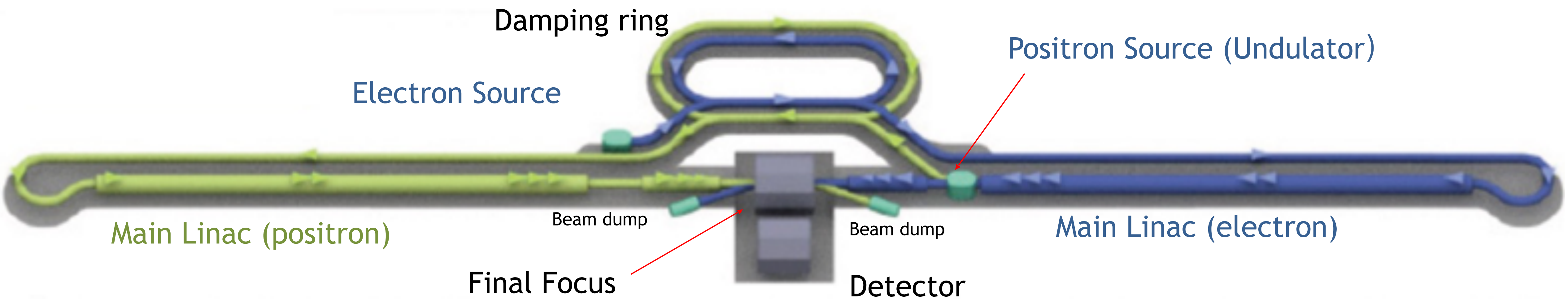
Introduction to ILC Experiment



Junping Tian (U. Tokyo)

school for future e+e- colliders, Feb. 24-28, 2020 @ KEK

plan

(i) Accelerator

Lecture 1

(ii) Detector

(iii) Physics analyses

Lecture 2

(iv) Higgs couplings

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focus is introduction to principles & concepts
find details and technicalities from references

(i) introduction to accelerators

theorists usually
only need input $\sqrt{s}$ L $(\int L\mathrm{d}t)$ P

	$\sqrt{s}$	beam polarisation	$\int$Ldt for Higgs	R&D phase
ILC	0.1 - 1 TeV	e-: 80% e+: 30% (20%)	2000 fb^{-1} @ 250 GeV 200 fb^{-1} @ 350 GeV 4000 fb-1 @ 500 GeV 8000 fb-1 @ 1 TeV	TDR
CLIC	0.35 - 3 TeV	e-: (80%) e+: 0%	500 fb^{-1} @ 380 GeV 1500 fb^{-1} @ 1.4 TeV 2500 fb^{-1} @ 3 TeV	CDR
CEPC	90 - 240 GeV	e-: 0% e+: 0%	5600 fb^{-1} @ 240 GeV	CDR
FCC-ee	90 - 365 GeV	e-: 0% e+: 0%	5000 fb^{-1} @ 240 GeV 1500 fb^{-1} @ 365 GeV	CDR

(i) introduction to accelerators

what behind $\sqrt{s}$ L $(\int L\mathrm{d}t)$ P

(i.1) basic principles for acceleration

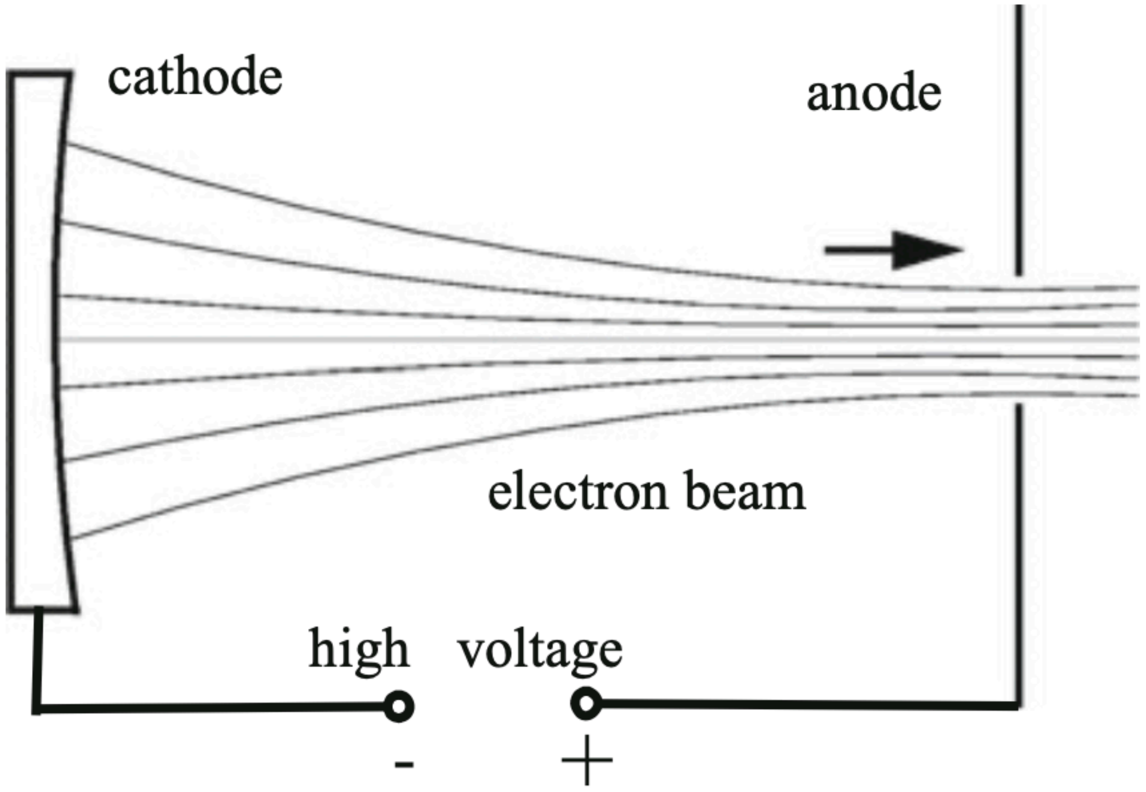
(i.2) luminosity & a little beam dynamics

(i.3) beam polarizations

(i.4) ILC & its specifications

(i.1) basic principles of acceleration

- **electrostatic accelerator**

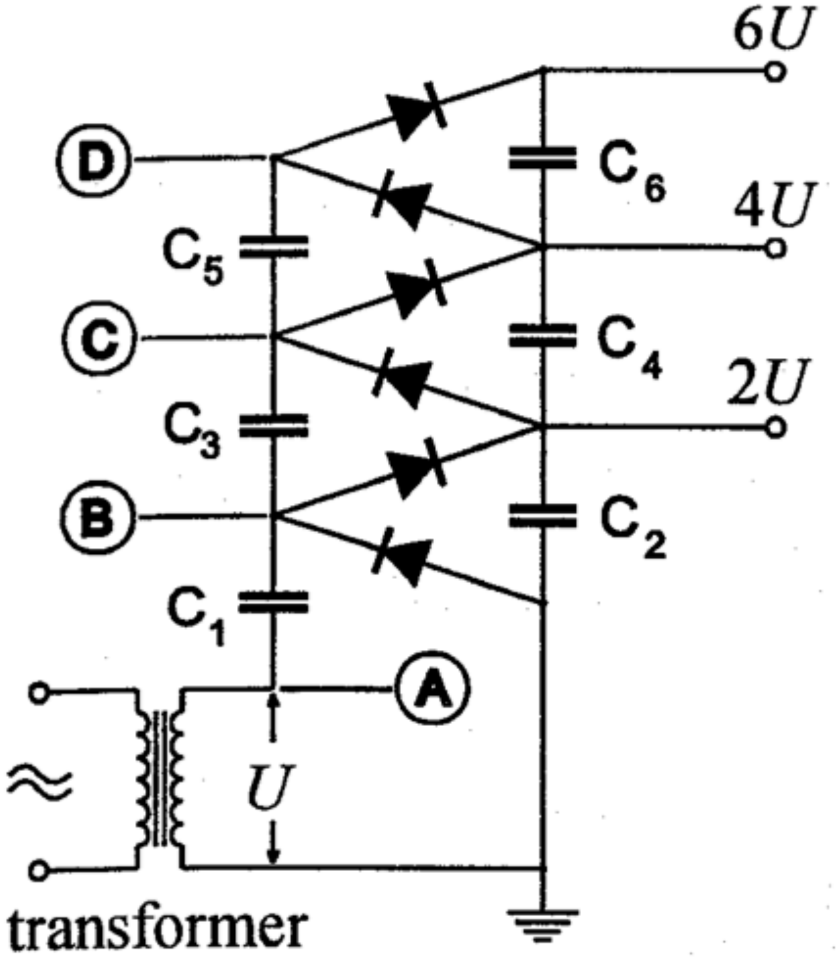


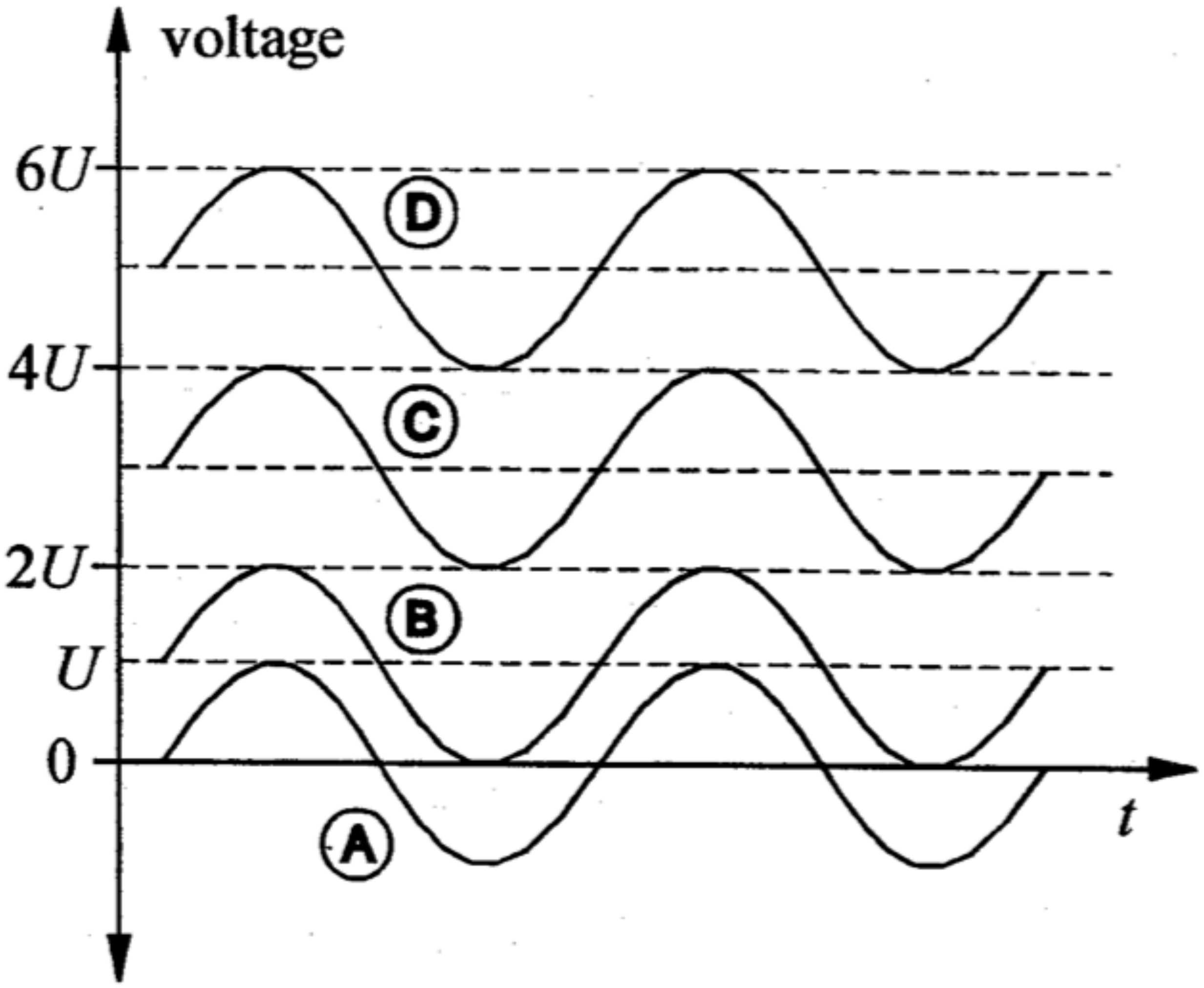
$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

early development: mainly about generating high voltage

(i.1) basic principles of acceleration

- Cockcroft-Walton cascade generator

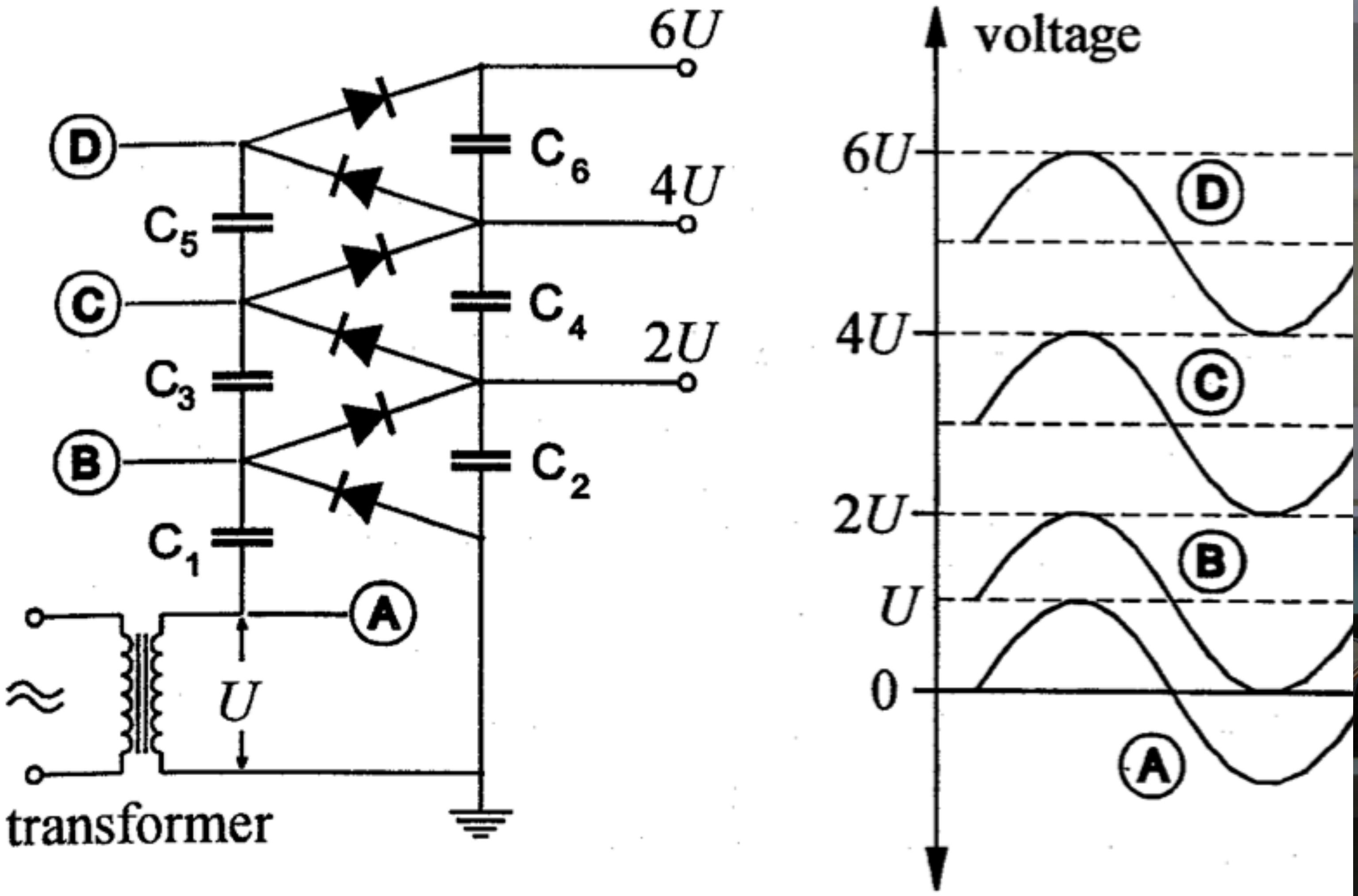


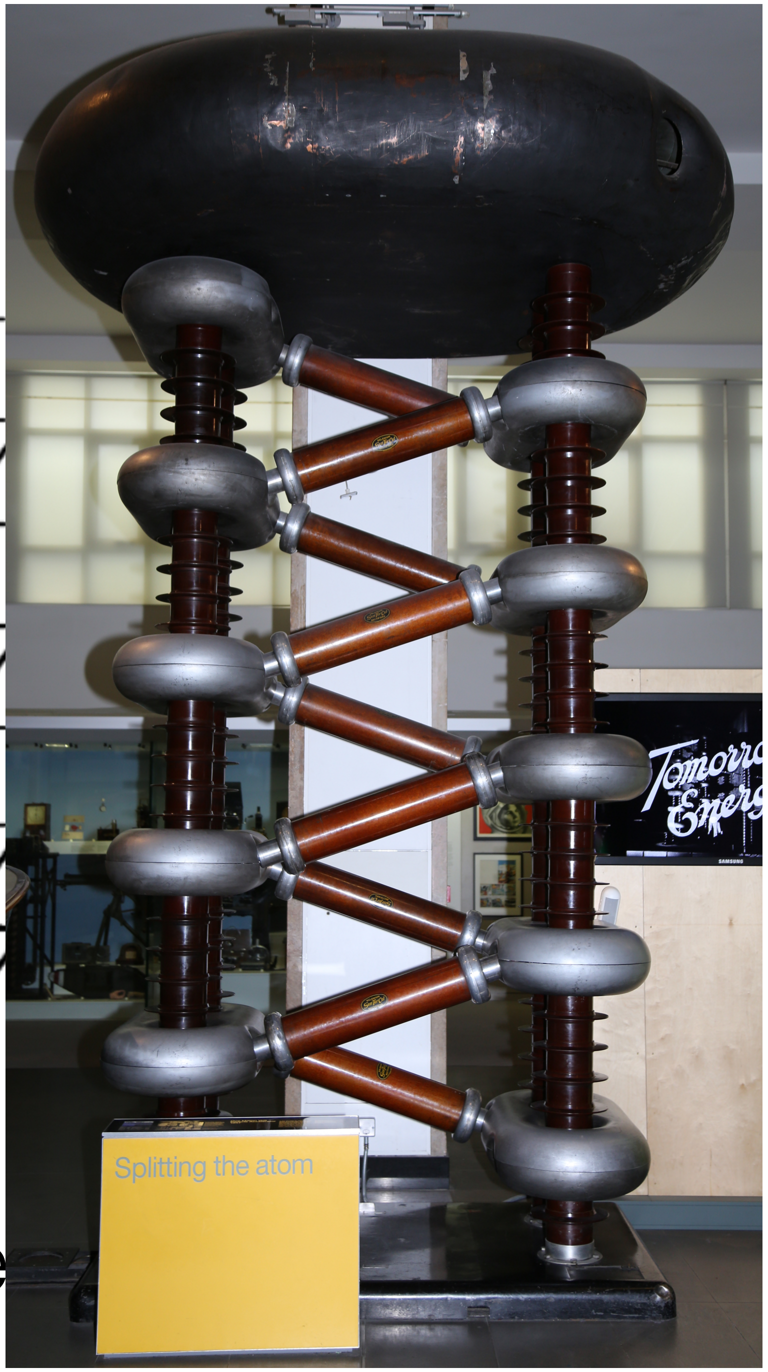


based on a system with multiple rectifiers
reached ~O(1) MV

(i.1) basic principles of acceleration

- Cockcroft-Walton cascade generator



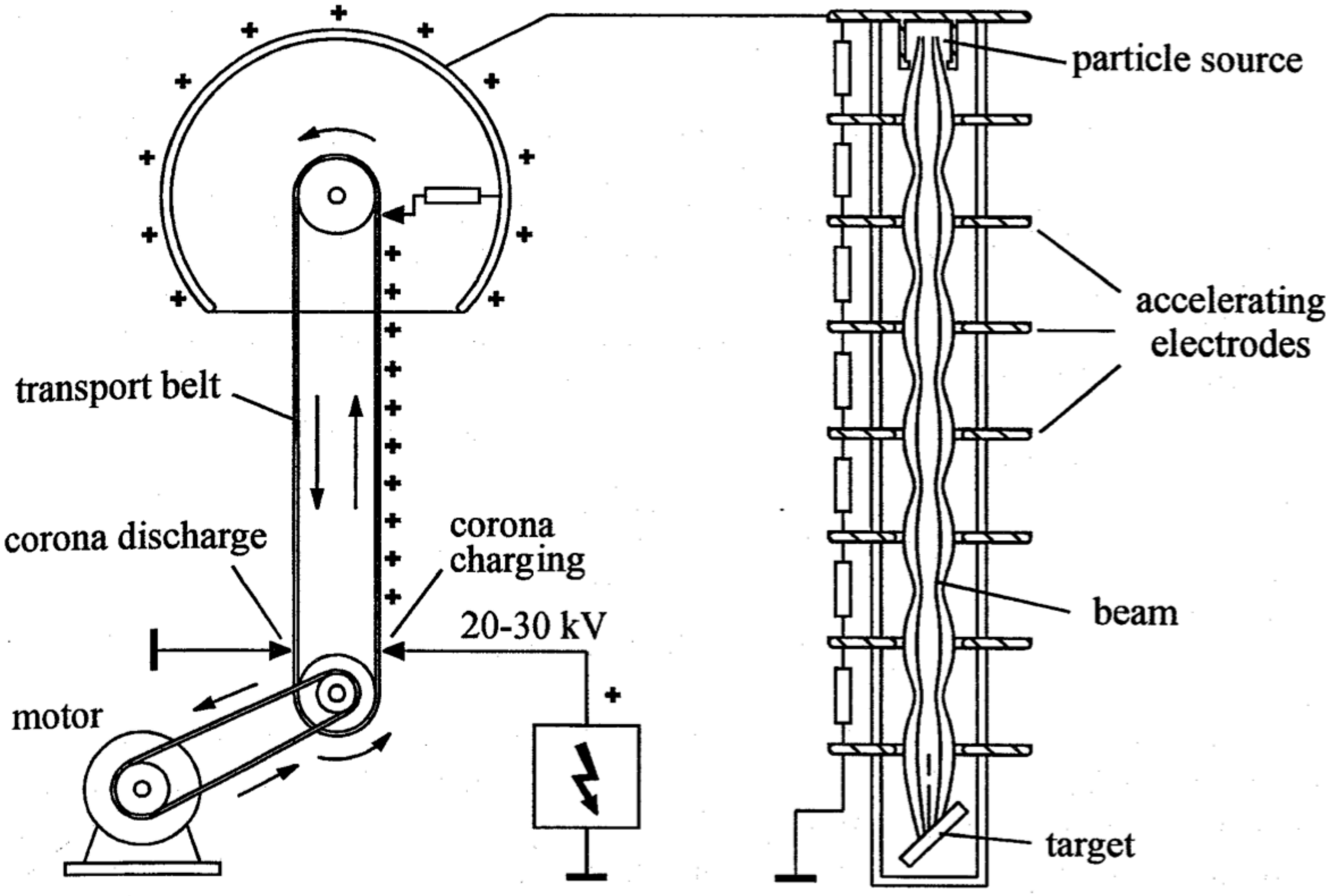


Nat'l Science Museum, London

based on a system with multiple re
reached ~O(1) MV

(i.1) basic principles of acceleration

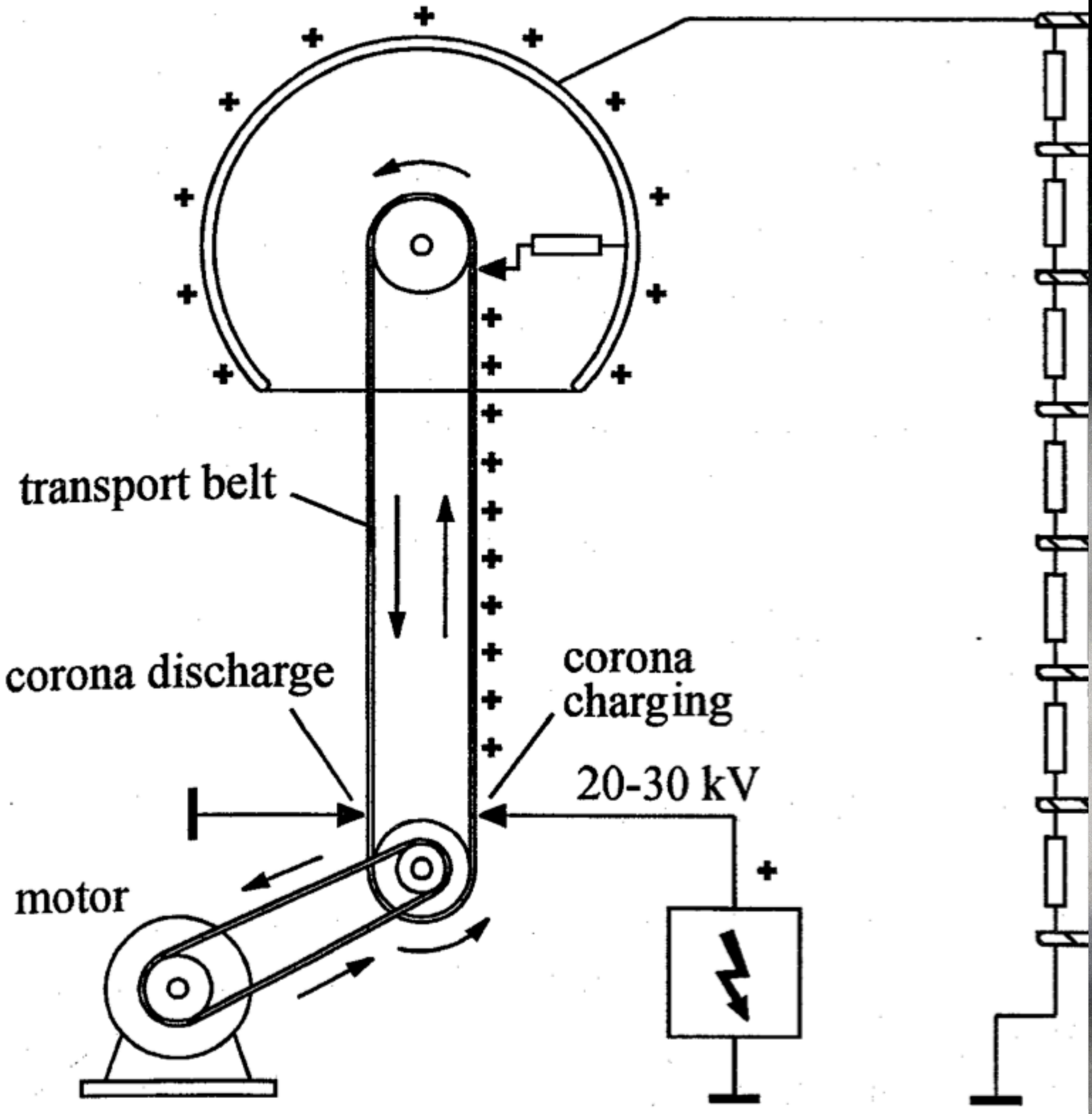
- Van de Graaff generator



an isolating belt continuously transports charge
to a conducting dome: O(1-1000) MeV

(i.1) basic principles of acceleration

- Van de Graaff generator

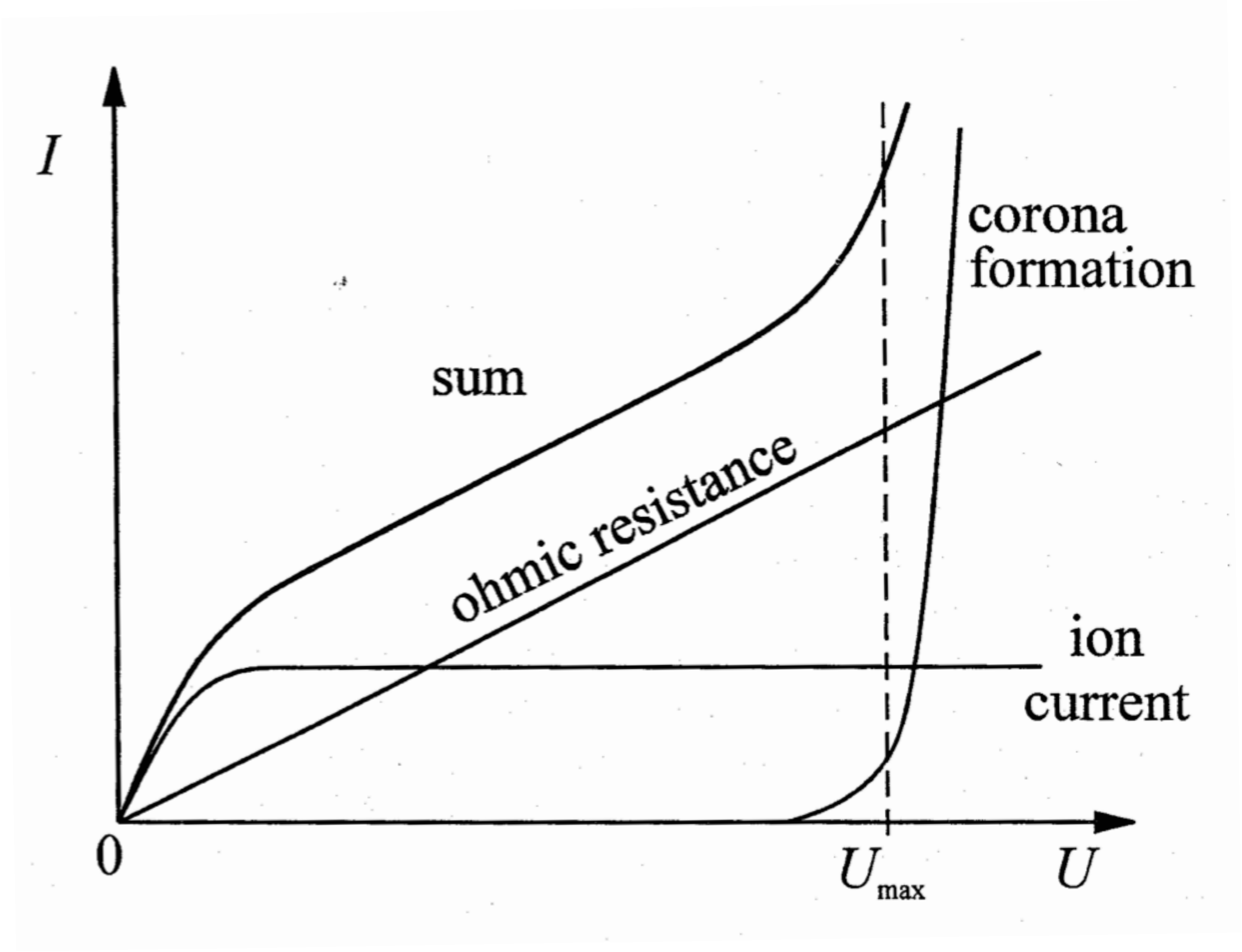


Westinghouse Atom Smasher (1937) 5MV

an isolating belt continuously t
to a conducting dome: O(

(i.1) basic principles of acceleration

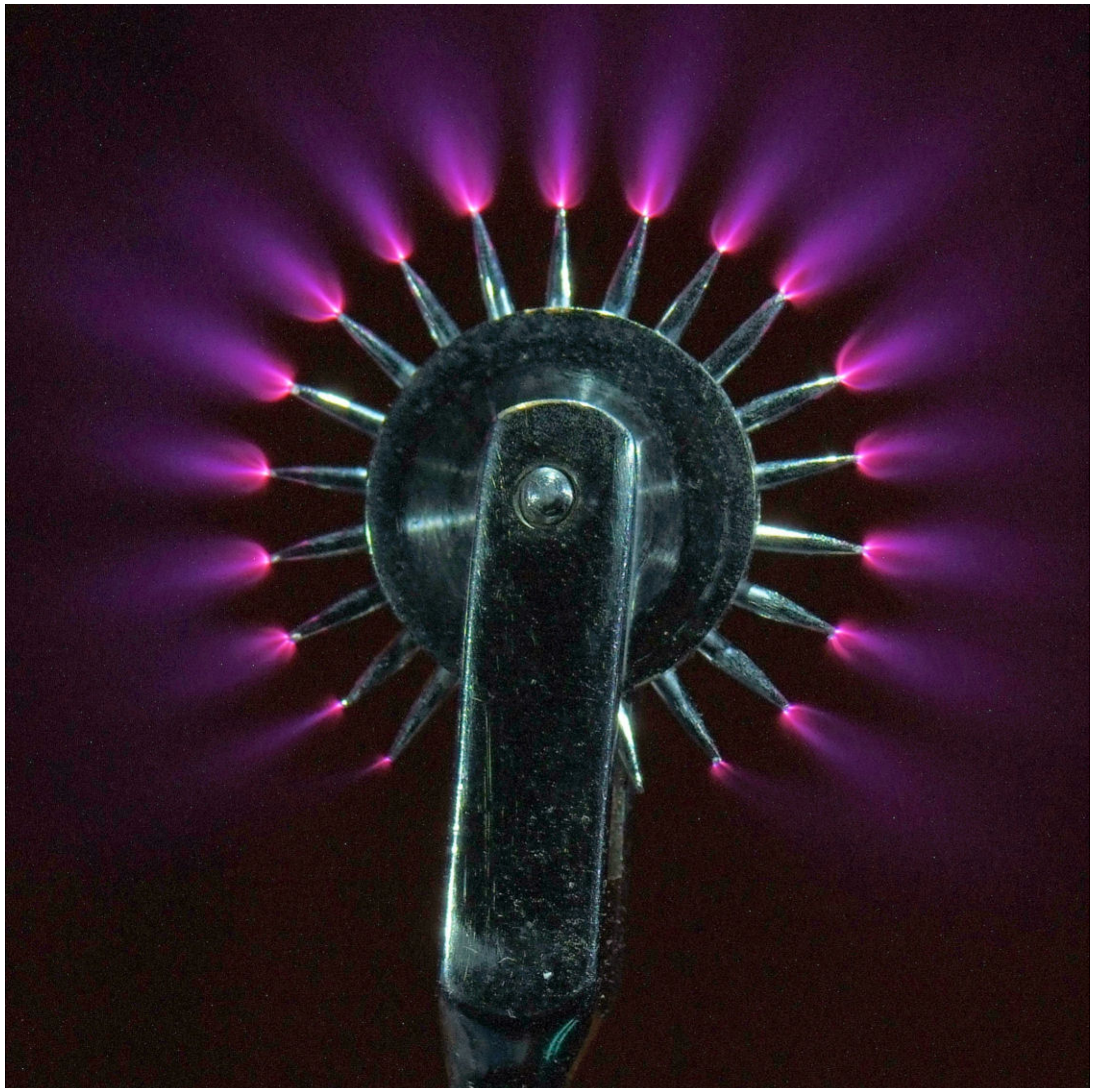
- high-voltage limitation



corona discharge: ionization avalanche near electrode

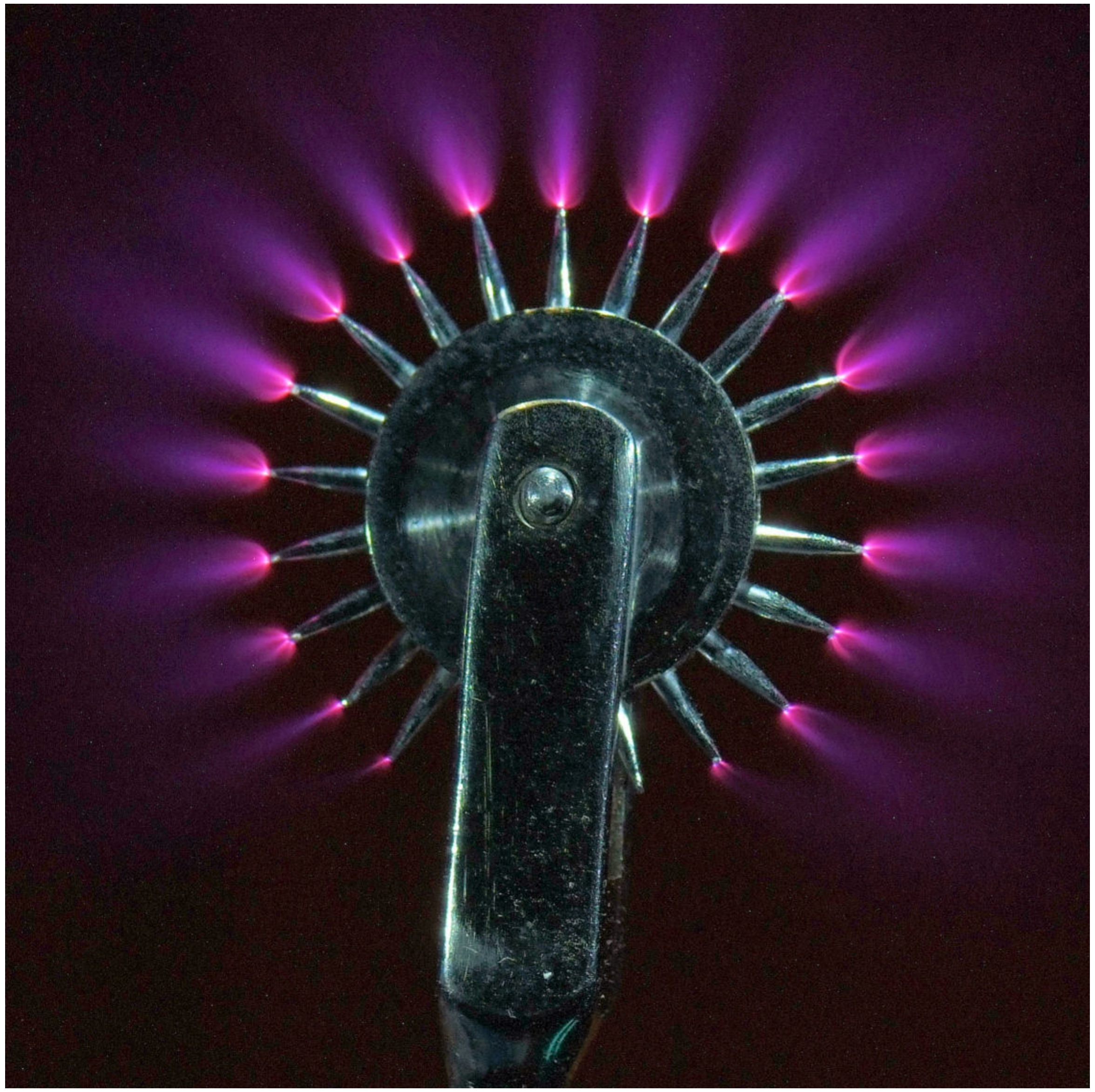
(i.1) basic principles of acceleration

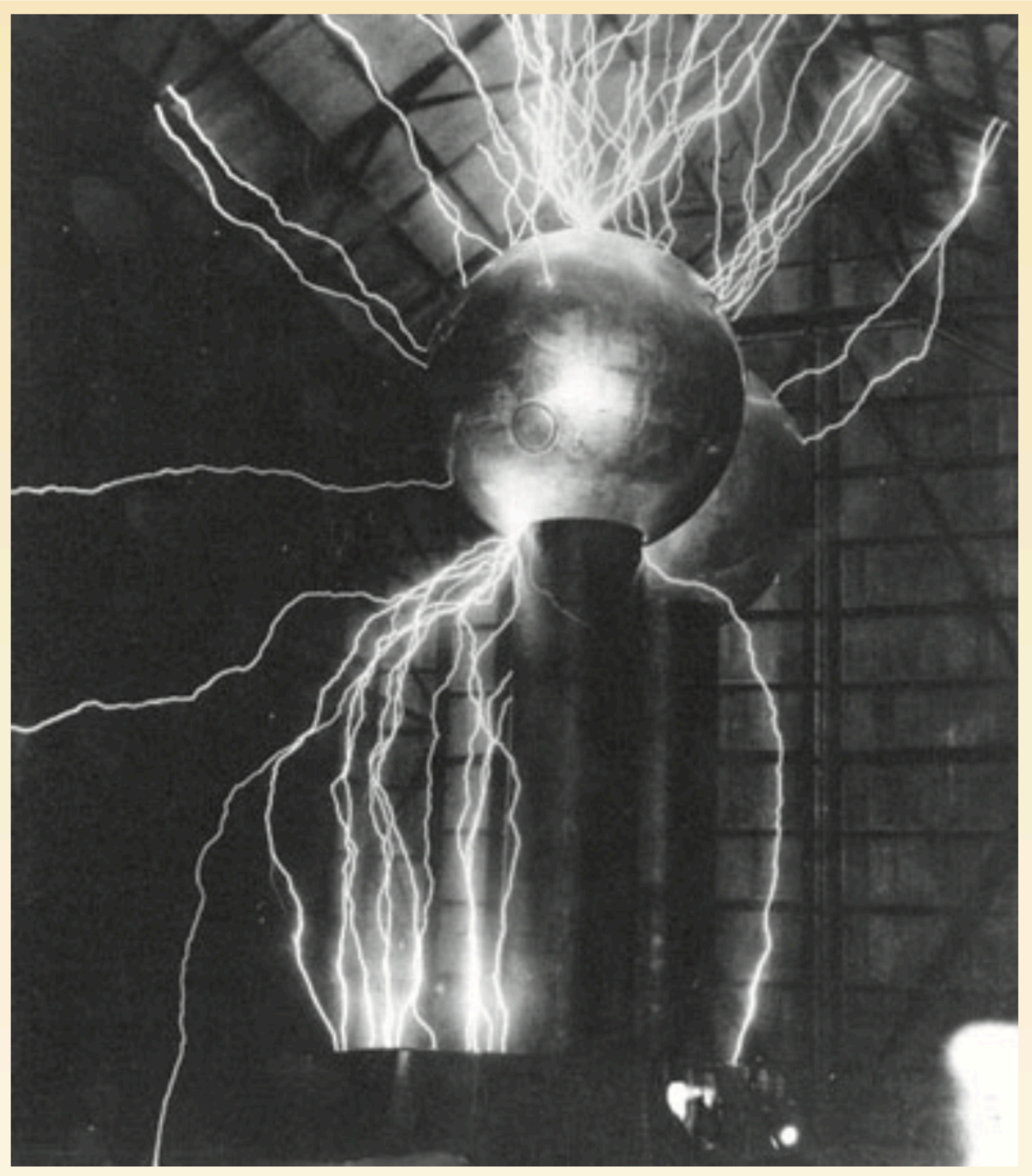
- high-voltage limitation



(i.1) basic principles of acceleration

- high-voltage limitation



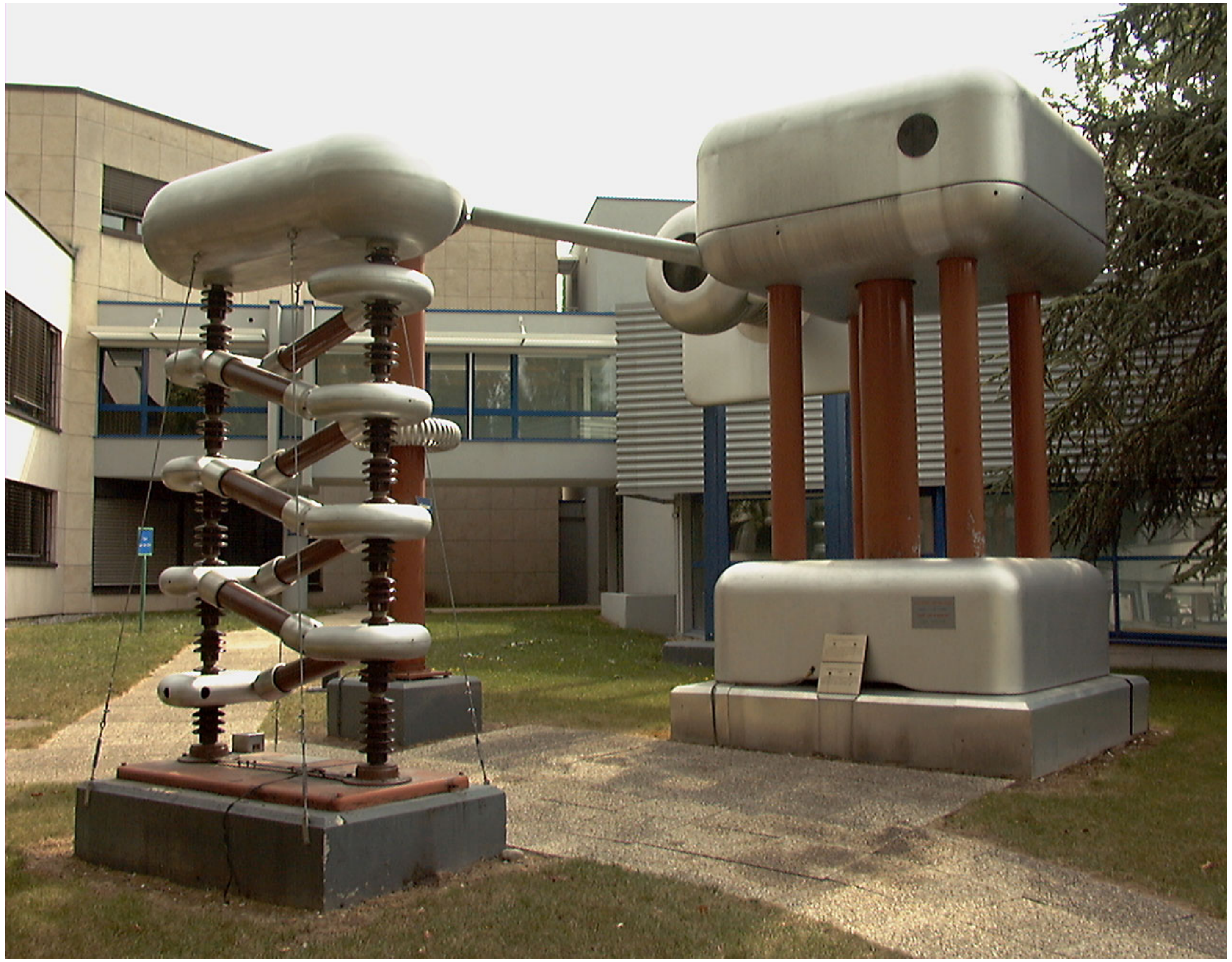


(i.1) basic principles of acceleration

- **electrostatic accelerator**

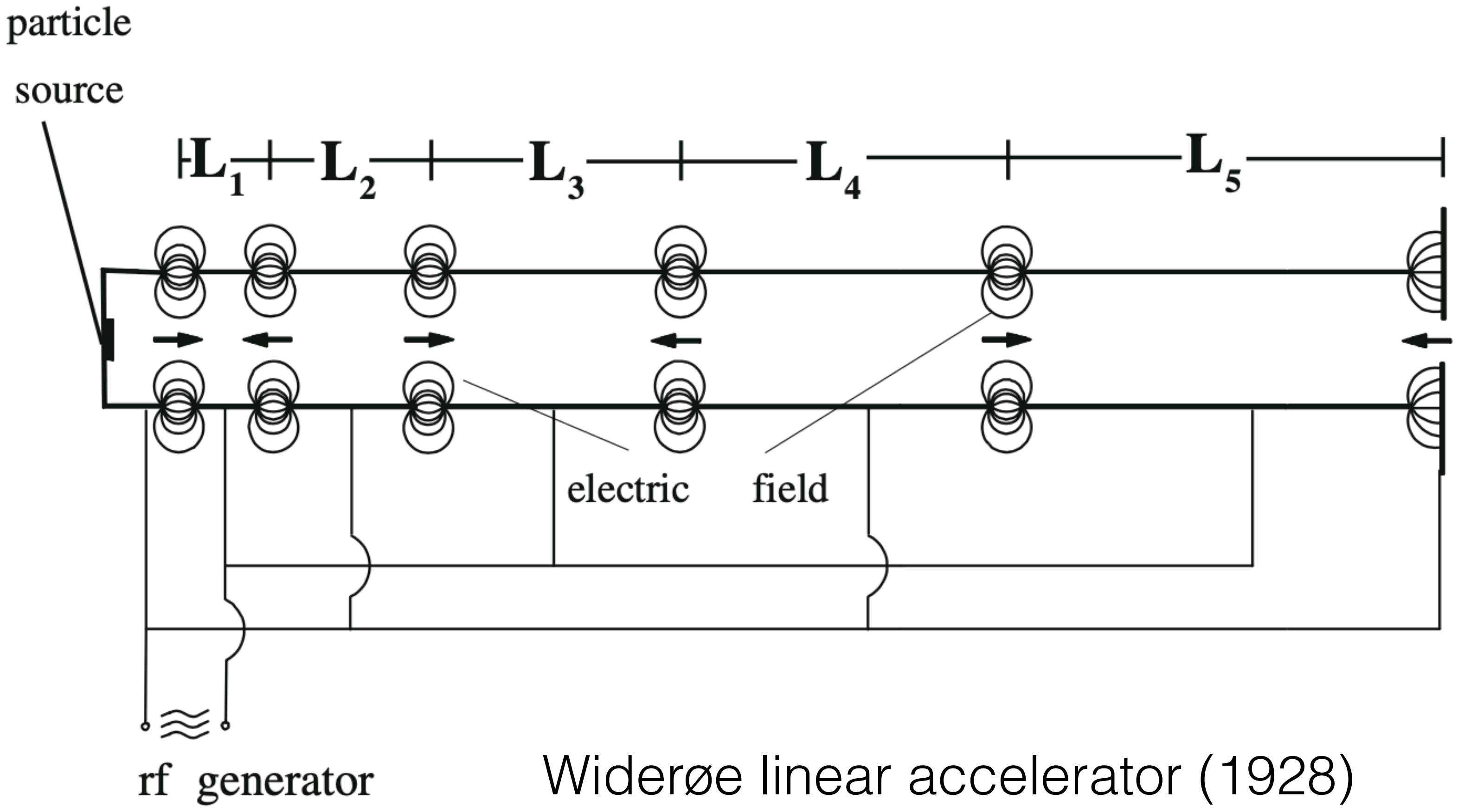
played crucial role for the nuclear physics

still used nowadays as pre-injector



@ CERN Exhibition

◉ Radio-Frequency (RF) accelerator



Widerøe linear accelerator (1928)

crucial: synchronization of particle motion & RF field

$$L_i = v_i \frac{\tau_{\mathrm{RF}}}{2} = \frac{v_i}{c} \frac{\lambda_{\mathrm{RF}}}{2} = \beta_i \frac{\lambda_{\mathrm{RF}}}{2}$$

for 10 MHz
λ_{RF} = 30m

(i.1) basic principles of acceleration

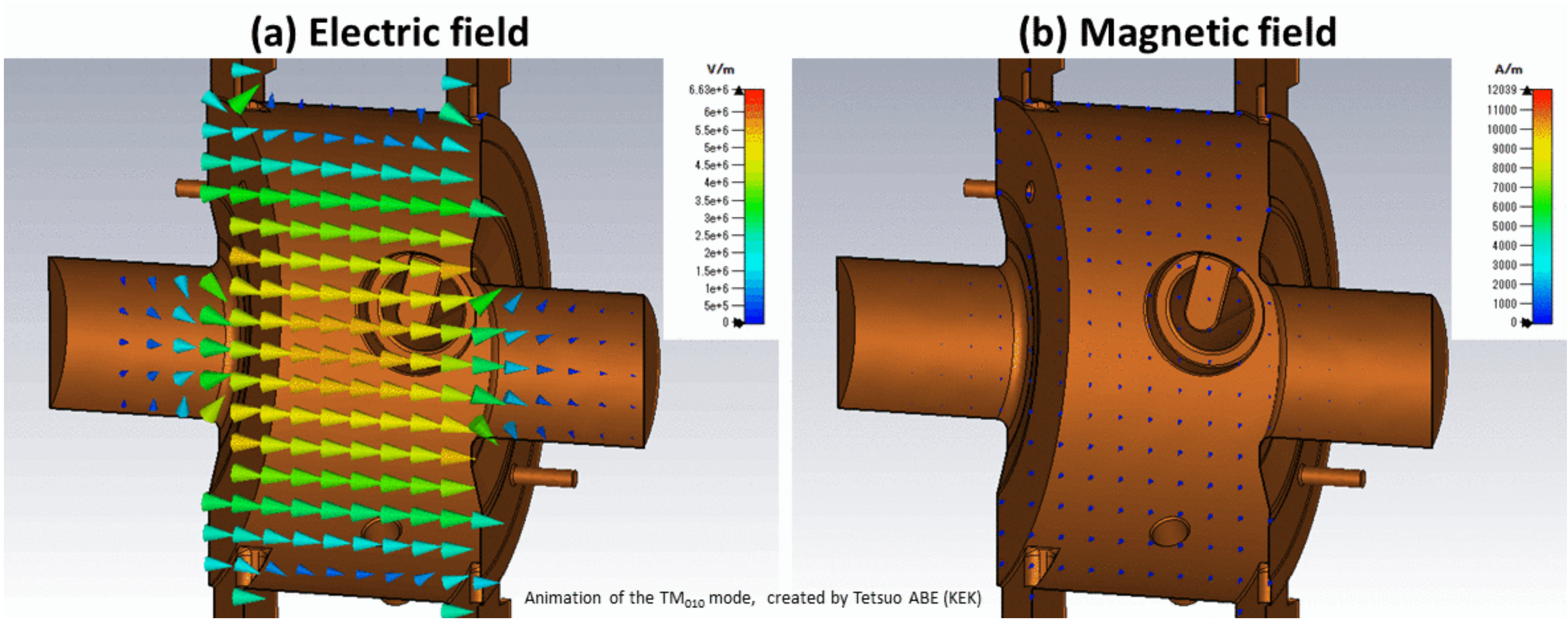
- RF cavity

  a metal resonator that can store electromagnetic fields

(i.1) basic principles of acceleration

- RF cavity

  a metal resonator that can store electromagnetic fields



(a) Electric field

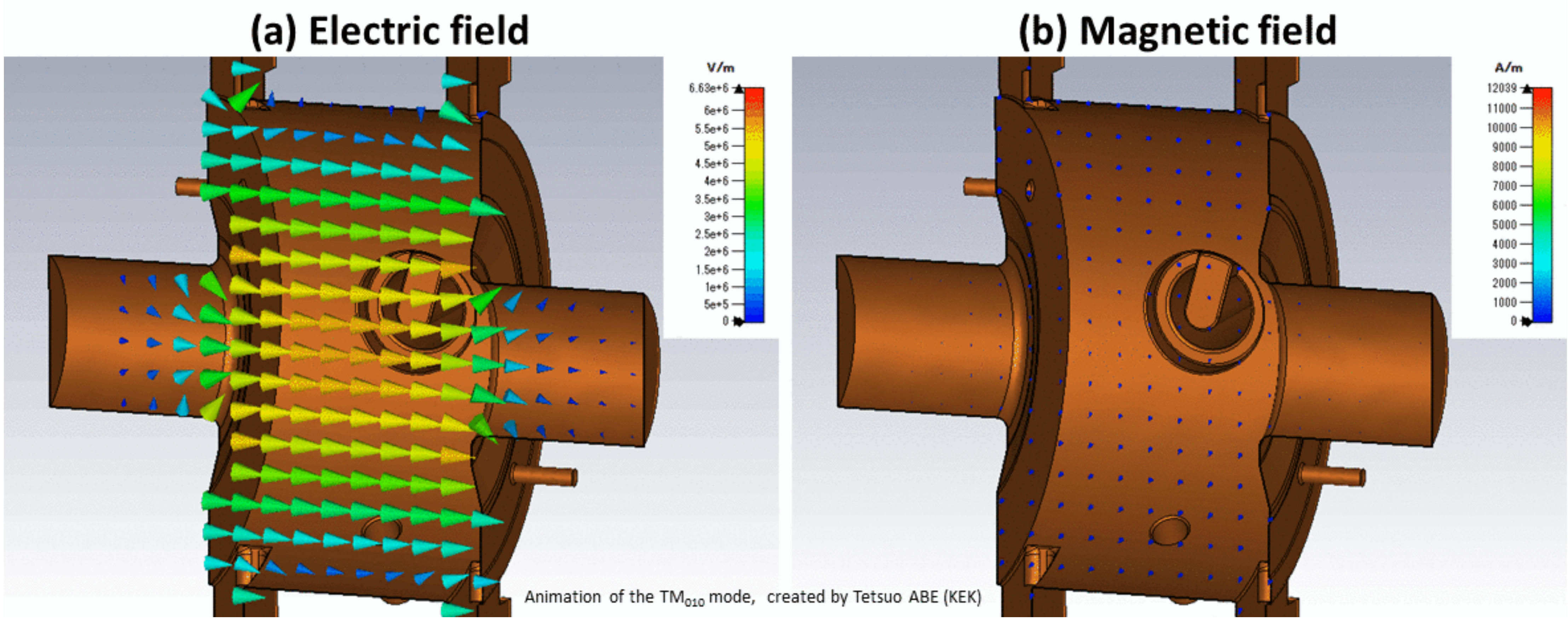
(b) Magnetic field

Animation of the TM_{010} mode, created by Tetsuo ABE (KEK)

(i.1) basic principles of acceleration

- RF cavity

a metal resonator that can store electromagnetic fields



(a) Electric field

(b) Magnetic field

Animation of the TM_{010} mode, created by Tetsuo ABE (KEK)

most important performance:

Acceleration Gradient [MeV/m]

Q0 (quality factor)~Peak Energy / Energy Loss

(i.1) basic principles of acceleration

- Klystron: produce the RF for cavity

$$L_i = v_i \frac{\tau_{\mathrm{RF}}}{2} = \frac{v_i}{c} \frac{\lambda_{\mathrm{RF}}}{2} = \beta_i \frac{\lambda_{\mathrm{RF}}}{2}$$

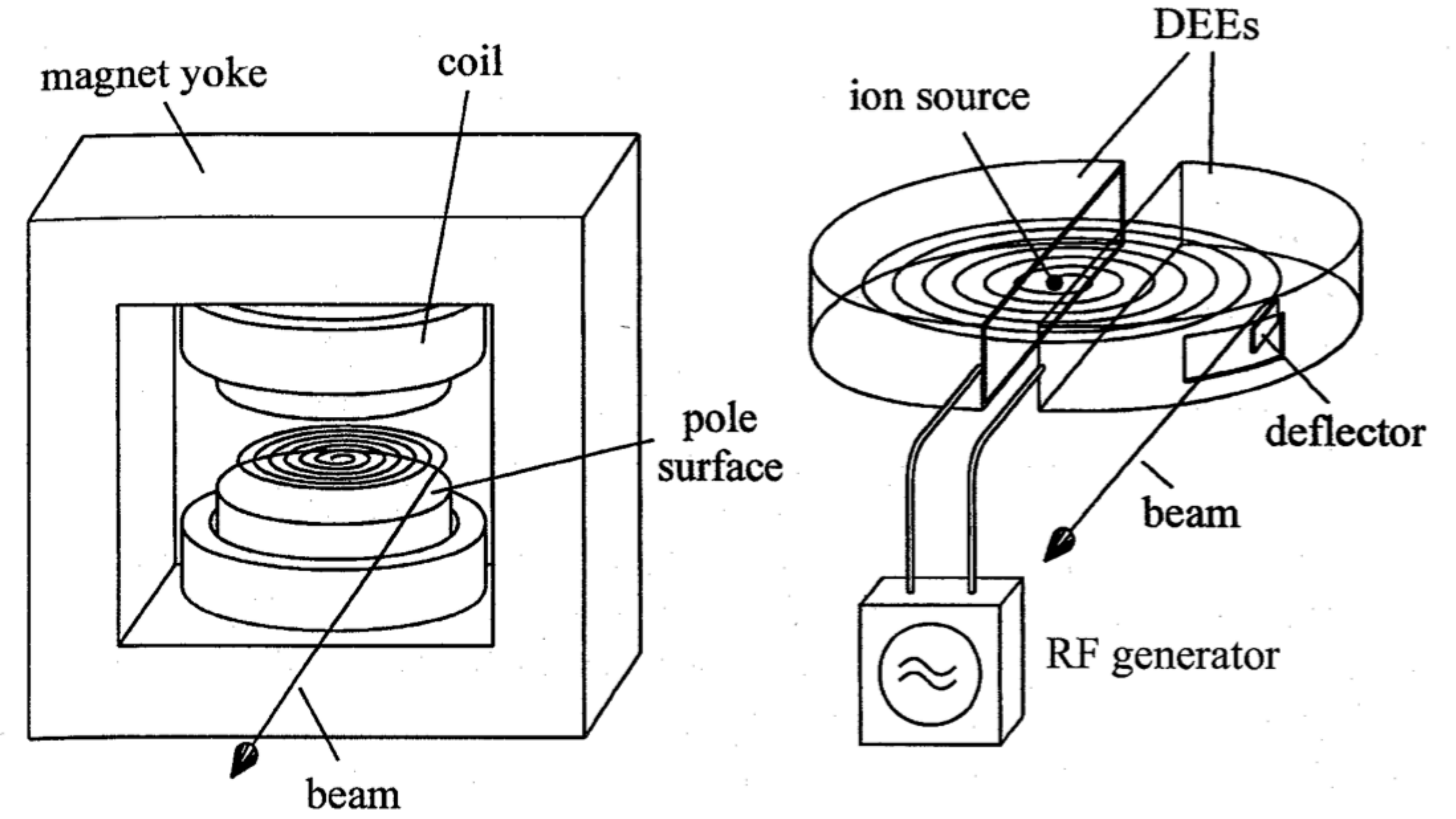
e.g. if for 10 MHz RF, $\lambda_{\mathrm{RF}} = 30\mathrm{m}$

it is crucial to develop high frequency & high power Klystron

was highly developed during WW II for radar system

(i.1) basic principles of acceleration

- Cyclotron



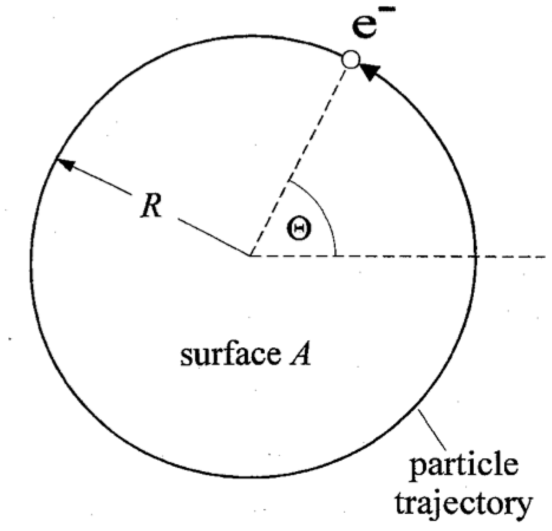
fixed frequency (for non-relativistic particle)

$$w = \frac{e}{m} B_z$$ matched exactly by RF

(i.1) basic principles of acceleration

- Betatron

increasing B-field rapidly, keeping particle orbit fixed



raw of induction -> no need any extra acceleration section

$$\oint \vec{E}\cdot \mathrm{d}\vec{r} = -\iint \frac{\mathrm{d}\vec{B}}{\mathrm{d}t}\cdot \mathrm{d}\vec{s}$$

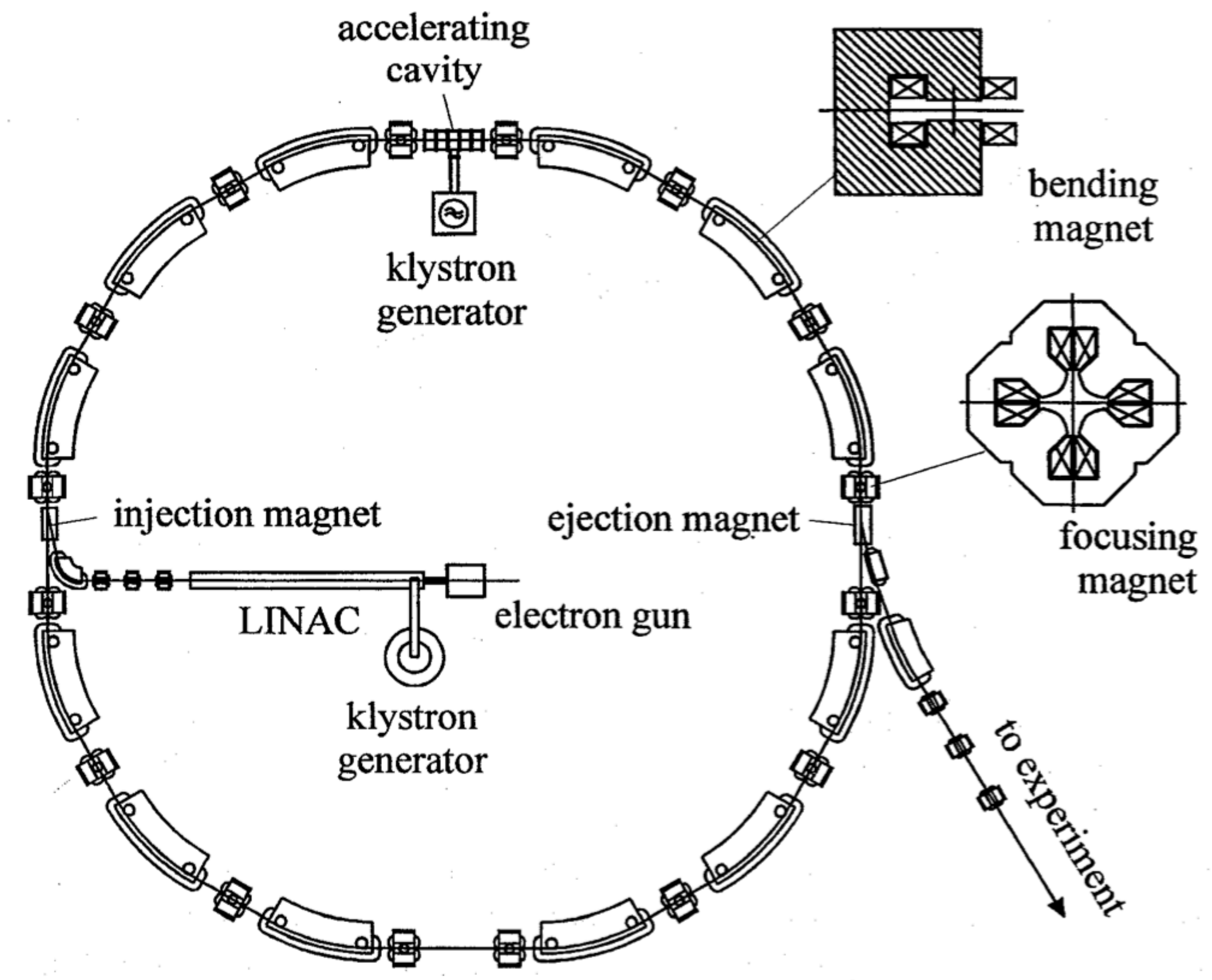
Widerøe’s betatron condition: $|B(t)| = 1/2 <|B(t)|> + |B_0|$

(i.1) basic principles of acceleration

- synchrotron

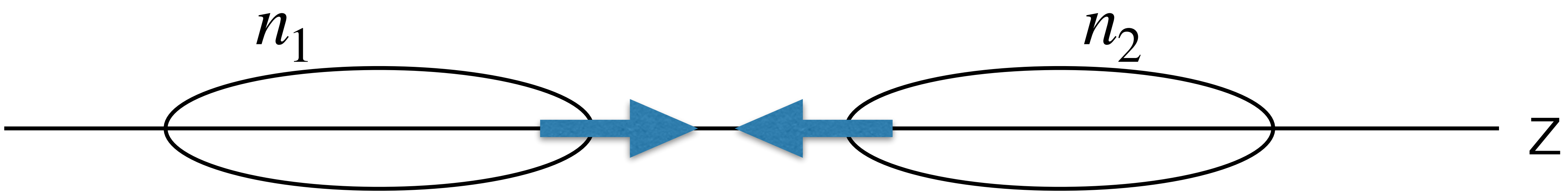
fixed orbit; magnet only around orbit; RF acc. section; synchronizing magnetic field with energy

$$R = \frac{E}{ecB}$$



(i.2) luminosity & beam dynamics

- Luminosity



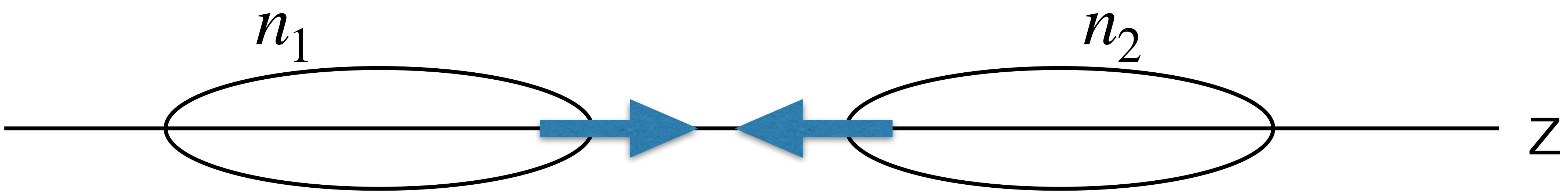
$$L = f_{coll}\frac{n_1 n_2}{4\pi\sigma_x^*\sigma_y^*}F$$

n1, n2: # particles in a bunch
f_{coll}: average collision frequency
F: ~1, geometric effect (crossing angle, etc)

σ_x, σ_y: bunch size in the transverse direction
most non-trivial part

(i.2) luminosity & beam dynamics

- emittance & beta function



$$L = f_{coll}\frac{n_1 n_2}{4\pi\sigma_x^*\sigma_y^*}F$$

$$\sigma_x^2 = \epsilon \cdot \beta$$

emittance

beta function

(i.2) luminosity & beam dynamics

- beam dynamics

in an accelerator, by construction particles follow a nominal trajectory (obit)

but particles in a beam will always have certain angular divergence, if not steered, after a long travel will hit the accelerator wall

beam steering is necessary

Lorentz force:

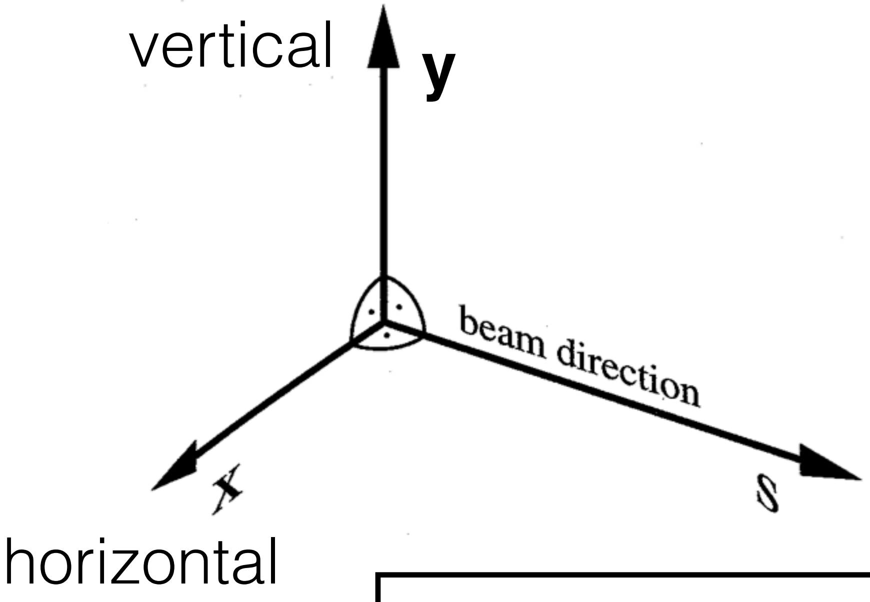
$$\boldsymbol{F} = e(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

v=c, for B=1T, E would be 300 MV/m to compete
beam steering is almost always done by magnets

(i.2) luminosity & beam dynamics

- magnets

take as example motion in horizontal plane



$$\frac{1}{R(x)} = \frac{e}{p} B_z(x)$$

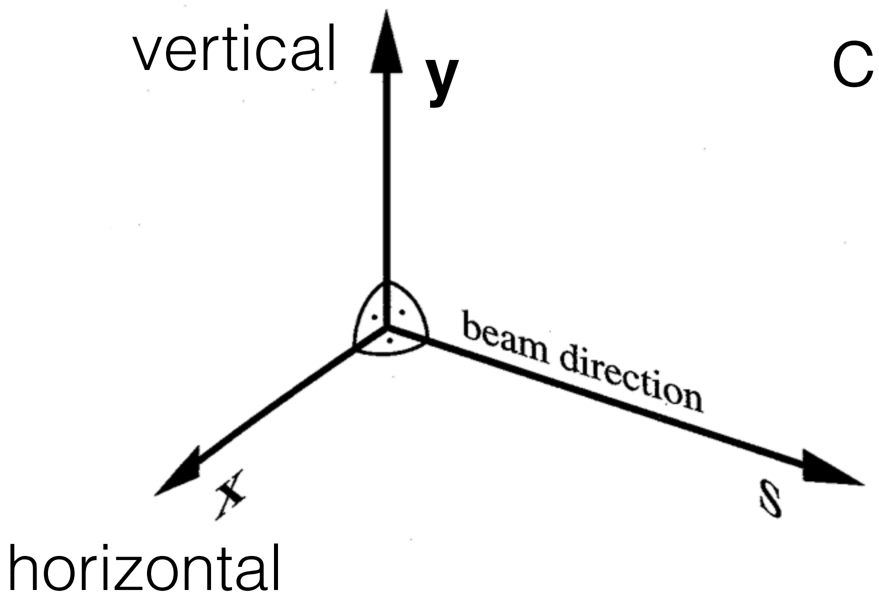
$$B_z(x) = B_{z0} + \frac{dB_z}{dx} x + \frac{1}{2!} \frac{d^2 B_z}{dx^2} x^2 + \frac{1}{3!} \frac{d^3 B_z}{dx^3} x^3 + \ldots .$$

$$\boxed{\begin{array}{cccccccccc}
\frac{e}{p} B_z(x) & = & \frac{e}{p} B_{z0} & + & \frac{e}{p} \frac{dB_z}{dx} x & + & \frac{1}{2!} \frac{e}{p} \frac{d^2 B_z}{dx^2} x^2 & + & \frac{1}{3!} \frac{e}{p} \frac{d^3 B_z}{dx^3} x^3 & + \ldots \\
 & = & \frac{1}{R} & + & kx & + & \frac{1}{2!} m x^2 & + & \frac{1}{3!} o x^3 & + \ldots . \\
 & & \text{dipole} & & \text{quadrupole} & & \text{sextupole} & & \text{octupole} &
\end{array}}$$

bending

focusing (k>0)
defocusing (k<0)

- linear beam optics



co-moving coordinate system (x,y,s)

s: along the nominal trajectory

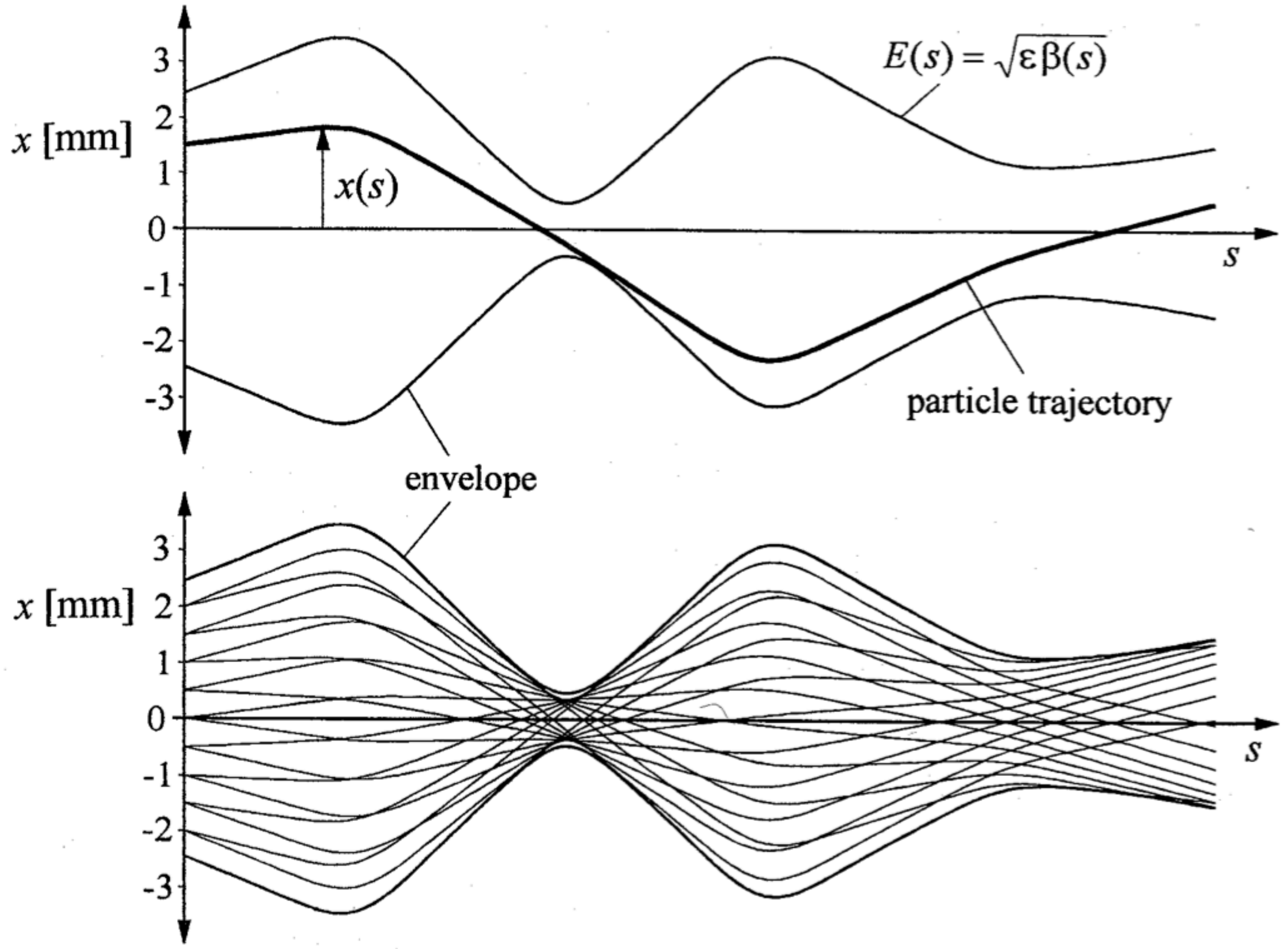
$$\boxed{\begin{aligned} x''(s) + (\frac{1}{R^2} - k(s))x(s) &= 0 \\ y''(s) + k(s)y(s) &= 0 \end{aligned}}$$

$$x' \equiv \frac{\mathrm{d}x}{\mathrm{d}s}$$

(betatron oscillations)

(i.2) luminosity & beam dynamics

- back to luminosity



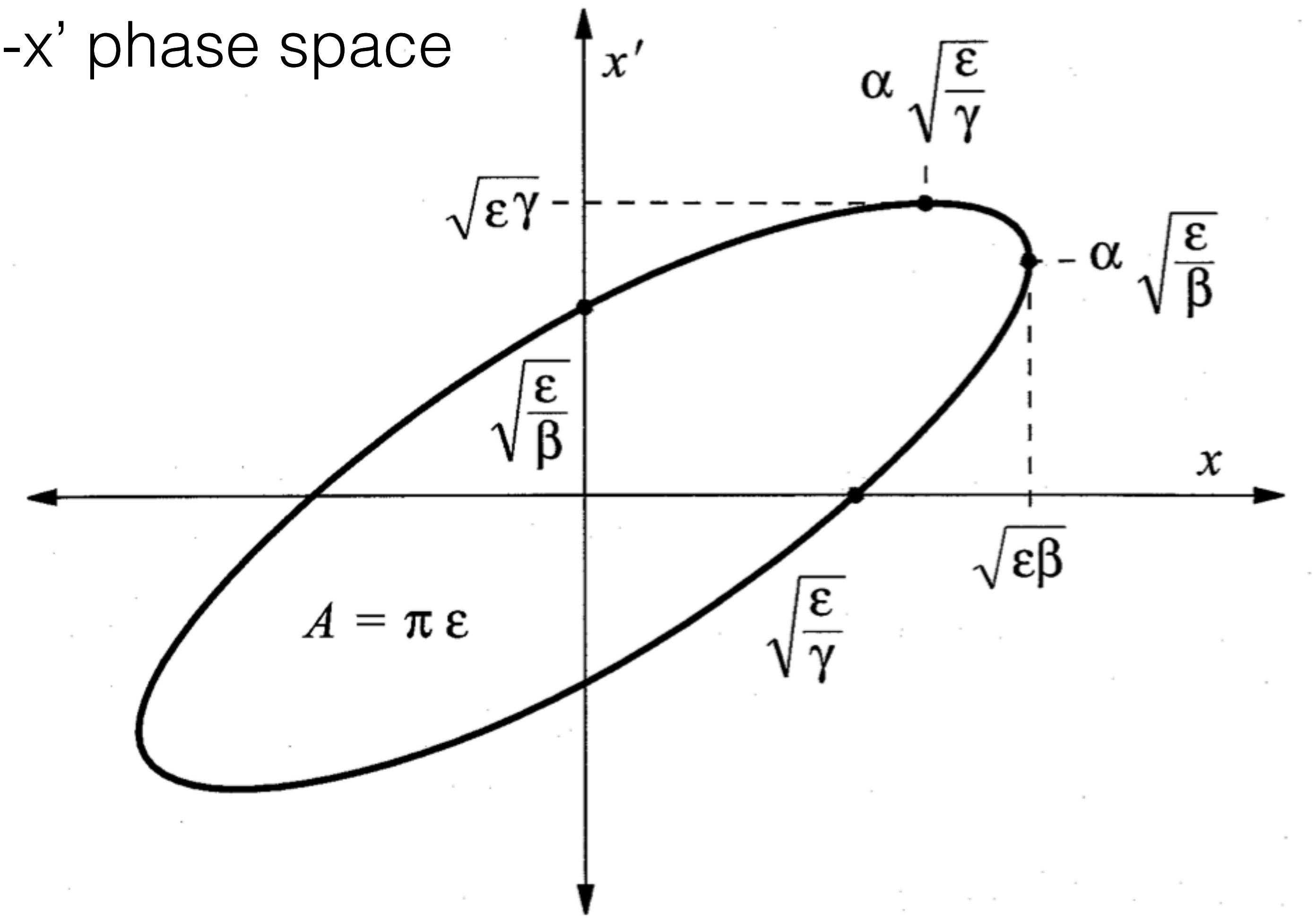
$$L = f_{coll}\frac{n_1 n_2}{4\pi\sigma_x^*\sigma_y^*}F$$

$$\sigma_x^2 = \epsilon \cdot \beta$$

(i.2) luminosity & beam dynamics

- back to luminosity

x-x' phase space



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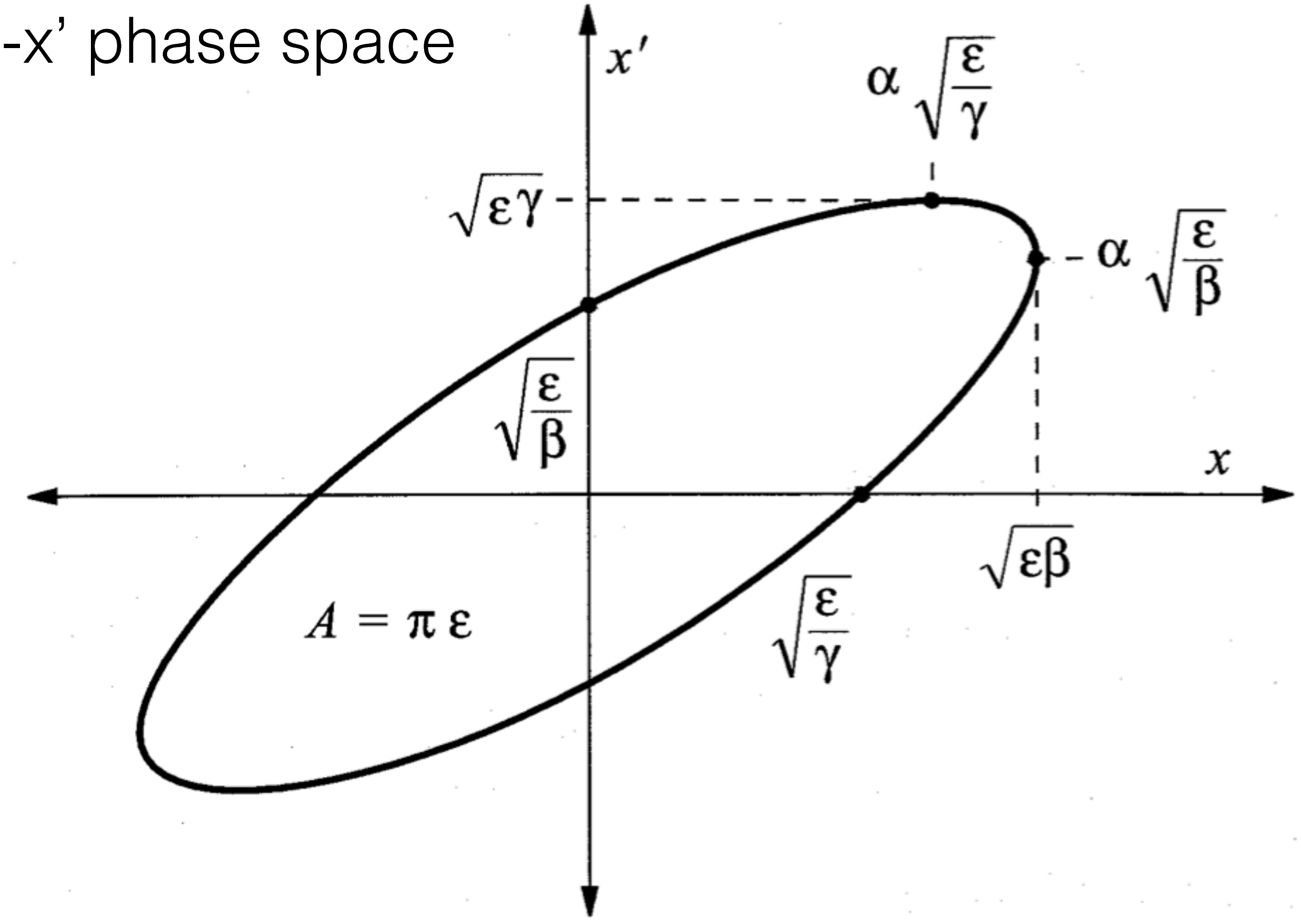
back to luminosity

x-x’ phase space



$$L = f_{coll}\frac{n_1 n_2}{4\pi\sigma_x^*\sigma_y^*}F$$

$$\sigma_x^2 = \epsilon\cdot\beta$$

emittance x π = area of the ellipse

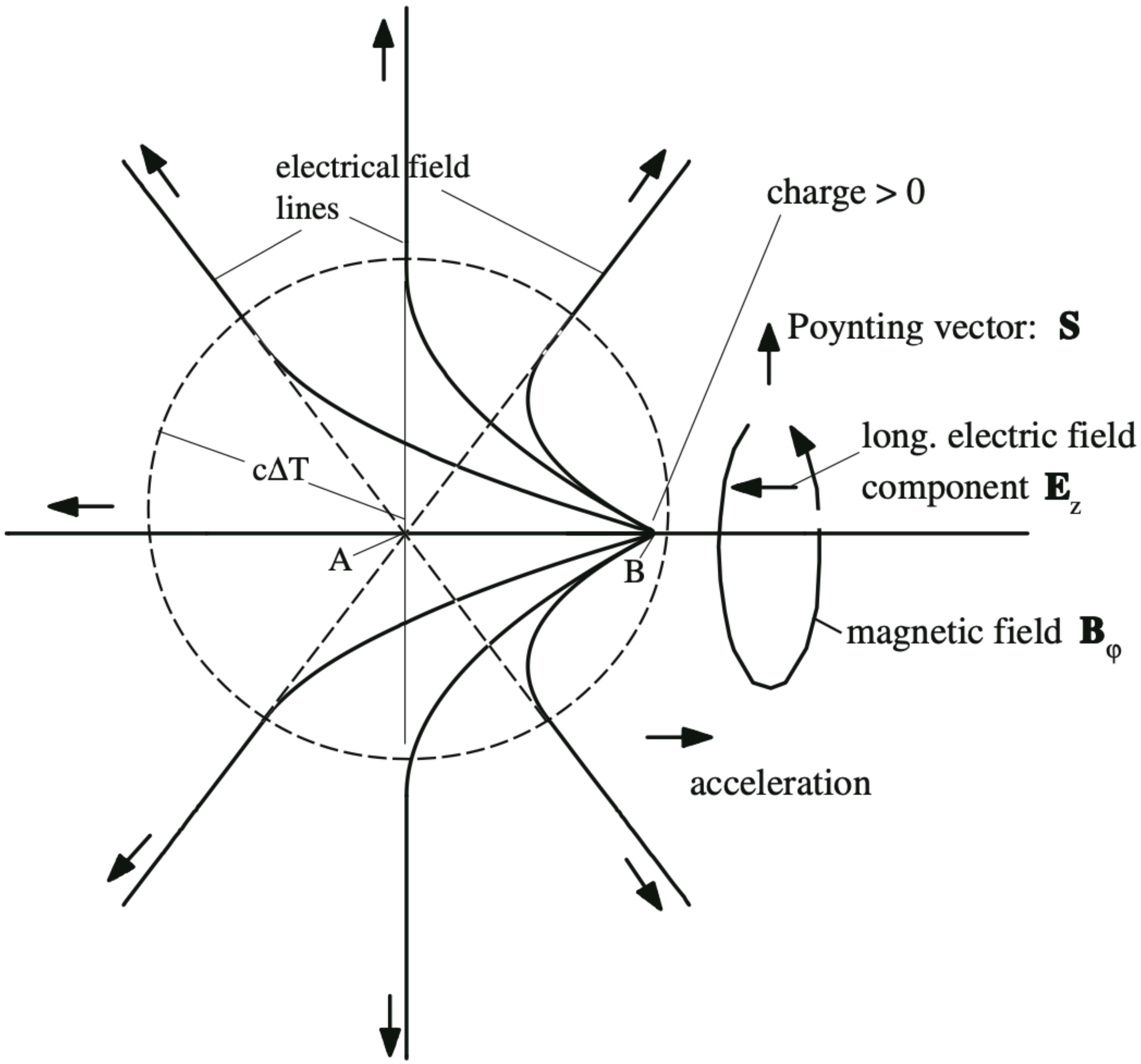
(i.3) synchrotron radiation

- fundamental process

an accelerating charge

distort electromagnetic field

speed of light c is finite



propagation of distorted electromagnetic field = synchrotron radiation

(was first seen by eye at a synchrotron)

(i.3) synchrotron radiation

- qualitatively: linear vs circular

synchrotron radiation depends on size of acceleration |***a***|

at a linear accelerator

for E=100GeV, G=30MeV/m; |***a***|=1.4×10^{3} m/s^2

at a circular accelerator

for E=100GeV, R=100km; |***a***|=9×10^{11} m/s^2

|***a***| differ enormously

(i.3) synchrotron radiation

- synchrotron radiation power

at a circular accelerator

$$P = \frac{e^2 c}{6\pi\epsilon_0} \frac{1}{(m_0 c^2)^4} \frac{E^4}{R^2}$$

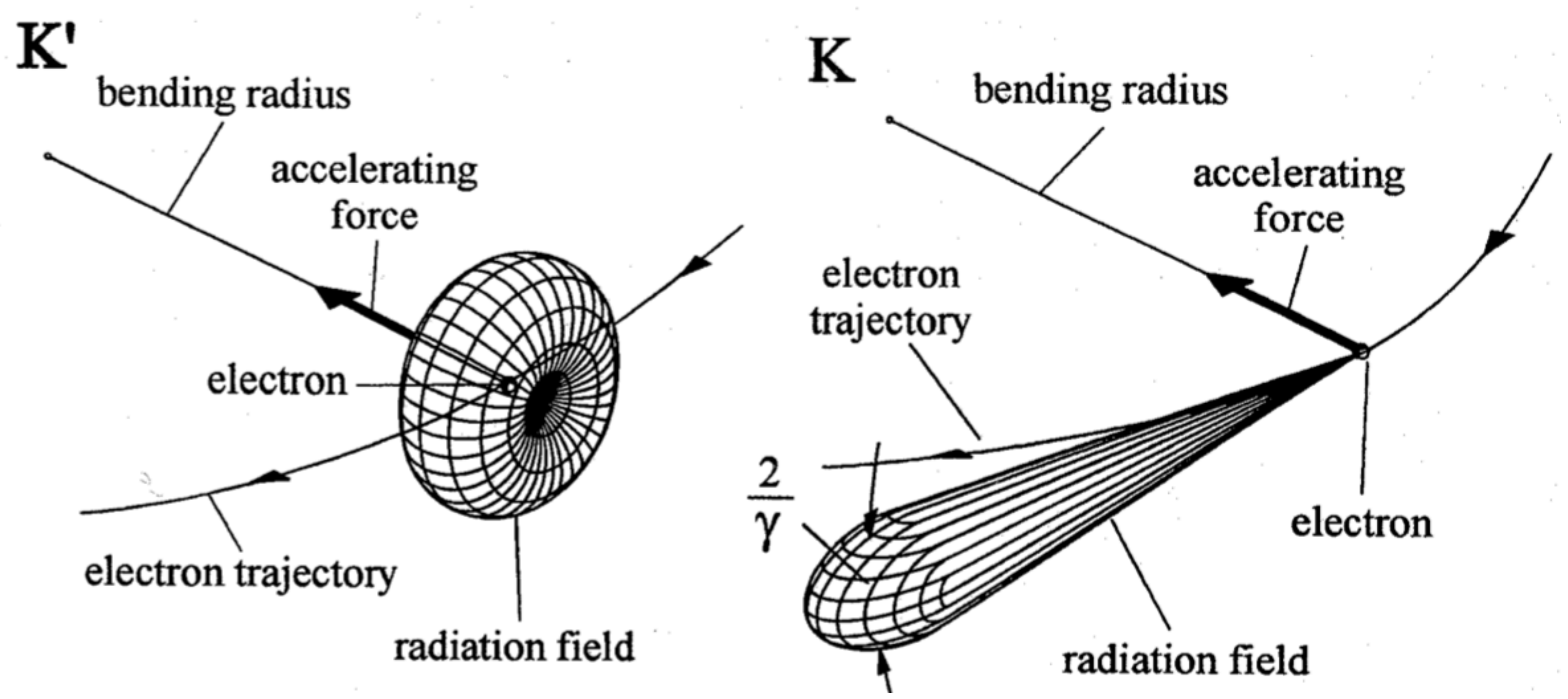
energy loss per turn (for electron)

$$\Delta E[\mathrm{keV}] = 88.5 \frac{E^4[\mathrm{GeV}]^4}{R[\mathrm{m}]}$$

(i.3) synchrotron radiation

- angular distribution

$$\tan\theta = \frac{1}{\gamma}$$



E.O.M. frame

Lab frame

(i.3) synchrotron radiation

- crucial for linear colliders as well

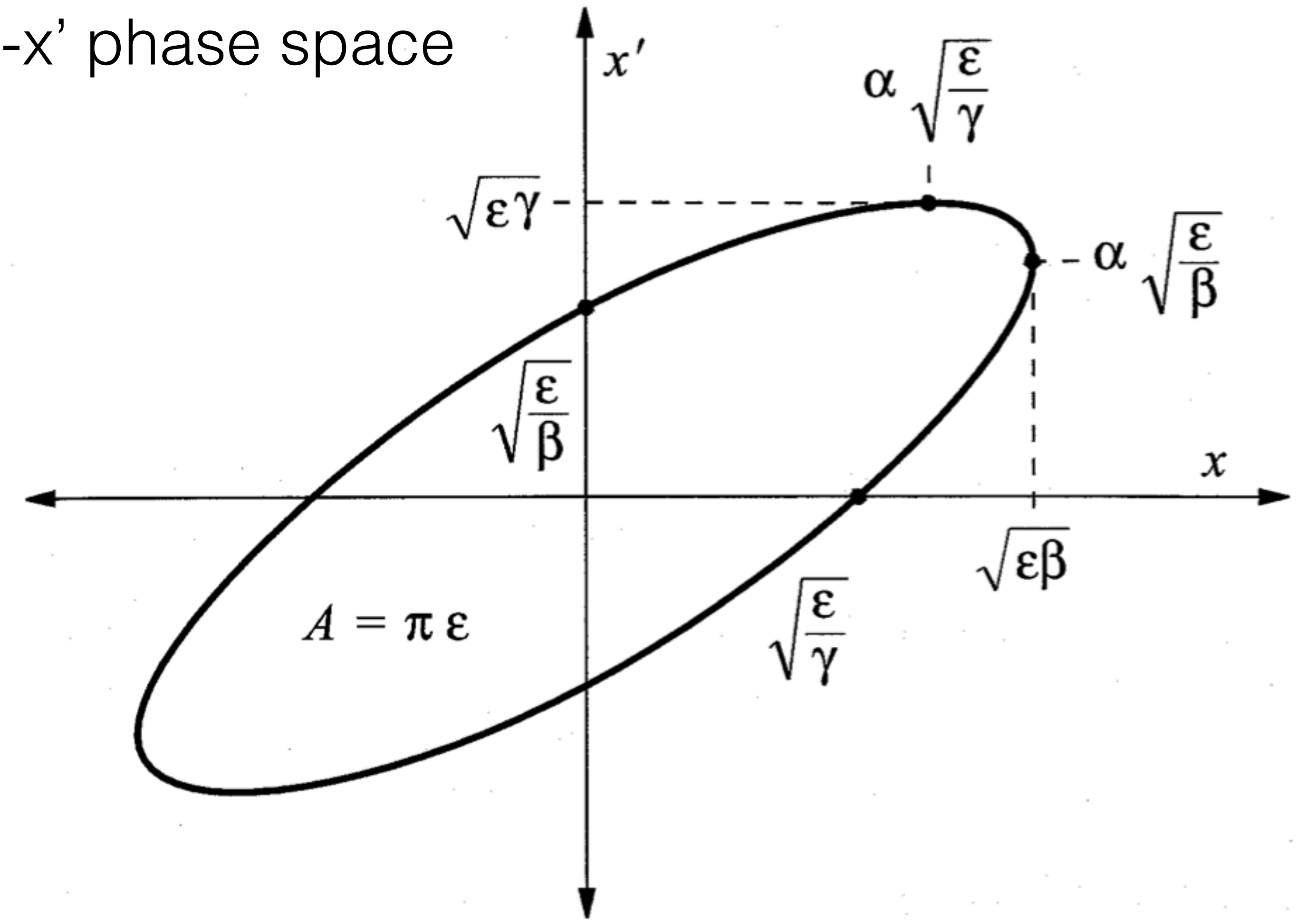
damping ring: synchrotron radiation can reduce emittance

(i.3) synchrotron radiation

- crucial for linear colliders as well

damping ring: synchrotron radiation can reduce emittance

x-x’ phase space



(i.4) beam polarization

- definitions

$$P = \frac{N_R - N_L}{N_R + N_L}$$

$N_{R/L}$: number of R/L-handed e-(e+)

can be longitudinal or transverse

polarized electron source:

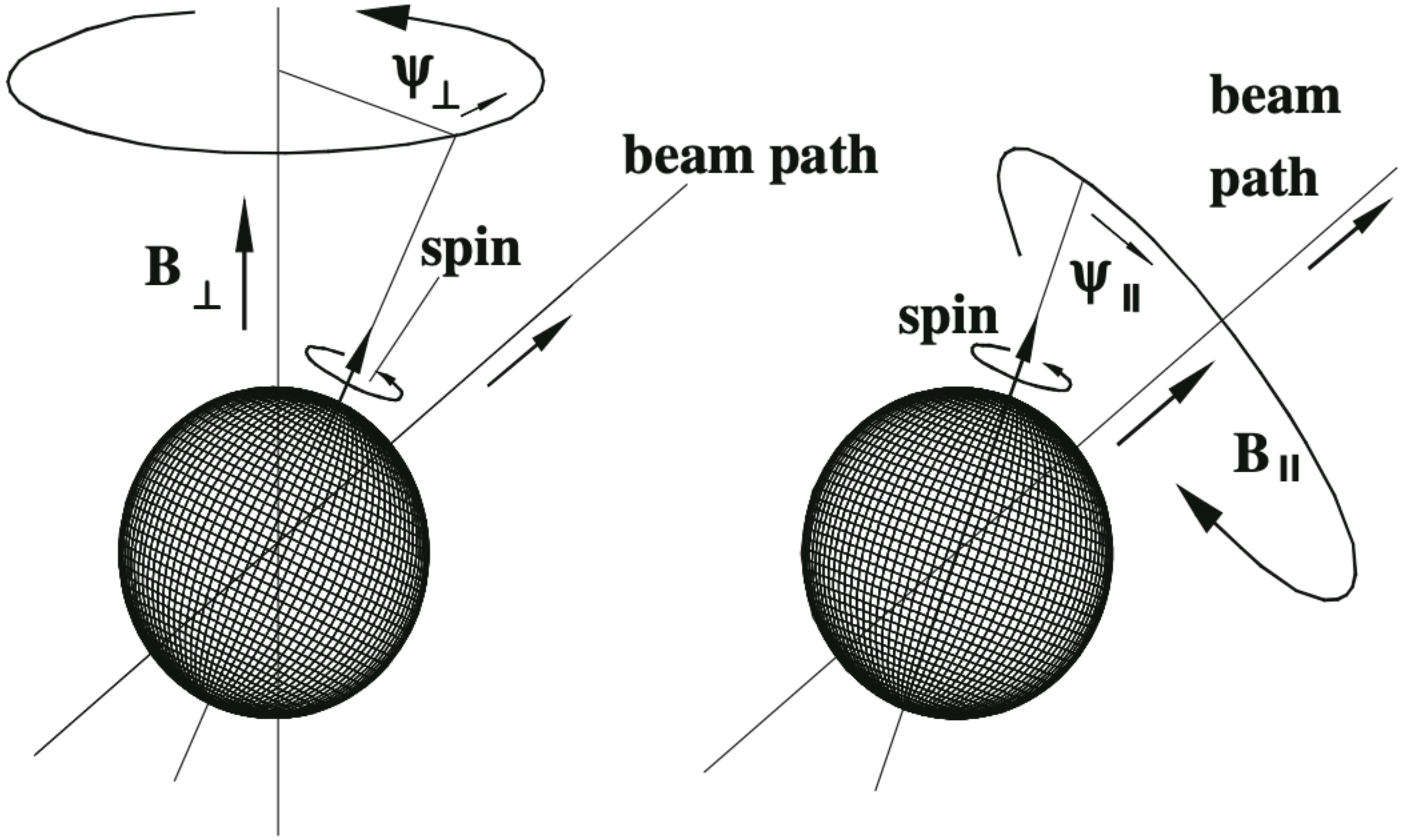
a polarized laser to hit a photocathode
P=80% demonstrated at SLC

polarized positron source:

undulator @ ILC; P=30%

(i.4) beam polarization

- precession of particle spin under B-field



at a linear collider, to preserve longitudinal beam polarizations,

spin rotators are needed before & after damping ring

at a circular collider, transverse beam polarizations are possible

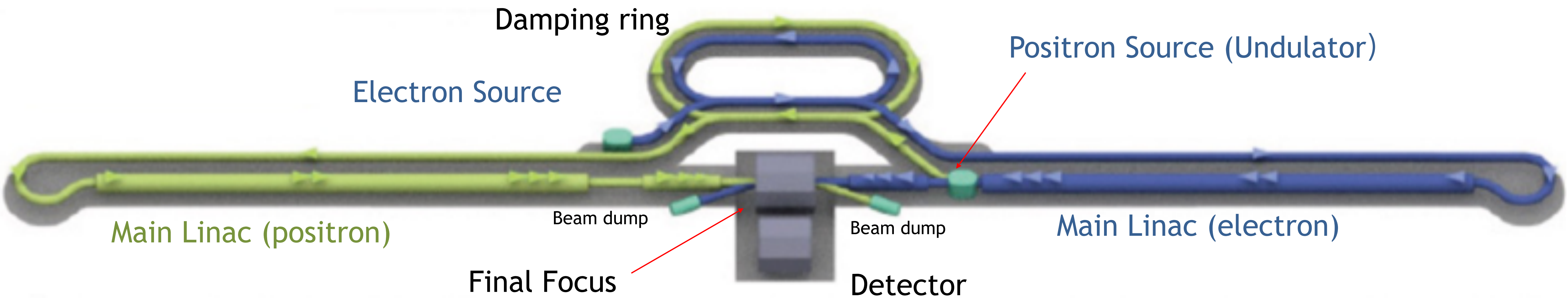
(i.5) ILC

- International Linear Collider (ILC)

key technologies

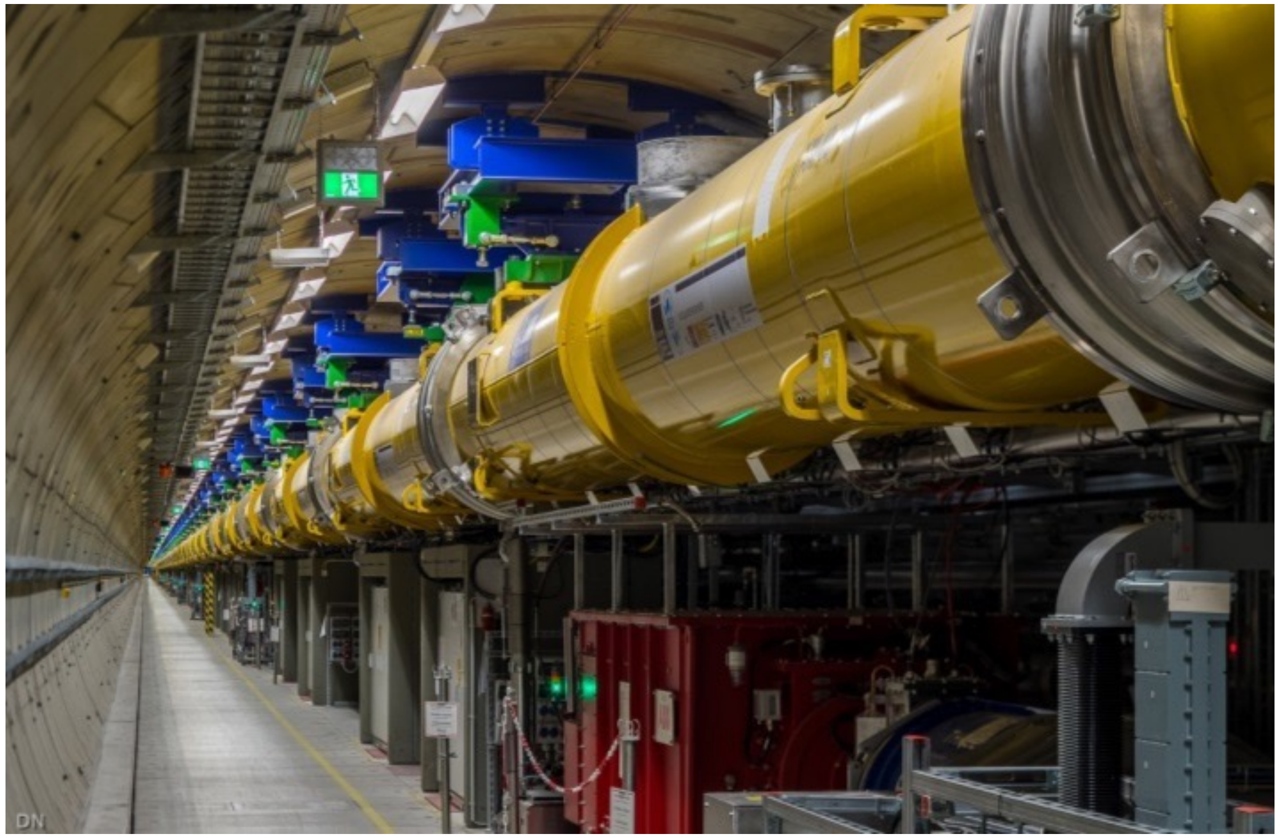
Superconducting RF: 1.3GHz; ~31.5MeV/m

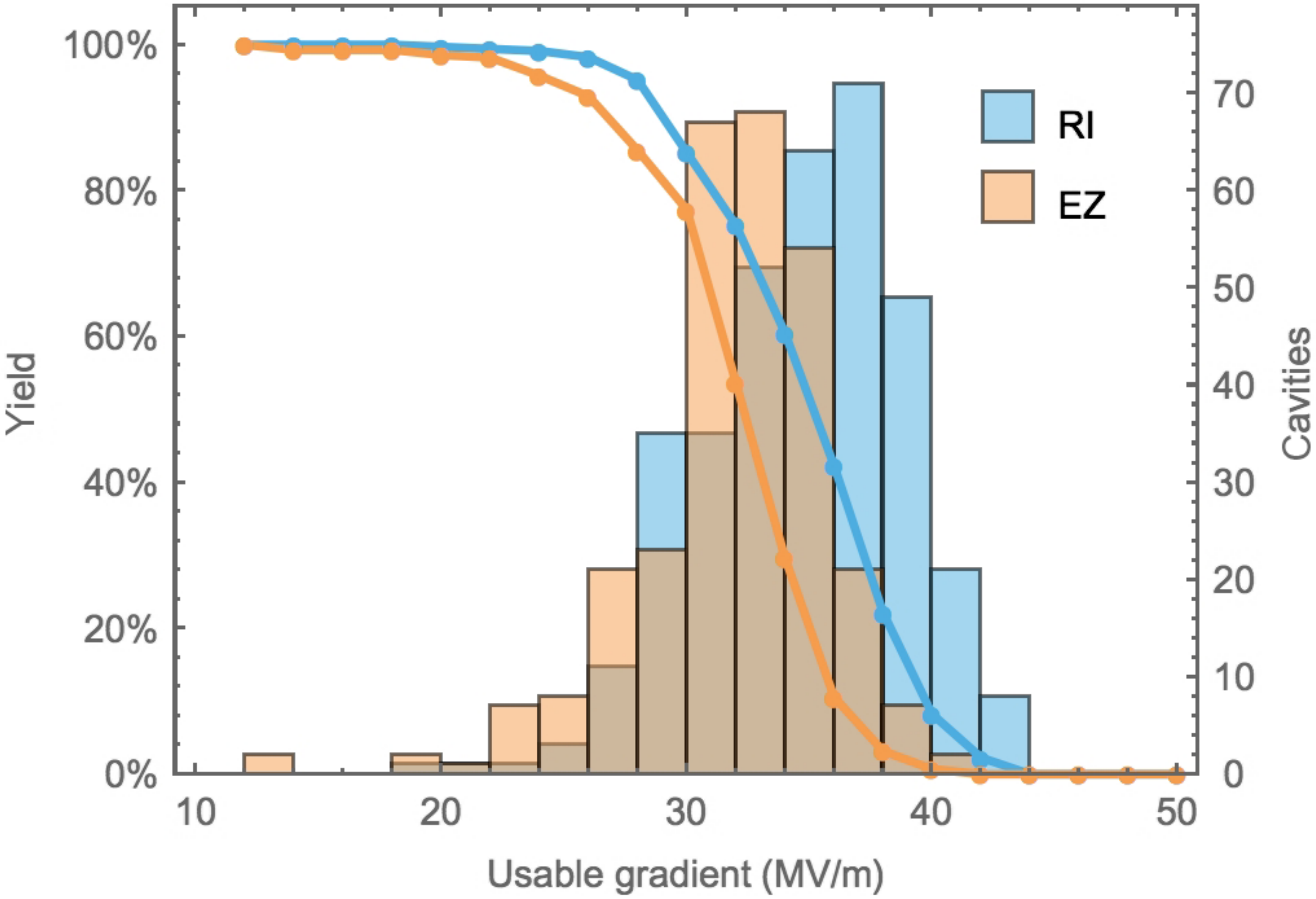
Nano beam: σ_y~8nm; σ_x~500nm



(i.5) ILC

- SRF technology: mature & robust

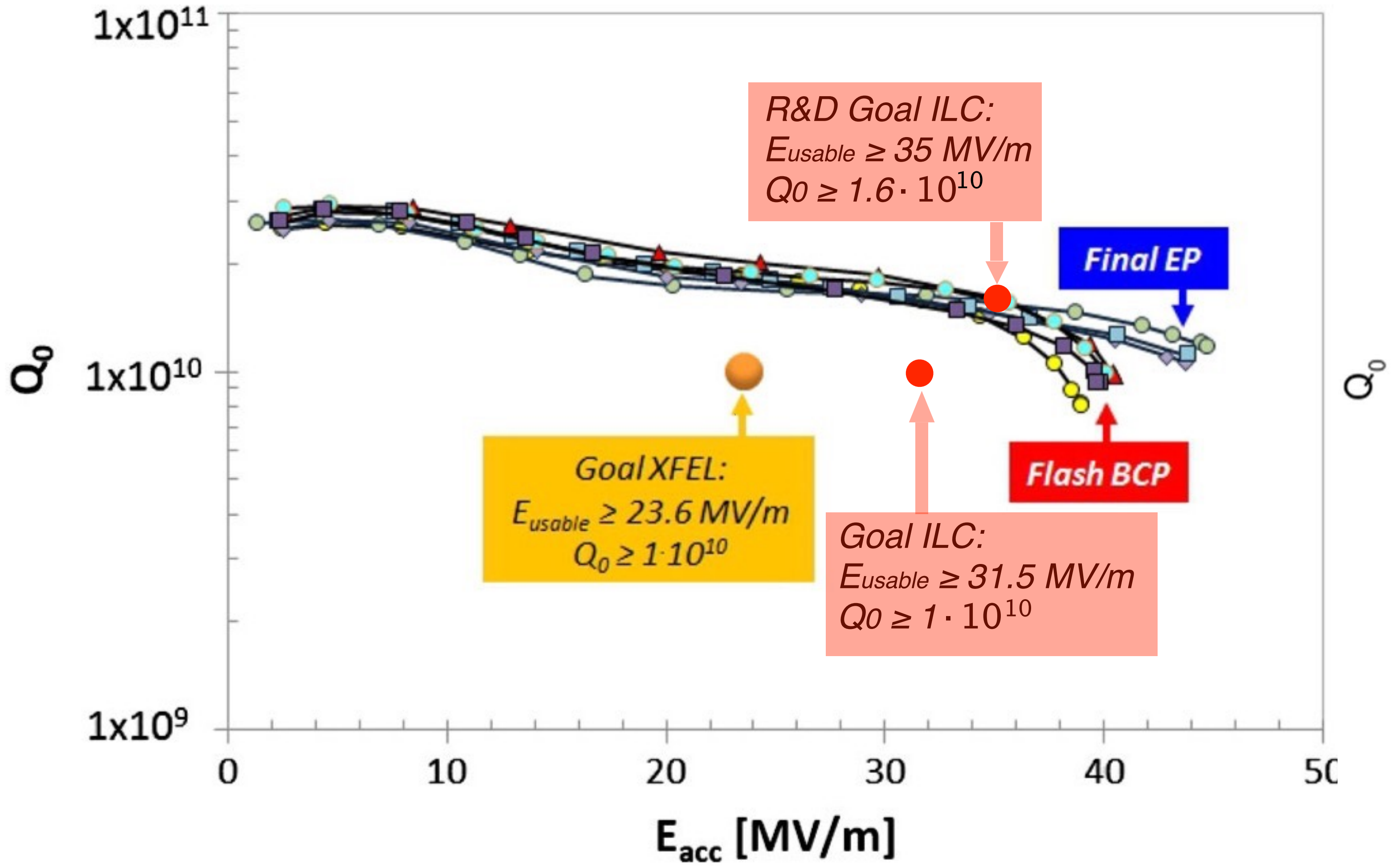




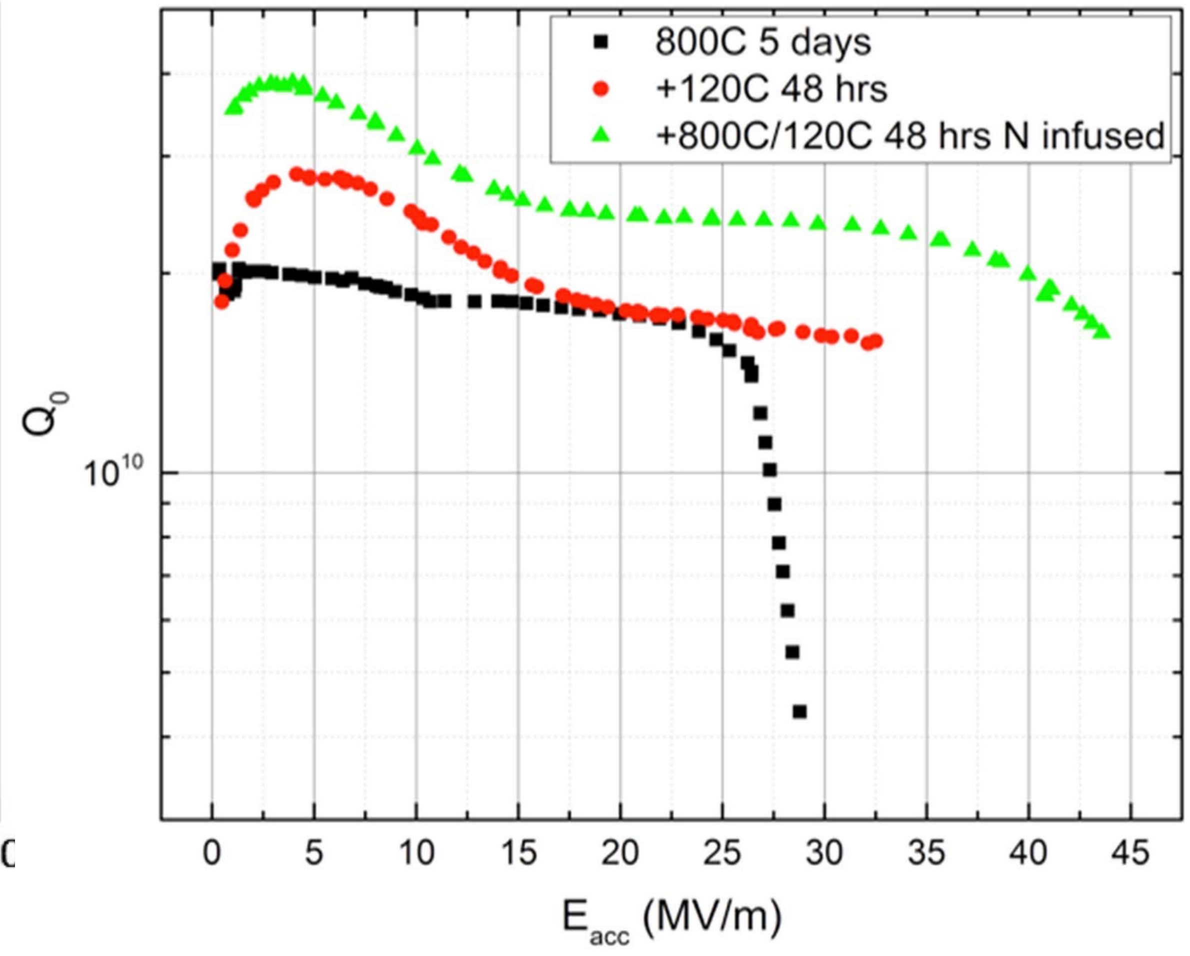
~800 cavities installed & running @ E-XFEL

(i.5) ILC

- SRF technology: potential for further improvement



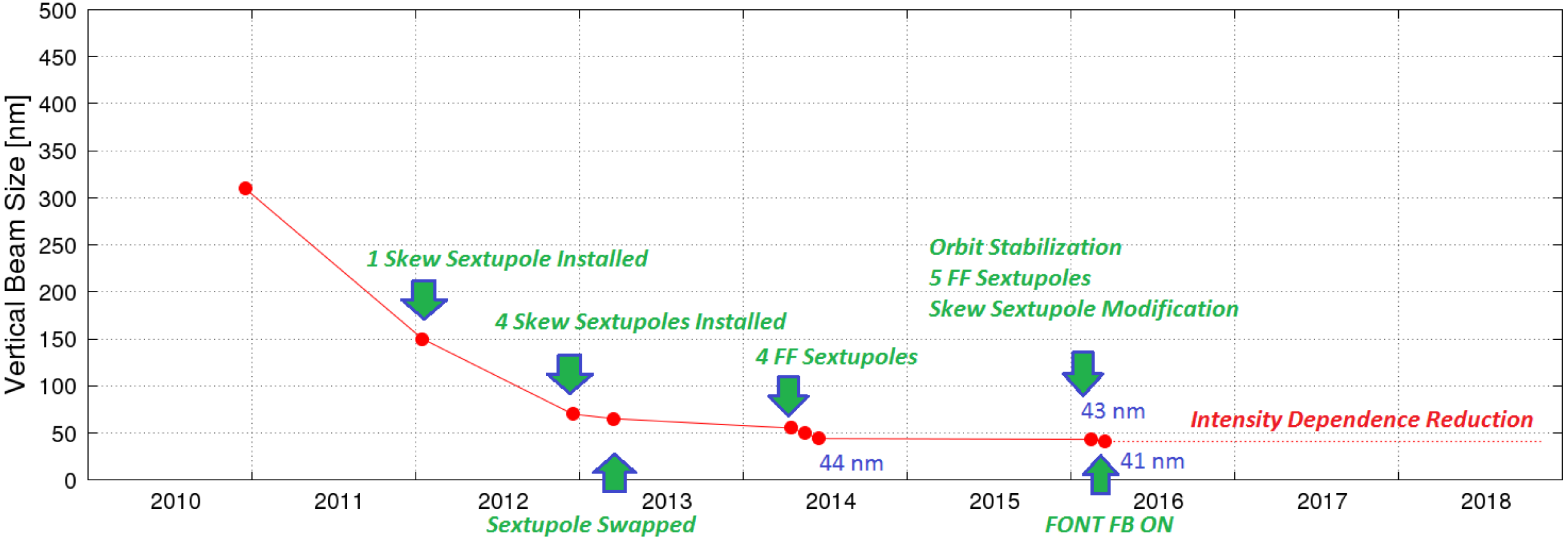
some of the best cavities
produced for E-XFEL



ongoing R&D
Nitrogen infusion

(i.5) ILC

- Nano beam: demonstration @ ATF2, KEK



37nm @ 1.3 GeV ~ 5.7nm @ 250 GeV

status of ILC

- it’s been a too long way (>30 years)
- very recently (January 30, 2020), ILC finally passed the barrier from academic side (SCJ Master Plan 2020: got to hearing)
- extremely positive messages from ministers (cabinet & MEXT)
- very positive statement by ICFA 2020 (released this morning); see the details from ICFA homepage
- (personally) ILC is about to fly soon (just get onboard)

(ii) introduction to detectors

(ii.1) passage of particles through matter

(ii.2) type of detectors

(ii.3) detector concepts @ ILC

(ii.4) detector simulation / reconstruction

(ii.1) passage of particle through matter

- electronic energy loss by charged particles (m>m_e)

from ionization, atomic excitation

Bethe’s equation:

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] .$$

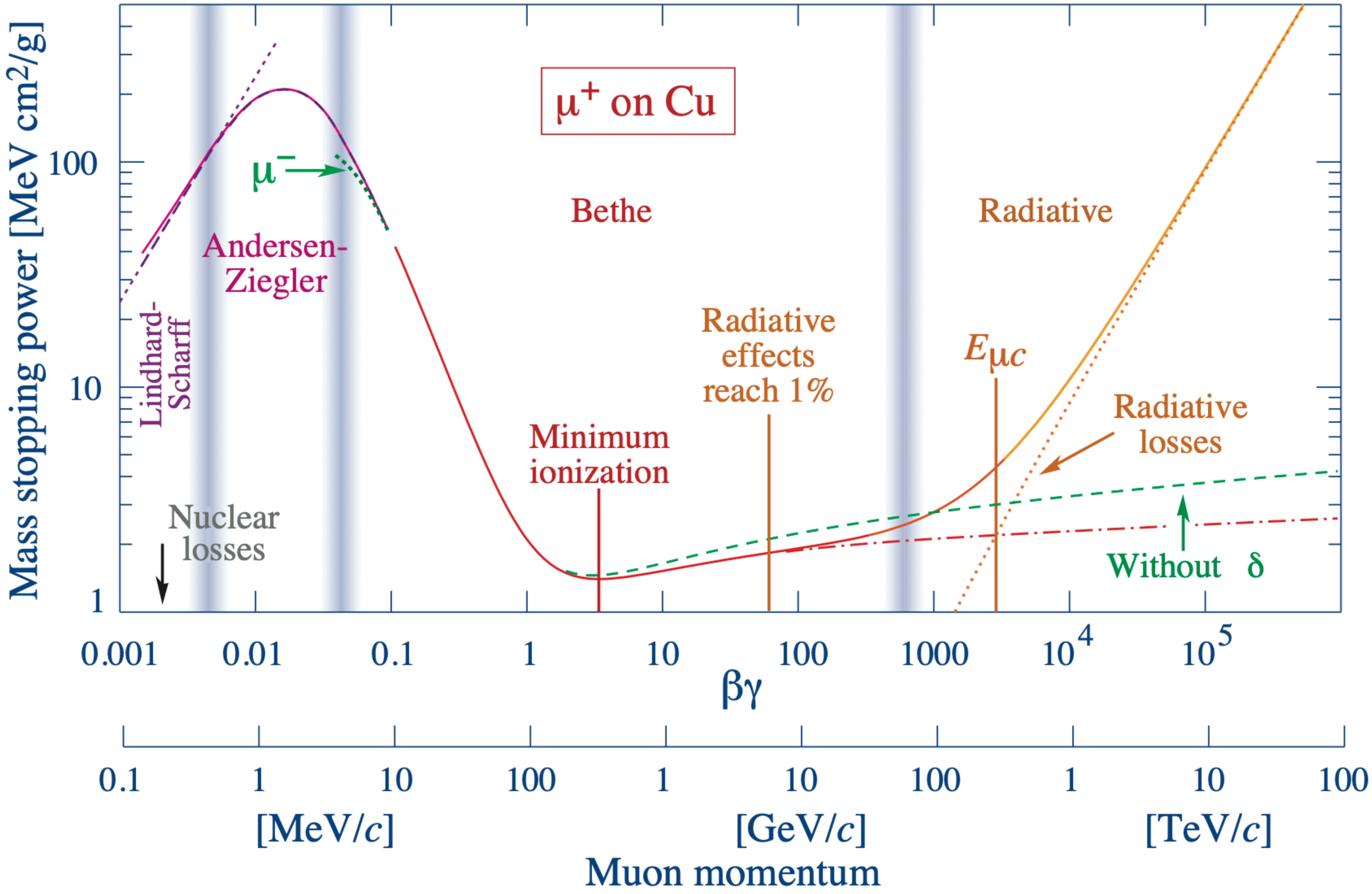
mass stoping power

linear stoping power: x ρ

logarithmic increase for relativistic particles

(ii.1) passage of particle through matter

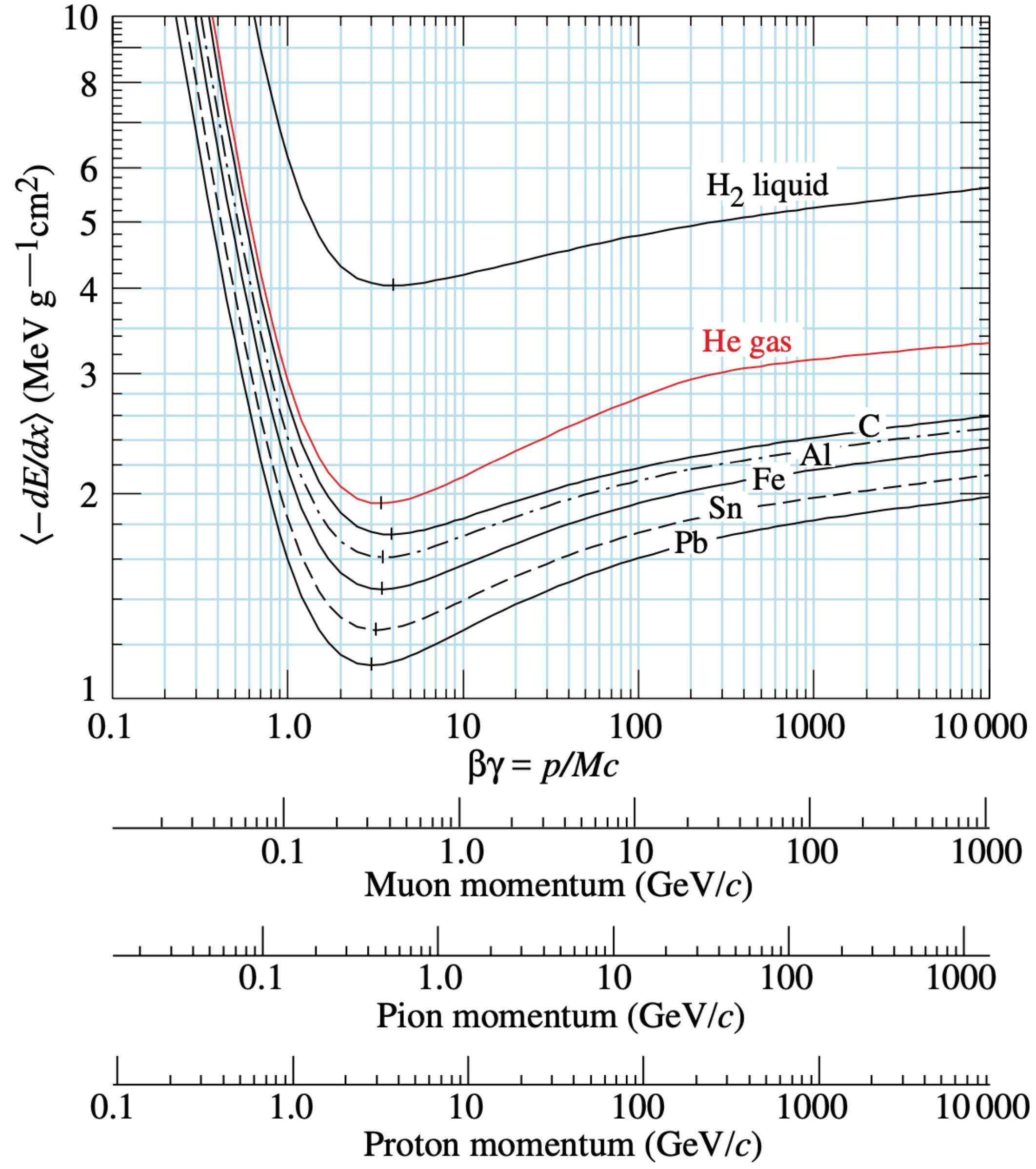
- electronic energy loss by charged particles



(ii.1) passage of particle through matter

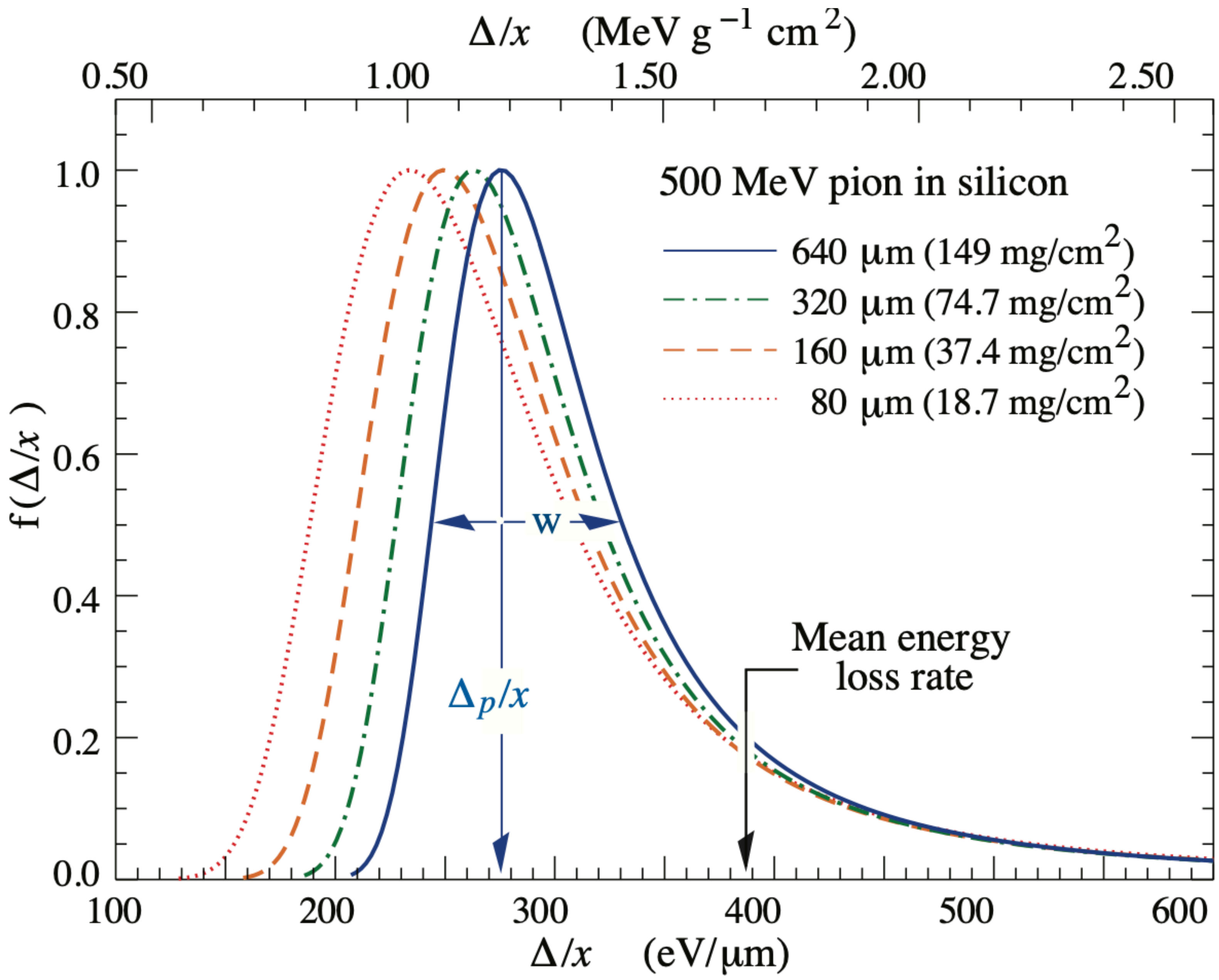
- concept of MIP

1 MIP: an energy deposition of one minimum ionizing particle



(ii.1) passage of particle through matter

- dE/dx fluctuations: Landau distribution



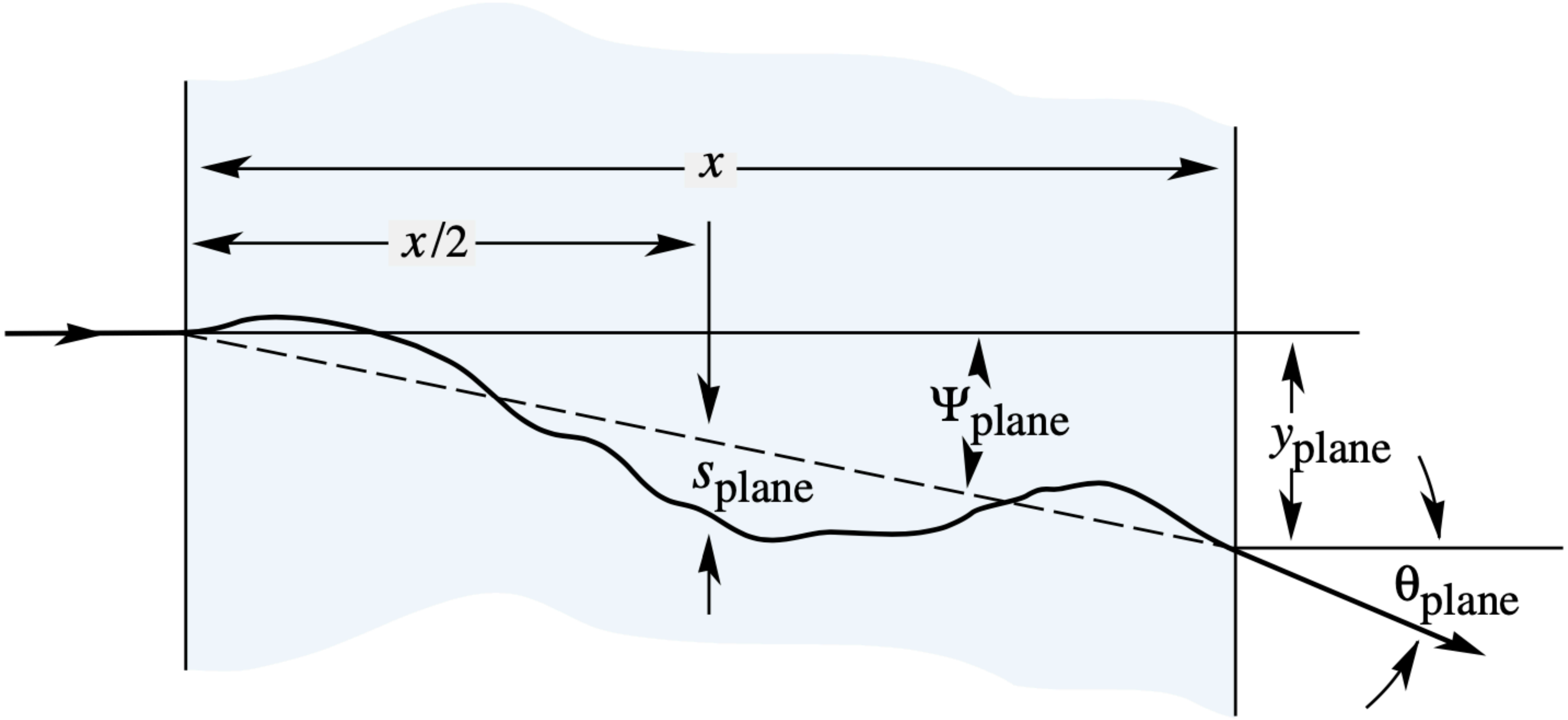
experimentally, the most probable energy loss should be used

(ii.1) passage of particle through matter

- multiple scattering

a charged particle is deflected by many small scatters

most due to Coulomb scattering from nuclei



important for detector design: material budget

(ii.1) passage of particle through matter

- electromagnetic shower (electron / photon)

electron at rest can’t radiate a photon: violate 4-p conservation

$$e^-(P) \to e^-(p') + \gamma(q)$$

$$\frac{m_e^2}{E}$$

at relativistic regime, it becomes possible by requiring a small amount of energy transfer from nuclei

for a GeV electron, ~keV transfer

this is Bremsstrahlung

similarly, photon can convert to e+e-: pair production

(ii.1) passage of particle through matter

- radiation length X_0

to characterize energy loss from bremsstrahlung or pair production

use the averaged effects like <dE/dx> is not proper

since they occur infrequently but can loose energy significantly

properer characterization

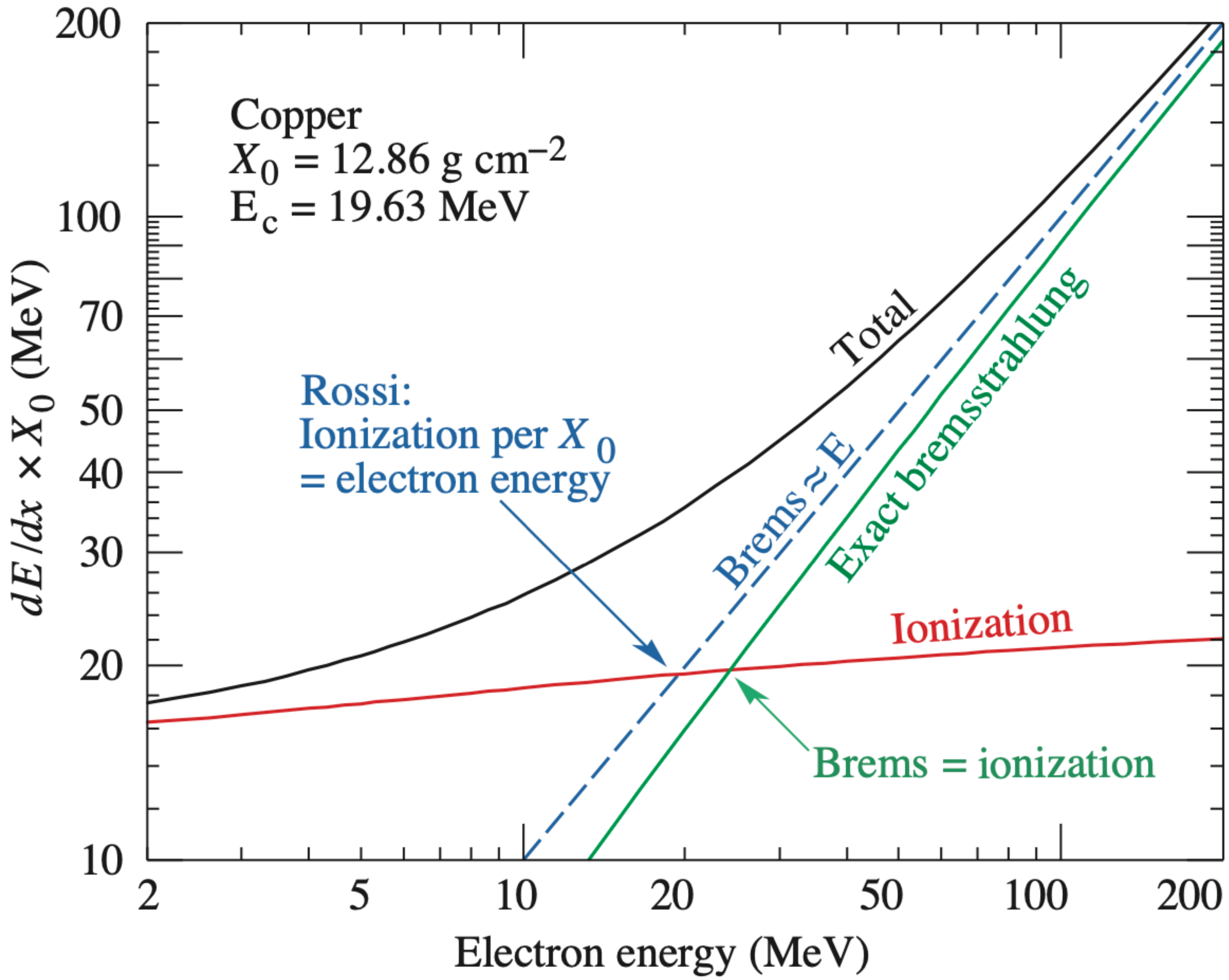
radiation length (X_0): the mean distance an electron loses all but 1/e

$$E = E^{-d/X_0}$$

(ii.1) passage of particle through matter

- critical energy E_c

bremsstrahlung energy loss ~ ionization loss

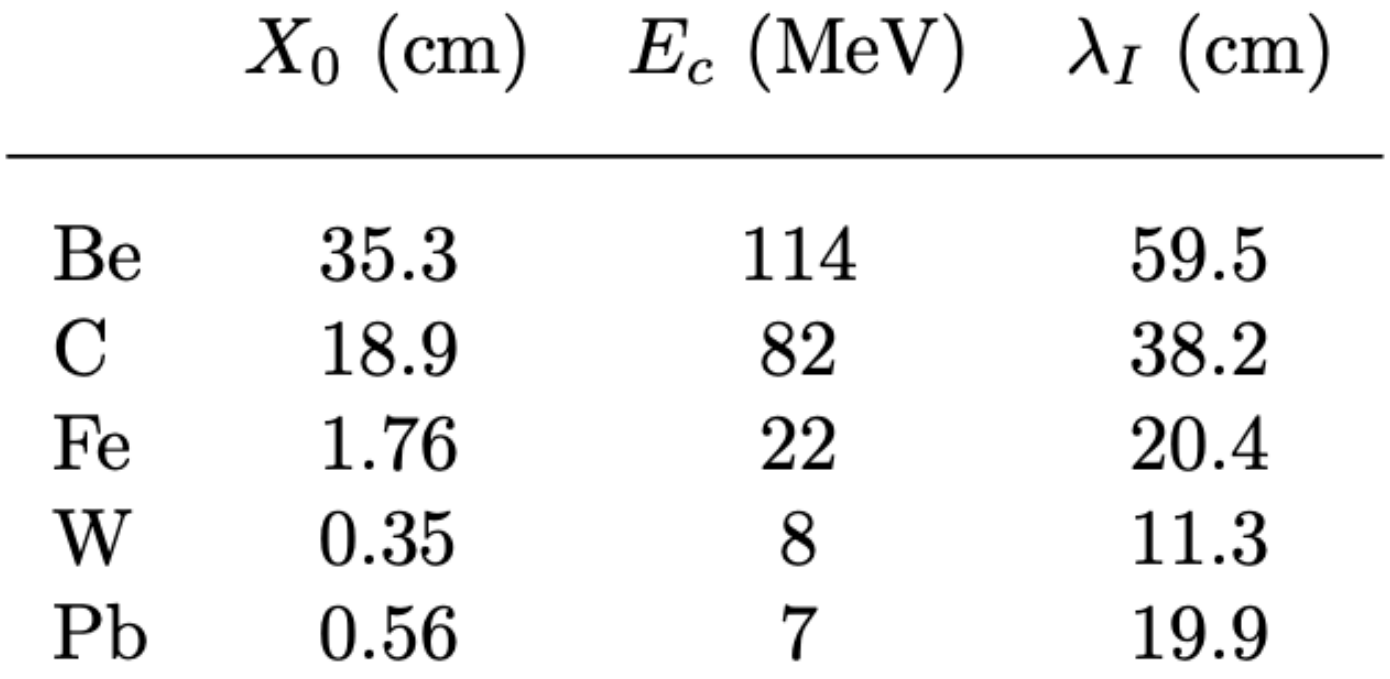


(ii.1) passage of particle through matter

- hadronic shower (π/K/p/n)

strong interaction with nuclei; more complicated shower structure

characterize by interaction length λ_I (in a way similar to X_0)

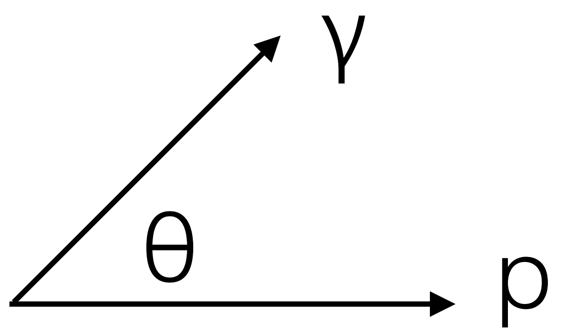


	X_0 (cm)	E_c (MeV)	λ_I (cm)
Be	35.3	114	59.5
C	18.9	82	38.2
Fe	1.76	22	20.4
W	0.35	8	11.3
Pb	0.56	7	19.9

(ii.1) passage of particle through matter

- Cherenkov radiation

when particles move faster than light in the matter



$$\cos\theta_C = \frac{1}{n\beta}$$

n: index of refraction

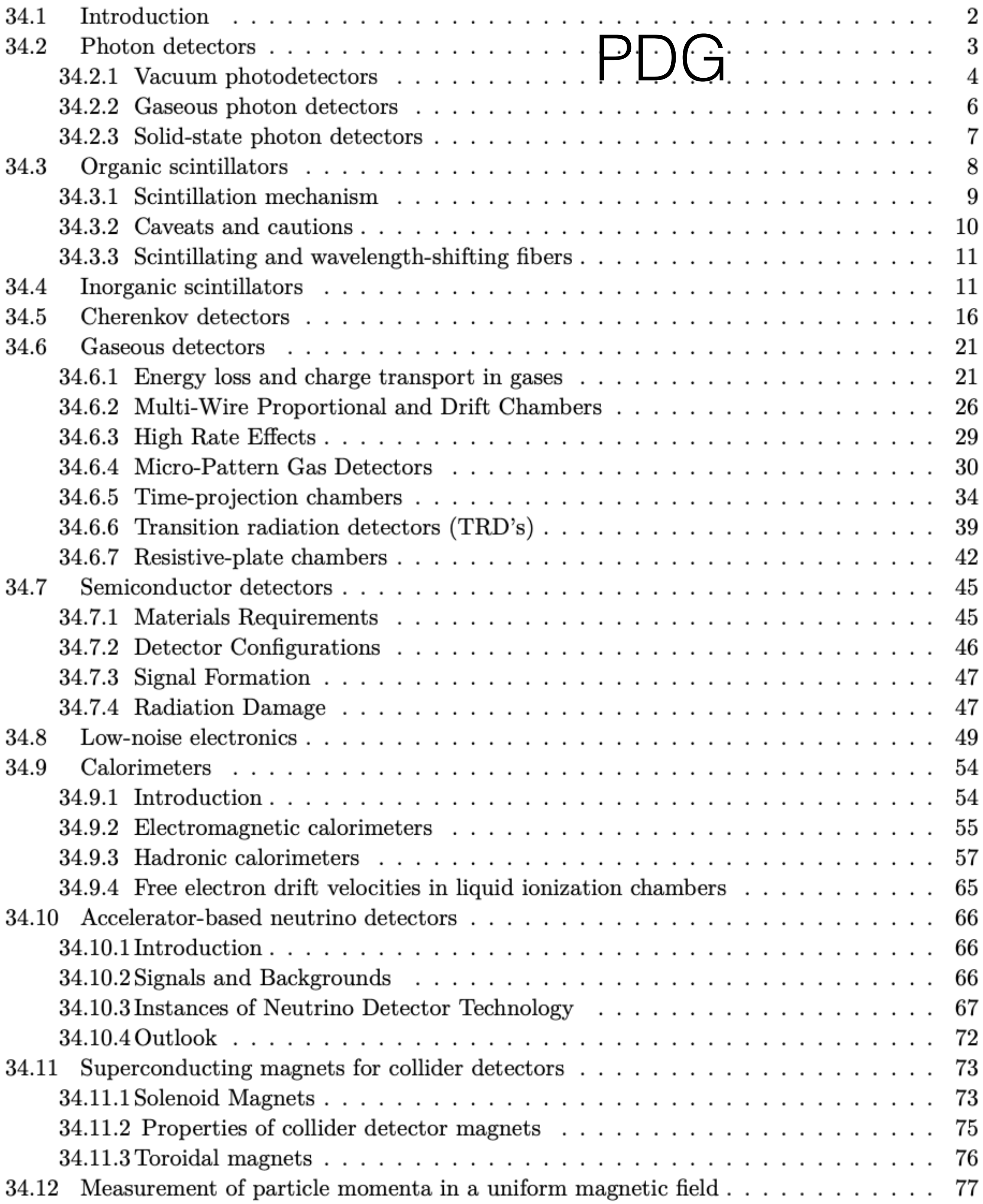
similar transition radiation happens when particles move across a border of two different index of refraction

(ii.2) types of detectors

- basic types
    - tracker
    - calorimeter

(ii.2) types of detectors

- basic types
  - tracker
  - calorimeter



PDG

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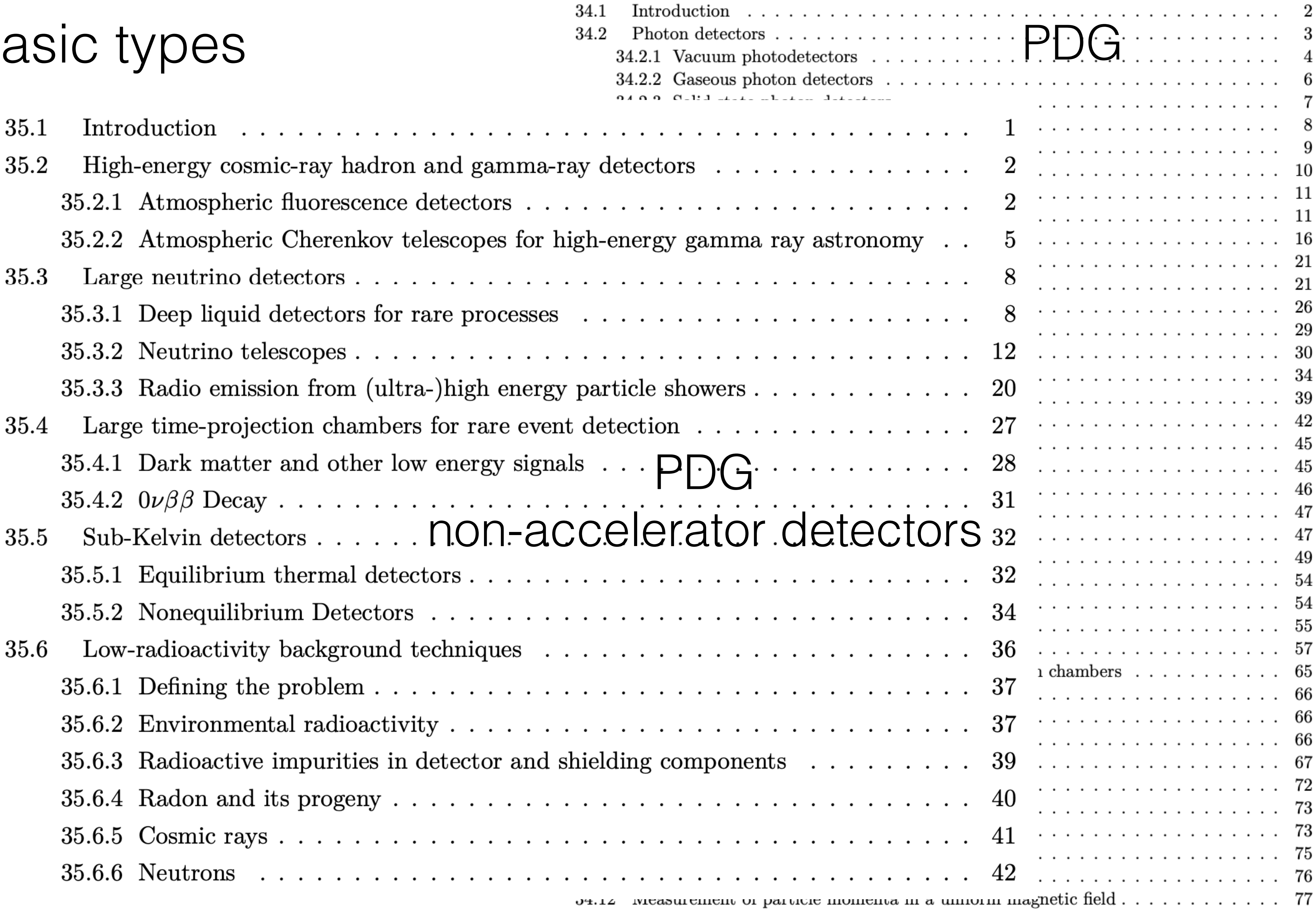
(ii.2) types of detectors

- basic types



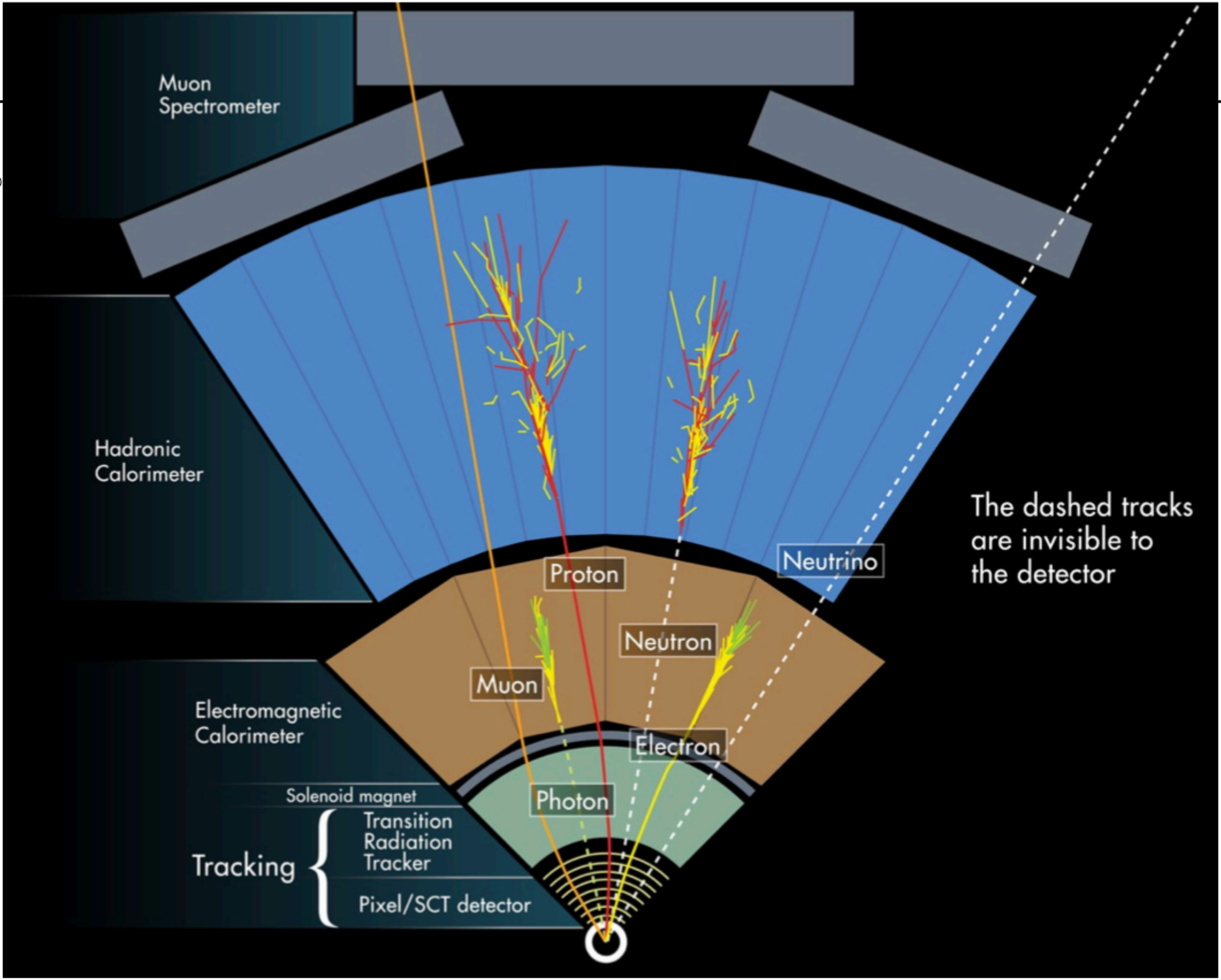
PDG

PDG

non-accelerator detectors

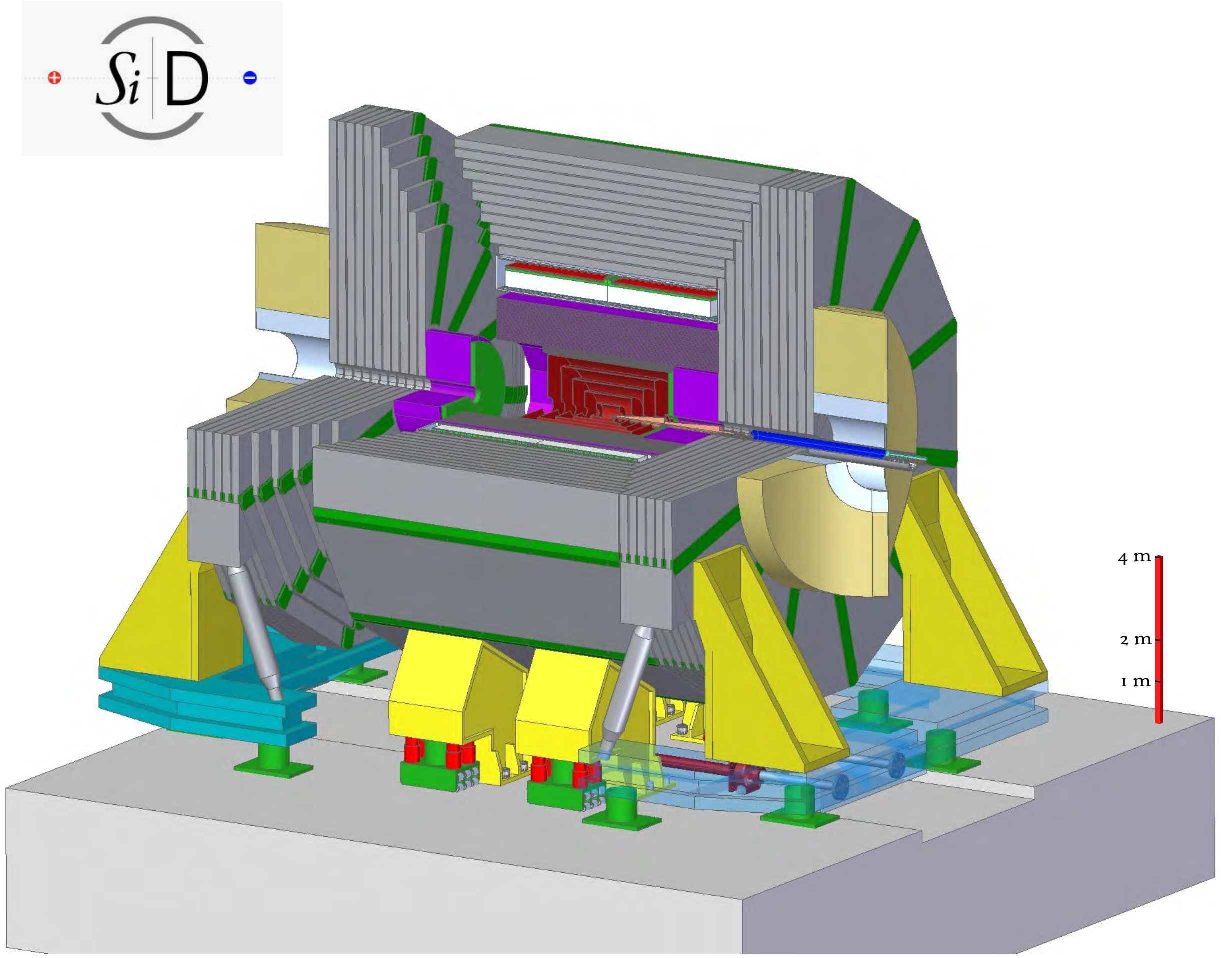
(ii.2) types of detectors

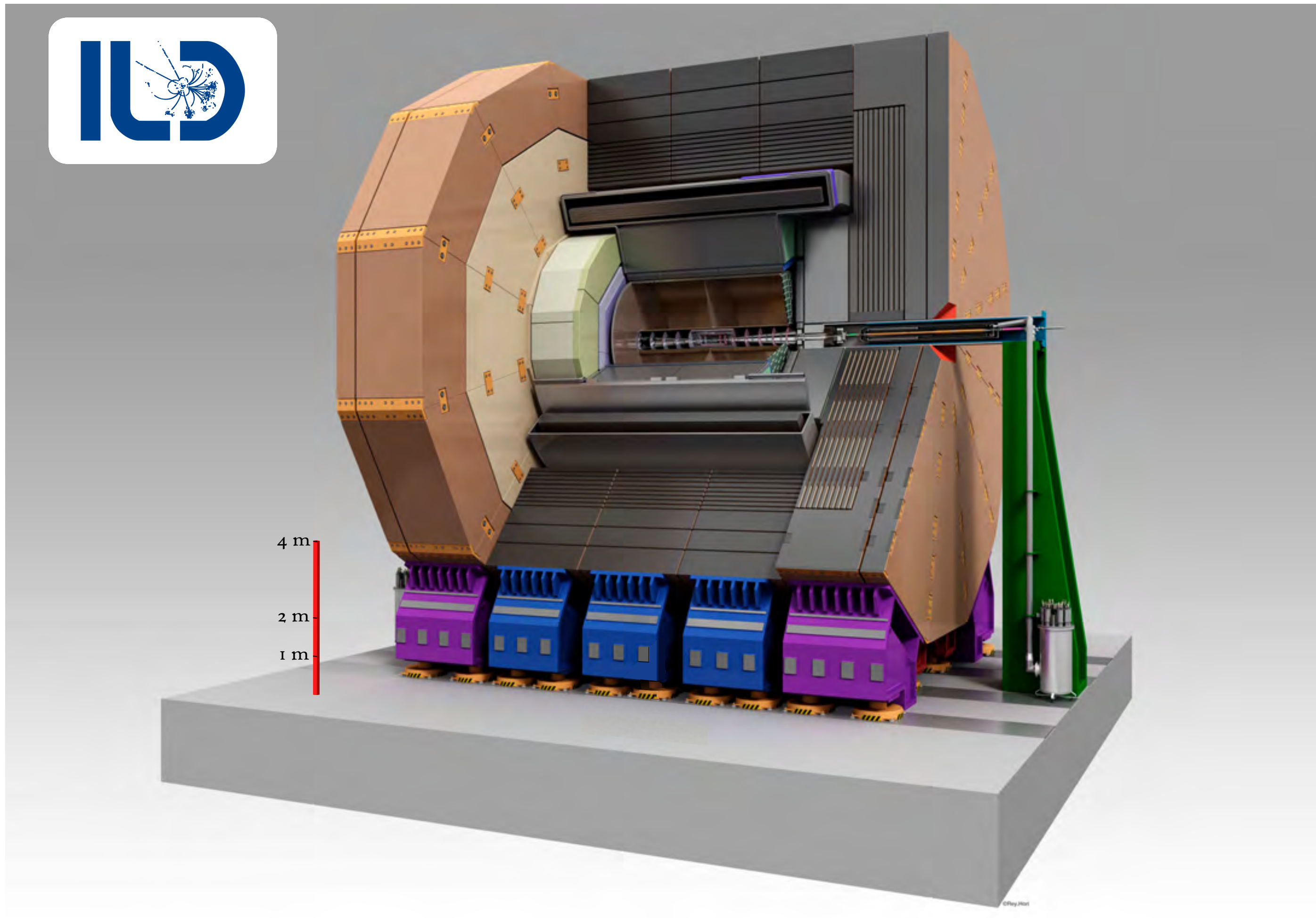
- an example: various high energy particles in ATLAS


Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Proton
Neutrino
Neutron
Muon
Electron
Photon
The dashed tracks are invisible to the detector

(ii.3) detectors @ ILC

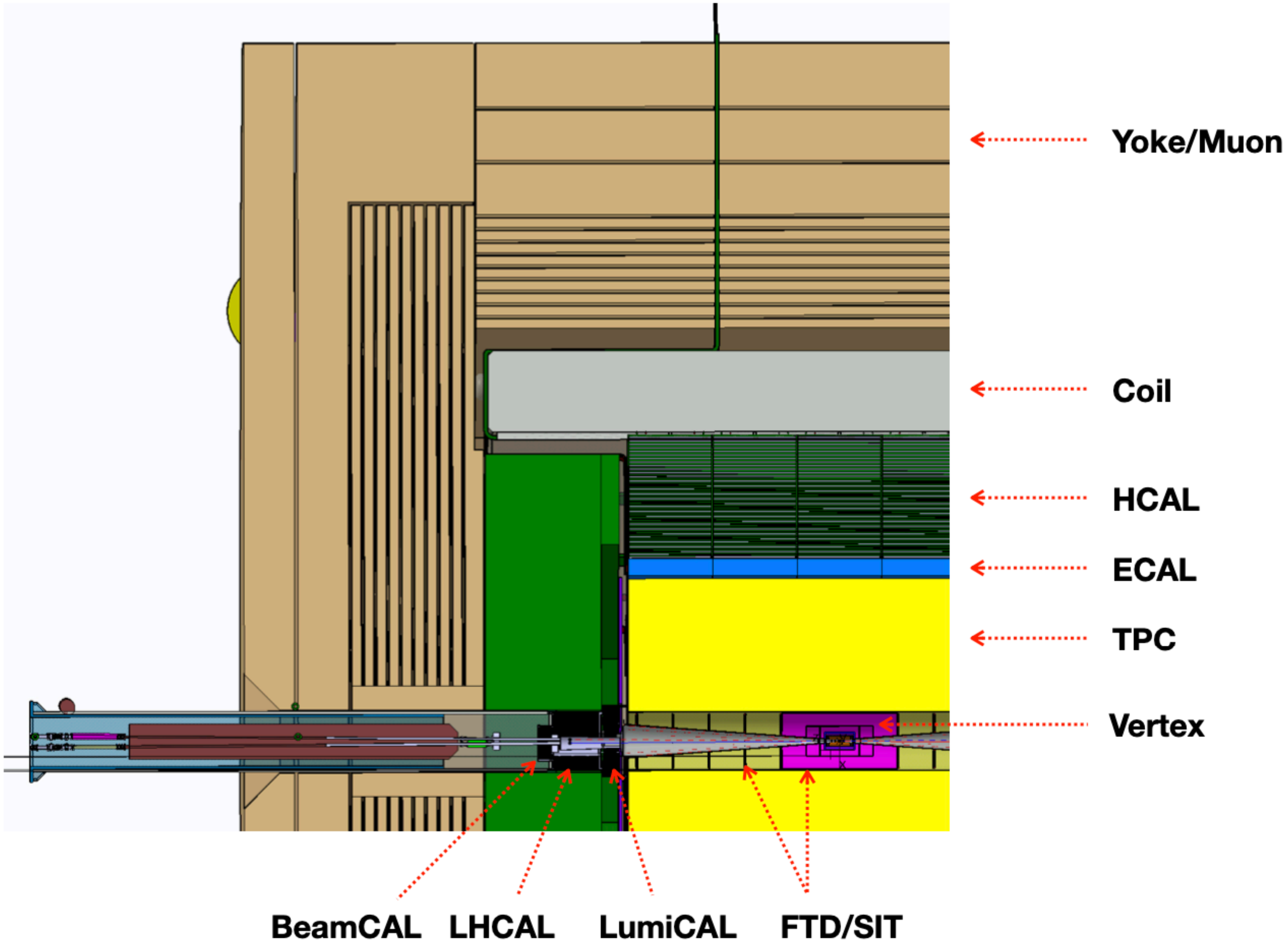
- two detector concepts; push-pull mechanism in IP





(ii.3) detectors @ ILC

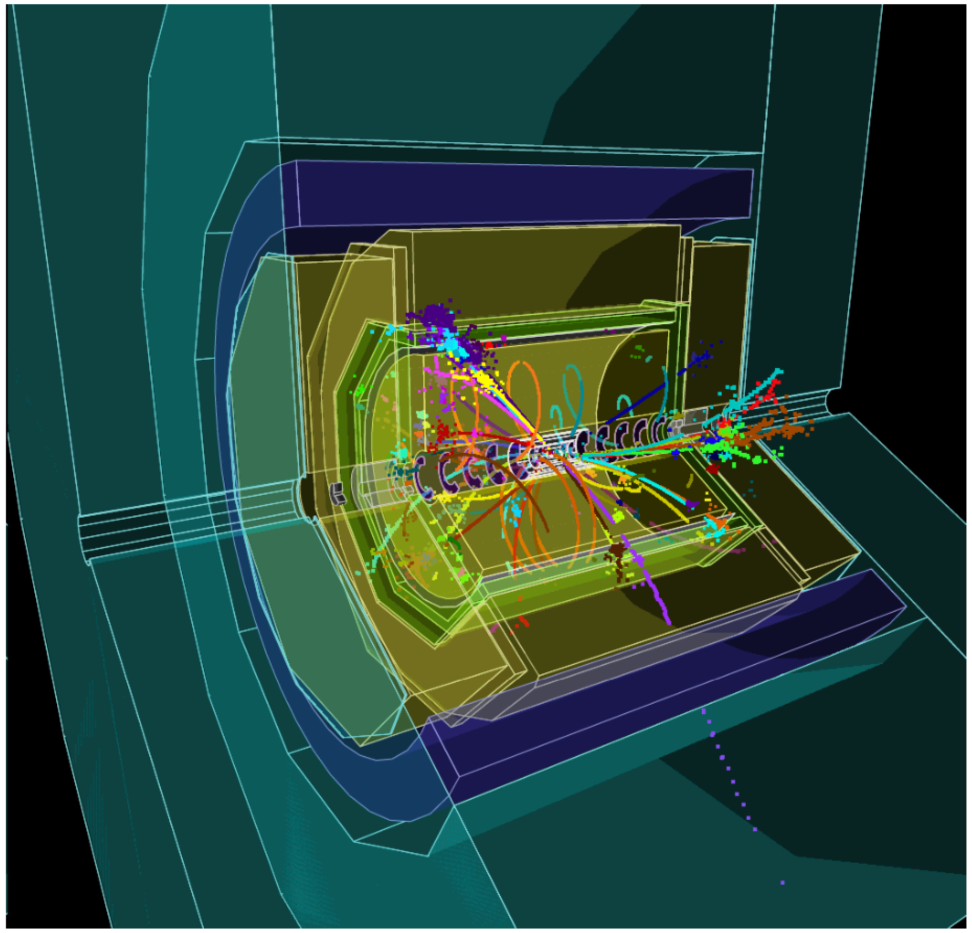
- ILD: International Large Detector



(ii.3) detectors @ ILC

- concept of Particle Flow

particle flow approach tries to reconstruct every individual particle produced in an event



key challenge is to separate the showers produced by particles from a same jet
-> highly granular calorimeters

Component	Detector	Energy Fract.	Energy Res.	Jet Energy Res.
Charged Particles ($X^{\pm}$)	Tracker	$\sim 0.6\,E_j$	$10^{-4}\,E_{X^{\pm}}^2$	$< 3.6 \times 10^{-5}\,E_j^2$
Photons (γ)	ECAL	$\sim 0.3\,E_j$	$0.15\,\sqrt{E_\gamma}$	$0.08\,\sqrt{E_j}$
Neutral Hadrons (h^0)	HCAL	$\sim 0.1\,E_j$	$0.55\,\sqrt{E_{h^0}}$	$0.17\,\sqrt{E_j}$

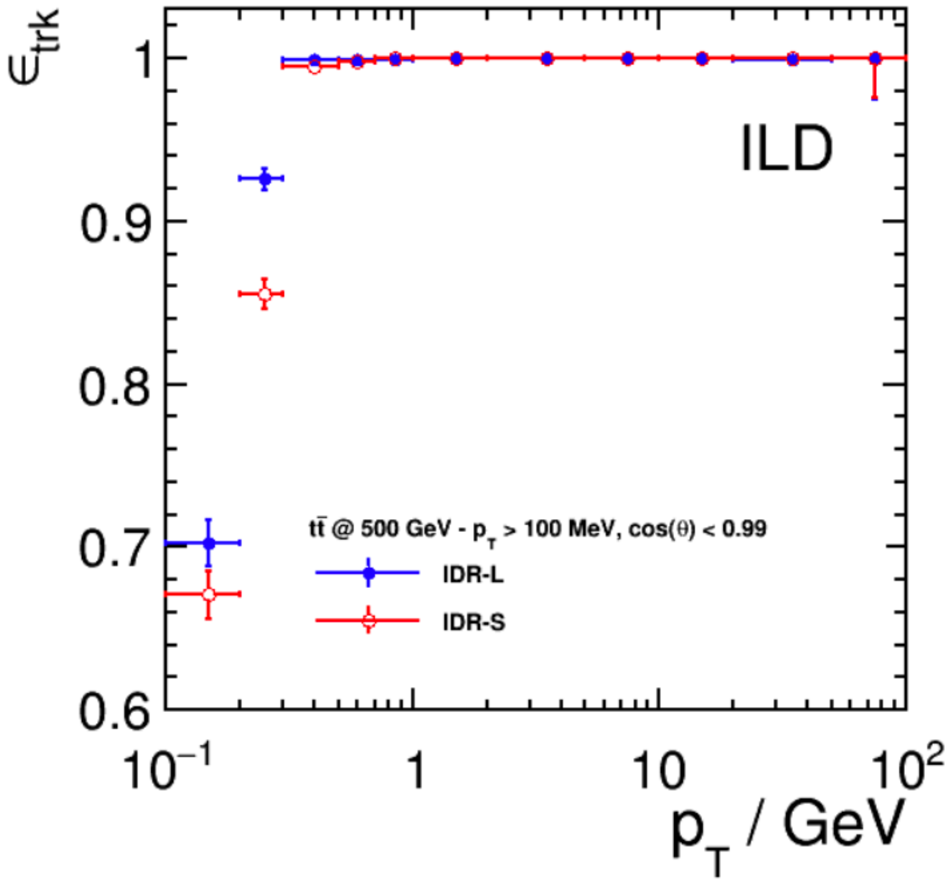
(ii.3) detectors @ ILC

- typical performance
  - tracking

momentum resolution $$\Delta_{1/P_t} = \frac{\Delta P_t}{P_t^2} \sim 2 \times 10^{-5} [\mathrm{GeV}^{-1}]$$

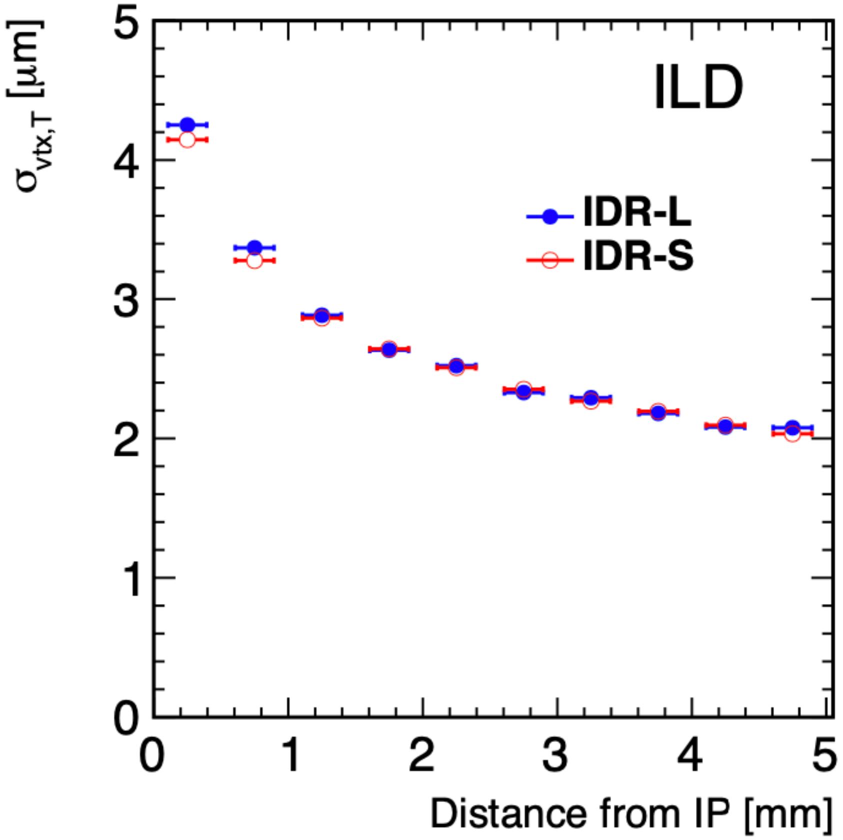
tracking efficiency

~100% for P_T > 300 MeV

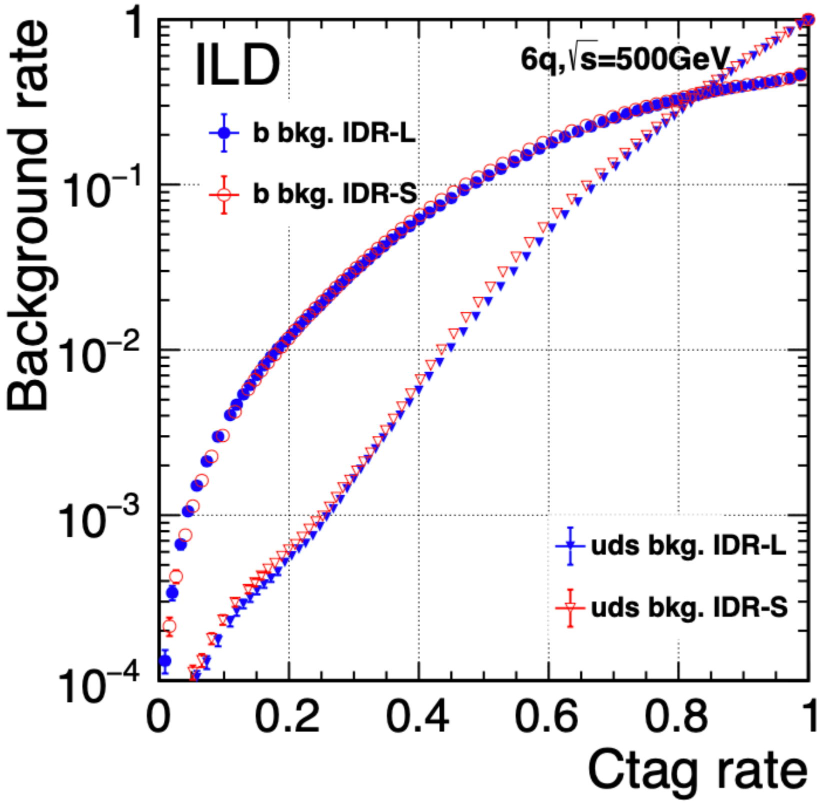


(ii.3) detectors @ ILC

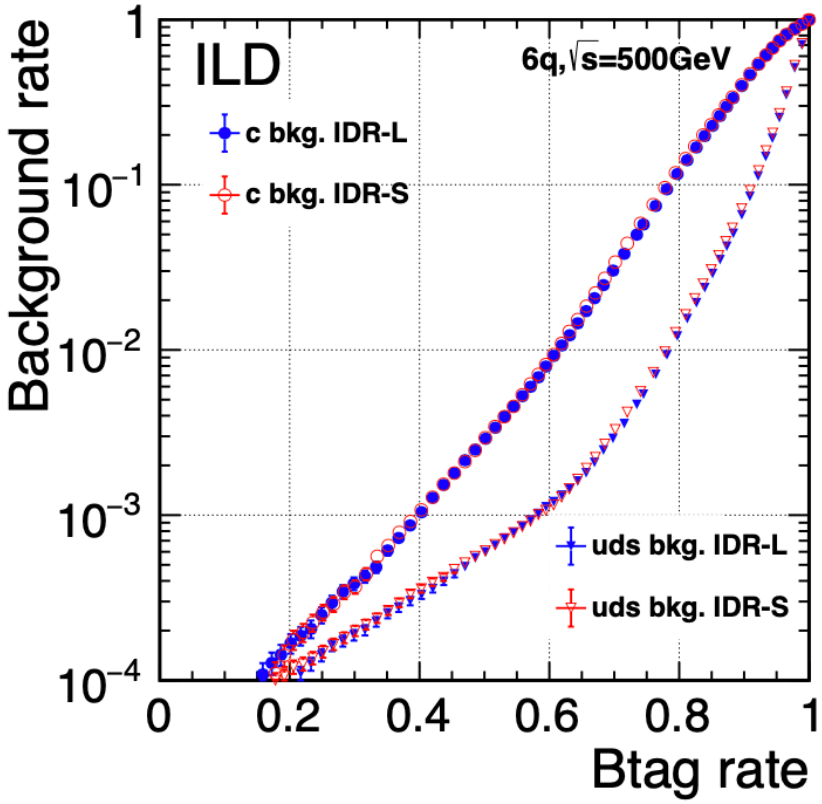
- typical performance
  - vertexing



secondary vertex position from c-jets



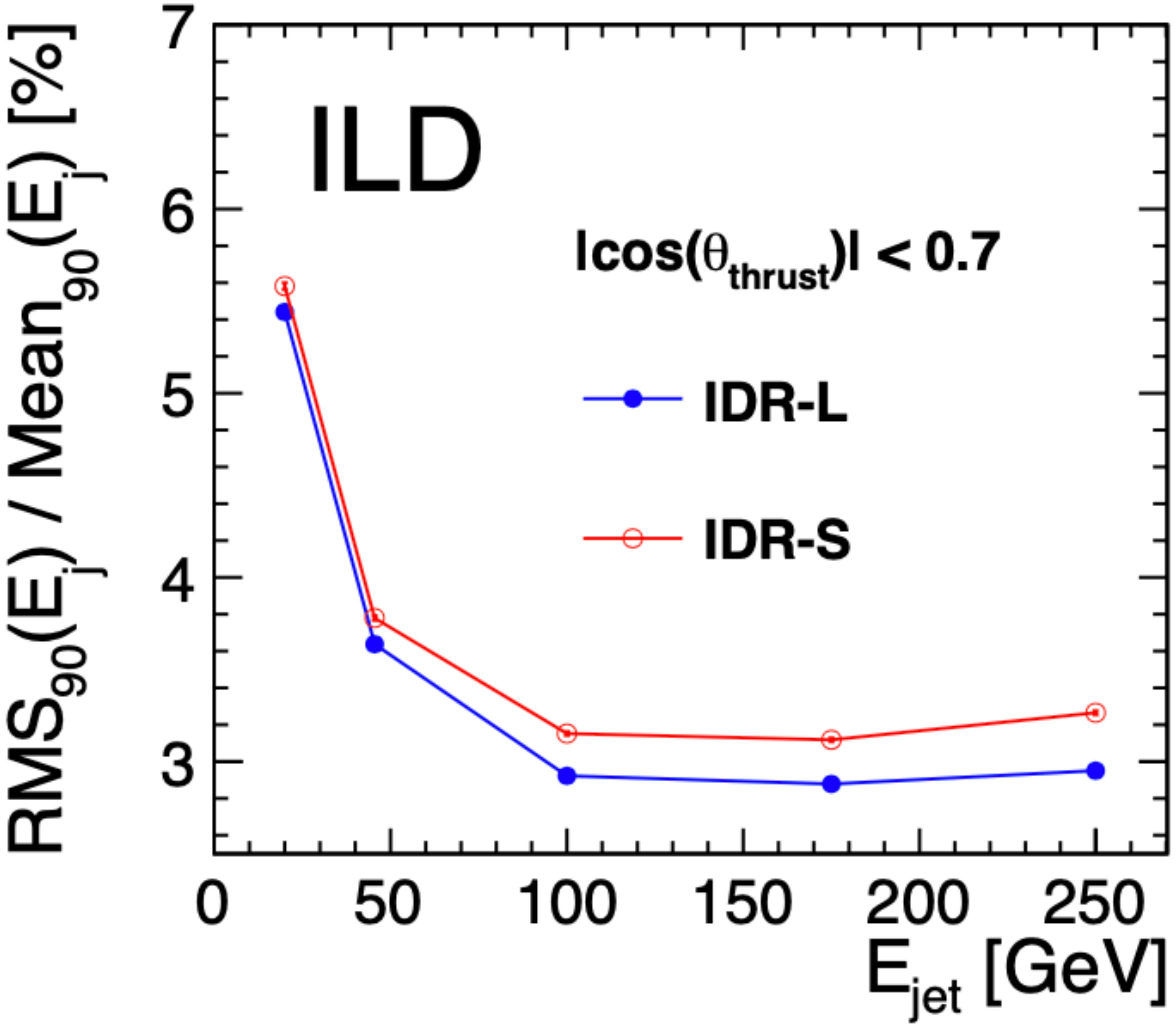
flavor-tagging c-jet



flavor-tagging b-jet

(ii.3) detectors @ ILC

- typical performance
  - jet energy resolution



(ii.4) tools for event simulation & reconstruction

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- event generator: WHIZARD

  including effects from ISR & beamstralung

  parton showering & hadronization by Pythia

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- detector simulation: GEANT4
  - full detector simulation; including pile-up events
  - one can also use fast simulation (DELPHES, SGV)

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- event reconstruction

  digitization; tracking; particle flow analysis (PandoraPFA)
  vertex reconstruction; jet clustering; flavor tagging (LCFIPlus)

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- physics analysis

- question: why quadrupole magnets are always placed as a pair?

famous “FODO” structure

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famous “FODO” structure

$$x''(s) + (\frac{1}{R^2} - k(s))x(s) = 0$$

$$y''(s) + k(s)y(s) = 0$$

(betatron oscillations)

plan

(i) Accelerator

Lecture 1

(ii) Detector

(iii) Physics analyses

Lecture 2

(iv) Higgs couplings

---

focus is introduction to principles & concepts
find details and technicalities from references

(iii) physics analysis @ future e+e-

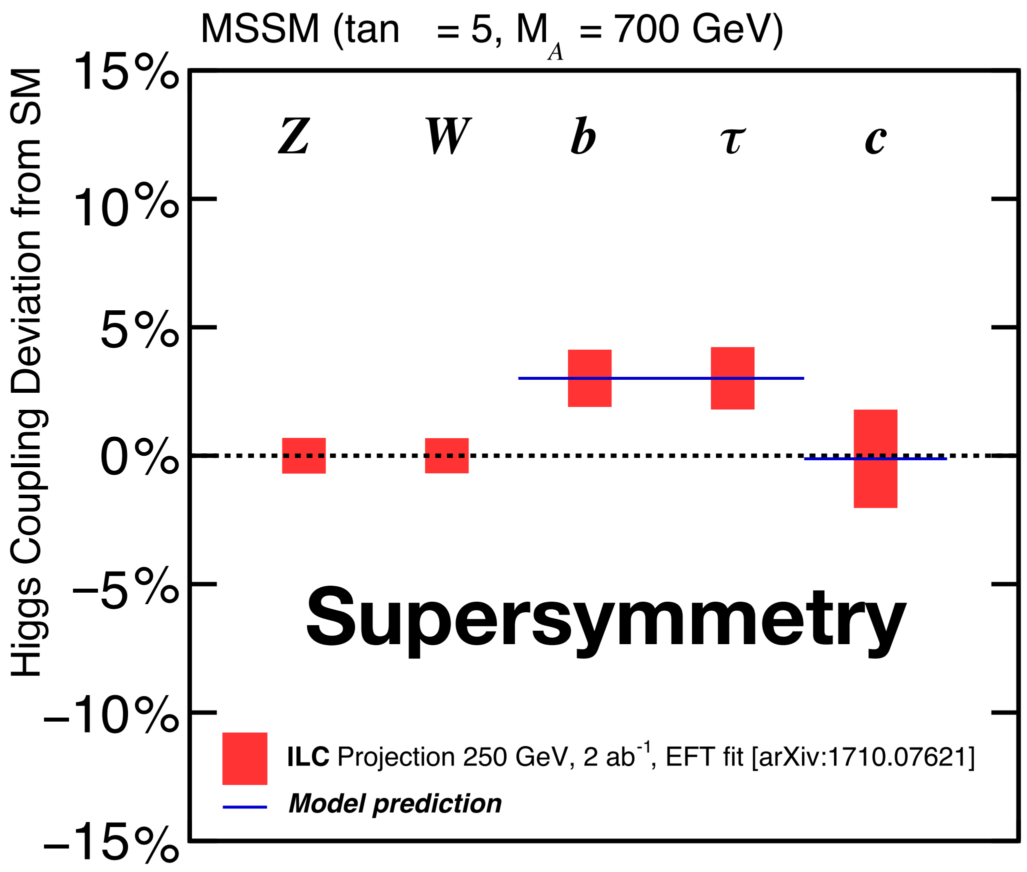
(iii.1) general introduction to observables

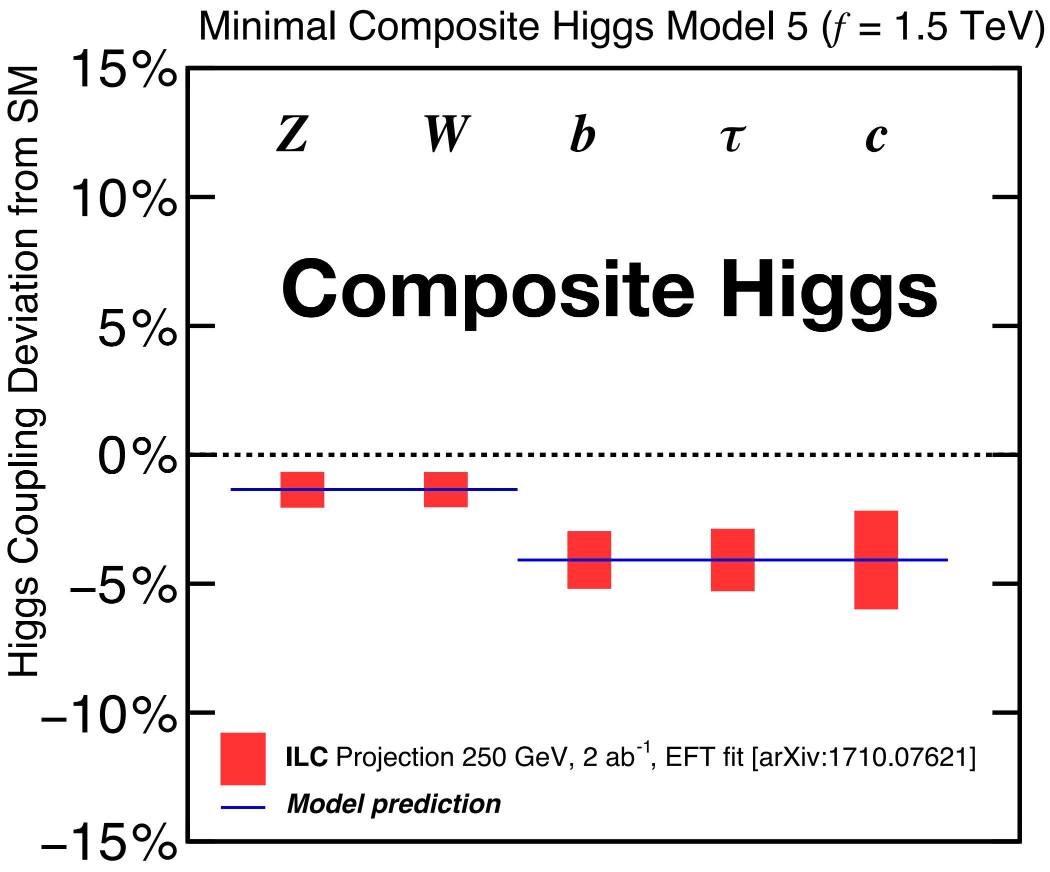
(iii.2) a few key Higgs measurements

(iv.1) global fit frameworks

(iv.2) Higgs couplings

precision measurement is meant to find deviations from SM

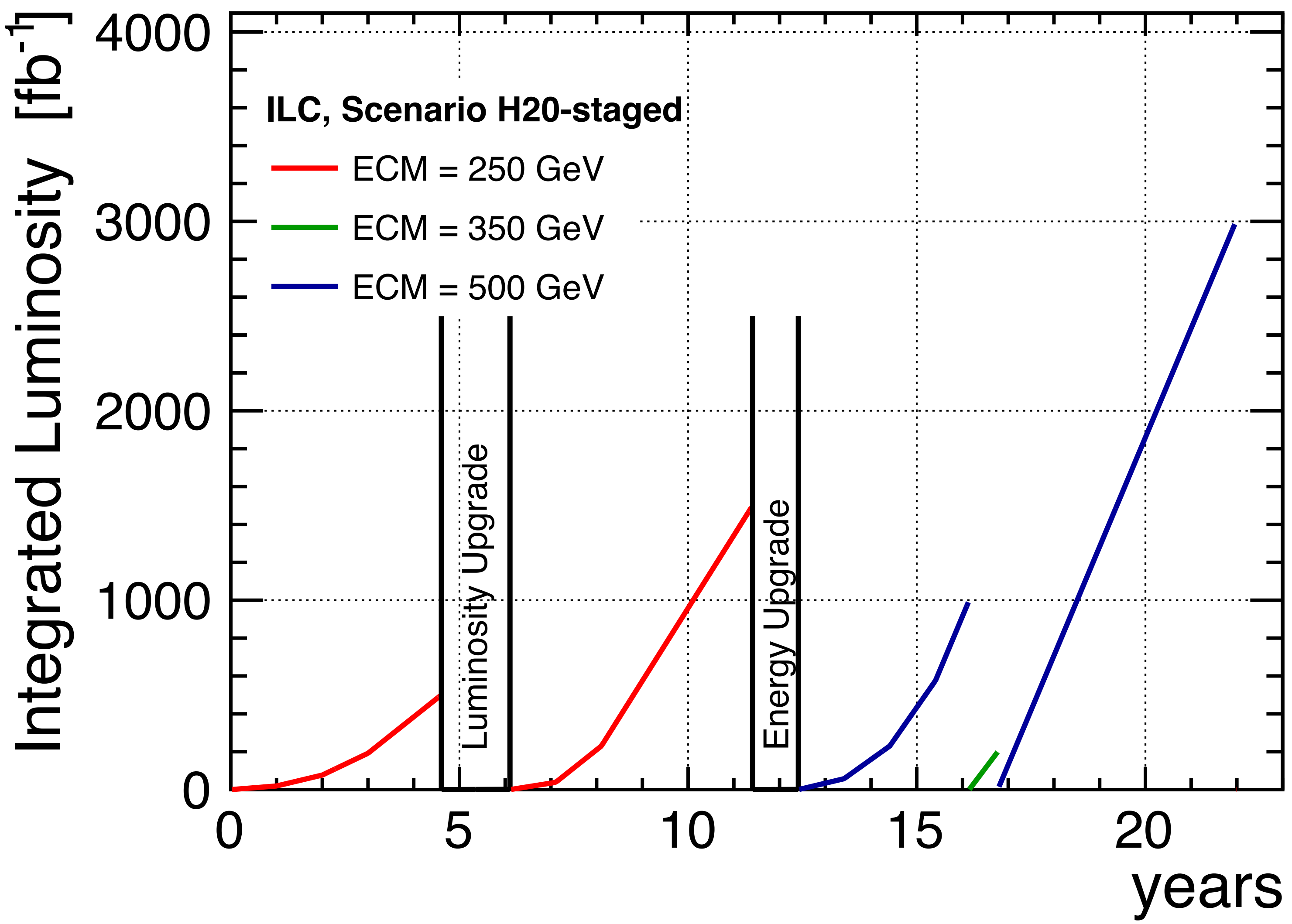




though physics analysis was often done assuming SM

estimated meas. uncertainty would not change much, except when there are very large deviations

ILC operating scenario



	fraction with $\text{sgn}(P(e^-), P(e^+)) =$			
	(-,+)	(+,-)	(-,-)	(+,+)
$\sqrt{s}$	[%]	[%]	[%]	[%]
250 GeV (2015)	67.5	22.5	5	5
250 GeV (update)	**45**	**45**	5	5
350 GeV	67.5	22.5	5	5
500 GeV	40	40	10	10

proposals of future lepton colliders

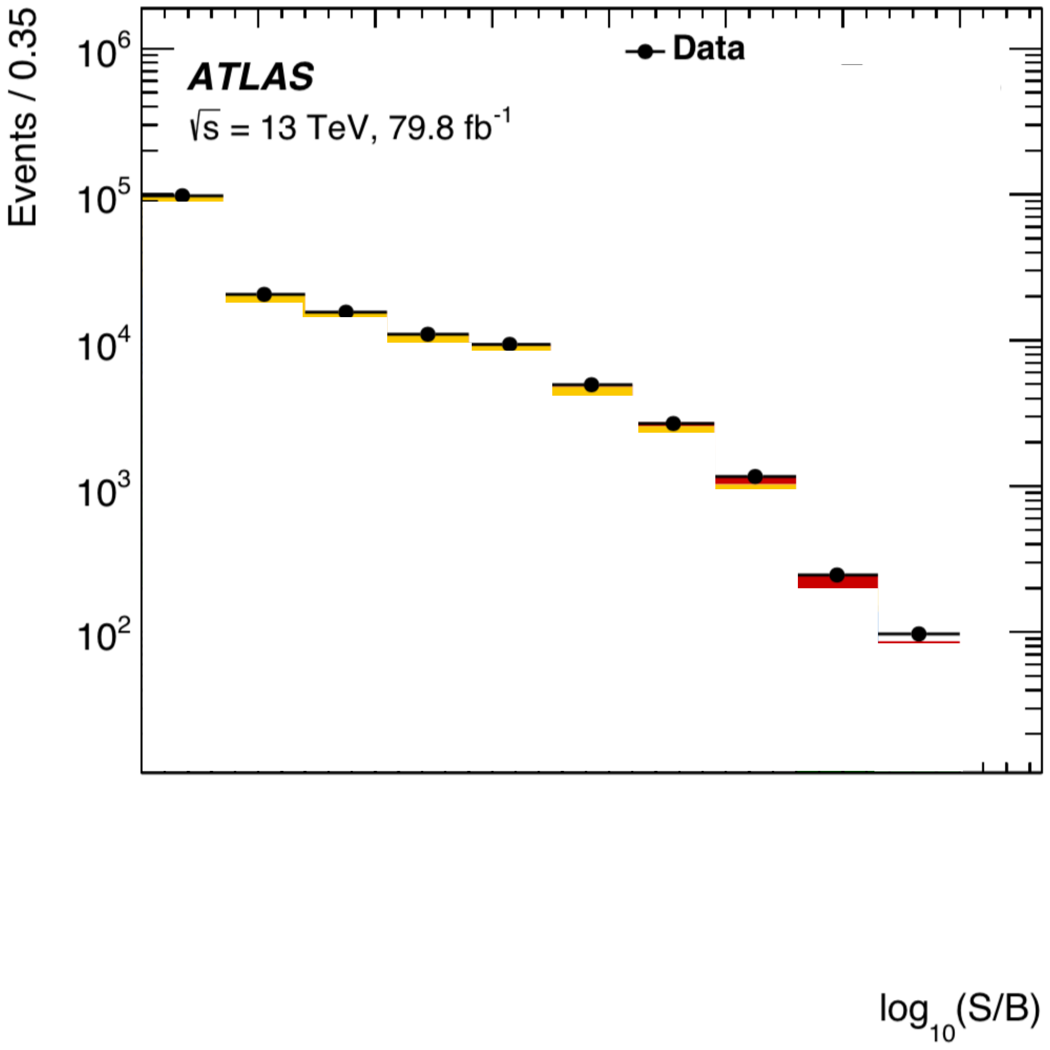
	$\sqrt{s}$	beam polarisation	∫Ldt for Higgs	R&D phase
ILC	0.1 - 1 TeV	e-: 80% e+: 30% (20%)	2000 fb^{-1} @ 250 GeV 200 fb^{-1} @ 350 GeV 4000 fb-1 @ 500 GeV 8000 fb-1 @ 1 TeV	TDR
CLIC	0.35 - 3 TeV	e-: (80%) e+: 0%	500 fb^{-1} @ 380 GeV 1500 fb^{-1} @ 1.4 TeV 2500 fb^{-1} @ 3 TeV	CDR
CEPC	90 - 240 GeV	e-: 0% e+: 0%	5600 fb^{-1} @ 240 GeV	CDR
FCC-ee	90 - 365 GeV	e-: 0% e+: 0%	5000 fb^{-1} @ 240 GeV 1500 fb^{-1} @ 365 GeV	CDR

common: Higgs factory with O(10^6) Higgs events “that is much much easier, infinitely easier, on a e+e- machine than on a proton machine”

youtube: Burton Richter #mylinearcollider, 2015

for example: H->bb discovery

at LHC



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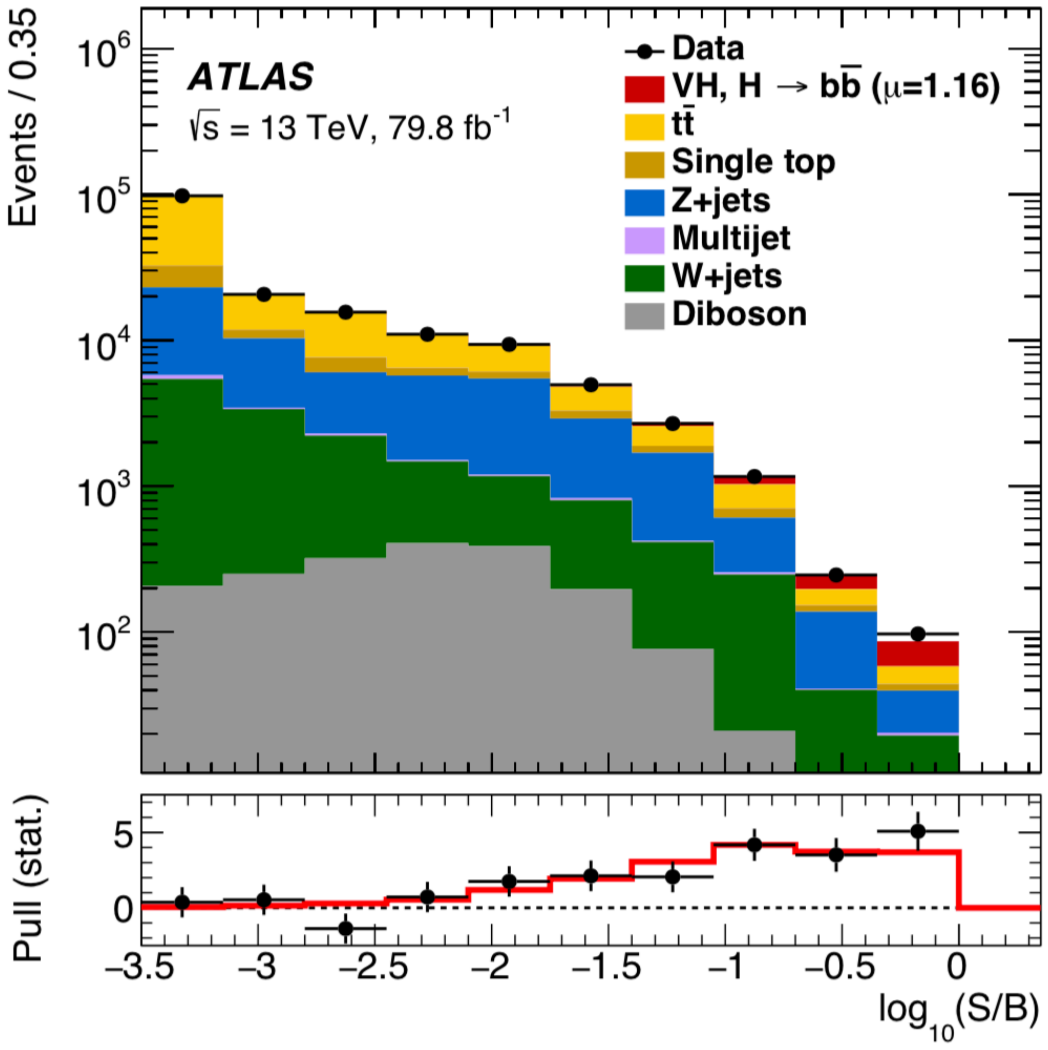

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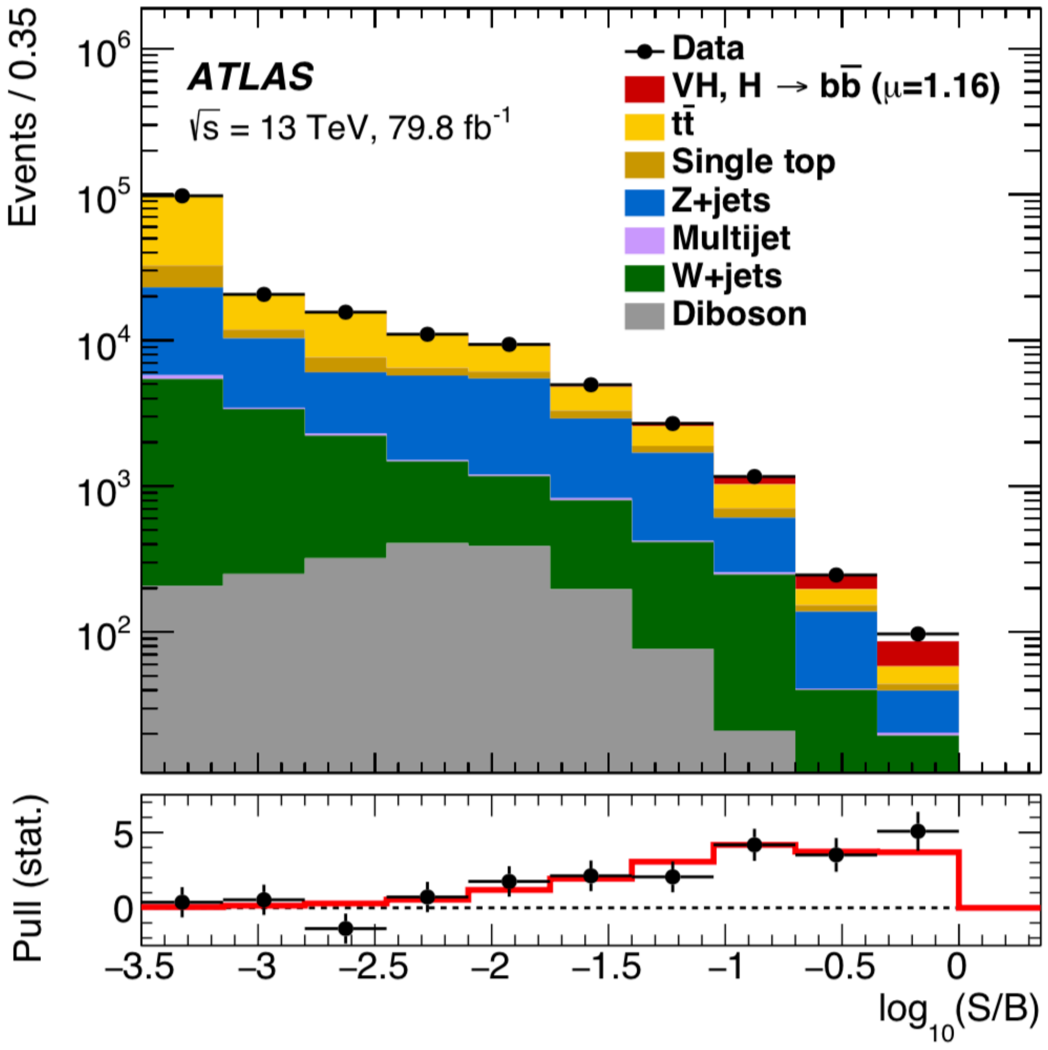

# of Higgs produced: ~4,000,000

significance: 5.4σ

(ATLAS, 1808.08238; CMS, 1808.08242)

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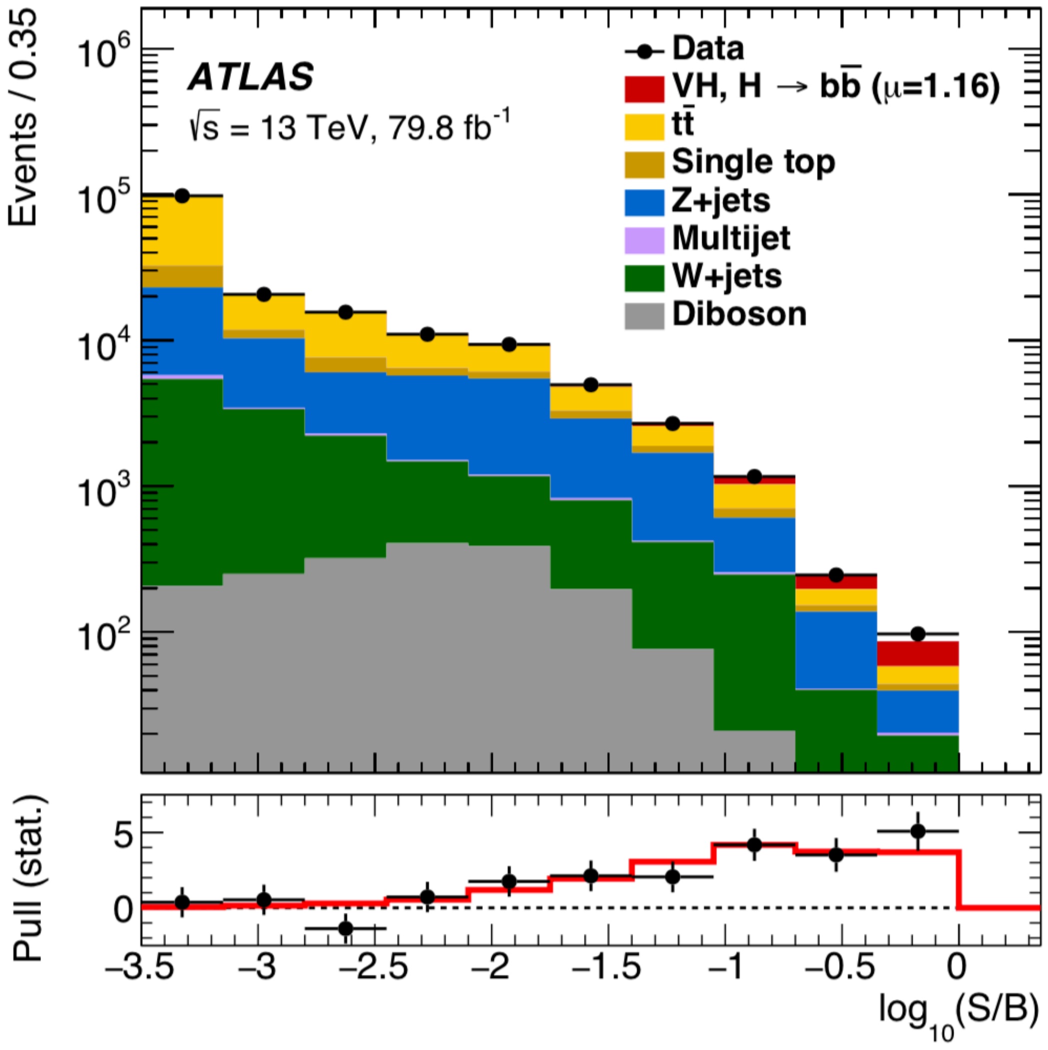
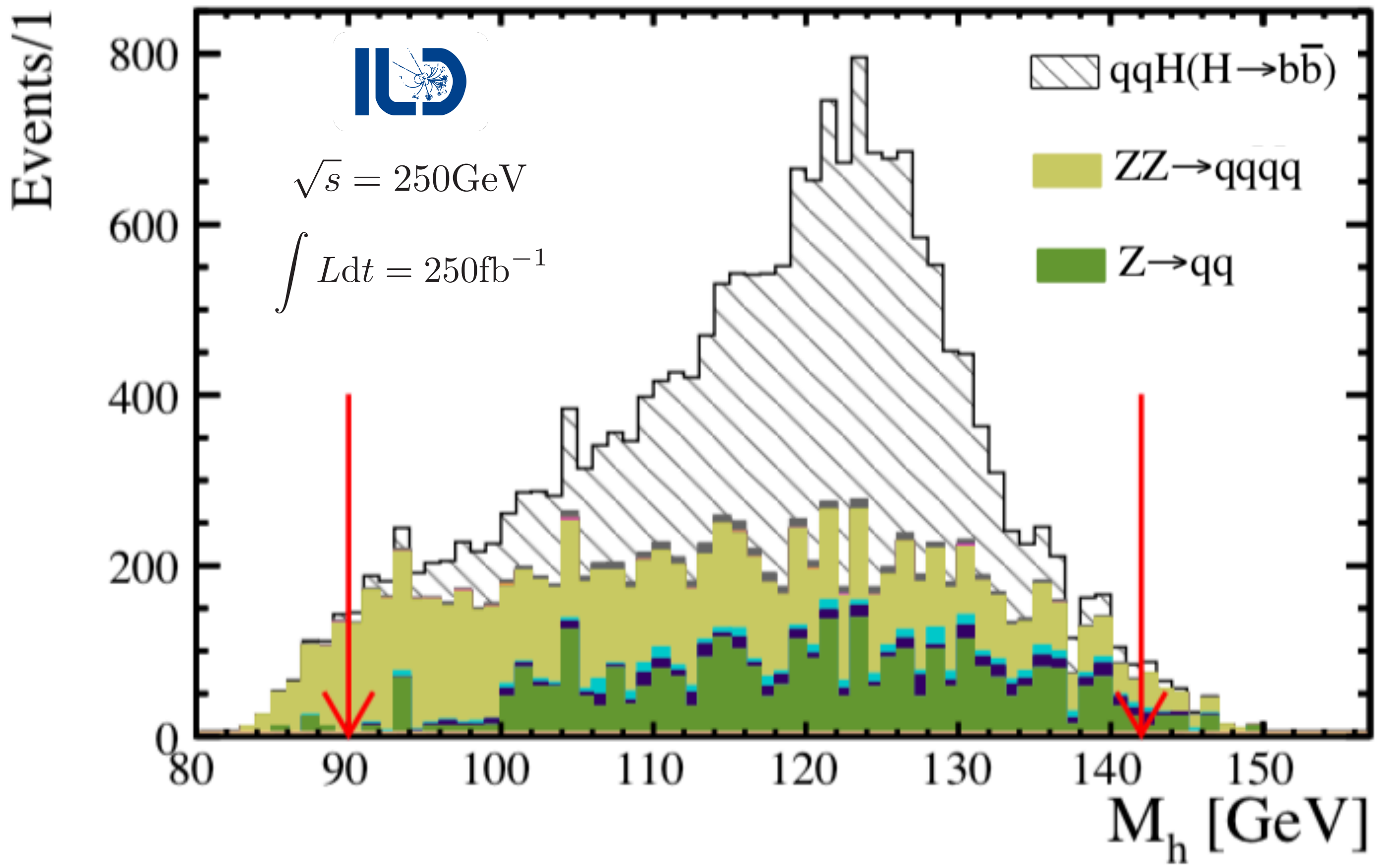


at e+e-



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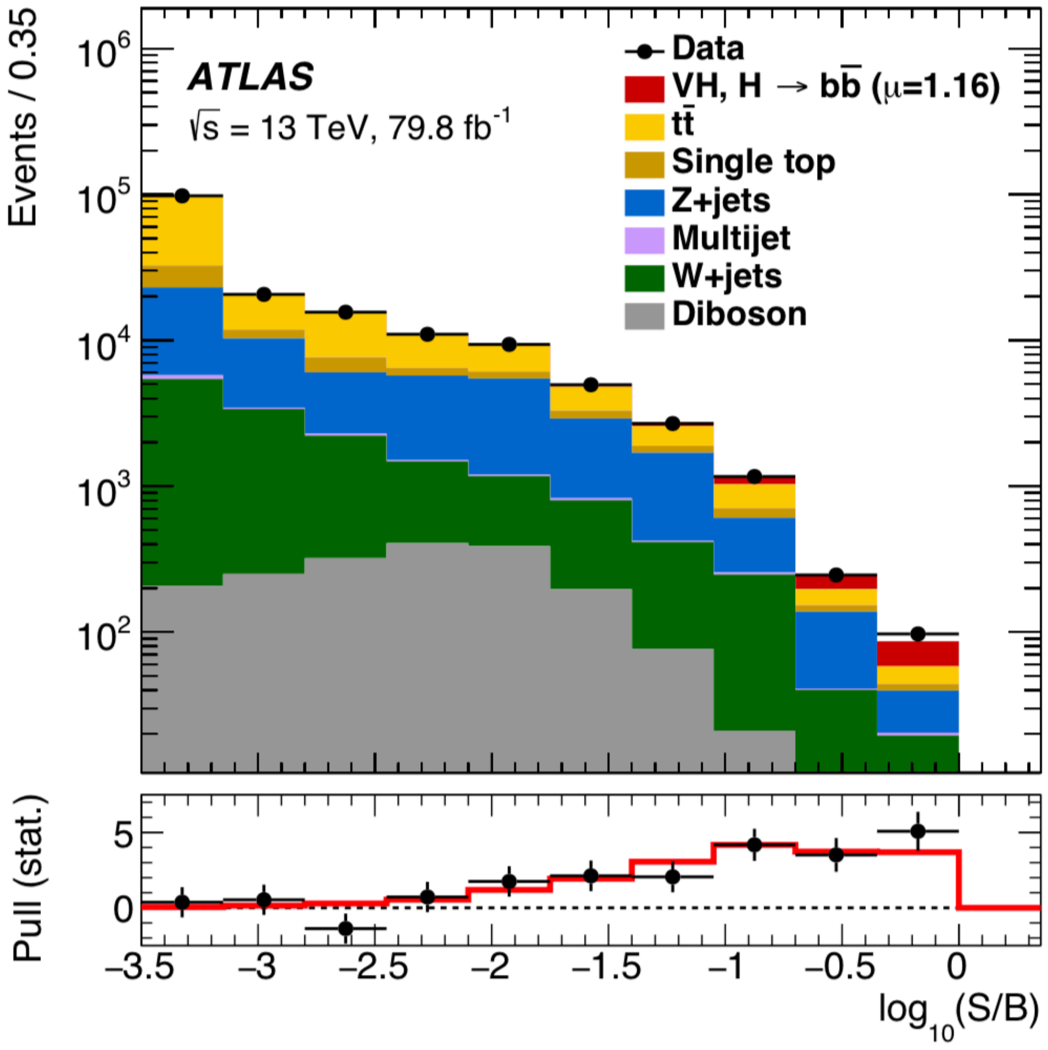
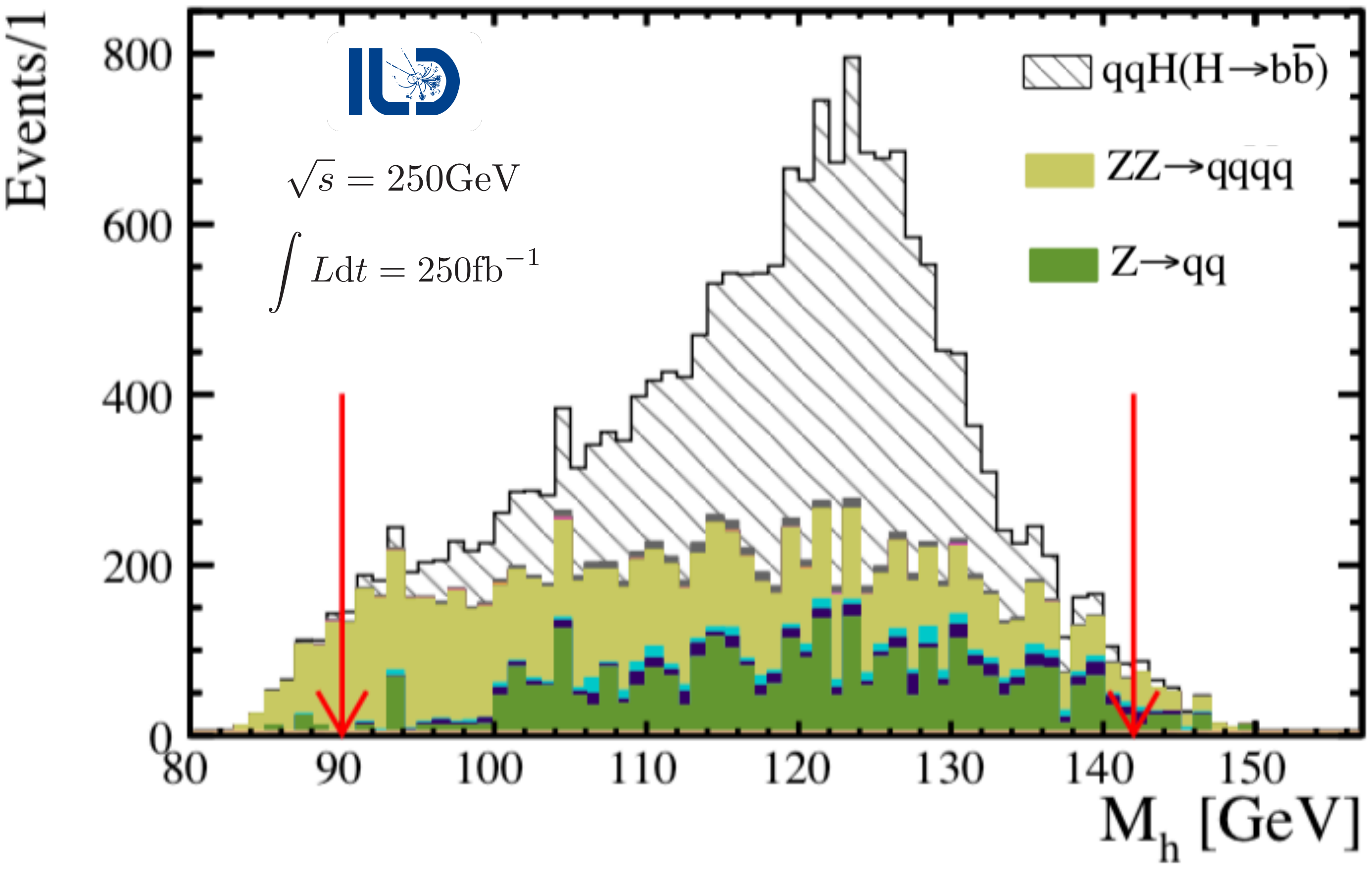


at e+e-



with 1.3 fb^{-1} data ~ 2 days running

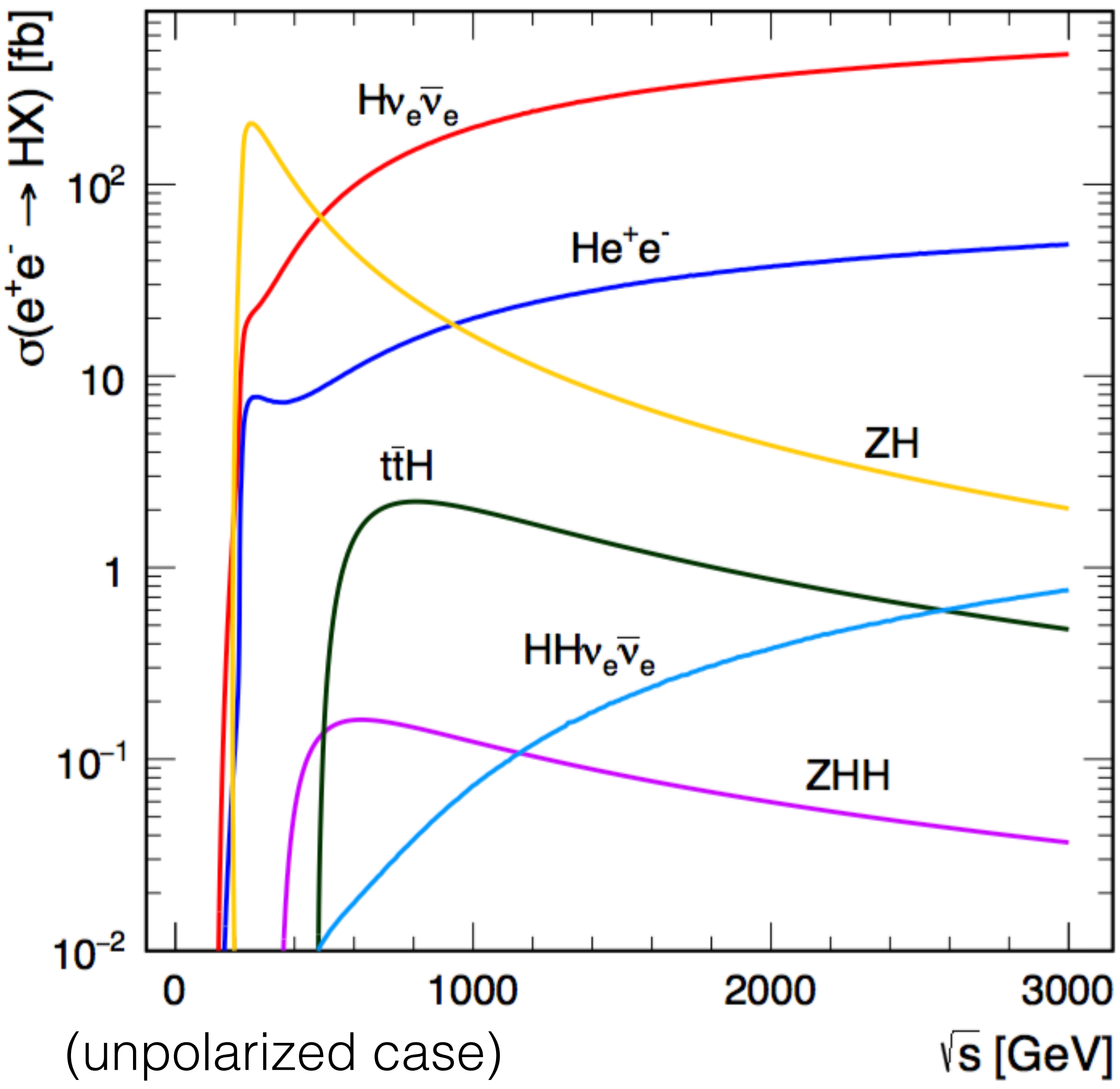
# of Higgs produced: ~4,000,000 ~400

significance: 5.4σ 5.2σ

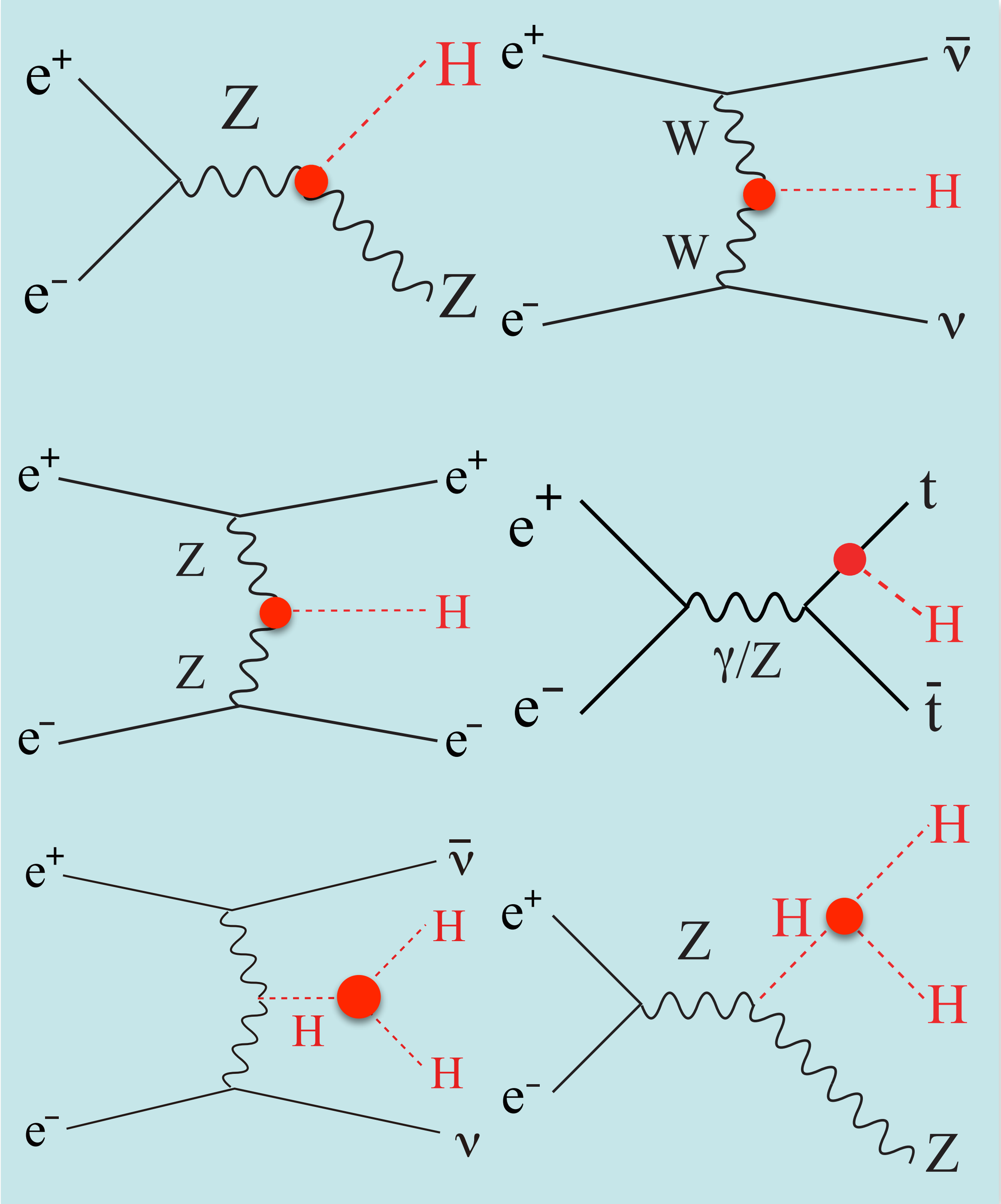
(ATLAS, 1808.08238; CMS, 1808.08242)

(Ogawa, PhD Thesis, ILD full simulation)

Higgs productions at e+e-



(unpolarized case)



- two apparent important thresholds: √s ~ **250** GeV for ZH, ~**500** GeV for ZHH and ttH
- + another threshold for t t-bar, important for vacuum stability

what are the direct experimental observables

☑ σ_{ZH}

☑ $\sigma_{ZH}\times \mathrm{Br}(H\longrightarrow bb)$, $\sigma_{\nu\nu H}\times \mathrm{Br}(H\longrightarrow bb)$

☑ $\sigma_{ZH}\times \mathrm{Br}(H\longrightarrow cc)$, $\sigma_{\nu\nu H}\times \mathrm{Br}(H\longrightarrow cc)$

☑ $\sigma_{ZH}\times \mathrm{Br}(H\longrightarrow gg)$, $\sigma_{\nu\nu H}\times \mathrm{Br}(H\longrightarrow gg)$

☑ $\sigma_{ZH}\times \mathrm{Br}(H\longrightarrow WW^*)$, $\sigma_{\nu\nu H}\times \mathrm{Br}(H\longrightarrow WW^*)$

☑ $\sigma_{ZH}\times \mathrm{Br}(H\longrightarrow ZZ^*)$, $\sigma_{\nu\nu H}\times \mathrm{Br}(H\longrightarrow ZZ^*)$

☑ $\sigma_{ZH}\times \mathrm{Br}(H\longrightarrow \tau\tau)$, $\sigma_{\nu\nu H}\times \mathrm{Br}(H\longrightarrow \tau\tau)$

☑ $\sigma_{ZH}\times \mathrm{Br}(H\longrightarrow \gamma\gamma/\gamma Z)$, $\sigma_{\nu\nu H}\times \mathrm{Br}(H\longrightarrow \gamma\gamma/\gamma Z)$

☑ $\sigma_{ZH}\times \mathrm{Br}(H\longrightarrow \mu\mu)$, $\sigma_{\nu\nu H}\times \mathrm{Br}(H\longrightarrow \mu\mu)$

☑ $\sigma_{ZH}\times \mathrm{Br}(H\longrightarrow \mathrm{inv./exotic})$

☑ $\sigma_{ttH}\times \mathrm{Br}(H\longrightarrow bb)$

☑ $\sigma_{ZHH}\times \mathrm{Br}^2(H\longrightarrow bb)$, $\sigma_{\nu\nu HH}\times \mathrm{Br}^2(H\longrightarrow bb)$

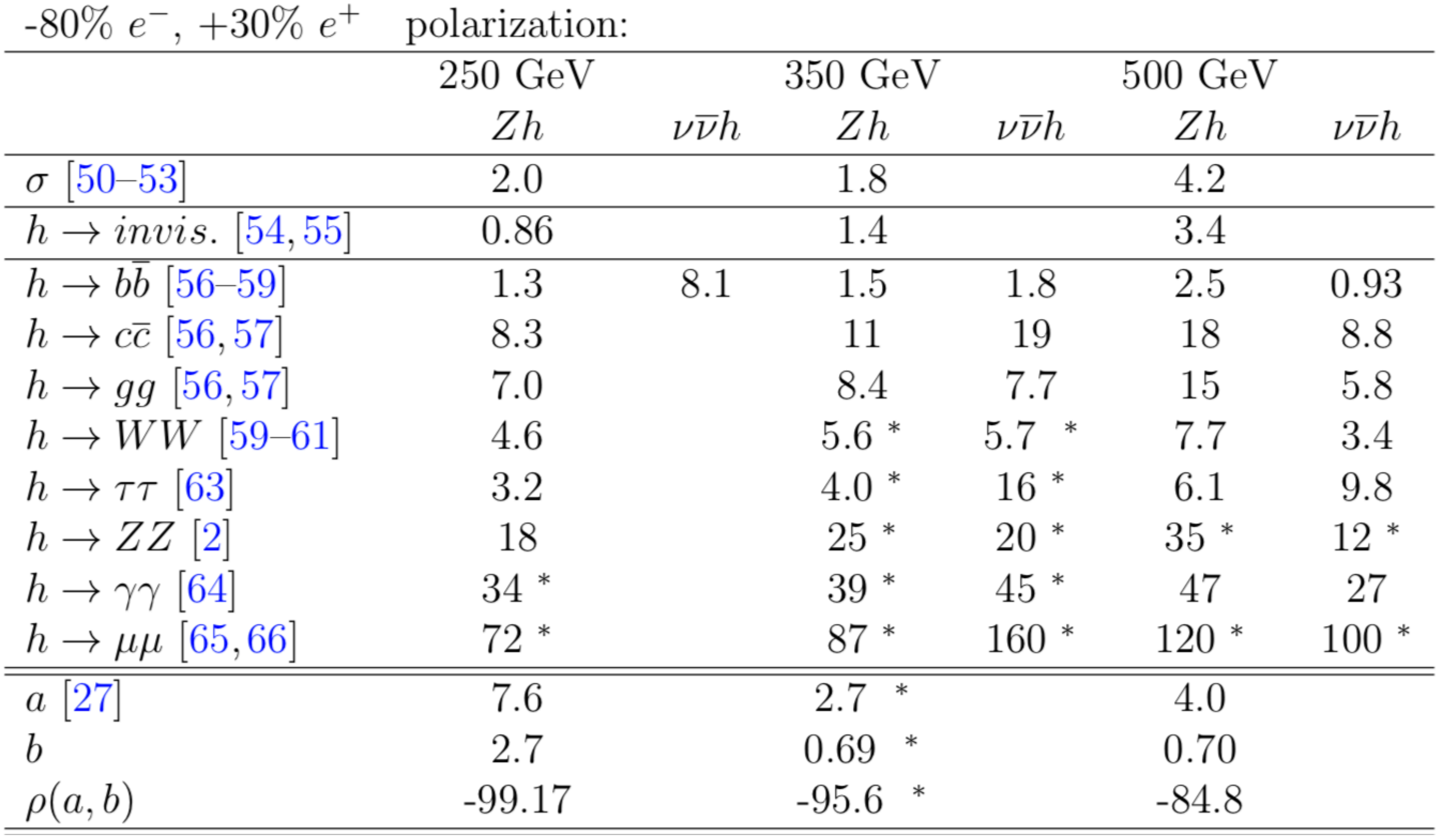
what are the direct experimental observables

- ☑ σ_{ZH}
- ☑ $\sigma_{ZH}\times$Br(H—>bb), $\sigma_{\nu\nu H}\times$Br(H—>bb)
- ☑ $\sigma_{ZH}\times$Br(H—>cc), $\sigma_{\nu\nu H}\times$Br(H—>cc)
- ☑ $\sigma_{ZH}\times$Br(H—>gg), $\sigma_{\nu\nu H}\times$Br(H—>gg)
- ☑ $\sigma_{ZH}\times$Br(H—>WW*), $\sigma_{\nu\nu H}\times$Br(H—>WW*)
- ☑ $\sigma_{ZH}\times$Br(H—>ZZ*), $\sigma_{\nu\nu H}\times$Br(H—>ZZ*)
- ☑ $\sigma_{ZH}\times$Br(H—>$\tau\tau$), $\sigma_{\nu\nu H}\times$Br(H—>$\tau\tau$)
- ☑ $\sigma_{ZH}\times$Br(H—>$\gamma\gamma/\gamma Z$), $\sigma_{\nu\nu H}\times$Br(H—>$\gamma\gamma/\gamma Z$)
- ☑ $\sigma_{ZH}\times$Br(H—>$\mu\mu$), $\sigma_{\nu\nu H}\times$Br(H—>$\mu\mu$)
- ☑ $\sigma_{ZH}\times$Br(H—>inv./exotic)
- ☑ $\sigma_{ttH}\times$Br(H—>bb)
- ☑ $\sigma_{ZHH}\times$Br^2(H—>bb), $\sigma_{\nu\nu HH}\times$Br^2(H—>bb)

note the important complementarity with LHC

what are the direct experimental observables

estimates at ILC by simulation



-80% e^-, +30% e^+ polarization:

	250 GeV		350 GeV		500 GeV	
	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$
σ [50–53]	2.0		1.8		4.2	
$h \to invis.$ [54, 55]	0.86		1.4		3.4	
$h \to b\bar{b}$ [56–59]	1.3	8.1	1.5	1.8	2.5	0.93
$h \to c\bar{c}$ [56, 57]	8.3		11	19	18	8.8
$h \to gg$ [56, 57]	7.0		8.4	7.7	15	5.8
$h \to WW$ [59–61]	4.6		5.6 *	5.7 *	7.7	3.4
$h \to \tau\tau$ [63]	3.2		4.0 *	16 *	6.1	9.8
$h \to ZZ$ [2]	18		25 *	20 *	35 *	12 *
$h \to \gamma\gamma$ [64]	34 *		39 *	45 *	47	27
$h \to \mu\mu$ [65, 66]	72 *		87 *	160 *	120 *	100 *
a [27]	7.6		2.7 *		4.0	
b	2.7		0.69 *		0.70	
$\rho(a, b)$	-99.17		-95.6 *		-84.8	

(arXiv: 1708.08912; numbers are in %, for nominal ∫Ldt = 250 fb^{-1})

(iii.2) a few key Higgs measurements

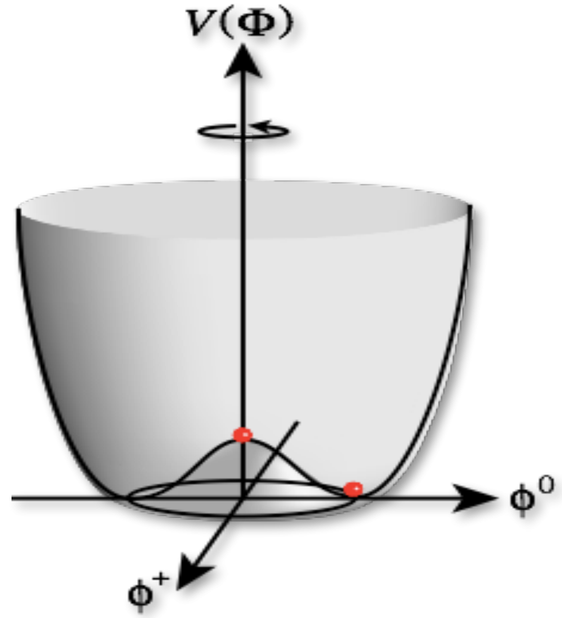
I will explain some details in one/two analyses, talk very briefly in other ones; mainly focus on physics issues instead of analysis techniques, which are important as well and can be learned from the references.

(1) Higgs self-coupling analysis
(2) recoil mass analysis
(3) Higgs CP
(4) H->bb/cc/gg
(5) Higgs total width
(6) H->invisible
(7) top-Yukawa coupling
(8) …

as usual, selection is always biased

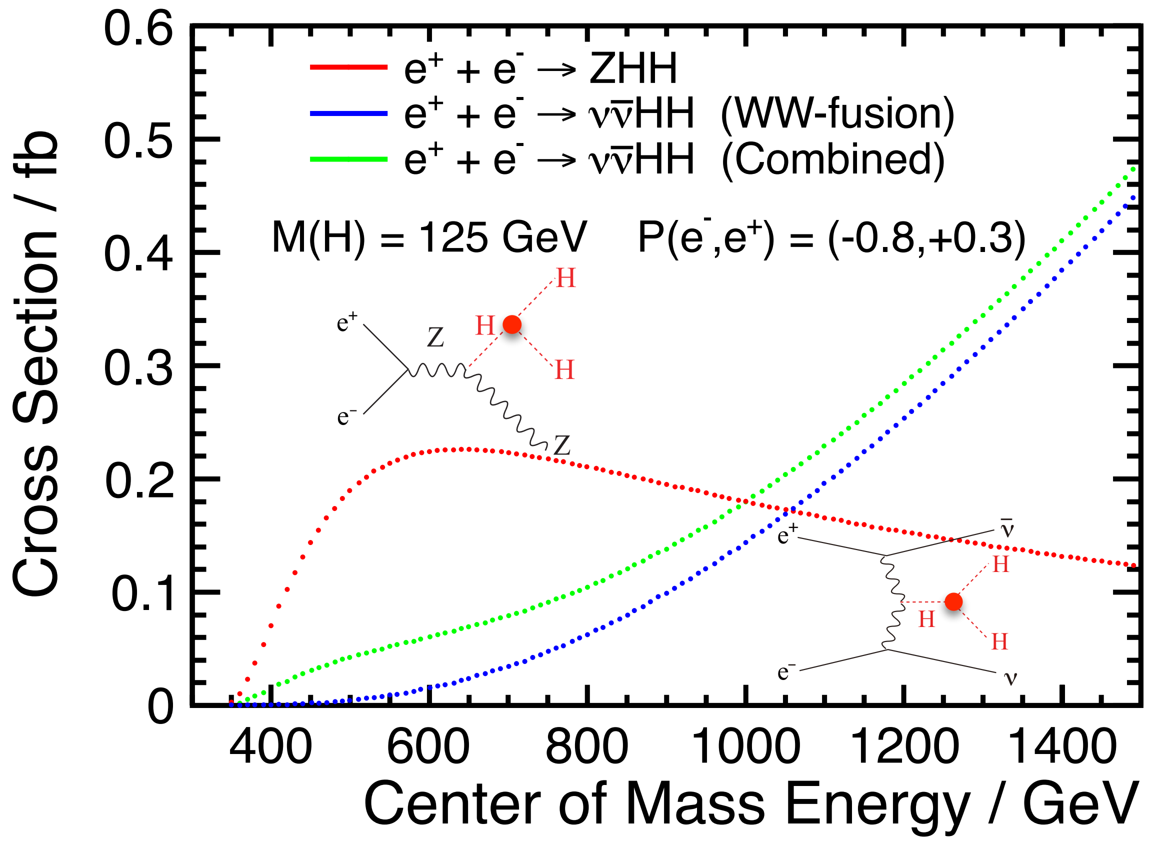
(iii.2.1) Higgs self-coupling

- direct probe of the Higgs potential
- large deviation (> 20%) motivated by electroweak baryogenesis, could be ~100%
- √s>=500 GeV, e+e- —> ZHH
- √s>=1 TeV, e+e- —> vvHH (WW-fusion)

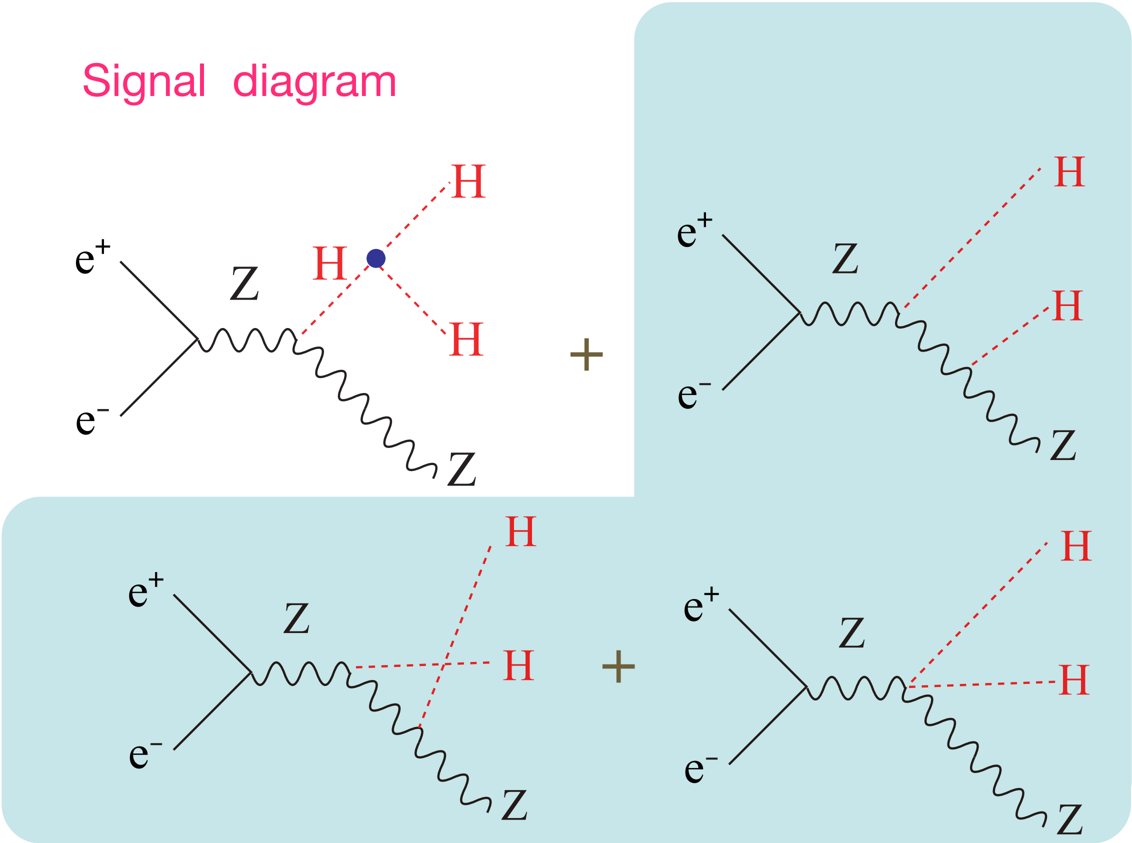


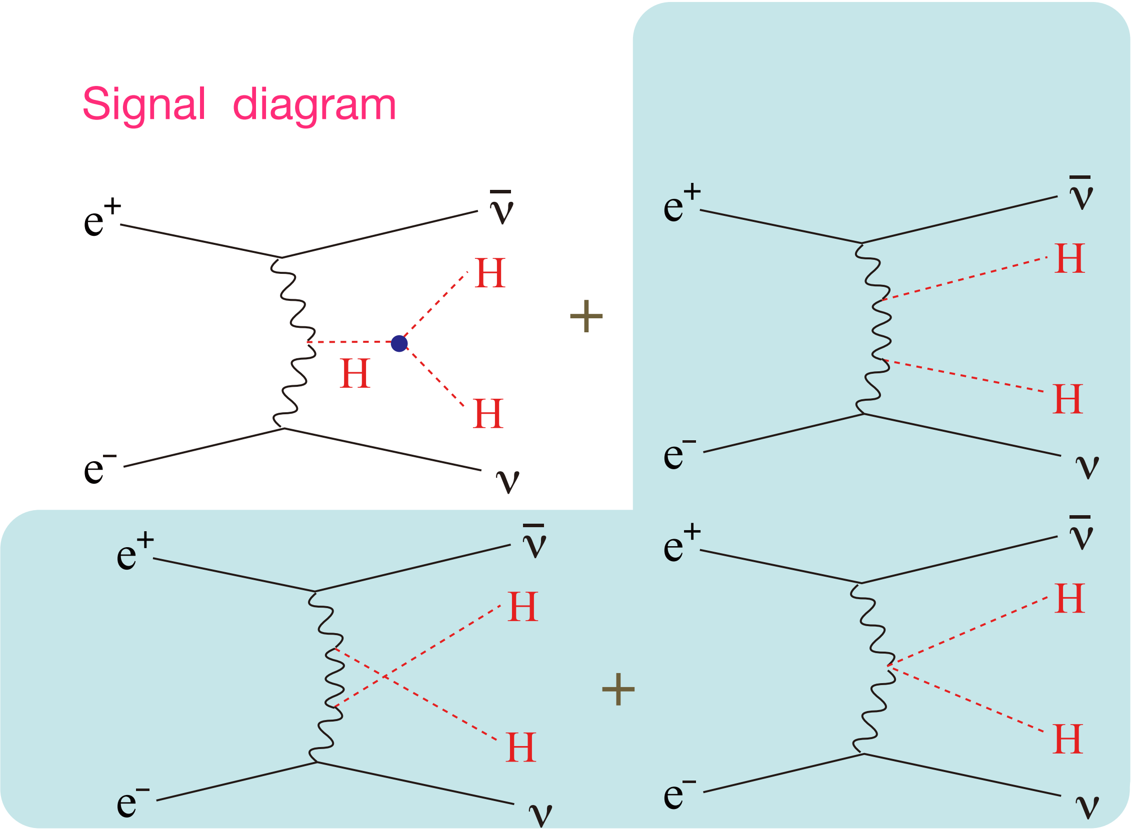
	$\Delta\lambda_{HHH}/\lambda_{HHH}$	500 GeV	+ 1 TeV
ILC	Snowmass	46%	13%
	H20	27%	10%

	1.4 TeV	+3 TeV
CLIC	24%	11%



physics issues: diagrams for double Higgs production


Signal diagram


Signal diagram

$$\sigma = S\lambda^2 + I\lambda + B$$

(signal diagram) (interference) (background diagram)

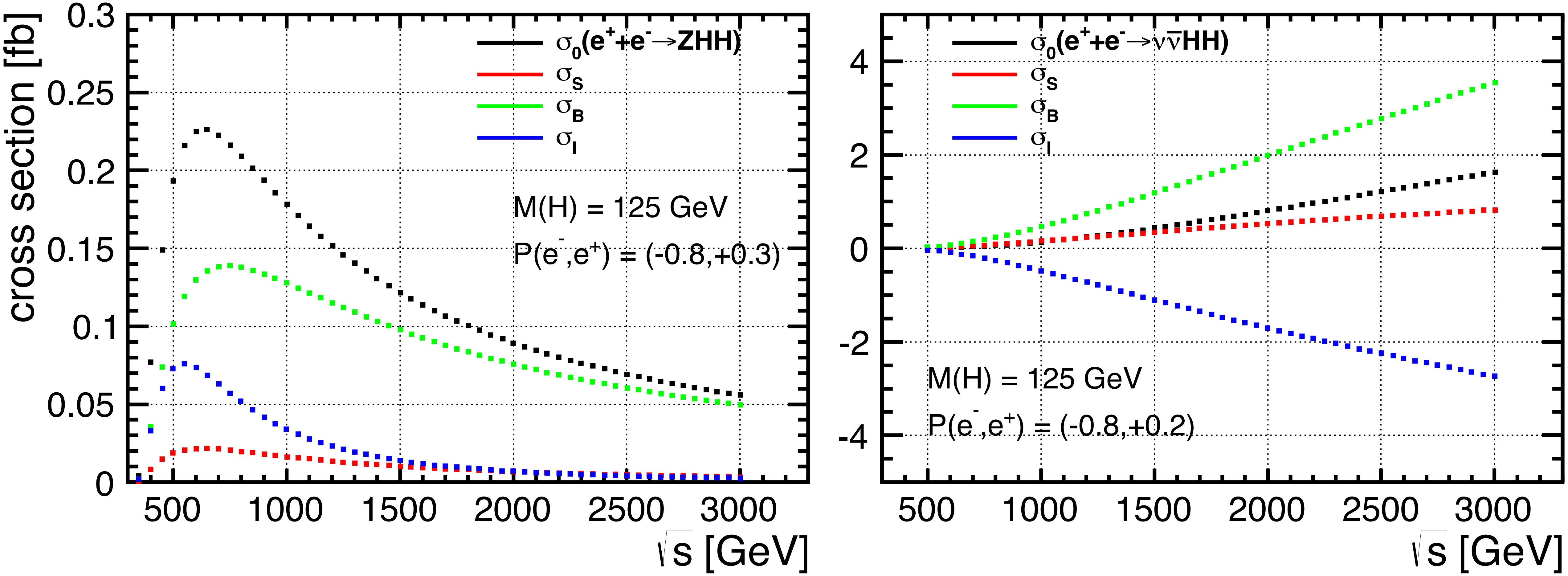
- the sensitivity of λ is determined not just by the apparent total cross section, in fact is determined by S and I term;
- if B term dominates, measurement would be very difficult

double Higgs x-section: breakdown for each diagram

$$\sigma = S\lambda^2 + I\lambda + B$$

ZHH

νν HH

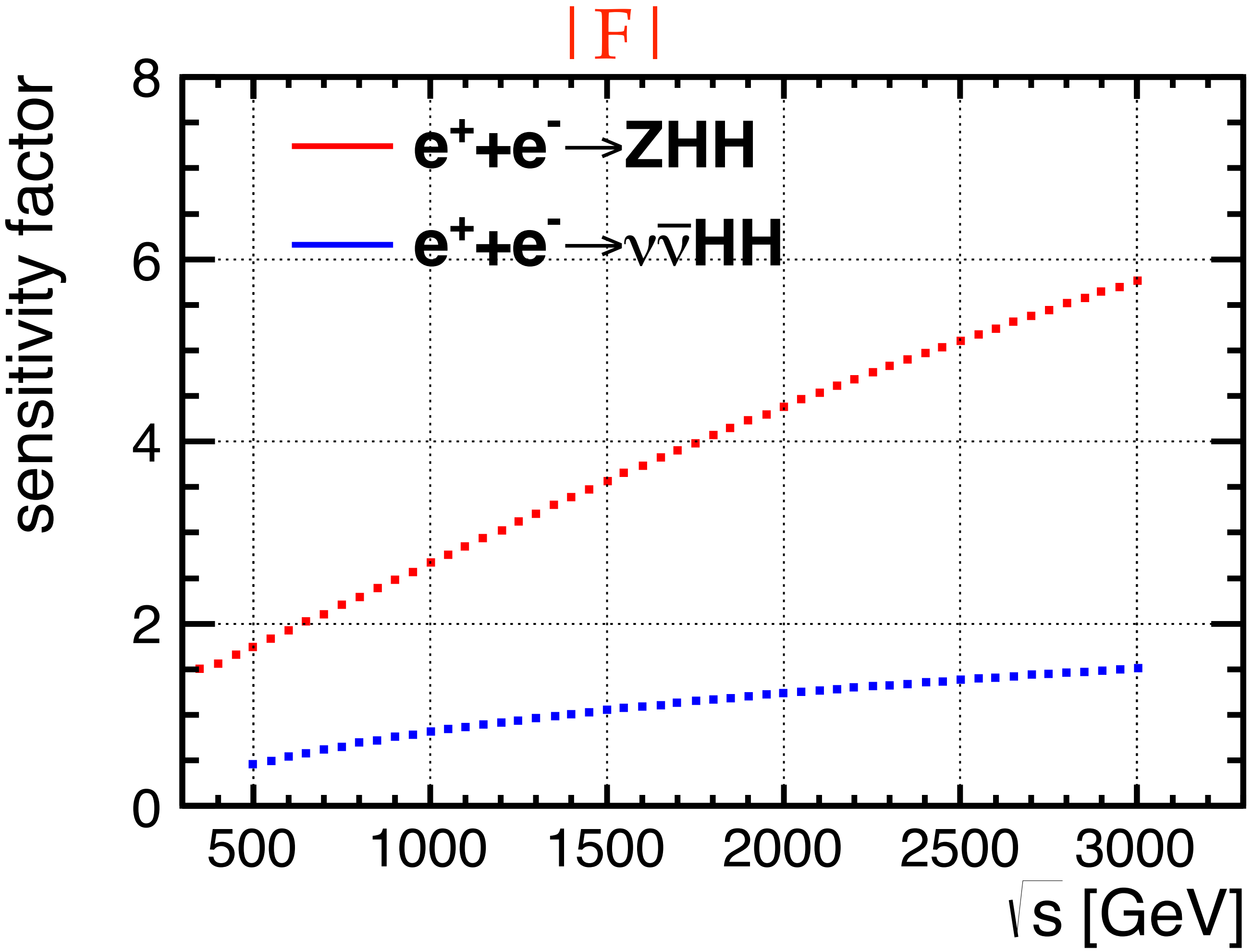


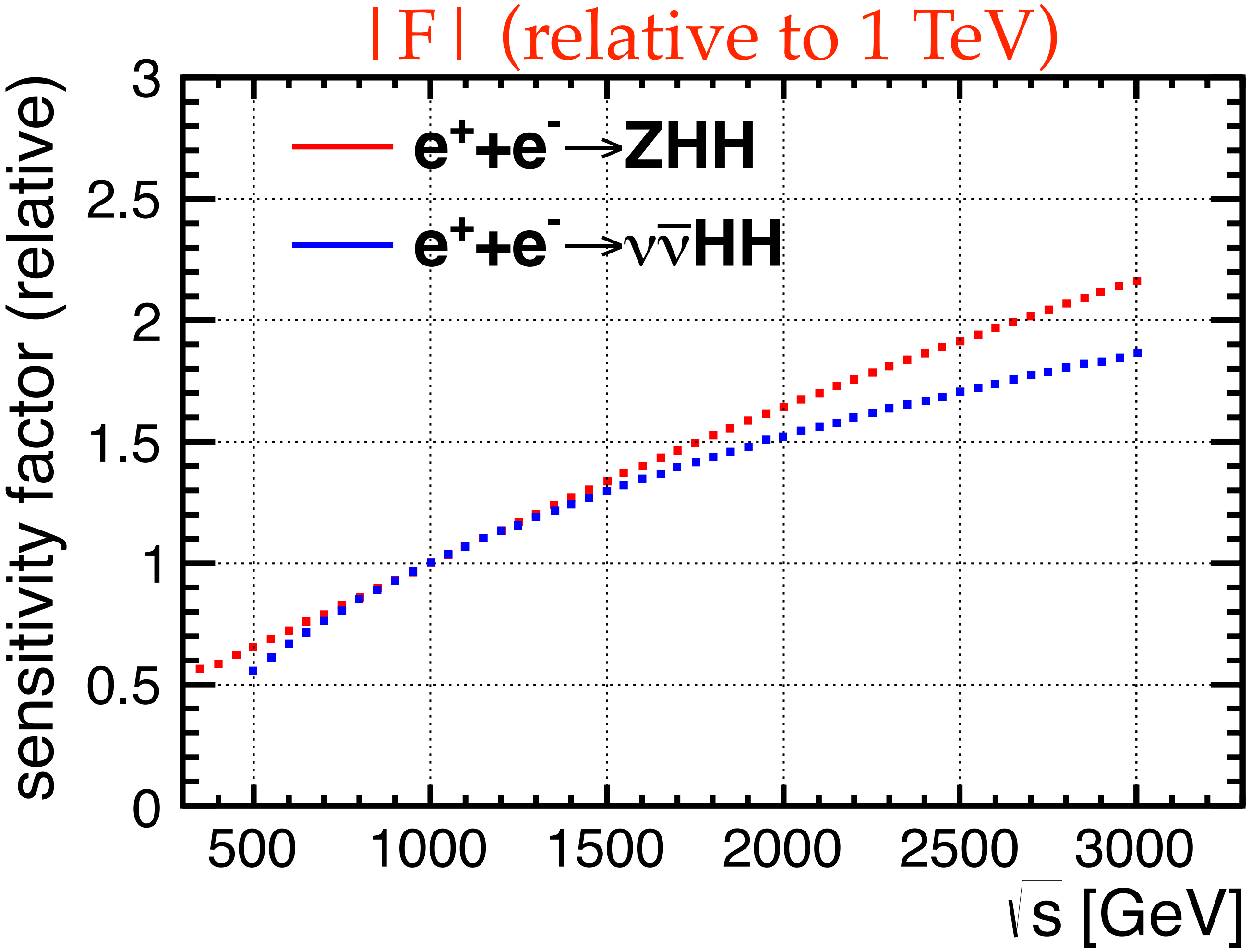
Higgs self-coupling: from σ to λ

$$\frac{\delta\lambda}{\lambda} = F \cdot \frac{\delta\sigma}{\sigma}$$

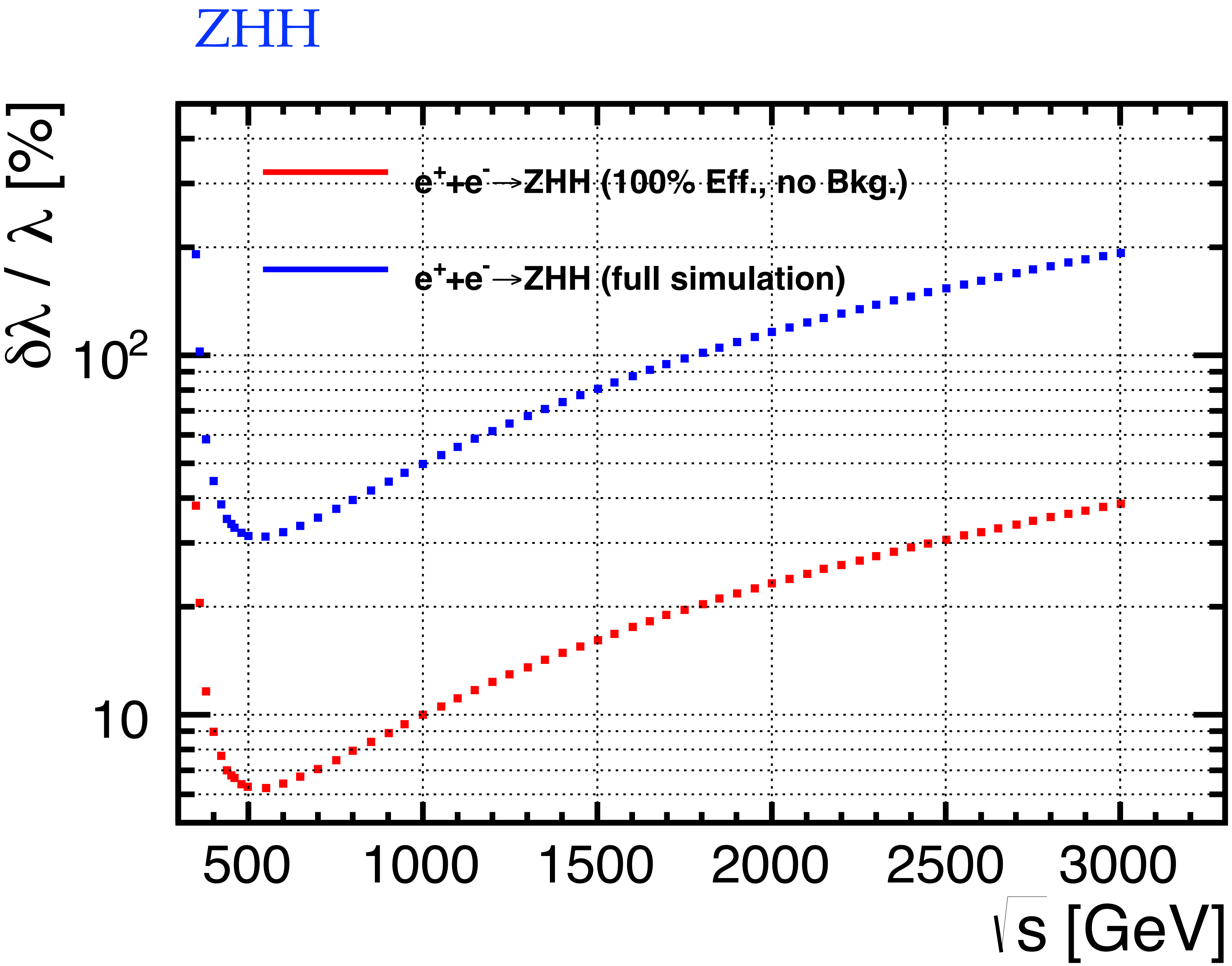
$$F = \frac{\sigma}{2S\lambda^2 + I\lambda}$$

sensitivity factor





expected precision of λ: impact from analysis & √s

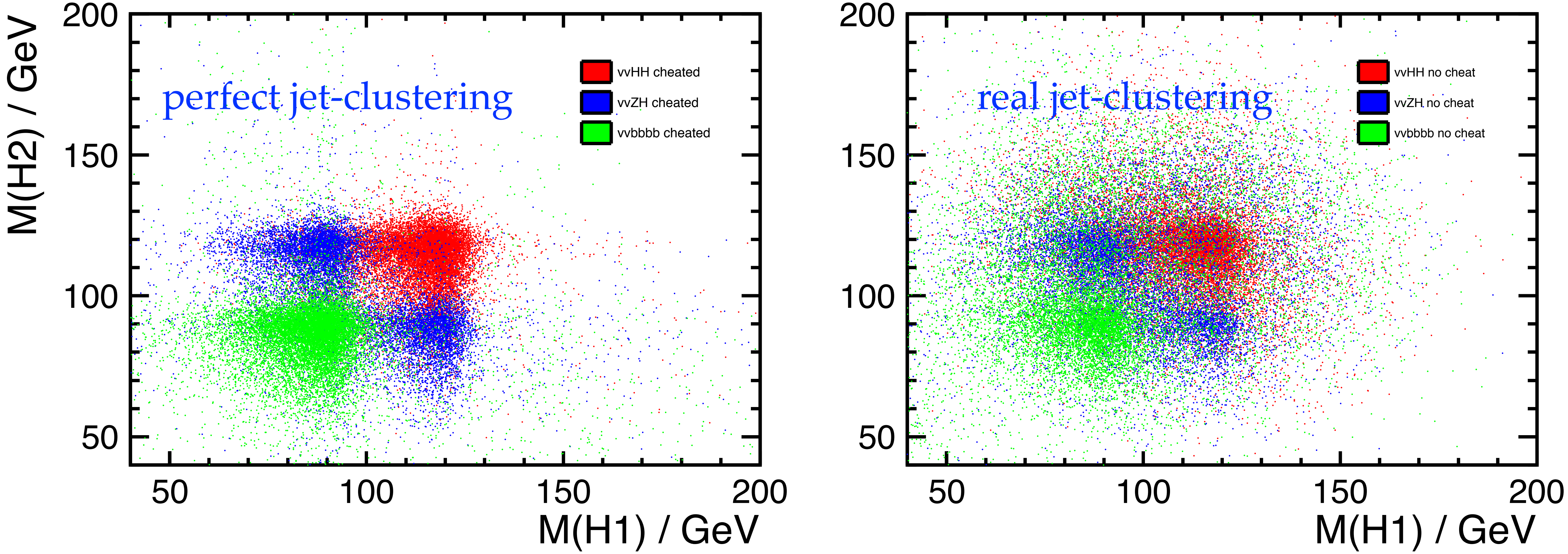


- for ννHH: significantly better from 500 GeV to 1 TeV, δλ/λ~10% achievable at >= 1TeV; not drastically better, from 1 TeV to 3 TeV, improved by 50%

one limiting factor: jet-clustering algorithm

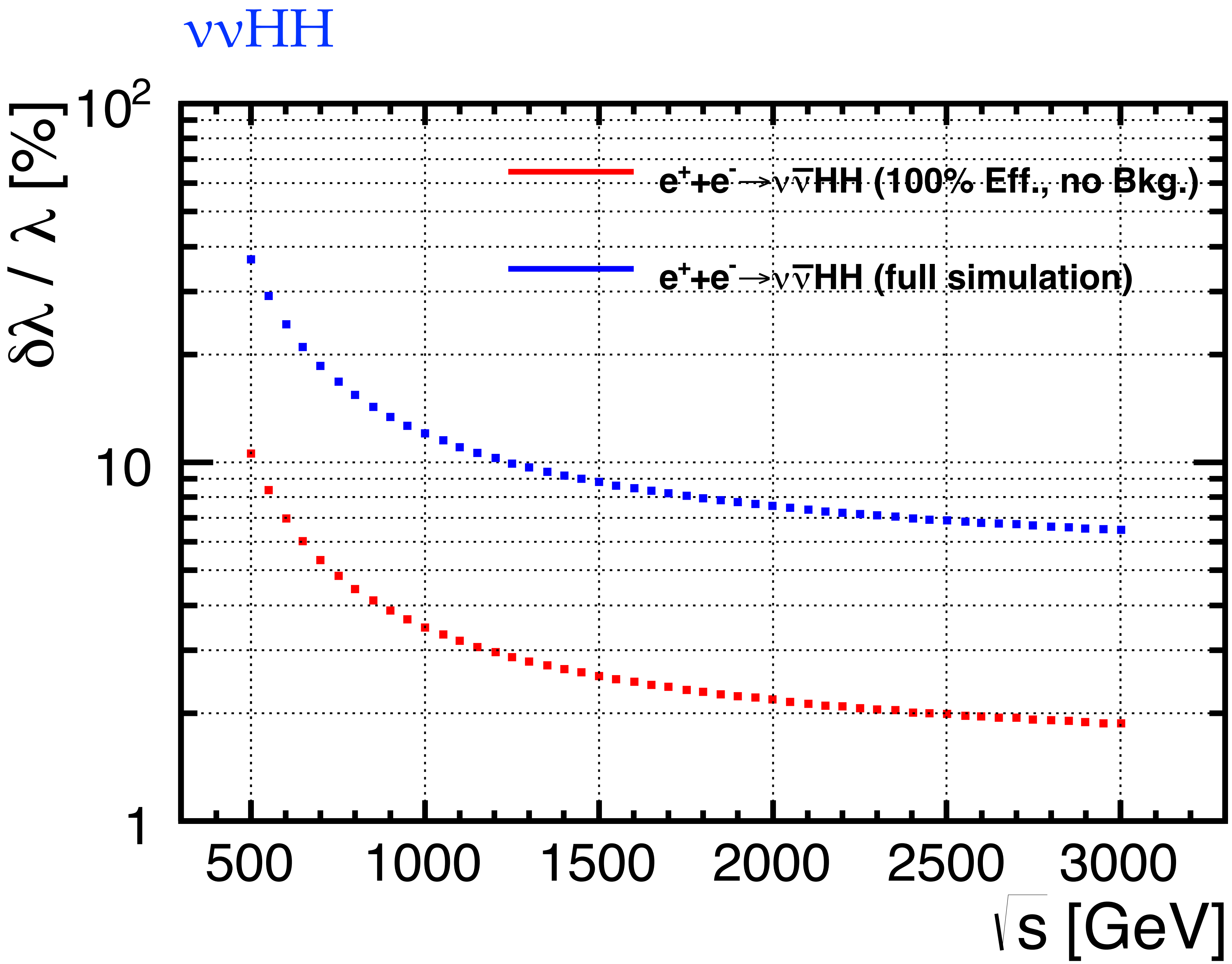
ZHH->ννbbbb (BG: ZZH and ZZZ)

scatter plot of two Higgs masses



- the mis-clustering of particles degrades significantly the separation between signal and BG.
- it is studied that using perfect color-singlet-jet-clustering can improve $\delta\lambda/\lambda$ by 40%!

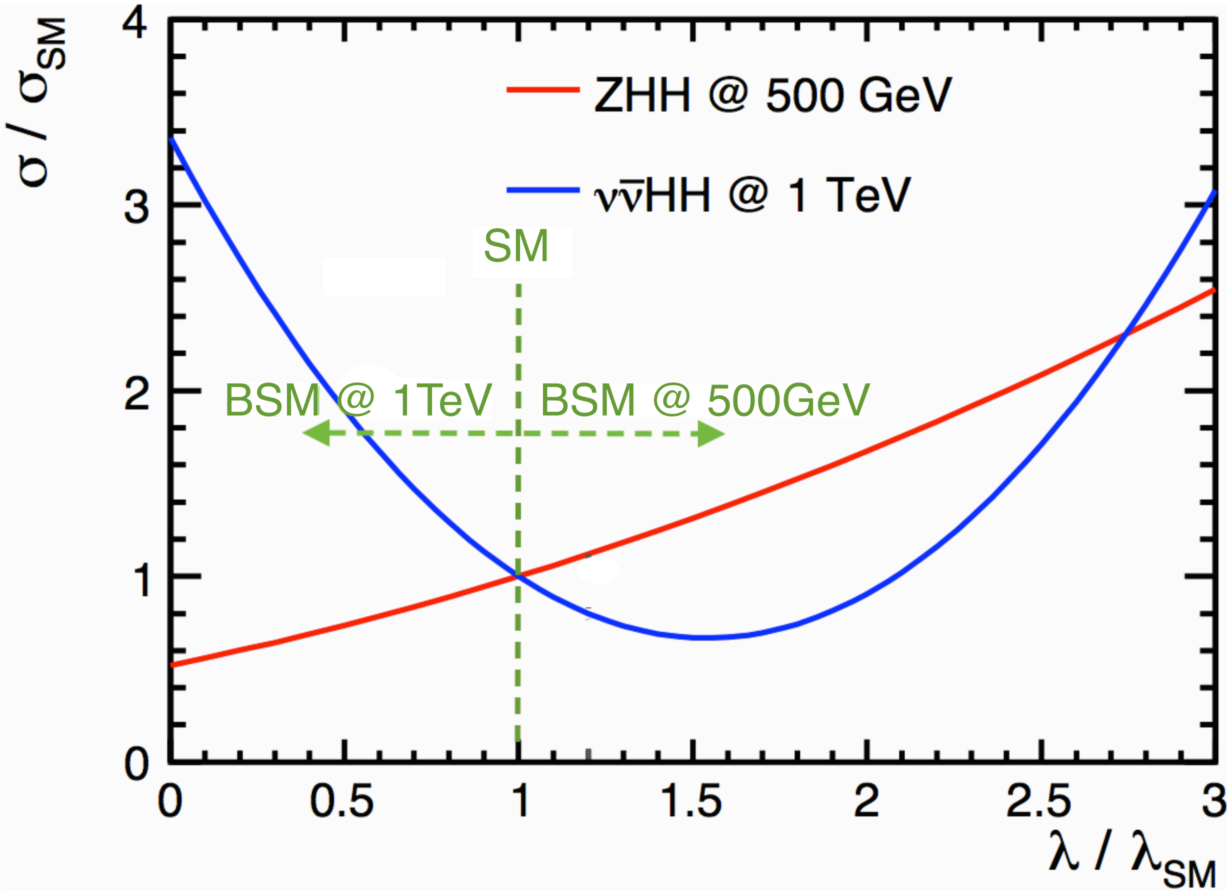
expected precision of λ: impact from analysis & √s

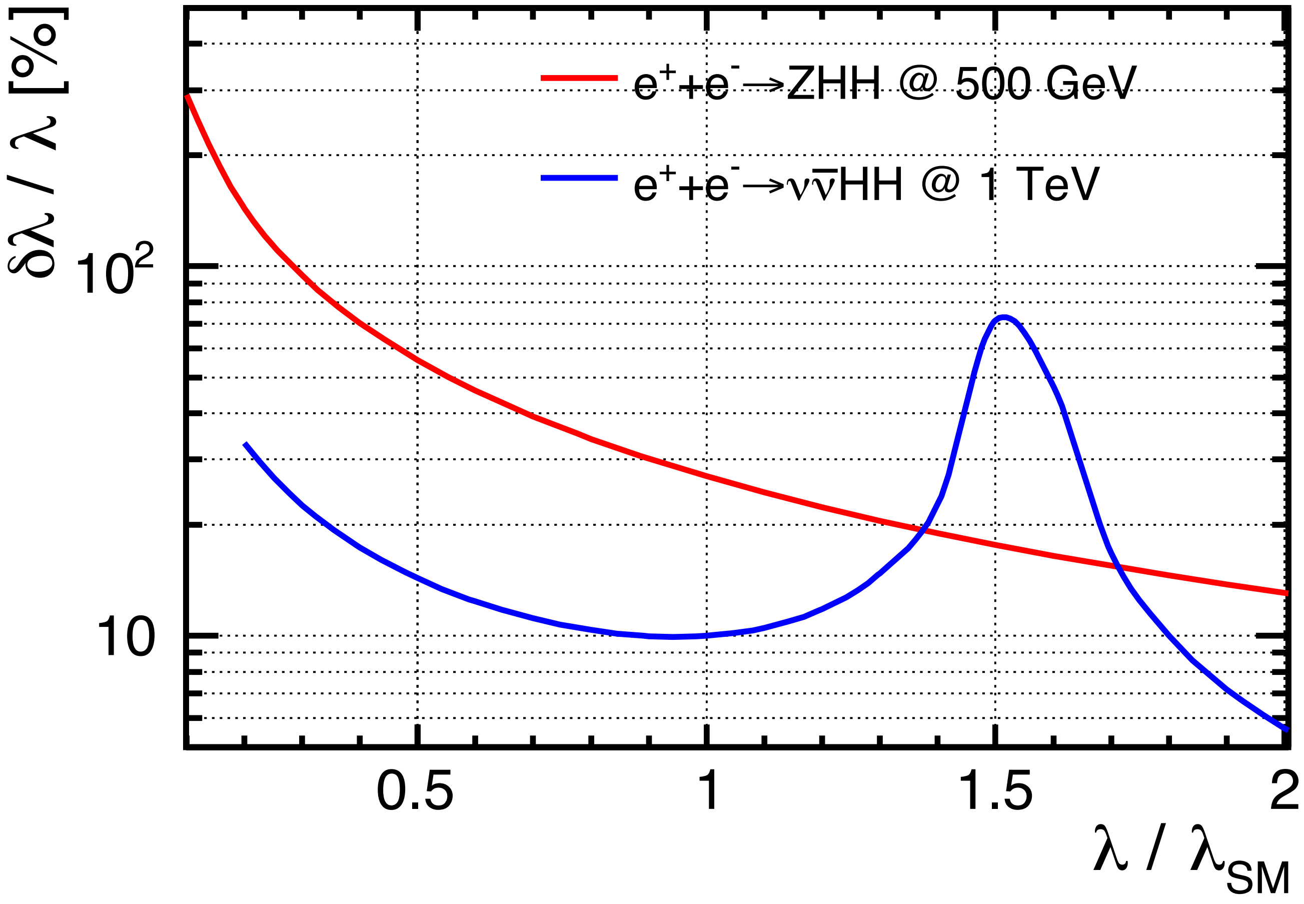


- huge gap of these two expectations —> room of improvement
- for ZHH: optimal at 500-600 GeV; significantly worse at higher √s

Higgs self-coupling: when $\lambda_{HHH} \neq \lambda_{SM}$?

- constructive interference in ZHH, while destructive in ννHH (& LHC) —> complementarity between ILC & LHC, between √s ~500 GeV and >1TeV
- if $\lambda_{HHH} / \lambda_{SM} = 2$, Higgs self-coupling can be measured to ~15% using ZHH at 500 GeV e+e-

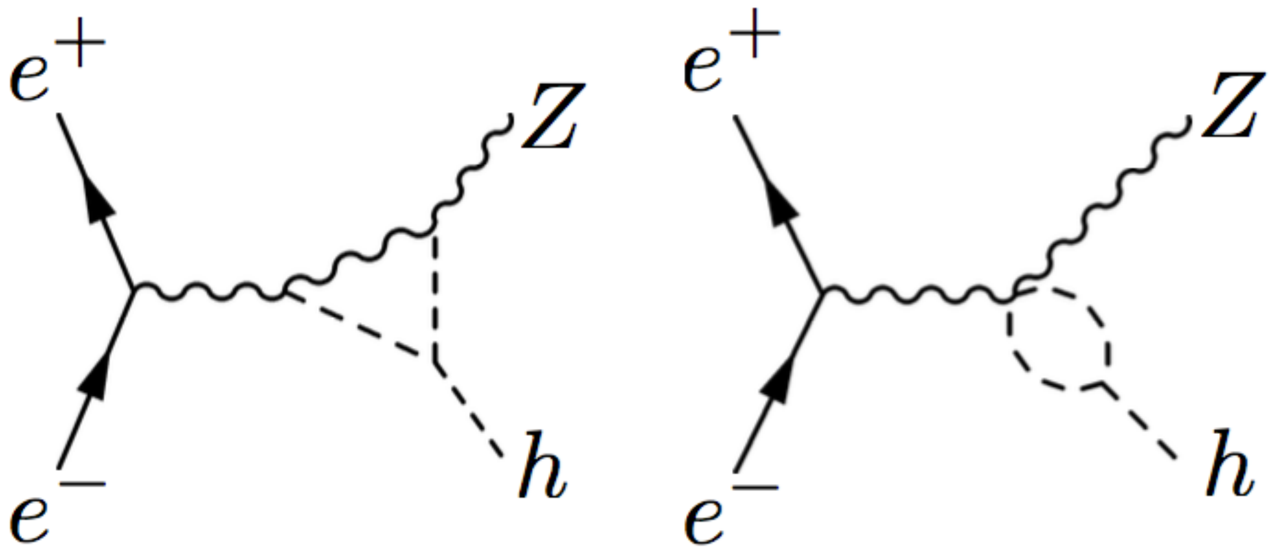




references for large deviations

e.g. Grojean, et al., PRD71, 036001; Kanemura, et al., 1508.03245; Kaori, Senaha, PHLTA,B747,152; Perelstein, et al., JHEP 1407, 108

Higgs self-coupling: indirect determination

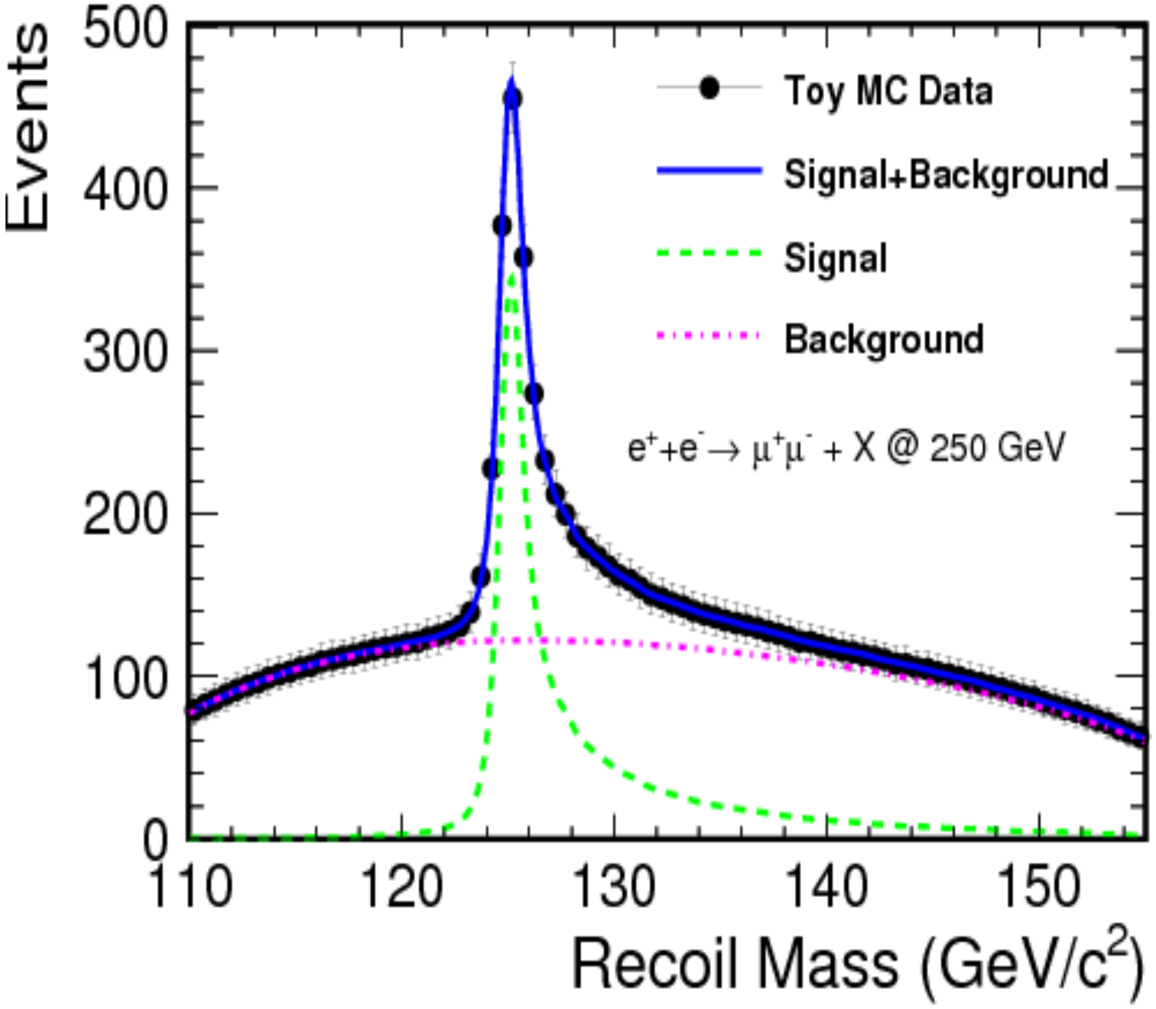


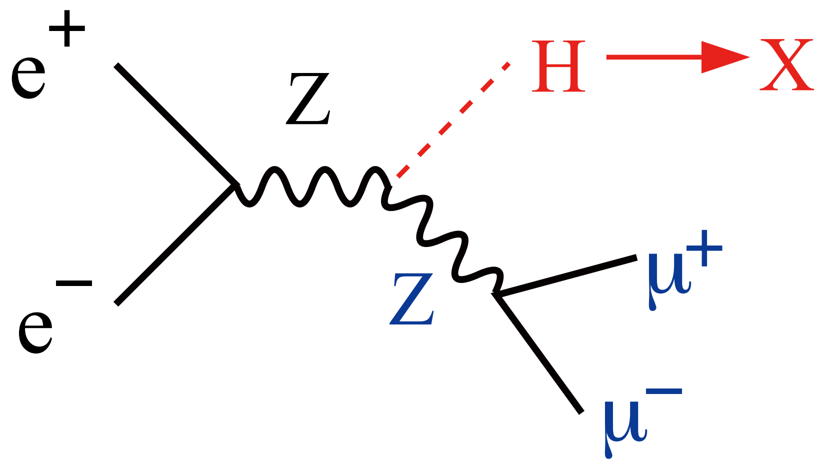
McCullough, arXiv:1312.3322

$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

- if only δh is deviated —> δh ~ 28%
- if both δz and δh deviated —> δh ~ 90%
- δσ could receive contributions from many other sources
- open question: what happens after taking into account all possible modifications?

(iii.2.2) inclusive σ_{ZH}: unique key @ e+e-





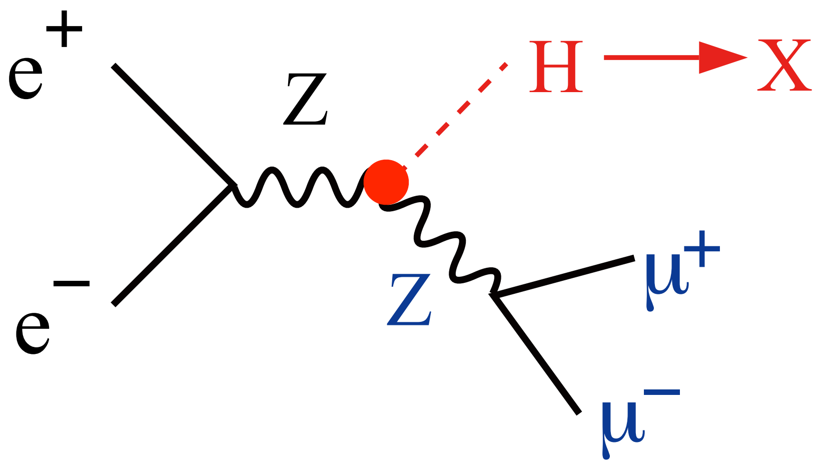
$$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-})\right)^2$$

$$\Delta m_H = 14\text{MeV}$$

- well defined initial states at e+e-
- recoil mass technique —> tag Z only
- Higgs is tagged without looking into H decay
- absolute cross section of e^+e^- —> ZH

for Z->ll (leptonic recoil), Yan et al, arXiv:1604.07524;
for Z->qq (hadronic recoil), Thomson, arXiv:1509.02853

what does model independence mean?



$$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-})\right)^2$$

- meas. of σ_{ZH} doesn't depend on how Higgs decays
- meas. of σ_{ZH} doesn't depend on underlying HZZ vertex

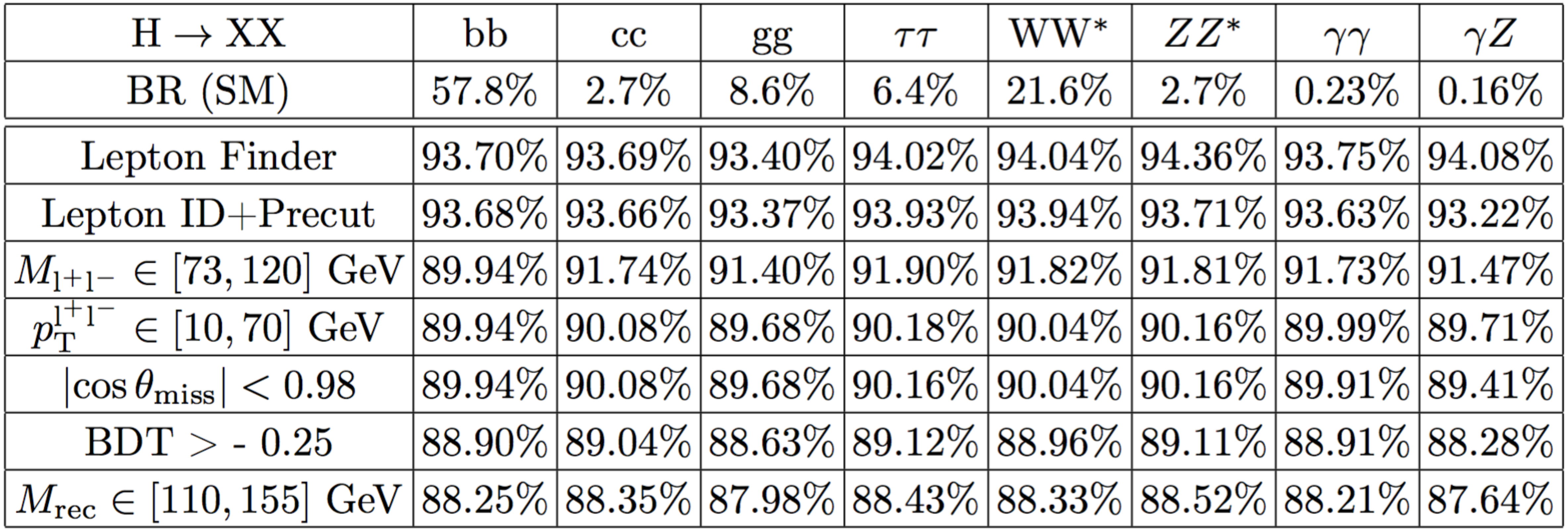
is it really possible?

independent of H decay modes?

$$e^+ + e^- \to ZH \to l^+ l^- / q\bar{q} + X$$

- this question is almost equivalent to whether we can tag the Z decay products unambiguously
- might be easy in Z->ll, certainly not trivial in Z->qq
- even in Z->ll mode, we know there can be isolated leptons from Higgs decay, e.g. H->WW*/τ τ/ZZ, which get mis-identified as leptons from Z decay
- keep in mind we are targeting 0.1-1% precision measurement

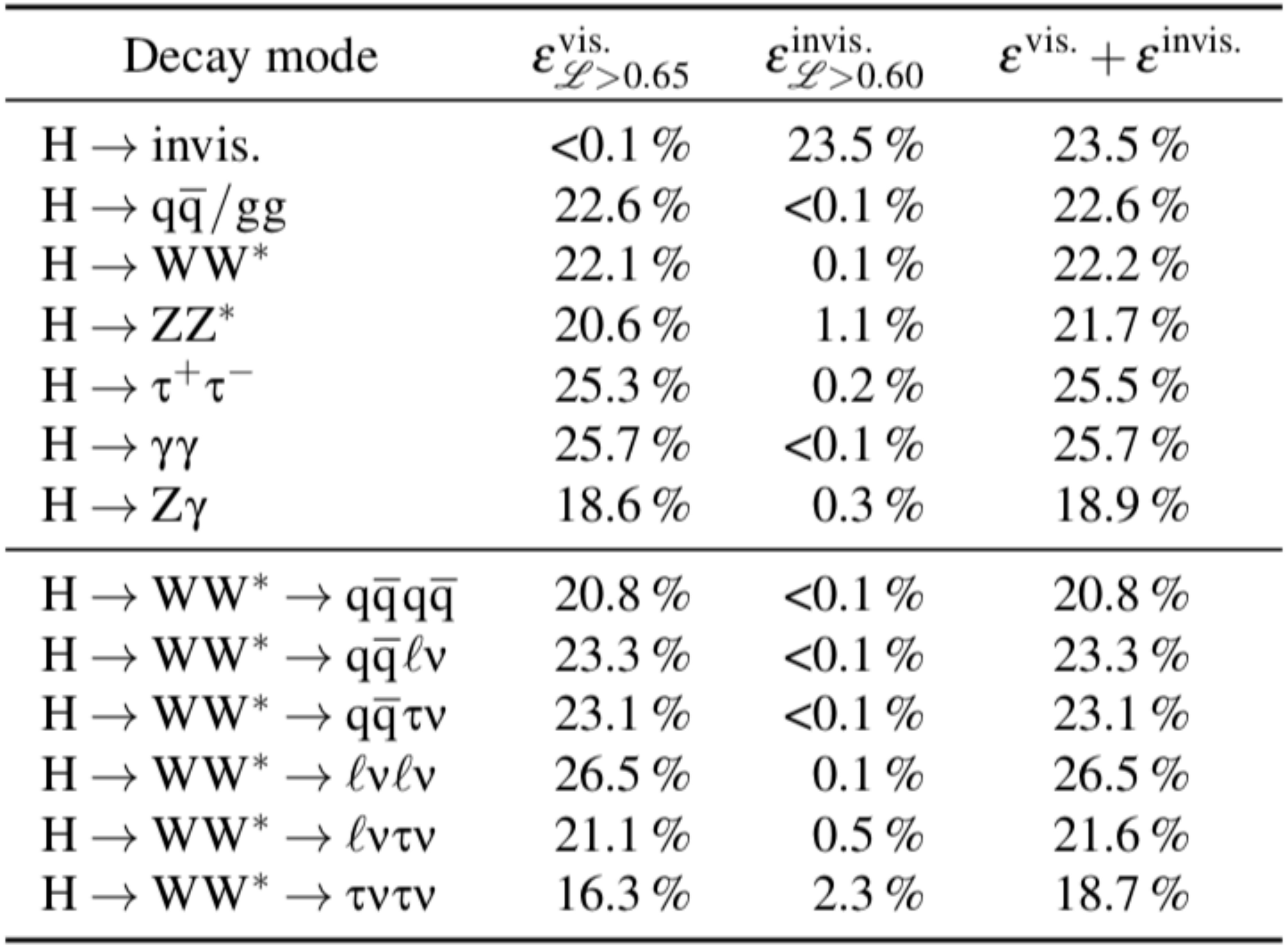
efficiencies breakdown (leptonic recoil)



H → XX	bb	cc	gg	$\tau\tau$	WW*	ZZ^*	$\gamma\gamma$	γZ
BR (SM)	57.8%	2.7%	8.6%	6.4%	21.6%	2.7%	0.23%	0.16%
Lepton Finder	93.70%	93.69%	93.40%	94.02%	94.04%	94.36%	93.75%	94.08%
Lepton ID+Precut	93.68%	93.66%	93.37%	93.93%	93.94%	93.71%	93.63%	93.22%
$M_{l^+l^-} \in [73, 120]$ GeV	89.94%	91.74%	91.40%	91.90%	91.82%	91.81%	91.73%	91.47%
$p_T^{l^+l^-} \in [10, 70]$ GeV	89.94%	90.08%	89.68%	90.18%	90.04%	90.16%	89.99%	89.71%
$\lvert\cos\theta_{miss}\rvert < 0.98$	89.94%	90.08%	89.68%	90.16%	90.04%	90.16%	89.91%	89.41%
BDT > - 0.25	88.90%	89.04%	88.63%	89.12%	88.96%	89.11%	88.91%	88.28%
$M_{rec} \in [110, 155]$ GeV	88.25%	88.35%	87.98%	88.43%	88.33%	88.52%	88.21%	87.64%

- every cut is applied very carefully to avoid large bias, still ~1%
- nevertheless, it becomes almost a paradox:
  - ☑ no cut, no bias; looser cuts, less bias
  - ☑ extremely tighter cuts, less bias;
  - ☑ too loose or too tight cuts -> remain too much background or too little signal -> bad precision measurement

efficiencies breakdown (hadronic recoil)



Decay mode	$\varepsilon^{\text{vis.}}_{\mathscr{L}>0.65}$	$\varepsilon^{\text{invis.}}_{\mathscr{L}>0.60}$	$\varepsilon^{\text{vis.}} + \varepsilon^{\text{invis.}}$
$H \rightarrow$ invis.	<0.1 %	23.5 %	23.5 %
$H \rightarrow q\bar{q}/gg$	22.6 %	<0.1 %	22.6 %
$H \rightarrow WW^*$	22.1 %	0.1 %	22.2 %
$H \rightarrow ZZ^*$	20.6 %	1.1 %	21.7 %
$H \rightarrow \tau^+\tau^-$	25.3 %	0.2 %	25.5 %
$H \rightarrow \gamma\gamma$	25.7 %	<0.1 %	25.7 %
$H \rightarrow Z\gamma$	18.6 %	0.3 %	18.9 %
$H \rightarrow WW^* \rightarrow q\bar{q}q\bar{q}$	20.8 %	<0.1 %	20.8 %
$H \rightarrow WW^* \rightarrow q\bar{q}\ell\nu$	23.3 %	<0.1 %	23.3 %
$H \rightarrow WW^* \rightarrow q\bar{q}\tau\nu$	23.1 %	<0.1 %	23.1 %
$H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$	26.5 %	0.1 %	26.5 %
$H \rightarrow WW^* \rightarrow \ell\nu\tau\nu$	21.1 %	0.5 %	21.6 %
$H \rightarrow WW^* \rightarrow \tau\nu\tau\nu$	16.3 %	2.3 %	18.7 %

- relative bias can be as large as ~15%

a nice trick: categorization

$$\sigma_{ZH} = \sigma^{cat1} + \sigma^{cat2} + \sigma^{cat3} + \sigma^{cat4} + \cdots$$

- if we have a complete list of categories
- then we only need to keep all selection cuts independent of decay mode in each category;
- selections cuts among categories can be very different

for example

$$\sigma_{ZH} = \sigma^{H \to \text{invisible}} + \sigma^{H \to \text{visible}}$$

a realistic solution: make use of individual BR measurement

$$\sigma_{ZH} = \frac{N_S}{R_f L \bar{\epsilon}} \qquad \bar{\epsilon} \equiv \sum_i B_i \epsilon_i$$

N_S: # of signal
R_f: BR of Z->ff
L: int. luminosity
Bi: BR of H decay mode i
εi: efficiency of mode i

○ if every ε_i is same -> $\Sigma B_i = 1$; no need for any knowledge about B_i

○ nevertheless, we can measure many of the $\sigma \times B_i$; assume i=1..n is known with ΔBi; i=n+1,… is unknown, sum up to Bx;

known modes

systematic error to σ_{ZH}

unknown modes

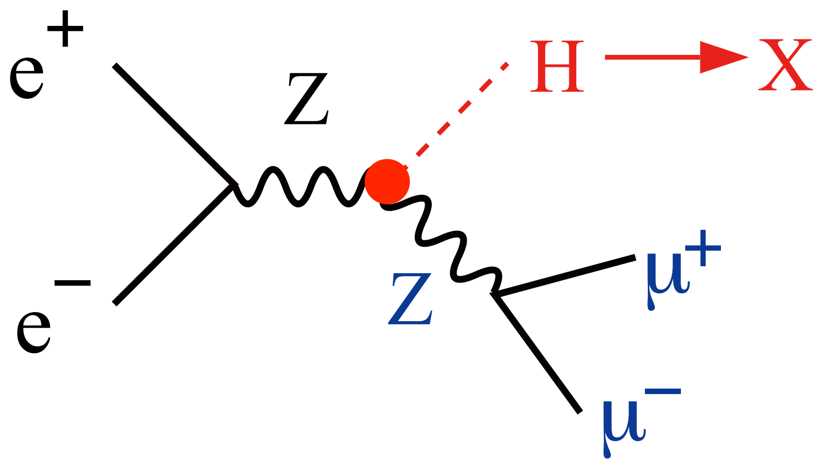
$$\frac{\Delta\sigma_{\mathrm{ZH}}}{\sigma_{\mathrm{ZH}}} = \frac{\Delta\bar{\varepsilon}}{\bar{\epsilon}} = \sqrt{\sum_{i=1}^{n} \Delta B_i^2 \left(\frac{\varepsilon_i}{\varepsilon_0} - 1\right)^2}.$$

$$\frac{\Delta\sigma_{\mathrm{ZH}}}{\sigma_{\mathrm{ZH}}} = \frac{\Delta\bar{\varepsilon}}{\bar{\epsilon}} < \sum_{i=n+1} B_i \frac{\delta\varepsilon_{\max}}{\varepsilon_0} = B_x \frac{\delta\varepsilon_{\max}}{\varepsilon_0}$$

○ leptonic recoil, demonstrated possible $\delta\sigma_{ZH}$~0.1% for Bx<10%

☐ hadronic recoil, still need more work for $\delta\sigma_{ZH}$ <1% for Bx<10%

independent of HZZ vertex?



- different HZZ vertex might change angular distributions of Z
- hence, this question is equivalent to whether the selections cuts are democratic for all production angles of Z
- open question, this is not sufficiently studied yet

(iii.2.3) determine Higgs CP (admixture)

- find CP-violating source in Higgs sector —> EW baryongenesis
- essential to understand structures of all Higgs couplings

through H—>$\tau^+\tau^-$

(or ttH)

$$L_{Hff} = -\frac{m_f}{v} H \bar{f} (\cos\Phi_{CP} + \underline{i\gamma^5 \sin\Phi_{CP}}) f$$

$$\Delta\Phi_{CP} \sim 4.3^\circ$$

Jeans et al, 1804.01241

through HZZ/HWW

$$L_{HVV} = 2C_V M_V^2 (\frac{1}{v} + \frac{a}{\Lambda}) H V_\mu V^\mu + C_V \frac{b}{\Lambda} H V_{\mu\nu} V^{\mu\nu} + \underline{C_V \frac{\tilde{b}}{\Lambda} H V_{\mu\nu} \tilde{V}_{\mu\nu}}$$

(CP-odd)

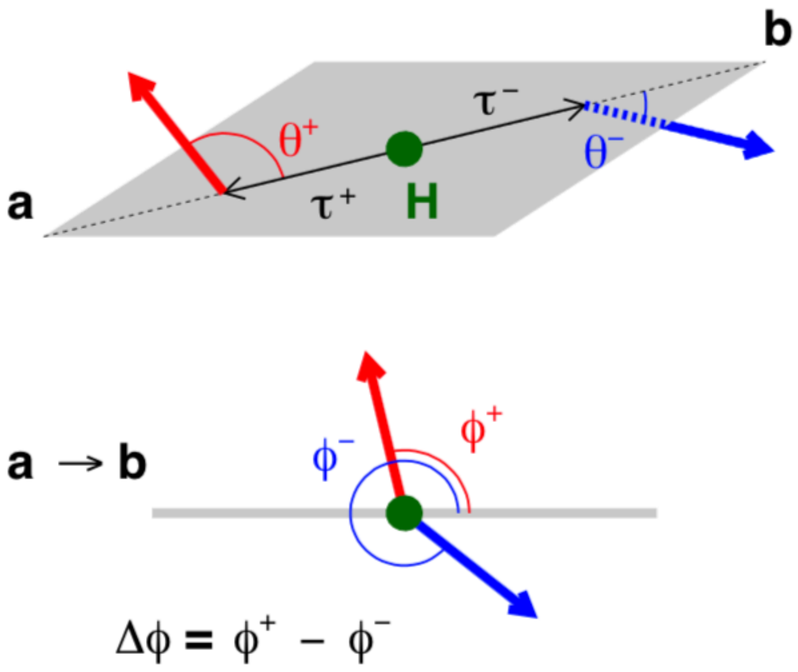
$\Delta\tilde{b} \sim 0.016$ (for Λ=1TeV)

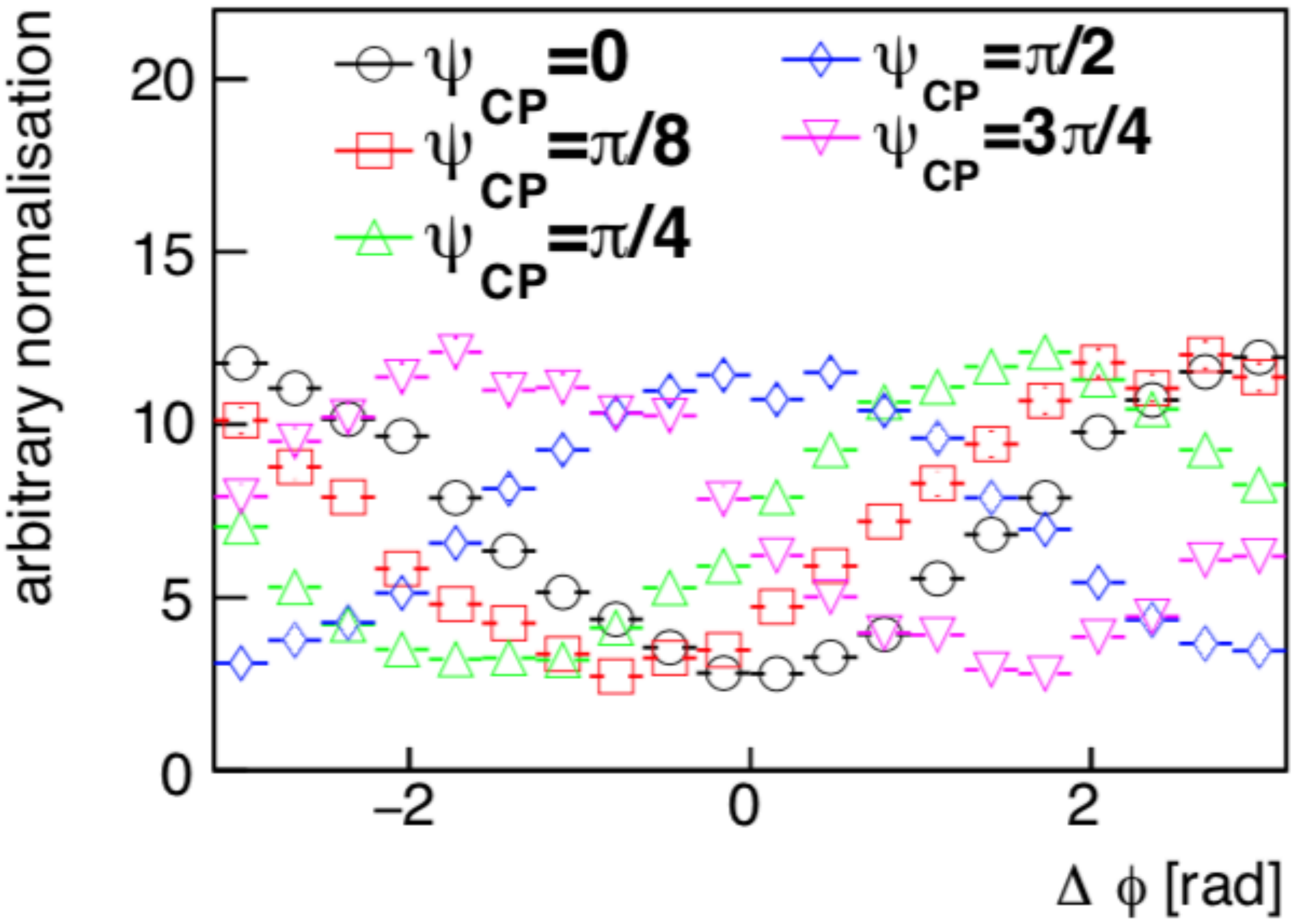
Ogawa, 1712.09772

for BR(H—>τ+τ-): Kawada, et. al, Eur.Phys.J. C75 (2015), 617

CP sensitive observable in H->$\tau^+\tau^-$

$$L_{Hff} = -\frac{m_f}{v} H \bar{f} (\cos\Phi_{CP} + i\gamma^5 \sin\Phi_{CP}) f$$



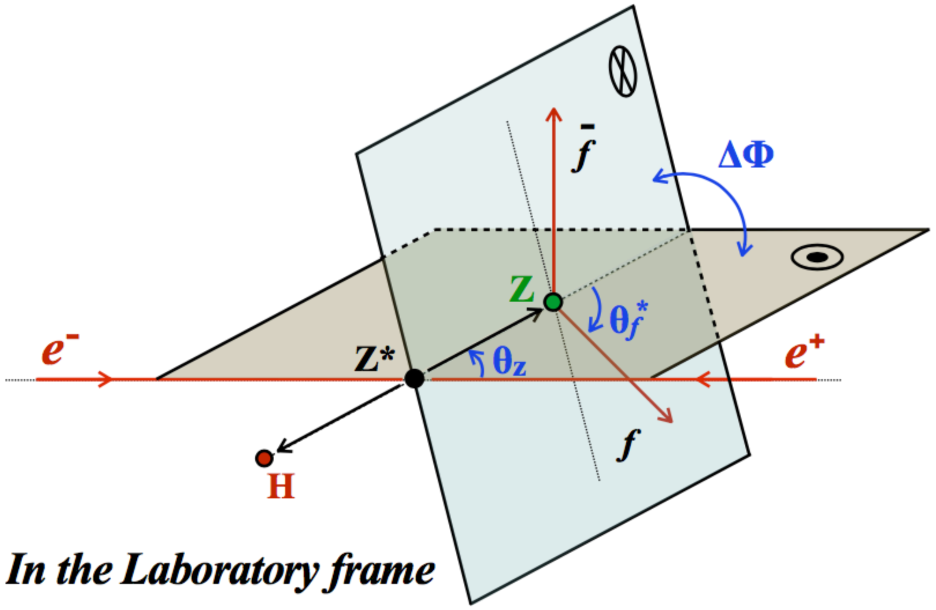


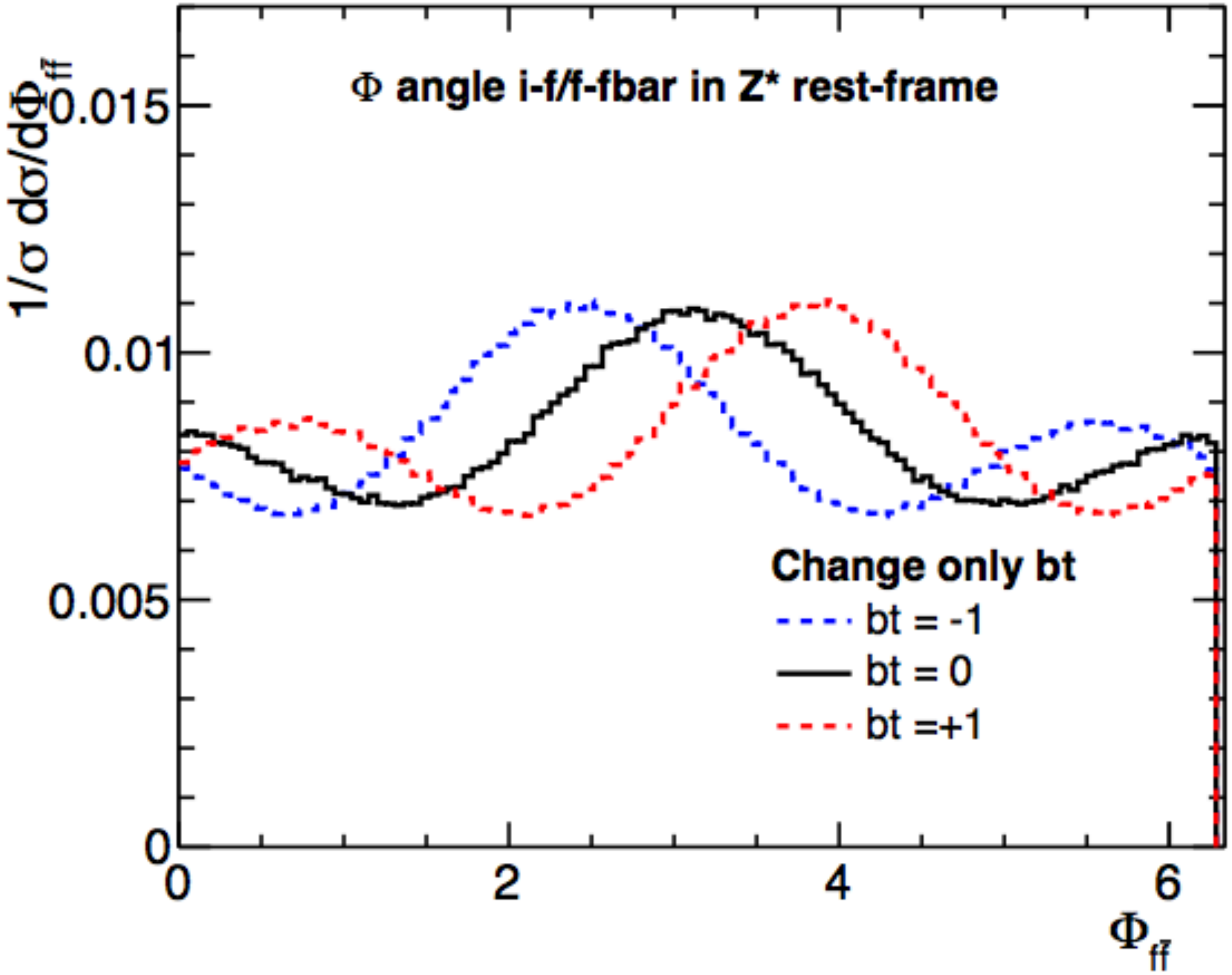
CP sensitive observable in HZZ coupling

$$L_{hZZ} = M_Z^2\left(\frac{1}{v} + \frac{a}{\Lambda}\right)hZ_\mu Z^\mu + \frac{b}{2\Lambda}hZ_{\mu\nu}Z^{\mu\nu} + \underline{\frac{\tilde{b}}{2\Lambda}hZ_{\mu\nu}\tilde{Z}_{\mu\nu}}$$

(CP-odd)

$$e^+ + e^- \rightarrow Zh \rightarrow f\bar{f}h$$



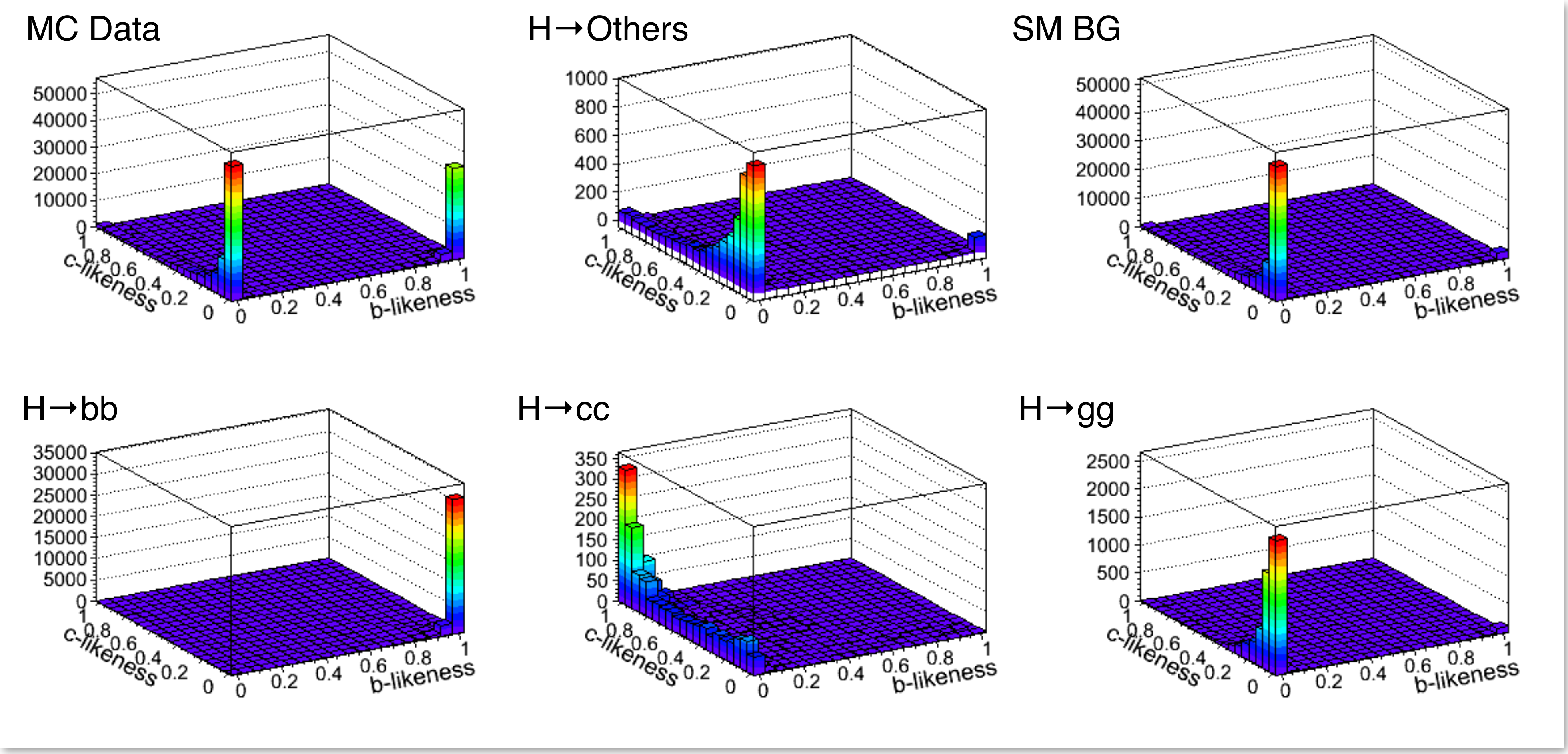


$$@\ \sqrt{s} = 250\mathrm{GeV}$$

(iii.2.4) Higgs direct couplings to bb, cc and gg

- clean environment at e+e-; excellent b- and c-tagging performance
- bb/cc/gg modes can be separated simultaneously by template fitting

e+e- —> ZH —> ff(jj): b-likeness .vs. c-likeness



directly measured →

$$\sigma_{ZH} \cdot \mathrm{Br}(H \to b\bar{b}) \propto g^2_{HZZ} g^2_{Hbb}/\Gamma_H$$
$$\sigma_{ZH} \cdot \mathrm{Br}(H \to c\bar{c}) \propto g^2_{HZZ} g^2_{Hcc}/\Gamma_H$$
$$\sigma_{ZH} \cdot \mathrm{Br}(H \to gg) \propto g^2_{HZZ} g^2_{Hgg}/\Gamma_H$$

with Γ_H →

δg_{Hbb}
δg_{Hcc}
δg_{Hgg}

Ono, et. al, Euro. Phys. J. C73, 2343; F.Mueller, PhD thesis (DESY)

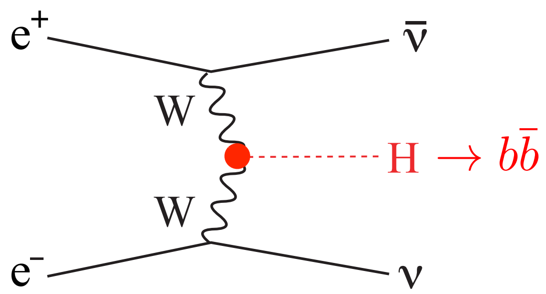
(iii.2.5) WW-fusion channel & Higgs total width Γ_H

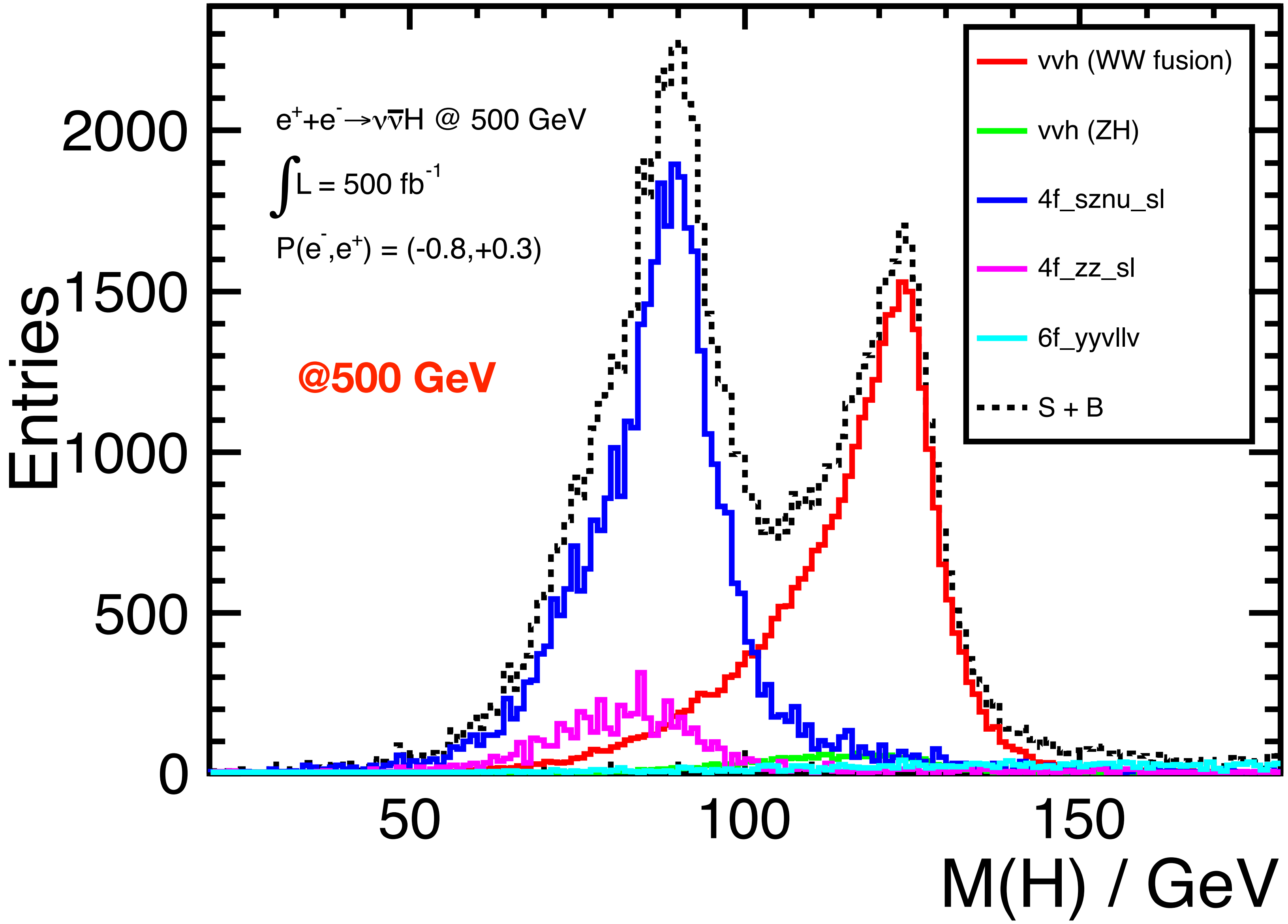
$$\Gamma_H = \frac{\Gamma_{HZZ}}{\mathrm{Br}(H \to ZZ^*)} \propto \frac{g^2_{HZZ}}{\mathrm{Br}(H \to ZZ^*)}$$

—>Br(H->ZZ*) very small

★ $$\Gamma_H = \frac{\Gamma_{HWW}}{\mathrm{Br}(H \to WW^*)} \propto \frac{g^2_{HWW}}{\mathrm{Br}(H \to WW^*)}$$

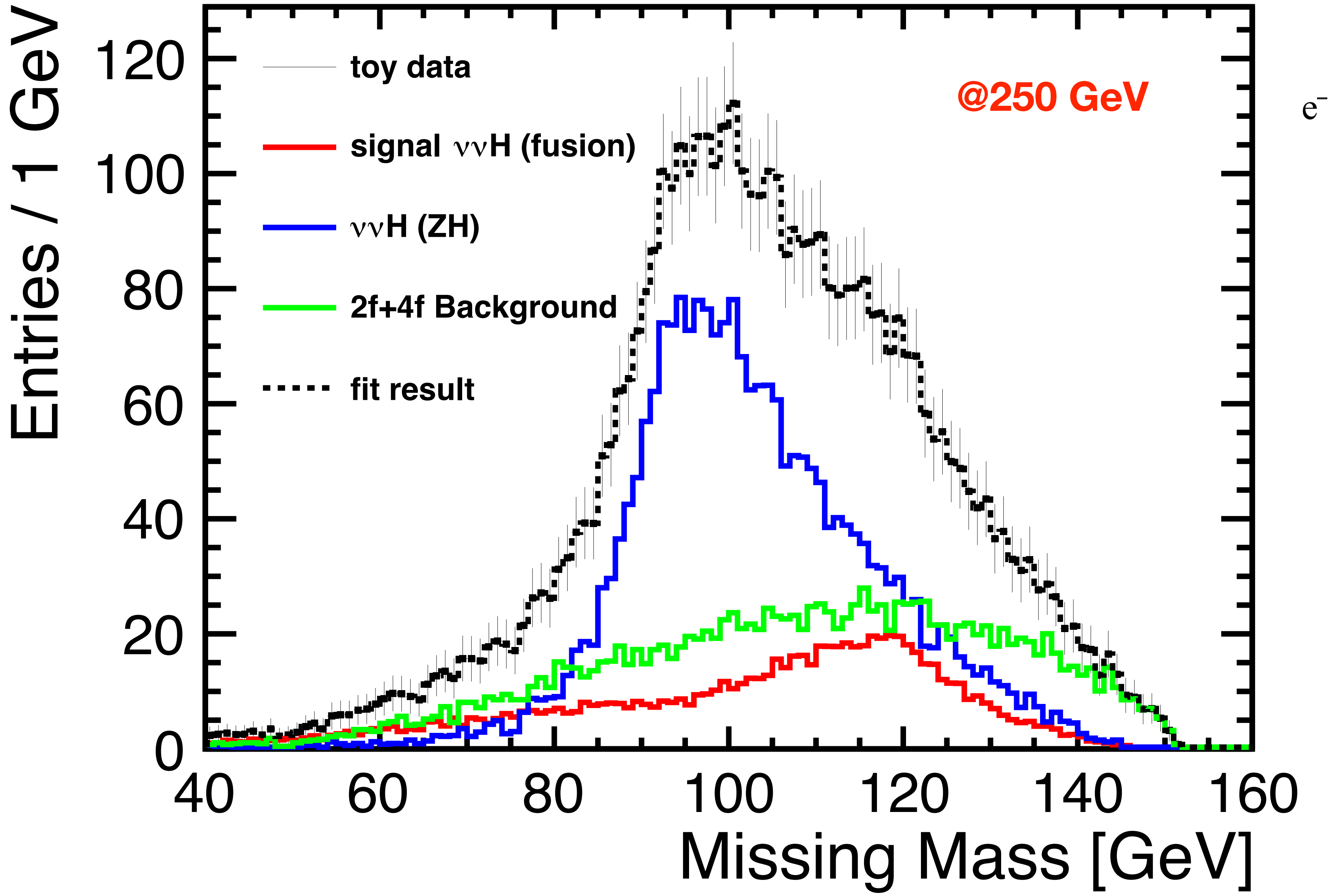
—> better option!

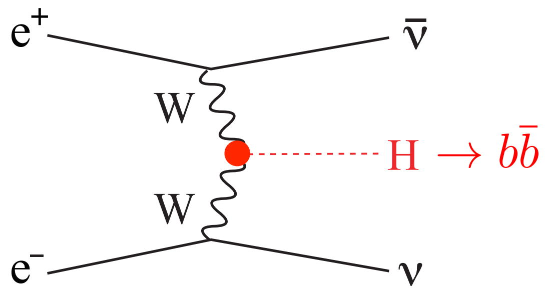




Duerig, et al., arXiv:1403.7734

very different at $\sqrt{s}=250$ GeV



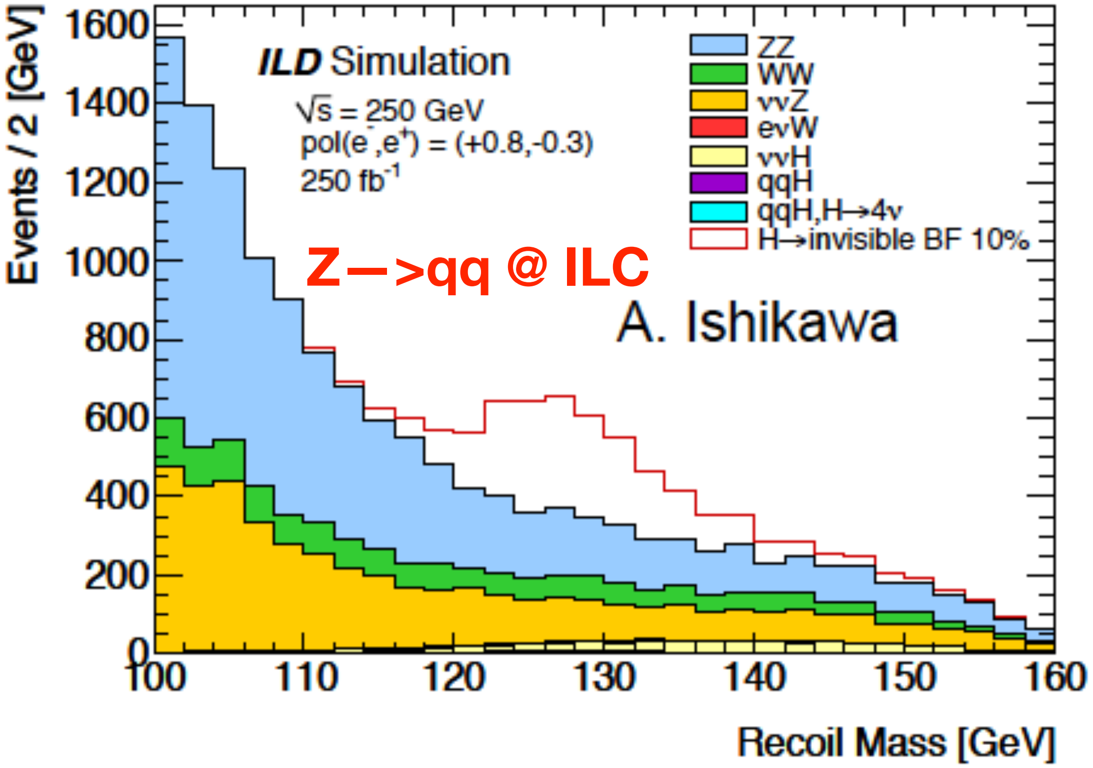


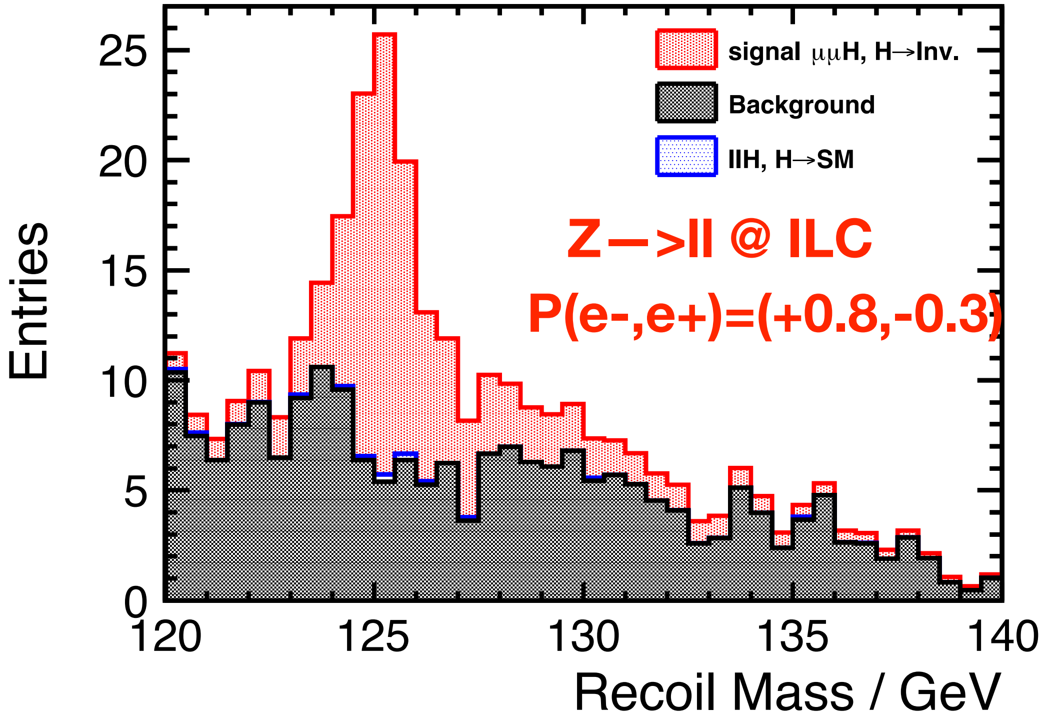
$\rho = -34\%$ correlation between

$Y_2=\sigma_{\nu\nu H}$xBR(H->bb) and $Y_3=\sigma_{ZH}$xBR(H->bb)

(iii.2.6) Higgs —> invisible at ILC250

$$e^+ + e^- \to ZH \to l^+l^-/q\bar{q} + \text{Missing}$$

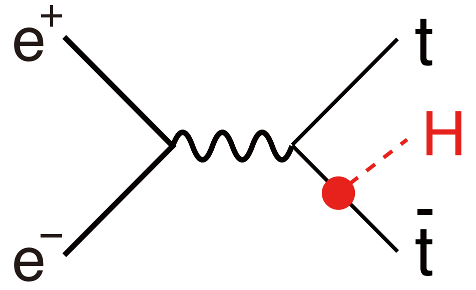




- recoil technique: Higgs mass fully reconstructed even it decays invisibly
- right-handed beam polarization helps: much lower background
- BR(H—>inv.) < 0.3% (CL95%)

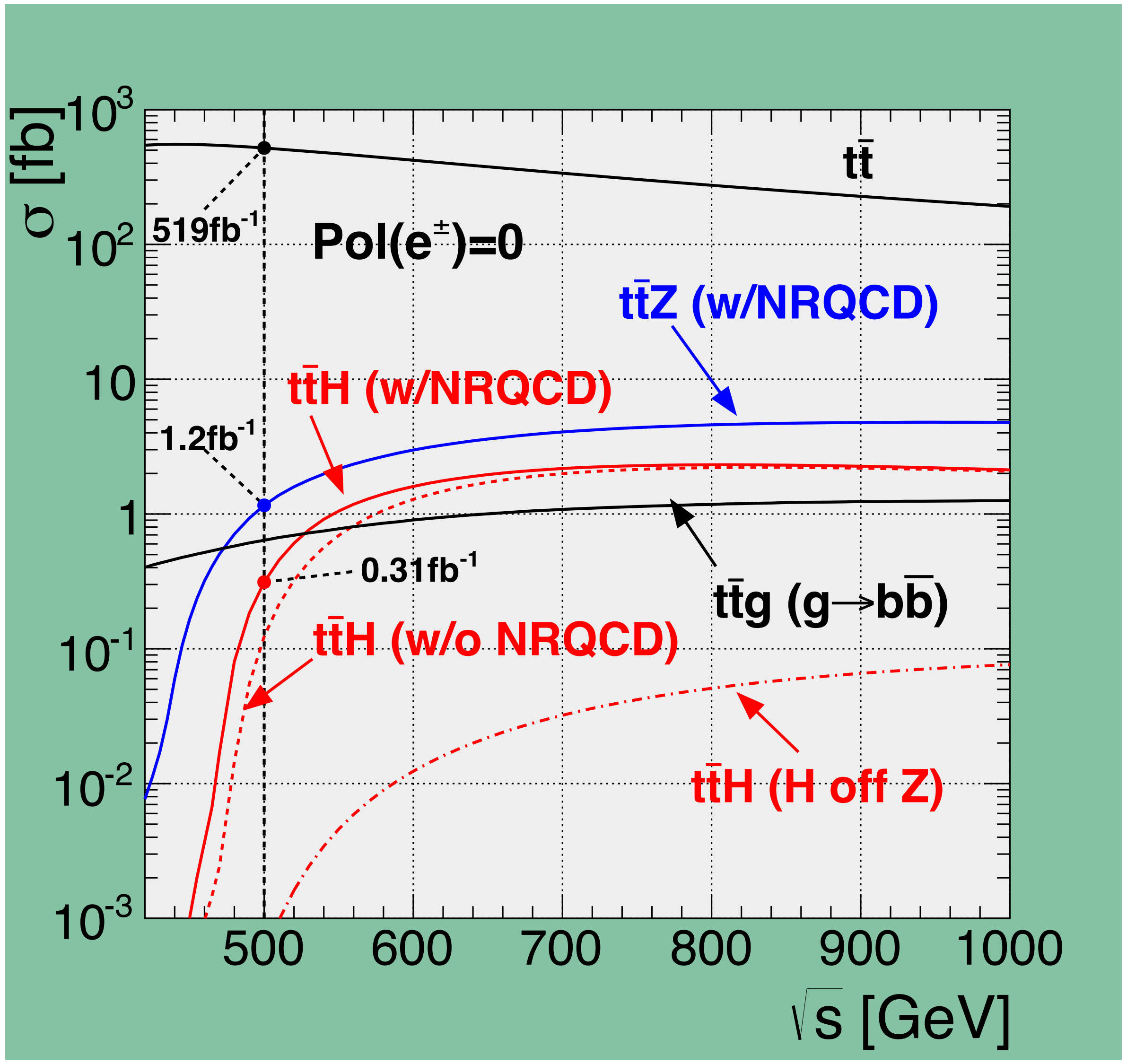
(iii.2.7) Top-Yukawa coupling

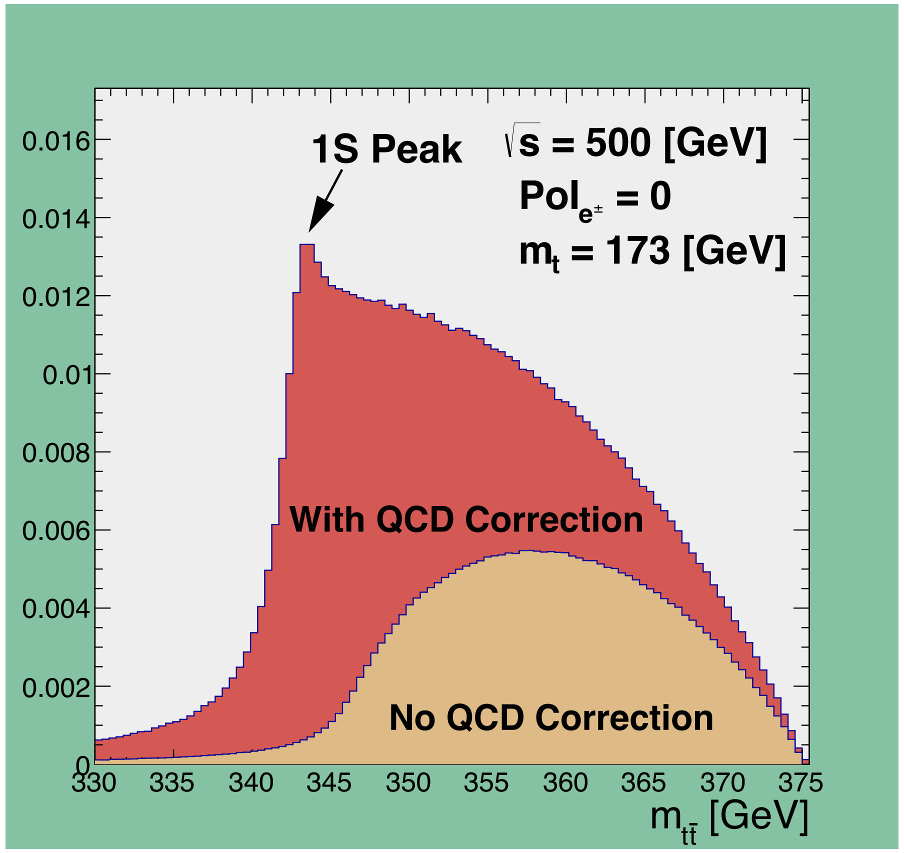
- largest Yukawa coupling; crucial role
- non-relativistic tt-bar bound state correction: enhancement by ~2 at 500 GeV
- Higgs CP measurement



H-> bb

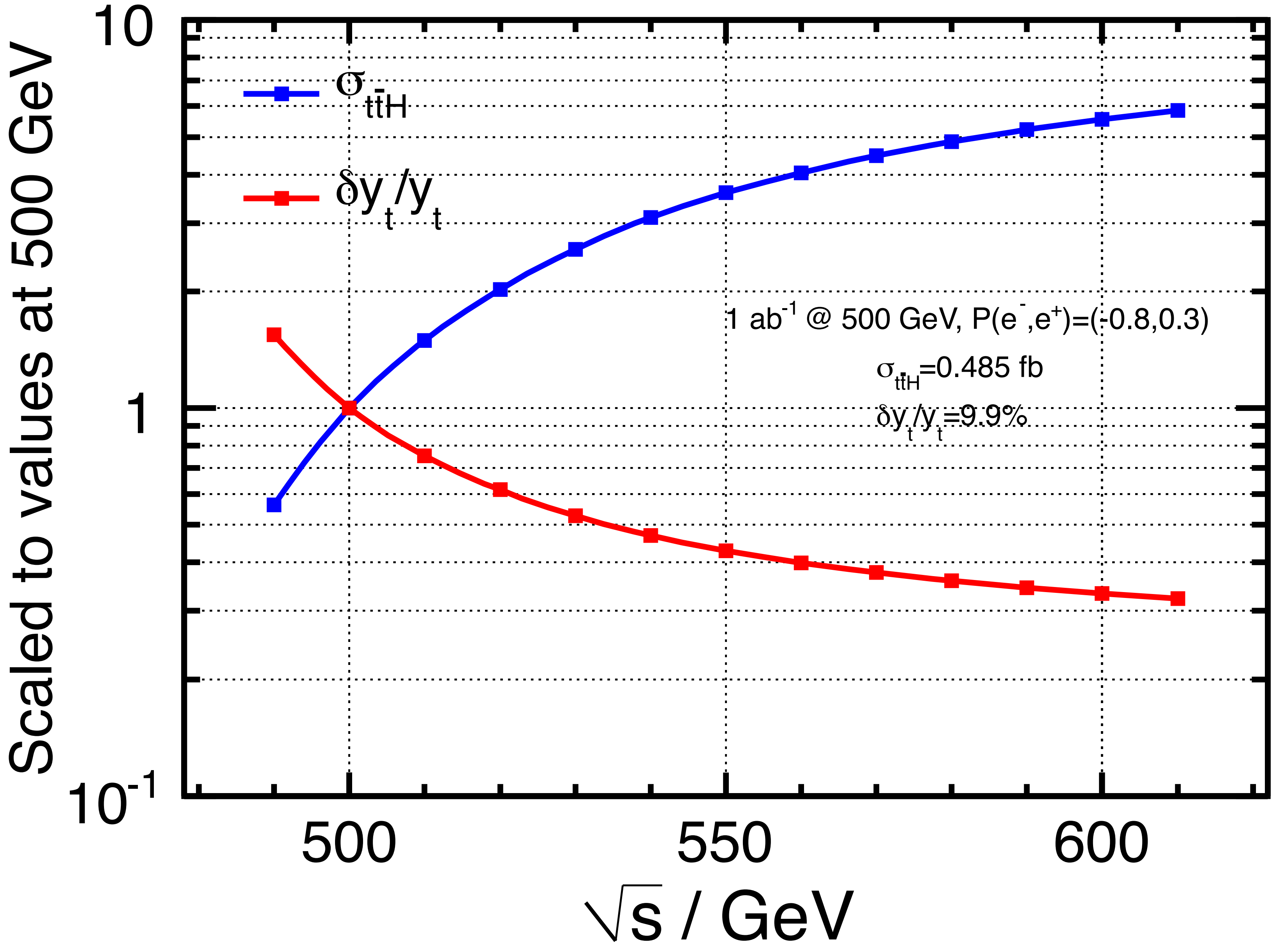
$\Delta g_{ttH}/g_{ttH}$	500 GeV	+ 1 TeV
Snowmass	7.8%	2.0%
H20	6.3%	1.5%





Yonamine, et al., PRD84, 014033;
Price, et al., Eur. Phys. J. C75 (2015) 309

Top-Yukawa coupling



Y. Sudo

(iv) precision determination of Higgs couplings

(iv.1) global fit frameworks

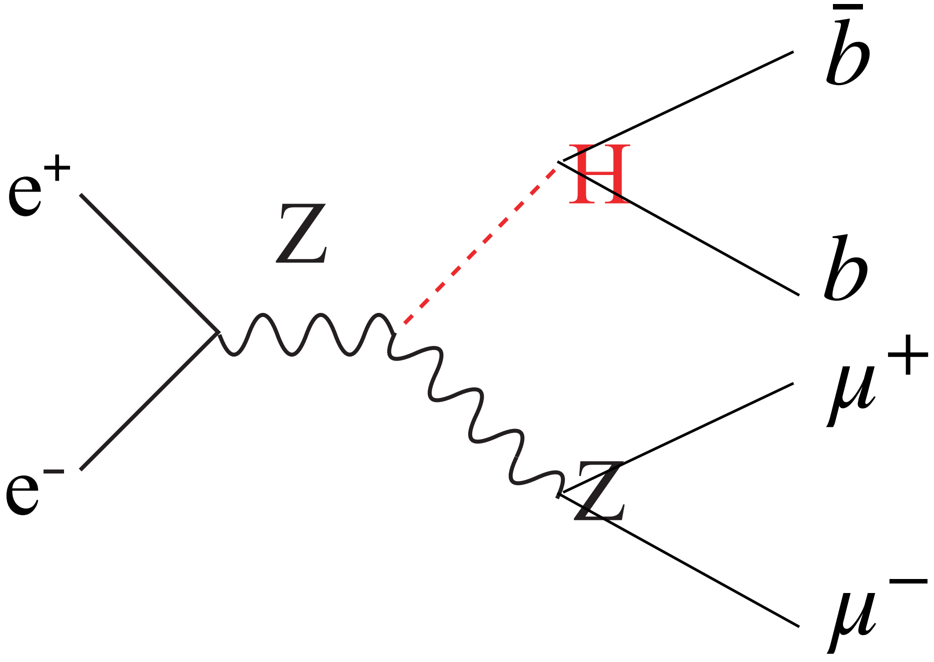
(iv.2) Higgs couplings by SMEFT

Global Fit: why do we need it?

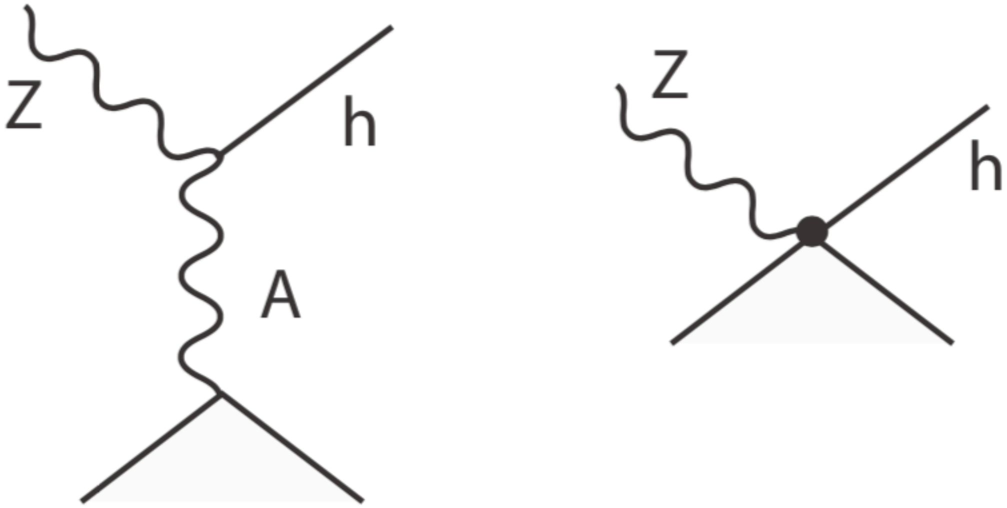
suppose we discover a deviation in, e.g. cross section of

e+e- -> ZH -> (μμ) (bb)

then we would like to know which coupling is deviated:



- hbb coupling?
- hZZ coupling?
- Zμμ coupling?
- Zee coupling?
- new diagrams?



From observables to couplings — Global Fit

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{Y_i - Y_i'}{\Delta Y_i}\right)^2$$

Yi: measured values by experiments

Yi’: predicted values by underlying theory

ΔYi: measurement uncertainty

n: number of independent observables

- kappa formalism

$$Y_i' = F_i \cdot \frac{g^2_{HA_iA_i} \cdot g^2_{HB_iB_i}}{\Gamma_0} \qquad (A_i = Z, W, t) \quad (B_i = b, c, \tau, \mu, g, \gamma, Z, W \ : \text{decay})$$

$$g_{HXX} = \kappa_X \cdot g^{SM}_{HXX}$$

- effective field theory formalism (Lecture 2)

From observables to couplings — Global Fit

in case there are correlated observables

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{Y_i - Y_i'}{\Delta Y_i}\right)^2 + (Y_j - Y_j')^T C_j^{-1} (Y_j - Y_j')$$

Yj: column vector of correlated observables

Cj: covariance matrix for those observables

to learn from Prof. Erler's lectures

Higgs coupling determination — kappa formalism

1) recoil mass technique —> inclusive $\boldsymbol{\sigma_{Zh}}$

2) σ_{Zh} —> $\boldsymbol{\kappa_Z}$ —> $\Gamma(h\text{->}ZZ^*)$

3) W-fusion $\nu_e\nu_e h$ —> $\boldsymbol{\kappa_W}$ —> $\Gamma(h\text{->}WW^*)$

4) total width $\boldsymbol{\Gamma_h}$ = $\Gamma(h\text{—>}ZZ^*)/BR(h\text{->}ZZ^*)$

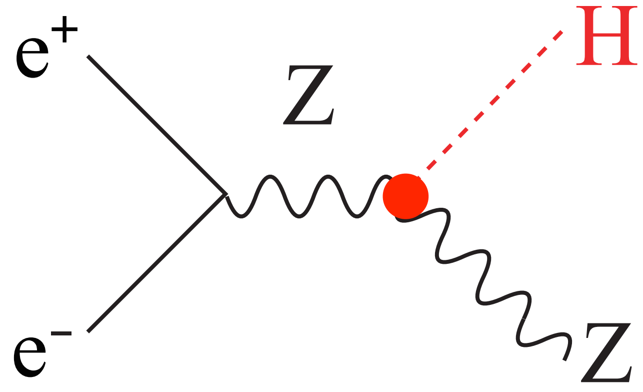
5) or $\boldsymbol{\Gamma_h}$ = $\Gamma(h\text{—>}WW^*)/BR(h\text{->}WW^*)$

6) then all other couplings $BR(h\text{->}XX)$ $^*\Gamma_h$ -> $\boldsymbol{\kappa_X}$

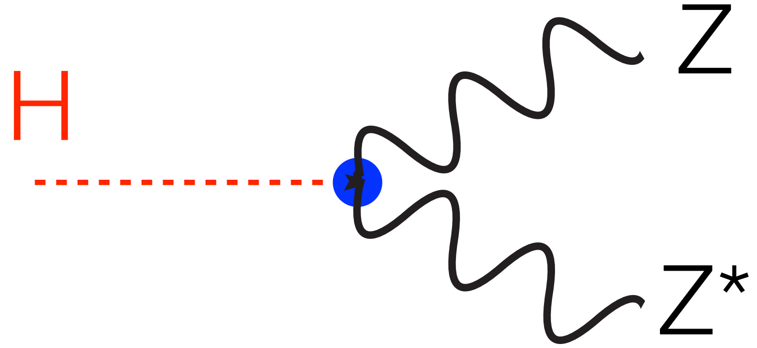
JT, et al, PoS EPS-HEP2013 (2013) 316 Nucl.Part.Phys.Proc. 273-275 (2016) 826-833

one question in kappa formalism:

$$\frac{\sigma(e^+e^- \to Zh)}{SM} = \frac{\Gamma(h \to ZZ^*)}{SM} = \kappa_Z^2 \qquad \textbf{?}$$



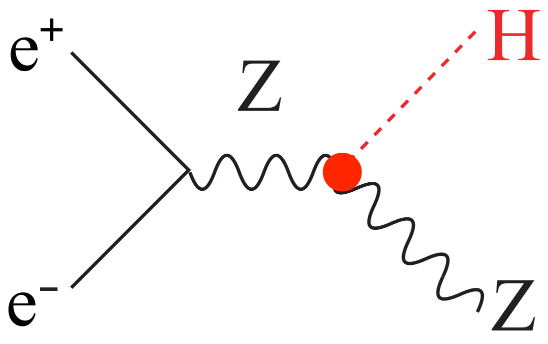
$$\propto \qquad \kappa_Z^2\ ? \qquad \reflectbox{$\propto$}$$

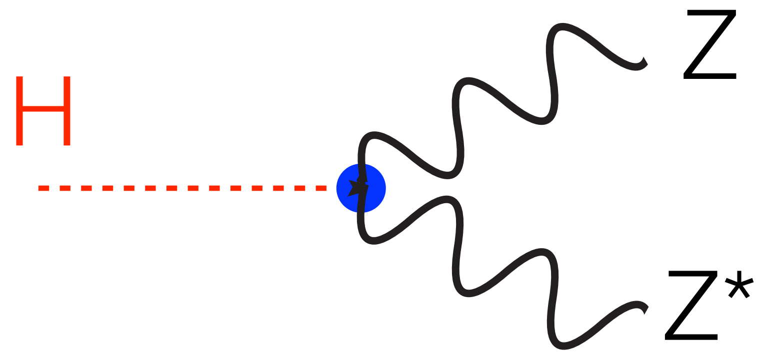


BSM territory: can deviations be represented by single κ_Z?

the answer is model dependent

$$\delta\mathcal{L} = (1+\eta_Z)\frac{m_Z^2}{v} h Z_\mu Z^\mu + \zeta_Z \frac{h}{2v} Z_{\mu\nu} Z^{\mu\nu}$$





$$\sigma(e^+e^- \to Zh) = (SM)\cdot (1+2\eta_Z+(5.5)\zeta_Z)$$

$$\neq$$

$$\Gamma(h \to ZZ^*) = (SM)\cdot (1+2\eta_Z-(0.50)\zeta_Z)$$

- BSM can induce new Lorentz structures in hZZ
- need a better, more theoretical sound framework

new strategy: SM Effective Field Theory

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \Delta\mathcal{L}$$

$$= \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^{d_i-4}} O_i$$

- a more model independent formalism
- most general effects from BSM represented
- respect SU(3)xSU(2)xU(1) gauge symmetries
- a consistent quantum field theory unifying BSM effects in Higgs, W/Z, top, 2-fermion physics

SM Effective Field Theory: some simplifications

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \Delta\mathcal{L}$$

$$= \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^{d_i-4}} O_i$$

the new particle searches at LHC Run 2 suggest ***Λ>500*** GeV

justify the analysis at dimension-**6** operators

there are ***84*** of such operators for 1 fermion generation

assuming B & L number conservation, there are ***59***

- there exists a smaller but complete set relevant to Higgs physics at e+e-

SM Effective Field Theory @ e+e-

(Barklow, Fujii, Jung, Peskin, JT, arXiv:1708.09079)

$$\begin{aligned}\Delta\mathcal{L} = {} & \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3 \\ & + \frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu} \\ & + \frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu} \\ & + i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + 4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L) \\ & + i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e) \; .\end{aligned}$$

Φ: higgs field
W, B: SU(2), U(1) gauge
L, e: left/right electron

- 10 operators modifying couplings for h/Z/W/γ
- in total, 23 parameters (see later slides)

next: highlight a few important implications

recap 1: absolute Higgs couplings (unique role of inclusive σ_{Zh})

$$\boxed{\frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi)}$$

$\frac{c_H}{2}\partial^\mu h \partial_\mu h$ ⟶ renormalize kinetic term of SM Higgs field

$h \longrightarrow (1-c_H/2)h$

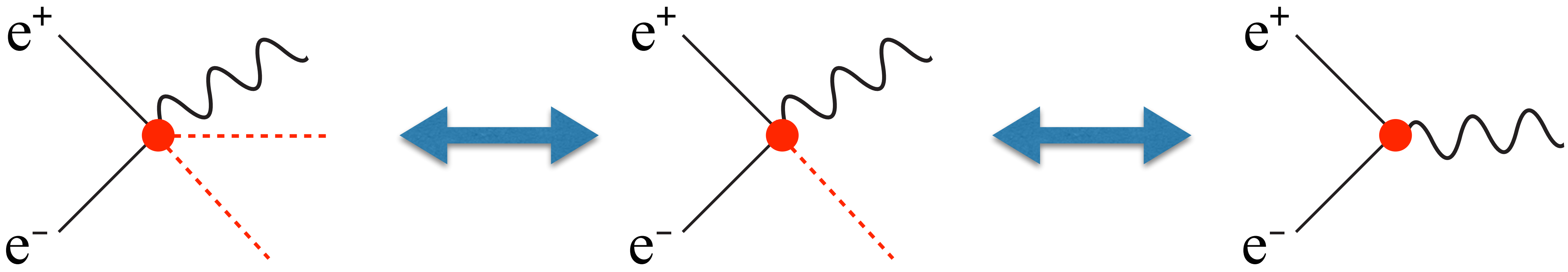
⟶ **shift all SM Higgs couplings by $-c_H/2$**

- c_H can not be determined by any BR or ratio of couplings

- c_H has to rely on inclusive cross section of e^+e^- -> Zh, enabled by recoil mass technique at e+e-

recap 2: Higgs couplings are related to W-/Z- couplings (EWPOs)

$$\boxed{i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^{\mu}\Phi)(\overline{L}\gamma_\mu L)} \qquad +(c'_{HL},\, c_{HE})$$



e^+e^- ->Zhh

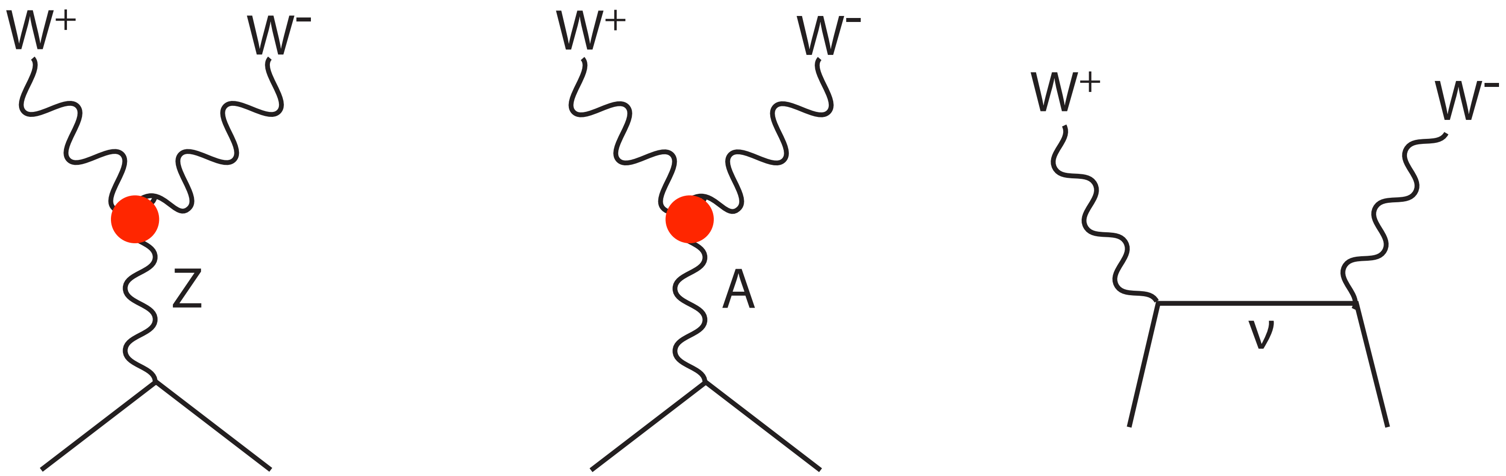
e^+e^- ->Zh

Z-pole

- Higgs coupling helped by EWPOs at Z-pole: $\boldsymbol{A_{LR}}$, $\boldsymbol{\Gamma_l}$
- Z coupling helped by Higgs meas. at high $\sqrt{s}$: $\boldsymbol{\delta\sigma \sim s/m_Z^2}$

recap 2: Higgs couplings are related to W-/Z- couplings (TGCs)

$$\boxed{\frac{4gg'c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu}} \qquad +(c_{WW},\, c_{BB})$$



- longitudinal modes of W/Z are from Higgs fields
- higgs coupling helped by meas. of TGCs in e+e- -> WW

recap 3: Higgs couplings are related to themselves

$$
\begin{aligned}
\Delta\mathcal{L}_h = {} & \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2} m_h^2 h^2 - (1+\eta_h)\bar{\lambda} v h^3 + \frac{\theta_h}{v} h \partial_\mu h \partial^\mu h \\
& + (1+\eta_W)\frac{2m_W^2}{v} W_\mu^+ W^{-\mu} h + (1+\eta_{WW})\frac{m_W^2}{v^2} W_\mu^+ W^{-\mu} h^2 \\
& + (1+\eta_Z)\frac{m_Z^2}{v} Z_\mu Z^\mu h + \frac{1}{2}(1+\eta_{ZZ})\frac{m_Z^2}{v^2} Z_\mu Z^\mu h^2 \\
& + \zeta_W \hat{W}_{\mu\nu}^+ \hat{W}^{-\mu\nu}\left(\frac{h}{v} + \frac{1}{2}\frac{h^2}{v^2}\right) + \frac{1}{2}\zeta_Z \hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu}\left(\frac{h}{v} + \frac{1}{2}\frac{h^2}{v^2}\right) \\
& + \frac{1}{2}\zeta_A \hat{A}_{\mu\nu}\hat{A}^{\mu\nu}\left(\frac{h}{v} + \frac{1}{2}\frac{h^2}{v^2}\right) + \zeta_{AZ}\hat{A}_{\mu\nu}\hat{Z}^{\mu\nu}\left(\frac{h}{v} + \frac{1}{2}\frac{h^2}{v^2}\right) .
\end{aligned}
$$

(SM structure: kappa like)

$$
\begin{aligned}
\eta_h &= \delta\bar{\lambda} + \delta v - \frac{3}{2} c_H + c_6 \\
\eta_W &= 2\delta m_W - \delta v - \frac{1}{2} c_H \\
\eta_{WW} &= 2\delta m_W - 2\delta v - c_H \\
\eta_Z &= 2\delta m_Z - \delta v - \frac{1}{2} c_H - c_T \\
\eta_{ZZ} &= 2\delta m_Z - 2\delta v - c_H - 5c_T
\end{aligned}
$$

(Anomalous: new Lorentz structure)

$$
\begin{aligned}
\theta_h &= c_H \\
\zeta_W &= \delta Z_W && = (8c_{WW}) \\
\zeta_Z &= \delta Z_Z && = c_w^2(8c_{WW}) + 2s_w^2(8c_{WB}) + s_w^4/c_w^2(8c_{BB}) \\
\zeta_A &= \delta Z_A && = s_w^2\Big((8c_{WW}) - 2(8c_{WB}) + (8c_{BB})\Big) \\
\zeta_{AZ} &= \delta Z_{AZ} && = s_w c_w\Big((8c_{WW}) - (1 - \frac{s_w^2}{c_w^2})(8c_{WB}) - \frac{s_w^2}{c_w^2}(8c_{BB})\Big)
\end{aligned}
$$

- hZZ/hWW/hγZ/hγγ highly related: SU(2)xU(1) gauge symmetries

recap 3: Higgs couplings are related to themselves (synergy w/ LHC)

two measurements from LHC (model independent)

$$R_{\gamma\gamma} = \frac{BR(h \to \gamma\gamma)}{BR(h \to ZZ^*)} \qquad R_{\gamma Z} = \frac{BR(h \to \gamma Z)}{BR(h \to ZZ^*)}$$

$$\delta\Gamma(h \to \gamma\gamma) = 528\,\delta Z_A - c_H \quad + \ldots$$

$$\delta\Gamma(h \to Z\gamma) = 290\,\delta Z_{AZ} - c_H \quad + \ldots$$

$$\delta\Gamma(h \to ZZ^*) = -0.50\delta Z_Z \; - c_H \quad + \ldots$$

- loop induced h->γγ/γZ depend strongly on $c_{WW}/c_{WB}/c_{BB}$

- h->γγ/γZ at LHC can nicely help higgs couplings at e+e-

recap 3: Higgs couplings are related to themselves (hWW/hZZ)

$$\Gamma(h \to ZZ^*) = (SM) \cdot (1 + 2\eta_Z - (0.50)\zeta_Z) \ ,$$

$$\Gamma(h \to WW^*) = (SM) \cdot (1 + 2\eta_W - (0.78)\zeta_W)$$

SM-like hVV

$$\eta_W = -\frac{1}{2} c_H$$

$$\eta_Z = -\frac{1}{2} c_H - c_T$$

custodial symmetry is broken by c_T -> constrained by EWPOs

$c_i \sim O(10^{-4}\text{-}10^{-3})$

anomalous hVV

$$\zeta_W = (8c_{WW})$$

$$\zeta_Z = c_w^2(8c_{WW}) + 2s_w^2(8c_{WB}) + (s_w^4/c_w^2)(8c_{BB})$$

- hWW/hZZ ratio can be determined to <0.1%

- very important for physics case of any 250 GeV e+e-
- hWW can be determined as precisely as hZZ at 250 GeV; hence precision total width & other couplings

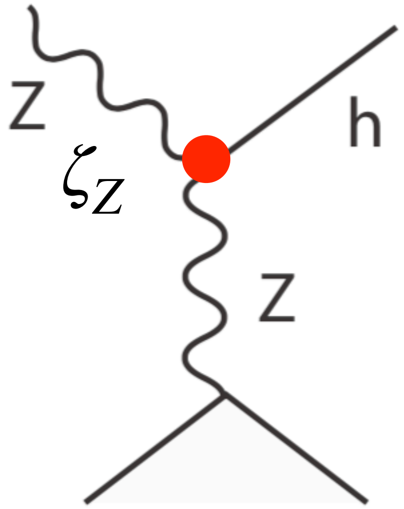
SMEFT fit: typical difference with kappa fit

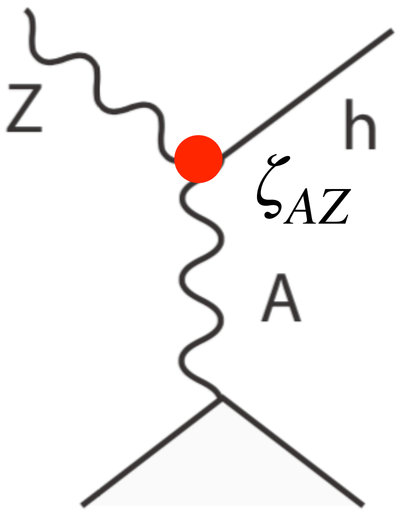
ILC250: $\int L dt = 2\ \mathrm{ab}^{-1}$ @ 250 GeV

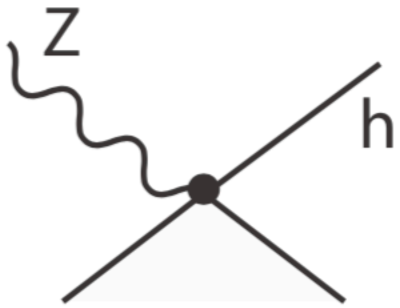
coupling $\Delta g/g$	kappa-fit	EFT-fit
hZZ	0.38%	0.50%
hWW	1.8%	0.50%
hbb	1.8%	0.99%
Γ_h	3.9%	2.3%

(definition for higgs coupling precision: 1/2 of partial width precision)

recap 4: role of beam polarizations







$P(e^-,e^+)$			
(-1,+1)	$\frac{g}{\cos\theta_w}(\frac{1}{2}-\sin^2\theta_w)$	$g\sin\theta_w$	$\frac{g}{\cos\theta_w}(c_{HL}+c'_{HL})$
(+1,-1)	$\frac{g}{\cos\theta_w}(-\sin^2\theta_w)$	$g\sin\theta_w$	$\frac{g}{\cos\theta_w}(c_{HE})$

- sensitive to different couplings -> lift degeneracy
- A_{LR} in σ_{ZH} -> improve c_{WW}, $c_{HL}+c_{HL}'$ and c_{HE}
- large cancellation in **(+1,-1)** -> weaker dependence on c_{WW}

recap 4: role of beam polarizations (e+e- -> Zh)

$$\delta\sigma_L = -c_H + 7.7(8c_{WW}) + \dots$$

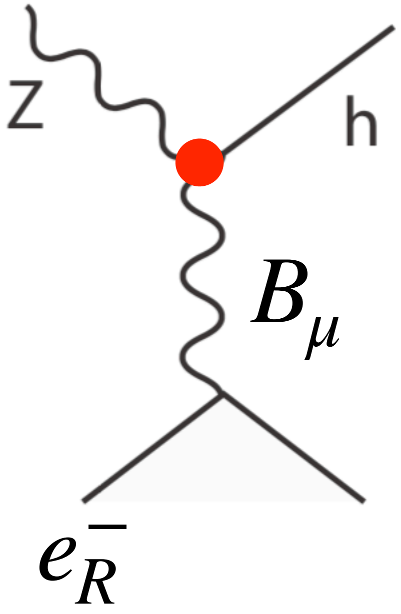
√s=250 GeV

$$\delta\sigma_R = -c_H + 0.6(8c_{WW}) + \dots$$

why?

$$\delta\sigma_0 = -c_H + 4.6(8c_{WW}) + \dots$$

(8cWW) ~ 0.16% from other meas.



contribution from

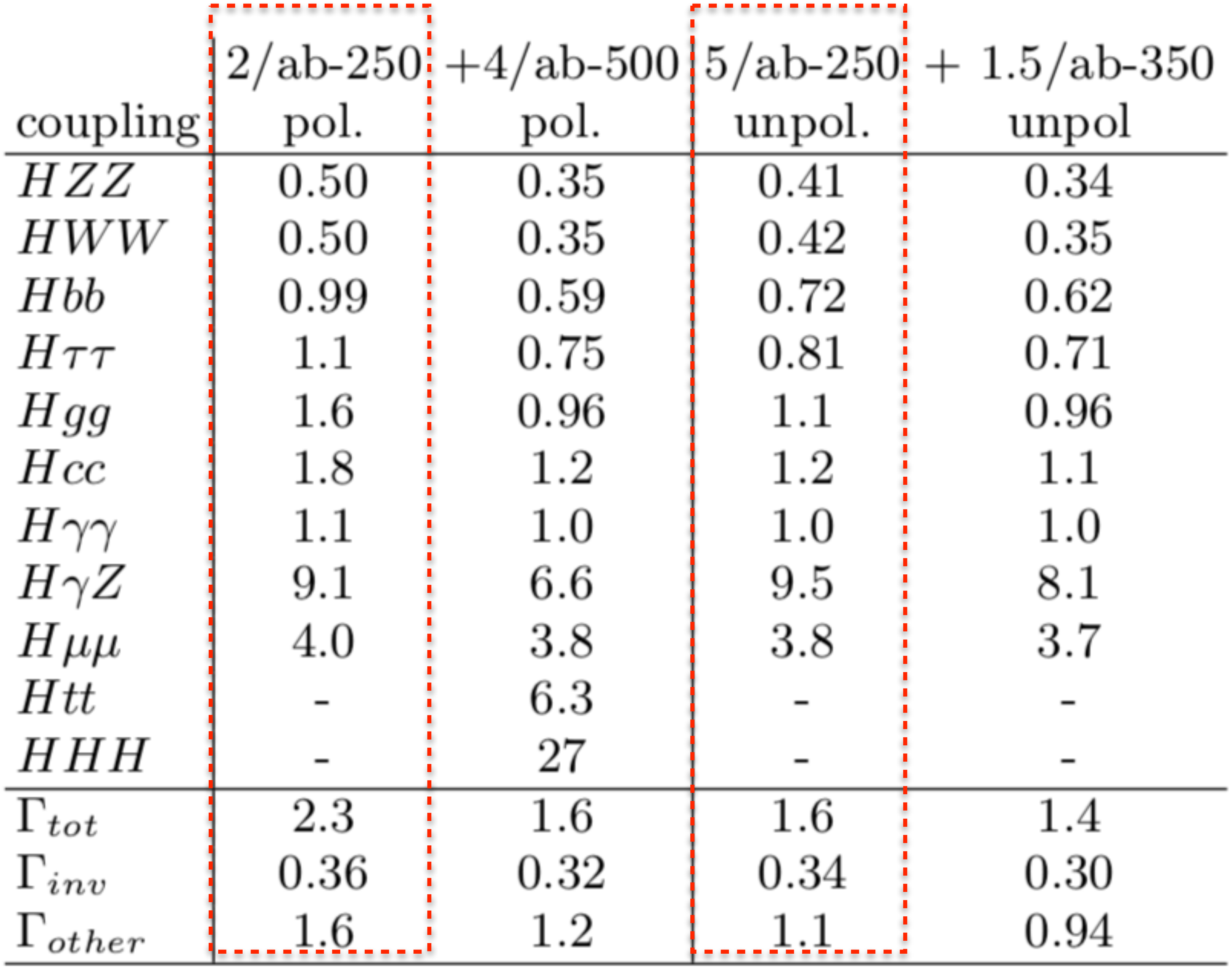
almost cancels out

$$\boxed{\frac{g^2 c_{WW}}{m_W^2} \Phi^\dagger \Phi W^a_{\mu\nu} W^{a\mu\nu}}$$

up to a difference in Z/γ propagator suppressed by $\frac{m_Z^2}{s}$

recap 4: role of beam polarizations (overall effects)

ILC250: 2 ab^{-1} **FCCee240: 5 ab^{-1}**



coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+ 1.5/ab-350 unpol
HZZ	0.50	0.35	0.41	0.34
HWW	0.50	0.35	0.42	0.35
Hbb	0.99	0.59	0.72	0.62
$H\tau\tau$	1.1	0.75	0.81	0.71
Hgg	1.6	0.96	1.1	0.96
Hcc	1.8	1.2	1.2	1.1
$H\gamma\gamma$	1.1	1.0	1.0	1.0
$H\gamma Z$	9.1	6.6	9.5	8.1
$H\mu\mu$	4.0	3.8	3.8	3.7
Htt	-	6.3	-	-
HHH	-	27	-	-
Γ_{tot}	2.3	1.6	1.6	1.4
Γ_{inv}	0.36	0.32	0.34	0.30
Γ_{other}	1.6	1.2	1.1	0.94

- 250 GeV e+e-: power of 2 ab^{-1} polarized ≈ 5 ab^{-1} unpolarized

(arXiv:1903.01629)

SM Effective Field Theory: full formalism (23 pars.)

$$\begin{aligned}\Delta\mathcal{L} = {}& \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3 \\ & + \frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a \Phi W^a_{\mu\nu}B^{\mu\nu} \\ & + \frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu} \\ & + i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\bar{L}\gamma_\mu L) + 4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu \Phi)(\bar{L}\gamma_\mu t^a L) \\ & + i\frac{c_{HE}}{v^2}(\Phi^\dagger\overleftrightarrow{D}^\mu\Phi)(\bar{e}\gamma_\mu e)\ .\end{aligned}$$

10 operators (h,W,Z,γ): c_H, c_T, c_6, c_{WW}, c_{WB}, c_{BB}, c_{3W}, c_{HL}, c'_{HL}, c_{HE}

+ 4 SM parameters: g, g’, v, λ

+ 5 operators modifying h couplings to b, c, τ, μ, g

+ 2 operators for contact interactions with quarks

+ 2 parameters for h->invisible and exotic

strategy to determine all the 23 parameters at e+e-

Electroweak Precision Observables (9)

+

Triple Gauge boson Couplings (3)

+

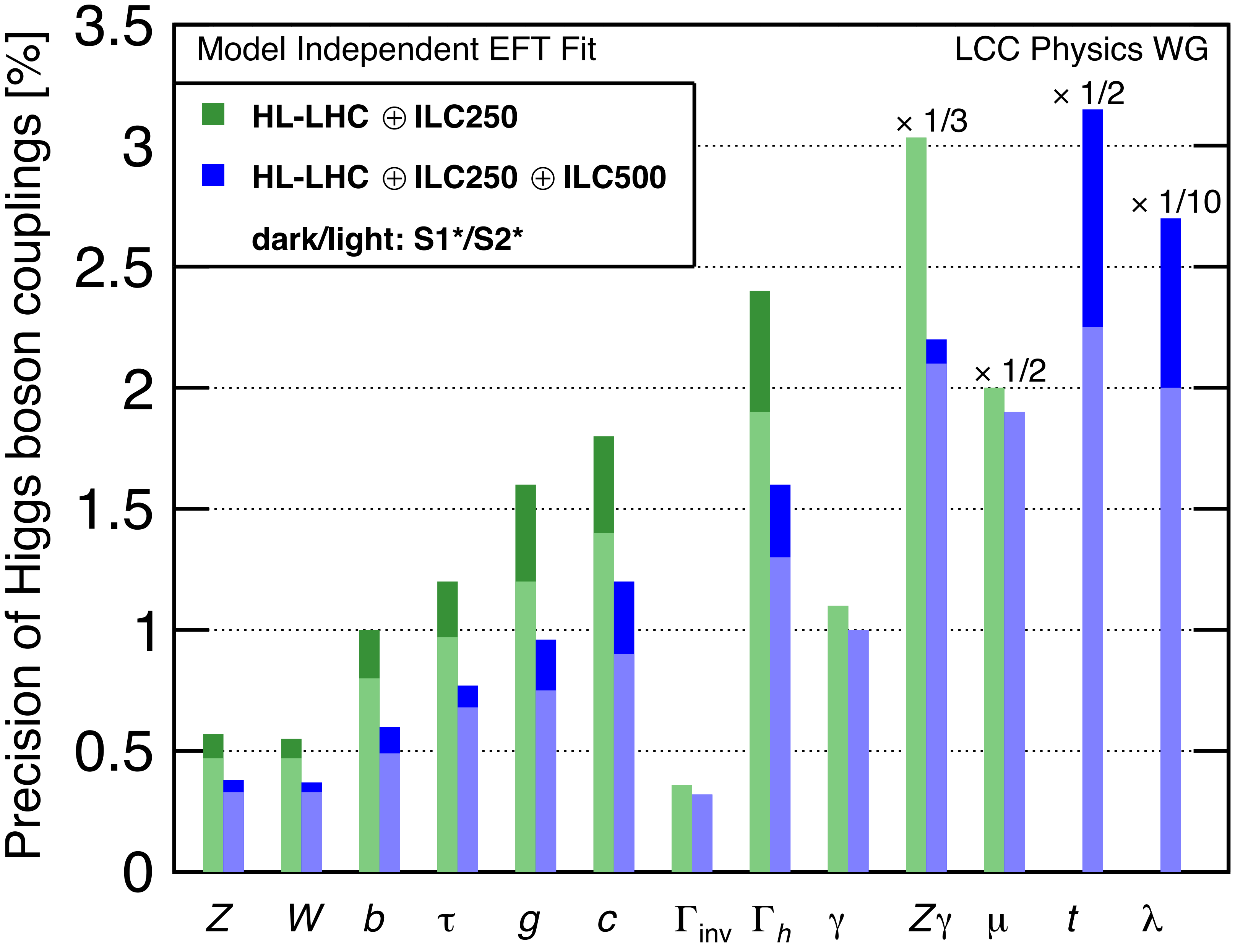
Higgs observables at LHC & e+e- (3+12x2)

↑ 2 for polarized

- at e+e-, all the 23 parameters can be determined ***simultaneously***

(details in backup)

precisions at Higgs factories: complementarity with LHC



(arXiv:1903.01629)

#qualitative:

model independence,
hcc coupling

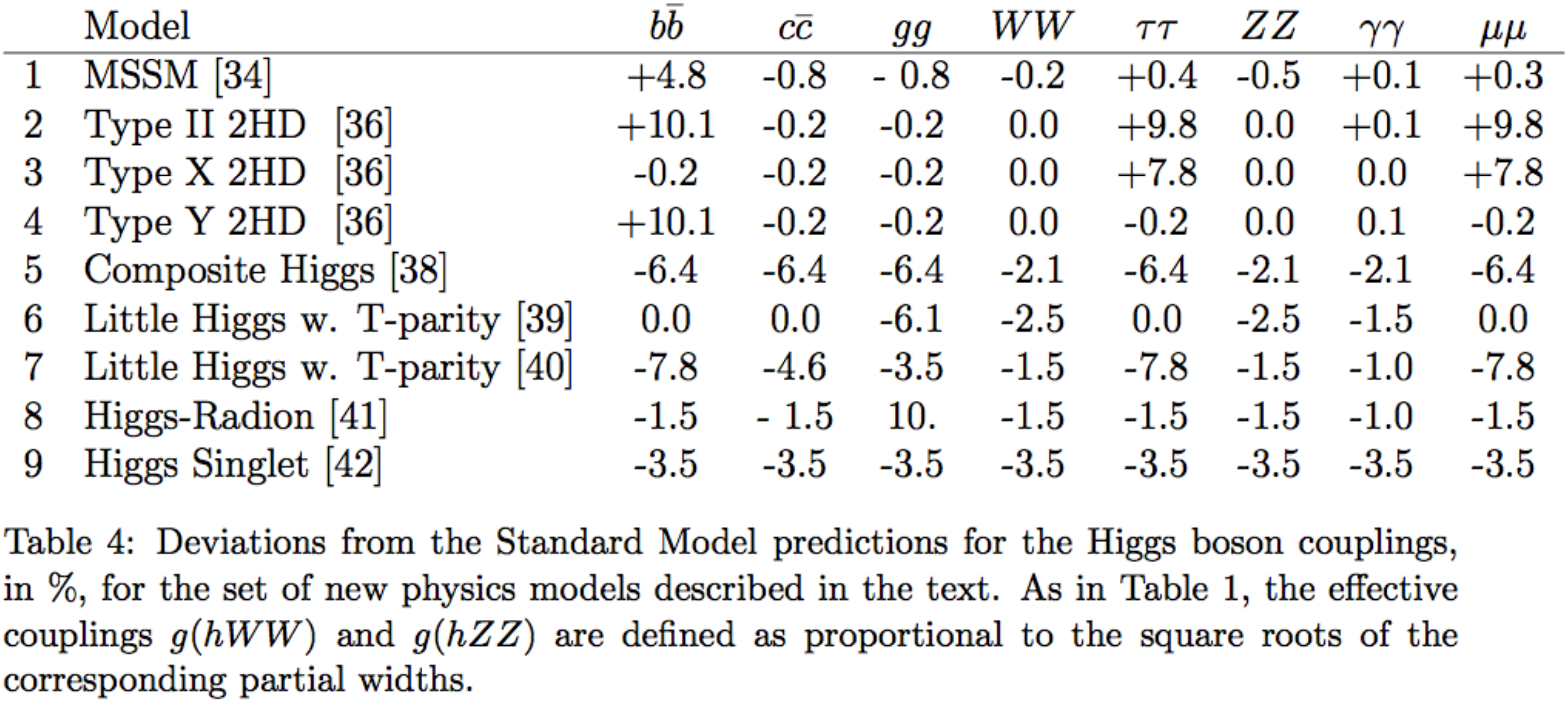
#quantitative (<~1%):

hZZ, hWW, hbb, h$\tau\tau$
h->invisible/exotic

#synergy:

h$\gamma\gamma$, hγZ, h$\mu\mu$, htt, λ

benchmark BSM models



	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [34]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [36]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [36]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [36]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [38]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [39]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [40]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [41]	-1.5	- 1.5	10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [42]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

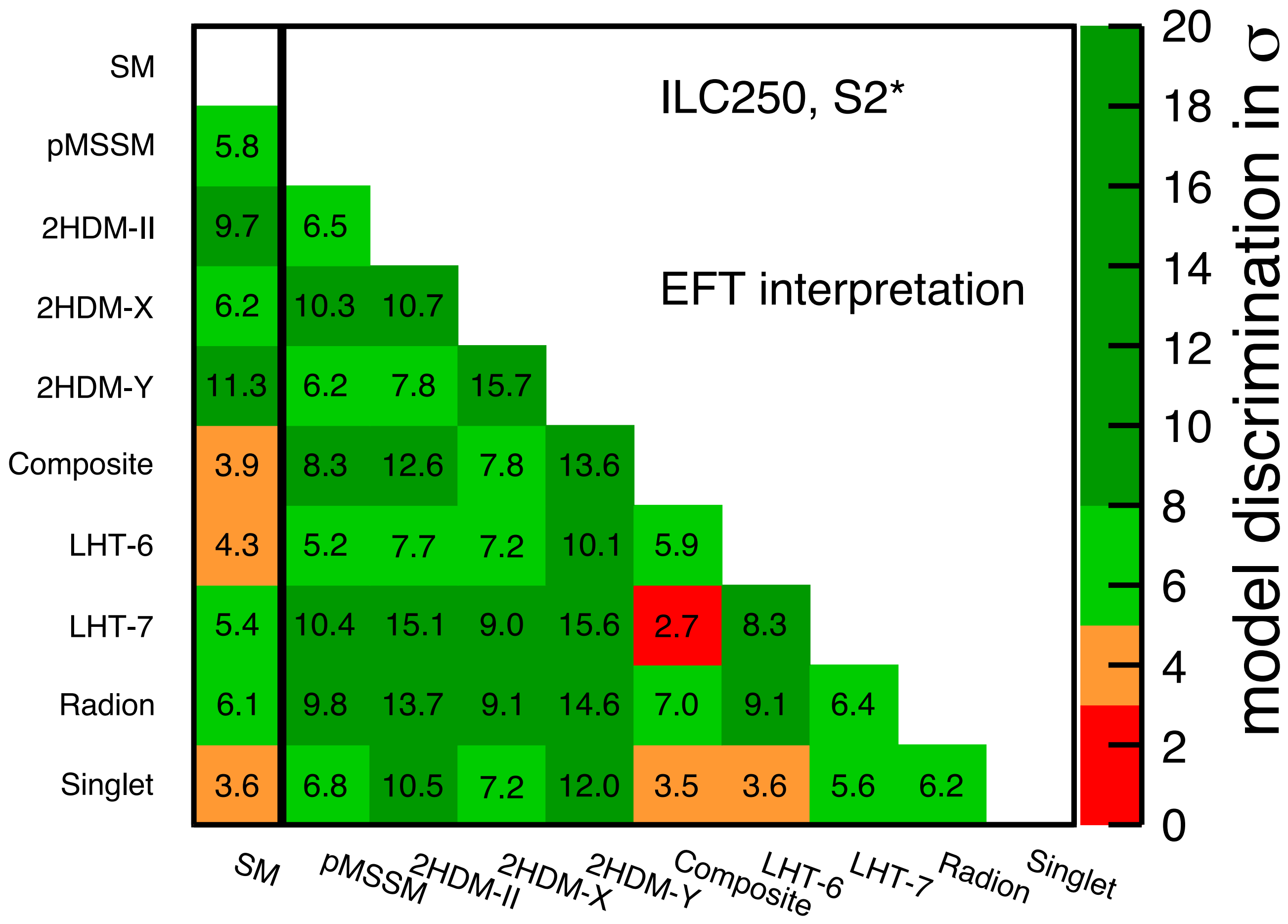
Table 4: Deviations from the Standard Model predictions for the Higgs boson couplings, in %, for the set of new physics models described in the text. As in Table 1, the effective couplings $g(hWW)$ and $g(hZZ)$ are defined as proportional to the square roots of the corresponding partial widths.

—> quantitative assessment for models discrimination

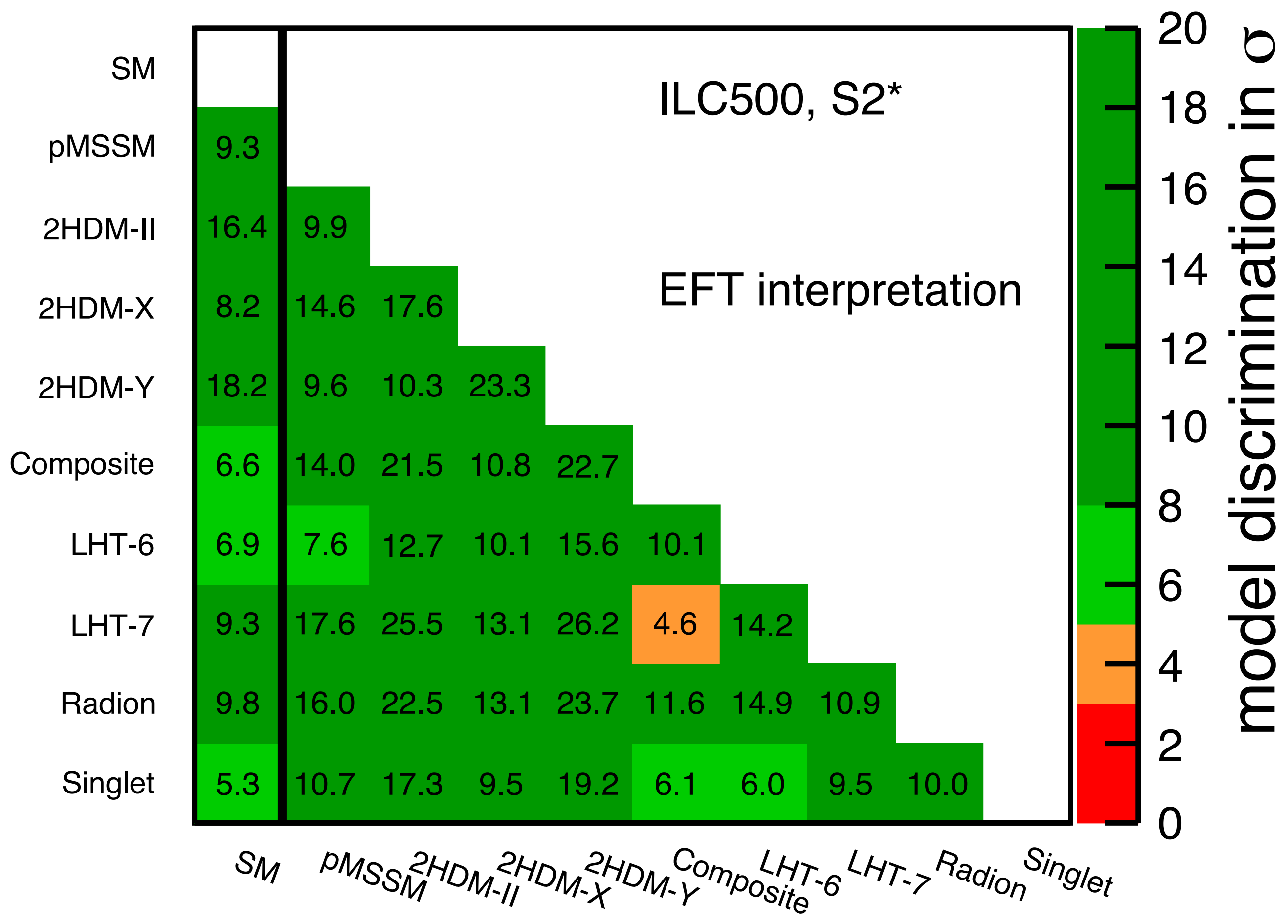
model parameters (chosen as escaping direct search at HL-LHC)

- a PMSSM model with b squarks at 3.4 TeV, gluino at 4 TeV
- a Type II 2 Higgs doublet model with $m_A = 600 \text{ GeV}, \tan\beta = 7$
- a Type X 2 Higgs doublet model with $m_A = 450 \text{ GeV}, \tan\beta = 6$
- a Type Y 2 Higgs doublet model with $m_A = 600 \text{ GeV}, \tan\beta = 7$
- a composite Higgs model MCHM5 with $f = 1.2 \text{ TeV}, m_T = 1.7 \text{ TeV}$
- a Little Higgs model with T-parity with $f = 785 \text{ GeV}, m_T = 2 \text{ TeV}$
- A Little Higgs model with couplings to 1st and 2nd generation with $f = 1.2 \text{ TeV}, m_T = 1.7 \text{ TeV}$
- A Higgs-radion mixing model with $m_r = 500 \text{ GeV}$
- a model with a Higgs singlet at 2.8 TeV creating a Higgs portal to dark matter and large λ for electroweak baryogenesis

BSM benchmark models discrimination at ILC250

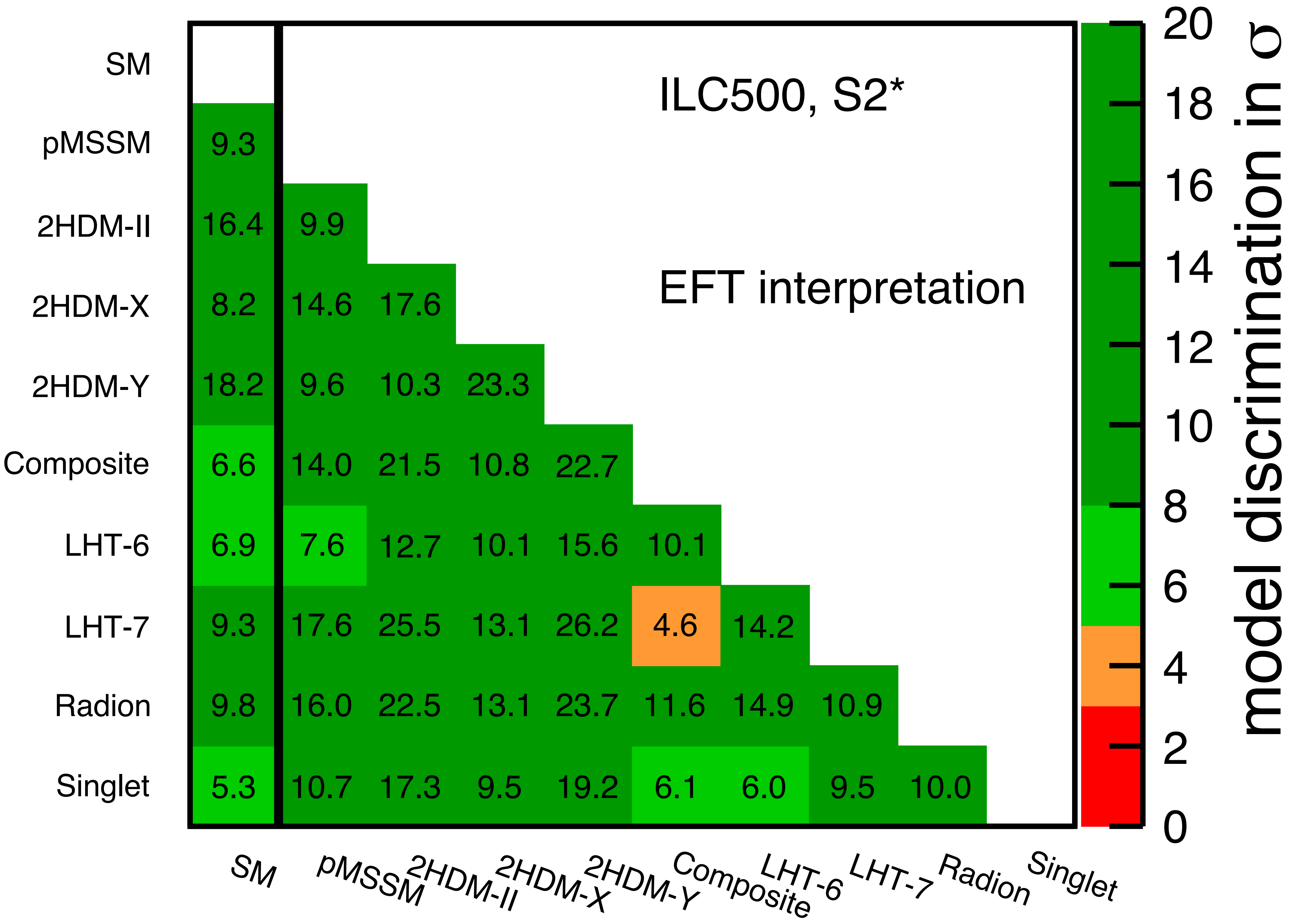


	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	5.8									
2HDM-II	9.7	6.5								
2HDM-X	6.2	10.3	10.7							
2HDM-Y	11.3	6.2	7.8	15.7						
Composite	3.9	8.3	12.6	7.8	13.6					
LHT-6	4.3	5.2	7.7	7.2	10.1	5.9				
LHT-7	5.4	10.4	15.1	9.0	15.6	2.7	8.3			
Radion	6.1	9.8	13.7	9.1	14.6	7.0	9.1	6.4		
Singlet	3.6	6.8	10.5	7.2	12.0	3.5	3.6	5.6	6.2	



	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	9.3									
2HDM-II	16.4	9.9								
2HDM-X	8.2	14.6	17.6							
2HDM-Y	18.2	9.6	10.3	23.3						
Composite	6.6	14.0	21.5	10.8	22.7					
LHT-6	6.9	7.6	12.7	10.1	15.6	10.1				
LHT-7	9.3	17.6	25.5	13.1	26.2	4.6	14.2			
Radion	9.8	16.0	22.5	13.1	23.7	11.6	14.9	10.9		
Singlet	5.3	10.7	17.3	9.5	19.2	6.1	6.0	9.5	10.0	

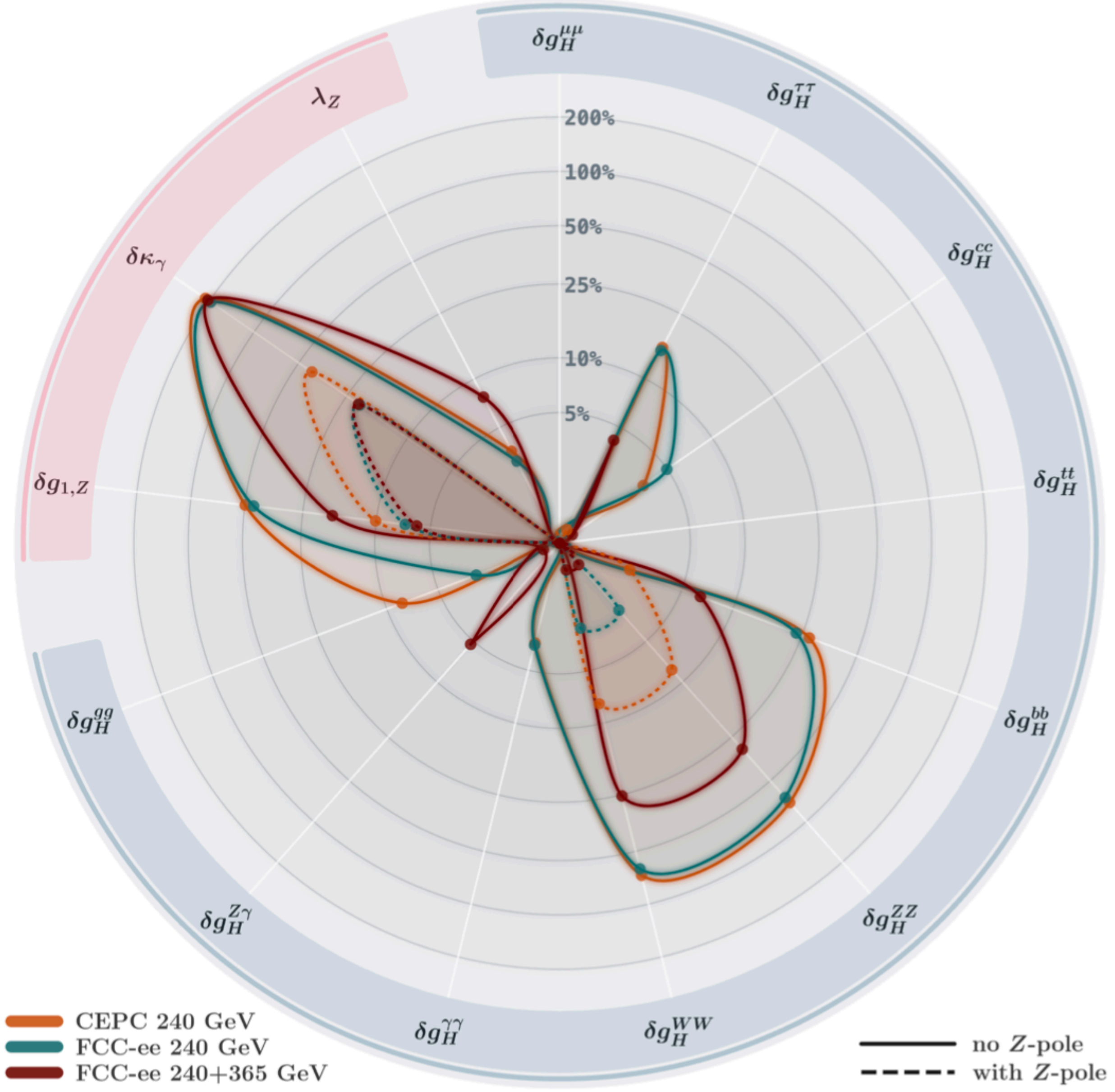
effect of improvement from TGC, ννH, ZH at 500GeV

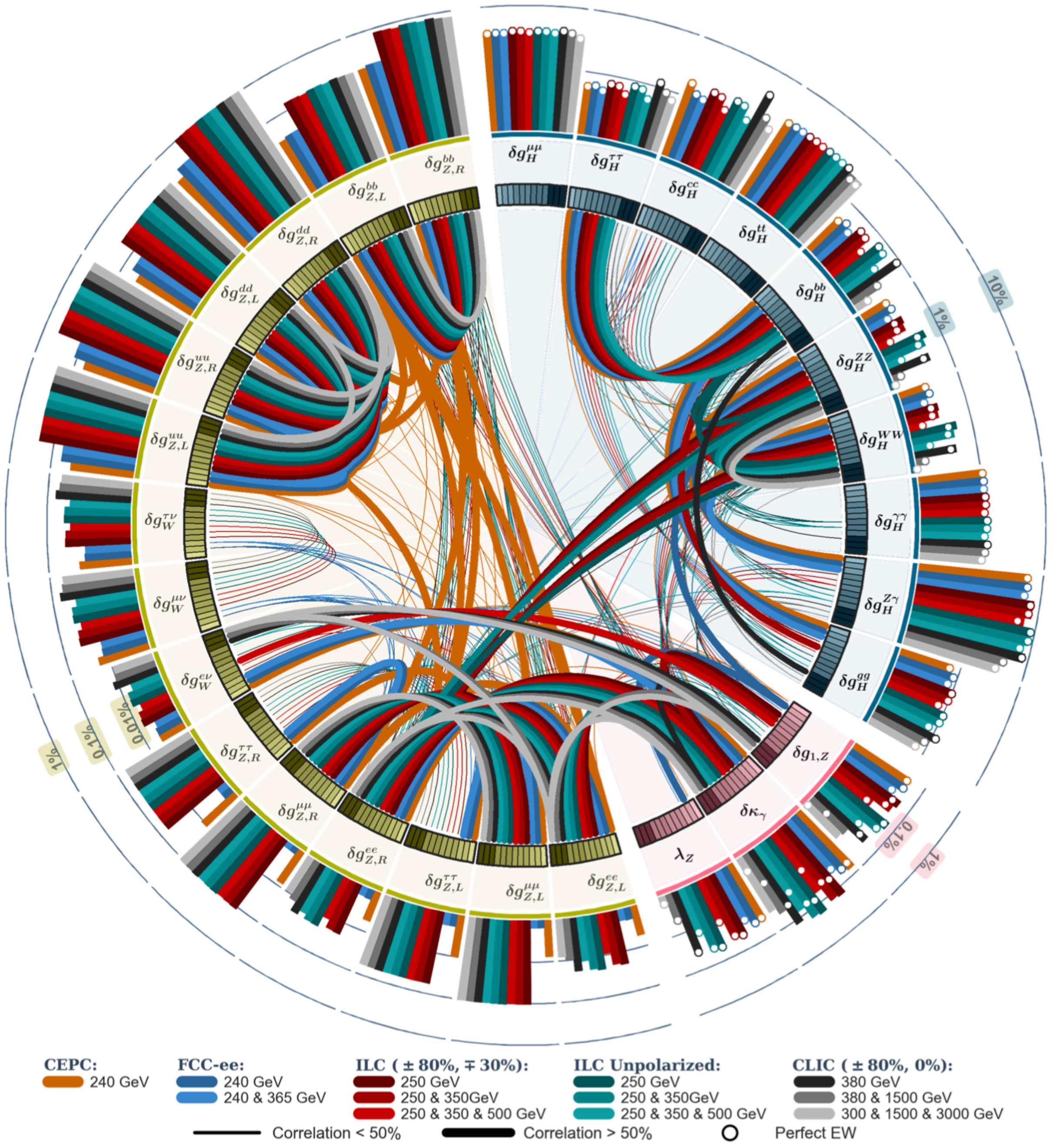


	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	9.3									
2HDM-II	16.4	9.9								
2HDM-X	8.2	14.6	17.6							
2HDM-Y	18.2	9.6	10.3	23.3						
Composite	6.6	14.0	21.5	10.8	22.7					
LHT-6	6.9	7.6	12.7	10.1	15.6	10.1				
LHT-7	9.3	17.6	25.5	13.1	26.2	4.6	14.2			
Radion	9.8	16.0	22.5	13.1	23.7	11.6	14.9	10.9		
Singlet	5.3	10.7	17.3	9.5	19.2	6.1	6.0	9.5	10.0	

role of each measurement

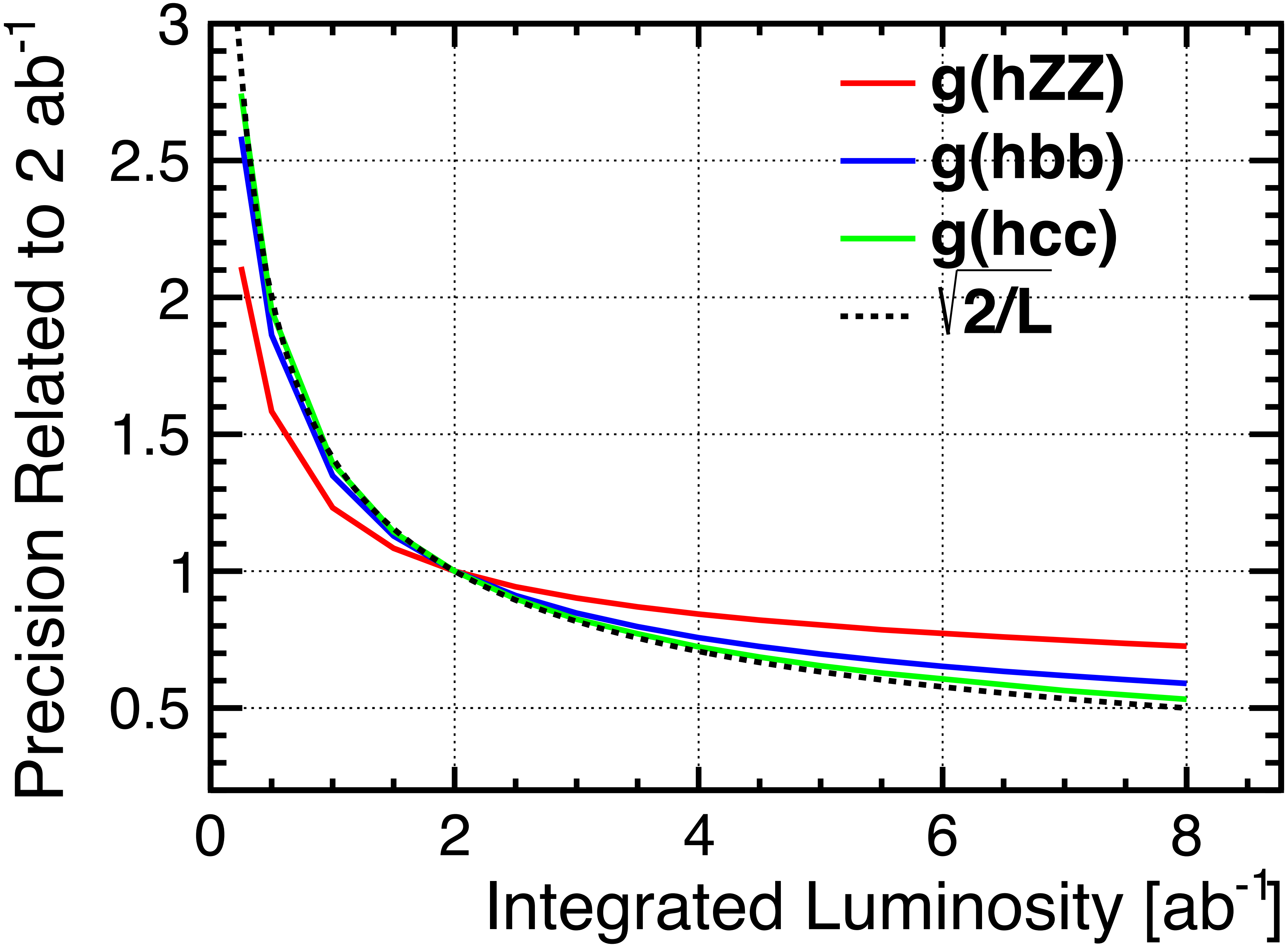
(see Prof. Grojean’s lectures, also arXiv:1907.04311)





role of each measurement: more transparent understanding

(Fujii, Peskin, JT, paper in preparation)



why not following $1/\sqrt{L}$? why so different for hZZ/hbb/hcc?

role of each measurement: more transparent understanding

(Fujii, Peskin, JT, paper in preparation)

every EFT coefficient and Higgs coupling
can be expressed directly by a set of input observables

for example: unpolarized e+e- at 250 GeV

$$\boxed{\delta g_{hZZ} = \frac{1}{2}\delta\sigma_{Zh} + 6.4\delta\Gamma_l + 5.3\delta g_{Z,eff} - 0.015\delta R_{\gamma Z} - 2.4\delta\kappa_{A,eff} + 8.9\delta m_h + 0.098\delta A_l + \cdots}$$

$$\delta X = \frac{\Delta X}{X}$$

σ_{Zh} : cross section of e+e- -> Zh

A_l, Γ_l : A_{LR} and Γ(Z->ll) at Z-pole

g_{Zeff}, κ_{Aeff} : Triple Gauge Couplings

$R_{\gamma Z}$: BR(h->γZ) / BR(h->ZZ*)

m_h : Higgs mass

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plug in measurement precisions for current EWPOs + 2 ab-1

$$\delta g_{hZZ} = \frac{1}{2}\delta\sigma_{Zh} + 6.4\delta\Gamma_l + 5.3\delta g_{Z,eff} - 0.015\delta R_{\gamma Z} - 2.4\delta\kappa_{A,eff} + 8.9\delta m_h + 0.098\delta A_l + \cdots$$

$$= 41 \oplus 66 \oplus 30 \oplus 23 \oplus 14 \oplus 11 \oplus 8.7 \oplus \cdots \times 10^{-4}$$

σ_{Zh}

EWPOs

TGCs

BR(h->γZ)

Higgs mass

importance hierarchy

role of each measurement: more transparent understanding

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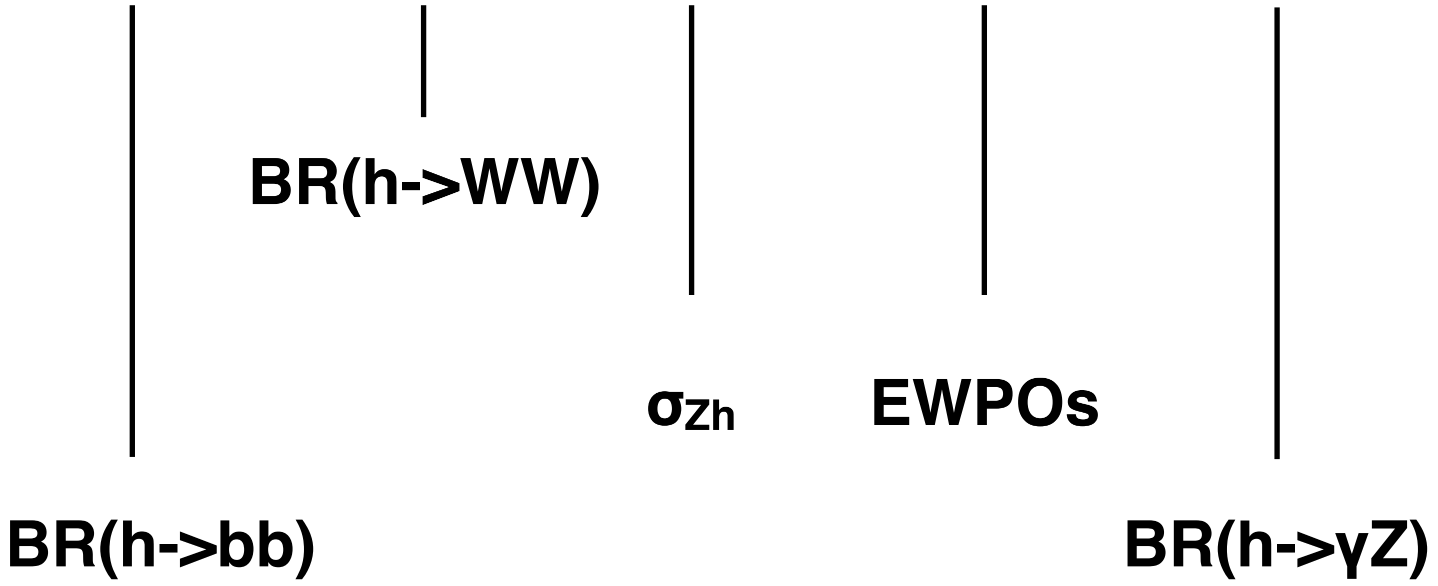
for example: unpolarized e+e- at 250 GeV

plug in measurement precisions for current EWPOs + 2 ab-1

$$\delta g_{hbb} = \frac{1}{2}\delta B_{bb} - \frac{1}{2}\delta B_{WW} + \frac{1}{2}\delta\sigma_{Zh} - 5.79\delta\Gamma_l - 0.016\delta\Gamma_{\gamma Z} + \cdots$$

$$= 28 \oplus 91 \oplus 41 \oplus 59 \oplus 32 \oplus \cdots \times 10^{-4}$$



BR(h->WW)

σ_{Zh}

EWPOs

BR(h->bb)

BR(h->γZ)

role of each measurement: more transparent understanding

(Fujii, Peskin, JT, paper in preparation)

for example: unpolarized e+e- at 250 GeV

plug in measurement precisions for current EWPOs + 2 ab-1

$$\delta g_{hcc} = \frac{1}{2}\delta B_{cc} - \frac{1}{2}\delta B_{WW} + \frac{1}{2}\delta\sigma_{Zh} - 5.79\delta\Gamma_{l} - 0.016\delta\Gamma_{\gamma Z} + \cdots$$

$$= 160 \oplus 91 \oplus 41 \oplus 59 \oplus 32 \oplus \cdots \times 10^{-4}$$

BR(h->cc)

BR(h->WW)

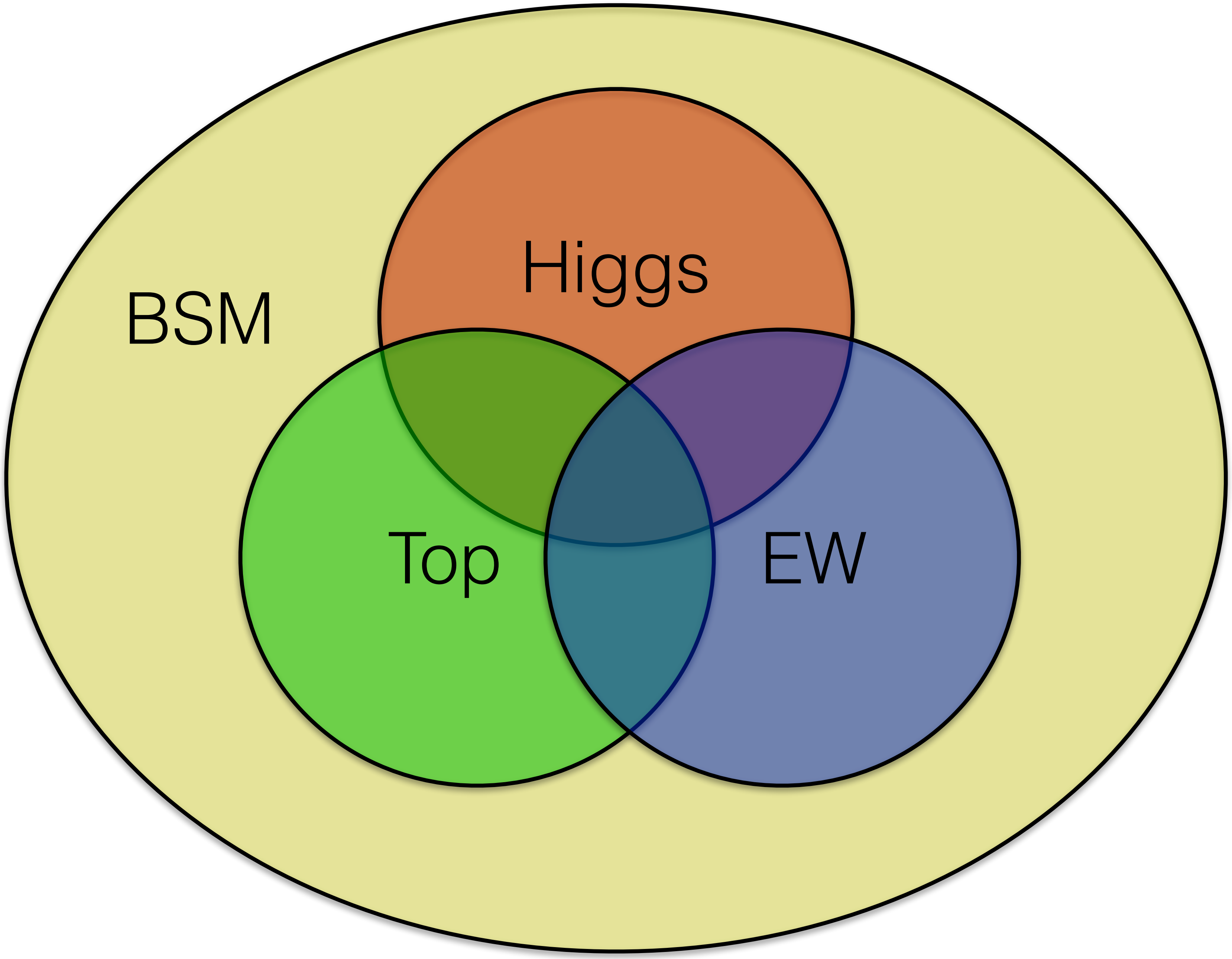
σ_{Zh}

EWPOs

BR(h->γZ)

stay tuned

a global view of physics @ e+e-



references

- Klaus Wille, *The Physics of Particle Accelerators - an introduction*, Oxford University Press
- Helmut Wiedemann, *Particle Accelerator Physics*, Springe

- PDG review, *Passage of Particles Through Matter*
- Michael Peskin, *Concepts of Elementary Particle Physics*, Oxford

- ILC input for European Strategy Update: 1903.01629
- ILC TDR, 1306.6352; ILC Higgs White Paper, 1310.0763
- ILC Operation Scenario, 1506.07830
- ILC Physics Case, 1506.05992, 1710.07621
- CLIC Higgs Physics, 1608.07538