Plans for FCC-\(e^+e^-\) WG5: QCD & \(\gamma-\gamma\) physics

FCC kick-off meeting
Geneva – 14\(^{\text{th}}\) Feb. 2014

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CERN
FCC-e⁺e⁻ Working-Group-5 mandate:
- Physics objectives

QCD physics at FCC-e⁺e⁻ (non-exhaustive list):
- High-precision (<1% uncertainty) strong coupling determination
- Precision multi-jets and parton-hadronization studies
- Two-photon measurements: $F_2(x,Q^2)$ gluon in photon, BFKL via VV..

Non-QCD physics via $\gamma\gamma$ at FCC-e⁺e⁻ (non-exhaustive list):
- Effective two-photon luminosities
- Examples: $\gamma\gamma \rightarrow \gamma\gamma$, aQGC via $\gamma\gamma WW$, $\gamma\gamma \rightarrow$ Higgs,...
  - anomalous tau e.m. moments via $\gamma\gamma \rightarrow \tau\tau$

Summary & next steps:
- WG5 managerial objectives
- WG5 milestones & deliverables
WG5 mandate: Physics objectives

- Determine best achievable EXP & TH precision on $\alpha_s$ measurement via: Z,W,\(\tau\) hadronic decays widths, jet rates, event shapes, ....

- Explore other competitive QCD physics opportunities opened in e+e-.

- Evaluate photon-photon physics possibilities via EPA fluxes: Higgs, anomalous quartic gauge couplings, anomalous top,\(\tau\) e.m. moments,...

- Set goals for sub-detector performance (including forward e\(\pm\) taggers for $\gamma\gamma$ physics) and experimental-conditions so that syst.~stat. Uncertainties for the measurements

- Define experimental/phenomenological software needs to make possible these measurements and their interpretation with the required precision.

- Help evaluating the QCD impact on rest of FCC measurements. Provide design study for “background” event generators for QCD and $\gamma\gamma$ processes.
(1) QCD physics at FCC-e⁺e⁻

- e⁺e⁻ collisions provide an extremely clean environment with fully-controlled initial-state to probe q,g dynamics:

Advantages compared to p-p at the LHC:
- Electroweak initial-state with known kinematics
- No QCD “underlying event”
- Smaller QCD radiation (only in final-state)
- Smaller non-pQCD uncertainties (no PDFs)

- FCC vs. LEP2: Orders-of-magnitude higher statistics (and higher Q²)

- Key measurements:
  - Strong coupling \( \alpha_s \) with <1% uncertainties through various observables.
  - Colour reconnection (\( m_{top} \))
  - High-precision QCD: multi-jets
  - High-precision QCD: q,g,c,b fragmentation
  - γγ physics: \( F_2^\gamma(x,Q^2) \), BFKL via VV,…
  - …
(2) Photon-photon physics at FCC-e⁺e⁻

- Electromagnetic field of high-energy charge = equivalent photon flux. Weizsäcker-Williams (EPA) spectrum for e± beam:

\[
\frac{dN_\gamma}{dz} \approx \frac{\alpha_{em}}{2\pi} \left[ \frac{1}{z} \left( 1 + (1 - z)^2 \right) \ln \frac{Q_{\text{max}}^2}{Q_{\text{min}}^2} \right], \quad z = \omega / E_e
\]

Soft bremsstrahlung γ spectrum

- Two-photon collisions provide complementary QCD, EW, Higgs, BSM physics opportunities, although with reduced lumis & energies:

  - \( \mathcal{L}_{\gamma\gamma} (W_{\gamma\gamma} > 0.1 \cdot E_e) \sim 10^{-2} \mathcal{L}_{e^+e^-} \)
  - \( \mathcal{L}_{\gamma\gamma} (W_{\gamma\gamma} > 0.5 \cdot E_e) \sim 0.4 \cdot 10^{-3} \mathcal{L}_{e^+e^-} \) (Main reason for Compton-backscattered laser-photons at PLC: \( E_\gamma \sim E_{e^+} \), \( \mathcal{L}_{\gamma\gamma} \sim 0.8 \cdot \mathcal{L}_{e^+e^-} \))
QCD physics at FCC-e^+e^-
**Multi-prong determination of $\alpha_s$ coupling**

- $\alpha_s$ = crucial parameter for SM precision fits, couplings unification, ...
  - <1% uncertainties required

- Event shapes/thrust (NNLO+N^3LL), jet rates (NNLO): reduced npQCD uncertainties at FCC.

- $Z,W$ hadronic decays ($N^3,4$LO):
  \[ R_Z = \frac{\Gamma(Z \to h)}{\Gamma(Z \to l)} = R_Z^{EW} N_C (1 + \sum_{n=1}^{4} c_n \left(\frac{\alpha_s}{\pi}\right)^n + O(\alpha_s^5) + \delta_m + \delta_{np}) \rightarrow 10^{12} Z's \]
  \[ B_h \equiv \frac{\Gamma_{had}}{\Gamma_{tot}} \rightarrow 5 \times 10^7 WW's \]

- $\tau$ hadron decay ($N^3,4$LO)
  \[ R_\tau = \frac{\Gamma(\tau^- \to \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau \bar{\nu}_e)} = S_{EW} N_C (1 + \sum_{n=1}^{4} c_n \left(\frac{\alpha_s}{\pi}\right)^n + O(\alpha_s^5) + \delta_{np}) \]

<table>
<thead>
<tr>
<th>Method</th>
<th>Current relative precision</th>
<th>Future relative precision</th>
</tr>
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</table>
| $e^+e^-$ evnt shapes | expt $\sim 1\%$ (LEP)  
               thry $\sim 1$–$3\%$ (NNLO+up to N^3LL, n.p. signif.) | $<1\%$ possible (ILC/TLEP)  
               $\sim 1\%$ (control n.p. via $Q^2$-dep.) |
| $e^+e^-$ jet rates | expt $\sim 2\%$ (LEP)  
               thry $\sim 1\%$ (NNLO, n.p. moderate) | $<1\%$ possible (ILC/TLEP)  
               $\sim 0.5\%$ (NLL missing) |
| precision EW     | expt $\sim 3\%$ ($R_Z$, LEP)  
               thry $\sim 0.5\%$ (N^3LO, n.p. small) | 0.1% (TLEP 10]), 0.5% (ILC 11])  
               $\sim 0.3\%$ (N^4LO feasible, $\sim 10$ yrs) |
| $\tau$ decays    | expt $\sim 0.5\%$ (LEP, B-factories)  
               thry $\sim 2\%$ (N^3LO, n.p. small) | $<0.2\%$ possible (ILC/TLEP)  
               $\sim 1\%$ (N^4LO feasible, $\sim 10$ yrs) |

Snowmass'13, arXiv:1310.5189
**Color reconnection, \( m_{\text{top}} \) & universe stability**

- Running of the Higgs self-coupling with energy:

\[
(4\pi)^2 \frac{d\lambda}{d \ln \mu} = -6y_t^4 + \frac{9}{8}g_2^4 + \frac{27}{200}g_1^4 + \frac{9}{20}g_2^2g_1^2 + \lambda(12y_t^2 - 9g_2^2 + \frac{9g_1^2}{5}) + 24\lambda^2 + \text{higher loops}
\]

If \( m_H \) too large: \( \lambda \rightarrow \) non perturbative

If \( m_{\text{top}} \) too large: \( \lambda \rightarrow \) negative

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If \( m_{\text{top}} \) (pole) > 171.2 GeV:
the universe is in a meta-stable state
(it will decay to true vacuum eventually)

**CMS average:**

\[ m_{\text{top}} = 173.49 \pm 0.36 \pm 0.91 \text{ GeV} \]

\( \pm 0.45 \text{ GeV} \)
(color reconnection)

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**FCC-160:** WW hadronic decays will reduce this uncertainty
High-precision multi-jets dynamics

- LEP/SLD data: Max. N=4 jets. Large uncertainties in regions of phase-space. Differential measurements not useable for high-precision (<10%, i.e. beyond LO+LL) theory. Ex.: jet rates vs. jet resolution (4→5,5→6 jets)

LEP Perturbative Region (k_T≥5GeV)

- Durham Jet resolution scale
- FCC multijets: ~1% precision (large stats, higher-Q^2, better detectors). Fractal jet structure, scale breaking, power corrections, coherence, subleading colour corrections, subleading logs (compressed hierarchies), mass corrections, spin correlations, n-loop corrections, g→qq, IR limits,...
High-precision $q,g,c,b$ fragmentation

- **LHC data**: Parton fragmentation complicated by IS and FS effects: multi-parton interactions, colour reconnection, collective effects, ...

- **High-$n$ events** probe hard + soft QCD. (+reference for pp)

- **Baryon rates** (beyond $p,\Lambda$) known only to $\sim 10\% - 20\%$ Spectra likewise or worse

- **High Multiplicity Events**

- **Rare states**

- **D and B fragmentation**
  - Few clean spectra
  - Uncertainties $> 10\%$
  - Especially in soft and hard regions

- **FCC**: Huge jet statistics with flavour ID. Rates & fragmentation spectra at $1\%$ level also for rare/exotic states, in extrema of distributions

- **Tera-Z?**
  - $c$ or doubly charmed?

- **pQCD 3 charm**

- **+ Improve LEP limits on colour reconnections**
  - clear signal?
  - STUDY colour reconnections
  - Feedback to pp
**QCD in \(\gamma-\gamma\) collisions at FCC-\(e^+e^-\) (I)**

- **Hadron production cross section versus \(\sqrt{s}\):**

  - **Hadronic cross-sections versus \(\sqrt{s}\):**
    
    - **\(e^+e^-\rightarrow\) hadrons (total)**
    - **\(\gamma\gamma\rightarrow\) hadrons (total)**

  \[ \sigma(\gamma\gamma\rightarrow\text{hadrons}) \sim \ln(s) \]

  \[ \sigma(e^+e^-\rightarrow\text{hadrons}) \sim 1/s \]

- **At \(\sqrt{s}\sim300\) GeV, \(\gamma\gamma\) x-sections are \(\sim5\cdot10^4\) times higher:**
  
  - \(\sigma(\gamma\gamma\rightarrow\text{hadrons})\sim\) 5 \(\mu\)b
  - \(\sigma(ee\rightarrow\text{hadrons})\sim\) 0.1 nb

  Hadron yields “just” \(\sim2\) orders of magnitude higher, taking into account \(\mathcal{L}\)\(_{\text{eff}}\sim10^{-(2-3)}\) reduction penalty

- **Hadronic backgrounds** for all other FCC physics studies

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**FCC Kickoff Meeting, Geneva, Feb. 2014**

David d'Enterria (CERN)
QCD in $\gamma$-$\gamma$ collisions at FCC-e$^+$e$^-$ (II)

- Leading QCD contributions in $\gamma$-$\gamma$ collisions:

  - Soft (VMD)
  - Direct
  - $\gamma$-"hadron"
  - "hadron"-"hadron"

- $\sigma_{tot}(\gamma\gamma)$, (di)jets, resonances, incl. hadrons, heavy-Q, ... via untagged e$^\pm$

- Photon QED & QCD structure functions:

  - $F_{2,QCD/QED}^\gamma$ over wide $(x,Q^2)$, gluon content of $\gamma$
  - Quasireal/virtual $\gamma$ via single/double tags

- BFKL dynamics via $\gamma\gamma \rightarrow \rho\rho, J/\psi, J/\psi, YY$:
Non-QCD physics via $\gamma\gamma$ collisions at FCC-$e^+e^-$
Non-QCD $\gamma$-$\gamma$ physics at FCC-e$^+$e$^-$

- Convolve e$^+$e$^-$ EPA spectra, scale by beam $\mathcal{L}_{ee}$
- Thanks to large FCC lumi: $\mathcal{L}_{\gamma\gamma}$~20 times higher than p-p($\gamma\gamma$) at LHC without huge LHC p-p pileup.
- Double tagging outgoing e$^+$e$^-$: Forward detectors ($\sim$mrad) needed

Examples:

- $\gamma\gamma \rightarrow \tau\tau$: $\sim 10^8$ di-$\tau$/year
- $\gamma\gamma \rightarrow H$: $\sim 10^3$ LbyL/year ($m_H > 5$GeV)
- $\gamma\gamma \rightarrow WW$: $\sim 10^4$ WW/year
- $\gamma\gamma \rightarrow \tau\tau$: $\sim 10^8$ di-$\tau$/year
- $\gamma\gamma \rightarrow H$: $\sim 10^3$ LbyL/year ($m_H > 5$GeV)
- $\gamma\gamma \rightarrow WW$: $\sim 10^4$ WW/year

$N_x = \int dW_{\gamma\gamma} \frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}} \sigma_{x}^{\gamma\gamma}(W_{\gamma\gamma})$
Anomalous e.m. $\tau$ moments via $\gamma\gamma \rightarrow \tau\tau$

- Magnetic moment of tau-lepton: $a_\tau = 1.17734(2)e^{-4}$ (QED)
  Current LEP bounds: $-0.052 < a_\tau < 0.013$

- Electric dipole-moment of tau-lepton: $|d_\tau| < 10^{-34}$ e cm
  Current LEP (also BELLE) limit: $|d_\tau| < 3.1 \cdot 10^{-16}$ e cm

- Anomalous moments via $\gamma\gamma \rightarrow \tau\tau$ (x-section=270 pb at FCC-Z):

  \[\Gamma^\nu = F_1(q^2)\gamma^\nu + \frac{i}{2m_\tau}F_2(q^2)\sigma^{\nu\mu}q_\mu + \frac{1}{2m_\tau}F_3(q^2)\sigma^{\nu\mu}q_\mu \gamma^5\]

  \[F_1(0) = 1, \ F_2(0) = a_\tau, \ F_3(0) = \frac{2m_\tau d_\tau}{e}.\]

- Two-photon di-tau at CLIC (or FCC-ee) at 0.5 TeV, $2 \cdot 10^{34}$ cm$^{-2}$s$^{-1}$:
  x20 improved limits
**Summary: QCD & $\gamma \gamma$ physics at FCC-$e^+e^-$**

- $\alpha_s(Q)$ with <1% uncertainty with high stats and different methods:
  - Color reconnection
  - High-precision multi-jet final-states
  - High-precision $q,g,c,b$ fragmentation
  - $\sigma_{tot}(\gamma\gamma)$, $\gamma$ structure function, BFKL,...

- Non-QCD physics accessible via EPA fluxes:
  $$\mathcal{L}_{\text{eff}}(\text{FCC},\gamma\gamma) \sim 20 \times \mathcal{L}_{\text{eff}}(pp,\gamma\gamma)$$
  - Anomalous $\tau$ e.m. moments ($\gamma\gamma \rightarrow \tau\tau$)
  - Constraints on a aQGC ($\gamma\gamma WW$)
  - Other processes: $\gamma\gamma \rightarrow H$, $\gamma\gamma \rightarrow \gamma\gamma$, ...

- Unique physics programme with rich opportunities! More to explore!

Impact on other FCC-ee sectors (top, Higgs, EW, ...)

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David d'Enterria (CERN)
WG5 mandate: Managerial objectives

- Joint experiment-phenomenology group with 2 (bi-annual) conveners: 2014-2016: D. d'Enterria (dde@cern.ch), P. Skands (Peter.Skands@cern.ch)

- Build international collaboration with synergies with similar $e^+e^-$ (linear or circular) collider studies.

- Attract people for the studies relevant to the group.

- Maintain high level of contacts with the other WGs.

- Create sub-groups (with sub-conveners) matching the scientific objectives.

- Appoint editors towards the production of intermediate reviews and a contributions to final Yellow Report.

- Report progress to the physics coordination at monthly FCC-ee physics meetings.
**WG5 mandate: Timescales & deliverables**

- **“Exploration” phase (Feb'14 – March'15):** Identify all possible options and potential studies, including requirements and constraints.
  - **Deliverable:** Interim written report for review milestone workshop

- **“Analysis” phase (March'15 – Sept'16):** Detailed studies of the identified baselines.
  - **Deliverable:** Interim written report for review milestone workshop

- **“Elaboration” phase (Sept'16 – Dec'17):** Delivery of all information required for the final Conceptual Design Report (CDR) of the study.
  - **Final Yellow Report (early 2018):** to be included into the FCC CDR.

**JOIN THE QCD & PHOTON-PHOTON WG5 ACTIVITIES !**
Backup slides
### "Golden" $\gamma \gamma$ physics channels at FCC-e$^+e^-$

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<th>Remarks</th>
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<td>SM/MSSM Higgs, $M_{H,h} &lt; 160$ GeV</td>
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<tr>
<td>$\gamma \gamma \rightarrow H \rightarrow WW(*)$</td>
<td>SM Higgs, $140 &lt; M_H &lt; 190$ GeV</td>
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<tr>
<td>$\gamma \gamma \rightarrow H \rightarrow ZZ(*)$</td>
<td>SM Higgs, $180 &lt; M_H &lt; 350$ GeV</td>
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<tr>
<td>$\gamma \gamma \rightarrow H \rightarrow \gamma \gamma$</td>
<td>SM Higgs, $120 &lt; M_H &lt; 160$ GeV</td>
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<tr>
<td>$\gamma \gamma \rightarrow H \rightarrow t\bar{t}$</td>
<td>SM Higgs, $M_H &gt; 350$ GeV</td>
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<tr>
<td>$\gamma \gamma \rightarrow H, A \rightarrow bb$</td>
<td>MSSM heavy Higgs, intern. tan $\beta$</td>
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<tr>
<td>$\gamma \gamma \rightarrow f \bar{f}, \tilde{\chi}_i^+ \tilde{\chi}_i^-$</td>
<td>large cross sections</td>
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<tr>
<td>$\gamma \gamma \rightarrow \tilde{g} \tilde{g}$</td>
<td>measurable cross sections</td>
</tr>
<tr>
<td>$\gamma \gamma \rightarrow H^+ H^-$</td>
<td>large cross sections</td>
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<tr>
<td>$\gamma \gamma \rightarrow S[\tilde{t}\tilde{t}]$</td>
<td>$\tilde{t}\tilde{t}$ stoponium</td>
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<tr>
<td>$e\gamma \rightarrow \tilde{e}^{-} \tilde{\chi}_1^0$</td>
<td>$M_{\tilde{e}^{-}} &lt; 0.9 \times 2E_0 - M_{\chi_1^0}$</td>
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<td>$\gamma \gamma \rightarrow \gamma \gamma$</td>
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<td>$e\gamma \rightarrow eG$</td>
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<td>$\gamma \gamma \rightarrow \phi$</td>
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<td>$e\gamma \rightarrow \tilde{e}\tilde{G}$</td>
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<tr>
<td>$e\gamma \rightarrow W^- \nu_e$</td>
<td>anom. $W$ couplings</td>
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<td>$\gamma \gamma \rightarrow 4W/(Z)$</td>
<td>$WW$ scatt., quartic anom. $W,Z$</td>
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<td>$\gamma \gamma \rightarrow t\bar{t}$</td>
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<td>$e\gamma \rightarrow t\bar{b}\nu_e$</td>
<td>anomalous $Wtb$ coupling</td>
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<td>$\gamma \gamma \rightarrow$ hadrons</td>
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<td>$e\gamma \rightarrow e^- X, \nu_e X$</td>
<td>NC and CC structure functions</td>
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<td>$\gamma g \rightarrow q\bar{q}$, $c\bar{c}$</td>
<td>gluon in the photon</td>
</tr>
<tr>
<td>$\gamma \gamma \rightarrow J/\psi J/\psi$</td>
<td>QCD Pomeron</td>
</tr>
</tbody>
</table>
Anomalous couplings at FCC-e⁺e⁻ (γγ)

- **γγ → WW** quartic/trilinear couplings:

  \[ \sigma \sim 20–90 \text{ pb} \quad (160–500 \text{ GeV}) \]

- **γγ → t\bar{t}**:

  \[ \sigma \sim 1 \text{ pb} \quad (>340 \text{ GeV}) \]

- **γγ → ZZ, γγ → WWZ** quartic couplings:

  \[ \sigma \sim 20–150 \text{ fb} \quad (280–500 \text{ GeV}) \]

- Also nice opportunities in eγ mode:

  e.g. eγ → Wν (again for anomalous couplings)

[PLC, TESLA hep-ex/0108012]