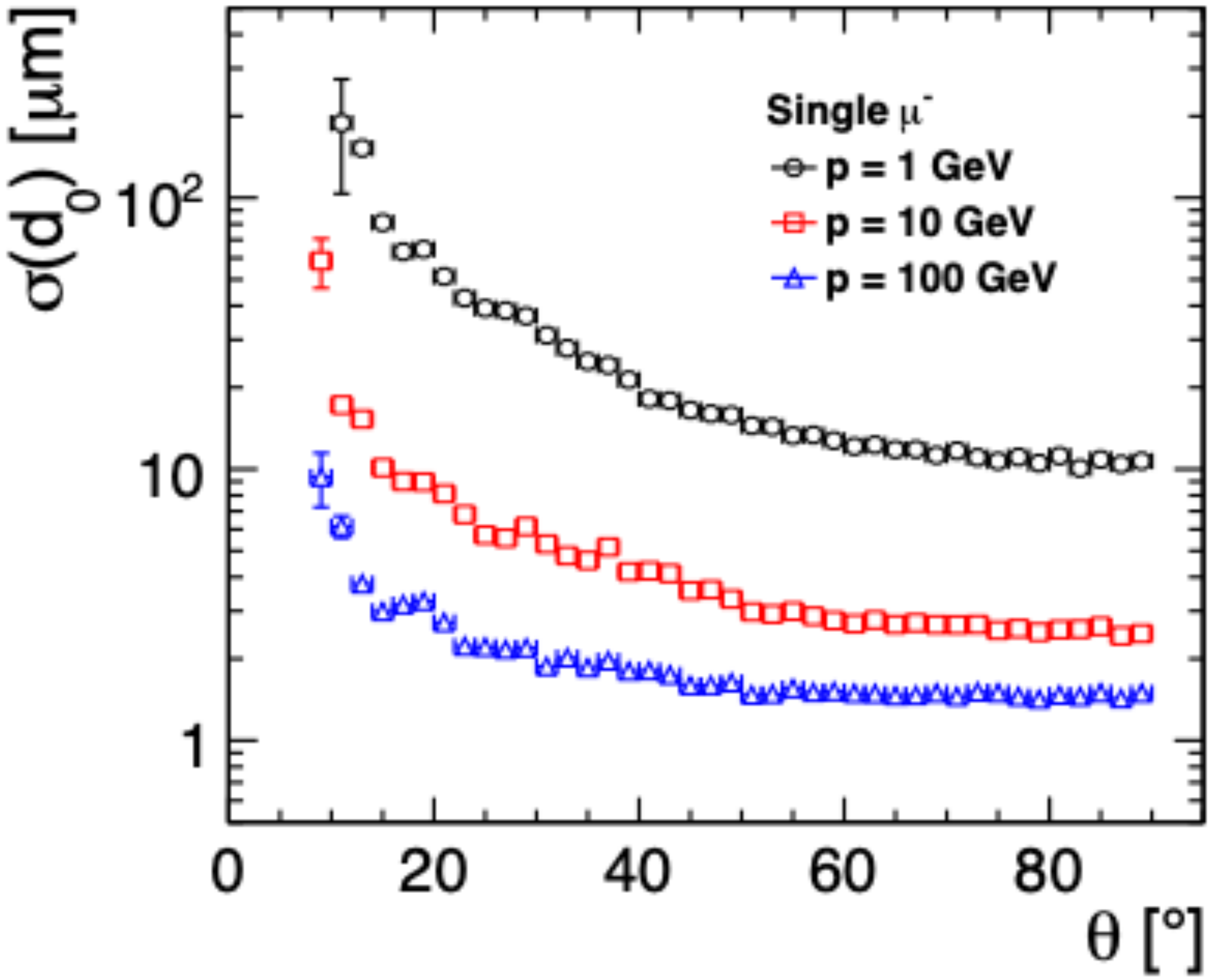
$$\sigma_{d_0} = \boxed{a} \oplus \boxed{\frac{b}{p_T sin^{1/2}\theta}}$$

Constant term depending on geometry

space point resolution and radii of the vertex detector

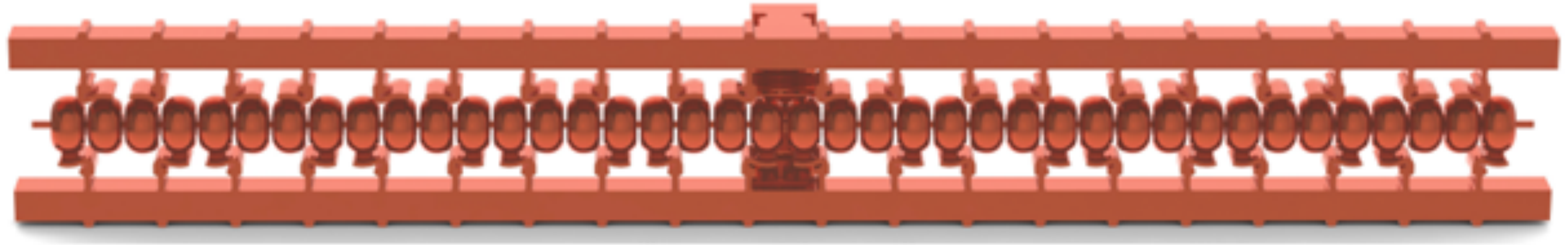
Multiple scattering term decreasing with p_T ~ 15μm* GeV

1306.6329



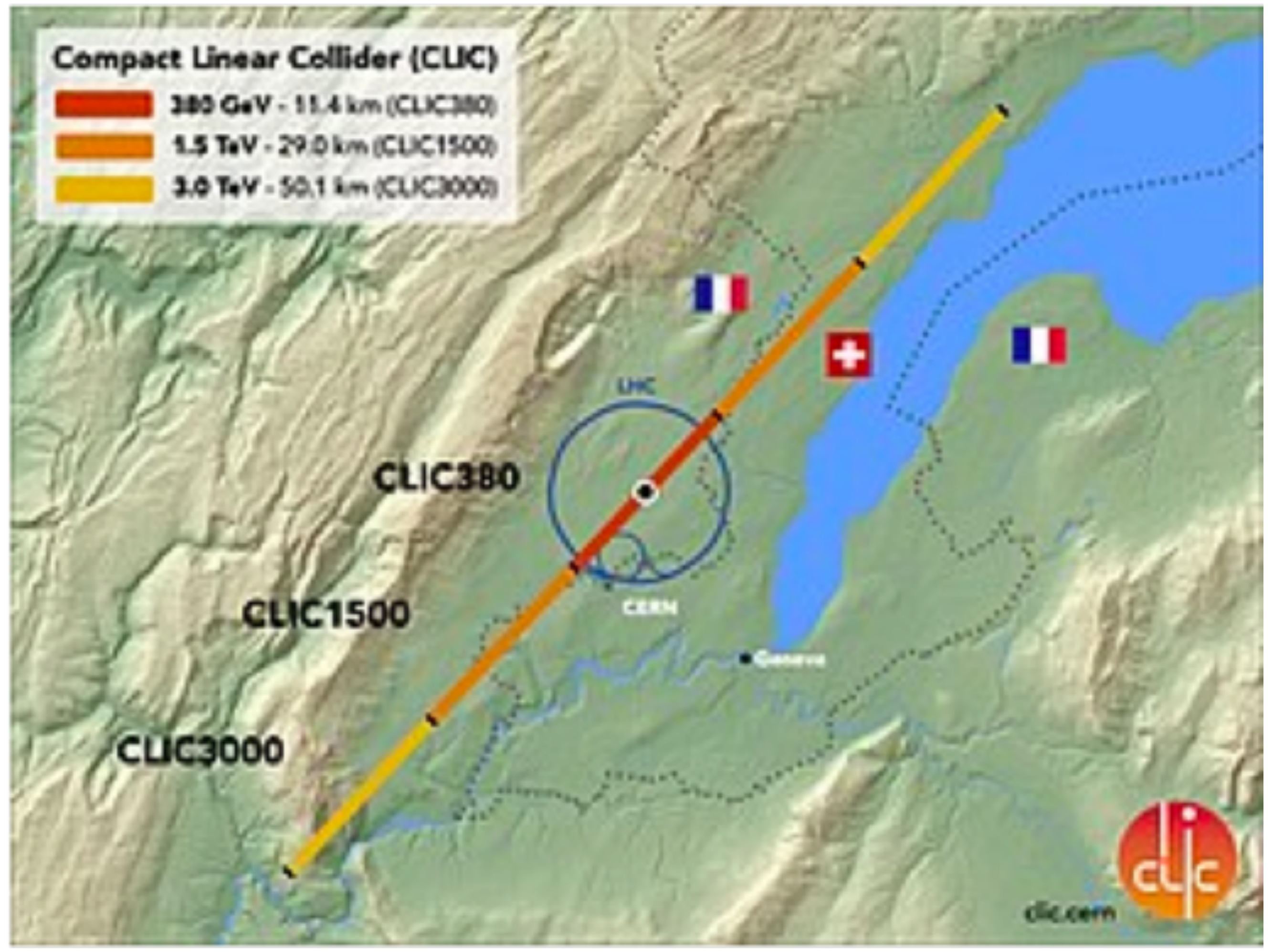
A variety of Linac Proposals

ILC 250/500 GeV



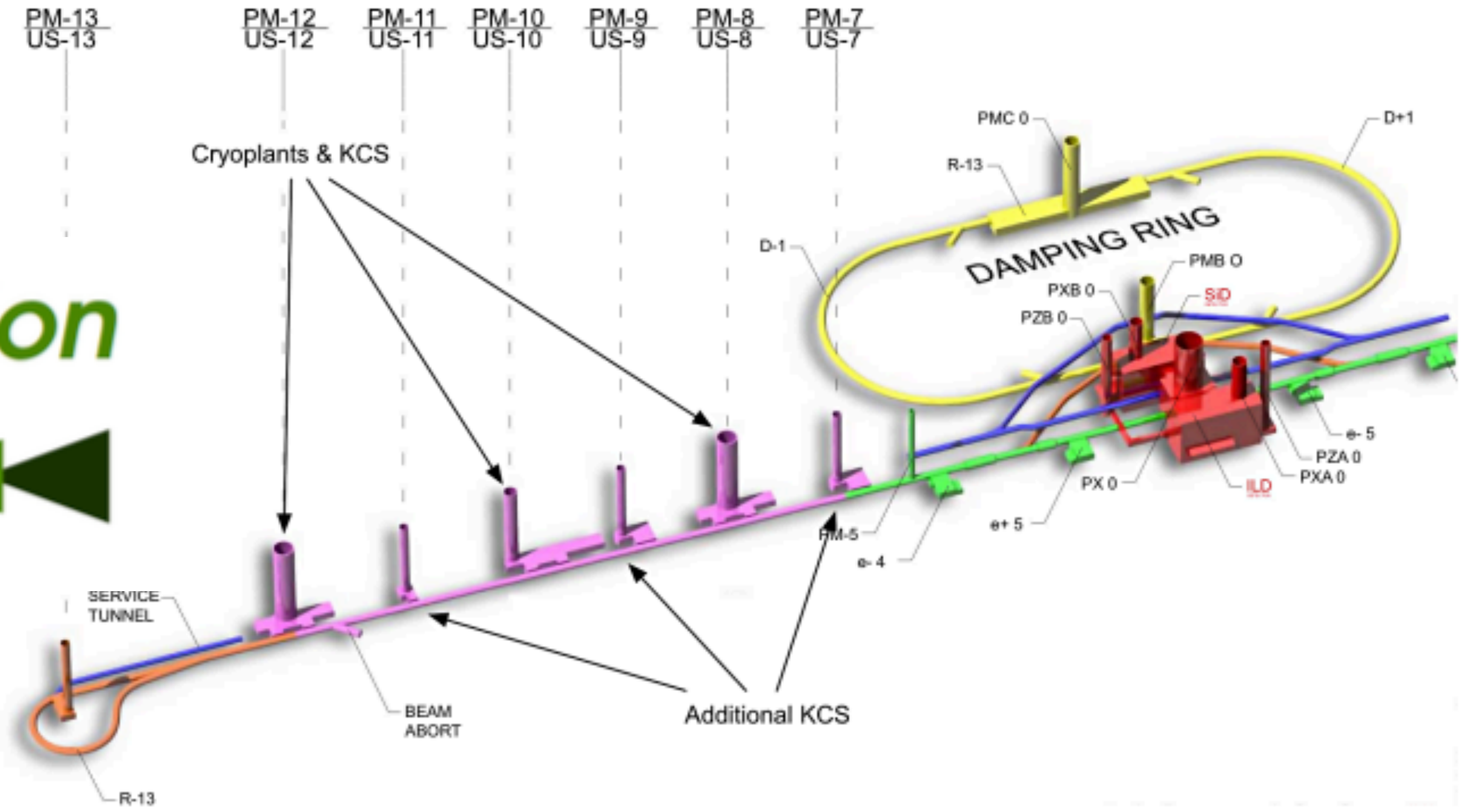
250/550 GeV
… > TeV

CLIC 380/1000/3000 GeV



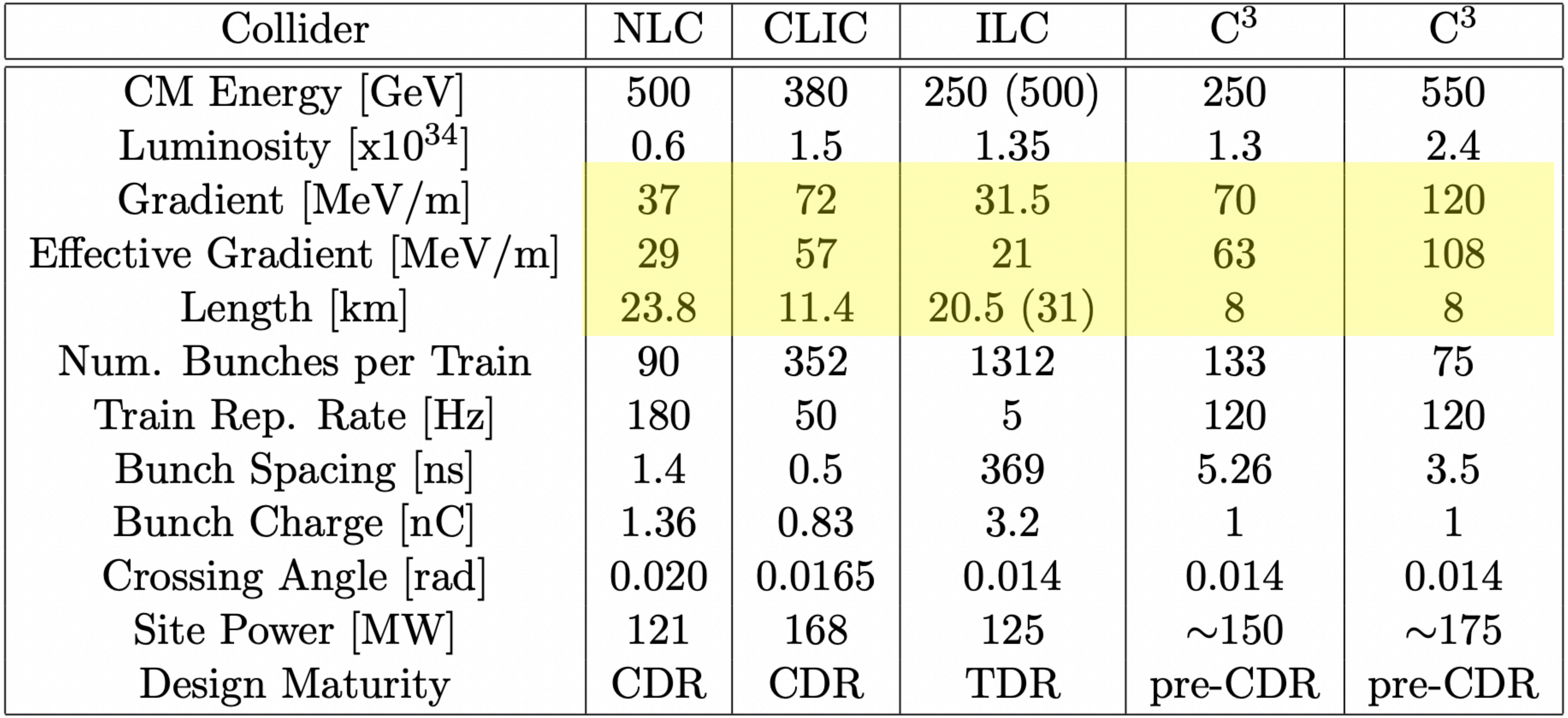
Linear Collider Vision

2503.24049



2503.24049
2110.15800

Linac parameters



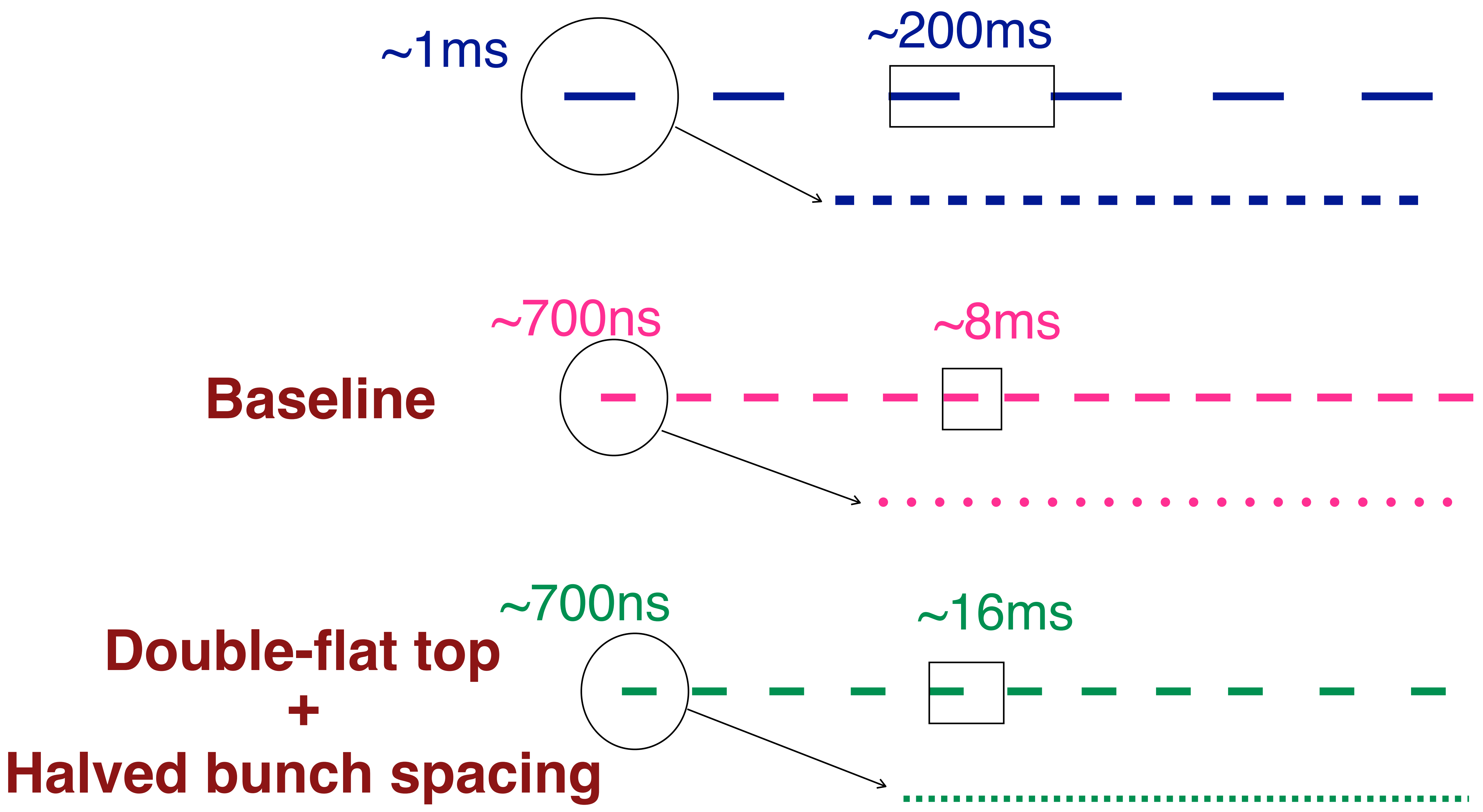
Collider	NLC	CLIC	ILC	C^3	C^3
CM Energy [GeV]	500	380	250 (500)	250	550
Luminosity [x10^{34}]	0.6	1.5	1.35	1.3	2.4
Gradient [MeV/m]	37	72	31.5	70	120
Effective Gradient [MeV/m]	29	57	21	63	108
Length [km]	23.8	11.4	20.5 (31)	8	8
Num. Bunches per Train	90	352	1312	133	75
Train Rep. Rate [Hz]	180	50	5	120	120
Bunch Spacing [ns]	1.4	0.5	369	5.26	3.5
Bunch Charge [nC]	1.36	0.83	3.2	1	1
Crossing Angle [rad]	0.020	0.0165	0.014	0.014	0.014
Site Power [MW]	121	168	125	~150	~175
Design Maturity	CDR	CDR	TDR	pre-CDR	pre-CDR

Linear Collider Vision

Compared to ILC, LCF plans for 10 Hz Rep. rate, 2625 Bunches per train

Beam Format and Detector Design Requirements

2003.01116



ILC Trains at 5Hz, 1 train 1312 bunches
Bunches are 369 ns apart

C³ Trains at 120Hz, 1 train 133 bunches
Bunches are 5 ns apart

C³ Trains at 60Hz, 1 train 266 bunches
Bunches are 2.65 ns apart

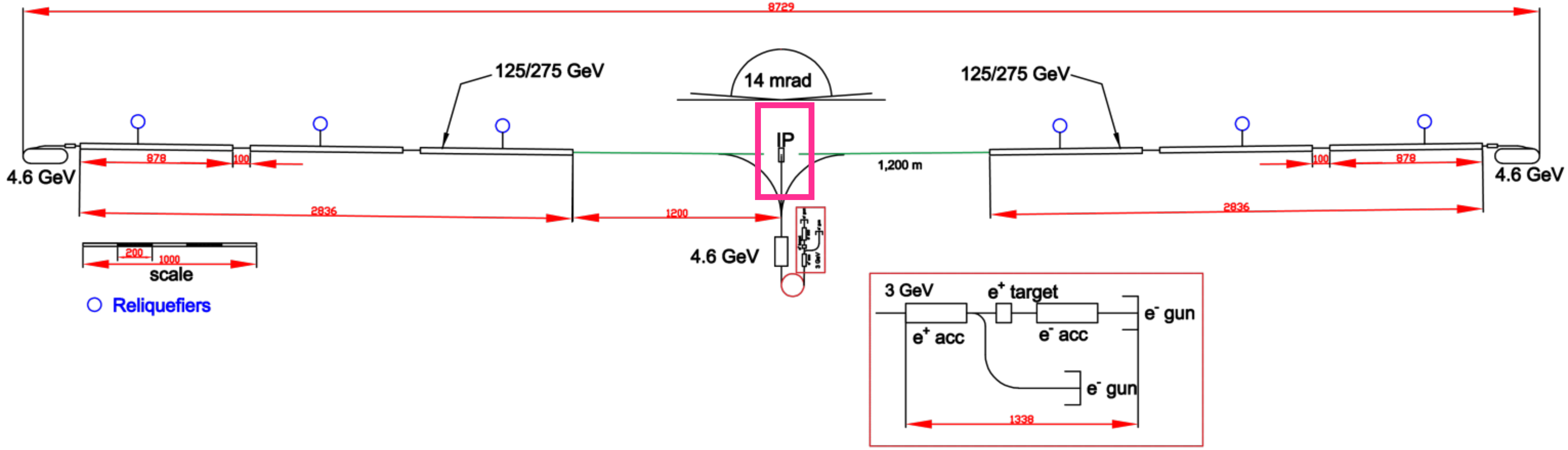
Constant luminosity

Very low duty cycle at LC (0.5% ILC, 0.03% C³) allows for trigger-less readout and power pulsing

- Factor of 100 power saving for front-end analog power and signal integration through the trains, then leisurely readout
- **O(1-100) ns bunch identification capabilities**

One thing about the IP

2503.20829



Main linac: beam particles are accelerated from O(10) GeV up to a maximum of 275 GeV over few kms (4/15 for C^3/ILC)

$\epsilon_x : \mathcal{O}(100\,\mathrm{nm})\ \epsilon_y : \mathcal{O}(10\,\mathrm{nm})$

Beam Delivery System (BDS): energy and betatron collimation, then the final-doublet quads achieve very high focusing:

$\beta_x^* : \mathcal{O}(10\,\mathrm{mm})\ \beta_y^* : \mathcal{O}(0.1\,\mathrm{mm})$

Interaction Point (IP) the two beams collide with beam parameters

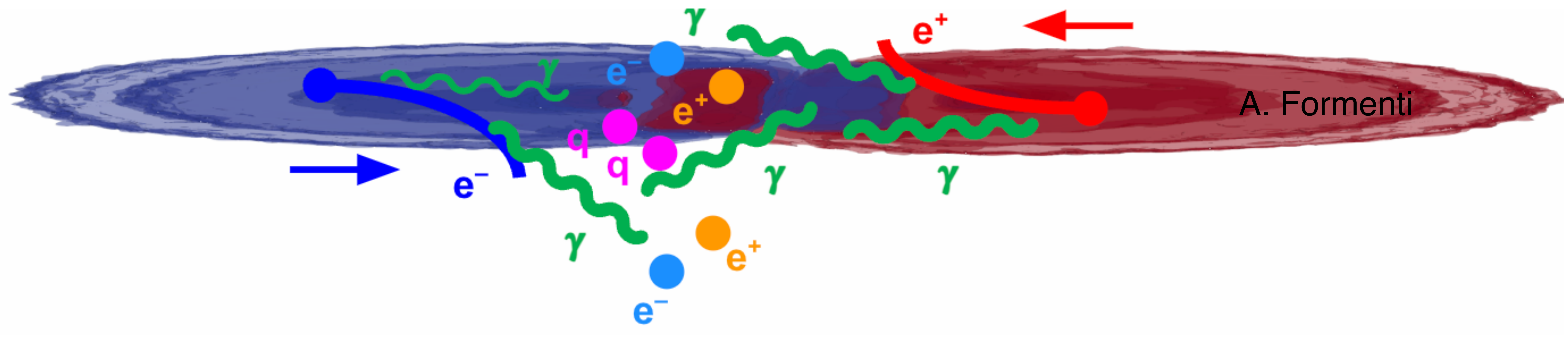
$\sigma_x^* : \mathcal{O}(100\ \mathrm{nm})\ \sigma_y^* : \mathcal{O}(\mathrm{nm})$

# of particles per bunch, # of bunches per train, repetition rate determine

$$\mathscr{L} \sim \frac{N_e^2 n_b f_r}{4\pi\sigma_x^*\sigma_y^*} = \mathcal{O}(10^{34})\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

Luminosity vs. Beam-Beam interactions

Machine parameters optimization can lead to luminosity increases but …



- Beam-beam interactions are strictly dependent on the emittances, leading to enhanced background production which can compromise detector performance
- It directly impacts the beam pipe radius and hence the first layer of the vertex detector position
- Beam-beam effects are simulated with Guinea-Pig, and more recently WarpX has been developed to include a self-consistent treatment of the fields produced by the pairs

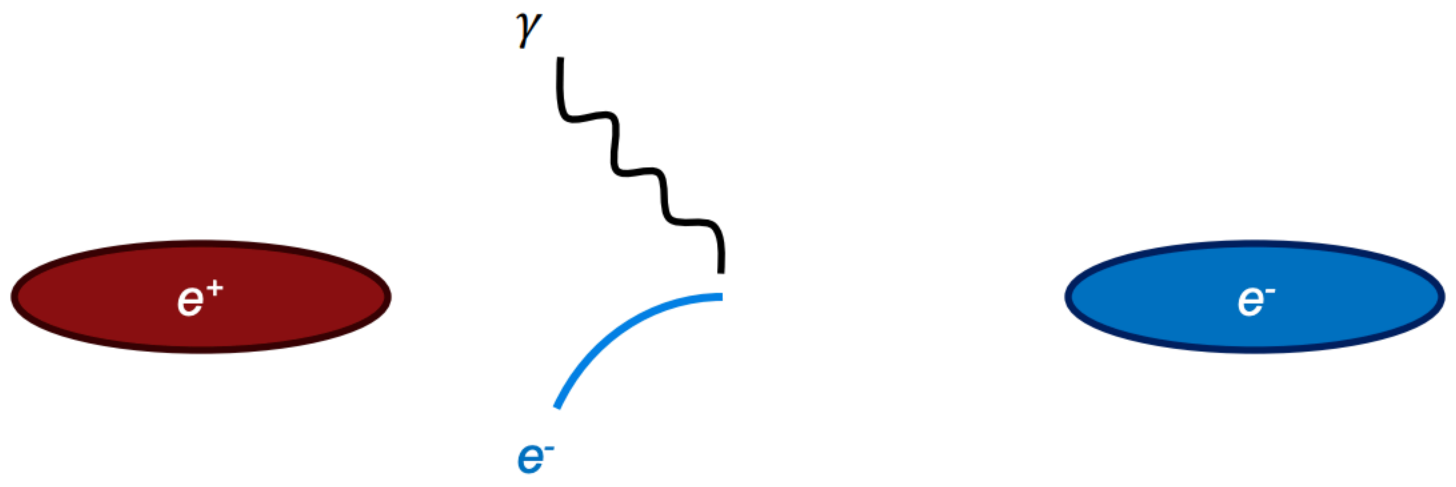
Importance of beam-beam background

PRAB 2024 27.061001

The effects of beam-beam interactions have to be careful simulated for physics and detector performance

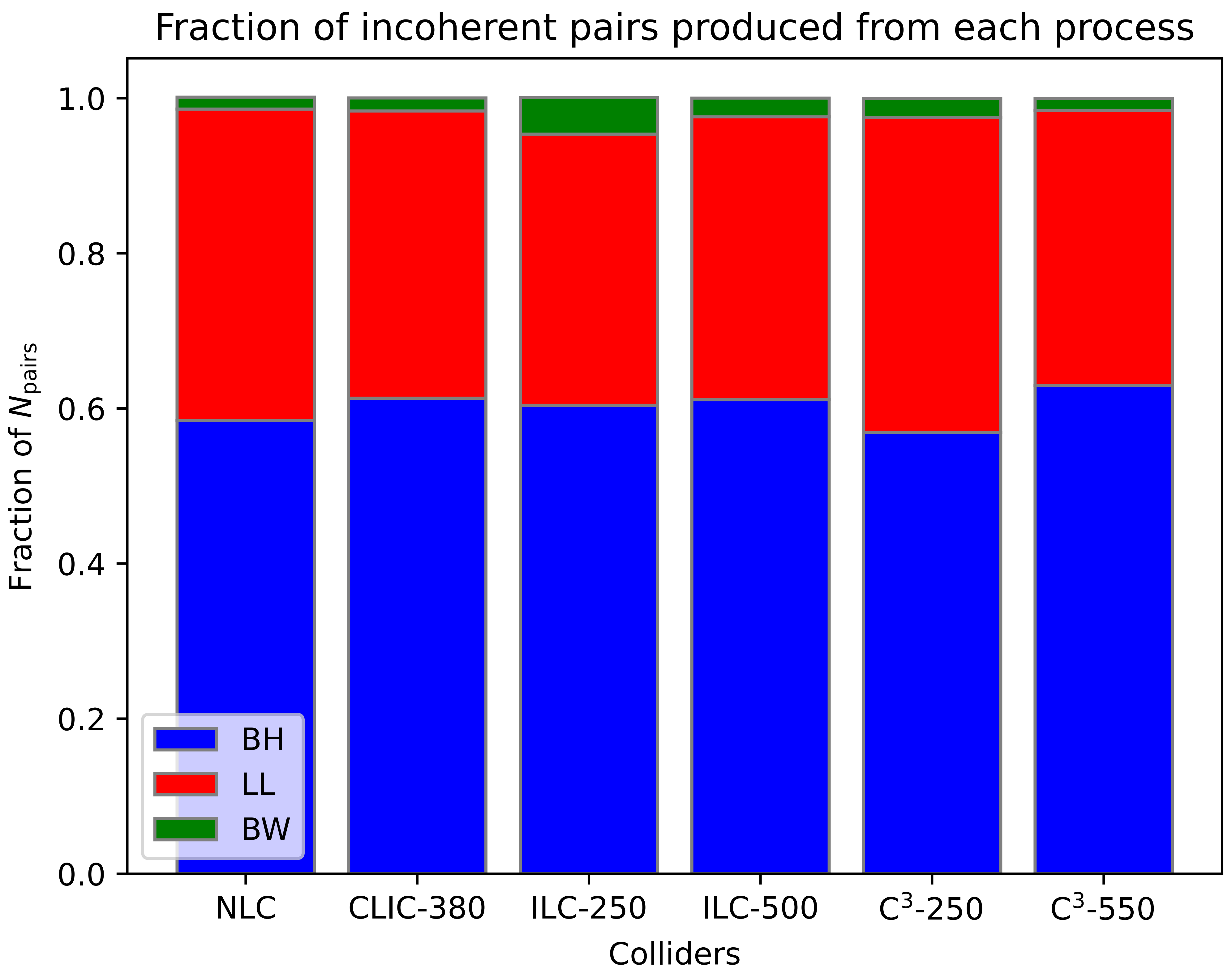
Beamstrahlung photons are radiated at the IP and can produce:

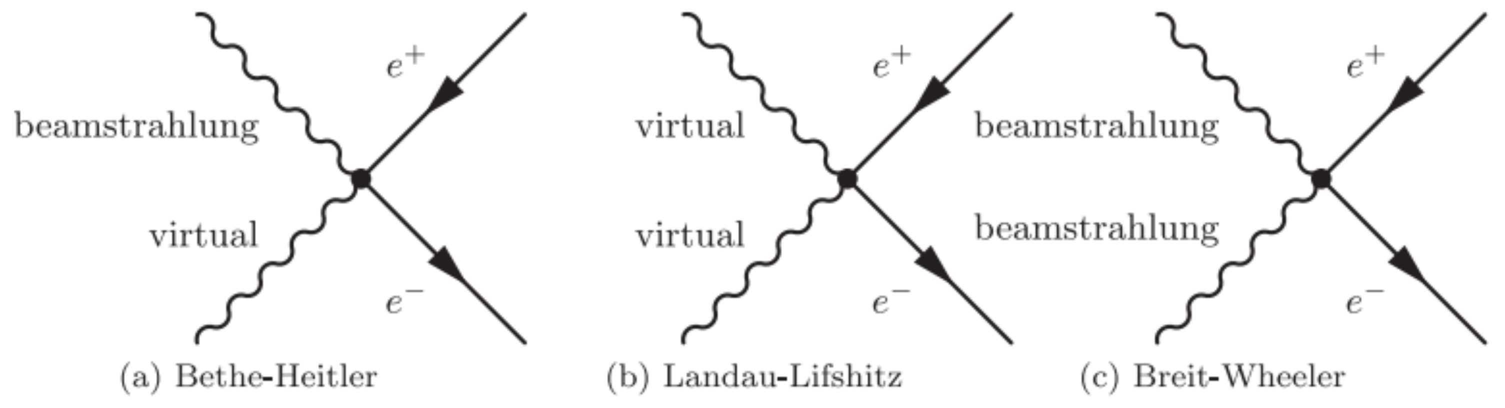
- Incoherent pair production
- Muon and Hadron photo-production



Beamstrahlung widens the luminosity spectrum

- Enables collisions at lower $\sqrt{s}$
  → important for physics observables (ZH)
- High flux (occupancy) in vertex barrel and forward sub detectors
  → **Impacts (vertex) detector design**



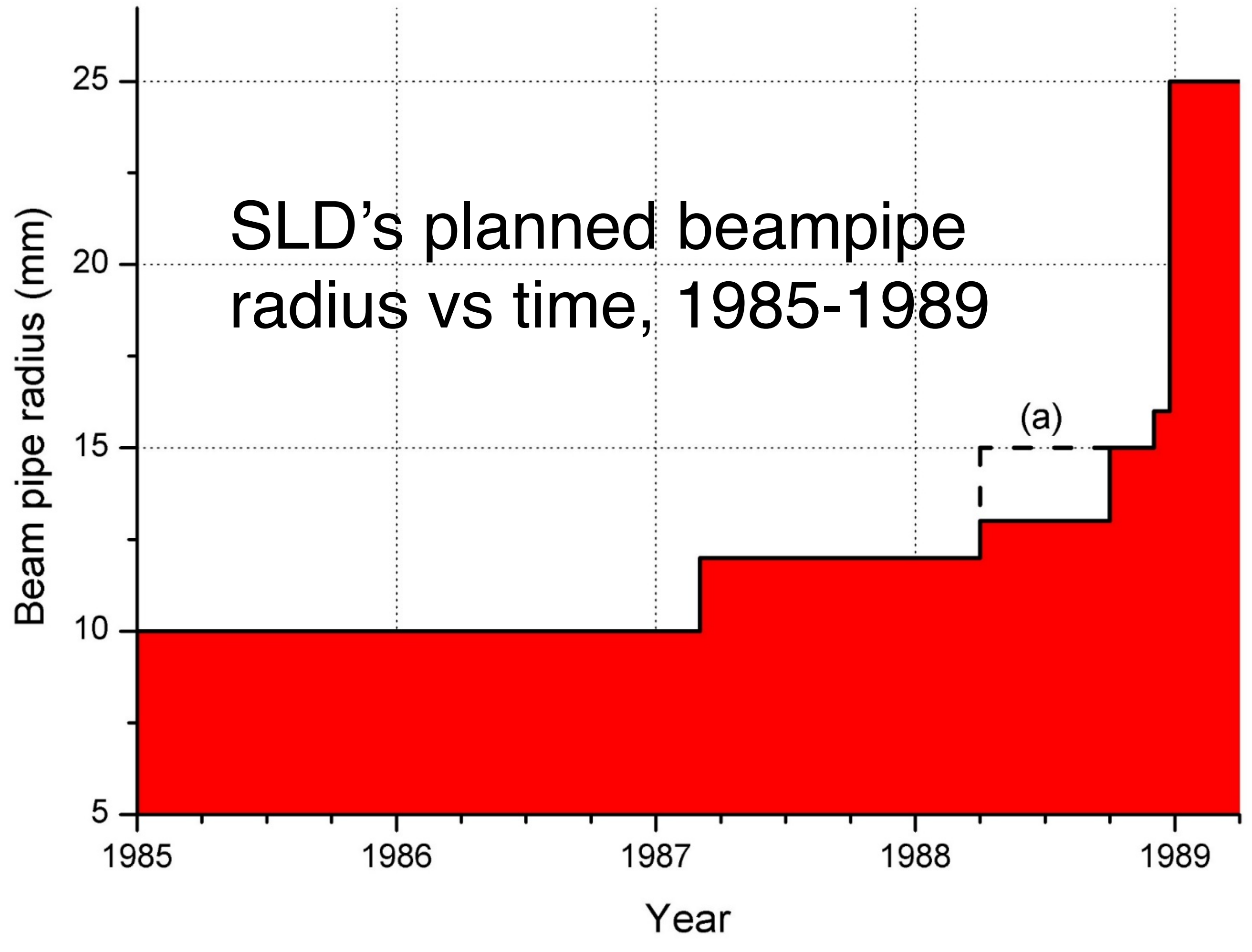


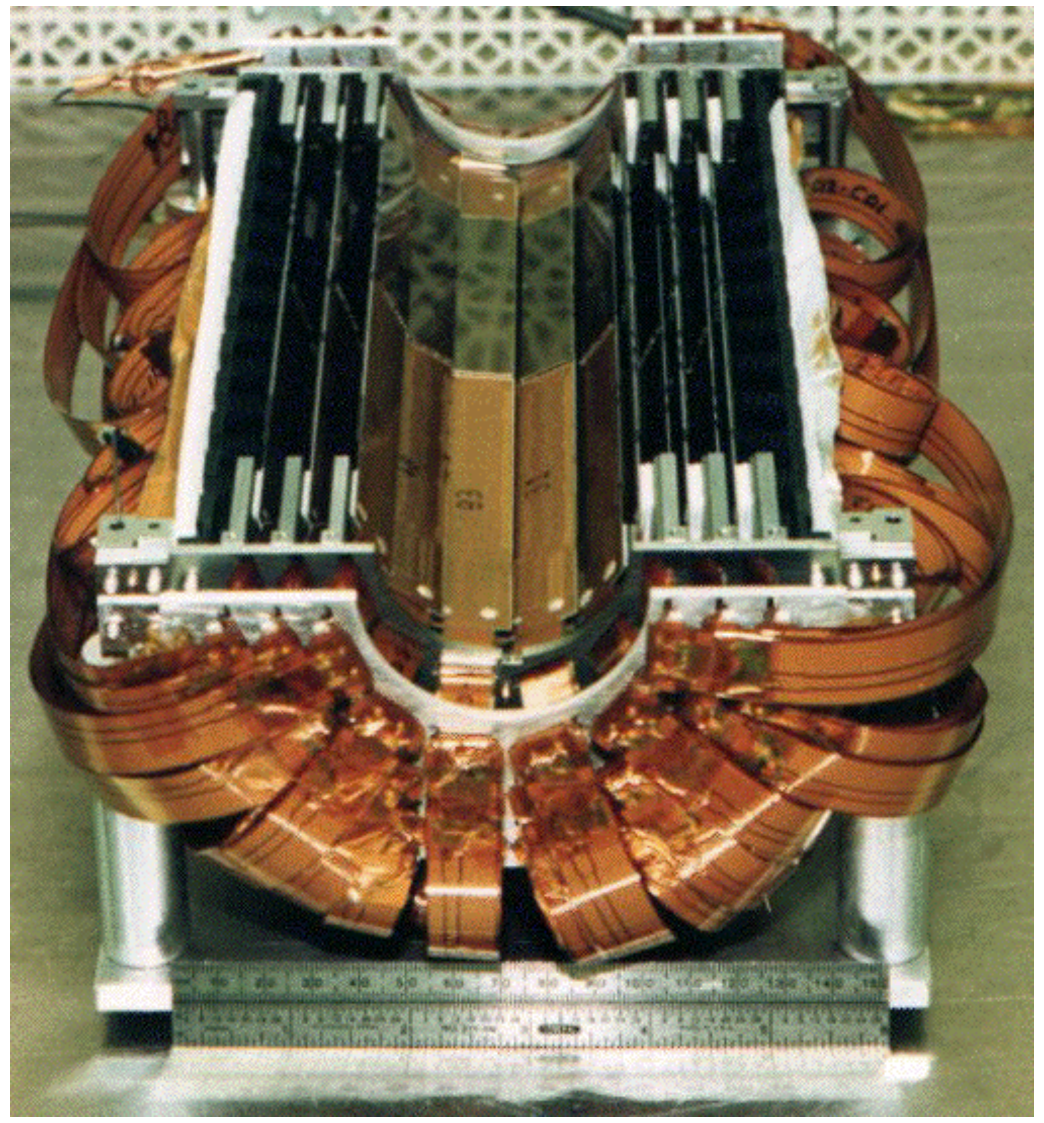
A lesson from the past

Courtesy of Chris Damerell

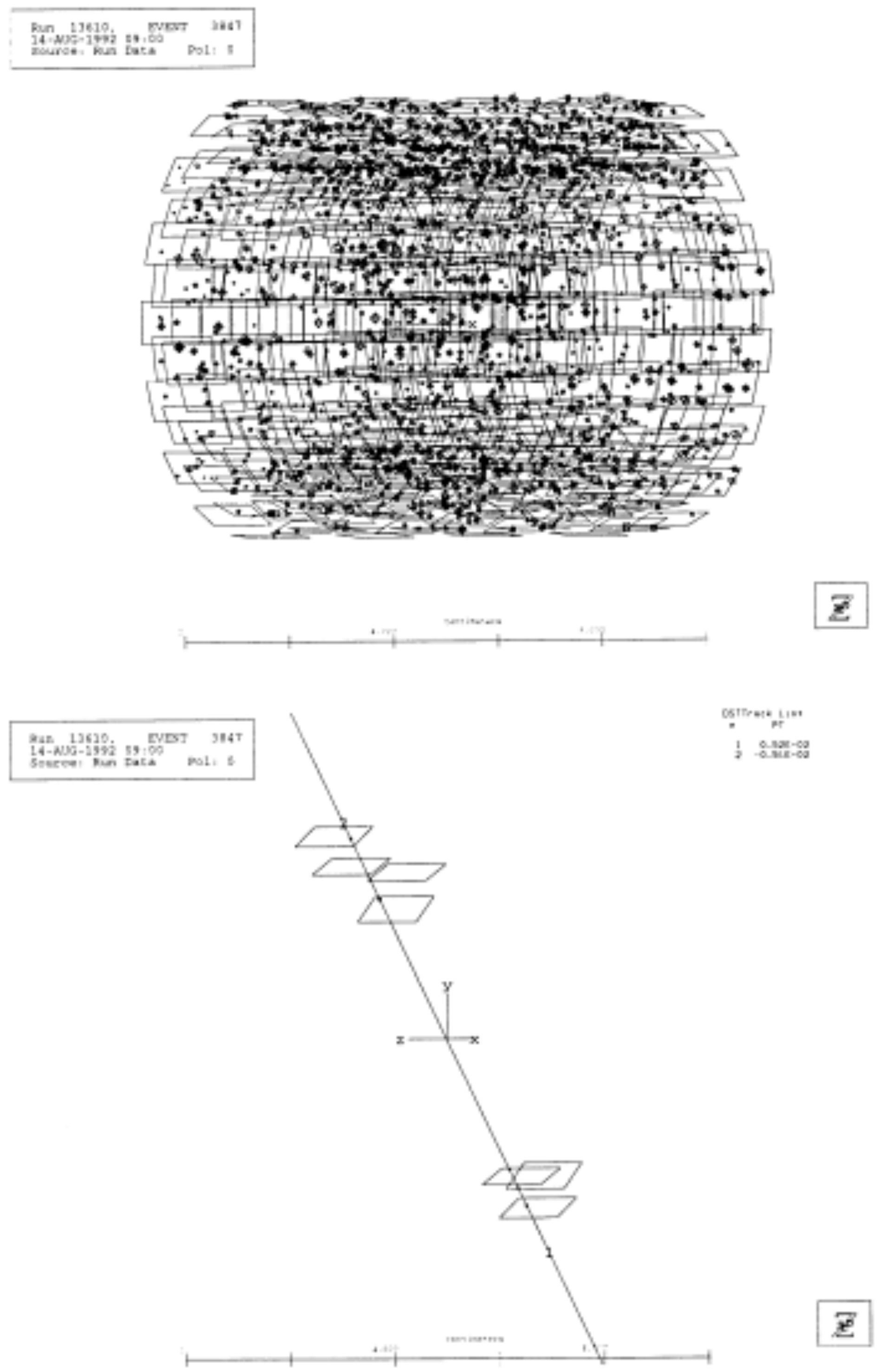
SLD at the SLAC Linear Collider (SLC)

- Incoherent pair production was not very well understood at that time (1980s)
- SLD’s CCD readout sparsification used ~150 e^- thresholds, achieving 3.6 *μ*m resolution
  - occupancy was very low (0.002%) and event reconstruction worked well
- SLD vertex detector backgrounds dominated by low-energy x-rays (0.5–10 keV) ~ pixel clusters of ~150–800 e^-
  - Incoherent e^+e^- pairs at the IP producing diffuse photon fields (~500 keV → cascaded x-rays).
  - Two-photon interactions (π^0 decay, pion charge exchange → cascades).
  - Quad synchrotron radiation from beam tails


SLD’s planned beampipe radius vs time, 1985-1989



1996, R_{bp} = 25 mm
60 *stitched* CCDs
307 Mpixels

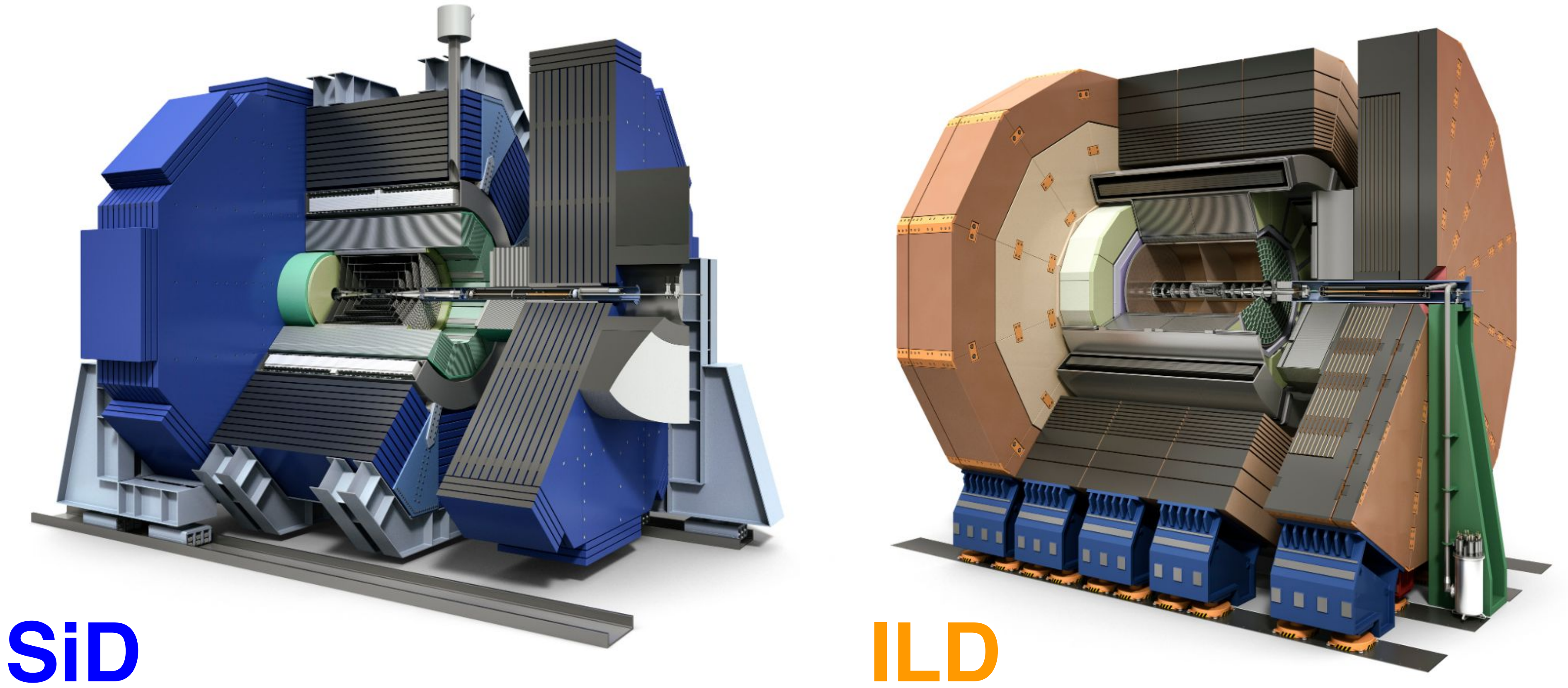


From physics to detector

2110.09965
2003.01116

Stringent detector requirements from ZH & flavor tagging

- Strong **magnetic field** 4-5 T
- (Ultra) low material budget & high granularity **tracker** close to the interaction point for optimal b/c separation
  - <1% X0 per layer for Si-tracker
  - At least 5 μm hit resolution (17-25μm pitch)
- High granularity **calorimeter** with resolution of
  - 3-4% for E_{jet} 30-100 GeV for separation of W/Z/H→qq peaks



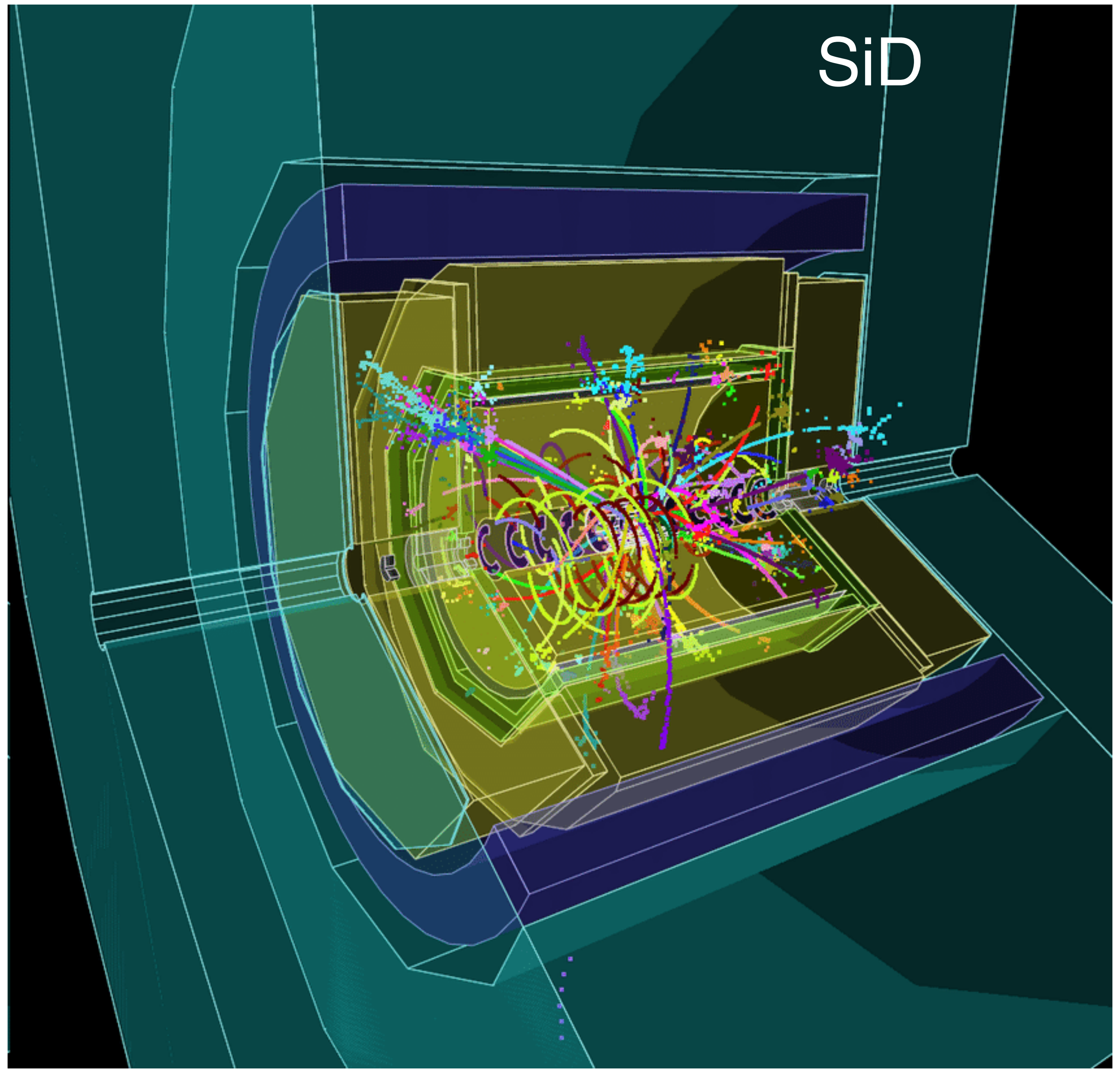
SiD - Compact all silicon tracking systems with highly segmented calorimeters optimized for PFA

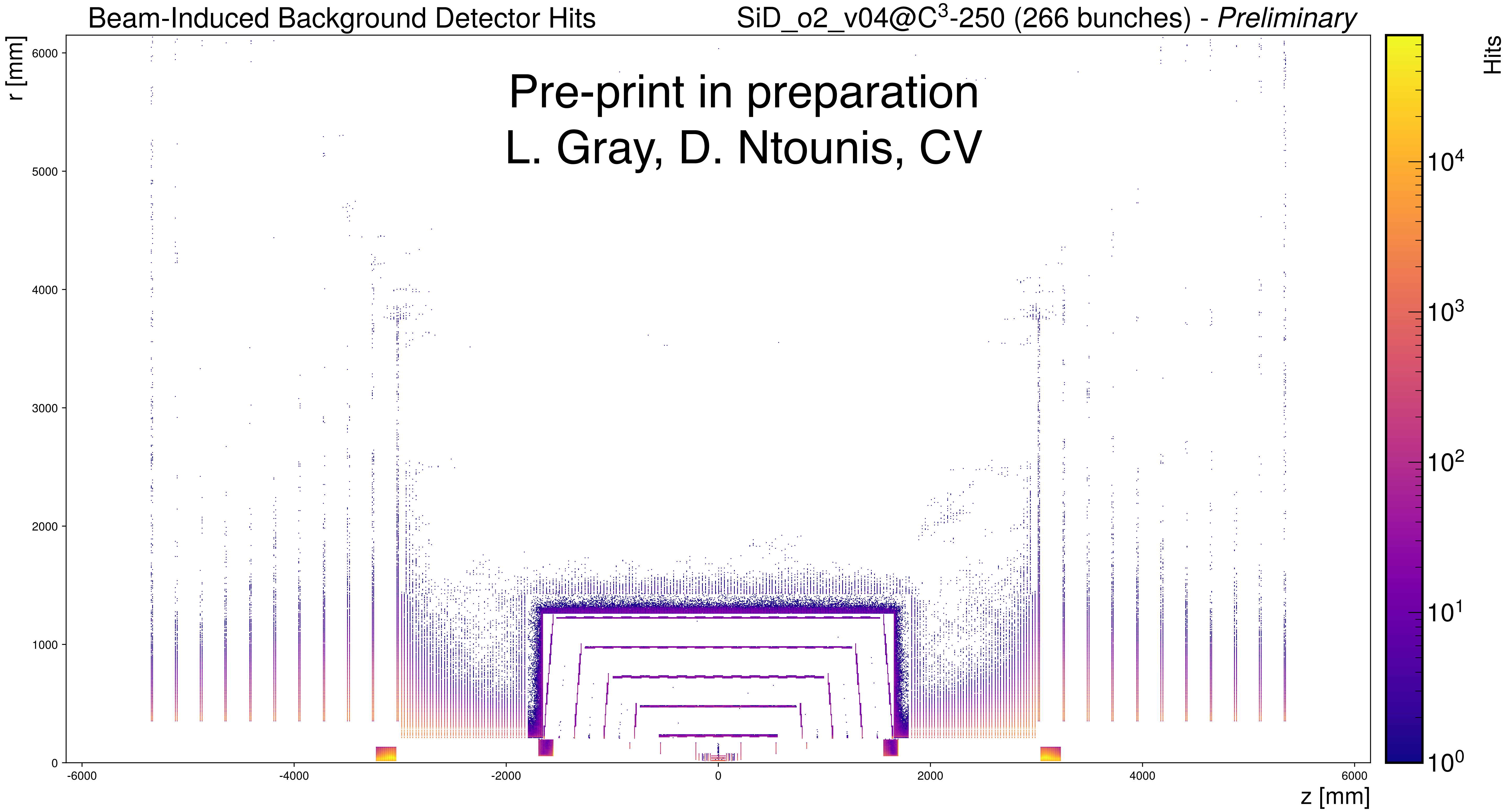
ILD - Larger detector with TPC tracker with PFA calorimeter

F. Palla ECFA 2024
ILC WG3 March 21
arXiv:2403.07093

Importance of beam-beam background

The effects of beam-beam interactions have to be careful simulated for physics and detector performance





Detector Hits from beam-beam background pairs for an entire C^3 bunch train
Full detector simulation in Key4hep using the SiD detector concept

BBB as a function of machine parameters

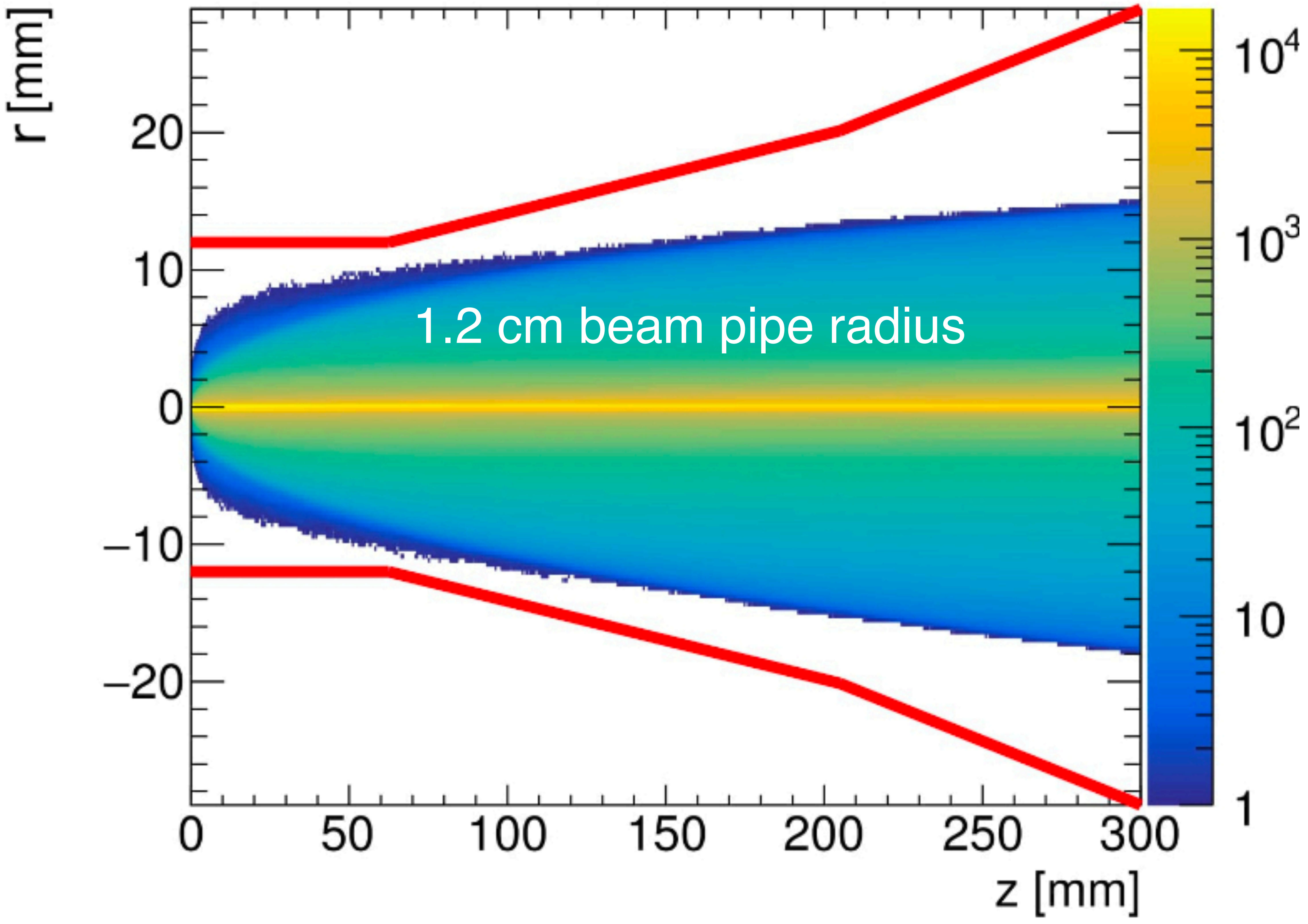
Anne Schutz’s PhD thesis

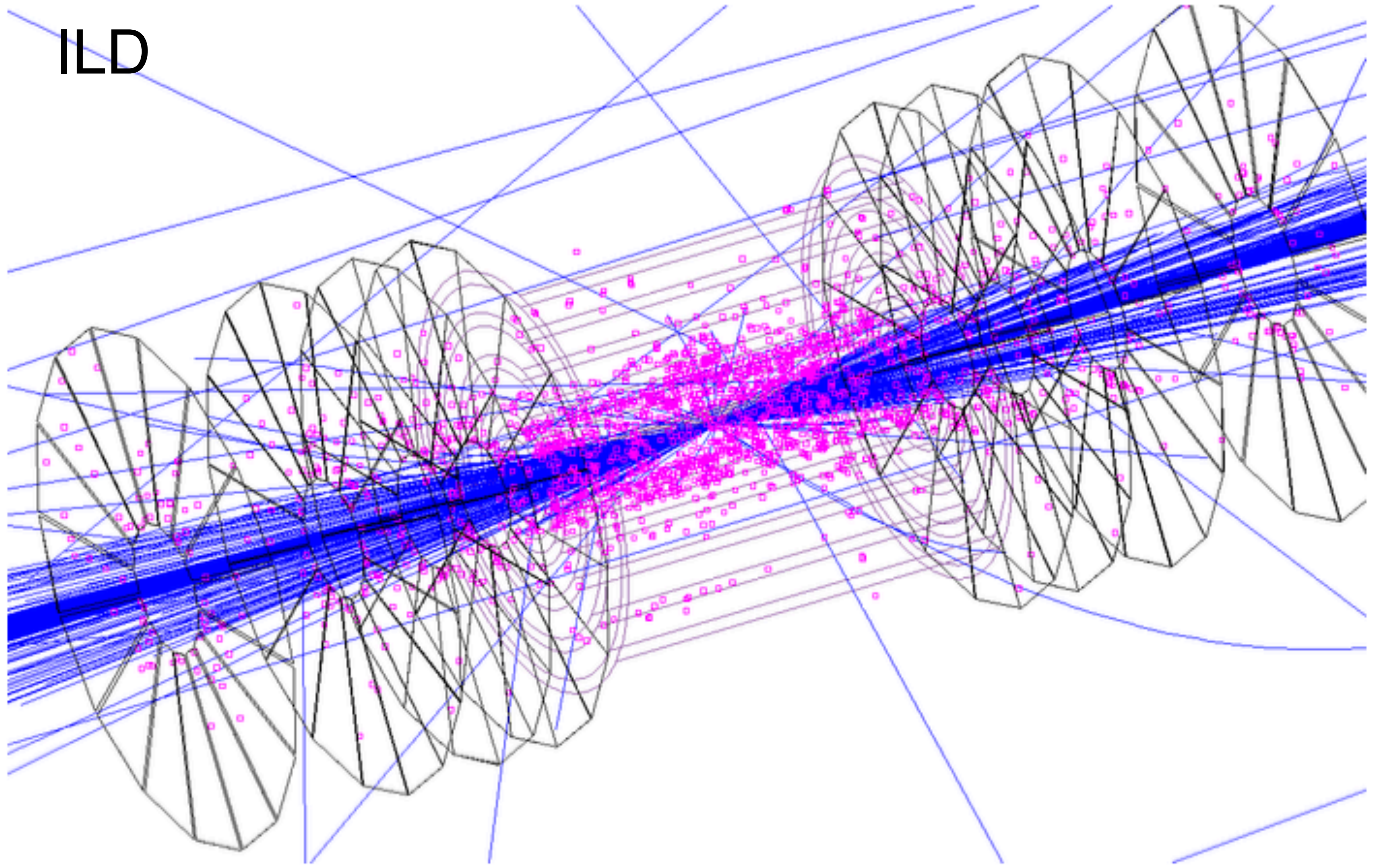
Same tools and methodology between ILC & FCC within Key4HEP

ILC physics studies estimated a maximum occupancy of 0.03 hits/mm^2/BX for a pixel occupancy of ~10% per bunch train

Time stamping - resolution of O(μs) - to reduce occupancy to 10^{-4}

ILC-250 $\varepsilon_X = 10\ \mu m$





Averaged for one bunch-crossing

BBB as a function of machine parameters

Anne Schutz's PhD thesis

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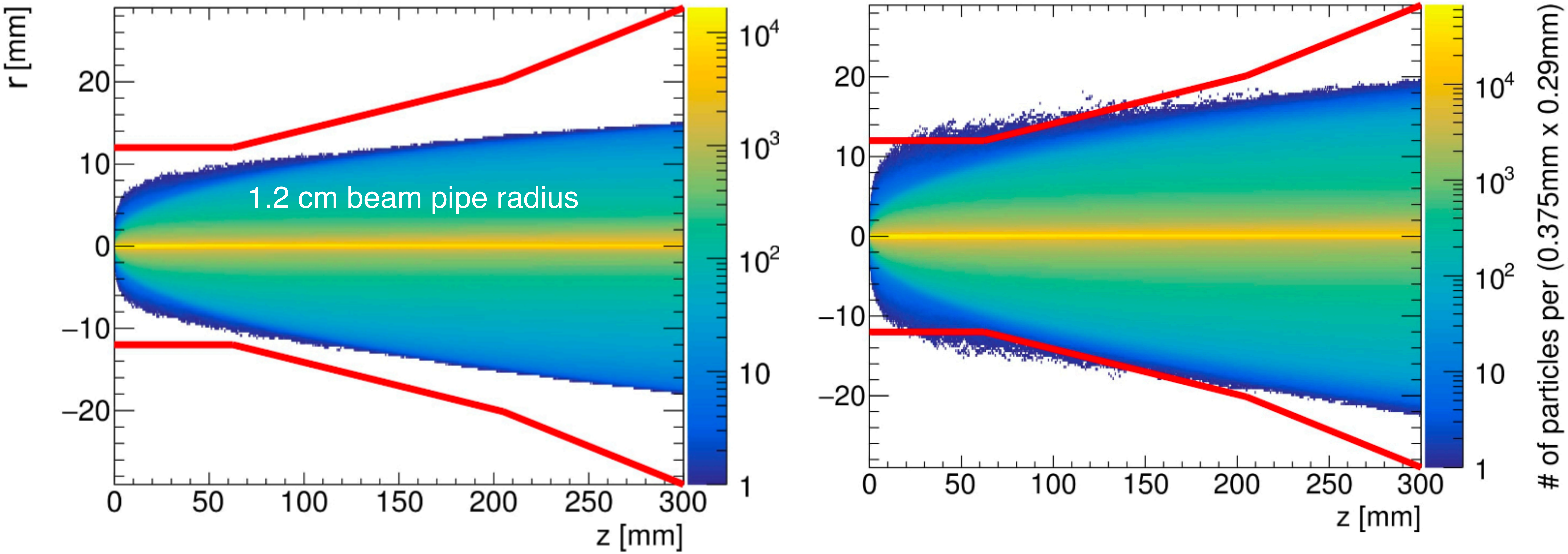

ILC-250 $\varepsilon_X = 10\ \mu m$

$\varepsilon_X = 5\ \mu m$

Averaged for one bunch-crossing

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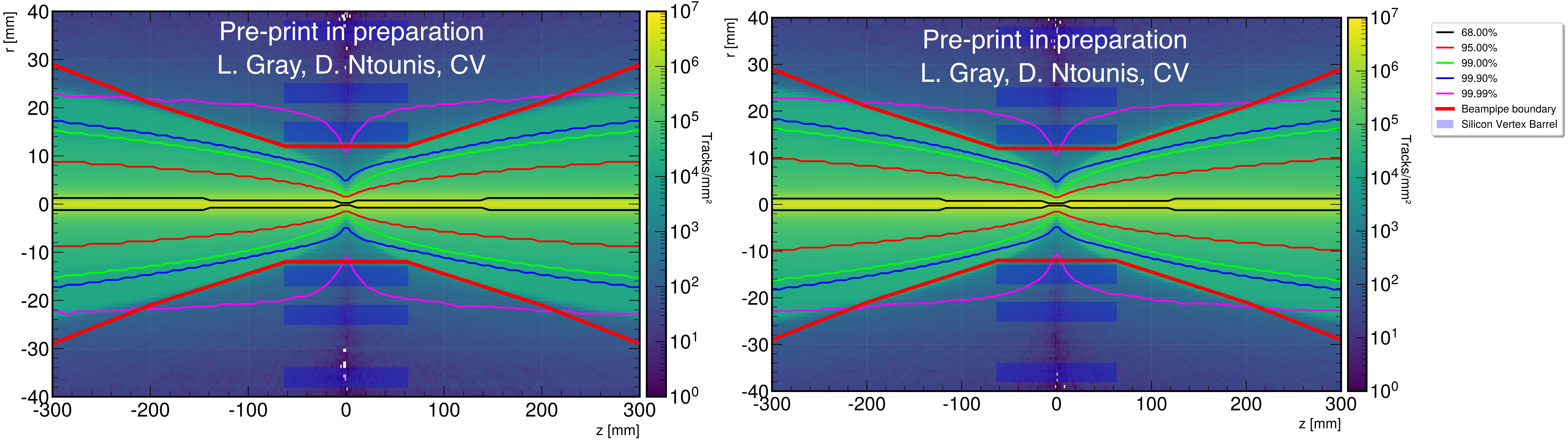
arXiv:2403.07093
Anne Schutz's PhD thesis

Compared to ILC, C^3 shows an increase on level of background, as the transverse momentum of the secondary particles increases due to reduced emittance ε_Y (35 nm vs 20 nm)

Impact of beam induced backgrounds also increases with center of mass of energy


C3-250

C3-550

Integrated per one bunch train

BBB as a function of machine parameters

arXiv:2403.07093
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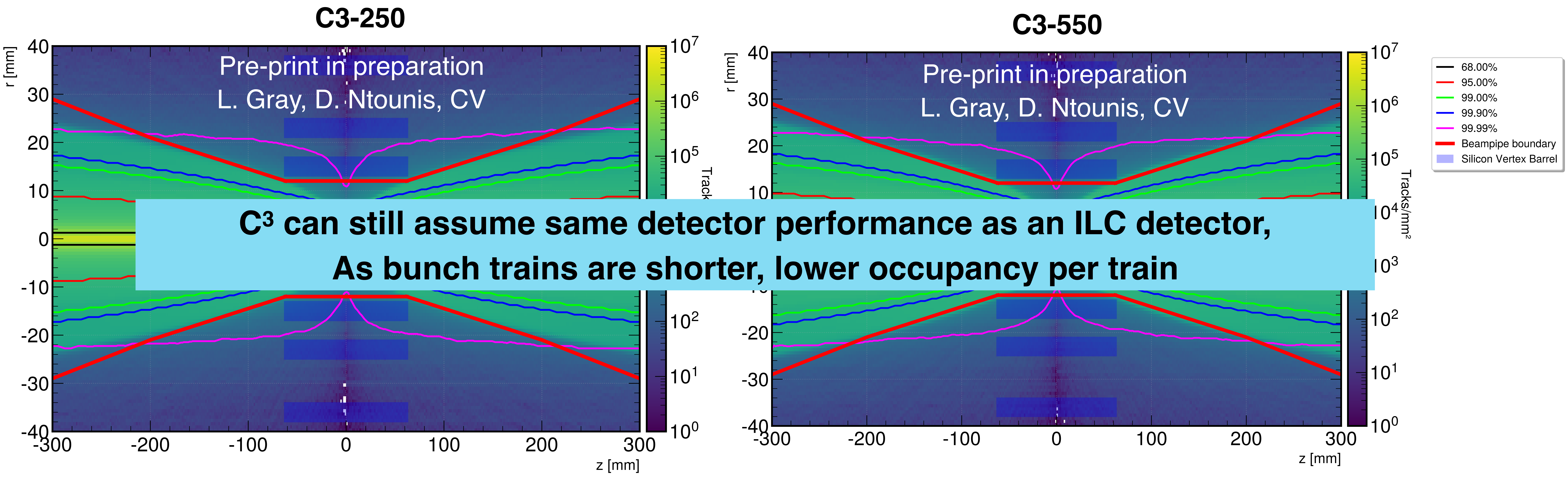


Pre-print in preparation
L. Gray, D. Ntounis, CV

C^3 can still assume same detector performance as an ILC detector,
As bunch trains are shorter, lower occupancy per train

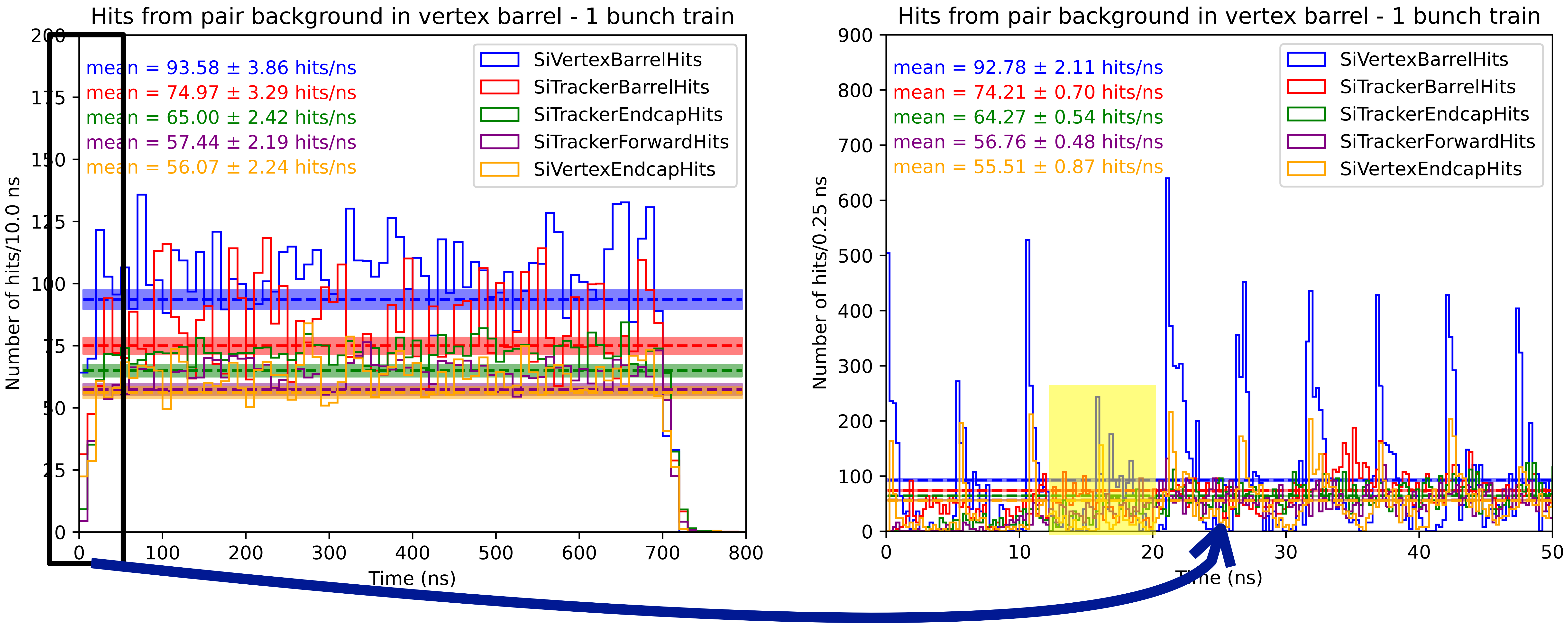
Integrated per one bunch train

D. Ntounis (2023)

Time structure also matters

The secondary peak at ~20-25 ns is due to backscattering from the BeamCal

Time distribution of hits per unit time and area on 1st layer $\sim 4.4 \cdot 10^{-3}$ hits/(ns$\cdot$mm^2) $\simeq 0.03$ hits/mm^2 /BX within the limits set for SiD from previous studies for ILC



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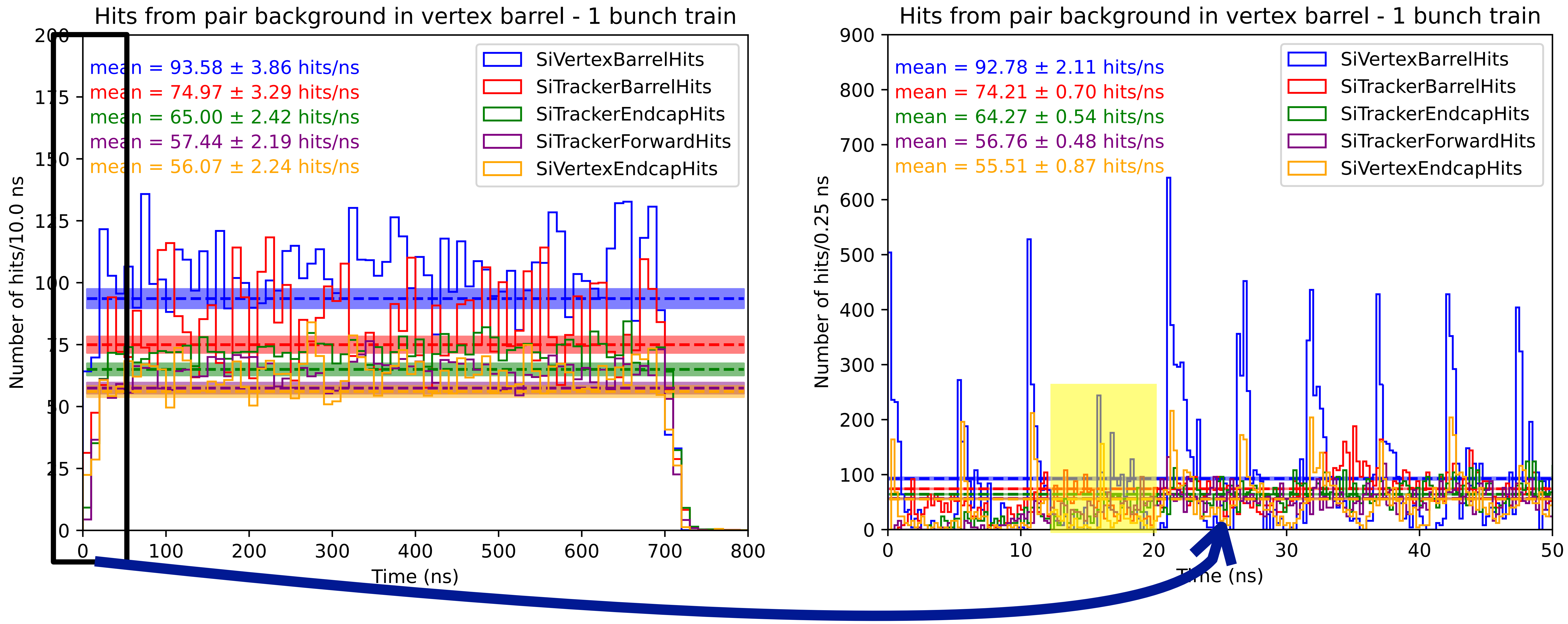


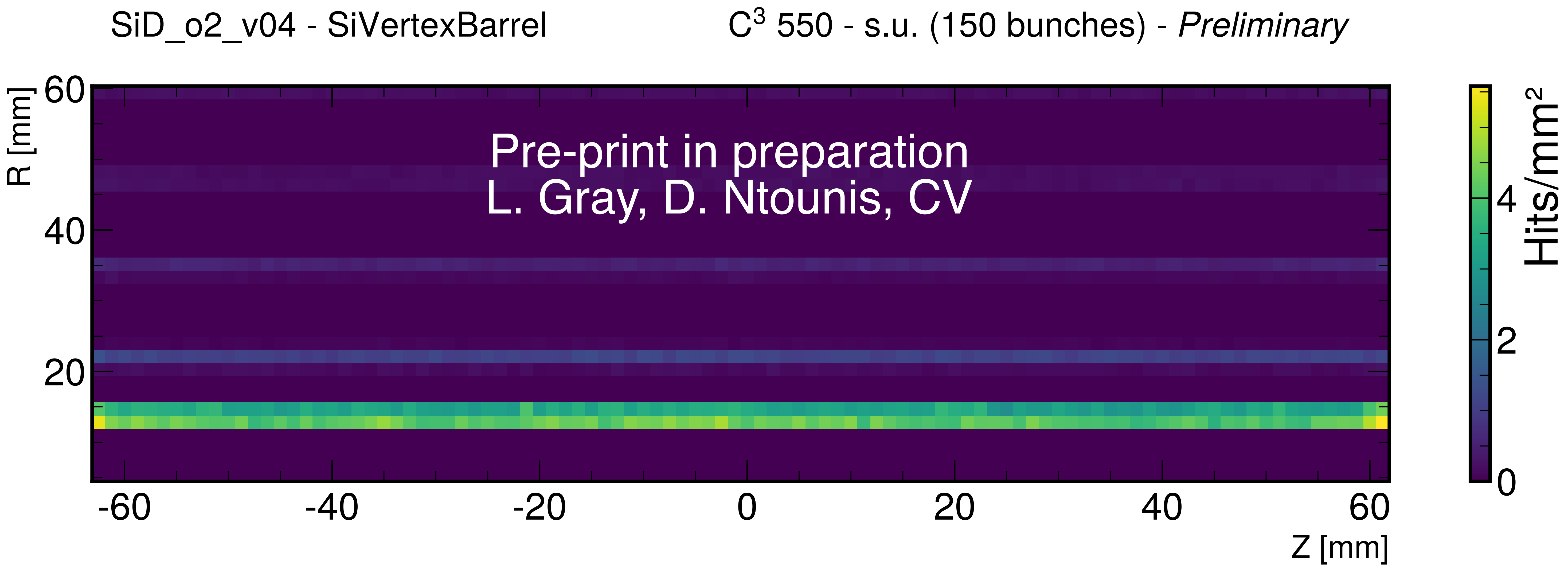
Impact of beam-induced background to be mitigated through MDI and detector design

O(1-10) ns for beam background rejection and/or trigger decision before reading out the detector

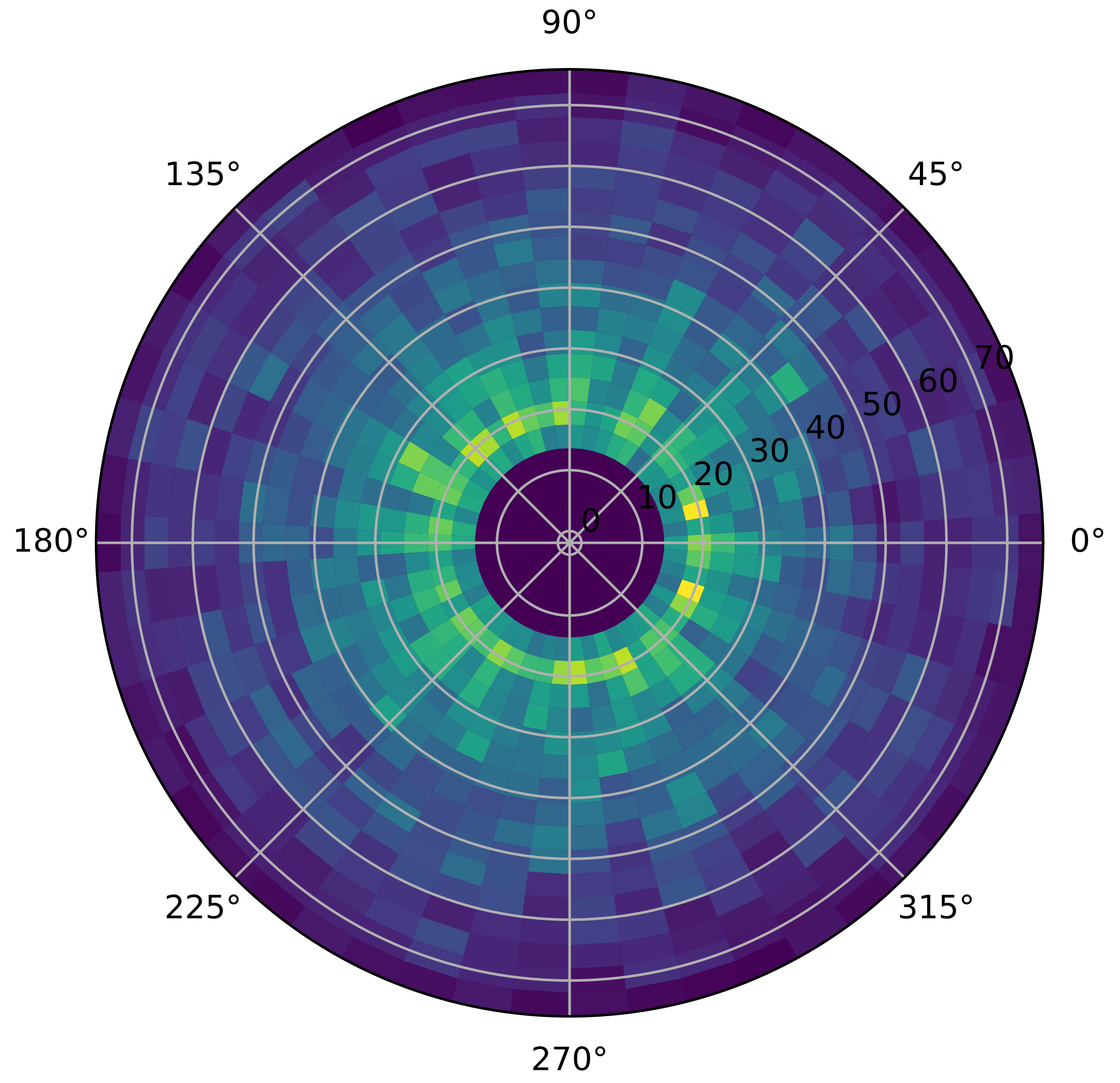
arXiv:2403.07093

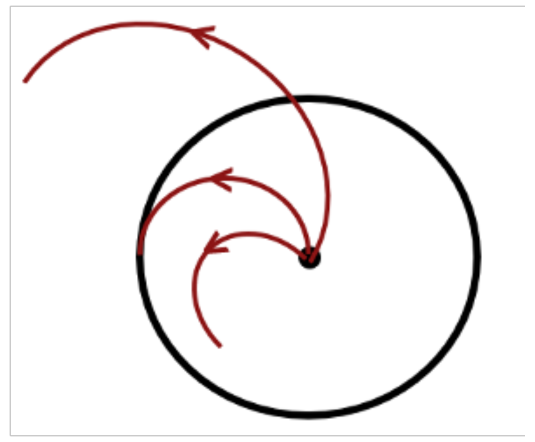
Occupancy per bunch train

For ILC detectors, an occupancy upper limit of 10^{-4} and buffer depth of 4 has been proposed.
Studies have been recently repeated for C^3 and found the level of the backgrounds to be compatible with an ILC like-detector



Pre-print in preparation
L. Gray, D. Ntounis, CV





$$p_T^{(\mathrm{min})}[\mathrm{MeV}] = 0.3 \cdot B[\mathrm{T}] \cdot \frac{\rho}{2}[\mathrm{mm}] \simeq 10\ \mathrm{MeV}$$

Note that at low momentum incoherent pairs deflected by B field

Occupancy per bunch train

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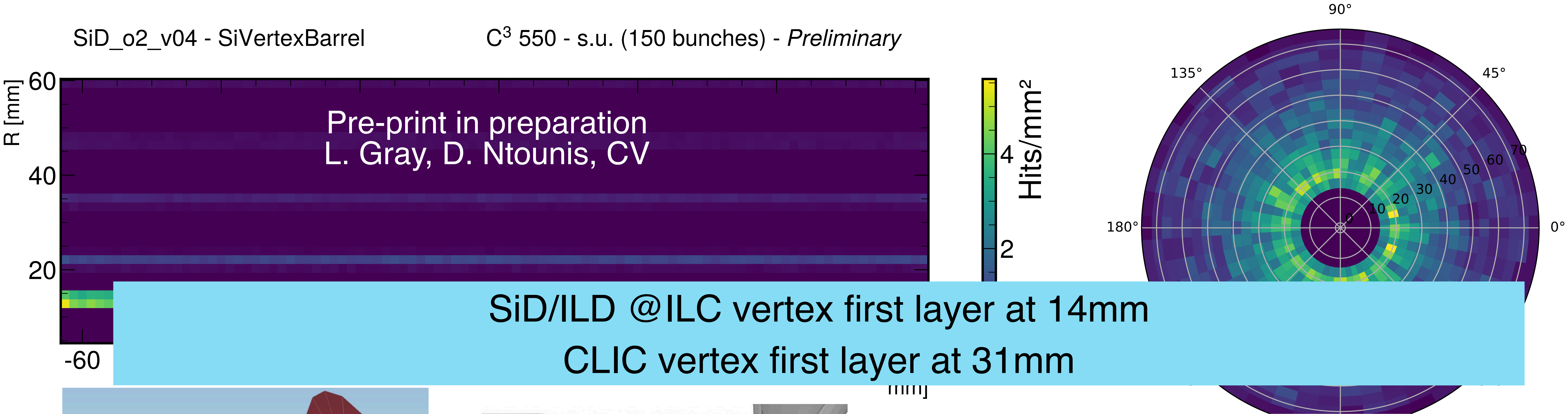
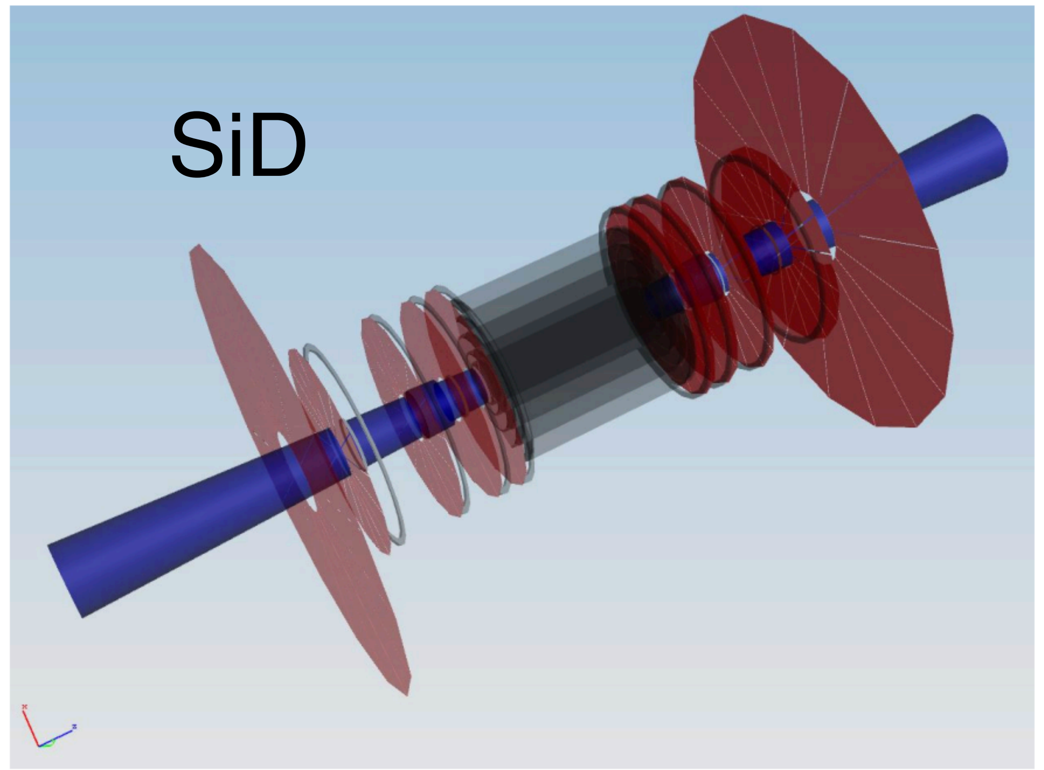
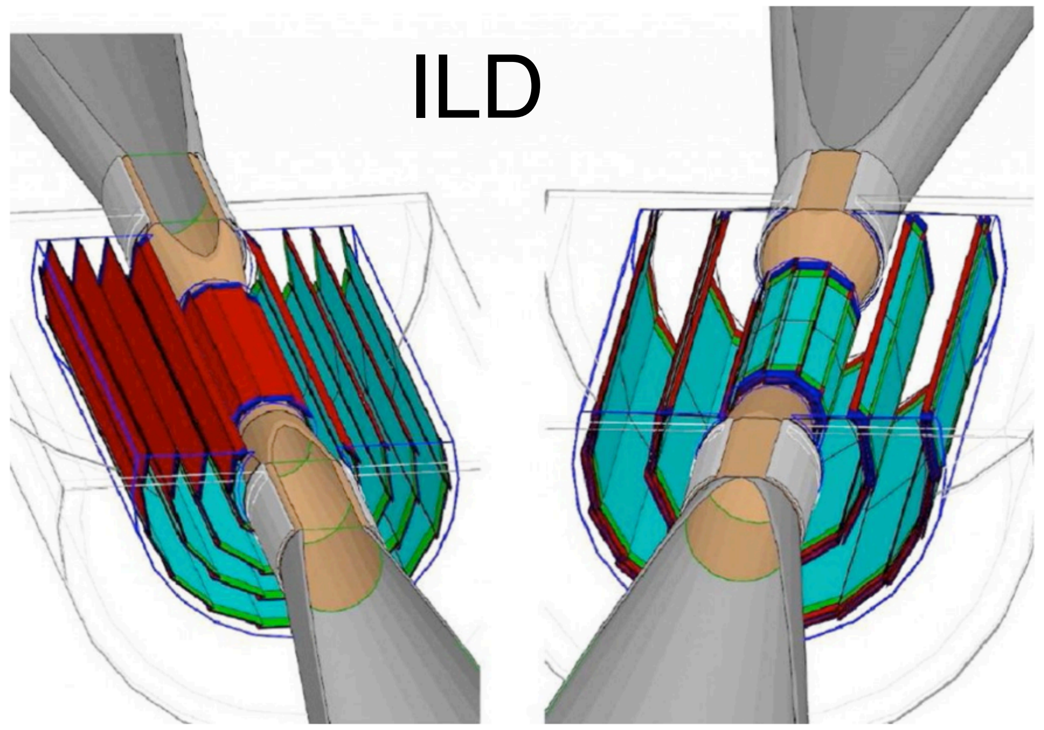


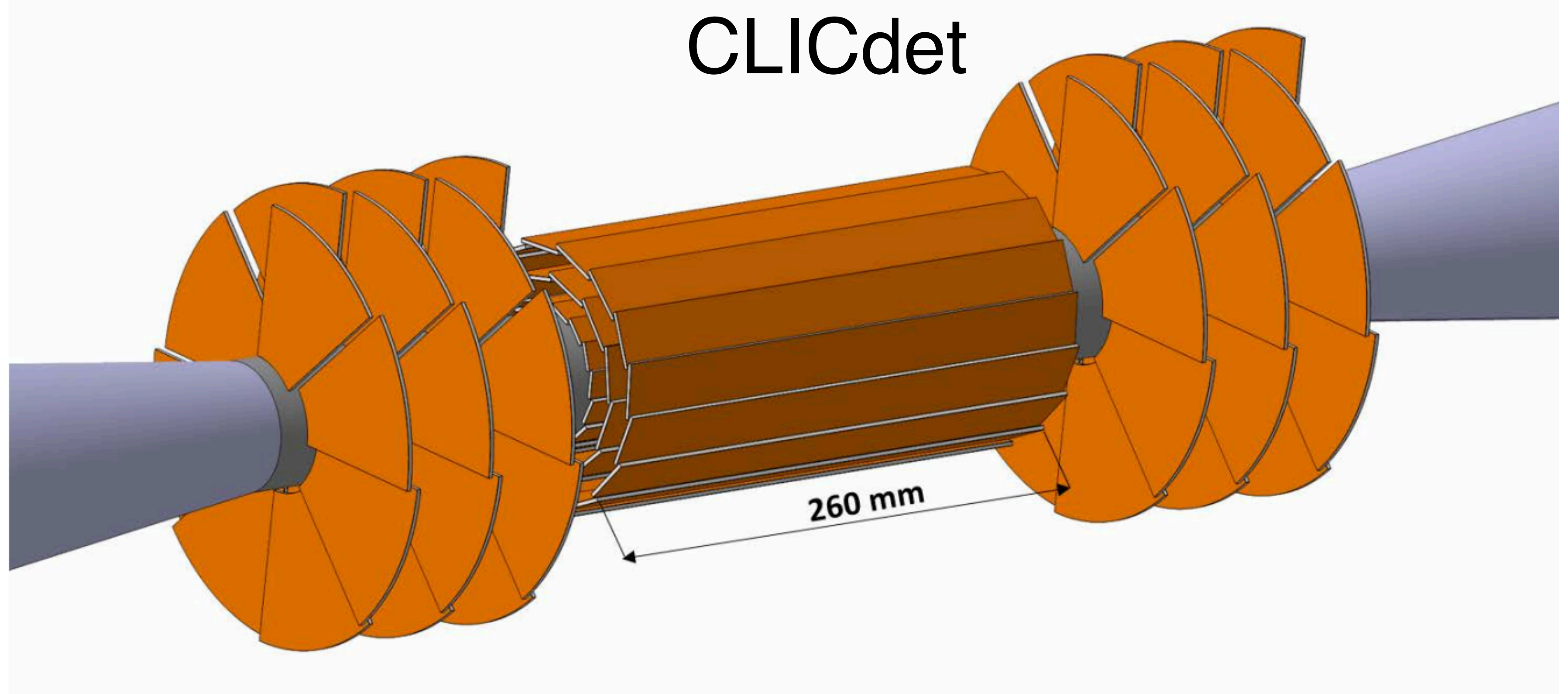
Pre-print in preparation
L. Gray, D. Ntounis, CV

SiD/ILD @ILC vertex first layer at 14mm

CLIC vertex first layer at 31mm



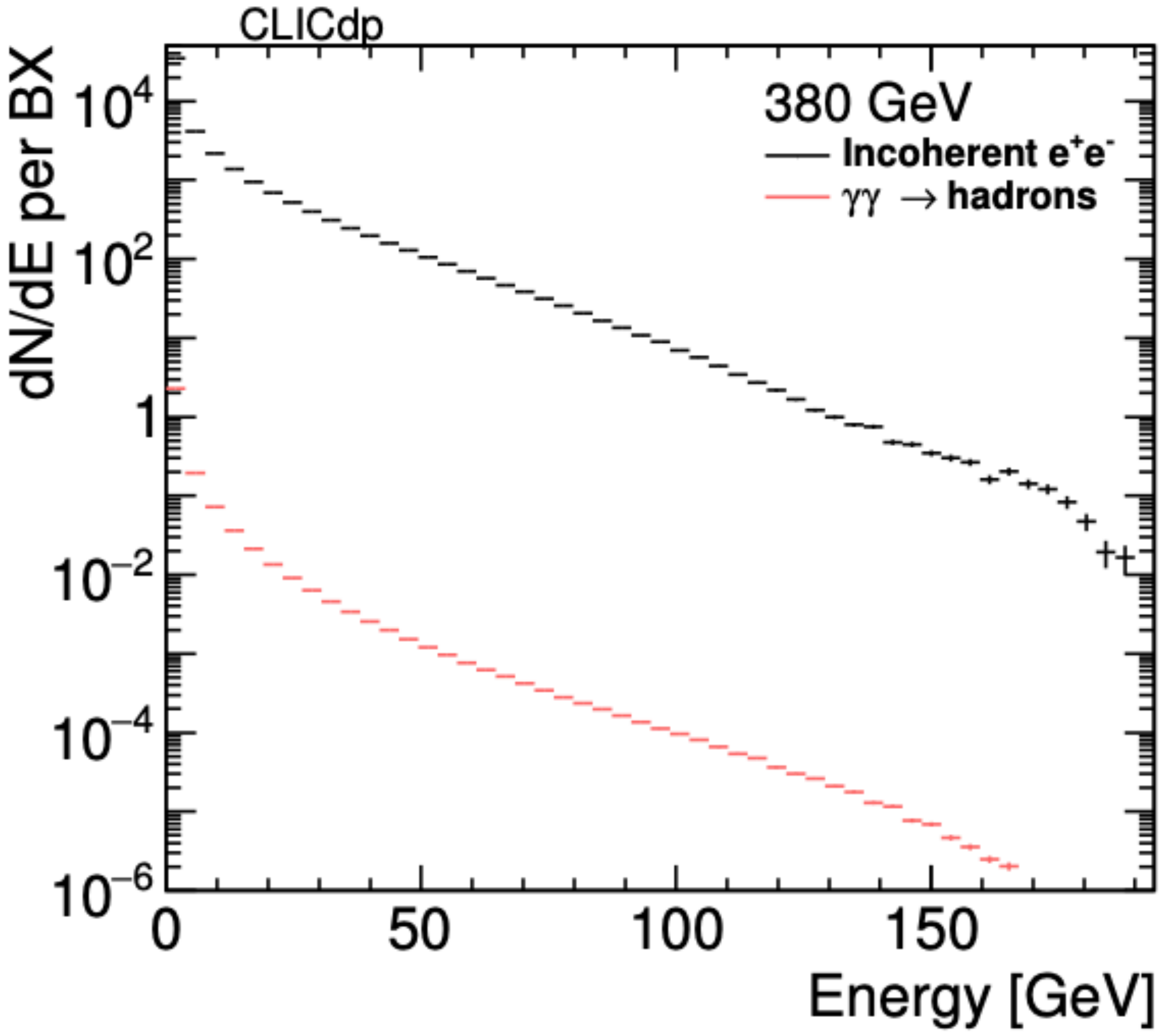


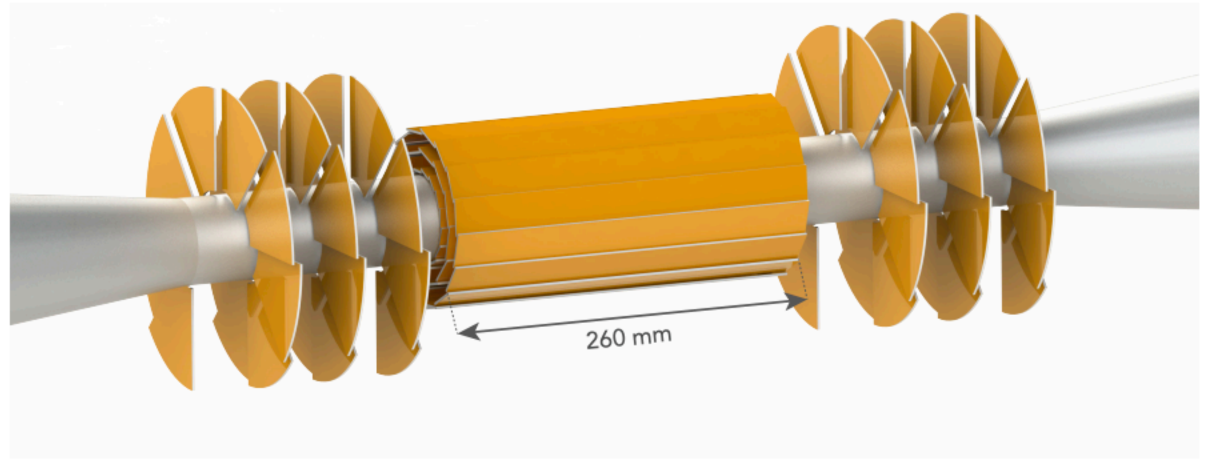


ILC Technical Design Report 2013
CLIC-det post-CRD design 2017
1812.07337

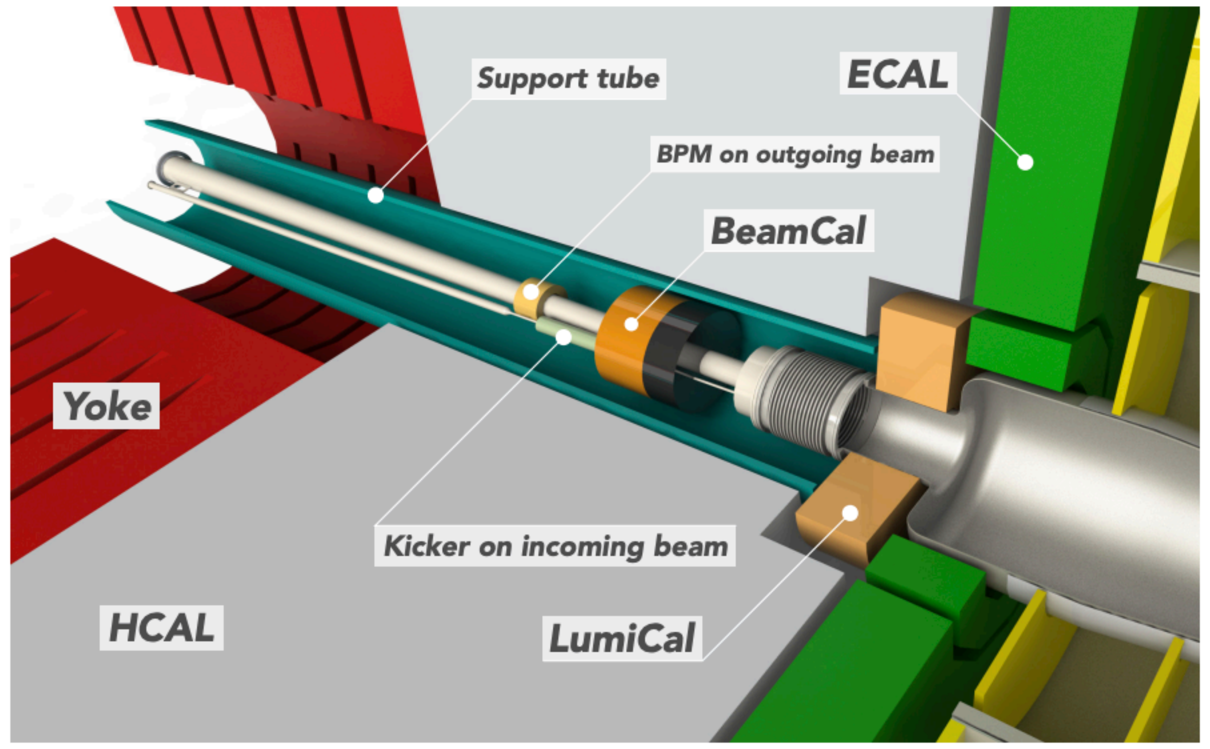
Evolution of detector concepts

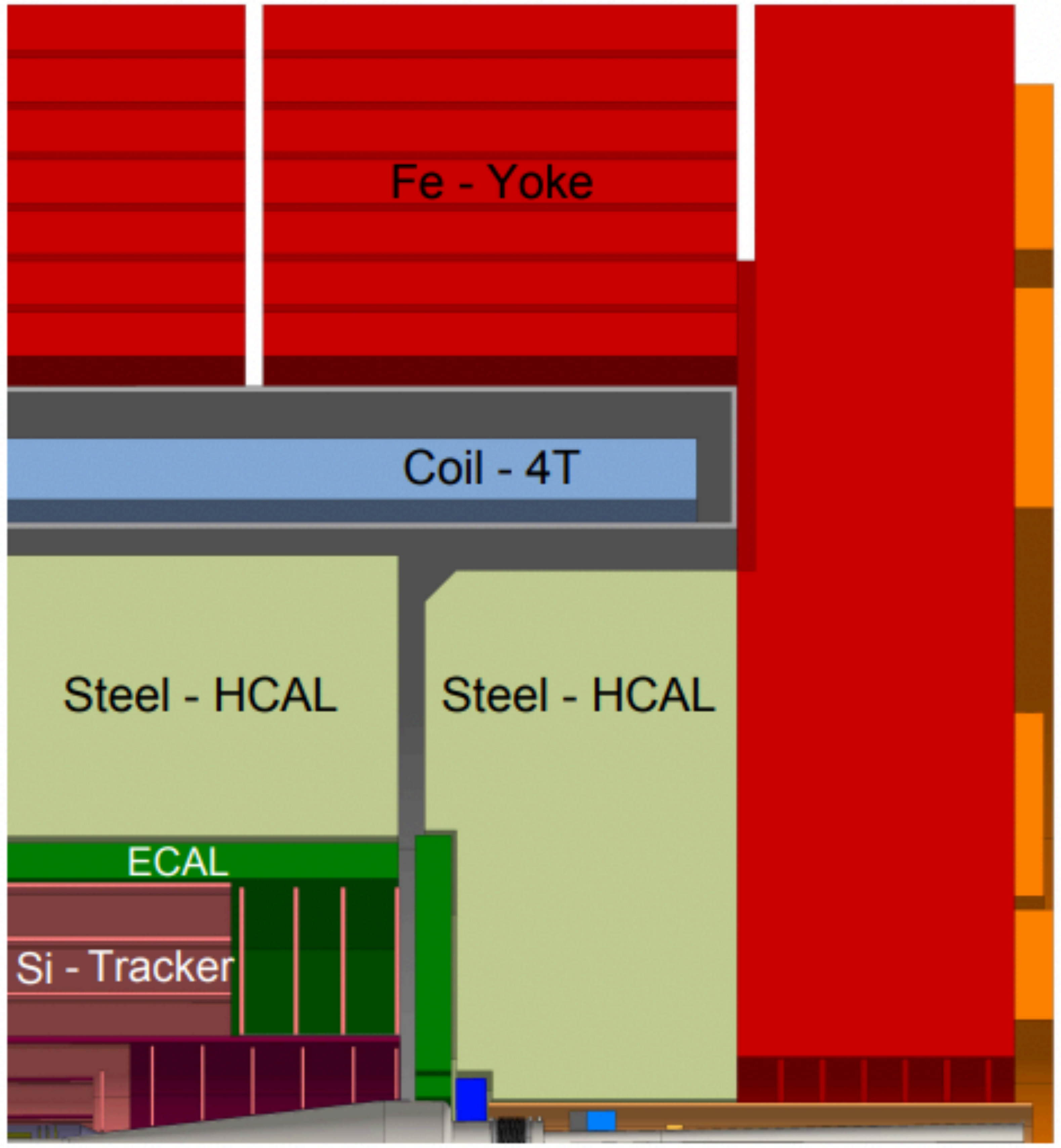
From ILC to CLIC to account for higher energy collisions (1 → 3 TeV)





(b)





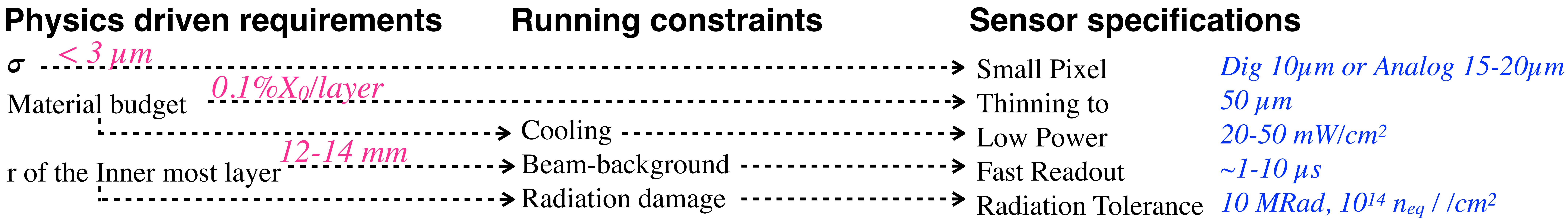
The hit density and rates from beam induced background particles increases with COM

To keep occupancies below 3% per bunch train, including safety factors of 5 for incoherent pairs, and 2 for γγ → hadron events

- First vertex layer at 31 mm (beam pipe radius 29.4mm)

Sensors technology requirements for Vertex Detector

Services cables + cooling + support make up most of the detector mass



Physics driven requirements | **Running constraints** | **Sensor specifications**

σ $< 3\ \mu m$ → Small Pixel — *Dig 10µm or Analog 15-20µm*

Material budget $0.1\% X_0/\text{layer}$ → Thinning to — *50 µm*

Material budget → Cooling → Low Power — *20-50 mW/cm²*

r of the Inner most layer $12\text{-}14\ mm$ → Beam-background → Fast Readout — *~1-10 µs*

r of the Inner most layer → Radiation damage → Radiation Tolerance — *10 MRad, $10^{14}\ n_{eq}$ / /cm²*

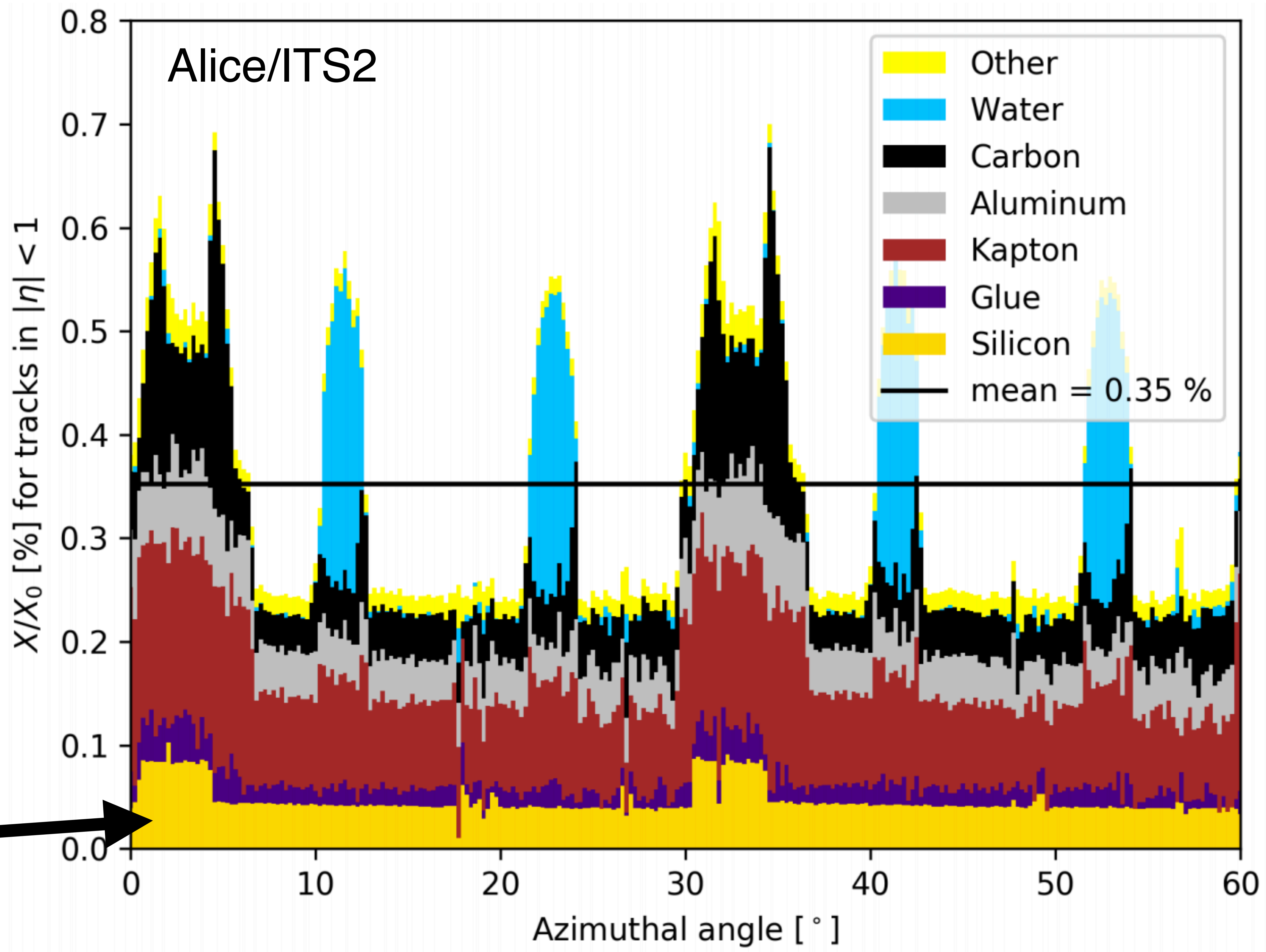
Sensors technology requirements for Vertex Detector

Services cables + cooling + support make up most of the detector mass

Serial Powering and Optical powering could further reduce the impact of the services

Sensor’s contribution to the total material budget is 15-30%

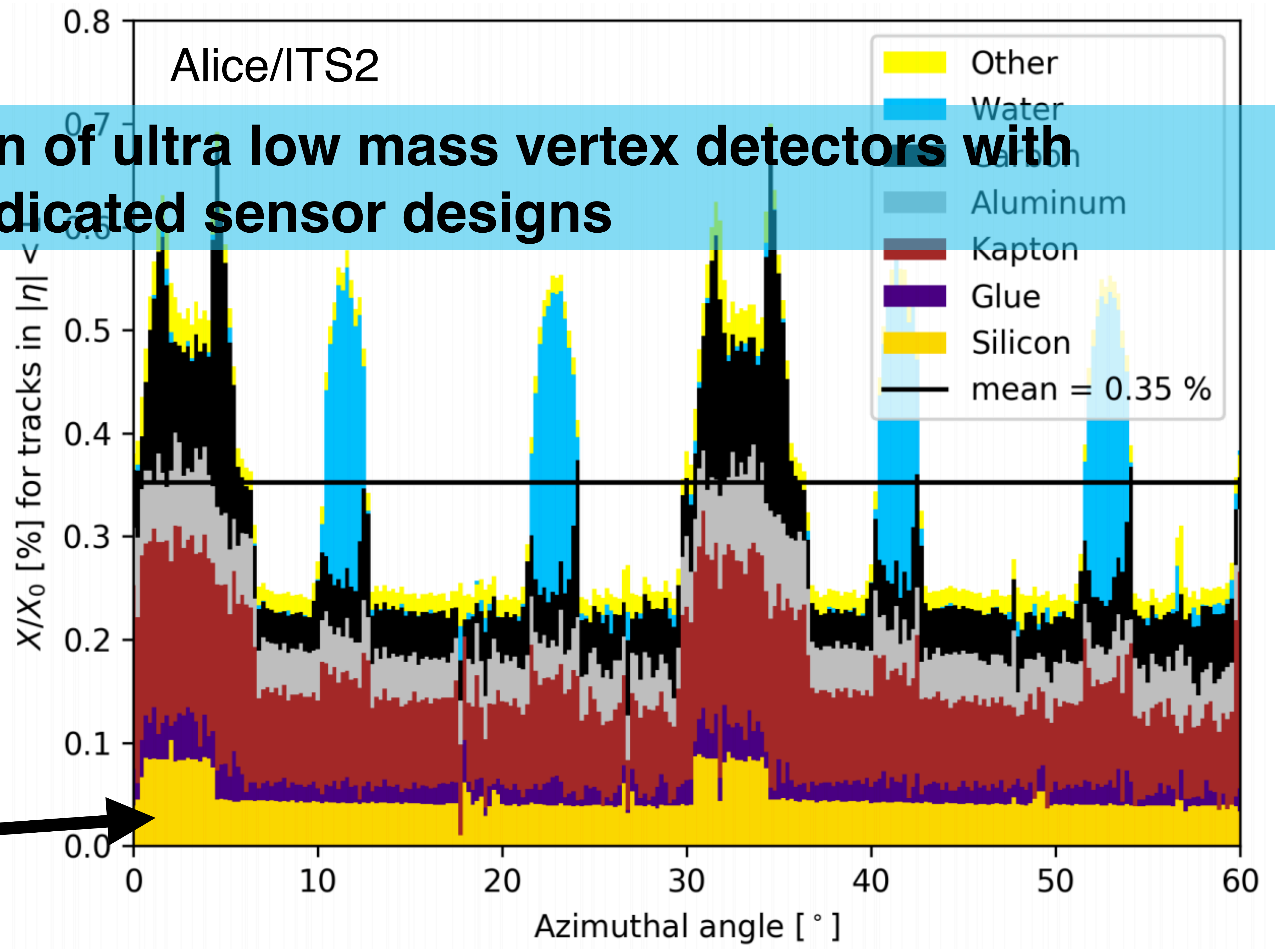
CERN-LHCC-2019-018



Sensors technology requirements for Vertex Detector

Services cables + cooling + support make up most of the detector mass

CERN-LHCC-2019-018



Need new generation of ultra low mass vertex detectors with dedicated sensor designs

Serial Powering and Optical powering could further reduce the impact of the services

Sensor's contribution to the total material budget is 15-30%

Monolithic Active Pixel Sensors - MAPS

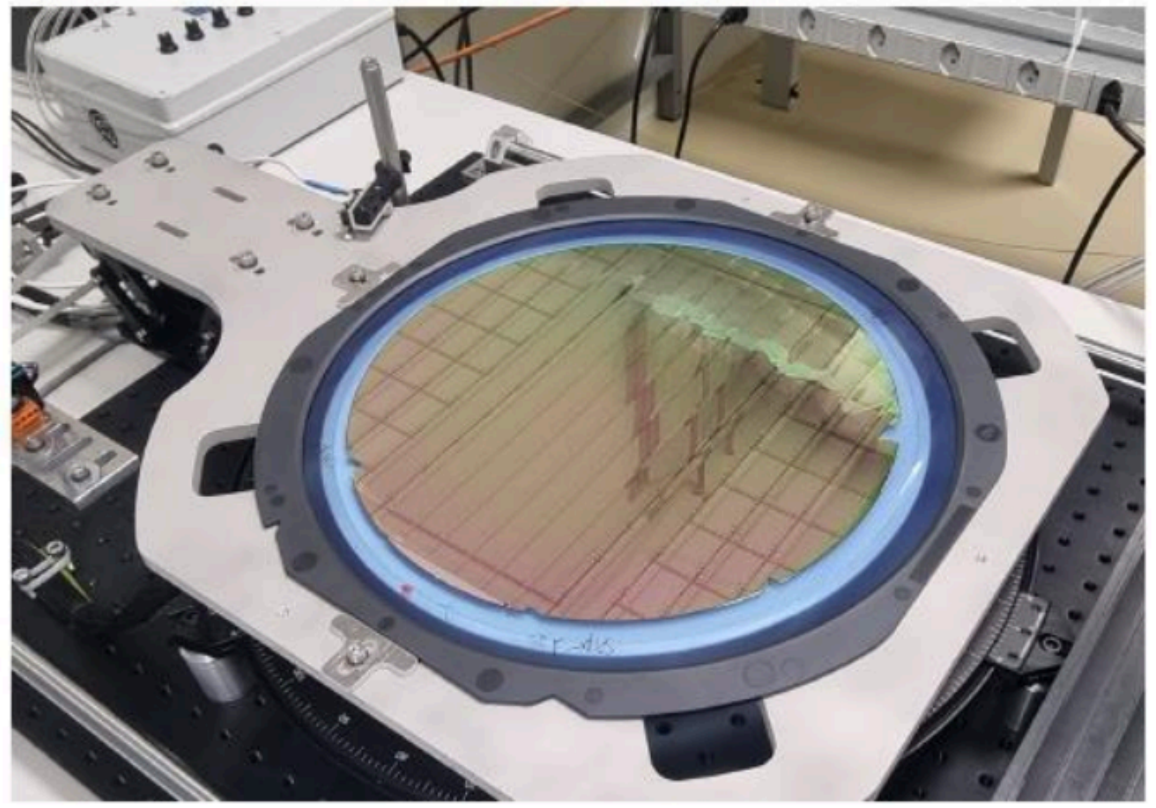
A suitable technology for high precision tracker and high granularity calorimetry

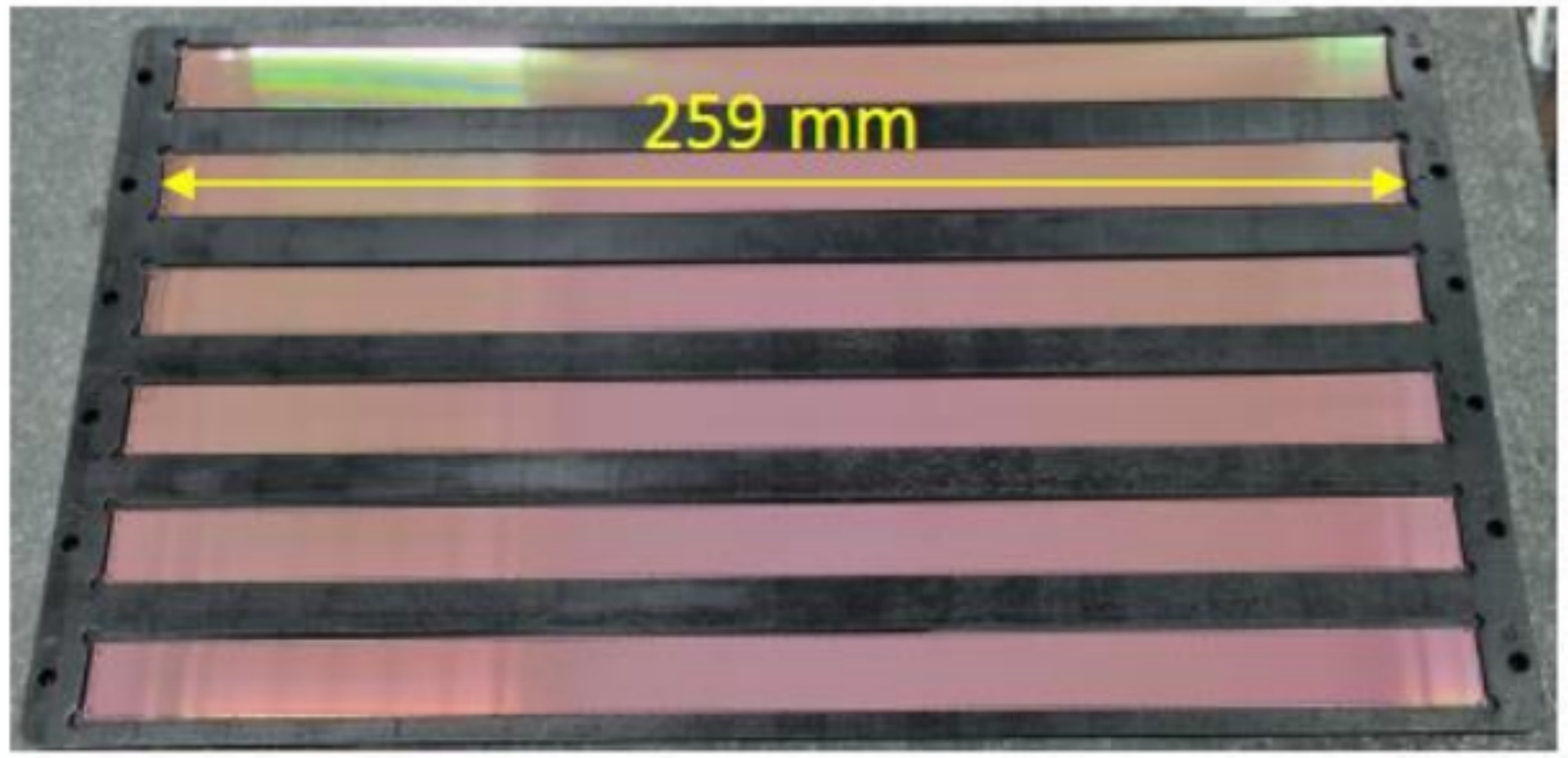
Significantly lower material budget: sensors and readout electronics are integrated on the same chip

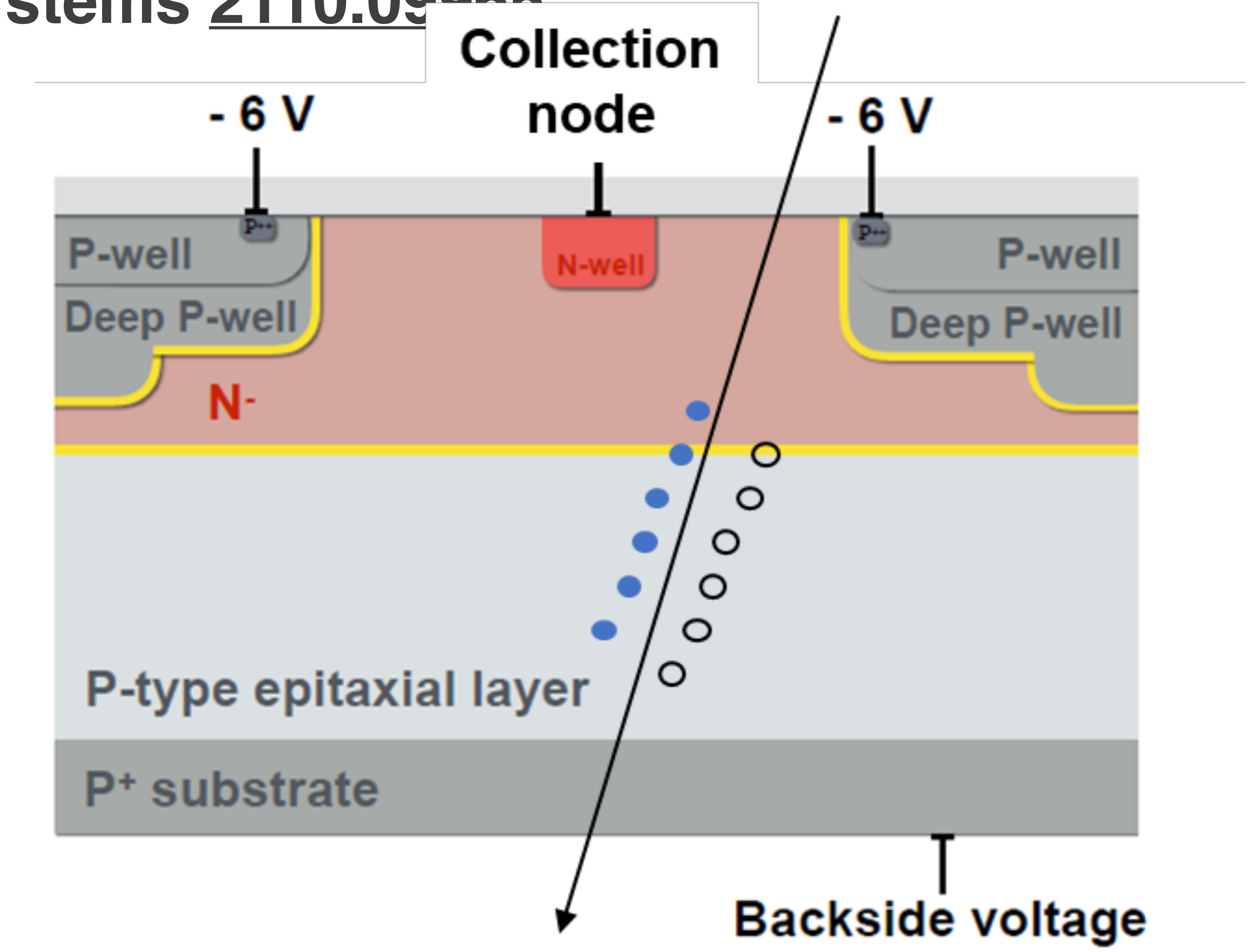
- Eliminate the need for bump bonding : thinned to less to 50μm
- Smaller pixel size, not limited by bump bonding (<25μm)
- Lower costs : implemented in standard commercial CMOS processes technologies
- Target big sensors (up to wafer size) through use of “stitching” (step-and-repeat of reticles) to reduce further the overall material budget

New SiD layout update features MAPS for both tracking and calorimeter systems 2110.09965

M. Winter, 2024



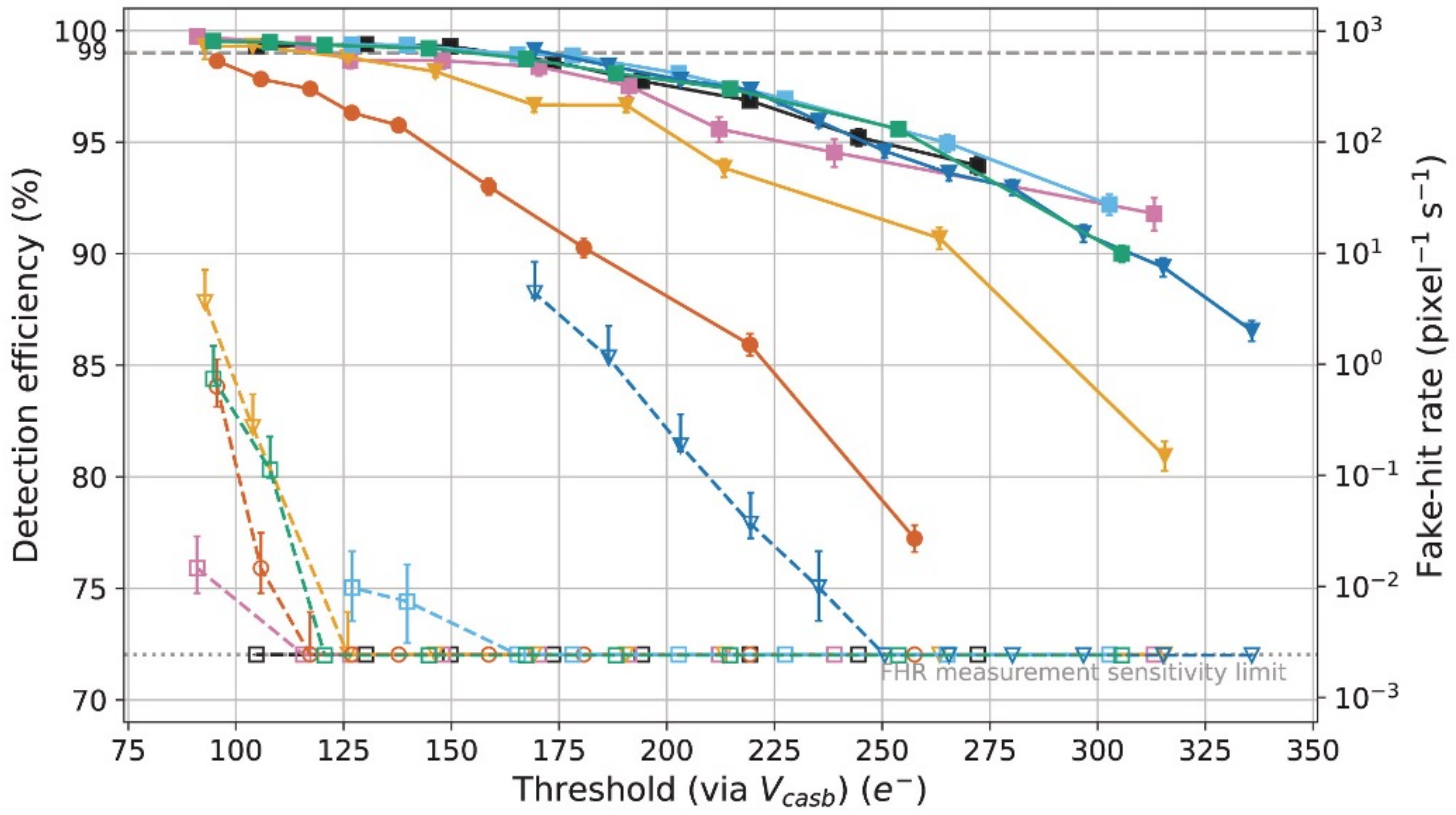


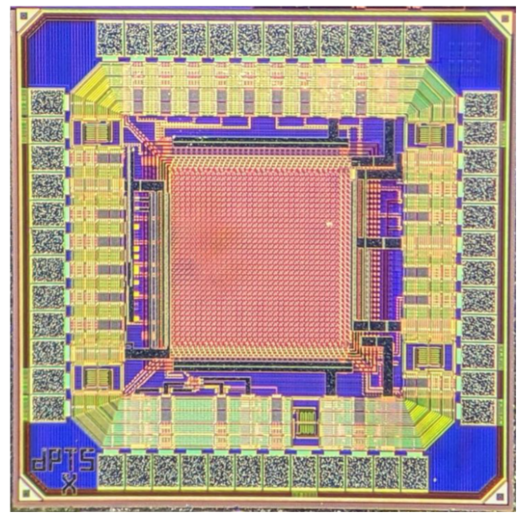


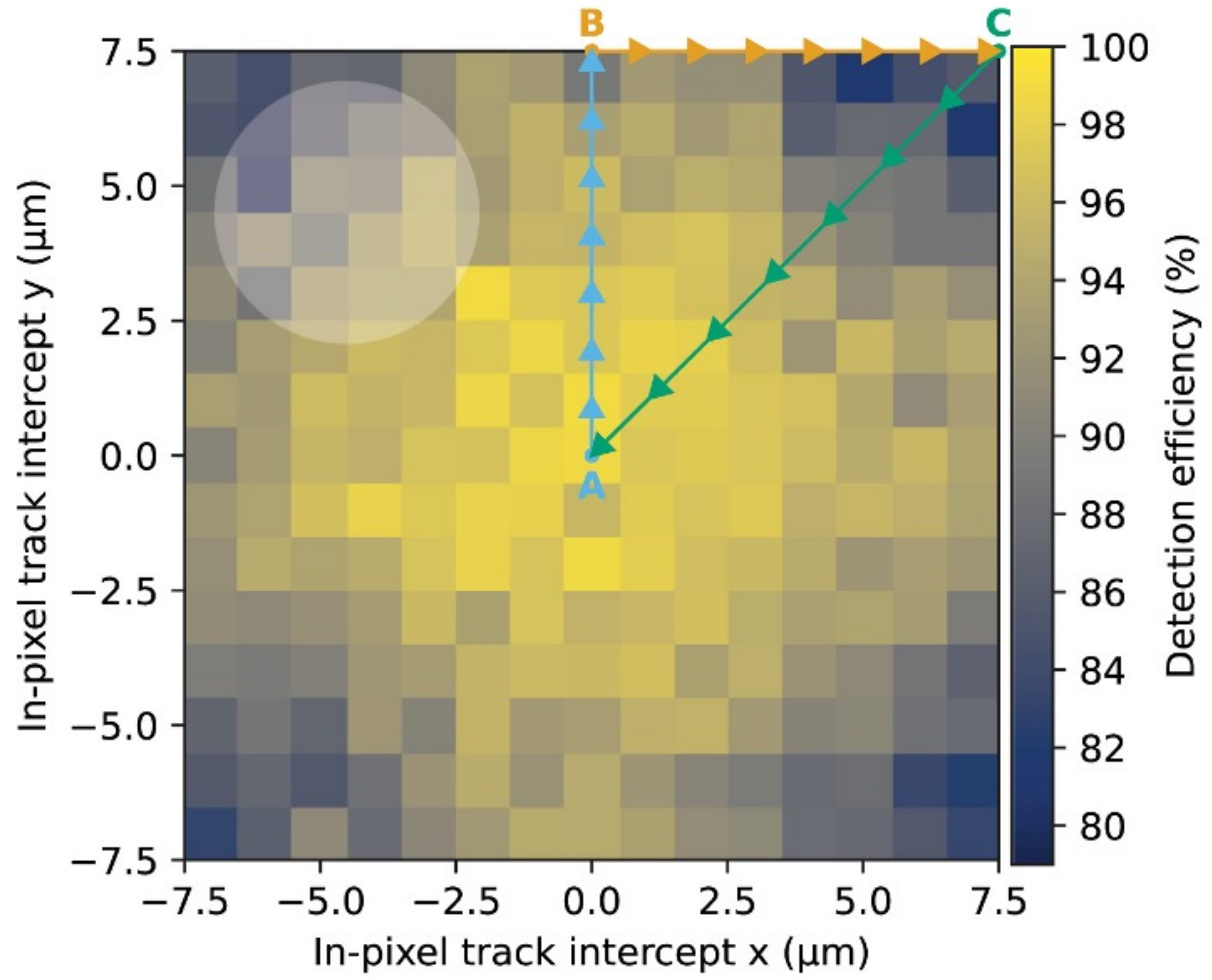
Recent results with Digital Pixel Test Structures

Synergies with DPTS characterization at CERN test beam facility within ALICE Collaboration

Characterization done up to 10^{15} 1 MeV n_{eq} cm^{-2}





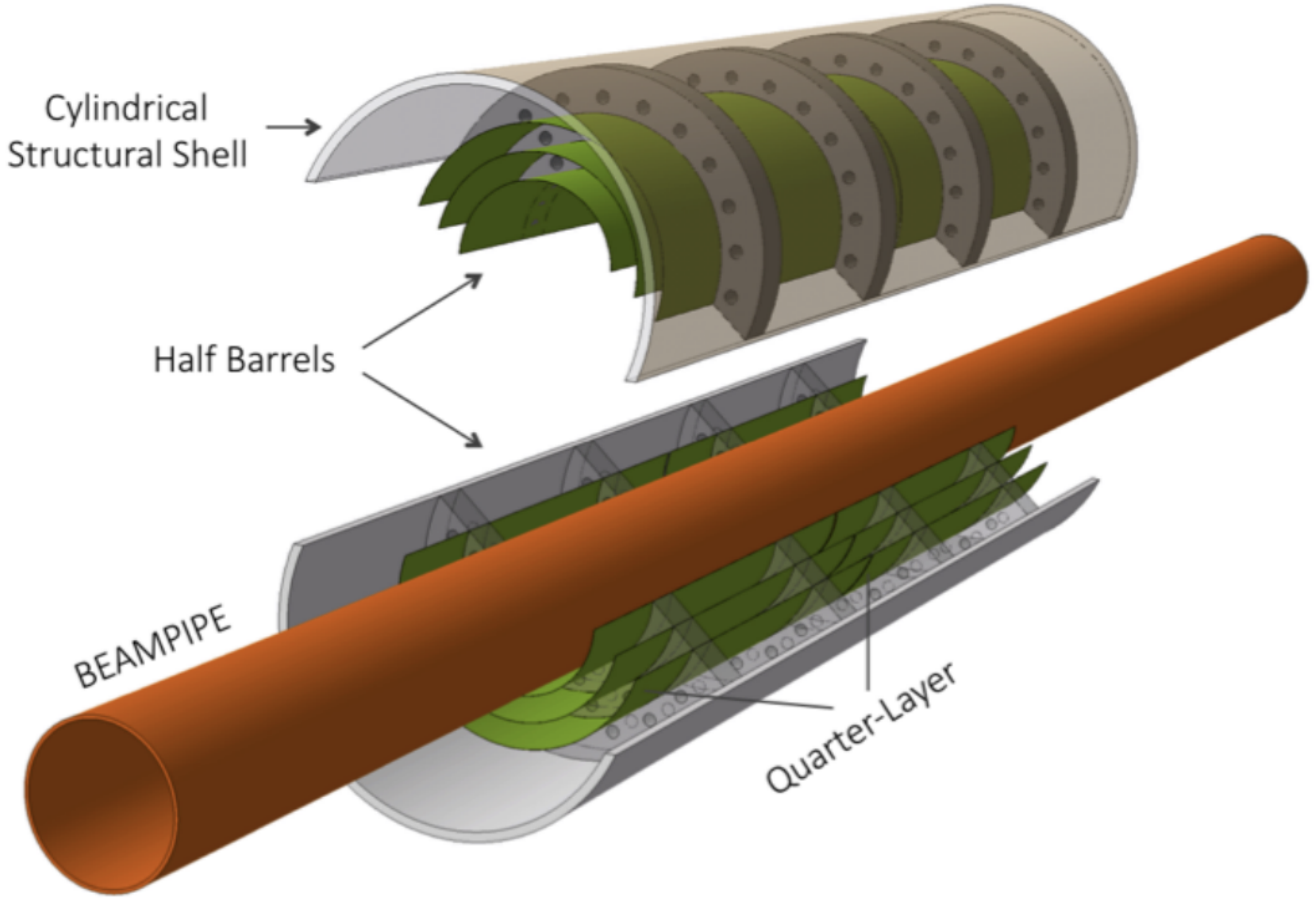


Digital pixel test structures implemented in a 65 nm CMOS process

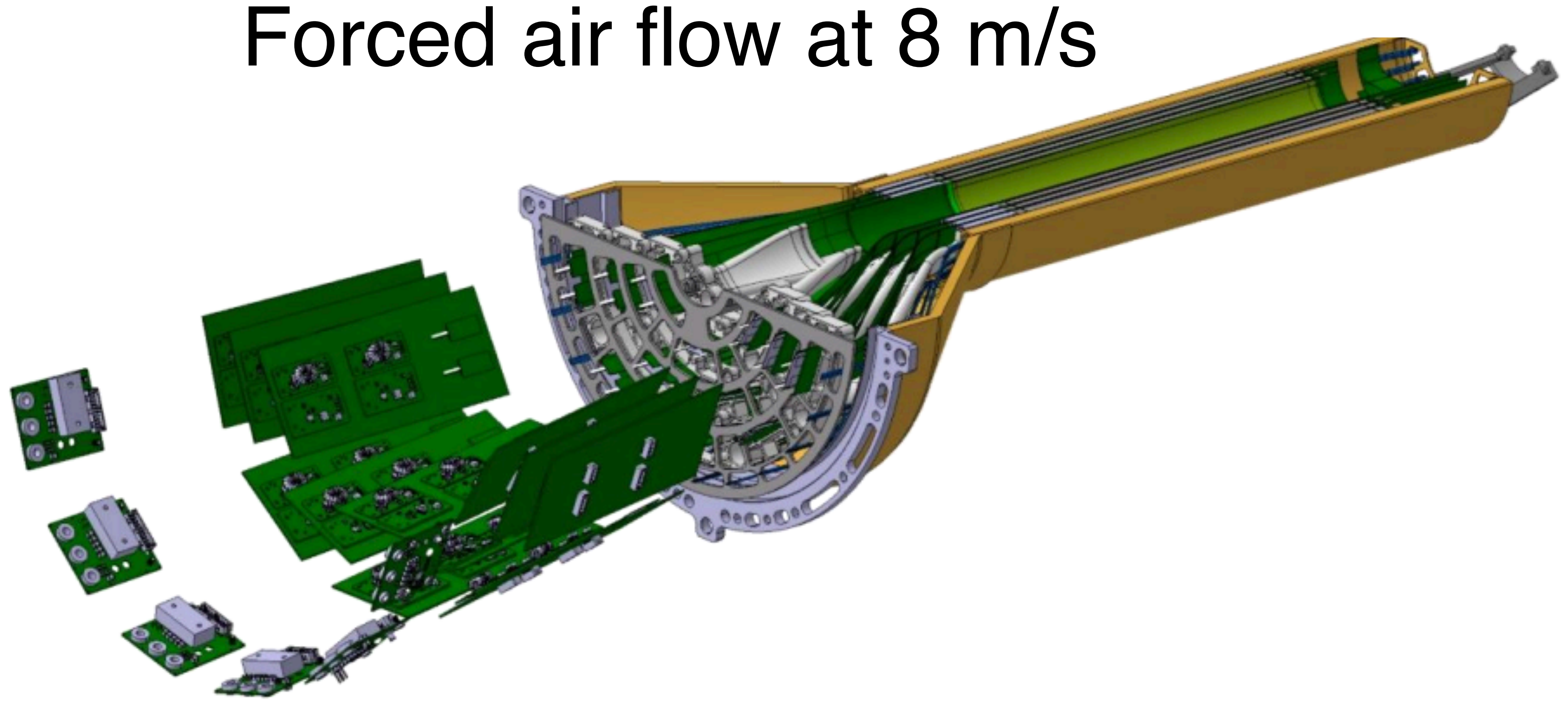
A Compact Front-End Circuit for a Monolithic Sensor in a 65-nm CMOS Imaging Technology

ALICE: Bent MAPS for ITS3

CERN-LHCC-2019-018
ALICE-PUBLIC-2018-013



Forced air flow at 8 m/s



Bending Si wafers + circuits is possible

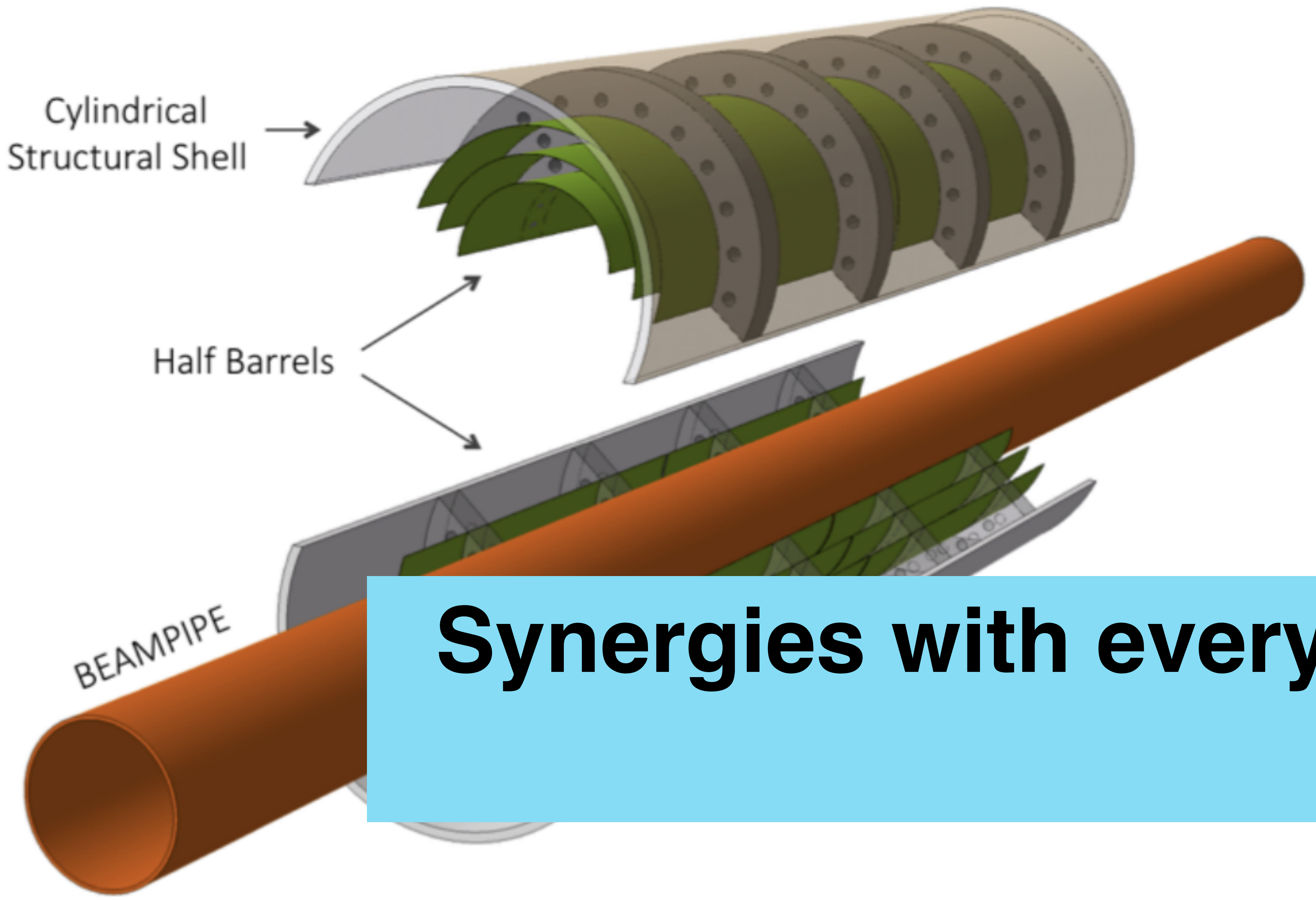
For ITS3: Industrial stitching & curved structures with TJ 65 nm process:

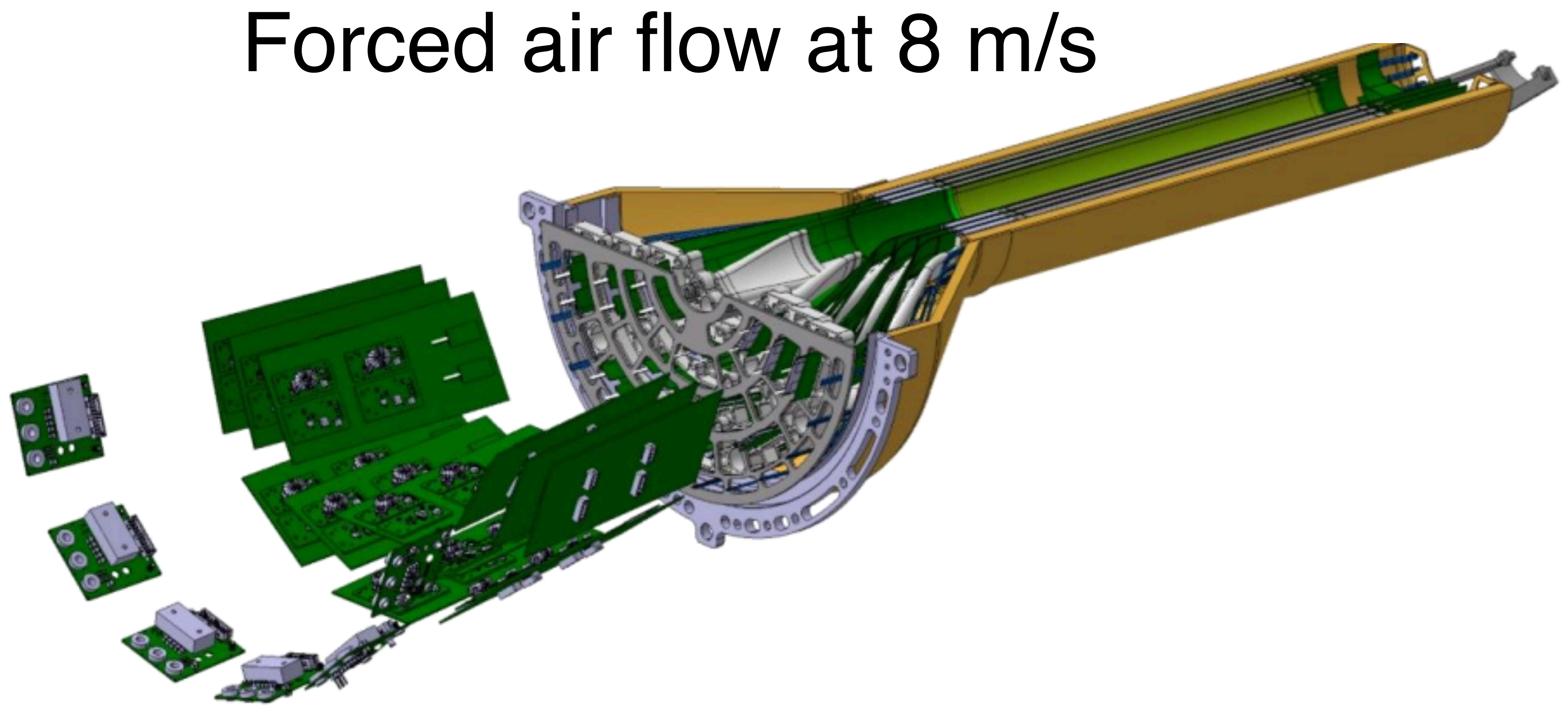
- Sensor thickness of 20-40 µm - 0.02-0.04% X_0
- Sensors arranged with a perfectly cylindrical shape
  - a sensors thinned to ~30μm can be curved to a radius of 10-20mm
- Pitch 18-22μm — **R&D needs for the resolution requirement at e+e-**

Livia's overview talk

ALICE: Bent MAPS for ITS3

CERN-LHCC-2019-018
ALICE-PUBLIC-2018-013




Forced air flow at 8 m/s

Synergies with every detector concepts at e^+e^- colliders
Including EIC

For ITS3: Industrial stitching & curved structures with TJ 65 nm process:

- Sensor thickness of 20-40 µm - 0.02-0.04% X_0
- Sensors arranged with a perfectly cylindrical shape
  - a sensors thinned to ~30μm can be curved to a radius of 10-20mm
- Pitch 18-22μm — **R&D needs for the resolution requirement at e+e-**

Livia's overview talk

Time resolution vs. power

O(ns) time resolution for beam-background suppression requires dedicated optimizations

Current designs that can achieve ns or sub-ns time resolutions compensate with higher power consumption

- Target power consumption is less than 20 mW/cm^2

Chip name	**Experiment**	**Subsystem**	**Technology**	**Pixel pitch [μm]**	**Time resolution [ns]**	**Power Density [mW/cm^2]**
ALPIDE	ALICE-ITS2	Vtx, Trk	Tower 180 nm	28	< 2000	5
Mosaic	ALICE-ITS3	Vtx	Tower 65 nm	25x100	100-2000	<40
FastPix	HL-LHC		Tower 180 nm	10 - 20	0.122 – 0.135	>1500
DPTS	ALICE-ITS3		Tower 65 nm	15	6.3	112
NAPA	HF	Trk, Calo	Tower 65 nm	25x100	<1	< 20
Cactus	FCC/EIC	Timing	LF 150 nm	1000	0.1-0.5	145
MiniCactus	FCC/EIC	Timing	LF 150 nm	1000	0.088	300
Monolith	FCC/Idea	Trk	IHP SiGe 130 nm	100	0.077 – 0.02	40 - 2700
Malta	LHC, ..	Trk	Tower 180 nm	36	25	> 100
Arcadia	FCC/Idea	Trk	LF 110 nm	25	-	30

Dedicated ongoing effort to target O(ns) resolution with MAPS
First prototype (Napa-p1) produced in TJ 65 nm process 5x5 mm^2, 25 μm pitch

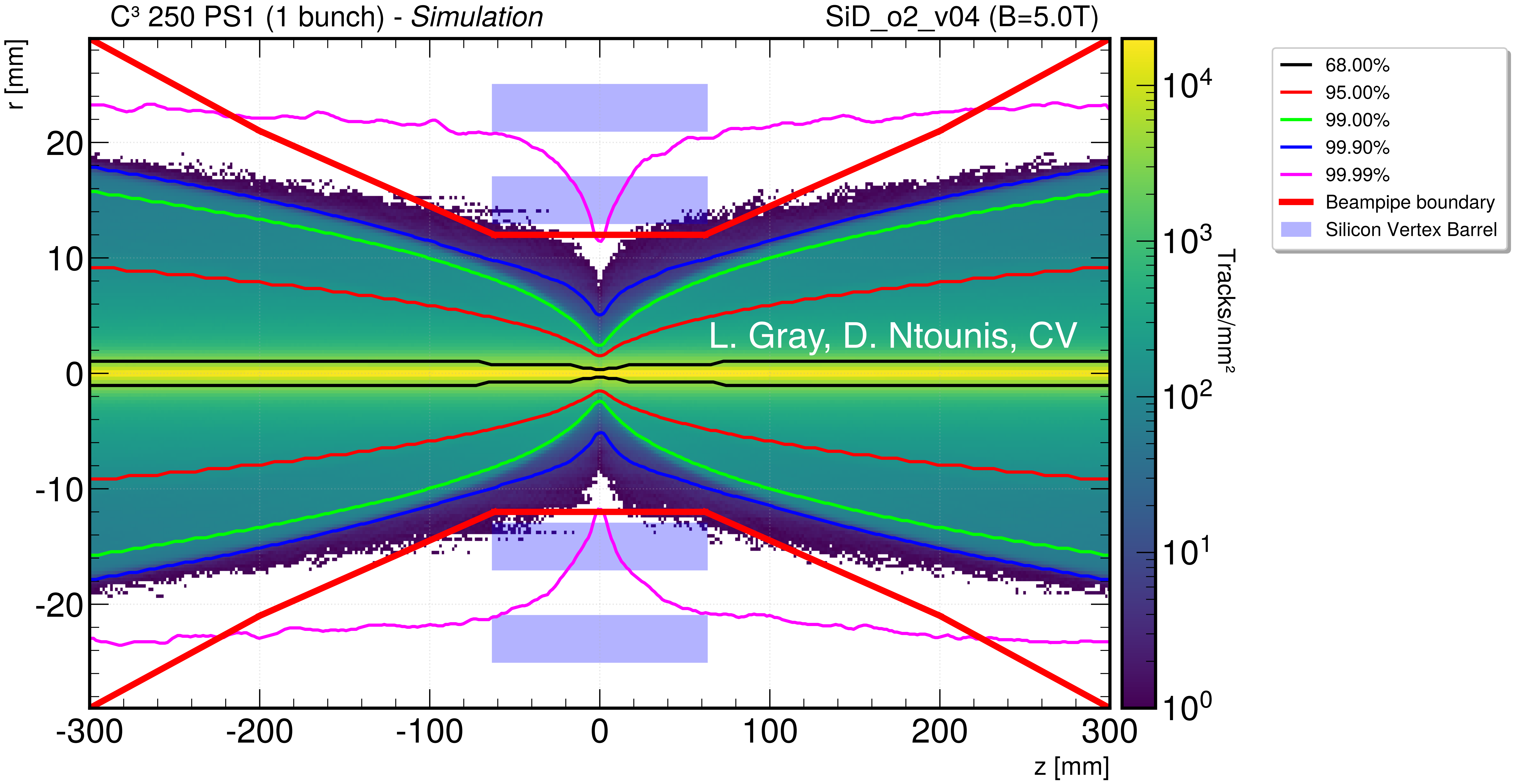
Conclusions & outlook

- Future linear lepton colliders have the potential to develop high precision silicon detectors to help reach unprecedented physics goals
  - Requires excellent momentum and impact parameter resolution while keeping power consume
- Bunch time structure allows high precision trackers with very low X_0 at linear lepton colliders
  - CLIC, ILC, but also C^3 share similar features **but careful simulation of the beam backgrounds is needed (besides GuineaPig, WarpX as an additional tool for high lumi scenarios)**
- **Different beam backgrounds at LC energies require an upgradable Vertex Detector, enabling optimal performance at each energy**
- Pixel detectors with very fine pixel pitch, excellent single point resolution, while maintaining a very low X_0
  - Favors technologies which allow to focus on resolution and material budget
  - **Reaching the specifications all together is the real challenge**
  - **Vertex Detector will be installed last, so technology choices can be deferred and benefit from the latest advances.**

Accelerator parameters and detector specifications are intertwined and simulation tools are key to guide the detector design to maximize the physics potential of a future e+e- machine

thank you!

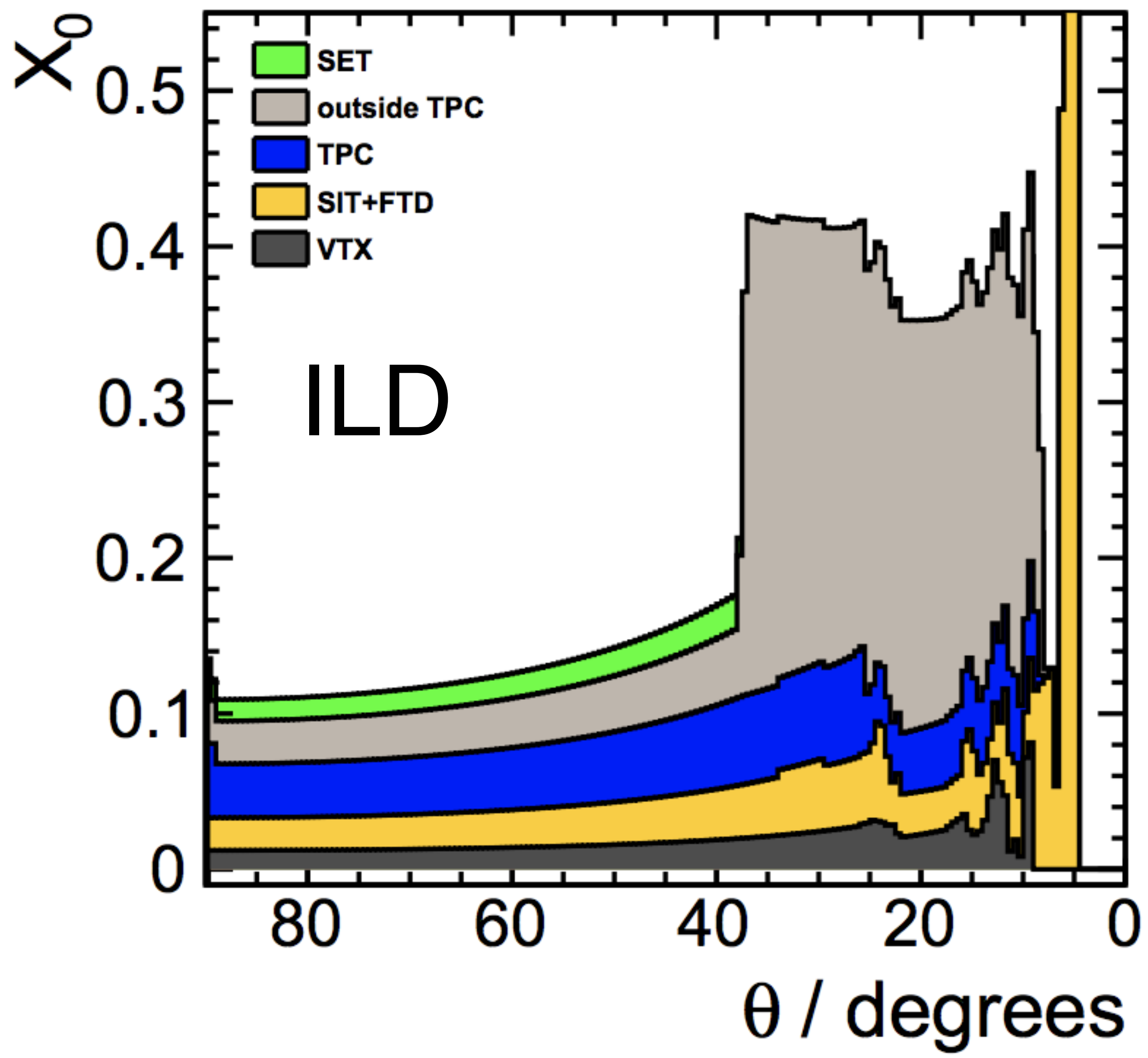
Averaged per bunch crossing.

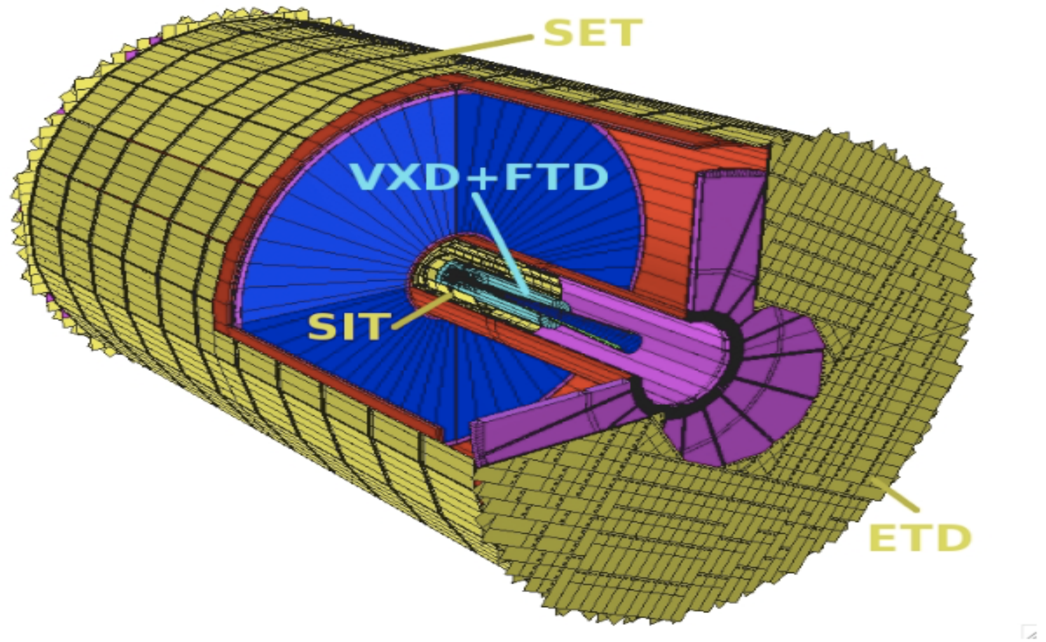


arXiv:2003.01116

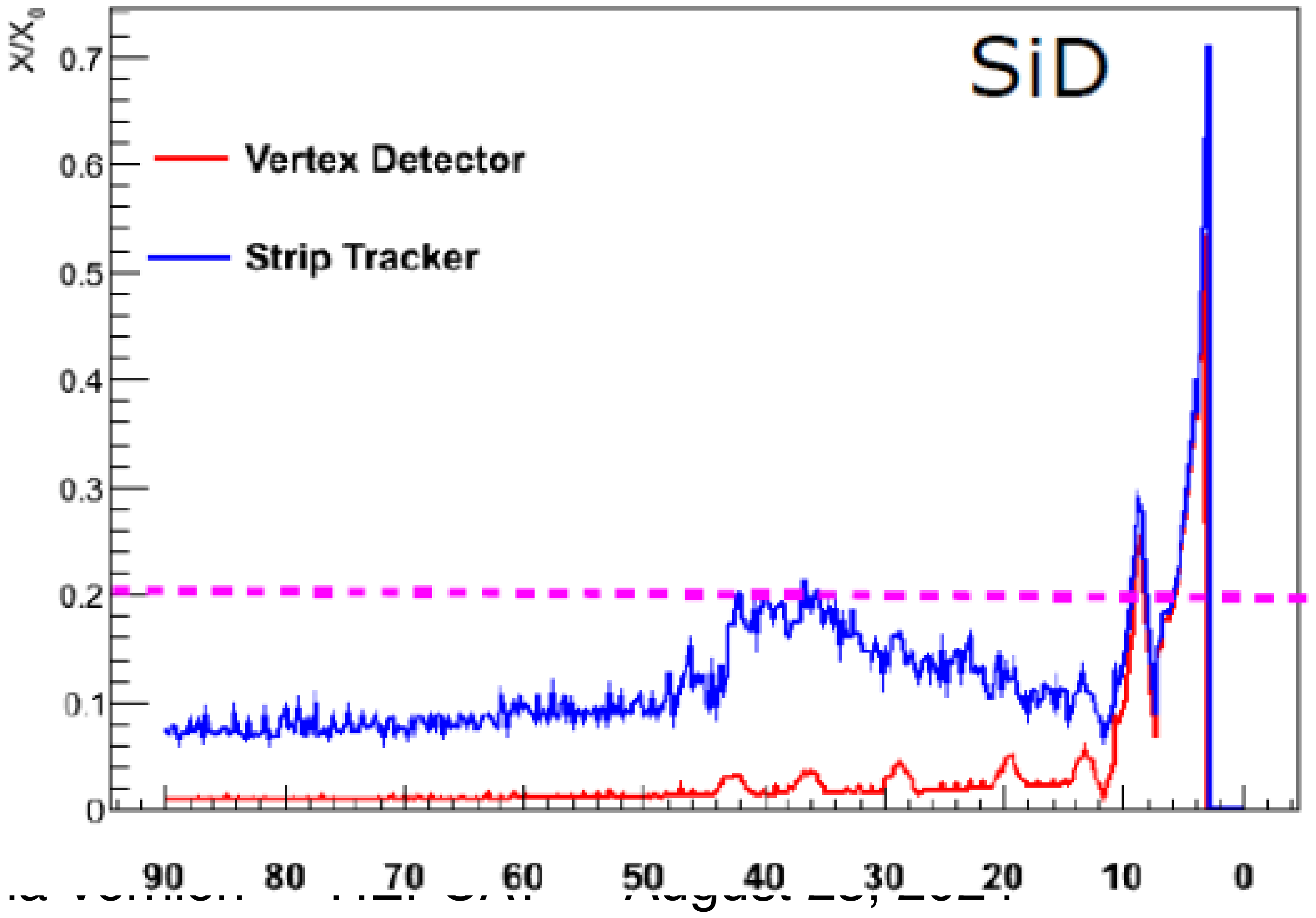
arXiv:2003.01116

From physics to detector



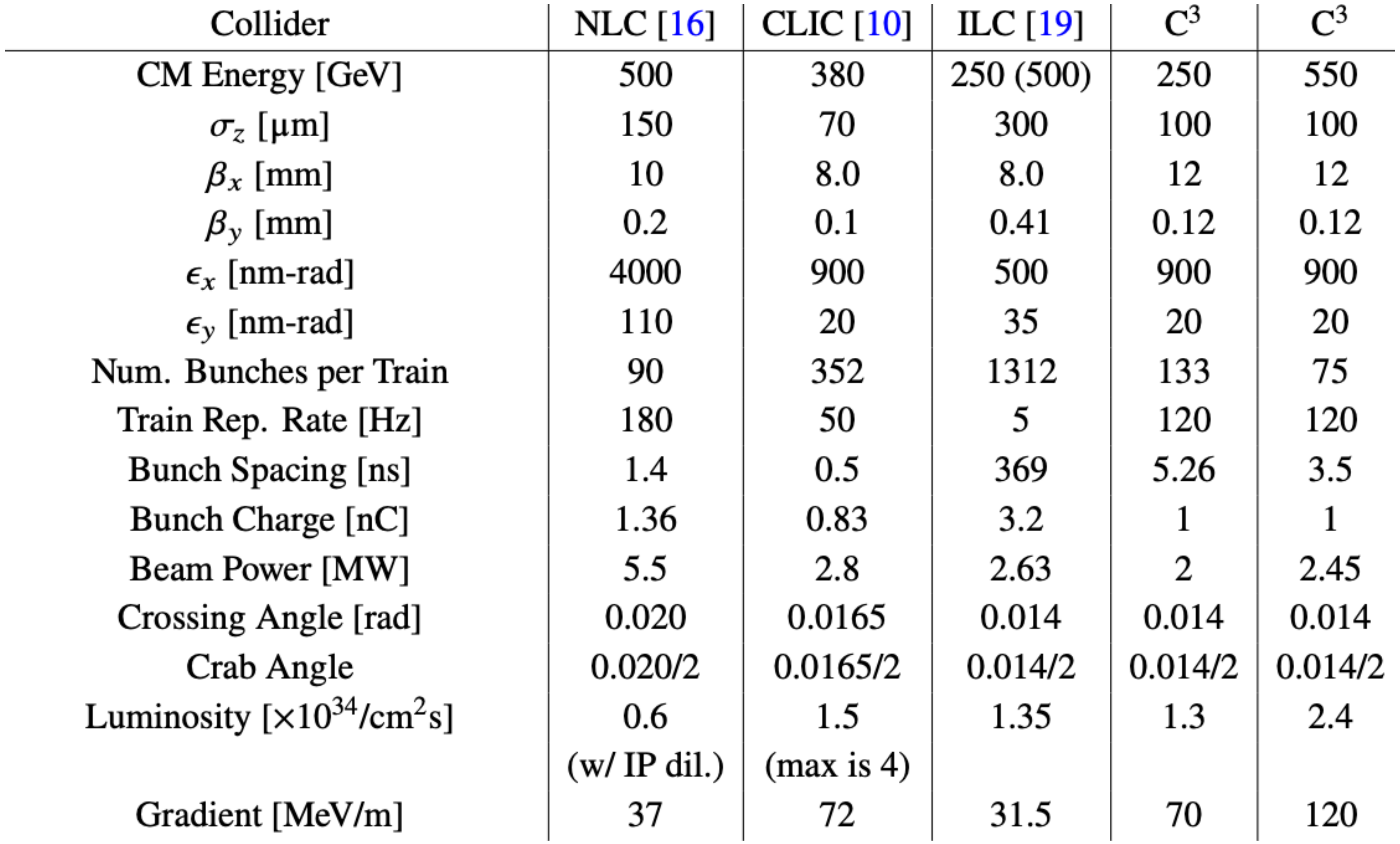


	ILD	SID
Vertex Inner Radius (cm)	1.6	1.4
Tracker technology	TPC+Silicon	Silicon
Outer Tracker Radius (m)	1.77	1.22
ECal thickness	24 X_0	26 X_0
HCal thickness	5.9 λ_0	4.5 λ_0
HCal Outer Radius (m)	3.3	2.5
Solenoid field (T)	3.5	5
Solenoid length (m)	7.9	6.1
Solenoid Radius (m)	3.4	2.6



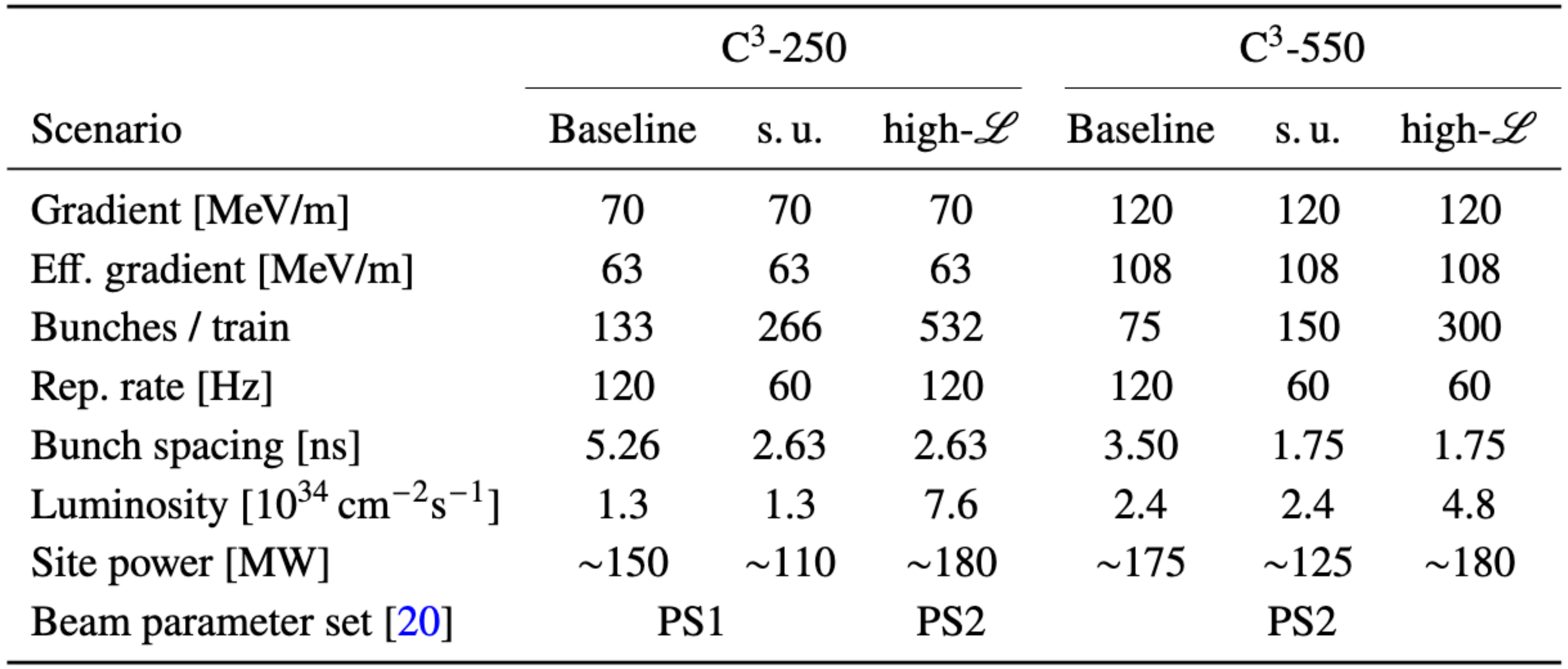
Machine parameters

JINST 18 P07053



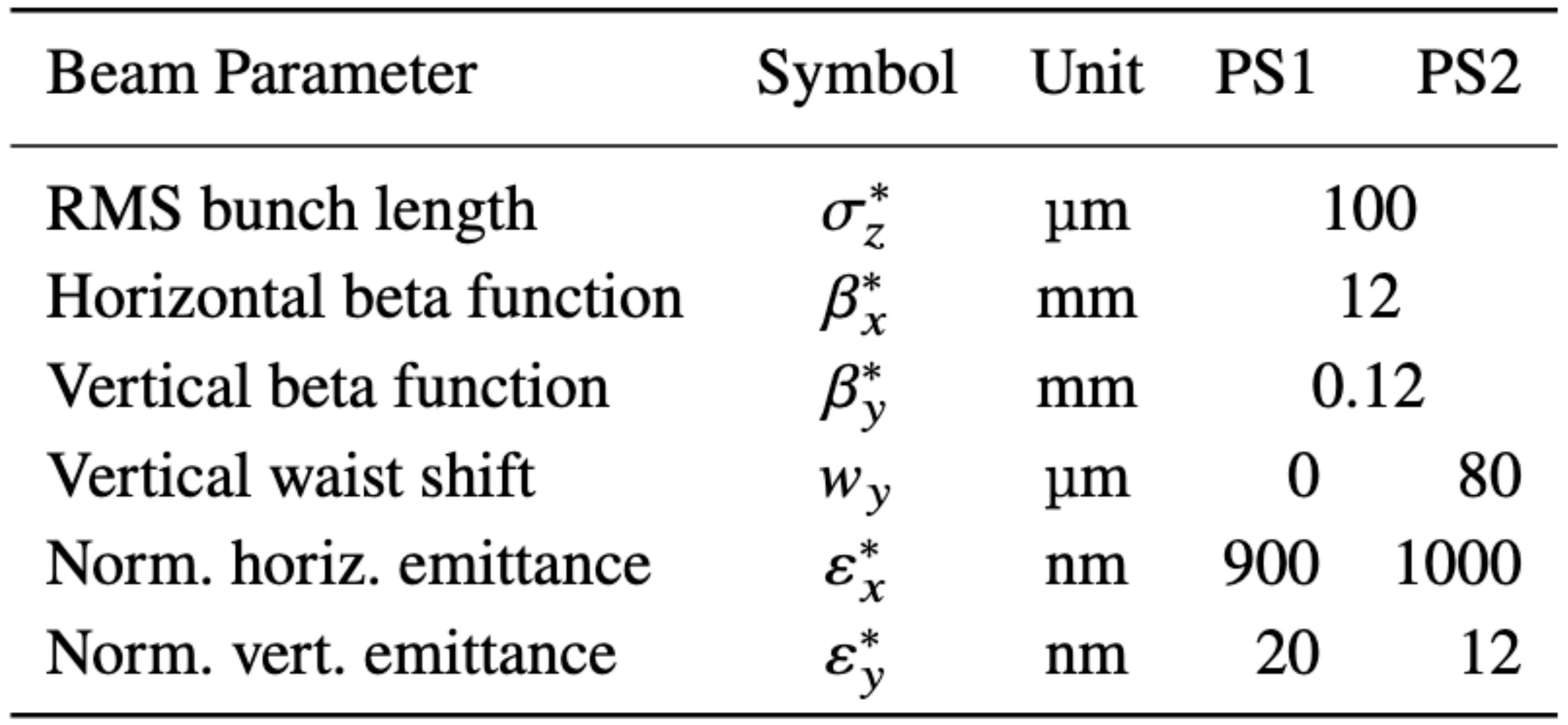
Collider	NLC [16]	CLIC [10]	ILC [19]	C^3	C^3
CM Energy [GeV]	500	380	250 (500)	250	550
σ_z [µm]	150	70	300	100	100
β_x [mm]	10	8.0	8.0	12	12
β_y [mm]	0.2	0.1	0.41	0.12	0.12
ϵ_x [nm-rad]	4000	900	500	900	900
ϵ_y [nm-rad]	110	20	35	20	20
Num. Bunches per Train	90	352	1312	133	75
Train Rep. Rate [Hz]	180	50	5	120	120
Bunch Spacing [ns]	1.4	0.5	369	5.26	3.5
Bunch Charge [nC]	1.36	0.83	3.2	1	1
Beam Power [MW]	5.5	2.8	2.63	2	2.45
Crossing Angle [rad]	0.020	0.0165	0.014	0.014	0.014
Crab Angle	0.020/2	0.0165/2	0.014/2	0.014/2	0.014/2
Luminosity [$\times 10^{34}/\text{cm}^2\text{s}$]	0.6 (w/ IP dil.)	1.5 (max is 4)	1.35	1.3	2.4
Gradient [MeV/m]	37	72	31.5	70	120

Machine parameters



	C^3-250			C^3-550		
Scenario	Baseline	s. u.	high-$\mathscr{L}$	Baseline	s. u.	high-$\mathscr{L}$
Gradient [MeV/m]	70	70	70	120	120	120
Eff. gradient [MeV/m]	63	63	63	108	108	108
Bunches / train	133	266	532	75	150	300
Rep. rate [Hz]	120	60	120	120	60	60
Bunch spacing [ns]	5.26	2.63	2.63	3.50	1.75	1.75
Luminosity [10^{34} cm^{-2}s^{-1}]	1.3	1.3	7.6	2.4	2.4	4.8
Site power [MW]	~150	~110	~180	~175	~125	~180
Beam parameter set [20]	PS1		PS2	PS2		

Table 2: Main parameters at the IP for the two C^3 beam-dynamics working points.



Beam Parameter	Symbol	Unit	PS1	PS2
RMS bunch length	σ_z^*	µm	100	
Horizontal beta function	β_x^*	mm	12	
Vertical beta function	β_y^*	mm	0.12	
Vertical waist shift	w_y	µm	0	80
Norm. horiz. emittance	ε_x^*	nm	900	1000
Norm. vert. emittance	ε_y^*	nm	20	12

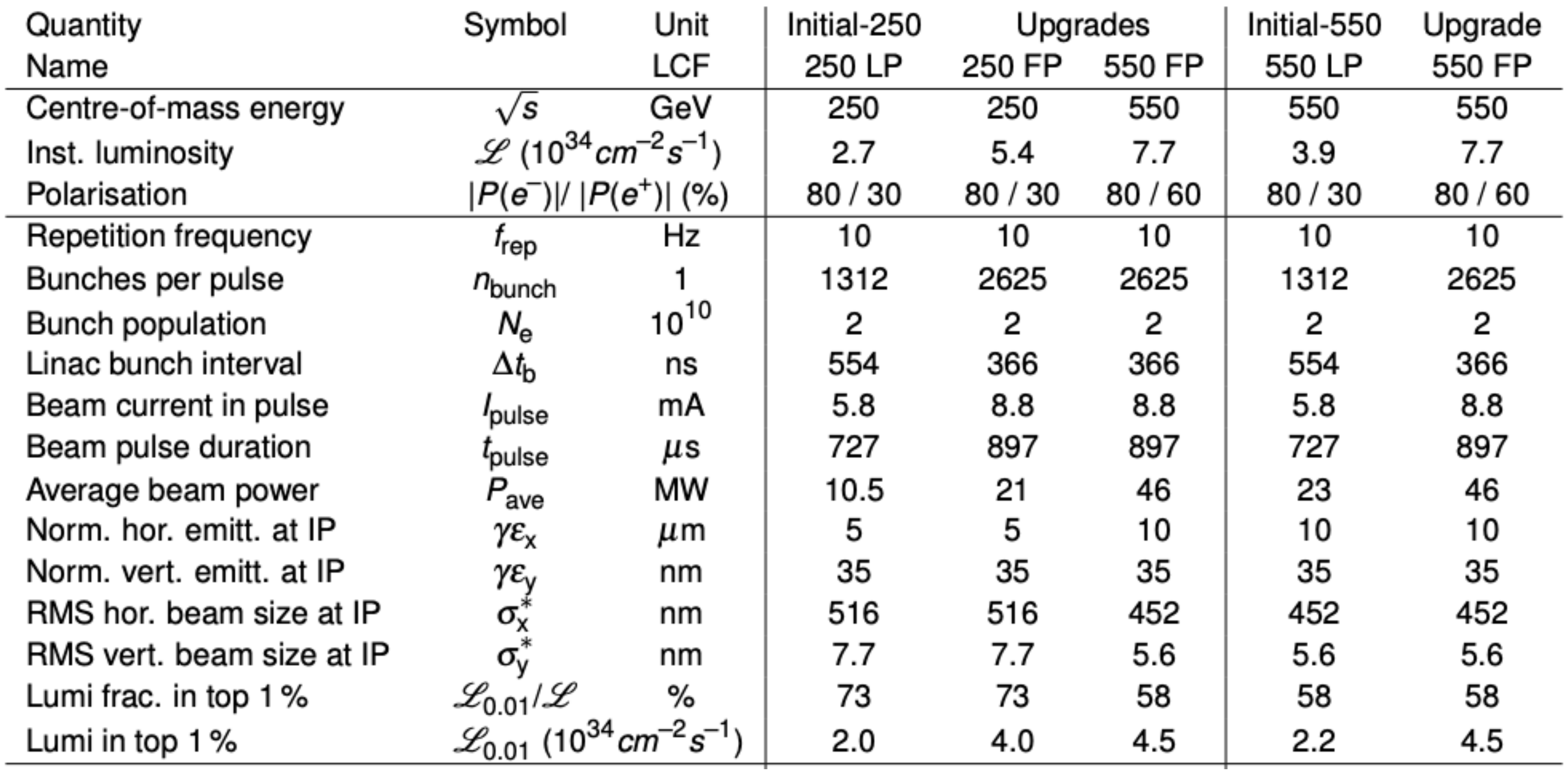
Pre-print in preparation

LCF parameters

Linear Collider Vision

2503.24049

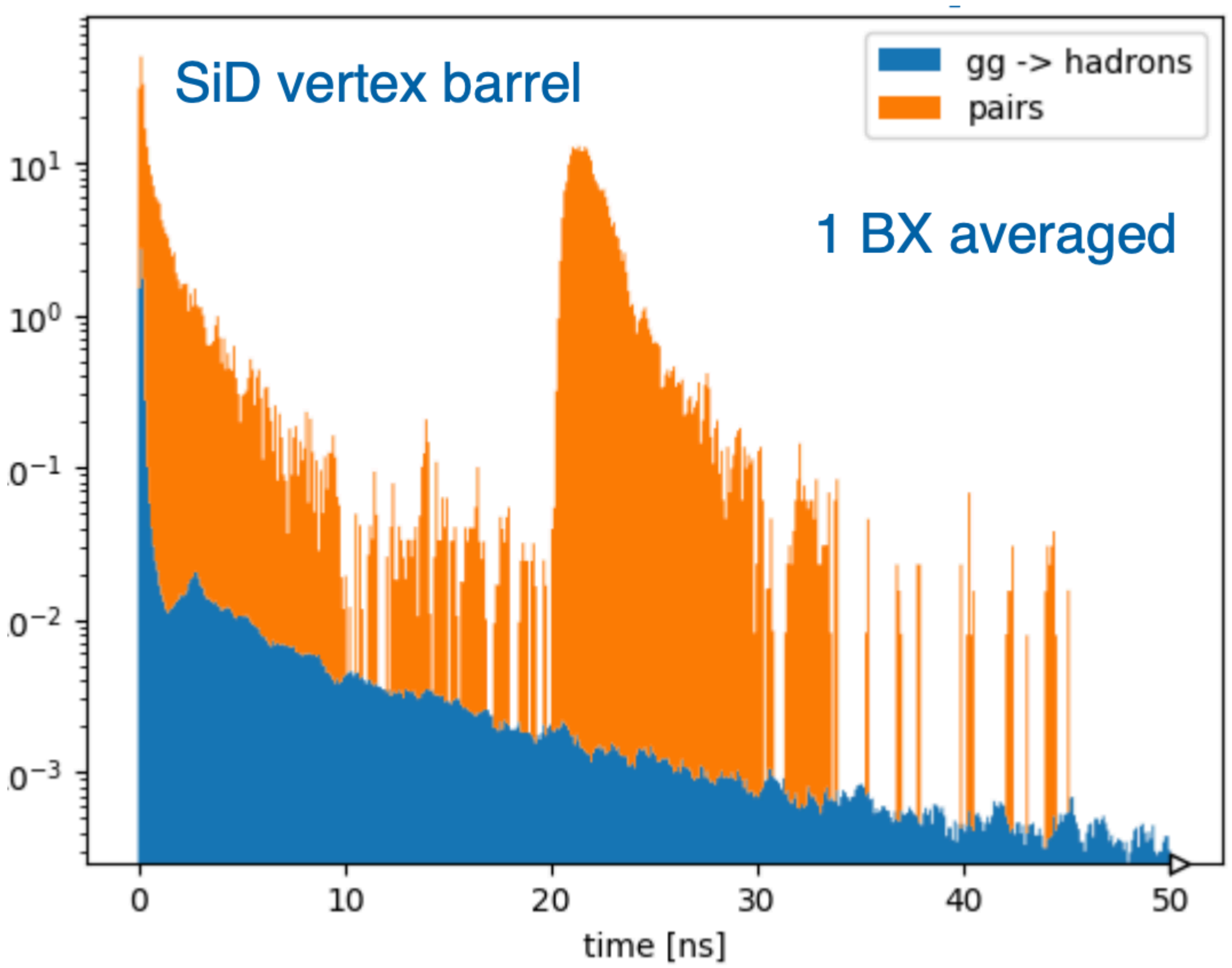
Beam backgrounds in the detectors will increase for smaller βx and need to be assessed



Quantity Name	Symbol	Unit	Initial-250 250 LP	Upgrades 250 FP	 550 FP	Initial-550 550 LP	Upgrade 550 FP
Centre-of-mass energy	$\sqrt{s}$	GeV	250	250	550	550	550
Inst. luminosity	$\mathscr{L}$	$(10^{34} cm^{-2} s^{-1})$	2.7	5.4	7.7	3.9	7.7
Polarisation	$\lvert P(e^-)\rvert / \lvert P(e^+)\rvert$	(%)	80 / 30	80 / 30	80 / 60	80 / 30	80 / 60
Repetition frequency	f_{rep}	Hz	10	10	10	10	10
Bunches per pulse	n_{bunch}	1	1312	2625	2625	1312	2625
Bunch population	N_e	10^{10}	2	2	2	2	2
Linac bunch interval	Δt_b	ns	554	366	366	554	366
Beam current in pulse	I_{pulse}	mA	5.8	8.8	8.8	5.8	8.8
Beam pulse duration	t_{pulse}	μs	727	897	897	727	897
Average beam power	P_{ave}	MW	10.5	21	46	23	46
Norm. hor. emitt. at IP	$\gamma\epsilon_x$	μm	5	5	10	10	10
Norm. vert. emitt. at IP	$\gamma\epsilon_y$	nm	35	35	35	35	35
RMS hor. beam size at IP	σ_x^*	nm	516	516	452	452	452
RMS vert. beam size at IP	σ_y^*	nm	7.7	7.7	5.6	5.6	5.6
Lumi frac. in top 1 %	$\mathscr{L}_{0.01}/\mathscr{L}$	%	73	73	58	58	58
Lumi in top 1 %	$\mathscr{L}_{0.01}$	$(10^{34} cm^{-2} s^{-1})$	2.0	4.0	4.5	2.2	4.5

Hadron Photonproduction

L. Gray (ECFA 2024)

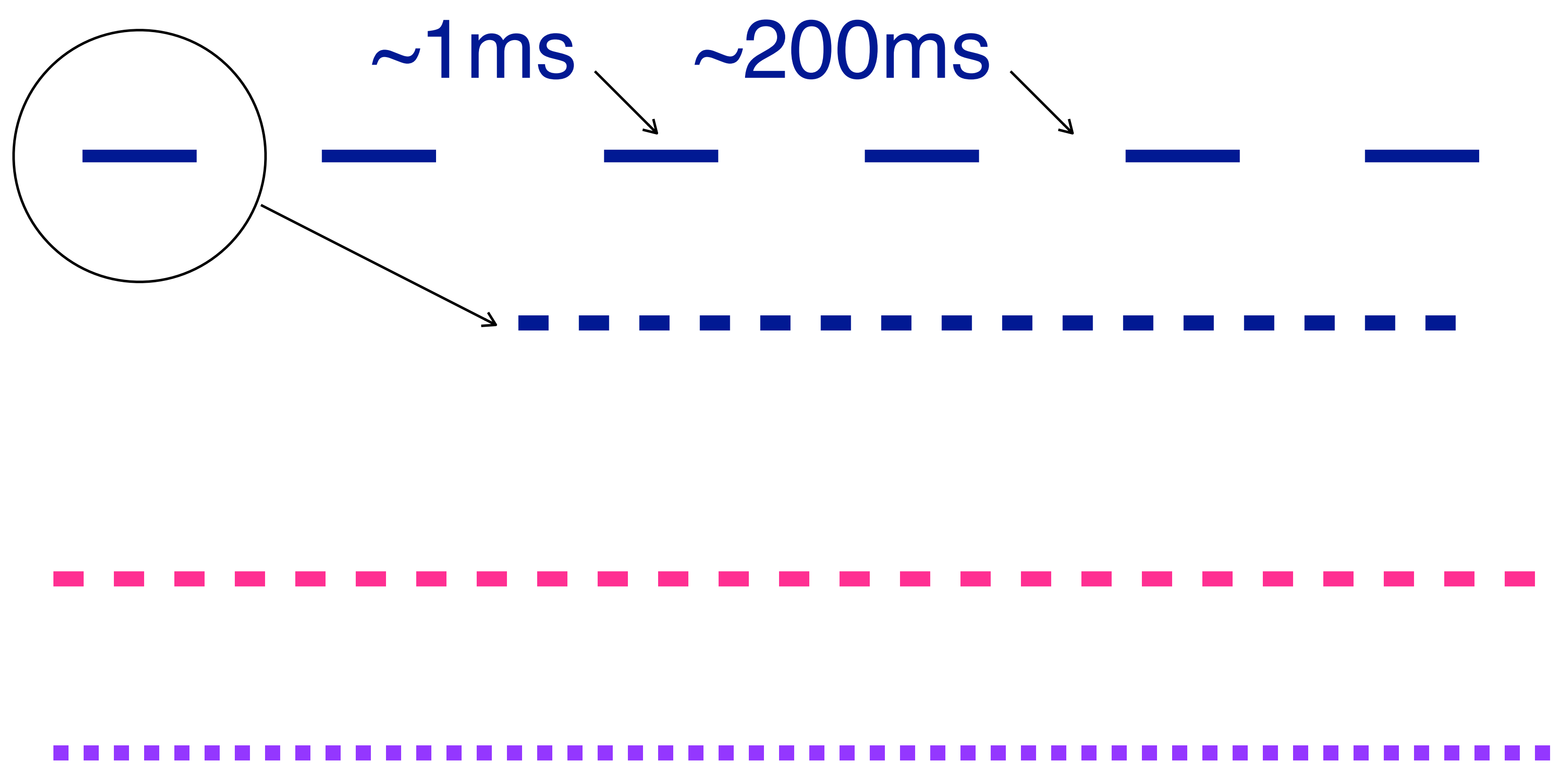


gg→hadrons much more central, pairs mostly forward (outside acceptance)
σ: $\gamma\gamma\to$hadrons ~0.3 μb, pairs → 16 mb

Hadron photoproduction has ~0.1-1% effect compared to pairs when in-time with that background
But ~50% effect out of time with the two major components
This corresponds to ~5e-6 occupancy effects at C3

arXiv:2003.01116
FCC Mid Term Report

Beam Format and Detector Design Requirements



ILC Trains at 5Hz, 1 train 1312 bunches
Bunches are 369 ns apart

FCC@ZH Bunches 1 μs apart

FCC@Z Bunches 20 ns apart

Beam-background suppression :

- LC - evolve time stamping towards O(1-100) ns (bunch-tagging)
- FCC, continuous r/o integrated over ~10μs with O(1) ns timing resolution for beam background suppression

Evaluating tracker design parameters

Fast calculation of tracking resolution package has been developed at SLAC (Feng Chen)

- Based on the Gluckstern Formula assuming hit resolution, material, and position of each layer

SiD (B= 5T)	sigma(p_T)/p_T		sigma(d)	
	p_T = 10 GeV	100 GeV	10 GeV	100 GeV
5μm res. for VTX 0.3%X_0	0.179%	0.293%	4.083	2.567
3μm res. for VTX 0.3%X_0	0.177%	0.287%	3.088	1.654
5μm res. for VTX 0.1%X_0	0.178%	0.293%	3.434	2.552

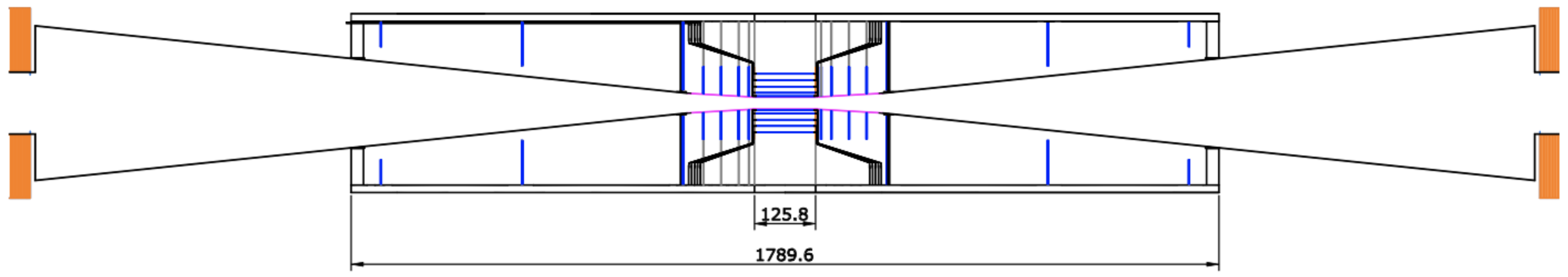
Note on **Timing** that can potentially help to separate lower momentum particles - although tracks in jets from Higgs can have significant momentum

→ Need sub-ps timing resolution at the price of more material

Arxiv: 1306.6329

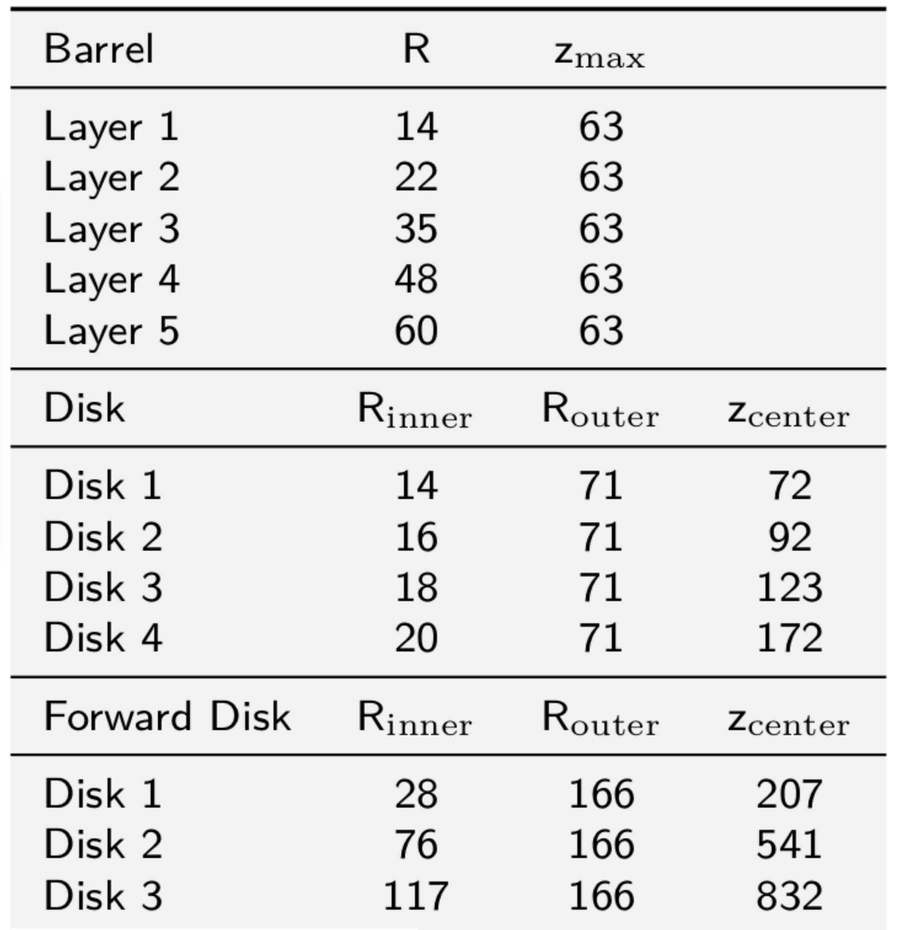
SiD

Compact, cost constrained detector

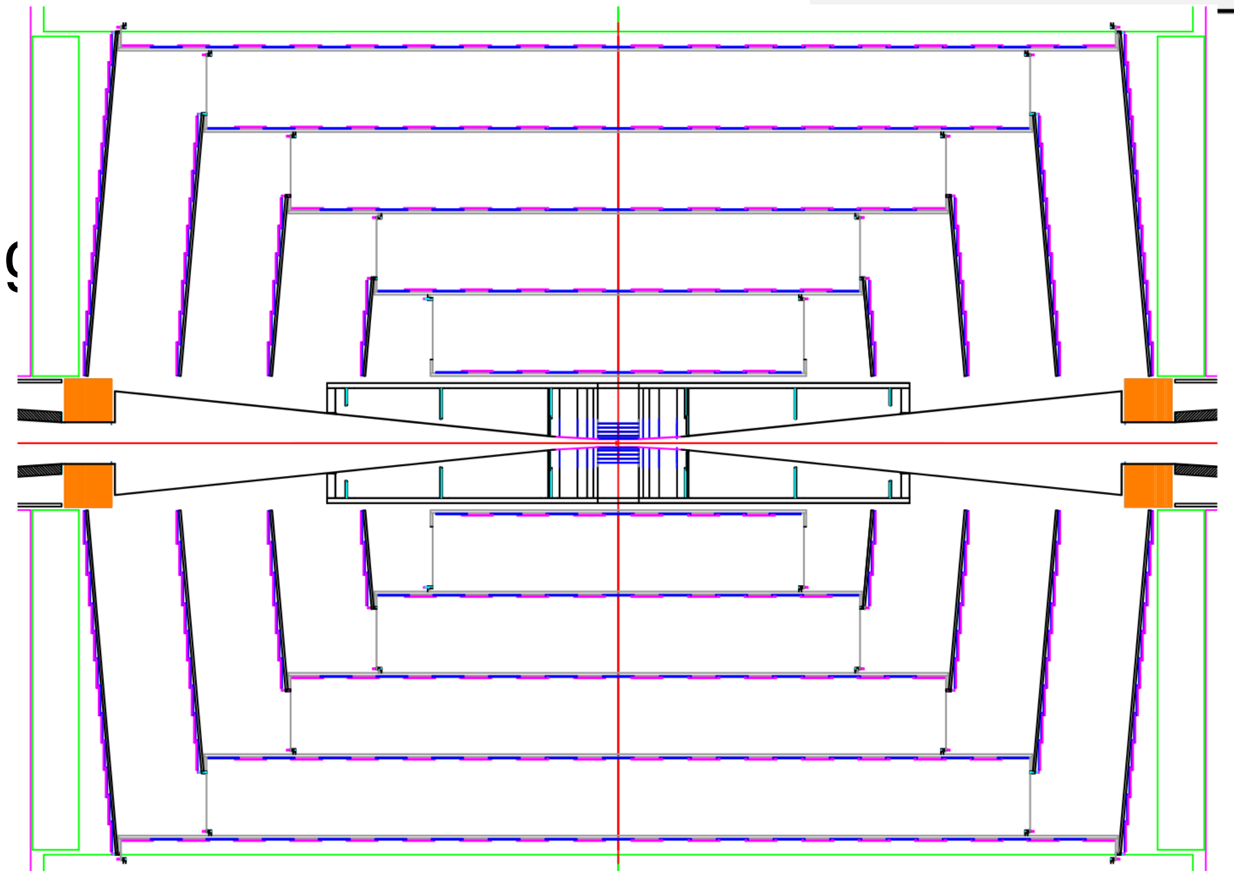


- Compact, cost constrained detector
  - 5 T solenoid B-field with with R_{ECAL}=1.27 m
  - All silicon pixel + strips tracking system
  - Highly granular calorimeter optimized for PFLOW
- Pixel Vertex detector
  - 1 kGy and 10^{11} n_{eq}/cm^2 per year
  - **Pixel hit resolution** better then 5 μm in barrel
    - Better if charge sharing is used
  - Less than **0.3% X_0** per pixel layer
    - air cooling → low-mass sensor
  - Single bunch time resolution
    - Low capacitance and high S/N allows for acceptable power dissipation for single-crossing
- Strip Tracker:
  - Silicon micro-strips, double metal layers
  - 0.1-0.15% X_0 in the central region

20x20 μm pixels in the central region
50x50 μm for the forward tracker disks



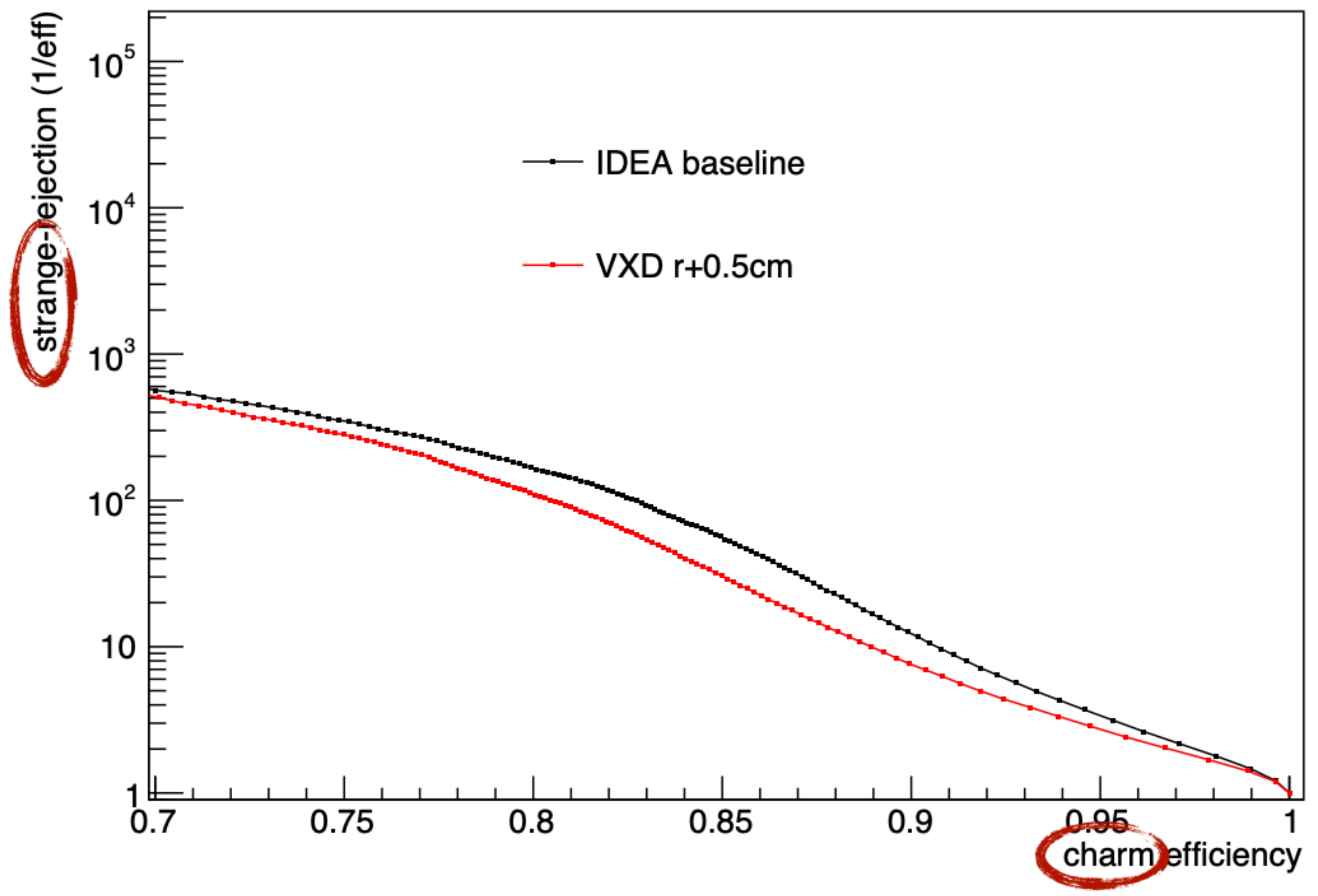
Barrel	R	z_{max}	
Layer 1	14	63	
Layer 2	22	63	
Layer 3	35	63	
Layer 4	48	63	
Layer 5	60	63	
Disk	R_{inner}	R_{outer}	z_{center}
Disk 1	14	71	72
Disk 2	16	71	92
Disk 3	18	71	123
Disk 4	20	71	172
Forward Disk	R_{inner}	R_{outer}	z_{center}
Disk 1	28	166	207
Disk 2	76	166	541
Disk 3	117	166	832

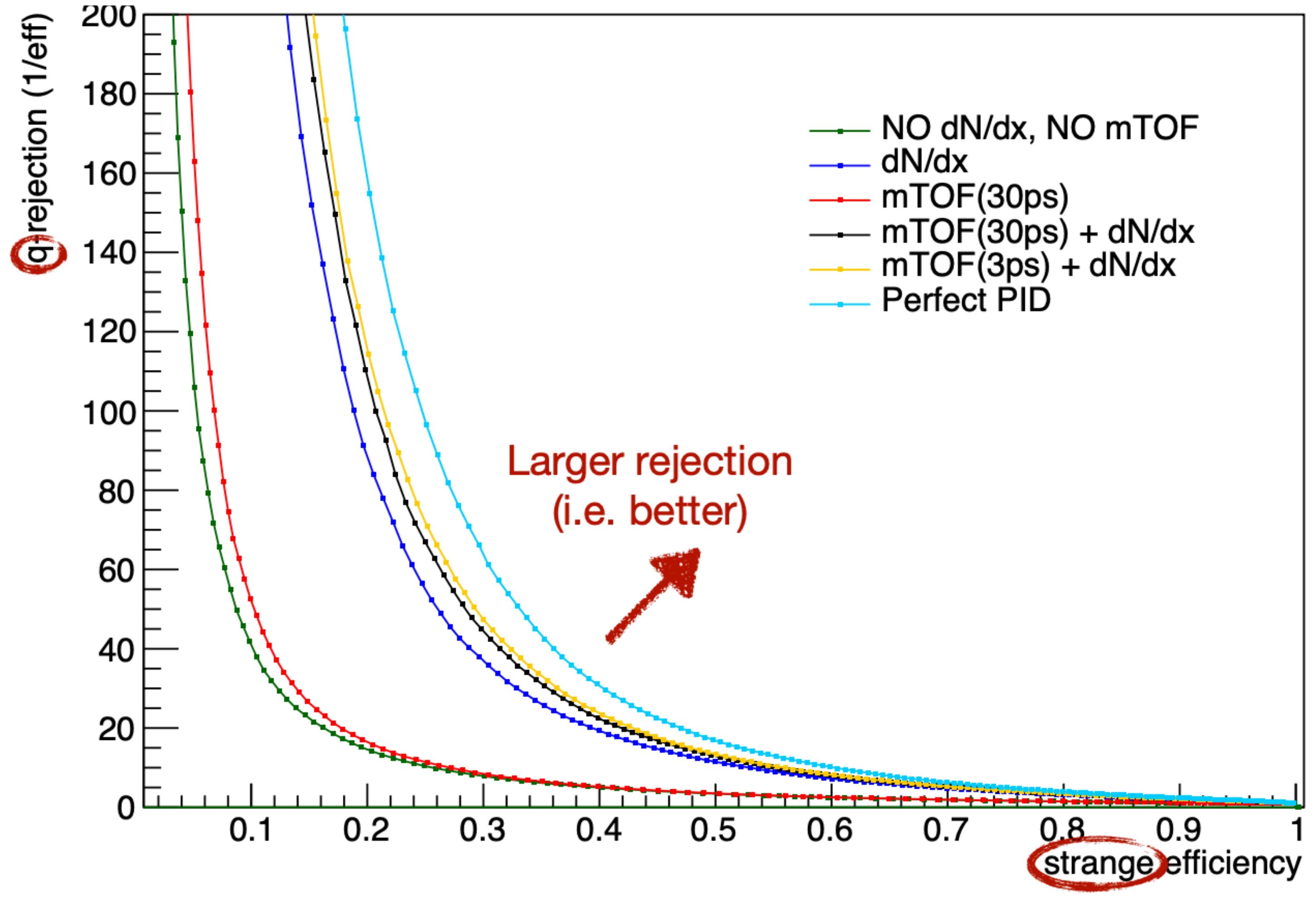


IDEA: tagging performance vs detector configurations

Evaluating impact of different silicon and particle-identification detector configurations

- Current IDEA pixel/tracking system:
  - beam pipe at 1cm and 3 innermost silicon barrel layers: 1.2cm, 2cm, 3.15cm
  - PID: cluster-counting (dN/dx) + 30ps ToF system
- Number of pixel layers and various configurations have been tested
  - Hit resolution & position first layer
  - PID capabilities: timing, energy loss (gas/silicon)
- ***Findings***:
  - Very limited impact of TOF mass measurement on strange tagging
  - Ideal PID shows visible enhancement, especially at low efficiency



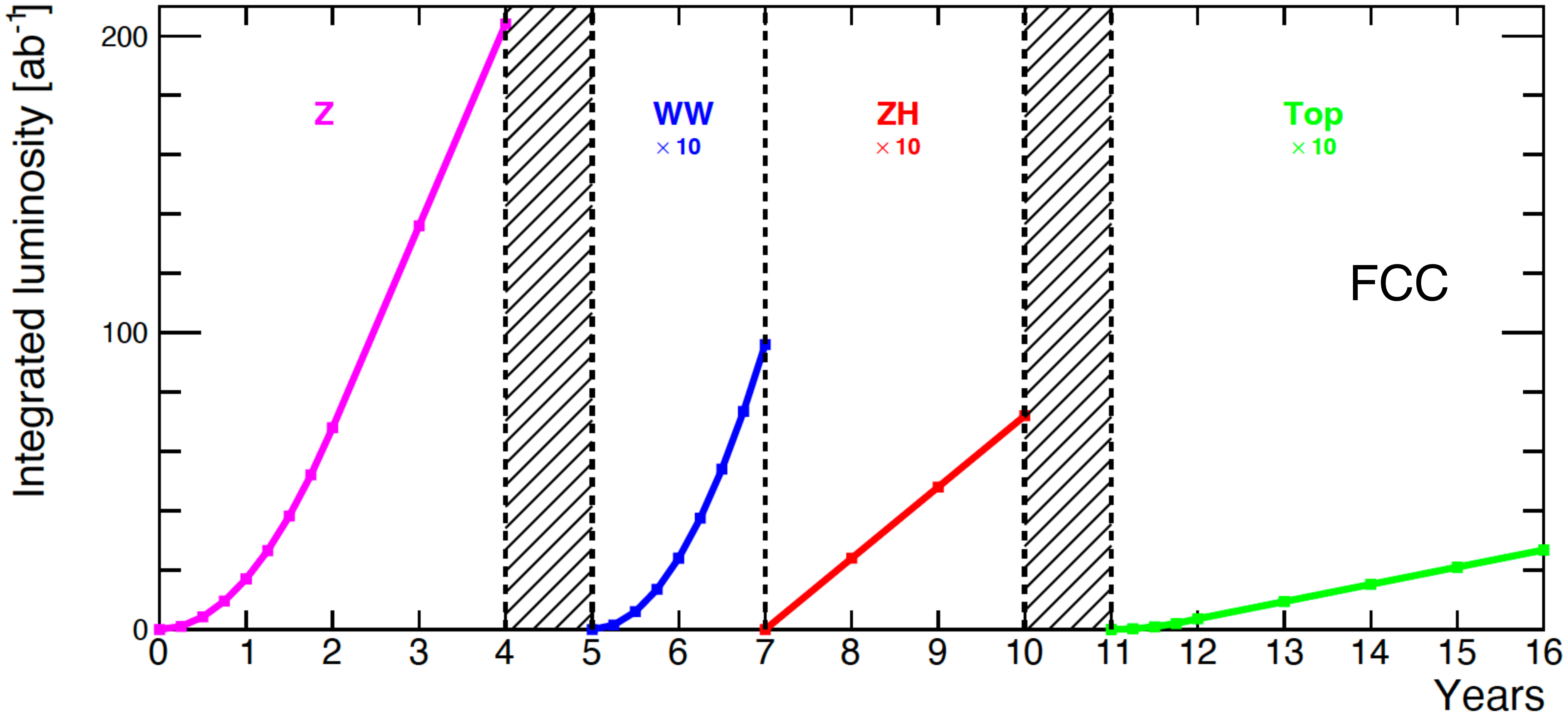


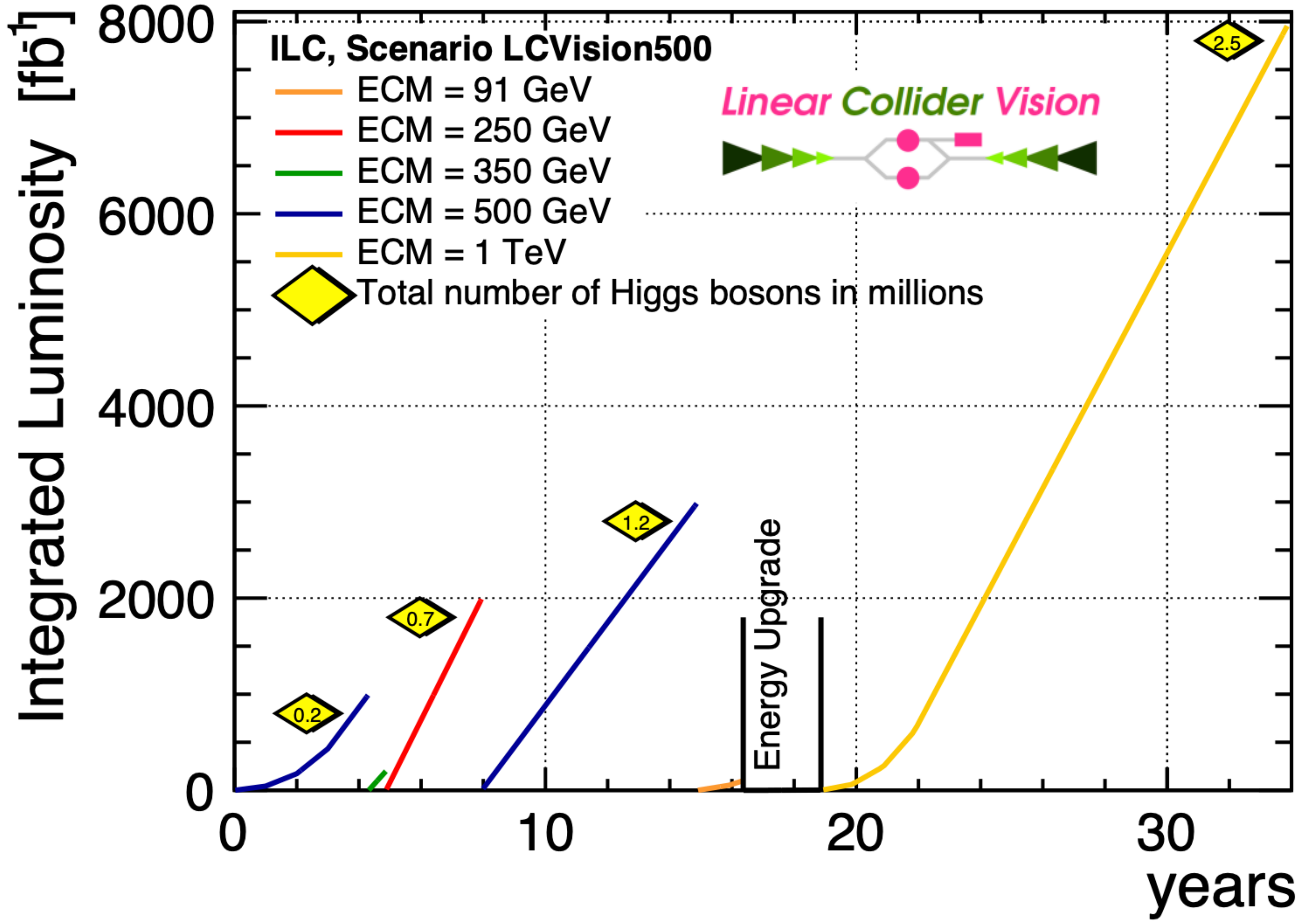
A. Sciandra ECFA 2024

Run Plans

1710.07621
FCC Mid Term Report

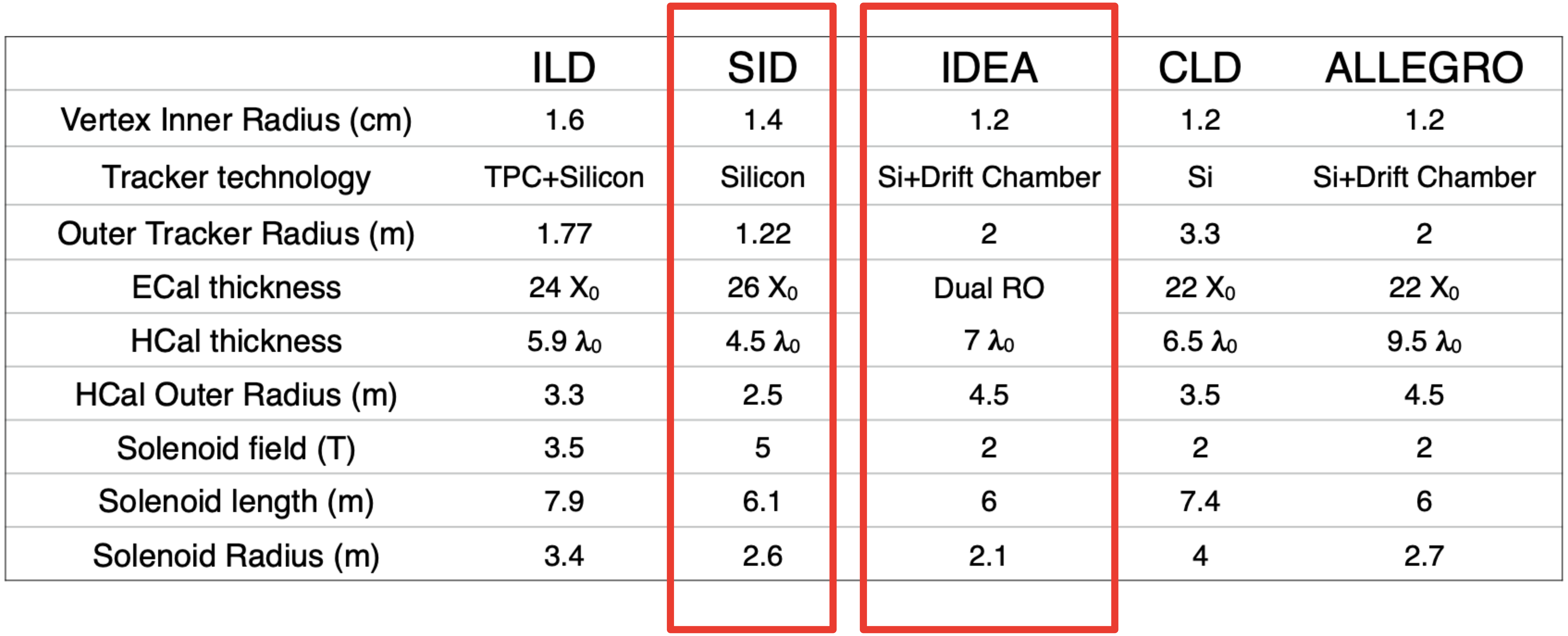
ILC and FCC



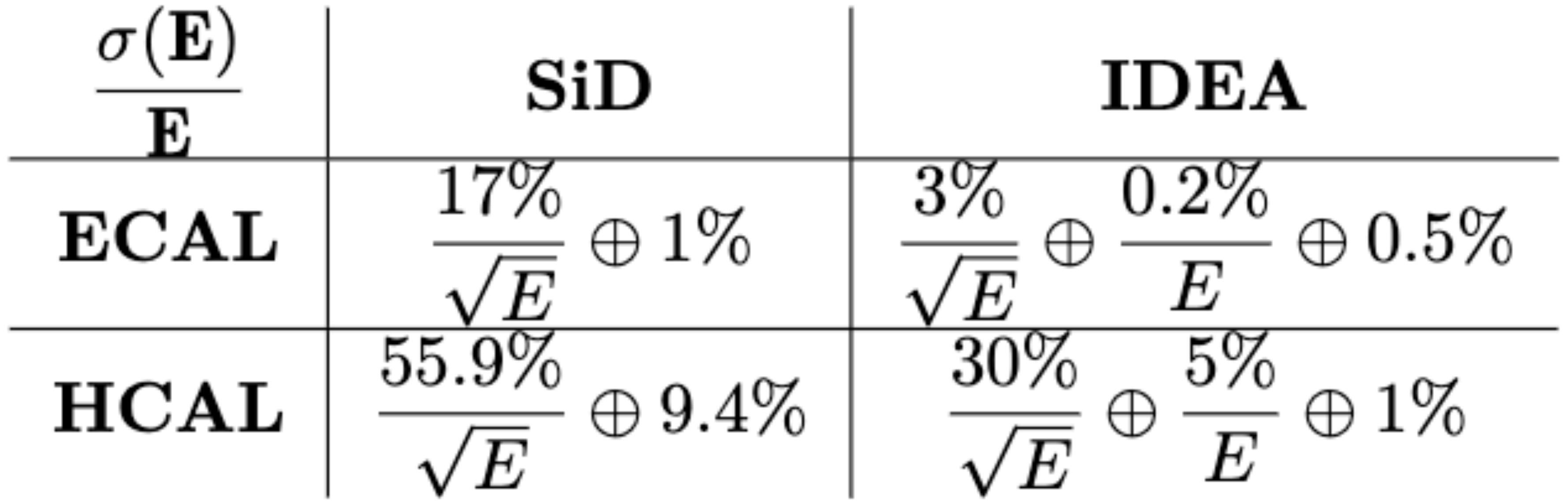


NEW - SiD detector studies

Using FCC/IDEA results as a benchmark



	ILD	SID	IDEA	CLD	ALLEGRO
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
Outer Tracker Radius (m)	1.77	1.22	2	3.3	2
ECal thickness	24 X_0	26 X_0	Dual RO	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
HCal Outer Radius (m)	3.3	2.5	4.5	3.5	4.5
Solenoid field (T)	3.5	5	2	2	2
Solenoid length (m)	7.9	6.1	6	7.4	6
Solenoid Radius (m)	3.4	2.6	2.1	4	2.7

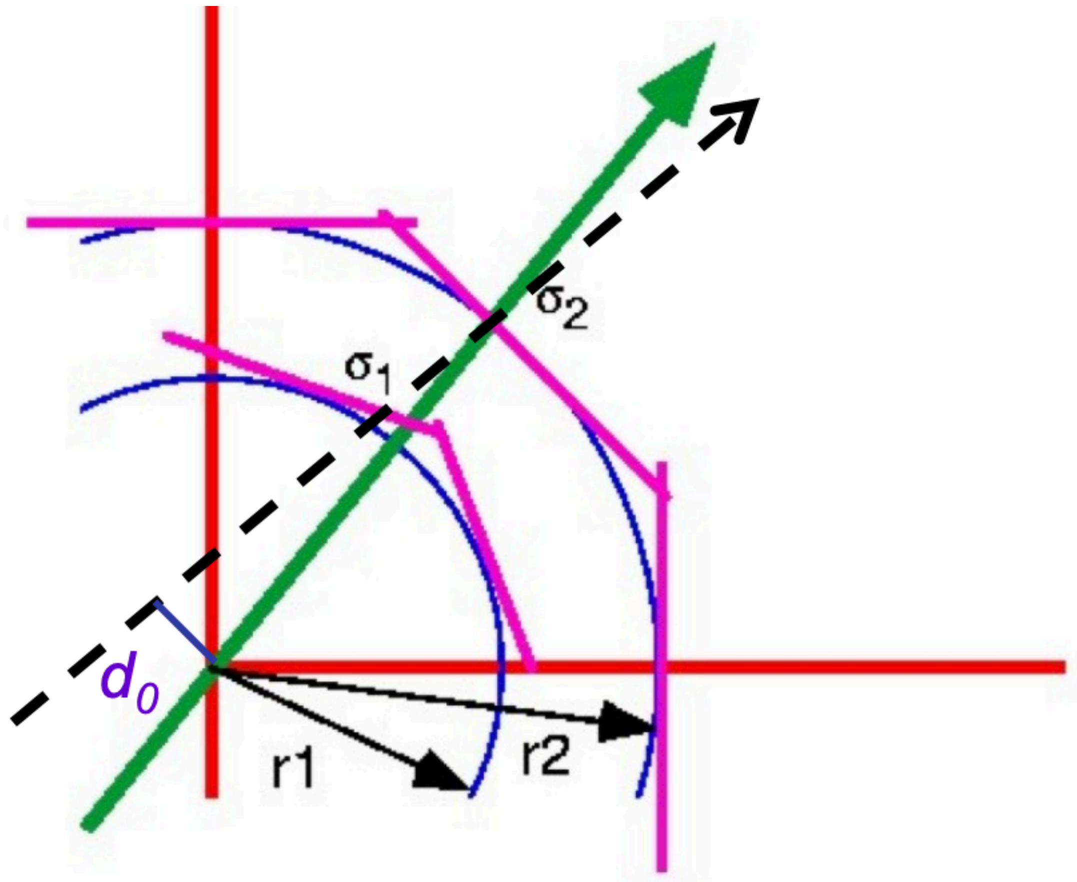


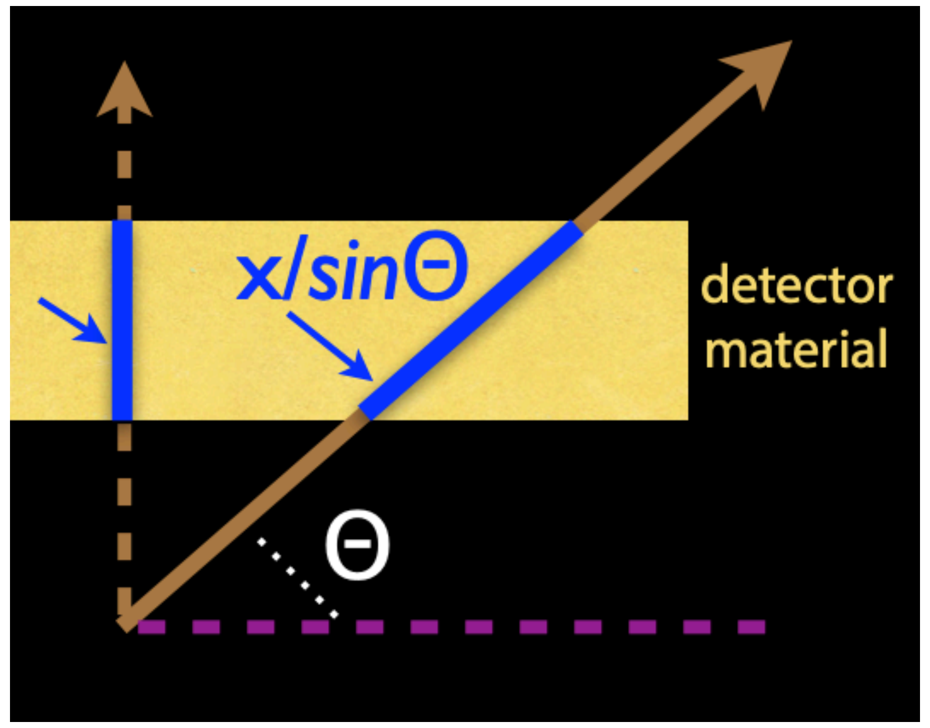
$\frac{\sigma(\mathbf{E})}{\mathbf{E}}$	**SiD**	**IDEA**
ECAL	$\frac{17\%}{\sqrt{E}} \oplus 1\%$	$\frac{3\%}{\sqrt{E}} \oplus \frac{0.2\%}{E} \oplus 0.5\%$
HCAL	$\frac{55.9\%}{\sqrt{E}} \oplus 9.4\%$	$\frac{30\%}{\sqrt{E}} \oplus \frac{5\%}{E} \oplus 1\%$

ILC TDR

2008.00338

Impact Parameter resolution





Uncertainty on the transverse impact parameter, d_0, depends on the radii and space point precision:

$$\sigma_{d_0}^2 = \frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}$$

This suggests: small r_1, large r_2, small error but precision is degraded by **multiple scattering** (r→r/sin ϑ, x→x/sin ϑ)

$$\sigma_{d_0}|_{MS} = \frac{r}{p} 13.6\mathrm{MeV}\sqrt{\frac{\mathrm{x}}{\mathrm{X}_0}}$$

$$\sigma_{d_0} = a \oplus \frac{b}{p_T sin^{1/2}\theta}$$

Constant term describing resolution
Multiple scattering term decreasing with p_T
Best precision with small radius, r, and minimum thickness x