CEPC Meeting, Oxford, April 2019 `EU edition’
Opening

Thanks to everyone for a fantastic workshop!
- There is rapid progress here
- And it has been great to see it

But I cannot do justice to the physics in 30 mins
- Right after the conference dinner

Apologies for leaving out your work, and for all my misunderstandings
Joao laid out the programme
And the physics

### The Physics Goals — Shopping List

(see Matthew McCullough talk)

#### Precision tests of Standard Model
- Higgs, W and Z
- Potential to find new physics
- Higgs boson and electroweak symmetry breaking

#### Directly exploring new physics
- Exotic Higgs boson decays
- Exotics Z boson decays
- Dark matter and hidden sectors
- Extended Higgs sector

#### QCD precision measurements
- Precision $\alpha_s$ determination
- Jet rates at CEPC
- QCD dynamics, soft QCD effects
- QCD event shapes and light-quark Yukawa couplings

#### Flavor physics at the Z pole
- Rare B decays
- Tau lepton decays
- Flavor violating Z decays

*Tuesday 4:20 pm*

*Tuesday 2 pm*
Grojean quoted D’Hondt:

High Energy Physics with a Higgs

Towards new discoveries via the Higgs sector

- No clear indication where new physics is hiding, hence experimental observations will have to guide us in our exploration.
- One of the avenues is to explore as fast as possible, and as wide as possible, the Higgs sector.
  - Yukawa couplings
  - Self-couplings (HHH and HHHH)
  - Couplings to Z/W/γ/g
  - Rare SM and BSM decays (H→Meson+γ, Zγ, FCNC, μe/τμ/τe, ...)
  - CP violation in Higgs decays
  - Invisible decay
  - Mass and width
  - ...
- Important progress will be made on Higgs physics with the LHC and the HL-LHC.
- To discover new physics inaccessible to the (HL-)LHC, future colliders will be complementary.
Direct v Indirect studies

**Example:** SUSY Higgs sector, $m_A$ and tan $\beta$

- **Direct** searches (solid) and **indirect** (purple line) have comparable impact on plane.
- We learn a lot from Higgs couplings.
The method
The method

The Higgs-strahlung from known initial state is the unique and best feature of the Higgs factory

- Higgs-tagging from the Z
  - Leptonic and hadronic Z decays to maximise rate
- Total width can be extracted
- The result is $g_{HZZ}$ is much the best measured Higgs coupling at CepC

But many Higgs decays are accessible in clean $ee$ environment
All the Higgs decay modes shown can be studied

- Unlike LHC where gg and cc are not measurable

And the tagging opens the door for new & unexpected decays

Higgs decay modes

- bb
- \(\tau\tau\)
- cc
- gg
- yy
- WW
- ZZ
Higgs couplings precision

Big gains expected – but especially on Z couplings
The CepC adds nearly a factor 4 in most operators

Searching deep into the unknown
Exotic Higgs decays

Huge potential for unexpected Higgs decay modes

Electron colliders deliver up to $10^4$ over LHC
This is testing the couplings/mixings of the only fundamental scalar
There are similar gains in rare $Z$ decays
Even more expanded list

Decay Topologies | Decay mode $F_i$
--- | ---
$h \rightarrow 2$ | $h \rightarrow E_T$ $
\rightarrow \gamma + E_T$
$h \rightarrow (bb) + E_T$
$h \rightarrow (jj) + E_T$
$h \rightarrow (\tau^+\tau^-) + E_T$
$h \rightarrow (\gamma\gamma) + E_T$
$h \rightarrow (e^+e^-) + E_T$

$h \rightarrow 2 \rightarrow 3$ | $h \rightarrow (bb) + E_T$
$h \rightarrow (jj) + E_T$
$h \rightarrow (\tau^+\tau^-) + E_T$
$h \rightarrow (\gamma\gamma) + E_T$
$h \rightarrow (e^+e^-) + E_T$

$h \rightarrow 2 \rightarrow 3 \rightarrow 4$ | $h \rightarrow (bb) + E_T$
$h \rightarrow (jj) + E_T$
$h \rightarrow (\tau^+\tau^-) + E_T$
$h \rightarrow (\gamma\gamma) + E_T$
$h \rightarrow (e^+e^-) + E_T$

$h \rightarrow (\ell^+\ell^-)(\ell^+\ell^-)$
$h \rightarrow (\ell^+\ell^-)(\mu^+\mu^-)$
$h \rightarrow (\mu^+\mu^-)(\mu^+\mu^-)$
$h \rightarrow (\gamma\gamma)(\gamma\gamma)$
$h \rightarrow (\gamma\gamma)(\gamma\gamma)$

$h \rightarrow 2 \rightarrow (1 + 3)$ | $h \rightarrow bb + E_T$
$h \rightarrow jj + E_T$
$h \rightarrow \tau^+\tau^- + E_T$
$h \rightarrow (\gamma\gamma) + E_T$
$h \rightarrow (e^+e^-) + E_T$

$h \rightarrow (\ell^+\ell^-)(\ell^+\ell^-) + E_T$
$h \rightarrow (\ell^+\ell^-)(\mu^+\mu^-) + E_T$
$h \rightarrow (\mu^+\mu^-)(\mu^+\mu^-) + E_T$
$h \rightarrow (\gamma\gamma)(\gamma\gamma) + E_T$
$h \rightarrow (\gamma\gamma)(\gamma\gamma) + E_T$

$h \rightarrow 2 \rightarrow 6$ | $h \rightarrow (\ell^+\ell^-)(\ell^+\ell^-)$
$h \rightarrow (\ell^+\ell^-)(\mu^+\mu^-)$
$h \rightarrow (\mu^+\mu^-)(\mu^+\mu^-)$
$h \rightarrow (\gamma\gamma)(\gamma\gamma)$
$h \rightarrow (\gamma\gamma)(\gamma\gamma)$

$h \rightarrow (\ell^+\ell^-) + E_T + X$
$h \rightarrow (\ell^+\ell^-) + E_T + X$

$h \rightarrow (\ell^+\ell^-) + E_T + X$
$h \rightarrow (\ell^+\ell^-) + E_T + X$

$h \rightarrow (\ell^+\ell^-) + E_T + X$
$h \rightarrow (\ell^+\ell^-) + E_T + X$

Strong areas of Higgs factories

More hadronic
With MET, less lepton
Great sensitivity from the LHC
Higgs to dark matter is 100% invisible
CepC offers an order of magnitude increase in sensitivity
Especially useful at low mass
First order phase transition

- So far we probe the Higgs potential near 250GeV
- There could be a barrier between the origin and vacuum?
- If so the symmetric vacuum is meta-stable
- Universe does not smoothly evolve to the observed Higgs VeV
- But will start from local fluctuations which spread
Why do we care?

The inhomogeneities associated could drive matter asymmetry,
create gravitational waves
Or seed primordial black holes

1st Order EWPT has profound implications for cosmology

\[ \langle \text{Higgs} \rangle = v(T) \quad \langle \text{Higgs} \rangle = 0 \]
Can CepC tell?

Probably; via the hZZ coupling through loops
If a big enough distortion comes from an EFT $\Phi^6$ term, that can is testable

But simplified models are less clear. e.g.
- add a new scalar singlet
- Mixing with $h$
- Then a lot of models can be seen
  - But not all
**h^3 prospects**

DiVita et al, arXiv: 1711.03978 (updated with latest HL-LHC) projections

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**bounds on δκ_λ** from EFT global fit

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**HL-LHC**
-1.90

**HE-LHC**
-0.4

**FCC-hh**
-0.05

**FCC-ee**
-0.39

**ILC**
-0.18

**CLIC (stage III)**
-0.07

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**Dark:** 68%CL, **Light:** 95%CL

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**ee colliders** will establish at 95%CL that the Higgs self-coupling exists.

**ILC** will establish it at 5σ.

**FCC-hh** will probe the quantum corrections of the Higgs potential.
**Improved analysis: precision 17% → 12%**

**Also gains in invisible 0.41% → 0.26%**
Left is $\mu\mu H$, right $qqH$

- Overall precision 0.8% dominated by $qqH$ channel
EW measurement’s impact on Higgs

De Blas, Durieux, Grojean, Gu, Paul ’in progress

Grojean

EFT fit translated into postdicted Higgs couplings
(e.g. $g_{hzz} \propto \sqrt{\Gamma_{h \rightarrow zz}}$)

$\times$ CEPC alone

Z-pole run needed
LEP/SLD is not enough
Issue for ILC?

Linear: L $\rightarrow$ w/E
Circular: L $\rightarrow$ w/E

How many Z are needed?
Giga-Z enough?

350GeV run & polarisation could help alleviating the need for Z-pole run

Christophe Grojean

CEPC, Oxford, April 15, 2019
EW measurement’s impact on Higgs

Z pole runs remove some correlations among SM deformations
Decouple Higgs data from EW data

w/ LEP EW

w/ CEPC/FCC-ee EW
Don't worry. I don't understand it either.

EW measurement's impact on Higgs

Z pole runs remove some correlations among SM deformations

Decouple Higgs data from EW data

W/ LEP EW

W/ CEPC/CC-ee EW

CEPC. Oxford, April 15, 2019
Electroweak precision

CepC offers an order of magnitude over LEP in many key electroweak observables.

“One Ring to rule them all” - J.R.R. Tolkien

Thanks Jeurgen
Now turn to other physics..

There is a lot going on
These studies are not perhaps the main course
But the range and variety adds enormously to the community interest
Which matters
And sometimes the sidechannels pay off
Kamiokande was designed for proton decay
Who remembers that, now the Nobel Prize is in?
Long lived particles

- LHC designed for high mass prompt
  - Searches for long lived need bespoke solutions
- CepC should be ready for long lived
  - Weakly coupled/mass degenerate
  - 3μm resolution allows sub-fs lifetimes to be probed
  - axion: H → Za, with a → ll or γγ could look like a π^0
- Leptogenesis also gives candidates e.g. in Z decay
- How do different detectors do for LLP’s?
Higgs to displaced jets at CepC

- **CepC study**
  - Assumes 3\(\mu\)m vertex resolution
  - Requires ZH, H to jj
  - The paper suggests further work: try following a CMS study on distribution of track \(d_0\) in clusters to help sensitivity to low ctau

**BR (H to XX 95% limits)**

```
<table>
<thead>
<tr>
<th>Proper Decay Length (m)</th>
<th>BR (H to XX 95% limits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^{-5}</td>
<td>\times 10^{-5}</td>
</tr>
<tr>
<td>0.001</td>
<td>\times 10^{-4}</td>
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<tr>
<td>0.001</td>
<td>\times 10^{-4}</td>
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<td>0.001</td>
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<td>\times 10^{-4}</td>
</tr>
</tbody>
</table>
```

- “**long lifetime analysis**”
- “**large mass analysis**”

Alipour-Fard et al. arXiv:1812.05

Farrington

S. Farrington, University of Edinburgh
B physics at CepC

Beauty hadrons @CEPC

<table>
<thead>
<tr>
<th></th>
<th>CEPC ($10^{12}$ Z)</th>
<th>Belle II ($50$ ab$^{-1}$ @γ(4S))</th>
<th>LHCb ($50$ fb$^{-1}$) &amp; $5$ fb$^{-1}$ @γ(5S))</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^{\pm}/B^0$</td>
<td>$6 \times 10^{10}$</td>
<td>$3 \times 10^{10}$</td>
<td>$3 \times 10^{13}$</td>
</tr>
<tr>
<td>$B_s$</td>
<td>$2 \times 10^{10}$</td>
<td>$3 \times 10^{8}$</td>
<td>$8 \times 10^{12}$</td>
</tr>
<tr>
<td>$B_c$</td>
<td>$10^8$</td>
<td>-</td>
<td>$6 \times 10^{10}$</td>
</tr>
<tr>
<td>$b$ baryons</td>
<td>$10^{10}$</td>
<td>-</td>
<td>$10^{13}$</td>
</tr>
</tbody>
</table>

- Yield matches or exceeds Belle
- However it is well below LHCb

But:
- B’s are produced back to back, unlike LHCb
- With predictable momenta, unlike LHCb
B hadrons

Tau decay modes might be accessible at CepC?
- Bs→ττ or B→Kττ
- The B flavor anomalies make this very interesting
- B→Kττ with 3-prong tau decays allows 4 vertex positions and thus full mass reconstruction
  - O(100) events seen with CepC?
- DD background in LHCb
- Belle-II/LHCb fail here?

B to Kνν CepC can look for MET+K – promising
B_c→τν also promising
Large charm yields; predictable spectra
3 \times 10^9 D^{*+} \rightarrow D^0 \pi^+ \rightarrow K\pi\pi^+ - comparable to LHCb
- Good \pi^0 reconstruction would help a lot!
- EM calorimetry is important
Possibility to observe CPV in charm baryons?
- Yield of reconstructed \Lambda_c 600 times LHCb

Heavy quark spectroscopy:
- QCD-stable bbud tetraquarks predicted
- should be visible at CepC

Use radiative return to study lower thresholds
- Is a dedicated detector needed to study most forward boosted?
**Rare Z decays**

\[ Z \rightarrow \mu e, e\tau \text{ or } \mu\tau \]

- Sensitivity should be 2 orders of magnitude better than HL-LHC.
- There are constraints from \( \mu \rightarrow e\gamma \), \( \mu \rightarrow 3e \) etc.
  - Strongly constraining for \( \mu e \) case.
  - But not so for decays with taus.

**Lepton universality in Z decay**

- \( ee: \mu\mu: \tau\tau \)
- 3 per mille constraints from LEP.
- These are important constraints on the B flavour anomalies.
- CepC will have to understand e/\( \mu \)/\( \tau \) efficiencies well.

Question to experimentalists: What can be achieved here?
In several areas LEP results still dominate
- Large B-factory tau yields but poor efficiency
- With $10^6$ more tau CepC has a rich tau program
- $\mu/e$ universality is one key
Other Tau prospects

- CPV in the tau sector: There is a hint of new dynamics in CPV symmetries in the tau sector
  - BaBar result does not agree with SM expectation but needs to be confirmed
  - A lot of new measurements possible ($A_{CP}$, $A_{FB}$, etc.) to shed light on CP violation
- EDM, $g-2$ of the tau also very interesting to study but difficult
- Also interest in hadronic $\tau$ decays
  - Inclusive for $\alpha_S$, $|V_{us}|$ and $m_s$
  - Exclusive for form factors extraction, $|V_{us}|$, resonances etc..
CepC as γγ collider

- Two photons processes dominate rate at 240 Gev
  - e.g. $a_\tau$ was measured best via
  - $\gamma\gamma \rightarrow \tau\tau$ at LEP
    - At 1% level
    - Useful to compare $a_e$, $a_\mu$
  - Systematics limited but CepC will give major improvement
- Photon structure function can also be improved
- Hadron spectroscopy will be possible too
QCD studies

- $\alpha_s$ measurement
- Non-linear soft gluon evolution & Non-global logs resummation
- Hadronization models & Monte-Carlo tuning
- Fragmentation function
- Interplay with Higgs & Electroweak physics
- Charmonium physics
- Top quark physics
Non-linear soft gluon evolution & Non-global logs resummation

- Extending jet mass calculation beyond NLL
- Important e.g. when separating quark states from hadronic boson decays

\[ \frac{1}{\sigma} \frac{d\sigma}{d\rho} \]

\[ \rho = \frac{M_J^2}{Q^2} \]
Radiative return

Many thresholds unexplored. e.g.
- $B_c \bar{B}_c$ @ 12.551 GeV, $\Xi_{bb} \Xi_{bb}$ @ 20.3 GeV

Is a dedicated detector needed to study most boosted?
Dreaming of top

• Fcc-ee, CLIC and ILC plan top threshold scan

• $m_t$ errors:
  • 20-30 MeV statistical
  • 25-50 MeV systematic
  • 40 MeV theoretical

• Autoscan – radiative return
  • 100 MeV stat
  • 100 MeV theoretical

• Top polarization is a sensitive measurement too

• CepC does not have energy reach….or does it?
Looking forward
Looking forward

Today:
- Detector R&D – Hongbo Zhu
- Accelerator R&D – Brian Foster
- Tools and Performance – Michele Selvaggi
- Round table
- Conclusions – Nima Arkani-Hamed

July 1\textsuperscript{st} – 5\textsuperscript{th}, Peking University
- https://indico.ihep.ac.cn/event/9832/

“All we have to decide, is what to do with the time that is given us.” J.R.R. Tolkien
Jet Clustering

- Marcel Vos reviewed jet clustering algorithms.
- Moving from $p$ to $p_T$ makes for more robust jet finding.
- Presence of beam related background forces distortions on the jet geometry.
Monte Carlo developments

- Parallelised integration in Whizard
- Herwig:
  - Cluster hadronisation model can be swapped from Lund string (Pythia)