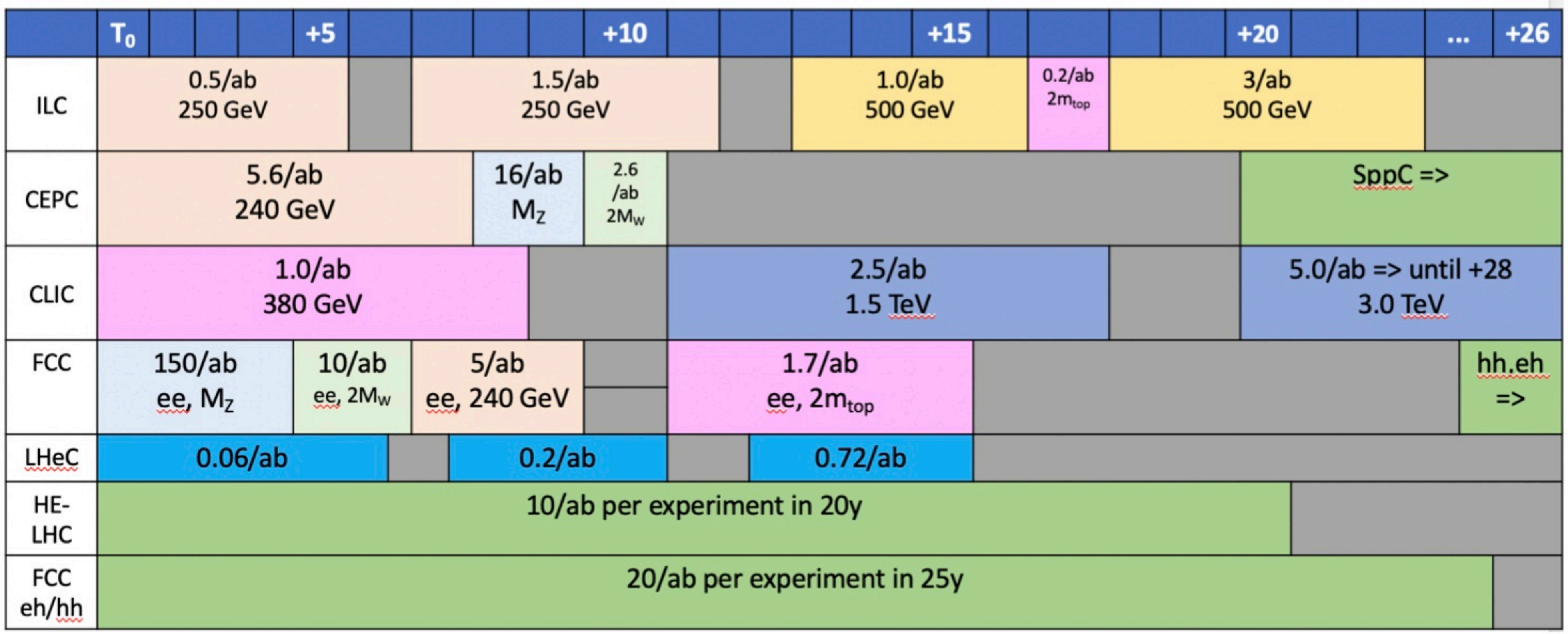
Introduction to e+e- Physics & Simulation



	T_0	+5	+10	+15	+20	...	+26
ILC	0.5/ab 250 GeV	1.5/ab 250 GeV	1.0/ab 500 GeV	0.2/ab $2m_{top}$	3/ab 500 GeV		
CEPC	5.6/ab 240 GeV	16/ab M_Z	2.6 /ab $2M_W$	SppC =>			
CLIC	1.0/ab 380 GeV	2.5/ab 1.5 TeV	5.0/ab => until +28 3.0 TeV				
FCC	150/ab ee, M_Z	10/ab ee, $2M_W$	5/ab ee, 240 GeV	1.7/ab ee, $2m_{top}$	hh,eh =>		
LHeC	0.06/ab	0.2/ab	0.72/ab				
HE-LHC	10/ab per experiment in 20y						
FCC eh/hh	20/ab per experiment in 25y						

Junping Tian (U. Tokyo)

MCnet Beijing School for Event Generators, June 28-July 2, 2021

plan

(i) Mini-intro to future e+e- experiments

Lecture 1

(ii) Higgs Property Measurements

(iii) New Particle Searches

(iv) Top-quark & EW Measurements

Lecture 2

(v) Global Interpretation in SM EFT

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focus will be on experimental concepts “why / what / how”
please learn theoretical concepts “why” from other lectures

(i) future e+e- collider proposals

	$\sqrt{s}$	beam polarisation	∫Ldt (baseline)	R&D phase
ILC	0.1 - 1 TeV	e-: 80% e+: 30% (20%)	2 ab^{-1} @ 250 GeV 0.2 ab^{-1} @ 350 GeV 4 ab-1 @ 500 GeV 8 ab-1 @ 1 TeV	TDR 2013
CLIC	0.35 - 3 TeV	e-: (80%) e+: 0%	1 ab^{-1} @ 380 GeV 2.5 ab^{-1} @ 1.5 TeV 5 ab^{-1} @ 3 TeV	CDR 2012
CEPC	90 - 240 GeV	e-: 0% e+: 0%	5.6 ab^{-1} @ 250 GeV 16 ab^{-1} @ M_Z 2.6 ab^{-1} @ $2M_W$	CDR 2018
FCC-ee	90 - 350 GeV	e-: 0% e+: 0%	150 ab^{-1} @ M_Z 10 ab^{-1} @ $2M_W$ 5 ab^{-1} @ 250 GeV 1.7 ab^{-1} @ 365 GeV	CDR 2018

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- O(10^6) Higgs; O(10^9-10^{12}) Z; O(10^8) W; O(10^6) t-quark; ? #BSM; etc
- What physics can be advanced? Roles played by $\sqrt{s}$, $\int L$, Polarisation?

(i-1) basic concepts on accelerators

know better our tools which often constrain physics exploration

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

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- **Radio-Frequency acceleration**

Electromagnetic fields oscillate at a perfect timing $l_i = \beta_i \frac{\lambda_{\mathrm{RF}}}{2}$

Gradient: ILC 31.5 MV/m; CLIC 100 MV/m

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- **Magnetic field (transverse acceleration)**

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

SPPC / FCC-hh: E = 100TeV, R = 100km; B ~ 16T

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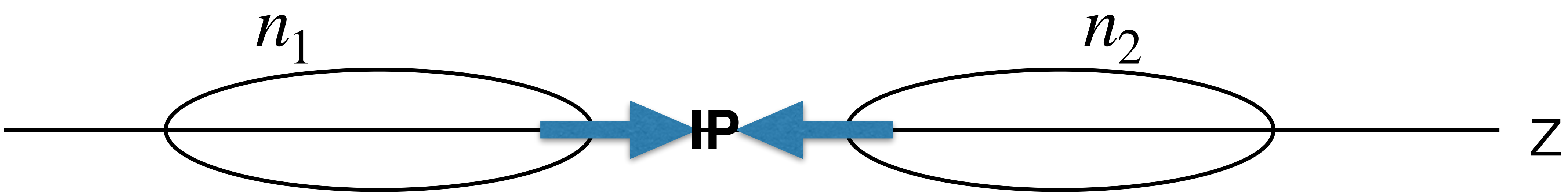
- **Plasma Wakefield acceleration (~10 GV/m)** long way to go

(i-1) basic concepts on accelerators

- **Luminosity (beam dynamics)**



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

f_{coll}	average collision frequency	(large in storage ring)
σ_x^*, σ_y^*	bunch size in transverse direction	(“Nano Beam”)
n_1, n_2	# of particles in a beam bunch	

(i-1) basic concepts on accelerators

- **Synchrotron Radiation**

$$P = \frac{e^2 c}{6\pi\epsilon_0}\frac{1}{(m_0c^2)^4}\frac{E^4}{R^2}$$

radiation power

(—> muon collider)

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

E loss per turn for electron

(~3GeV! for R=100km E=240GeV)

- **Beam Polarisation**

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

spinning particles precess around B-field direction

hard to preserve longitudinal polarisation in a ring; transverse possible

(i-2) basic concepts on detectors

what behind

Vertex / timing resolution
Momentum / Jet Energy Resolution
Flavor-tagging Efficiency
Particle Identification Efficiency

?

(i-2) basic concepts on detectors

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Vertex / timing resolution
Momentum / Jet Energy Resolution
Flavor-tagging Efficiency
Particle Identification Efficiency

?

- **passage of particles through matter**
  - ionization / atom excitation
  - multiple scattering
  - bremsstrahlung / pair production
  - nuclear interaction
  - Cherenkov radiation

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Vertex / timing resolution
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?

- **passage of particles through matter**
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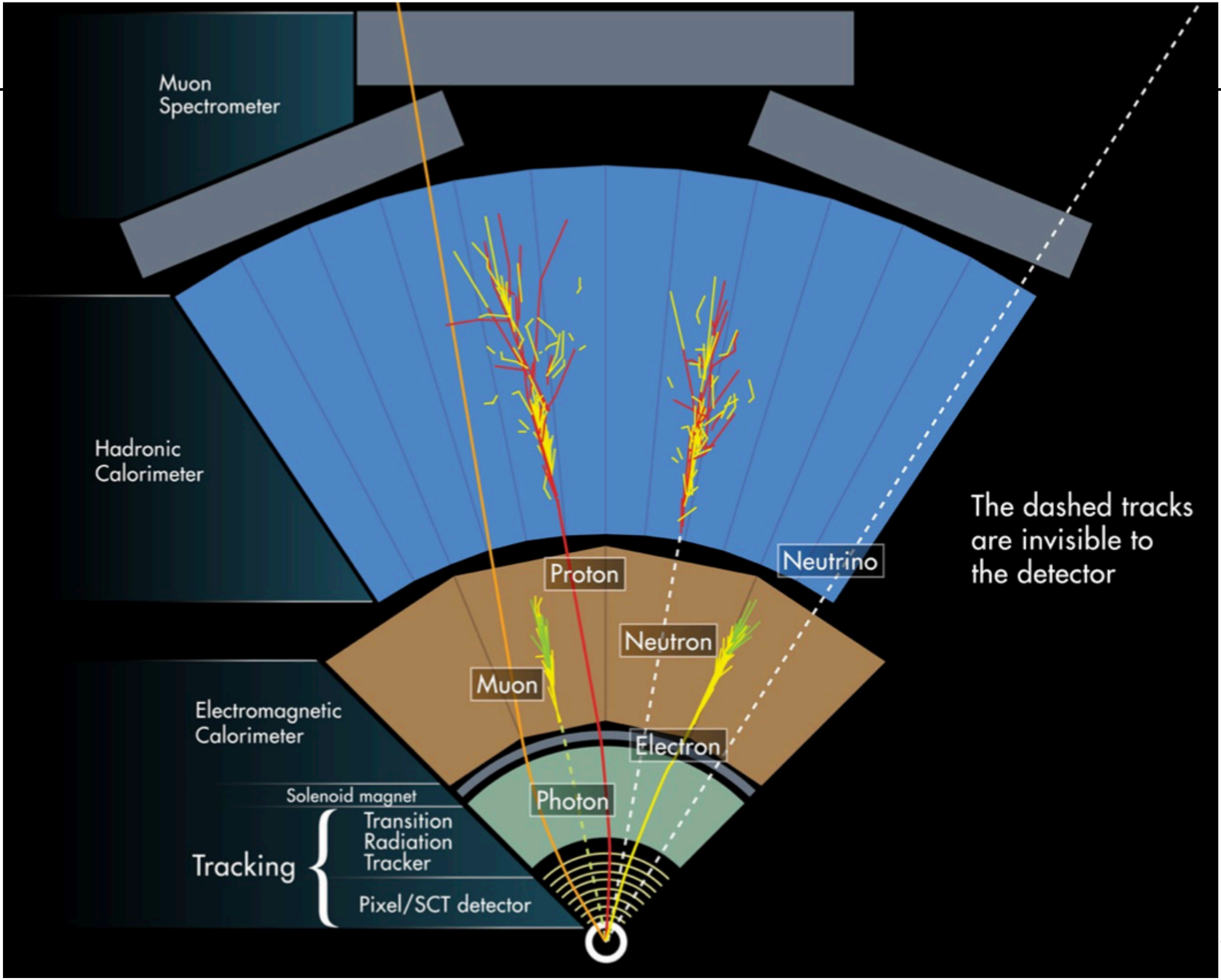
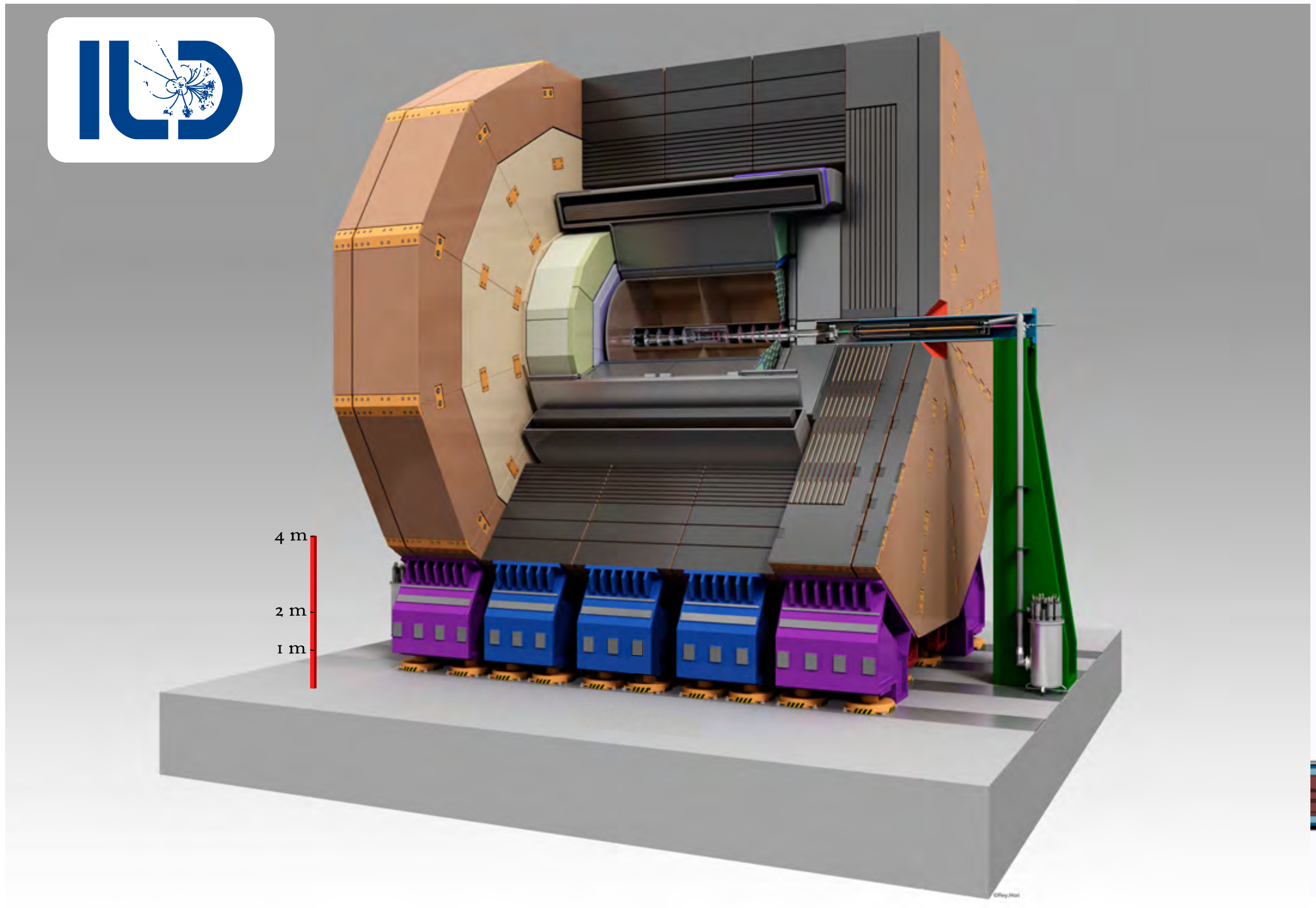
- **type of detectors**
  - vertex / tracking
  - sampling calorimeters
  - homogeneous calorimeters
  - timing detectors
  - …

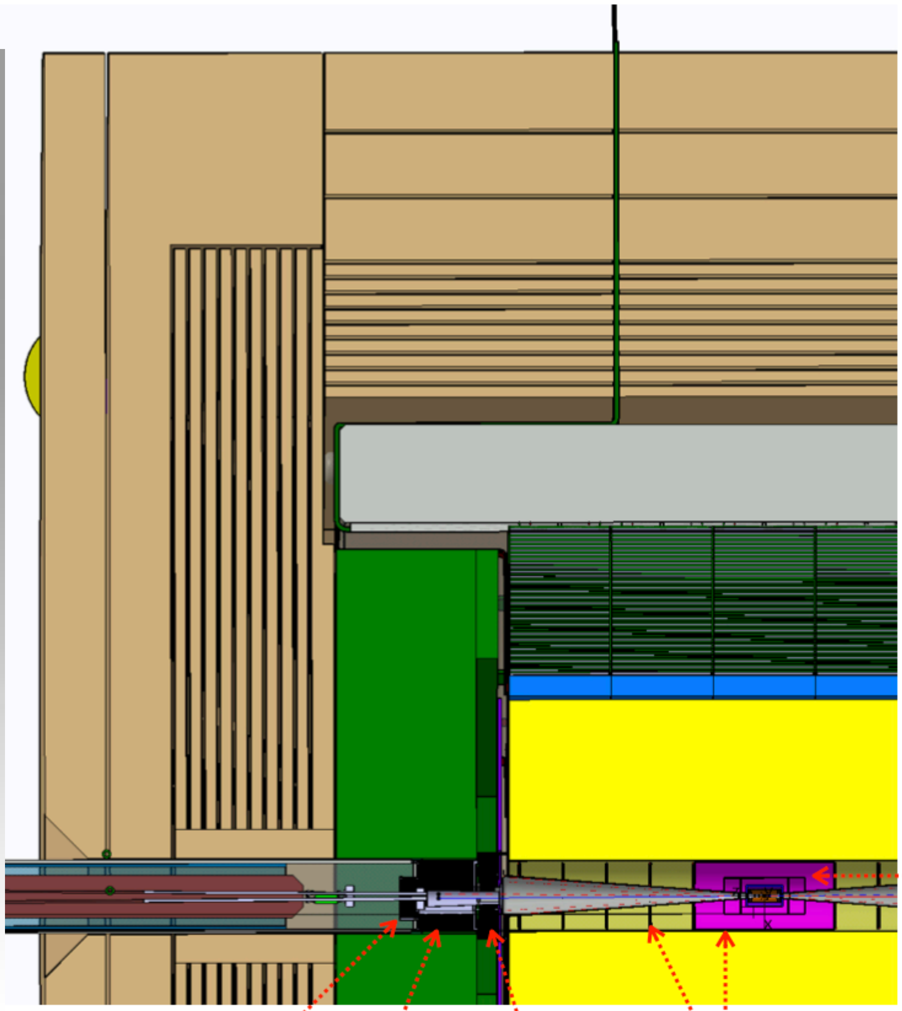
$\left\{ \begin{array}{l} \text{gaseous} \\ \text{silicon} \\ \text{scintillator} \\ \ldots \end{array} \right.$

$\left\{ \begin{array}{l} \text{digital} \\ \text{analog} \\ \text{semi-digi} \\ \ldots \end{array} \right.$


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

(i-2) basic concepts on detectors





Yoke/Muon

Coil

HCAL

ECAL

TPC

Vertex

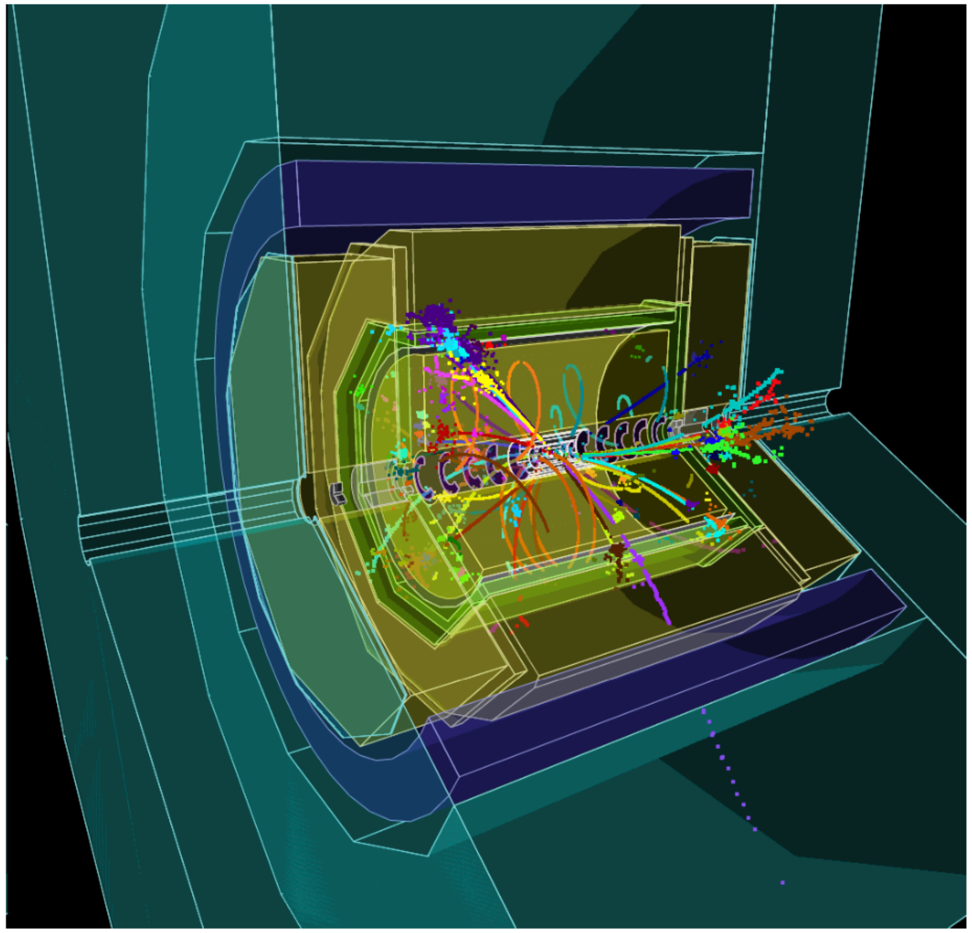
BeamCAL LHCAL LumiCAL FTD/SIT

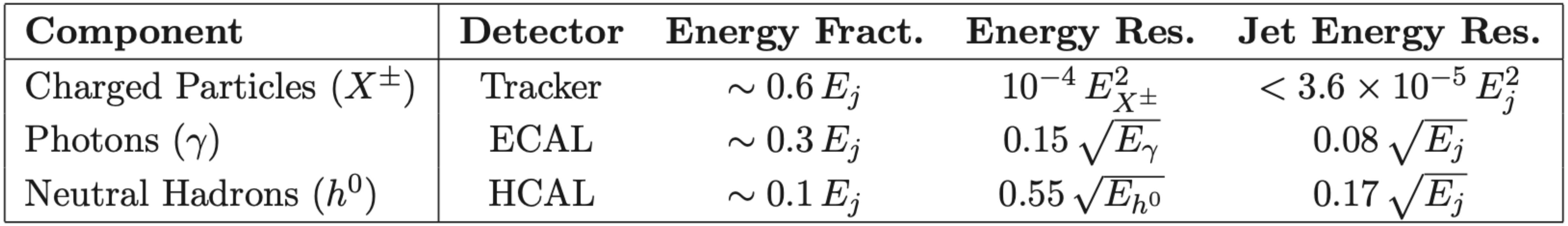
(i-2) basic concepts on detectors

- **Particle Flow Detector**

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	$\sim 0.6\,E_j$	$10^{-4}\,E^2_{X^{\pm}}$	$< 3.6 \times 10^{-5}\,E^2_j$
Photons (γ)	ECAL	$\sim 0.3\,E_j$	$0.15\,\sqrt{E_\gamma}$	$0.08\,\sqrt{E_j}$
Neutral Hadrons (h^0)	HCAL	$\sim 0.1\,E_j$	$0.55\,\sqrt{E_{h^0}}$	$0.17\,\sqrt{E_j}$

(i-2) basic concepts on detectors

- **typical tracking performance**

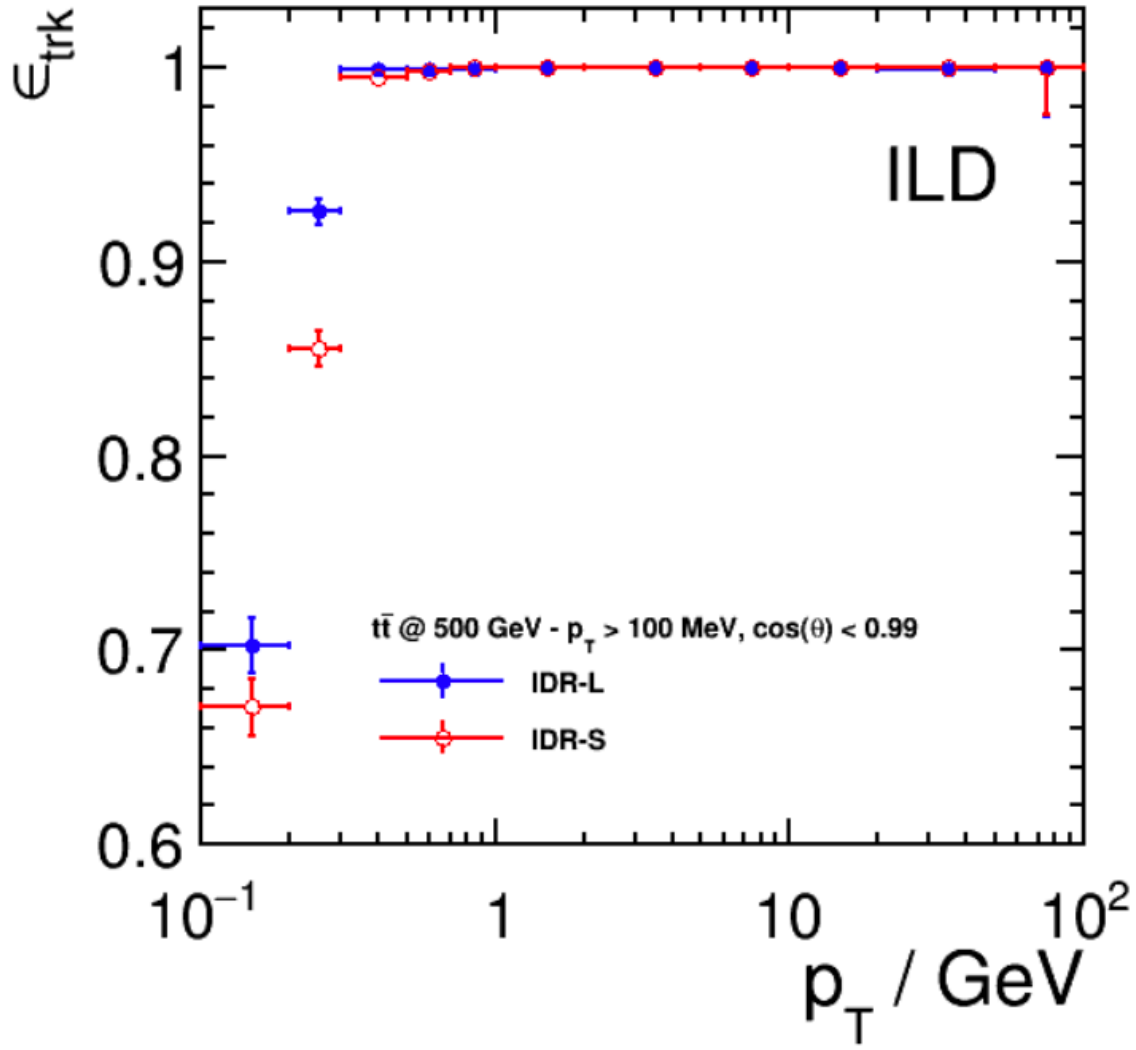
momentum resolution

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

~0.2% for Pt~100GeV

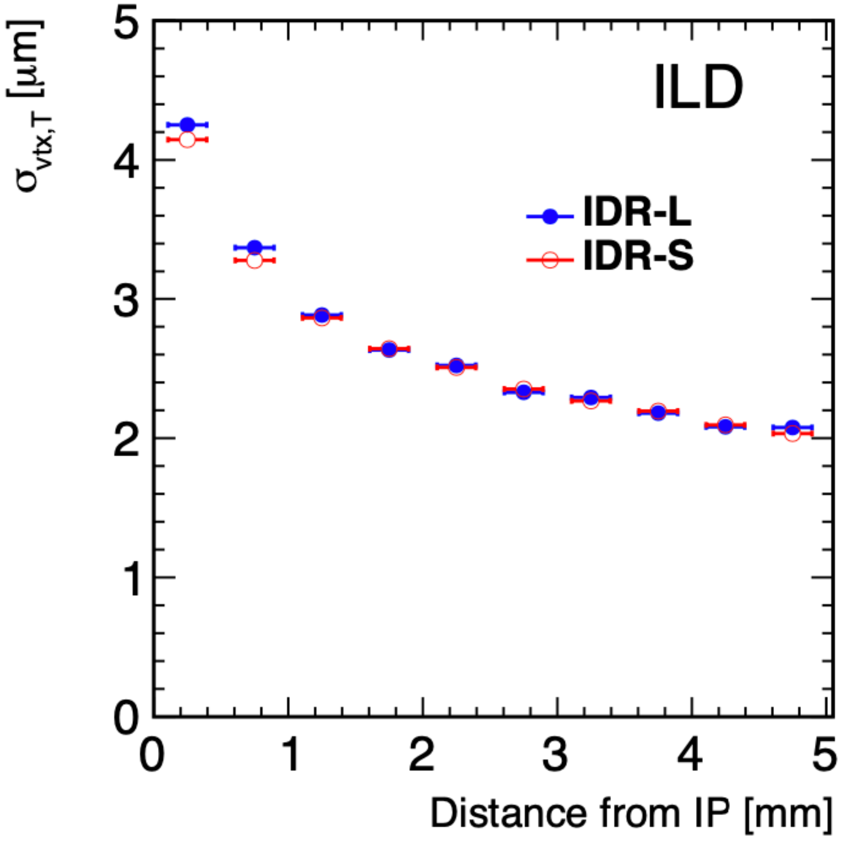
tracking efficiency

~100% for P_T > 300 MeV



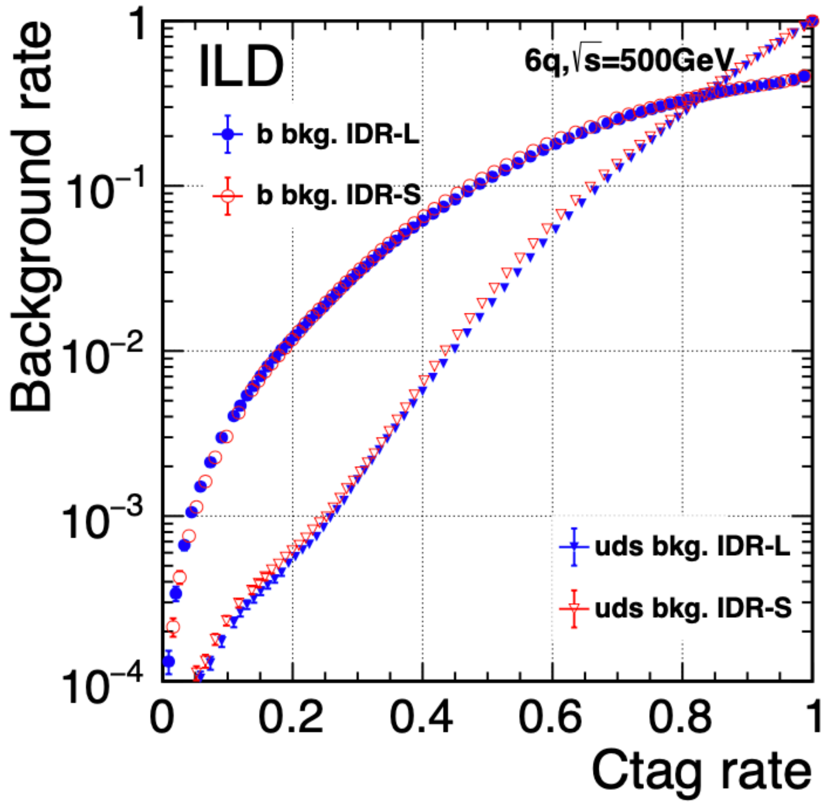
(i-2) basic concepts on detectors

vertex / flavor-tagging performance



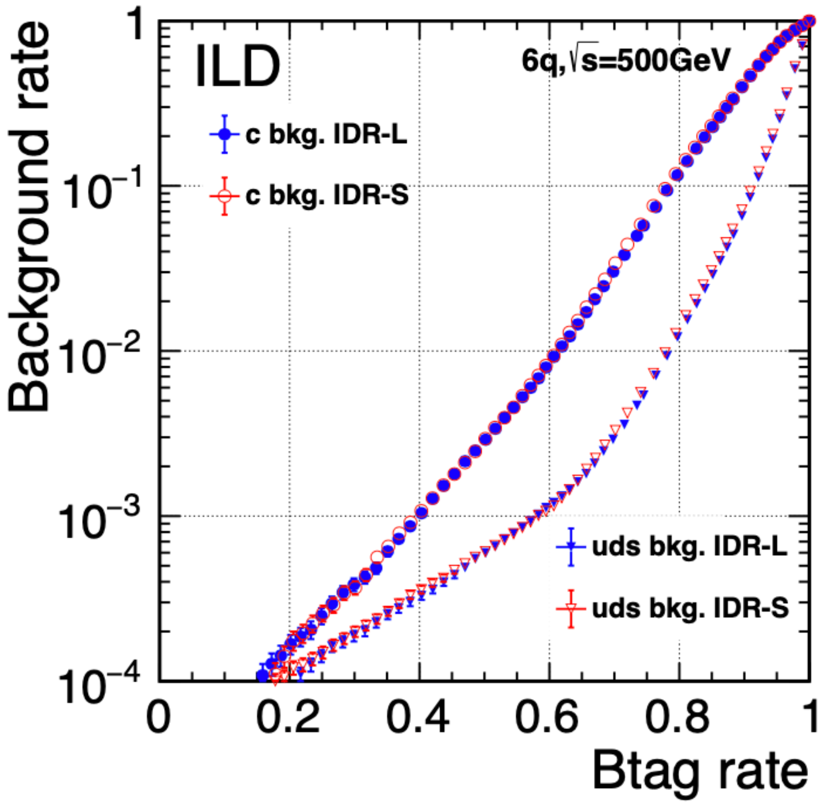
secondary vertex
position from c-jets

Δr ~ 2μm



flavor-tagging
c-jet

ε ~ 50% (10% b)



flavor-tagging
b-jet

ε ~ 80% (10% c)

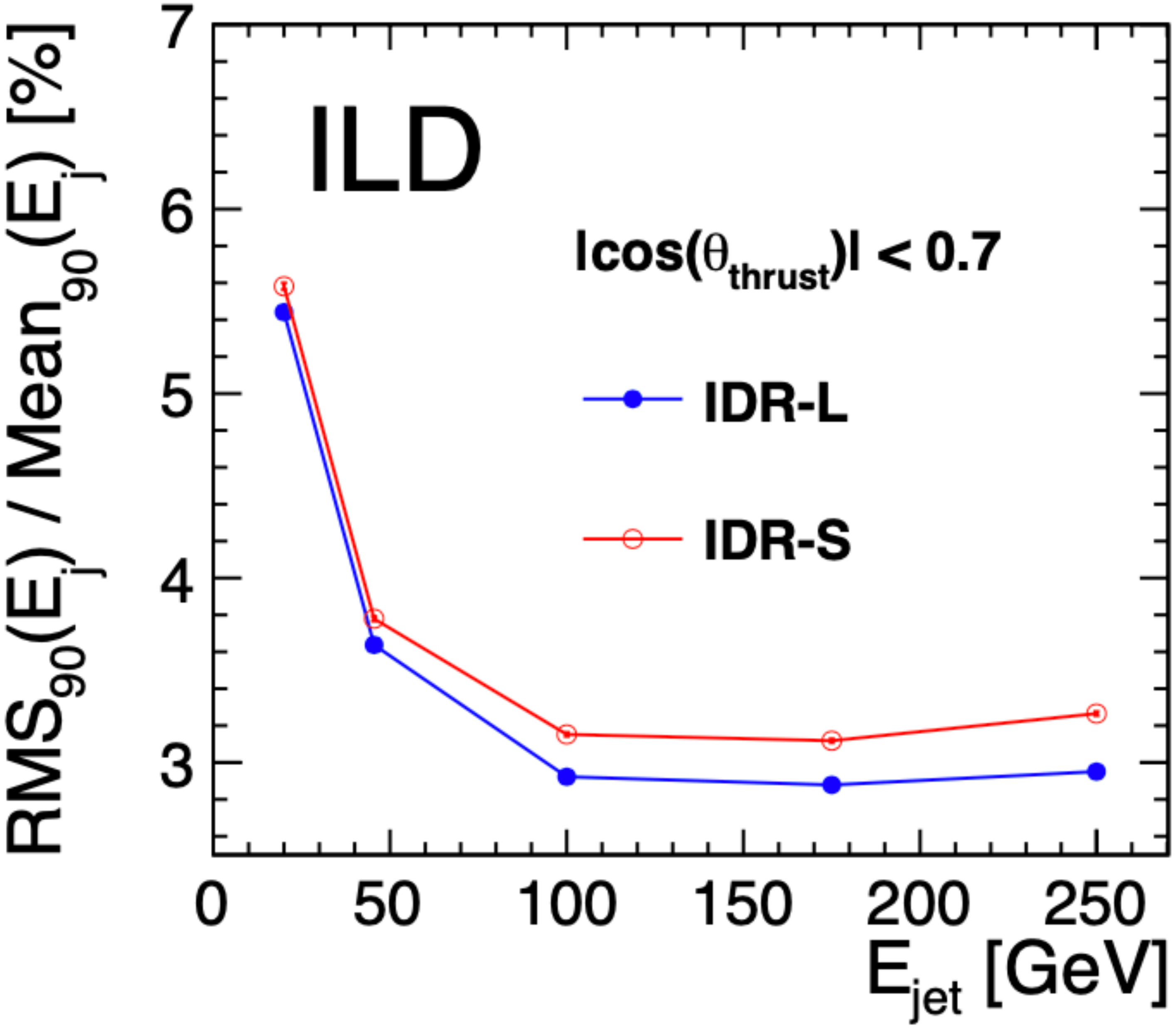
(i-2) basic concepts on detectors

- **performance on jet energy resolution**

$$\frac{\Delta E}{E} = \frac{30\,\%}{\sqrt{E}} + c$$

(E in GeV)

$\Delta E / E \sim 3\text{-}4\%$



(i) from event generators to real life

- **event generator: WHIZARD / MadGraph / Sherpa / Pythia…**

  hard interaction; ISR; beamstralung

  parton showering; hadronization; decay

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- **detector simulation**

  full detector simulation; pile-up; (GEANT4)

  fast simulation; simple smearing; (DELPHES / SGV)

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  vertex reconstruction; jet clustering; flavor tagging (LCFIPlus)

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- **physics analysis**

(ii) e+e- physics: big questions

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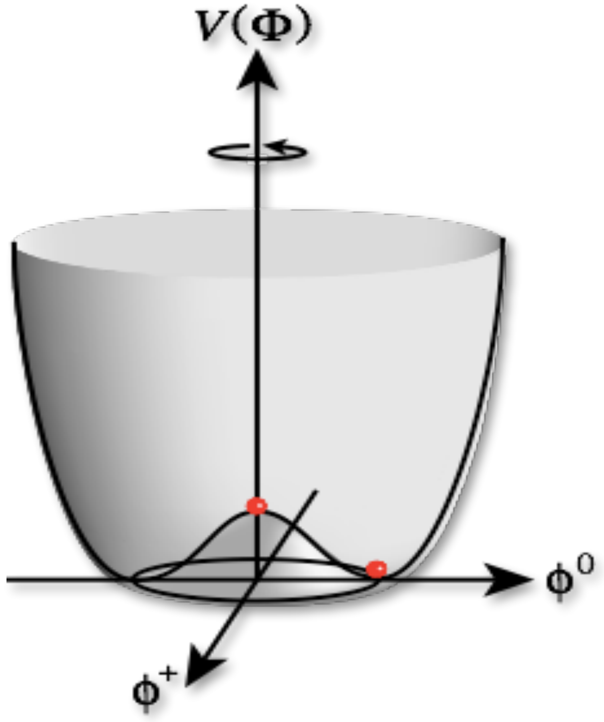
- data say there are at least five missing pieces in the SM
  - dark matter (2003)
  - neutrino mass (1998)
  - dark energy (1998)
  - inflation (2003)
  - matter anti-matter asymmetry (2003)

[H. Murayama]

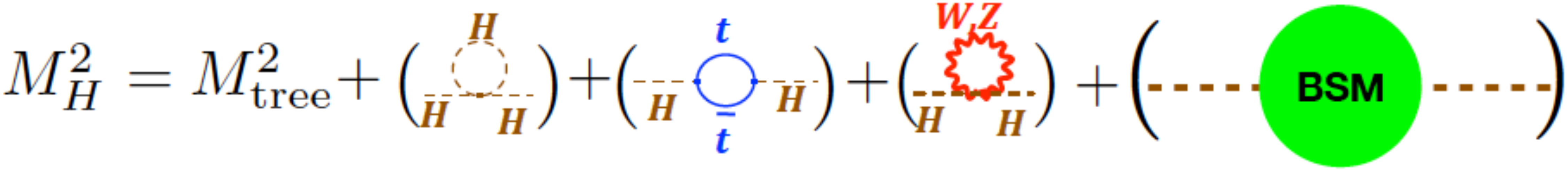
how can future e+e- colliders help?

(ii) Higgs physics: mystery in Electroweak Symmetry Breaking

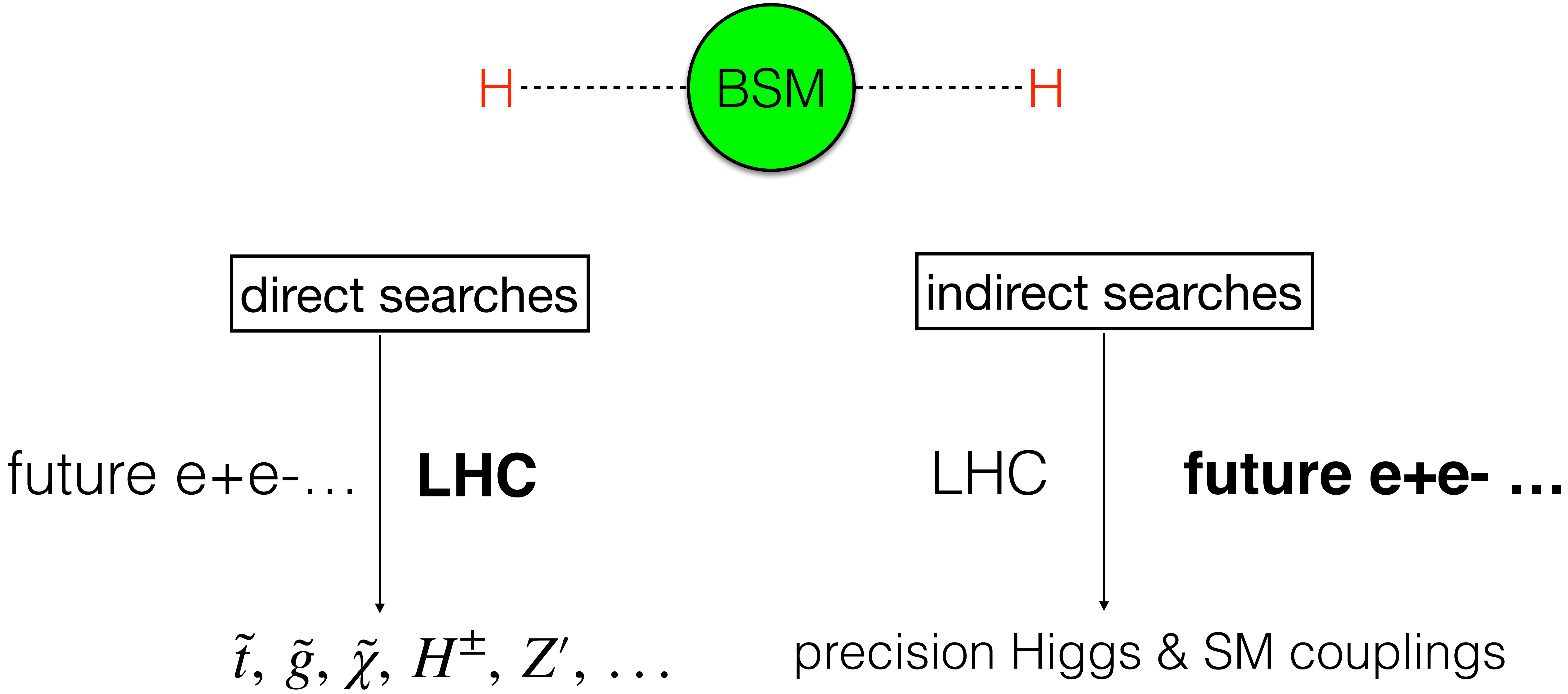
$$V(|\Phi|) = \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$



- H(125) discovery
  - elementary or composite? any siblings?
- What is the origin of EWSB?
  - why $\mu^2<0$? underlying dynamics?
- What BSM protects m_H?
- Connection to big questions?



golden time: BSM hunting



H - BSM - H

direct searches

future e+e-… | **LHC**

$\tilde{t}, \tilde{g}, \tilde{\chi}, H^{\pm}, Z', \ldots$

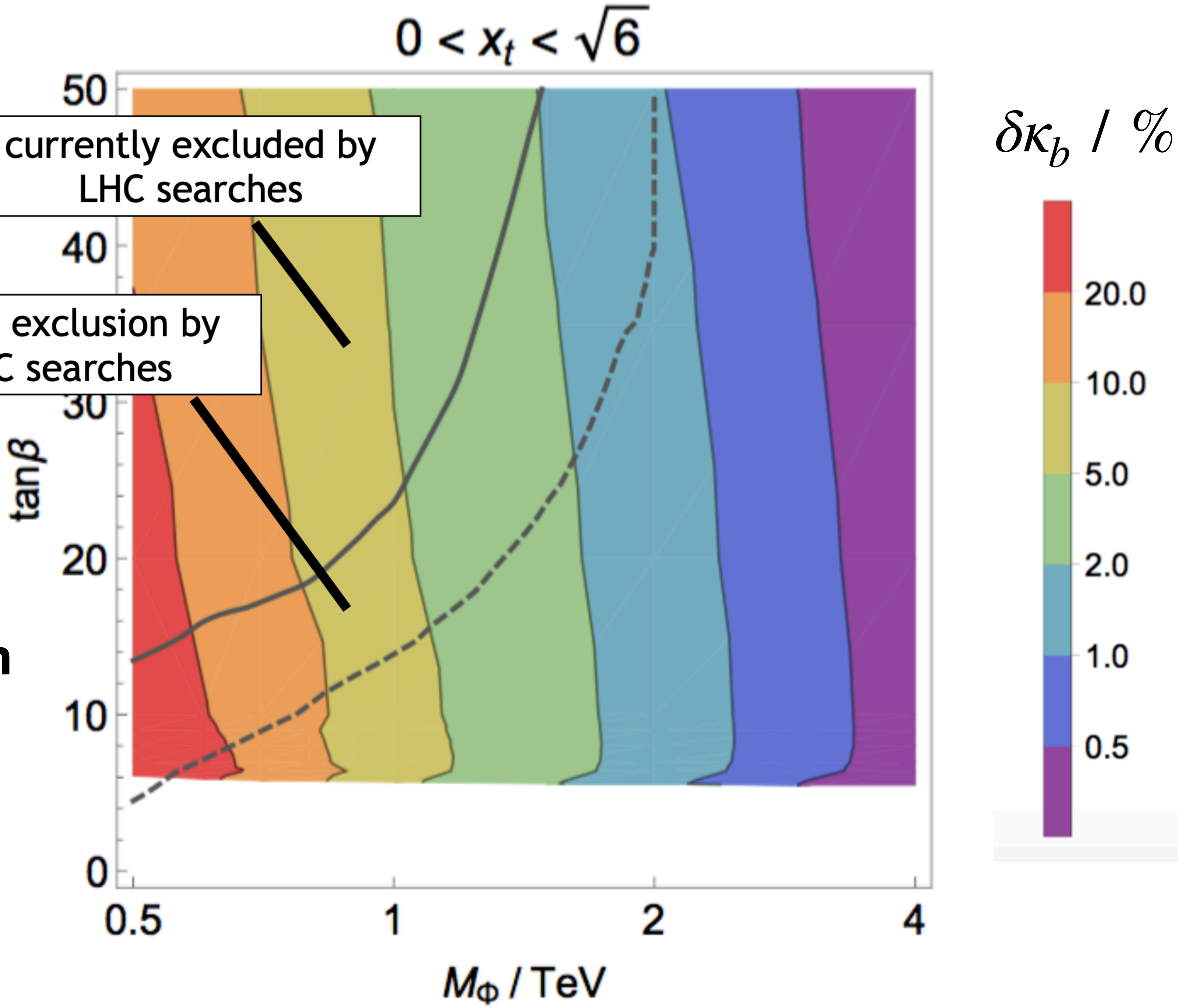
indirect searches

LHC | **future e+e- …**

precision Higgs & SM couplings

- there must be BSM around EW scale, we just need to find it out

direct vs indirect searches: complementarity



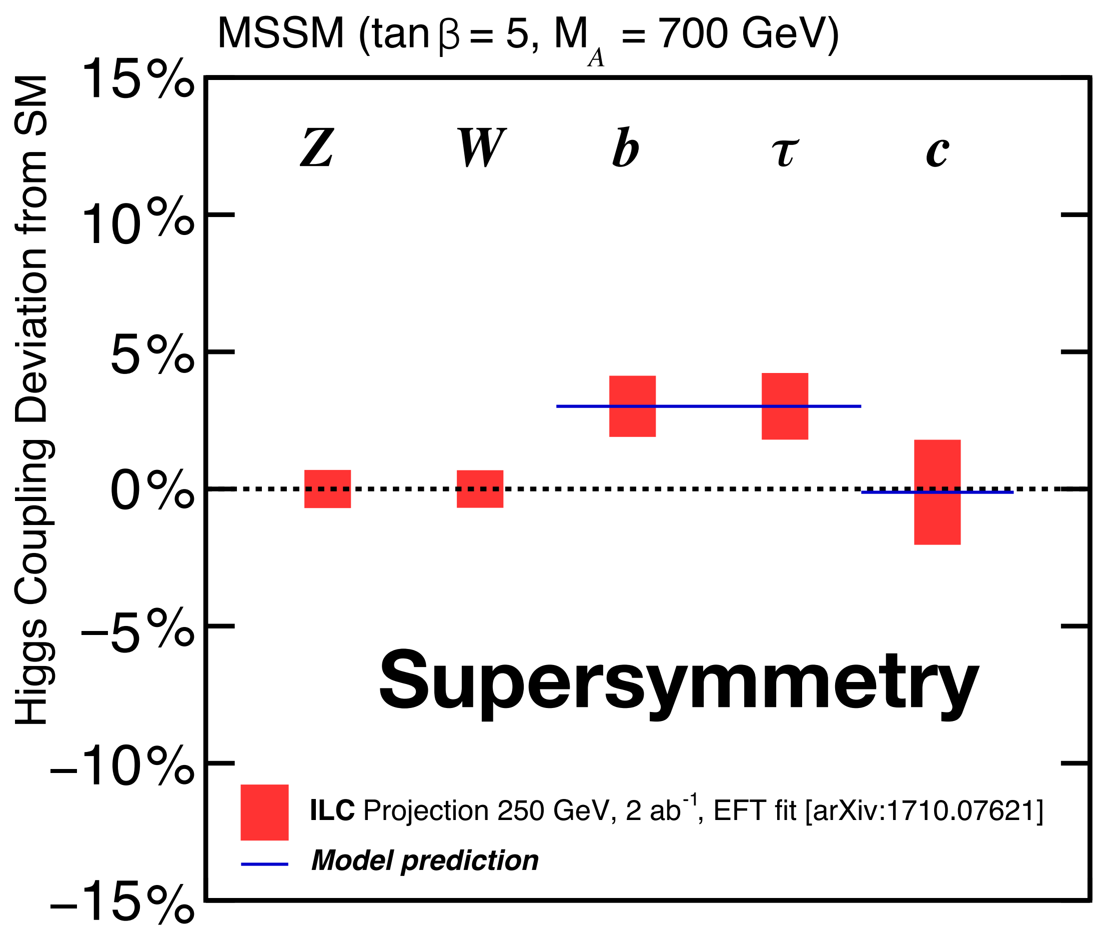
currently excluded by LHC searches

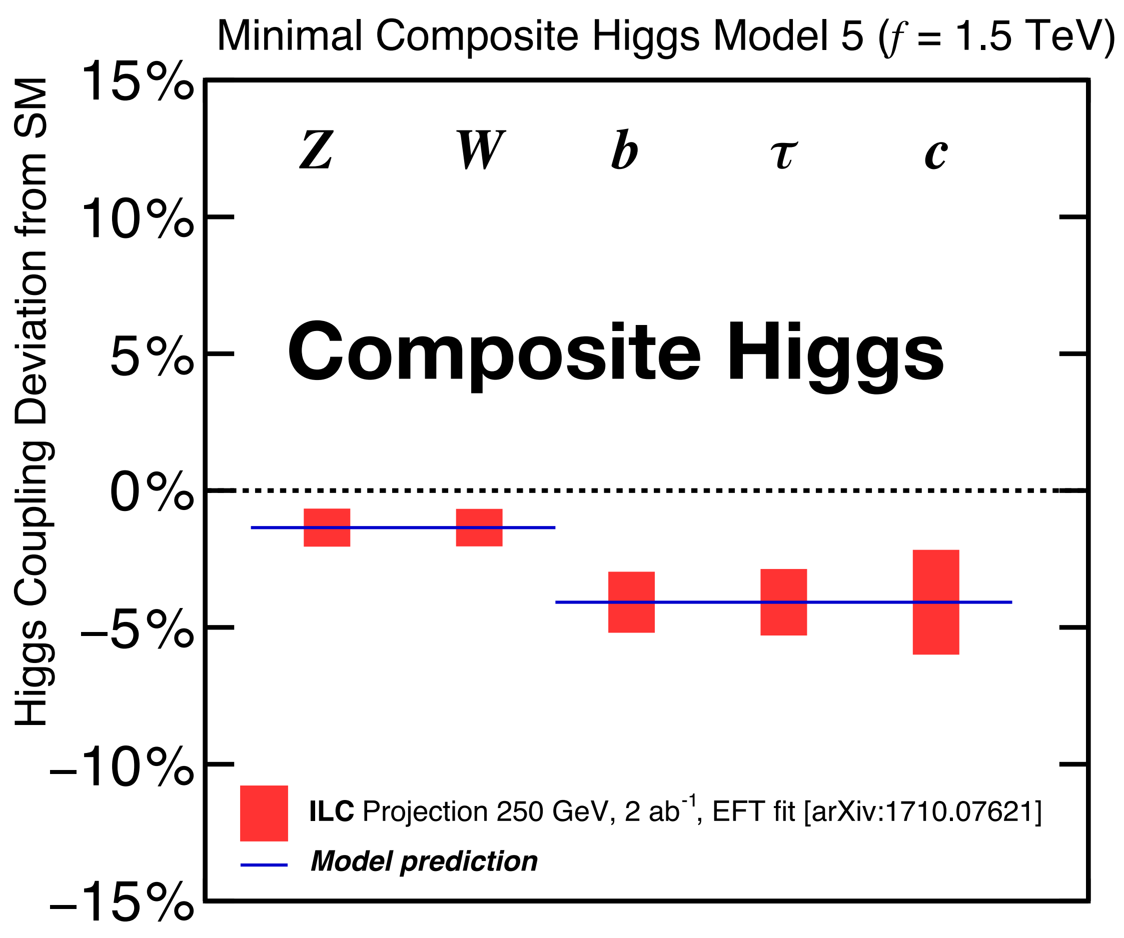
expected exclusion by HL-LHC searches

MSSM with b-τ unification

[Wells, Zhang, arXiv:1711.04774]

opportunities from precision Higgs couplings


MSSM (tan β = 5, M_A = 700 GeV)


Minimal Composite Higgs Model 5 (f = 1.5 TeV)

arXiv: 1306.6352

- measuring deviation pattern will tell a lot about BSM

general guidelines for Higgs coupling meas. @ future e+e-

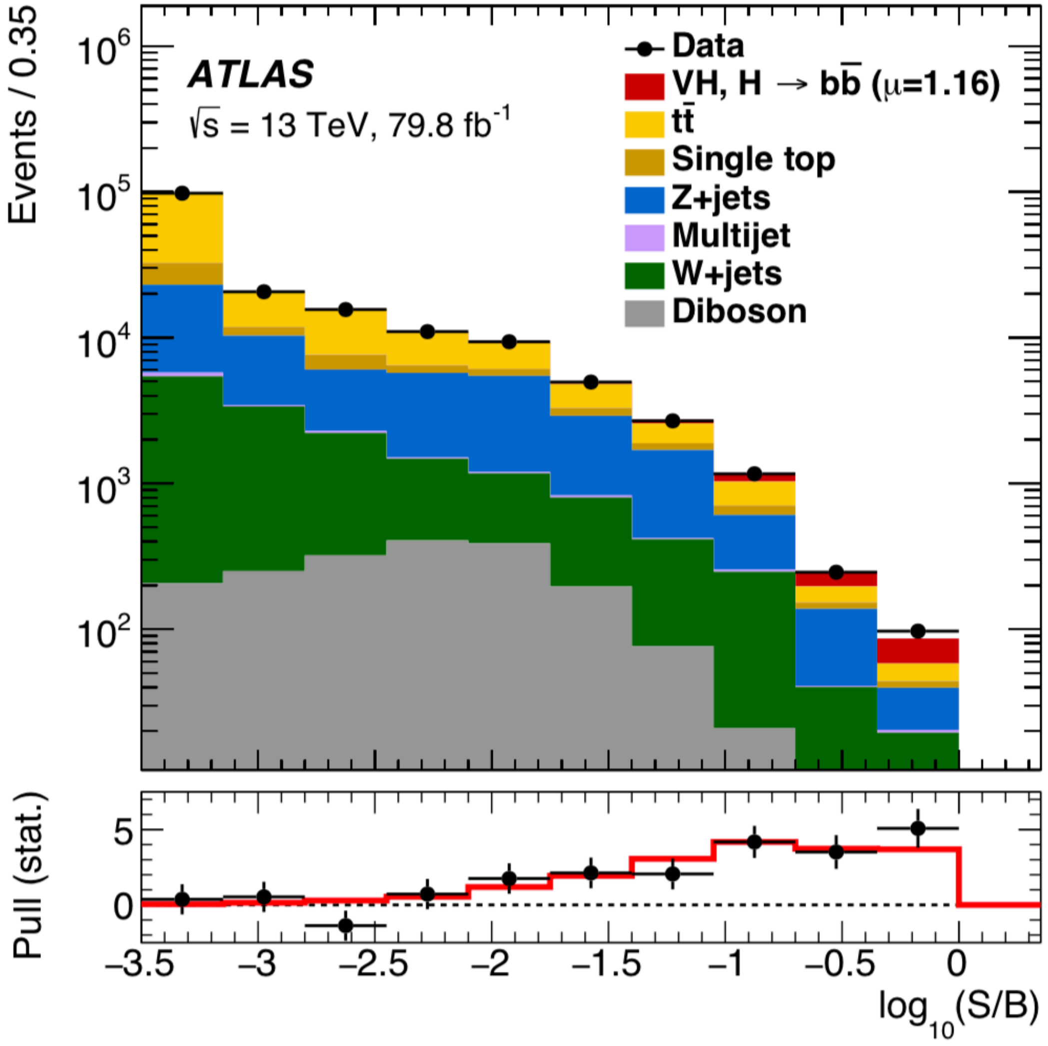
—in light of what have been found at LHC

- new particles are heavy, deviation is small, 1-10% for m_{BSM}~1TeV: need measurement with 1% precision or below so that deviations with SM can be discovered
- measurement needs to be as model-independent as possible: so that the true BSM model can be discriminated from others, future HEP direction hence can be decided

statistics vs S/B: example on H→bb discovery

LHC (super Higgs factory #10^8)

e+e- (Higgs factory #10^6)



# of Higgs produced: ~4,000,000

significance: 5.4σ

[ATLAS, 1808.08238; CMS, 1808.08242]

statistics vs S/B: example on H→bb discovery

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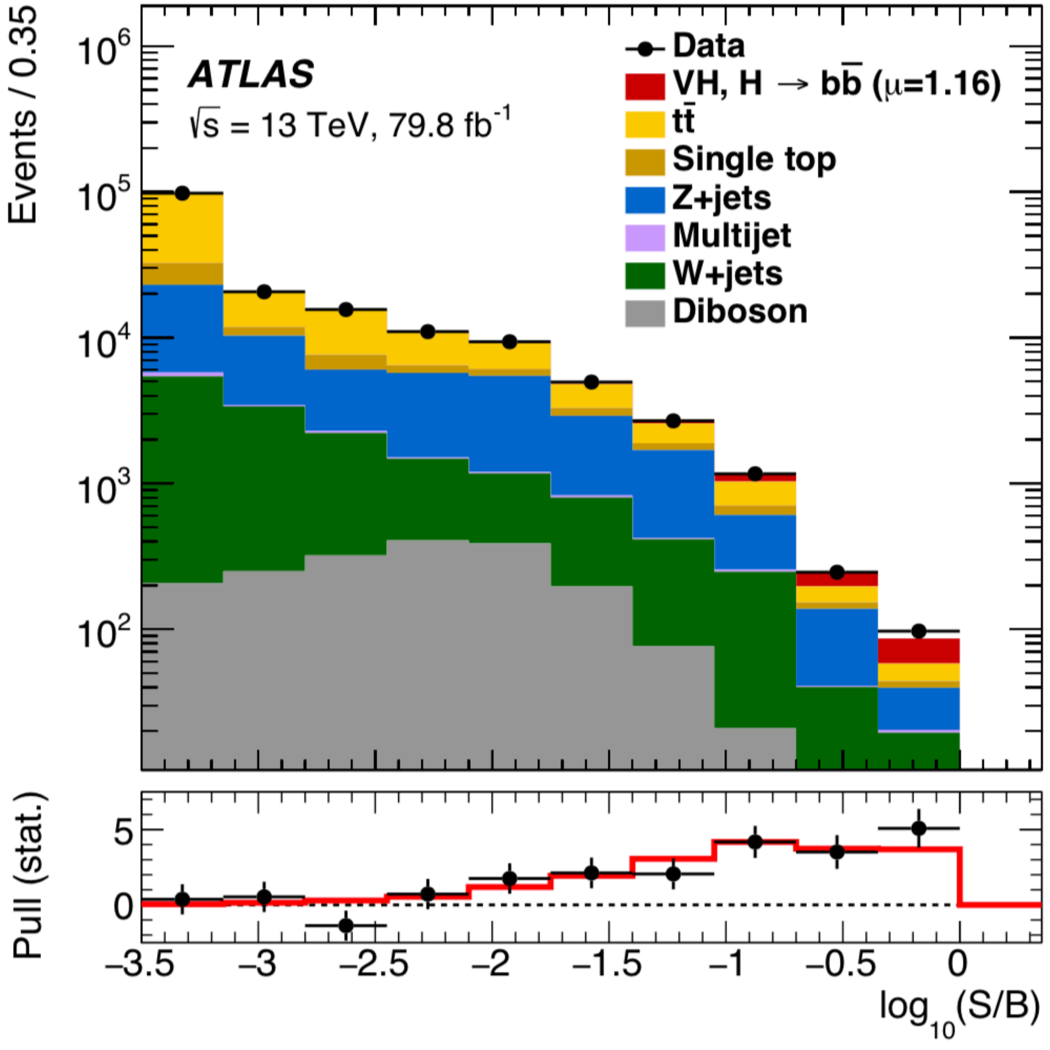
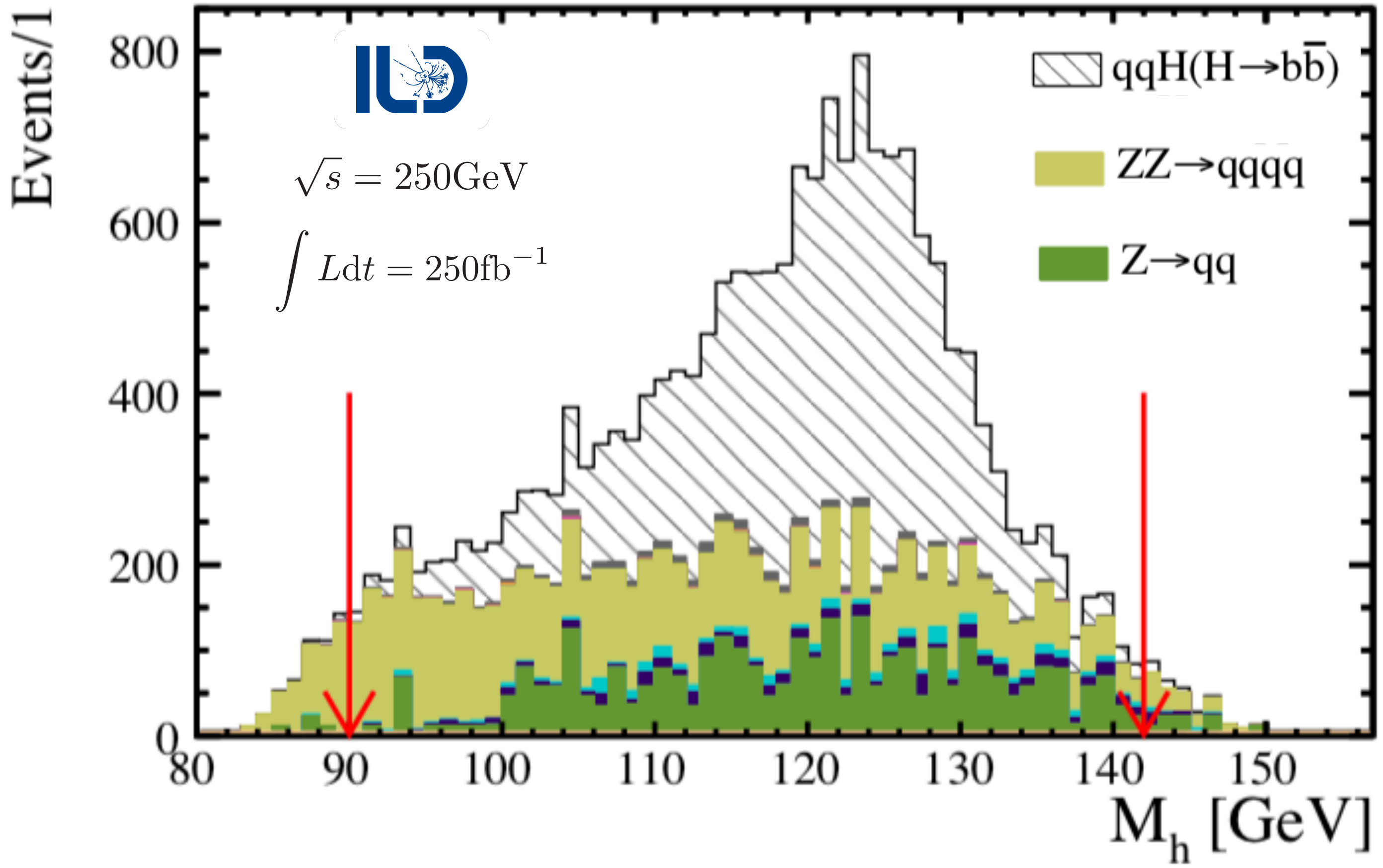


e+e- (Higgs factory #10^6)



full detector simulation

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

significance: 5.4σ 5.2σ

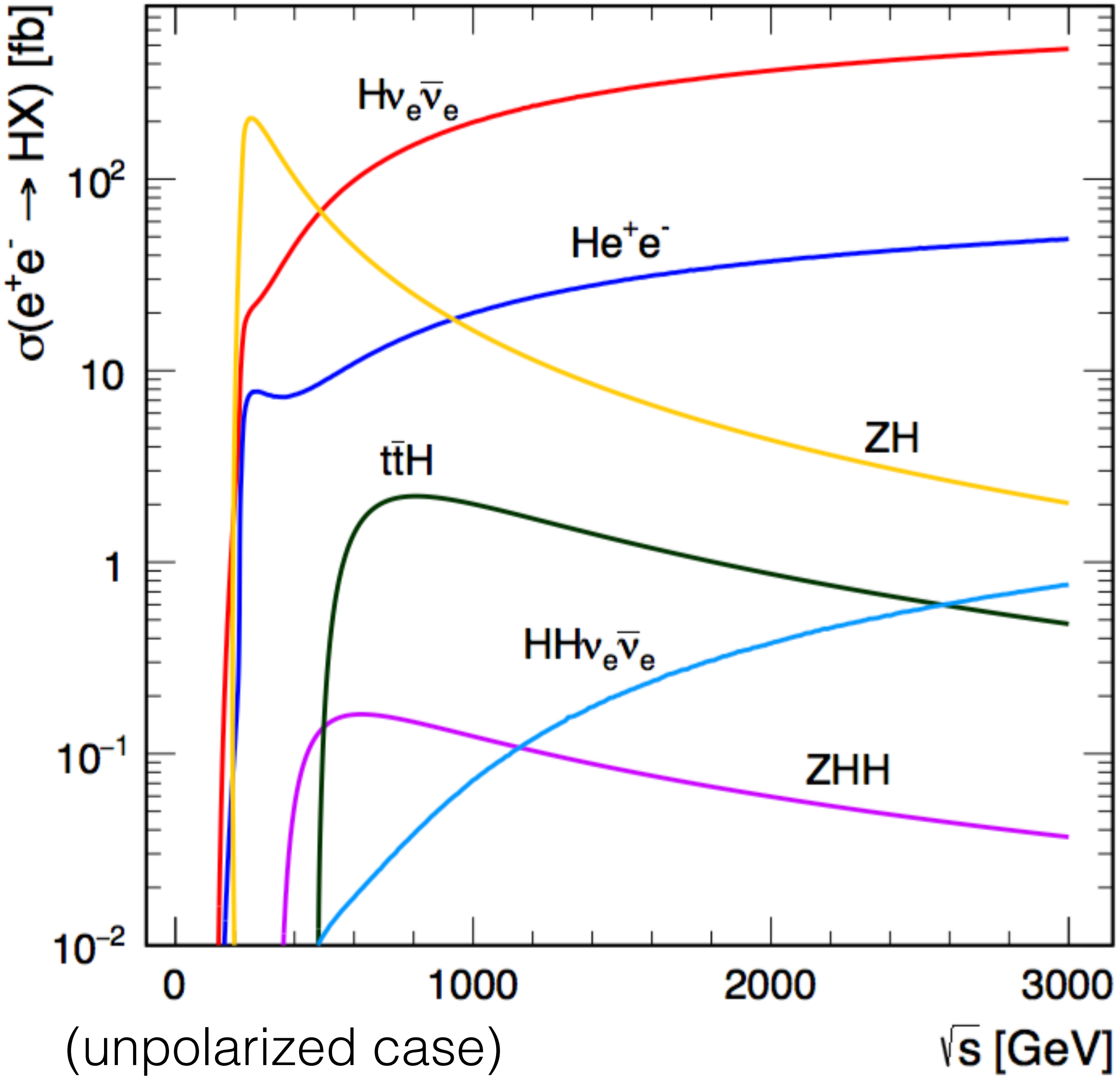
[ATLAS, 1808.08238; CMS, 1808.08242]

[Ogawa, PhD Thesis (Sokendai)]

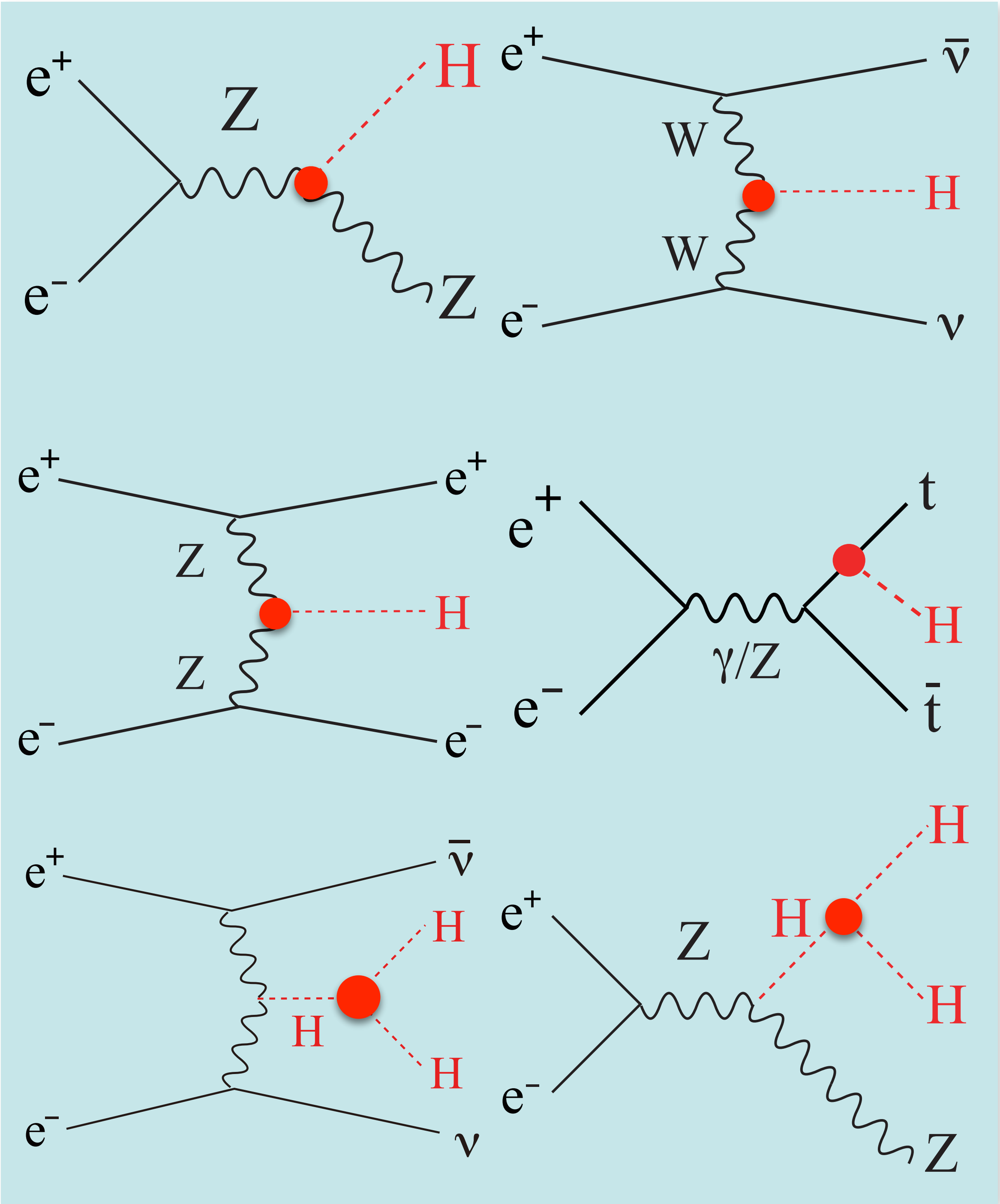
“that is much much easier, infinitely easier, on a e+e- machine than on a proton machine”

youtube: Burton Richter #mylinearcollider, 2015

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

Higgs properties: what we would like to measure

reconstruct the Higgs sector in a bottom-up and model independent way

Mass & J^{CP} $\quad M_h \quad \Gamma_h \quad J^{\mathrm{CP}}$

new CP violating source?

$L_{\mathrm{Higgs}} \quad hhh: \quad -6i\lambda v = -3i\frac{m_h^2}{v}, \quad hhhh: \quad -6i\lambda = -3i\frac{m_h^2}{v^2}$

probe Higgs
potential, EWBG?

L_{Gauge}

$$W_\mu^+ W_\nu^- h: \; i\frac{g^2 v}{2} g_{\mu\nu} = 2i\frac{M_W^2}{v} g_{\mu\nu}, \quad W_\mu^+ W_\nu^- hh: \; i\frac{g^2}{2} g_{\mu\nu} = 2i\frac{M_W^2}{v^2} g_{\mu\nu},$$

$$Z_\mu Z_\nu h: \; i\frac{g^2 + g'^2 v}{2} g_{\mu\nu} = 2i\frac{M_Z^2}{v} g_{\mu\nu}, \quad Z_\mu Z_\nu hh: \; i\frac{g^2 + g'^2}{2} g_{\mu\nu} = 2i\frac{M_Z^2}{v^2} g_{\mu\nu}$$

SU(2) nature?
m$_V$ from SSB?

$L_{\mathrm{Yukawa}} \quad h\bar{f}f: \quad -i\frac{y^f}{\sqrt{2}} = -i\frac{m_f}{v}$

m$_f$ from Yukawa coupling?
2HDM?

$L_{\mathrm{Loop}} \quad h\gamma\gamma \quad hgg \quad h\gamma Z$

new particles in the loop?

+ possible exotic/anomalous interactions of Higgs

what are the direct experimental observables

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

what are the direct experimental observables

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

- note the important complementarity with LHC

(ii) Higgs property measurements at e+e-

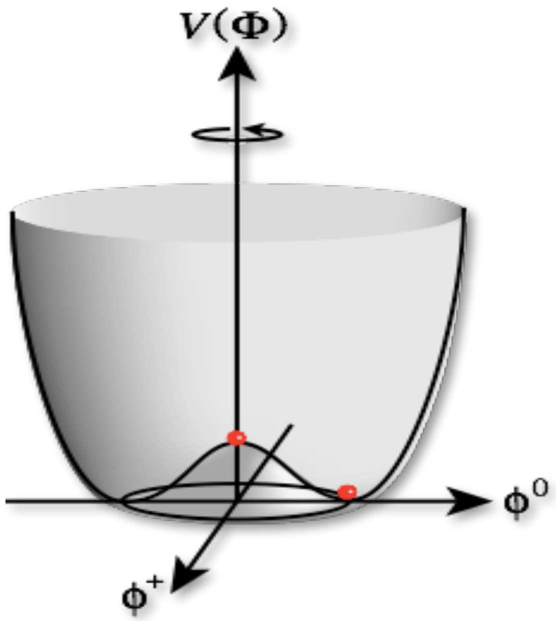
I will explain in fare details for 1-2 analyses, talk very briefly in other ones; mainly focus on physics issues instead of analysis techniques, which are important as well and can be learned from the references.

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

as usual, selection is always biased

(ii-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- —> ννHH (WW-fusion)

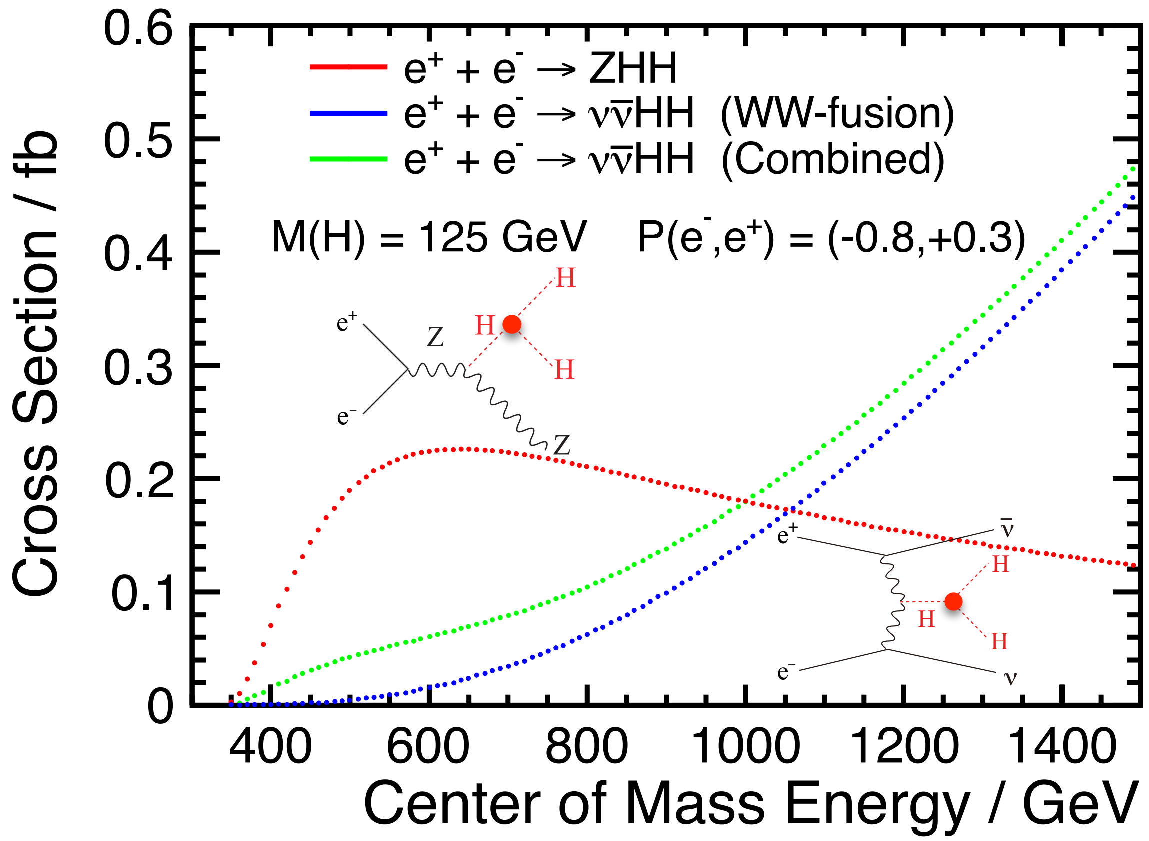


ILC

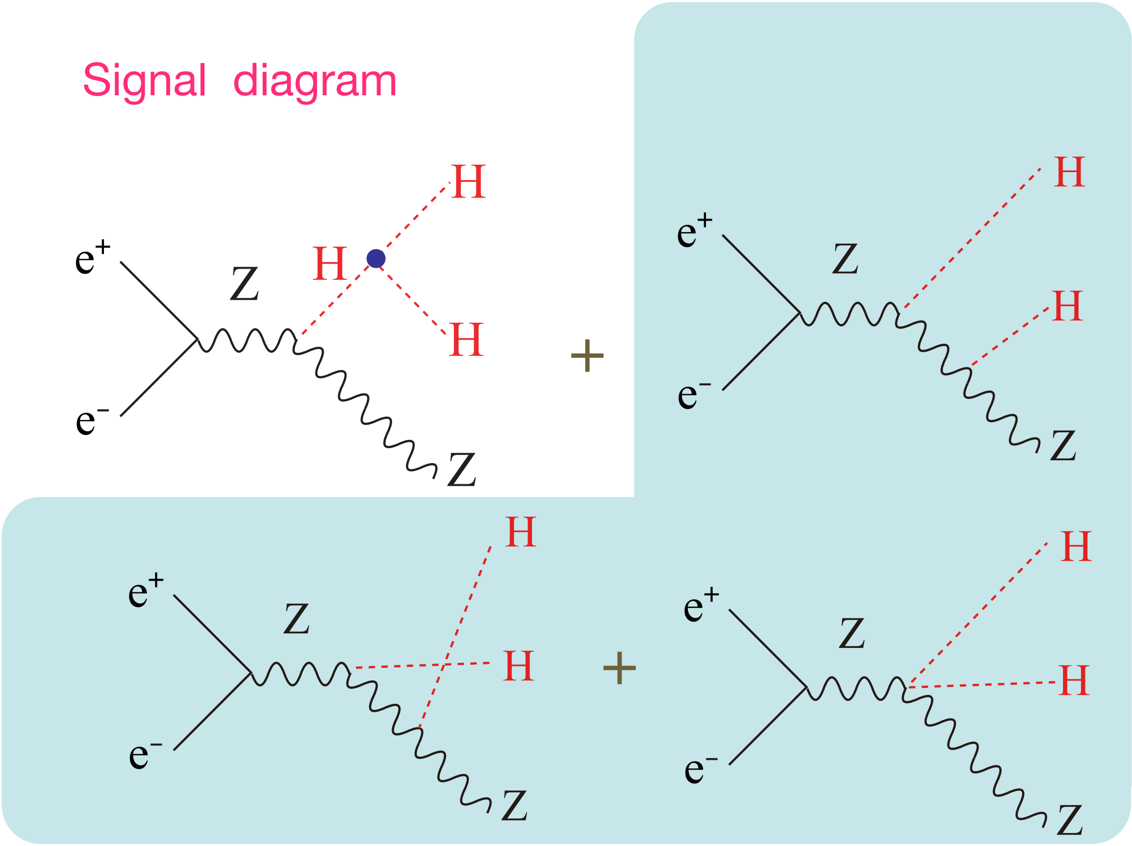
$\Delta\lambda_{HHH}/\lambda_{HHH}$	500 GeV	+ 1 TeV
H20	27%	10%

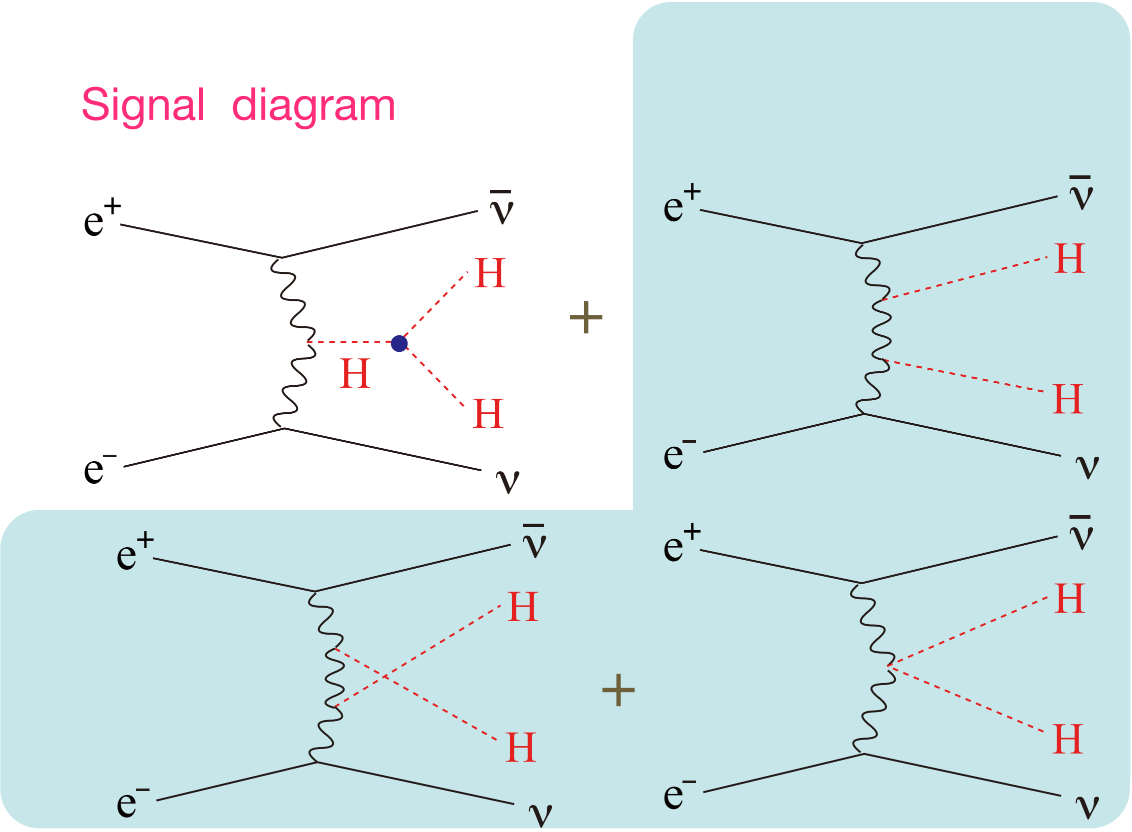
CLIC

1.4 TeV	+3 TeV
24%	11%



physics issues: diagrams for double Higgs production





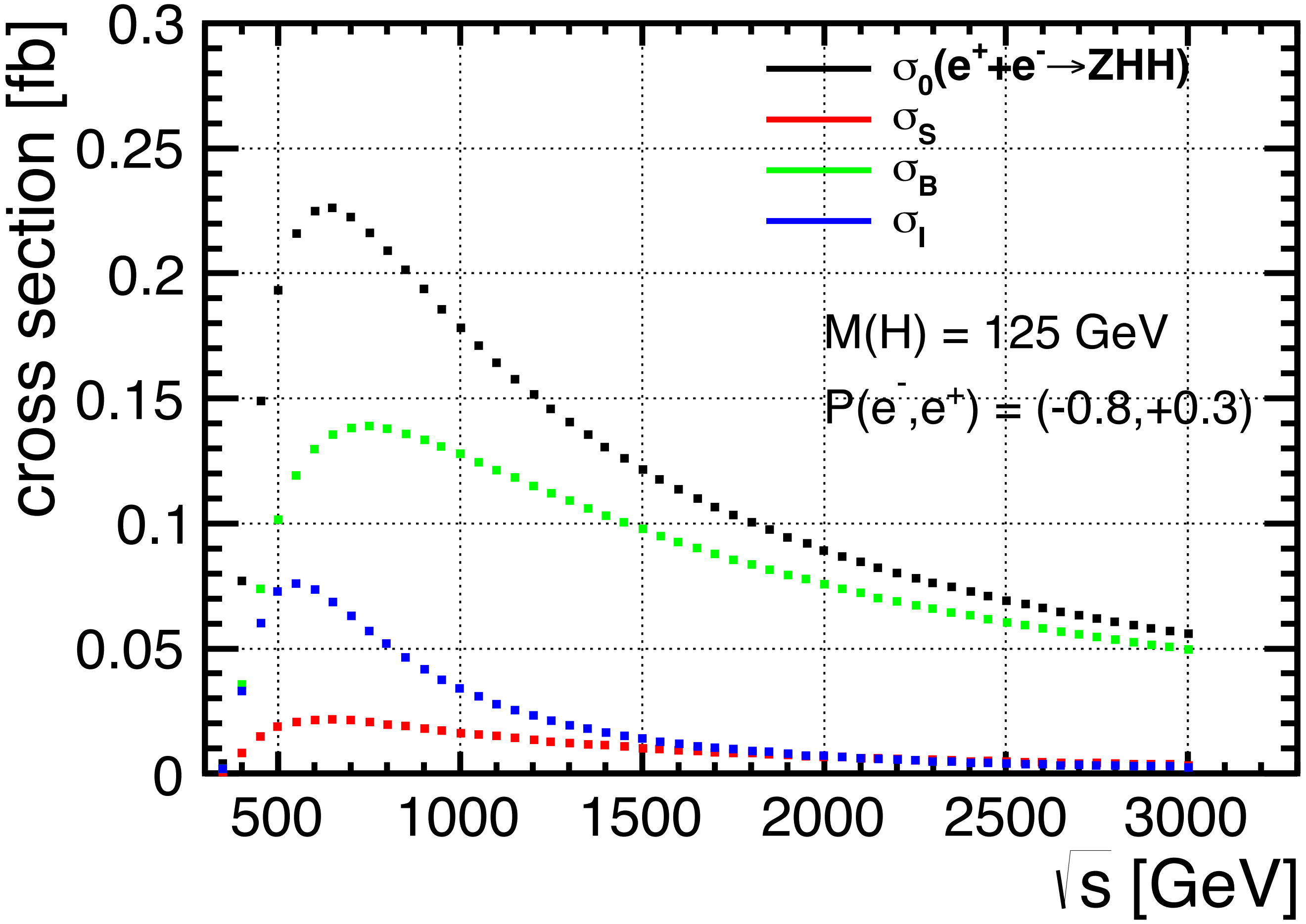
$$\sigma = \underset{\text{(signal diagram)}}{S\lambda^2} + \underset{\text{(interference)}}{I\lambda} + \underset{\text{(background diagram)}}{B}$$

- 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

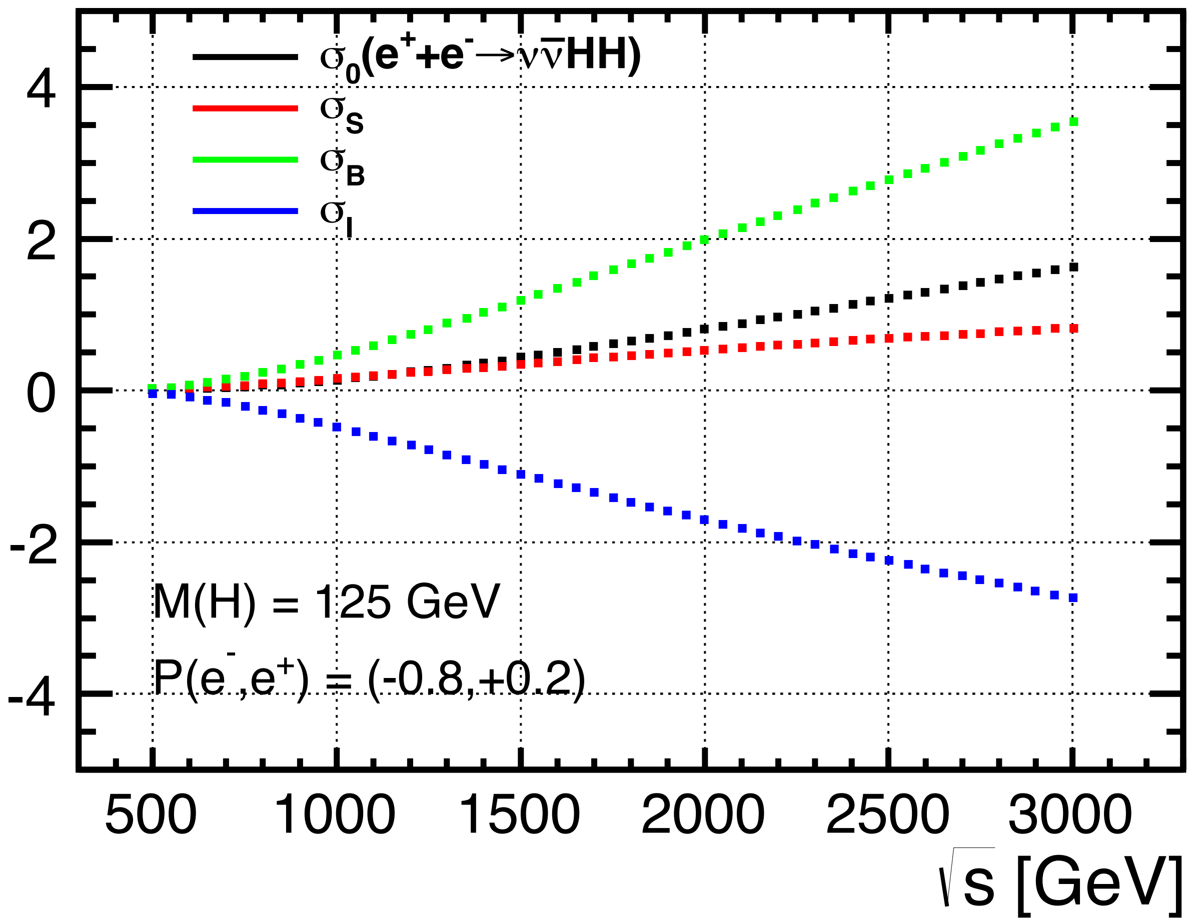
double Higgs x-section: breakdown for each diagram

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

ZHH



ννHH

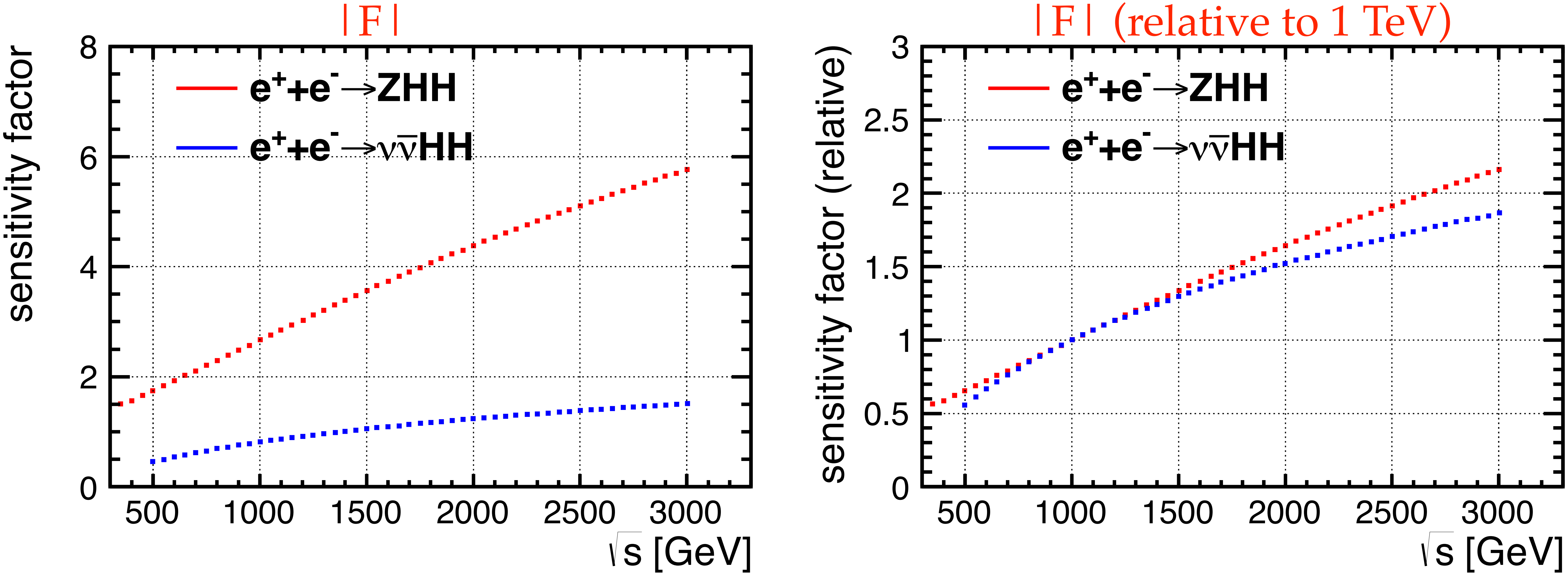


Higgs self-coupling: from σ to λ

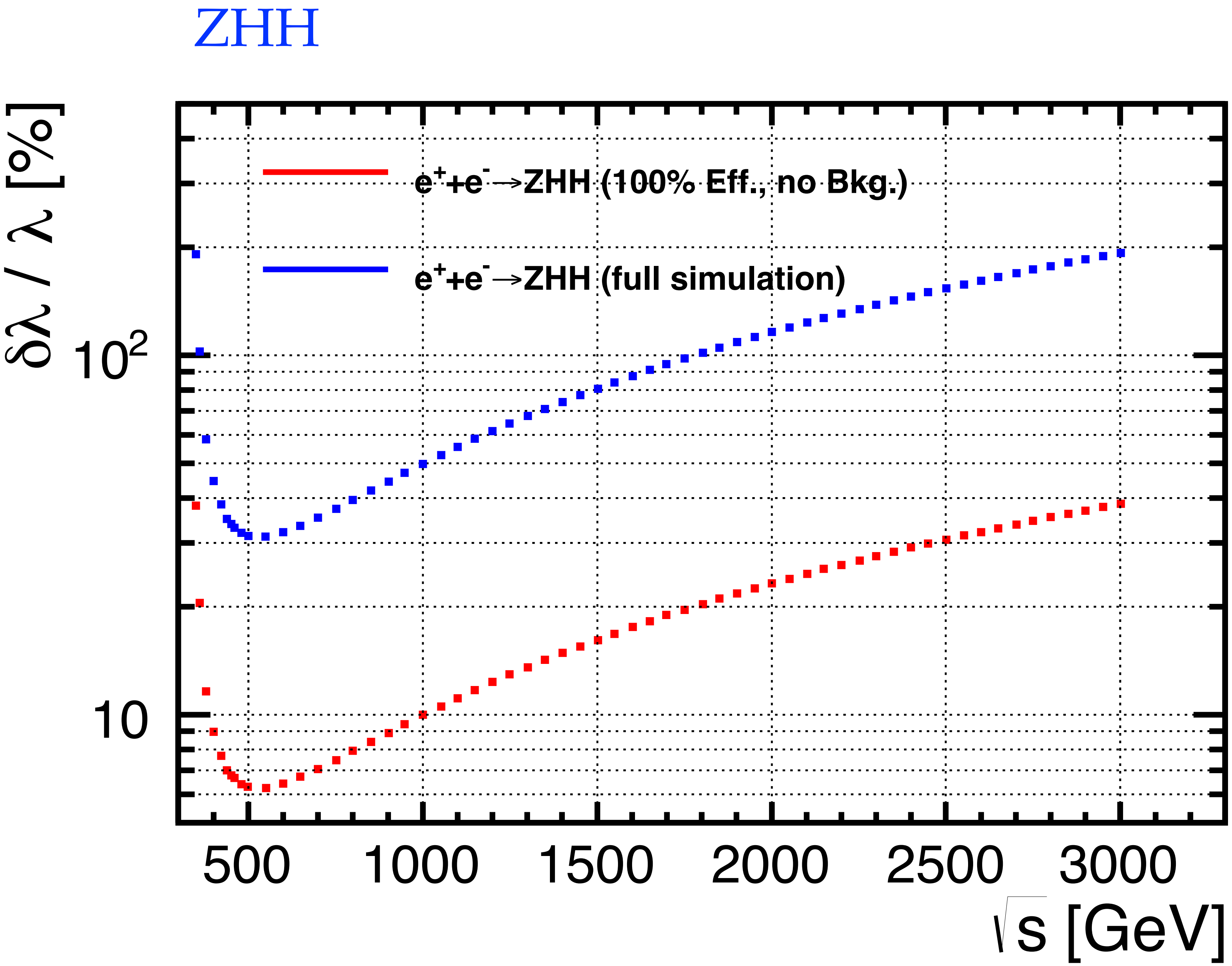
$$\frac{\delta\lambda}{\lambda} = F \cdot \frac{\delta\sigma}{\sigma}$$

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

sensitivity factor

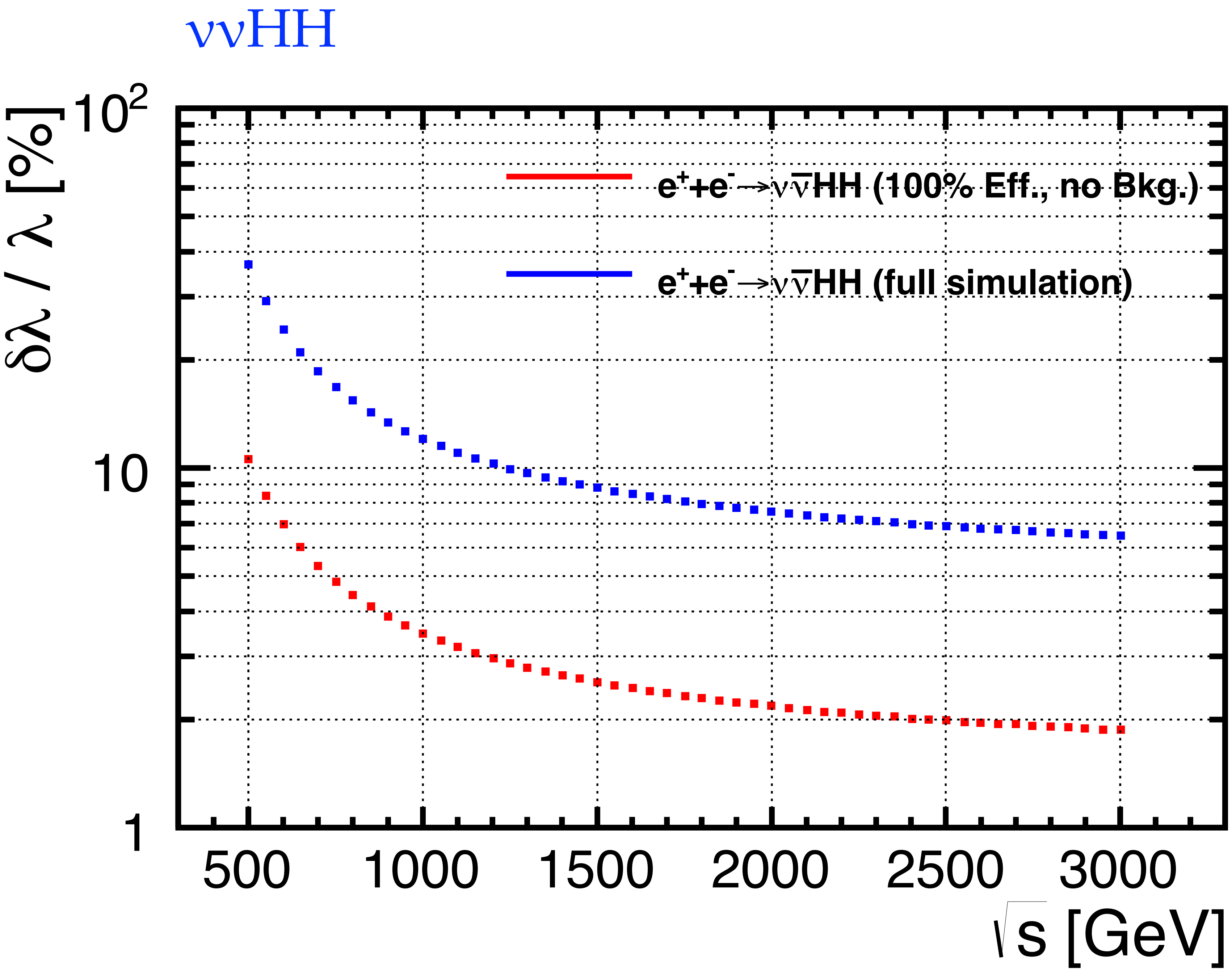


expected precision of λ: impact from analysis & √s



- **for ZHH**: **500 GeV** is optimal, **δλ/λ ~ 6% : 30%**, mild dependence between around **500-600** GeV, significantly worse at much lower or higher √s
- **huge room for improvement** (waiting for you to narrow down the gap)

expected precision of λ: impact from analysis & √s

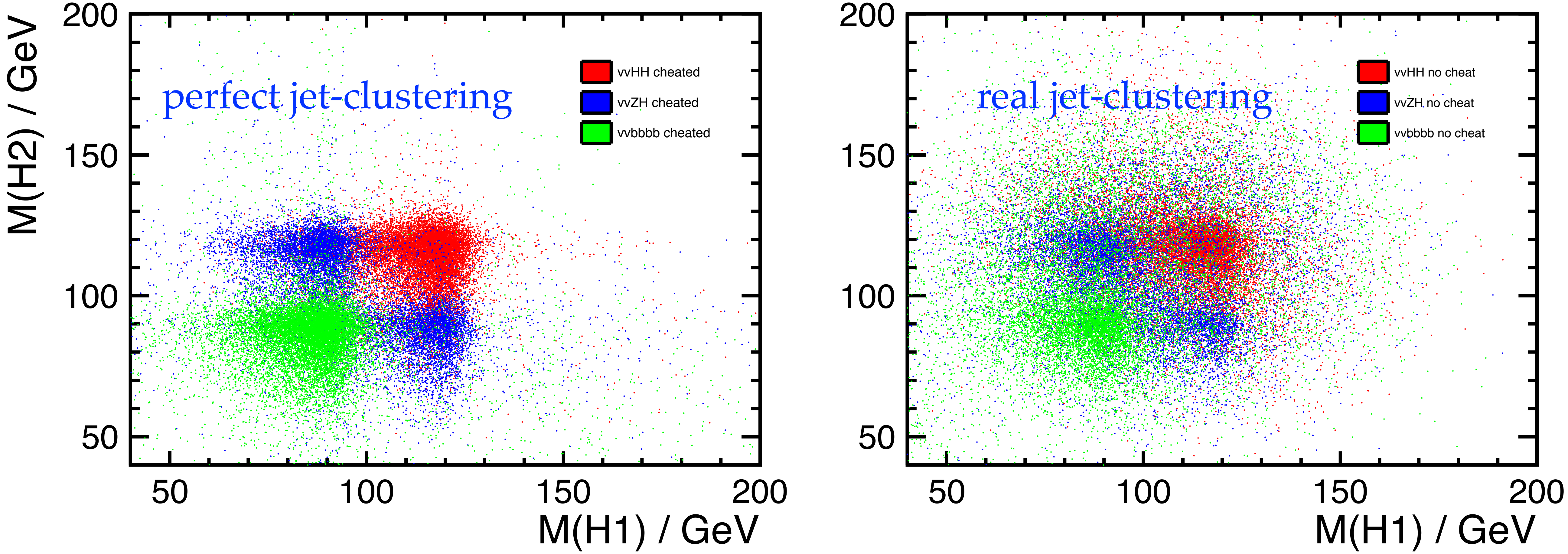


- **for ννHH**: significantly better going from 500 GeV to **1 TeV, δλ/λ~10%** achievable when √s >= 1TeV;
- better at higher √s, not drastically, from 1 TeV to 3 TeV, improved by 50%

one limiting factor: jet-clustering algorithm

ZHH->ννbbbb (BG: ZZH and ZZZ)

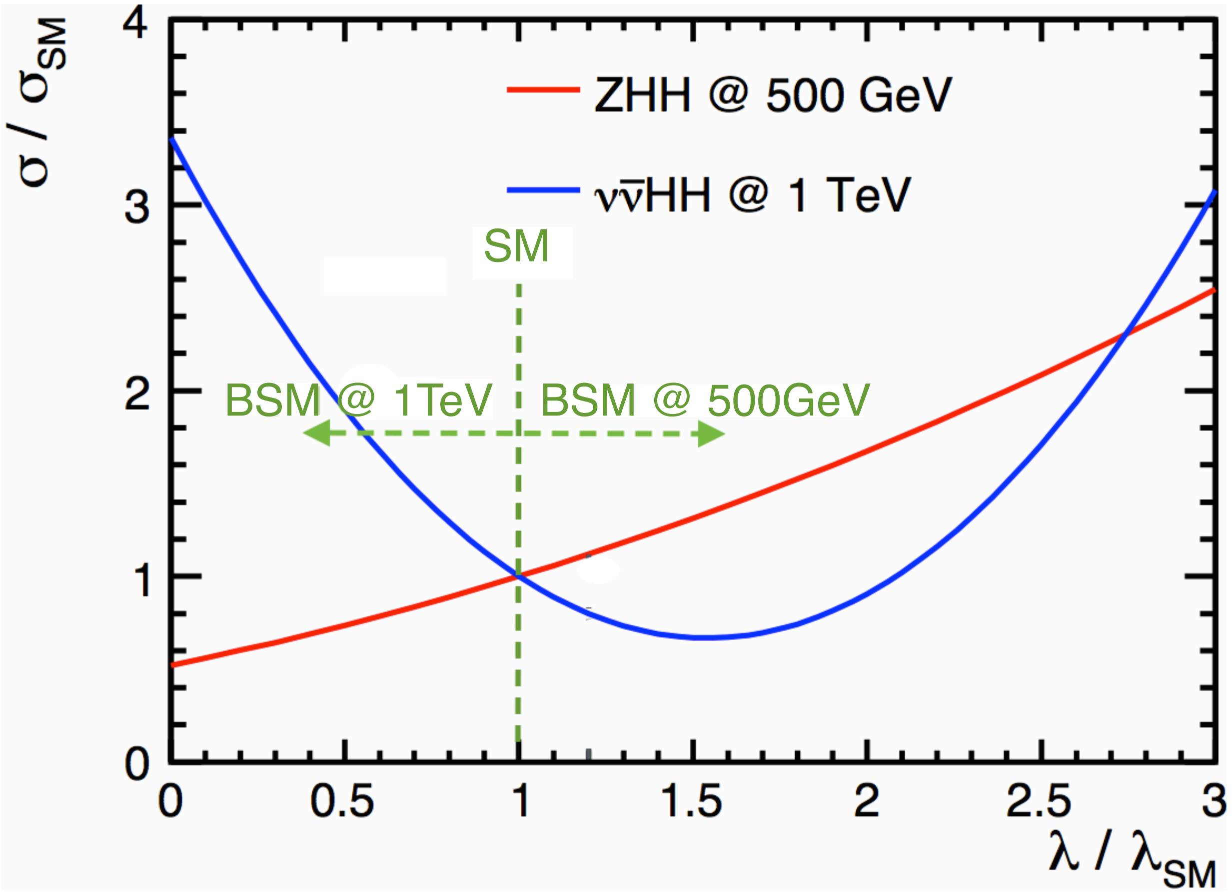
scatter plot of two Higgs masses

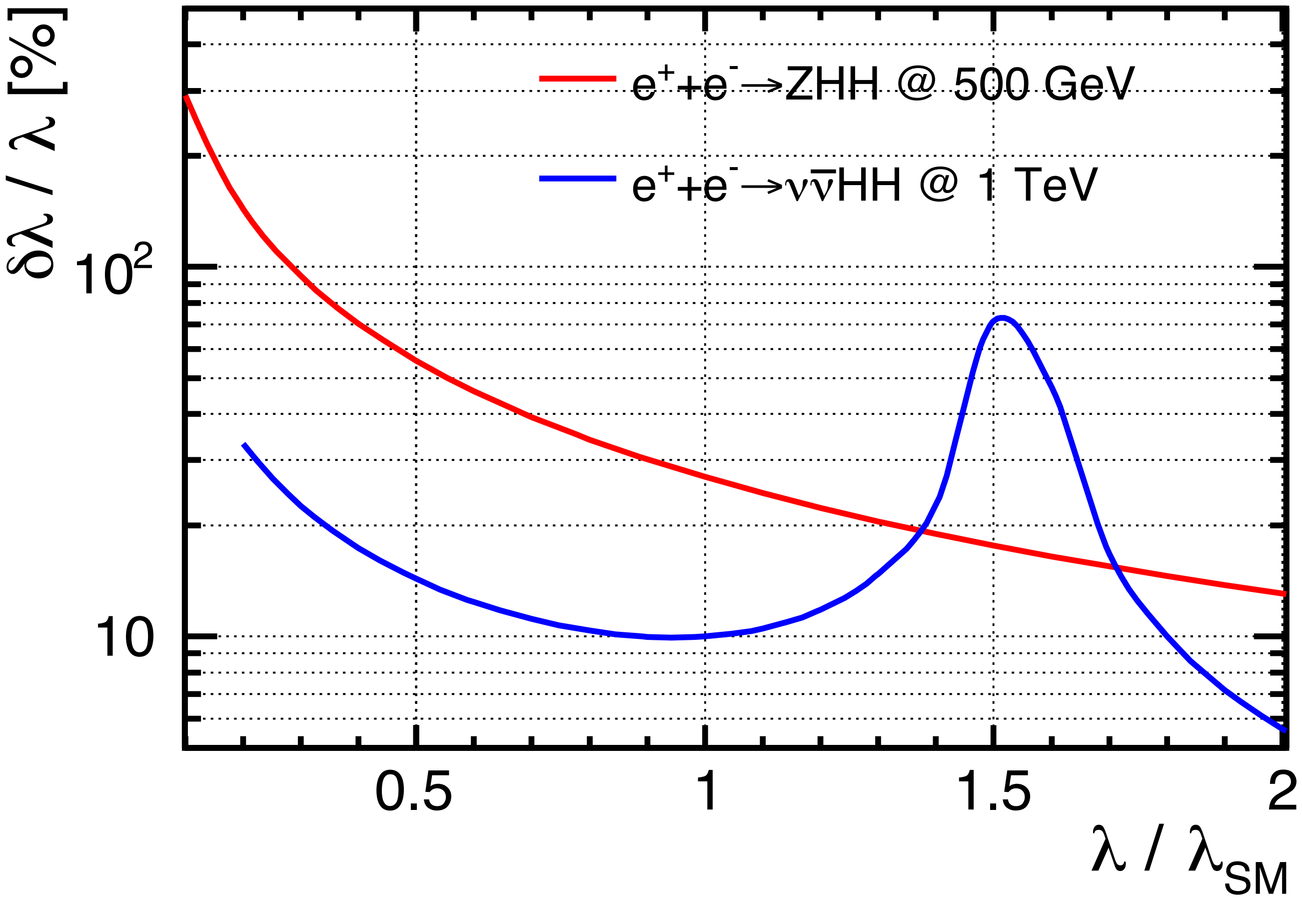


- the **mis-clustering** of particles degrades significantly the separation between signal and BG.
- it is studied that using perfect **color-singlet jet-clustering** can improve δλ/λ by **40%**!

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

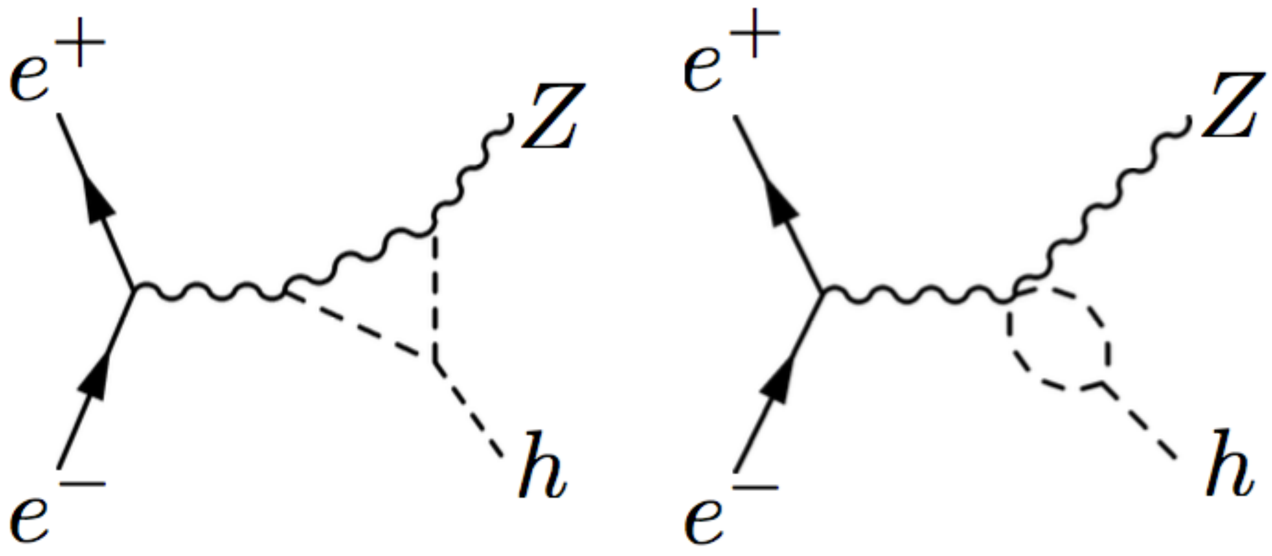
- **constructive** interference in **ZHH**, while **destructive** in **vvHH** (& LHC): **complementarity** between ILC & LHC, between √s ~500 GeV and >1TeV
- if $\boldsymbol{\lambda_{HHH} / \lambda_{SM} = 2}$, Higgs self-coupling can be measured to ~**15%** using ZHH at 500 GeV e+e-





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

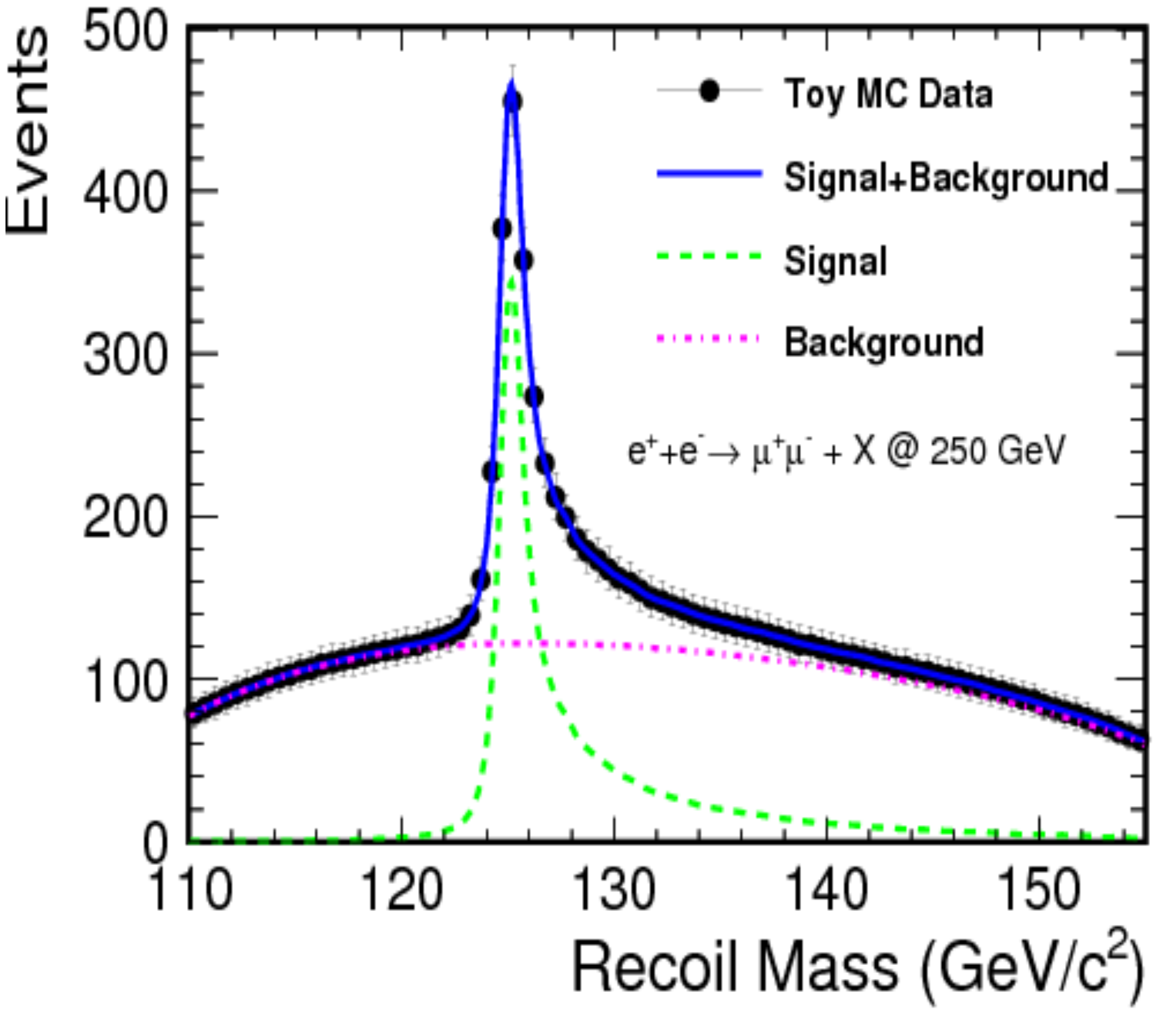


McCullough, arXiv:1312.3322

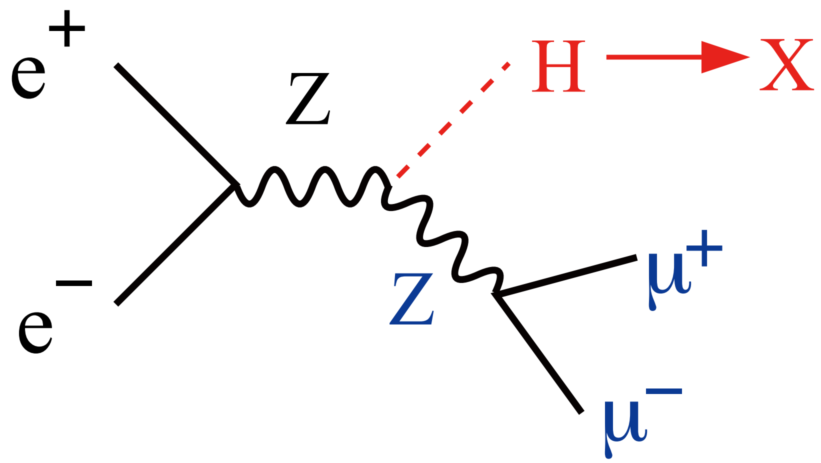
$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

- 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? (Lecture 2)
    - can we measure quartic Higgs self-coupling?

(ii-2) inclusive σ$_{ZH}$: unique key @ e+e-



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

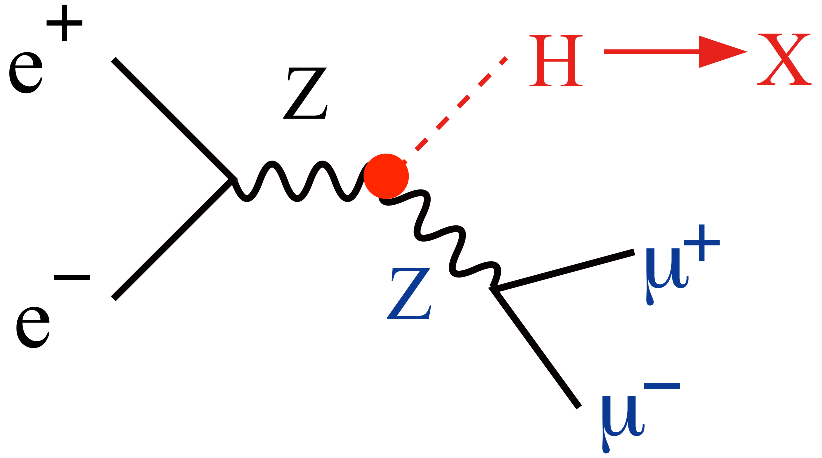


$$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-})\right)^2$$

- 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

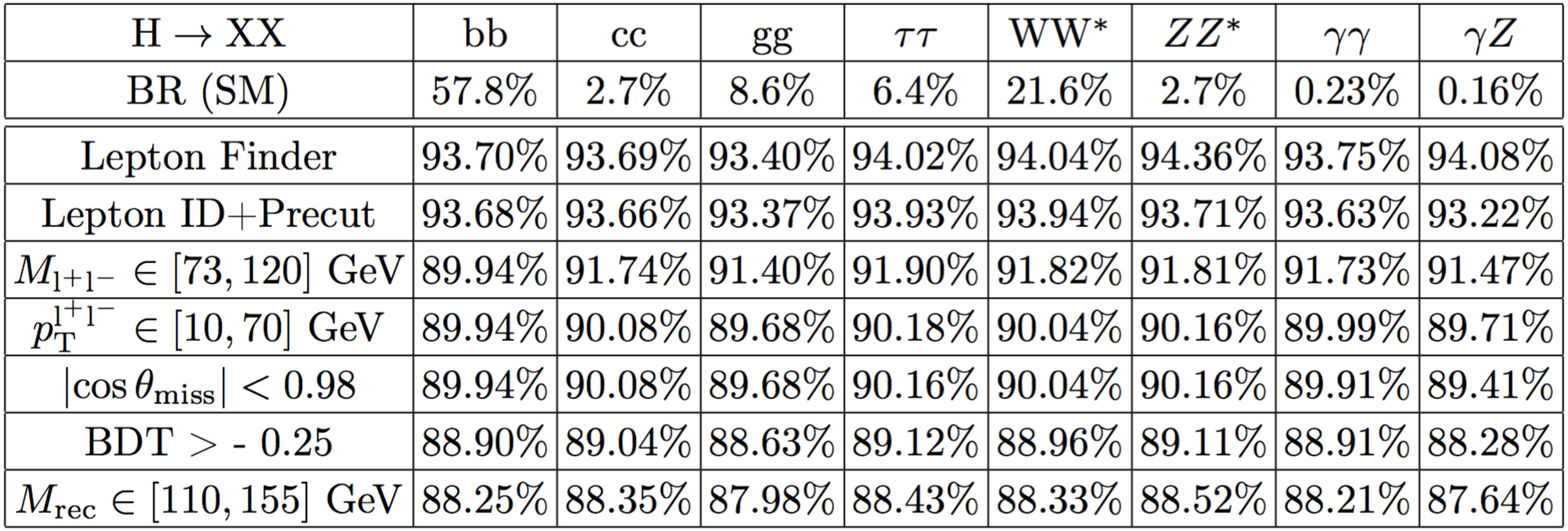
is it really possible?

independent of H decay modes?

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

- 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

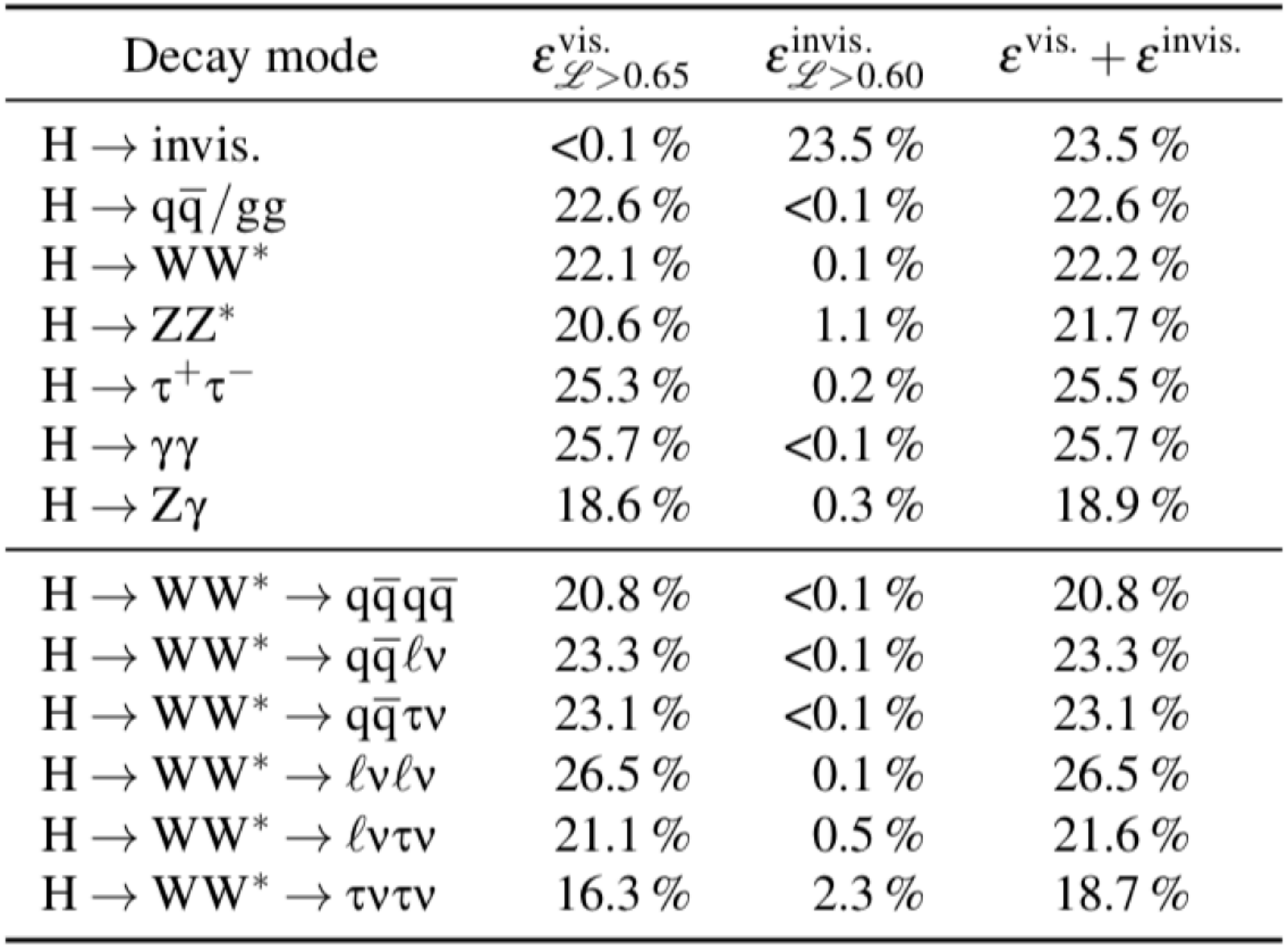
efficiencies breakdown (leptonic recoil)



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

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

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 σxB_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}

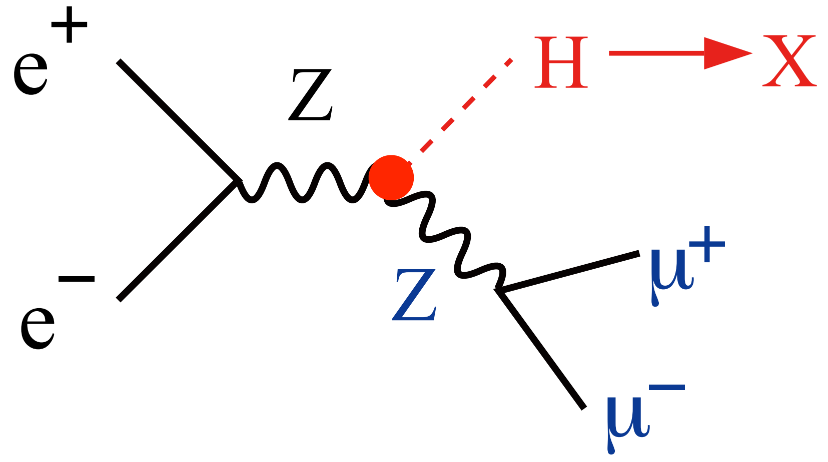
unknown modes

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

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

- 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

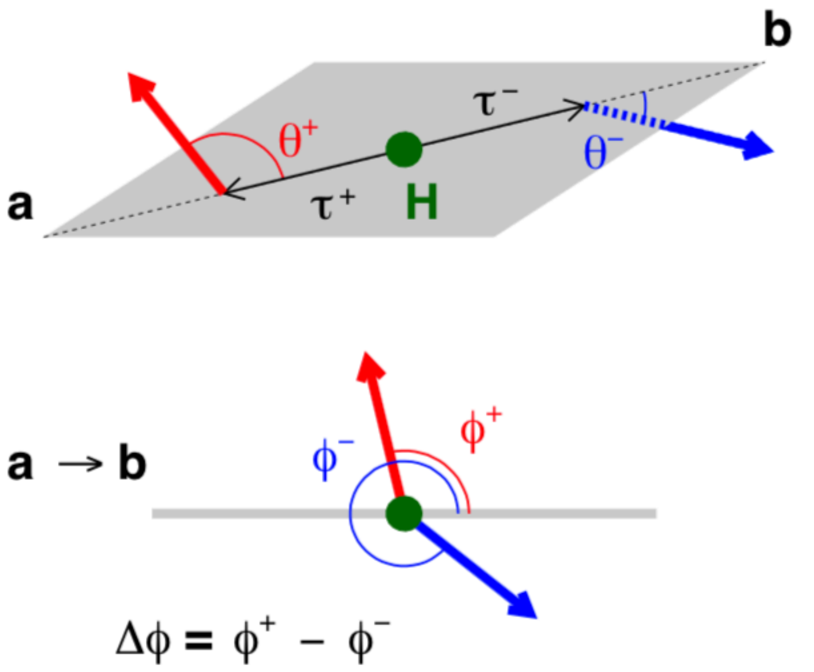
- hence, this question is equivalent to whether the selections cuts are democratic for all production angles of Z

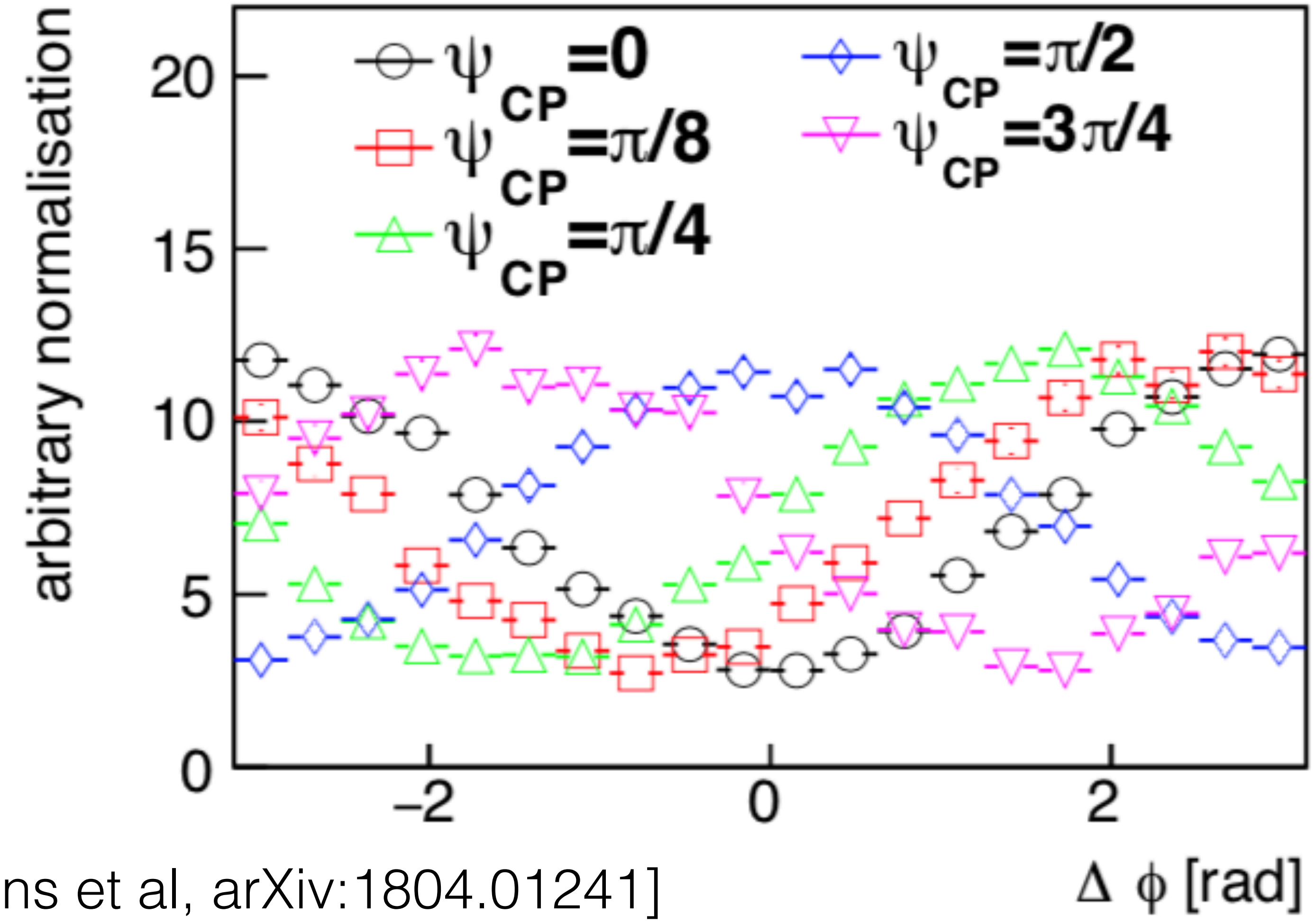
☐ **open question, this is not sufficiently studied yet**

(ii-3) Higgs CP in H—>$\tau^+\tau^-$

- CP is essential to understand structures of all Higgs couplings

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





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

[Jeans et al, arXiv:1804.01241]

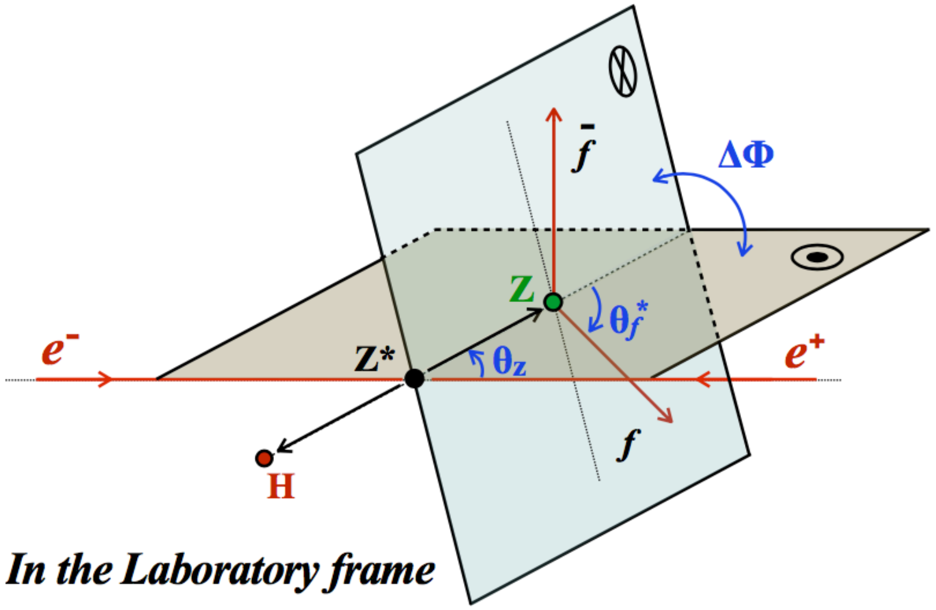
- ☐ **is it good enough for discovering EW Baryogengesis?**
- ☐ **large room to improve in experiment**

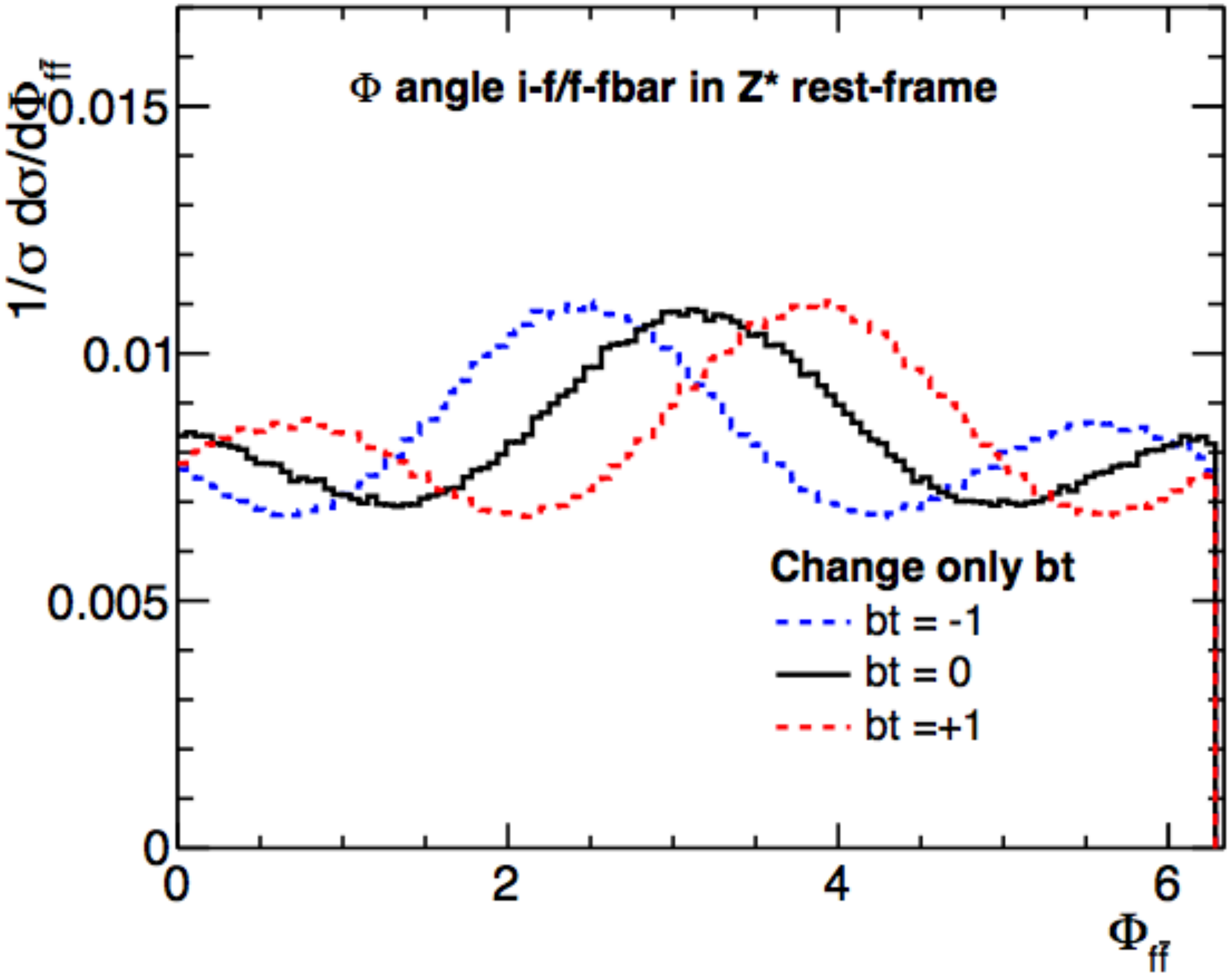
(ii-3) Higgs CP in HZZ coupling

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

(CP-odd)

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





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

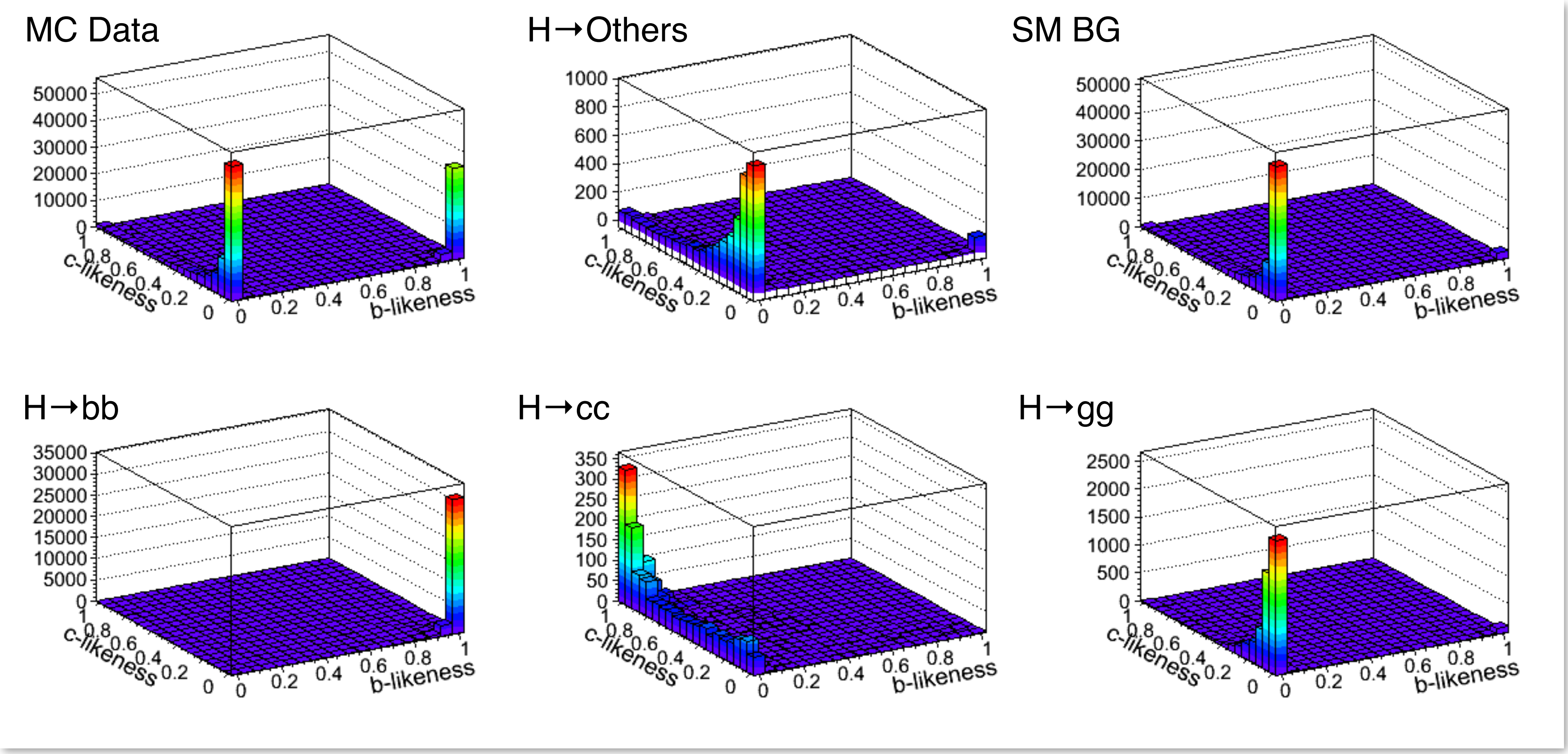
$\Delta\tilde{b} \sim 0.016$ (for Λ=1TeV)

[Ogawa et al, arXiv:1712.09772]

(ii-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)]

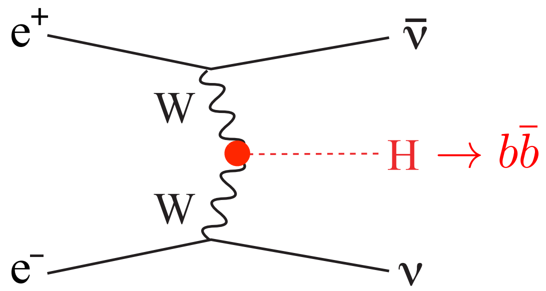
(ii-5) WW-fusion channel & Higgs total width Γ_H

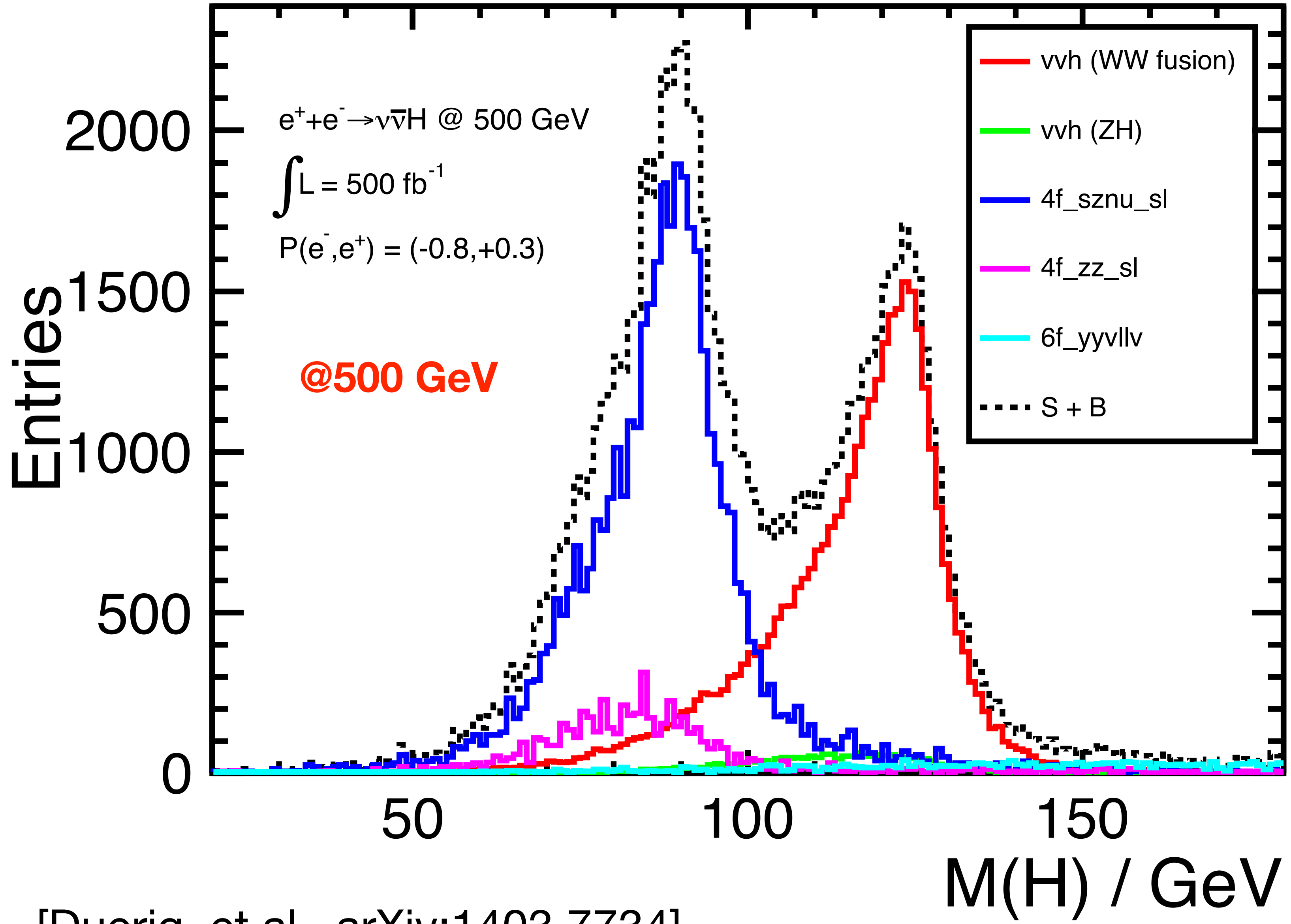
$$\Gamma_H = \frac{\Gamma_{HZZ}}{\mathrm{Br}(H \to ZZ^*)} \propto \frac{g^2_{HZZ}}{\mathrm{Br}(H \to ZZ^*)}$$

—>Br(H->ZZ*) very small

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

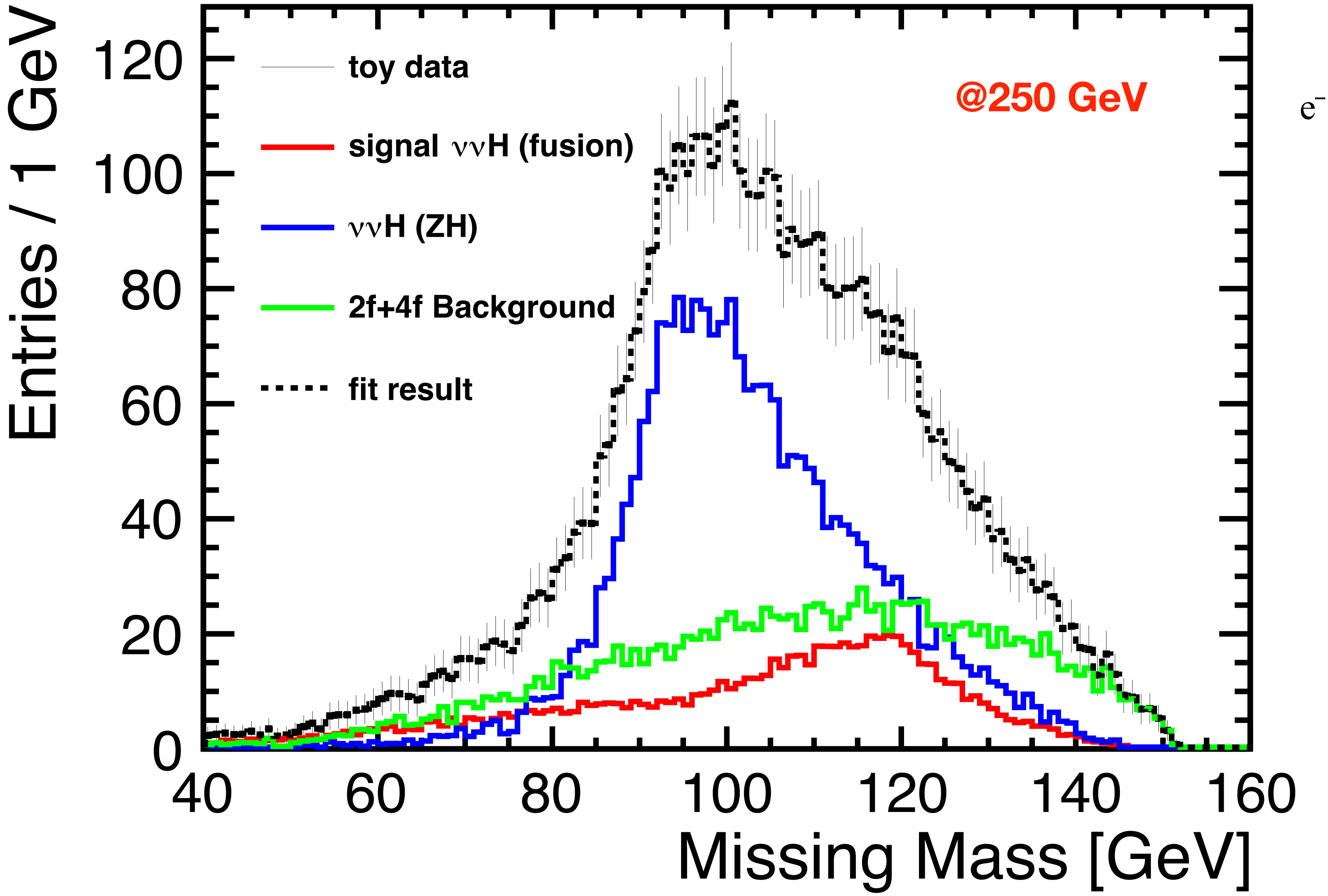
—> better option!

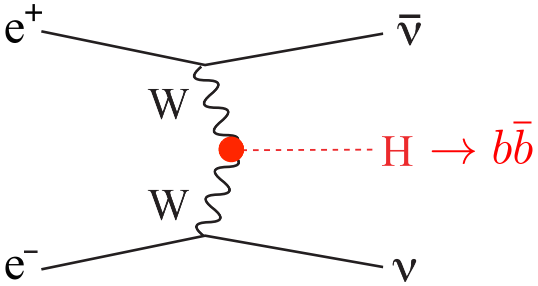




[Duerig, et al., arXiv:1403.7734]

very different at √s=250 GeV



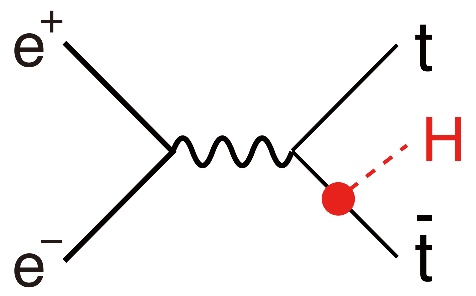


ρ = -34% correlation between

$\sigma_{\nu\nu H}$xBR(H—>bb) and σ_{ZH}xBR(H—>bb)

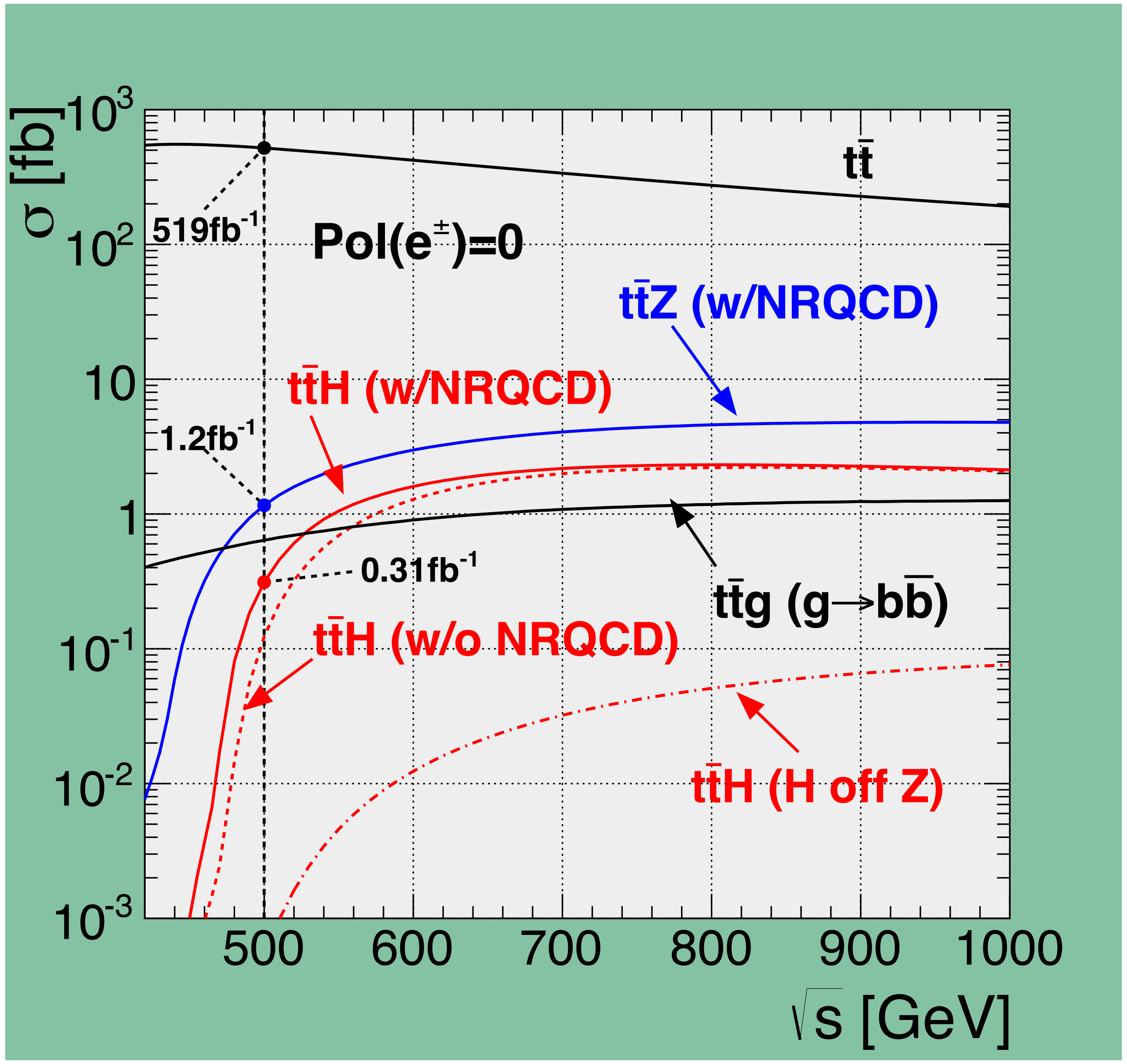
(ii-6) Top-Yukawa coupling

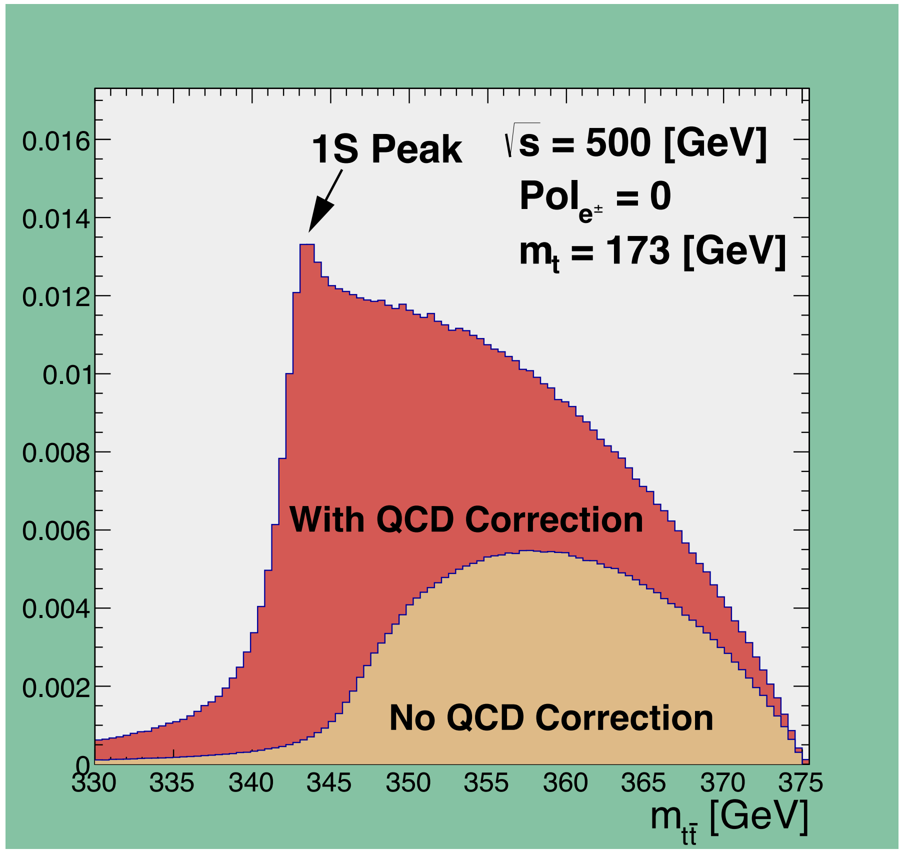
- largest Yukawa coupling; crucial role
- non-relativistic tt-bar bound state correction: enhancement by ~2 at 500 GeV
- Higgs CP measurement



H-> bb

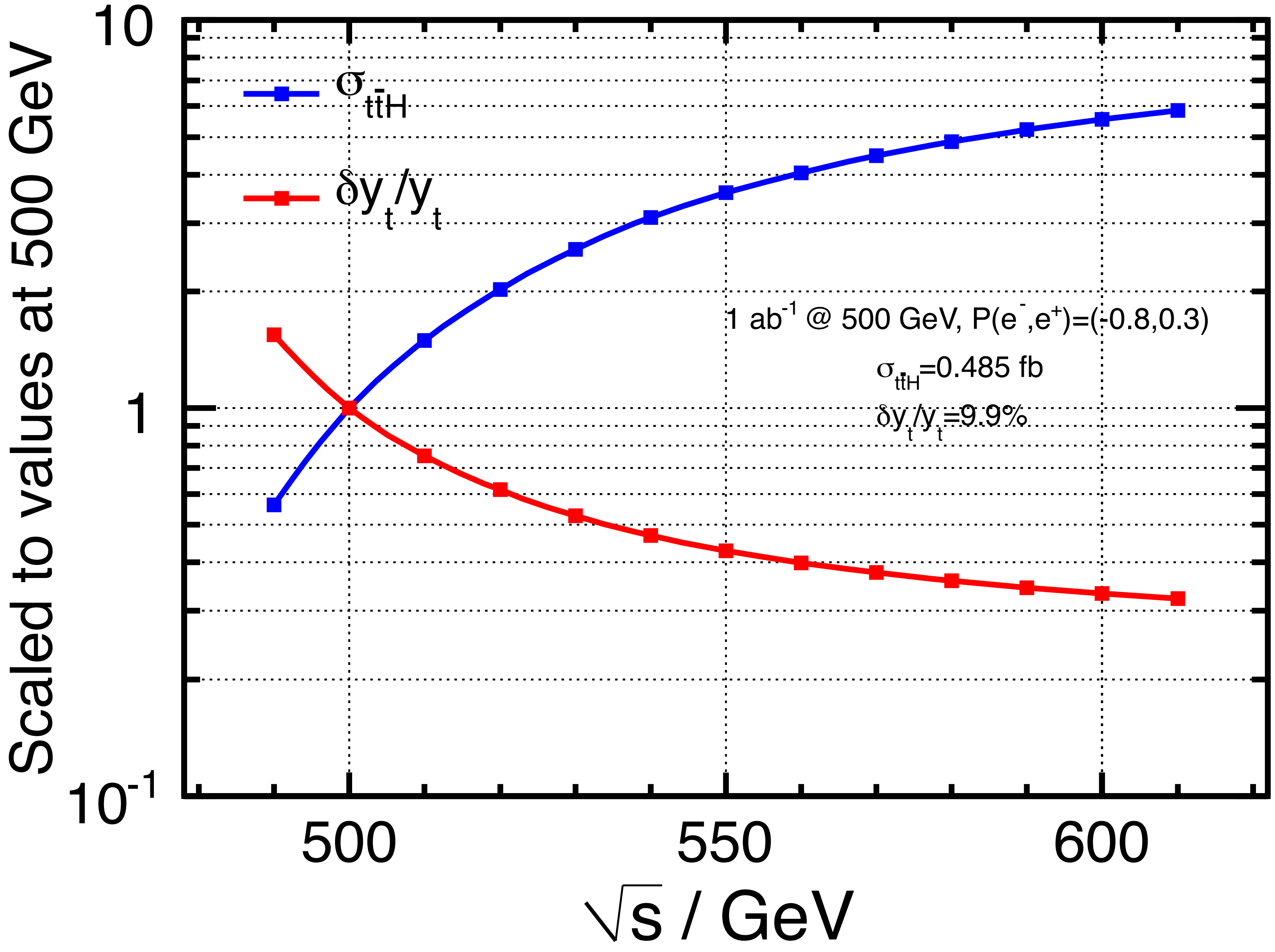
$\Delta g_{ttH}/g_{ttH}$	500 GeV	+ 1 TeV
ILC	6.3%	1.5%





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

Top-Yukawa coupling: impact of √s



[Y. Sudo]

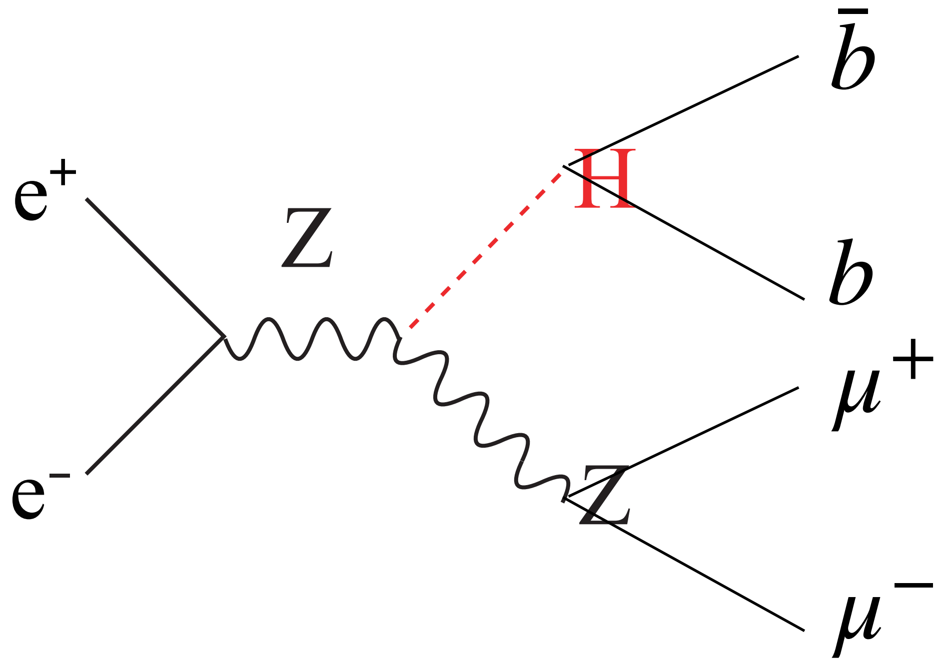
- increase √s slightly by 50GeV can improve δy_t by a factor of 2

(ii-7) how do we actually determine Higgs couplings?

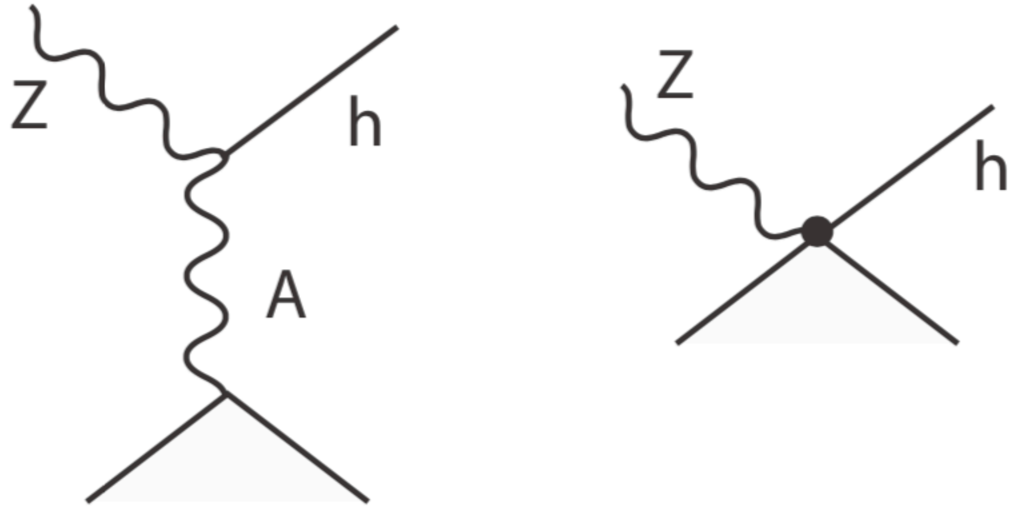
suppose we discover a deviation in, e.g. cross section of

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

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

Yi: measured values by experiments

Yi’: predicted values by underlying theory

ΔYi: measurement uncertainty

n: number of independent observables

- **kappa formalism**

$$Y_i' = F_i \cdot \frac{g^2_{HA_iA_i} \cdot g^2_{HB_iB_i}}{\Gamma_0} \qquad (A_i = Z, W, t)$$

$$(B_i = b, c, \tau, \mu, g, \gamma, Z, W : \text{decay})$$

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

- **effective field theory formalism (Lecture 2)**

From observables to couplings — Global Fit

in case there are correlated observables

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

Y_j: column vector of correlated observables

C_j: covariance matrix for those observables

Higgs coupling determination — kappa formalism

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

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

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

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

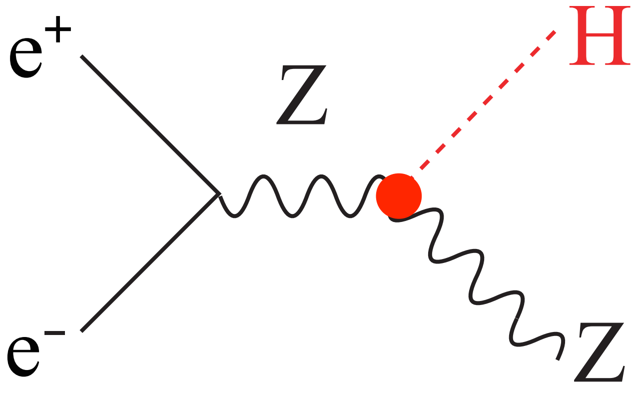
5) or $\boldsymbol{\Gamma_h}$ = Γ(h—>WW*)/BR(h->WW*)

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

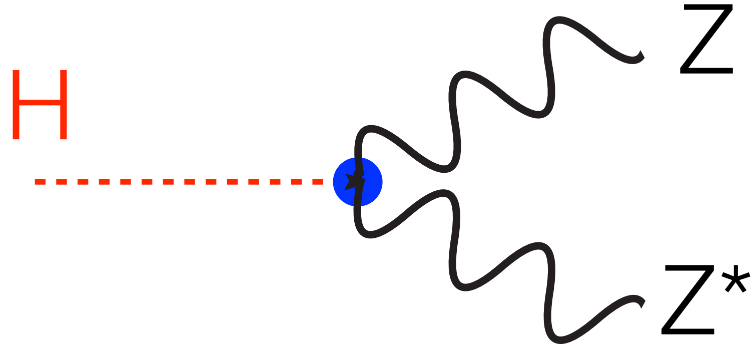
JT, et al, PoS EPS-HEP2013 (2013) 316 Nucl.Part.Phys.Proc. 273-275 (2016) 826-833

question in kappa formalism:

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



$$\propto \quad \kappa_Z^2\ ? \quad \propto$$



- BSM territory: can deviations be represented by single κ_Z?
- How to include radiative corrections in kappa formalism?

plan

(i) Mini-intro to future e+e- experiments

Lecture 1

(ii) Higgs Property Measurements

(iii) New Particle Searches

(iv) Top-quark & EW Measurements

Lecture 2

(v) Global Interpretation in SM EFT

---

focus will be on experimental concepts "why / what / how"
please learn theoretical concepts "why" from other lectures

supplementary reading for accelerator & detector concepts

(i) introduction to accelerators

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

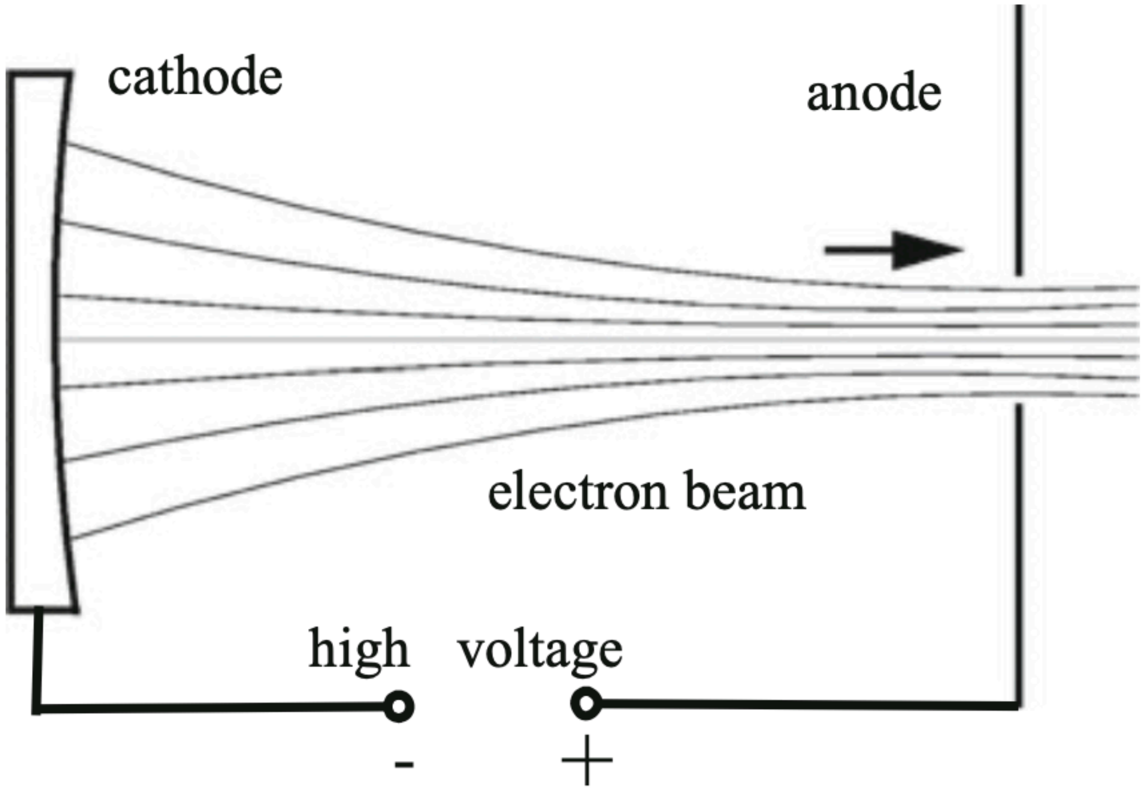
(i.1) basic principles for acceleration

(i.2) luminosity & a little beam dynamics

(i.3) beam polarizations

(i.4) ILC & its specifications

- **electrostatic accelerator**

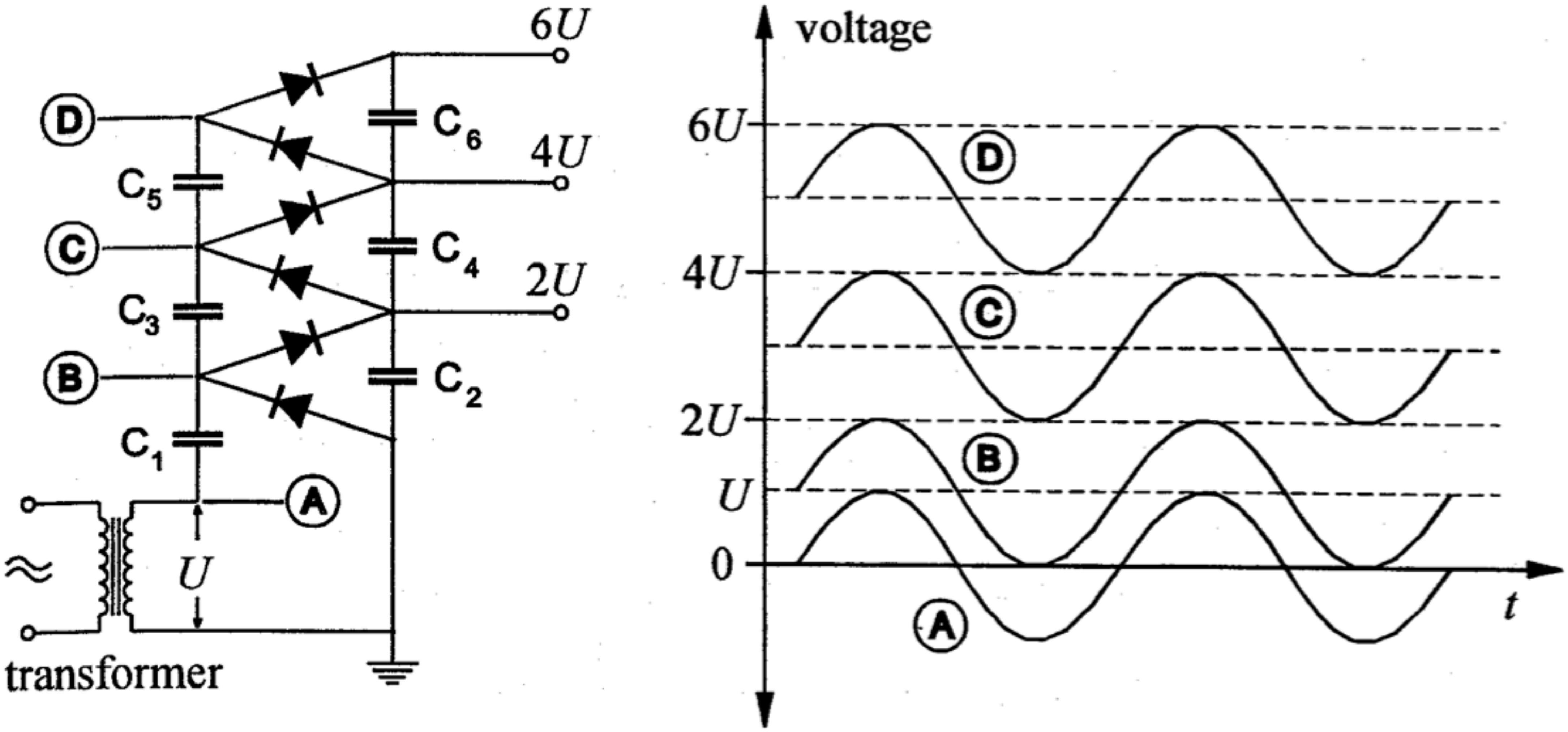


$$1\ \text{eV} = 1.6 \times 10^{-19}\ \text{J}$$

early development: mainly about generating high voltage

(i.1) basic principles of acceleration

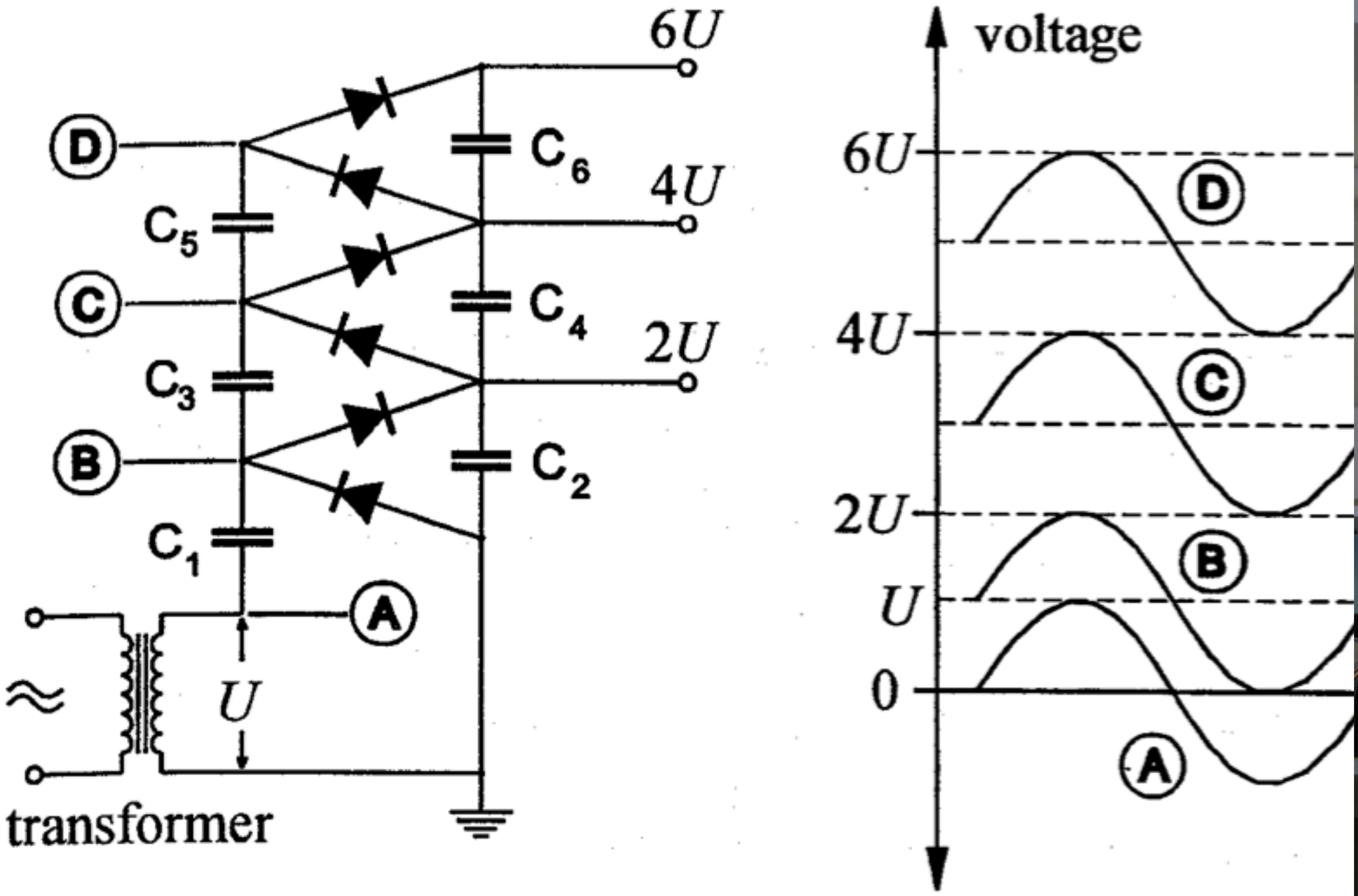
- Cockcroft-Walton cascade generator

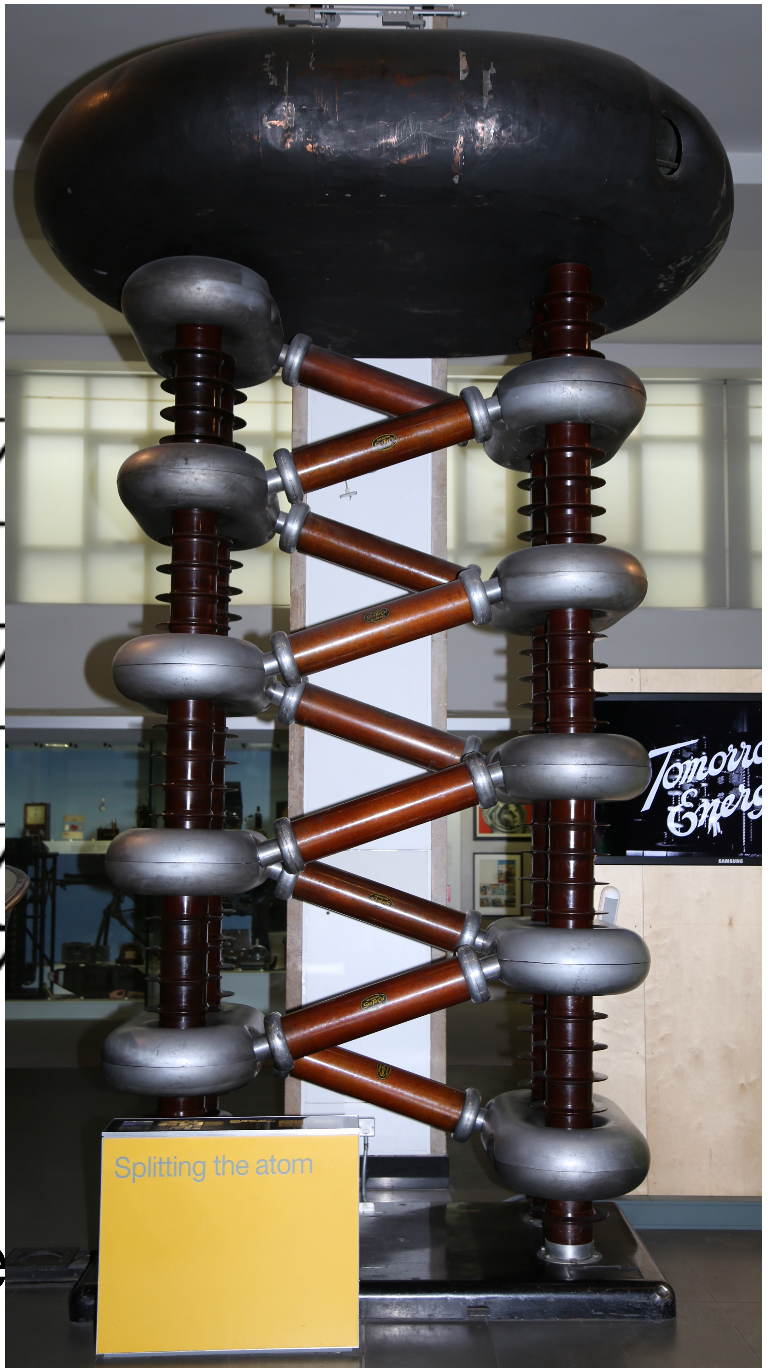


based on a system with multiple rectifiers
reached ~O(1) MV

(i.1) basic principles of acceleration

- Cockcroft-Walton cascade generator



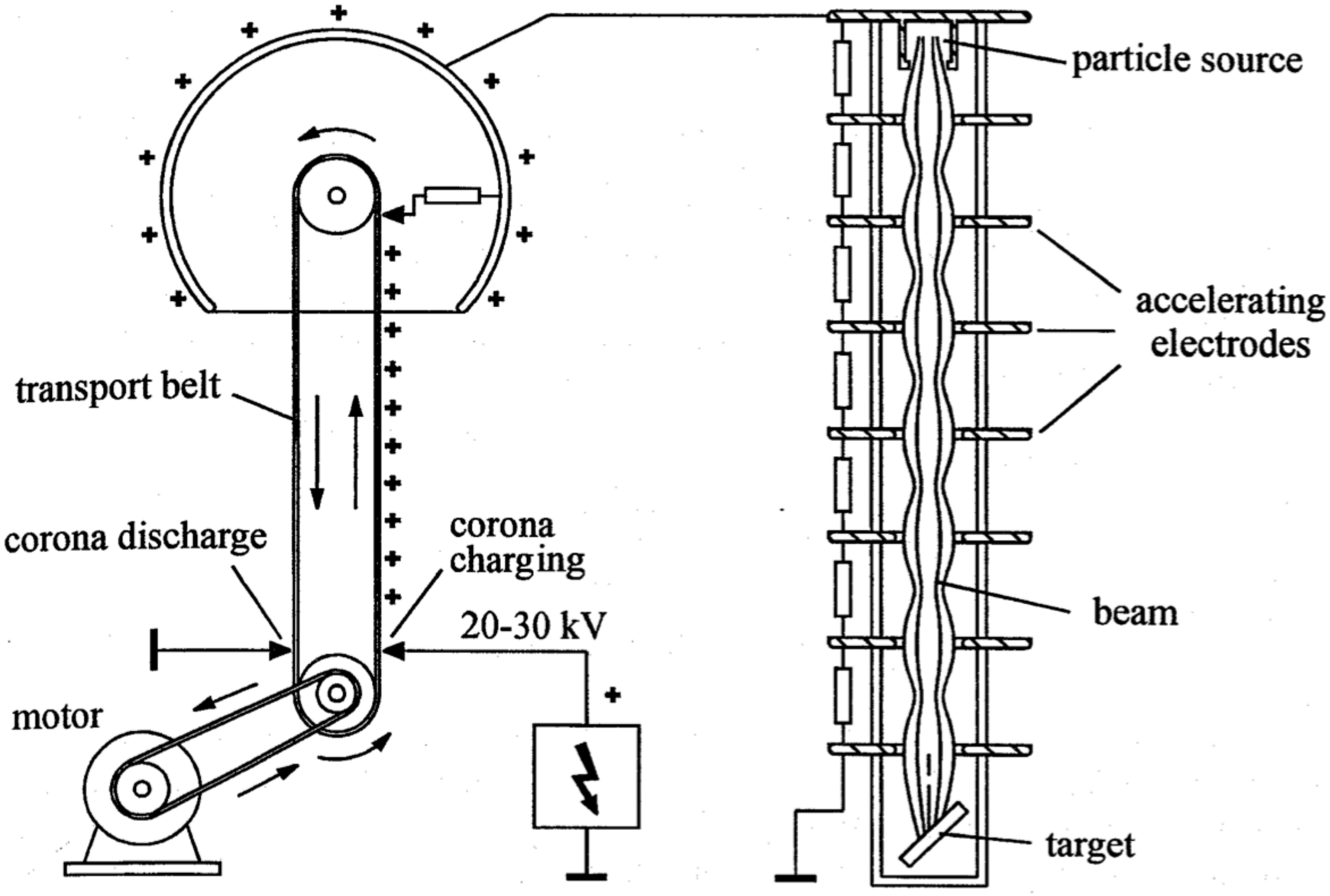


Nat'l Science Museum, London

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

(i.1) basic principles of acceleration

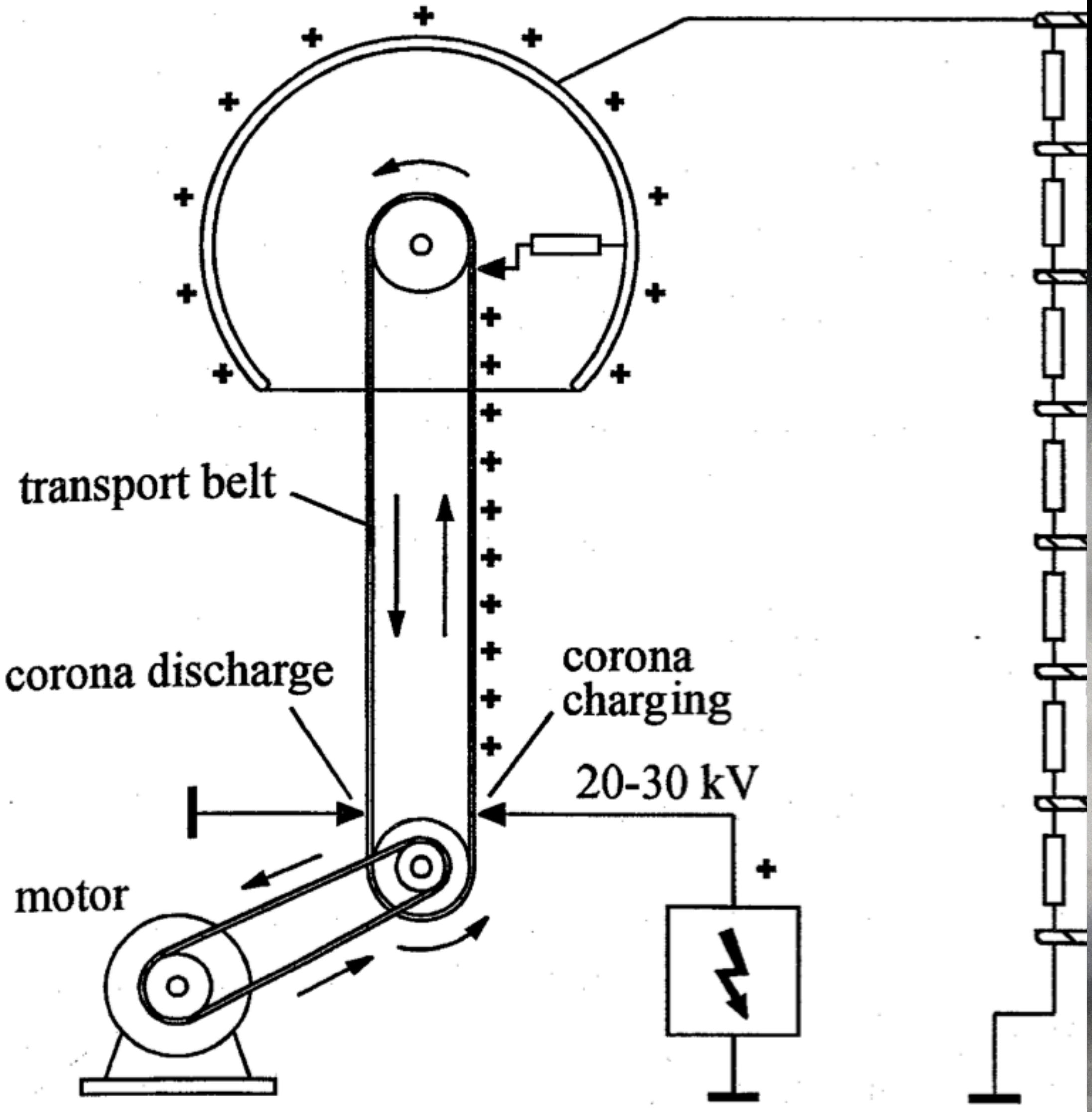
- Van de Graaff generator



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

(i.1) basic principles of acceleration

- Van de Graaff generator

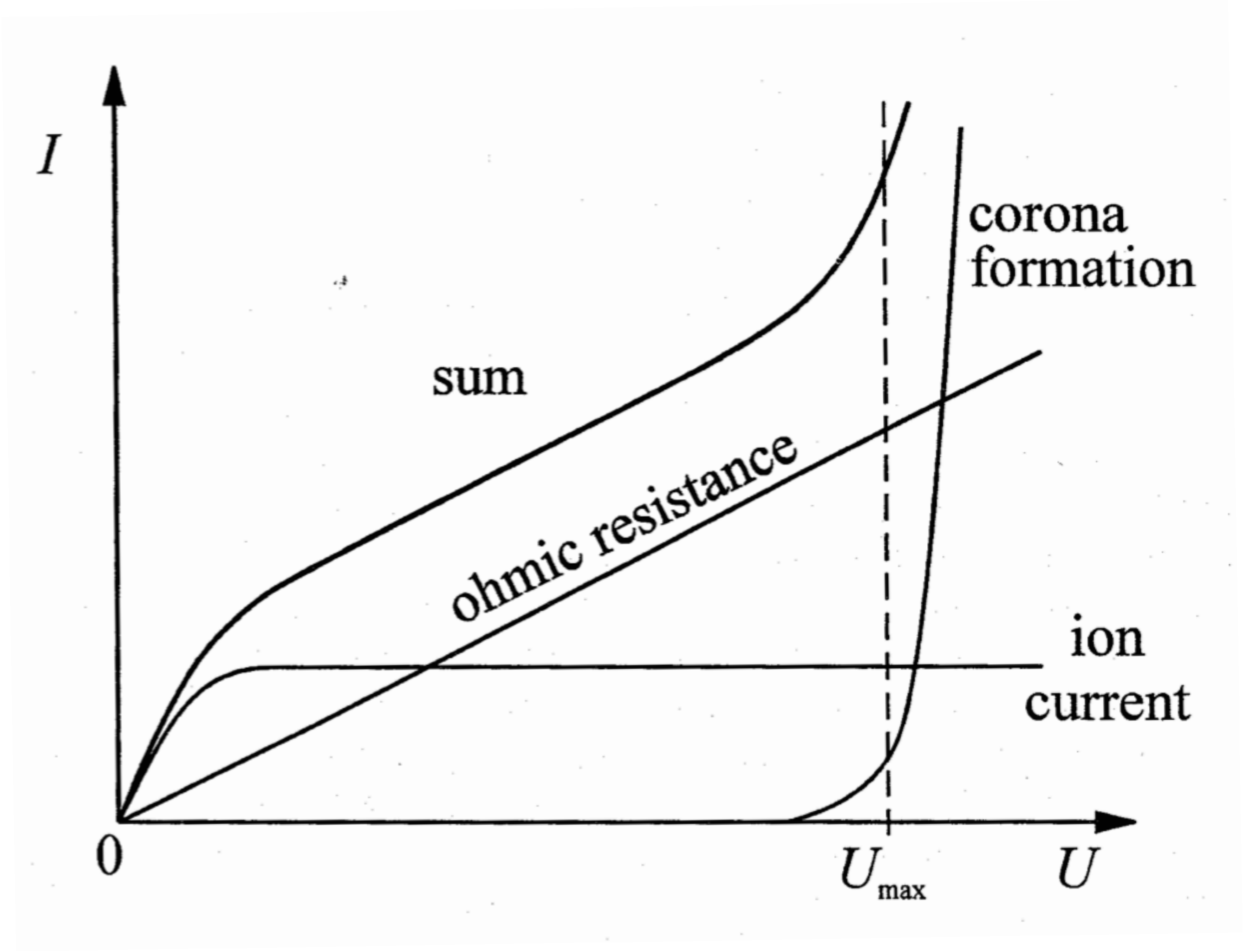


Westinghouse Atom Smasher (1937) 5MV

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

(i.1) basic principles of acceleration

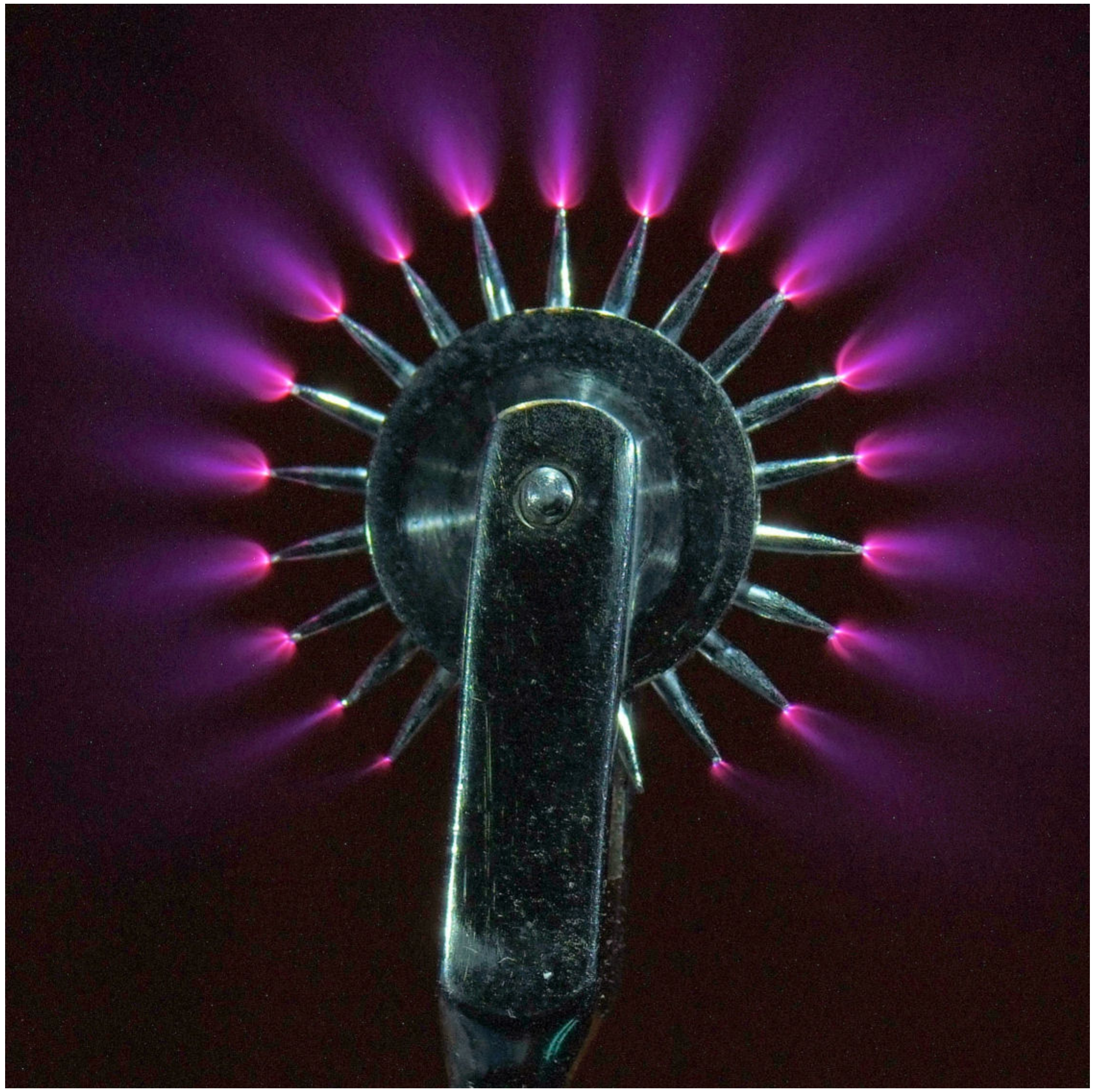
- high-voltage limitation



corona discharge: ionization avalanche near electrode

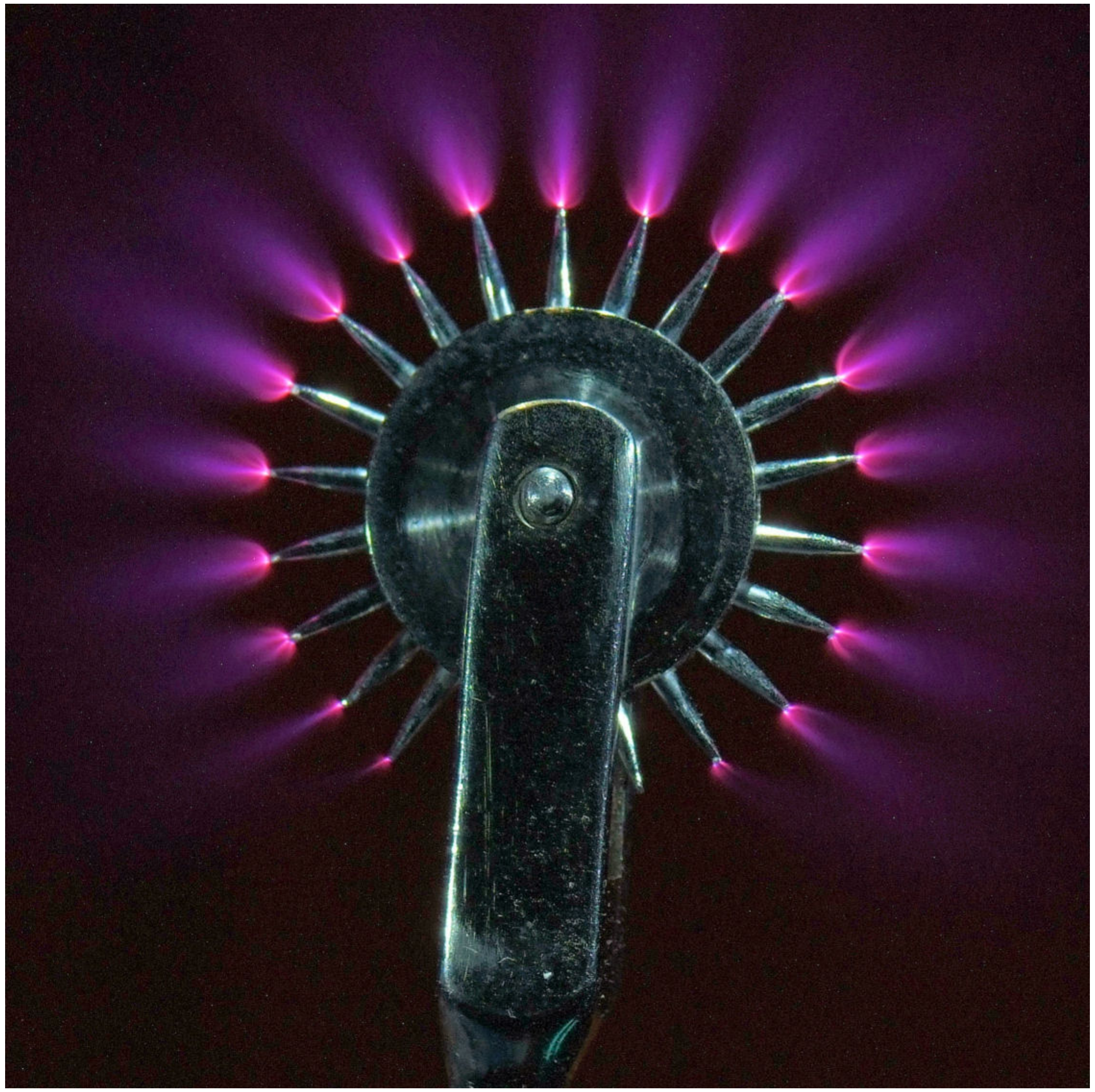
(i.1) basic principles of acceleration

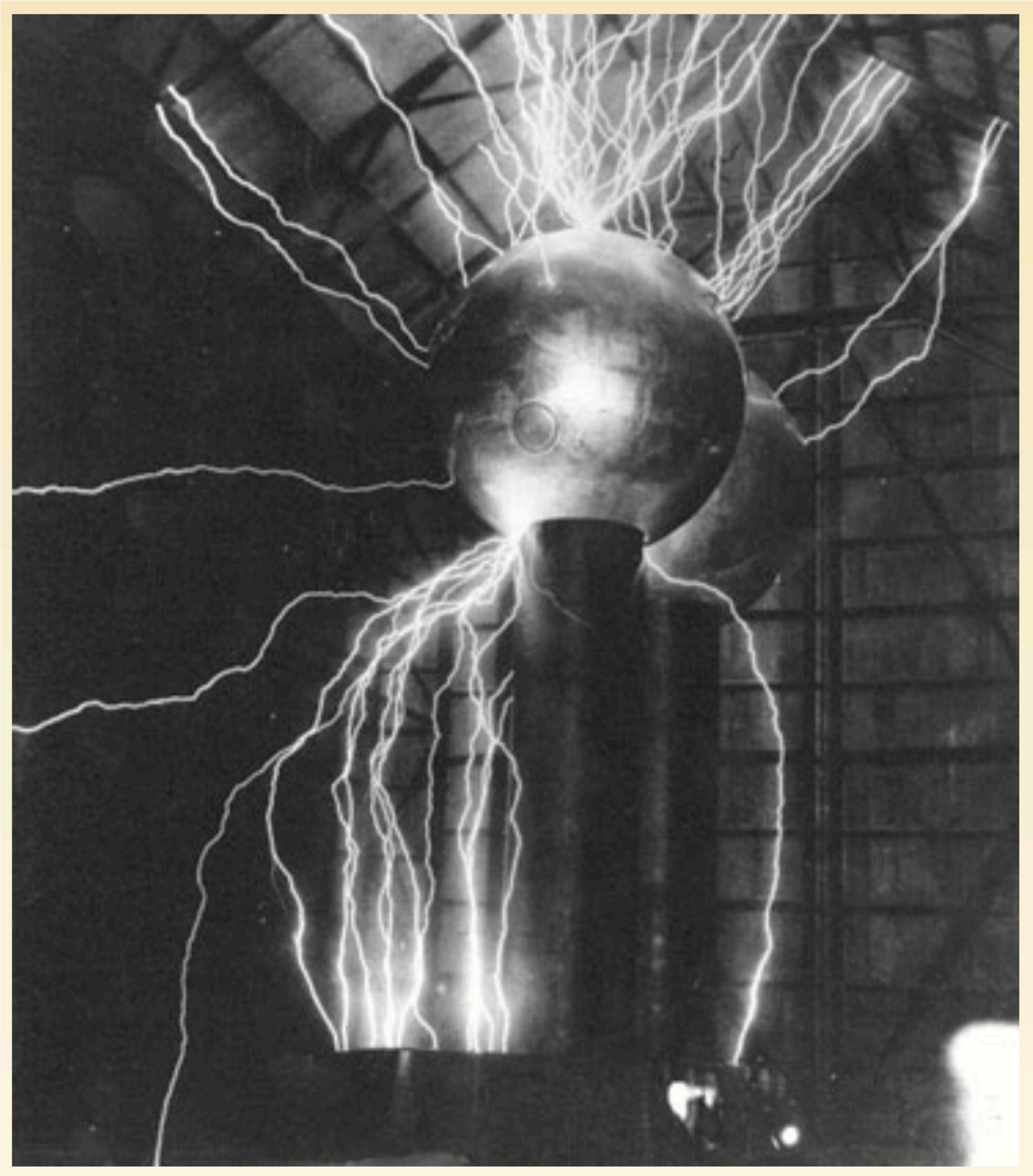
- high-voltage limitation



(i.1) basic principles of acceleration

- high-voltage limitation



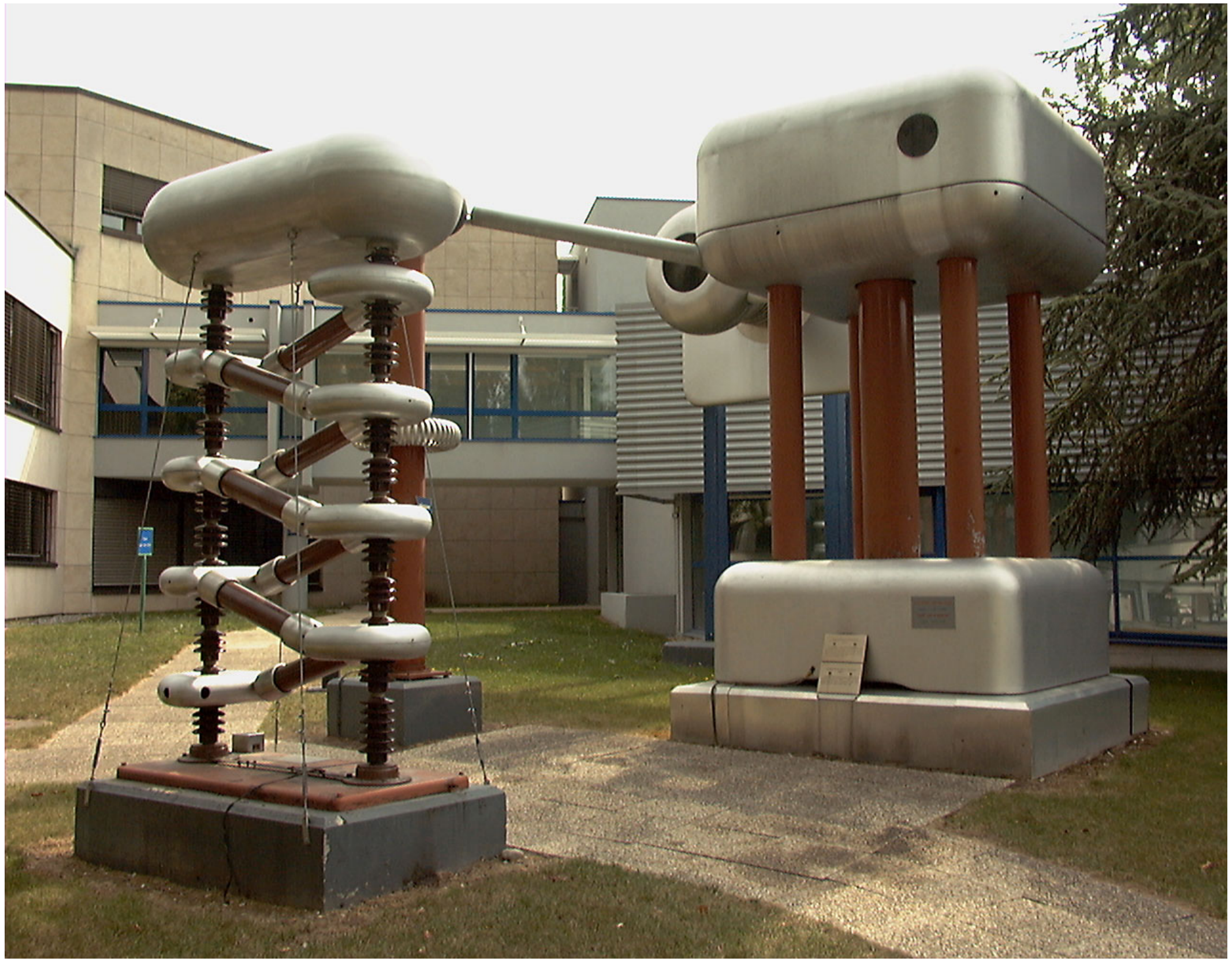


(i.1) basic principles of acceleration

- **electrostatic accelerator**

played crucial role for the nuclear physics

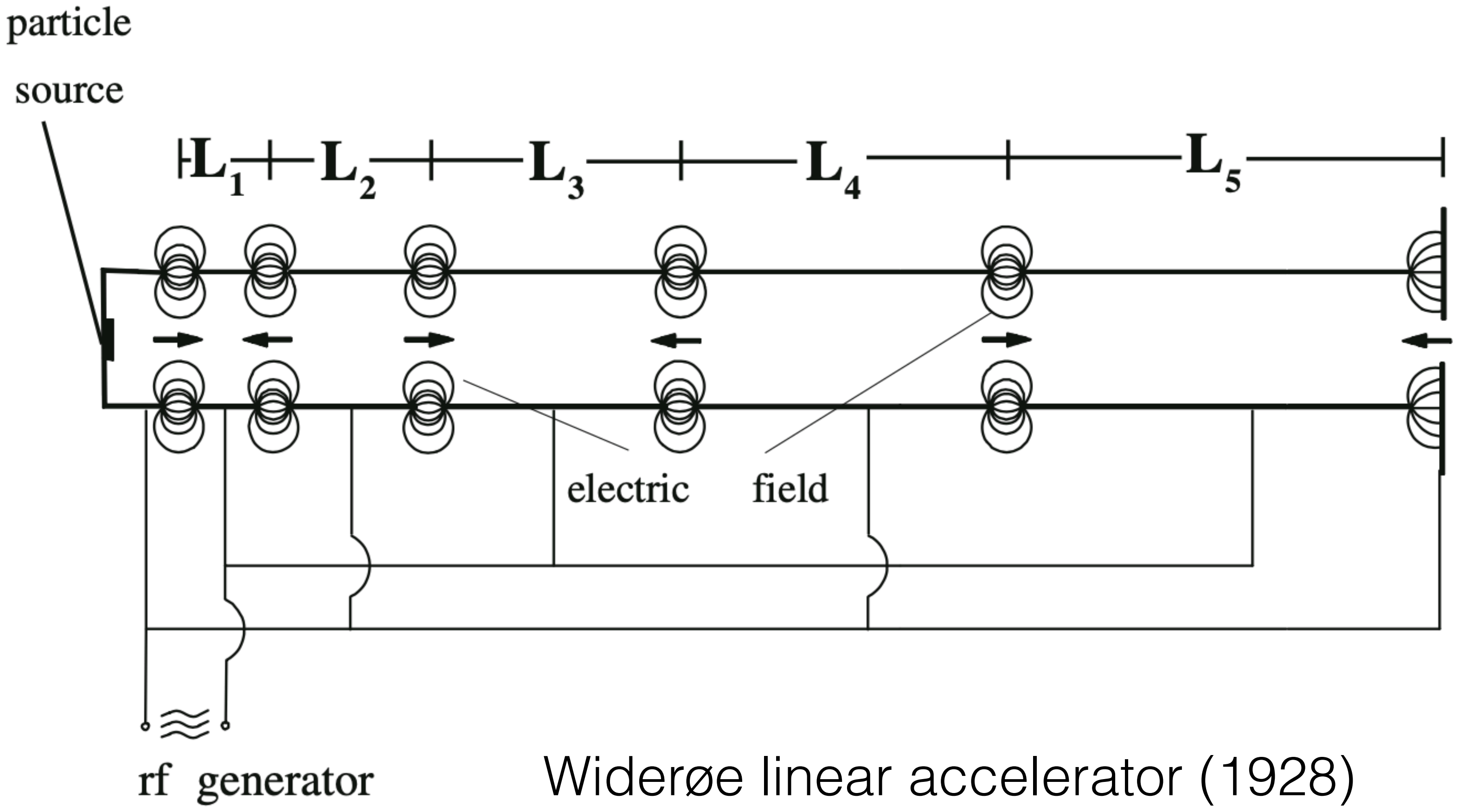
still used nowadays as pre-injector



@ CERN Exhibition

(i.1) basic principles of acceleration

- **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

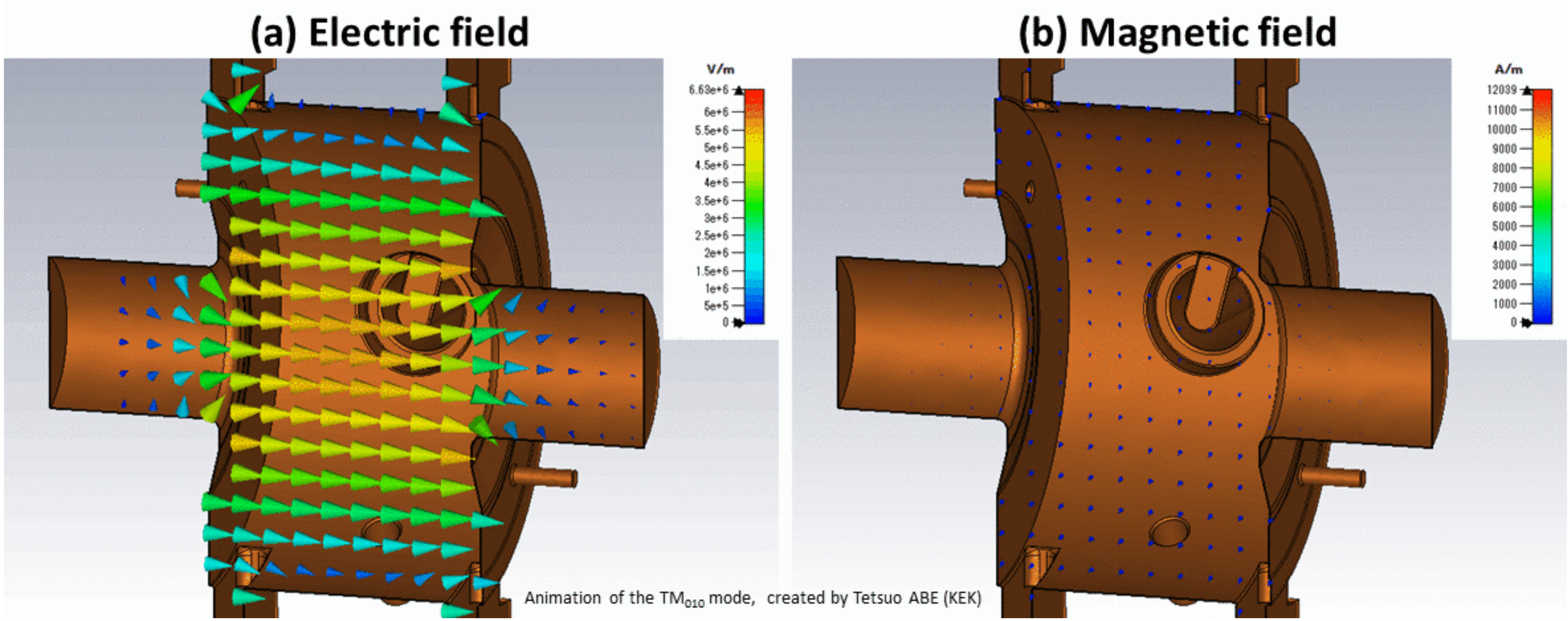
- RF cavity

  a metal resonator that can store electromagnetic fields

(i.1) basic principles of acceleration

- RF cavity

  a metal resonator that can store electromagnetic fields

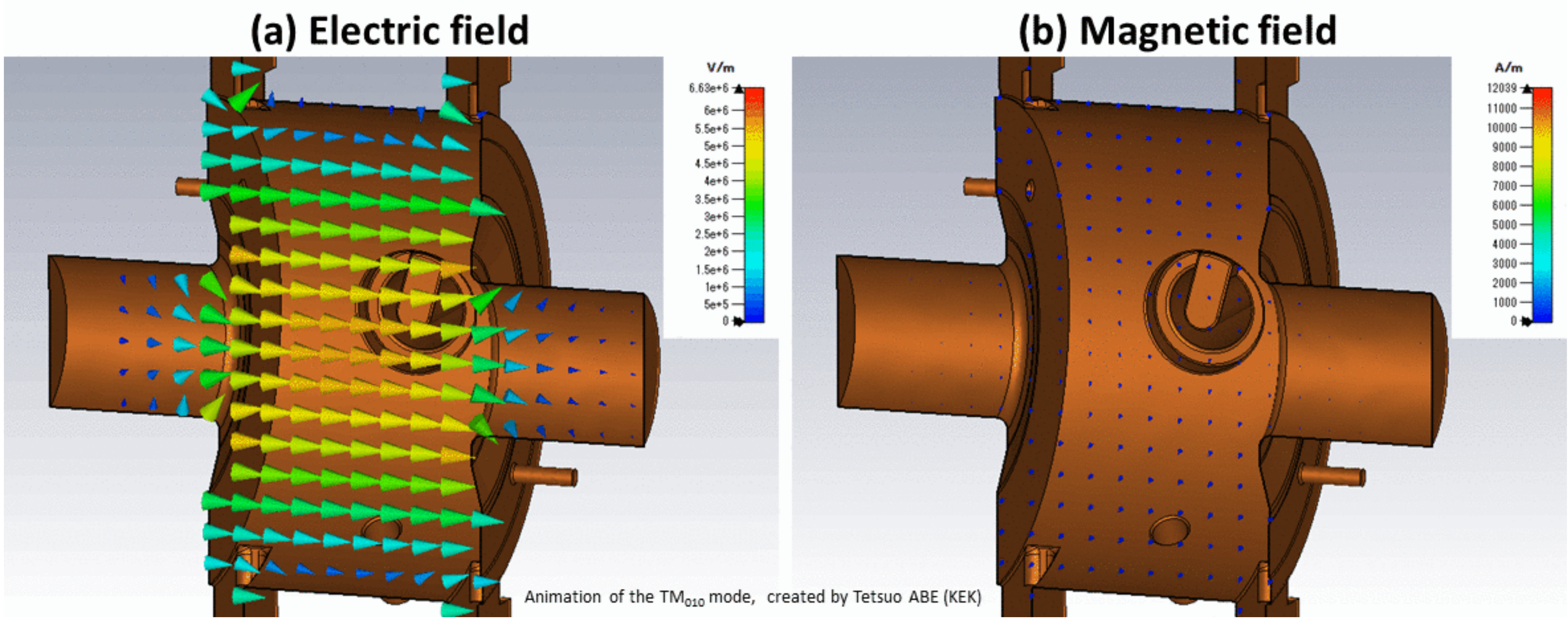


Animation of the TM_{010} mode, created by Tetsuo ABE (KEK)

(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

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

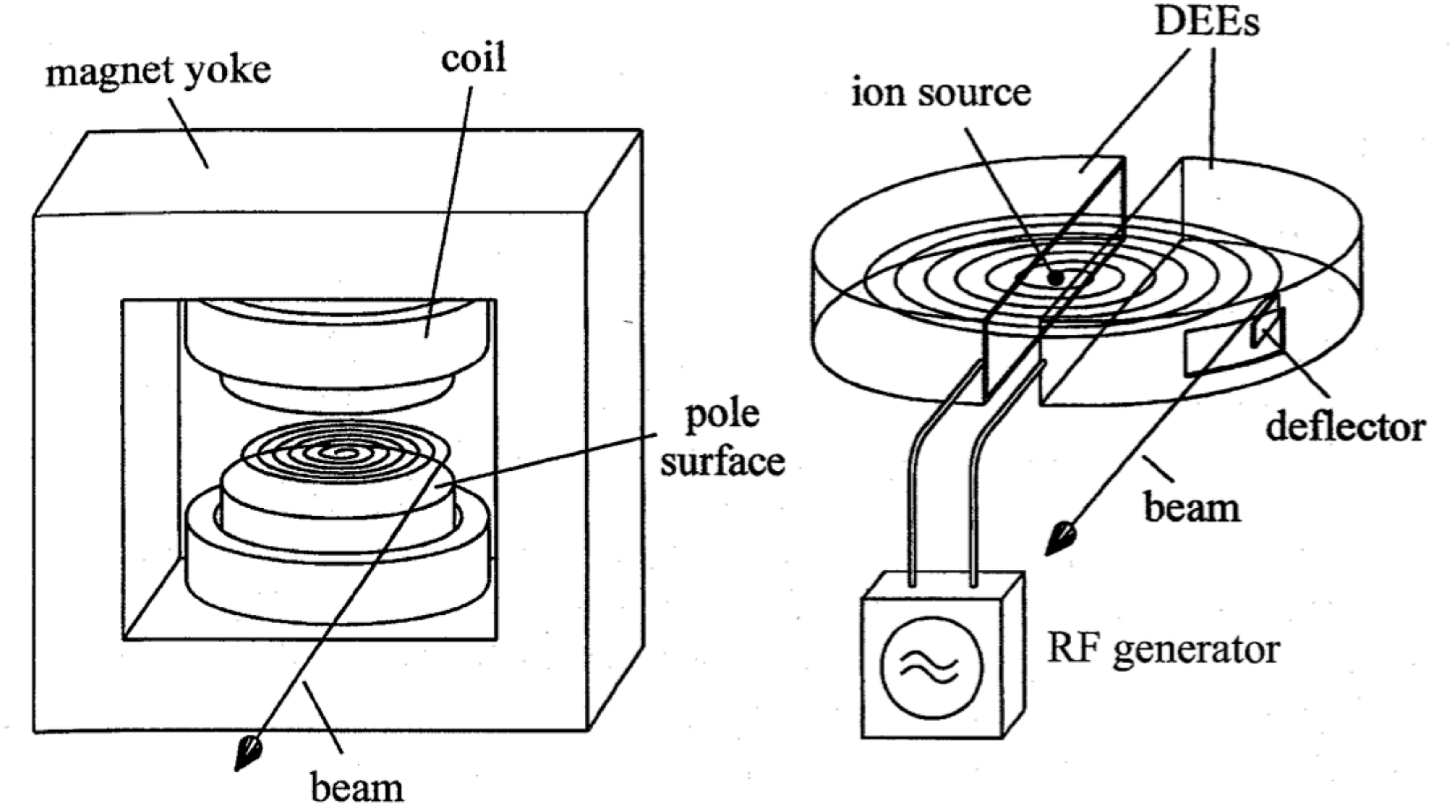
e.g. if for 10 MHz RF, $\lambda_{\mathrm{RF}} = 30\mathrm{m}$

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



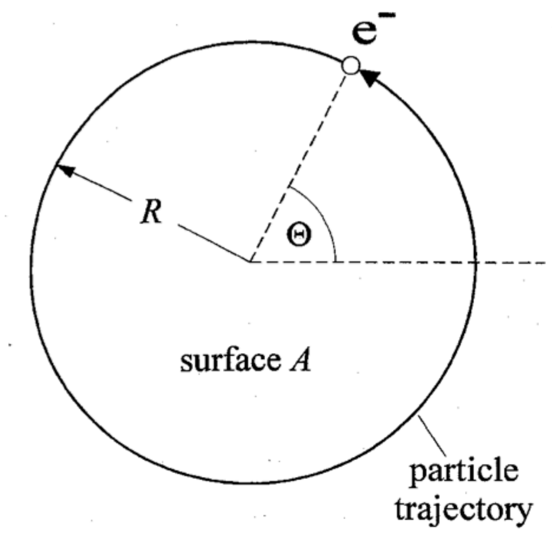
fixed frequency (for non-relativistic particle)

$$w = \frac{e}{m} B_z$$ 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

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

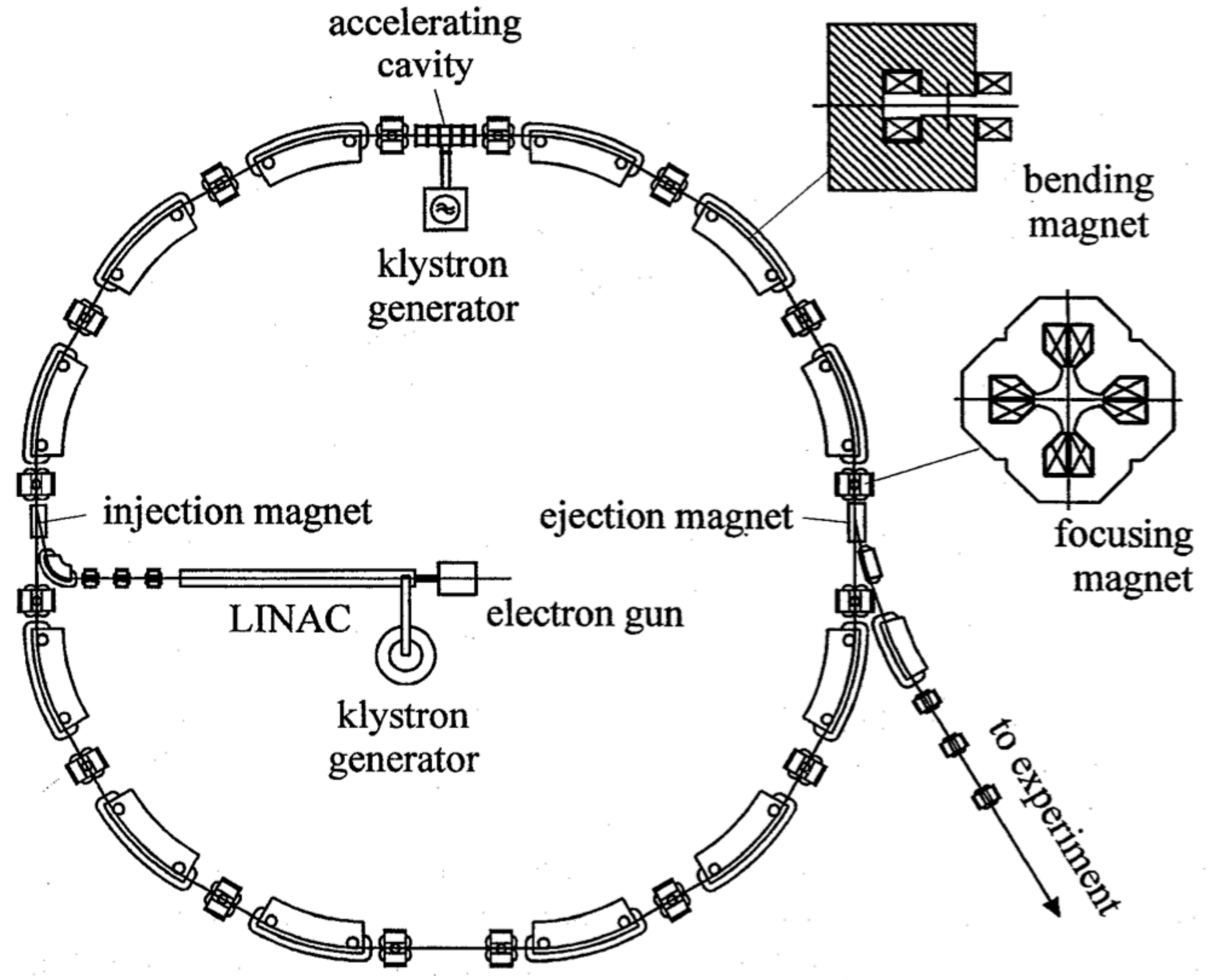
Widerøe's betatron condition: $|B(t)| = 1/2 \langle |B(t)| \rangle + |B_0|$

(i.1) basic principles of acceleration

- synchrotron

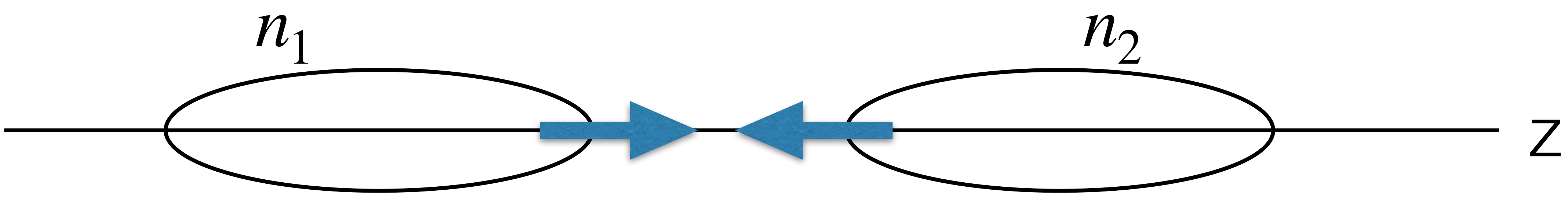
fixed orbit; magnet only around orbit; RF acc. section; synchronizing magnetic field with energy

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



(i.2) luminosity & beam dynamics

- Luminosity



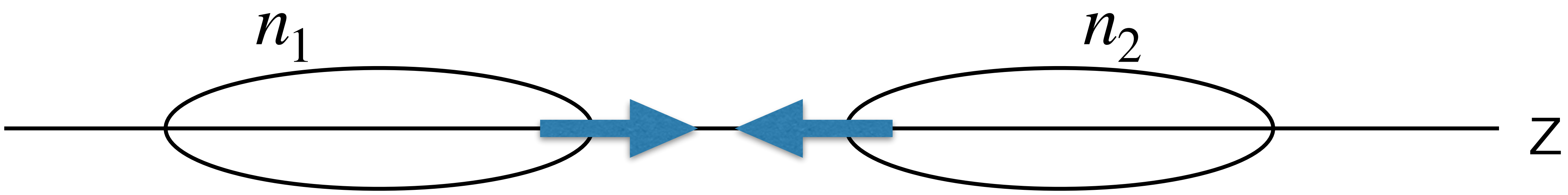
$$L = f_{coll} \frac{n_1 n_2}{4\pi \sigma_x^* \sigma_y^*} F$$

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

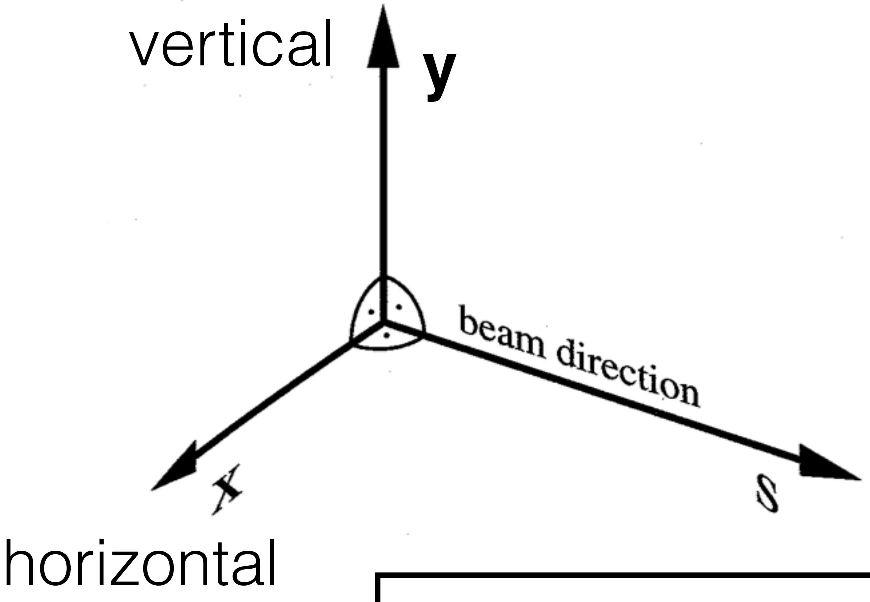
Lorentz force:

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

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

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

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

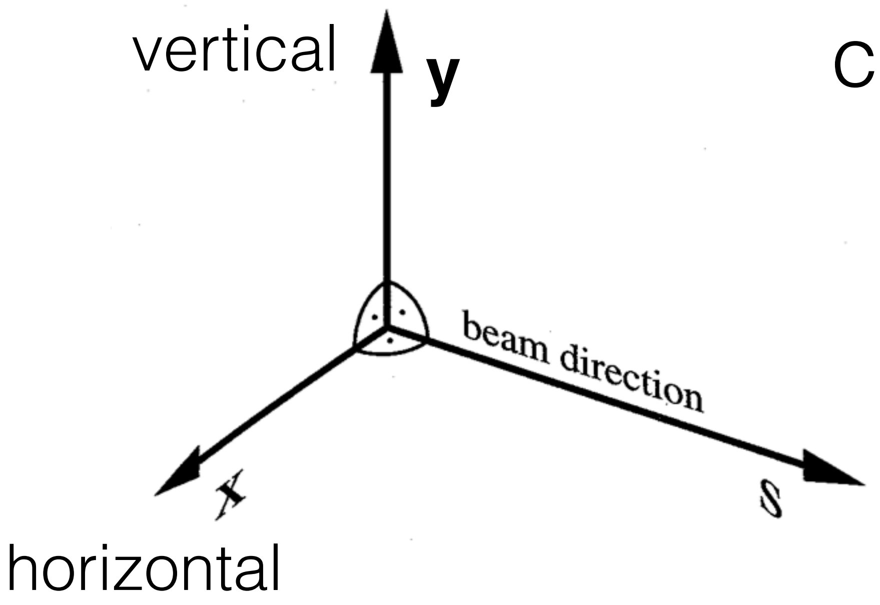
$$\boxed{\begin{array}{ccccccccccc} \frac{e}{p}B_z(x) & = & \frac{e}{p}B_{z0} & + & \frac{e}{p}\frac{dB_z}{dx}x & + & \frac{1}{2!}\frac{e}{p}\frac{d^2B_z}{dx^2}x^2 & + & \frac{1}{3!}\frac{e}{p}\frac{d^3B_z}{dx^3}x^3 & + & \ldots \\ & = & \frac{1}{R} & + & kx & + & \frac{1}{2!}mx^2 & + & \frac{1}{3!}ox^3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

bending

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

(i.2) luminosity & beam dynamics

- linear beam optics



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

s: along the nominal trajectory

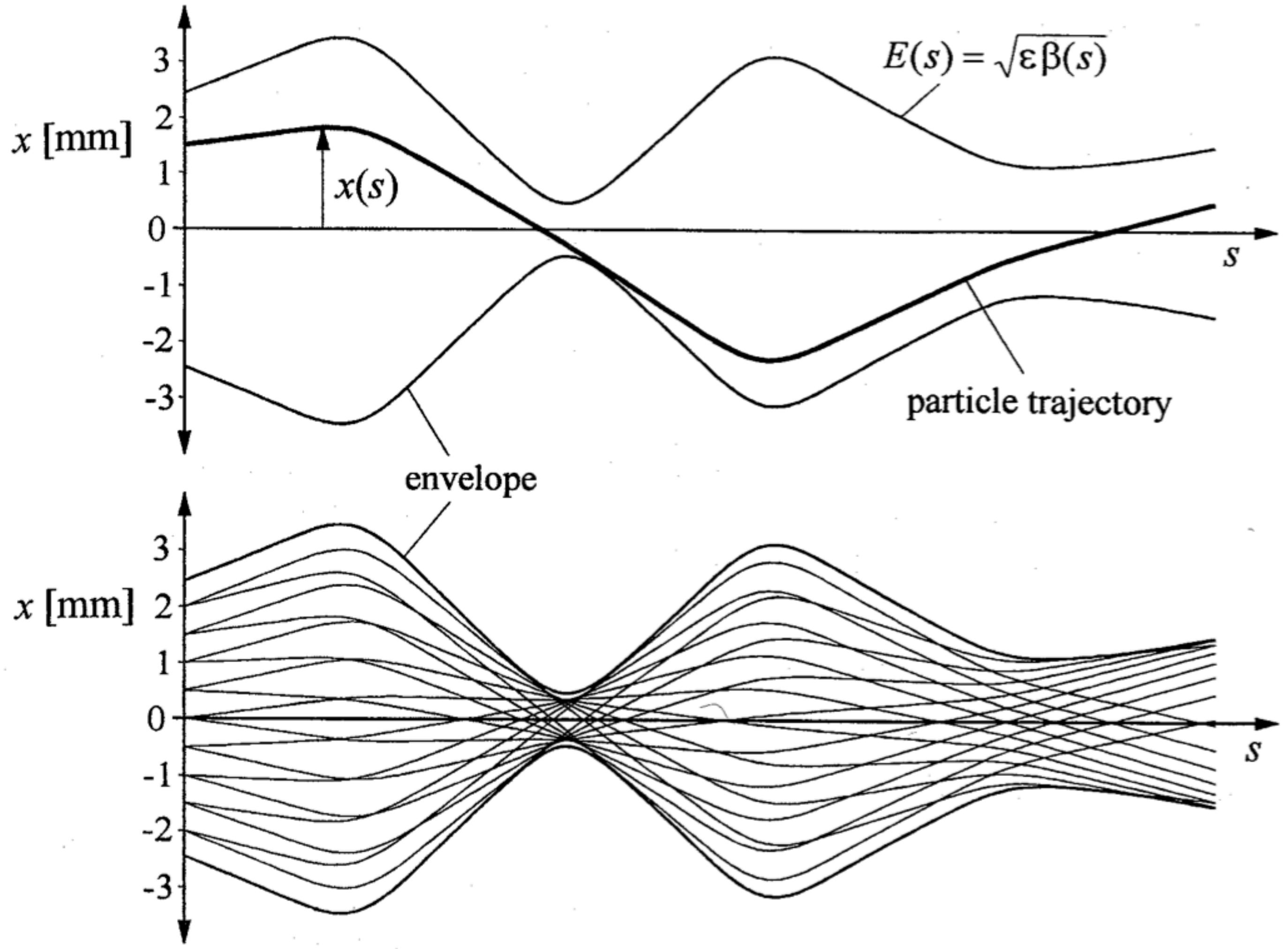
$$x' \equiv \frac{\mathrm{d}x}{\mathrm{d}s}$$

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

(betatron oscillations)

(i.2) luminosity & beam dynamics

- back to luminosity



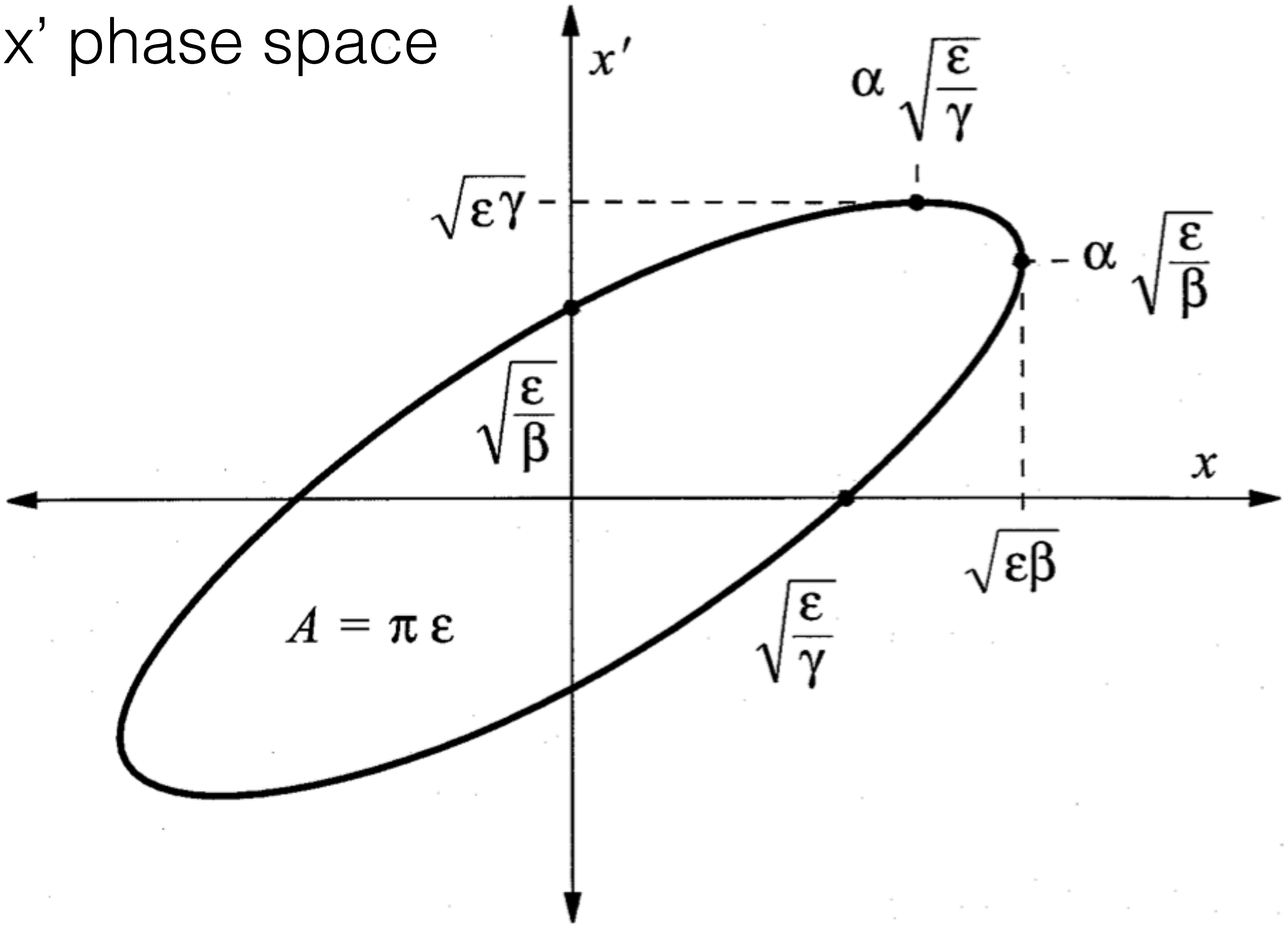
$$L = f_{coll} \frac{n_1 n_2}{4\pi\sigma_x^* \sigma_y^*} F$$

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

(i.2) luminosity & beam dynamics

- back to luminosity

x-x' phase space



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

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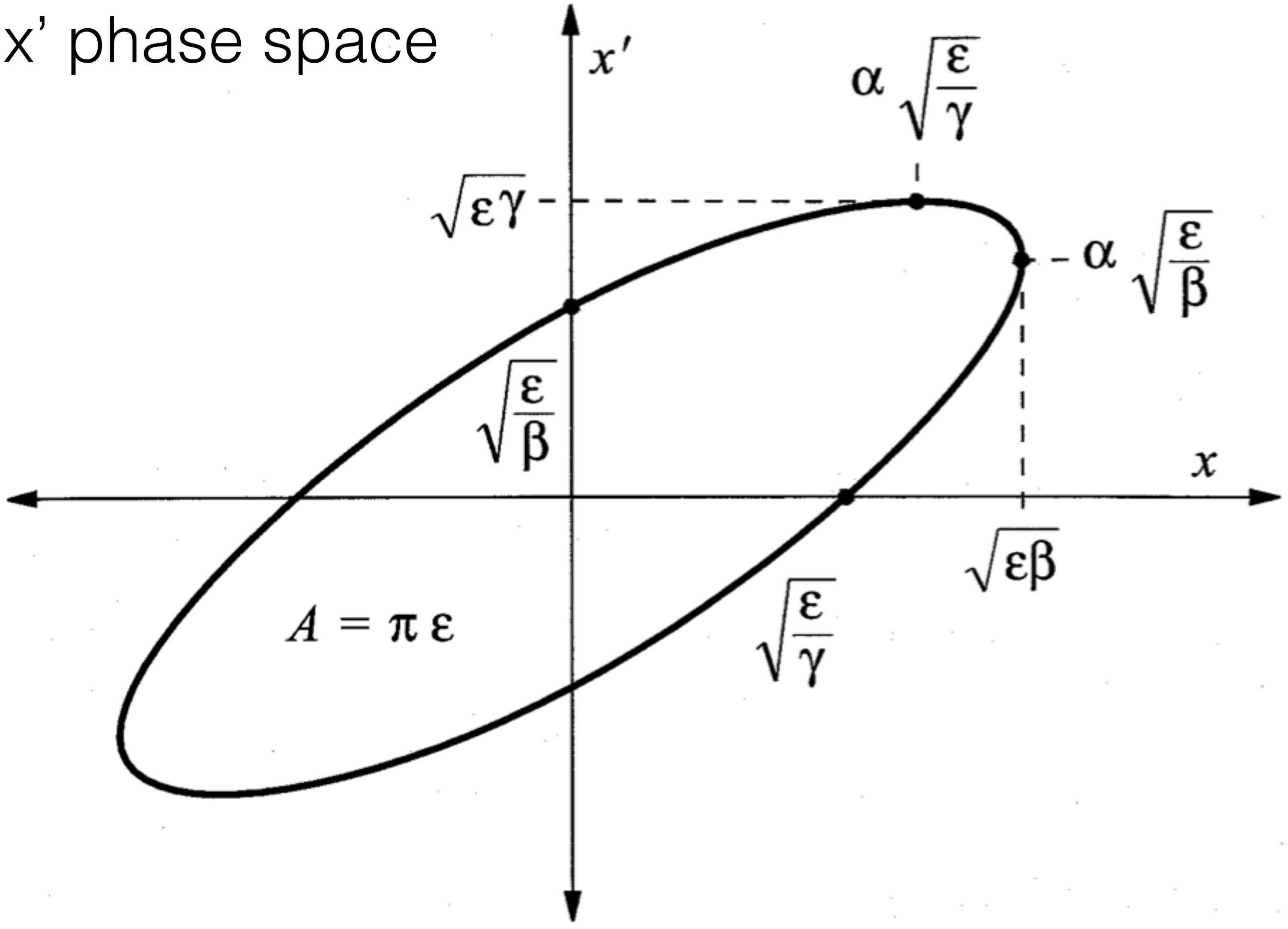
(i.2) luminosity & beam dynamics

- 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

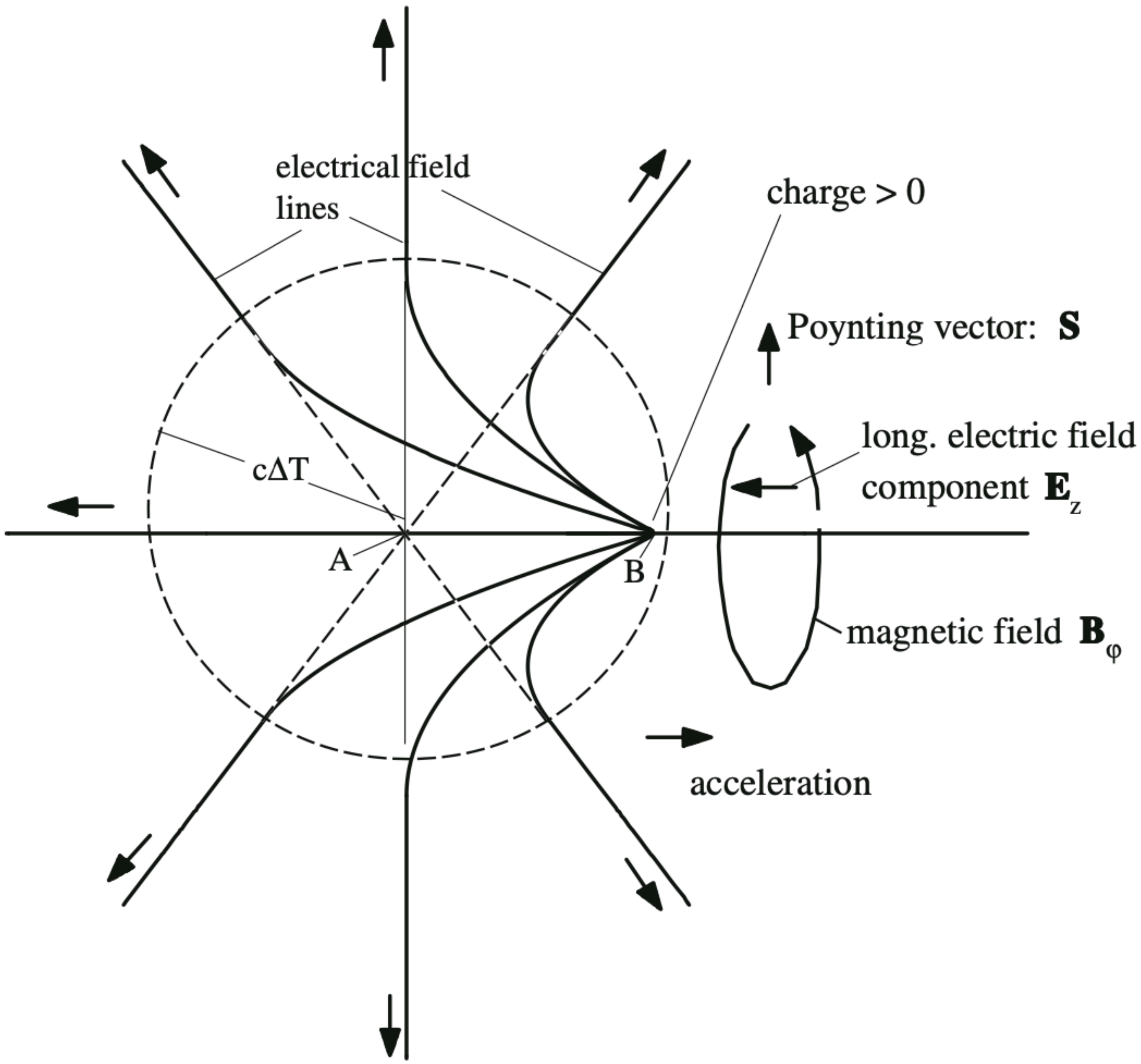
(i.3) synchrotron radiation

- 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 $|\boldsymbol{a}|$

at a linear accelerator

for E=100GeV, G=30MeV/m; $|\boldsymbol{a}|=1.4\times10^{3}$ m/s^2

at a circular accelerator

for E=100GeV, R=100km; $|\boldsymbol{a}|=9\times10^{11}$ m/s^2

$|\boldsymbol{a}|$ differ enormously

(i.3) synchrotron radiation

- synchrotron radiation power

at a circular accelerator

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

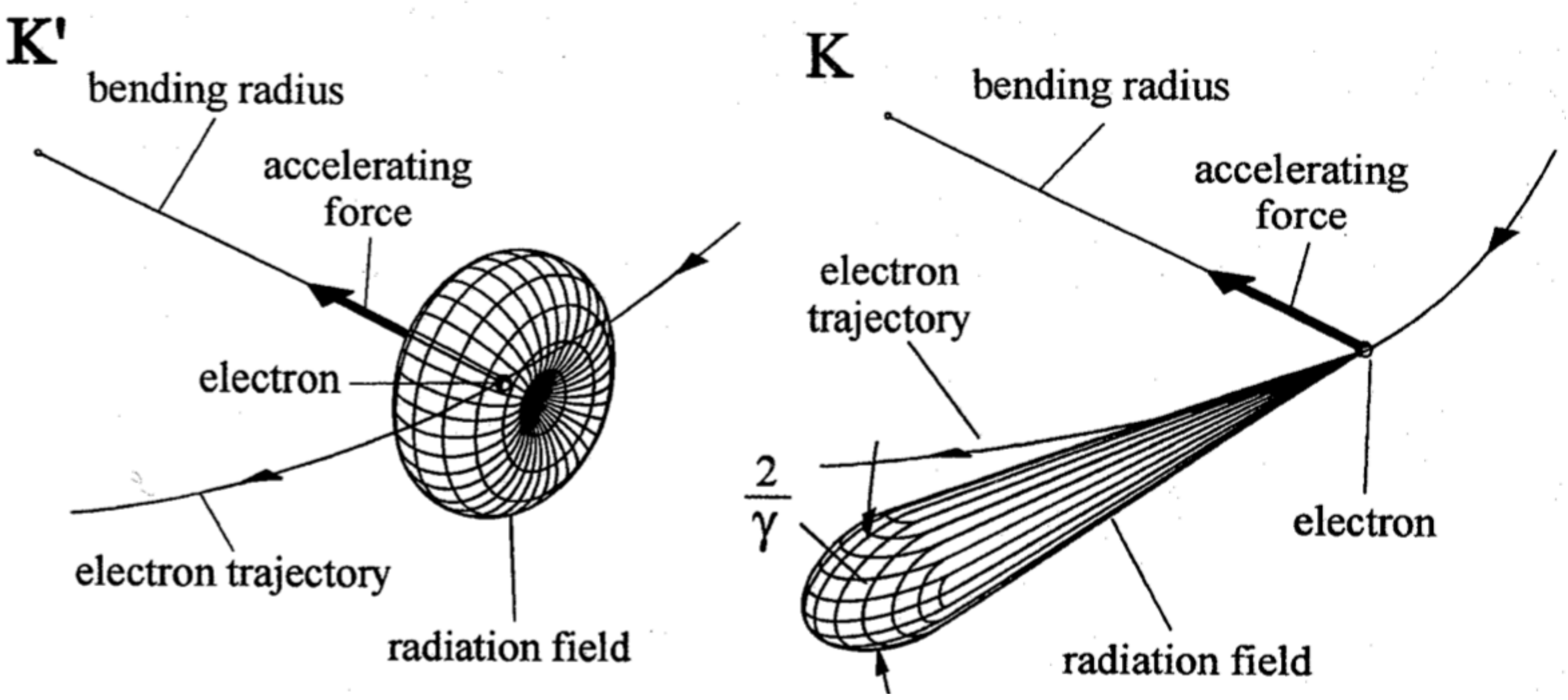
energy loss per turn (for electron)

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

(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

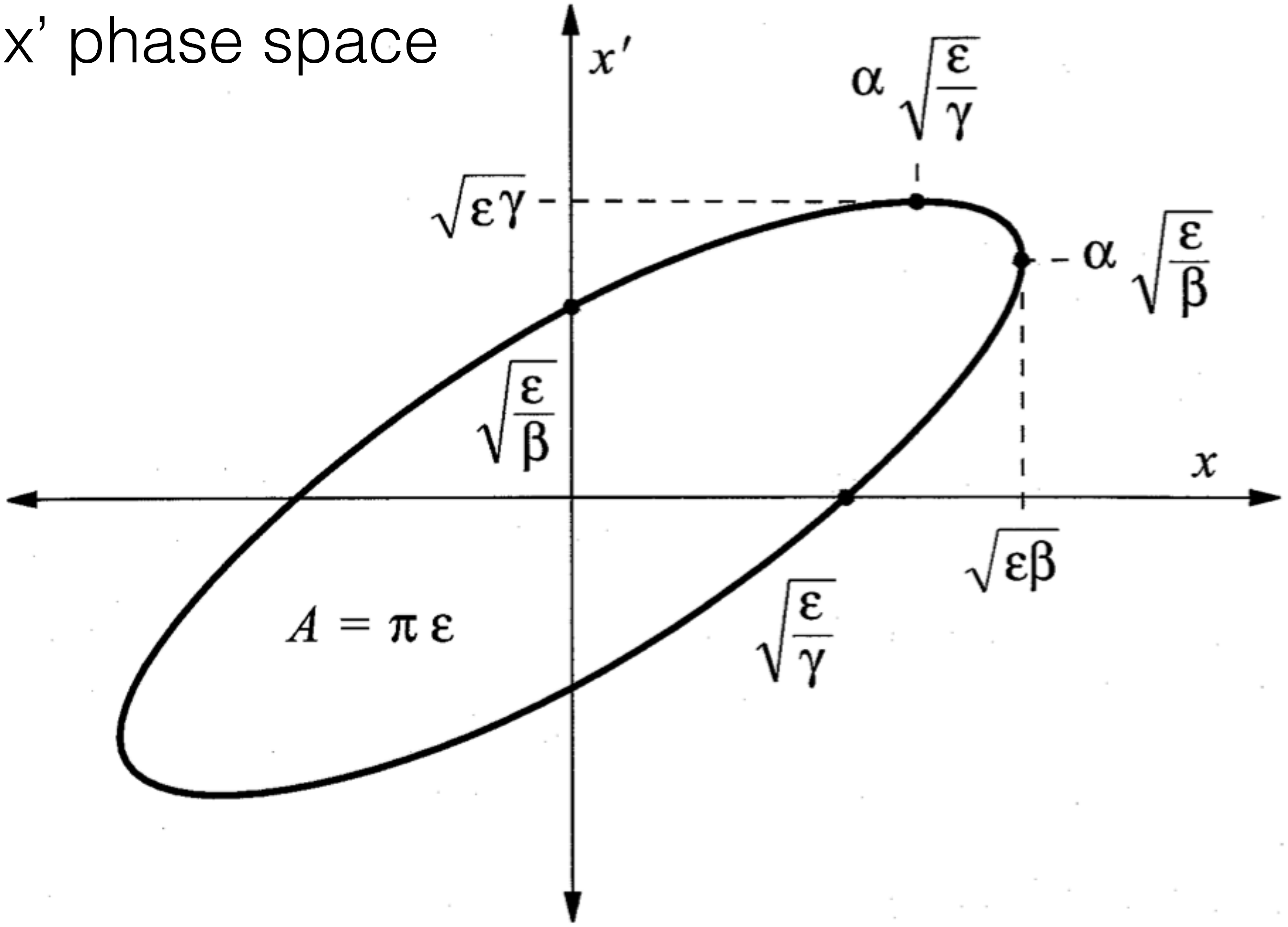
  damping ring: synchrotron radiation can reduce emittance

(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:

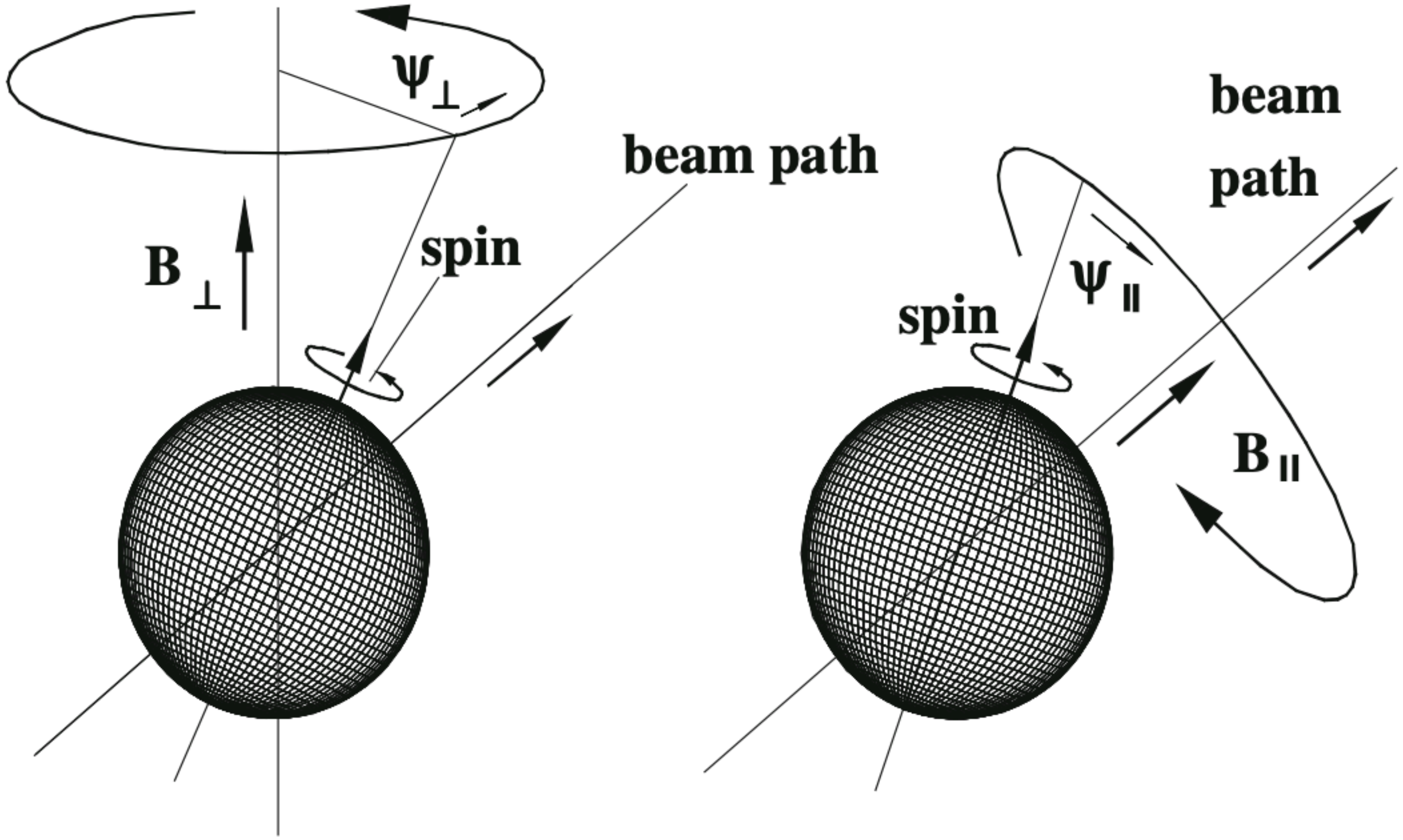
a polarized laser to hit a photocathode
P=80% demonstrated at SLC

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

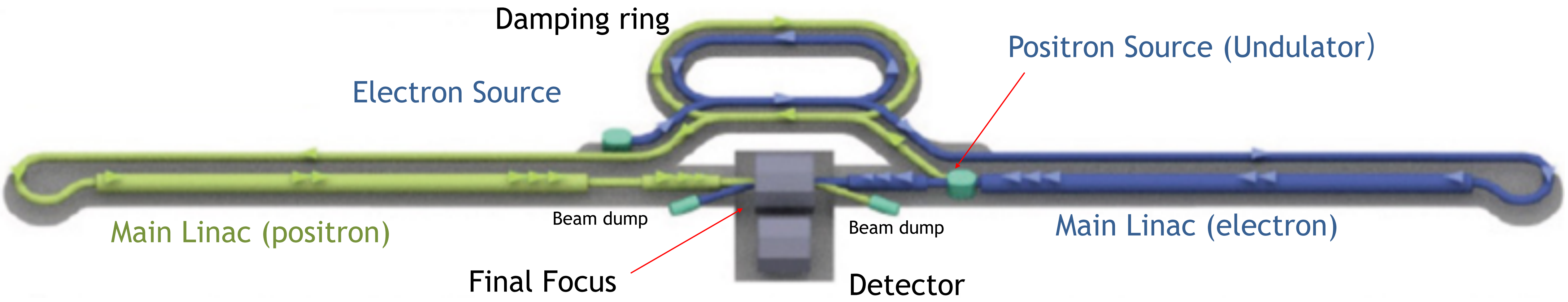
(i.5) ILC

- International Linear Collider (ILC)

  key technologies

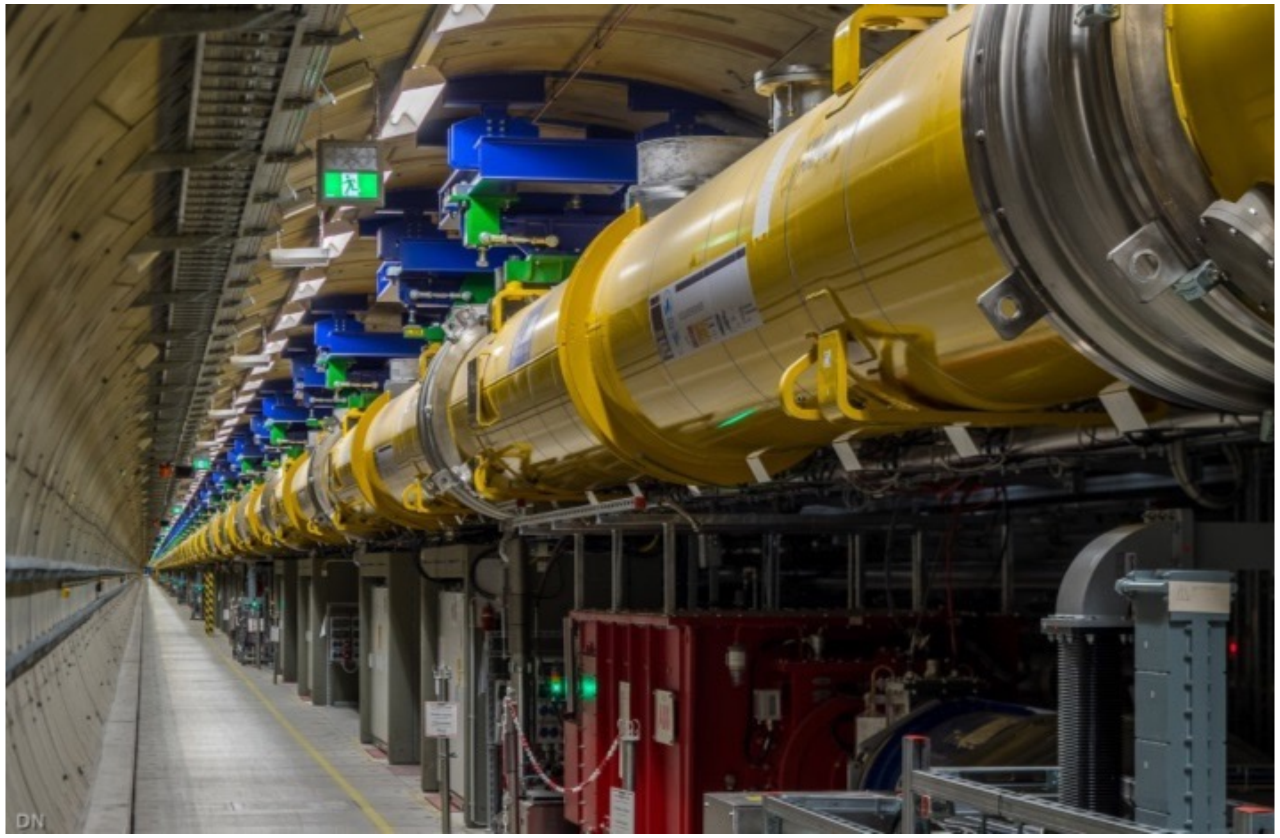
  Superconducting RF: 1.3GHz; ~31.5MeV/m

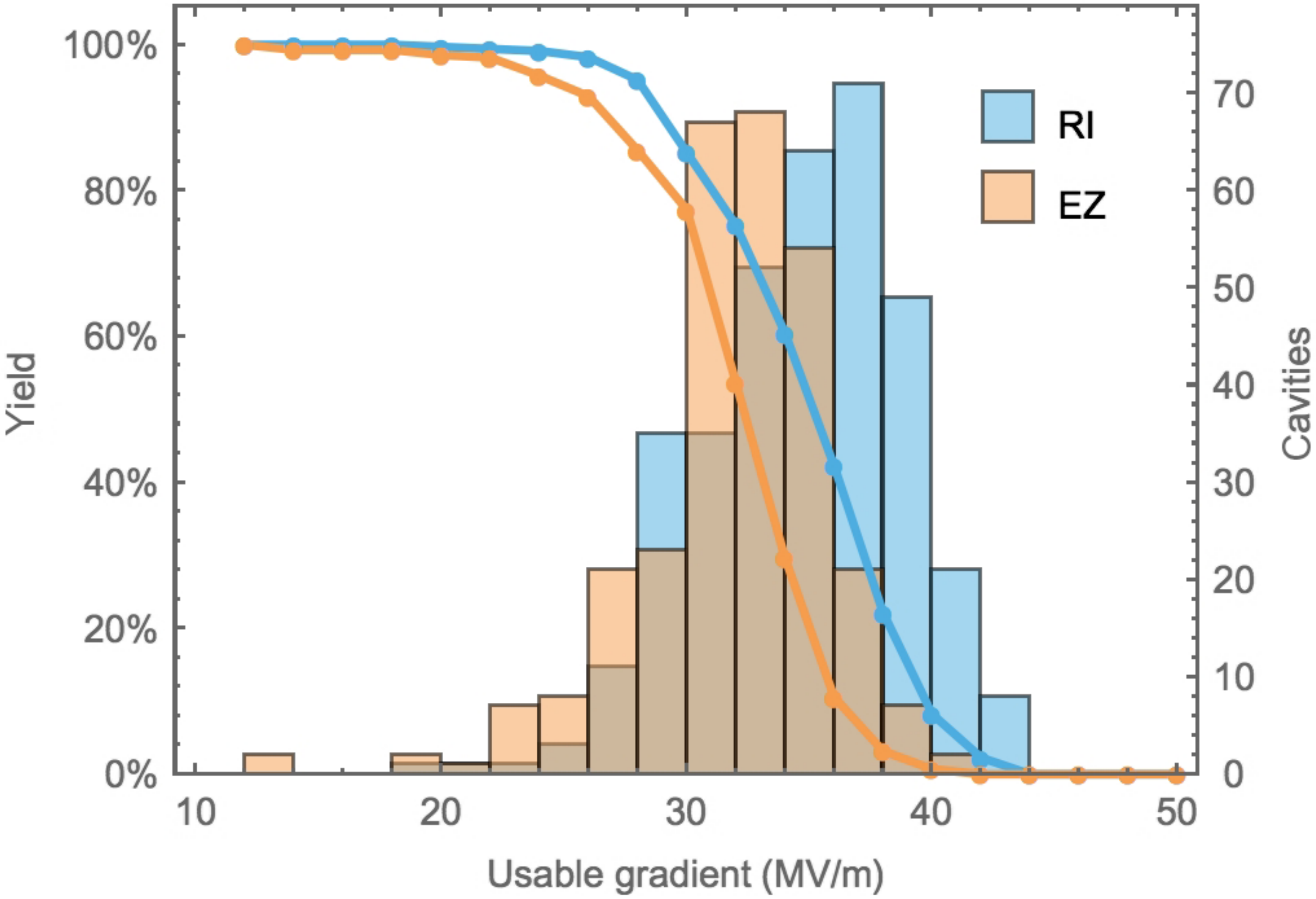
  Nano beam: σ_y~8nm; σ_x~500nm



(i.5) ILC

- SRF technology: mature & robust

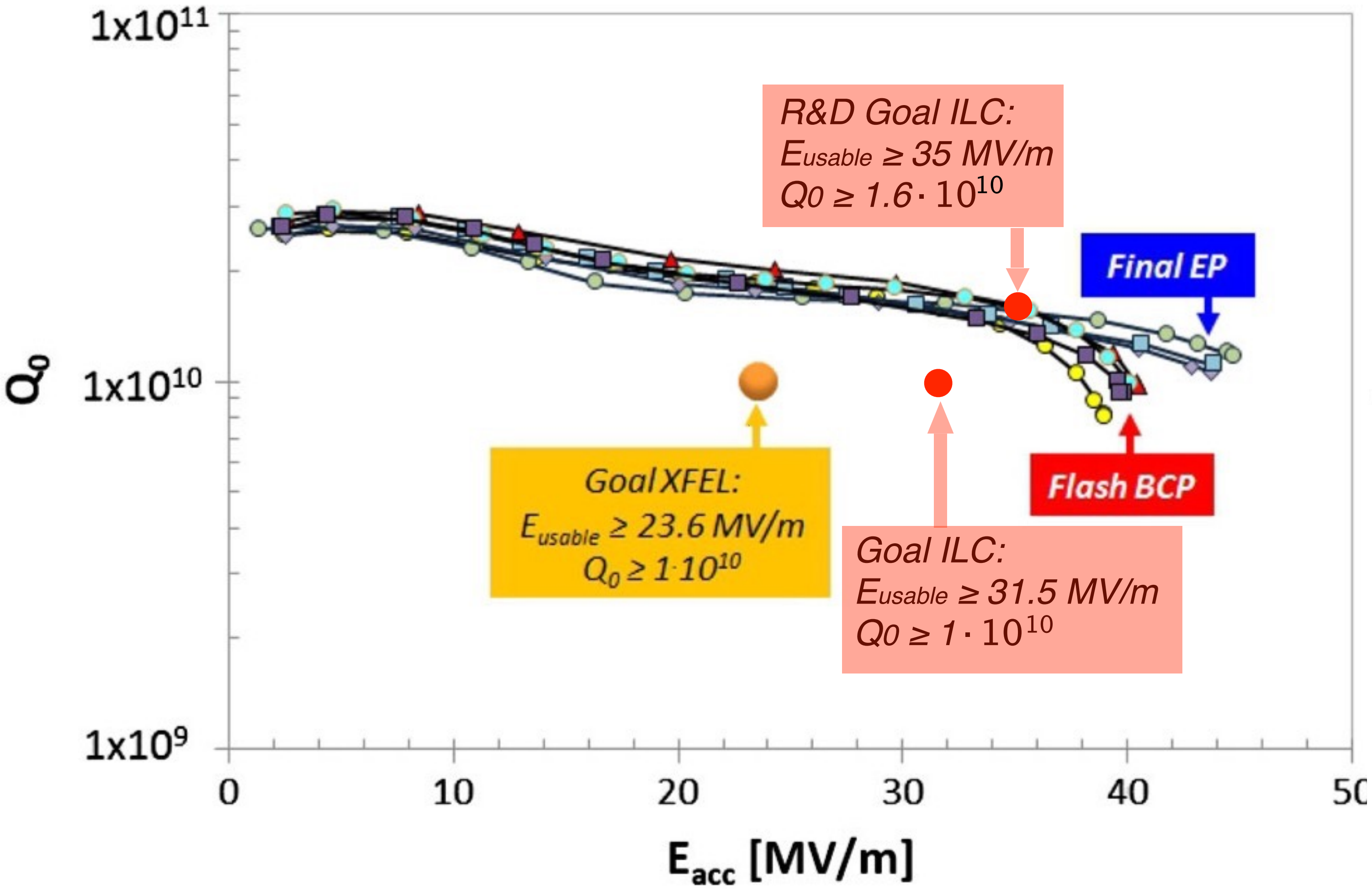




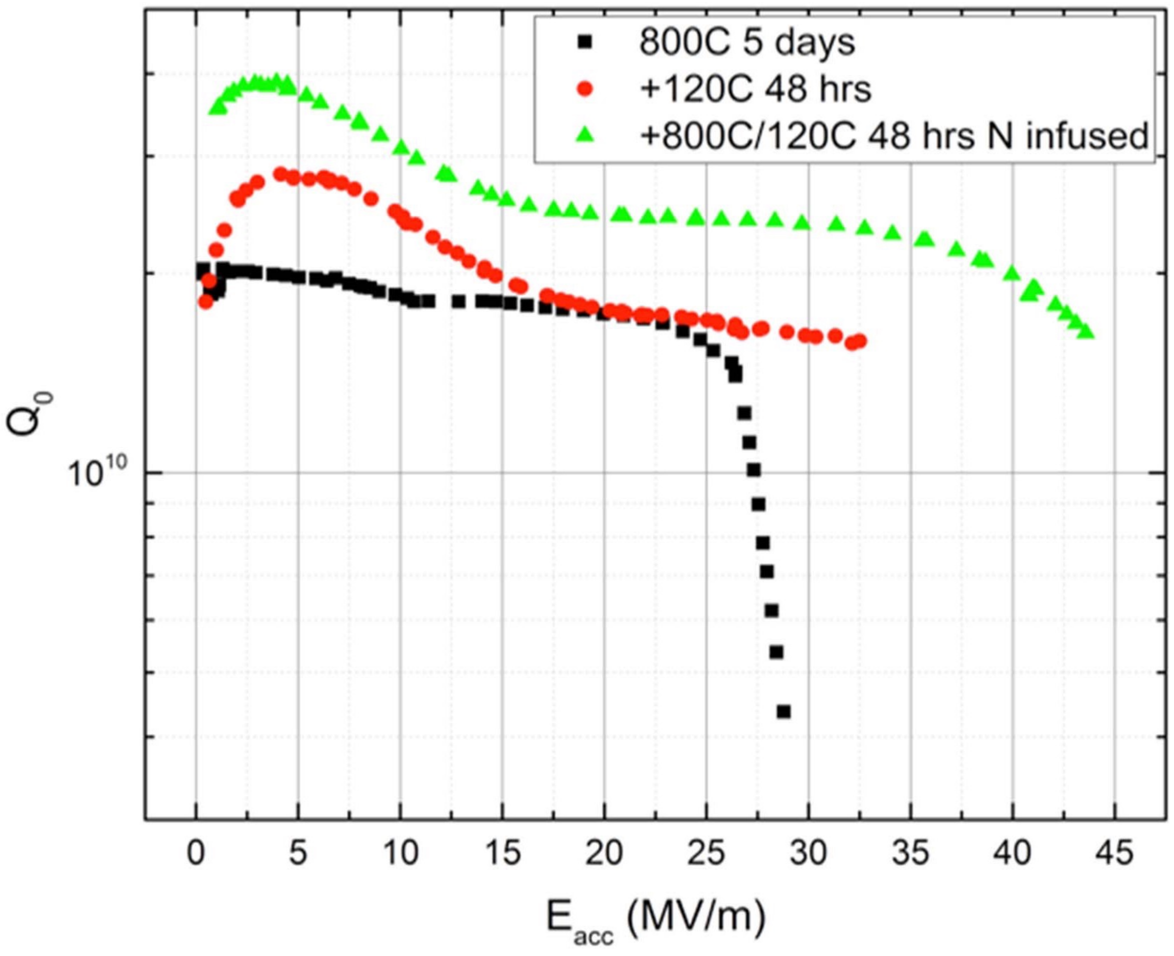
~800 cavities installed & running @ E-XFEL

(i.5) ILC

- SRF technology: potential for further improvement



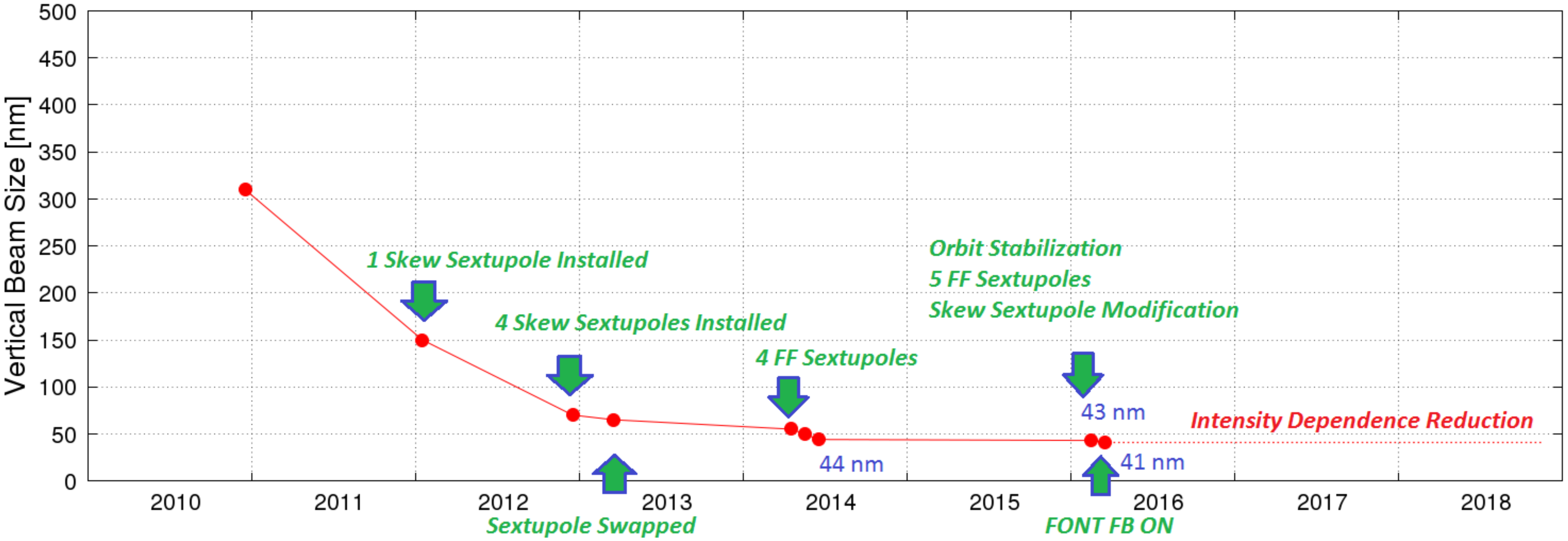
some of the best cavities produced for E-XFEL



ongoing R&D Nitrogen infusion

(i.5) ILC

- Nano beam: demonstration @ ATF2, KEK



37nm @ 1.3 GeV ~ 5.7nm @ 250 GeV

(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:

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

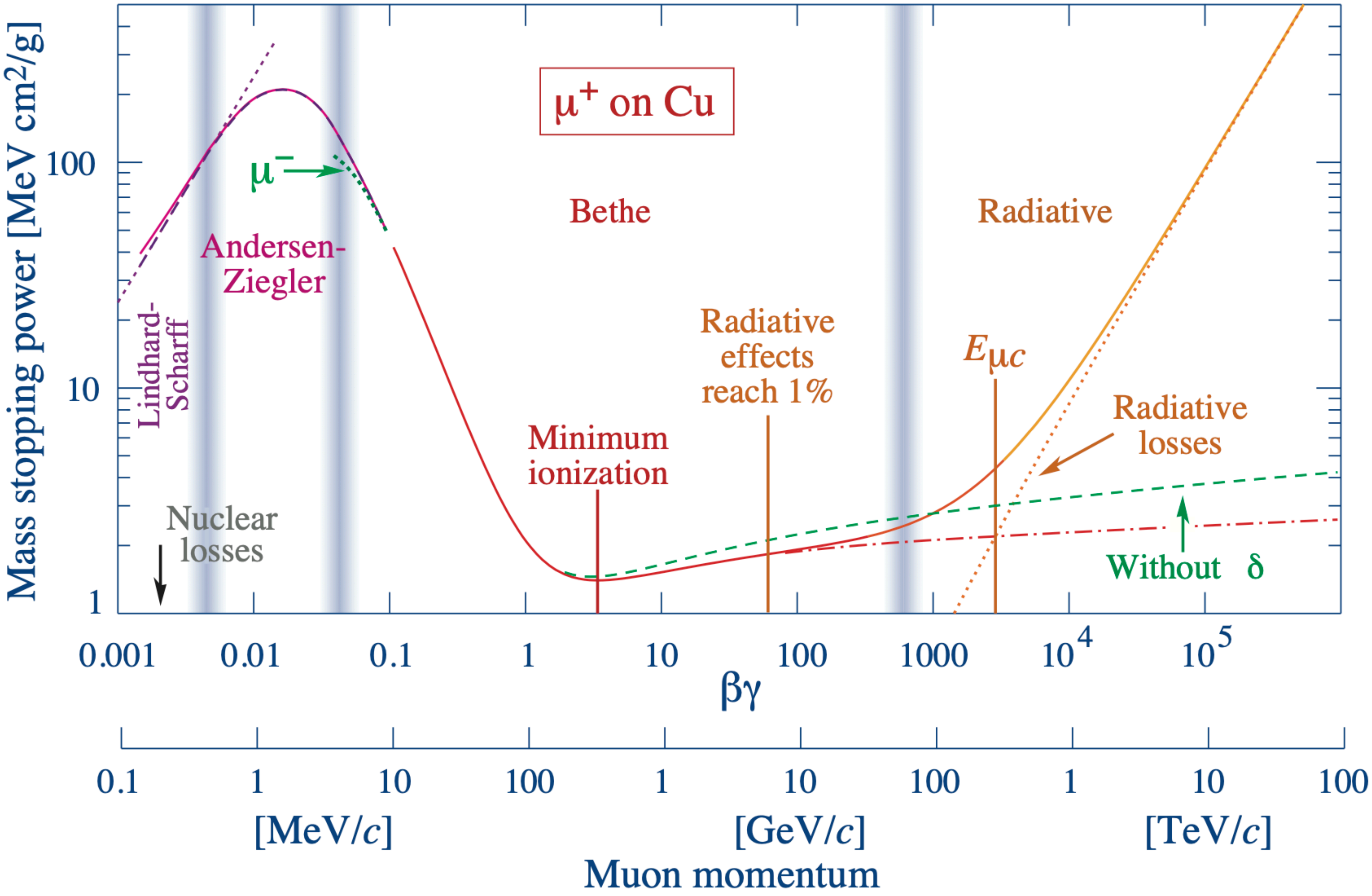
mass stoping power

linear stoping power: x ρ

logarithmic increase for relativistic particles

(ii.1) passage of particle through matter

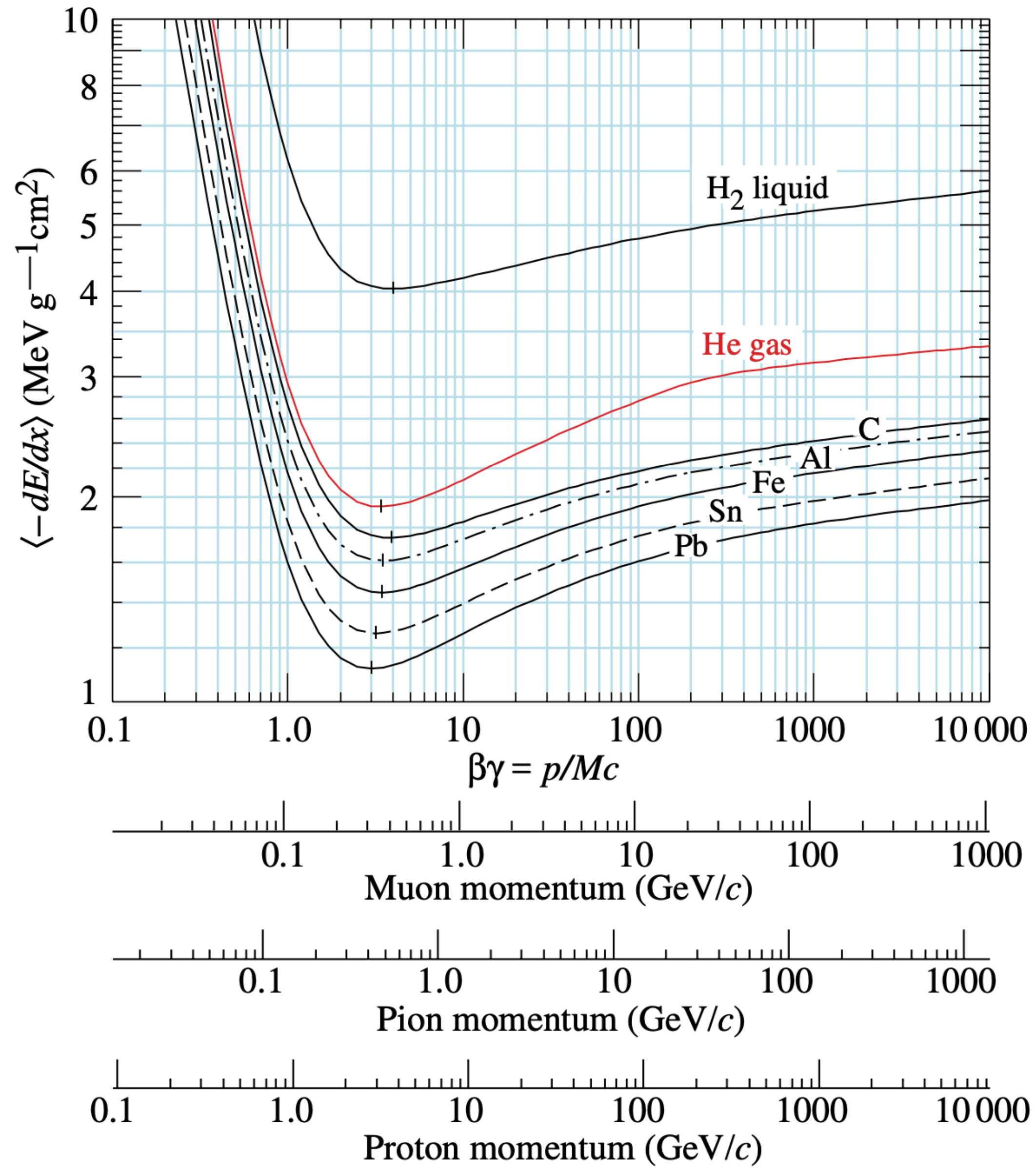
- electronic energy loss by charged particles



(ii.1) passage of particle through matter

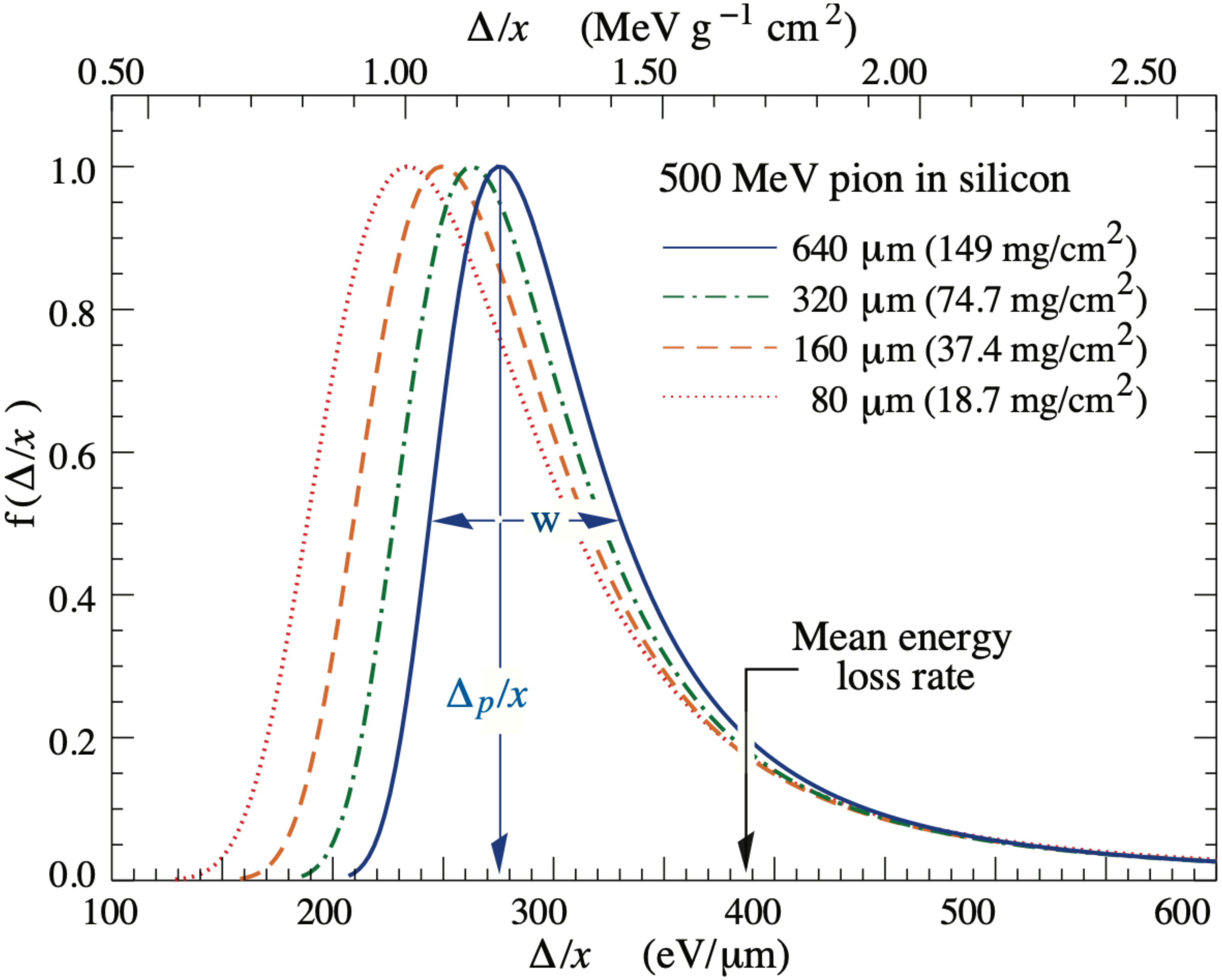
- concept of MIP

1 MIP: an energy deposition of one minimum ionizing particle



(ii.1) passage of particle through matter

- dE/dx fluctuations: Landau distribution



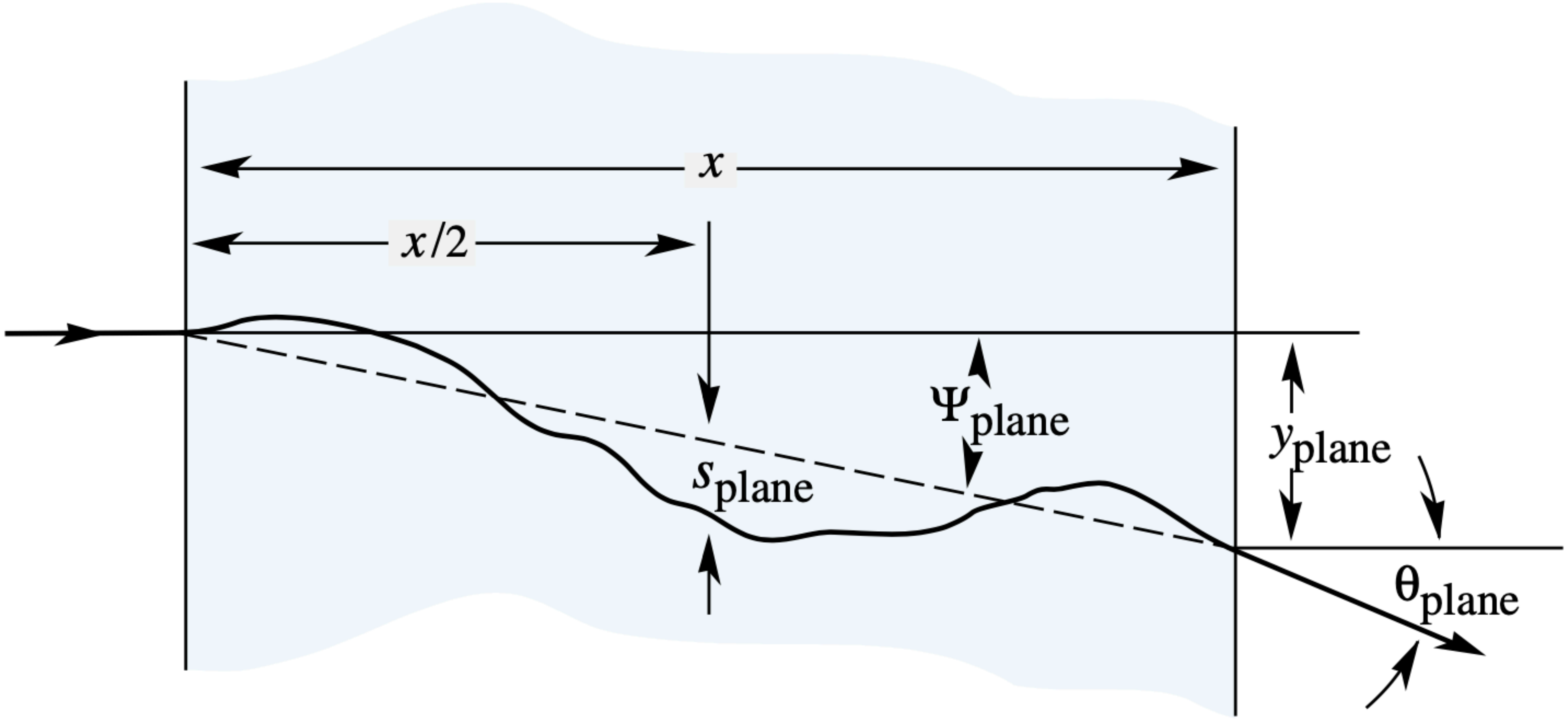
experimentally, the most probable energy loss should be used

(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

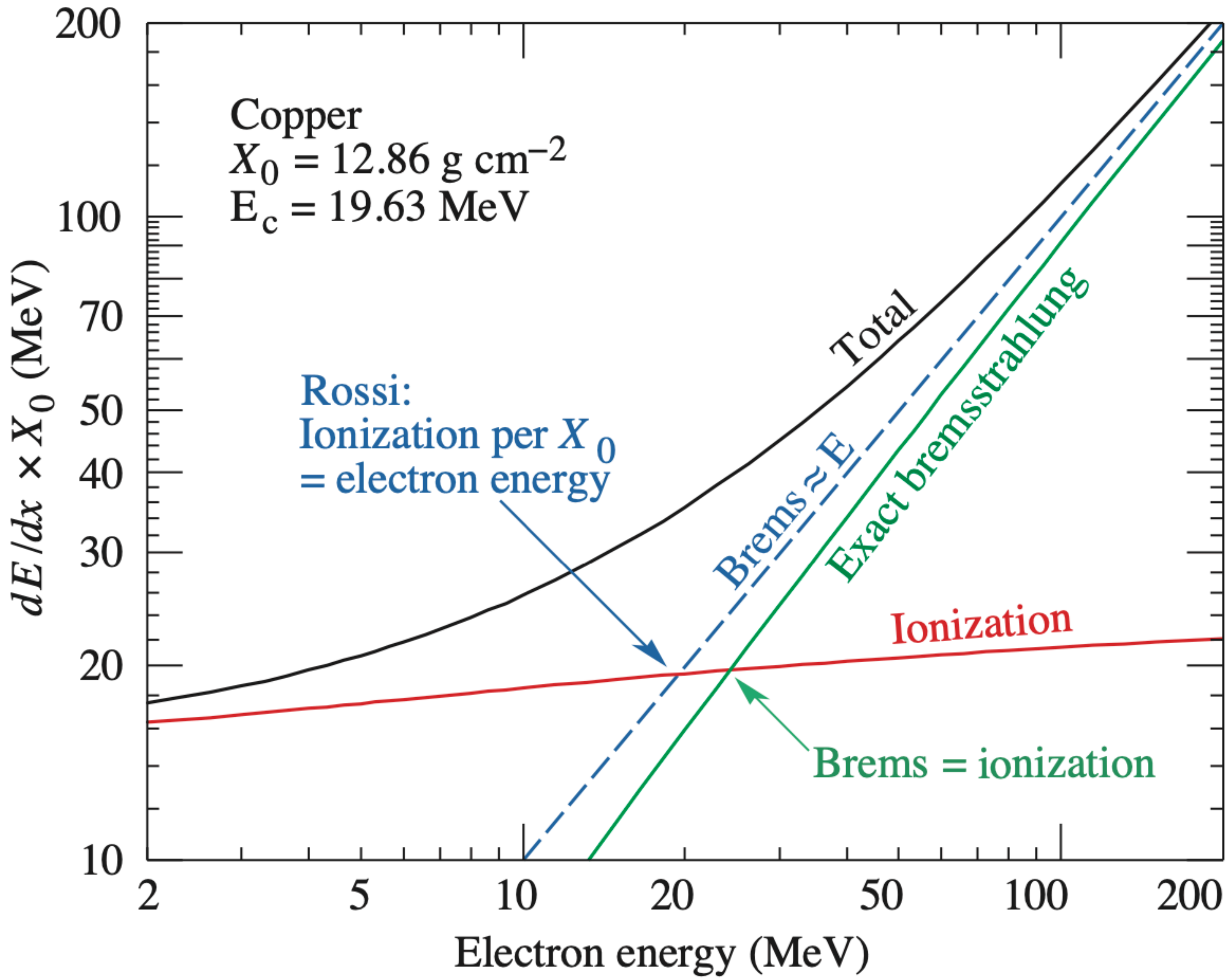
radiation length (X_0): the mean distance an electron loses all but 1/e

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

(ii.1) passage of particle through matter

- critical energy E_c

bremsstrahlung energy loss ~ ionization loss

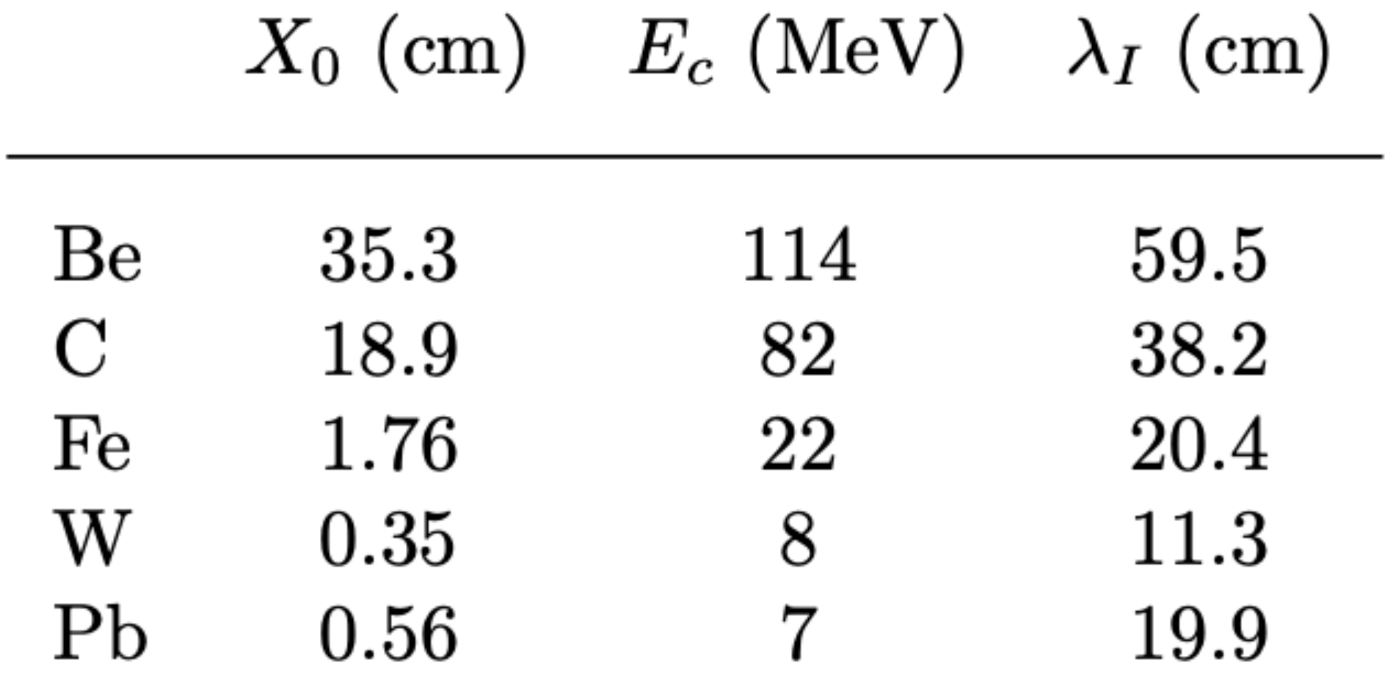


(ii.1) passage of particle through matter

- 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)

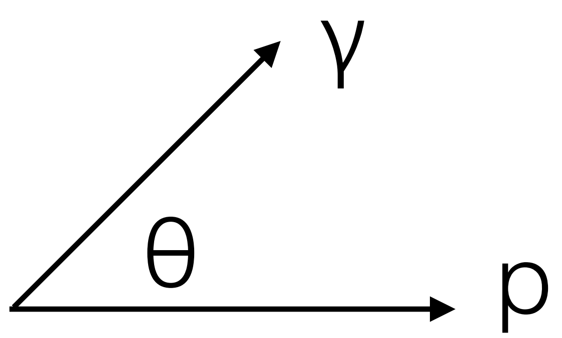


	X_0 (cm)	E_c (MeV)	λ_I (cm)
Be	35.3	114	59.5
C	18.9	82	38.2
Fe	1.76	22	20.4
W	0.35	8	11.3
Pb	0.56	7	19.9

(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

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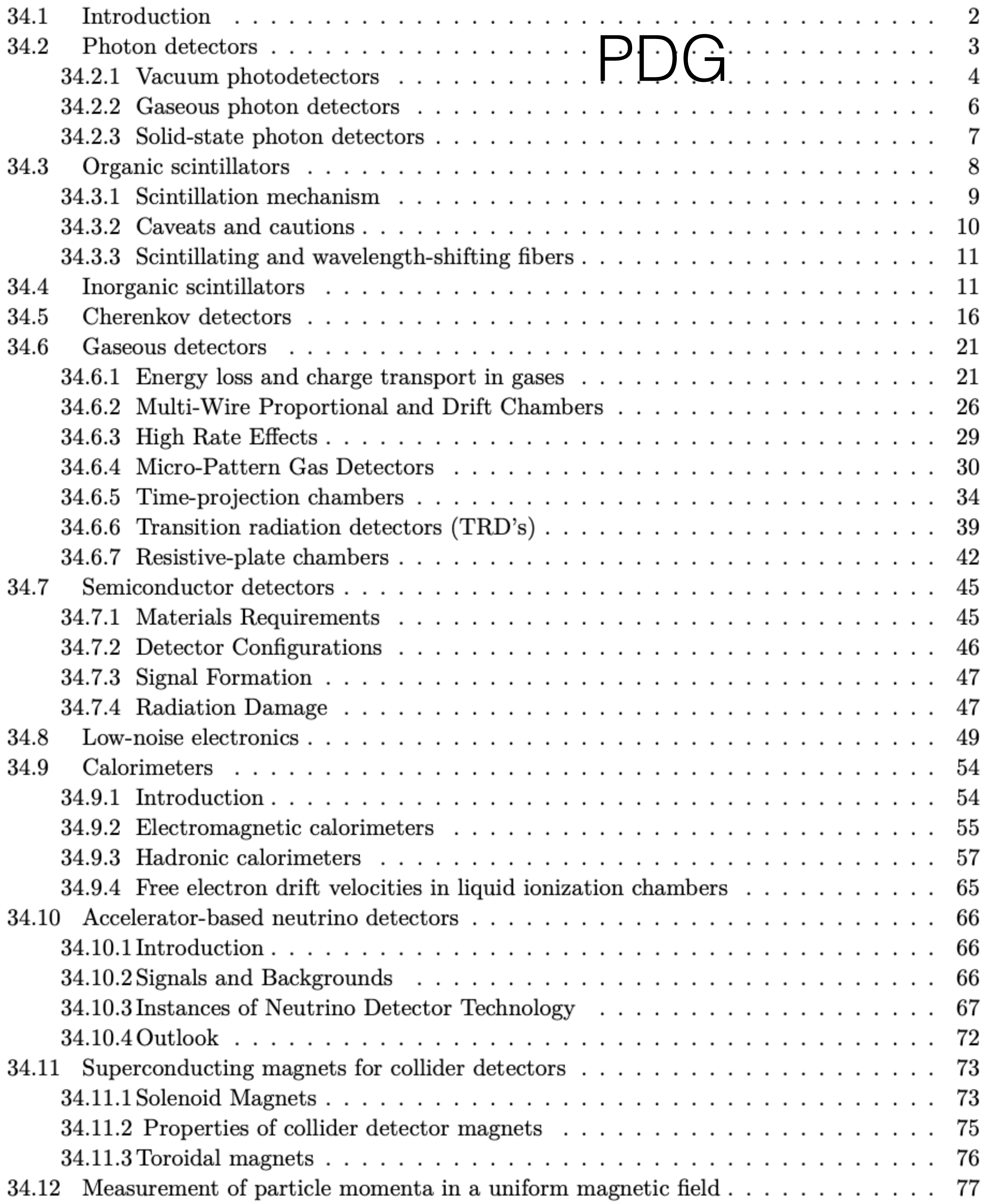

PDG

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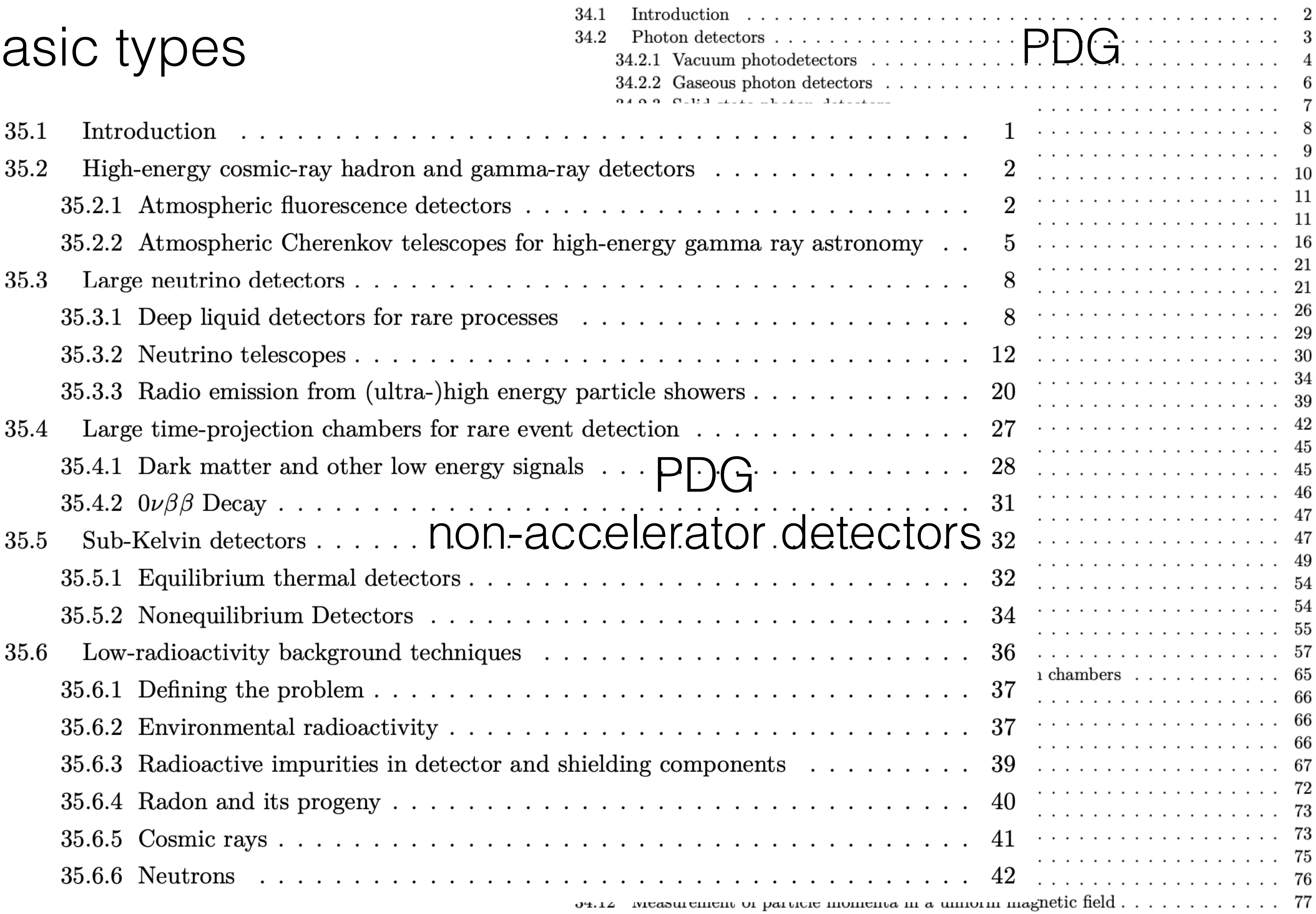
- basic types



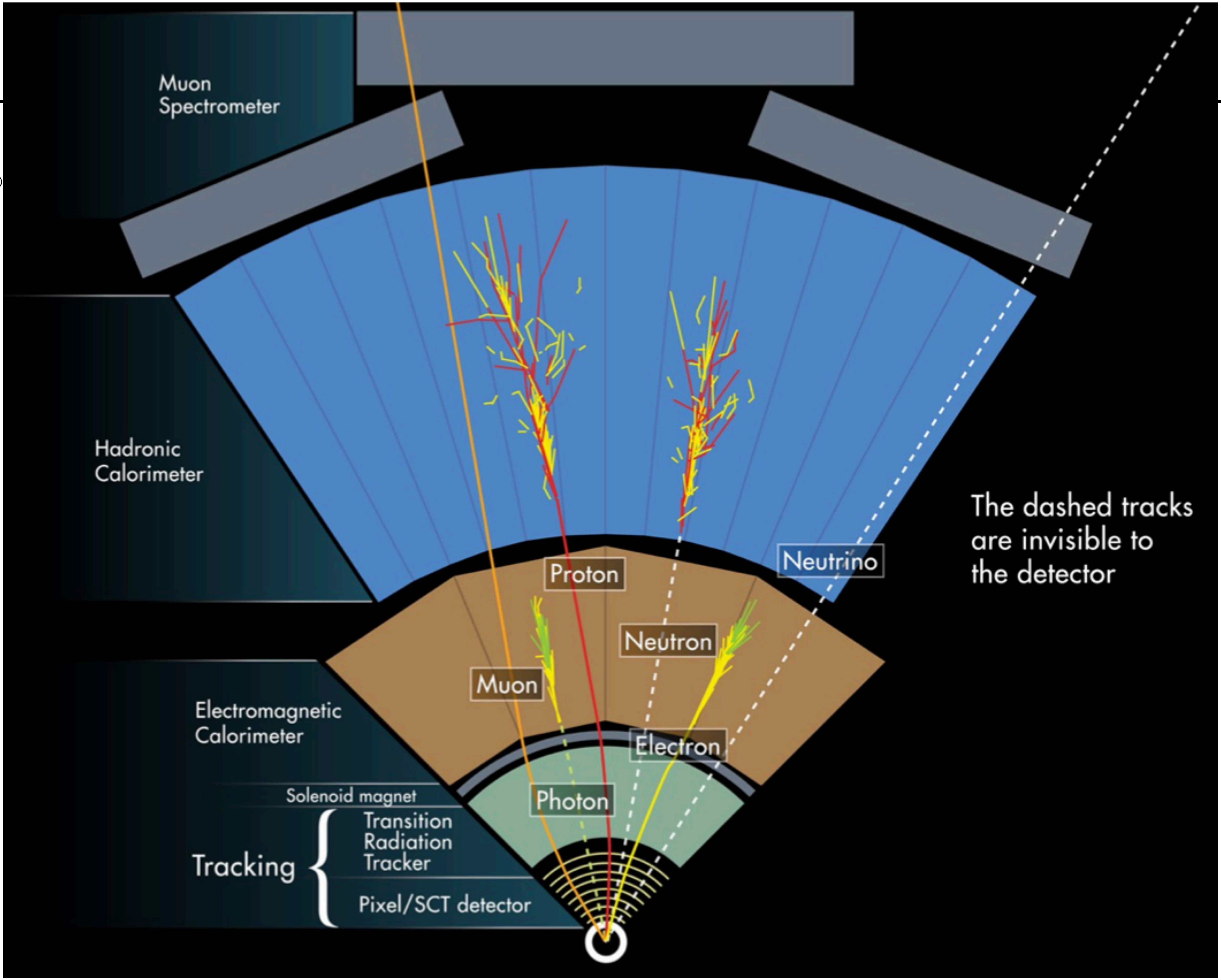
PDG

PDG

non-accelerator detectors

(ii.2) types of detectors

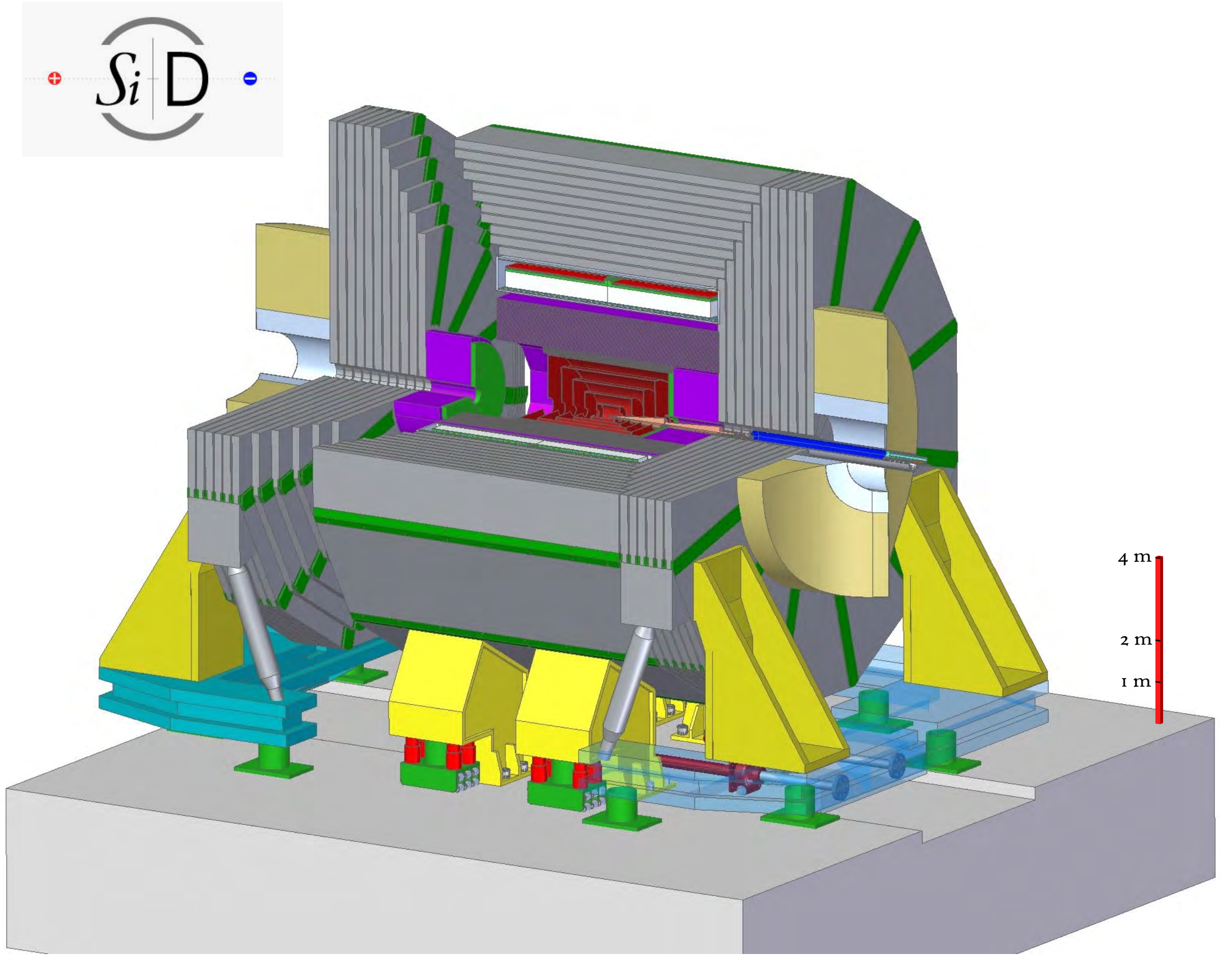
- an example: various high energy particles in ATLAS

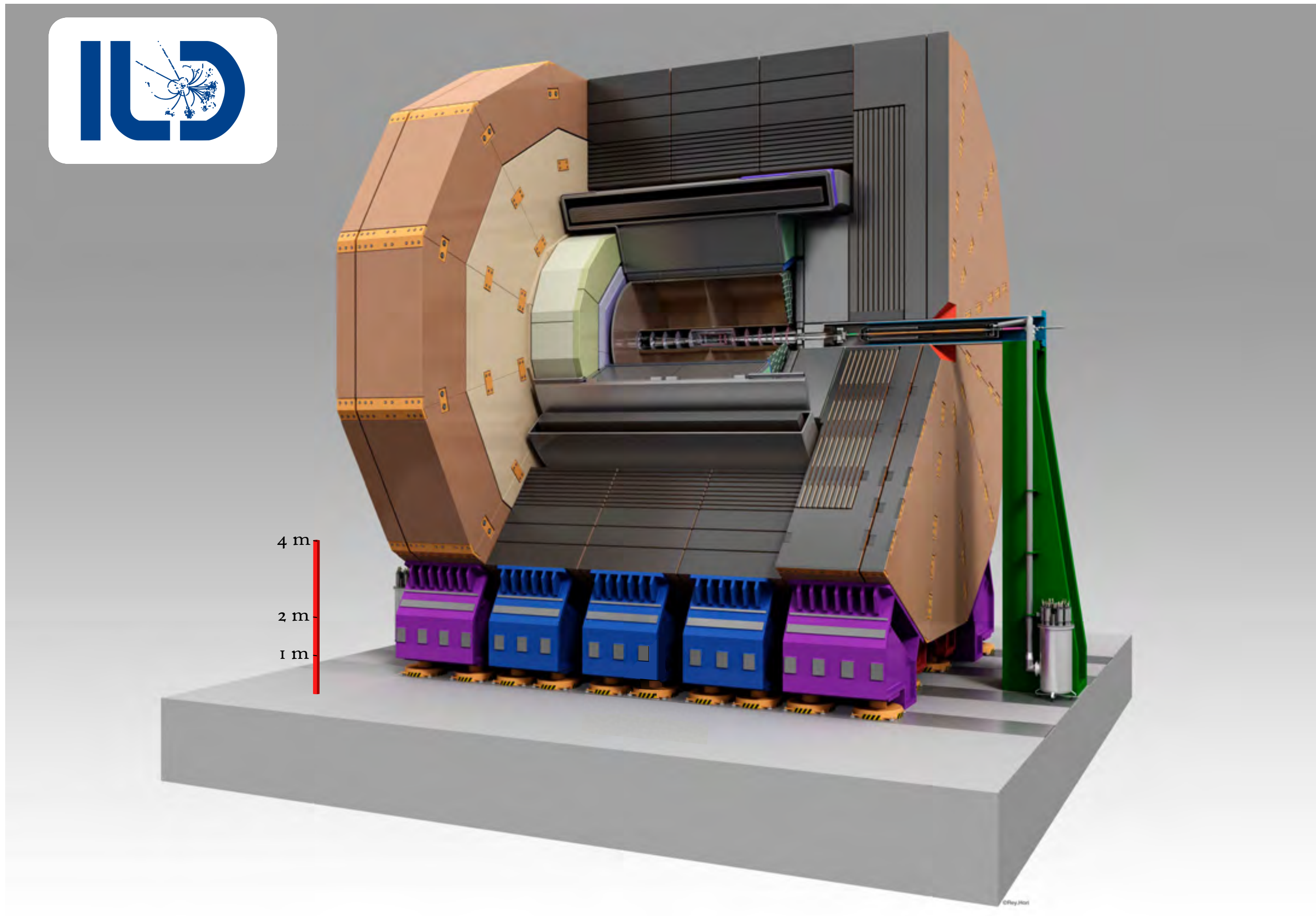


The dashed tracks are invisible to the detector

(ii.3) detectors @ ILC

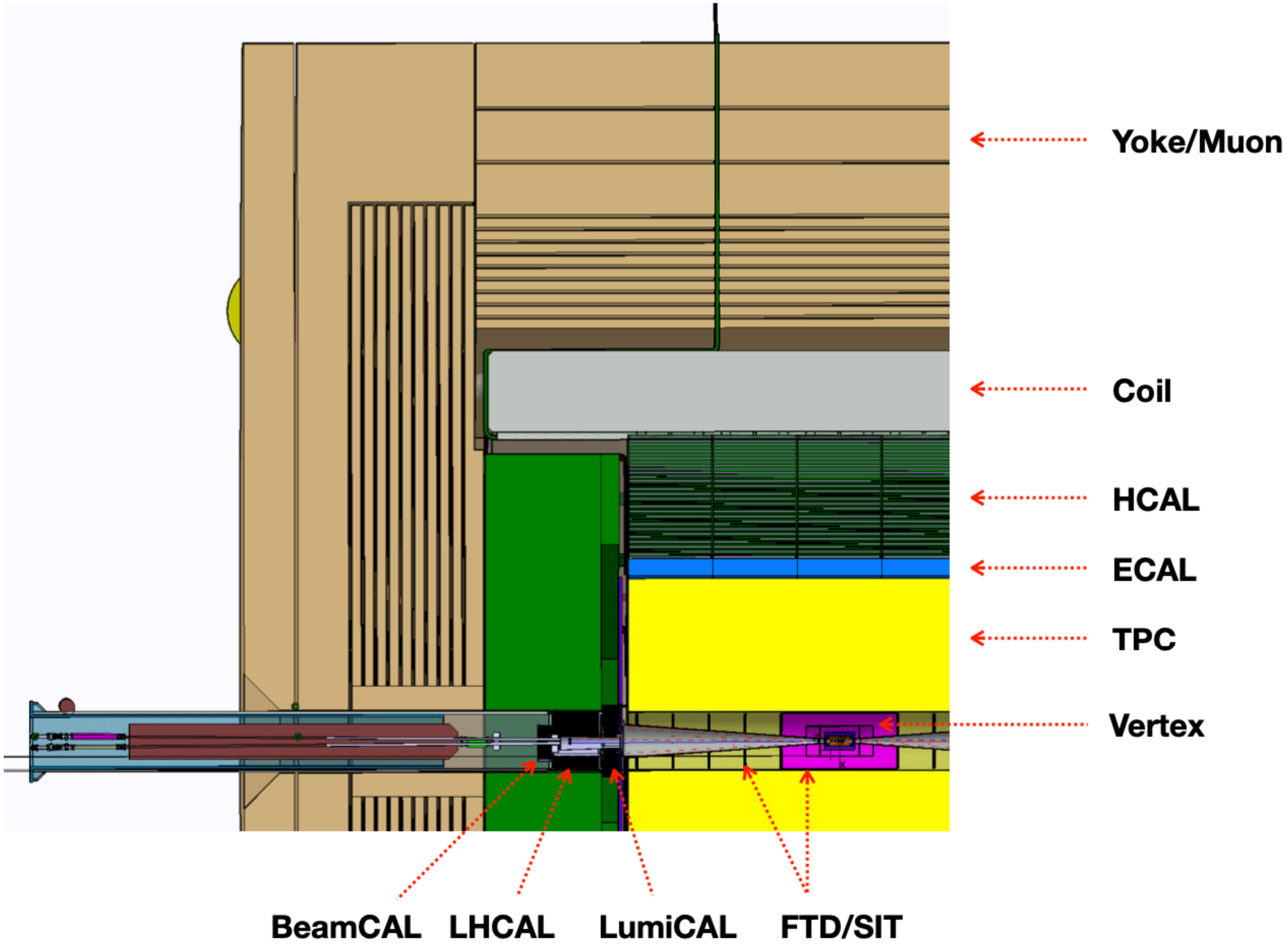
- two detector concepts; push-pull mechanism in IP





(ii.3) detectors @ ILC

- ILD: International Large Detector

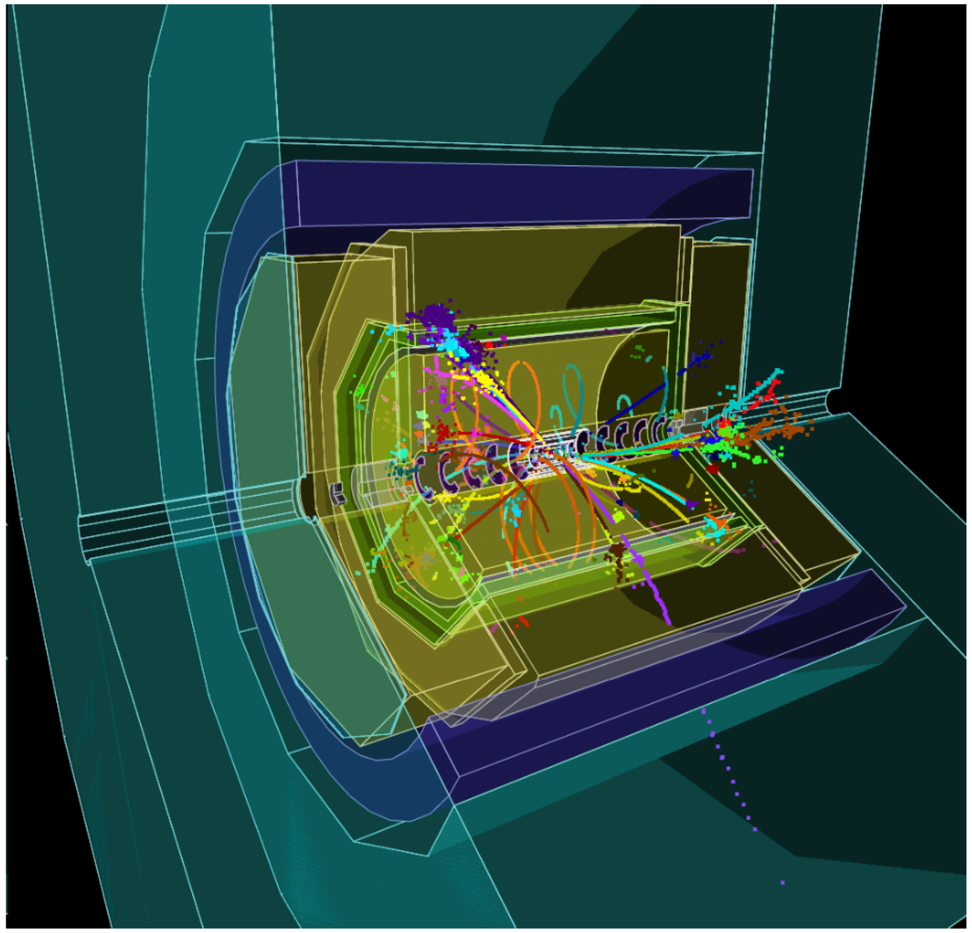


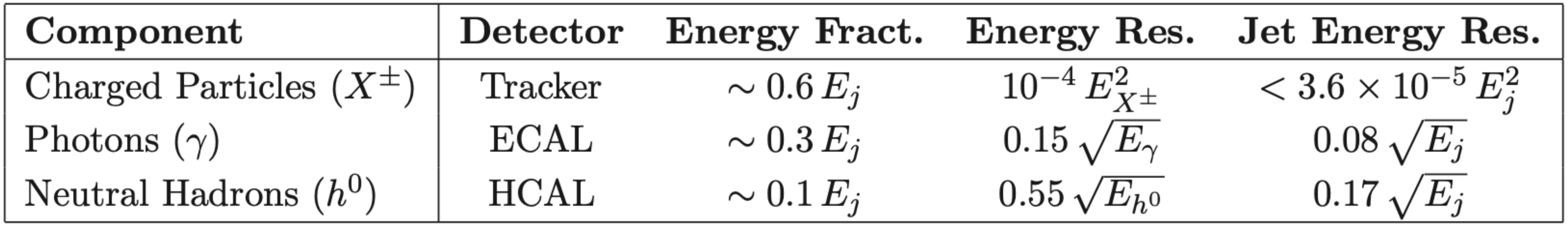
(ii.3) detectors @ ILC

- 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

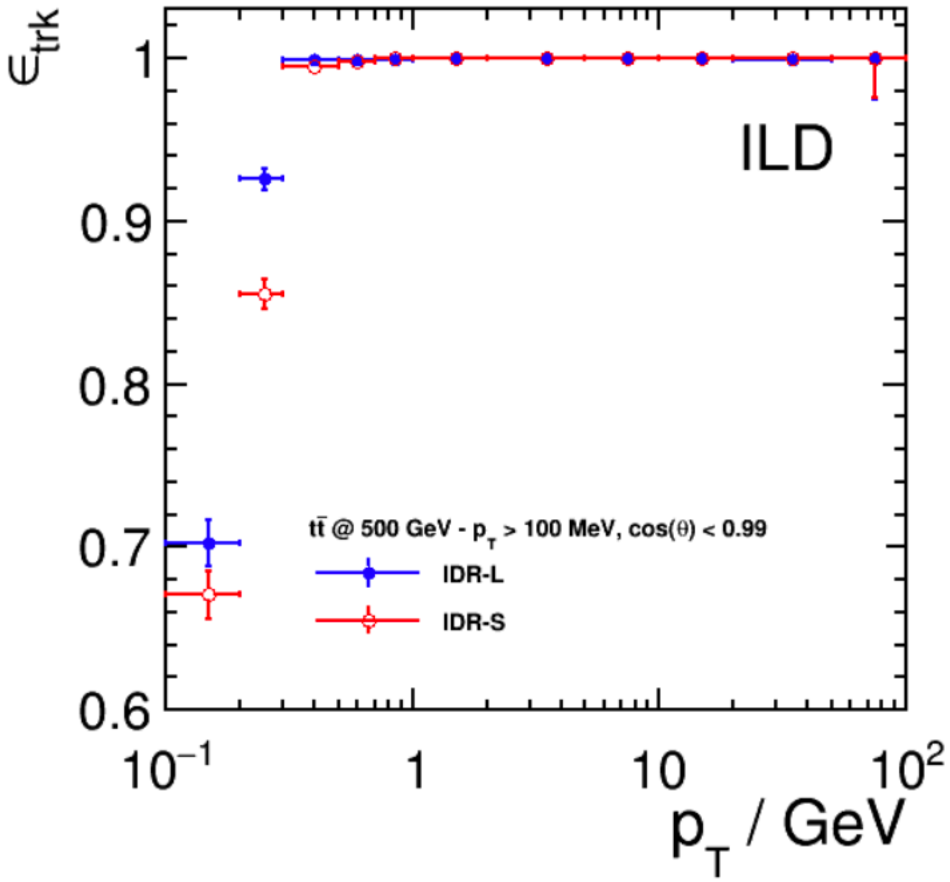
- typical performance
  - tracking

momentum resolution

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

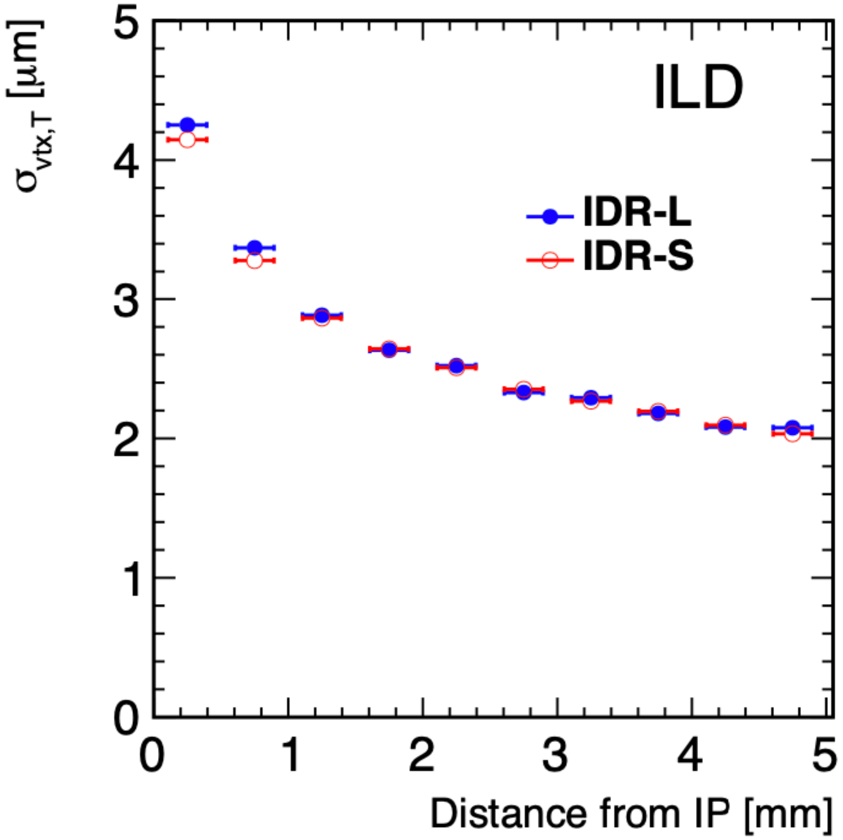
tracking efficiency

~100% for $P_T > 300$ MeV

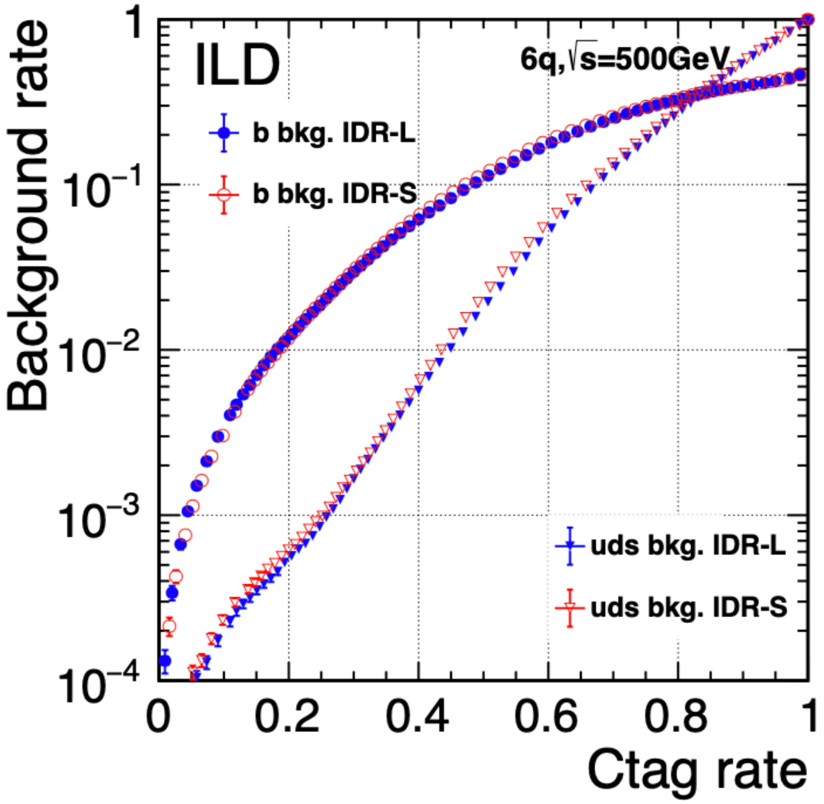


(ii.3) detectors @ ILC

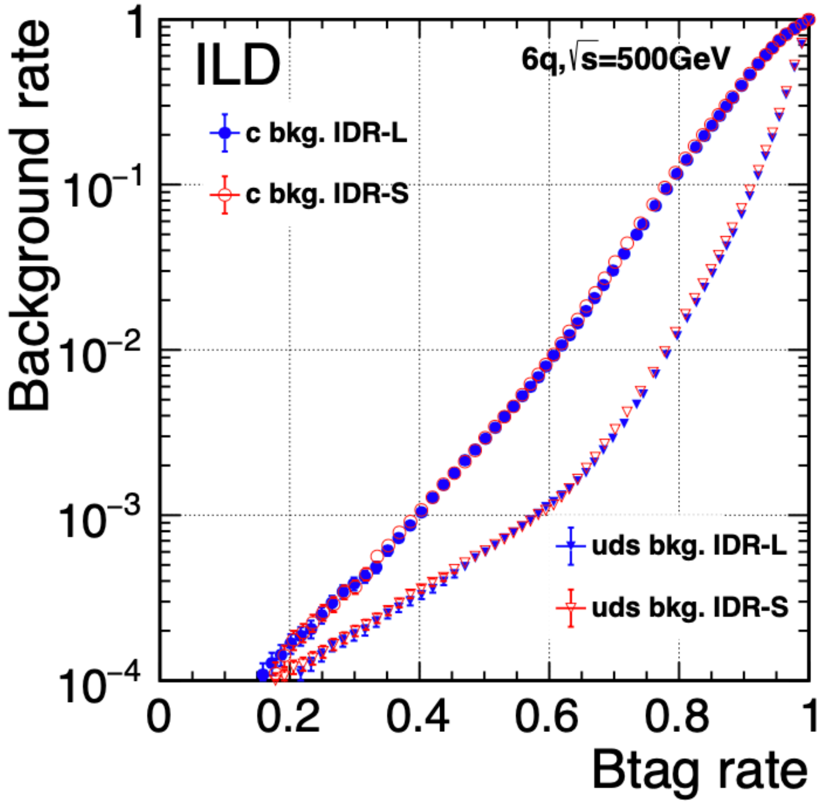
- typical performance
  - vertexing



secondary vertex
position from c-jets



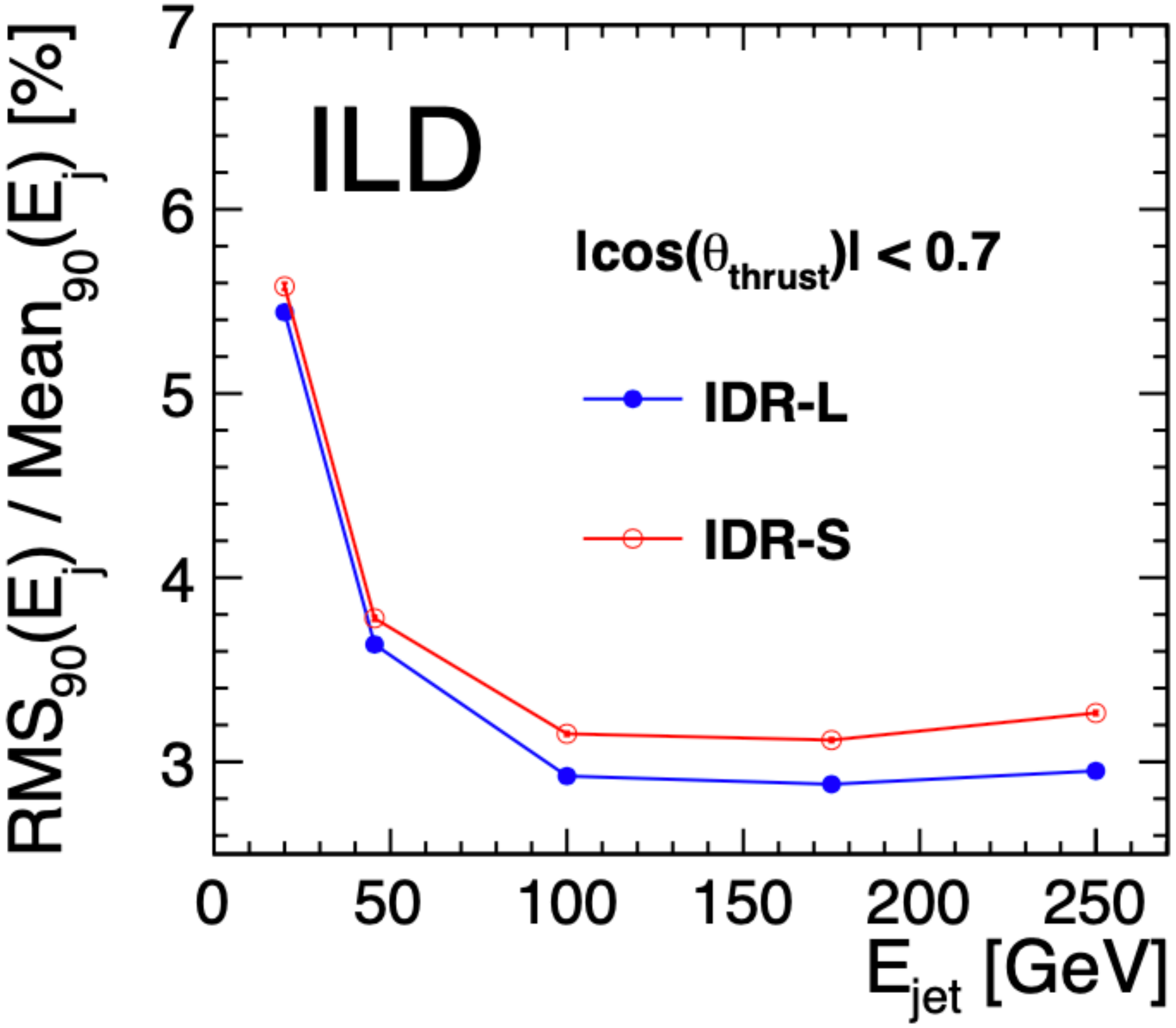
flavor-tagging
c-jet



flavor-tagging
b-jet

(ii.3) detectors @ ILC

- typical performance
  - jet energy resolution



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- event generator: WHIZARD

  including effects from ISR & beamstralung

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  full detector simulation; including pile-up events

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  vertex reconstruction; jet clustering; flavor tagging (LCFIPlus)

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- physics analysis

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

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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)