From the ILC250 Vertex Detector toward Higgs Physics at FCCee

M. Winter (IJCLab-Orsay & IPHC-Strasbourg)

FCC Workshop / IN2P3 / 15 May 2020

Contents

- General Remarks on a Vertex Detector suited to a Higgs Factory
- Case of ILC: Physics oriented requirements and Running conditions
- ILC vertex detector: Achievements & Prospects
- Extension to FCCee vertex detector
- Summary & Conclusions

see also: A. Besson (talk at FCC workshop, CERN, January 2020)

Acknowledgement : A. Besson (IPHC-Strasbourg), R. Poeschl (IJCLab-Orsay)

Role of Vertex Detector for a Higgs Factory

- DISPLACED VERTEX RECONSTRUCTION AND CHARACTERISATION :
  - reconstruction of collision point
  - reconstruction of D-meson and τ-lepton vertices
  - reconstruction of b-quark decays in (top-quark) jets
  - determination of displaced vertex electrical charge
  - etc.

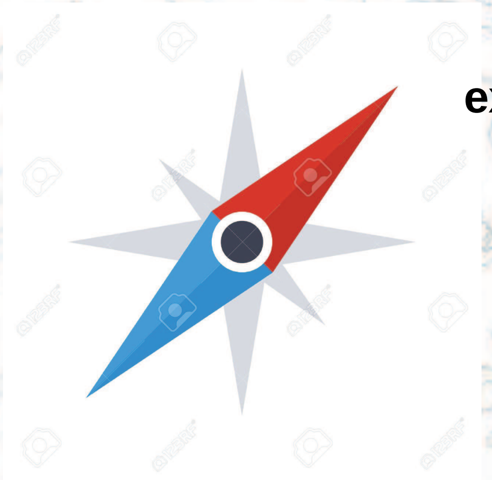
- ROLE IN THE TRACKING :
  - track seeding (depending on main tracker)
  - low P_t track reconstruction
  - track momentum determination (in particular low P_t)
  - fake tracks mitigation (E_{miss} determination)

Generic Vertex Detector Requirements for a Higgs Factory

complete geometrical coverage extending to lowest possible polar angle

exquisite spatial resolution

extremely modest material budget



excellent alignment capability

time stamping against
beam related background

sufficiant heat removal
from active elements

compliance with beam
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inner layer very close to IP

very good link to surrounding tracking systems

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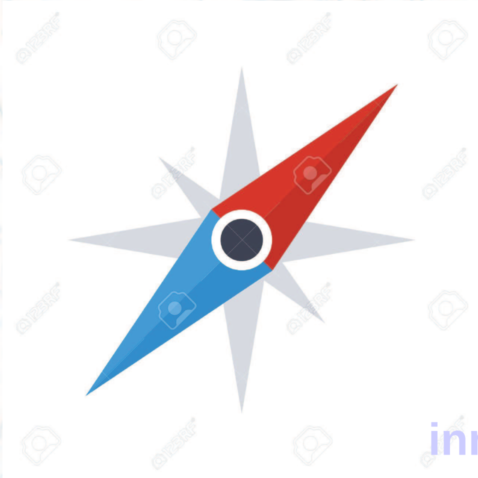

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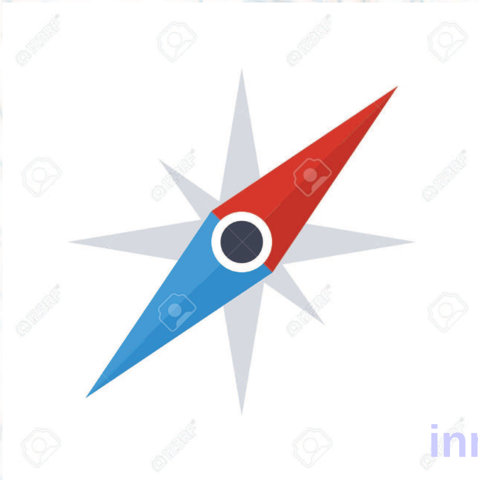

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COLLIDER SPECIFIC TRADE-OFFS !

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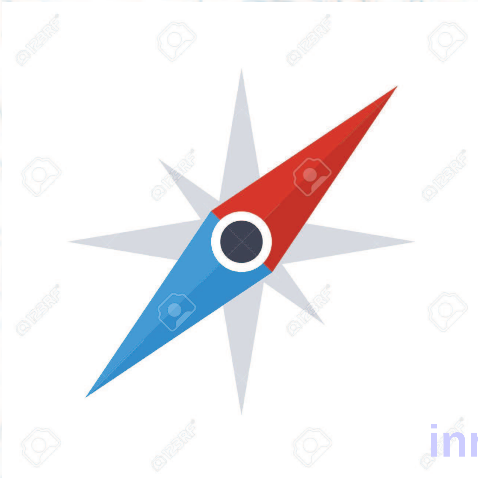

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BONUS OF TIME: **EVOLUTION OF INDUSTRIAL TECHNOLOGY MAY MITIGATE SOME OBSTACLES**

Major Aspects of the ILC Detector Concepts

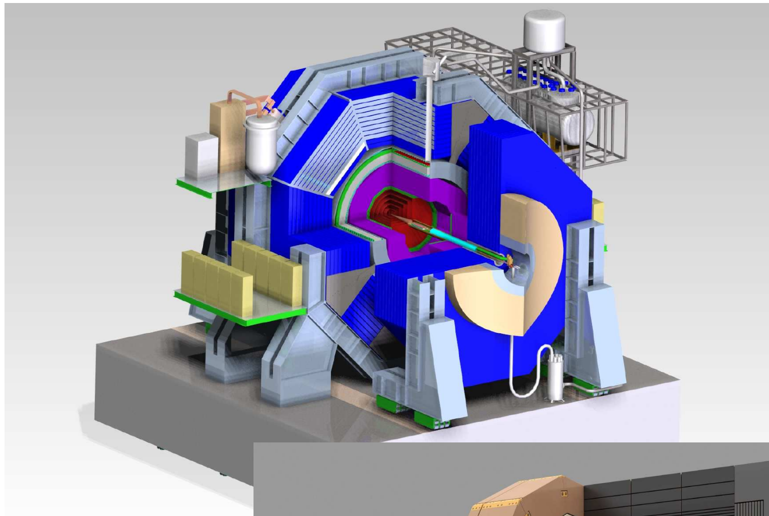
- 2 DETECTOR CONCEPTS :
  - SiD: full silicon tracker (most compact)
  - ILD: gaseous main tracker (TPC)
- PRIORITY: GRANULARITY & SENSITIVITY
- EXPLOIT COLLIDER SPECIFICITIES:
  - **e^+e^- collisions:**
    - precisely known collision conditions (E_{cm}, Pol., Lumi.)
    - suppressed QCD background $\Rrightarrow$ moderate radiation level

      H occur in 1% of coll. (LHC: 1 H for 10^{10} collisions)

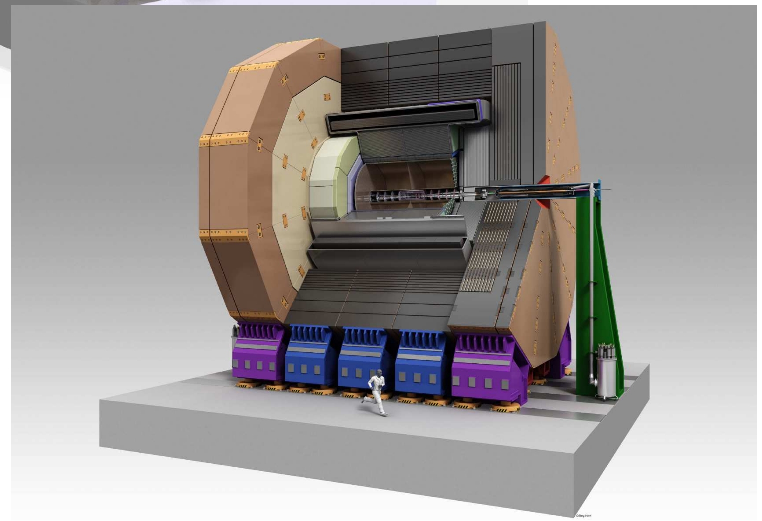
      $\Rrightarrow$ triggerless data taking adapted to faint & rare phenomena
  - **beam time structure:**
    - $\lesssim$ 1% duty cycle $\Rrightarrow$ power cycling $\equiv$ saving $\Rrightarrow$ allows high granularity
    - $\gtrsim$ 300 ns bunch separation $\Rrightarrow$ moderate Δt required
- AMBITIONNED PERFORMANCE HIGHLIGHTS:
  - $\Delta_{2ryVx} < 10\ \mu m$
  - charged track rec.: $\Delta(1/p) = 2\cdot10^{-5}$ GeV^{-1}

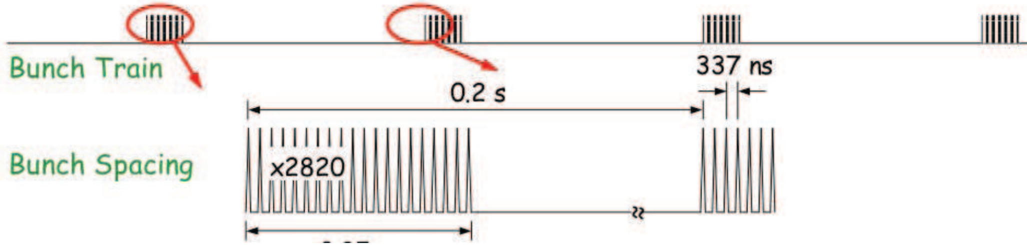
    $Q_{2ryVx} \Rrightarrow$ rec. $P_t \lesssim 100$ MeV tracks
  - mat. budget: $\lesssim 10\%\ X_0$ in front of calorimetres
  - $\sigma_E^{jet}/E^{jet} \simeq 30\%/\sqrt{E^{jet}}$ (neutral had. !) $\Rrightarrow$ PFA

SiD



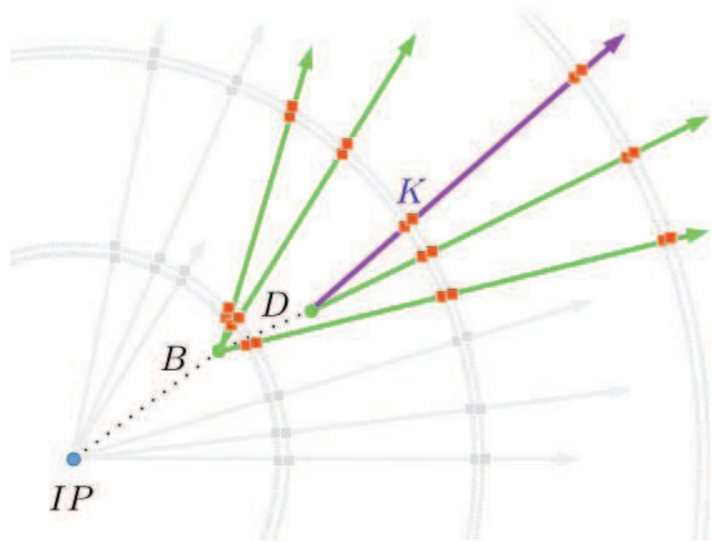
ILD





Vertex Detector Performance Goals

- **Vertex detector requirements governed by physics oriented parametres rather than running conditions**
  - ⋇ emphasis on granularity & material budget (very low power)
  - ⋇ much less demanding running conditions than at LHC
    - $\Rrightarrow$ alleviated read-out speed & radiation tolerance requests
  - ⋇ ILC duty cycle $\gtrsim$ 1/200 $\Rrightarrow$ power saving by power pulsing

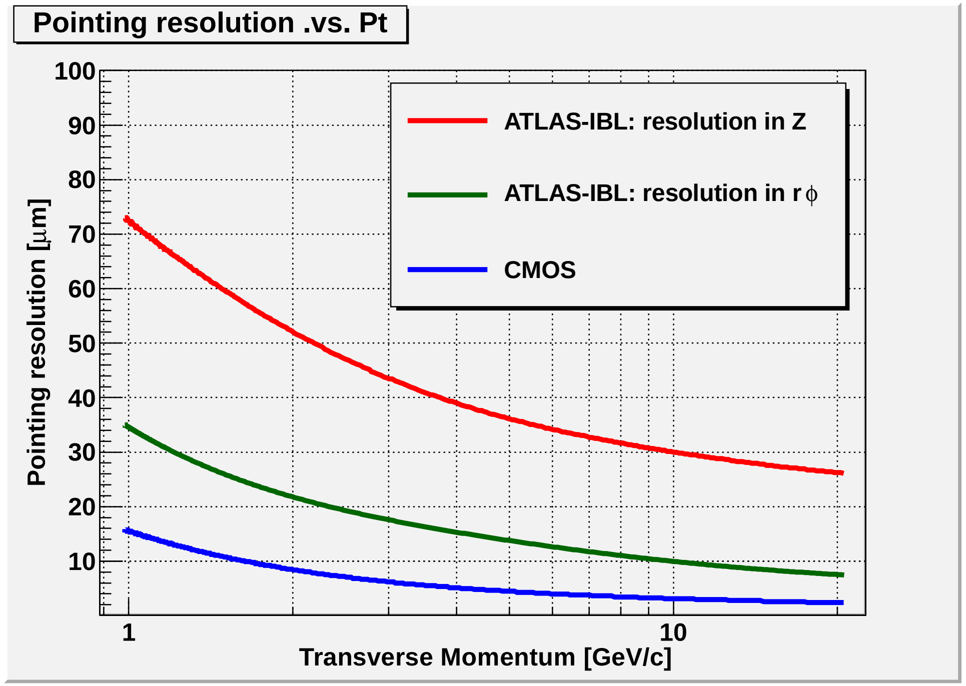


- **Vertexing goal:**
  - ⋇ achieve high efficiency & purity flavour tagging
    - $\rightarrowtail$ charm & tau, jet-flavour !!!
  - ⋇ reconstruct momentum of soft tracks ($P_t <$ 100 MeV)
  - ⋇ reconstruct displaced vertex charge

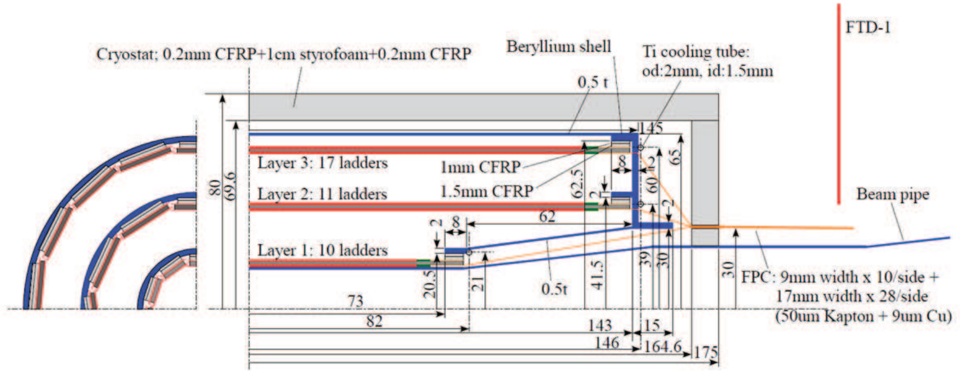
$\hookrightarrow$ $\sigma_{R\phi,Z} \leq 5 \oplus 10/p \cdot sin^{3/2}\theta \;\; \mu m$

▷ LHC: $\sigma_{R\phi} \simeq 12 \oplus 70/p \cdot sin^{3/2}\theta$

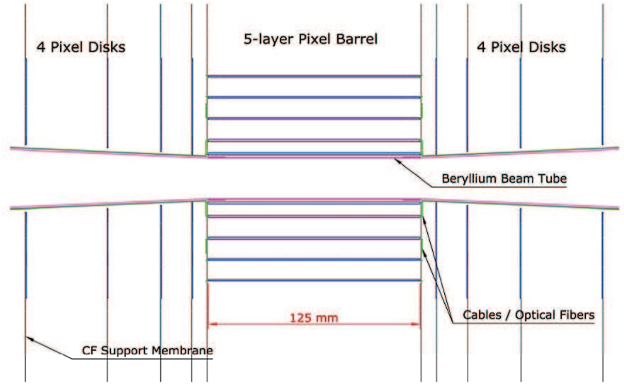
▷ Comparison: $\sigma_{R\phi,Z}$(ILD) with VXD made of ATLAS-IBL or ILD-VXD pixels $\rightarrowtail$



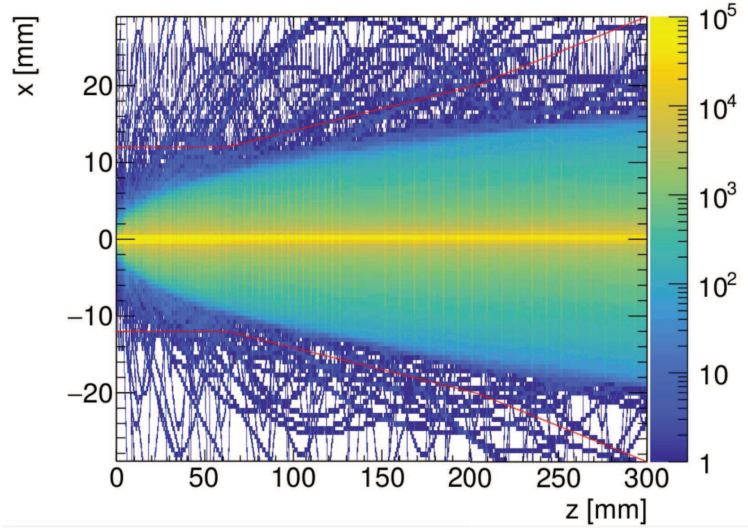
Vertexing Concepts & Challenges



- TWO ALTERNATIVE PIXELATED DESIGNS :
  - **ILD:** long barrel of 3 dble layers (R: 16 - 60 mm)
    0.3% X_0 / dble layer, $\sigma_{sp} \lesssim 3\ \mu m$
  - **SiD:** short barrel of 5 single layers (R: 14 - 60 mm)
    0.15% X_0 / layer, $\sigma_{sp} \lesssim$ 3-5 μm
  - several (small & thin) pixel technology options under development
  - other devts: mat. budget suppression, cooling, 2-sided ladders, ...

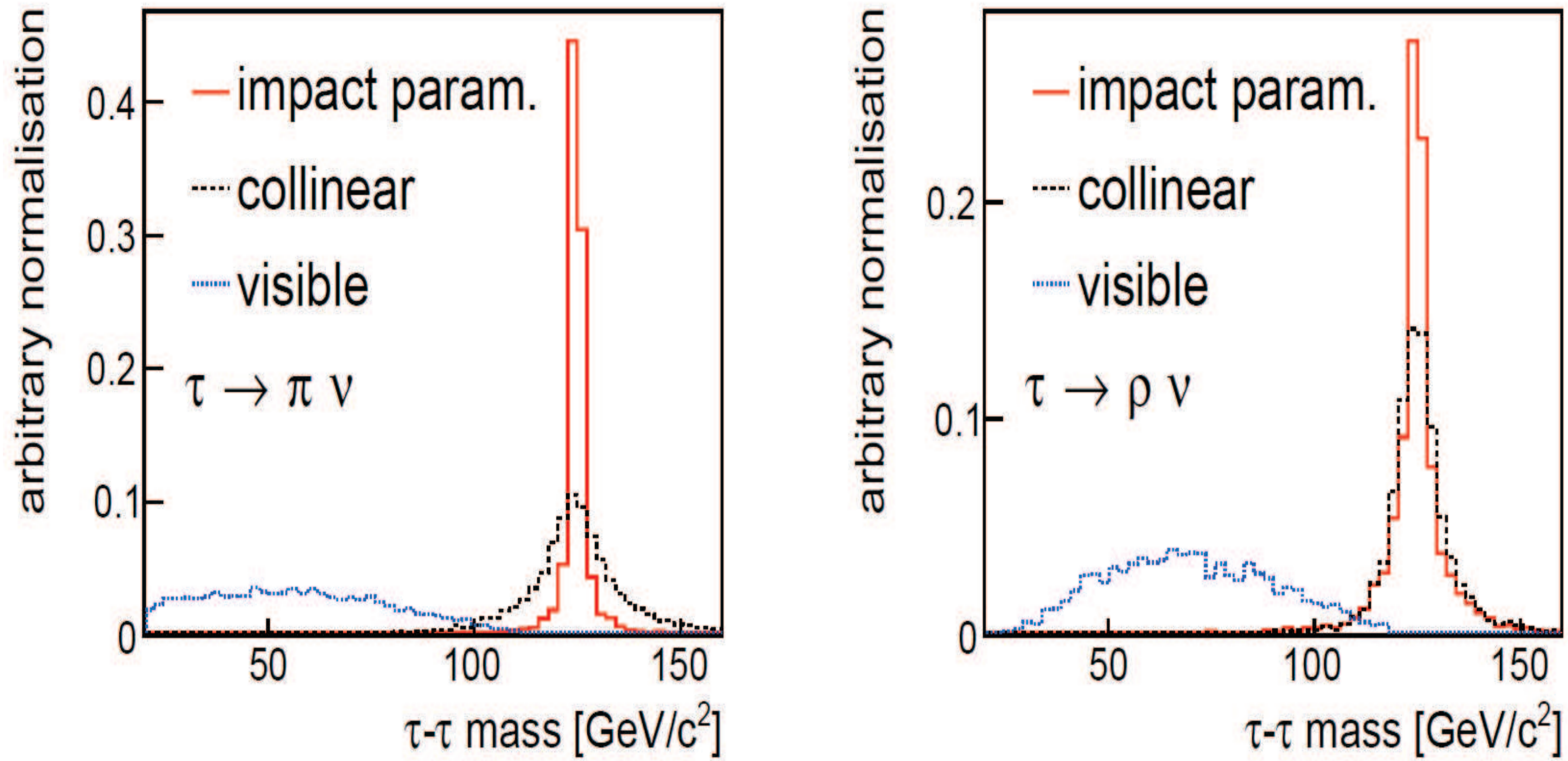


- RUNNING CONDITIONS DOMINATED BY BEAMSTRAHLUNG $e^{\pm}$:
  - Radiation doses: O(100) kRad, $< 10^{12}$ n_{eq}/cm^2/yr
  - Rate of $e^{\pm}_{BS}$ impacts: possibly up to several tens/cm^2/BX
    - $\Rrightarrow$ governs time resolution requirements
  - sizeable uncertainties: σ_{BS}, luminosity
    - $\Rrightarrow$ substantial safety factors mandatory !



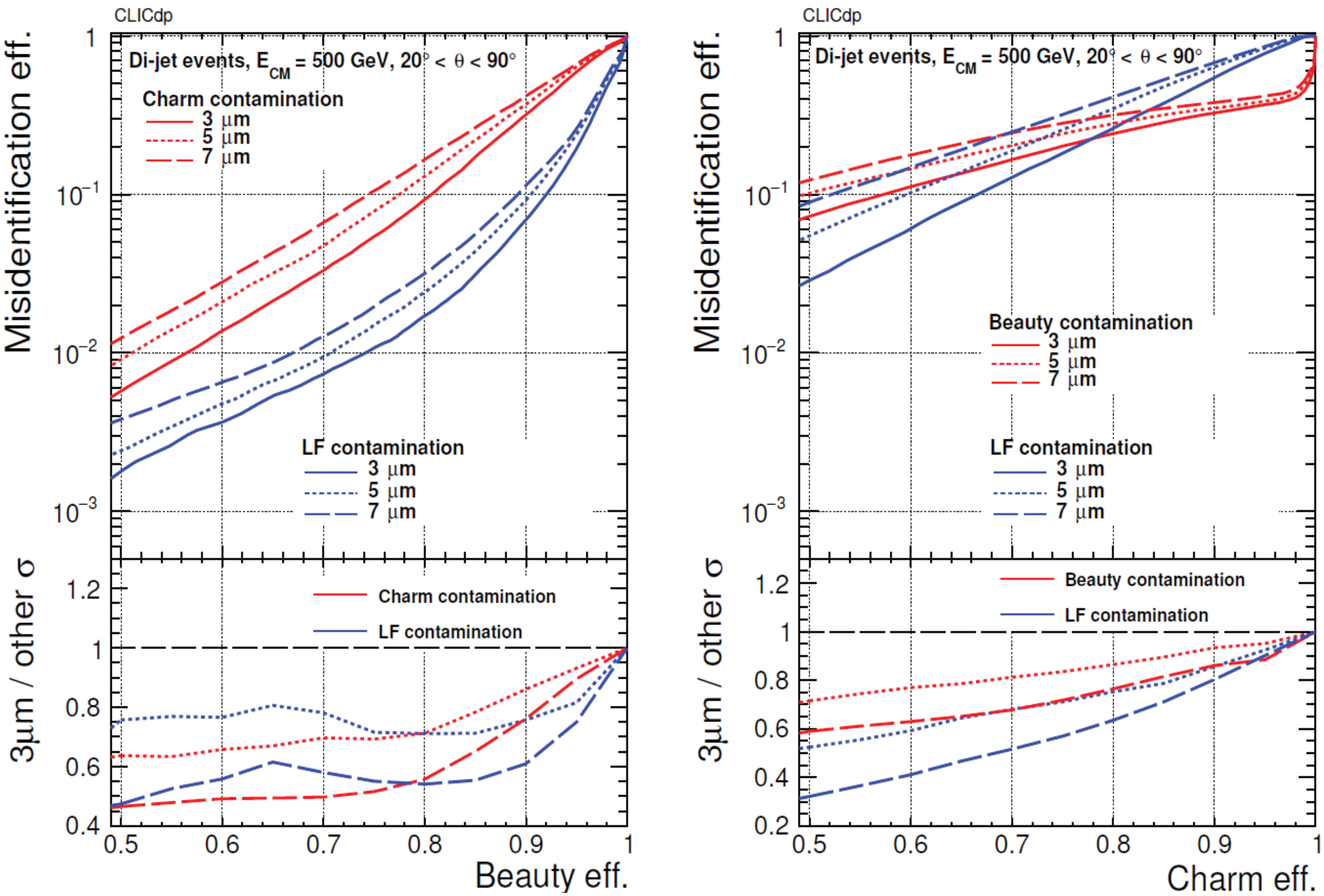
Role of Vertex Detector: Reconstruction of τ lepton

- IMPACT OF VERTEX DETECTOR ON τ RECONSTRUCTION: EXAMPLE OF ILD
  - use measurements of τ spin state in $e^+e^- \rightarrowtail ZH \rightarrowtail \mu^+\mu^-\tau^+\tau^-$ to probe the CP nature of the Higgs boson and search for BSM manifestation by investigating CP conservation in Higgsstrahlung process and Higgs decay
  - concentrate on hadronic decays of τs (one ν only) using displaced vertex reconstruction



  - D. Jeans, Nucl. Instrum. Meth. A810, 51 (2016), arXiv:1507.01700 [hep-ex]
  - D. Jeans and G. Wilson, Phys. Rev. D 98, 013007 (2018), arXiv:1804.01241 [hep-ex]

Role of Vertex Detector: Impact of Spatial Resolution on b, c Tagging

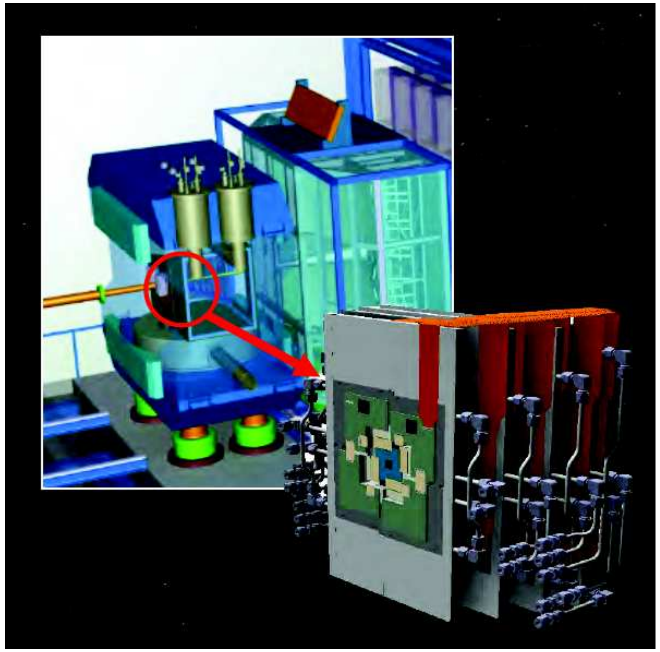


- fermion-pair production at E_{CM} = 500 GeV (CLICdet vertex detector : R_{in} = 31 mm)

  D. Arominski et al., CLICdp-Note-2018-005, arXiv:1812.07337 [physics.ins-det] (2018)

- σ_{sp} = 7 $\mu m \rightarrowtail$ 3 $\mu m \Rrightarrow$ contaminations suppressed by $\sim$ 20% to 40% for 90% tagging efficiency

Monolithic CMOS Pixel Sensors (CPS)



- **ILC requirements similar to those of Heavy Ion expts**

  $\Rrightarrow$ CPS developed for CBM expt (FAIR/GSI)

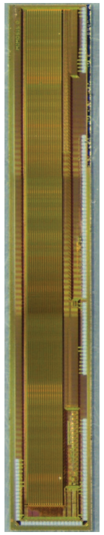
  $\equiv$ acts as a forerunner for ILC vertex detectors

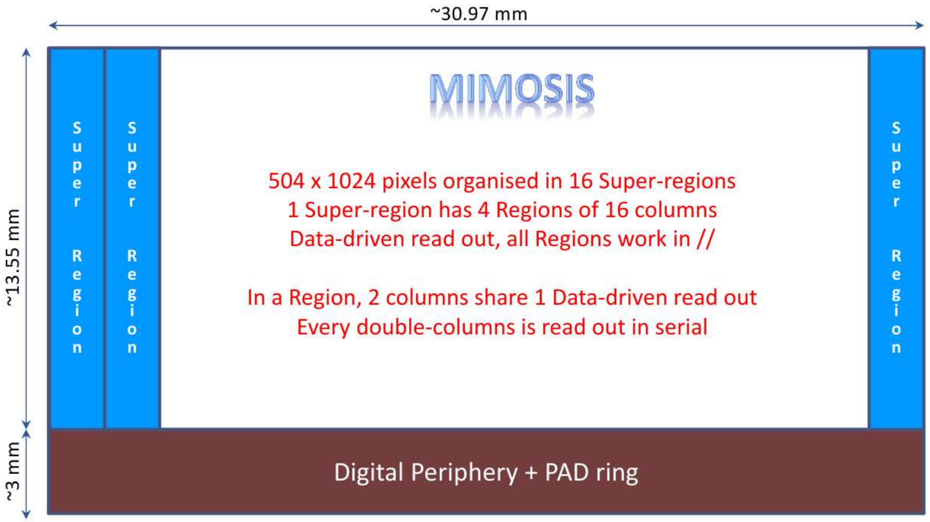
- **Main characteristics of MIMOSIS**
  - ⋇ TJsc 180 nm imager process with high-res (25 μm thick) epitaxy
  - ⋇ modified high-res (25 μm thin) epitaxy $\Rrightarrow$ full depletion
    $\Rrightarrow$ sub-ns charge collection time (+ enhanced rad. tol.)
  - ⋇ 1024 col. of 504 pixels with asynchronous r.o. (ALPIDE)
    in-pixel discri. with binary charge encoding
  - ⋇ pixel: 27x30 μm^2 $\Rrightarrow$ $\sigma_{sp} \gtrsim$ 5 μm (vs depletion depth)
  - ⋇ affordable hit density $\simeq 10^8$ hits/cm^2/s
  - ⋇ $\Delta t \sim$ 5 μs
  - ⋇ Power density $\sim$ 40–50 mW/cm^2 (vs hit density)

- Step-1: MIMOSIS-0 proto. $\equiv$ 1/32 slice of final sensor
  - ⋇ pixel array μcircuitry validated at 5 μs
  - ⋇ measured rad.tol.: 10 MRad, 10^{14} n$_{eq}$/cm^2

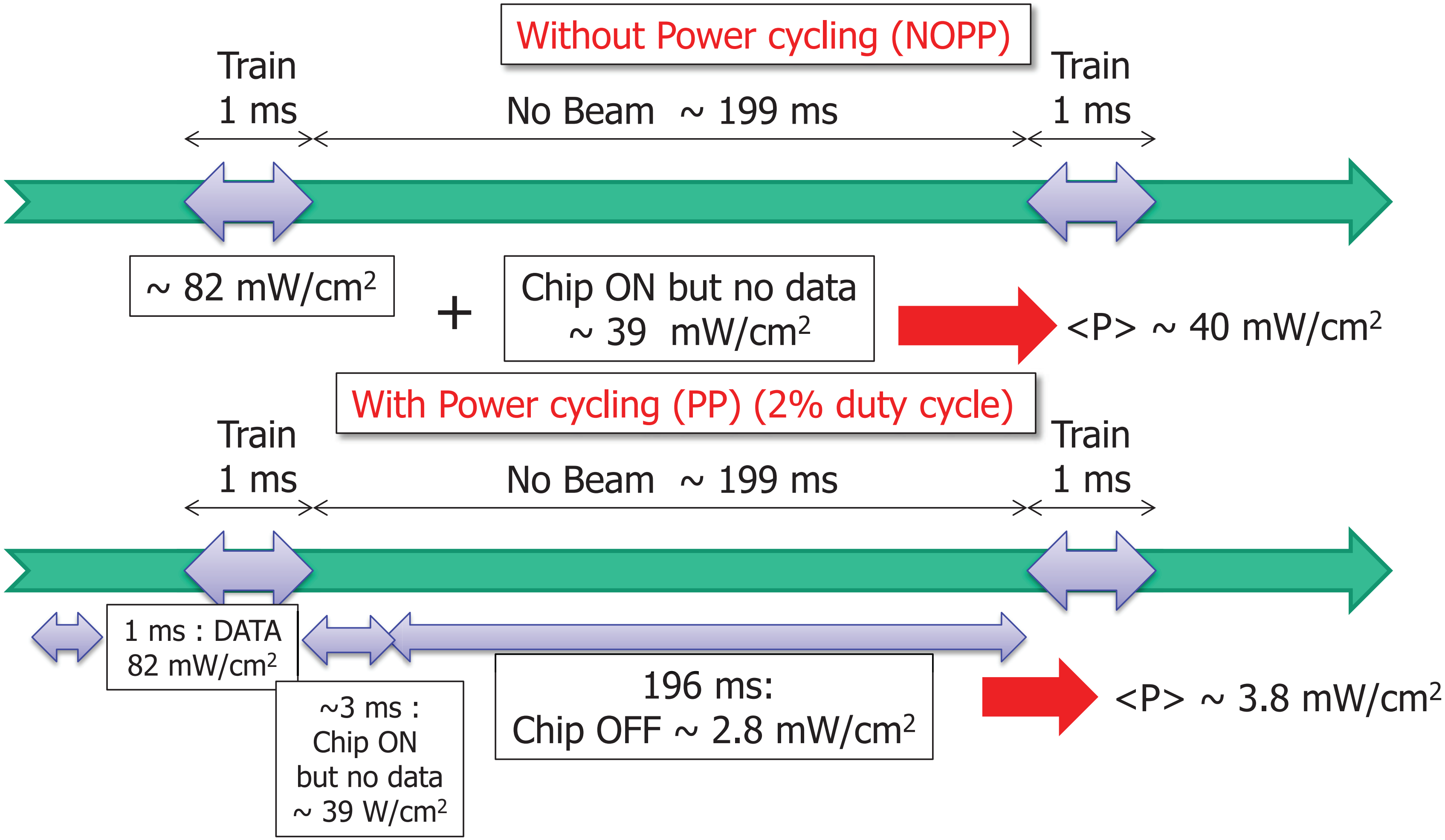
- Step-2: MIMOSIS-1 full size proto.

  $\Rrightarrow$ back from fab. in June



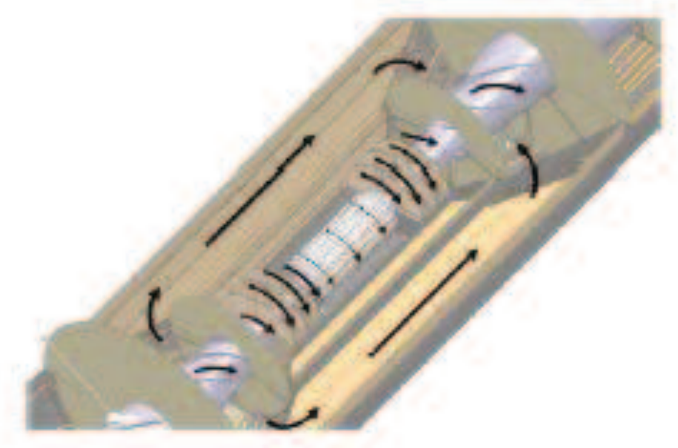


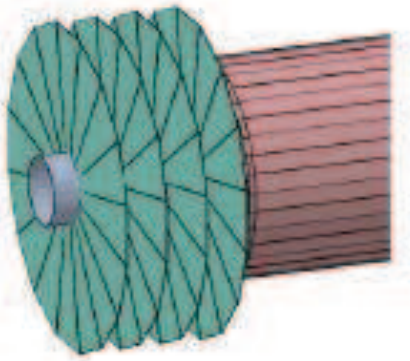
Power scheme for VTX-ILD (inner layer)

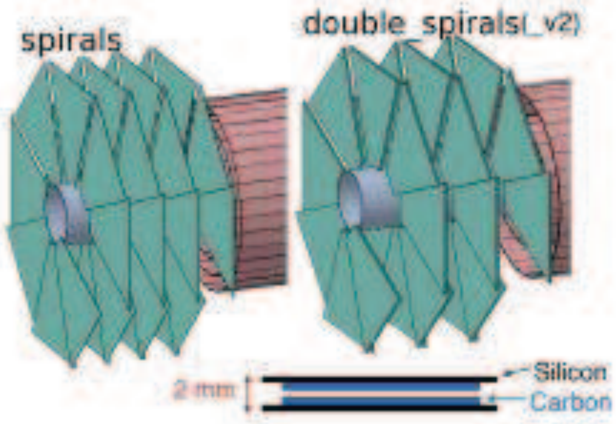


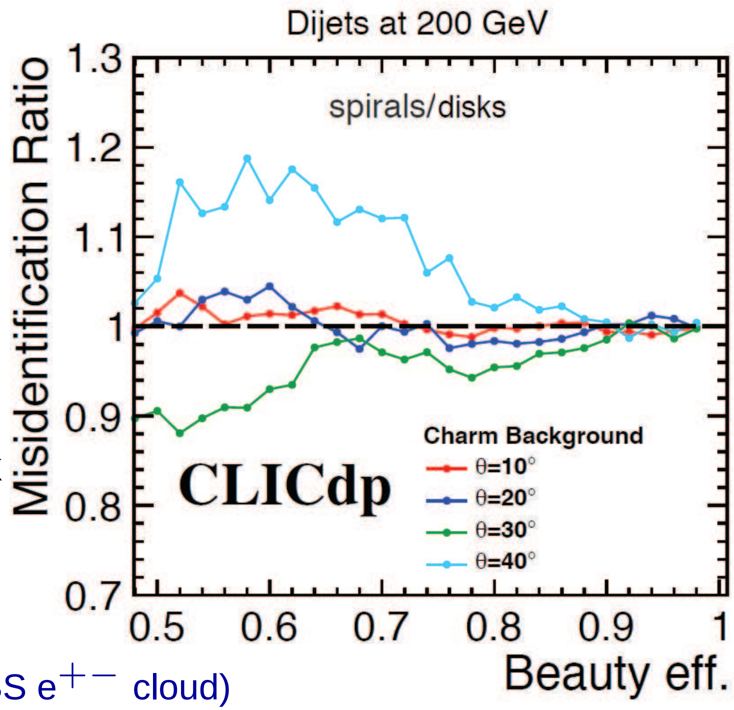
Hypothesis: 3 double sided layers (3483 cm^2), PSIRA architecture (4 μs / 4 μm), TDR background @ $\sqrt{s}$ = 500 GeV, no safety factor

Issue: Link to Forward Tracking System









- Cooling pipes introduce dead material near the IP

$\Rrightarrow$ alternative (CLICdp approach) : cooled air flowing from outside through end-cap tracking sub-system & traversing vertex detector volume
(see N. Alipour Tehrani & P. Roloff, "Optimisation studies for the CLIC vertex-detector geometry", CLICdp-Note-2014-002).

- "40° corner":

  b-tagging impacted by increased $<$distance$>$ from barrel edge to 1st disk
  c-tagging suspected to be significantly more impacted: how much ?

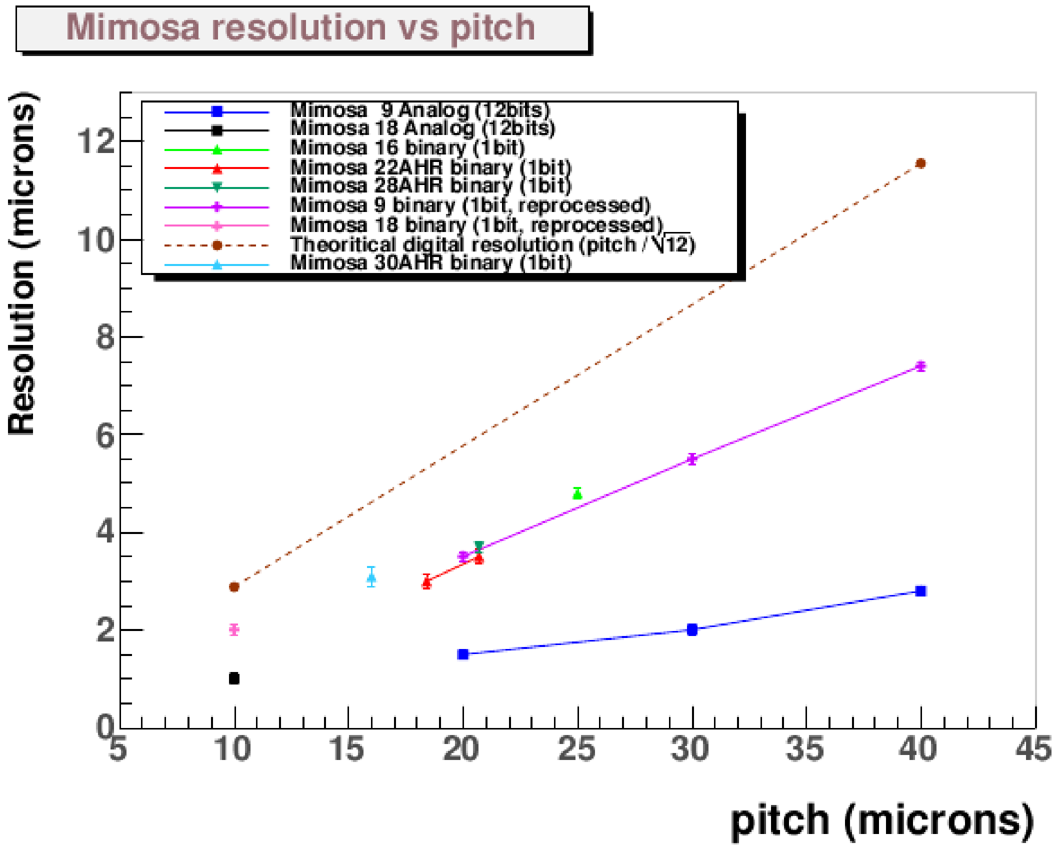
- Other delicate areas:

  ⋇ near the beam pipe (cone ?) $\Rrightarrow$ minimal polar angle intercepted (fct of outgoing BS e^{+-} cloud)

  ⋇ distance between barrel end and first foward disk $\Rrightarrow$ impact on small polar angle tagging

Issue: σ_{sp} & Δ_t in same sensor

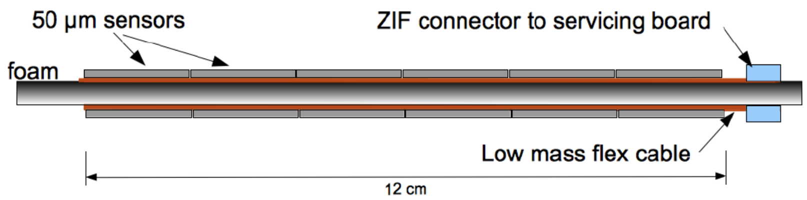
- **SPATIAL RESOLUTION :**
  - Target value: $\lesssim$ 5 to 3 μm
  - Function of pixel pitch
    $\times$ signal charge sharing
    $\times$ charge amplitude
    $\times$ charge encoding (nb of bits, SNR)
    Ex: 25 μm pitch $\times$ M$_{clus}$ = 1 (full depletion, $\theta \sim 90^\circ$)
    $\Rrightarrow \sigma_{sp} \simeq 7\ \mu m$!
  - Correlation with read-out speed:
    $\Delta_t \simeq$ few ns imposes fast charge collection
    (full depletion, large collection diode, ...)
    $\Rrightarrow$ charge sharing suppressed
  - Tension mitigated IF $\Delta_t \gtrsim$ 100 ns

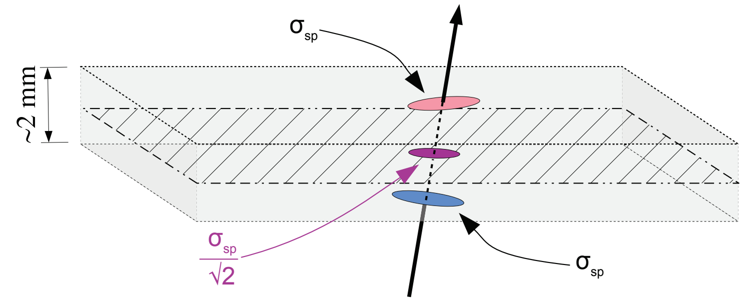


- **TIME STAMPING :**
  - mainly dictated by beam related background rate (similar at ILC & FCCee)
  - $\sigma_t \lesssim 1\ \mu s \Rrightarrow$ hit rate $\sim$ few 10^{-4}/cm^2/s $\times$ safety factor (e.g. 3-5)
    $\Rrightarrow$ pixel array occupancy $\sim$ O(10^{-3}) at ILC250 & FCCee $\Rrightarrow$ Affordable !

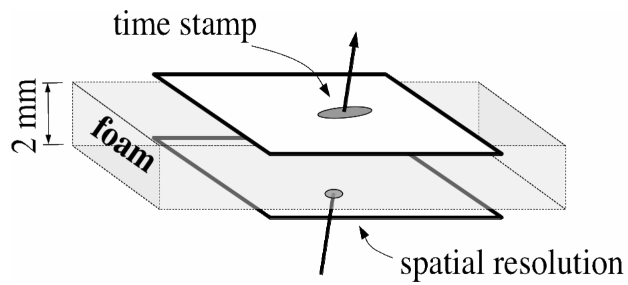
Ultra-Light Double-Sided Pixelated Tracker Modules

- **General remarks:**
  - Double-sided ladders for
    - excellent spatial resolution (granularity, face-to-face correlation)
    - coping with very high hit densities (speed, face-to-face correlation
  - Caveate: material budget oughts to be suppressed enough
  - PLUME $\equiv$ Existing prototype, based on MIMOSIS:
    8 million pixels, $\gtrsim 3\ \mu m$, 115 μs, 0.4 % X_0
  - 1st goal: improve r.o. speed to O(1) μs & squeeze mat. budget
    to $\lesssim 0.3$ % X_0, validate face-to-face sensor correlation
  - 2ry goal: investigate wireless face-to-face signal transmission
  - Possibly: investigate power pulsing in mag. field ? (tbc)





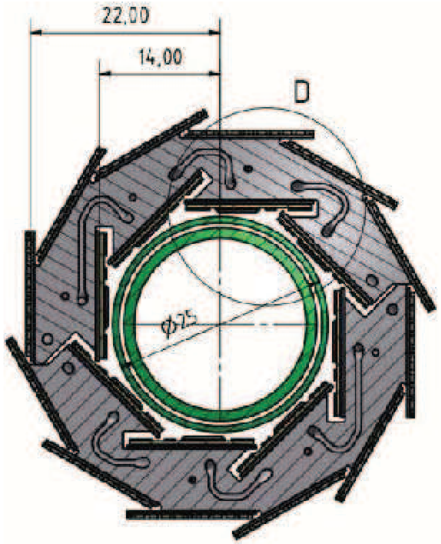
- **Sensor related objectives:**
  - Baseline MIMOSIS proto.: $\gtrsim 4\ \mu m$ (tbc), $\lesssim 5\ \mu s$, $\lesssim 50$ mW/cm^2, $\gtrsim 50$ MHz/cm^2
  - Assess spatial resolution of ladder based on face-to-face correlations
  - Ideally: develop mixed MALTA-MIMOSIS ladders (complicated !)

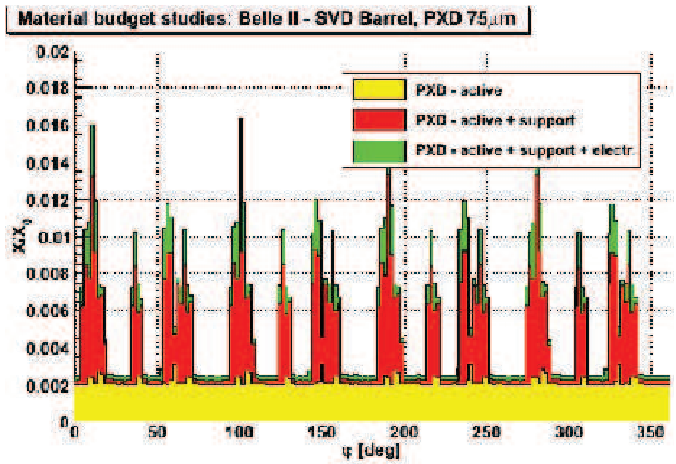


- **System related objectives:**
  - revisit structure of PLUME to compress its material budget
  - investigate new materials & micro-channel cooling

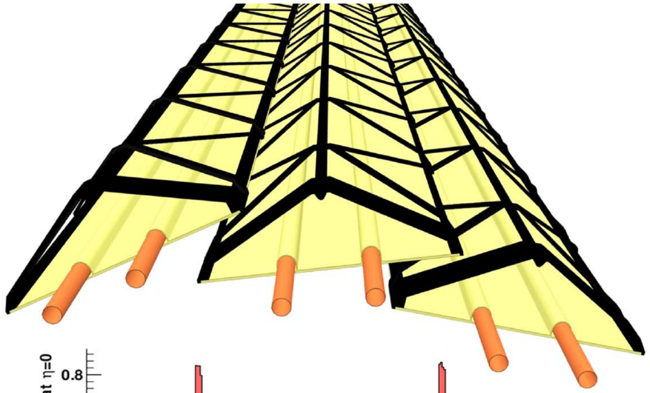
Objectives of R&D in coming Years: Material budget reduction

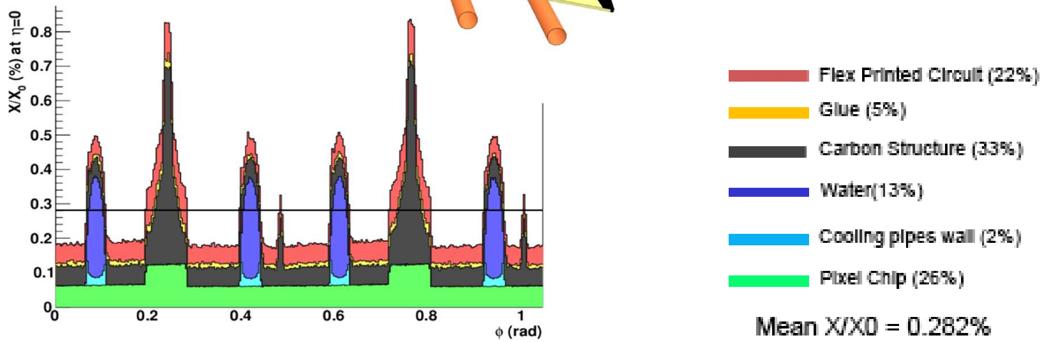
- Physics perfo. limited by material budget of services & overlaps of neighbouring modules/ladders





BELLE-II PXD

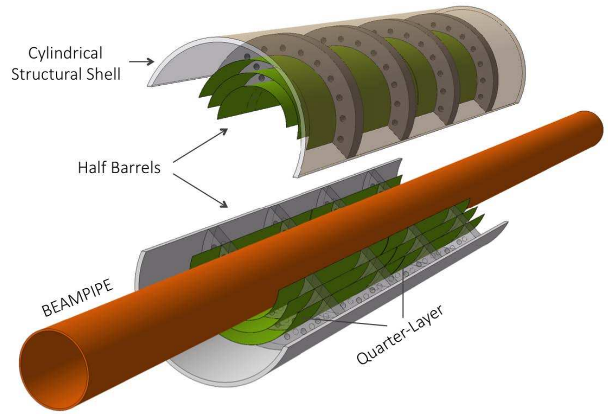




ALICE-ITS

- Contribution of sensors to total material budget of vertex detector layer is modest: 15 - 30%

- **R&D objective beyond TDR/DBD concepts:**
  - Innermost layer: try stitched & curved CPS along goals of ALICE-ITS3, possibly with 65 nm process
  - Concept with minimised mechanical support (e.g. using beam pipe) See Talk of M. Mager at Vertex-19, Lopud Island, Oct.'19



SUMMARY & CONCLUSIONS

- Outcome of extensive ILC oriented R&D offers quite well defined starting point for the design of a vertex detector suited to Higgs physics at FCCee

- The sensor technology and system integration issues have similar degree of maturity
  $\Rrightarrow$ next developpement steps should address comprehensively all aspects of the vertex detector: geometry vs vertexing & tracking issues, mechanics, powering, signal transmission, sensors, ...)

- Industrial CMOS ASIC technology provides well suited granular & thin pixel sensors for an ILC vertex detector, exploiting the beam time structure to achieve power saving complying with air cooling

- Achieved performances still call for improvement, which may profit from attractive perspectives anticipated from industry $\Rrightarrow$ smaller pixels, wafer-scale sensors, power saving, ..., 2-tier sensors ?

- Adapting ILC-CPS to FCCee (continous beam) $\Rrightarrow$ R&D on power saving or innovative cooling

- The concept of 2-sided detector module, which allows in particular to alleviate the conflict between ambitionned spatial resolution & read-out speed, is of common interest for FCCee and ILC
  $\rightarrowtail$ evolve double-sided PLUME ladders using forthcoming MIMOSIS sensor and beyond

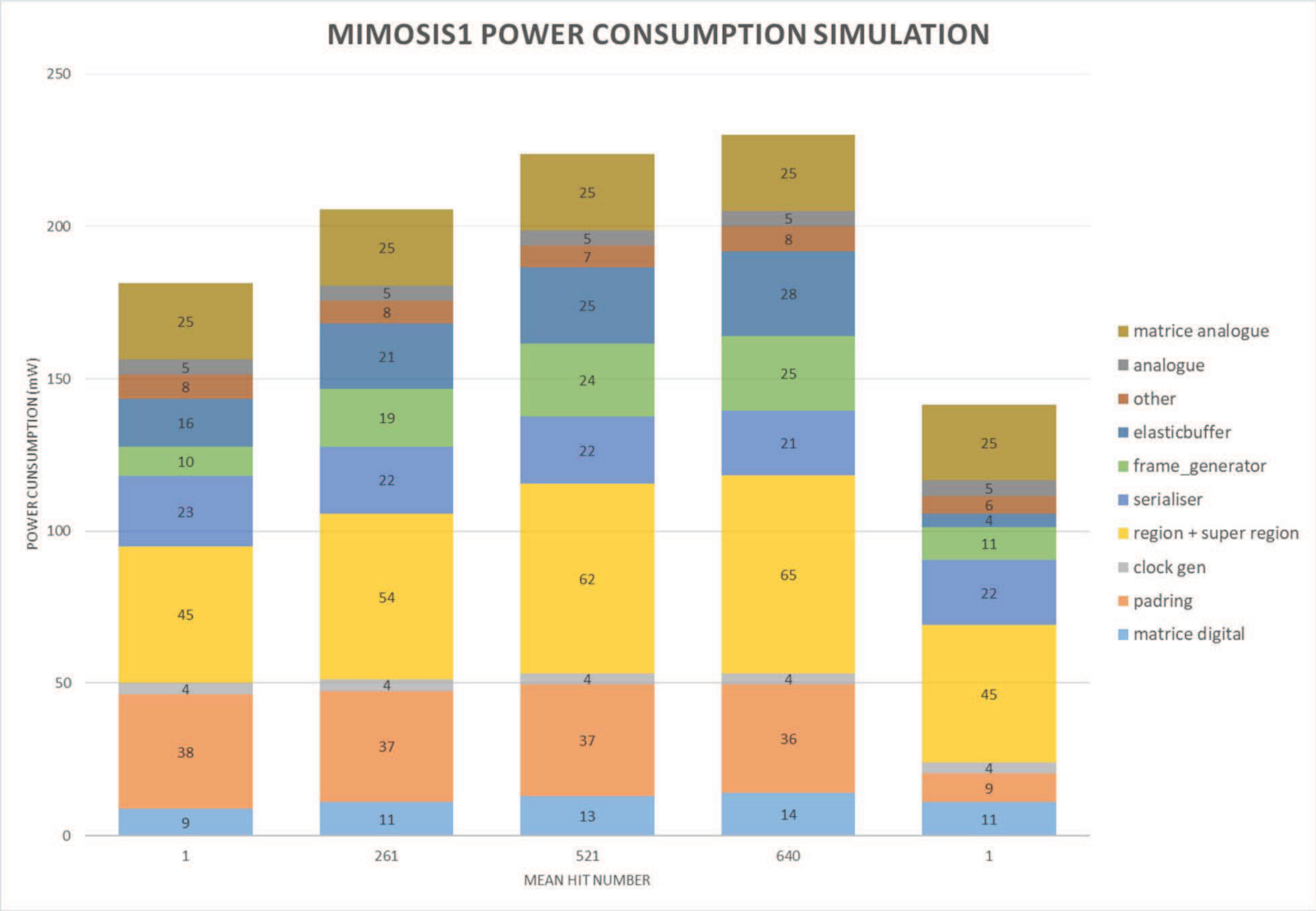
- Defining optimal detector design for each collider requires detailed simulation & engineering studies based on same tools & expertise $\Rrightarrow$ opportunity for shared effort

Power Consumption of MIMOSIS-1 (1/2)

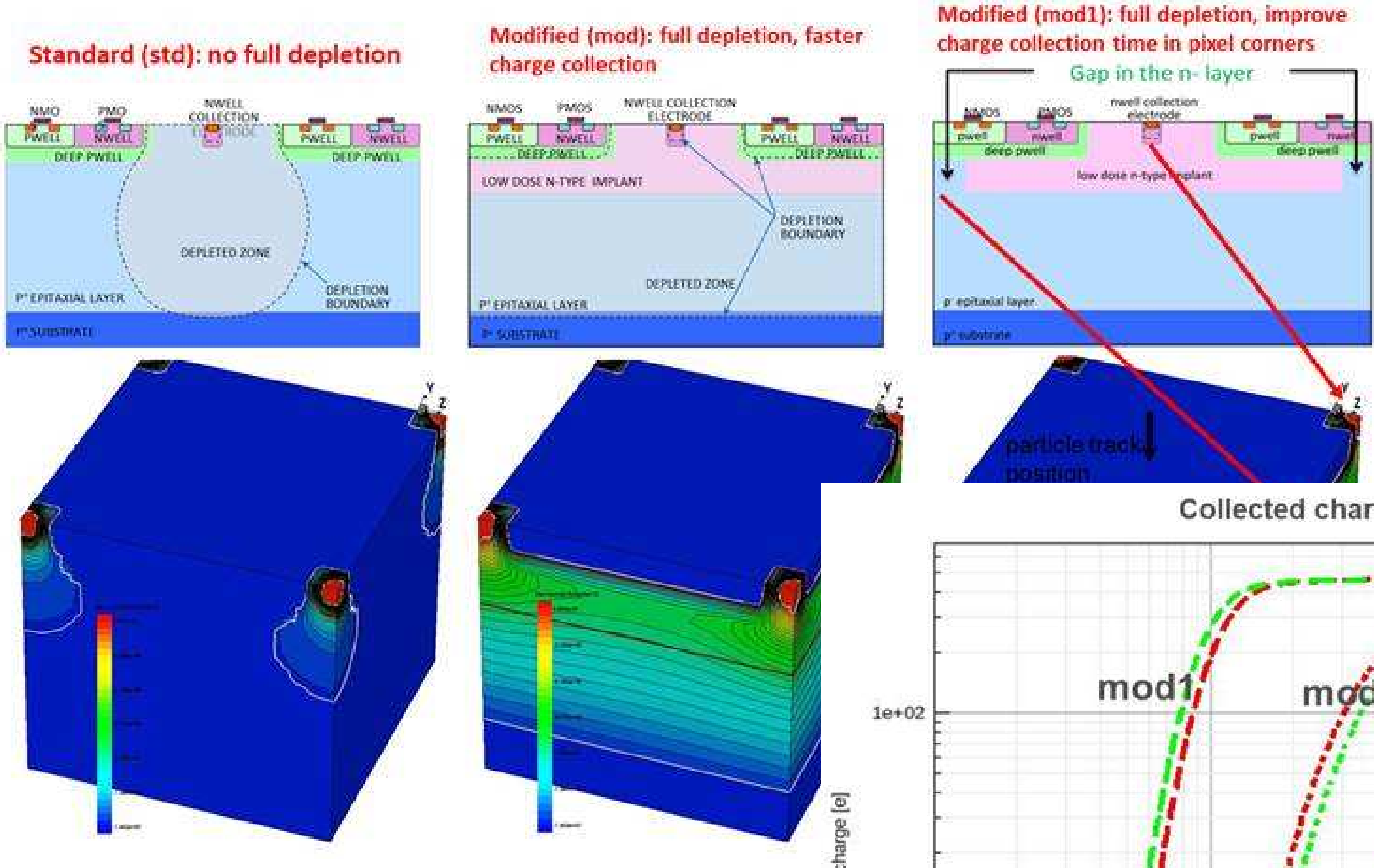
- Analogue Power: 30 mW (analogue pixel+PLL+DAC+ analogue buffers)
- Total Power = Analogue Power + Digital Power
- Total Power Density 1= Total Power/5.33 cm^2 (total surface)
- Total Power Density 2= Total Power/4.20 cm^2 (active surface)
- Power consumption with 8 outputs

	1 pixel/frame	~260 pixels/frame	~520 pixels/frame	~640 pixels/frame	1 pixel/frame 2 outputs
Digital Power mW	150	175	195	200	110
Total Power mW	180	205	225	230	140
Total Power Density 1 mW/cm^2	34	39	42	43	27
Total Power Density 2 mW/cm^2	43	49	53	55	34

Power Consumption of MIMOSIS-1 (2/2)



MIMOSIS Spin-Off: Starting Material Options

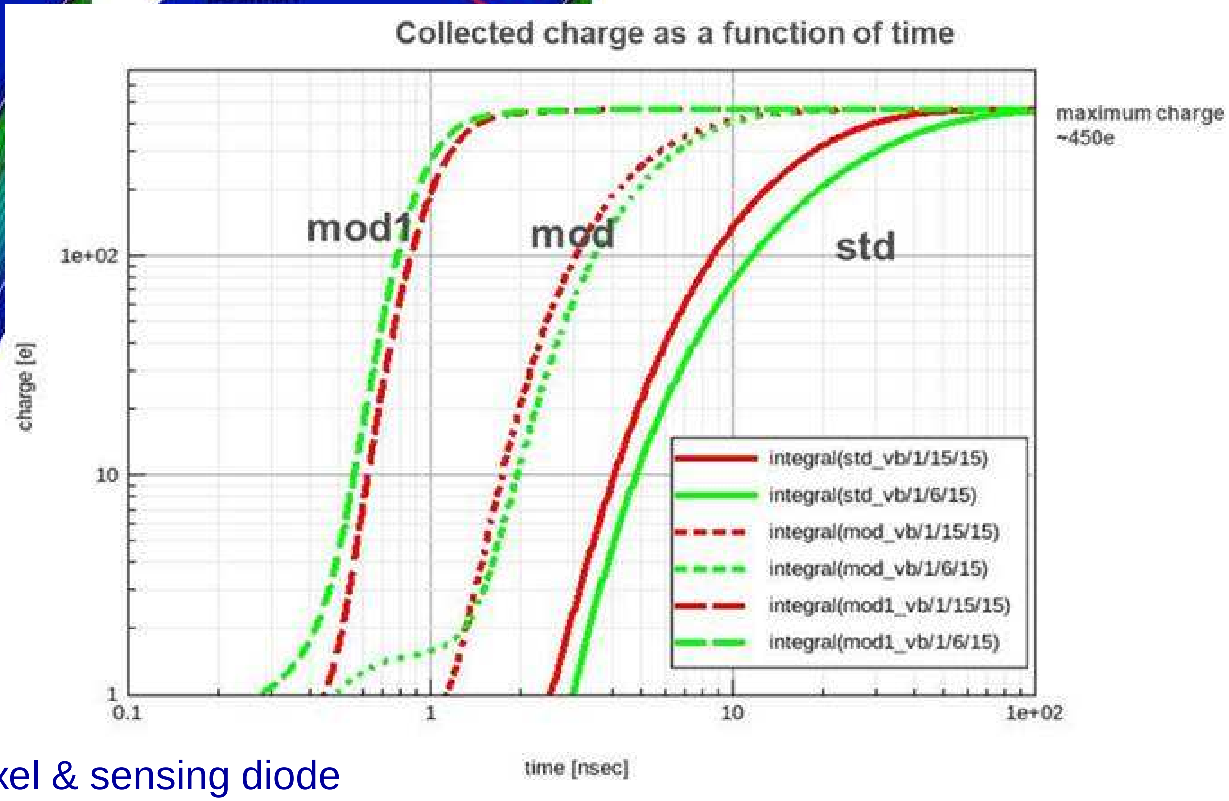


TCAD simulation:

Tower-Jazz 180 nm CIS

27x30 μm^2 pixels

3x3 μm^2 sensing diode



- Q coll. time improved by factor $\sim$ 10
- radiation tolerance improvement being assessed
- 1st HEP application: CBM-MVD HI expt / FAIR
- still O(10) improvement expected from smaller pixel & sensing diode