

Precision electroweak physics at the LHC and at future colliders

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universität freiburg

- **Introduction**

- Where do we stand and where are we heading

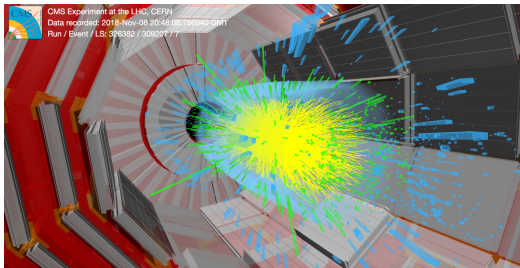
- **Precision at the LHC**

- Illustration with Drell-Yan and Vector-boson scattering

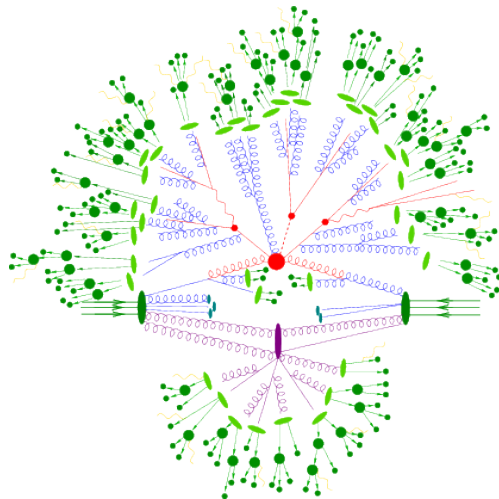
- **Precision at future colliders**

- Illustration with Z- and W-boson physics

How to learn from high energy collision about fundamental physics



- Experimental data
- Theoretical predictions
(based on first principle / modeling)



[source: Sherpa]

More physical -
Difficult interpretation



Less physical -
Easy interpretation

- 1 Full measurement vs. Full calculation (all contr.)
→ [Measurement of leptons and jets]

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- ① Full measurement vs. Full calculation (all contr.)
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- ② Full measurement - QCD background (MC) vs. EW contr.
(pb of interference)
→ [Measurement of EW contr.]



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- ③ Full measurement - undesired (MC) vs. desired process
→ [Measurement of process X] ...
... extract quantities
(mass, coupling, EFT coefficients, polarisation, ...)

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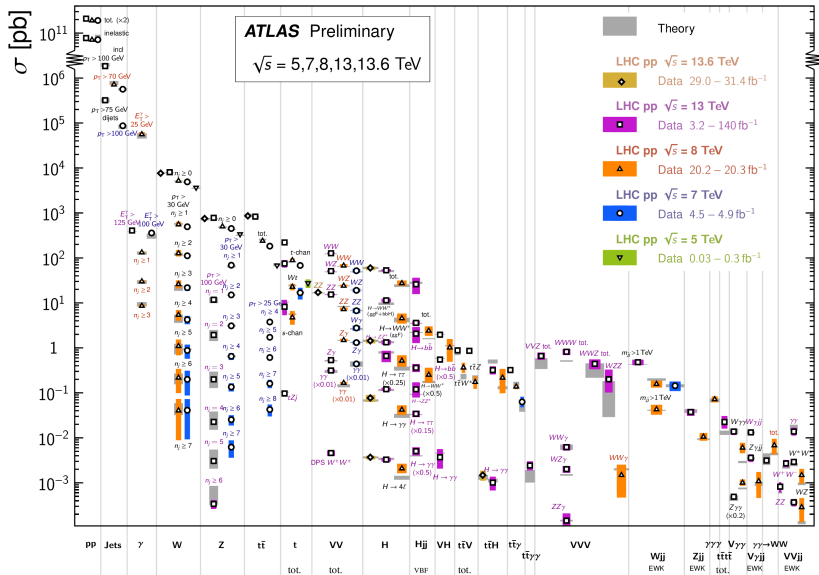


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Crucial interplay between theory and experiment!

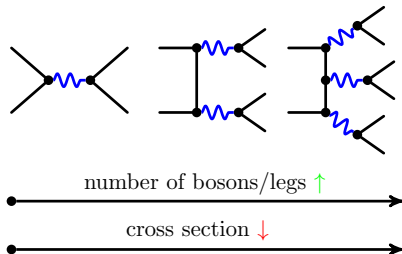




process	known	desired
$pp \rightarrow V$	$N^3\text{LO}_{\text{QCD}} + N^{(1,1)}\text{LO}_{\text{QCD} \otimes \text{EW}}$ NLO_{EW}	$N^2\text{LO}_{\text{EW}}$
$pp \rightarrow VV'$	$\text{NNLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$ + Full NLO_{QCD} ($gg \rightarrow ZZ$), approx. NLO_{QCD} ($gg \rightarrow WW$)	Full NLO_{QCD} (gg channel, w/ massive loops) $N^{(1,1)}\text{LO}_{\text{QCD} \otimes \text{EW}}$
$pp \rightarrow V + j$	$\text{NNLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$	hadronic decays
$pp \rightarrow V + 2j$	$\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$ (QCD component) $\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$ (EW component)	NNLO_{QCD}
$pp \rightarrow V + b\bar{b}$	NLO_{QCD}	$\text{NNLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$
$pp \rightarrow W + b\bar{b}$	NNLO_{QCD}	
$pp \rightarrow VV' + 1j$	$\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$	NNLO_{QCD}

[Huss, Huston, Jones, MP, Röntsch; 2504.06689]

- Les Houches wishlist
(updated every two years)
- Situation very much process dependent

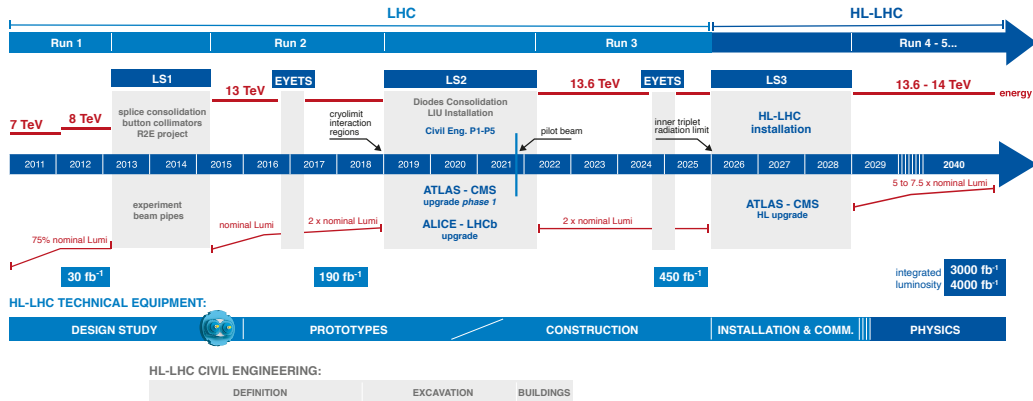


- **Precision at the LHC**

→ Illustration with Drell-Yann and VBS



LHC / HL-LHC Plan



- Very high-precision measurements
- Access to new rare processes

- Era of precision
- Challenges on theory and experiment sides!

• Drell-Yan

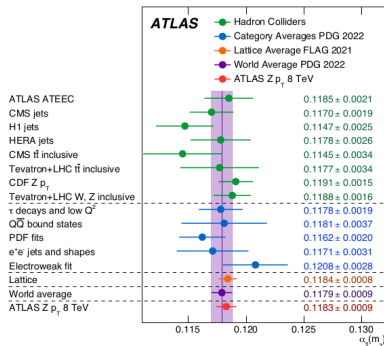
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[Huss, Huston, Jones, MP, Röntsch; 2504.06689]

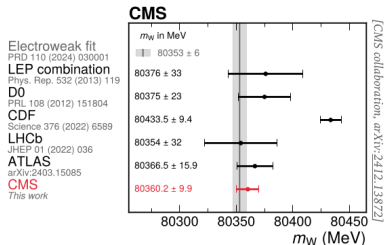
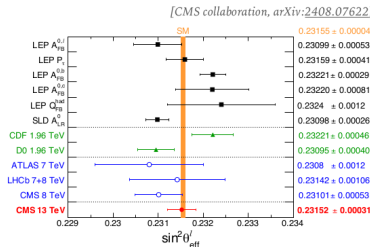
MOTIVATIONS FOR PRECISION: TODAY

Drell-Yan as a precision probe
of the Standard Model:

$$m_Z, m_W, \alpha_S, \sin \theta_{\text{eff}}^2 \dots$$



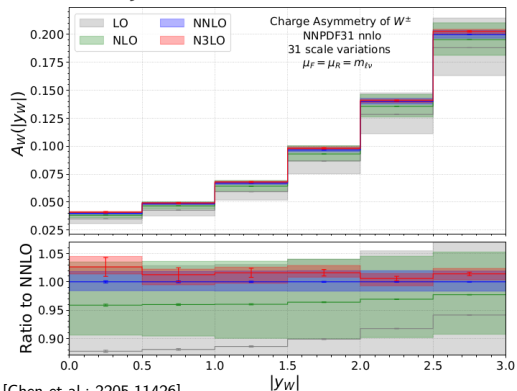
[ATLAS collaboration, arXiv:2309.12986]



[CMS collaboration, arXiv:2412.13872]

LHCP 2026, 19.05.2026 - Simone Devoto

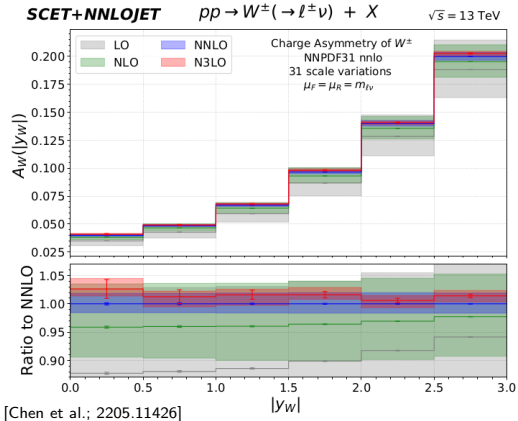
SCET+NNLOJET $pp \rightarrow W^\pm(\rightarrow \ell^\pm \nu) + X$ $\sqrt{s} = 13 \text{ TeV}$



[Chen et al.; 2205.11426]

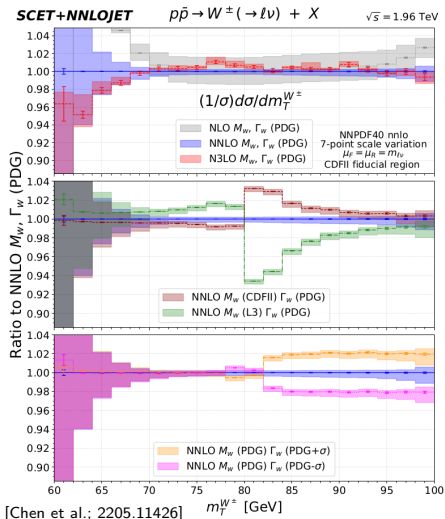
- Asymmetry at **N3LO QCD**

- $$A_W(|y_W|) = \frac{d\sigma/d|y_{W+}| - d\sigma/d|y_{W-}|}{d\sigma/d|y_{W+}| + d\sigma/d|y_{W-}|}$$

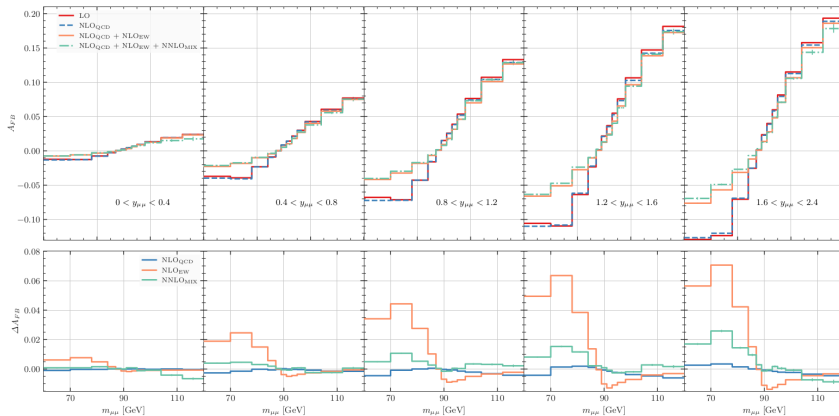


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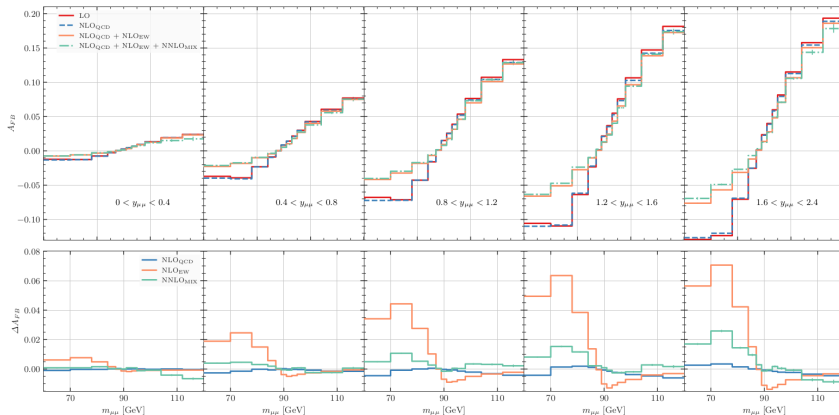


- Perturbative corrections vs. variations of EW parameters



[Armadillo et al.; 2412.16095]

- **NNLO QCD-EW** corrections
- Forward-Backward asymmetry
→ weak mixing angle



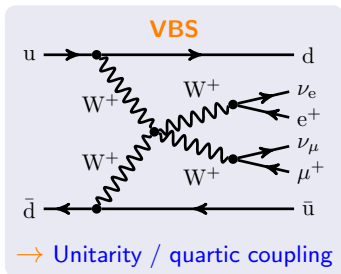
[Armadillo et al.; 2412.16095]

- **NNLO QCD-EW** corrections
- Forward-Backward asymmetry
→ weak mixing angle
- Next step NNLO EW
→ see Simone's talk next
- ⚠ Still no accepted proxy for EW missing higher-orders

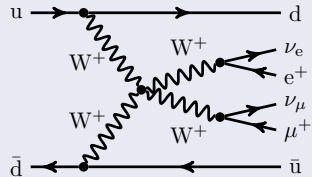
• Vector-boson scattering

process	known	desired
$pp \rightarrow VV' + 2j$	NLO _{QCD} (QCD component) NLO _{QCD} + NLO _{EW} (EW component)	Full NLO _{QCD} + NLO _{EW}
$pp \rightarrow W^+W^+ + 2j$	Full NLO _{QCD} + NLO _{EW}	
$pp \rightarrow W^+W^- + 2j$	NLO _{QCD} + NLO _{EW} (EW component)	
$pp \rightarrow W^+Z + 2j$	NLO _{QCD} + NLO _{EW} (EW component)	
$pp \rightarrow ZZ + 2j$	Full NLO _{QCD} + NLO _{EW}	

[Huss, Huston, Jones, MP, Röntsch; 2504.06689]

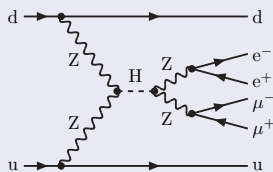


VBS



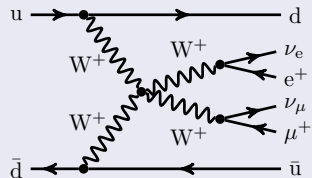
→ Unitarity / quartic coupling

VBF



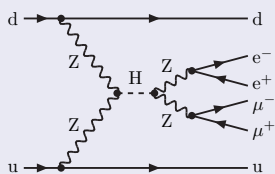
→ Higgs properties

VBS



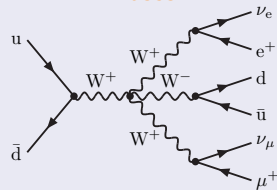
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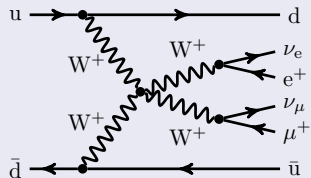
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Triboson



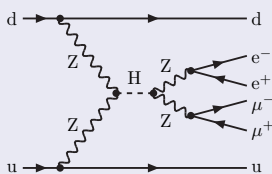
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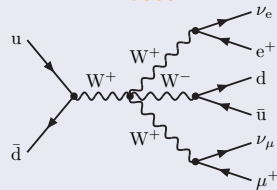
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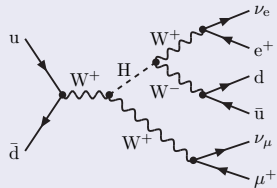
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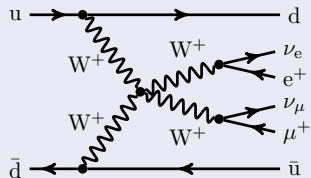
→ Quartic coupling

VH



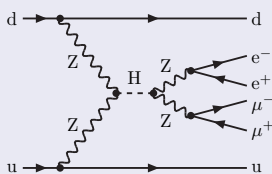
→ Higgs properties

VBS



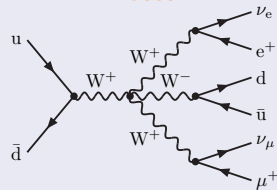
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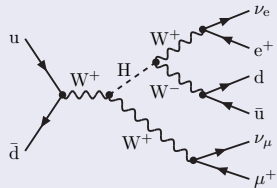
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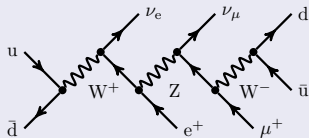
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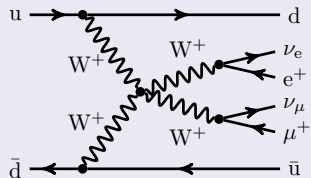


→ Higgs properties

Decay chain

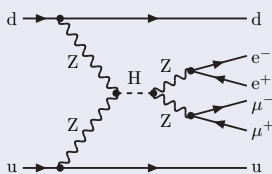


VBS



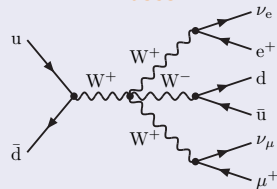
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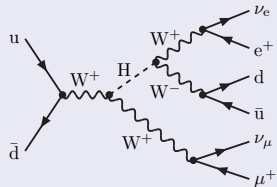
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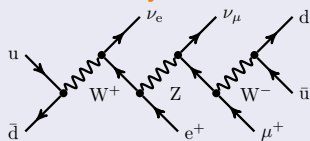
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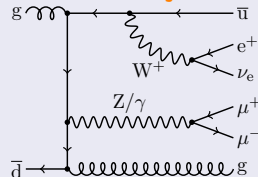


→ Higgs properties

Decay chain



VV+2j



→ QCD

Integrated Luminosity	36 fb	150 fb	300 fb	3000 fb-
Year	2016	2019	2022	2038
EW(VBS) $W\pm W\pm$	20%	10%	7%	2%
EW (VBS) ZZ	35%	18%	13%	6%
EW (VBS) WZ	35% personally anticipated	18%	13%	6%

source: Jakob Salfeld-Nebgen, <https://indico.cern.ch/event/711256>

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→ Theory status for ss-WW: (more in Review [Covarelli, MP, Zaro; 2102.10991])

Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_S \alpha^6)$	$\mathcal{O}(\alpha_S^2 \alpha^5)$	$\mathcal{O}(\alpha_S^3 \alpha^4)$
NLO	✓	✓	✓	✓
NLO+PS	✓	✓*	✗	✓

(*) Computations in the VBS-approximation *i.e.* t-u interferences and tri-boson contributions neglected

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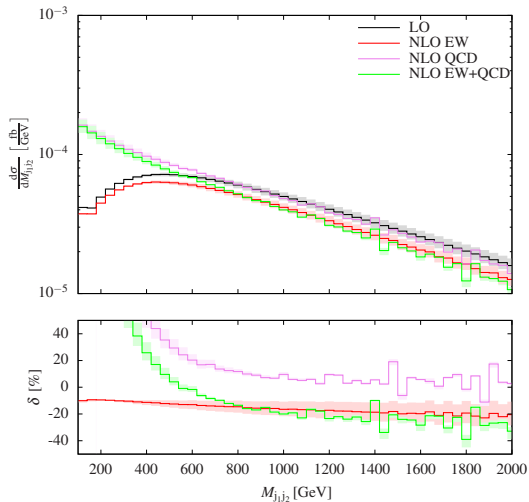
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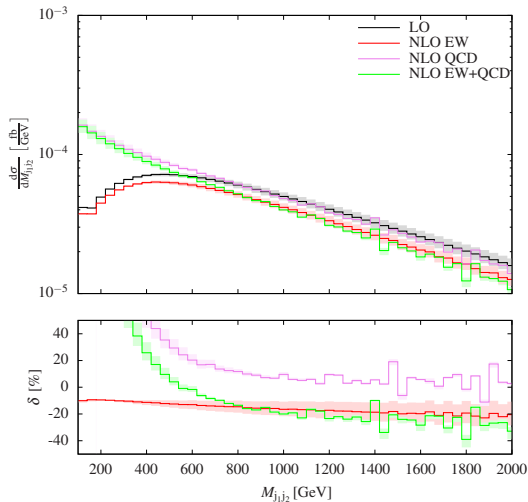
- Experimental uncertainty $\sim$ few per cent
 - For the high-luminosity LHC, we should tick all the boxes!
 - NNLO QCD might even be needed...

→ Illustration of th./exp. interplay

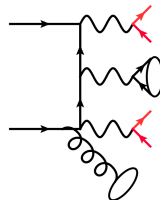


[Denner, Franken, MP, Schmidt; 2009.00411]

→ Illustration of th./exp. interplay



→ Example: ZZ VBS at NLO



→ Effects of tri-boson (at NLO)
even when using $m_{jj} > 100 \text{ GeV}$

[Denner, Franken, MP, Schmidt; 2009.00411]

Weak Interactions at Very High Energies: the Role
of the Higgs Boson Mass

BENJAMIN W. LEE, C. QUIGG^{*}, and H. B. THACKER
Fermi National Accelerator Laboratory[†], Batavia, Illinois 60510

ABSTRACT

We give an S-matrix theoretic demonstration that if the Higgs boson mass exceeds $M_C = (8\pi\sqrt{2}/3G_F)^{\frac{1}{2}}$ partial-wave unitarity is not respected by the tree diagrams for two-body scattering of gauge bosons, and the weak interactions must become strong at high energies. We exhibit the relation of this bound to the structure of the Higgs-Goldstone Lagrangian, and speculate on the consequences of strongly-coupled Higgs-Goldstone systems. Prospects for the observation of massive Higgs scalars are noted.

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March 1977

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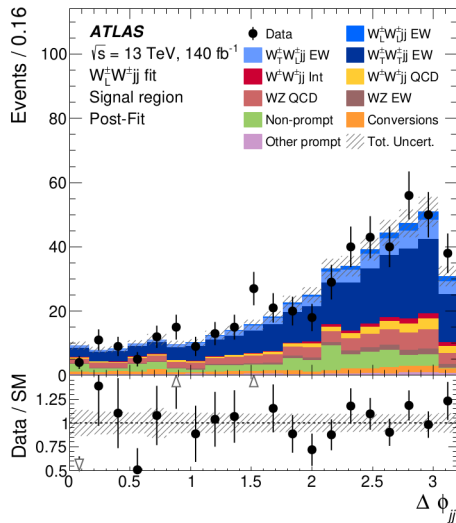
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Because we wish to explore a regime in which the weak interactions can become strong it is natural to approach the problem from an S-matrix point of view⁸ with a particular concern for unitarity.⁹ Our treatment provides a systematic investigation of the minimal Weinberg-Salam theory from this point of view. In Section II we discuss and calculate in tree approximation the Weinberg-Salam model amplitudes for all two-body reactions of gauge bosons with zero total electric charge in the s-channel. We display only those terms that are potentially relevant to the question of unitarity, omitting, for example, terms which are of ordinary electromagnetic strength at all energies. Logarithmic violations of unitarity that occur at exponentially high energies $\sim M_W e^{1/\alpha}$ will be of no concern to us here.

By focusing only on those amplitudes that constitute a potential threat to unitarity one finds a remarkable simplification of the problem. The relevant amplitudes are those which involve only longitudinal gauge bosons and the Higgs boson. The system of these particles is the subject of Section III. There it is shown that at energies large compared with the intermediate boson mass, this system is a clear reflection of the underlying Higgs-Goldstone system of the Weinberg-Salam model, with the longitudinal W^+ , W^- and Z^0 behaving much like the Goldstone bosons from which they sprang. Up to terms of order $M_W/\sqrt{s}$, the S-matrix for $W_L^\pm$, Z_L , and H (the subscript L denotes longitudinal polarization) is identical to that for the self-interactions of a complex doublet of scalar particles, as we show in detail in an Appendix. Consequently exploration

After almost 50 years, exciting time!



[ATLAS; 2503.11317]

Comparison to

• [Denner, Haitz, Pelliccioli; 2409.03620]

→ NLO QCD+EW for ss-WW

• [Hoppe, Schönherr, Siegert; 2310.14803]

→ Approximate NLO QCD+PS in SHERPA

→ Automation of NLO QCD+EW for polarised predictions

Theoretical predictions at the LHC in very good state
Each further step become increasingly more complicated

Theoretical predictions at the LHC in very good state
Each further step become increasingly more complicated

- N3LO QCD for colourless processes (Higgs, Drell-Yan, di-photon, etc.)
→ N3LO QCD PDFs
- Mixed NNLO QCD-EW corrections (Drell-Yan)
- 2-loop amplitudes for $2 \rightarrow 2/3$ with many scales
- NLO QCD+EW for $2 \rightarrow 8$ processes (ttbb, ttV, etc.)
- Matching of NNLO QCD to PS (colourless processes)
→ (N)NLO QCD+EW matching to PS (Drell-Yan, di-boson)
- Improvement of PS accuracy

Theoretical predictions at the LHC in very good state
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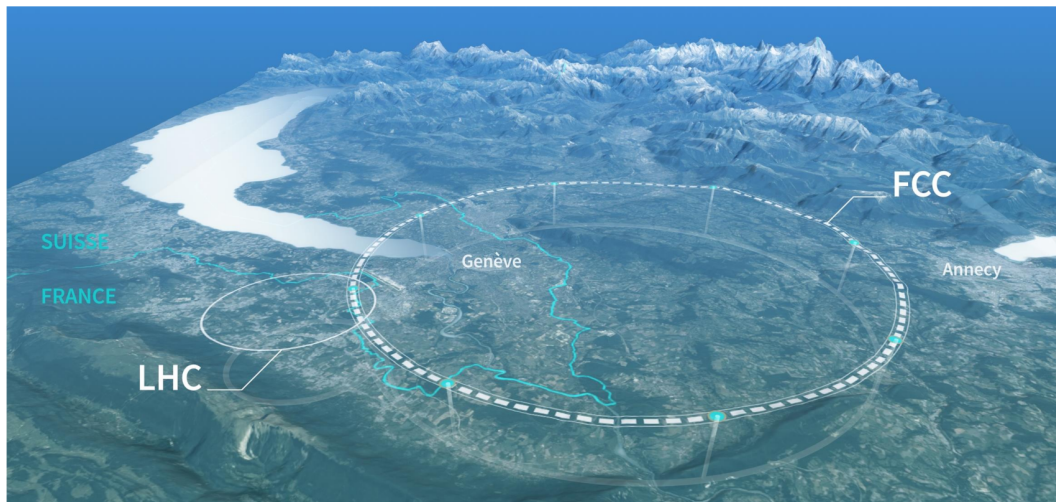
Limiting factors (?)

→ Non-perturbative physics: PDF, Hadronisation, Multiple-parton interaction (MPI)

- **Precision at future colliders**

→ Illustration with Z- and W-boson physics

- **FCC**: 90km-long tunnel to collide electron/proton up to even higher energy (100 TeV)
→ choice number 1 for the future of European community



→ Review of Christophe Grojean “Future Circular Collider: A Physics Manifesto”

<https://indico.cern.ch/event/1582427/>

Why FCC?

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Why is FCC-ee a precision machine (even more than the LHC)?

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Why is FCC-ee a precision machine (even more than the LHC)?

- Much cleaner initial state
- Known collision energy
- Huge luminosity at specific energies
- No QCD background

Why FCC?

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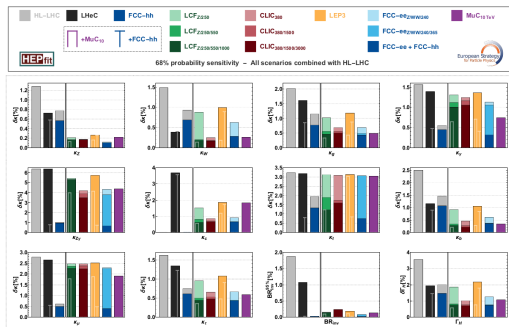
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LHC → FCC-ee

Dominant uncertainties shift from experimental modelling to theoretical predictions

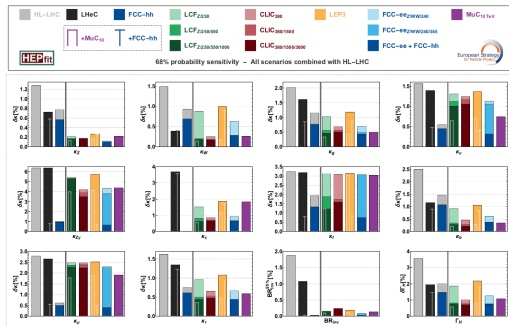
Illustration of precision physics



[de Blas et al.; 2511.03883]

Precision everywhere! Example for Higgs and EW physics

Illustration of precision physics

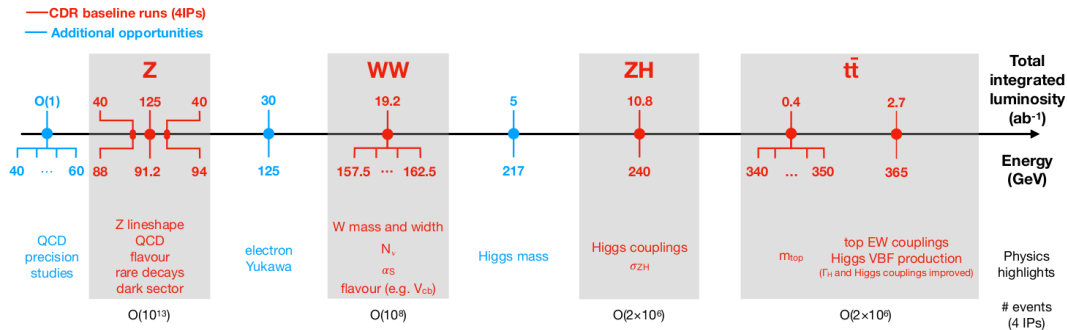


Observable	Current	FCC-ee	LCF	LEP3
Δm_Z (keV)	2000	4 (100)	200	7.5 (100)
$\Delta \Gamma_Z$ (keV)	2300	4 (12)	125	7.5 (23)
$\delta R_\mu (\times 10^{-6})$ $R_\mu \equiv \frac{\Gamma_{\text{had}}}{\Gamma_\mu}$	1600	2.4 (2.3)	90 (90)	4.5 (2.3)
$\delta R_b (\times 10^{-6})$ $R_b \equiv \frac{\Gamma_b}{\Gamma_{\text{had}}}$	3300	1.2 (1.6)	70 (60)	2.2 (3.0)
$\Delta \sin^2 \theta_W (\times 10^6)$	130	0.4 (0.5)	2.7 (2.3)	0.75 (0.95)
$\Delta \alpha(m_Z)^{-1} (\times 10^3)$	14	0.8, 3.8	—	1.4, 7.3
Δm_W (keV)	9900	180 (160)	500 (1600)	430 (700)
$\Delta \Gamma_W$ (keV)	42000	270 (200)	2000	650 (500)

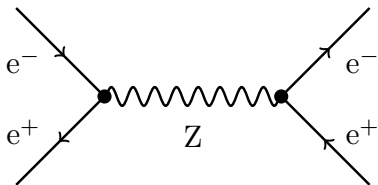
[de Blas et al.; 2511.03883]

Precision everywhere! Example for Higgs and EW physics

FCC-ee physics



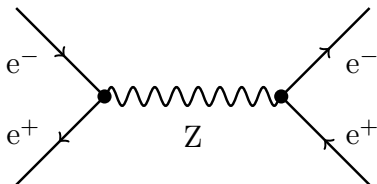
- Z physics at FCC-ee through Z production
- W physics at FCC-ee through WW production



State of the art:

Two-loop EW for $e^+e^- \rightarrow Z \rightarrow e^+e^-$

[Dubovyk, Freitas, Gluza, Riemann, Usovitsch; 1804.10236, 1906.08815]



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→ ΔM_Z [MeV]:
2.1 (LEP2), 2.0 (current world average),
... **0.1 (FCC-ee)**

→ Theory challenges

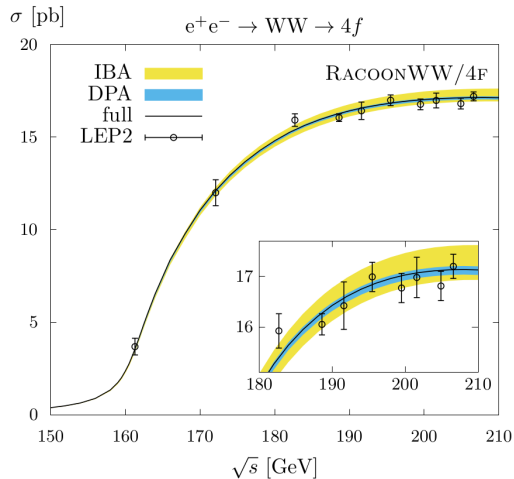
- N3LO EW and mixed EW-QCD!!!
- Matching resummed ISR/FSR to fixed-order
- **resonance treatment!**
(definition of pseudo-observable)

⚠ Parametric uncertainty!

→ α_s , quark masses, $\Delta\alpha_{\text{had}}$, etc.

State of the art:

→ NLO EW for $e^+e^- \rightarrow 4f$

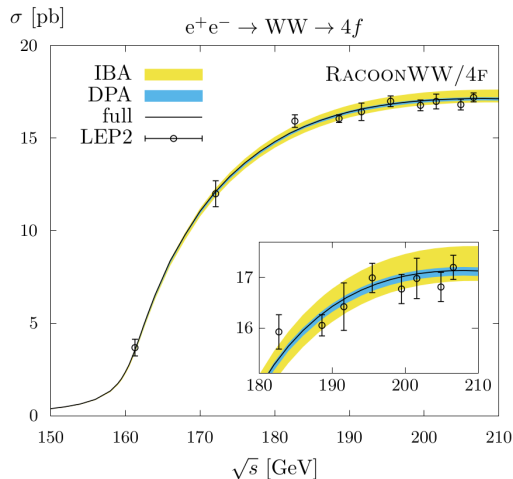


[Denner, Dittmaier, Roth, Wieders; hep-ph/0505042, hep-ph/0502063]

+ [Schael et al.; 1302.3415]

State of the art:

→ NLO EW for $e^+e^- \rightarrow 4f$



→ ΔM_W [MeV]:

33 (LEP2), 12 (current), 10 (CMS), ...

... **0.5 (FCC-ee)**

→ **Theory challenges**

- Considering also hadronic decays
- NNLO EW for $e^+e^- \rightarrow 4f$
 - use of EFT at threshold
 - **resonance treatment!**
- mixed NNLO QCD-EW and NNLO QCD for hadronic channels

[Denner, Dittmaier, Roth, Wieders; hep-ph/0505042, hep-ph/0502063]

+ [Schael et al.; 1302.3415]

List of priorities (draft)

1. Lay the foundations for the conceptual design studies of four (or more) detectors
2. Consolidate IR layout, detector integration, and related background mitigation
3. Collaborate with IT to develop a computing architecture model for experiments
4. Complete the software & analysis toolkit to ease detector performance comparison
5. Confirm, with full analyses, the current uncertainty estimates on EWPOs (Z and W)
6. Gather the worldwide theory community to address the theoretical challenges
7. Streamline and optimise the procedure for centre-of-mass energy calibration
8. Develop an efficient PED Education/Communication/OutReach/InReach strategy
9. Ascertain the detector cost estimate
10. Articulate the physics case, feasibility, and schedule implications of other $\sqrt{s}$ stages
11. Anticipate FCC-PED structure and management in the project phase (2027-2033)

C. Grojean, <https://indico.cern.ch/event/1582427/>

- Theory predictions are a critical aspect for the success of the FCC!
- Les Houches wishlist for FCC-ee?

Exciting physics at the LHC! (... and future colliders)

- Explore fundamental aspect of particle physics
- Precision era at the LHC (and even more at future colliders)

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- Explore fundamental aspect of particle physics
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- Theory calculations are decisive information:
 - Standard Model measurements
 - Searches for new phenomena
- Precision programme at the LHC
- Crucial interplay between theory and experiment
 - Big impact on physics results



BACK-UP