(Some) QCD aspects of FCC-ee

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FUTURE COLLIDERS: e.g. HIGGS

Rich programme & extreme precision. High complementarity with HL-LHC

Higgs@FC WG

Kappa-3, May 2019
› Technically non-trivial to reach desired precision in calculations \([\text{QCD} \oplus \text{EW}]\): attractive challenge for TH in the coming decades

› Extremely clean collider environment to *explore* certain aspects of the theory

› Crucial to *fully exploit* our TH knowledge to create new experimental opportunities (LHC docet)
Final state hadronic observables (e.g. jet rates, event/jet shapes, ...) are powerful probes of QCD dynamics from high to low energy scales.

In a $e^+e^-$ environment, perturbation theory allows for accurate predictions down to hadronic scales.

Shape info (+ in some cases, q/g jet discrimination) allows one to disentangle final states with different multiplicity e.g.

- $e^+e^- \rightarrow Z/\gamma^* \rightarrow qq +X$: probe of coherent QCD dynamics & $\alpha_s$ fits
- $e^+e^- \rightarrow WW / ZZ / ZH \rightarrow 4 q + X$: study of EW / Higgs couplings
- $e^+e^- \rightarrow ZH \rightarrow 6 q + X$: study of HWW / HZZ couplings
- ...

Heavy-Quark mass effects known to NLO
[Nason, Oleari ’98] [Brandenburg, Bernreuther, Uwer ’97]

NLO : $\alpha_s^2 + \alpha_s^3$
[Nagy, Trocsanyi ’99; Kosower, Weinzierl ’99; Campbell, Cullen, Glover ’99]

NLO : $\alpha_s^3 + \alpha_s^4$
[Frederix, Frixione, Melnikov, Zanderighi ’10]

NLO for 6 & 7 jets (leading colour)
[Becker, Goetz, Reuschle, Schwan, Weinzierl ’12]
Resummation for 2-jet global observables very well understood:
SCET provides a flexible tool for factorising observables (e.g. thrust @ N^3LL)
Numerical resummation for observables w/o a factorising measurement function (e.g. jet rates)

Recent progress in the description of 3-jet global observables; crucial to access gluon fragmentation
[D-param. @ NNLL: Arpino, Banfi, El-Menoufi ’19]
[3-point EEC: Chen, Luo, Moult, Yang, Zhang, Zhu ’19]
First steps towards formal understanding of non-global corrections beyond first order
[Dasgupta, Salam ’01; Banfi, Marchesini, Smye ’02]
[Caron-Huot ’15; Becher, Neubert, Shao et al. ’15-’19]

e^+e^- → Z/γ* → jets: ALL ORDERS QCD
e+e- → Z/γ* → jets: EW CORRECTIONS

- NLO EW known for e+e- → Z/γ* → 3 jets:
  
  [Denner, Dittmaier, Gehrmann, Kurz ’10]

- Weak corr. negligible, sizeable effects from photon radiation
  [mitigated by isolation]

- Radiative return (Z peak) still moderately visible at high energies,
  shifting towards the IR region
  [accurate QED necessary at FCC-ee]
STRONG COUPLING CONSTANT

- World average 2019:
  \[ \alpha_s(M_Z^2) = 0.1179 \pm 0.0010 \]

- Substantial tension among existing extractions (e.g. C-par. vs. lattice)

- Compelling evidence that main source of discrepancy may be hadronisation dynamics

Analytic hadronisation models lead to smaller couplings in e⁺e⁻ fits

\[ \alpha_s(M_Z^2) = 0.1123 \pm 0.0015 \] ~ 3.5 \( \sigma \)

\[ \alpha_s(M_Z^2) = 0.1182 \pm 0.0008 \]
An important difference between e⁺e⁻ fits is the modelling of non-perturbative corrections. Two options available:

- **Extract correction from Monte Carlo generators**, e.g.
  - Build bin-by-bin hadron/parton level migration matrix for an observable $\mathcal{O}$
  $$
  \mathcal{M}_{ij}(d\sigma^\text{parton}_{MC}(\mathcal{O}) \rightarrow d\sigma^\text{hadron}_{MC}(\mathcal{O})), \quad \text{total XS unchanged}
  $$
  
- Fold it with the higher-order perturbative calculation

**PROS:**
- accurate description of event kinematics

**CONS:**
- tuning of hadr. models performed with lower-accuracy MC generators

[HADRONISATION: ANALYTIC vs. MC?](#)

[Kardos et al. ‘19]
[Verbytskyi et al. ‘19]
An important difference between $e^+e^-$ fits is the modelling of non-perturbative corrections. Two options available:

- Estimate leading $1/Q^p$ correction from analytic models and fit to data, i.e.

$$d\sigma_{\text{MC}}^{\text{hadron}}(O) \simeq d\sigma_{\text{MC}}^{\text{parton}}(O - \frac{\alpha_0}{Q} \Delta(O))$$

**Extract from data**

- **PROS:** usable with state of the art perturbative calculations

- **CONS:** shift assumed to be constant, observable dependence poorly described
  
  i.e. $\Delta(O) = \text{constant}$

* At least for thrust and C-parameter
AN EXAMPLE: C PARAMETER

- Analytic power correction coefficient calculated in the 2-jet limit
- Fit of the coupling performed in the 3-jet regime (contribution from gluon jet substantial)

\[ C = 3 - \frac{3}{2} \sum_{i,j} \frac{(p_i \cdot p_j)^2}{(p_i \cdot Q)(p_j \cdot Q)} \]

Fit performed with state of the art PT ($N^3LL+NNLO$) returns a low value for the coupling, with small error

\[ \alpha_s(M_Z^2) = 0.1123 \pm 0.0015 \]

[Hoang, Kolodrubetz, Mateu, Stewart ’15]
AN EXAMPLE: C PARAMETER

- Analytic power correction coefficient calculated in the 2-jet limit
- Fit of the coupling performed in the 3-jet regime (contribution from gluon jet substantial)
- [NEW] direct calculation of leading power correction in the 3-jet symmetric limit reveals that $\Delta(O)$ is not constant & hadronisation is overestimated in the fit region

\[ \Delta_{3-\text{jet}} \lesssim \frac{\Delta_{2-\text{jet}}}{2} \]

Impact on $\alpha_S$ fits

Variation of non-perturbative shift impacts $\alpha_S$ fits by 3%-4% (becomes compatible with WA)
HADRONISATION AT FCC-ee

- A precise control of distributions requires a better modelling of hadronisation
- FCC-ee can be instrumental in this task [a lot of TH work required - much in common with HL-LHC and other future colliders]

- Collect data (e.g. event shapes) in IR regimes where factorisation theorems apply & perform full fits of non-perturbative models (e.g. soft factors)

  - exploit known universality across observables to constrain models with data

- Tune complete hadronisation models with more accurate Monte Carlo (e.g. NNLL+N(N)LO) - exploit data collected at different c.o.m. energies
Exploit better observables (i.e. less sensitive to hadronisation):

- use jet algorithms [better understanding of scaling of hadronisation corrections necessary in these observables]. Monte Carlo studies ongoing:

For anti-kt and SISCones:

\[ y = 1 - \cos(R) \]

\[ \varepsilon = \frac{E_{\text{cut}}}{Q} \]

See also talks by Gabor Somogyi and Andrii Verbytskyi on Wednesday.
Exploit better observables (i.e. less sensitive to hadronisation):

- use jet substructure to get rid of soft physics

e.g. soft-drop Thrust:
[Marzani, Reichelt, Schumann, Soyez, Theeuwes ‘19]

\[
\tau \equiv 1 - T = \min_{\vec{n}} \left( 1 - \frac{\sum_{i \in \varepsilon} |\vec{n} \cdot \vec{p}_i|}{\sum_{i \in \varepsilon} |\vec{p}_i|} \right)
\]

\[\tau_{SD} = \frac{\sum_{i \in \varepsilon_{SD}} |\vec{p}_i|}{\sum_{i \in \varepsilon} |\vec{p}_i|} \left[ 1 - \frac{\sum_{i \in \mathcal{H}_{SD}^L} |\vec{n}_L \cdot \vec{p}_i| + \sum_{i \in \mathcal{H}_{SD}^R} |\vec{n}_R \cdot \vec{p}_i|}{\sum_{i \in \varepsilon_{SD}} |\vec{p}_i|} \right]\]

See also talk by Zoltan Trocsanyi on Monday
HADRONISATION AT FCC-ee

- Exploit better observables (i.e. less sensitive to hadronisation):
  - use jet substructure to get rid of soft physics

  e.g. soft-drop Thrust: [Marzani, Reichelt, Schumann, Soyez, Theeuwes '19]

- Less discrepancy between analytic and MC models, but not enough phase space for grooming at LEP - better at FCCee?

  i.e. soft drop condition to each hemisphere

\[
\frac{\min(E_i, E_j)}{E_i + E_j} > z_{cut} (1 - \cos \theta_{ij})^{\beta/2}
\]

- Calculation of higher orders desirable …
### Precision in Higgs couplings in $\kappa$ framework / EFT fits

<table>
<thead>
<tr>
<th>Collider</th>
<th>HL-LHC</th>
<th>ILC$_{250}$</th>
<th>CLIC$_{380}$</th>
<th>CEPC$_{240}$</th>
<th>FCC-ee$_{240}$$\rightarrow$365</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumi (ab$^{-1}$)</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>5.6</td>
<td>5 + 0.2 + 1.5</td>
</tr>
<tr>
<td>Years</td>
<td>11.5$^5$</td>
<td>8</td>
<td>7</td>
<td>3 + 1 + 4</td>
<td></td>
</tr>
<tr>
<td>$g_{HZZ}$ (%)</td>
<td>1.5 / 3.6</td>
<td>0.29 / 0.47</td>
<td>0.44 / 0.66</td>
<td>0.18 / 0.52</td>
<td>0.17 / 0.26</td>
</tr>
<tr>
<td>$g_{HWW}$ (%)</td>
<td>1.7 / 3.2</td>
<td>1.1 / 0.48</td>
<td>0.75 / 0.65</td>
<td>0.95 / 0.51</td>
<td>0.41 / 0.27</td>
</tr>
<tr>
<td>$g_{Hbb}$ (%)</td>
<td>3.7 / 5.1</td>
<td>1.2 / 0.83</td>
<td>1.2 / 1.0</td>
<td>0.92 / 0.67</td>
<td>0.64 / 0.56</td>
</tr>
<tr>
<td>$g_{Hcc}$ (%)</td>
<td>SM / SM</td>
<td>2.0 / 1.8</td>
<td>4.1 / 4.0</td>
<td>2.0 / 1.9</td>
<td>1.3 / 1.3</td>
</tr>
<tr>
<td>$g_{Hgg}$ (%)</td>
<td>2.5 / 2.2</td>
<td>1.4 / 1.1</td>
<td>1.5 / 1.3</td>
<td>1.1 / 0.79</td>
<td>0.89 / 0.82</td>
</tr>
<tr>
<td>$g_{H\tau\tau}$ (%)</td>
<td>1.9 / 3.5</td>
<td>1.1 / 0.85</td>
<td>1.4 / 1.3</td>
<td>1.0 / 0.70</td>
<td>0.66 / 0.57</td>
</tr>
<tr>
<td>$g_{H\mu\mu}$ (%)</td>
<td>4.3 / 5.5</td>
<td>4.2 / 4.1</td>
<td>4.4 / 4.3</td>
<td>3.9 / 3.8</td>
<td>3.9 / 3.8</td>
</tr>
<tr>
<td>$g_{H\gamma\gamma}$ (%)</td>
<td>1.8 / 3.7</td>
<td>1.3 / 1.3</td>
<td>1.5 / 1.4</td>
<td>1.2 / 1.2</td>
<td>1.2 / 1.2</td>
</tr>
<tr>
<td>$g_{HZ\gamma}$ (%)</td>
<td>11. / 11.</td>
<td>11. / 10.</td>
<td>11. / 9.8</td>
<td>6.3 / 6.3</td>
<td>10. / 9.4</td>
</tr>
<tr>
<td>$g_{Htt}$ (%)</td>
<td>3.4 / 2.9</td>
<td>2.7 / 2.6</td>
<td>2.7 / 2.7</td>
<td>2.6 / 2.6</td>
<td>2.6 / 2.6</td>
</tr>
<tr>
<td>$g_{HHH}$ (%)</td>
<td>50. / 52.</td>
<td>28. / 49.</td>
<td>45. / 50.</td>
<td>17. / 49.</td>
<td>19. / 34.</td>
</tr>
<tr>
<td>$\Gamma_H$ (%)</td>
<td>SM</td>
<td>2.4</td>
<td>2.6</td>
<td>1.9</td>
<td>1.2</td>
</tr>
<tr>
<td>BR$_{\text{inv}}$ (%)</td>
<td>1.9</td>
<td>0.26</td>
<td>0.63</td>
<td>0.27</td>
<td>0.19</td>
</tr>
<tr>
<td>BR$_{\text{EXO}}$ (%)</td>
<td>SM (0.0)</td>
<td>1.8</td>
<td>2.7</td>
<td>1.1</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**Astonishing precision for Higgs couplings. Can we achieve more by looking at differential distributions?**

[de Blas et al. ’19]
Differential shapes rich of information due to different final states

Access to light quark Yukawa couplings, but precision TH necessary
Existing technology developed in recent years instrumental to achieve this precision

- e.g. exclusive $H \to bb + X$ at $N^3LO$
  (massless $b$ quarks)  [Mondini, Schiavi, Williams ’19]

- $b$-mass effects relevant at scales $y_{cut} \sim \frac{m_b^2}{m_H^2}$
  (known to NNLO for $H \to bb$)
  [Bernreuther, Chen, Si ’18]  
  [Primo, Sasso, Somogyi, Tramontano ’18]  
  [Behring, Bizon ’19]

- Calculation of all-order corrections for 2/3 jet observables very desirable
  (partly easy with existing technology)
Existing technology developed in recent years instrumental to achieve this precision

- e.g. Higgs event shapes in $H \rightarrow gg$ (large - $m_t$ limit)
- corrections to HEFT important to be sensitive to light-quark Yukawas - much progress recently in $H \rightarrow gg$

- bottleneck once again seems to be non-perturbative corrections ($Q \sim 125$ GeV, gluon jets, ...)

[Davies et al. '19] [Harlander '19] [Czakon, Niggetiedt '20]
[Bonciani et al. '19; Frellesvig et al. '19]
[Melnikov, Penin '16; Liu, Penin '17-'18]
[Liu, Neubert '19; Wang '19]
TOP MASS AT FUTURE LEPTON COLLIDERS

- FCC-ee offers extremely precise access to the top mass
- threshold scan: $\Delta m_t \sim 50$ MeV or better
- from $tt\gamma$ (rad. return): $\Delta m_t \sim 110 - 150$ MeV
  - complex QCD theory near threshold, but in excellent shape (NRQCD, resummation of velocity sing., …) [Boronat et al. ’19]
  - some technical aspects of matching (also incl. EW corrections) to be sorted out

See also talk by Andre Hoang on Wednesday

[Hoang, Stahlhofen ’12; Beneke et al. ’15, …]

Threshold scan at lepton colliders

- $tt$ threshold - 1S mass 174 GeV
- TOPPIK NNLO
- CLIC 350 LS+ISR
- ILC 350 LS+ISR
- FCCee 350 LS+ISR

based on CLIC/ILC Top Study EPJ C73, 2540 (2013)
The top mass measured this way can be used as input to explore important aspects of infrared physics that are hard to access in hadronic collisions.

- Linear renormalons in short-distance top-mass: 
  - $m_t$-sensitive jet observables are affected by a $O(\Lambda_{QCD})$ ambiguity due to infrared physics.

**e.g. $W^*$ decay**

Proportional to the coefficient of the linear renormalon

\[ \langle M \rangle = m_W + b - \text{jet} \]

[Ref: Ferrario-Ravasio, Nason, Oleari '18]
The top mass measured this way can be used as input to explore important aspects of infrared physics that are hard to access in hadronic collisions.

Monte Carlo top mass:

The top mass measured this way can be used as input to explore important aspects of infrared physics that are hard to access in hadronic collisions.

Monte Carlo top mass:

for MC based on angular ordering, the top pole mass receives a correction proportional to the shower cutoff scale $Q_0$

$$m^{(MC)} = m_{pole} - \frac{2}{3} \alpha_s(Q_0) Q_0 + \mathcal{O}(\alpha_s^2)$$

Position of the (hemisphere) mass peak in boosted $tt$ production can be related to the shift. Better understanding crucial for direct reconstruction, e.g. effect of MC tuning, finite width, ...
CONCLUSIONS

- FCC has huge physics potential with its very rich and diversified program
- Achieving the expected precision in many collider observables constitutes a massive challenge for the whole TH community

- Accurate control over a broad range of TH elements (QCD, EW - not mentioned much in this talk) is necessary; great opportunity to use data to explore aspects which are still poorly known (e.g. infrared dynamics, couplings/masses, ...)

- Crucial to think of new ways to exploit the modern knowledge of QFT and its tools to devise new measurements that will help exploit future collider machines effectively