Introduction on CEPC tracker design requirements

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UK workshop on HV-CMOS tracker for e+e- collider

University of Edinburgh, 10-Jan-2020

Outline

- Overview of the physics processes and charged particles kinematics
- Physics inputs for the tracker design
  - Occupancy and radiation
  - Momentum resolution
  - PID requirement on the dE/dx
  - Dynamic range
- Summary and conclusion

Accelerator parameters

- Z-pole running poses more stringent requirements: bunching spacing 15,000

Updated Parameters of Collider Ring since CDR

	Higgs		Z (2T)	
	CDR	Updated	CDR	Updated
Beam energy (GeV)	120	-	45.5	-
Synchrotron radiation loss/turn (GeV)	1.73	1.68	0.036	-
Piwinski angle	2.58	3.78	23.8	33
Number of particles/bunch N_e (10^{10})	15.0	17	8.0	15
Bunch number (bunch spacing)	242 (0.68μs)	218 (0.68μs)	12000	15000
Beam current (mA)	17.4	17.8	461.0	1081.4
Synchrotron radiation power /beam (MW)	30	-	16.5	38.6
Cell number/cavity	2	-	2	1
β function at IP β_x^* / β_y^* (m)	0.36/0.0015	0.33/0.001	0.2/0.001	-
Emittance $\varepsilon_x/\varepsilon_y$ (nm)	1.21/0.0031	0.89/0.0018	0.18/0.0016	-
Beam size at IP σ_x/σ_y (μm)	20.9/0.068	17.1/0.042	6.0/0.04	-
Bunch length σ_z (mm)	3.26	3.93	8.5	11.8
Lifetime (hour)	0.67	0.22	2.1	1.8
Luminosity/IP L (10^{34} cm^{-2}s^{-1})	2.93	5.2	32.1	101.6

FCC-ee: 8

FCC-ee: 230

Luminosity increase factor: × 1.8 × 3.2

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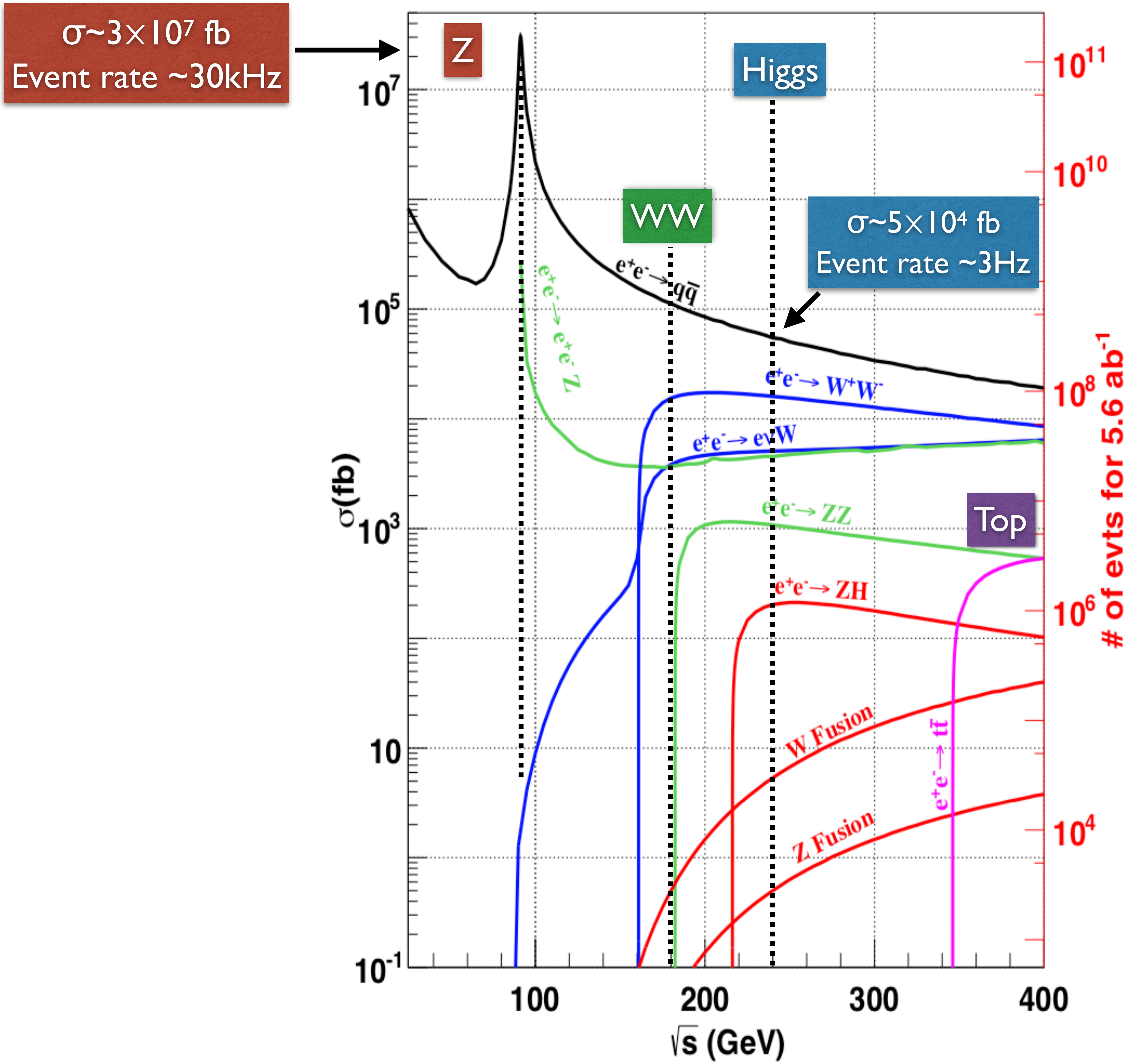
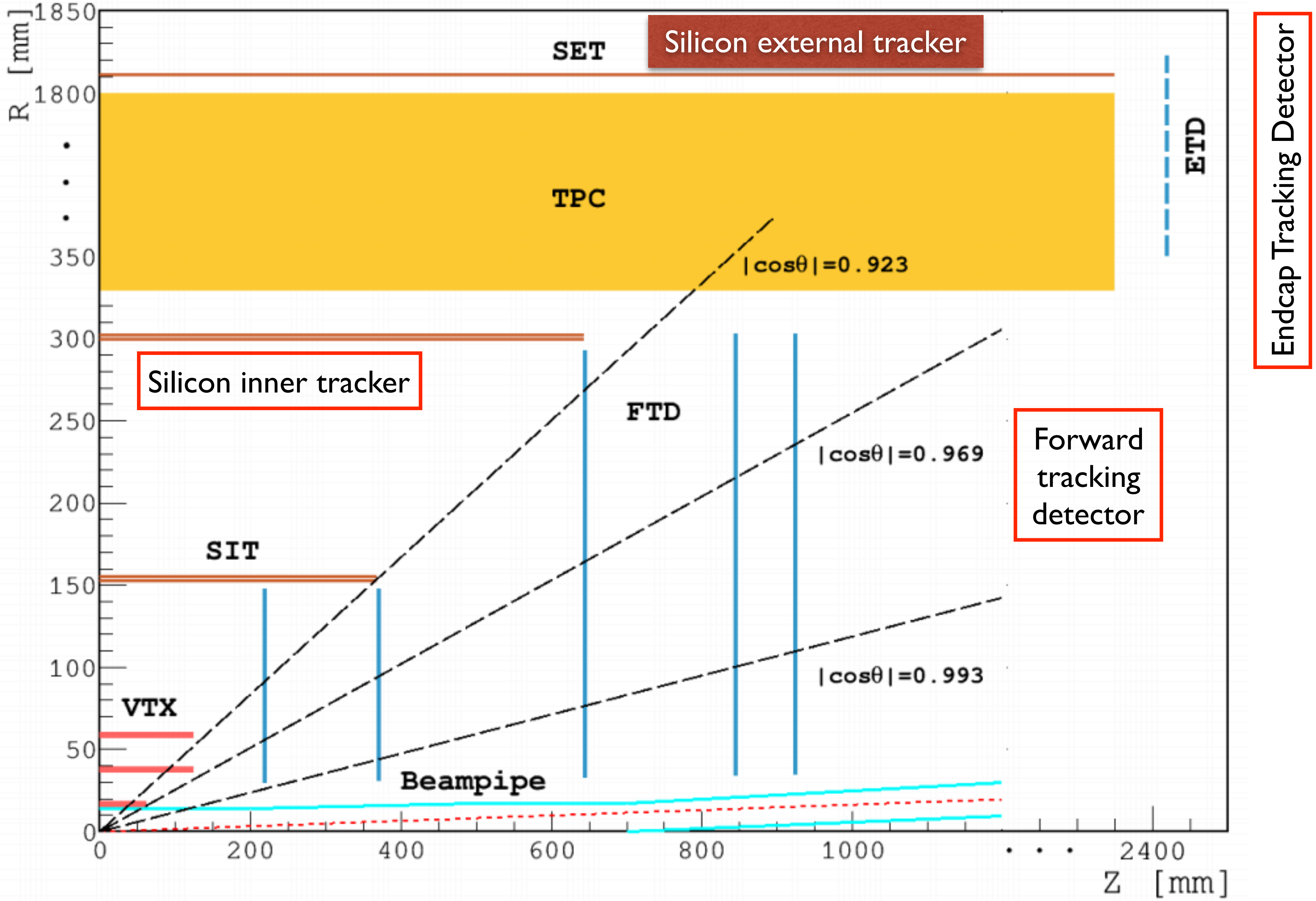
Physics processes



The “Baseline” Tracker in CDR

Caveat: baseline is really just a starting point, fresh physics and R&D program are ongoing to redefine this



Except FTD 1+2, all use 2 layers of back-to-back mounted single-sided strips at an stereo angle

Sensor: 10 × 10 cm², pitch 50μm, Thickness <200μm

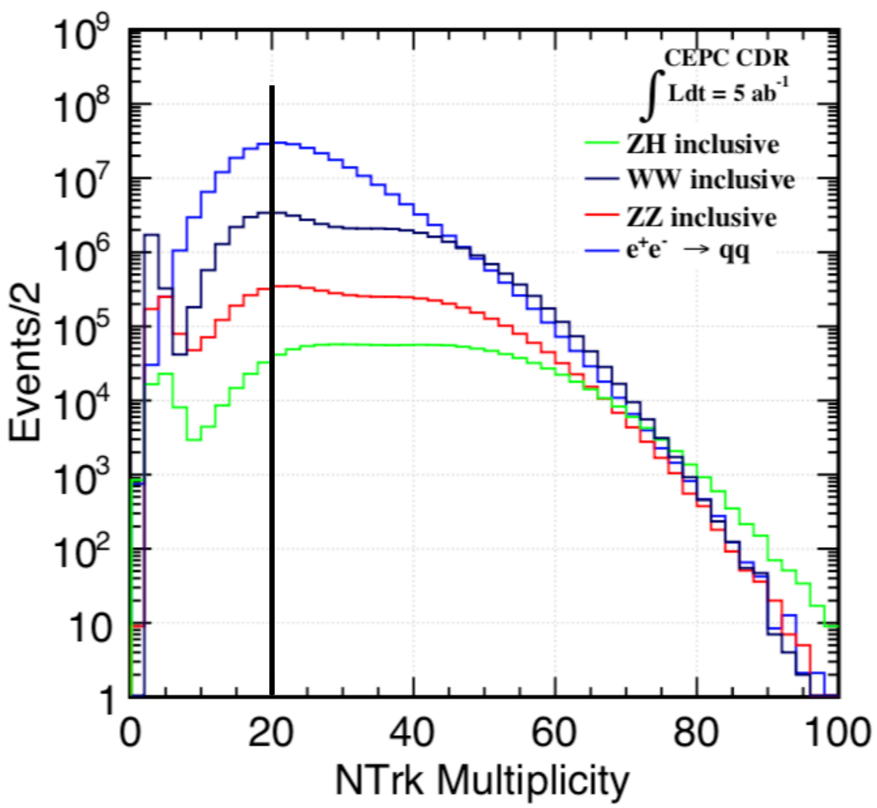
Strip design with ~300-400 μm thickness per layer alone gives 0.3-0.4% X_0

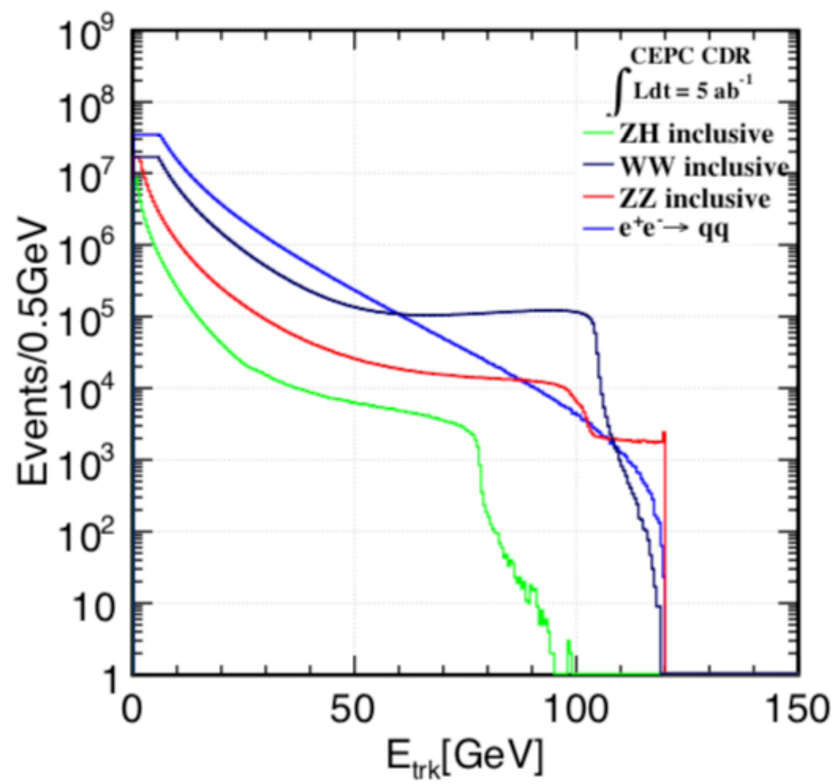
Effective silicon area for strip: 160m² , pixelated design reduces to 80m²

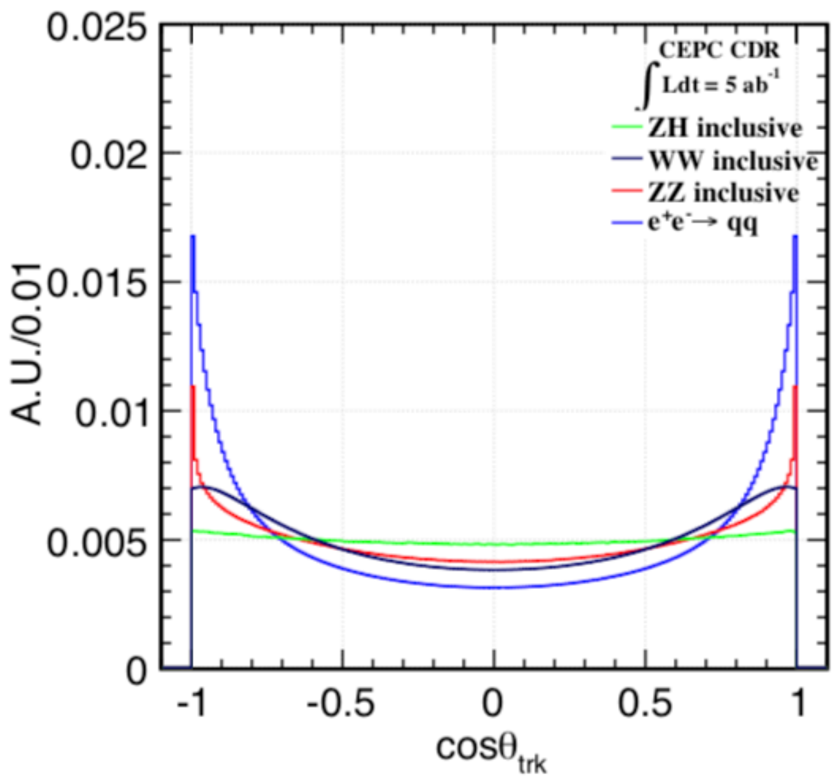
Event level charged particle multiplicity and kinematics

Higgs running @ 240 GeV

pT > 0.5 GeV







For the Z-pole running, track pT < 45 GeV, except a bit lower multiplicity

Hit occupancy and radiation

- Caveat
  - There are many different numbers in the literature, often inconsistent due to
    - CDR assumes a different Int Luminosity
      - A factor of 2 less Higgs L, a factor of 8 less in the Z inst. L
    - It is not always clear if a safety factor of 10 has been applied
- I will summarise some numbers in the next a few slides
  - Hopefully we can sort them out and arrive at a reasonable range to consider at the end

Estimate of occupancy

VtxL1:
R=1.6cm, |z|=6.25cm
→ A = 126 cm^2

Operation mode	H (240)	W(160)	Z (91)
Hit density (hits $\cdot$ $cm^{-2} \cdot BX^{-1}$)	2.4	2.3	0.25
Bunching spacing (μs)	0.68	0.21	0.025
Occupancy (%)	0.08	0.25	0.23

Table 4.2: Occupancies of the first vertex detector layer at different machine operation energies: 240 GeV for ZH production, 160 GeV near W-pair threshold and 91 GeV for Z-pole.

↓

Assumption: Pixel dimension: 50 μm × 350 μm, readout time: 10us, Cluster size: 9 hits per track

Not from simulation, inferred from above table

SIT-L1 area 0.7m^2
→ 40M pixels

Operation mode	H (240)	W (160)	Z (91)
Track multiplicity (BX^{-1})	310	300	32
Bunching spacing (ns)	680	210	25
SIT-L1 occupancy (%)	$\boxed{0.19}$*	0.58	0.52
FTD-D1 occupancy (%)	0.17	0.54	0.48

Table 4.6: Estimated occupancies of the first layers of the SIT (SIT-L1) and the FTD (FTD-D1). See context for more details.

↓

With the same assumption:

SIT-L2 (2.5m^2) occupancy	5×10^{-4}	1.5×10^{-3}	1.4×10^{-3}
SET (52m^2) occupancy	2.5×10^{-5}	7.8×10^{-5}	7×10^{-5}

**My calculation for SIT-L1 Higgs: 0.10% = 310*9*(10e3/680)/(2*TMath::Pi()*0.15*0.75/(50*350*1e-12))*

Radiation at the first vertex layer update in Nov 2019

Combine Results

H. Shi's talk

Preliminary 11/14/2019

Higgs Backgrounds on 1st layer of Vertex.
With a safety factor of 10.

Background Type	Hit Density($cm^{-2} \cdot BX^{-1}$)	TID($krad \cdot yr^{-1}$)	1 MeV equivalent neutron fluence ($n_{eq} \cdot cm^{-2} \cdot yr^{-1}$)
γγ→ee Pair production	2.26	591.14	1.11e+12
Synchrotron Radiation	0.026	15.65	
Radiative Bhabha	0.34	592.66	1.44e+12
Beam Gas	36.8372	39901.139	9.65e+13
Beam Thermal Photon	2.31	2325.49	5.48e+12
Total	41.7732	43426.079	10.453e+13

43 Mrad/year

10^{14}

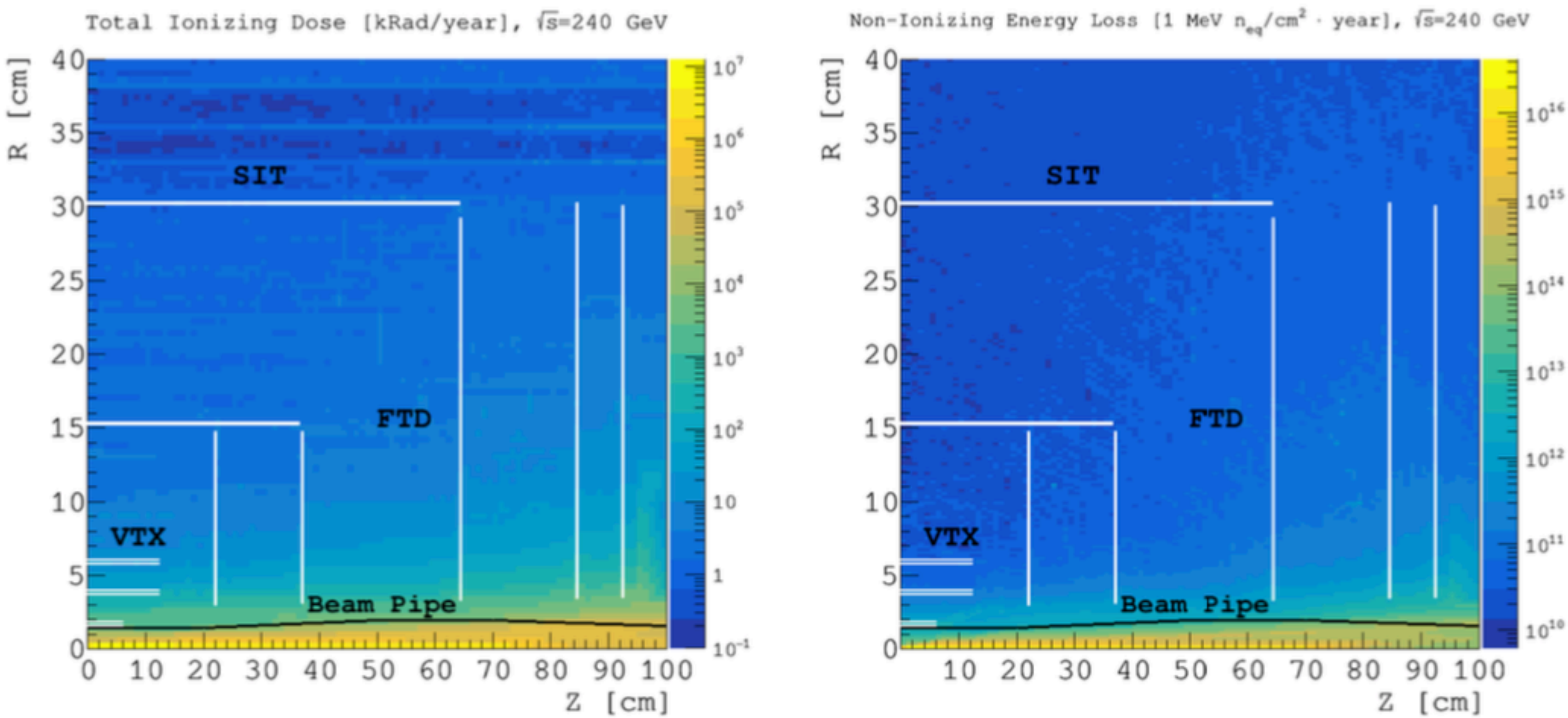
Significantly under-estimated in the CDR

Not affecting tracker

2019/11/19 CEPC Workshop 2019, H. Shi 36

Radiation estimate from CDR

- For SET and ETD: TID < 1kRad/year, NIEL < 10^{10} MeV n_{eq} /cm^2. year



(a)

(b)

Figure 9.8: Total ionizing dose (TID) and non-ionizing energy loss (NIEL) distribution in $r-z$ for the machine operation at $\sqrt{s} = 240$ GeV. The white lines indicate the locations of the vertex detector (VTX), the forward tracking disks (FTD) and the silicon inner tracker (SIT).

Momentum resolution requirements

- Main requirement is on the momentum resolution
  - pT < 50 GeV: dominated by Multiple scattering
  - pT > 50 GeV: dominated by single-point resolution

Physics process	Measurands	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$	$m_H, \sigma(ZH)$	Tracker	$\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$\cancel{H \to \mu^+\mu^-}$	$\cancel{\mathrm{BR}(H \to \mu^+\mu^-)}$		
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	Vertex	$\sigma_{r\phi} = 5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta}$ (μm)

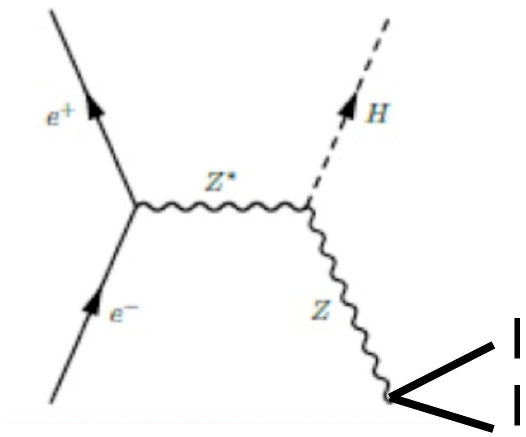
$$\sigma_{1/p_T} = a \oplus \frac{b}{p\sin\theta} \quad [\mathrm{GeV}^{-1}] \qquad \boxed{a = \frac{\sigma_{SP}}{0.3BL^2}\sqrt{\frac{720}{N+4}}} \qquad b = 0.045\frac{1}{BL}\sqrt{\frac{L}{X_0}}$$

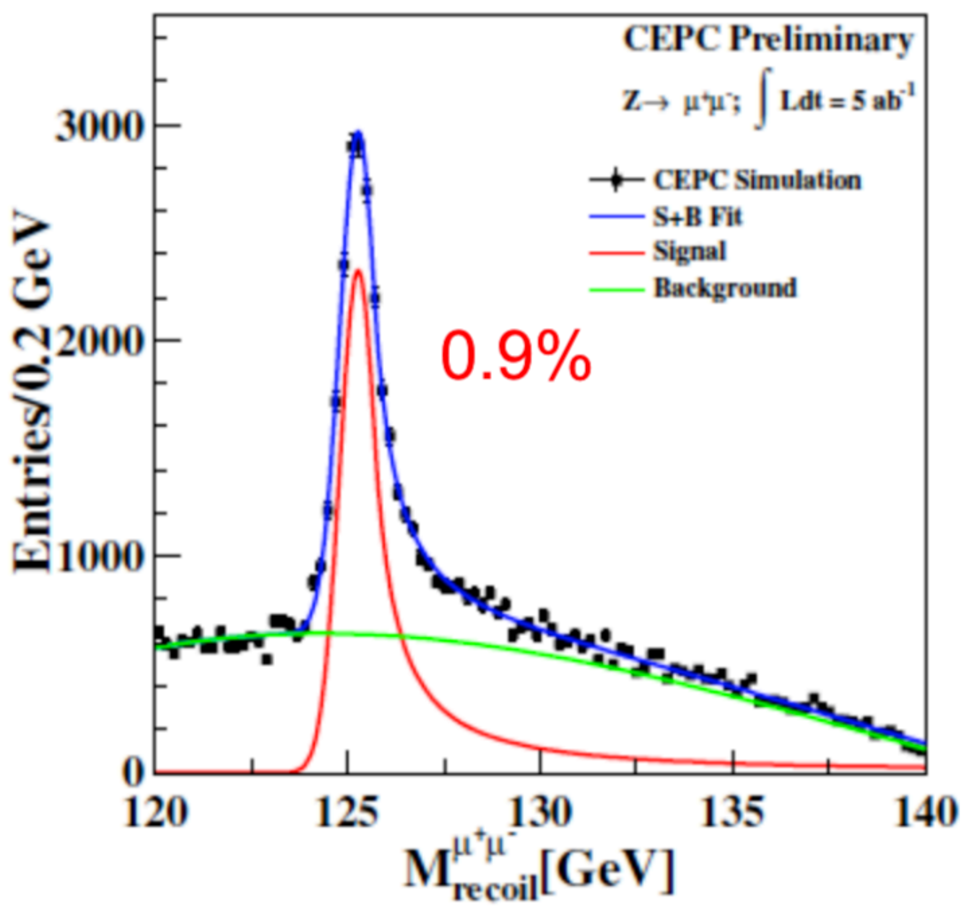
CDR studies assumes B=3.5 T for Higgs
B = 2T is being considered now

See Manqi's talk: https://indico.ihep.ac.cn/event/9960/session/5/contribution/184/material/slides/0.pdf

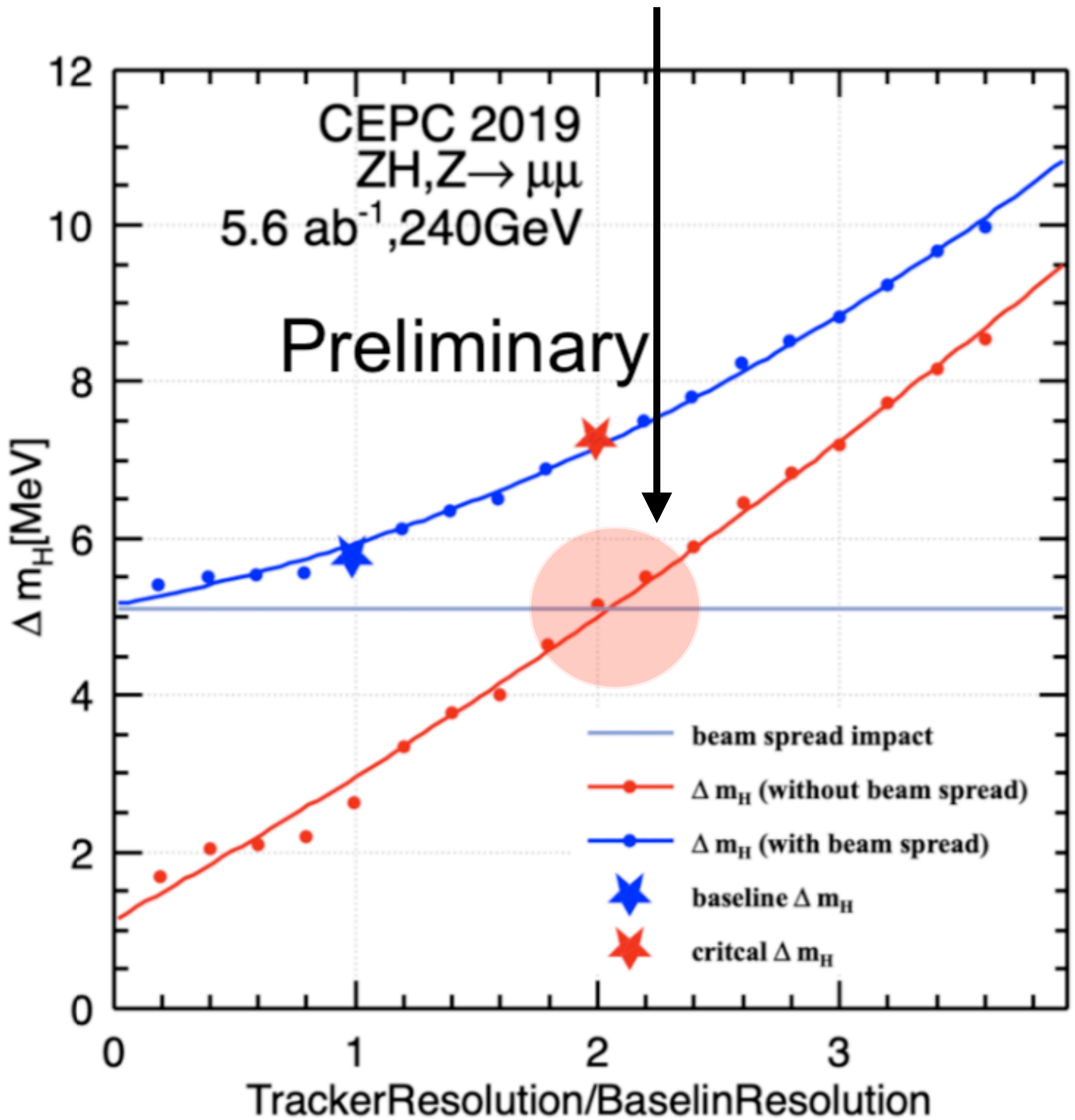
Higgs mass measurement

- The recoil mass determines the Higgs mass resolution
  - Mostly H→bb

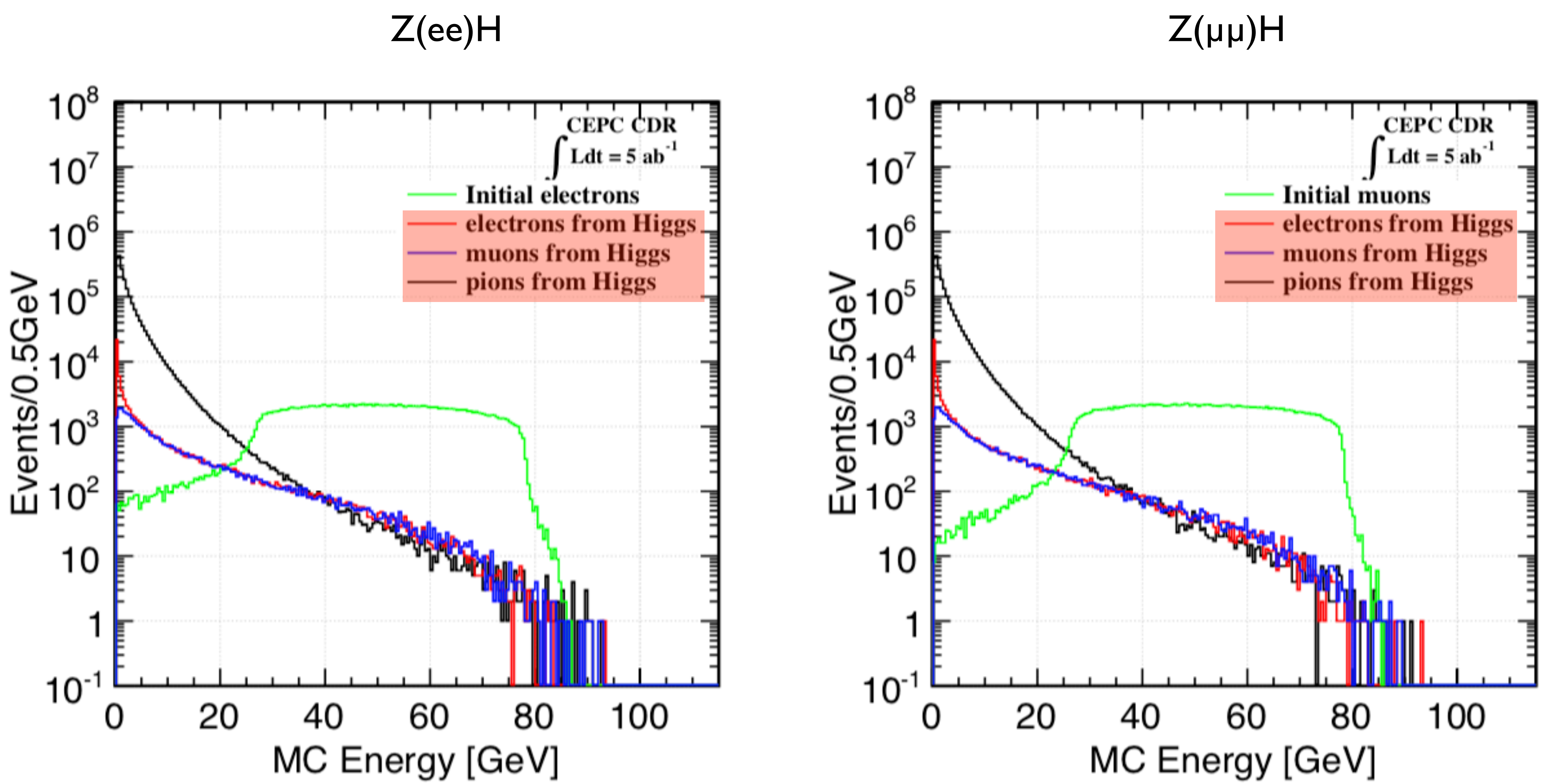




Key requirement:
Tracker resolution comparable to beam spread

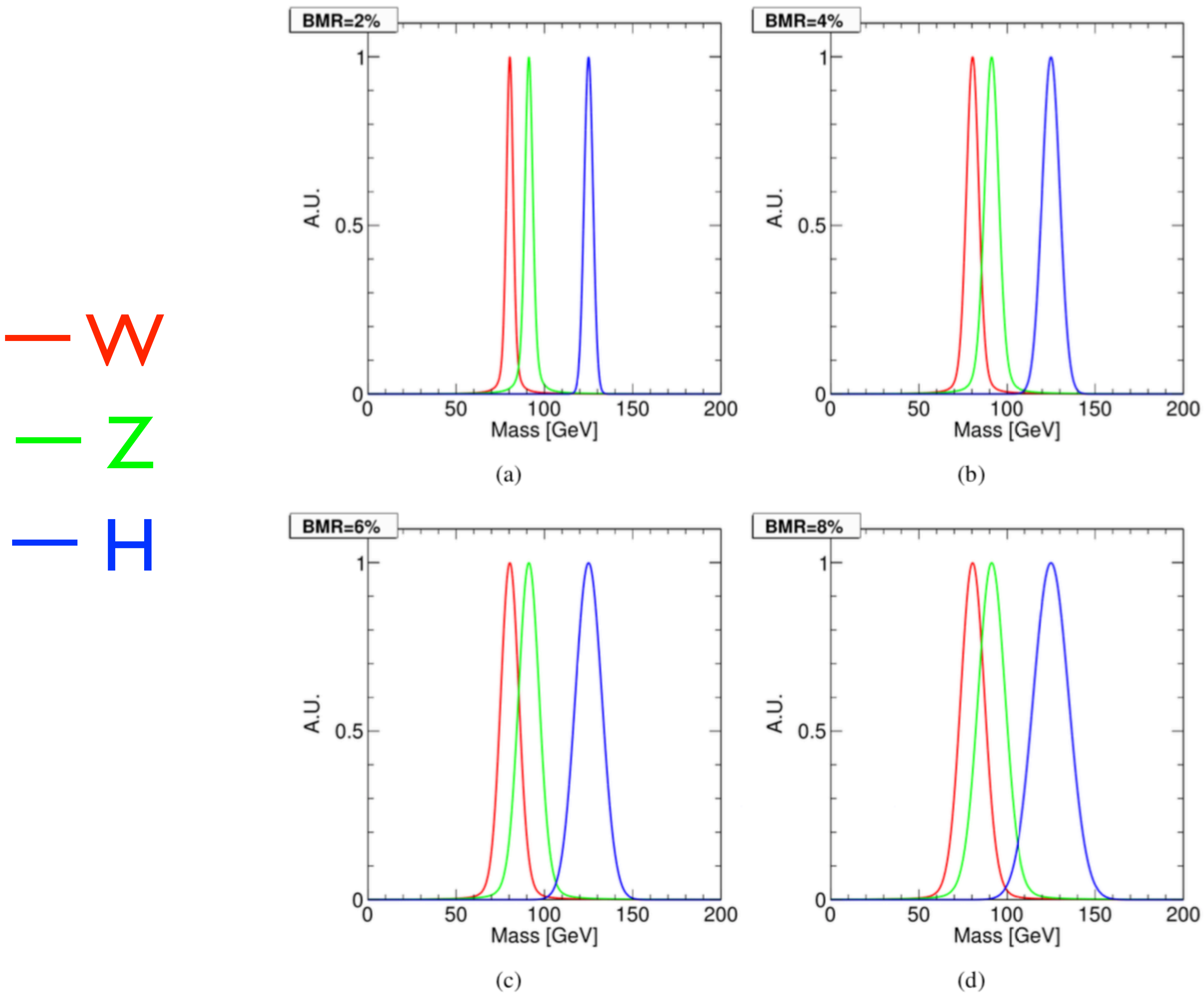


Leptons and charge hadrons from Higgs



- The tagging of the Z→ee/μμ depends largely on efficiency
- It is the particles from the Higgs decays that matter for the Higgs recoil
    - **pT range [20-80] GeV**

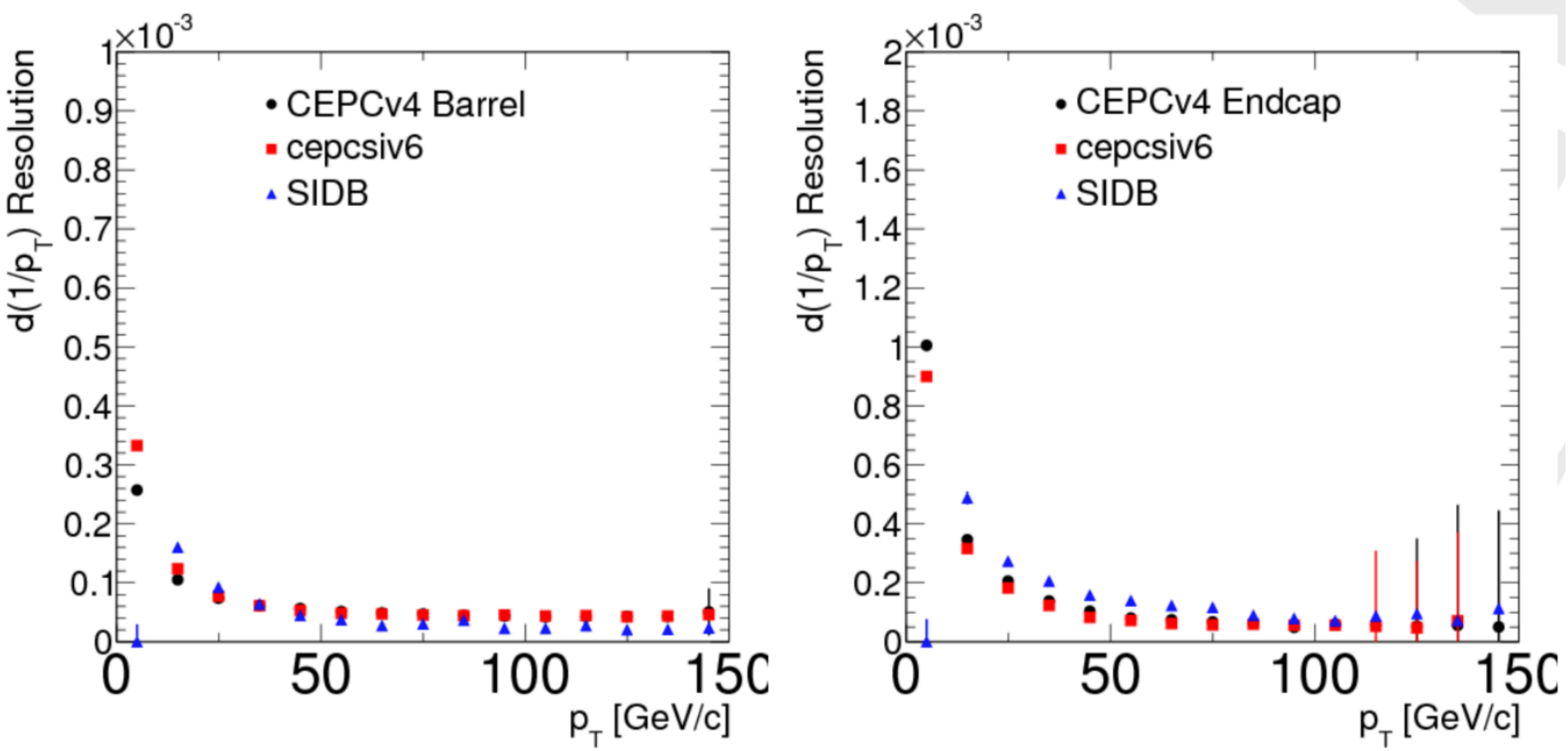
Boson Mass Resolution in hadronic decays



Minimum requirement: 2σ W/Z seperation

Has this been achieved from simulation?

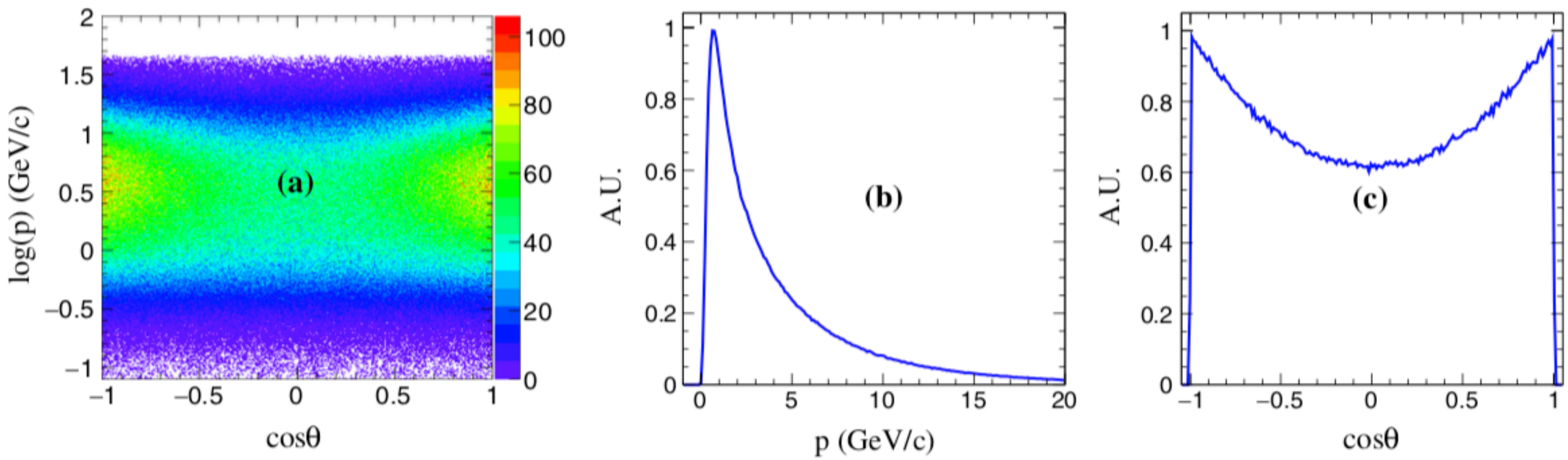
- Big caveat: still assumes 3.5T
  - Based on the baseline design..

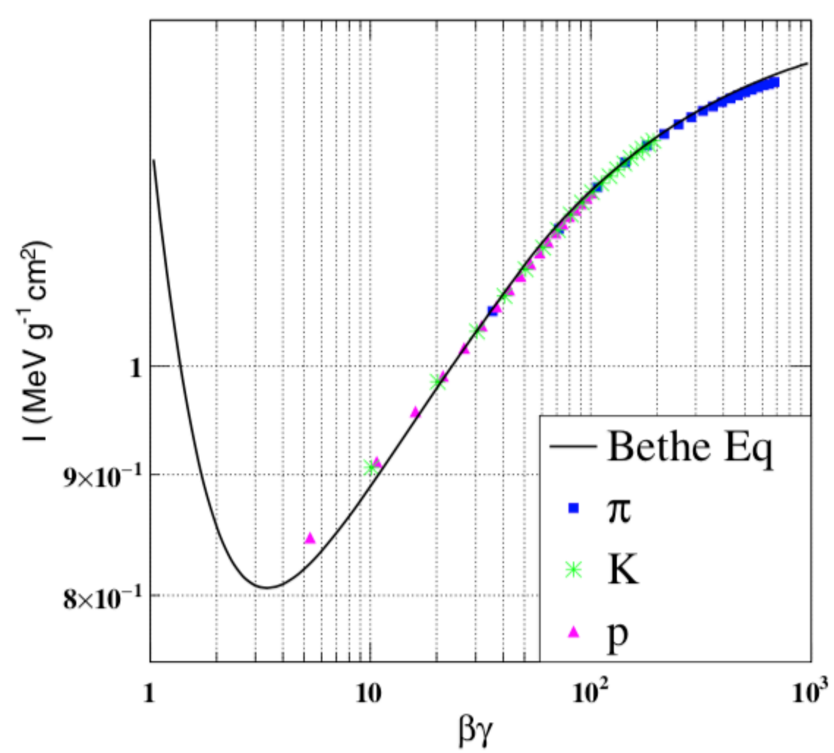


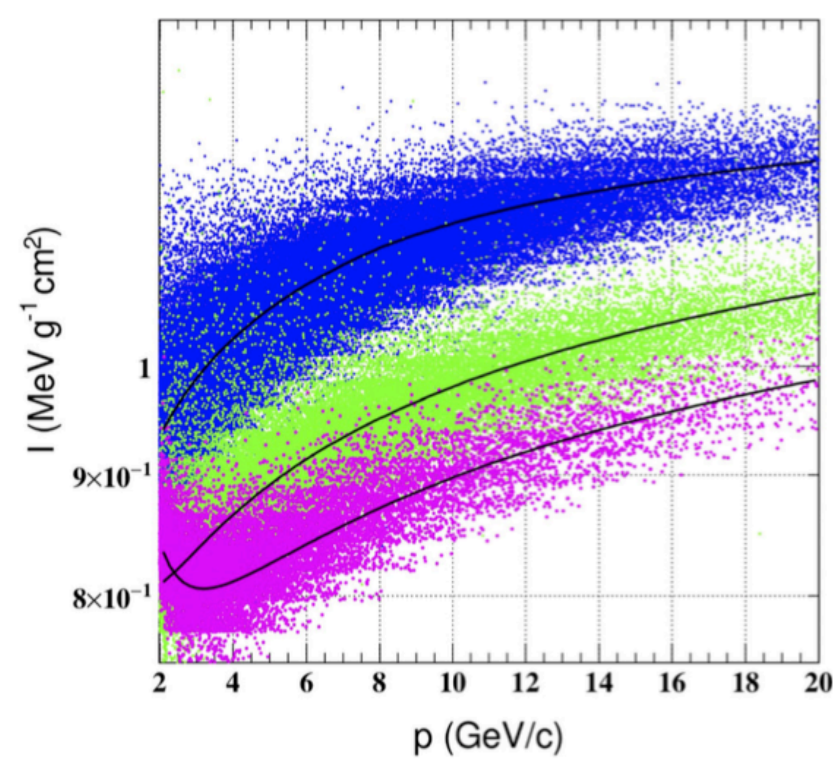
dE/dx for PID

- Aim for 3σ K/π and K/p separation for flavour physics
  - Improve b/c-tagging for the Higgs running, and more importantly PID for Z-pole running
  - Currently with the baseline detector, TPC + Ecal TOF information (Link to the EPJC paper)

Kaon kinematics $Z \to qq$

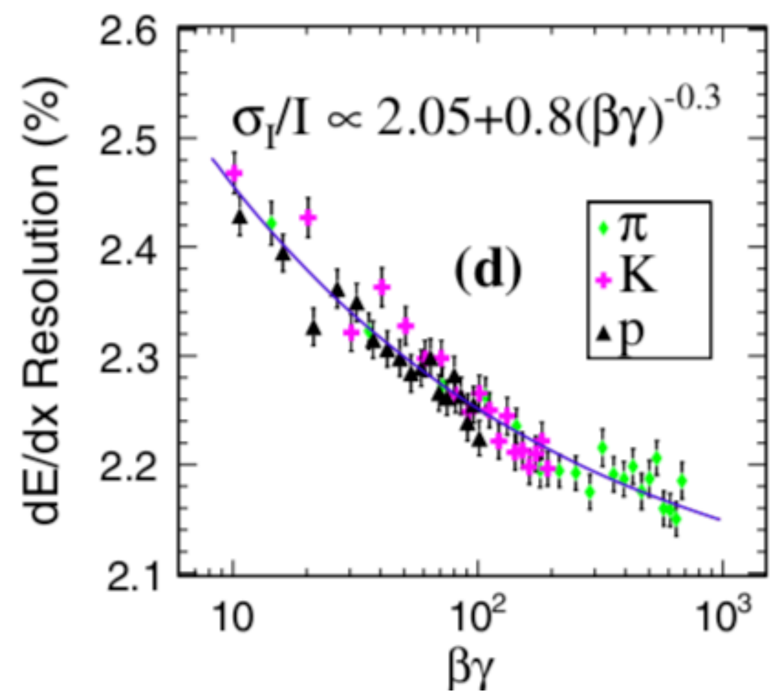


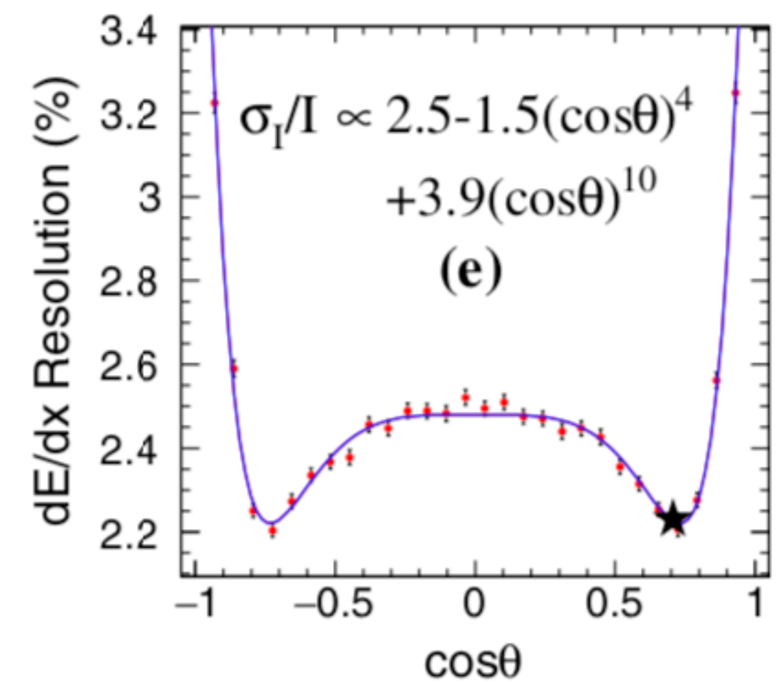




Baseline dE/dx performance

Intrinsic TPC performance

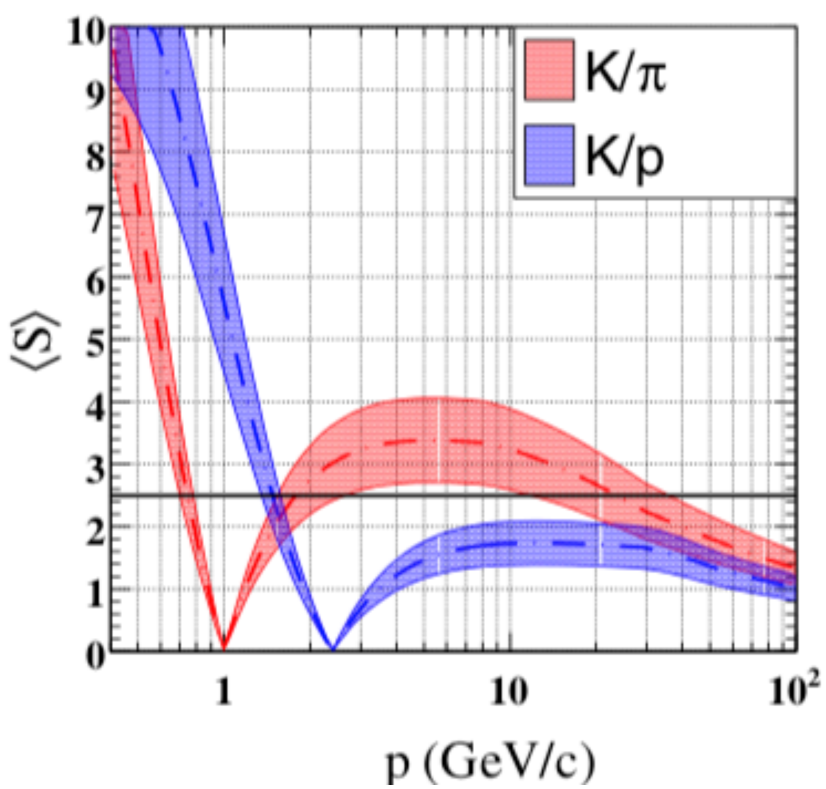


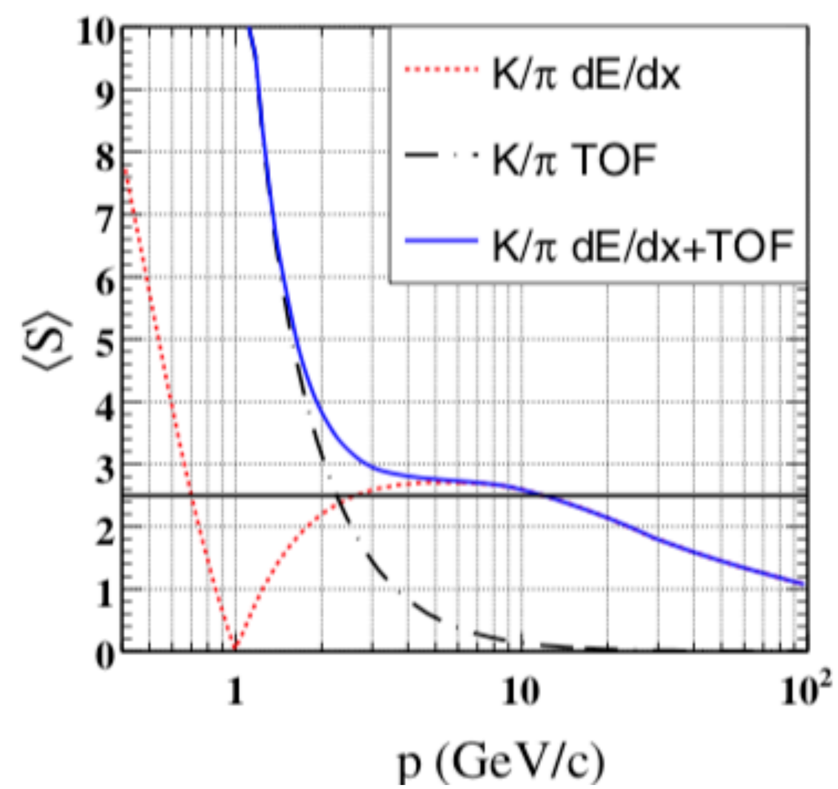


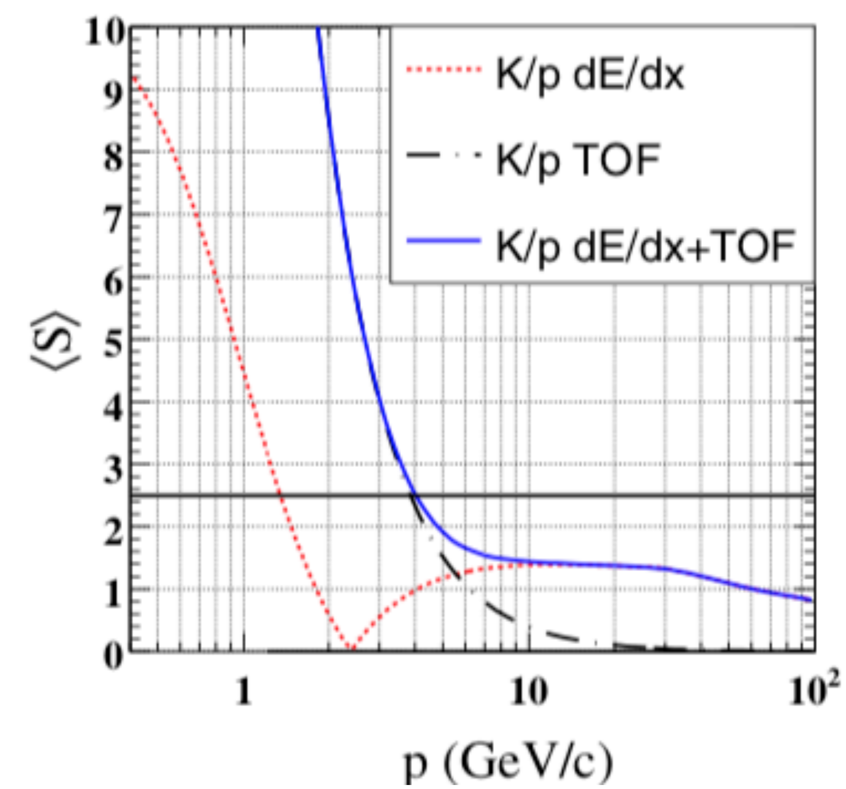
Average separation power:

$$S_{AB} = \frac{|I_A - I_B|}{\sqrt{\sigma_{I_A}^2 + \sigma_{I_B}^2}}$$

Low pT region driven by ECal TOF, dE/dx comes in >1 GeV







Dynamic range

- These are for the signatures that can leave large dE/dx in the tracker
- Areas of interest
  - Searches for stable BSM particles with large or fractional charges
  - Searches for quasi-stable heavy BSM particles

Summary

	With TPC	All silicon
Barrel	SIT-L1: R=0.15, L=0.75 → A=0.7m^2 SIT-L2: R=0.30, L=1.33 → A=2.5m^2 SET: R=1.81, L=4.70→ A=53m^2	?
Endcap	FTD D1-D5: 1.8 m^2 ETD: R_{out}=1.82, R_{in} =0.42m → A=20 m^2	
$\sigma_{SP\ (r\phi)}$	7 μm	
$\sigma_{SP\ (Z)}$	Very loose ~ 100 μm	
Timing	25 ns	
Max* Occupancy	SIT-L1: 0.6%, SIT-L2: 10^{-3}, SET: 10^{-4}	
Radiation	TID ~< 1kRad/year, NIEL ~< 10^{10} 1 MeV neq /cm^2. year	
dE/dX	-	2-3% @ pT [2-10]
X/X_0	0.65% Barrel 0.5-0.65% Endcap	?

*Assumption: Pixel dimension: 50 μm × 350 μm, readout time: 10us, Cluster size: 9 hits per track

Documentations

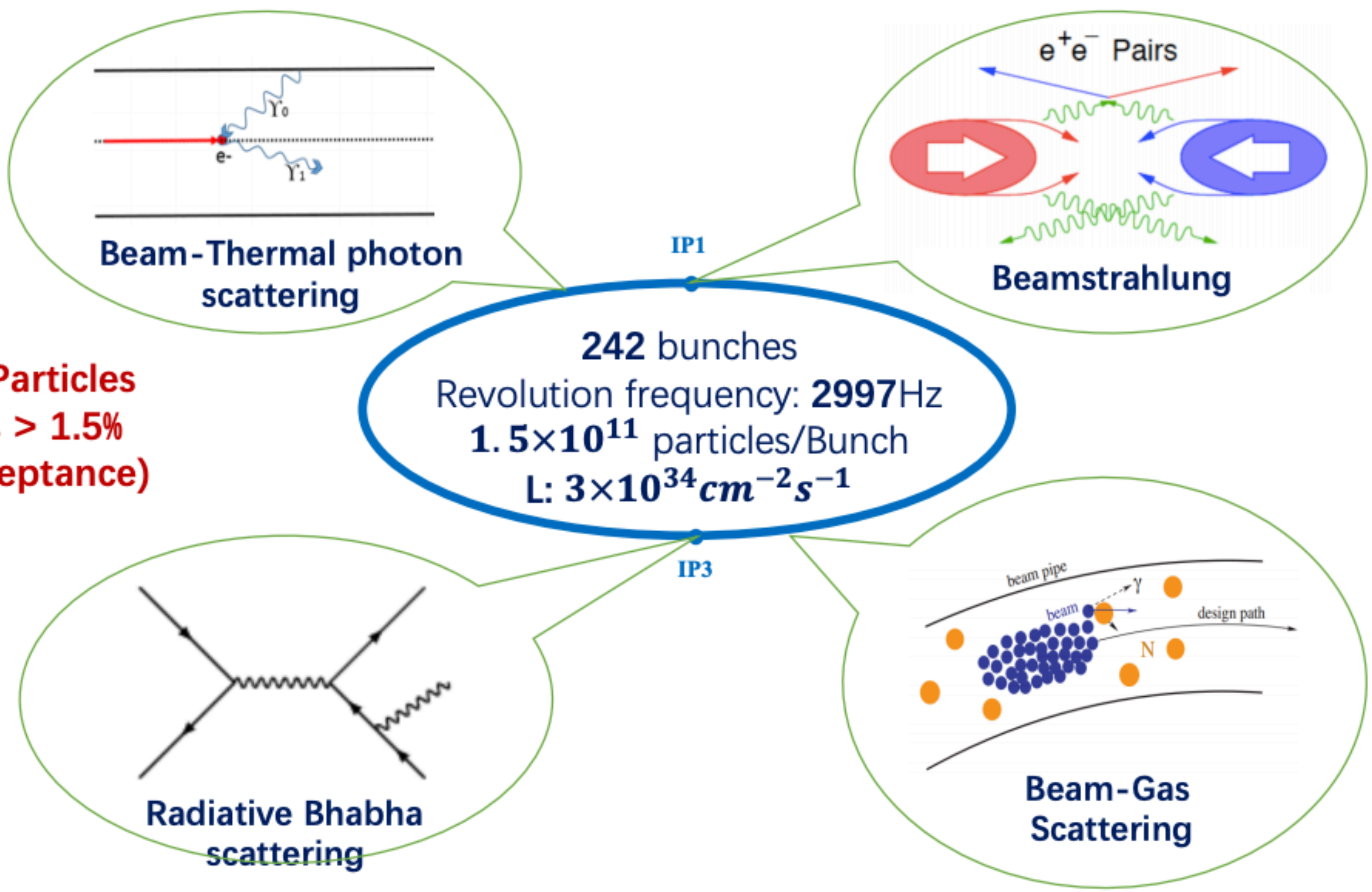
- Most of this material came from the CEPC Physics and Detector CDR
  - https://arxiv.org/pdf/1811.10545.pdf
  - However this was very vague and very much up for discussions.

Extra slides

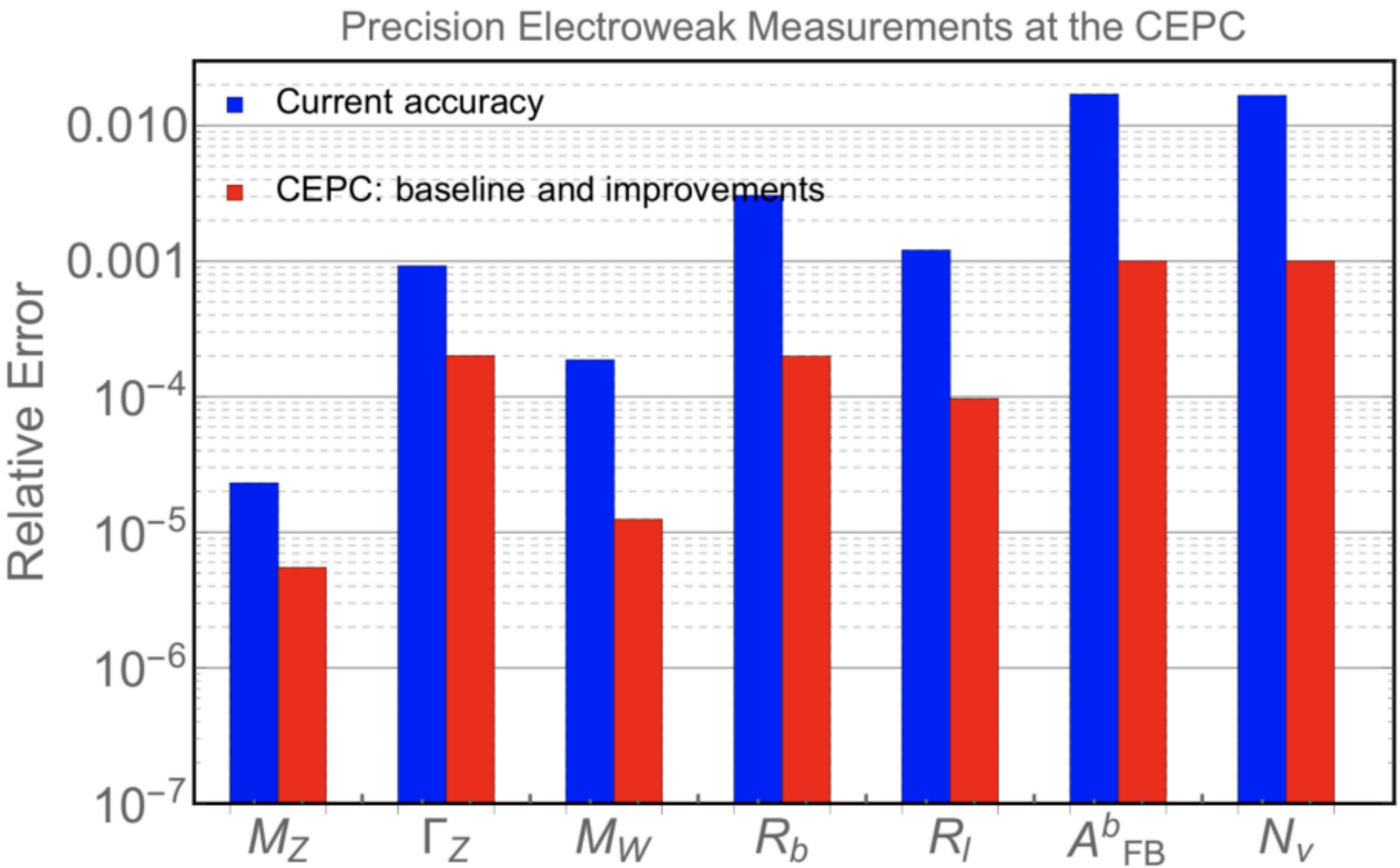
Radiation - off energy beam

Off Energy Beam

Beam Lost Particles
Energy Loss > 1.5%
(energy acceptance)



Z-pole running physics summary



Electroweak Physics at CEPC, Zhijun Liang

Overview slide in Nov 2019 workshop