Detectors and Physics in Higgs factories

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Most slides are from ILC-J collaboration task force meeting on 21st January

Contents

- Physics for Higgs factories
- Basic design of detectors and key technologies
- Key performances issues and related technologies
  - Particle flow and jet energy reconstruction
  - Tracking performance
  - Particle ID / Flavor tagging

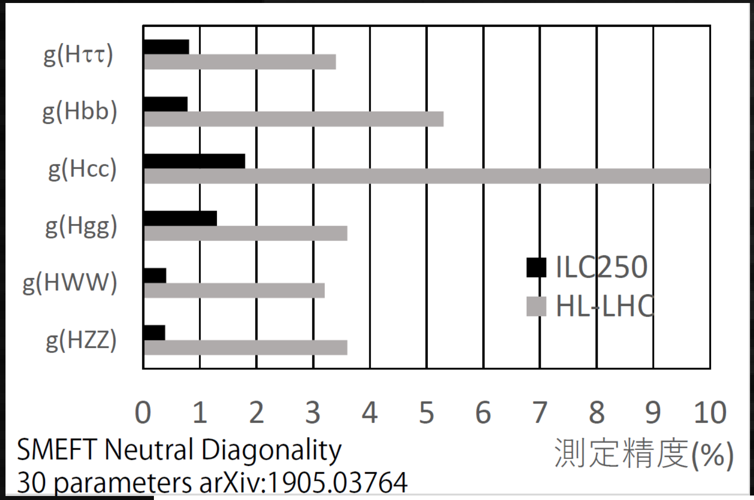
Physics for (Linear) Higgs factories

TeV-scale new physics

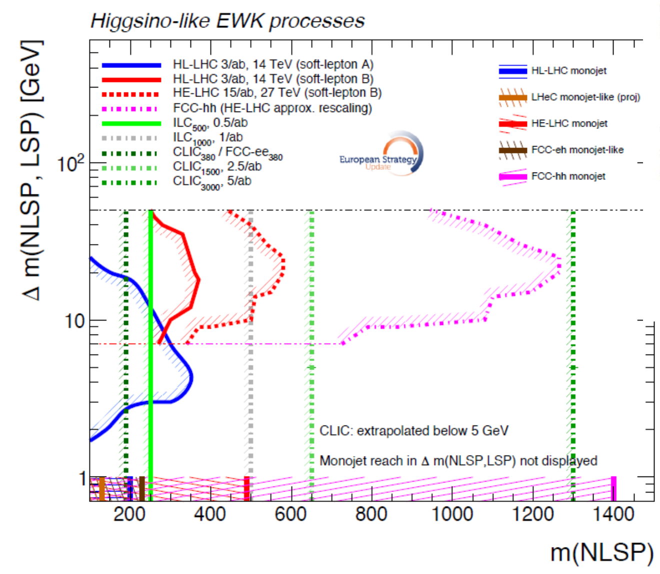
- Extended Higgs sector
  (SUSY, composite Higgs, …)
  - Higgs couplings, SMEFT
- Direct search (SUSY, …)
  - Compressed spectrum
  - Mono-photon for WIMP
  - Long-lived etc.
- Indirect search (Z’, WIMP, …)

Light new physics

- Higgs portal DM
  - Invisible/exotic decay of Higgs
- ALPs, dark photons, heavy stables
  - Fixed target, off-axis detectors

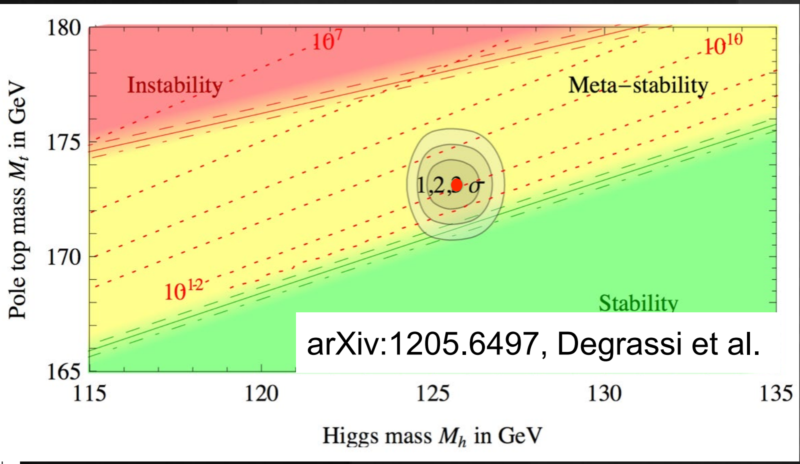


SMEFT Neutral Diagonality
30 parameters arXiv:1905.03764



Vacuum and spacetime

Higgs/top mass
Higgs self coupling
Higgs CP mixture



arXiv:1205.6497, Degrassi et al.

See JPS talk for details
https://kds.kek.jp/event/43097/contributions/222056/attachments/159589/204754/10pS1-04.pdf

Physics and Reconstruction performance

TeV-scale new physics

- Extended Higgs sector (SUSY, composite Higgs, …)
  - Higgs couplings, SMEFT
- Direct search (SUSY, …)
  - Compressed spectrum
  - Mono-photon for WIMP
  - Long-lived etc.
- Indirect search (Z’, WIMP, …)

Light new physics

- Higgs portal DM
  - Invisible/exotic decay of Higgs
- ALPs, dark photons, heavy stables
  - Fixed target, off-axis detectors

Detector challenges

b/c tagging
strange tagging

Low-p tracking
Forward detectors

Timing

Quark charge ID

Jet energy resolution

Vacuum and spacetime

Higgs/top mass

Momentum resolution
b tagging

Higgs self coupling

b tagging
Jet energy resolution(?)

Higgs CP mixture

Tau reconstruction
(track-photon separation)

Physics and Reconstruction performance

TeV-scale new physics

- Extended Higgs sector
  (SUSY, composite Higgs, …)
  - Higgs couplings, SMEFT
- Direct search (SUSY, …)
  - Compressed spectrum
  - Mono-photon for WIMP
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- Indirect search (Z', WIMP, …)

Light new physics

- Higgs portal DM
  - Invisible/exotic decay of Higgs
- ALPs, dark photons, heavy stables
  - Fixed target, off-axis detectors

Software challenges

b/c tagging
strange tagging

Low-p track finding

Track finding

Quark charge ID

Jet energy resolution

Vacuum and spacetime

Higgs/top mass

b tagging

Higgs self coupling

b tagging
Jet clustering

Higgs CP mixture

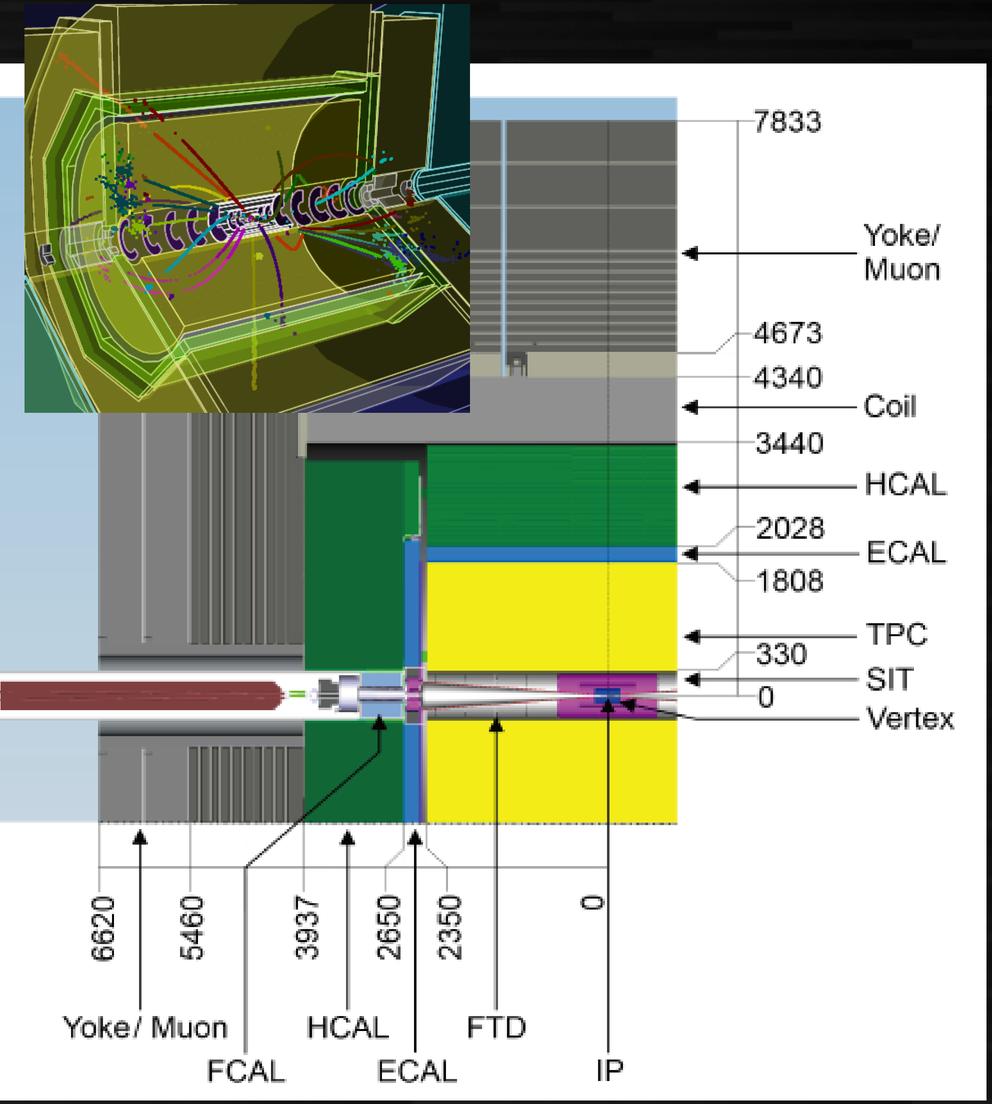
Tau reconstruction
(track-photon separation)

Interplay of hardware and software critical for most of the reconstruction

Contents

- Physics for Higgs factories
- Basic design of detectors and key technologies
- Key performances issues and related technologies
  - Particle flow and jet energy reconstruction
  - Tracking performance
  - Particle ID / Flavor tagging

A reference design for Particle Flow detector (ILD)



Vertex, Silicon Inner Tracker (SIT), Forward tracker (FTD)

- Monolithic silicon pixels (or strips possible at SIT/FTD)
  - Various technologies proposed (CMOS, SOI, Fine Pixel CCD, …)
- Point resolution of a few μm, 10^9 pixels & low material

Main tracker: Time Projection Chamber and Outer Silicon (SET)

- TPC: Continuous tracking & PID with dE/dx measurement
- SET: Silicon layer outside TPC, improving momentum resolution, optionally ToF measurement by picosec timing

High granular calorimeters (ECAL, HCAL)

- ECAL: Silicon or Scintillator, ~2500 m^2
  - Silicon: pad (5 x 5 mm^2) or pixel (50 x 50 μm^2, digital)
- HCAL: Scintillator or RPC, 1-3 cm cells

Superconducting solenoid (3.5-4 Tesla)

- Outside HCAL

Muon detector in Return yoke

Novel technologies: Two Big Waves

Picosec timing Target: 30 psec or less

Original interest for pileup rejection for HL-LHC

- Various competitive sensor technologies
  - Silicon – LGAD, SPAD, …
  - Scintillator – SiPM, but photon collection time is important
  - Cherenkov – same as above
  - RPC or GasPM
- Electronics
  - Power consumption issue
  - Clock distribution (serious for <10 ps)
- Industrial interest
  - Distance measurement (ToF-PET, driving) 1.5 mm / 10 psec

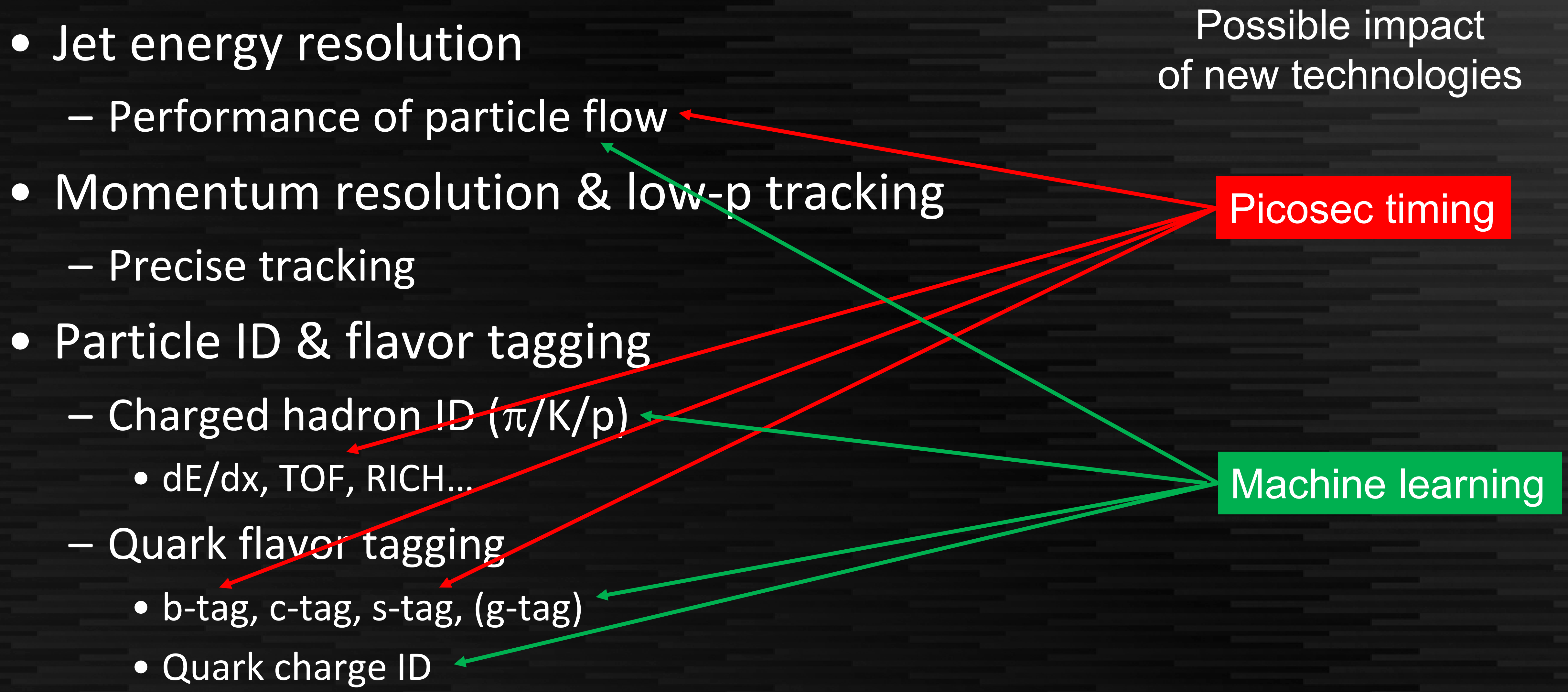
Machine learning

Rapid development on image and language processing based on Deep Neural Network

- Convolutional Neural Network
- Recurrent Neural Network and Transformer/Attention tech.
- Generative network
- Graph Neural Network
- Quantum machine learning

Dedicated design necessary for optimized performance
→ more efforts need to be put on

Key performances (revisited)

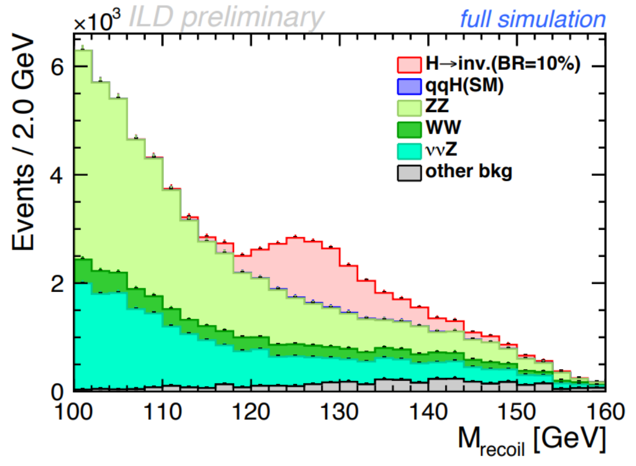


- Jet energy resolution
  - Performance of particle flow
- Momentum resolution & low-p tracking
  - Precise tracking
- Particle ID & flavor tagging
  - Charged hadron ID (π/K/p)
    - dE/dx, TOF, RICH…
  - Quark flavor tagging
    - b-tag, c-tag, s-tag, (g-tag)
    - Quark charge ID

Possible impact
of new technologies

Particle flow and granularity

Physics impact of jet energy resolution

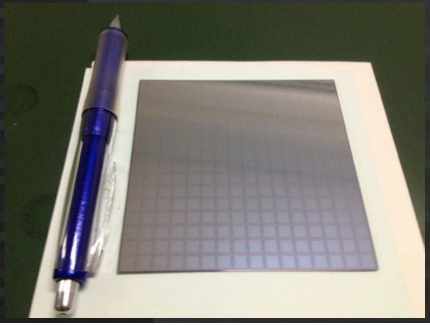


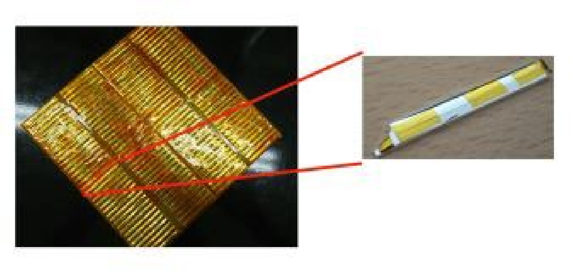
Recoil mass of ZH→ qqχχ
(Higgs invisible decay)

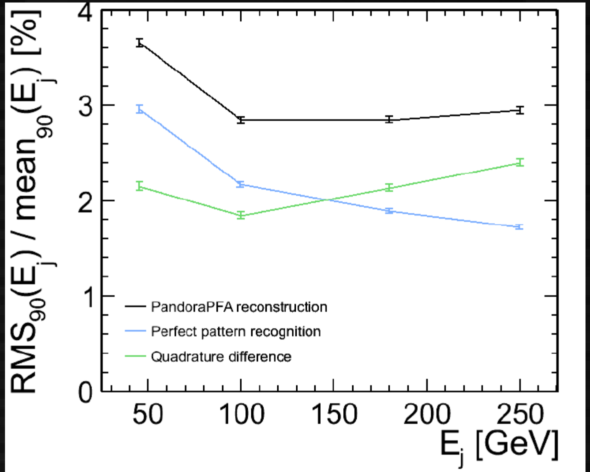
Higgs self coupling
(ZHH → qqbbbb)
Separation with
other 6q final states
(eg. ZZH → qqbbbb)

Medium-granular calorimeter (baseline)

Granularity: ~5 mm (silicon, scintillator)
Analog readout: requiring
wide dynamic range (1-1000 MIP)
Mature concept, working on
engineering issues on
electronics and mechanics







Confusion dominates
at higher energies

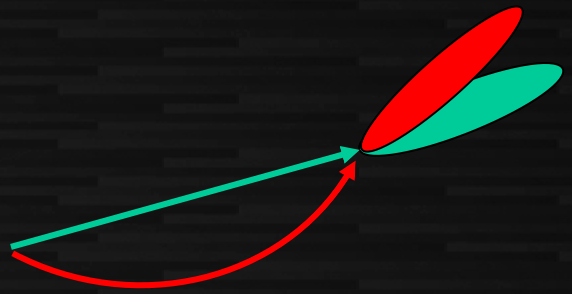
Ultra-granular calorimeter (advanced)

Granularity: < 100 μm (monolithic pixel)
Digital readout with integrated electronics
(or semi-digital better for higher energy?)
Large-area sensors (with low cost)
to be implemented and demonstrated

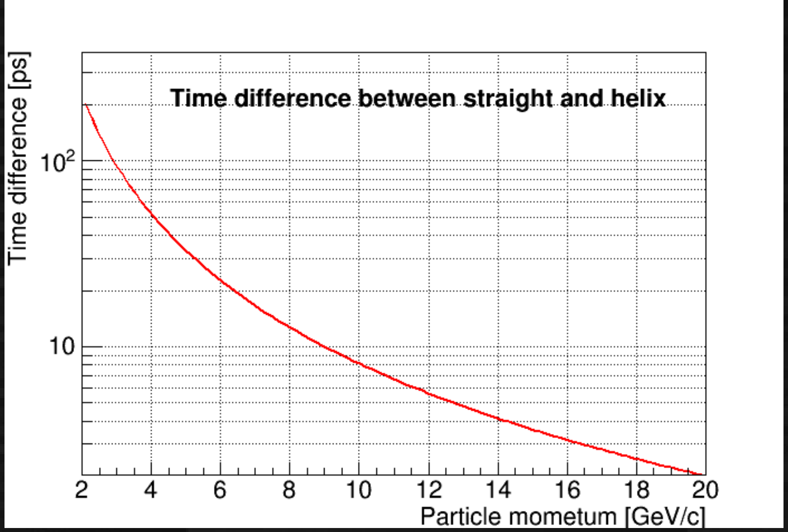
Particle flow and new technologies

Picosec timing

5-dimensional clustering



Timing difference on charged and neutral clusters



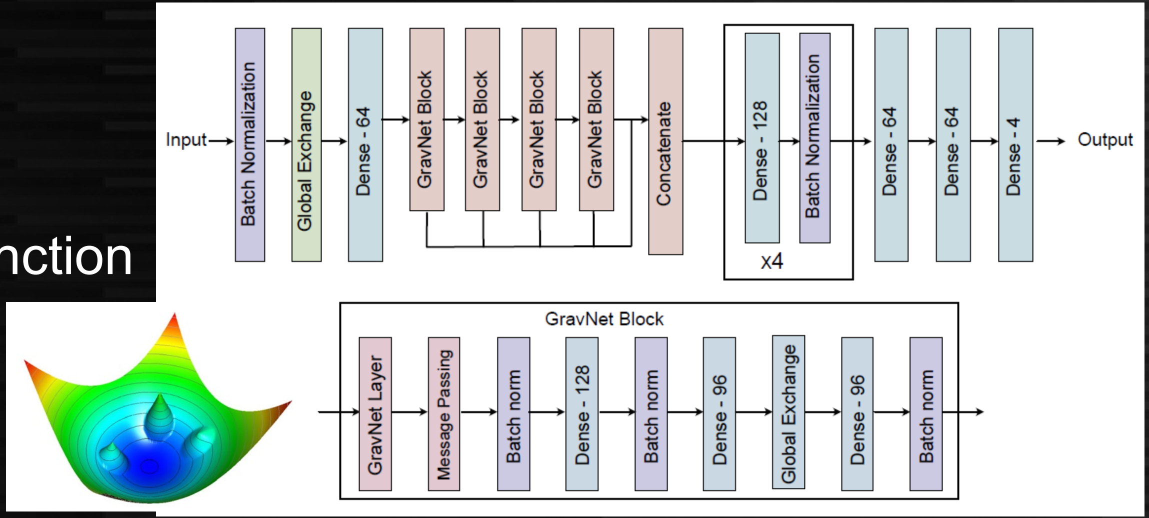
Timing resolution of EM cluster can be > 10 times higher than MIP thanks to averaging (intelligent pattern recognition necessary)

< 10 psec cluster resolution preferred

Machine learning

- Current PFA is human-tuned → dependence on detector performance difficult to be seen
- 5D clustering with timing information
- Better performance for physics

Loss function



CMS HGCAL algorithm
Now trying to apply to ILC simulation

Tracking-related performance

Physics impact of tracking

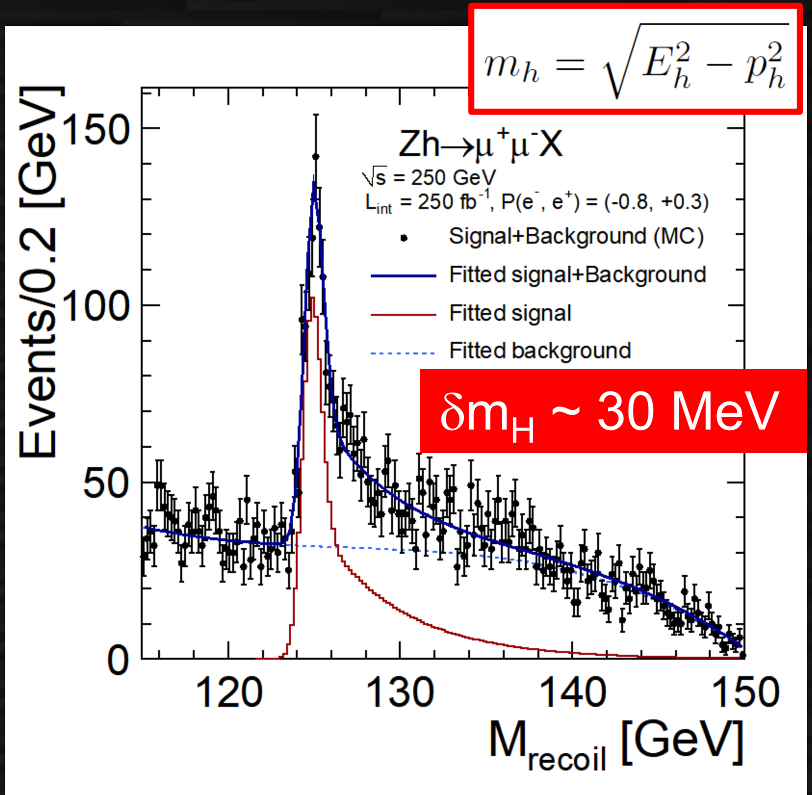
- Momentum resolution
  - Higgs recoil mass
- Low energy tracking
  - Low mass splitting BSM etc.

Silicon tracking

- Better point resolution (a few μm)
- Better timing
- Small hit points: discrete tracking

Gas tracking (TPC)

- Worse point resolution (60-100 μm in ILD)
- No timing
- Continuous tracking stronger for low-p
- dE/dx capability



$$m_h = \sqrt{E_h^2 - p_h^2}$$

$\delta m_H \sim 30$ MeV

Extreme position resolution with thin silicon

- Multiple scattering effectively limits momentum reso
- Ultra-thin (O(10 μm)) sensor possible with LGAD/SPAD techniques (thanks to gain) → realizing sub-μm (or even 100 nm) resolution?
- Can improve resolution or realize smaller tracker?

Charged hadron ID (track mass measurement)

Impact of hadron ID / track mass

- Strange tagging (p/K/π separation)
  - H → ss
  - EW form factor, Z'/WIMP
- b/c tagging (through s-tag) / charge
  - Reconstructing full decay chain
- Jet energy resolution (PFA)
  - Assign correct mass to tracks
- Heavy track (BSM)

Detailed studies for physics impact has not fully done yet.

How to perform hadron ID

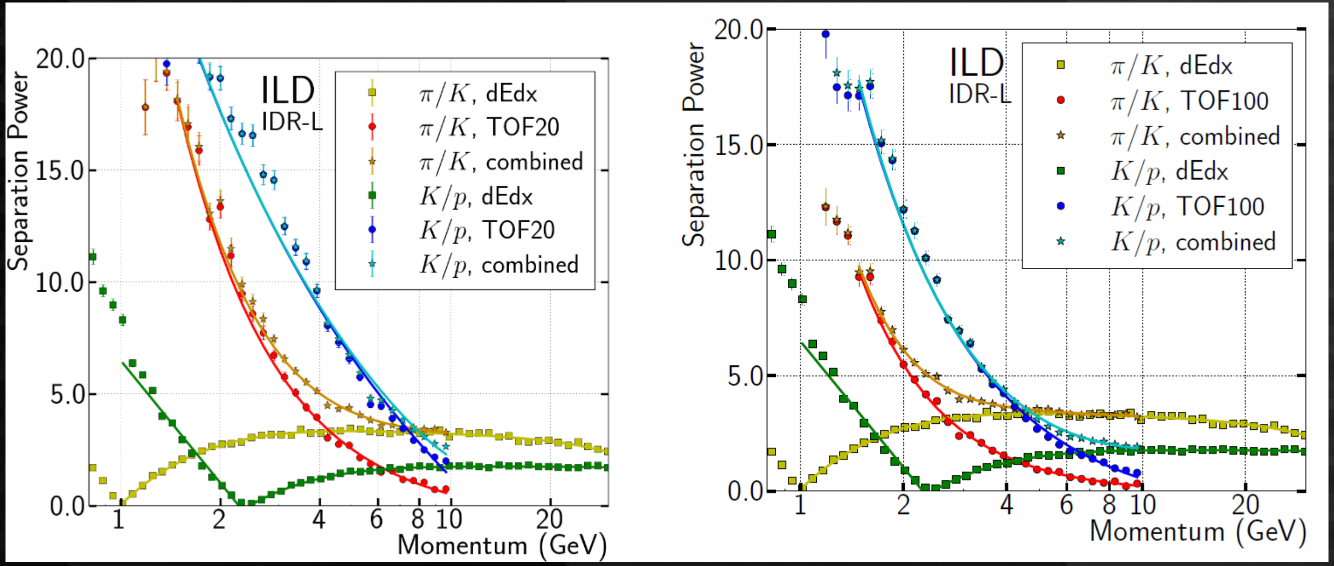
- dE/dx at tracker (TPC)
  - Moderate separation up to tens of GeV
  - Ineffective region at a few GeV
  - Better separation with pixel readout expected
- Time of Flight (ToF) (details on next page)
  - Good to cover the few GeV region (with O(100 psec))
  - O(10psec) can cover up to 5-10 GeV (not fully compensating dE/dx with TPC)
- Ring-imaging Cherenkov (RICH)
  - To be placed between tracker and calo
  - Being considered in SiD

Hadron ID and new technologies

Picosec timing

Time-of-flight at calo or tracker

- Outer tracker (silicon)
  - Fewer hits to average (require better MIP reso)
  - Capacitance of strips
  - No power on neutrals
- Calorimeter
  - Many hits to average (better)
  - Need intelligent algorithm (to remove slow hits)
  - Small pixel for capacitance → problem of electronics Maybe not realistic for implementation of full layers



Significance of p/K/p separation
TOF by calorimeter hits (~10 hits averaged)

Machine learning

Necessary for timing reconstruction at calo
DNN PFA can output timing information as well

ML is less important for ToF of trackers

Quark flavor tagging

Impact of flavor tagging

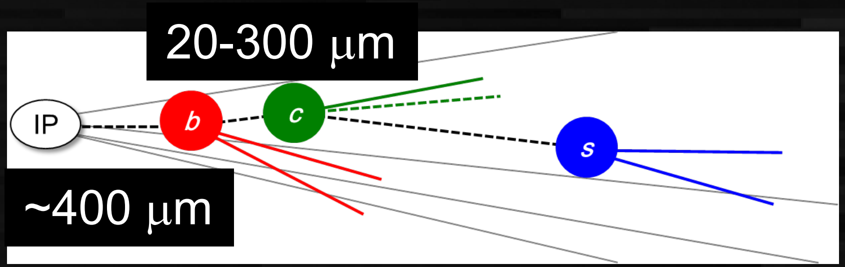
- Higgs couplings (Hbb, Hcc, Hgg)
  - c-tag especially important
- Higgs self coupling (ZHH)
  - Separation of tt background
- EW precision (2f, triple coupling)
- Exotic Higgs decay
  - eg. $H \rightarrow \phi\phi \rightarrow 4b / 2b2\chi$
- Various BSM models

Decay mode of ZHH	BR.	# events in 4 ab^{-1}
qqbbbb	22%	176
$\nu\nu$bbbb	7%	56
llbbbb	3%	24
tt -> bbqqqq		~1,000,000
ZZZ, ZZγ, ZZH -> qqbbbb		~1,000

Statistics of self coupling analysis

Hardware for flavor tagging

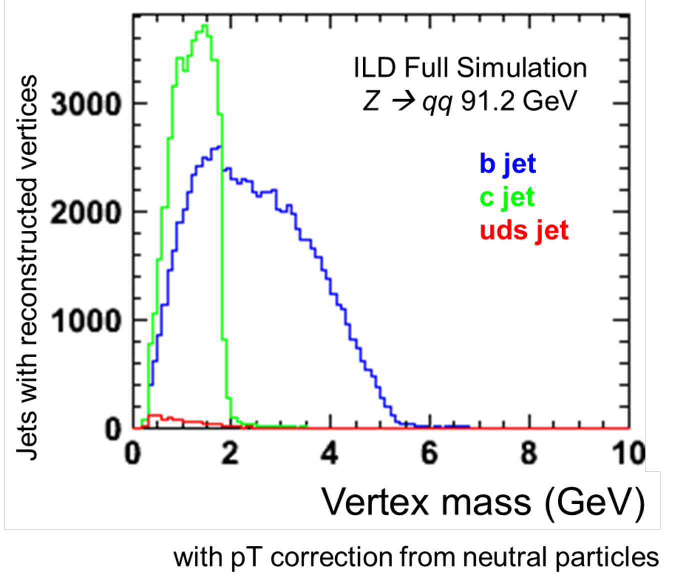
- Vertex detector
  - 15 – 60 mm from IP limited by pair background
  - A few μm resolution is more than enough for b-tag, can be smaller for c-tag
    - So smaller resolution only improves c-tag
- Particle (Kaon) ID
  - Can help reconstructing decay chain but software needs to be improved
- Off-IP photons by timing (next page)



Flavor tagging and new technologies

Picosec timing

- Identifying π^0 from secondary vertices
  - 1 psec = 0.3 mm for photons
    → 30 psec/MIP & 1000 MIP averaged
    to obtain 1 psec: ultimate goal



with pT correction from neutral particles

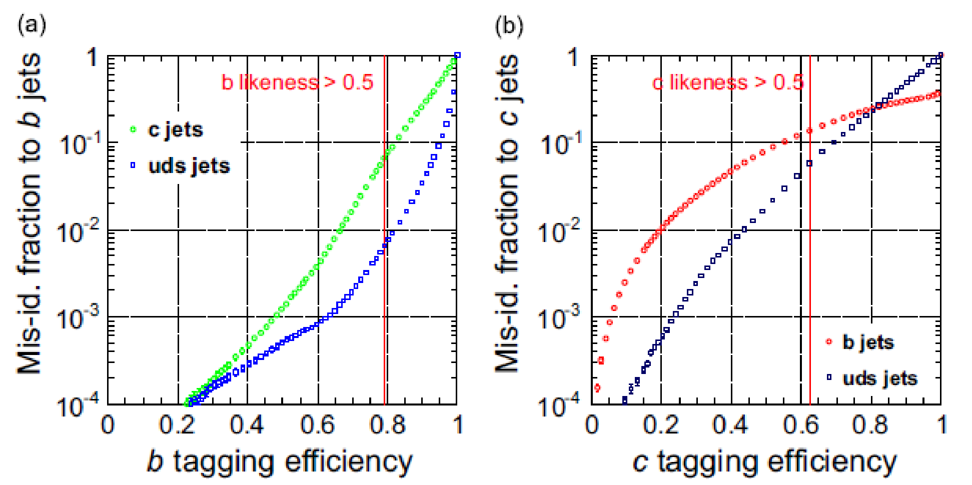
Vertex mass gives square distribution
with charged particle only:
should be peaky with neutrals

Machine learning

Current algorithm (LCFIPlus)

- Vertex finding (cut-based)
- Jet clustering (pairing)
- Flavor tagging (BDT)

Single DNN process with combined function?
Now trying graph neural network



LCFIPlus performance

Summary

- Physics performance depends on detector and software
  - Quark/lepton ID, jet energy/clustering, tracking, …
  - Sometimes not so clear, strongly dependent on analysis/software
- New technologies: timing and (deep) machine learning
  - Many cases to (possibly) improve the physics performance
  - But may not be a game changer (up to now…)
    - Innovative ideas very welcome! Please consider or do brainstorming
- Wider collaboration is desirable!

Backup

Contents

- Physics for Higgs factories
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  - Particle flow and jet energy reconstruction
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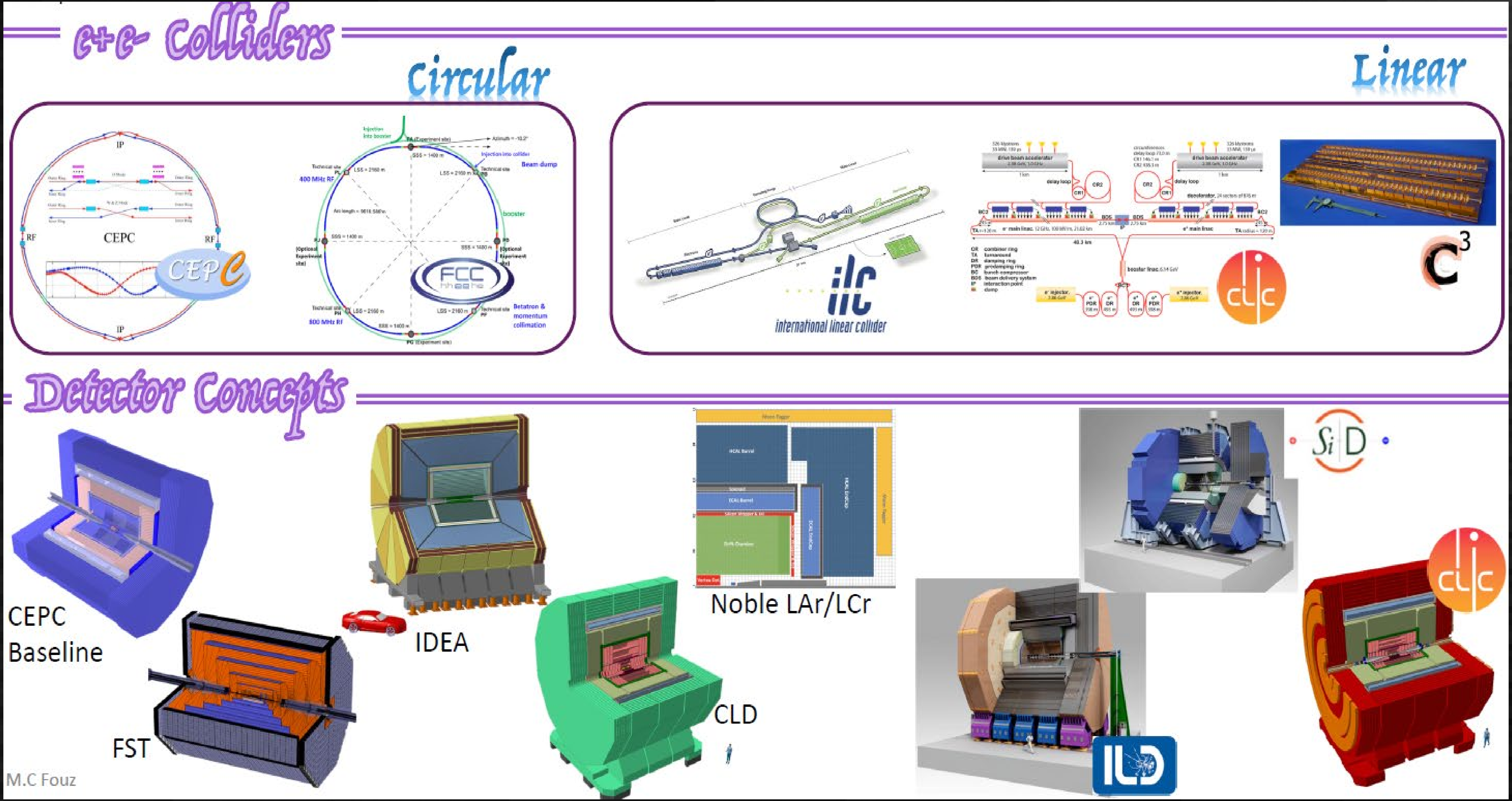
  - Particle ID / Flavor tagging

Detectors for Higgs factories



e+e- Colliders

Circular

Linear

Detector Concepts

CEPC Baseline

FST

IDEA

CLD

Noble LAr/LCr

SiD

ILD

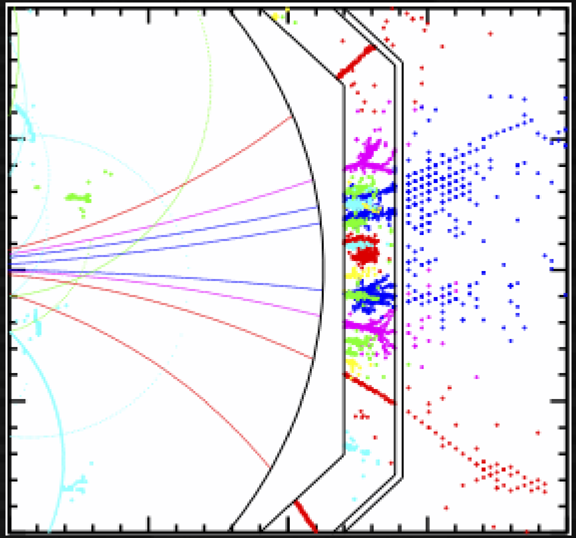
CLIC

M.C Fouz

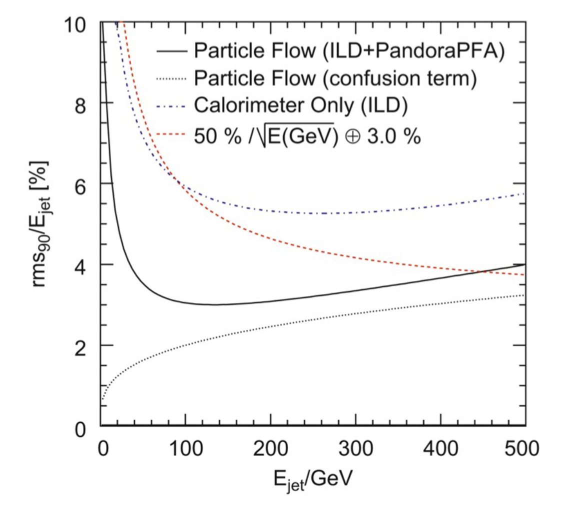
HF detector: particle flow vs dual readout

Particle flow

ILD, SiD, CLIC, CLD, CEPC, FST, LAr(?)



Separate particles in jets
with high-granular calorimeter
Large B field and big detector
for better separation of particles
Solenoid outside hadron calorimeter



2x better jet energy
resolution compared to
traditional calorimetry
More information on
jet substructure
→ ML-friendly info

Dual readout

IDEA (for FCCee/CEPC), 4th (for ILC)

Concurrent acquisition
of scintillator and Cherenkov

- Scintillator → energy dep.
- Cherenkov → # particles

Separate hadronic and
electromagnetic component
of shower by the ratio of 2

Smaller detector possible
because of no need of
separating jet particles

Key detector elements: Silicon sensors

Common key advantages

- Small pixels without physically-divided sensors (cf. assembly of small scintillators)
- Intrinsic integration with electronics (ie. Monolithic sensors)
- Good intrinsic resolution of energy deposit (3.6 eV/e-h pair)
- Relatively low material (disadvantage for calorimetry though)

Multiple technologies
Wide applications
on vertex, tracker,
calorimeter

Monolithic sensors

For vertex detector / inner tracker

- < 25 μm sensor cells, 50 μm thick for point resolution of a few μm
- Fast readout (>20 readout / 1ms)
- Low power consumption

For outer tracker / calorimeter

- Large area (100m^2 for outer tracker, ~2000 m^2 for ECAL)
- Low dead area with big sensors are one of the big issues of development
- Picosec timing? (impossible with plain CMOS)

Strip sensors (hybrid)

For main/outer tracker

- 25 μm pitch, 7 μm reso (in current ILD design)
- Or extreme resolution of 0.1-1 μm?

Pad sensors (hybrid)

For calorimeter

- 5 x 5 mm^2 cells, 10^8 ch
- 2500 m^2, cost sensitive
- Electronics & cooling

Picosec timing

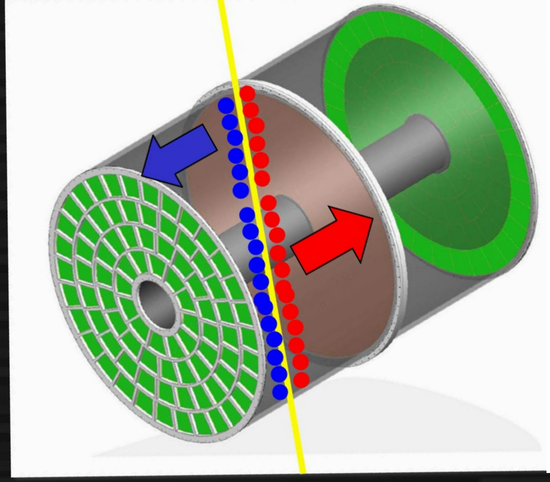
For outer tracker/calorimeter

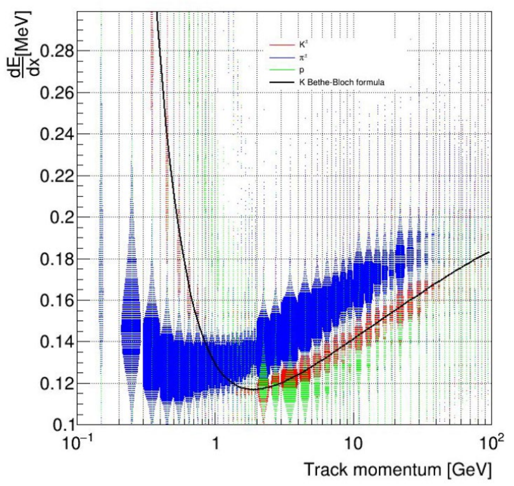
- Standard LGAD: ~30 psec
- New technologies
  - Thinner LGAD
  - Monolithic LGAD
  - SPAD
- Issues on electronics

Key detector elements: Gas & Optical sensors

Time Projection Chamber

- Continuous tracking by gas
  - 2D position at pad sensors
  - Z position by drifting time
- MPGD (GEM/Micromegas) for amplification
- dE/dx for particle ID
  - Better with cluster counting with silicon pixel instead of pads → connection to silicon sensor R&D





Optical calorimeter

- Finely-segmented scintillator strips or tiles with SiPMs for ECAL/HCAL
  - ECAL: crossing strips to realize effectively fine segmentation with smaller # of sensors
- Timing with SiPMs – similar technology to SPAD silicon sensor
- Essentially cheaper than silicon pads but more on assembly and calibration
- Options: adding Cherenkov absorber while maintaining fine segmentation (PFA + dual-readout)

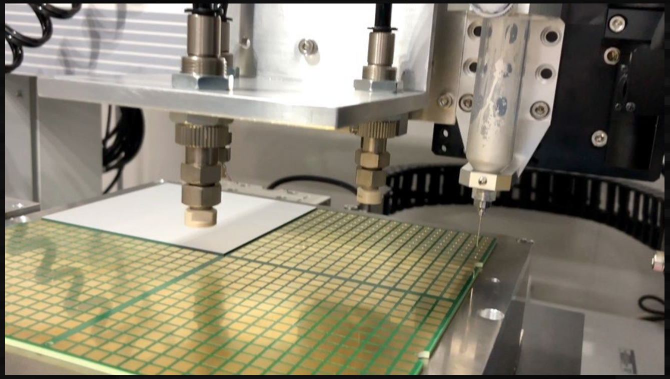
Key detector elements: electronics & mechanics

Readout electronics

- Frontend electronics
  - readout ASIC
  - Analog/digital combined
  - Power pulsing
    millisec (for trains) demonstrated
    nanosec (for bunches) possible?
  - Smaller design rules
    → more professional effort
    on development (not easy to contribute)
- Backend & DAQ
  - Large-scale design for full detector
    not seriously discussed yet
    → room for contributions!

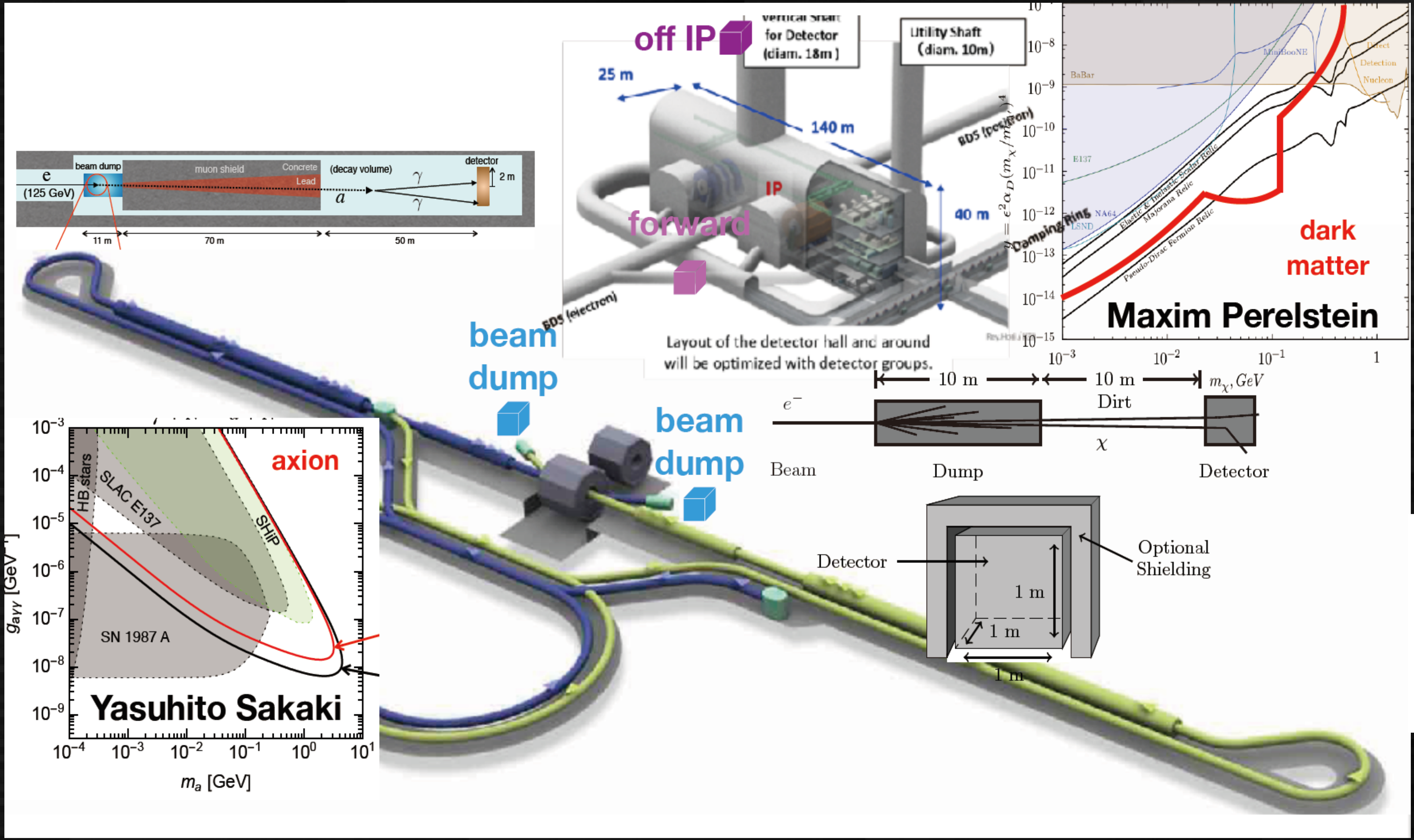
Assembly / Mechanics

- Assembly method for module
  - Assembly of sensors (esp. optical)
  - Interconnection of sensor/electronics
    (eg. silicon – WB, BB, ACF, glue, …)
  - Automatic assembly (robots, AI)
- Mechanical design
  (low material, stable, precise)
- Quality control / assurance etc.



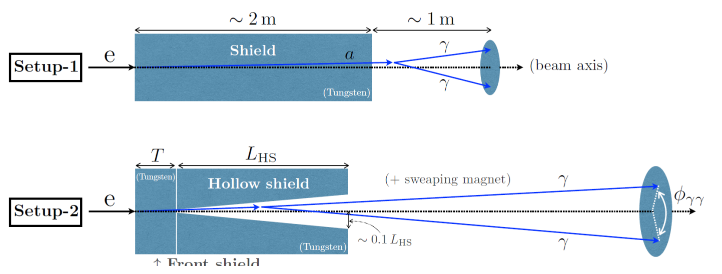
Gluing
silicon pads
to frontend

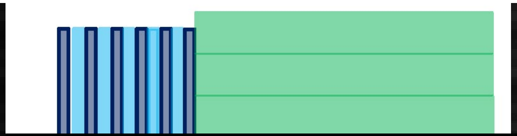
Appendix: Off-IP detectors



Fixed-target experiments are also important for application of HF detector technology
eg.) KEK Linac beam dump experiment (EBES)

T. Izawa, A. Ishikawa, H. Iwase, H. Oide, F. Miyahara, Y. Morikawa, Y. Sakaki, Y. Takubo, S. Higashino, H. Otono, T. Suehara, K. Yoshihara, S. Tsumura





High-granular calorimeter for 2-photon separation

Welcoming various ideas on detectors at beam dump and off-IP

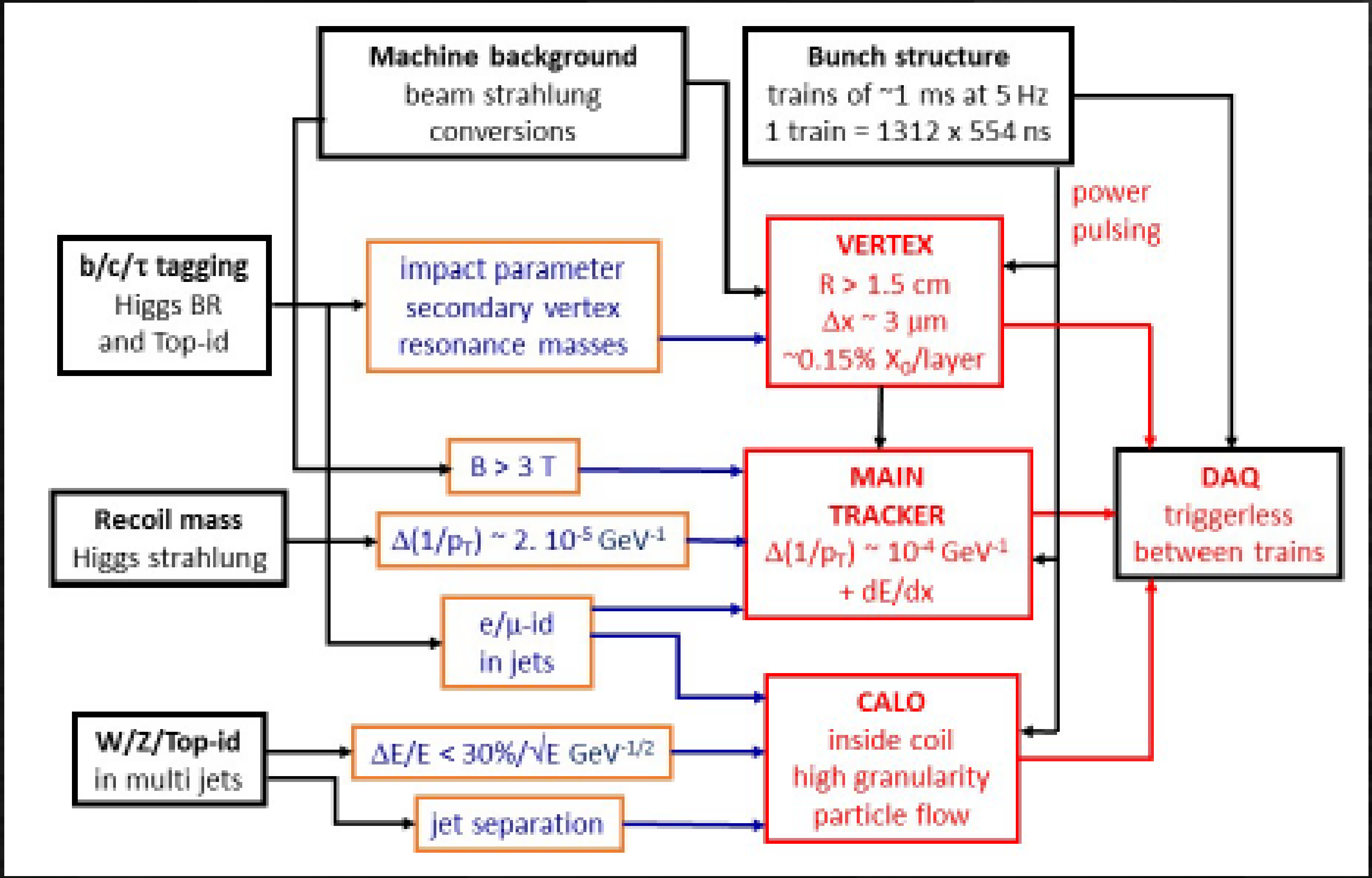
Final remarks

- Detector development has stages
  1. Proof-of-concept of novel ideas
  2. Conceptual demonstration of emerging technologies
     - Recent interest: pico-sec timing and machine learning
  3. Engineering design and prototyping of proven technologies
     - Many remaining issues on sensors, electronics, mechanics for each detector (pixel, tracker, calorimeter)
  4. Real construction

Today's focus

- We should pursue better performance with emerging technologies while getting ready for construction with proven technologies
  – Both are important and attractive targets!
- Let's discuss and work for the next-generation collider detectors!

ILD performance requirements



Machine background
beam strahlung
conversions

Bunch structure
trains of ~1 ms at 5 Hz
1 train = 1312 x 554 ns

power pulsing

b/c/τ tagging
Higgs BR
and Top-id

impact parameter
secondary vertex
resonance masses

VERTEX
$R > 1.5$ cm
$\Delta x \sim 3\ \mu m$
~0.15% X_0/layer

$B > 3$ T

Recoil mass
Higgs strahlung

$\Delta(1/p_T) \sim 2.\ 10^{-5}\ GeV^{-1}$

MAIN TRACKER
$\Delta(1/p_T) \sim 10^{-4}\ GeV^{-1}$
+ dE/dx

DAQ
triggerless
between trains

e/μ-id
in jets

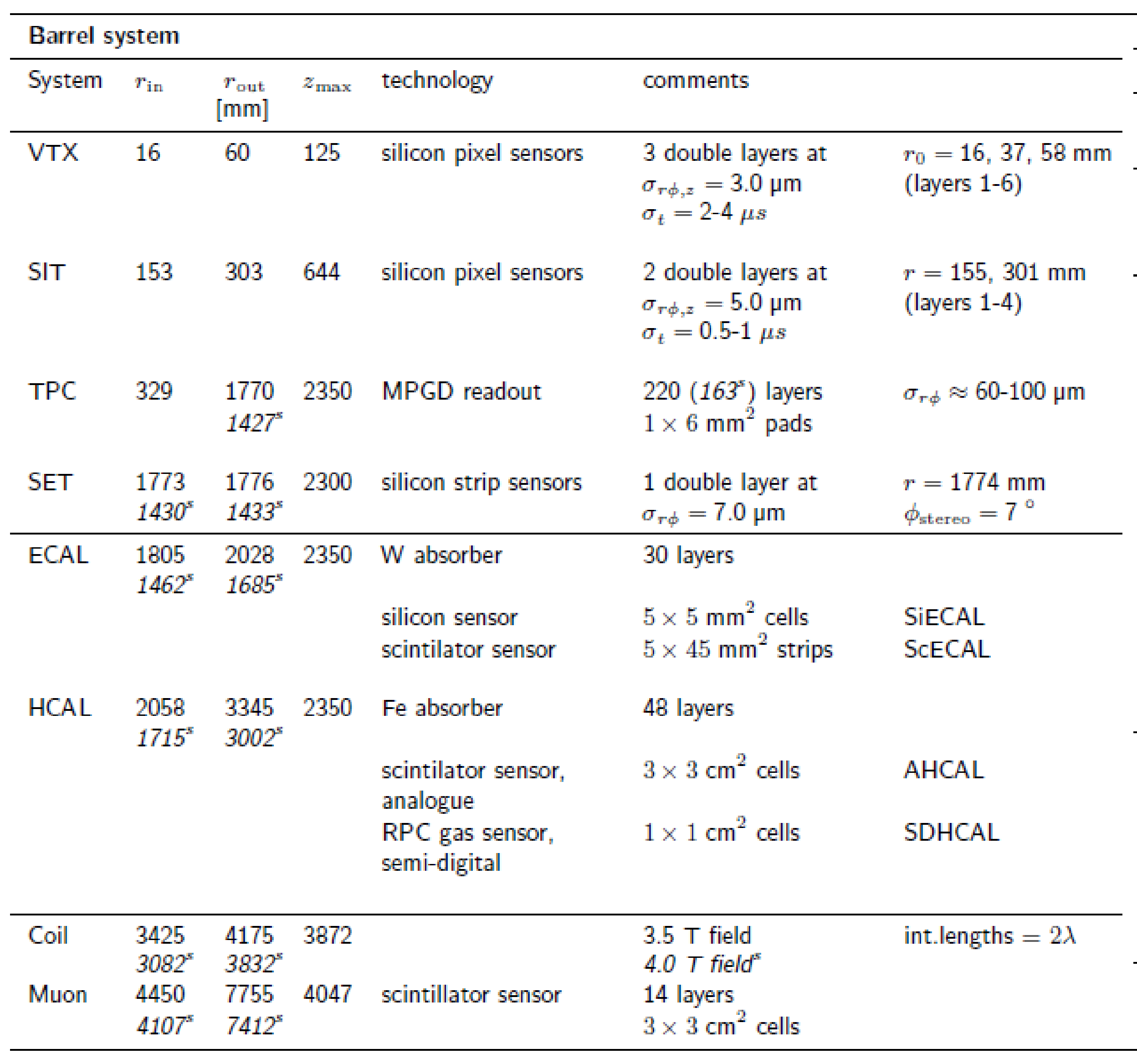
W/Z/Top-id
in multi jets

$\Delta E/E < 30\%/\sqrt{E}\ GeV^{-1/2}$

jet separation

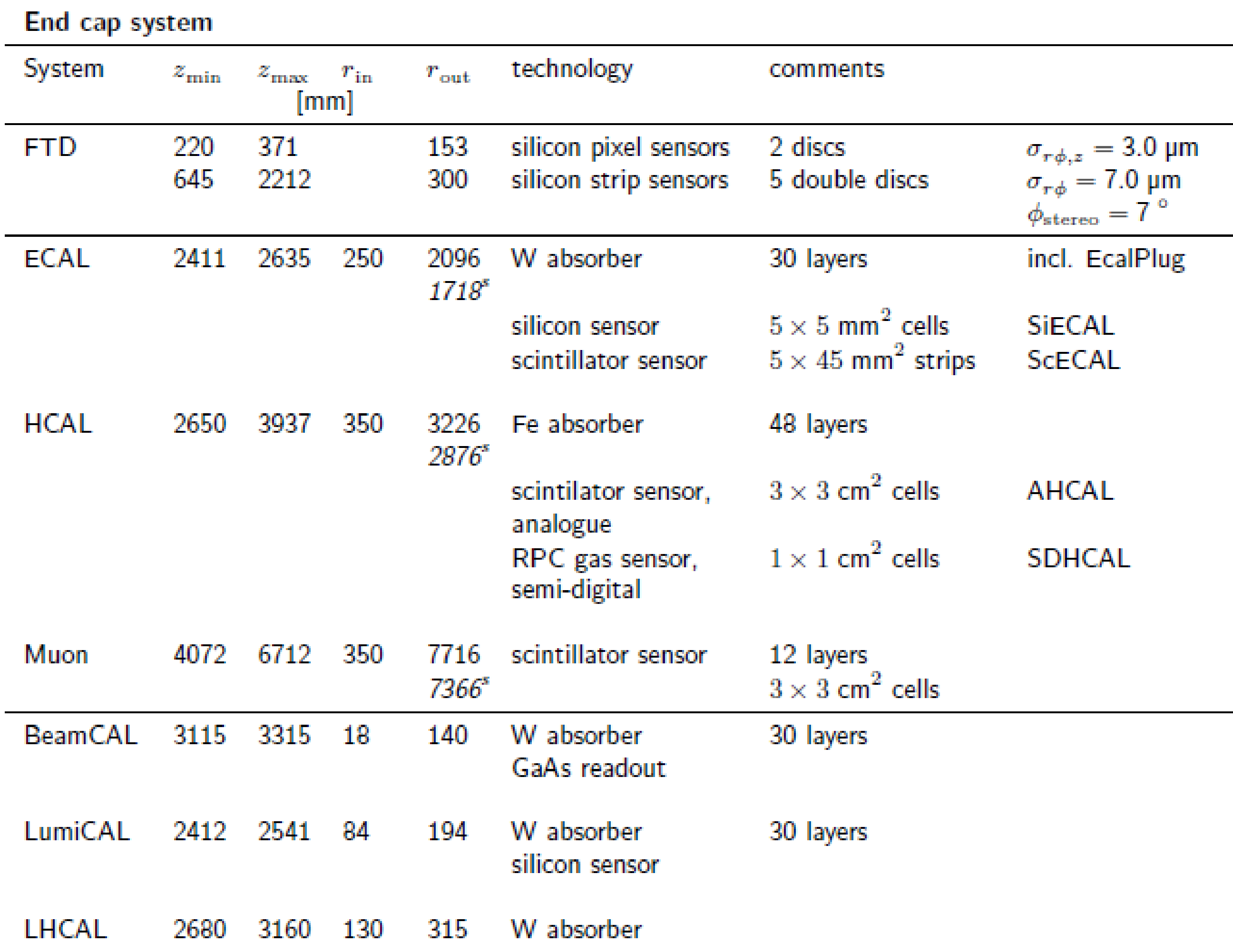
CALO
inside coil
high granularity
particle flow

ILD specifications



Barrel system

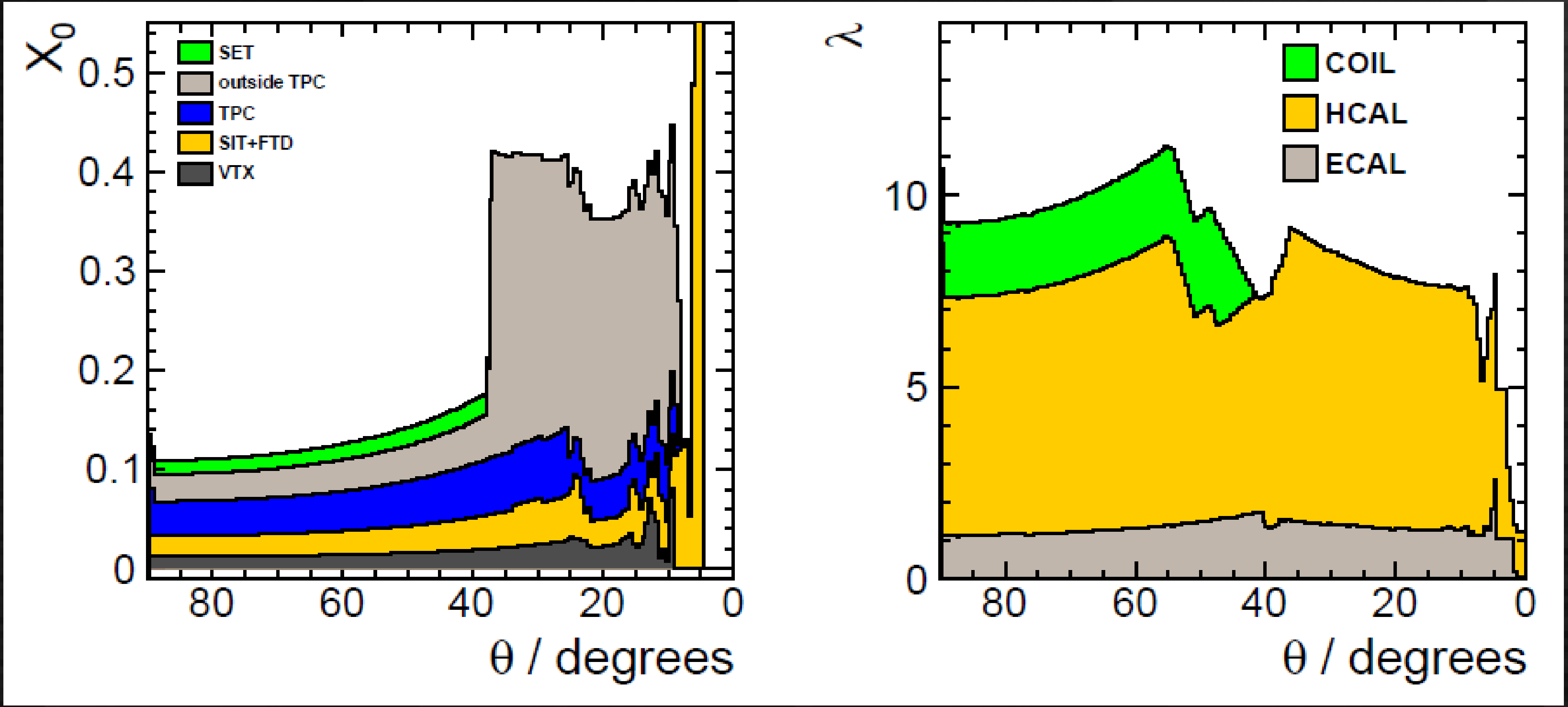
System	r_{in}	r_{out} [mm]	z_{max}	technology	comments	
VTX	16	60	125	silicon pixel sensors	3 double layers at $\sigma_{r\phi,z} = 3.0$ µm $\sigma_t = $ 2-4 μs	$r_0 = 16, 37, 58$ mm (layers 1-6)
SIT	153	303	644	silicon pixel sensors	2 double layers at $\sigma_{r\phi,z} = 5.0$ µm $\sigma_t = $ 0.5-1 μs	$r = 155, 301$ mm (layers 1-4)
TPC	329	1770 $\mathit{1427}^{s}$	2350	MPGD readout	220 ($\mathit{163}^{s}$) layers 1×6 mm^2 pads	$\sigma_{r\phi} \approx$ 60-100 µm
SET	1773 $\mathit{1430}^{s}$	1776 $\mathit{1433}^{s}$	2300	silicon strip sensors	1 double layer at $\sigma_{r\phi} = 7.0$ µm	$r = 1774$ mm $\phi_{\mathrm{stereo}} = 7\,^{\circ}$
ECAL	1805 $\mathit{1462}^{s}$	2028 $\mathit{1685}^{s}$	2350	W absorber	30 layers	
				silicon sensor scintillator sensor	5×5 mm^2 cells 5×45 mm^2 strips	SiECAL ScECAL
HCAL	2058 $\mathit{1715}^{s}$	3345 $\mathit{3002}^{s}$	2350	Fe absorber	48 layers	
				scintilator sensor, analogue	3×3 cm^2 cells	AHCAL
				RPC gas sensor, semi-digital	1×1 cm^2 cells	SDHCAL
Coil	3425 $\mathit{3082}^{s}$	4175 $\mathit{3832}^{s}$	3872		3.5 T field *4.0 T field*^{s}	int.lengths $= 2\lambda$
Muon	4450 $\mathit{4107}^{s}$	7755 $\mathit{7412}^{s}$	4047	scintillator sensor	14 layers 3×3 cm^2 cells	



End cap system

System	z_{min}	z_{max} [mm]	r_{in}	r_{out}	technology	comments	
FTD	220 645	371 2212		153 300	silicon pixel sensors silicon strip sensors	2 discs 5 double discs	$\sigma_{r\phi,z} = 3.0$ µm $\sigma_{r\phi} = 7.0$ µm $\phi_{\mathrm{stereo}} = 7\,^{\circ}$
ECAL	2411	2635	250	2096 $\mathit{1718}^{s}$	W absorber	30 layers	incl. EcalPlug
					silicon sensor scintillator sensor	5×5 mm^2 cells 5×45 mm^2 strips	SiECAL ScECAL
HCAL	2650	3937	350	3226 $\mathit{2876}^{s}$	Fe absorber	48 layers	
					scintilator sensor, analogue	3×3 cm^2 cells	AHCAL
					RPC gas sensor, semi-digital	1×1 cm^2 cells	SDHCAL
Muon	4072	6712	350	7716 $\mathit{7366}^{s}$	scintillator sensor	12 layers 3×3 cm^2 cells	
BeamCAL	3115	3315	18	140	W absorber GaAs readout	30 layers	
LumiCAL	2412	2541	84	194	W absorber silicon sensor	30 layers	
LHCAL	2680	3160	130	315	W absorber		

Material (ILD)



Timing resolution factors

Timing resolution factors: $\sigma_t{}^2 = \sigma_s{}^2 + \sigma_n{}^2$

- $\sigma_s{}^2$: Uncertainty in the timing response of the sensor itself
  - Landau noise: waveform changes depending on whether energy deposit occurs more on the upper side or lower side of the sensor.

    → Making the sensitivity layer thinner decrease Landau noise, but the signal becomes smaller, so the S/N ratio becomes worse.

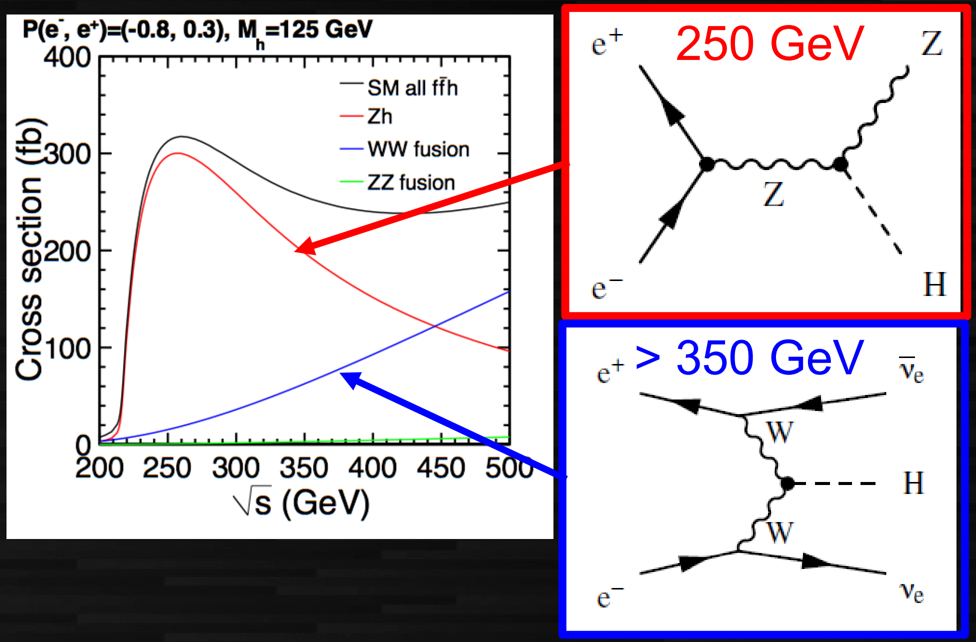
    (It seem that the thickness of sensitive layer of S8664-50K is 5 μm)
  - Avalanche amplification fluctuation: Uncertainty in time for accelerated electrons to knock out surrounding electrons

- $\sigma_n{}^2$: Uncertainty caused by noise
  - Capacitance of sensor: The smaller the capacitance of the sensor, the smaller the rise time of the waveform.

    → Capacitance is proportional to the size of the sensor → Smaller sensors are less affected by noise.
  - Thermal noise: caused by high temperatures in amplifiers and sensor → need cooling
  - Noise due to disturbance to the conduction path between the sensor and the amplifier or due to HV

    → devise wiring, Stabilization of supply voltage, etc…

ヒッグス生成@ILC

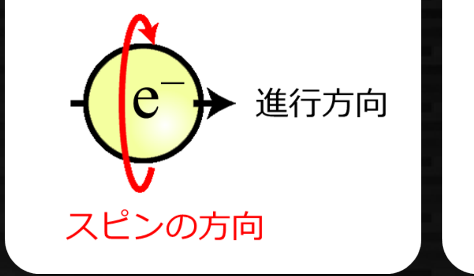


$$N_{\text{detected}} = \epsilon \sigma \mathcal{L}_{\text{int}}$$

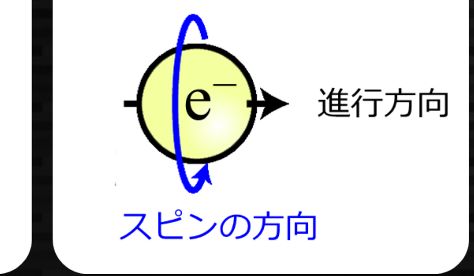
L_{int}は積分ルミノシティ
ILC 250 GeVでは
2 ab^{-1}を想定
(eLpR, eRpLを0.9 ab^{-1}ずつ)
εはほぼ100%。ただし
背景事象を選ぶ過程で
信号事象も一部が失われる
(解析手法による)

250 GeVでは e^+e^- → ZHが重要
断面積は電子・陽電子偏極にもよる
電子左偏極、陽電子右偏極(eLpR)
が最も生成断面積が大きい。
(eRpLで約6割程度)
0.9 x 300 x (1+0.6) = 432,000事象
200日x5年走るとして、432/day

左巻きスピン（左偏極）



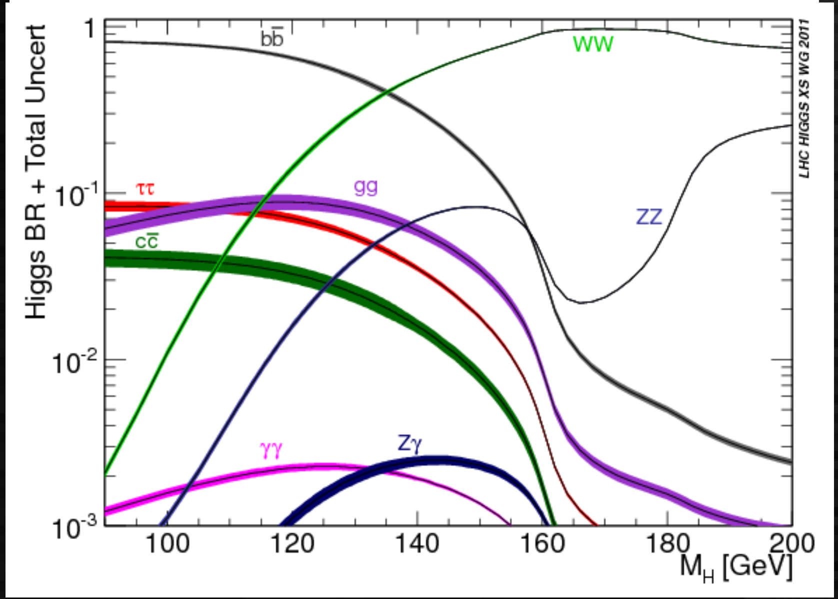
右巻きスピン（右偏極）



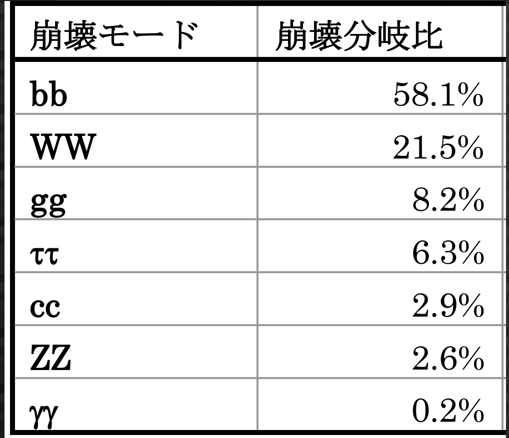
ヒッグスの崩壊

- 生成したヒッグス粒子は即座に崩壊する
  - ヒッグスは電荷もバリオン・レプトン数も持たないので粒子・反粒子ペアに崩壊
  - ヒッグス粒子の結合は質量の2乗に比例
    - 重い粒子に壊れやすい
    - ただしヒッグスの質量の½を越えるとエネルギー保存を満たさないため確率は下がる (off-shell崩壊と呼ぶ)

崩壊モード	崩壊分岐比	ILC 事象数
bb	58.1%	290,000
WW	21.5%	110,000
gg	8.2%	41,000
ττ	6.3%	32,000
cc	2.9%	15,000
ZZ	2.6%	13,000
γγ	0.2%	1,000

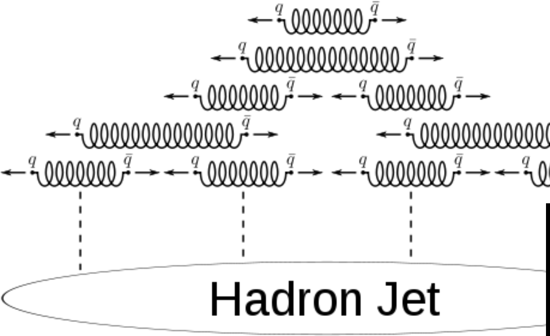


ヒッグスの測定

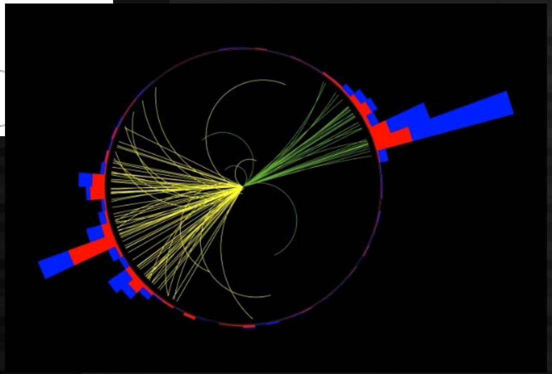


崩壊モード	崩壊分岐比
bb	58.1%
WW	21.5%
gg	8.2%
ττ	6.3%
cc	2.9%
ZZ	2.6%
γγ	0.2%

- ヒッグスの崩壊生成物は
  さらに崩壊する
  - b, c, gluon
    → ハドロンジェット
    (多数のハドロンの束)
  - W → qq (2/3), lν (1/3)
    Z → qq (70%), νν (20%), ll (10%)
    クォークはハドロンジェットになる
  - □ τ → 1～数個のハドロン/レプトンに崩壊 (tau jet)
  - □ γ → 高エネルギー光子としてそのまま検出可能
- ジェットやレプトンを測定器で検出する (後述)

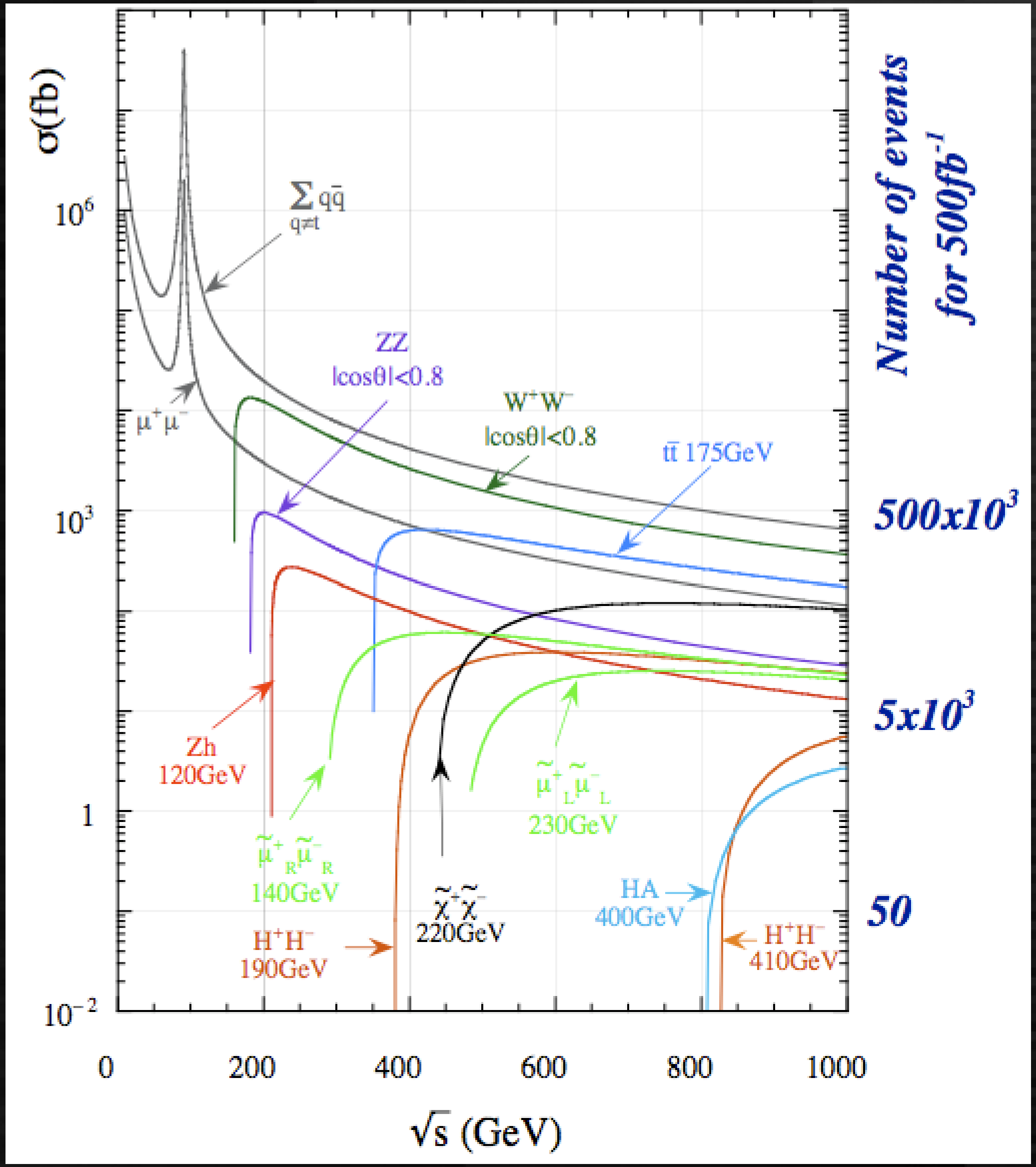


CMS



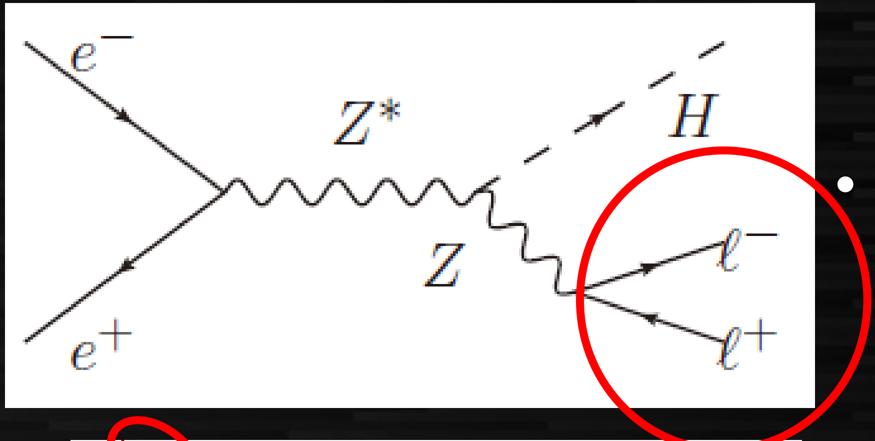
ヒッグスの測定 (2)

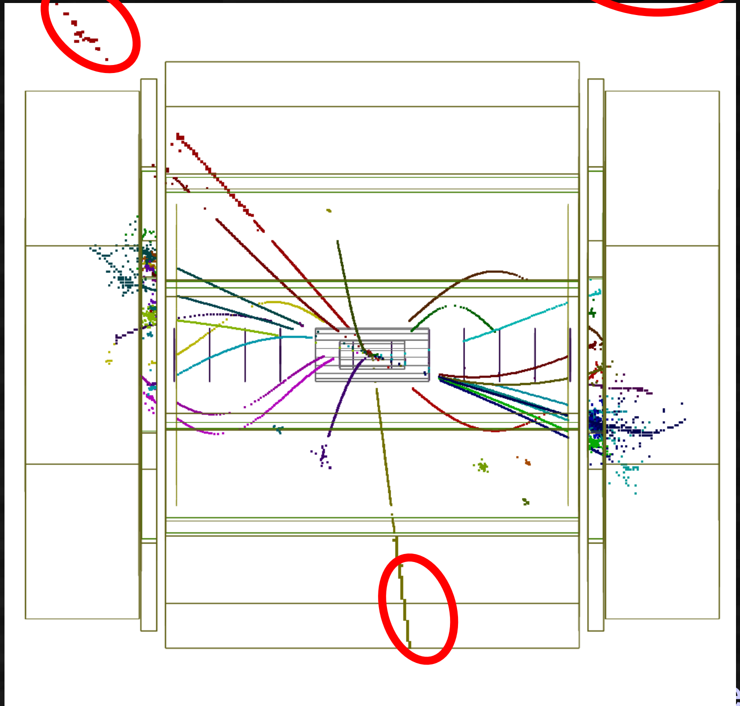
- 事象分離
  - 信号事象(ヒッグス)の10～100倍の背景事象がある
  - Z, Hの運動量・エネルギーや生成角、クォークの種類等の情報を駆使して背景と信号を分離する
  - ILCの始状態の4元運動量は明確

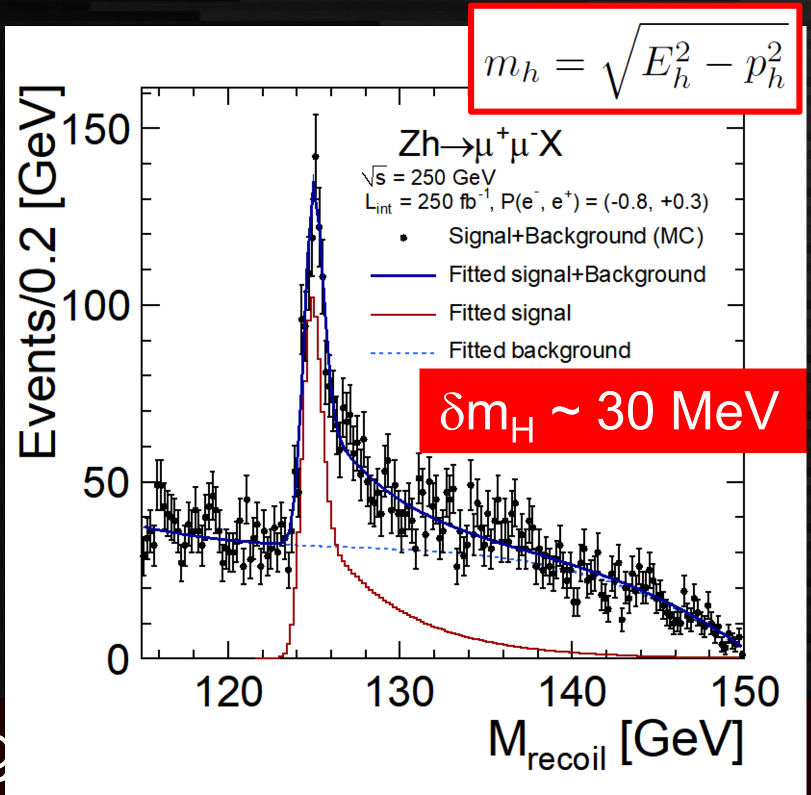


ヒッグス反跳質量測定

- “Higgsを見るのにHiggsを見ない”
→ 反跳されるZ → llのみを使う
(4-momentum conservation)
- “Higgsを見ない”のでどんな崩壊でも関係なく見える
→ ヒッグスの性質に依存しない







$$m_h = \sqrt{E_h^2 - p_h^2}$$

δm_H ~ 30 MeV

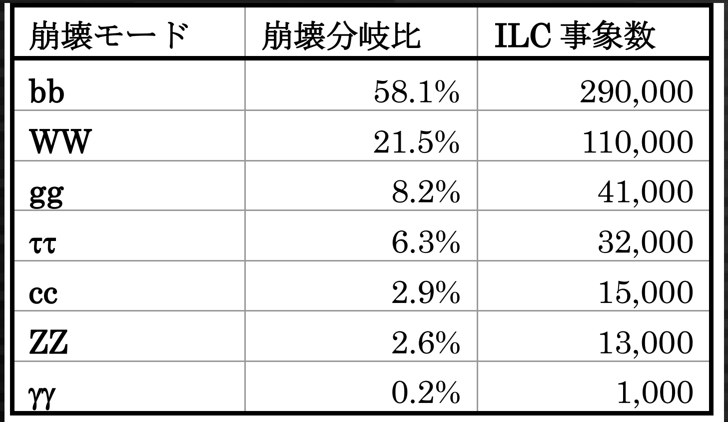
ヒッグスの結合定数測定

- 各崩壊の事象数を高精度測定
  - 精度: $\frac{\sqrt{S+N}}{S}$ S: 信号事象数 N: 背景事象数

テキスト訂正

  - 1万事象、背景なしで1%統計誤差
  - 1万事象、背景10万で3%統計誤差
- 精度: 統計誤差と系統誤差による。電子陽電子コライダーは理論予測の精度が高く系統誤差も1%以下に抑えられる。

ILCでは概ね1%以下の精度で各結合定数を決定する。



崩壊モード	崩壊分岐比	ILC 事象数
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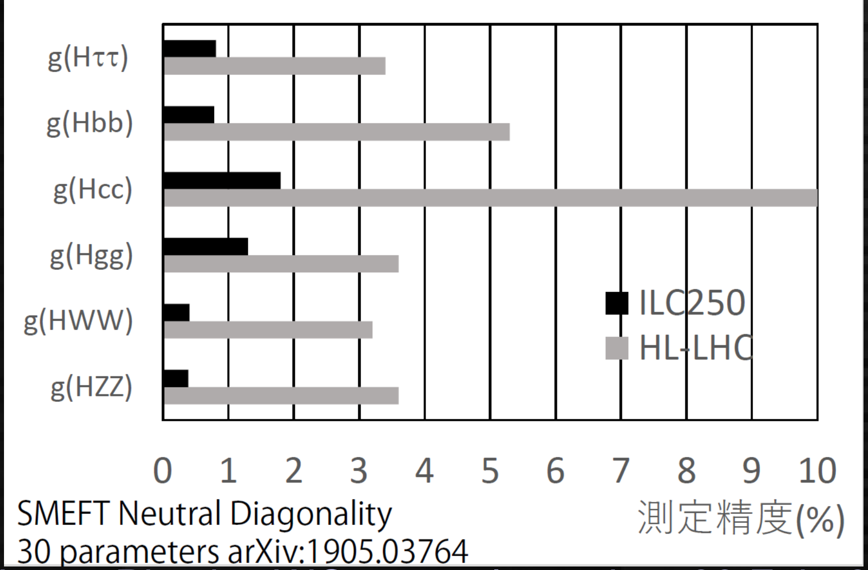
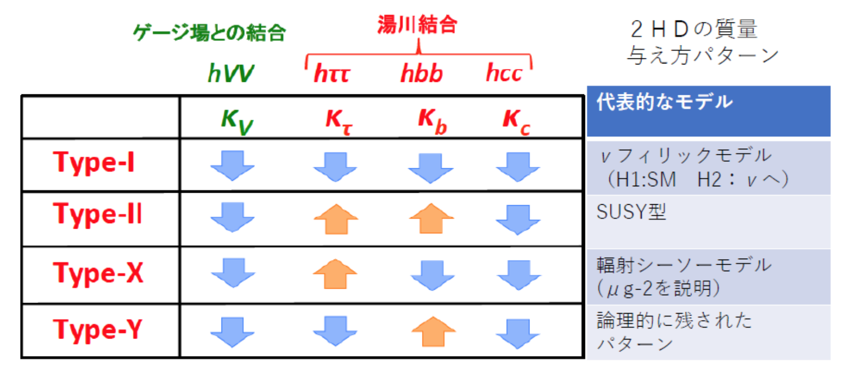


SMEFT Neutral Diagonality
30 parameters arXiv:1905.03764

ヒッグス結合定数による新物理探索

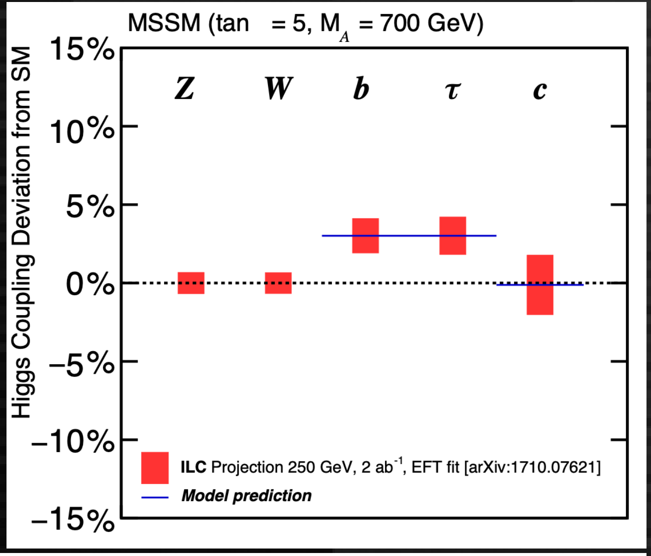
- ヒッグスの結合定数の標準理論からのずれが発見できれば、そのパターンから新物理を区別できる。
  - SUSY: b/τの結合が上昇
  - 複合ヒッグス: フェルミオンの結合定数が下がる

ずれが見えるかどうかは新物理のパラメータによるが、
ILCではTeV新物理の多くをカバーする

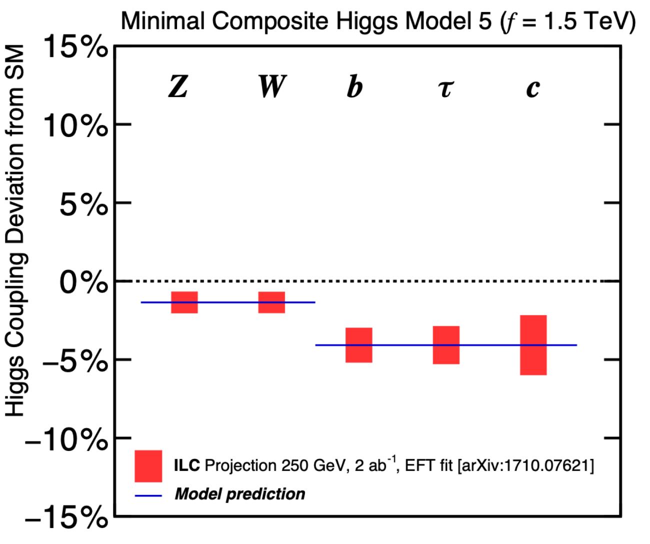


	ゲージ場との結合	湯川結合			２ＨＤの質量与え方パターン
	hVV	$h\tau\tau$	hbb	hcc	
	κ_V	κ_τ	κ_b	κ_c	代表的なモデル
Type-I	⬇	⬇	⬇	⬇	νフィリックモデル （H1:SM　H2：νへ）
Type-II	⬇	⬆	⬆	⬇	SUSY型
Type-X	⬇	⬆	⬇	⬇	輻射シーソーモデル （μg-2を説明）
Type-Y	⬇	⬇	⬆	⬇	論理的に残された パターン

MSSM (tan = 5, M_A = 700 GeV)

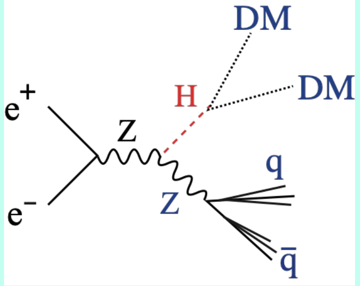


Minimal Composite Higgs Model 5 (f = 1.5 TeV)

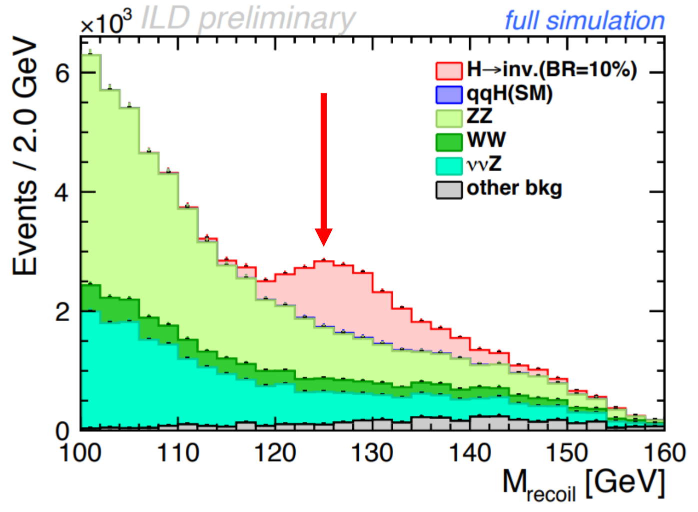


ヒッグスと新粒子の直接結合探索

Higgs Invisible Decays

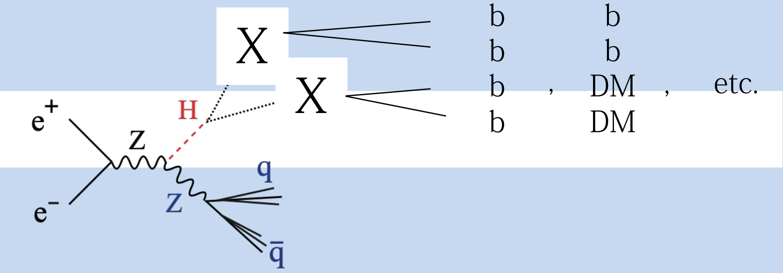


Hadronic Z decay (ILD), Kato, 2002.12048

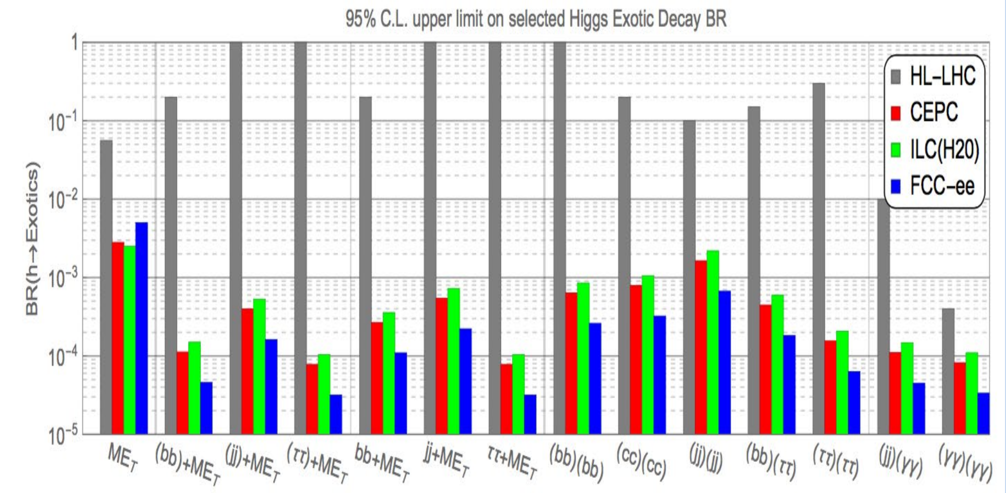


Invisible decay branching ratio: 0.3%
(95% CL upper limit)

Exotic Higgs Decays

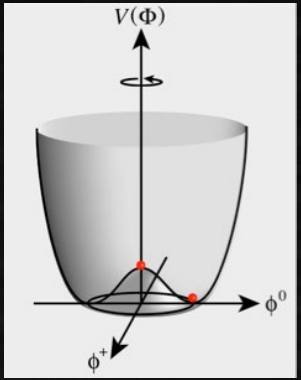


Liu, Wang, Zhang [1612.09284]

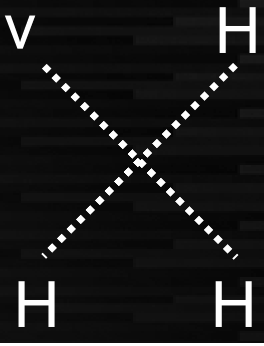


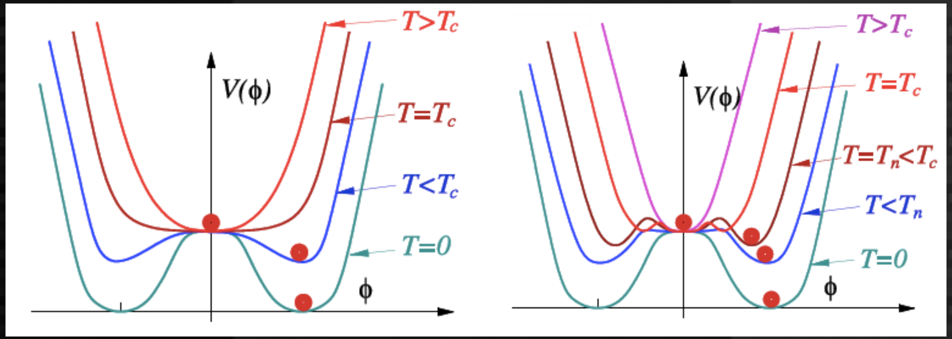
LC sensitive to various exotic Higgs decays

ヒッグス自己結合



ヒッグス
ポテンシャル
の4次の項
真空の構造
を決める





真空の2次相転移

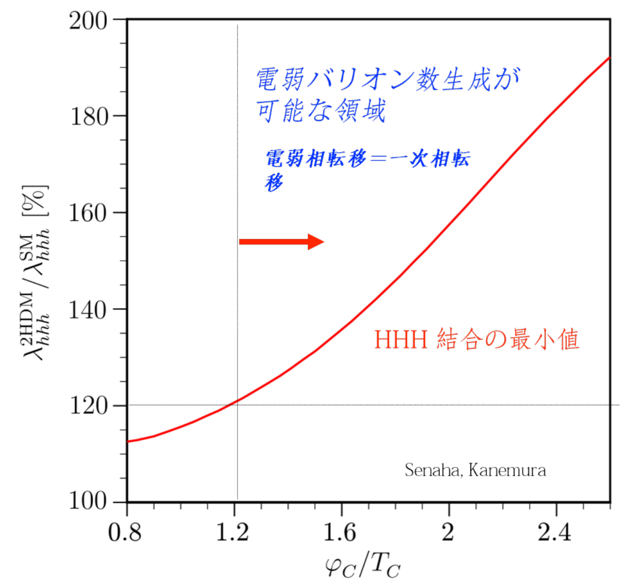
真空の1次相転移
スファレロンによる
電弱バリオジェネシス
に必要

$$V(\eta_H) = \frac{1}{2}m_H^2\eta_H^2 + \boxed{\lambda} v\eta_H^3 + \frac{1}{4}\lambda\eta_H^4$$

宇宙の物質生成を解き明かす
二つのプローブ

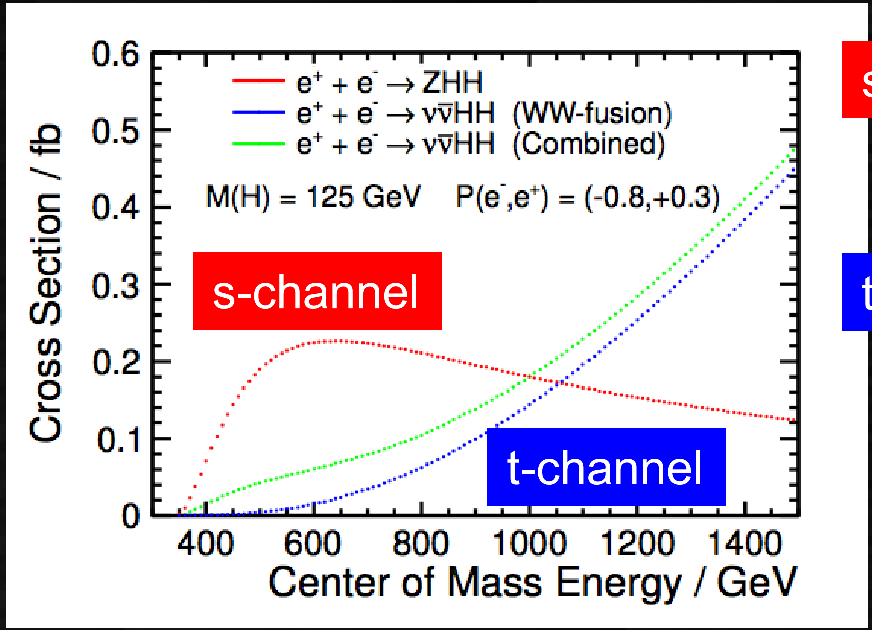
1. ヒッグスと電弱バリオジェネシス
   - 真空の一次相転移
2. ニュートリノとレプトジェネシス
   - 重いレプトン崩壊のCP破れ

例: 2 Higgs Doublet Model (2HDM)

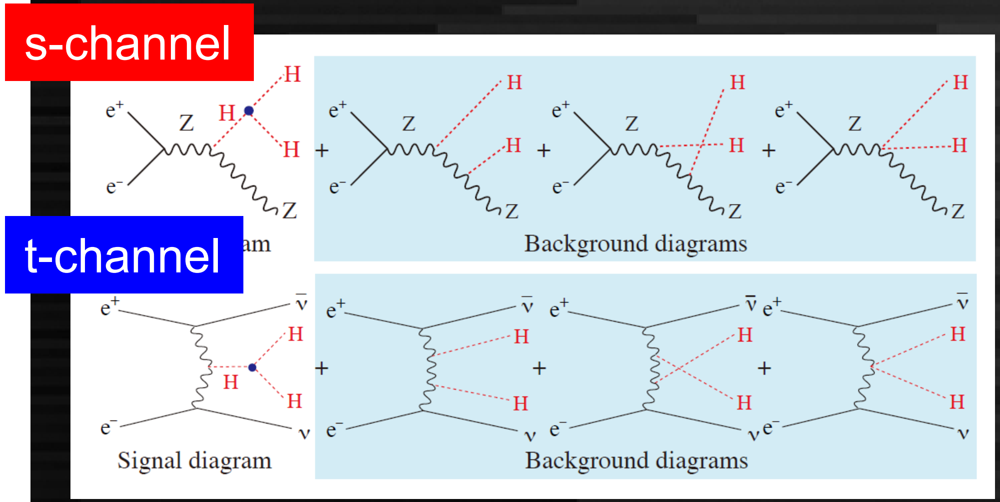


電弱バリオ
ジェネシスなら
λの値は
O(10%)以上
増加する

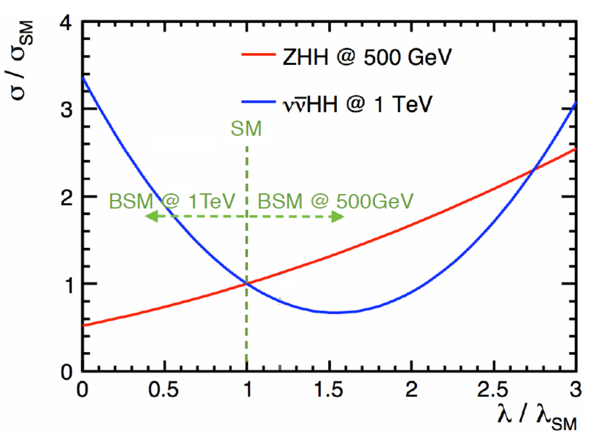
ヒッグス自己結合@ILC upgrade



断面積が小さく困難。1 ab^{-1}でO(100)事象



干渉項の効果でさらに実質断面積低下



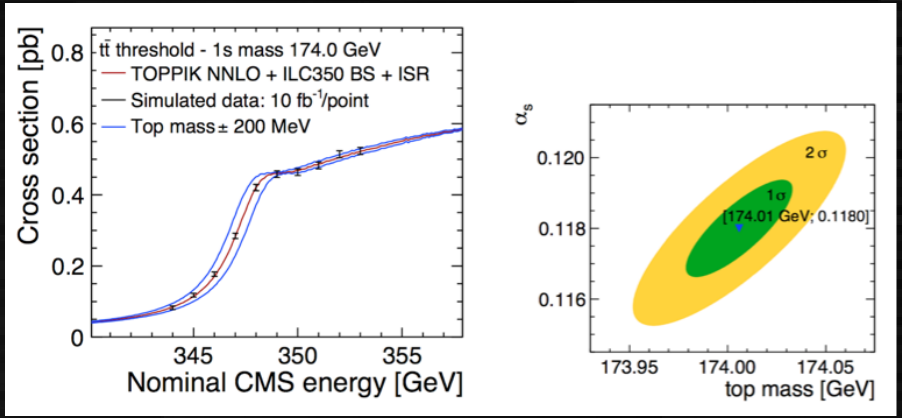
干渉項が3点結合の
測定精度に影響
s-channelは正の干渉,
t-channelは負の干渉
(LHCは負の干渉)

channel	√s[GeV]	λ精度
s (正の干渉)	500-600	~20%
t (負の干渉)	>1000	<10%

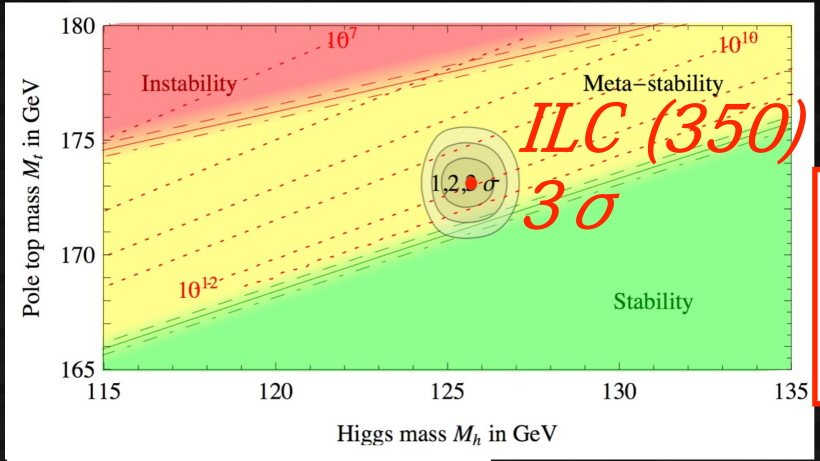
深層学習によるジェット
再構成性能の抜本的な
改善に取り組んでいる

トップ測定 @ ILC 350 GeV

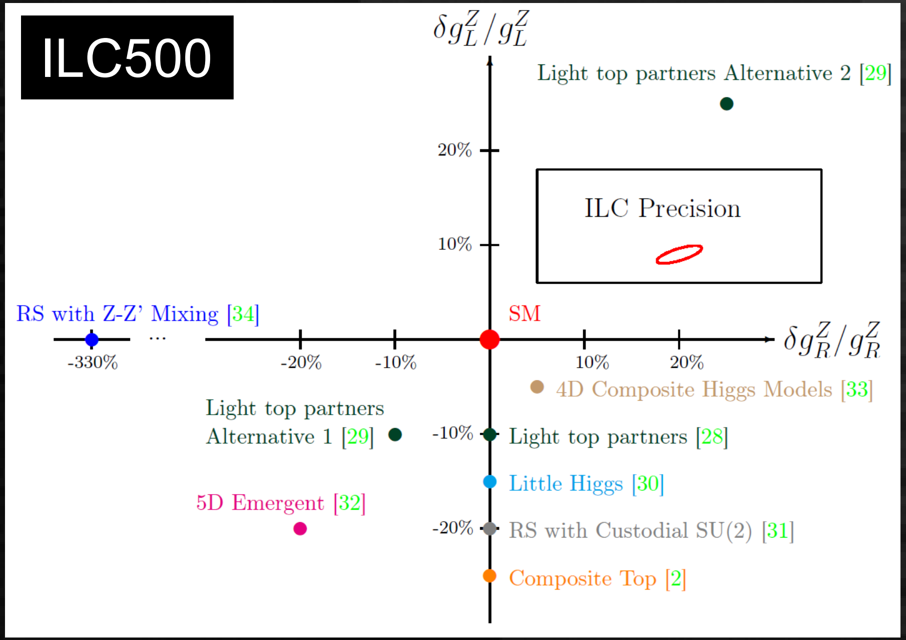
topの精密測定



Threshold scanによるtopの精密測定
MSbarに直接変換できる「理論的に扱いやすい」質量を直接求められる



arXiv:1205.6497, Degrassi et al.



偏極を用いて左巻き、右巻きの結合定数を求め、Topが関係する新物理の探索・モデル識別が可能

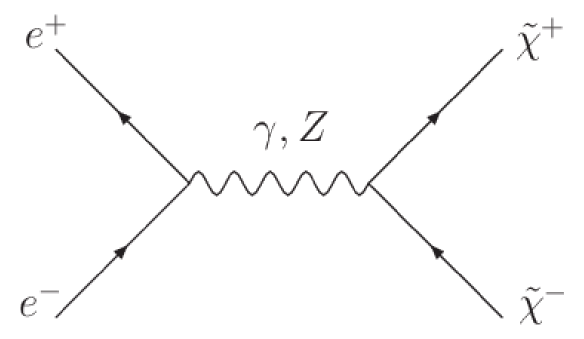
$$\Delta m_t(\overline{MS}) \lesssim 50\,\mathrm{MeV}$$

$$\Delta m_h \simeq 14\ \mathrm{MeV}$$

ILC で真空の位置を正確に決定

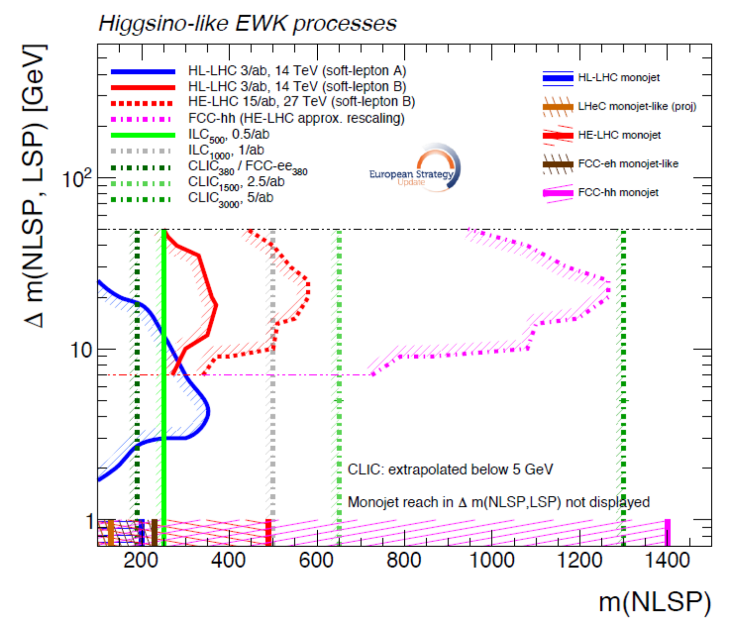
SUSY直接探索 @ ILC any energy

- SUSY粒子の探し方
  - 重い新粒子を対生成 → LSP (暗黒物質)と通常の粒子に崩壊 例) $\chi^+ \rightarrow \chi^0 qq$
    - □ χ^0 は検出不可能 (暗黒物質)
    - □ χ^+ と χ^0 の質量差が小さい場合、qqのエネルギーが小さくなりLHCでは検出困難に → Compressed SUSY
  - ILCでは検出・精密測定可能



→ χ^0 qq

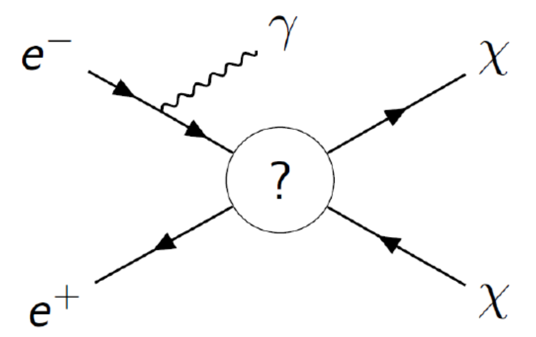
→ χ^0 qq



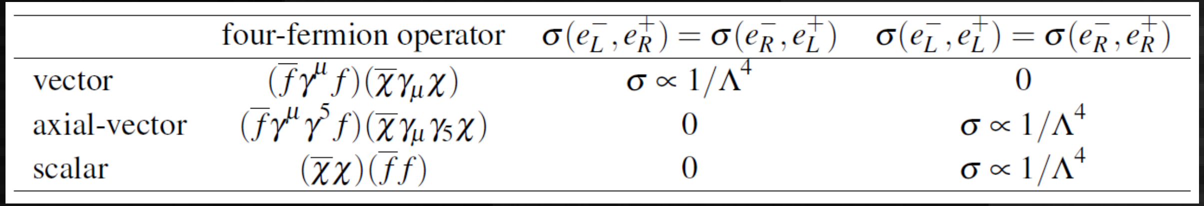
Mono-photon search

arXiv:2001.03011

モデル非依存にm < √s/2 の
暗黒物質を直接探索

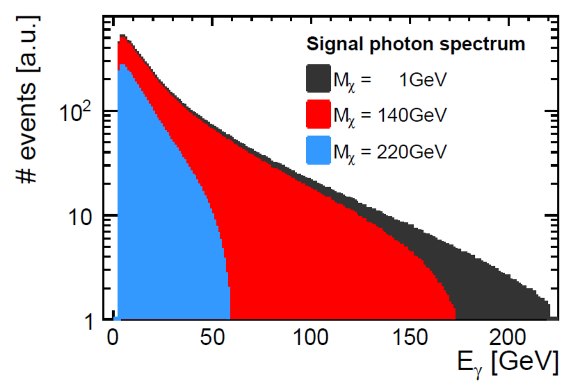


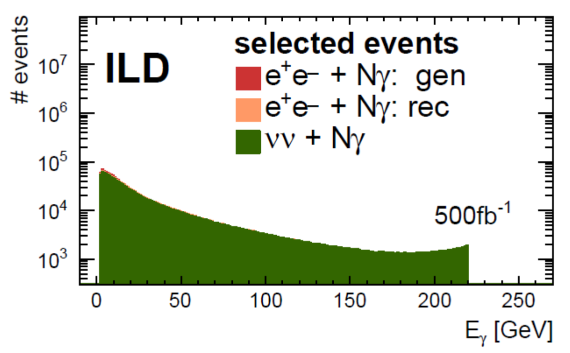
偏極を用いて暗黒物質のスピンの情報が得られる

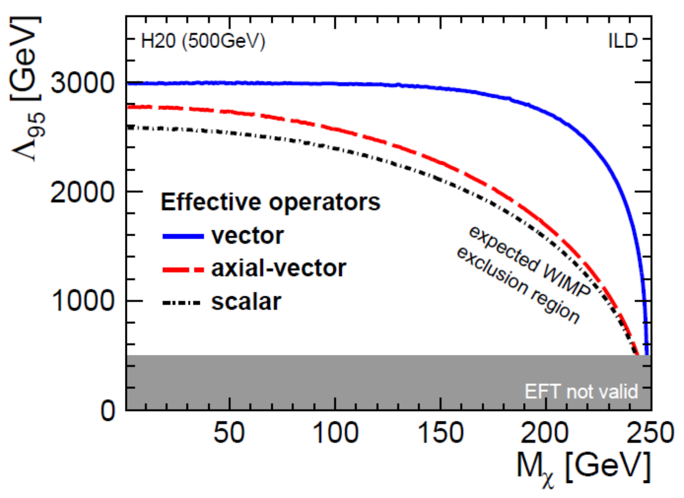


	four-fermion operator	$\sigma(e_L^-, e_R^+) = \sigma(e_R^-, e_L^+)$	$\sigma(e_L^-, e_L^+) = \sigma(e_R^-, e_R^+)$
vector	$(\bar{f}\gamma^\mu f)(\bar{\chi}\gamma_\mu\chi)$	$\sigma \propto 1/\Lambda^4$	0
axial-vector	$(\bar{f}\gamma^\mu\gamma^5 f)(\bar{\chi}\gamma_\mu\gamma_5\chi)$	0	$\sigma \propto 1/\Lambda^4$
scalar	$(\bar{\chi}\chi)(\bar{f}f)$	0	$\sigma \propto 1/\Lambda^4$

Λは新物理のエネルギースケール







複数の
衝突エネルギー
での測定により
スピン・質量を
さらに感度よく
決定できる

単一光子信号
とバックグラウンド

~3 TeVスケールの新物理に感度