

# Plans for FCC- $e^+e^-$ WG5: QCD & $\gamma\text{-}\gamma$ physics

**FCC kick-off meeting**

Geneva – 14<sup>th</sup> Feb. 2014

David d'Enterria, Peter Skands

**CERN**

# Outline

- 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:  $F_2^\gamma(x, Q^2)$  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

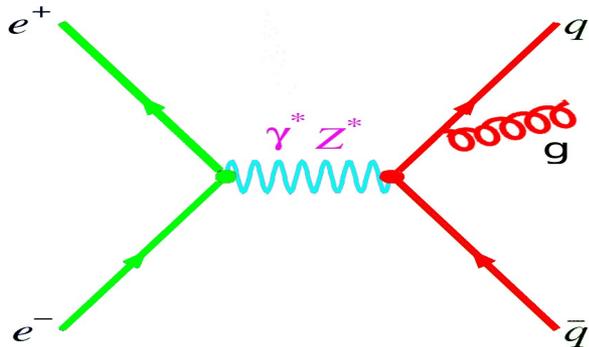
- Determine **best achievable EXP & TH precision on  $\alpha_s$  measurement** via: Z,W, $\tau$  hadronic decays widths, jet rates, event shapes, ....
- Explore **other competitive QCD physics** opportunities opened in e+e-.
- Evaluate **photon-photon physics possibilities via EPA fluxes**: Higgs, anomalous quartic gauge couplings, anomalous top, $\tau$  e.m. moments,...

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- 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:



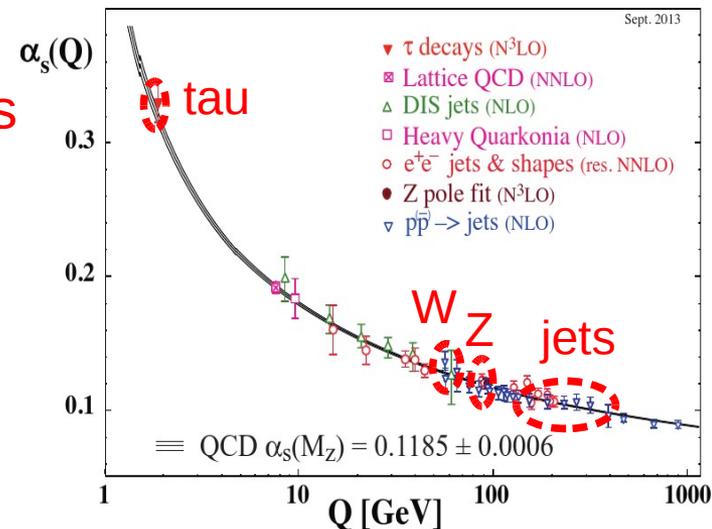
Advantages compared to p-p at the LHC:

- 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  $Q^2$ )**

- Key measurements:

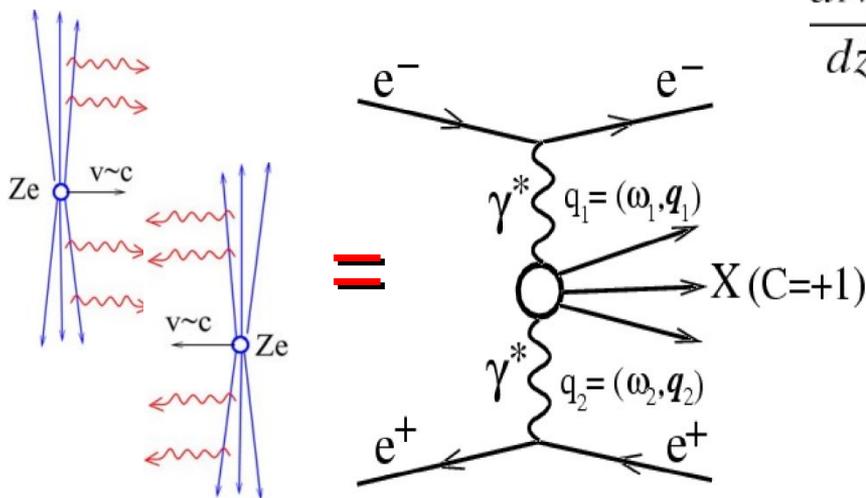
- **Strong coupling  $\alpha_s$  with <1% uncertainties** through various observables.
- **Colour reconnection** ( $m_{top}$ )
- High-precision QCD: **multi-jets**
- High-precision QCD: **q,g,c,b fragmentation**
- $\gamma\gamma$  physics:  **$F_2^\gamma(x,Q^2)$ , BFKL via VV,...**
- ...



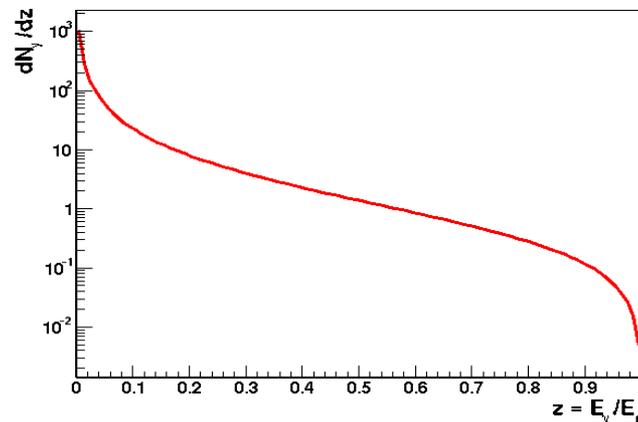
## (2) Photon-photon physics at FCC- $e^+e^-$

- **Electromagnetic field** of high-energy charge = equivalent photon flux.  
**Weizsäcker-Williams (EPA) spectrum** for  $e^\pm$  beam:

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



Soft bremsstrahlung  $\gamma$  spectrum



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

- $\mathcal{L}_\gamma(W_\gamma > 0.1 \cdot E_e) \sim 10^{-2} \mathcal{L}_{e^+e^-}$
- $\mathcal{L}_\gamma(W_\gamma > 0.5 \cdot E_e) \sim 0.4 \cdot 10^{-3} \mathcal{L}_{e^+e^-}$

(Main reason for Compton-backscattered laser-photons at PLC:  $E_\gamma \sim E_e$ ,  $\mathcal{L}_\gamma \sim 0.8 \cdot \mathcal{L}_{e^+e^-}$ )

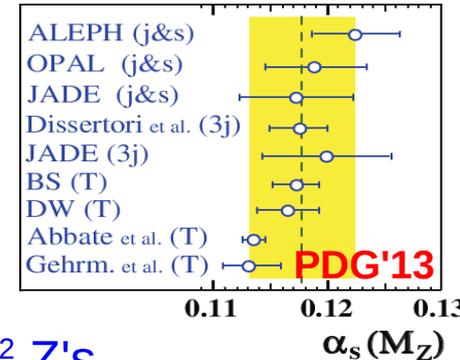
# QCD physics at FCC- $e^+e^-$

# 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<sup>3</sup>LL), jet rates (NNLO):  
reduced npQCD uncertainties at FCC.

- Z,W hadronic decays (N<sup>3,4</sup>LO):



$$R_Z \equiv \frac{\Gamma(Z \rightarrow h)}{\Gamma(Z \rightarrow l)} = R_Z^{\text{EW}} N_C \left( 1 + \sum_{n=1}^4 c_n \left( \frac{\alpha_s}{\pi} \right)^n + \mathcal{O}(\alpha_s^5) + \delta_m + \delta_{\text{np}} \right) \rightarrow 10^{12} \text{ Z's}$$

$$B_h \equiv (\Gamma_{\text{had}}/\Gamma_{\text{tot}})_W \rightarrow 5 \times 10^7 \text{ WW's}$$

$$\rightarrow 10^{11} \tau\text{'s}$$

- $\tau$  hadron decay (N<sup>3,4</sup>LO)  $R_\tau \equiv \frac{\Gamma(\tau^- \rightarrow \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \rightarrow \nu_\tau e^- \bar{\nu}_e)} = S_{\text{EW}} N_C \left( 1 + \sum_{n=1}^4 c_n \left( \frac{\alpha_s}{\pi} \right)^n + \mathcal{O}(\alpha_s^5) + \delta_{\text{np}} \right)$

Method	Current relative precision	<span style="color: red;">Snowmass'13, arXiv:1310.5189</span>	Future relative precision
$e^+e^-$ evt shapes	expt $\sim 1\%$ (LEP) thry $\sim 1\text{--}3\%$ (NNLO+up to N <sup>3</sup> LL, 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 <sup>3</sup> LO, n.p. small)		0.1% (TLEP [10]), 0.5% (ILC [11]) $\sim 0.3\%$ (N <sup>4</sup> LO feasible, $\sim 10$ yrs)
$\tau$ decays	expt $\sim 0.5\%$ (LEP, B-factories) thry $\sim 2\%$ (N <sup>3</sup> LO, n.p. small)		$< 0.2\%$ possible (ILC/TLEP) $\sim 1\%$ (N <sup>4</sup> LO feasible, $\sim 10$ yrs)

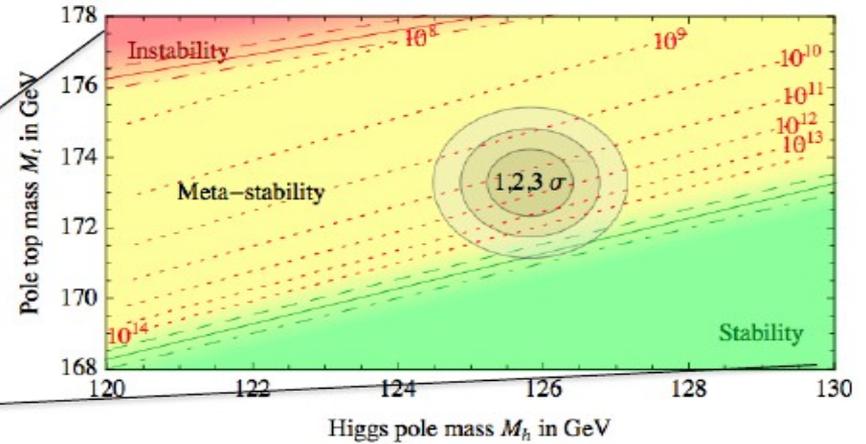
# Color reconnection, $m_{\text{top}}$ & universe stability

- Running of the Higgs self-coupling with energy:

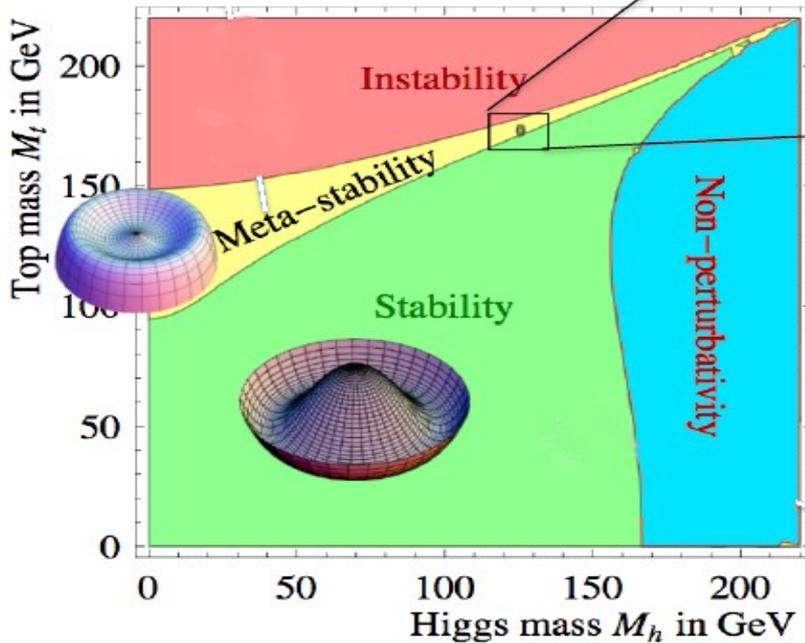
$$(4\pi)^2 \frac{d\lambda}{d \ln \mu} = -6y_t^4 + \frac{9}{8}g_2^4 + \frac{27}{200}g_1^4 + \frac{9}{20}g_2^2g_1^2 + \lambda(12y_t^2 - 9g_2^2 + \frac{9g_1^2}{5}) + 24\lambda^2 + \text{higher loops}$$

If  $m_H$  too large:  $\lambda \rightarrow$  non perturbative

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



[Strumia, Moriond EWK'13]



If  $m_{\text{top}}(\text{pole}) > 171.2$  GeV:

the universe is in a meta-stable state (it will decay to true vacuum eventually)

CMS average:

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

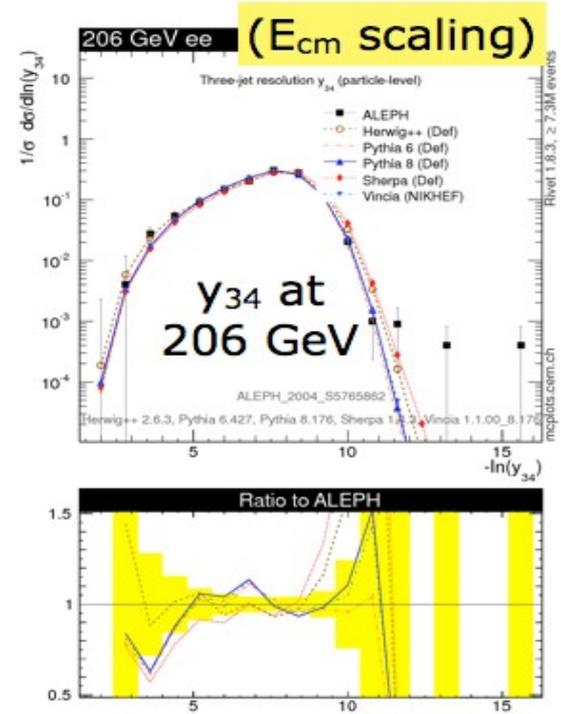
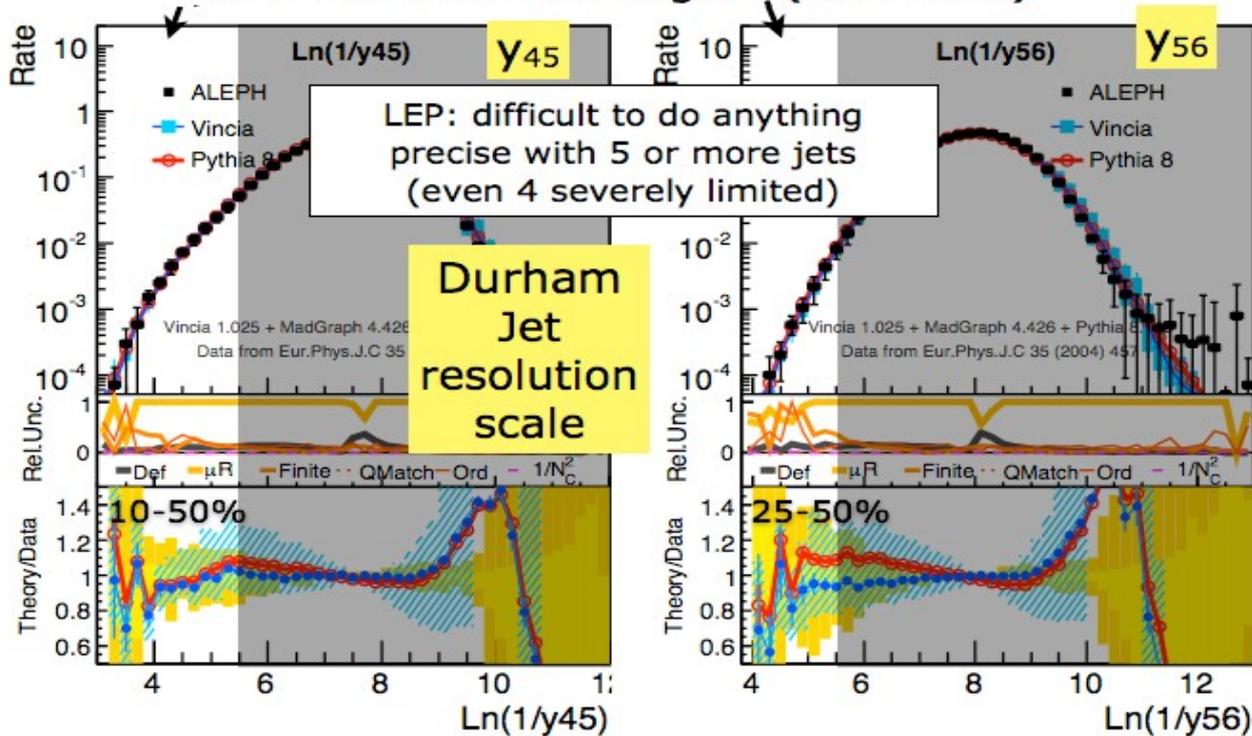
$\pm 0.45$  GeV  
(color reconnection)

- 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)

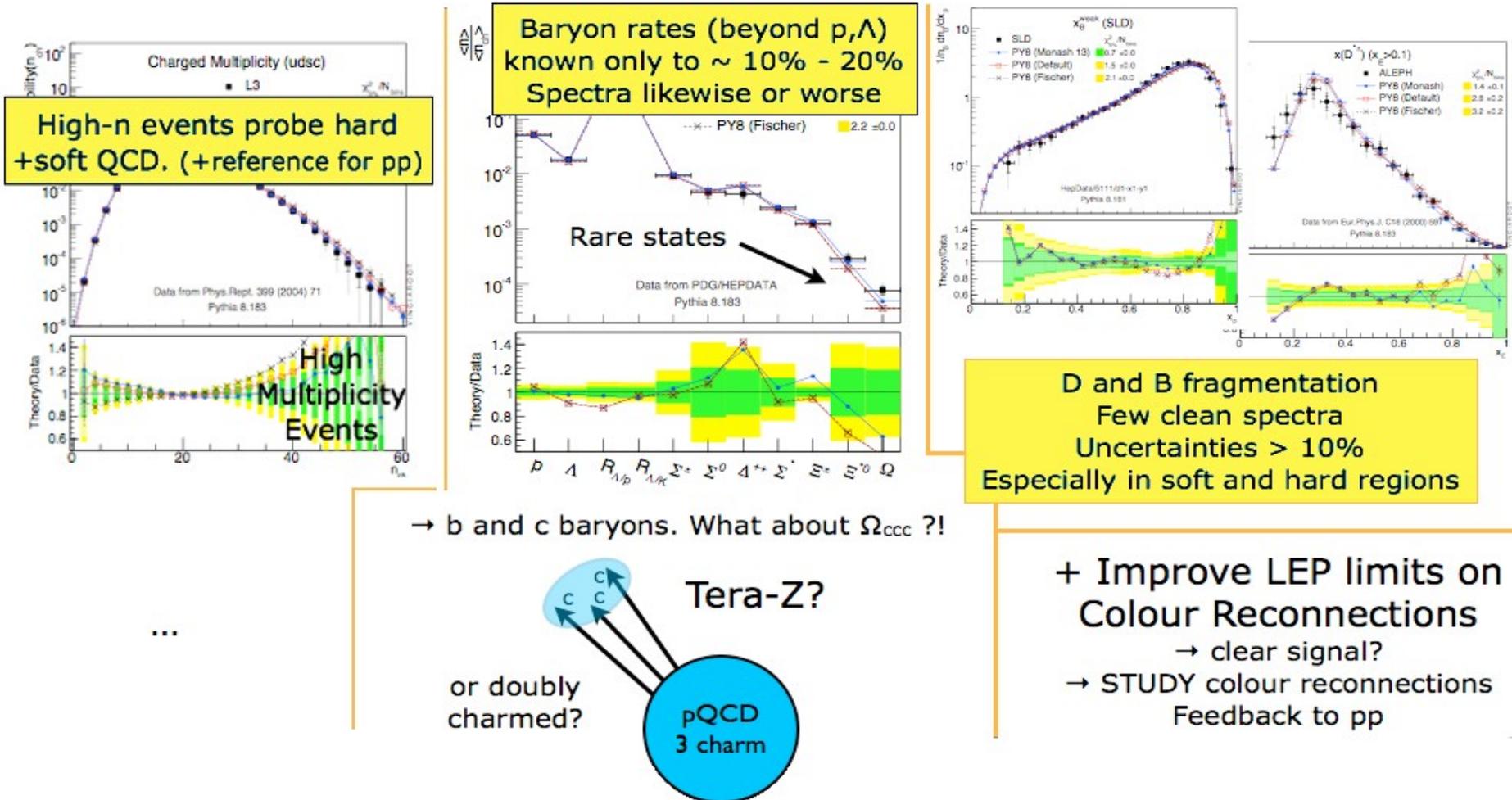
Hard Perturbative Region ( $k_T \geq 5\text{GeV}$ )



- **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,  $g \rightarrow qq$ , IR limits,...

# High-precision q,g,c,b fragmentation

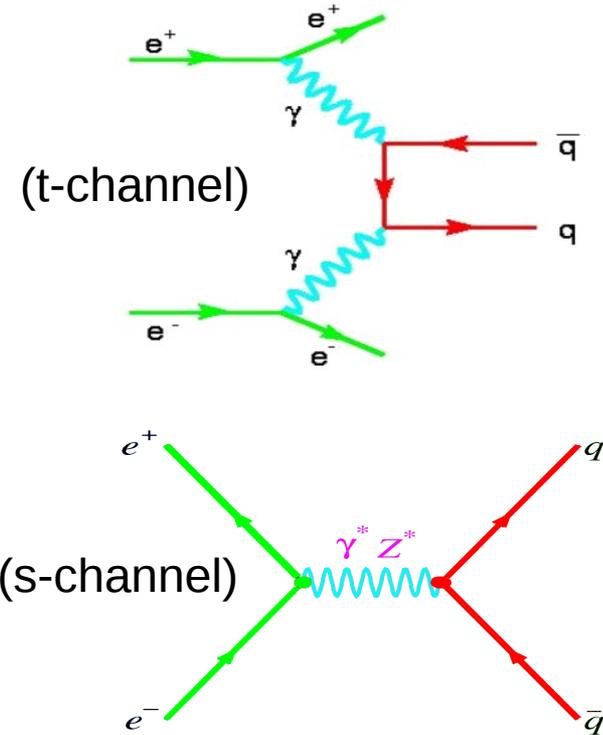
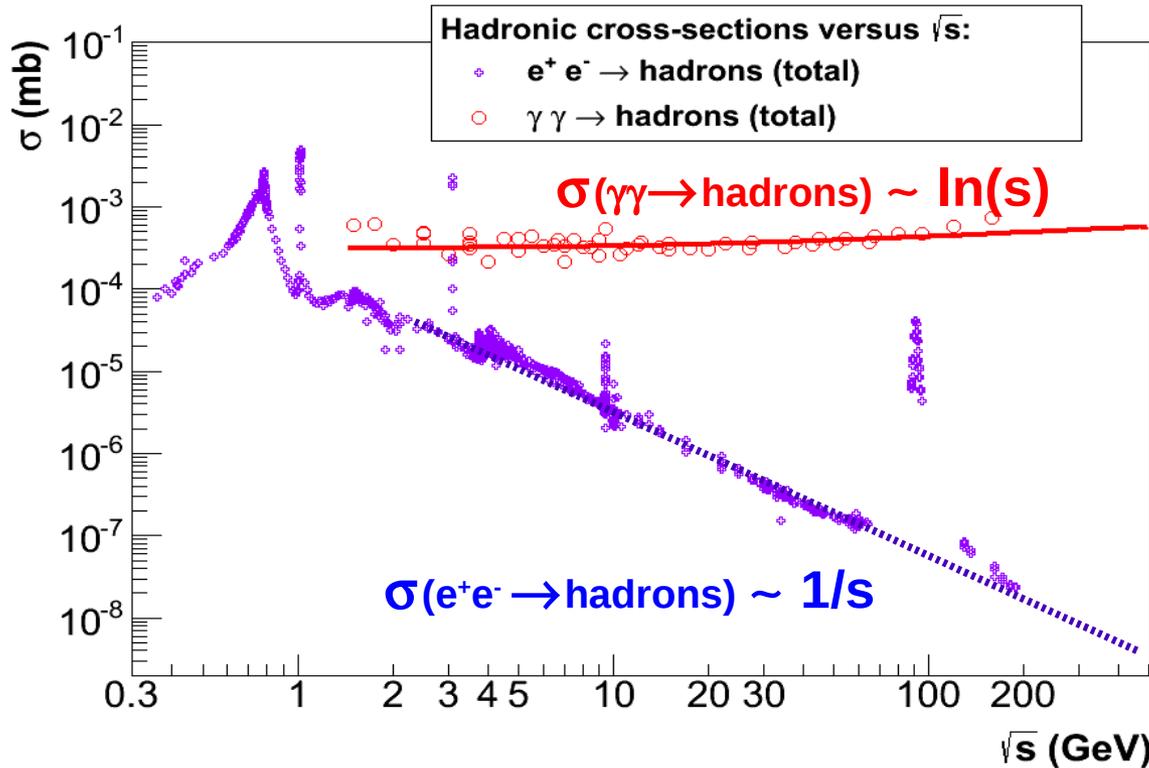
- **LHC data:** Parton fragmentation complicated by IS and FS effects: multi-parton interactions, colour reconnection, collective effects, ...



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

# QCD in $\gamma\text{-}\gamma$ collisions at FCC- $e^+e^-$ (I)

- Hadron production cross section versus  $\sqrt{s}$ :



- At  $\sqrt{s} \sim 300$  GeV,  $\gamma\gamma$  x-sections are  $\sim 5 \cdot 10^4$  times higher:

$$\sigma(\gamma\gamma \rightarrow \text{hadrons}) \sim 5 \mu\text{b}$$

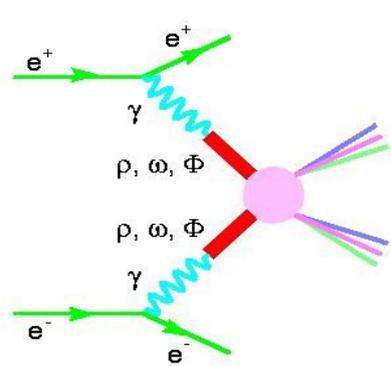
$$\sigma(ee \rightarrow \text{hadrons}) \sim 0.1 \text{ nb}$$

Hadron yields “just”  $\sim 2$  orders of magnitude higher, taking into account  $\mathcal{L}_{\text{eff}} \sim 10^{-(2-3)}$  reduction penalty

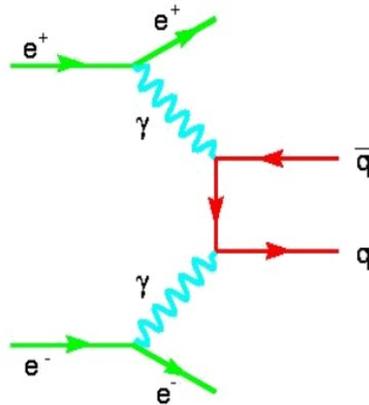
- Hadronic backgrounds for all other FCC physics studies

# QCD in $\gamma\text{-}\gamma$ collisions at FCC- $e^+e^-$ (II)

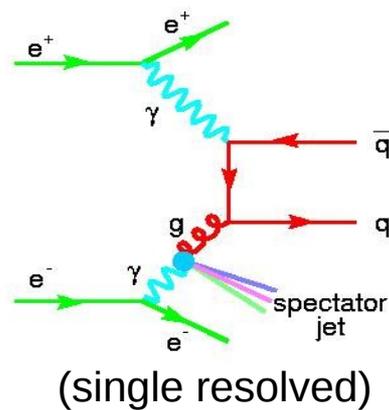
- Leading QCD contributions in  $\gamma\gamma$  collisions:



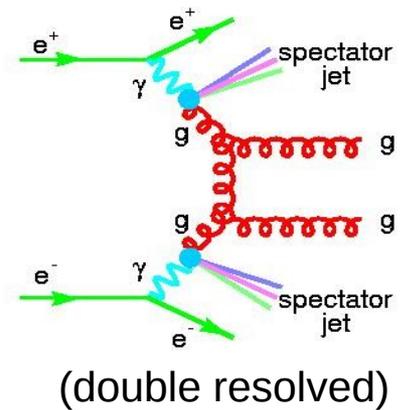
Soft (VMD)



Direct



$\gamma$ -"hadron"



"hadron"-"hadron"

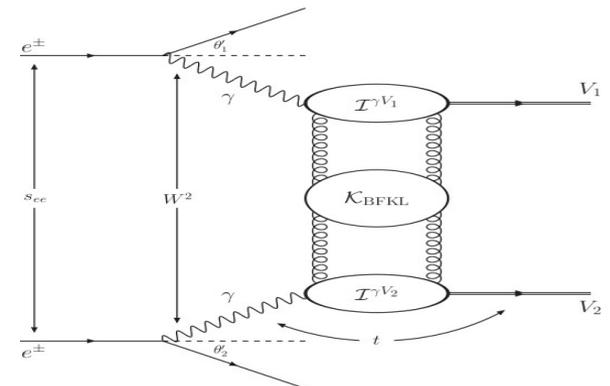
- $\sigma_{\text{tot}}(\gamma\gamma)$ , (di)jets, resonances, incl.hadrons, heavy- $Q$ ,... via untagged  $e^\pm$

- Photon QED & QCD structure functions:

$F_{2,\text{QCD/QED}}^\gamma$  over wide  $(x, Q^2)$ , gluon content of  $\gamma$

Quasireal/virtual  $\gamma$  via single/double tags

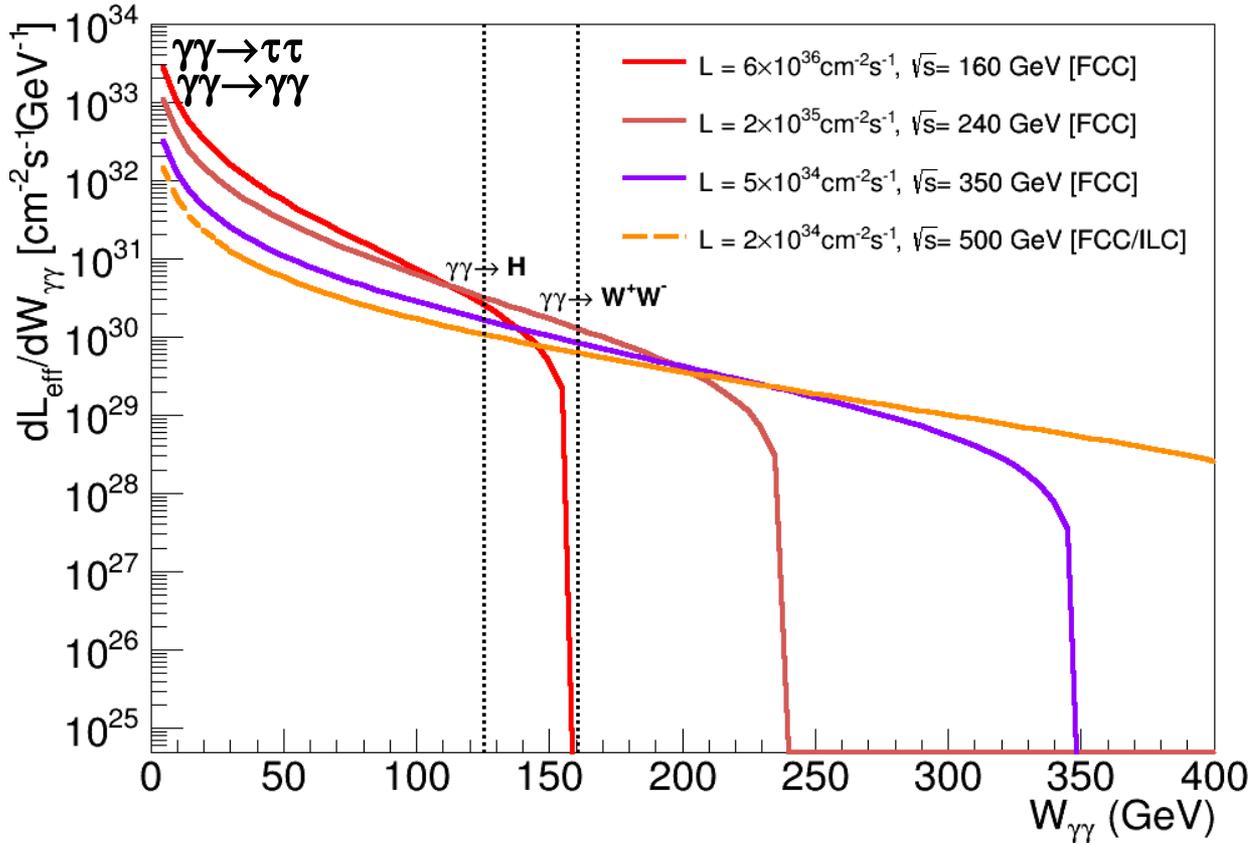
- BFKL dynamics via  $\gamma\gamma \rightarrow \rho\rho, J/\psi, J/\psi, YY$ :



# Non-QCD physics via $\gamma\gamma$ collisions at FCC- $e^+e^-$

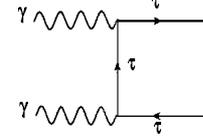
# Non-QCD $\gamma\gamma$ physics at FCC- $e^+e^-$

- Convolve  $e^+e^-$  EPA spectra, scale by beam  $\mathcal{L}_{ee}$

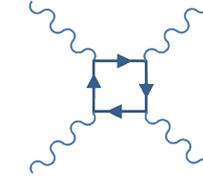


Examples:

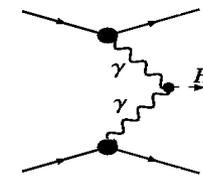
$$N_X = \int dW_{\gamma\gamma} \frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}} \sigma_X^{\gamma\gamma}(W_{\gamma\gamma})$$



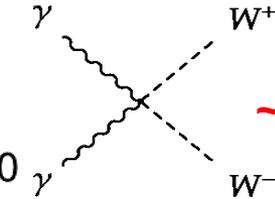
$\sim 10^8$  di- $\tau$ /year



$\sim 10^3$  LbyL/year  
( $m_{\gamma} > 5 \text{ GeV}$ )



$\sim 10^3$  Higgs/year



$\sim 10^4$  WW/year

- Thanks to large FCC lumi:  $\mathcal{L}_{\text{eff}}(\gamma\gamma) \sim 20$  times higher than p-p( $\gamma\gamma$ ) at LHC without huge LHC p-p pileup.
- Double tagging outgoing  $e^+e^-$ : Forward detectors ( $\sim \text{mrad}$ ) needed

# Anomalous e.m. $\tau$ moments via $\gamma\gamma \rightarrow \tau\tau$

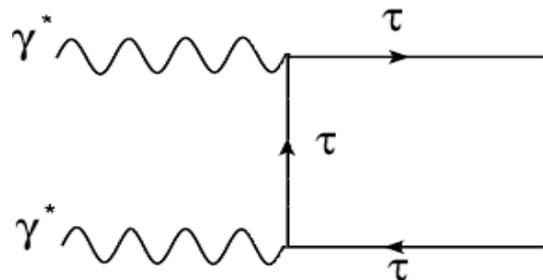
- **Magnetic moment** of tau-lepton:  $a_\tau = 1.17734(2)e-4$  (QED)

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

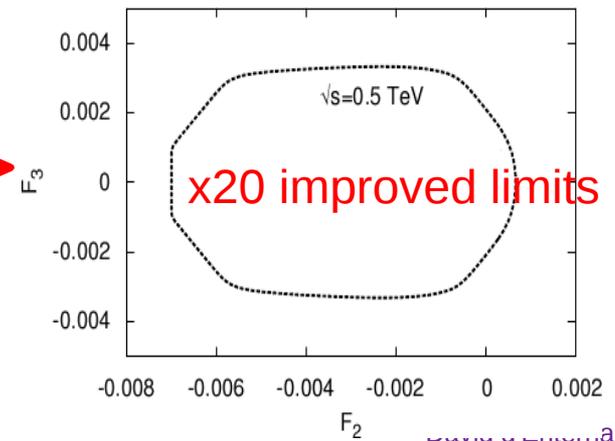
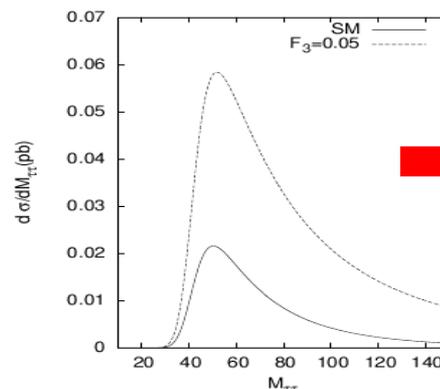
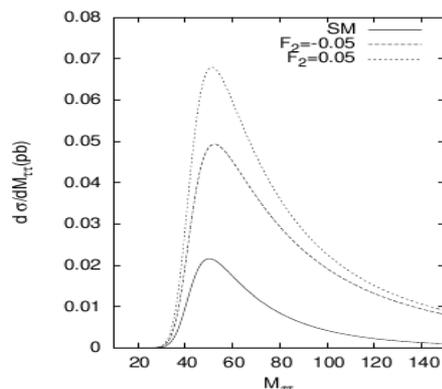
- **Anomalous moments via  $\gamma\gamma \rightarrow \tau\tau$**  (x-section=270 pb at FCC-Z):



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

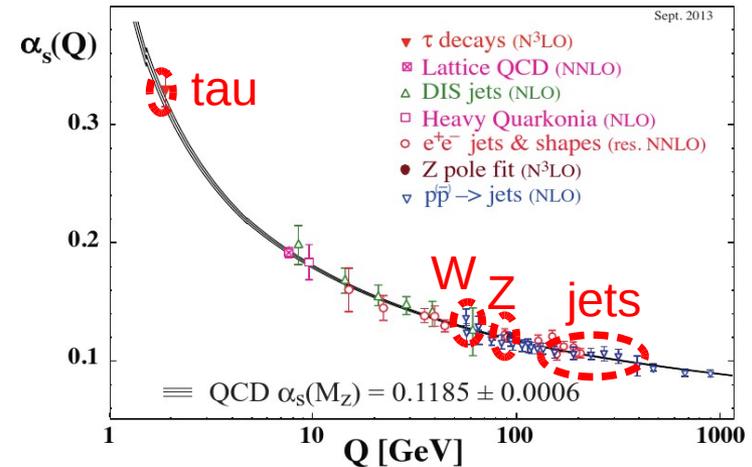
$$F_1(0) = 1, F_2(0) = a_\tau, F_3(0) = \frac{2m_\tau d_\tau}{e}.$$

- **Two-photon di-tau at CLIC (or FCC-ee) at 0.5 TeV,  $2 \cdot 10^{34}$  cm<sup>-2</sup>s<sup>-1</sup>:**



# Summary: QCD & $\gamma\gamma$ physics at FCC- $e^+e^-$

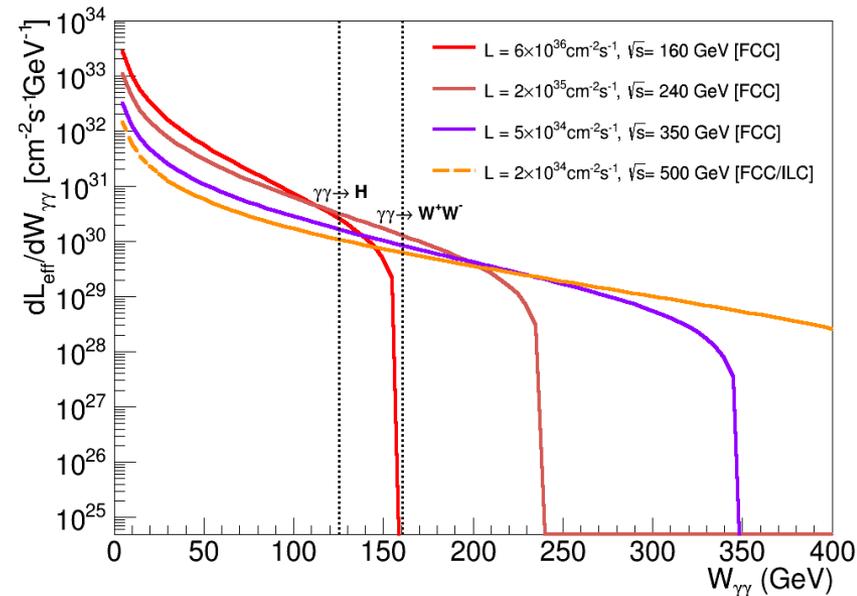
- $\alpha_s(Q)$  with <1% uncertainty with high stats and different methods:
- Color reconnection
- High-precision multi-jet final-states
- High-precision  $q, g, c, b$  fragmentation
- $\sigma_{\text{tot}}(\gamma\gamma)$ ,  $\gamma$  structure function, BFKL, ...



- Non-QCD physics accessible via EPA fluxes:

$$\mathcal{L}_{\text{eff}}(\text{FCC}, \gamma\gamma) \sim 20 \times \mathcal{L}_{\text{eff}}(\text{pp}, \gamma\gamma)$$

- 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, ...)

# 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 !**

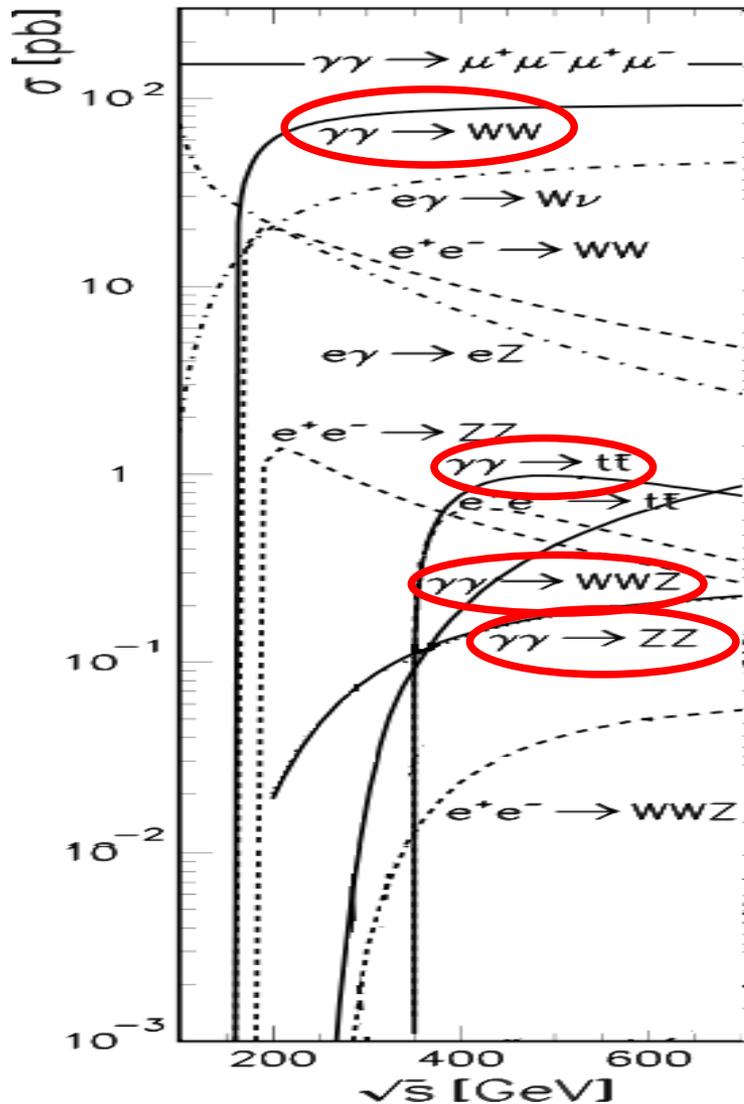
# Backup slides

# “Golden” $\gamma\gamma$ physics channels at FCC- $e^+e^-$

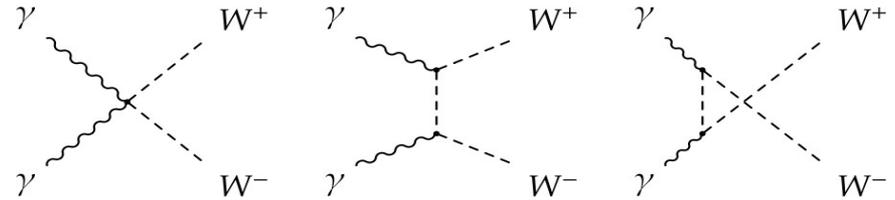
Reaction	Remarks	
→ $\gamma\gamma \rightarrow H, h \rightarrow bb$	SM/MSSM Higgs, $M_{H,h} < 160$ GeV	} SM Higgs
$\gamma\gamma \rightarrow H \rightarrow WW(*)$	SM Higgs, $140 < M_H < 190$ GeV	
$\gamma\gamma \rightarrow H \rightarrow ZZ(*)$	SM Higgs, $180 < M_H < 350$ GeV	
$\gamma\gamma \rightarrow H \rightarrow \gamma\gamma$	SM Higgs, $120 < M_H < 160$ GeV	
$\gamma\gamma \rightarrow H \rightarrow t\bar{t}$	SM Higgs, $M_H > 350$ GeV	
$\gamma\gamma \rightarrow H, A \rightarrow bb$	MSSM heavy Higgs, interm. $\tan\beta$	} SUSY
$\gamma\gamma \rightarrow \tilde{f}\tilde{f}, \tilde{\chi}_i^+ \tilde{\chi}_i^-$	large cross sections	
$\gamma\gamma \rightarrow \tilde{g}\tilde{g}$	measurable cross sections	
$\gamma\gamma \rightarrow H^+ H^-$	large cross sections	
$\gamma\gamma \rightarrow S[\tilde{t}\tilde{t}]$	$\tilde{t}\tilde{t}$ stoponium	
$e\gamma \rightarrow \tilde{e}^- \tilde{\chi}_1^0$	$M_{\tilde{e}^-} < 0.9 \times 2E_0 - M_{\tilde{\chi}_1^0}$	
→ $\gamma\gamma \rightarrow \gamma\gamma$	non-commutative theories	} BSM
$e\gamma \rightarrow eG$	extra dimensions	
$\gamma\gamma \rightarrow \phi$	Radions	
$e\gamma \rightarrow \tilde{e}\tilde{G}$	superlight gravitons	
→ $\gamma\gamma \rightarrow W^+W^-$	anom. $W$ inter., extra dimensions	} Anomalous couplings
$e\gamma \rightarrow W^- \nu_e$	anom. $W$ couplings	
$\gamma\gamma \rightarrow 4W/(Z)$	$WW$ scatt., quartic anom. $W, Z$	
$\gamma\gamma \rightarrow t\bar{t}$	anomalous top quark interactions	} top
$e\gamma \rightarrow \bar{t}b\nu_e$	anomalous $Wtb$ coupling	
→ $\gamma\gamma \rightarrow$ hadrons	total $\gamma\gamma$ cross section	} QCD
→ $e\gamma \rightarrow e^- X, \nu_e X$	NC and CC structure functions	
→ $\gamma g \rightarrow q\bar{q}, c\bar{c}$	gluon in the photon	
→ $\gamma\gamma \rightarrow J/\psi J/\psi$	QCD Pomeron	

[A.deRoeck  
PLHC'08]

# Anomalous couplings at FCC- $e^+e^-$ ( $\gamma\gamma$ )

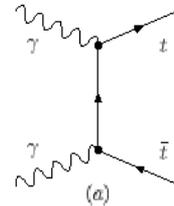


- $\gamma\gamma \rightarrow WW$  quartic/trilinear couplings:



$\sigma \sim 20\text{--}90 \text{ pb}$  (160–500 GeV)

- $\gamma\gamma \rightarrow t\text{-tbar}$  :



$\sigma \sim 1 \text{ pb}$  (>340 GeV)

- $\gamma\gamma \rightarrow ZZ, \gamma\gamma \rightarrow WWZ$  quartic couplings:

$\sigma \sim 20\text{--}150 \text{ fb}$  (280–500 GeV)

- Also nice opportunities in  $e\gamma$  mode:  
e.g.  $e\gamma \rightarrow W\nu$  (again for anomalous couplings)