QCD Physics

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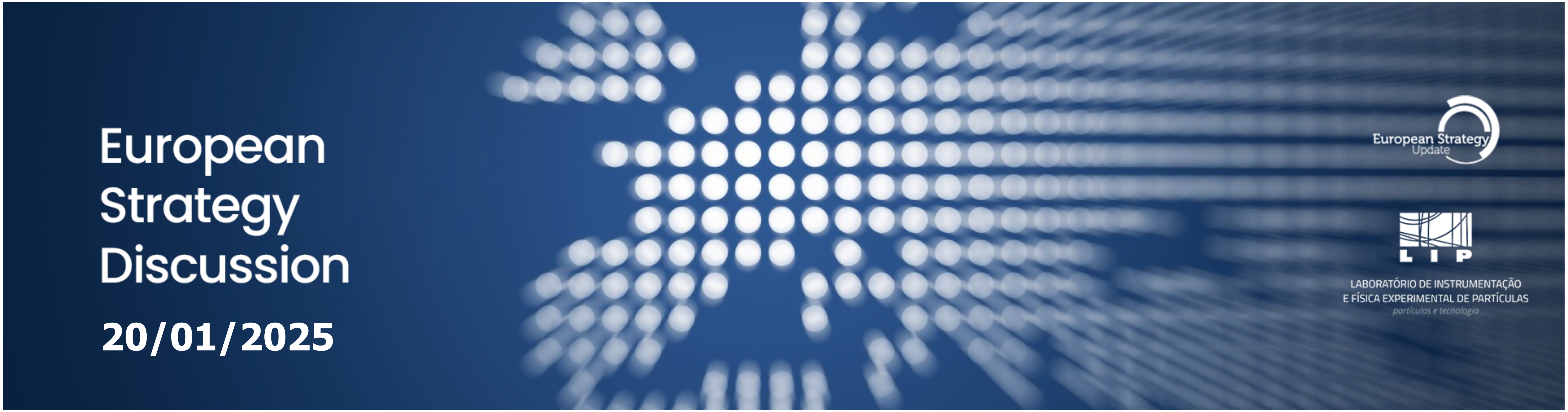

OPEN QUESTIONS/PUZZLES IN THE SM

- What is the origin of Dark Matter which constitutes approximately 27% of the universe's mass-energy content?
- Why is there more matter than anti-matter in the Universe?
- Why are there exactly three families of quarks and leptons?
- Why do particle masses in the SM span such an enormous range?
- Are elementary particles really elementary particles?
- Where does the form of the Higgs potential $V(H) = -\mu^2|H|^2 + \lambda|H|^4$ come from? Does the Higgs boson experience self-coupling?
- The answers to some of these puzzles and open questions can arise in the form on new particles or forces beyond the Standard Model at high energies above the LHC range
- The curiosity in finding out more about how the Universe works requires a new particle collider after the LHC to test our understanding of the SM at ever higher energies with increasing precision $\rightarrow$ Integrated FCC program@CERN

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- What is the origin of Dark Matter which constitutes approximately 27% of the universe's mass-energy content?

> - The successful interpretation of physics analyses at future colliders will necessitate a thorough understanding of QCD
> - In particular QCD effects that are negligible in LEP/LHC physics analyses may become significant at the FCC

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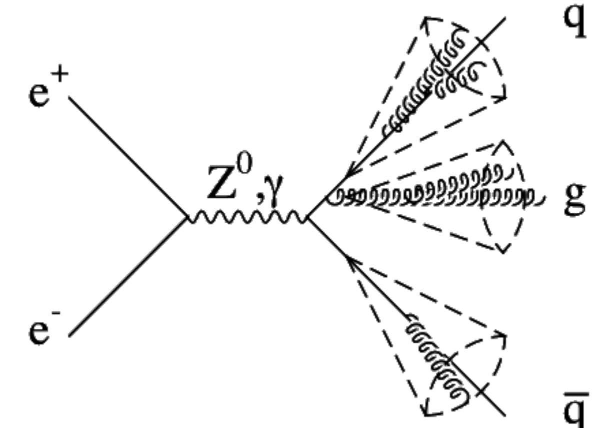
QCD PHYSICS OPPORTUNITIES AT FCC_EE

- Expect $5\cdot10^{12}$ hadronic Z-decays → precision physics with $Z/\gamma^* \rightarrow$ jets
- No parton distributions functions, hadron remnant, underlying event
- Provides clean environment to study QCD dynamics
- FCCee luminosity will enable precision analyses of multi-jet final states



Enormous statistics with $Z \rightarrow qq(g)$

5×10^{12} $e^+e^- \rightarrow Z$

LEP x 10^5

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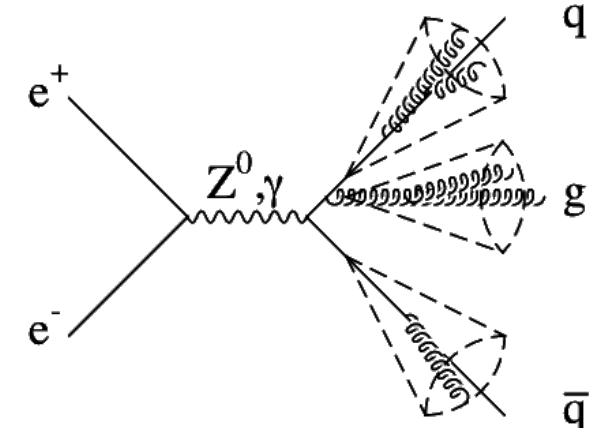

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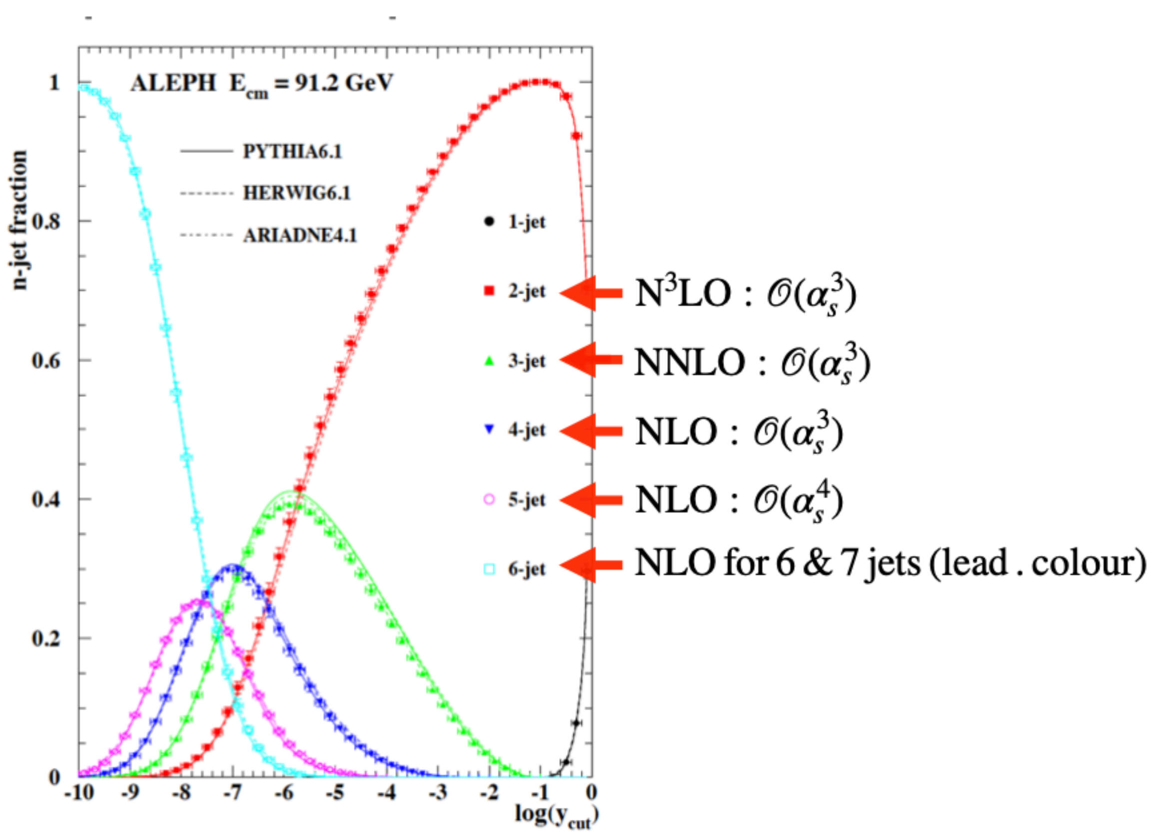

Integrated jet rates compared to ALEPH data

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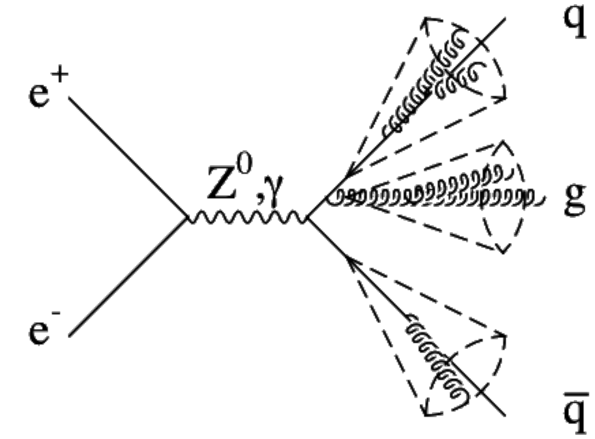

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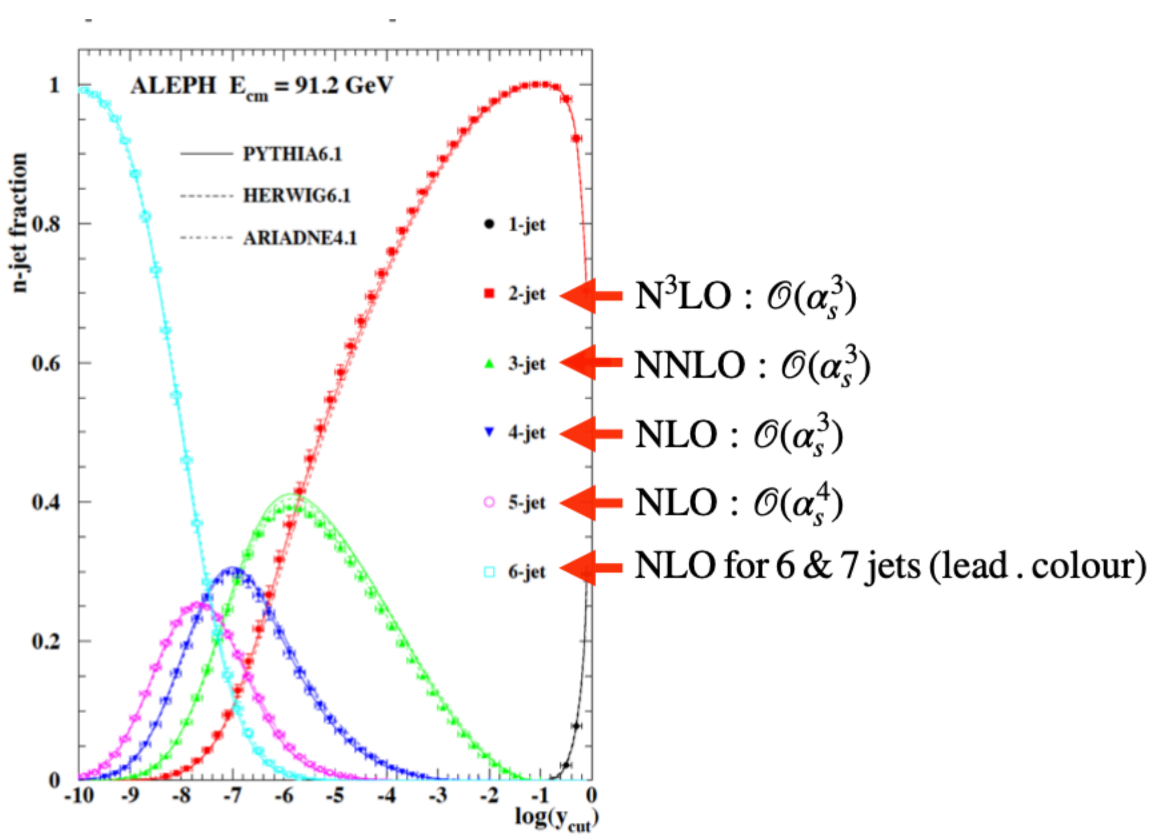

Integrated jet rates compared to ALEPH data

- Several examples of excesses reported in 4-jet event topologies at LEP
- Precision analyses at FCC require improvement for QCD calculations of at least one order of perturbative precision
- 3jets@N3LO and 4&5jets@NNLO in QCD
- Aim for an extraction of the strong coupling $\alpha_s(m_Z)$ with per-mil level accuracy

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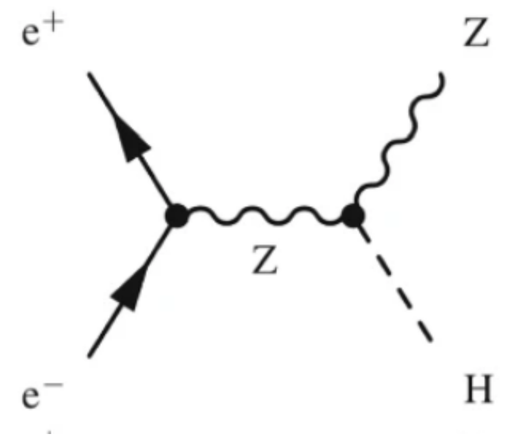

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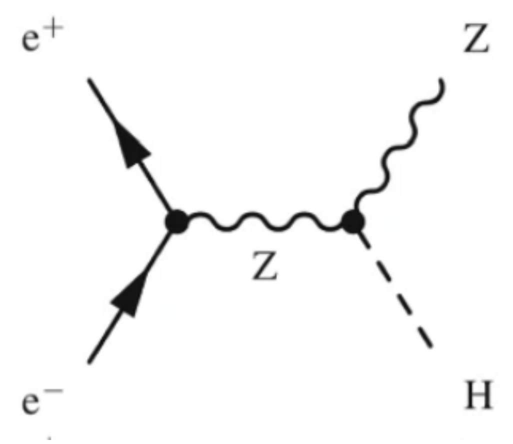

3 years 10^6 $e^+e^- \rightarrow ZH$

ch.	Br(%)
H→bb	57.7
H→cc	2.9
H→gg	8.6

Higgs hadronic decays

- Easy and clean way to select H→2jet final state
- Possible to have access to so-far unobserved subleading hadronic decay channels H→cc, H→gg
- Difficulty to separate the hadronic final states
- Opportunity to study 3 and 4 jet Higgs event shapes in perturbative QCD to discriminate fermionic and gluonic decay channels
- Aim for a percent level determination in *Hcc* and *Hgg* couplings

JET CROSS SECTIONS AT FCC_HH

- Inclusive production rate for central jets ($|\eta|<2.5$) as a function of the collider center of mass energy and projected statistical uncertainties at FCChh

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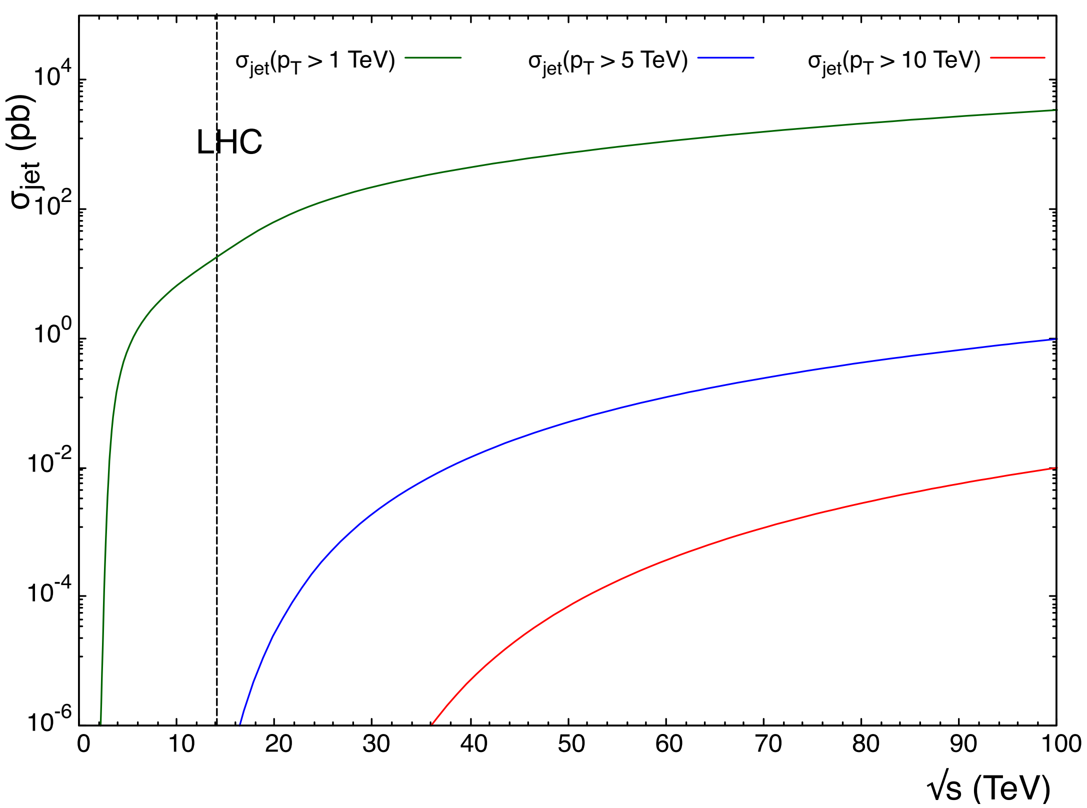

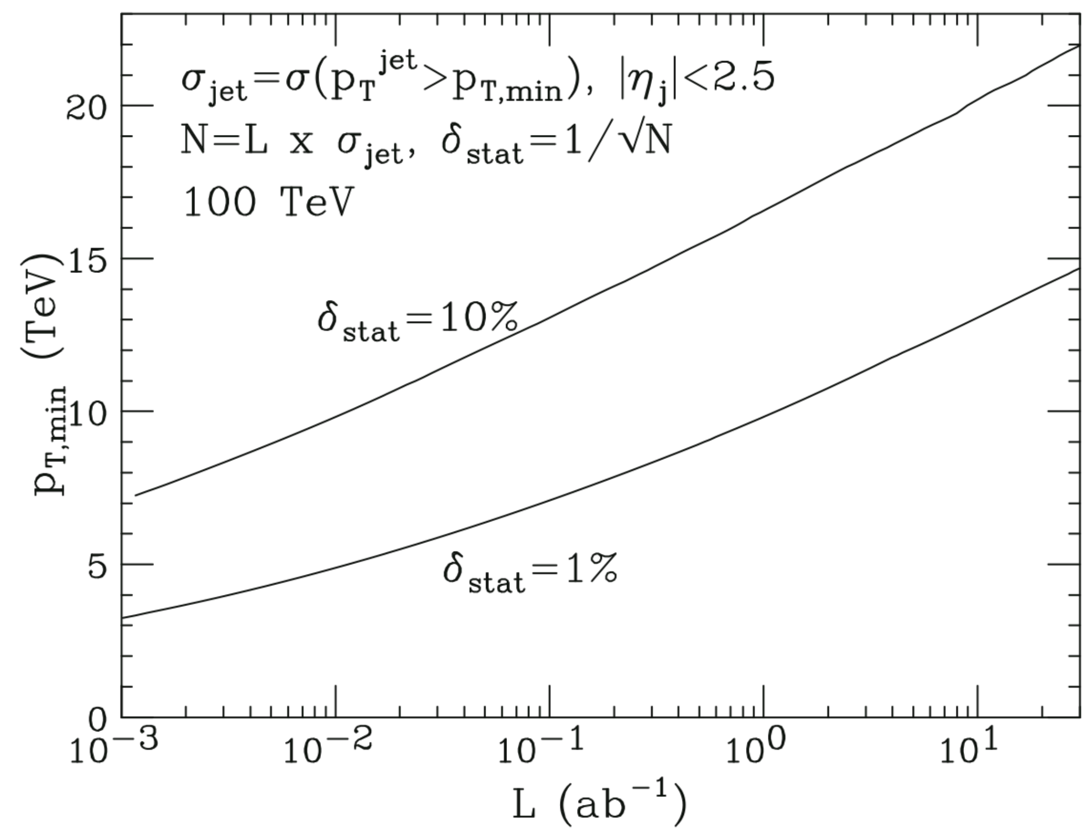

[*Eur.Phys.J.C* 79 (2019) 6, 474]

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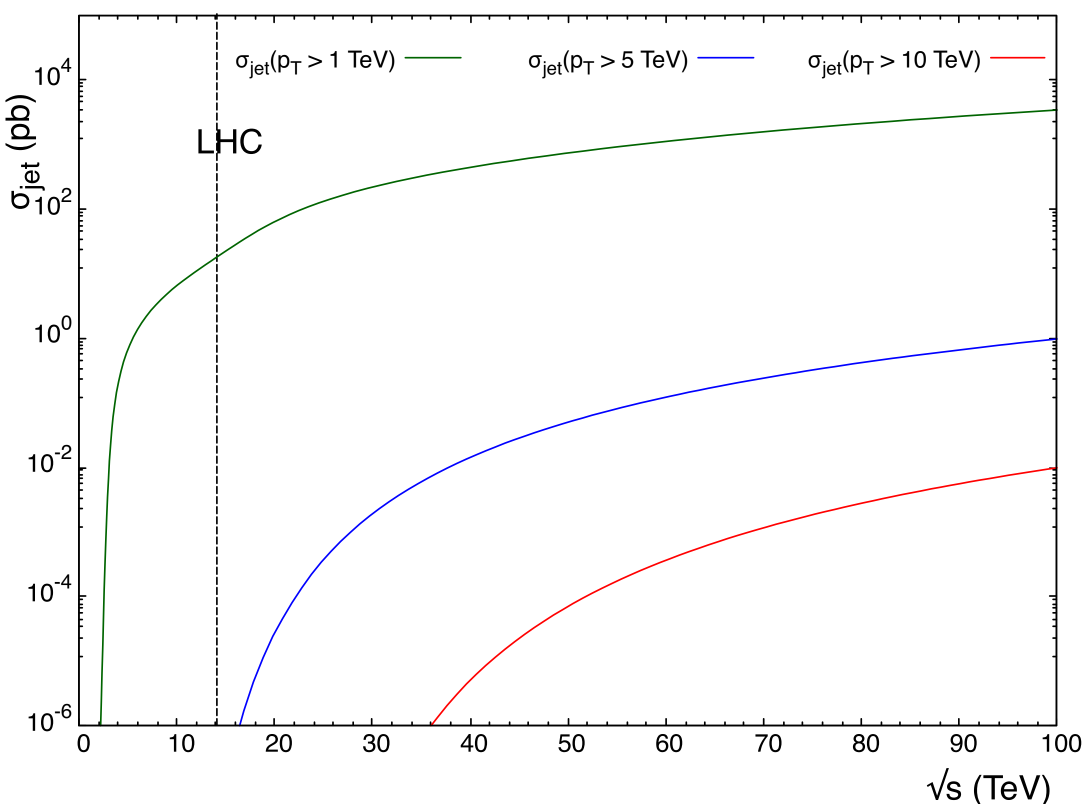

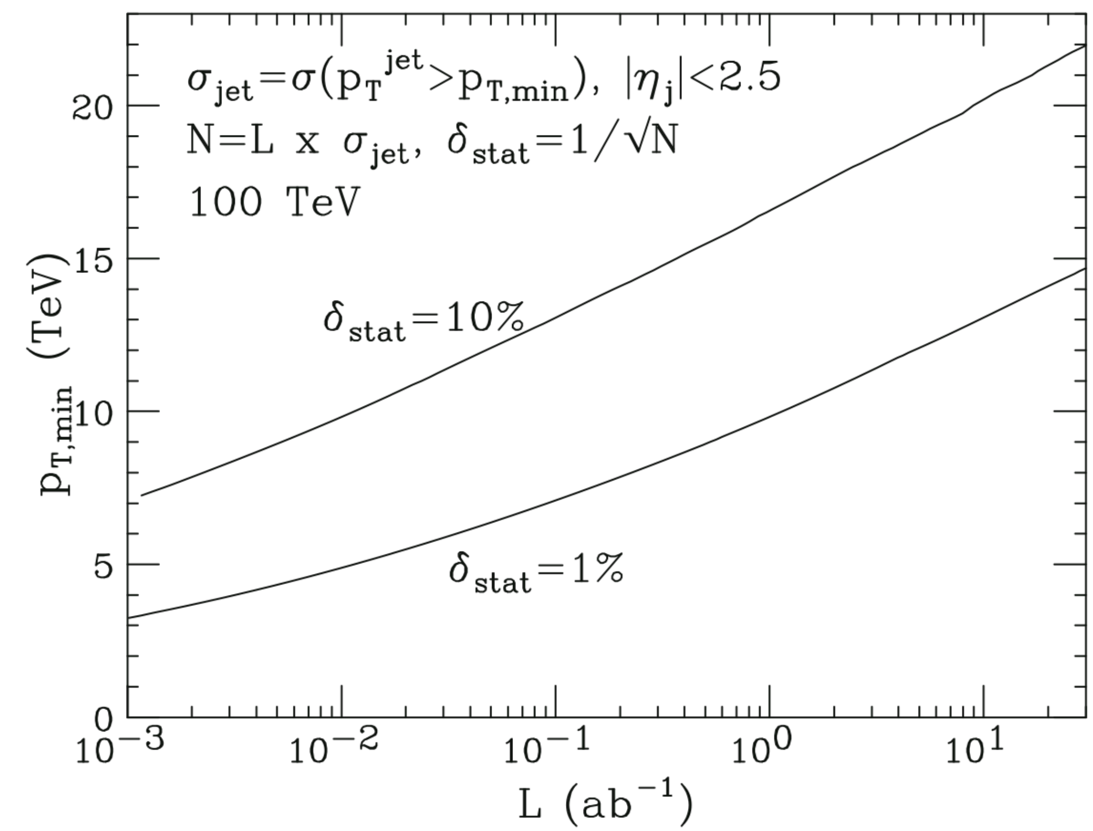

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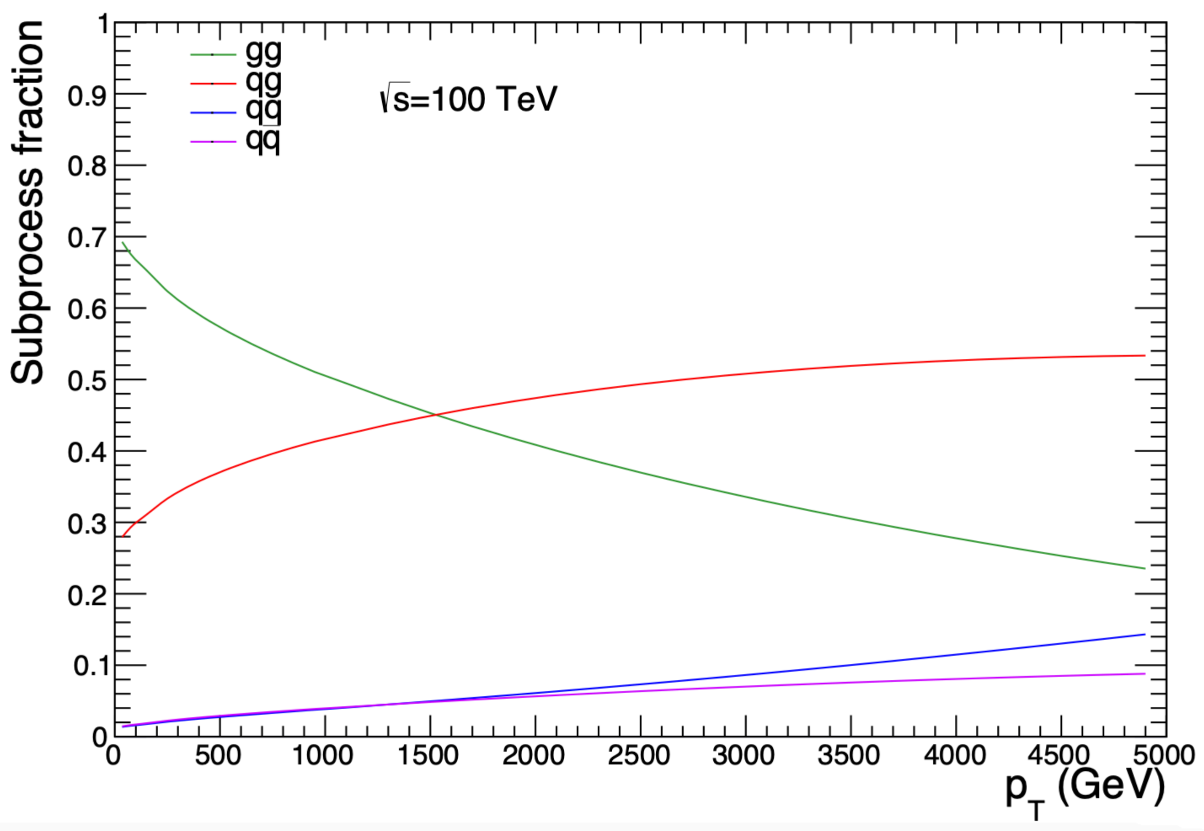
- With 30 ab^{-1} allows jet p_T values in the range of 25-30 TeV to be reached
- Uncertainties smaller than 10% up to $p_T \simeq 22$ TeV

JET CROSS SECTIONS AT FCC_HH

- For jet p_T values below 1.5 TeV the dominant subprocess arises from gluon scattering → opportunity to improve gluon PDF determinations



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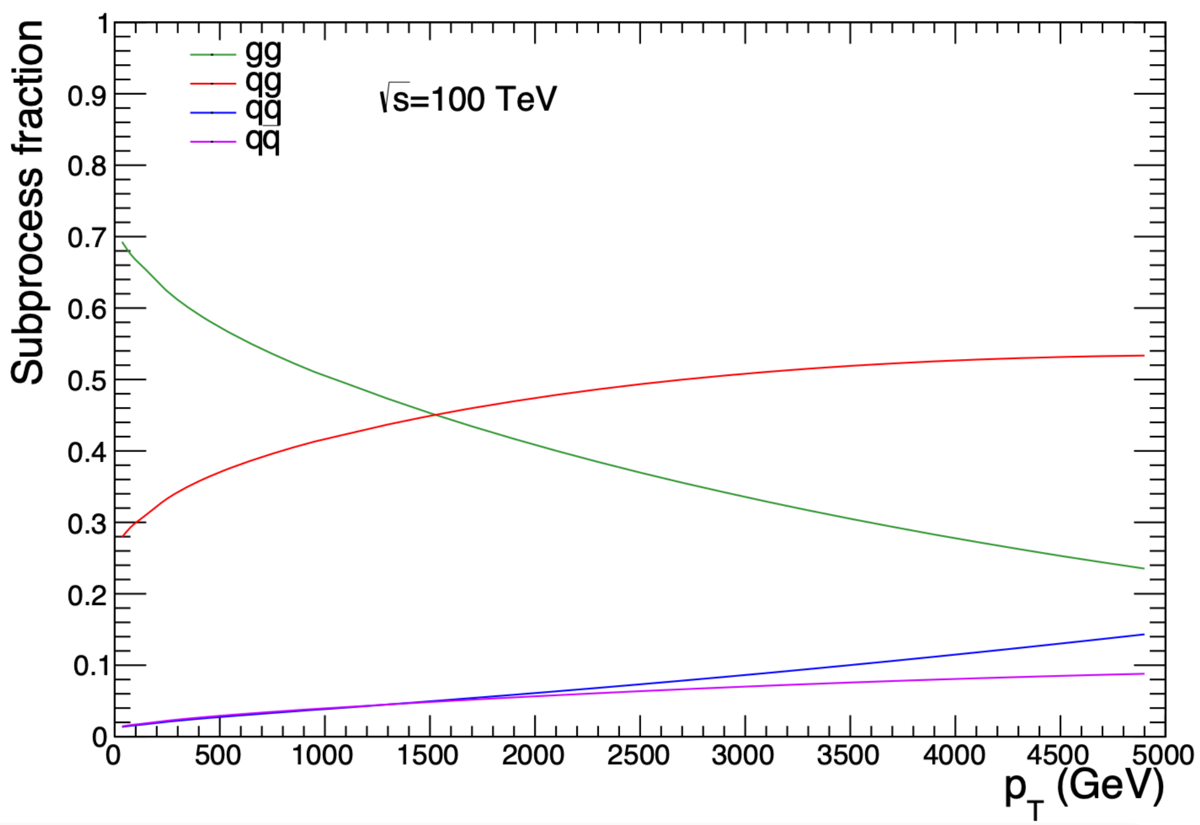
- For jet p_T values below 1.5 TeV the dominant subprocess arises from gluon scattering → opportunity to improve gluon PDF determinations
- To fully maximize the potential of FCC data would require N3LO PDFs determinations with four-loop DGLAP evolution N3LO hard scattering matrix elements (one order higher than at the LHC)



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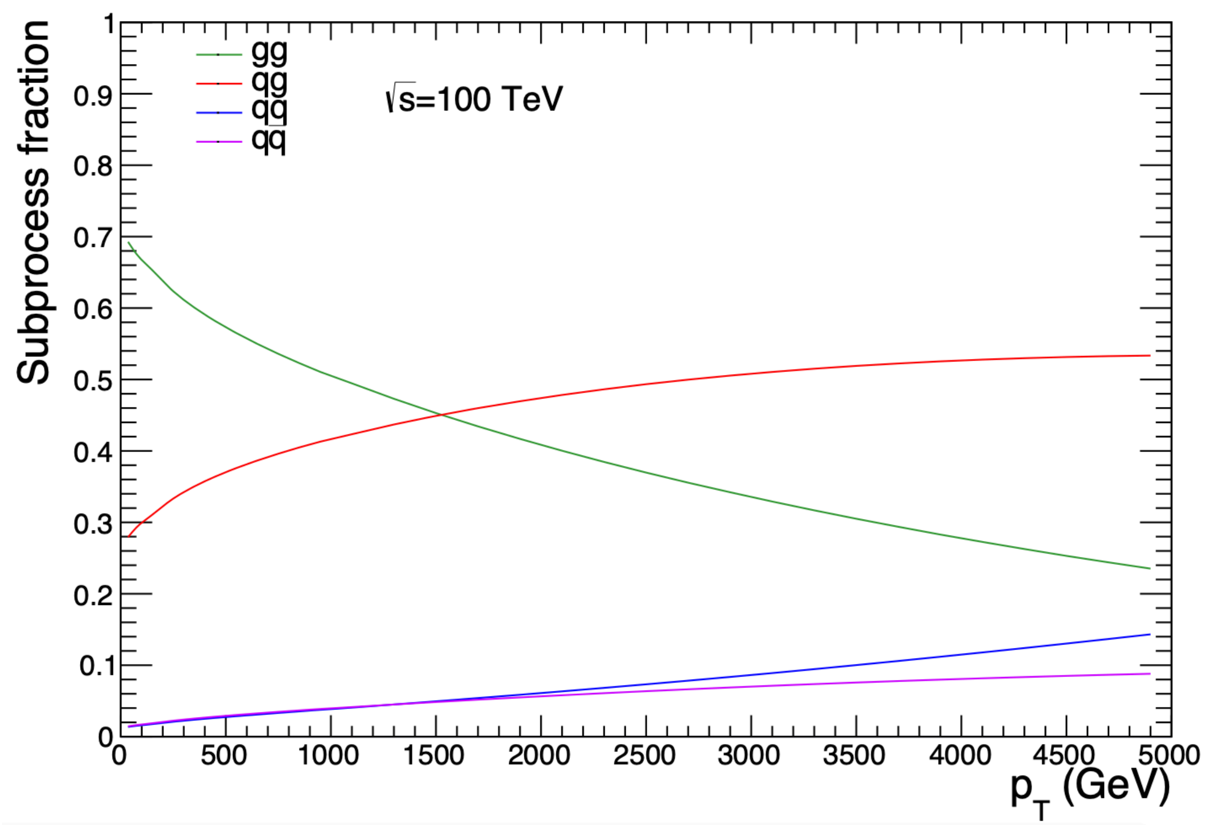

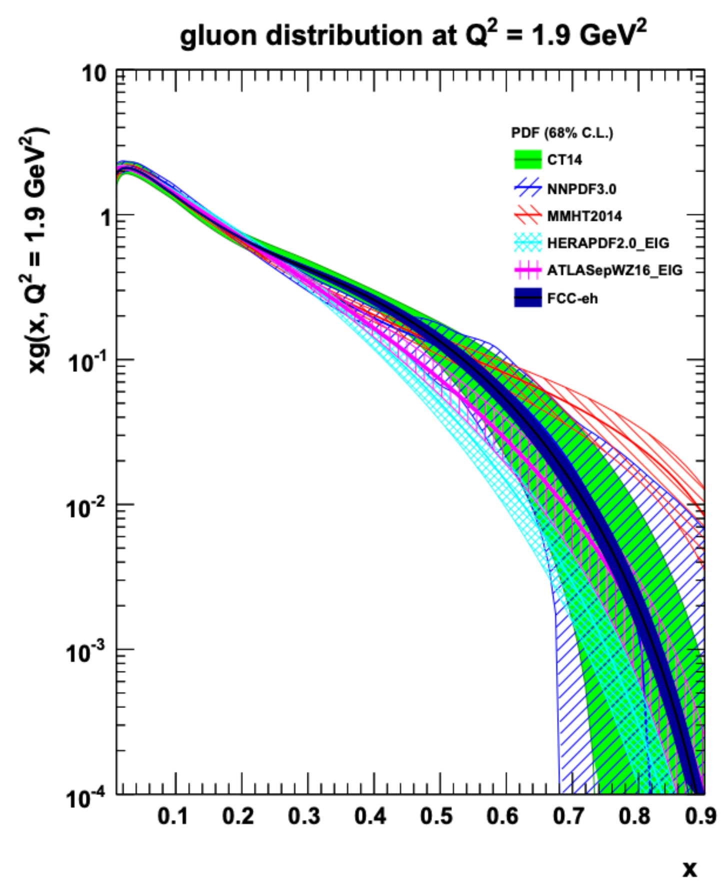

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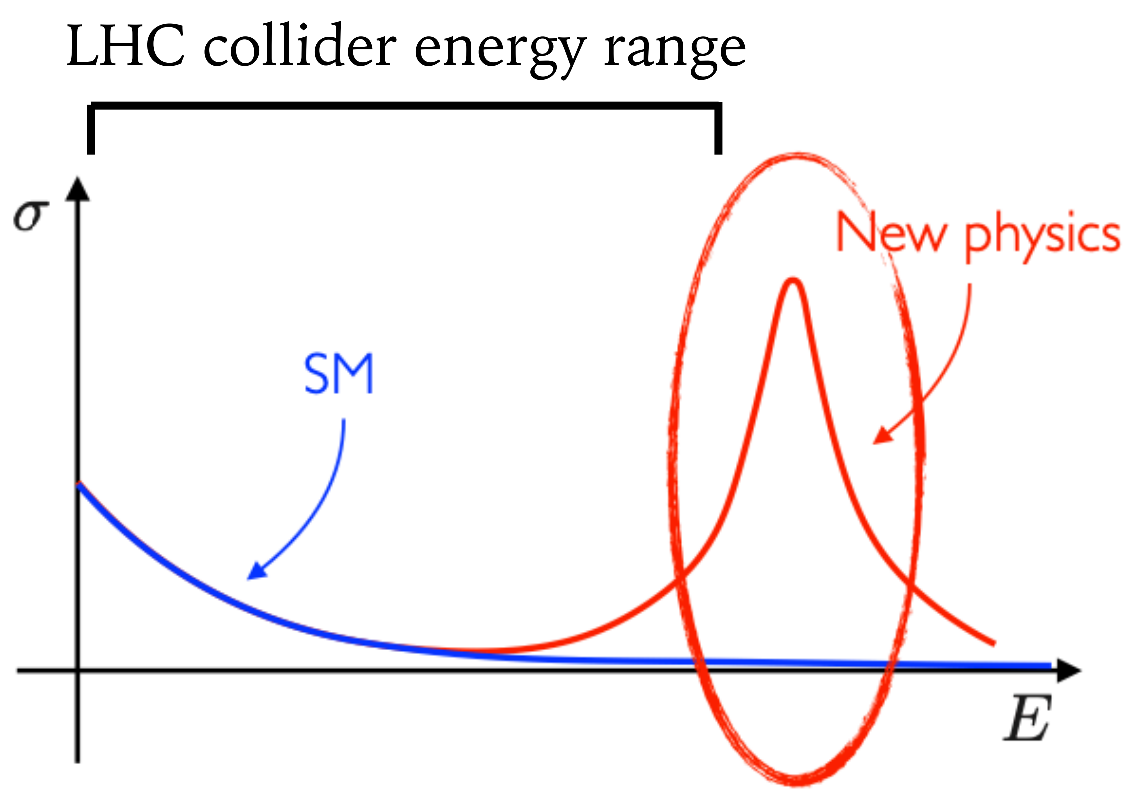
- Projected gluon distribution obtained from an FCCeh run
- Relevant for future precision studies of the Higgs boson couplings in gluon fusion processes, i.e., $gg \to H$ and $gg \to HH$

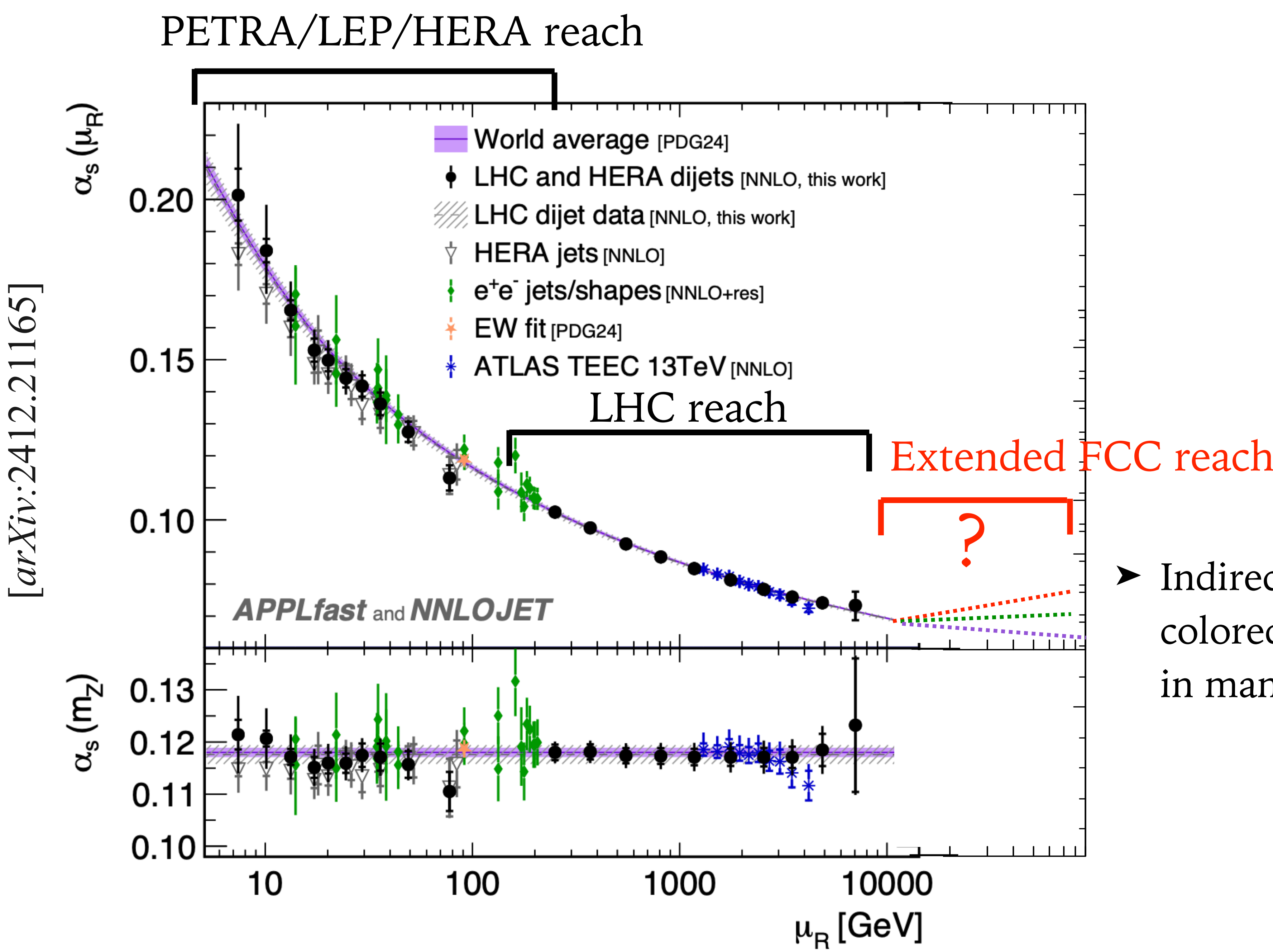
JET CROSS SECTIONS AT FCC_HH

- Looking for New Physics effects in QCD observables
- SM background prediction fixed by gauge symmetries and particle content of the Standard Model



JET CROSS SECTIONS AT FCC_HH

- Example: probe the running of the strong coupling in the TeV range



- Indirect search for extra colored states predicted in many SM extensions

- With dijet cross sections at the FCC asymptotic freedom can be tested up to 50 TeV

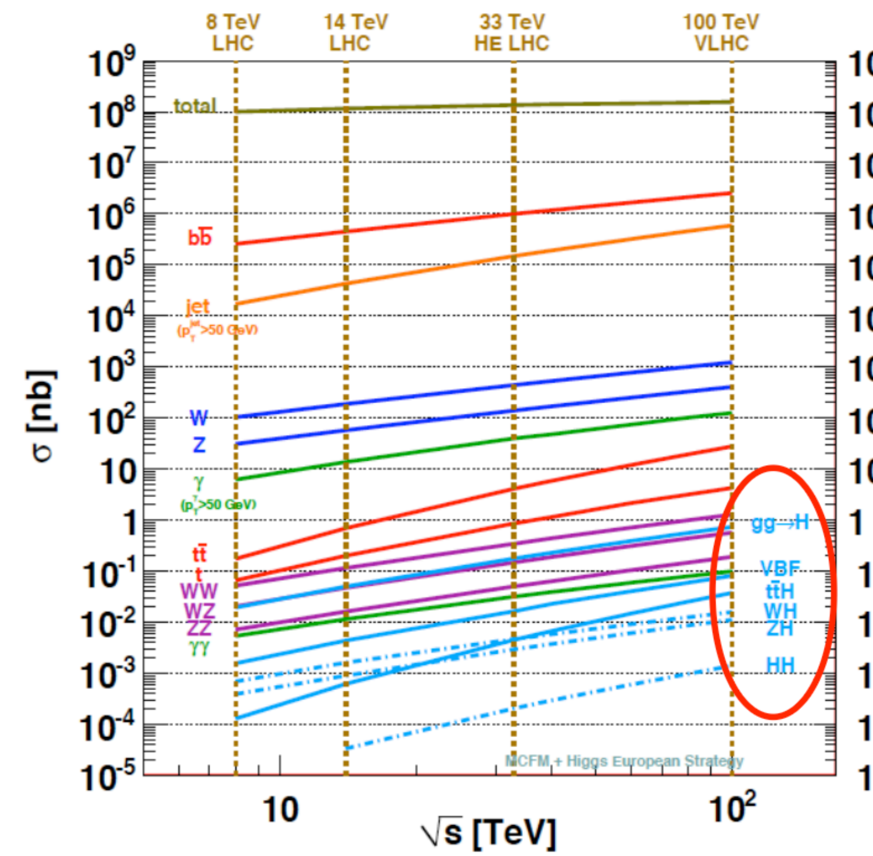
HIGGS COUPLINGS AT THE FCC_HH

- Complementary between FCC-ee and FCC-hh will allow us to pin down the Higgs couplings to the SM particles at the percent and sub-percent level

[arXiv:1905.03764]

Collider	HL-LHC	FCC-ee$_{240\to365}$	FCC-INT	
Lumi (ab^{-1})	3	5 + 0.2 + 1.5	30	
Years	10	3 + 1 + 4	25	
g_{HZZ} (%)	1.5	0.18 / 0.17	0.17/0.16	
g_{HWW} (%)	1.7	0.44 / 0.41	0.20/0.19*	
g_{Hbb} (%)	5.1	0.69 / 0.64	0.48/0.48	ee
g_{Hcc} (%)	SM	1.3 / 1.3	0.96/0.96	
g_{Hgg} (%)	2.5	1.0 / 0.89	0.52/0.5	
$g_{H\tau\tau}$ (%)	1.9	0.74 / 0.66	0.49/0.46	
$g_{H\mu\mu}$ (%)	4.4	8.9 / 3.9	0.43/0.43	
$g_{H\gamma\gamma}$ (%)	1.8	3.9 / 1.2	0.32/0.32	
$g_{HZ\gamma}$ (%)	11.	– / 10.	0.71/0.7	pp
g_{Htt} (%)	3.4	10. / 3.1	1.0/0.95	
g_{HHH} (%)	50.	44./33. 27./24.	3	
Γ_H (%)	SM	1.1	0.91	ee
BR_{inv} (%)	1.9	0.19	0.024	pp
BR_{EXO} (%)	SM (0.0)	1.1	1	ee

* g_{HWW} includes also ep



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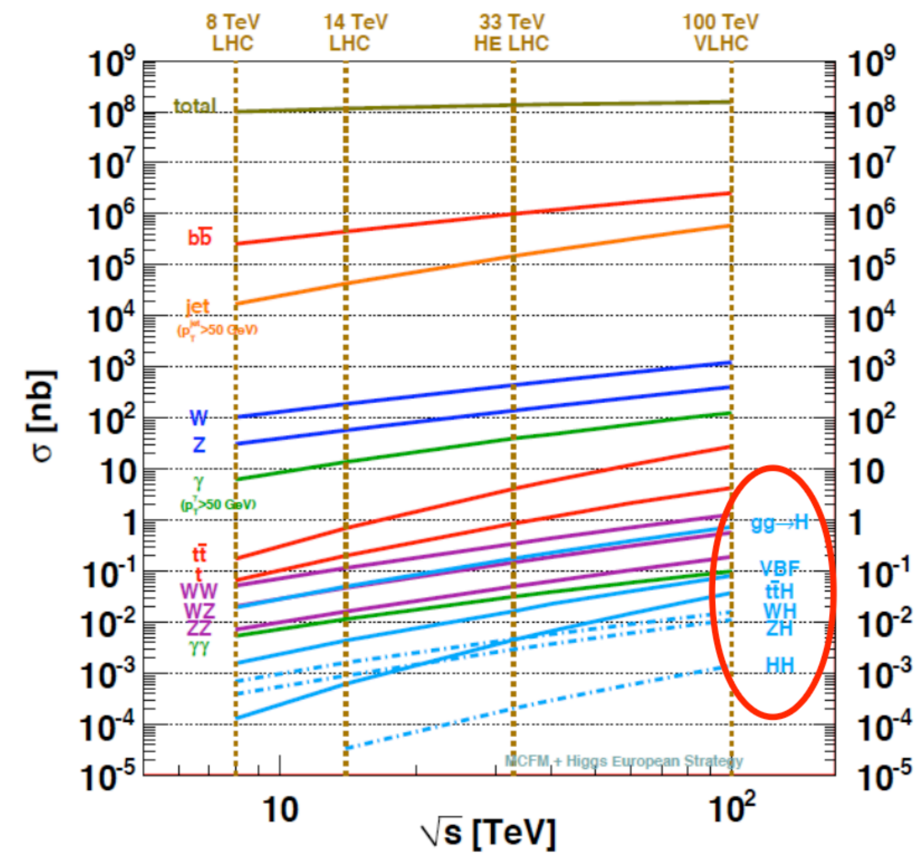

- *ttH* becomes the third largest Higgs production mechanism at the FCC-hh
- Also significant enhancement of the *HH* cross section
- Precision in the couplings measurement enables the possible detection of subtle deviations from Standard Model predictions, potentially signalling the presence of new physics phenomena such as extended Higgs sectors or interactions with undiscovered particles

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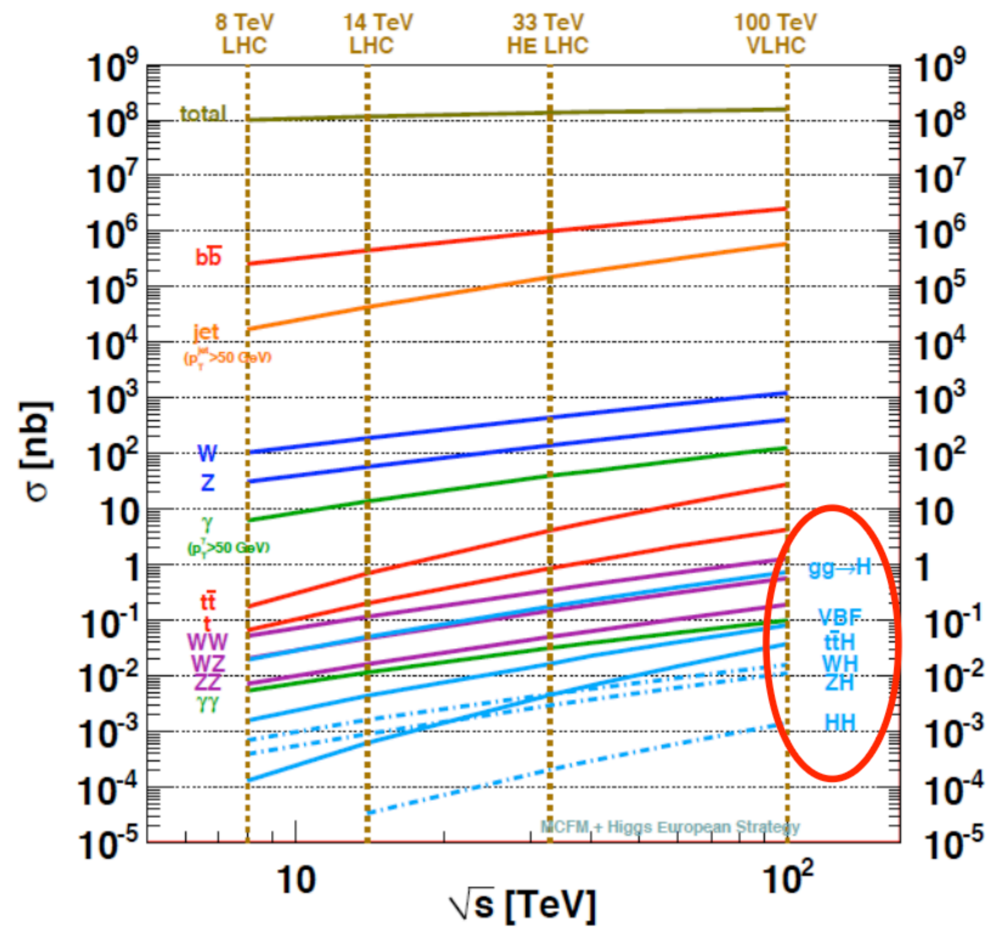

- Percent level precision on g_{Htt} and g_{HHH} requires continued effort on improving the accuracy of the SM calculations
- For *ttH* NNLO in QCD is required also *HH* with full top mass dependence (loop-induced → 4 point three-loop corrections with internal masses)
- In-house Monte Carlo NNLOJET in development at the LIP-pheno group for fully differential cross section studies of *ttH* production

CONCLUSIONS

- FCC integrated program offers unparalleled opportunities with unprecedented precision to address fundamental open questions in particle physics
- QCD studies are essential to the search for new physics at the FCC, as they provide the theoretical framework necessary for interpreting high-precision data
- Refining our understanding of the strong interaction will enable more accurate predictions of Standard Model (SM) processes, which form the foundation for identifying deviations that could signal new physics
- At the FCC, where energy and luminosity levels will far exceed current limits, the complexity of QCD phenomena increases, presenting a unique opportunity for the further development of precise theoretical calculations, which will be indispensable to the success of the FCC physics program
- The national level strategy covers a line of research in QCD phenomenology to address these challenges