Physics Reach and Detector optimization at the CEPC

Manqi Ruan

On behavior of the CEPC Study Group
Science at CEPC-SPPC

- **Tunnel ~ 100 km**

- **CEPC (90 – 250 GeV)**
  - Higgs factory: 1M Higgs boson
    - Absolute measurements of Higgs boson width and couplings
    - Searching for exotic Higgs decay modes (New Physics)
  - Z & W factory: 10B Z boson
    - Precision test of the SM
    - Rare decay
  - Flavor factory: b, c, tau and QCD studies

- **SPPC (~ 100 TeV)**
  - Direct search for new physics
  - Complementary Higgs measurements to CEPC g(HHH), g(Htt)
  - ...

- **Heavy ion, e-p collision...**

**Complementary**
CEPC: 1M Higgs & 10-100 B Z

Observables: EW Precision, tau physics, Flavor Physics...

Higgs mass, CP, $\sigma(ZH)$, event rates ( $\sigma(ZH, vvH) \times Br(H \rightarrow X)$ ), Diff. distributions

Derive: Absolute Higgs width, branching ratios, couplings

2/8/2017
## Higgs measurement at e+e- & pp

<table>
<thead>
<tr>
<th></th>
<th>Yield</th>
<th>efficiency</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC</td>
<td>Run 1: $10^6$</td>
<td>$\sim o(10^{-3})$</td>
<td>High Productivity &amp; High background, Relative Measurements, Limited access to width, exotic ratio, etc, Direct access to $g(ttH)$, and even $g(HHH)$</td>
</tr>
<tr>
<td></td>
<td>Run 2/HL: $10^{7-8}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CEPC</td>
<td>$10^6$</td>
<td>$\sim o(1)$</td>
<td>Clean environment &amp; Absolute measurement, Percentage level accuracy of Higgs width &amp; Couplings</td>
</tr>
</tbody>
</table>
Key science

- The nature of Higgs boson & EWSB, + flavor physics...
  - Higgs signal strengths (In kappa framework): expected accuracy roughly 1 order of magnitude better than HL-LHC
  - Absolute measurement to the Higgs boson: 2-3% level accuracy of Higgs boson width, $10^{-3} - 10^{-5}$ up limit to Higgs invisible/exotic decay modes (improved by at least 2 orders of magnitude comparing to HL-LHC)
  - Improve EW measurement precision by also 1 order of magnitude
Detector Designs

IDEA:
Wire Chamber + Dual Readout Calorimeter

PFA Oriented:
TPC/Silicon + High Granularity Calorimeter

Tracker, TPC: R = 1.8 m
ECAL: 84-90 mm W
ToF: dt ~ 50 ps
HCAL: ~1000 mm Iron
Solenoid (3T) + Yoke

Beam pipe (R~2 cm)
VTX: 4-7 MAPS layers
DCH: 4 m long, R 40-200 cm
2 T, R~2 m SC Coil
Preshower (1-2 $X_0$)
DR calorimeter (2 m/8 $\lambda_m$)
(yoke) muon chambers
PFA oriented Detector & Reconstruction

\[
\text{MET} = - \sum_{i} E_{T,i}
\]

Particles
PFA Oriented: reference & key questions

- Reference Detector Concept: **ILD, SiD, ALEPH**...
  - Light material tracker (TPC)
  - Ultra high granularity calorimeter
  - Strong B-Field (3.5 Tesla)

- Feasibility at Circular Collider
  - TPC @ CEPC Z pole?
  - No power pulsing – Is active cooling needed for CEPC Physics Program?
  - BDS/MDI suitable to the CEPC luminosity/collision environment

- Geometry/Parameter optimization
  - Re-design of the MDI system with much shorter $L^*$ (1.5 m)
  - Sub system size, design & layout, B-Field, etc.
PFA Concept:

Green lights granted for technology feasibilities (TPC Occupancy, Passive cooling, etc. 2017_JINST_12_P07005, ...)

Arbor Reconstruction

Goal: recon. Physics Objects at high efficiency. & high precision

Ultimate: 1-1 correspondence

Performance:

Tracker: Performance and Optimization

Lepton

Photon

Jets

Taus

Higgs analysis at e+e- and comparison to HL-LHC
Feasibility of TPC at Z pole

- 600 Ion Disks induced from Z->qq events at 2E34 cm^{-2} s^{-1}
- Voxel occupancy & Charge distortion from Ion Back Flow (IBF)
TPC Feasibility (Preliminary)

- Conclusion:
  - Voxel occupancy $\sim (10^{-4} - 10^{-6})$ level, safe
  - **Safe for CEPC If the ion back flow be controlled to per mille level** ($IBF\times Gain = k \sim 5$) - The charge distortion at ILD TPC would be one order of magnitude then the intrinsic resolution ($L = 2E34 \text{ cm}^2\text{s}^{-1}$)
TPC dEdx & future optimizations

- TPC dEdx + ToF at dt ~ 50 ps: pi-kaon separation of 3-4σ at Z pole (E < 20 GeV)
- Be iterate with hardware study & Test beam: Quantify the hardware requirements
- TPC in general:
  - Stability & Homogeneity requirement
  - Radiation Background, Gas optimization (Neutron Flux, Delta/Gamma Ray)
Tracker Radius

- Recommend CEPC TPC radius >= 1.8m:
  - Better $H \rightarrow \mu \mu$ measurement
  - Better separation & JER
  - Better $dE/dx$
Optimization Benchmarks

- **Lepton & Momentum resolution:** $Br = 6.7\%$
- **Flavor Tagging & JER:** $Br = 14\%$
- **Composition of Jet/MET, lepton:** $Br = 4\%$
- **Jet Clustering:** $Br = 50\%$
- **Photon/ECAL:** $Br = 0.2\%$
- **Tracking:** $H \rightarrow \mu\mu,$ $Br = 0.02\%$
- **qqH, H->inv. MET & NP:** SM $Br = 0.1\%$
- **EW, Br(tau->X) @ Z pole:** Separation
Leptons: identified by LICH: Lepton ID for Calorimeter with High granularity

**BDT method using 4 classes of 24 input discrimination variables.**

Test performance by requesting
Electron = E\_likeness > 0.5 ; Muon = Mu\_likeness > 0.5
Single charged reconstructed particle, for E > 2 GeV: lepton efficiency > 99.5% && Pion mis id rate ~ 1%
Photons & $\text{Br}(H\rightarrow\gamma\gamma)$ measurement

30 Layers, each layer with 0.5 mm Si + 2 mm PCB
ECAL only performance

σ/Mean = 1.69%
Jets @ vvH, H→gluons

Reconstructed Higgs Mass from vvH event, wi/wo cleaning

<table>
<thead>
<tr>
<th>Filter</th>
<th>Entries</th>
<th>Mean (GeV)</th>
<th>RMS (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>9900</td>
<td>125.2</td>
<td>7.082</td>
</tr>
<tr>
<td>cleaned</td>
<td>6458</td>
<td>125</td>
<td>5.122</td>
</tr>
</tbody>
</table>

Geo: CEPC_v1: Reco: ArborLICH_p2

 Jets @ vvH, H→gluons

<table>
<thead>
<tr>
<th>Filter</th>
<th>Entries</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISRPt &lt; 1</td>
<td>9335</td>
</tr>
<tr>
<td>ISRPt &lt; 1 &amp;&amp; N3Pt &lt; 1</td>
<td>8766</td>
</tr>
<tr>
<td>ISRPt &lt; 1 &amp;&amp; N3Pt &lt; 1 &amp;&amp;</td>
<td>cos(Theat)</td>
</tr>
</tbody>
</table>
In no-jet environment: counting number of charged particle – (pions & leptons), photons (pi0s) + restrict impact parameters leads to very high efficiency in Tau finding:

- At inclusive Higgs decay sample: Efficiency ~ 98% for of $H \rightarrow \tau \tau$ event finding, with $llH$ and $vvH$ final state. The remaining bkgrds are irreducible: $H \rightarrow WW/ZZ \rightarrow$ leptonic/tau final state
- In $\mu \mu H$ channel: $\delta N/N = 3\%$
Detector Power consumption

- Power pulsing
  - Reduce the power consumption by 2 orders of magnitude
  - Not applicable at Circular collider: the original design consumes ~o(MW) power @ CEPC

- Solution
  - Reduce the number of readout channels;
    Or
  - Implement dedicated cooling system;

- Passive cooling geometry: Readout channels reduced by 10 times
  - Object reconstruction efficiency: no significant impact
  - Event reconstruction efficiency (Defined as the efficiency of identify all the physics objects) Slightly (~1-2%) degrading in Higgs events
Br(H→WW) @ 10mm/20mm Cell size

Liao libo, H→WW*→lvqq, Z→ll

Br(H→WW) via vvH, H→WW*→lvqq

No lose in the object level efficiency: JER slightly degraded, ~ 5/10% at 10/20 mm

Over all: event reco. efficiency varies ~1%

2/8/2017
Impact of Separation: $Z\rightarrow\tau\tau$ @ $Z$ pole

<table>
<thead>
<tr>
<th>Cell Size/mm</th>
<th>1</th>
<th>5</th>
<th>10</th>
<th>20</th>
</tr>
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<tbody>
<tr>
<td>Crucial Dis/mm</td>
<td>4</td>
<td>9</td>
<td>16</td>
<td>37</td>
</tr>
<tr>
<td>Percentage of potentially overlap photon</td>
<td>0.07%</td>
<td>0.4%</td>
<td>1.7%</td>
<td>18.6%</td>
</tr>
</tbody>
</table>

2/8/2017

DPF@Fermilab
## Feasibility & Optimized Parameters

Feasibility analysis: TPC and Passive Cooling Calorimeter is valid for CEPC

<table>
<thead>
<tr>
<th></th>
<th>CEPC_v1 (~ ILD)</th>
<th>Optimized (Preliminary)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track Radius</td>
<td>1.8 m</td>
<td>&gt;= 1.8 m</td>
<td>Requested by Br(H-&gt;di muon) measurement</td>
</tr>
<tr>
<td>B Field</td>
<td>3.5 T</td>
<td>3 T</td>
<td>Requested by MDI</td>
</tr>
<tr>
<td>ToF</td>
<td>-</td>
<td>50 ps</td>
<td>Requested by pi-Kaon separation at Z pole</td>
</tr>
<tr>
<td>ECAL Thickness</td>
<td>84 mm</td>
<td>84(90) mm</td>
<td>84 mm is optimized on Br(H-&gt;di photon) at 250 GeV; 90mm for bhabha event at 350 GeV</td>
</tr>
<tr>
<td>ECAL Cell Size</td>
<td>5 mm</td>
<td>10 – 20 mm</td>
<td>Passive cooling request ~ 20 mm. 10 mm should be highly appreciated for EW measurements – need further evaluation</td>
</tr>
<tr>
<td>ECAL NLayer</td>
<td>30</td>
<td>20 – 30</td>
<td>Depends on the Silicon Sensor thickness</td>
</tr>
<tr>
<td>HCAL Thickness</td>
<td>1.3 m</td>
<td>1 m</td>
<td></td>
</tr>
</tbody>
</table>
| HCAL NLayer           | 48              | 40                      | Optimized on Higgs event at 250 GeV; Margin might be reserved for 350 GeV.
PFA Oriented Detector: Performance

- Solid Angle Coverage: $|\cos(\theta)| < 0.99$
- Lepton id: $\text{eff} > 99.5\%, \text{mis id} < 1\%$
- Calorimeter Shower Separation: $9 – 16$ mm
- Tracking: $\delta(1/Pt) \sim 2e-5 \text{ GeV}^{-1}$, 1 order of magnitude better than current status
- C-tagging is feasible
- Photon Energy resolution: $\sigma/\text{Mean} \sim 1.7 – 2.4\%$ for $H\rightarrow\gamma\gamma$ events
- Jet Energy resolution: $\sigma/\text{Mean} \sim 4\%$ for $H\rightarrow\gamma\gamma$ events
- Pi-Kaon Separation: at 3-4 sigma level with $E < 20$ GeV

- Systematic control: ~ 1 order of magnitude better
  - Beam energy monitoring, Calibration, Alignments...
Applied to CEPC Higgs analysis

Now: ~50 independent analyses at Full Simulation level

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>$\sigma(ZH)$</td>
<td>0.51%</td>
<td>0.50%</td>
</tr>
<tr>
<td>$\sigma(ZH) \times Br(H\rightarrow bb)$</td>
<td>0.28%</td>
<td>0.21%</td>
</tr>
<tr>
<td>$\sigma(ZH) \times Br(H\rightarrow cc)$</td>
<td>2.1%</td>
<td>2.5%</td>
</tr>
<tr>
<td>$\sigma(ZH) \times Br(H\rightarrow gg)$</td>
<td>1.6%</td>
<td>1.2%</td>
</tr>
<tr>
<td>$\sigma(ZH) \times Br(H\rightarrow WW)$</td>
<td>1.5%</td>
<td>1.0%</td>
</tr>
<tr>
<td>$\sigma(ZH) \times Br(H\rightarrow ZZ)$</td>
<td>4.3%</td>
<td>4.3%</td>
</tr>
<tr>
<td>$\sigma(ZH) \times Br(H\rightarrow \tau\tau)$</td>
<td>1.2%</td>
<td>1.0%</td>
</tr>
<tr>
<td>$\sigma(ZH) \times Br(H\rightarrow \gamma\gamma)$</td>
<td>9.0%</td>
<td>9.0%</td>
</tr>
<tr>
<td>$\sigma(ZH) \times Br(H\rightarrow Z\gamma)$</td>
<td>-</td>
<td>~4 $\sigma$</td>
</tr>
<tr>
<td>$\sigma(ZH) \times Br(H\rightarrow \mu\mu)$</td>
<td>17%</td>
<td>12%</td>
</tr>
<tr>
<td>$\sigma(vvH) \times Br(H\rightarrow bb)$</td>
<td>2.8%</td>
<td>2.8%</td>
</tr>
<tr>
<td>Higgs Mass/MeV</td>
<td>5.9</td>
<td>5.0</td>
</tr>
<tr>
<td>$\sigma(ZH) \times Br(H\rightarrow inv)$</td>
<td>95%. CL = $1.4e^{-3}$</td>
<td>$1.4e^{-3}$</td>
</tr>
<tr>
<td>Br($H\rightarrow ee/emu$)</td>
<td>-</td>
<td>1.7e-4/1.2e-4</td>
</tr>
<tr>
<td>Br($H\rightarrow bb\chi\chi$)</td>
<td>&lt;10$^{-3}$</td>
<td>3.0e-4</td>
</tr>
</tbody>
</table>
The “IDEA” detector concept

Test beam @ SPS - CERN

DREAM: Structure

Used particles (both polarities): 4 – 180 GeV electrons, pion/protons, muons

Fig. 18. Signal distribution for 125 GeV multiparticle events obtained with the rotation method described in the text. The energy scale is set by electrons showering in this detector.
Simulation initialized

- $N\phi = 28$
- $N_{barrel} = 10$
- $N_{encap} = 5$
- $\delta \theta = 0.1$
Summary

- **CEPC:**
  - A tremendous Higgs/EW factory, Boost the precision of Higgs/EW measurement by more than 1 order of magnitude
    - Higgs performance well understood;
    - Systematic study/controls would be essential for the EW measurement
  - Request detector(s) that can successfully reconstruct all kinds of physics objects: Photons, Leptons, Jets, Tau, MET
- **CEPC Detectors: PFA Oriented Concept & IDEA**
  - PFA Oriented Concept: TPC + HGC
    - Green light granted for technology feasibilities
    - Fully established in simulation/reconstruction, dedicated Reconstruction algorithm that reconstruct every physics objects
    - Optimized w.r.t Set of Benchmark Physics Performance/Processes
  - IDEA Concept: Dual Readout Calorimeter + Wire Chamber. Detector concept in implementation, much to be explored.
- New ideas & your participation is more than welcome!
The International Workshop on the CEPC aims at gathering scientists around the world to study the Circular Electron Positron Collider (CEPC) as a Higgs factory. The focuses will be the measurement of the Higgs properties with high precision, probing new physics through the Higgs boson, to study the full spectrum of the physics cases, to report on the conceptual design of the CEPC accelerator and the detector, as well as the simulation studies and the R&D of critical technologies. The possible upgrade path of the CEPC, including a high energy Super proton-proton Collider (SppC), will be explored.

One main purpose of the workshop is to make the CEPC study much more international by having broad participation and contributions globally, and to elevate the CEPC study group to an international organization.
Thanks
Timeline

Milestones

1\textsuperscript{st}, PreCDR (end of 2014)
2\textsuperscript{nd}, R&D funding from MOST (Middle 2016, 35 M CNY/5yr for the 1\textsuperscript{st} phase)
3\textsuperscript{rd}, CDR (end of 2017)
...
Vary the granularity

No Significant effect for $E > 2$ GeV charged Particles
LICH @ IIH events

Geom 1/2: 10 (20) mm ECAL/HCAL Cell
Initial Leptons identified at satisfactory efficiency & purity (limited by separation power)
More stringent requirement arrises from jet leptons...

2/8/2017
https://arxiv.org/abs/1701.07542
Photons & Br(H→γγ) measurement

30 Layers, each layer with 0.5 mm Si + 2 mm PCB
ECAL only performance

σ/Mean = 1.69%

Energy Resolution vs. mean [%]
Separation

Critical Distance:
~ 2 * Cell Size if Cell Size < Moliere Radius
~ Cell Size if Cell Size >> Moliere Radius

Figure 11. Event display of reconstructed di-photon.
Impact of Separation: $qqH, H\rightarrow\gamma\gamma$ @ 250 GeV

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<td>4</td>
<td>9</td>
<td>16</td>
<td>37</td>
</tr>
<tr>
<td>Percentage of potentially overlap photon: $E &gt; 30$ GeV</td>
<td>0%</td>
<td>0%</td>
<td>0.1%</td>
<td>0.4%</td>
</tr>
<tr>
<td>$E &lt; 30$ GeV</td>
<td>0.1%</td>
<td>0.35%</td>
<td>1.1%</td>
<td>6.4%</td>
</tr>
</tbody>
</table>
Impact of Separation: Z->tau tau @ Z pole

<table>
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<td>1.7%</td>
<td>18.6%</td>
</tr>
</tbody>
</table>
Composed object: converted photon

Save ~ 7% of the H→di photon statistic
Reducing the #Layers from 48 -> 40 (same layer thickness)
A degrading of 2% (relative) in JER

Performance depends on the version...
Composed object: $\pi_0$ (Preliminary)

Testing on Higgs to di tau events. Tau inclusive decay
($X$ axis, Energy of $\pi 0$, $Y$ axis, Angle between two photons decayed from $\pi 0$)

For $\pi 0$ with $E_n > 3$ GeV && $E_n < 30$ GeV, Reconstruction efficiency ~ 65%..

*Horizontal line* corresponding to 9 mm separation at ECAL.
CEPC two schemes towards CDR

CEPC Baseline Design
Better performance for Higgs and Z compared with alternative scheme, without bottle neck problems, but with higher cost

CEPC Alternative Design
Lower cost and reaching the fundamental requirement for Higgs and Z luminosities, under the condition that sawtooth and beam loading effects be solved
# Parameters of CEPC Double ring

<table>
<thead>
<tr>
<th></th>
<th>Higgs</th>
<th>W</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of IPs</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Energy (GeV)</td>
<td>120</td>
<td>80</td>
<td>45.5</td>
</tr>
<tr>
<td>SR loss/turn (GeV)</td>
<td>1.67</td>
<td>0.33</td>
<td>0.034</td>
</tr>
<tr>
<td>Half crossing angle (mrad)</td>
<td>16.5</td>
<td>16.5</td>
<td>16.5</td>
</tr>
<tr>
<td>Piwinski angle</td>
<td>3.19</td>
<td>5.69</td>
<td>4.29</td>
</tr>
<tr>
<td>N\textsubscript{b} /bunch (10\textsuperscript{11})</td>
<td>0.968</td>
<td>0.365</td>
<td>0.455</td>
</tr>
<tr>
<td>Bunch number</td>
<td>412</td>
<td>5534</td>
<td>21300</td>
</tr>
<tr>
<td>Beam current (mA)</td>
<td>19.2</td>
<td>97.1</td>
<td>465.8</td>
</tr>
<tr>
<td>SR power /beam (MW)</td>
<td>32</td>
<td>32</td>
<td>16.1</td>
</tr>
<tr>
<td>Bending radius (km)</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Momentum compaction (10\textsuperscript{-5})</td>
<td>1.14</td>
<td>1.14</td>
<td>4.49</td>
</tr>
<tr>
<td>$\beta_{\text{ip}}$ x/y (m)</td>
<td>0.171/0.002</td>
<td>0.171/0.002</td>
<td>0.16/0.002</td>
</tr>
<tr>
<td>Emittance x/y (nm)</td>
<td>1.31/0.004</td>
<td>0.57/0.0017</td>
<td>1.48/0.0078</td>
</tr>
<tr>
<td>Transverse $\sigma_{\text{ip}}$ (um)</td>
<td>15.0/0.089</td>
<td>9.9/0.059</td>
<td>15.4/0.125</td>
</tr>
<tr>
<td>$\xi/\xi_{\text{IP}}$</td>
<td>0.013/0.083</td>
<td>0.0055/0.062</td>
<td>0.008/0.054</td>
</tr>
<tr>
<td>RF Phase (degree)</td>
<td>128</td>
<td>126.9</td>
<td>165.3</td>
</tr>
<tr>
<td>$V_{\text{BE}}$ (GV)</td>
<td>2.1</td>
<td>0.41</td>
<td>0.14</td>
</tr>
<tr>
<td>$f_{\text{RF}}$ (MHz) (harmonic)</td>
<td>650</td>
<td>650 (217800)</td>
<td>650 (217800)</td>
</tr>
<tr>
<td>Nature $\sigma$ (mm)</td>
<td>2.72</td>
<td>3.37</td>
<td>3.97</td>
</tr>
<tr>
<td>Total $\sigma$ (mm)</td>
<td>2.9</td>
<td>3.4</td>
<td>4.0</td>
</tr>
<tr>
<td>HOM power/cavity (kw)</td>
<td>0.41(2cell)</td>
<td>0.36(2cell)</td>
<td>1.99(2cell)</td>
</tr>
<tr>
<td>Energy spread (%)</td>
<td>0.098</td>
<td>0.065</td>
<td>0.037</td>
</tr>
<tr>
<td>Energy acceptance (%)</td>
<td>1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy acceptance by RF (%)</td>
<td>2.1</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>$n_{\gamma}$</td>
<td>0.26</td>
<td>0.15</td>
<td>0.12</td>
</tr>
<tr>
<td>Life time due to beamstrahlung (min)</td>
<td>52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F$ (hour glass)</td>
<td>0.96</td>
<td>0.98</td>
<td>0.96</td>
</tr>
<tr>
<td>$L_{\text{max}}$/IP (10\textsuperscript{34}cm\textsuperscript{-2}s\textsuperscript{-1})</td>
<td>2.0</td>
<td>5.15</td>
<td>11.9</td>
</tr>
</tbody>
</table>
Sim Higgs @ CEPC

Reconstruction: From Hits to Objects...

Optimization: Performance at different geometries with adequate Reconstruction
Reconstruction

Higgs mass: $\sigma$/Mean = 3.8%

Photons
Higgs mass: $\sigma$/Mean = 1.7-2.4%

Flavor

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Photon energy measurement Vs Longitudinal structure: #Layer & Si Thickness

Performance @ Photon with $E > 1$ GeV:

Energy Resolution is comparable at:

- $20 \times 1.5$ mm Si + $4.5$ mm W
- $25 \times 1$ mm Si + $3.6$ mm W
- $30 \times 0.5$ mm Si + $3$ mm W

What's the maximal viable silicon wafer thickness?