Backgrounds at Lepton Colliders

Differences between linear and circular colliders

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ILD Main Meeting
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CNRS IN2P3 Les deux infinis
IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

Disclaimer

The following is a summary of talks given by other people. For details see:

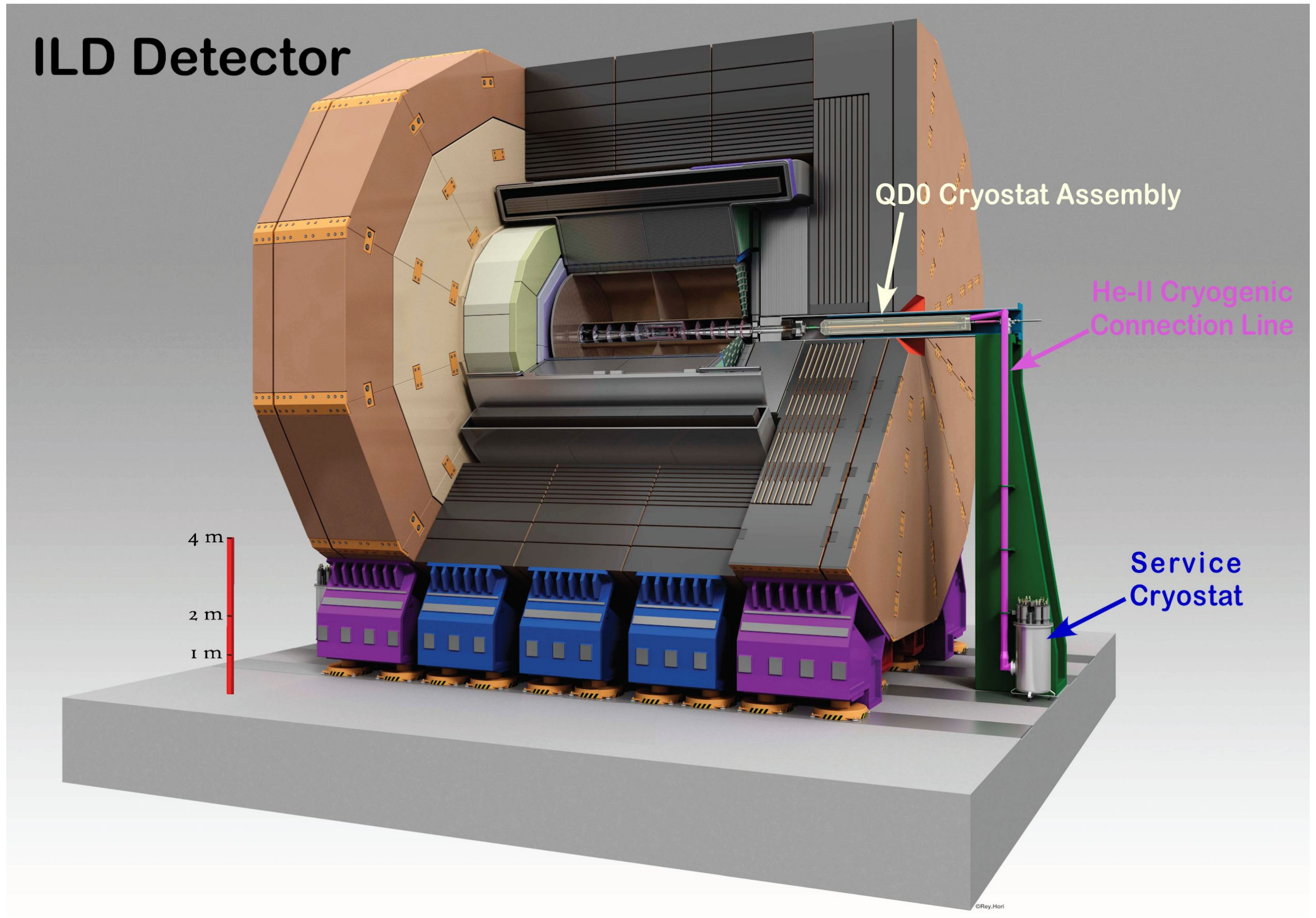
- **MDI Sessions at ILCX 2021**
- **MDI Sessions at FCC-ee Physics and Detector Workshop, Jan. 2023**
  - In particular the talks by A. Ciarma, A. Abramov and M. Boscolo
- **Daniel Jeans@ The ILD s/w ana meeting on 21/12/22**
- **I am indebted to Karsten for the summary of ILCX 2021 on which this talk is built uopn**
- **All faults are mine**

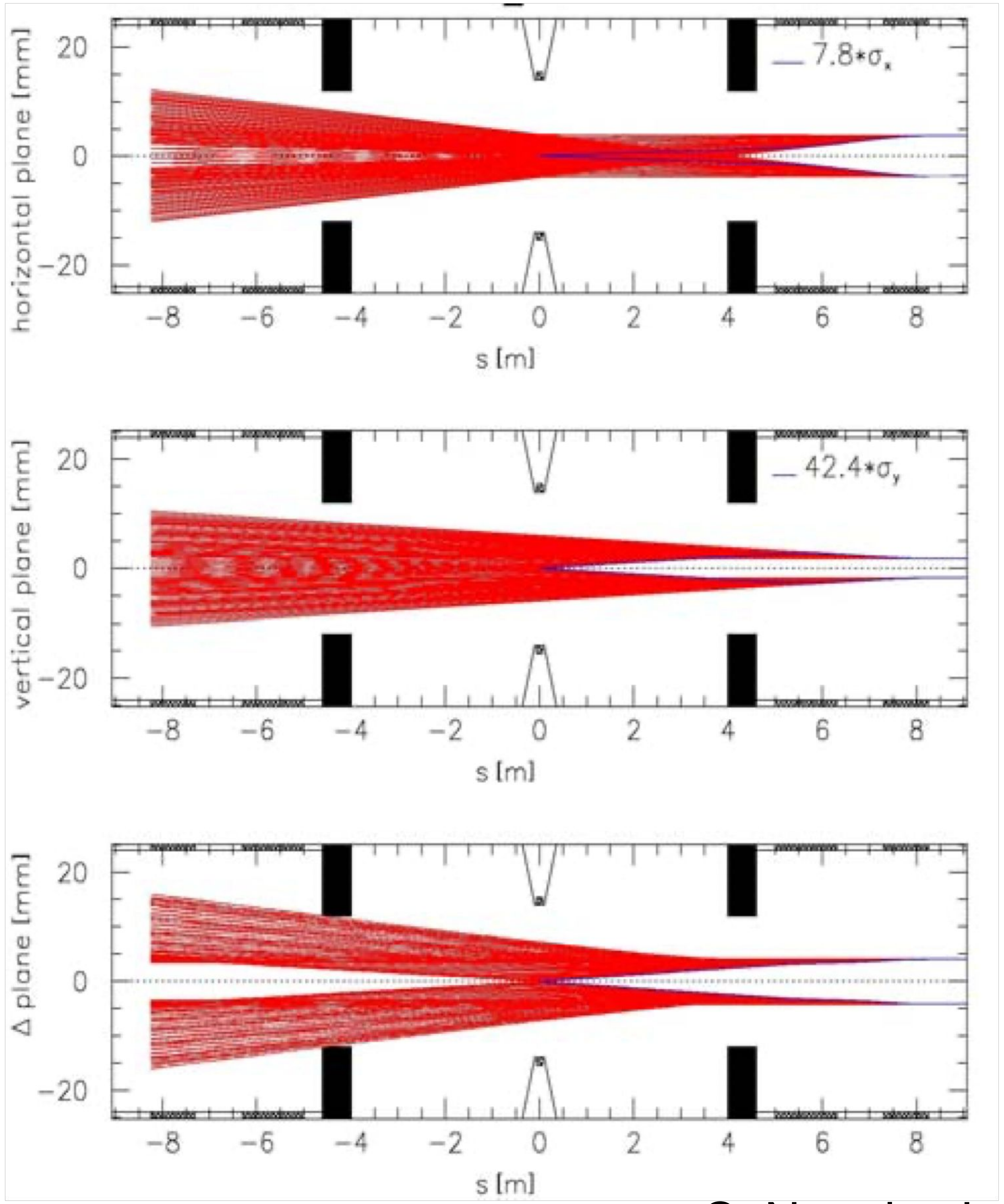
Machine Induced Backgrounds at the ILC - Examples

Synchrotron Radiation

Final-focus Quads are sitting inside the detectors

- Synchrotron radiation from beam halos in quads passes the interaction region
  - it better hits nothing!!!
- defines the requirements of the collimation system





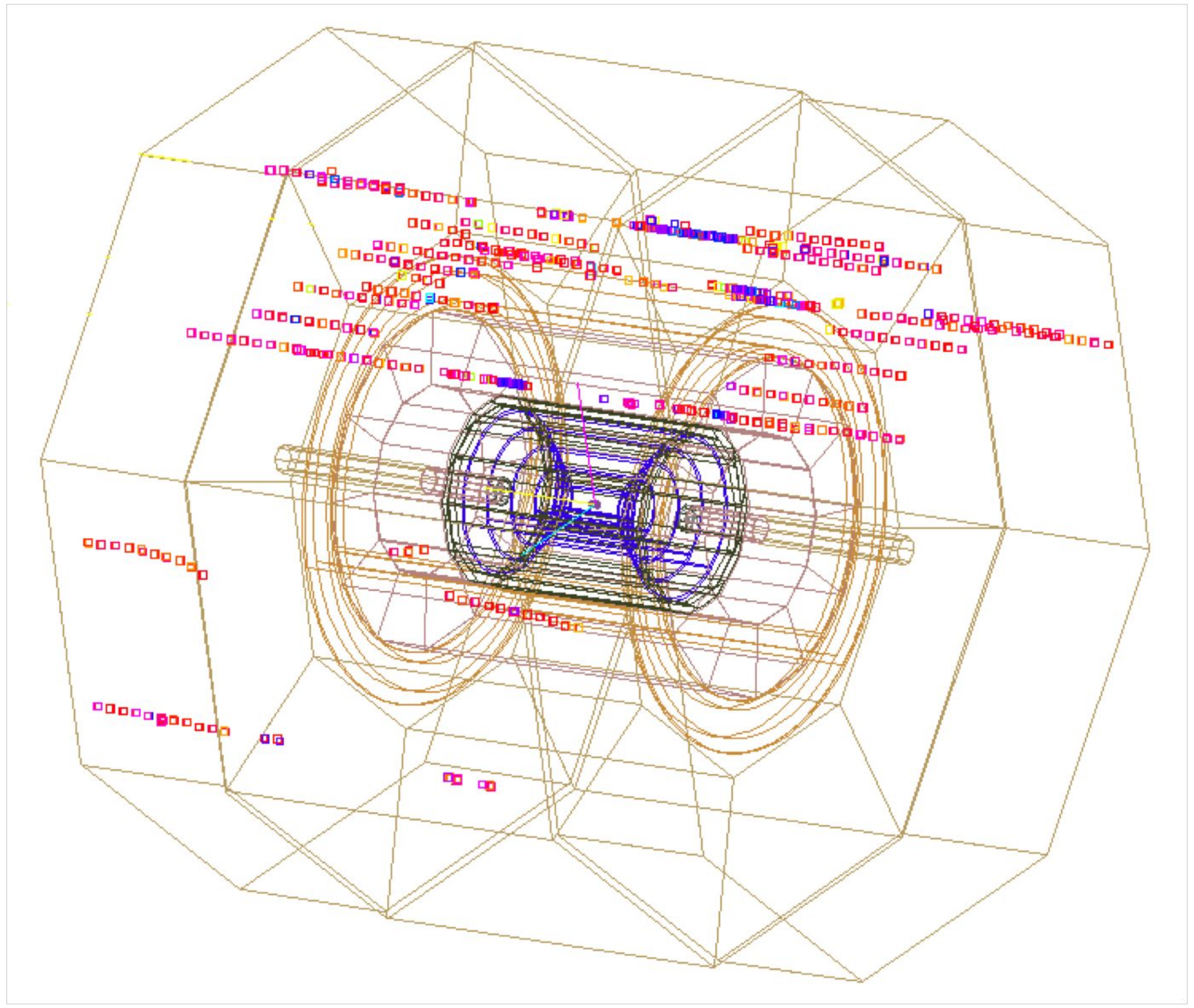
O. Napoly, J. Payet

Muons From Collimators

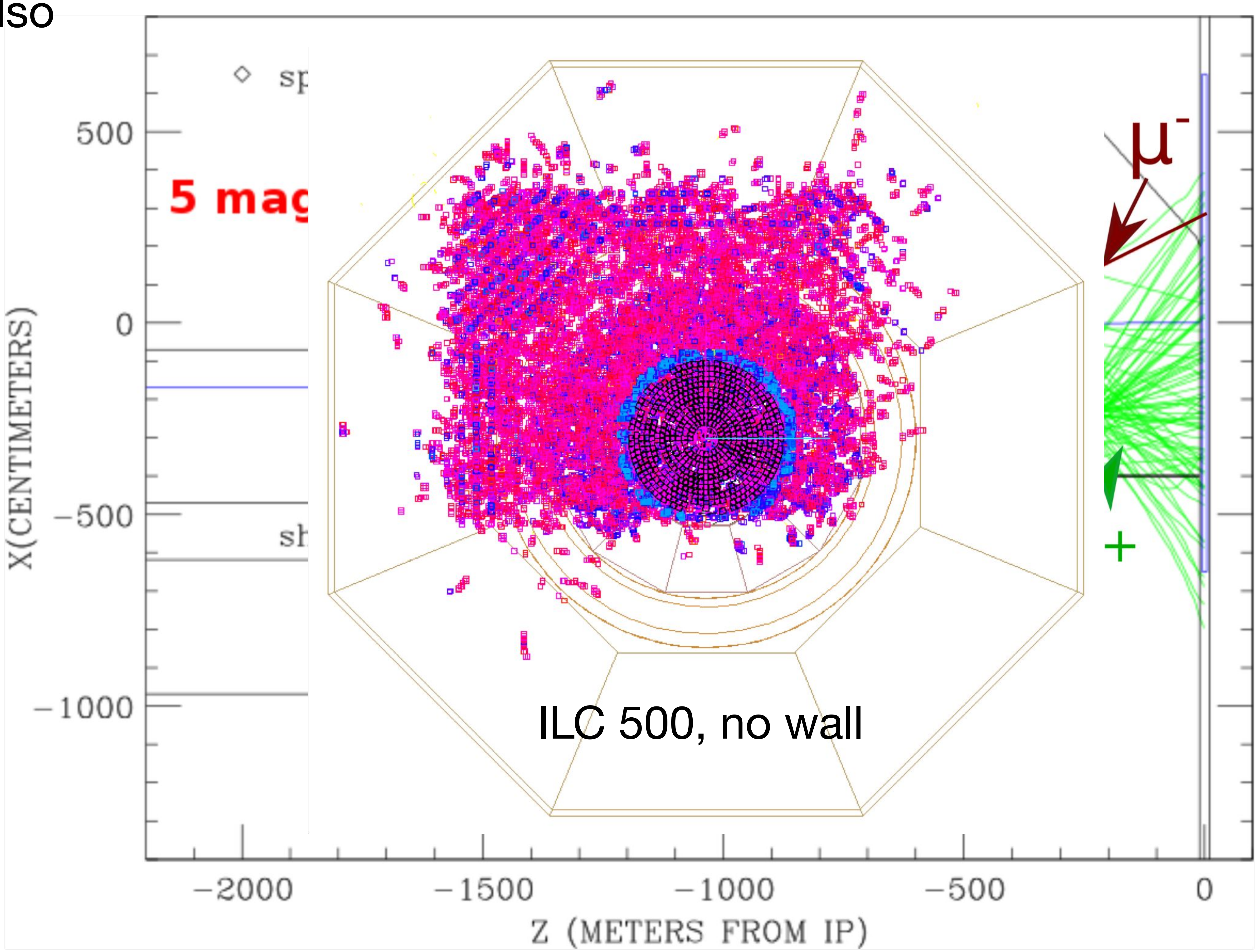
ILC Collimators are a source of muon background

- is a potential problem for the detectors but also for radiation protection
- magnetic deflectors and shields are foreseen

A. Schuetz



ILC 250, all shields

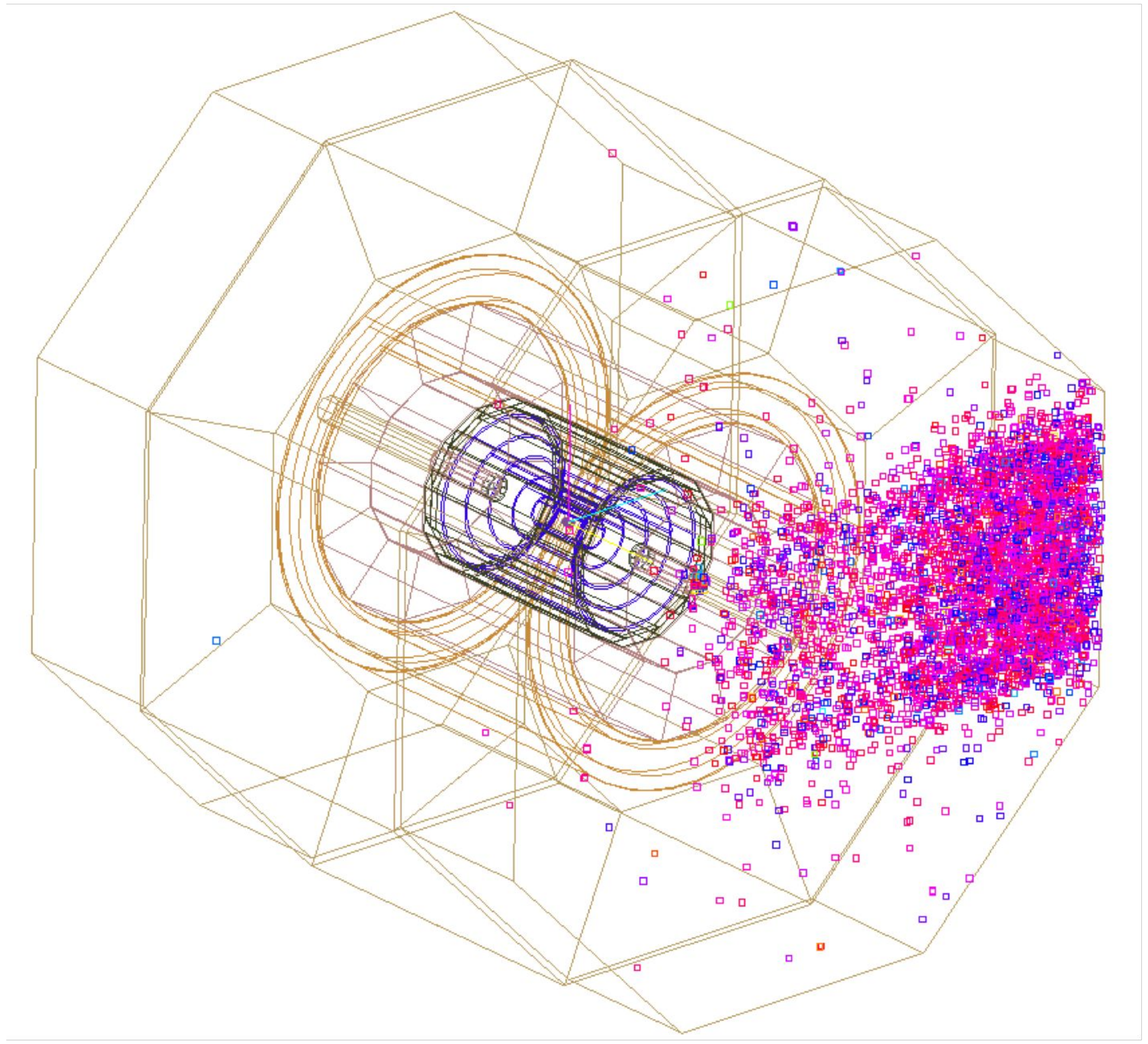


ILC 500, no wall

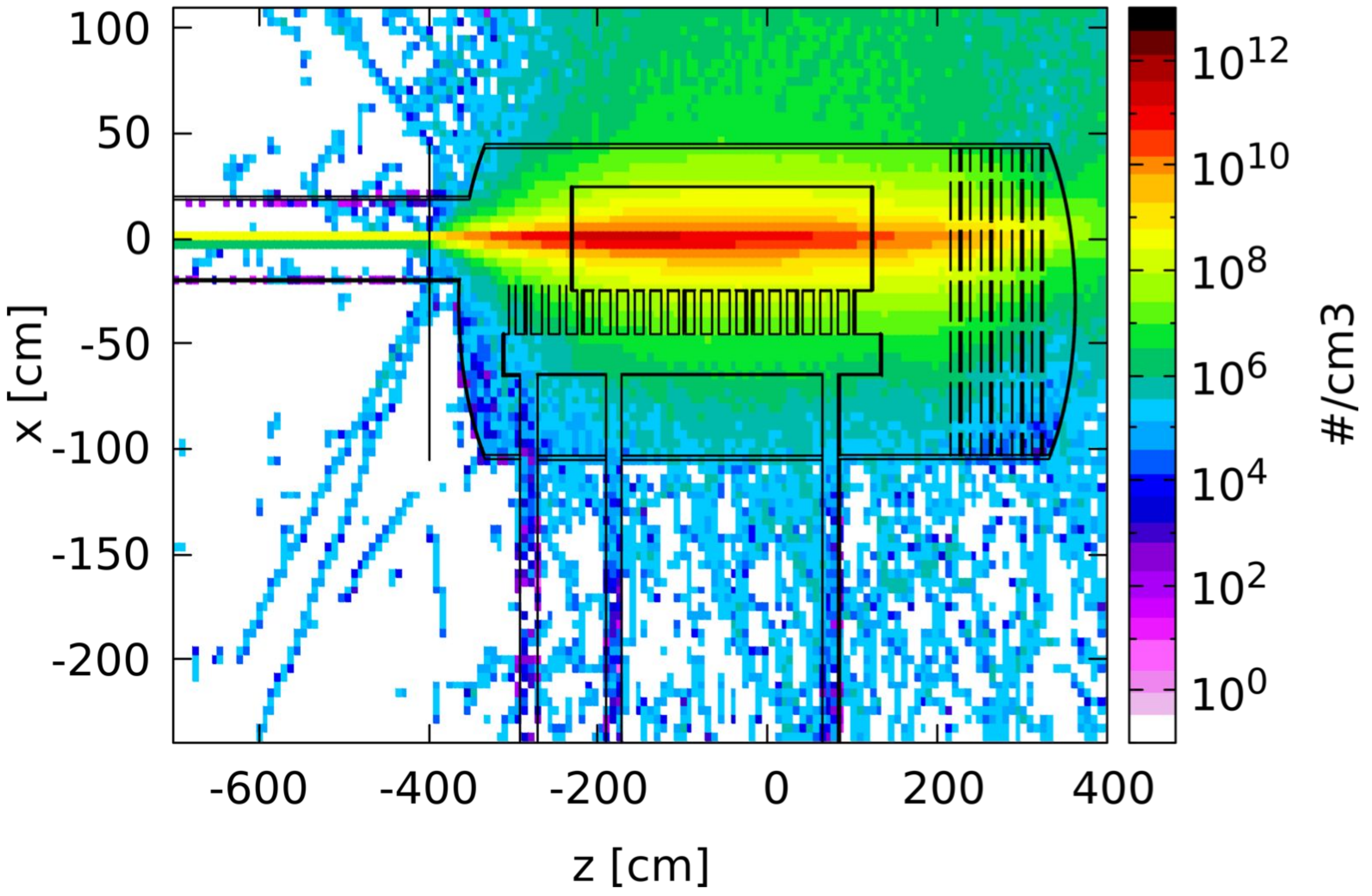
Backshine from Beam Dumps

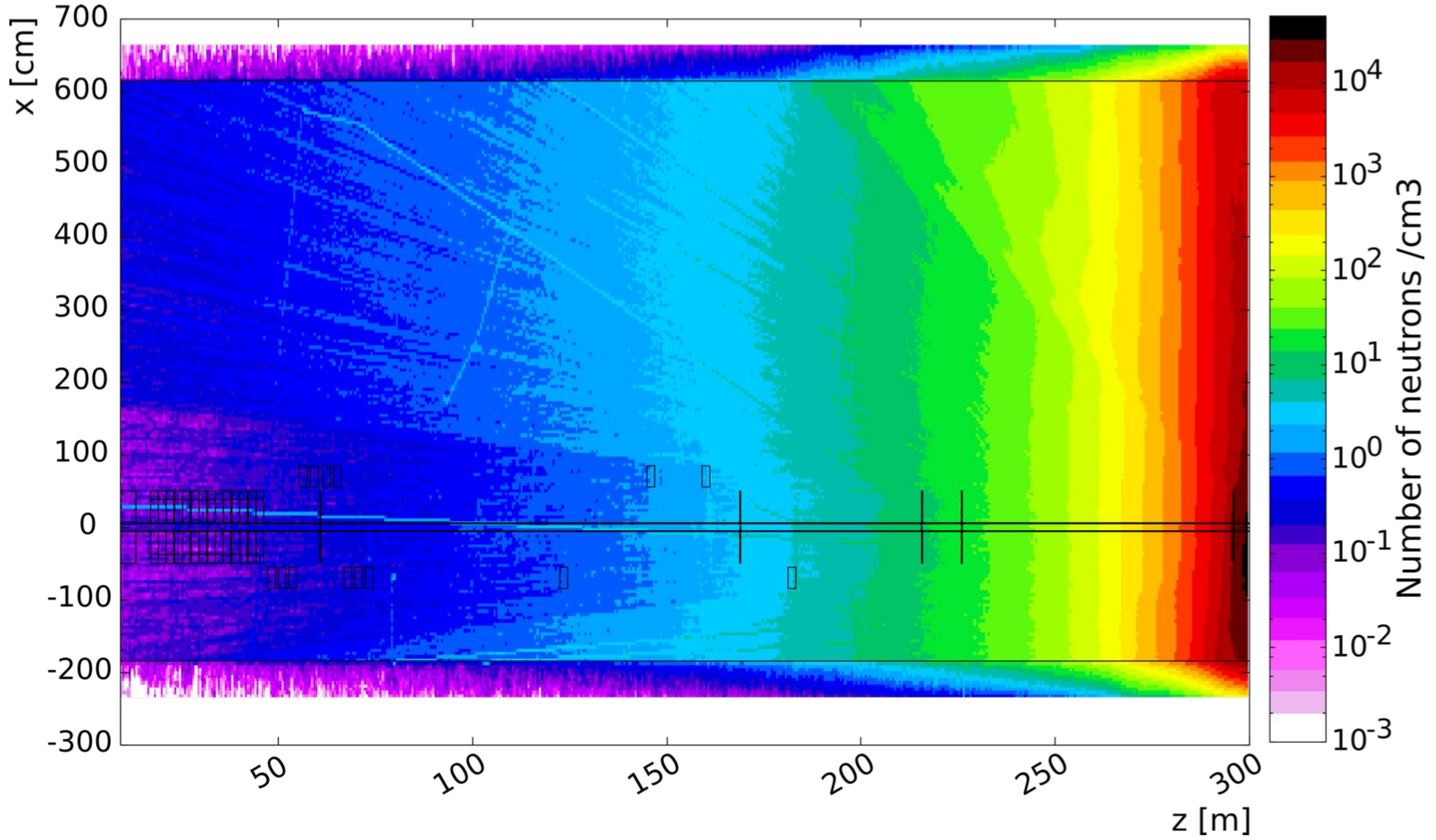
MW beam dumps ~300m away from detector

- hybrid high-pressure water and copper
- huge radiation challenge
- neutrons can travel back via extraction line tunnel to detectors



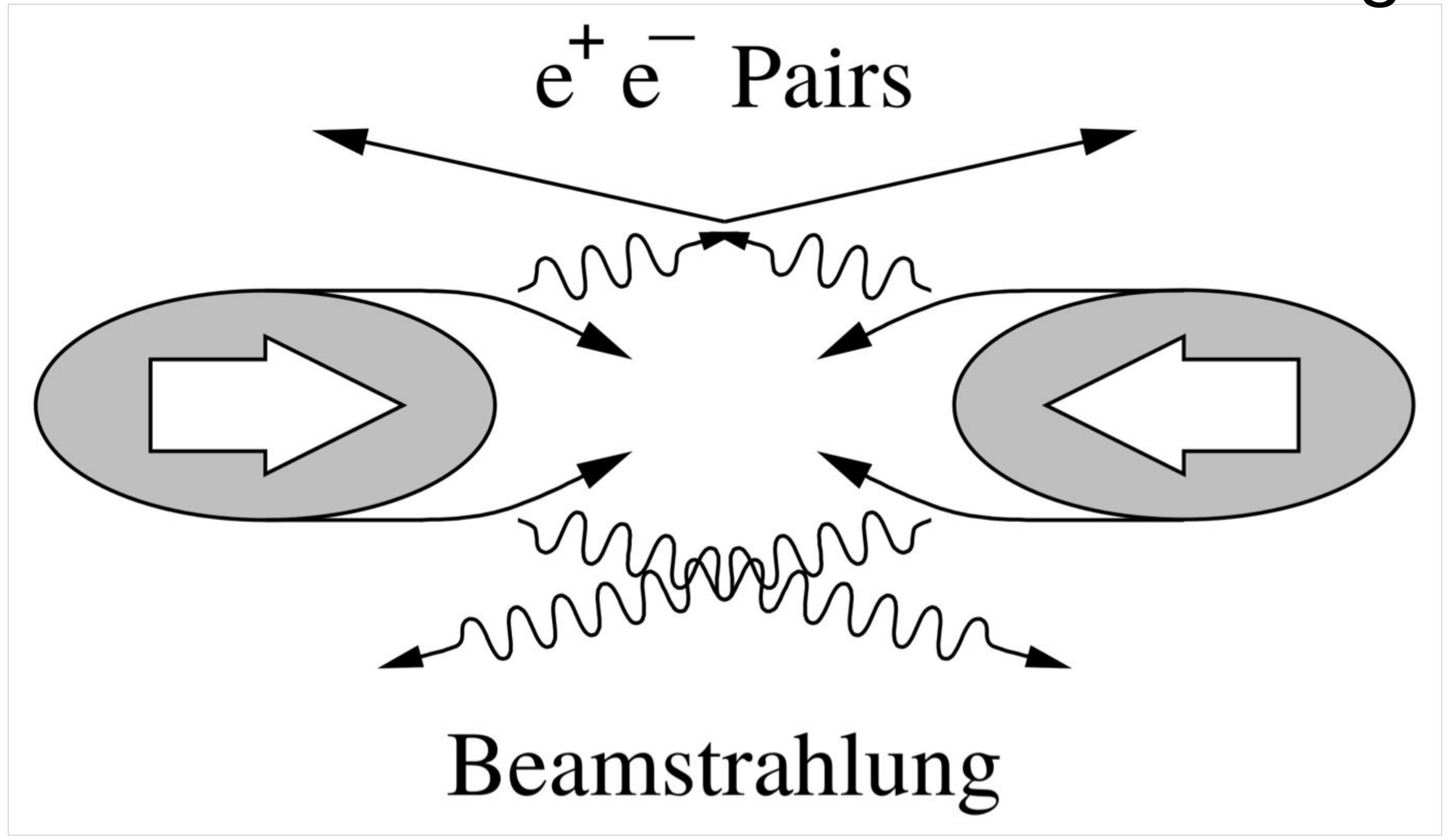
A. Schuetz





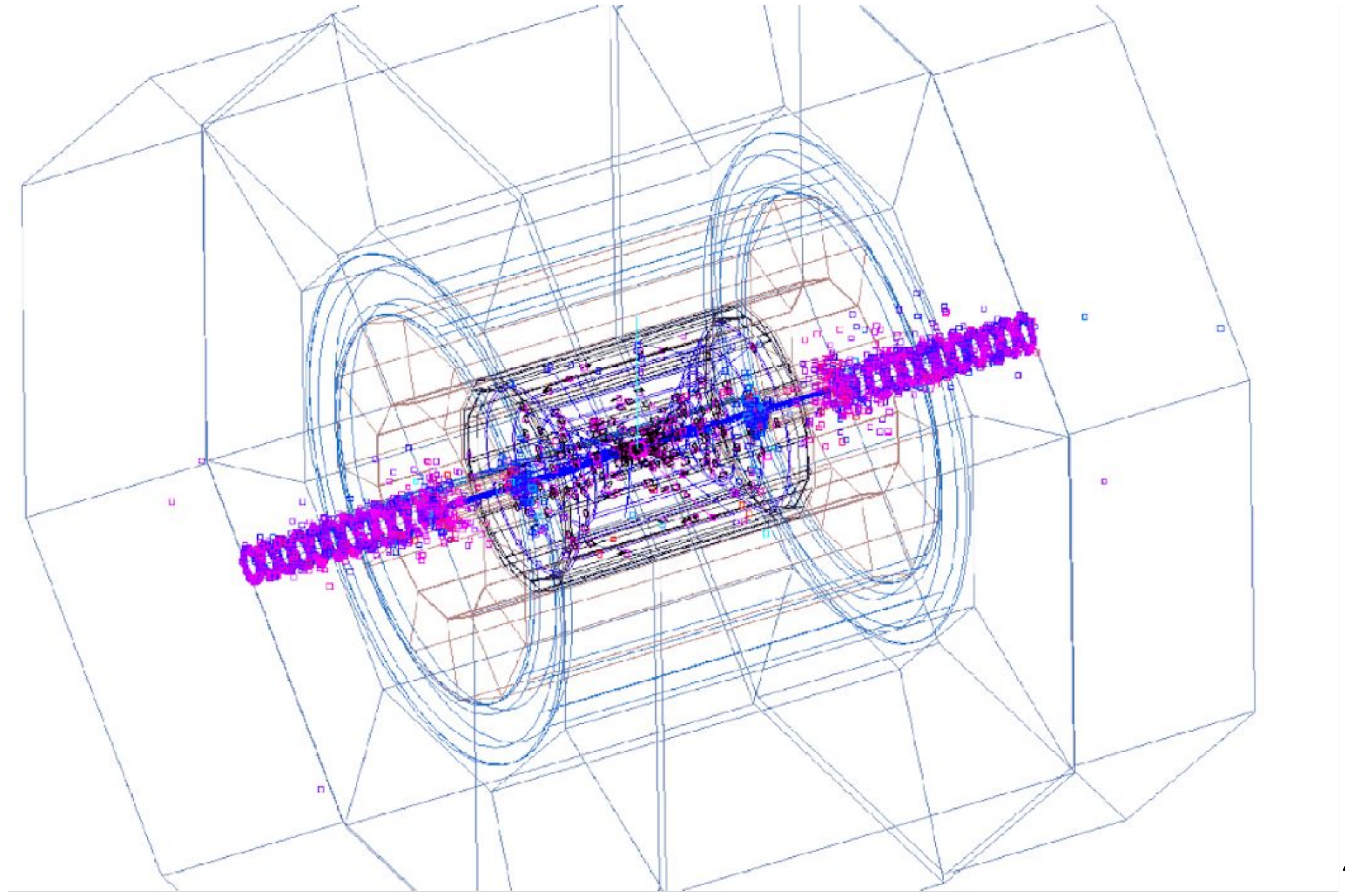
Beamstrahlung

A. Vogel

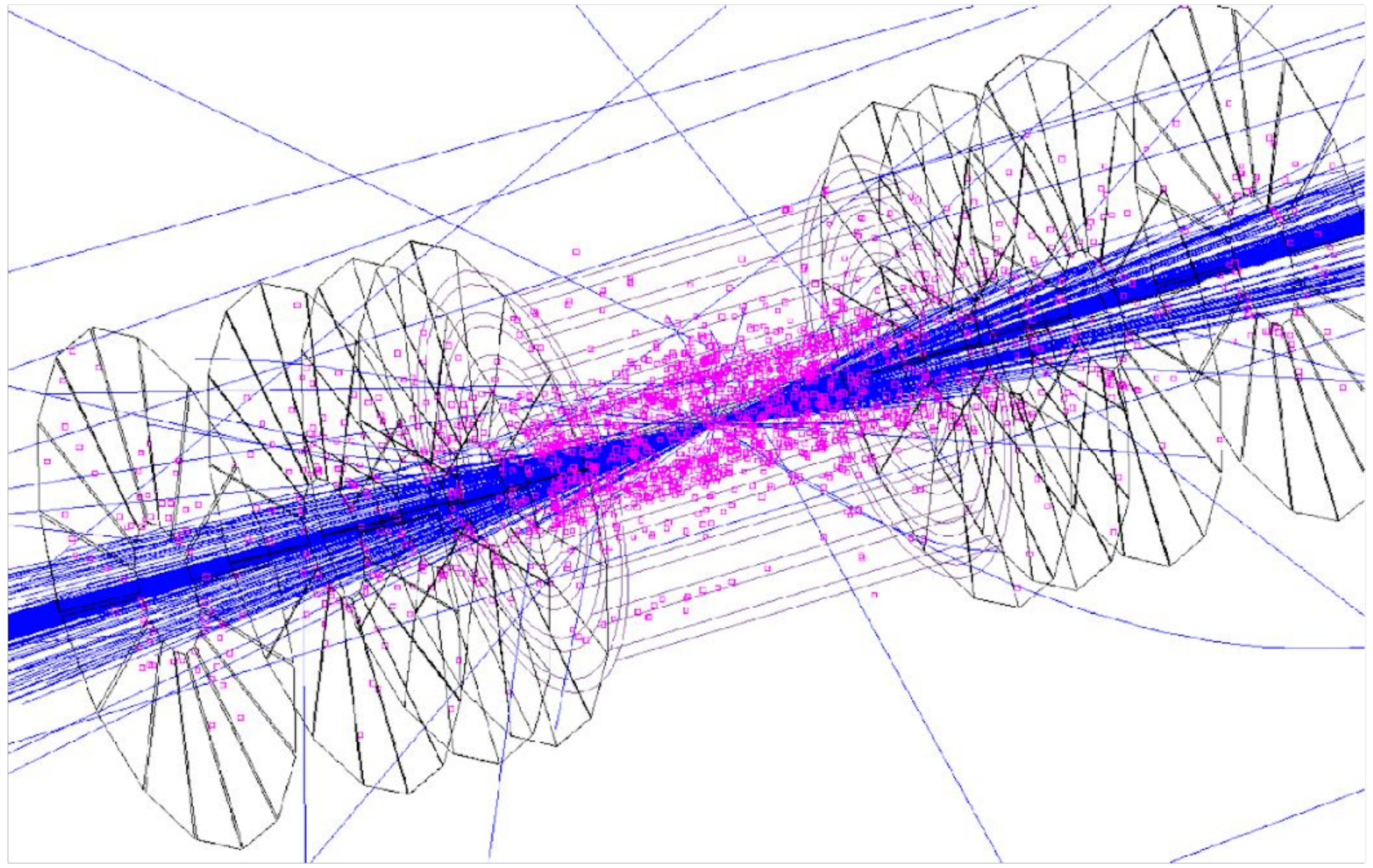


Electron-Positron Pairs from Beamstrahlung

- is expected to be the largest background in ILC experiments
- studied with full detector simulations
- detector interaction regions have been carefully designed w.r.t. to this background source
- but: this background will first be seen at a linear collider at 250GeV at high luminosity, so all theory so far

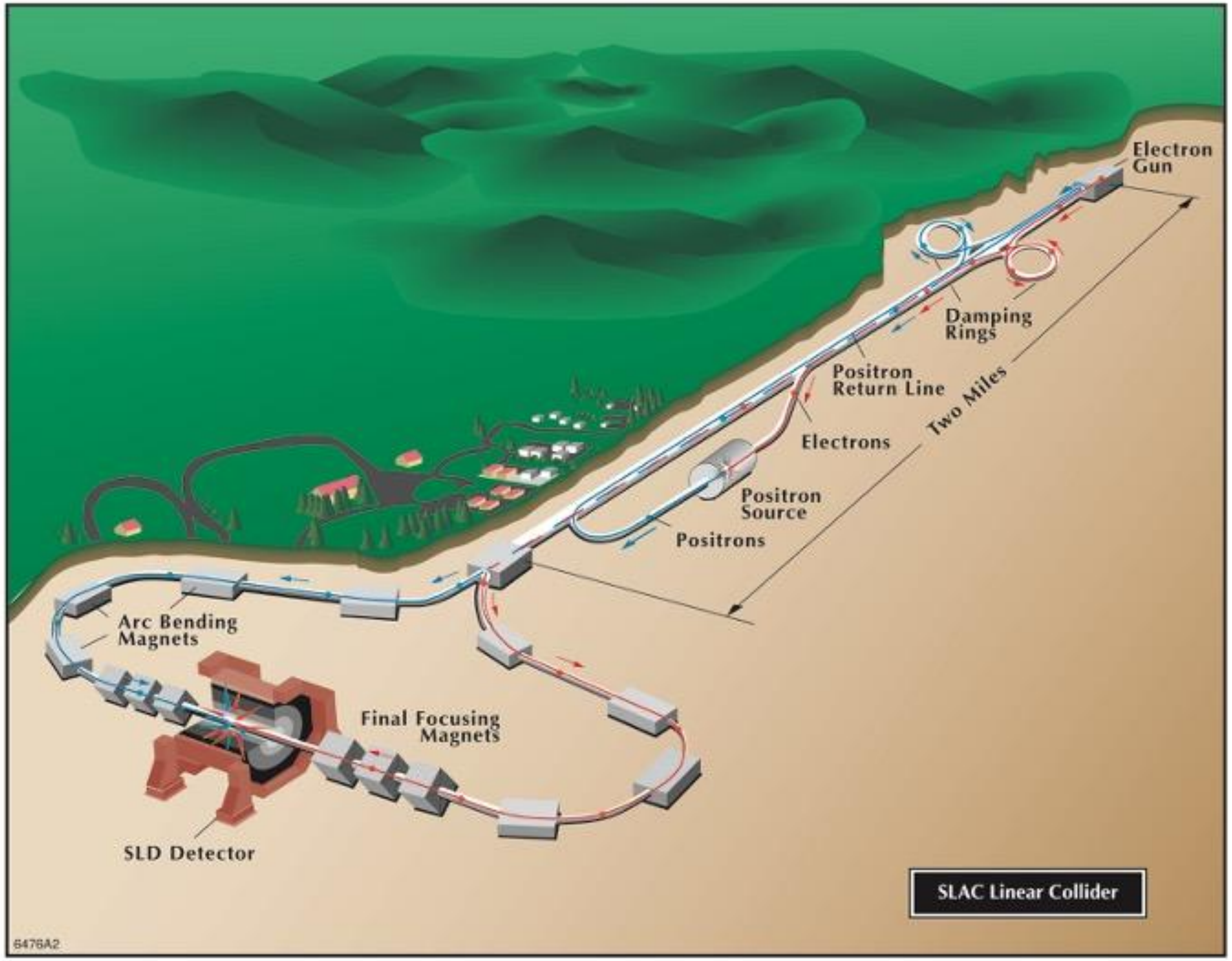


A. Schuetz

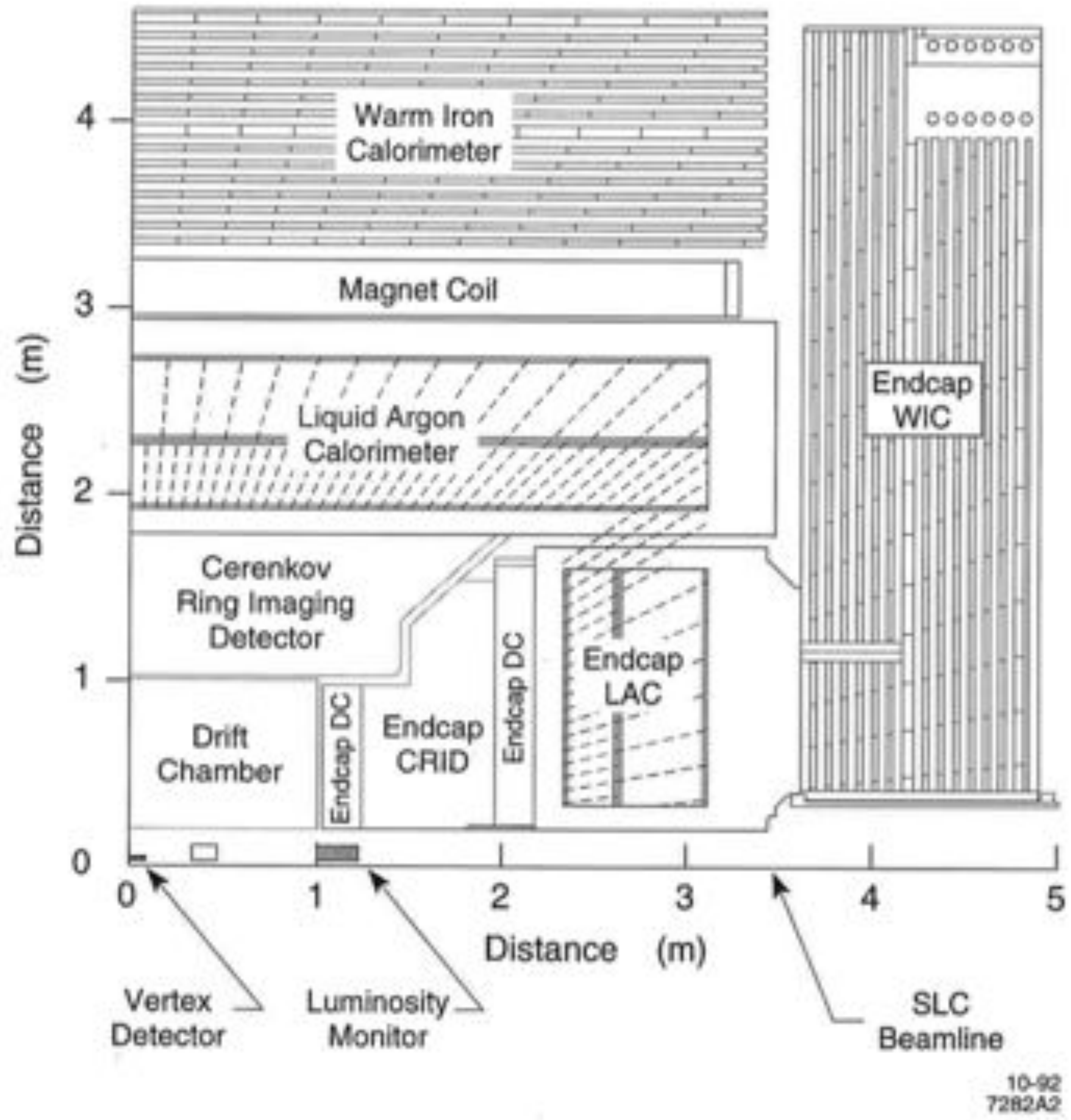


Backgrounds at Lepton Machines
Summary of ILCX Session
… contrasted with recent results for FCC-ee

SLD/SLC

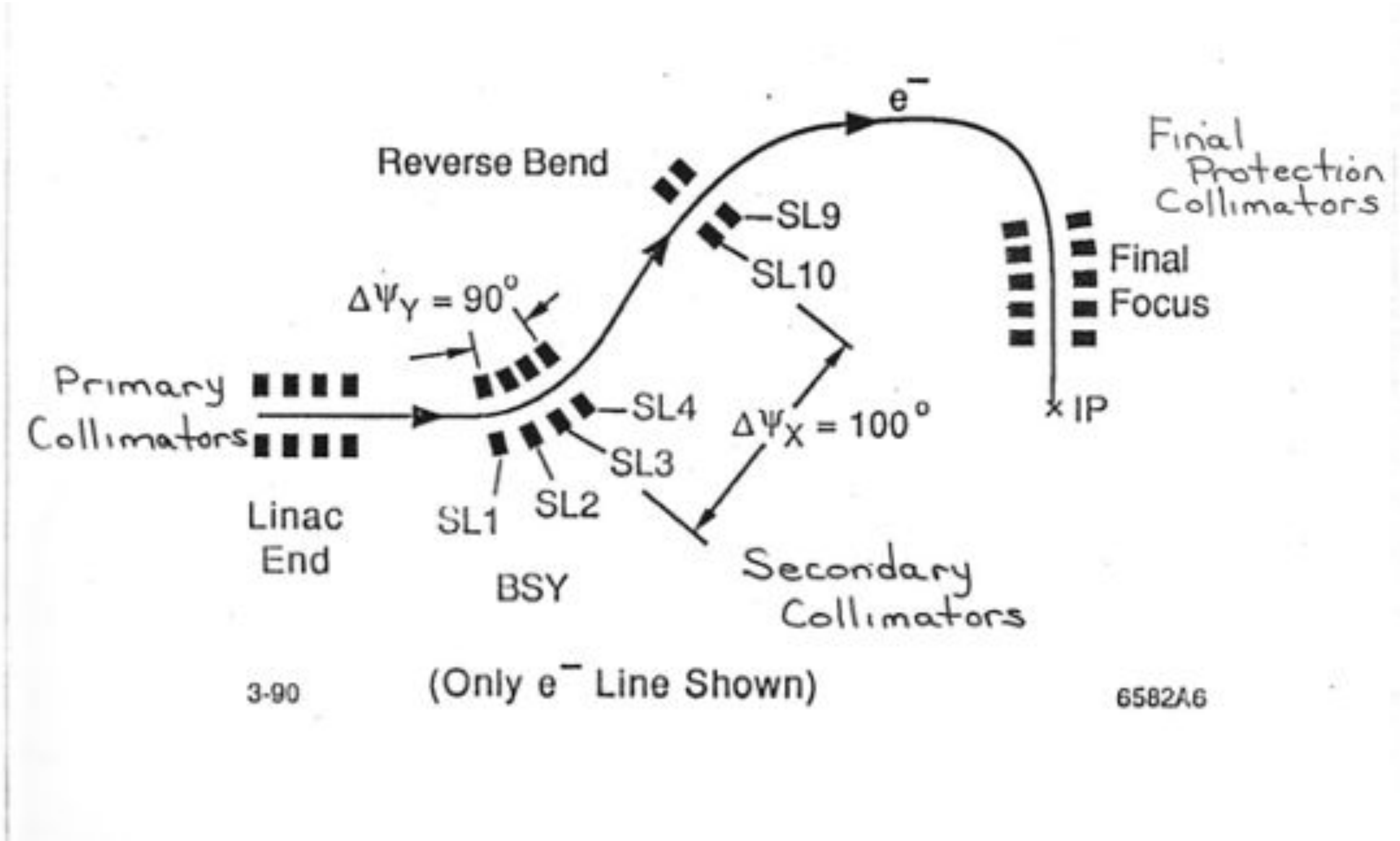


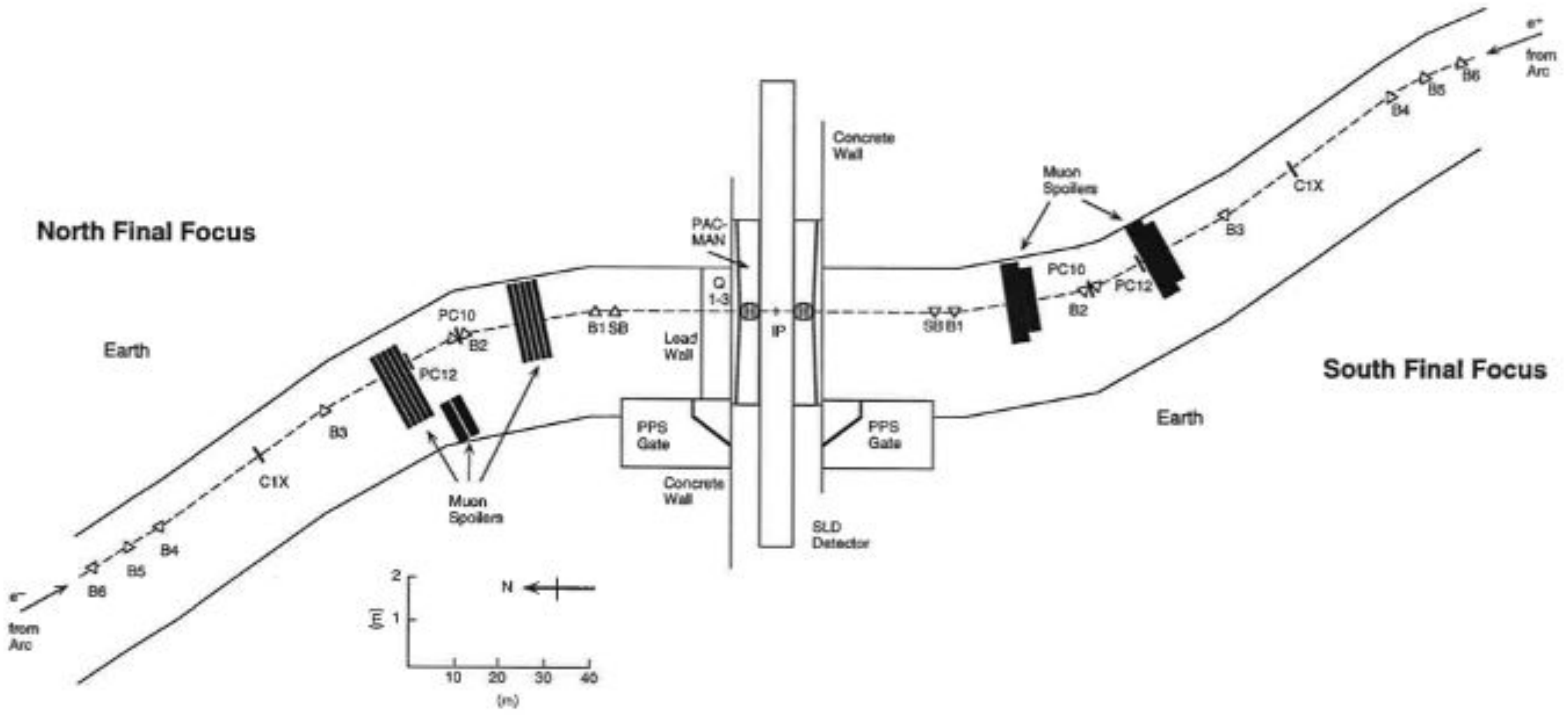
T. Markiewicz



SLC Collimation System

T. Markiewicz





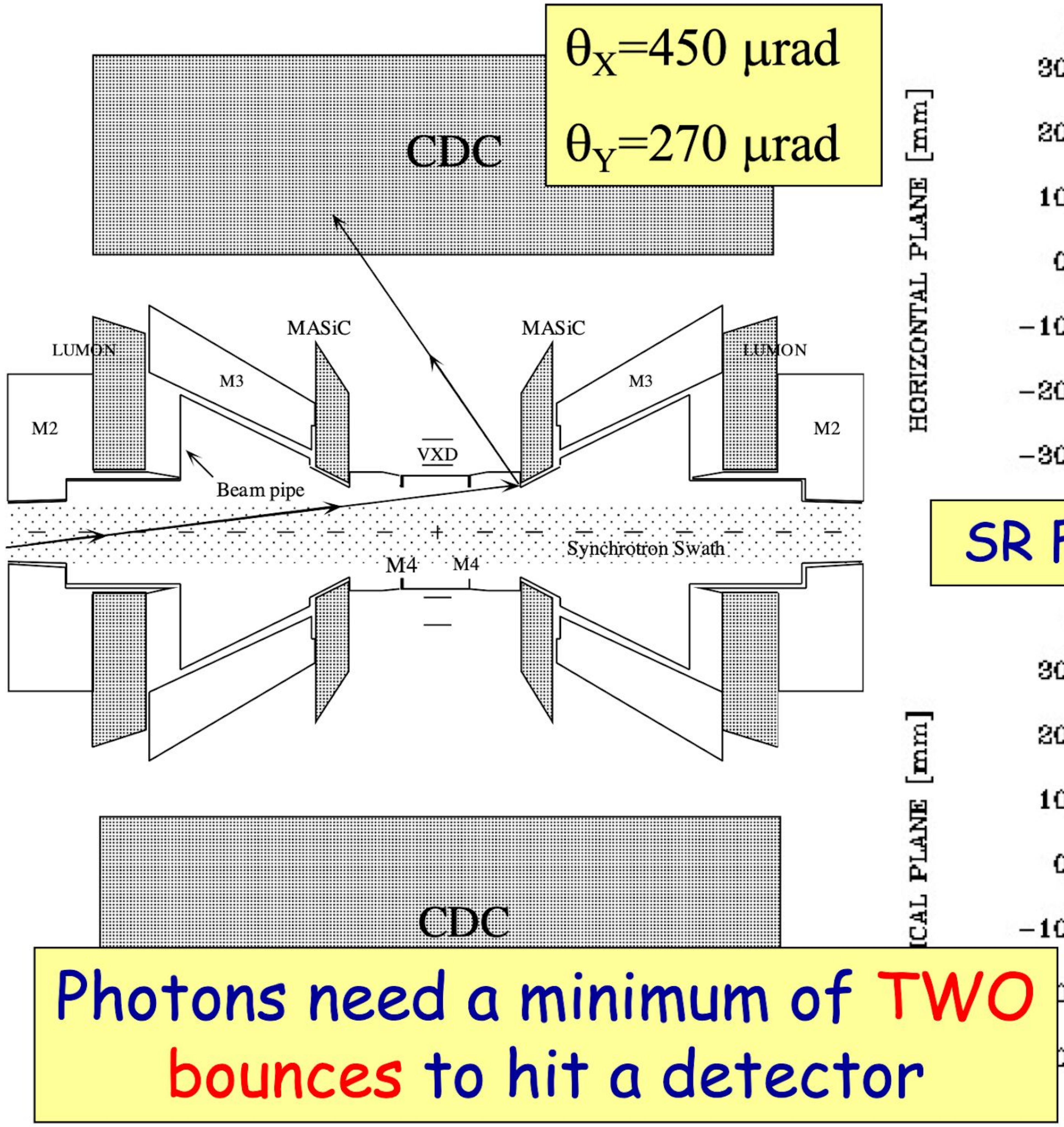
Synchrotron Radiation

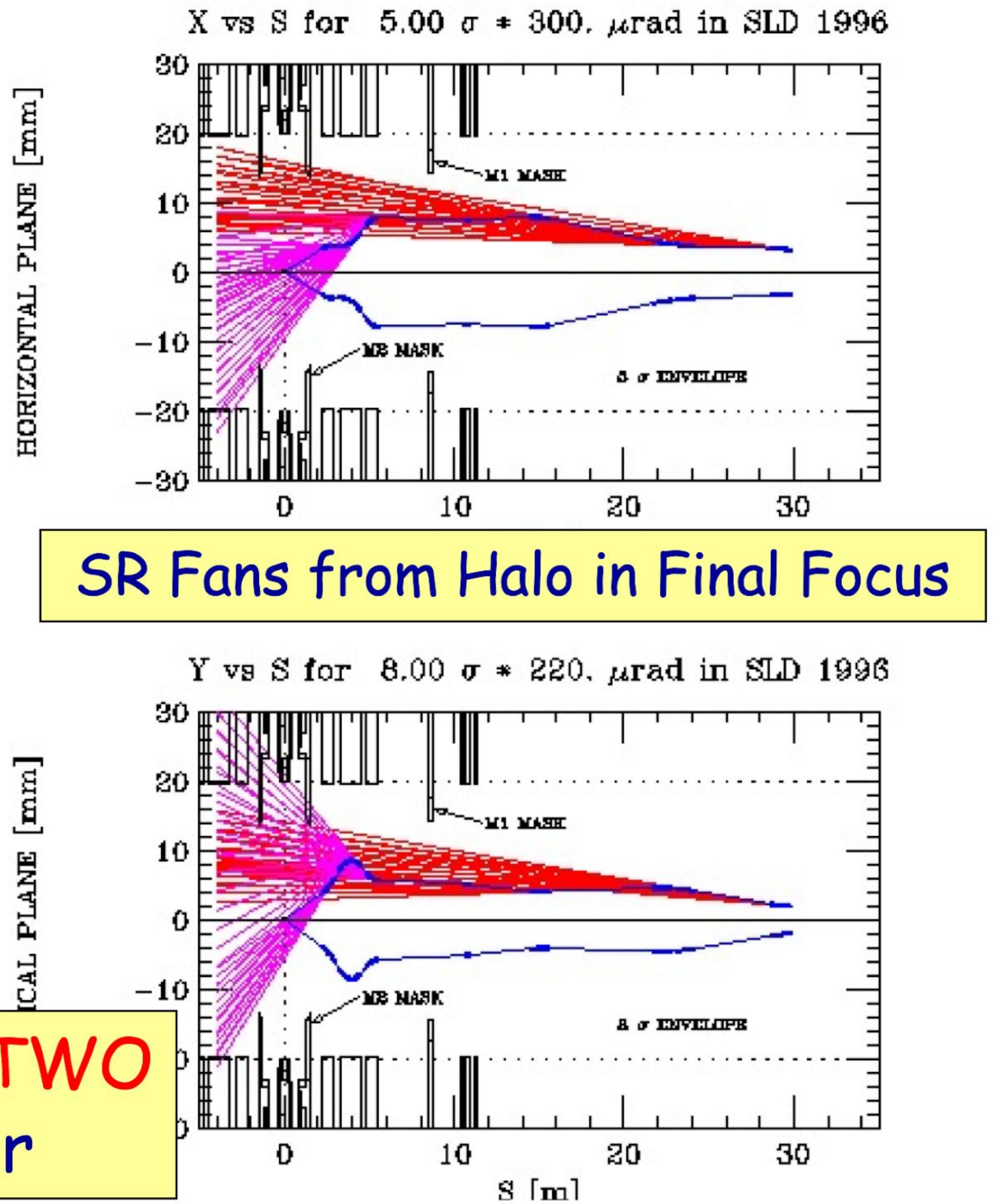
At SLD/SLC SR WAS THE PROBLEM

T. Markiewicz

Synchrotron radiation photons from final focus magnets could reach the detector

- minimum two bounces, but it happened…





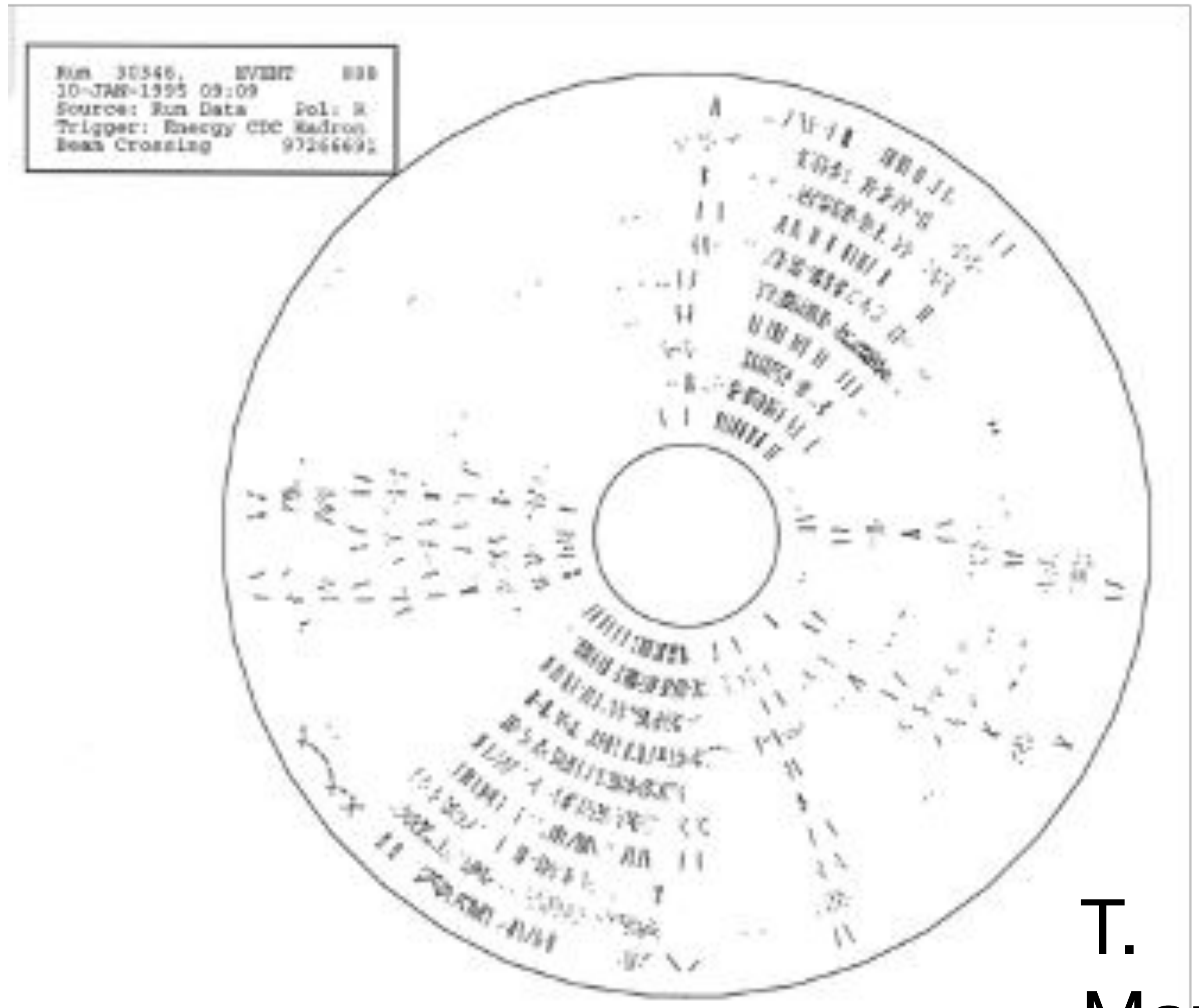
SLD Backgrounds

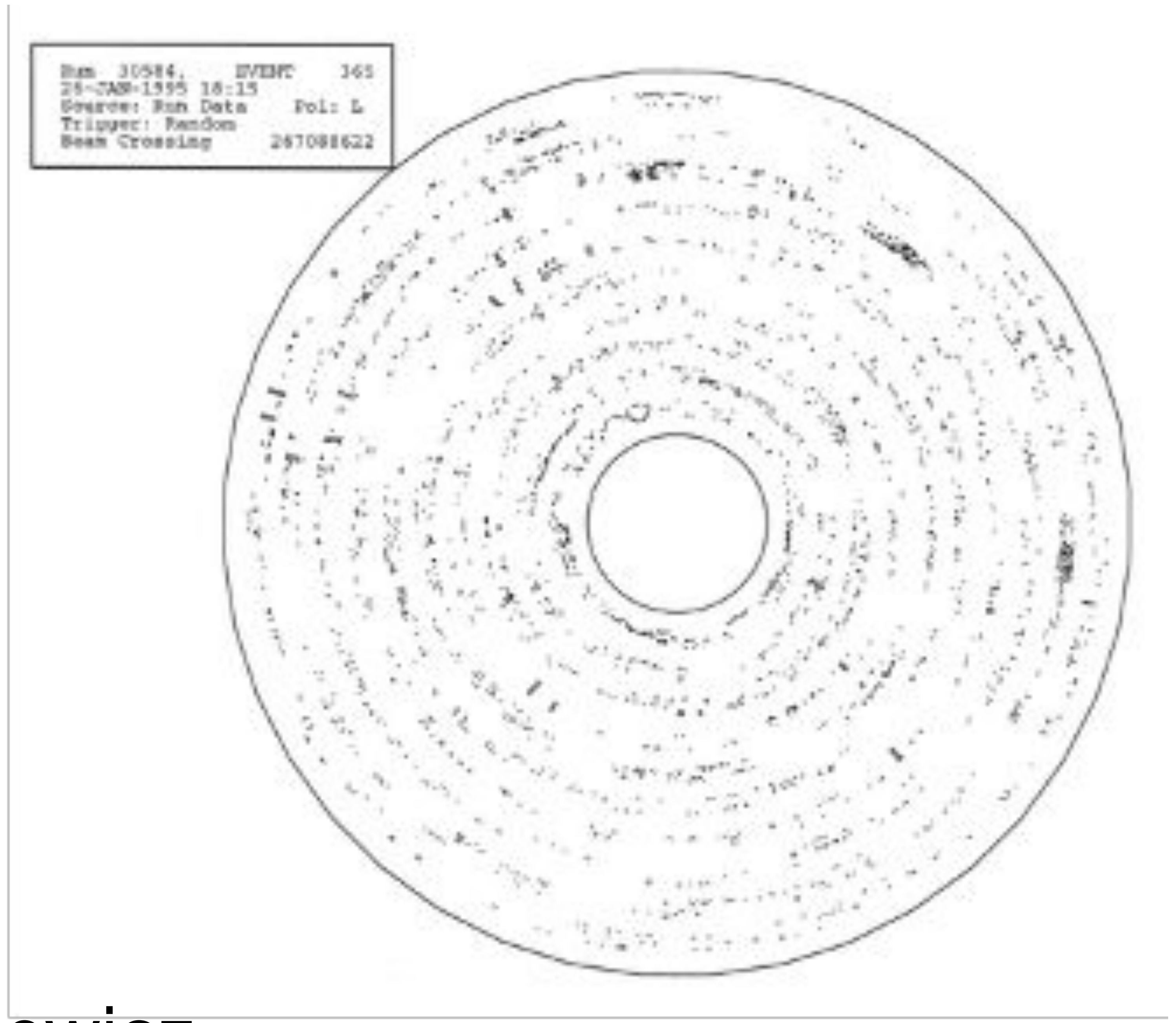
„Good occupancy event“

„Bad occupancy event“

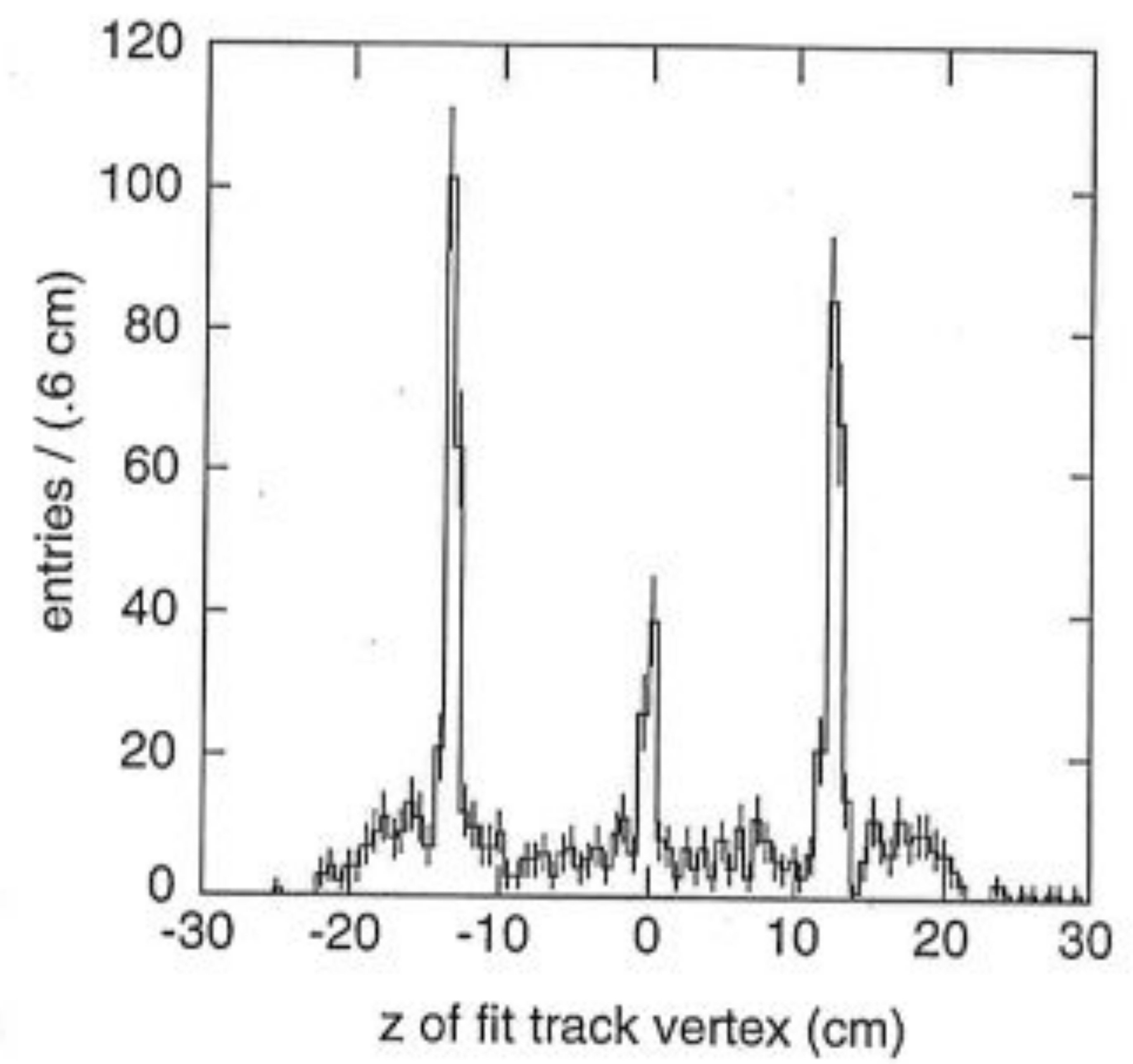
- Background events could be back-tracked to origins in the masks or the beam pipe

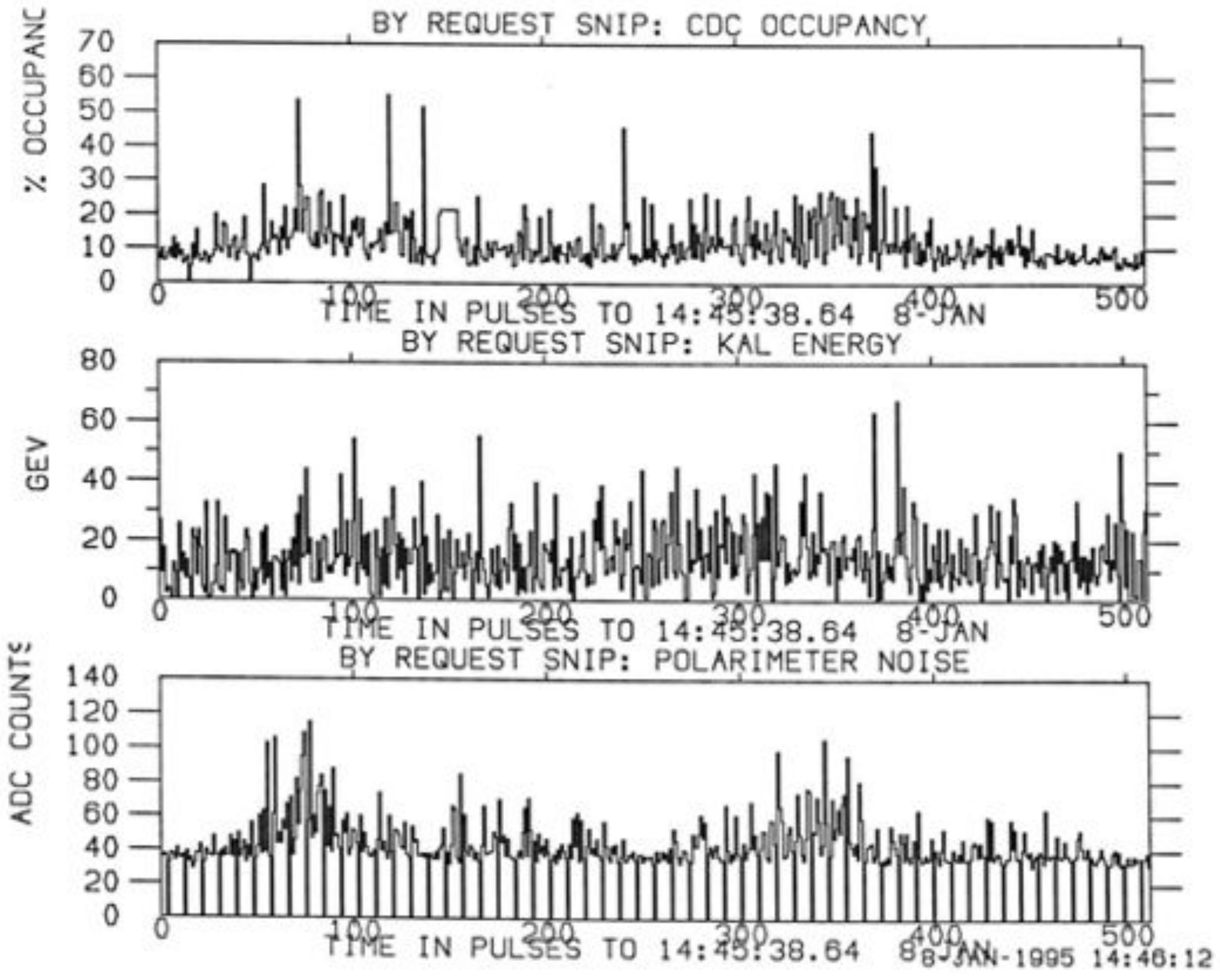
Large pulse-to-pulse variations in background levels





T. Markiewicz





SLD Lessons Learned

Design the IR region carefully

- ILC has more sophisticated collimation system and should not encounter the „multi-bounces“
- but are we prepared for the unexpected?

Diagnostics are critical

- Beam and loss monitors, but also in the detector
- link detector DAQ and machine controls
- good communication!

Stability is paramount

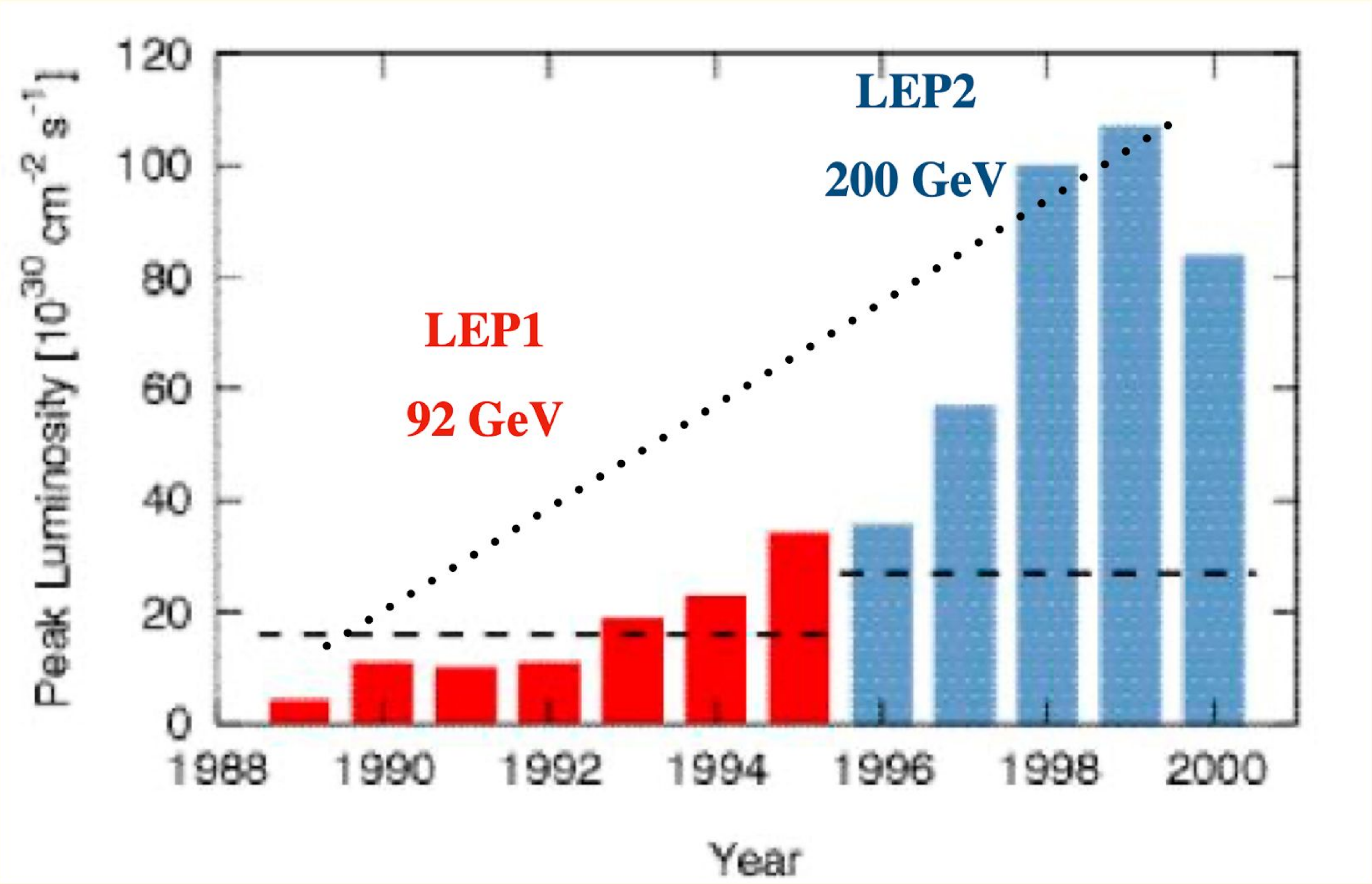
- Unstable conditions often occur

Build your subdetector with background issues in your mind

- don’t build devices which can fail catastrophically

LEP

H. Burkhardt



Performance increased steadily (slowly) over many years

not injector limited - beams accumulated, strong (SR) damping, equilibrium emittance

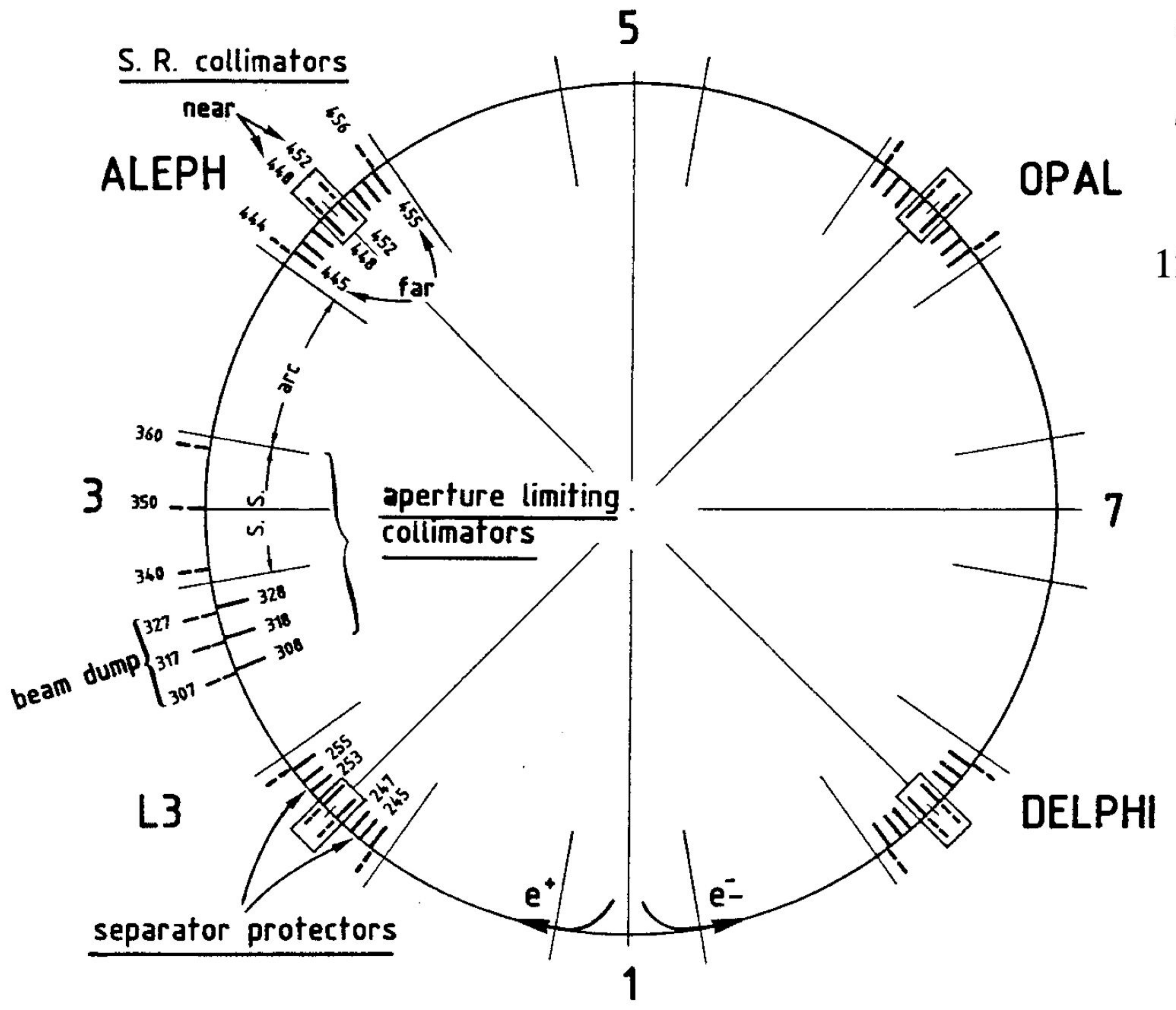
minimum β* and maximum tune shift were limited in LEP

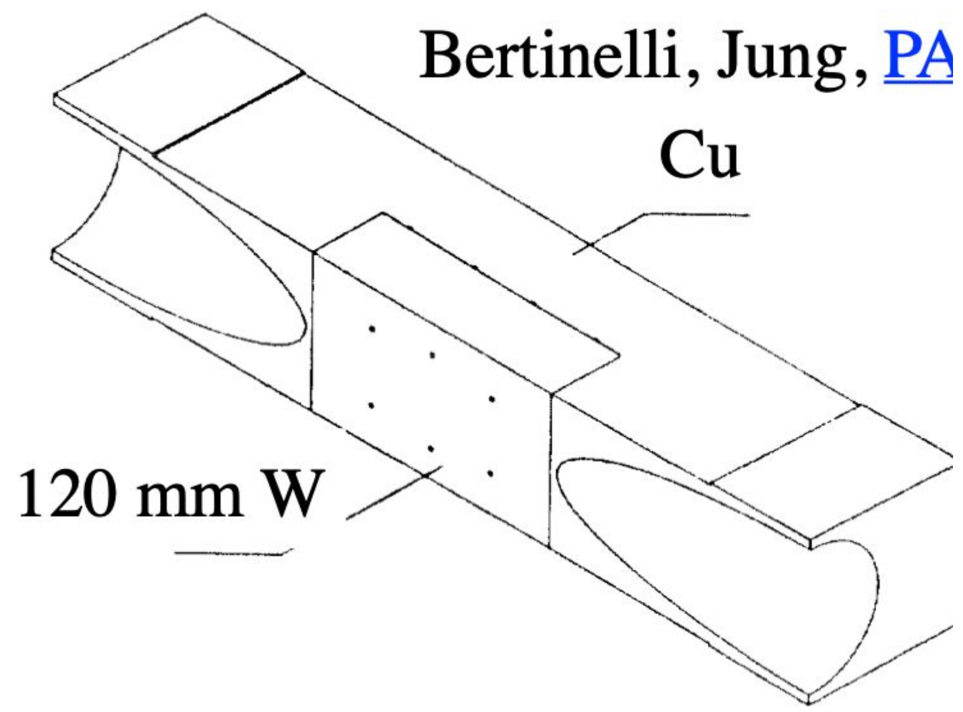
by the need of the experiments for stable low background running conditions

Collimation and Tracking is Crucial

H. Burkhardt

LEP movable collimators, essential for background





as originally designed,

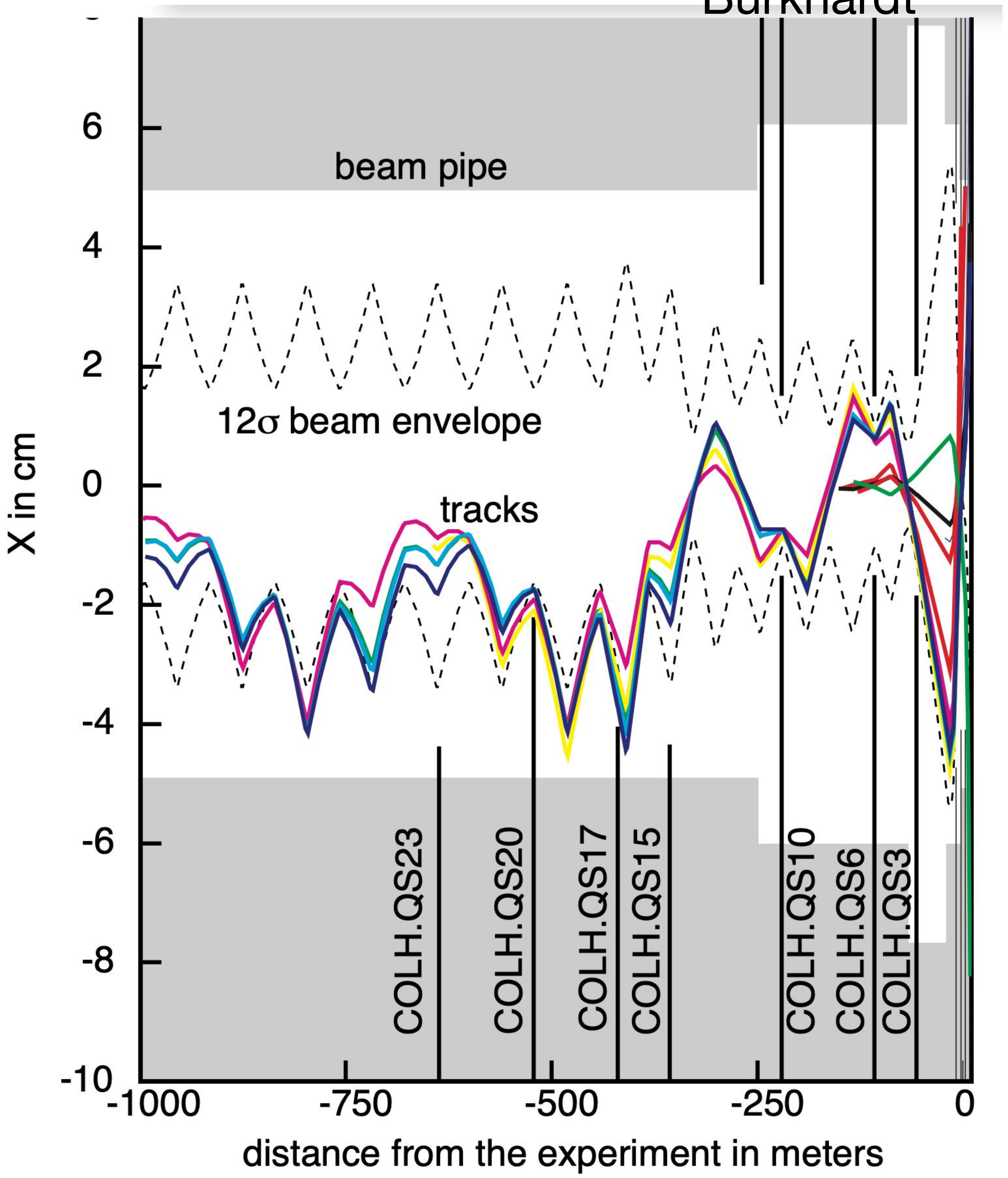
G. von Holtey. LEP main ring collimators. EP-BI-87-03

later modified (AP. limit IP5) and upgraded

settings of order
Aperture H 15.5 σ
Experim. H 18 σ

Vertical
~ 30 nominal σ
~ 100 measured σ

nominal :
10% coupling
σ E = 1.e-3

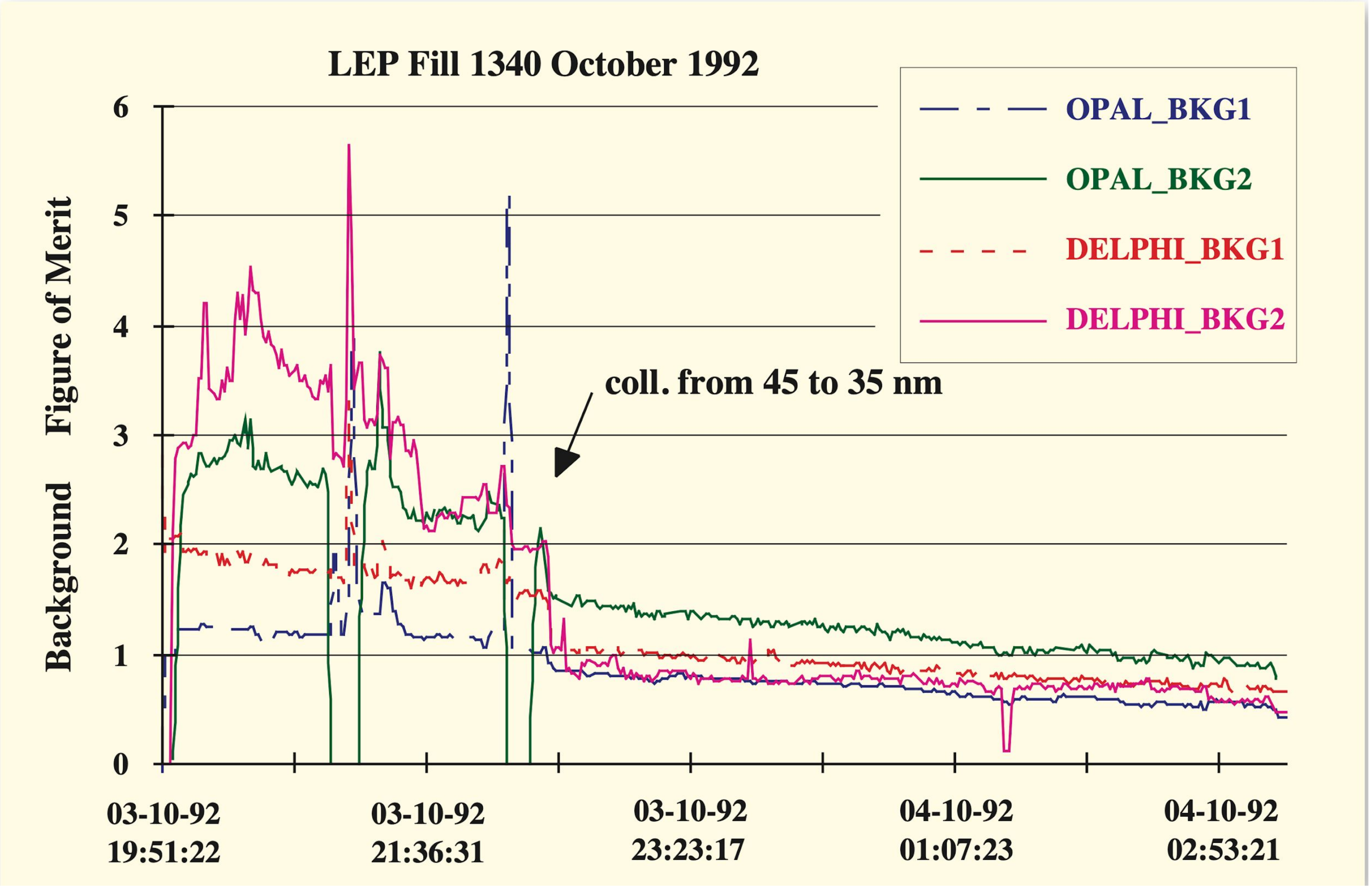


Background Observations by LEP Experiments

H. Burkhardt

Remark R.P.:

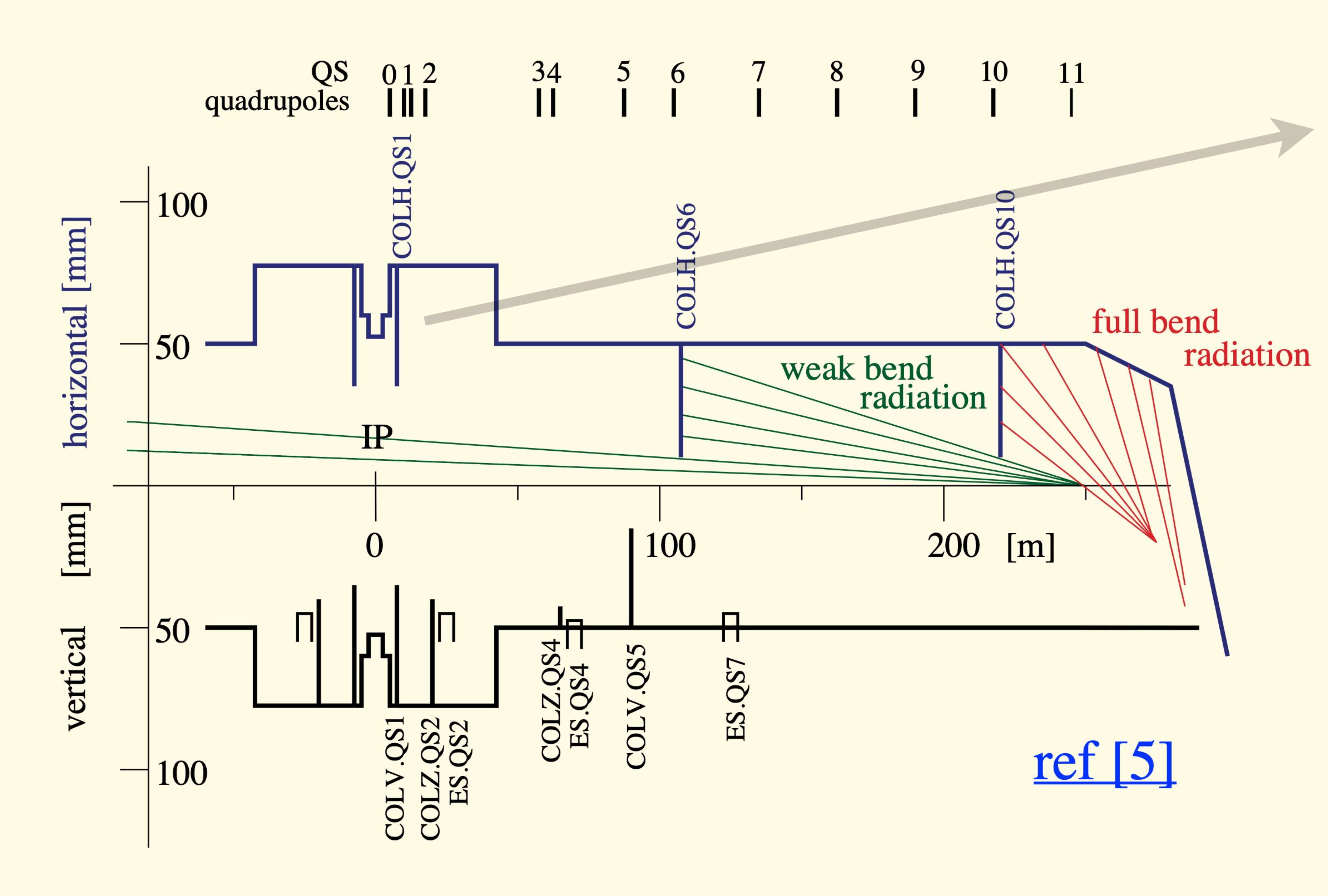
Length of LEP fill - several hours

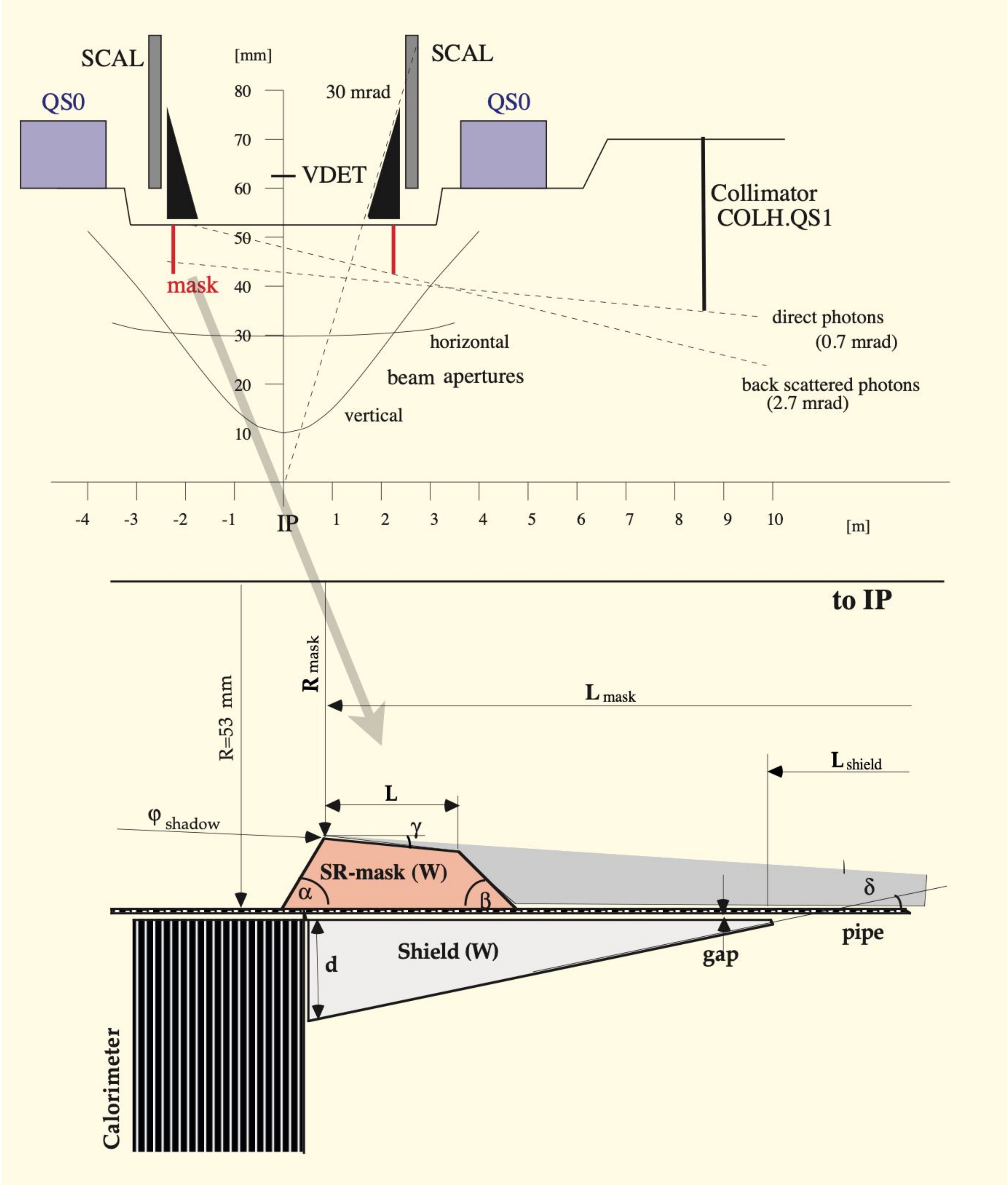


Careful IR Design

H. Burkhardt

Masking Synchrotron Radiation





LEP Lessons Learned

H. Burkhardt

LEP experiments required low backgrounds

« **e+, e- / crossing, low SR photon flux** (≲ 100 / crossing , almost invisible in event displays)

which limited pushing up luminosities, particularly at LEP1

Beamstrahlung + muon backgrounds were negligible for LEP — important for linear colliders

R.P.: However … see later

Important to have a continuous, close experiment + machine collaboration

with background monitoring by the experiments + signal exchange

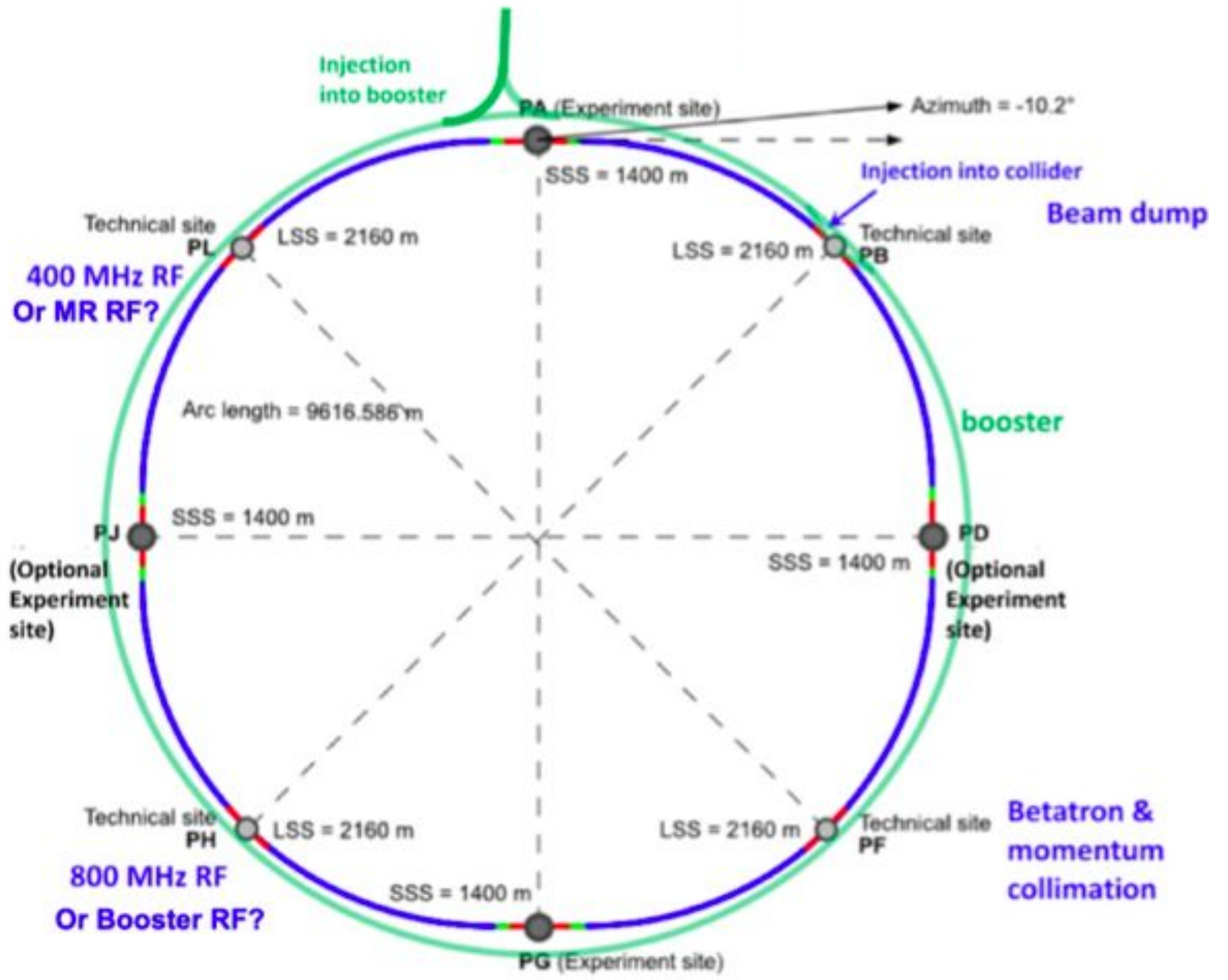
Even in a well (MDI) optimized IR with movable collimators + fixed masking

this can be expected to be essential to minimize synchrotron radiation + off momentum

backgrounds and maximise the precision physics potential reachable with an e+e- collider

FCC MDI Nutshell (and poor man's) Introduction

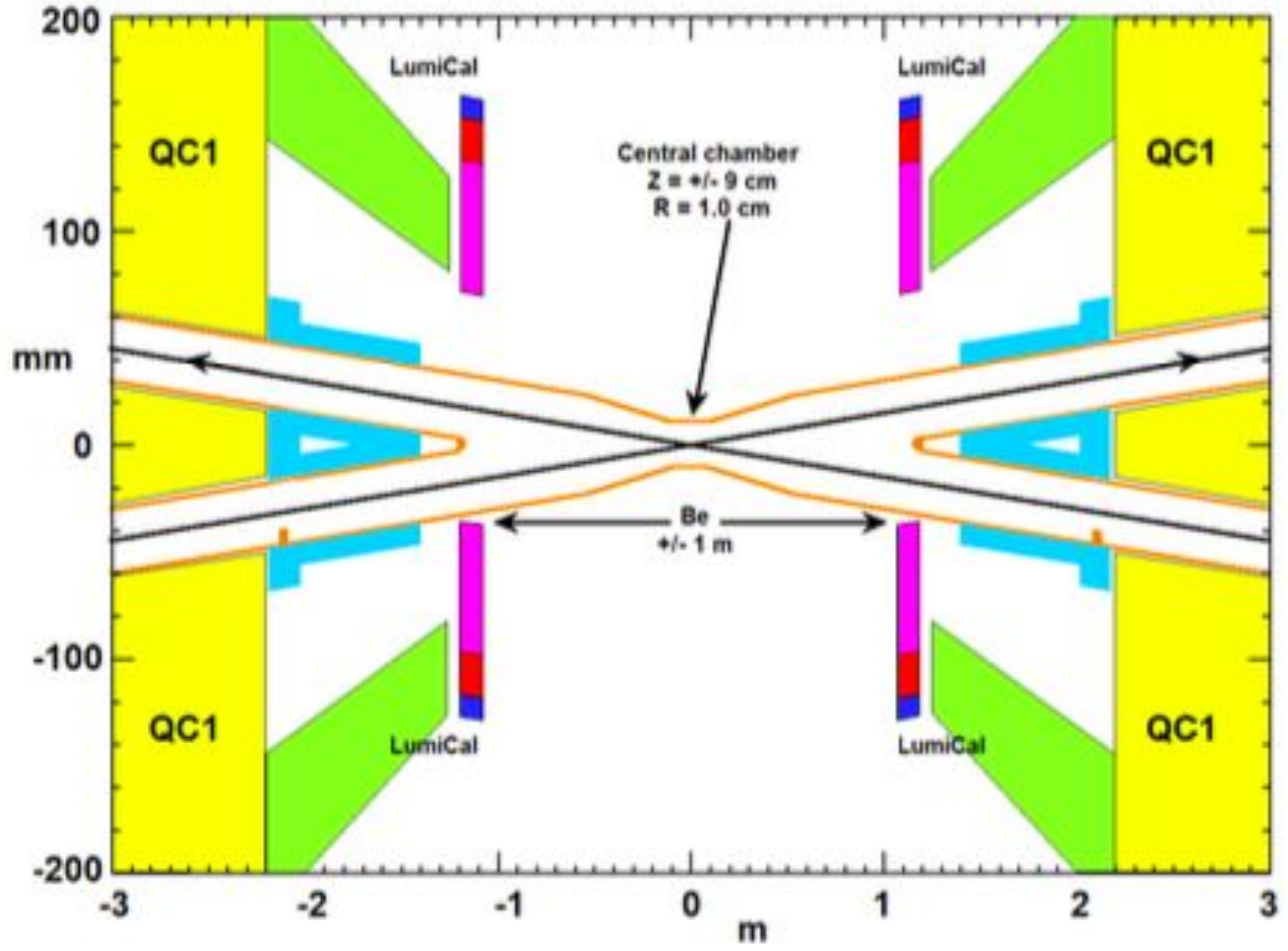
Machine layout
as shown during FCC Week 2023 Cracow



- Circumference 90,6 km
- 4IP (FCC-ee = FCC-hh)
  - IPA, IPD, IPG, IPJ

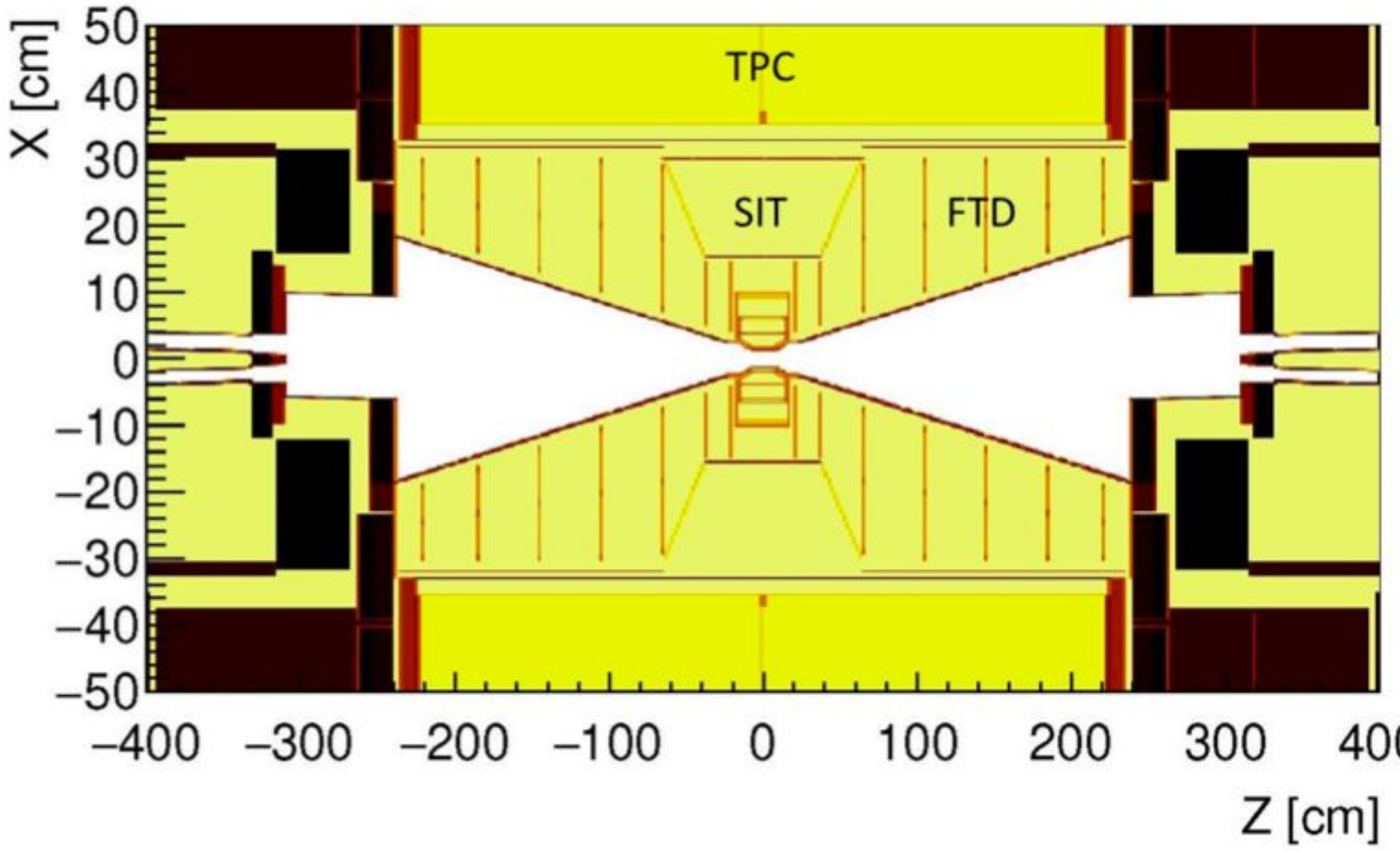
M. Boscolo, FCC Week Cracow

Typical FCC-ee MDI region



- L* ~ 2m
- Final quadropole inside detector region
- LumiCal at 1000mm
- => defines tracker acceptance cosθ ~0.984
- Inner beampipe radius 10mm
- Magnetic Field 2 T
- Crossing angle ~30 mrad

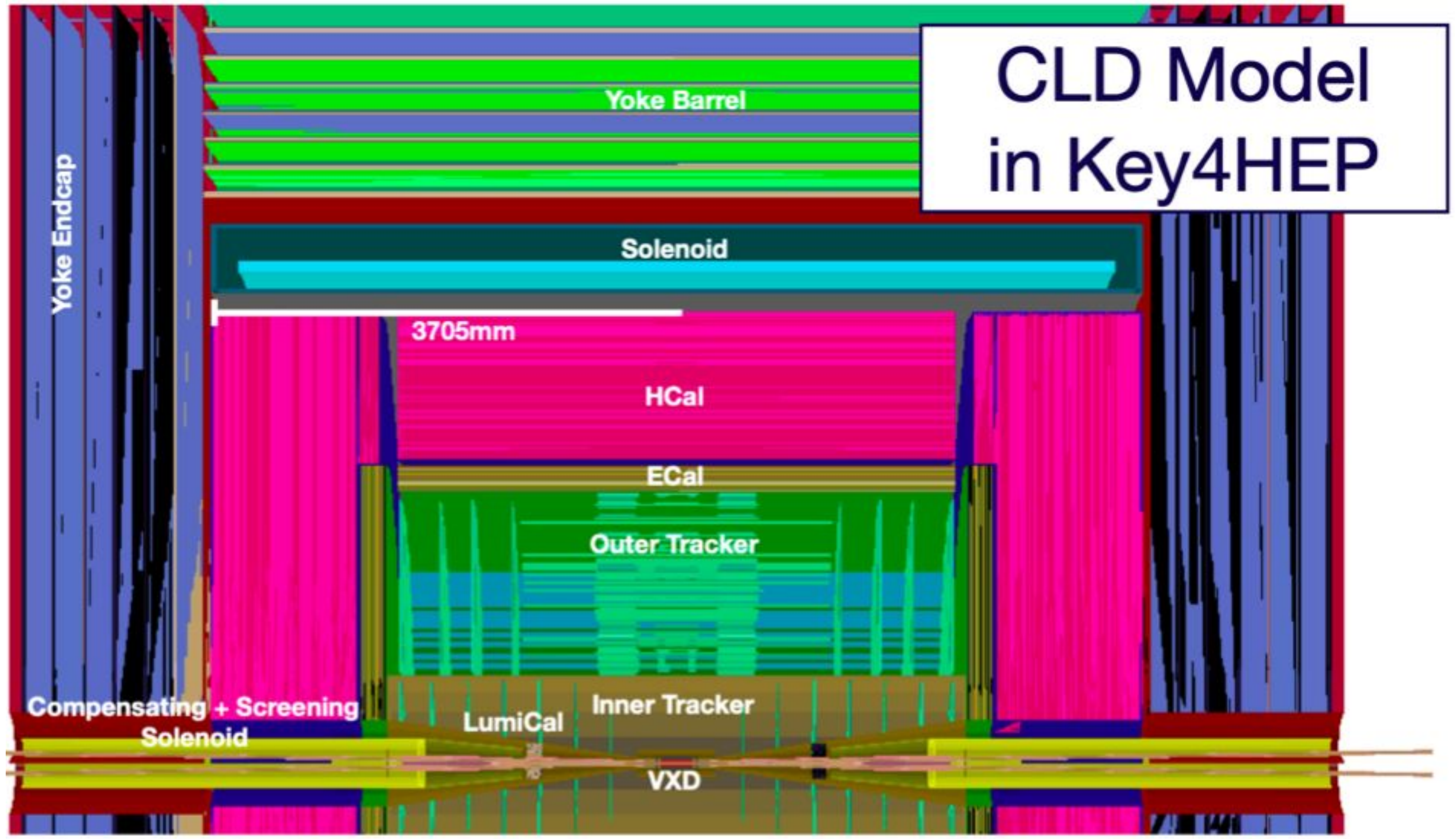
Compare with ILD MDI region



- L* = 4.1m
- Final quadropole outside of detector region
- Tracker acceptance defined by conical beam pipe (due to blown-up beam)
- cosθ ~0.995
- LumiCal at ~2500mm
- Inner beampipe radius 16 mm
- Magnetic Fiels 3.5-4 T
- Crossing angle 14 mrad

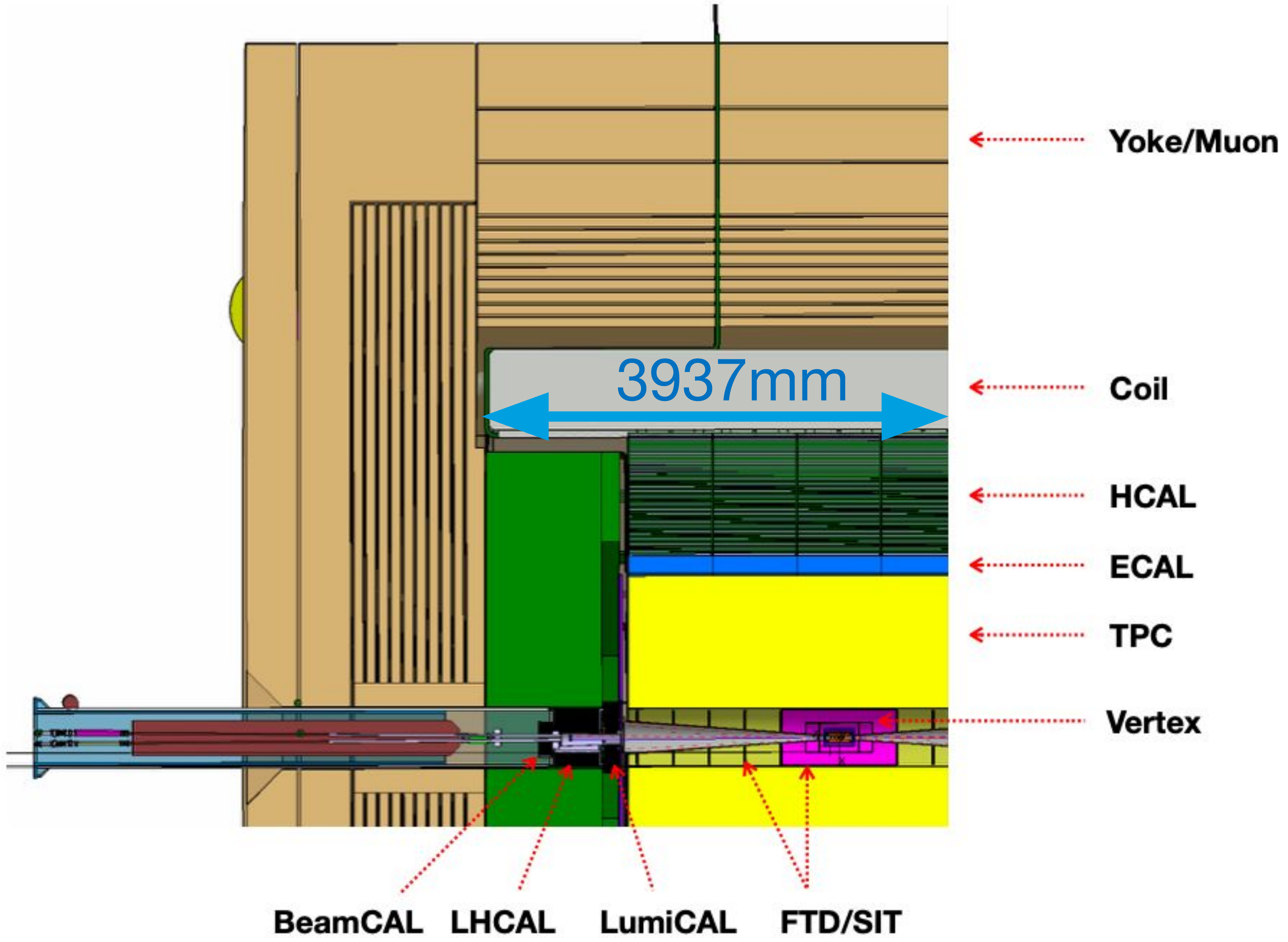
CLD Detector

In the following many studies will be shown that were carried out with CLD



Central Silicon Tracking

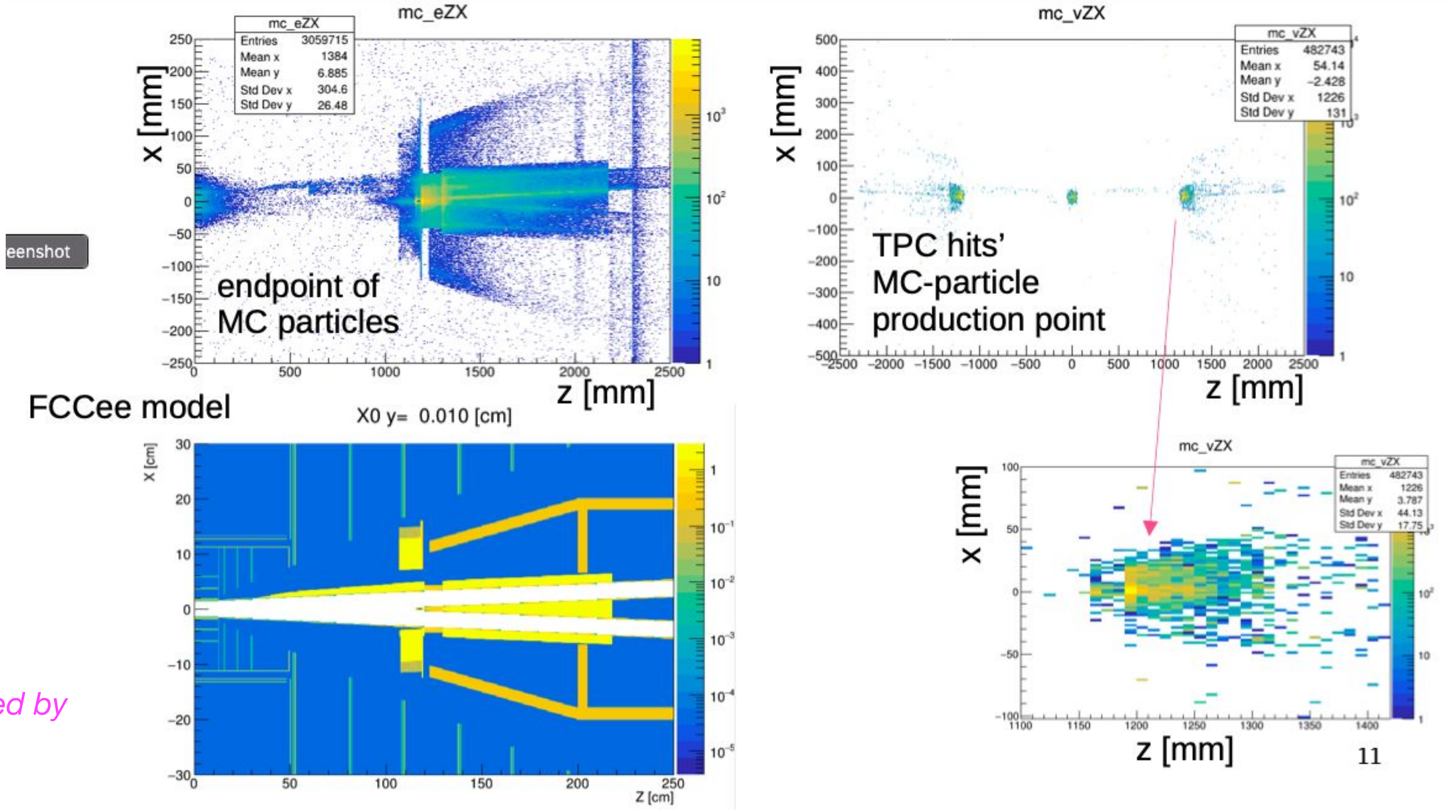
For reference: ILD



Central Tracking with TPC

Background from incoherent pairs in TPC at FCC-ee

Study on Z-Pole by Daniel [Link:]



Samples provided by
A. Ciarma

Background from incoherent pairs in TPC at FCC-ee - Numbers

Study on Z-Pole by Daniel Link:

Z-Production →

	primary ions / “event”	event rate	primary ions / 0.44 s “TPC frame*”
Z_had ILD_l5_v02 @ 2T	1.27M	54 kHz	30 $\times 10^9$
pairs ILD_l5_v02 @ 2T	75 k	33 MHz	1100 $\times 10^9$
pairs ILD TPC only @ 2T	15 k	33 MHz	220 $\times 10^9$
pairs FCCee w/ TPC	0.43 M	33 MHz	6200 $\times 10^9$

* maximum ion drift time in TPC = 0.44s

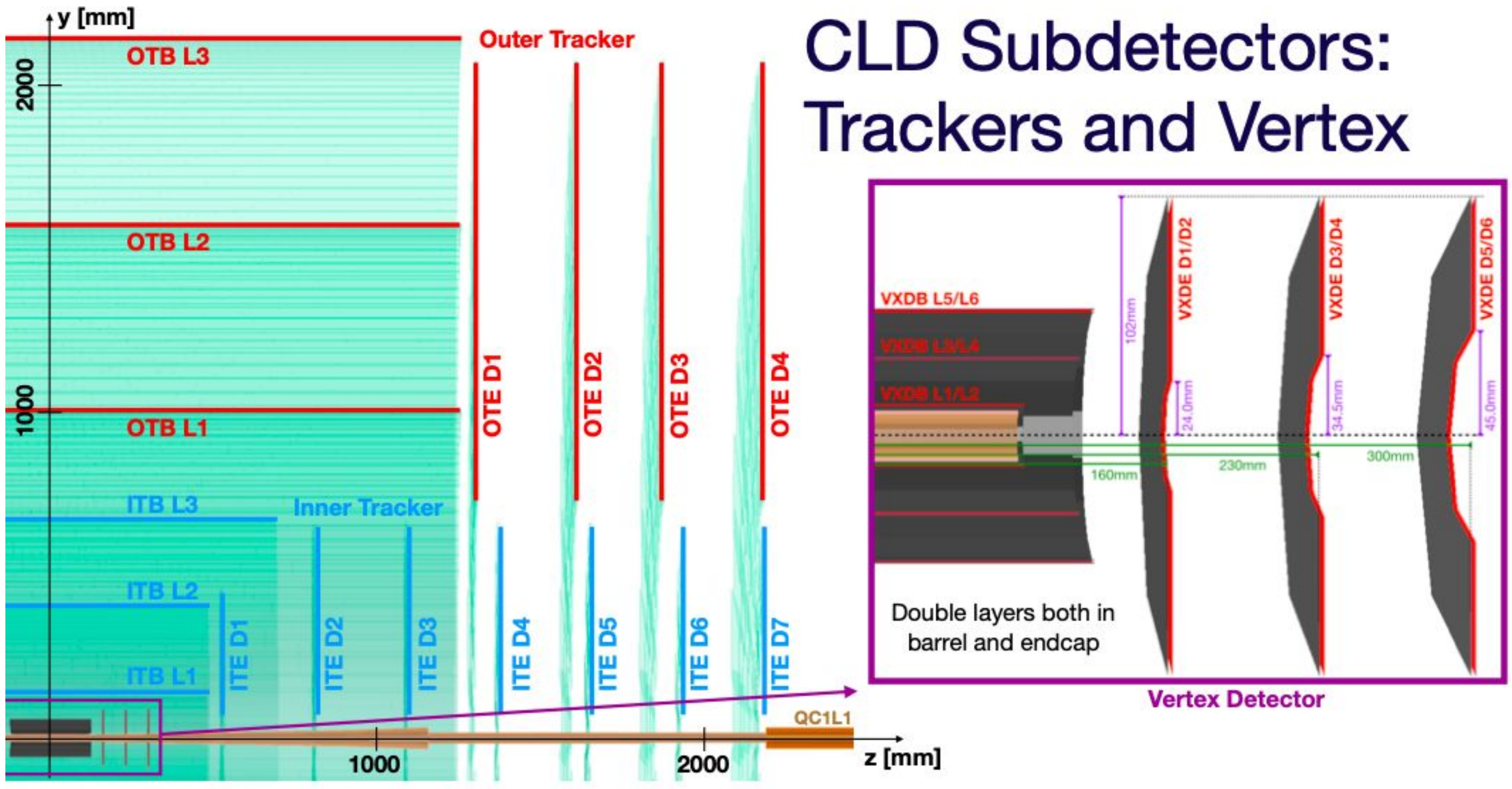
→ distortions O(100 μm)

For reference: Occupancies CLD

A. Ciarma (FCC Week Cracow)

	Z	WW	ZH	Top
Pairs/BX	1300	1800	2700	3300
Max occup. VXDB	80e-6	280e-6	410e-6	1150e-6
Max occup. VXDE	25e-6	95e-6	140e-6	220e-6
Max occup. TRKB	8e-6	20e-6	38e-6	40e-6
Max occup. TRKE	100e-6	150e-6	230e-6	290e-6

CLD Inner Region



A. Ciarma, FCC Week Cracow

(New) Synchrotron radiation mask for FCC-ee detector

TaShield_BH2	V = 3.595e-05 [m^3]	->	0.69 [kg]
TaShield_AH	V = 7.756e-03 [m^3]	->	149.69 [kg]
TaShieldTopPart	V = 1.235e-03 [m^3]	->	23.83 [kg]
TaShieldTopPart2	V = 6.852e-05 [m^3]	->	1.32 [kg]
TaShieldFiller1	V = 1.273e-04 [m^3]	->	2.46 [kg]
TaShieldFiller2	V = 1.238e-04 [m^3]	->	2.39 [kg]
Total	V = 9.346e-03 [m^3]	->	180.39 [kg]
QC1L1	V = 1.282e-03 [m^3]	->	4.32 [kg]
QC1L2	V = 2.289e-03 [m^3]	->	7.71 [kg]
QC1L3	V = 2.289e-03 [m^3]	->	7.71 [kg]

SR Mask and Shieldings

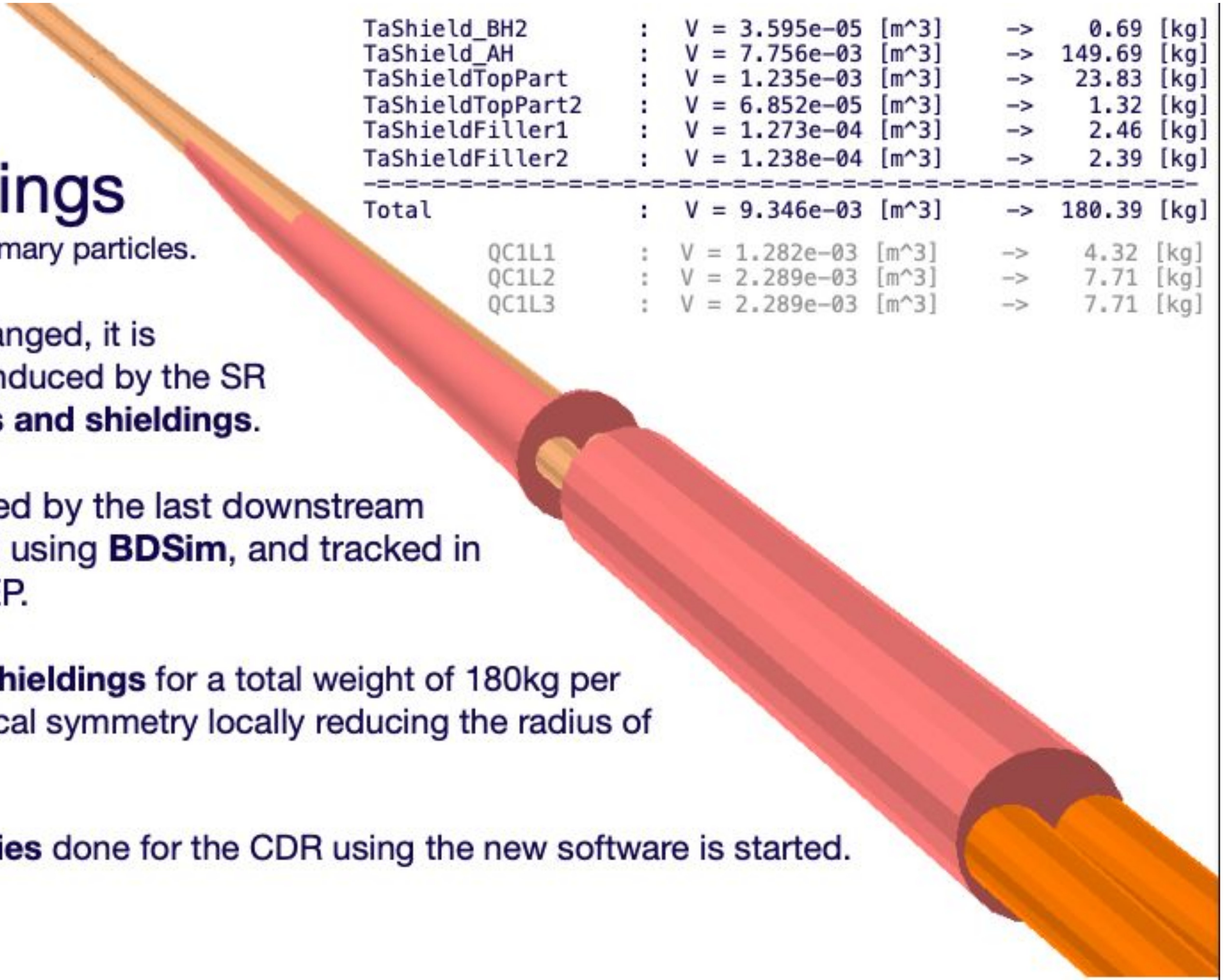
Thanks to K. André and M. Sullivan for the primary particles.

As the lattice and the beam pipe has changed, it is necessary to redefine the **background** induced by the SR and the features of the dedicated **masks and shieldings**.

Synchrotron radiation photons produced by the last downstream dipole (no FFQs for now) are produced using **BDSim**, and tracked in the CLD detector model using Key4HEP.

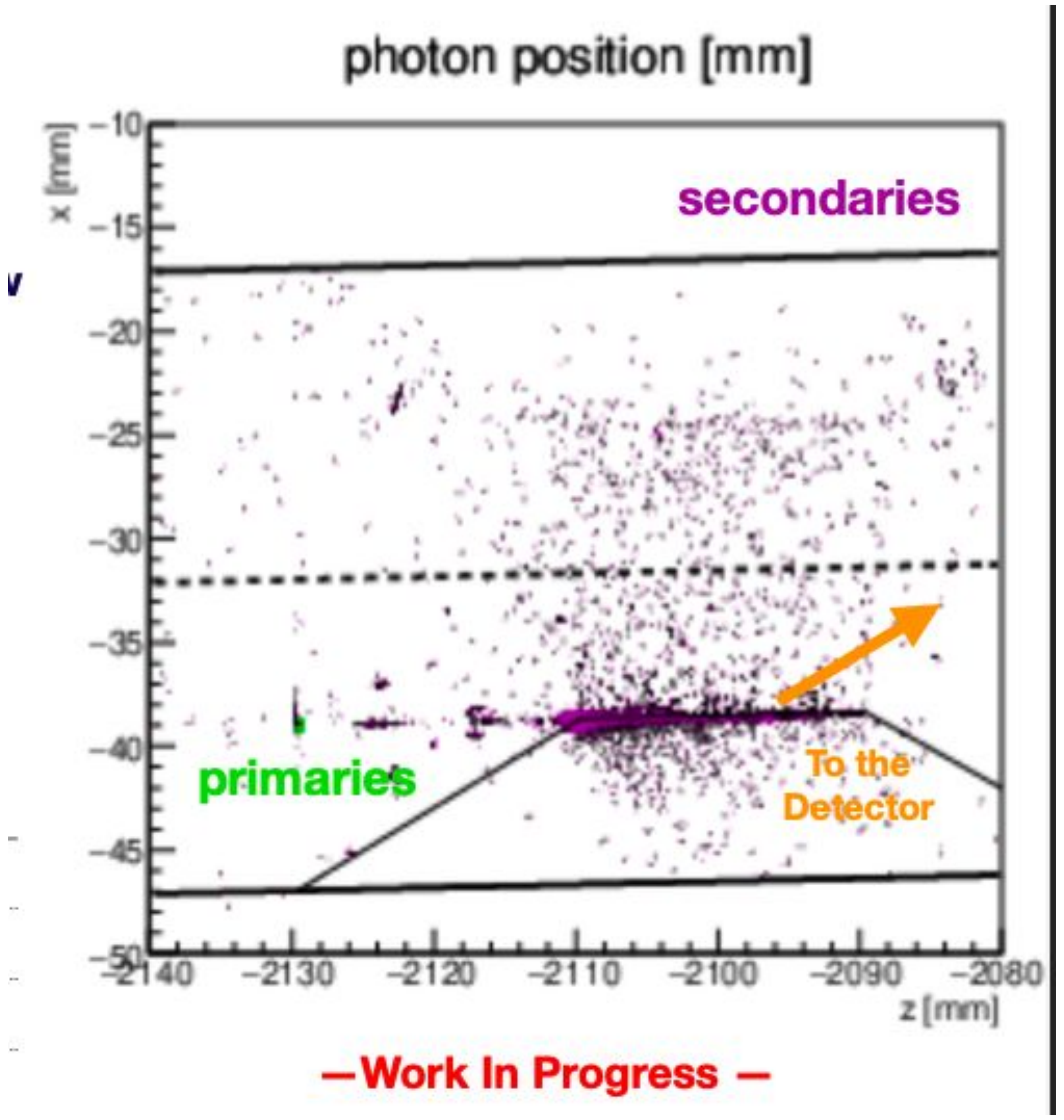
The implemented model has **Tungsten shieldings** for a total weight of 180kg per side, and a **Tantalum mask** with cylindrical symmetry locally reducing the radius of the beam pipe to 7mm.

Also the process of **replicating the studies** done for the CDR using the new software is started.



A. Ciarma, FCC Week Cracow

Photons from synchrotron radiation mask



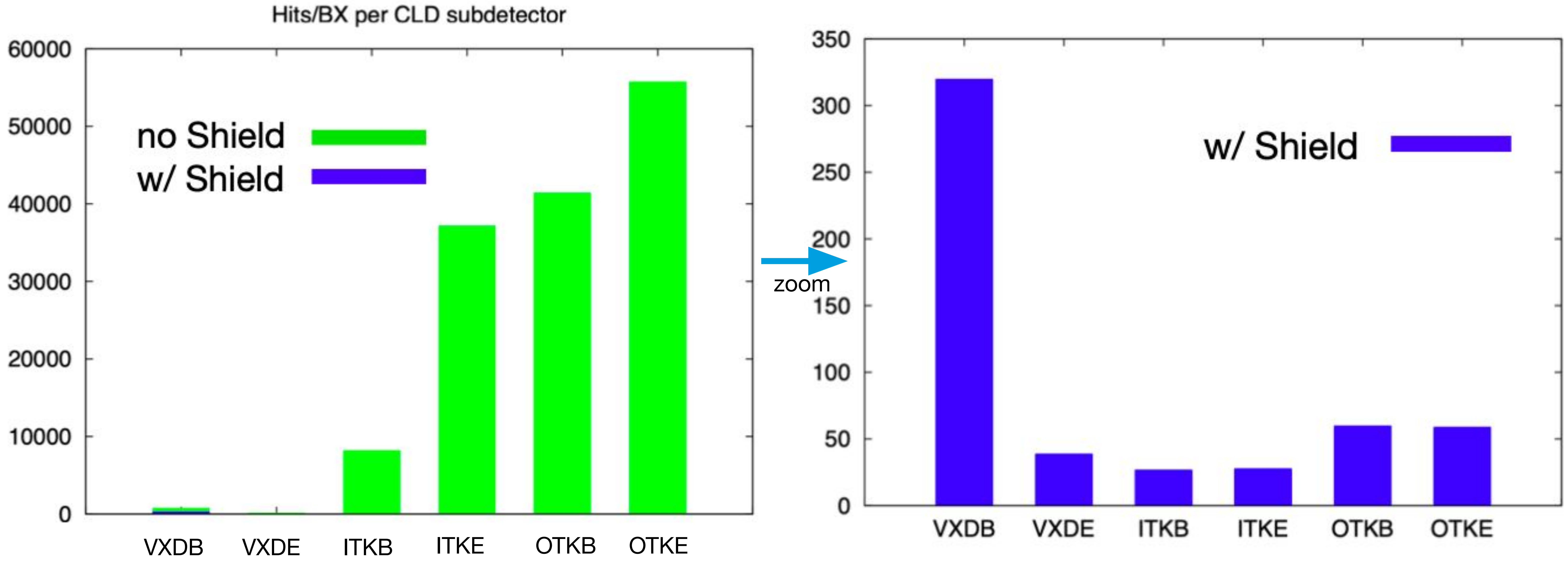
Tip of the mask is potential
Background source
Non-gaussian tails may become
an issue (SuperKEKB)
Study requires lots of statistics

(Preliminary) Study of CLD with Key4HEP

2 IP@Top

Typical occupancy 0.1% except for tracker endcaps O(1%)

Hits from SR w/o and with W shielding



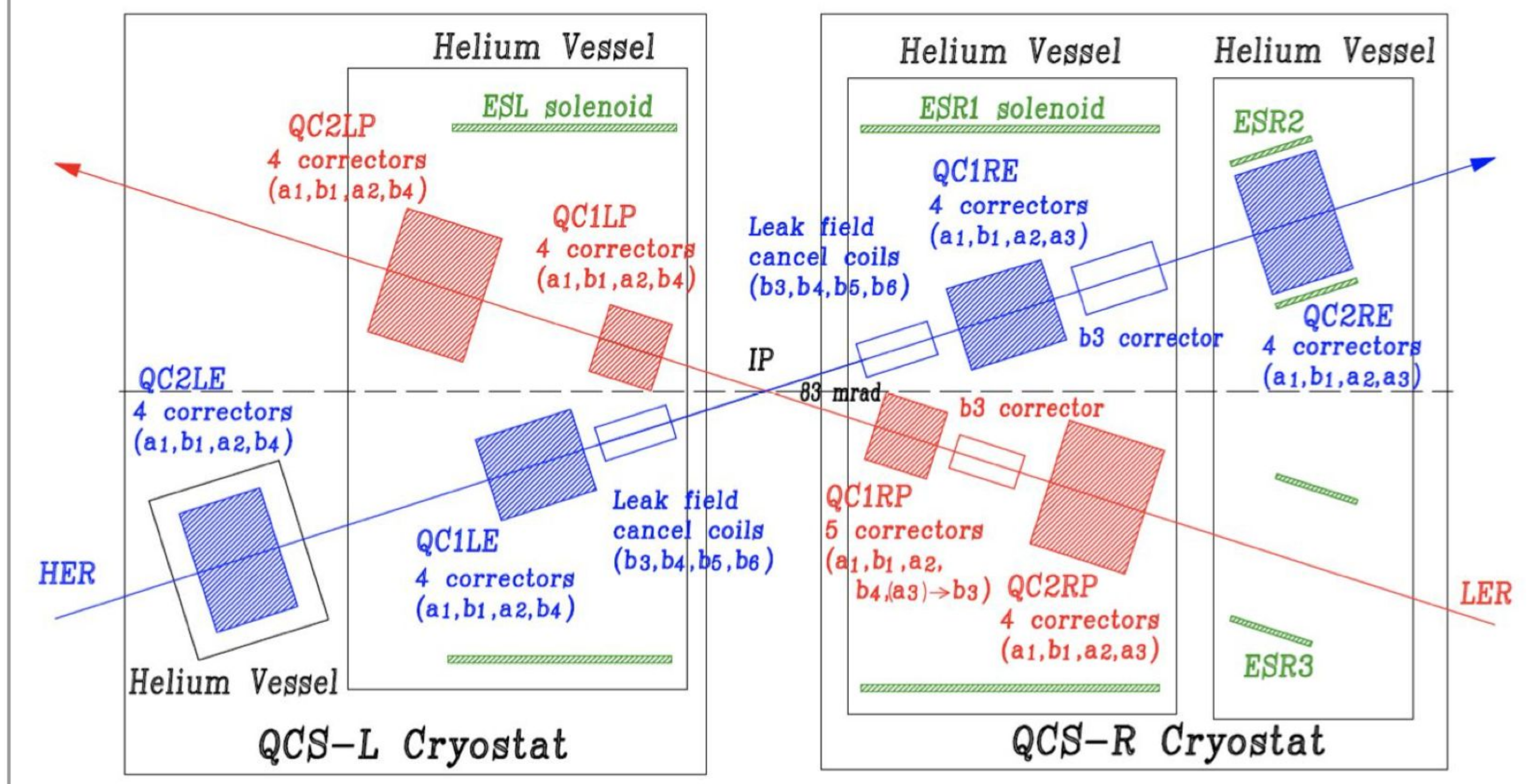
- Reduction of SR hits by W Shielding
- Except for Vtx detector, critical?
- CLD has Si-tracking <-> ILD with TPC

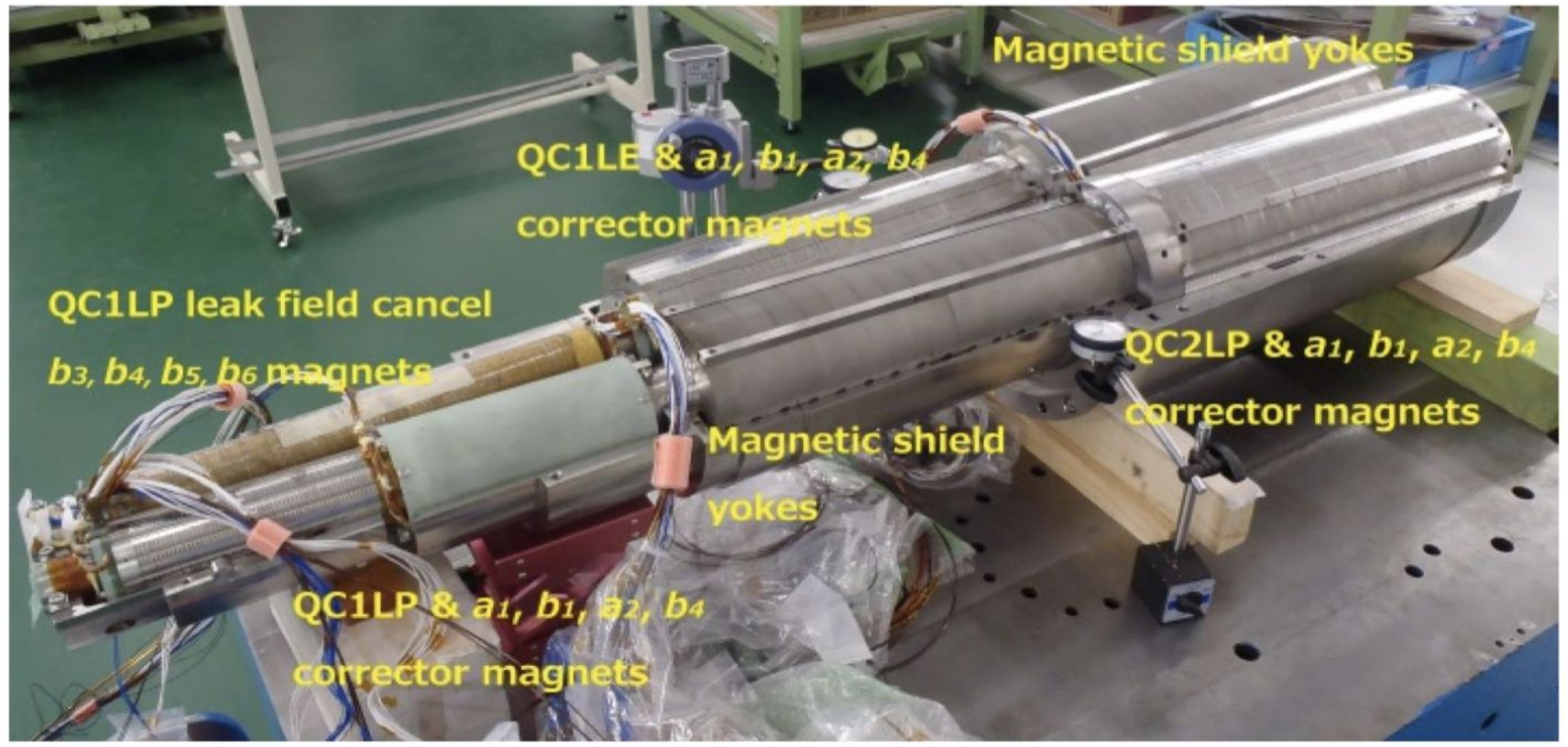
A. Ciarma, FCC Week Cracow

Belle-II

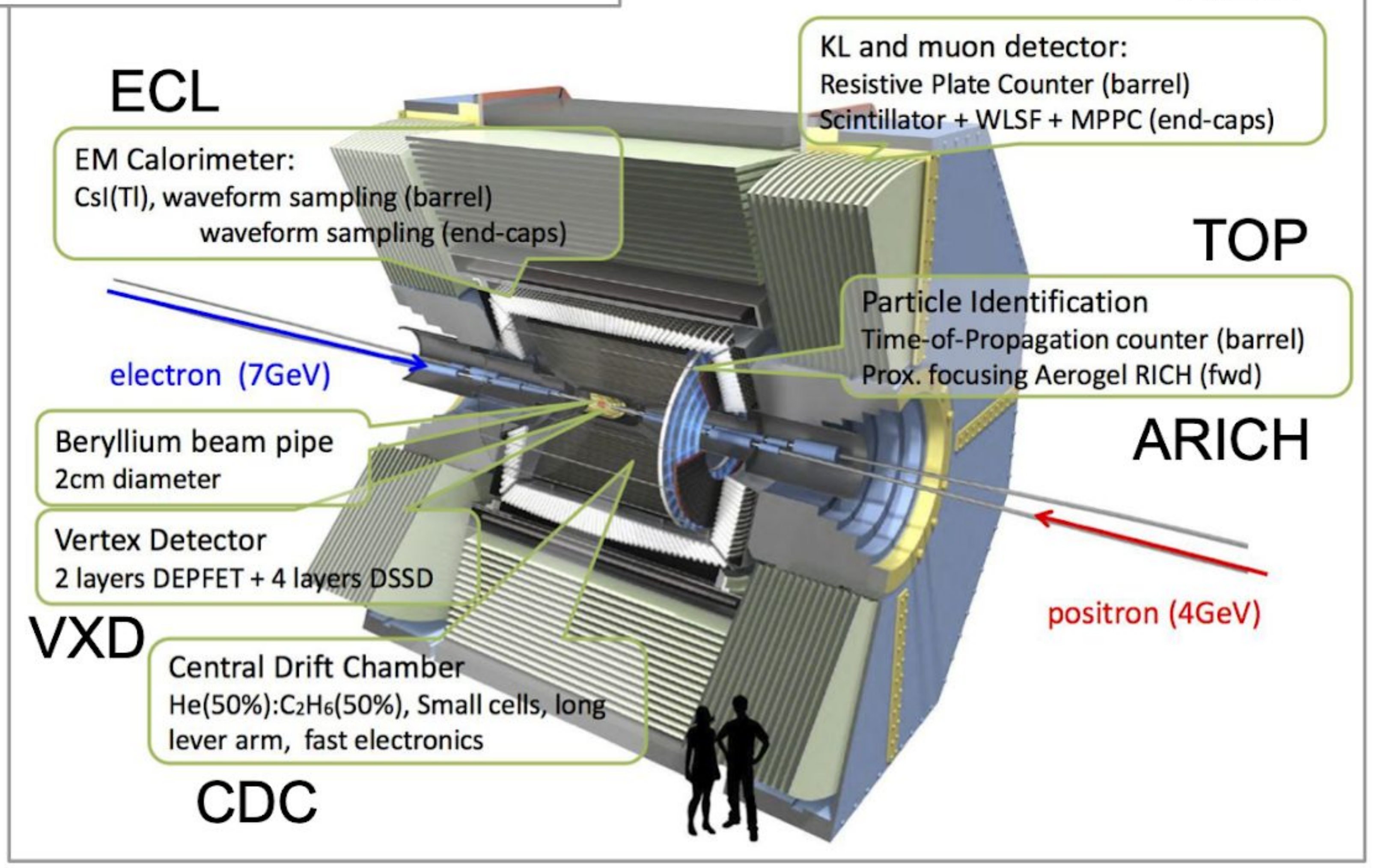
A. Natochii

SuperKEKB final focusing system (QCS)

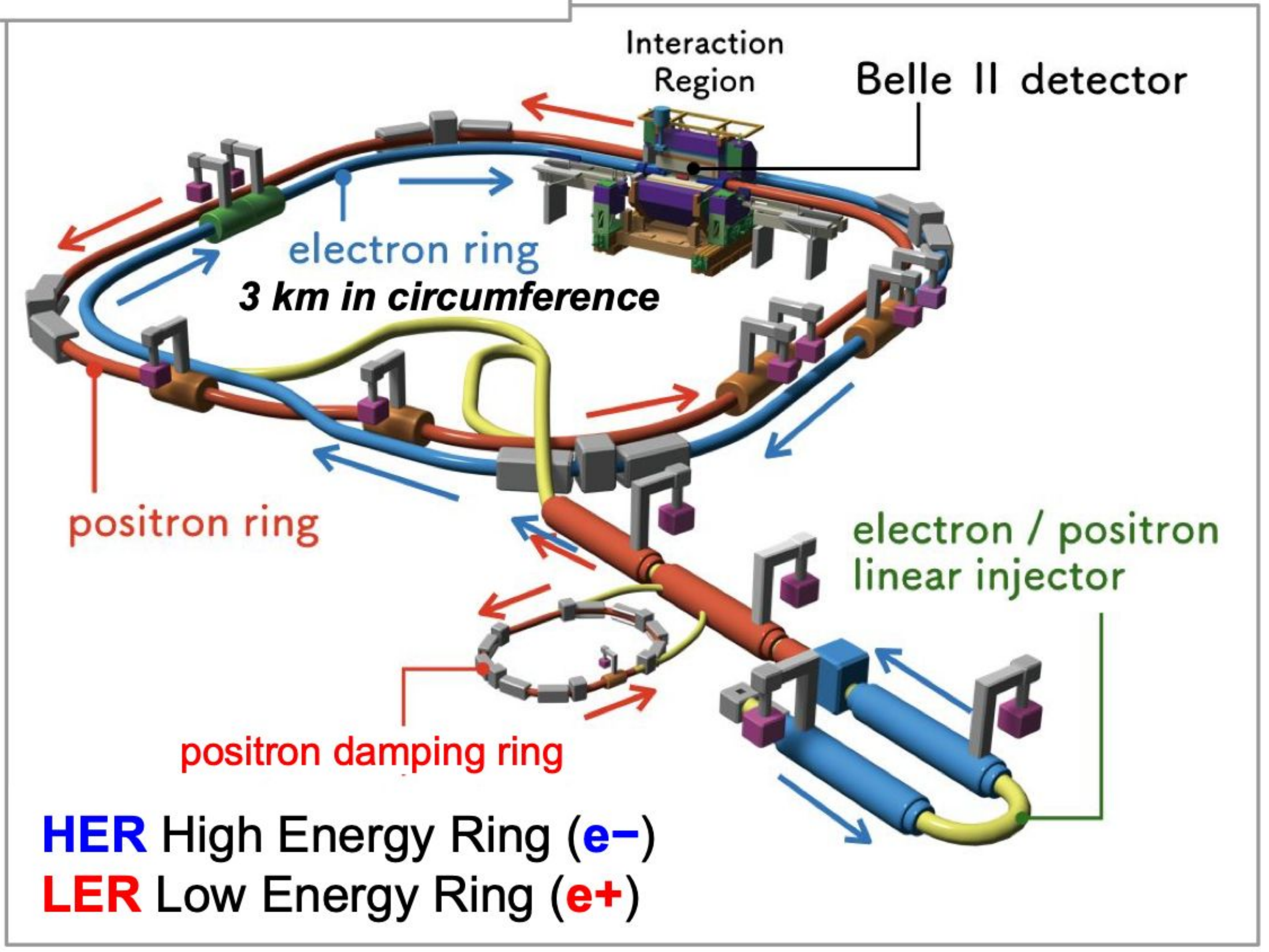




Belle II detector

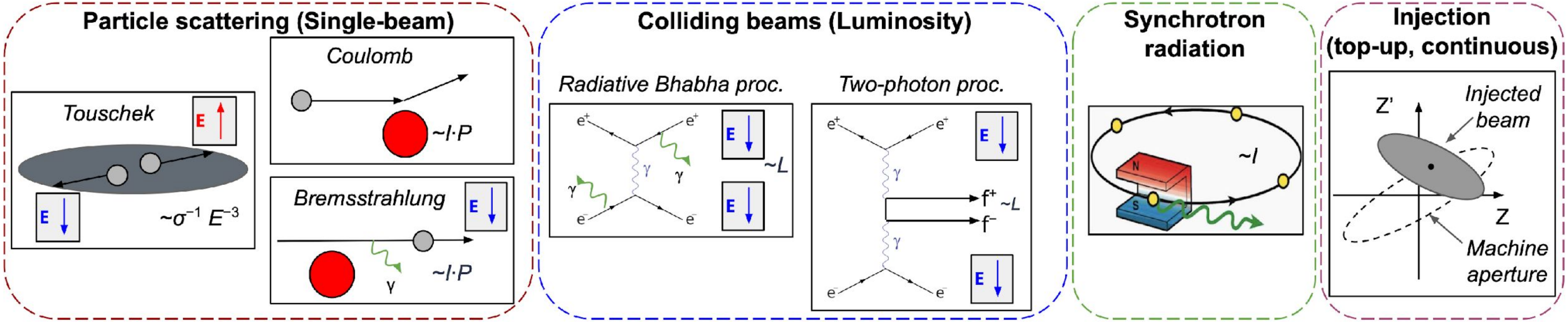


SuperKEKB collider



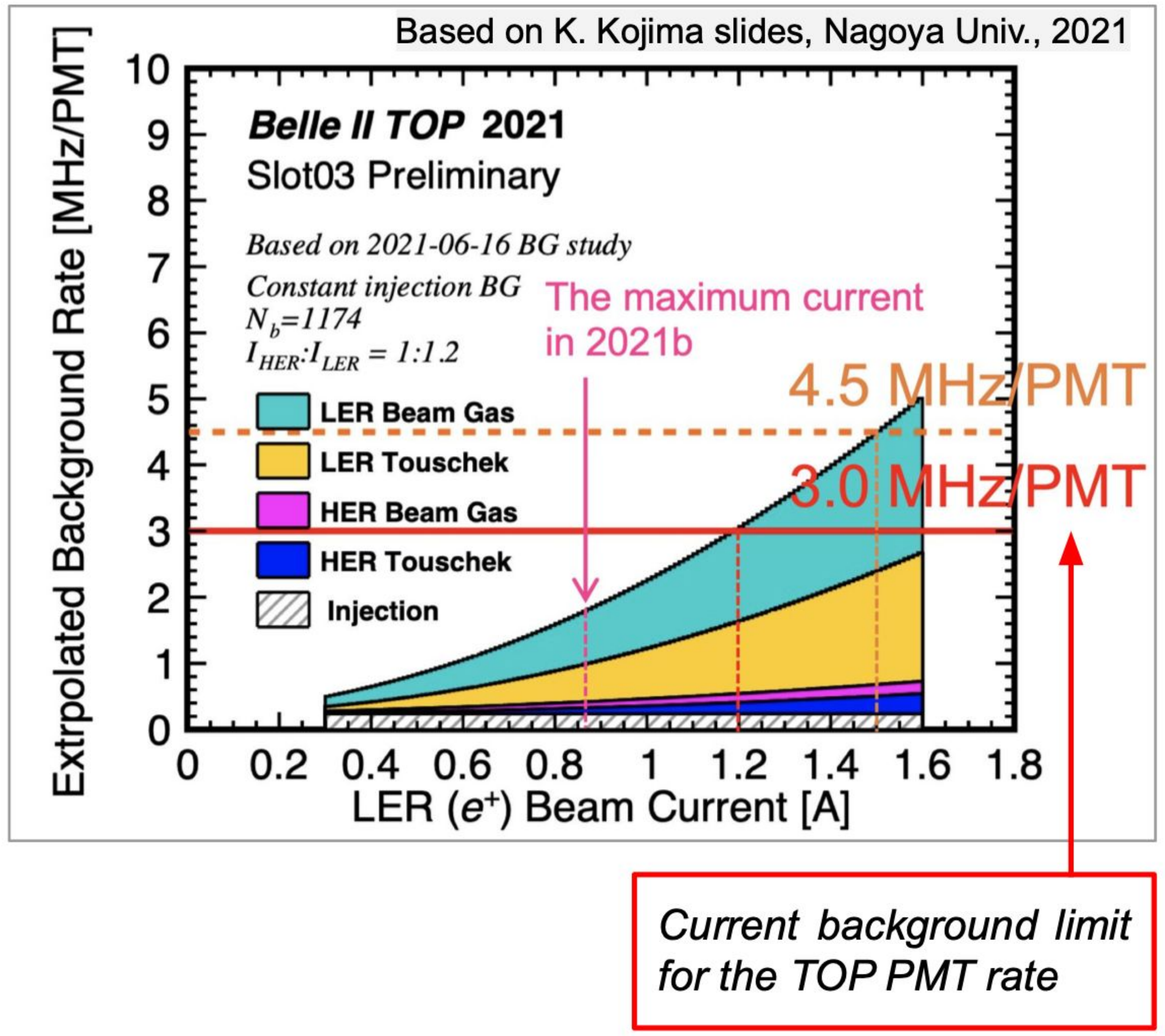
Belle-II Background Sources

A. Natochii



Currently, background levels are well below critical limits

- but they will become a problem on the way to the design luminosity
- mitigation strategies required



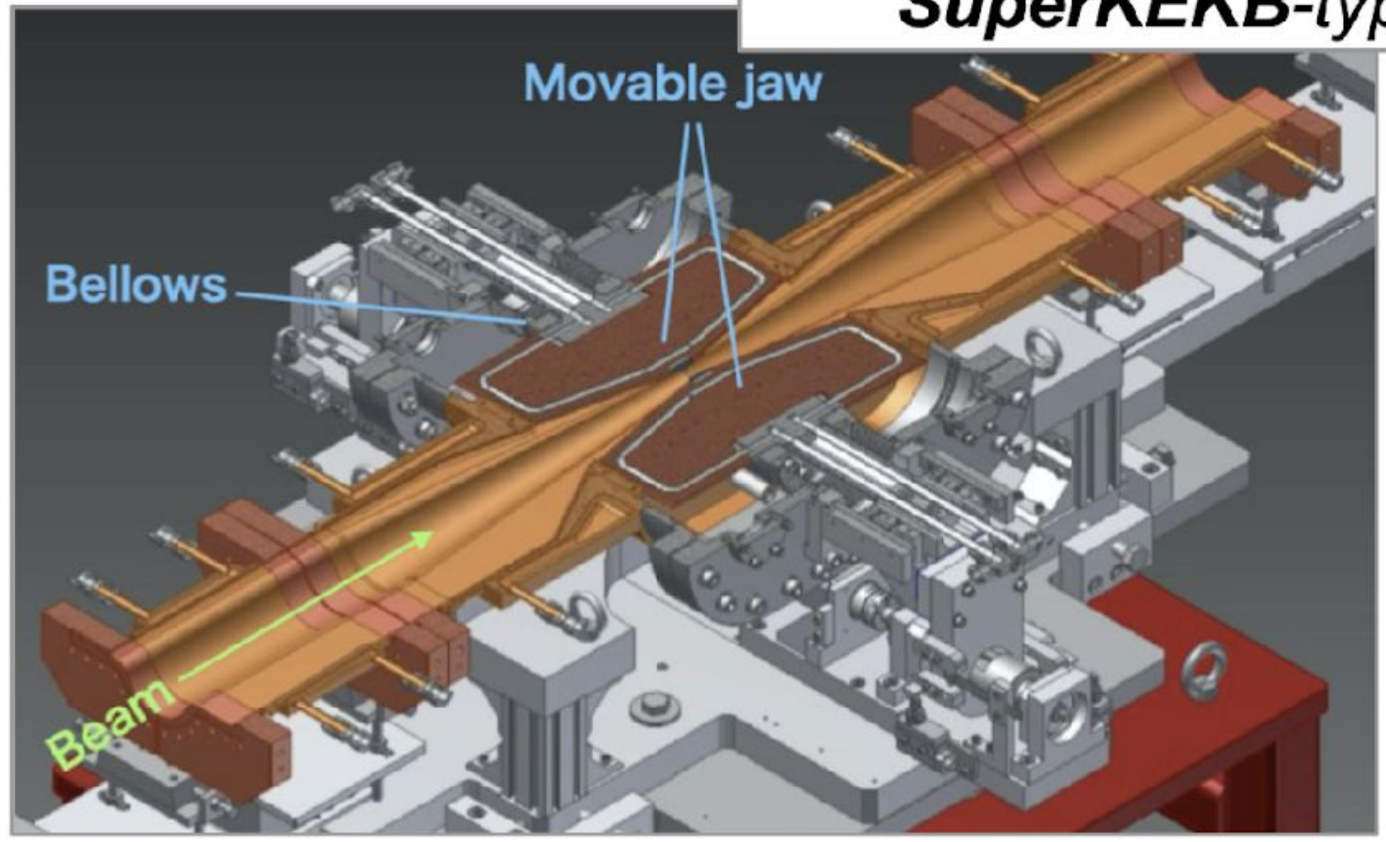
SuperKEKB Collimation System

A. Natochii

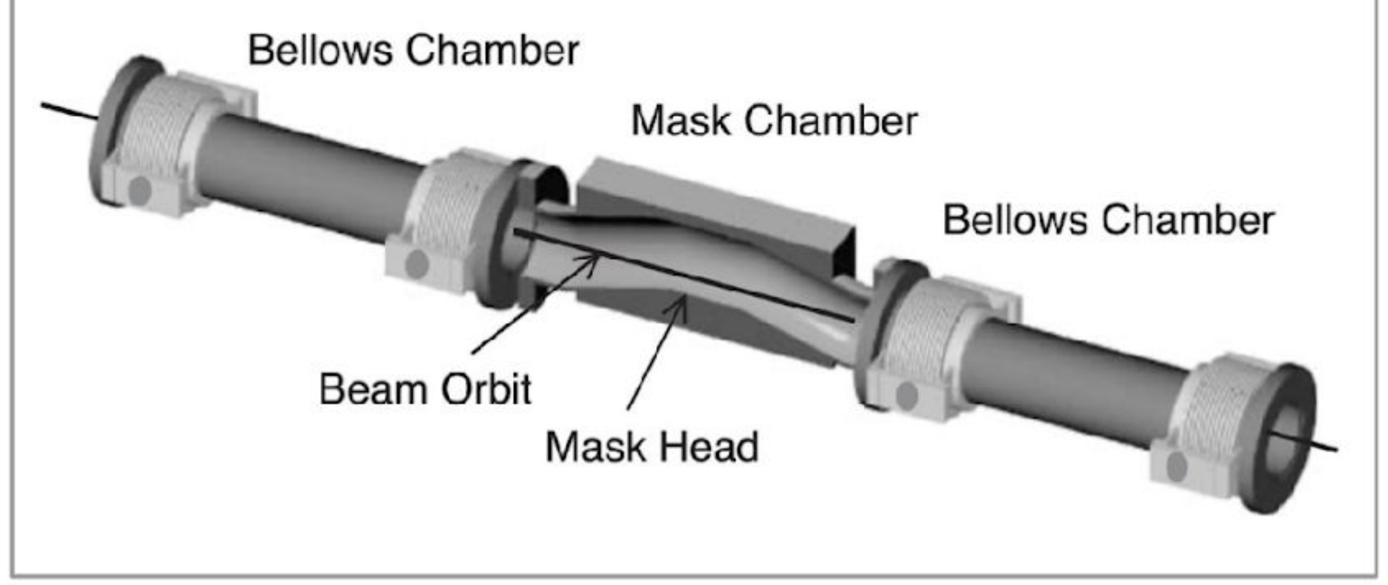
SuperKEKB collimation system

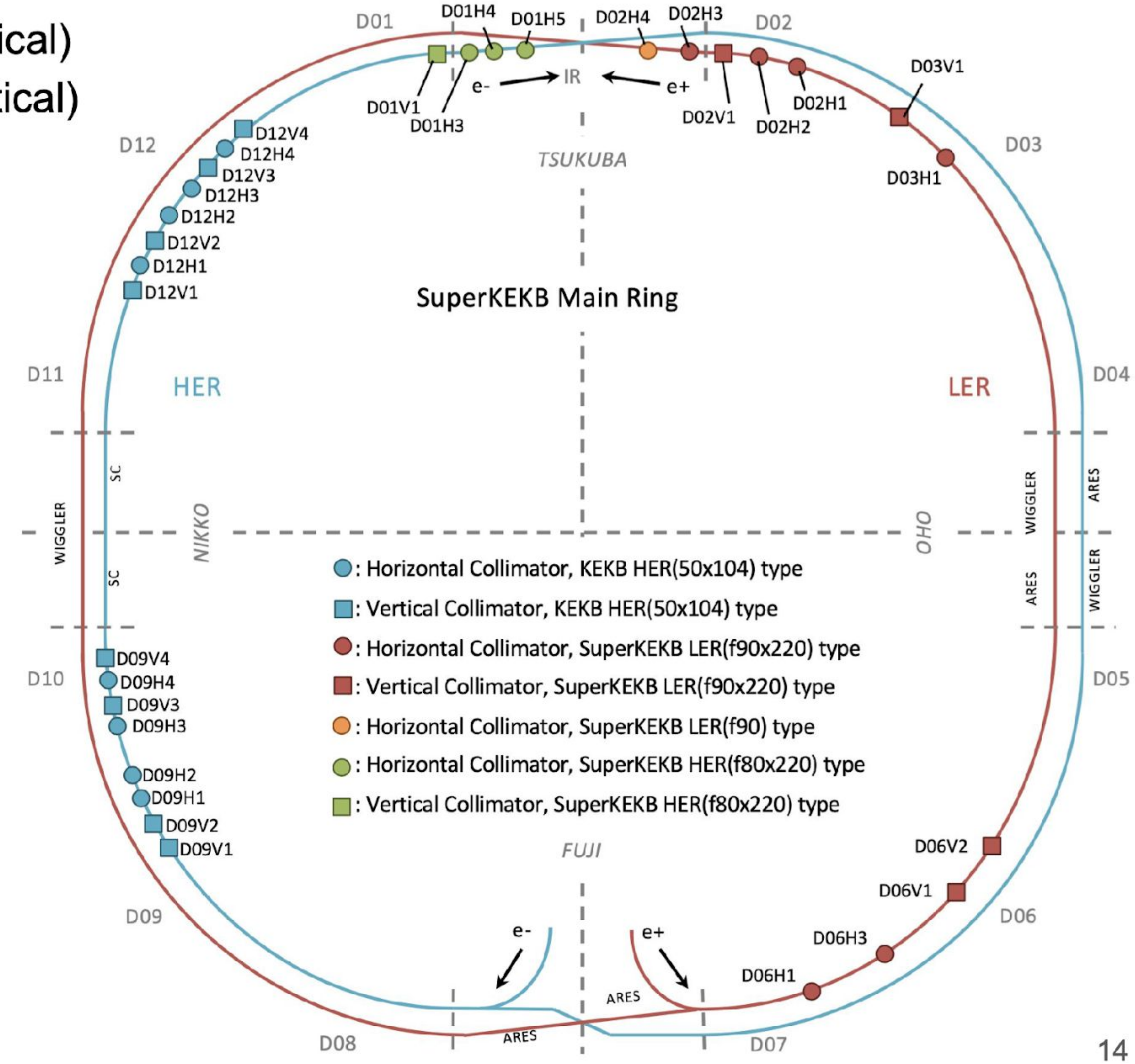
- LER → 11 collimators (7 horizontal & 4 vertical)
- HER → 20 collimators (11 horizontal & 9 vertical)

Two-sided collimator
***SuperKEKB**-type*



One-sided collimator
***KEKB**-type (D09 & D12)*





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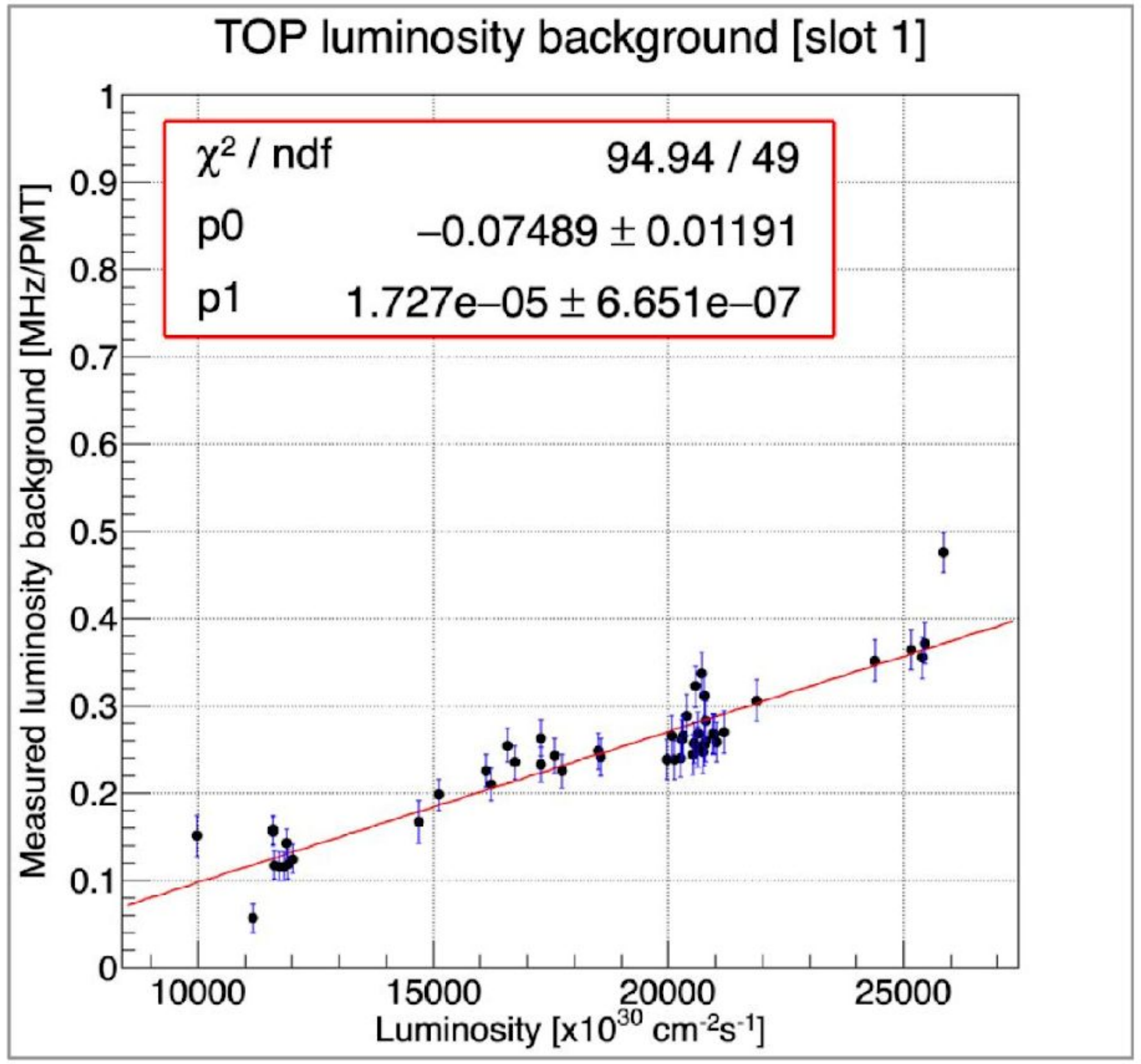
Colliding-beams Backgrounds

A. Natochii

Beam-induced background countermeasures: colliding beams

- **At the early stage**
  - Was assumed to be not dangerous
    - KEKB
      - The two beams share one QCS → strong kick to the outgoing beam after the IP for off-energy particles, back-scattering showers towards Belle II
    - SuperKEKB
      - Separate QCS for each beam → no kick from downstream quads
  - However, a larger crossing angle introduces a non-negligible angular kick to off-energy particles which can then be lost around the IP
  - **Dominant at design luminosities ~10^{35} $cm^{-2}s^{-1}$**
  - Installed a heavy-metal shield outside the IR beam pipe for detector protection against EM showers

- **Nowadays**
  - Luminosity BG is ≤ Single-beam BG, at the current luminosity ~10^{34} $cm^{-2}s^{-1}$



TOP [slot 1] single-beam backgrounds	
LER (I_{LER} = 0.73 A):	1.2 MHz/PMT
HER (I_{HER} = 0.65 A):	0.2 MHz/PMT

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Transverse Mode Coupling Instability

A. Natochii

Unexpected machine backgrounds: TMCI

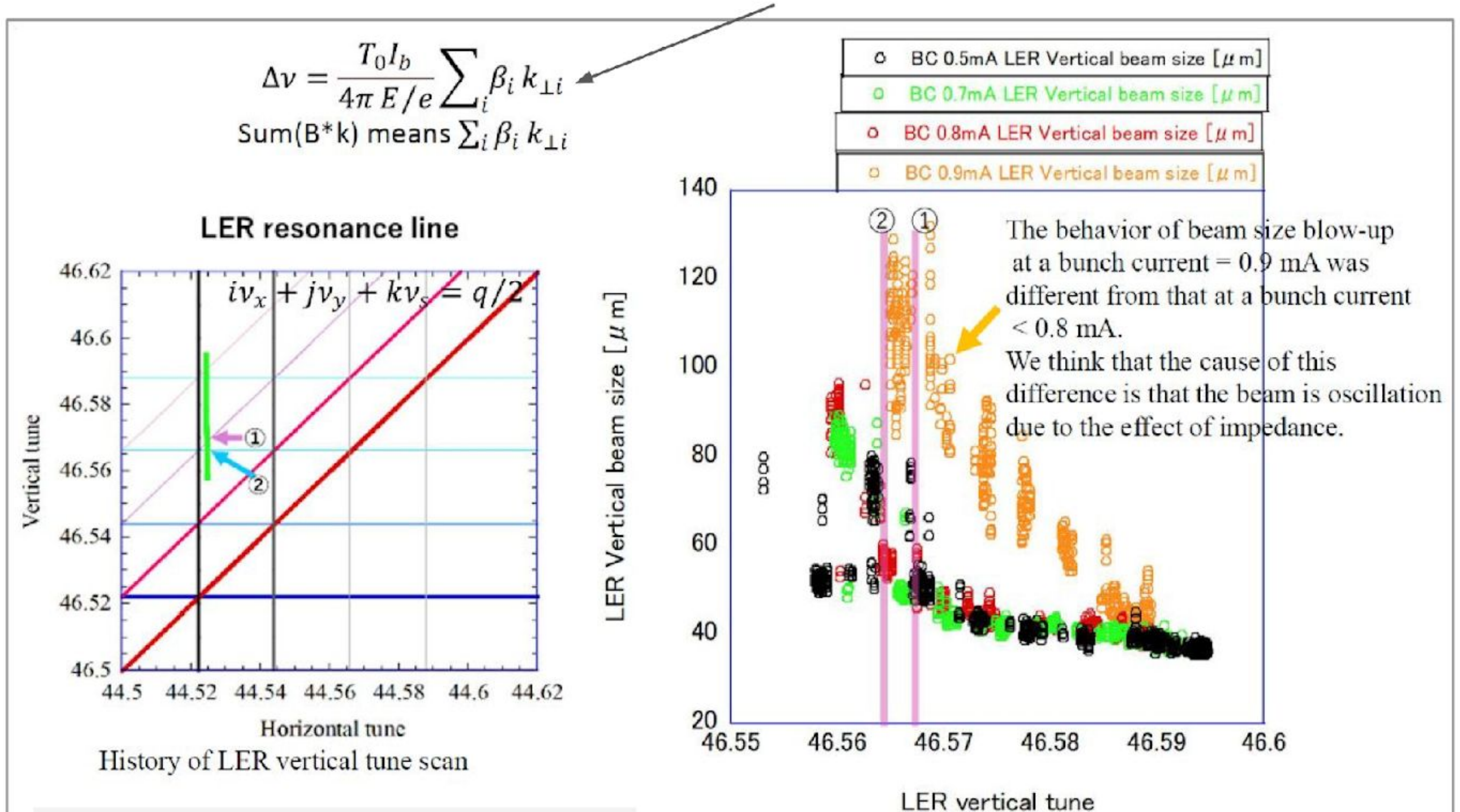
Transverse mode coupling instability (TMCI)

- a result of the wake-field effect from bunches traveling through the collimator aperture
- leading to the onset of the bunch current head-tail instability
    - **Beam size blow up**
    - **Betatron tune shift**

$$I_{\mathrm{thresh}} = \frac{8 f_s E/e}{\sum_j \beta_j k_j(\sigma_S, d)}$$

Synchrotron frequency (f_s), *Beam energy* (E/e), *Maximum bunch current before reaching beam instabilities* (I_{thresh}), *Collimator beta-function* (β_j), *Collimator kick-factor* (k_j)

Tune shift due to wakefield effects



Based on S. Terui slides, KEK, 2021

In 2020-2021, TMCI could be one of the sources limiting bunch current increase even below I_{thresh} ~1.4 mA/bunch.

Unexpected Injection Background

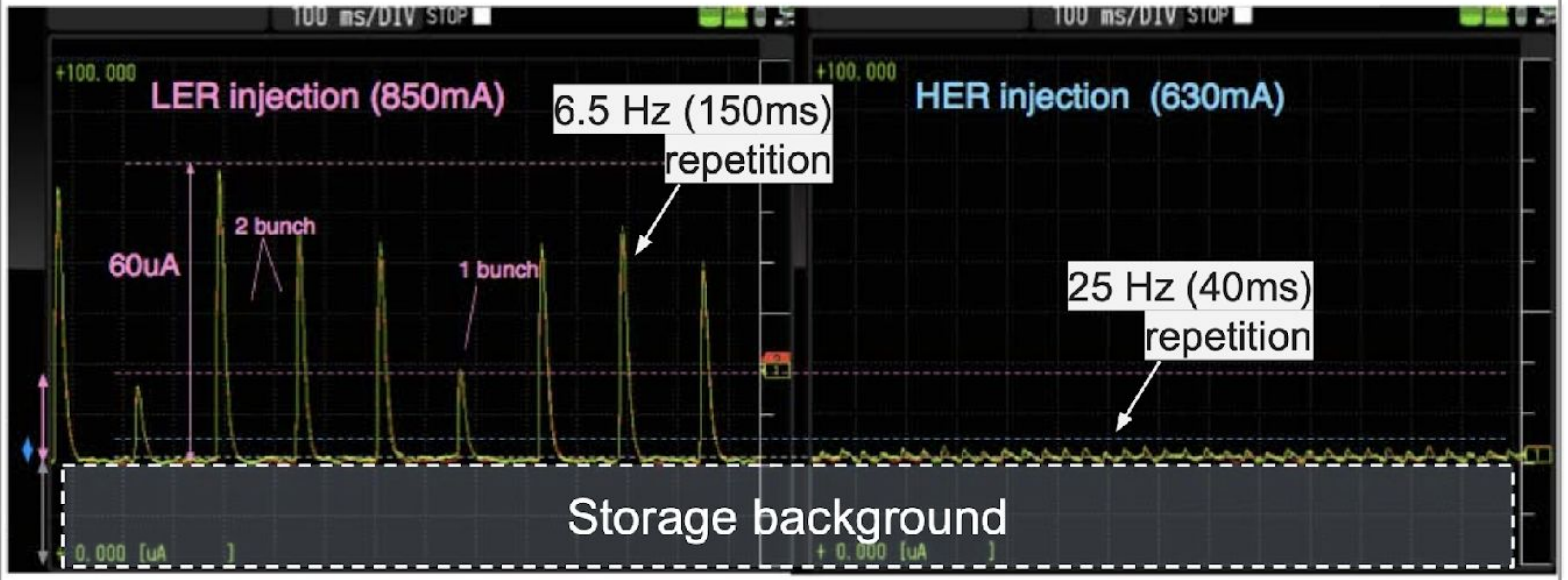
A. Natochii

Unexpected machine backgrounds: injection background

Remark R.P.: Beam lifetimes at SuperKEKB and later also at FCC-ee are of the order of several minutes (compare with hours for LEP)

- High beam losses during injection caused by
  - Injected charges with large amplitudes of oscillation due to injection kicker errors
  - Injection chain and main ring optics mismatch
- Up to 10 times higher instantaneous rates than the storaged beam background, see Figure
- Enlarges DAQ deadtime
- Reduces lifetime of the detector electronics, e.g. TOP PMTs

CDC leakage current during injection



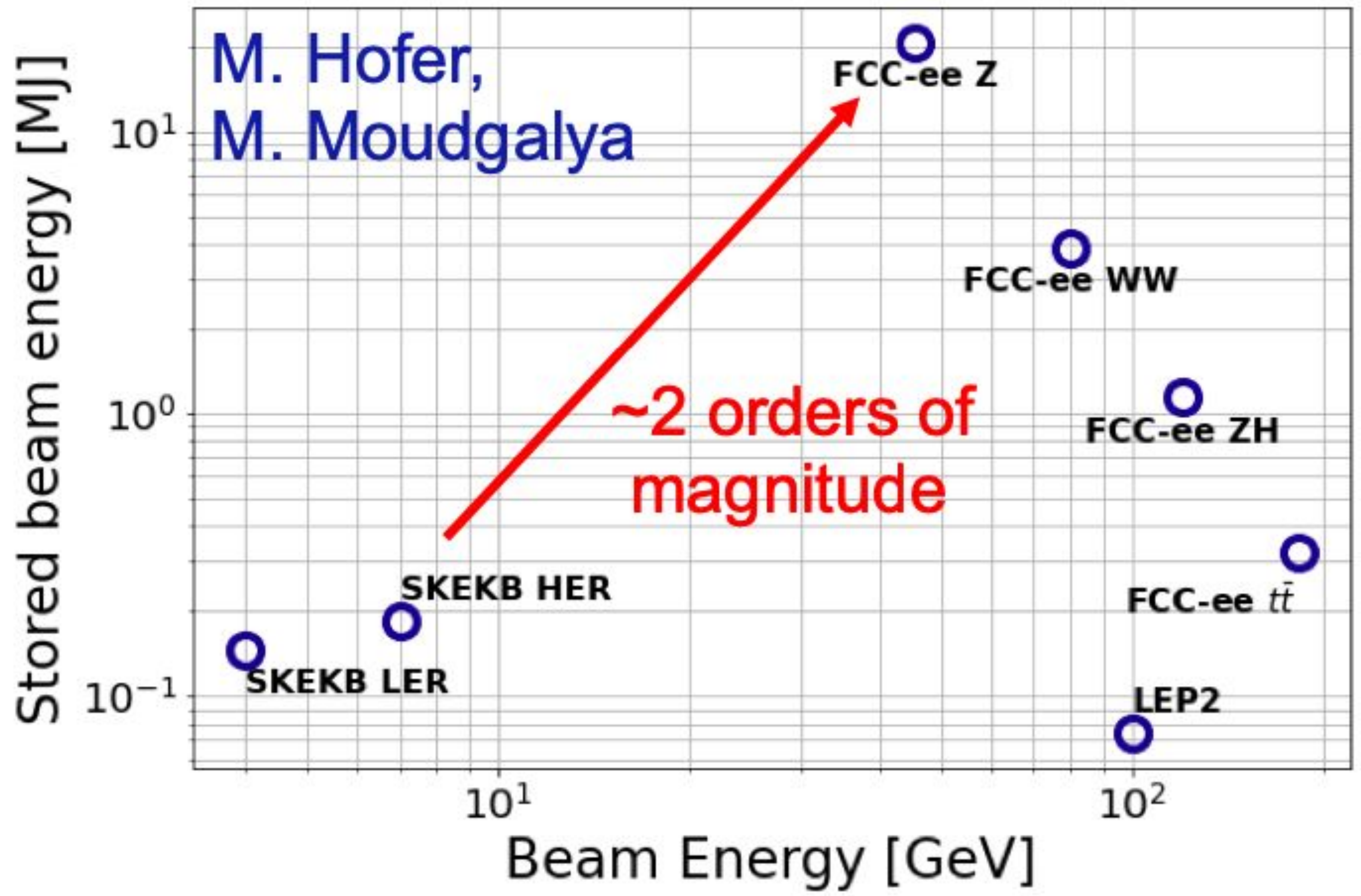
Based on S.Y. Ryu slides, RCNP/Osaka, 2021

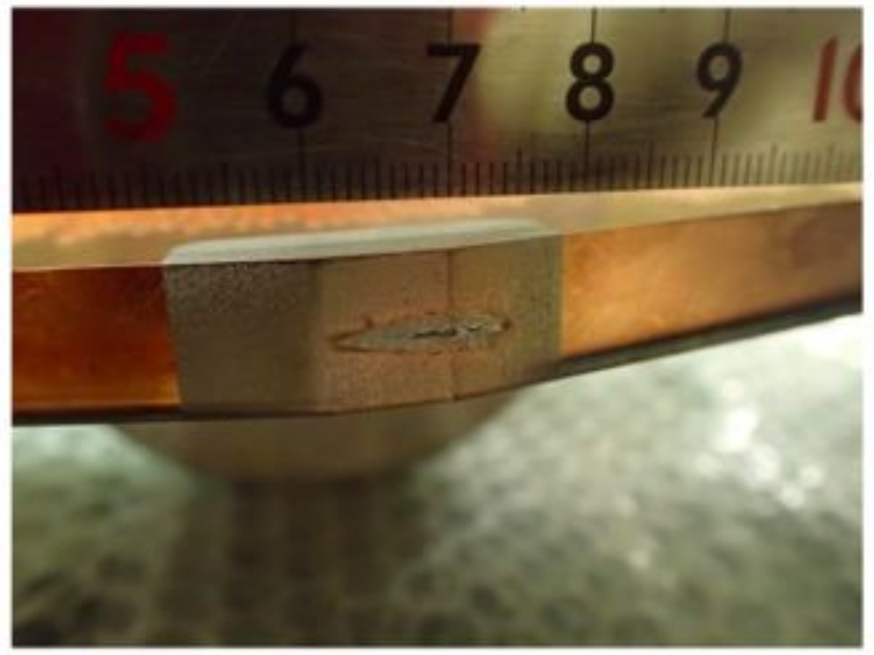
Recently dedicated simulation and measurement efforts have been started to study this source of machine backgrounds looking for possibilities to improve the injection quality and reduce IR beam losses.

FCC-ee beam losses and collimation

- The FCC-ee presents unique challenges
- The stored beam energy reaches **17.8 MJ** for the Z-running
- Such beams are highly destructive, a collimation system is required
- The main roles of the collimation system are
  - Protect the equipment from unavoidable losses
  - Reduce the background for the experiments
- Two types of collimation system foreseen for FCC-ee
  - Synchrotron Radiation collimation (near IP, see above)
  - The beam halo (global) collimation system
- **Beam loss and collimation systems are essential to ensure safe and efficient operation of FCC-ee**

Beam power of circular e+e- colliders



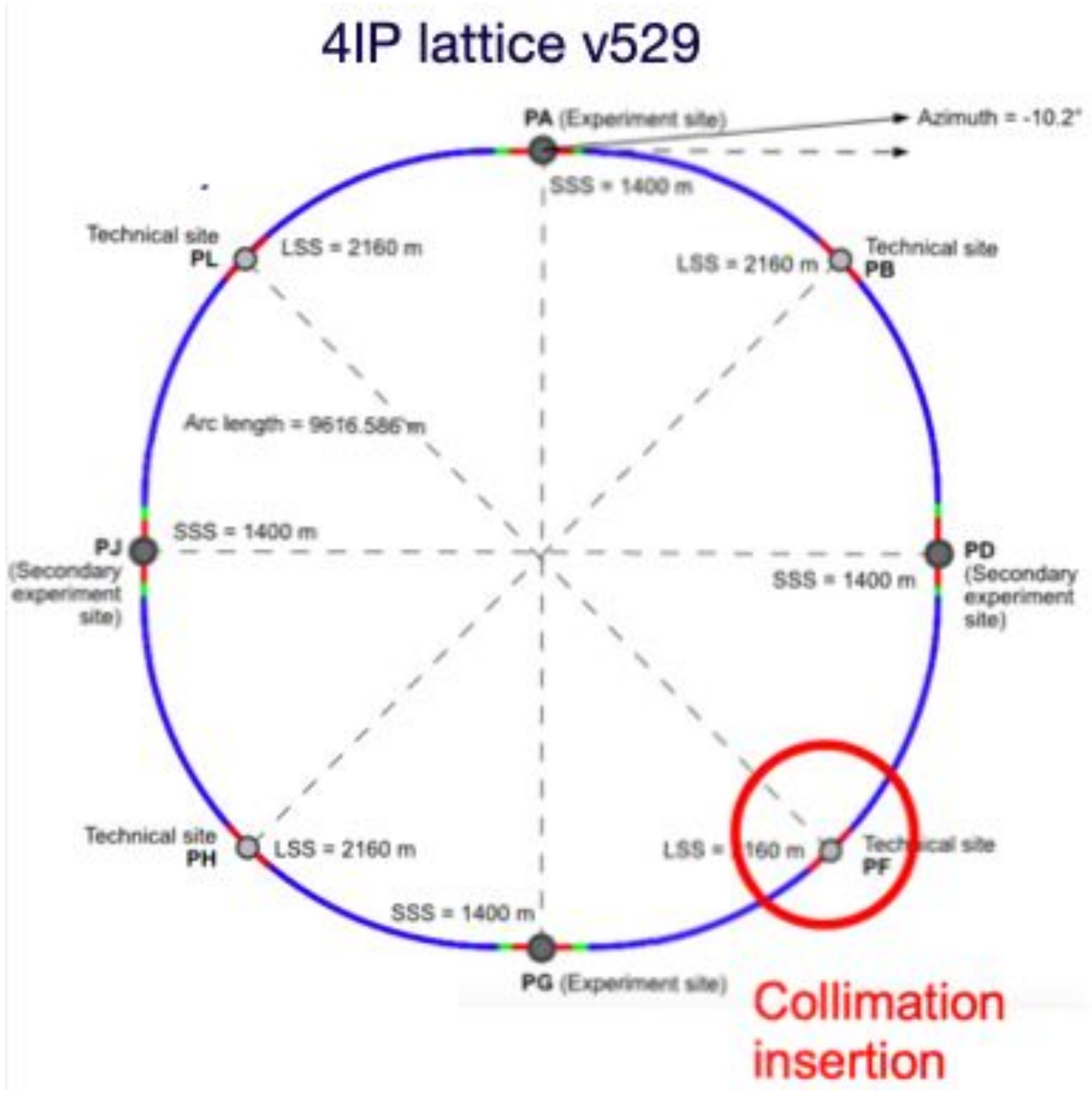


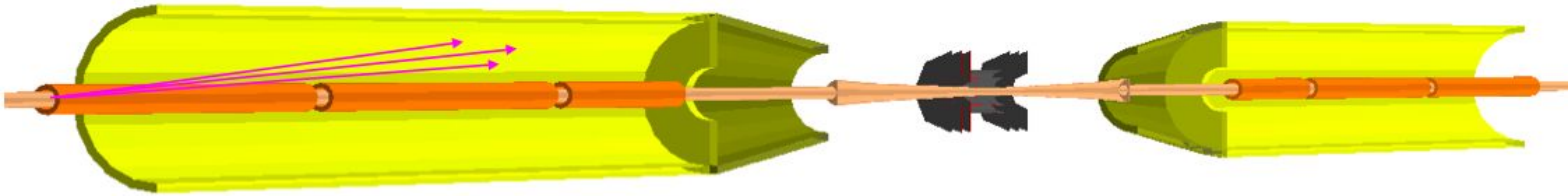
Damage to coated collimator jaw due to accidental beam loss in SuperKEKB

A. Abramov, FCC Week Cracow

Beam losses in IR due to failure scenarios

- Losses happen on the beam pipe a few meters upstream of the experiment
- Recent studies take into account realistic magnetic field (beyond plain 2T field, including screening and corrections by anti-solenoids



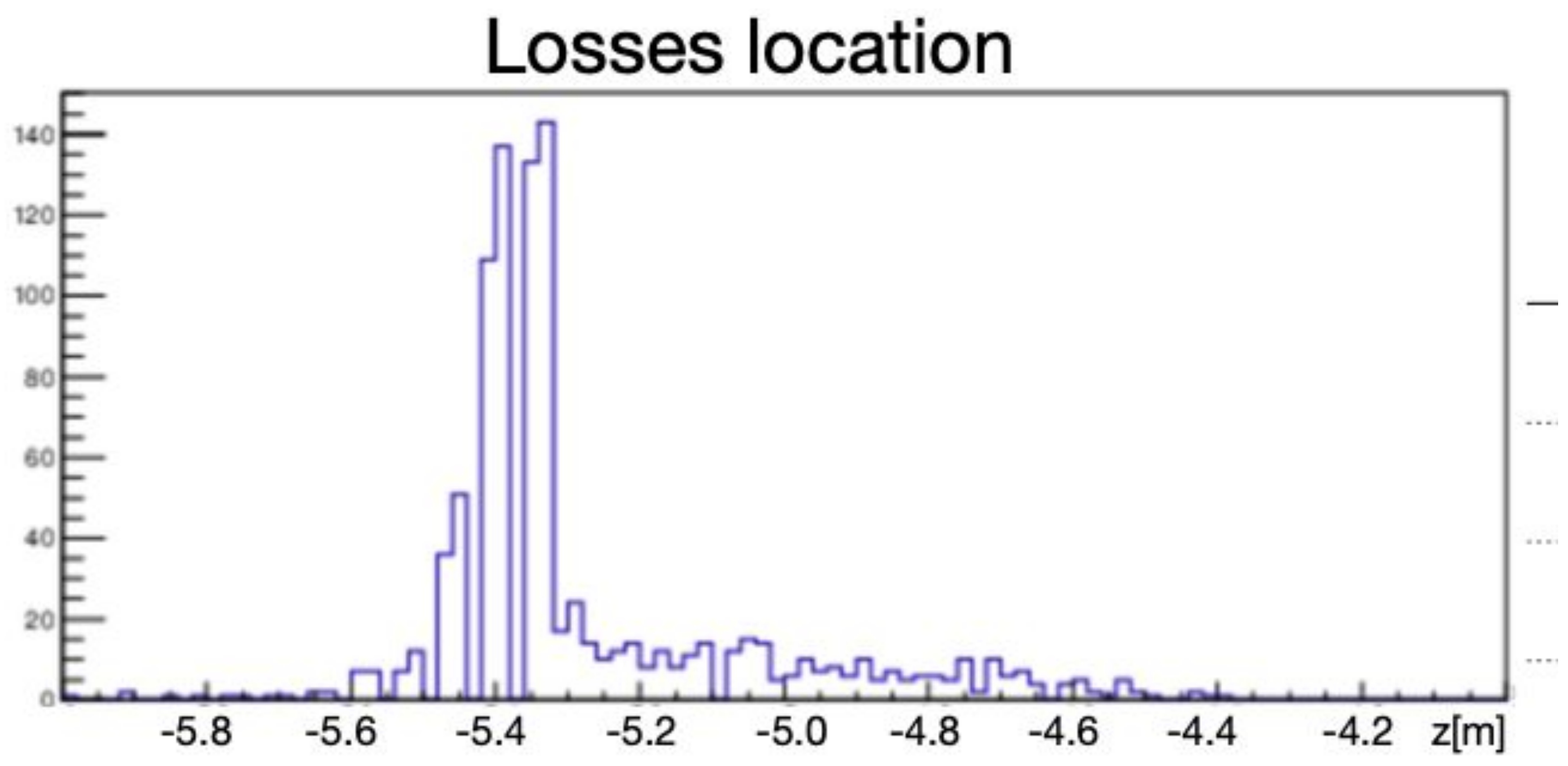


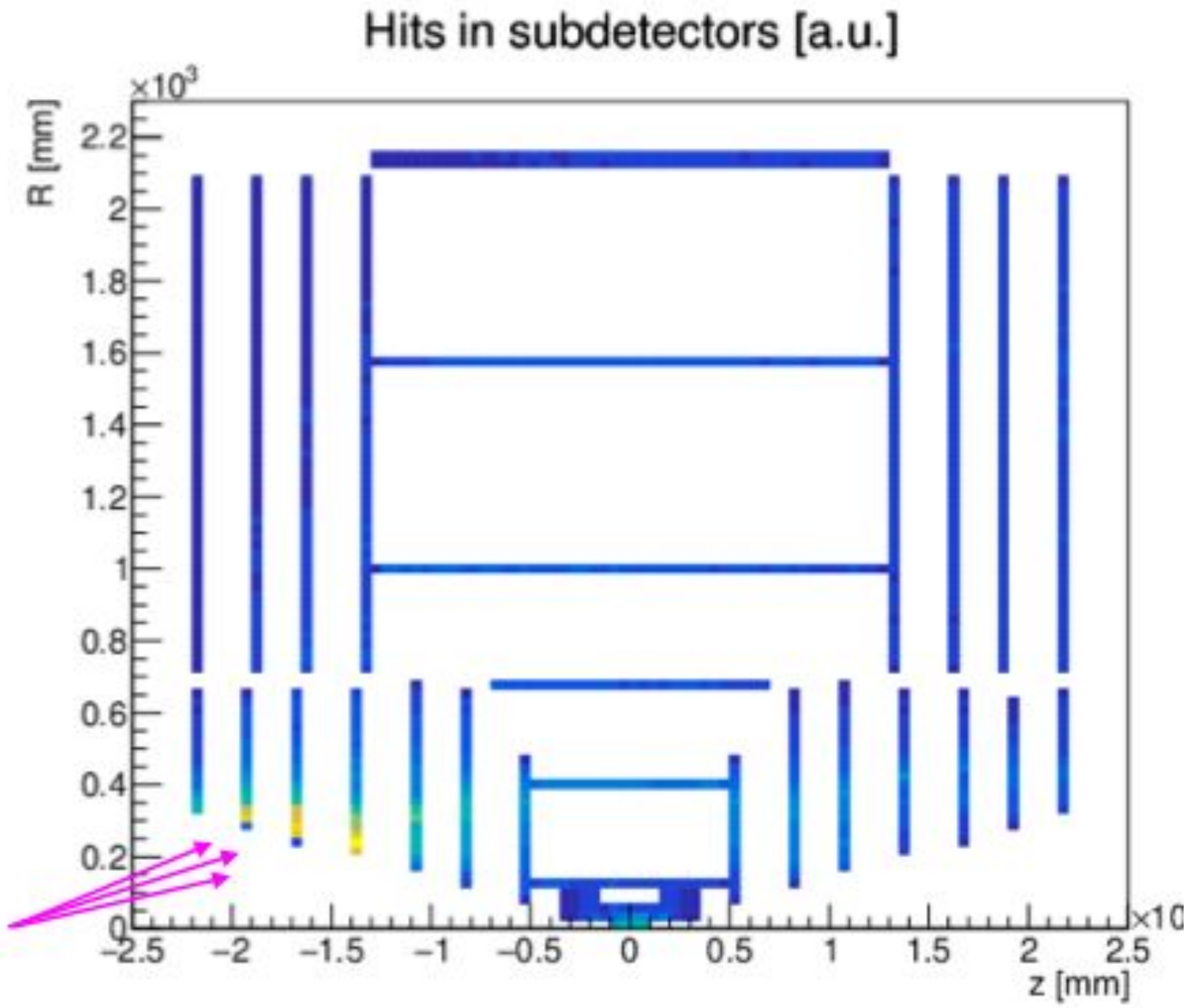
A. Ciarma, FCC Week Cracow

Beam Halo Losses: Background at top - Horizontal primary collimator

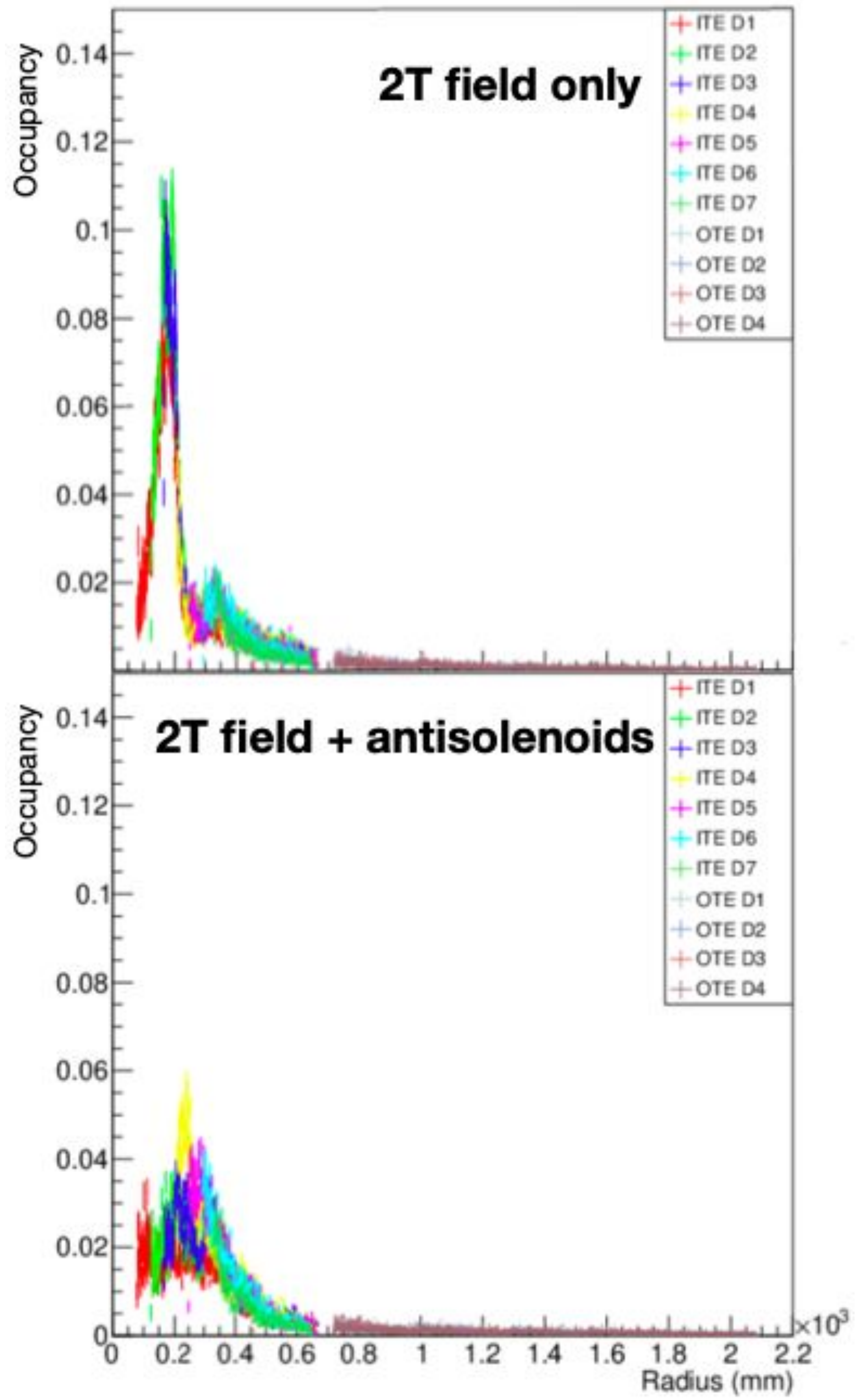
Study for Z Off-momentum collimator, see backup

- Realistic scenario implies reduction by factor two compared with Simple 2T scenario
- Peak in Inner Tracker Endcap disks





	Losses per second	Highest occupancy	w/out anti-solenoids
IPA	0.15	5.73% (ITE)	10.95% (ITE)
IPD	0.11	3.99% (ITE)	7.78% (ITE)
IPG	0.10	3.16% (ITE)	6.41% (ITE)
IPJ	0.16	8.88% (ITE)	12.62% (ITE)



A. Ciarma, FCC Week Cracow

Inner tracker endcap mostly affected for CLD
Again, will TPC cope with backgrounds?

Background/Effect of Beam Halo Losses – Some Numbers

	TT: horizontal primary collimator	Z: off-mom. collimator	Z: off-mom. collimator + betatron osc.
	Losses per second (10^9)		
IPA	0.15	1.66	0.15
IPD	0.11	0.38	0.24
IPG	0.10	12.21	182.10
IPJ	0.16	2.41	37.24
	Highest occupancy		
IPA	5.73% (ITE)	0.06% (ITE)	– – –
IPD	3.98% (ITE)	0.04% (ITE)	– – –
IPG	3.16% (ITE)	0.41% (ITE)	8.45% (ITE)
IPJ	8.88% (ITE)	0.09% (ITE)	1.60% (ITE)
	QC1 hottest spot (W/cm3 in a 2mm3 bin)		
IPA	0.035	0.077	– – –
IPD	0.026	0.005	– – –
IPG	0.013	0.278	4.311
IPJ	0.025	0.053	1.669
	Total power in QC1 (W)		
IPA	1.77	3.42	– – –
IPD	1.34	0.35	– – –
IPG	1.09	24.22	442.86
IPJ	1.92	5.88	96.10

Background and power dumped in Final Focus Quadrupoles depend on position along ring

Who wants/has to go to IPG? 😉

- Football tournament between 4 experiments?
- Singing contest between Spokespersons?
- What else ?

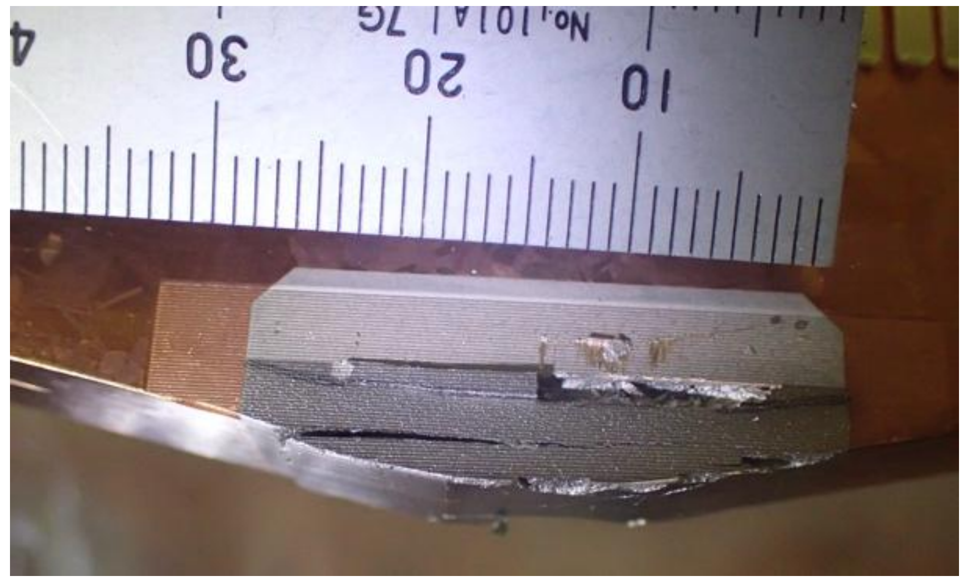
Table by A. Ciarma, FCC Week Cracow
Kidding by R.P.

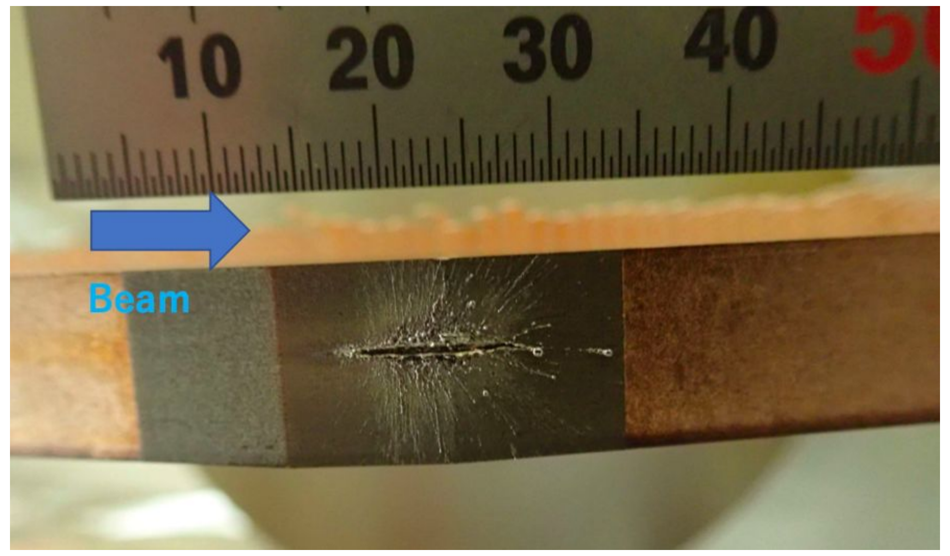
Sudden beam losses at SuperKEKB - “Crazy beam”

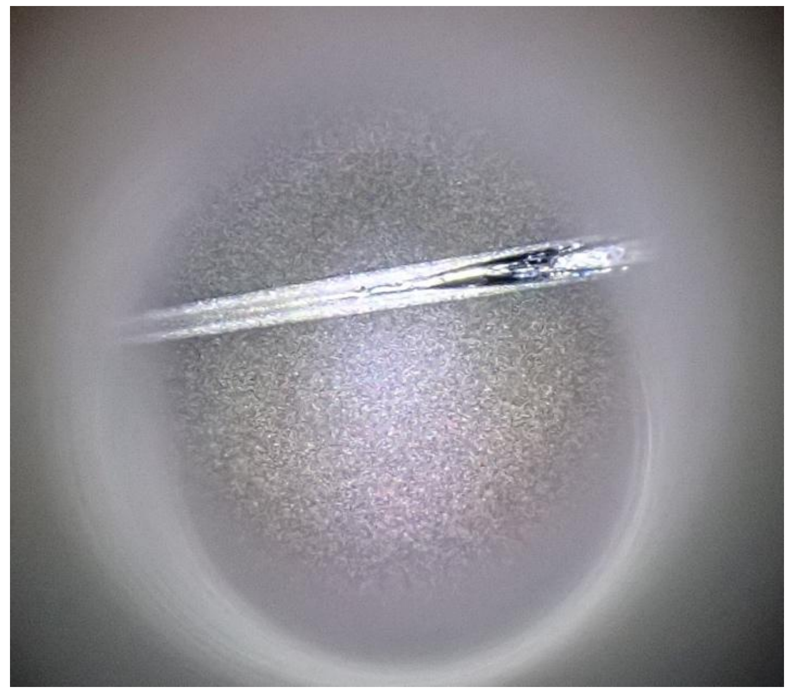
- SuperKEKB collimators have been frequently damaged due to beam hits.
- The source of beam instability that causes damage to the vertical collimators is still unknown (sudden beam loss).
- One reason are accidental-firings of injection kickers in Low Energy Ring (LER).
  - Countermeasures are new or replaces collimators

- Sudden beam loss has occurred within approximately 2-turn (~20 μs) before the beam abort.
  - Beam orbit displacements in horizontal and vertical direction has been observe (H. Fukuma and S. Terui).
  - No increase in the beam size has been observed by a fast beam size monitor (G. Mitsuka).
  - This beam loss has never happened in single beam operation (because the short operation time with single beam?).
- It is more common in LER, but has also occurred in High Energy Ring (HER).
- Candidates of the cause [kick-off meeting of ITF sudden beam loss working group, https://kds.kek.jp/event/43499/]:
  - X-abort, dust, fire-ball in collimators, electron cloud in vertical collimators, accidental-firings in abort kicker…

More damaged SuperKEKB Collimators

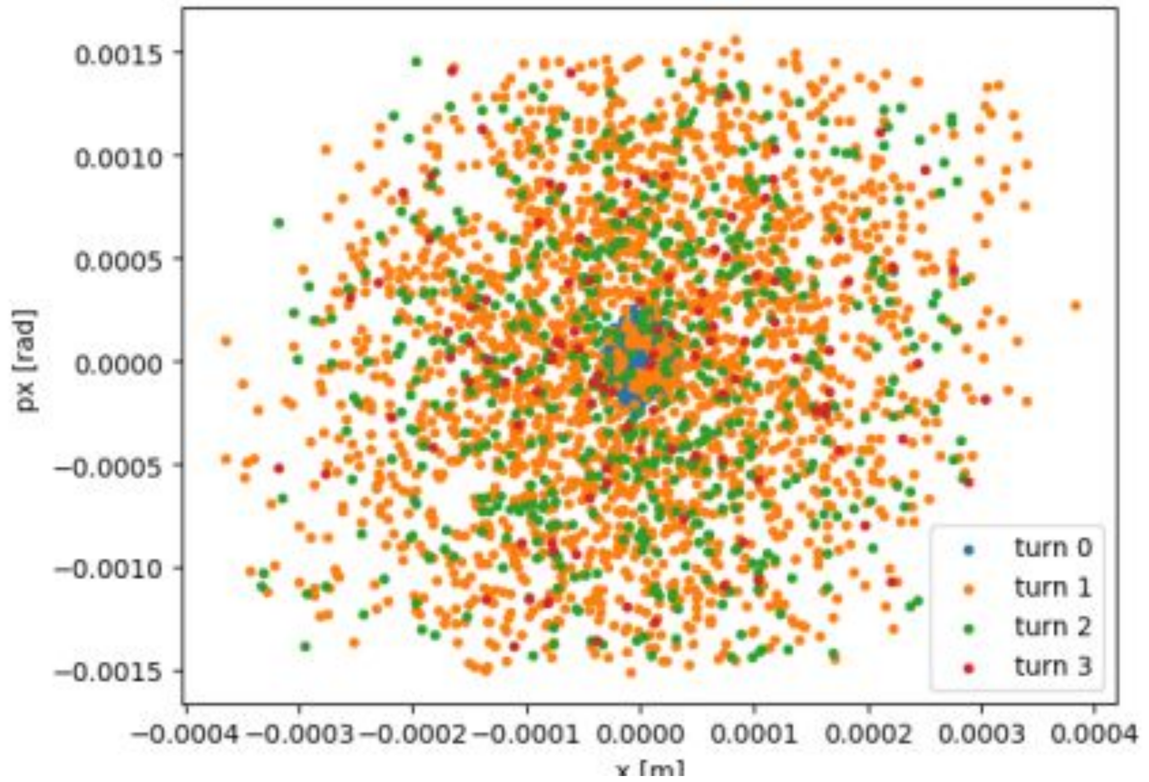




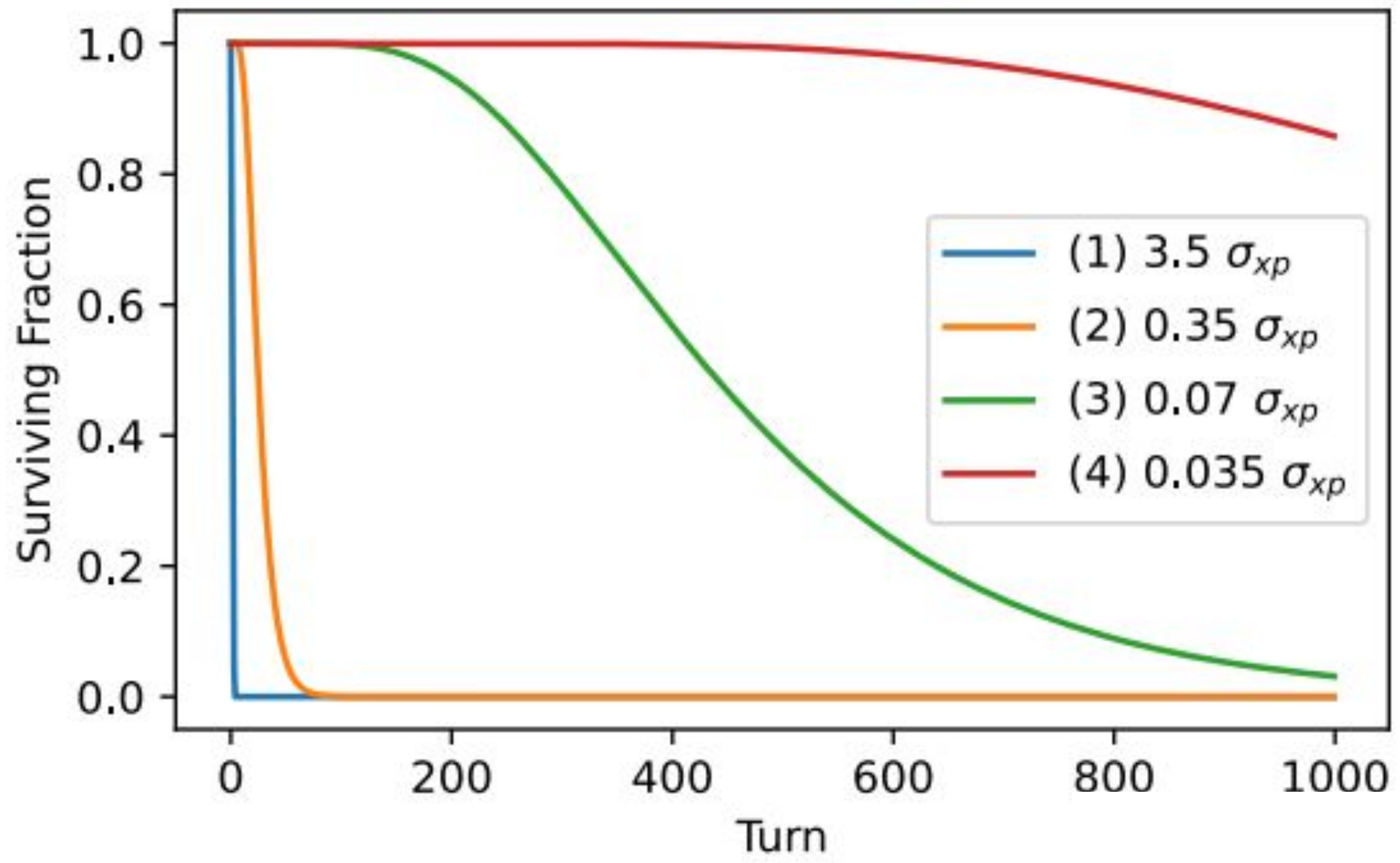


Z Mode Fast Losses

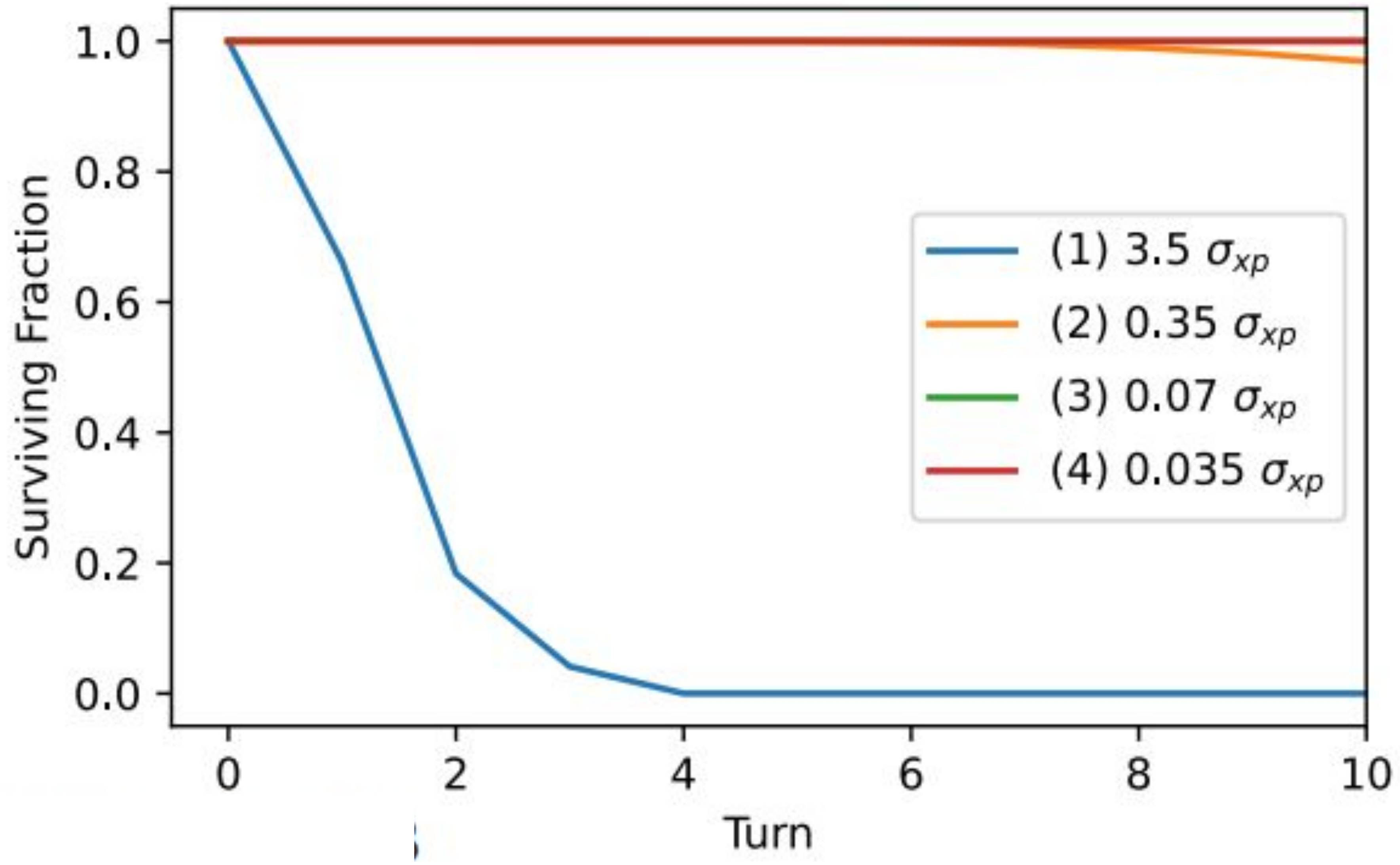
- Study of fast beam blow up in simulations
  - Random uniform per-particle kicks applied at 18 locations along the ring
  - Excitation amplitude adjusted to give different beam lifetimes
- Maybe not representative for a real beam loss



Beam blow up example IPA



zoom



(1) Lifetime [s]: 0.0004 +/- 0.0003
(2) Lifetime [s]: 0.0085 +/- 0.0070
(3) Lifetime [s]: 0.1638 +/- 0.1491
(4) Lifetime [s]: 4.4079 +/- 4.5599

A. Abramov, FCC Week Cracow

Beam lifetimes from exponential fit

Z Mode Fast Losses - Comments

- **Huge losses observed in the simulation scenario**
  - Losses of MJ/m is the final focus quadrupoles
  - The loss in energy is likely descructive for the final focus doublets, detectors and/or the tungsten SR collimators there (not simulated)
  - Due to the large excitation amplitude, particles impact the aperture bottlenecks directly, before being intercepted by the collimation system in PF
  - Primary losses outside the collimation system are possible for other types of fast beam losses

- **Mitigation**
  - This loss scenario (**80% loss over two turns**) is likely not tolerable without additional collimators, close-to an in-phase with the aperture bottlenecks, like the LHC tertiary collimators
  - Special protection devices can also be considered
  - The loss scenarios must also be better defined for the FCC-ee
    - **Timescale and percentage intensity loss**
    - **Driving process (location, transverse vs. longitudinal. etc.)**
  - **Protection cannot be designed until its understood how SuperKEKB translate to FCC-ee**
    - Remark R.P.: Remember intensity of FCC-ee beam would be 100 times higher than that of SuperKEKB

A. Abramov, FCC Week Cracow

Summary

- **Typical interaction (MDI) regions are very different for linear and circular colliders**
  - Compare L*=4.1 at ILC with typical L* of ~2m at circular machines
  - Different crossing angle (14mrad <-> ~30mrad)
  - An adaptation of ILD to circular machines has to take this into account
  - Elements within the (main) detector volume reduce acceptance and are potential sources of background
  - … in particular for a TPC on the Z-Pole

Different machines have different background issues

- **Linear e+e- colliders**
  - Main issue at linear colliders may be beamstrahlung due to extremely collimated beams
    - This is a background that has never been seen, estimation only from simulation
  - Muon background has to be taken into account
  - Synchrotron radiation has been a problem at SLC but is (hopefully) mitigated for LC
  - Neutron backshine from beam dump

- **Circular e+e- colliders**
  - Synchrotron radiation is an issue at circular colliders
    - Requires dedicated W shielding
  - Beamstrahlung likely minor issue for CLD but may become an issue when operating a TPC
  - Beam losses are a concern
    - Slow losses seem to be manageable, study requires detailed knowledge of field maps
      - Impact differs depending on position along the ring
    - Fast beam losses are a major problem and may lead to destructive effects
      - Fast losses (“crazy beam”) at SuperKEKB not (yet) understood and therefore difficult to study for FCC-ee
      - Beam power at FCC-ee on Z-Pole will be 100 times higher than SuperKEKB

Take home messages (= Karsten’s of ILCX Workshop 2021)

- Most problems came as a surprise
- Luminosity or energy upgrades had bigger background impacts than anticipated
- Be careful with machine elements in the detector volume
- Plan your interaction region carefully
- Design your subdetectors with sufficient background margins
- You are blind without sufficient diagnostics and simulation capabilities (single shots (LC) or top-up injection and very short beam lifetimes (CC))
- Close links between experiments and accelerator controls are mandatory

Backup

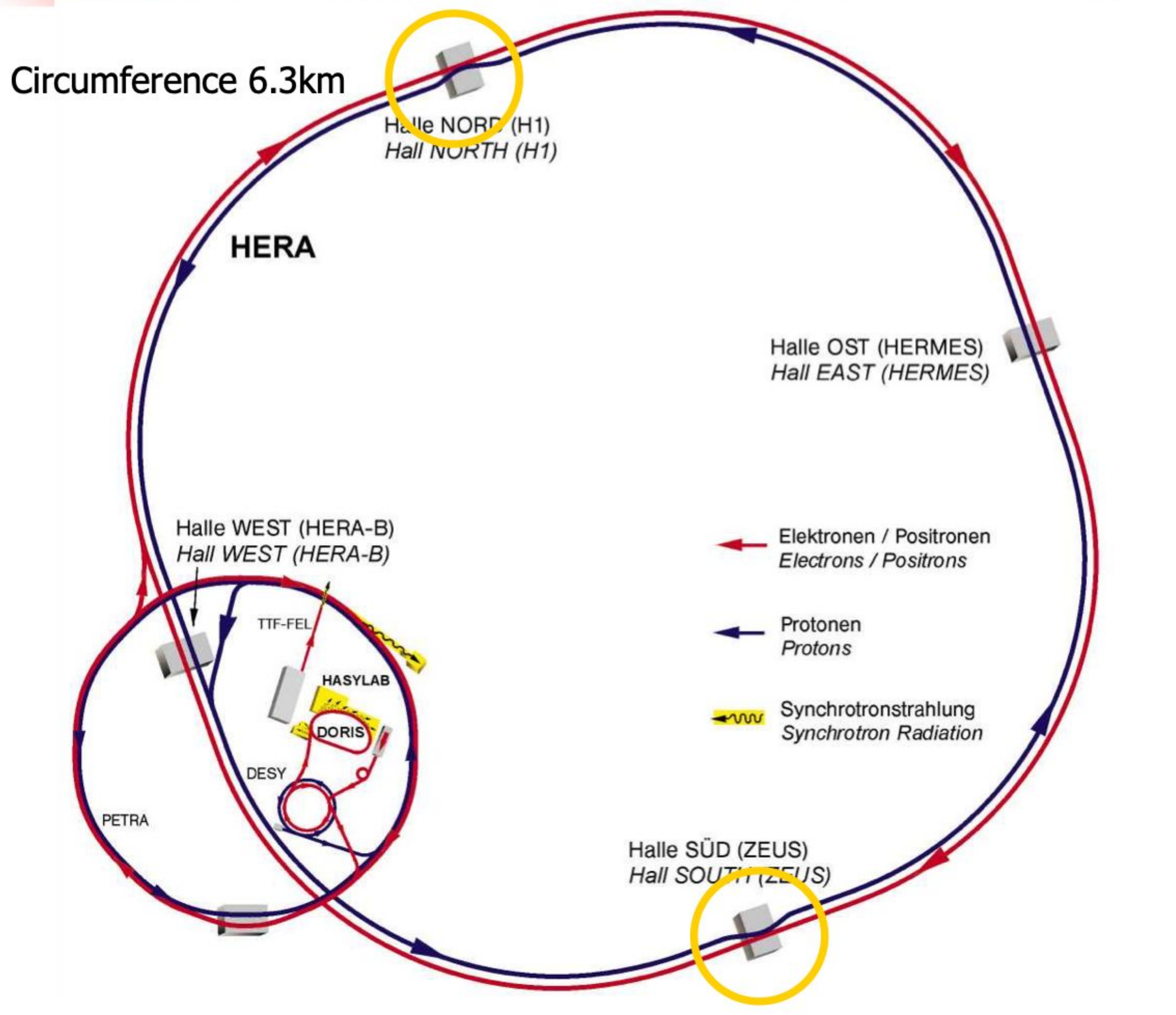
What can we learn for ILC?

HERA

U. Schneekloth

HERA encountered heavy background problems especially after the lumi upgrade

HERA Overview



Electron (positron) - proton collider, in operation 1992 - 2007

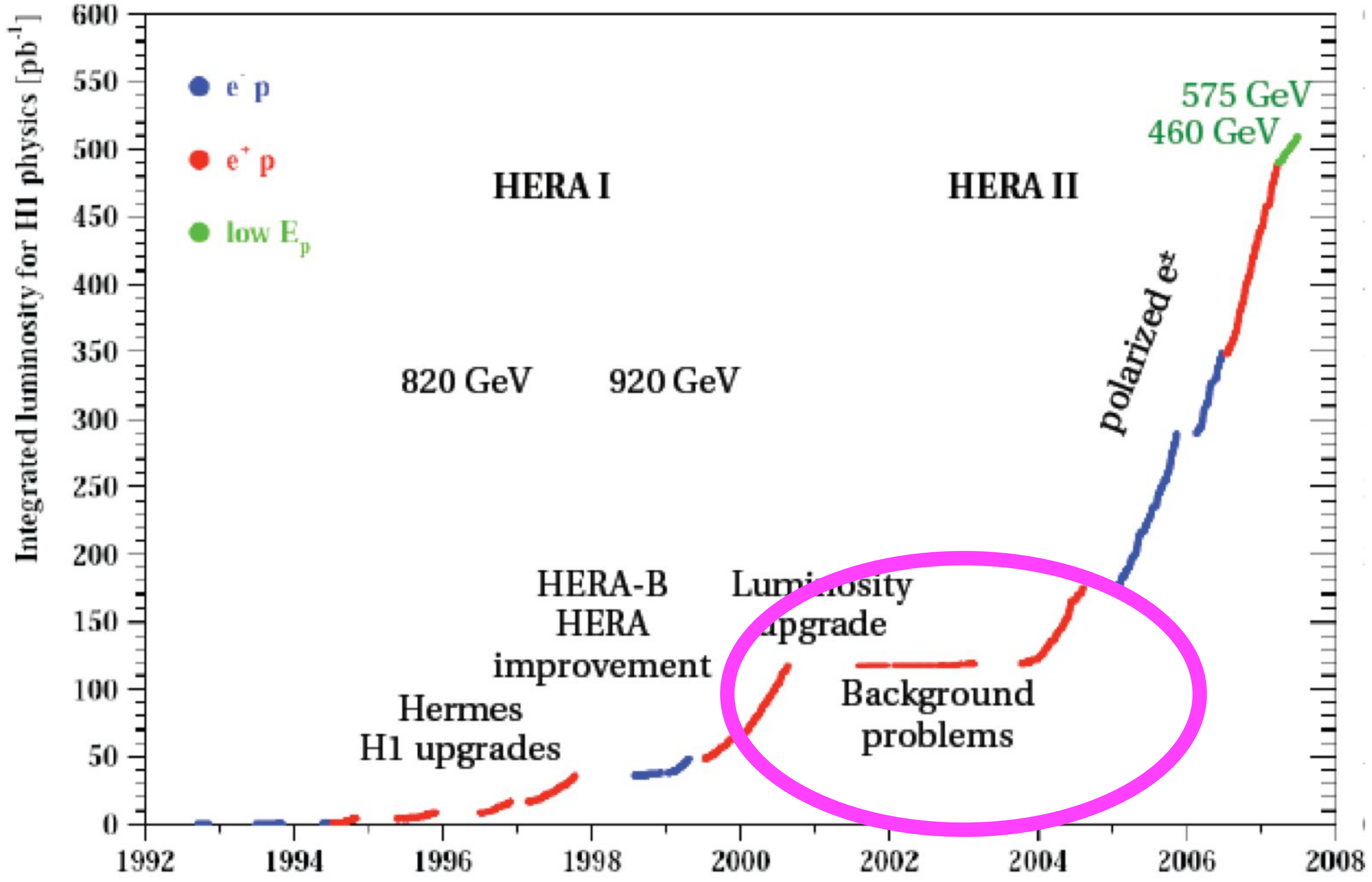
Beam energies:
- protons 920 GeV
- electrons 27.6 GeV

180 bunches
96 ns bunch spacing

About 140m long straig sections (either side) fo beam separation, focusing, acceleration, diagnostics and spin rotators

U. Schneekloth HERA Interaction Regions

HERA Operation



15 years of almost continuous beam operation

U. Schneekloth HERA Interaction Regions 4

HERA Lessons Learned

U. Schneekloth

HERA I IR
- Lower luminosity
- No machine magnets inside central detector volume
  - Detector: good forward and rear acceptance (hole < 1°, $\eta \sim 4.9$)
- No serious (background) problems.

HERA II IR
- Pushed for higher luminosity
- Challenging design
  - Synchrotron radiation, no upstream collimators close to IP
  - Beam steering very critical
  - Access to central beam pipe (masks, cooling, flanges, BMPs,…) required a few month shutdown
- Forward/rear detector acceptance limited (hole ~ 3°, $\eta \sim 3.8$)

HERA II IR
- Challenging design, continued
  - Several vacuum leaks due to constraint design, orbit movements and beam losses
  - Slow conditioning and vacuum improvement, almost continuous operation
  - Beam orbit control

    Active safety system:
    - Temperature, vacuum interlocks
    - Beam loss, high background rates
    - ⇒ Beam abort
  - Magnet alignment and position stability

Very close cooperation between machine and experiments during design and operation absolutely essential.

Design of interaction region is crucial

FCC-ee@Z - Off momentum collimator

Background @Z Off-momentum collimator Negative Momentum Offset

Pencil beam, $1\mu m$ impact par. $(\Delta p/p = -1.58\,\%)$

For negative offset, **IPG** showed extremely high backgrounds in **all of the subdetectors**, up to 15%, while negligible effects on IPJ and **no losses at all** in IPA and IPD.

Also in this case, with the antisolenoids the background is reduced of a factor 2, with the peak on the IT endcaps toward the losses location.

Similar results also are found including **betatron oscillations** to the momentum offset.