UNIVERSITÀ DEGLI STUDI DI MILANO

Istituto Nazionale di Fisica Nucleare

Precision theoretical predictions for future colliders

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Outline

Physics at the LHC and future colliders

every option under discussion will allow to collect huge luminosities $\rightarrow$ extremely small statistical errors

a meaningful interpretation of such data requires the development of tools adequate to extract information

Developments of new tools and ideas:

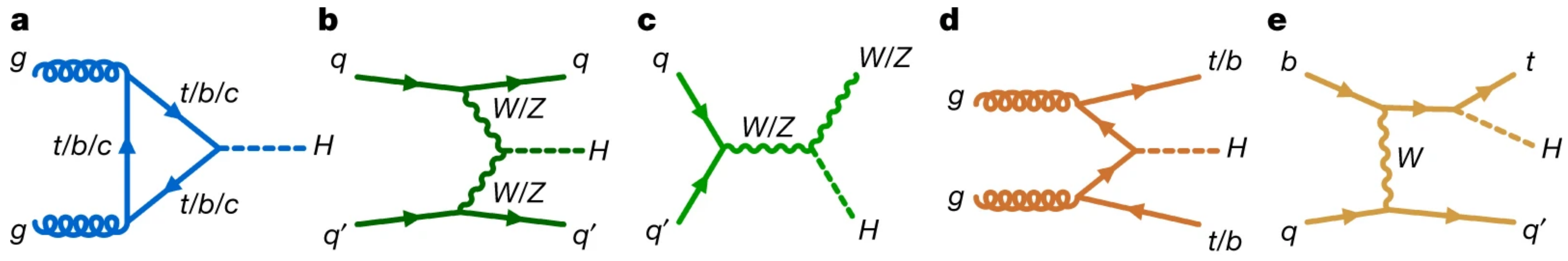
predictions in QFT

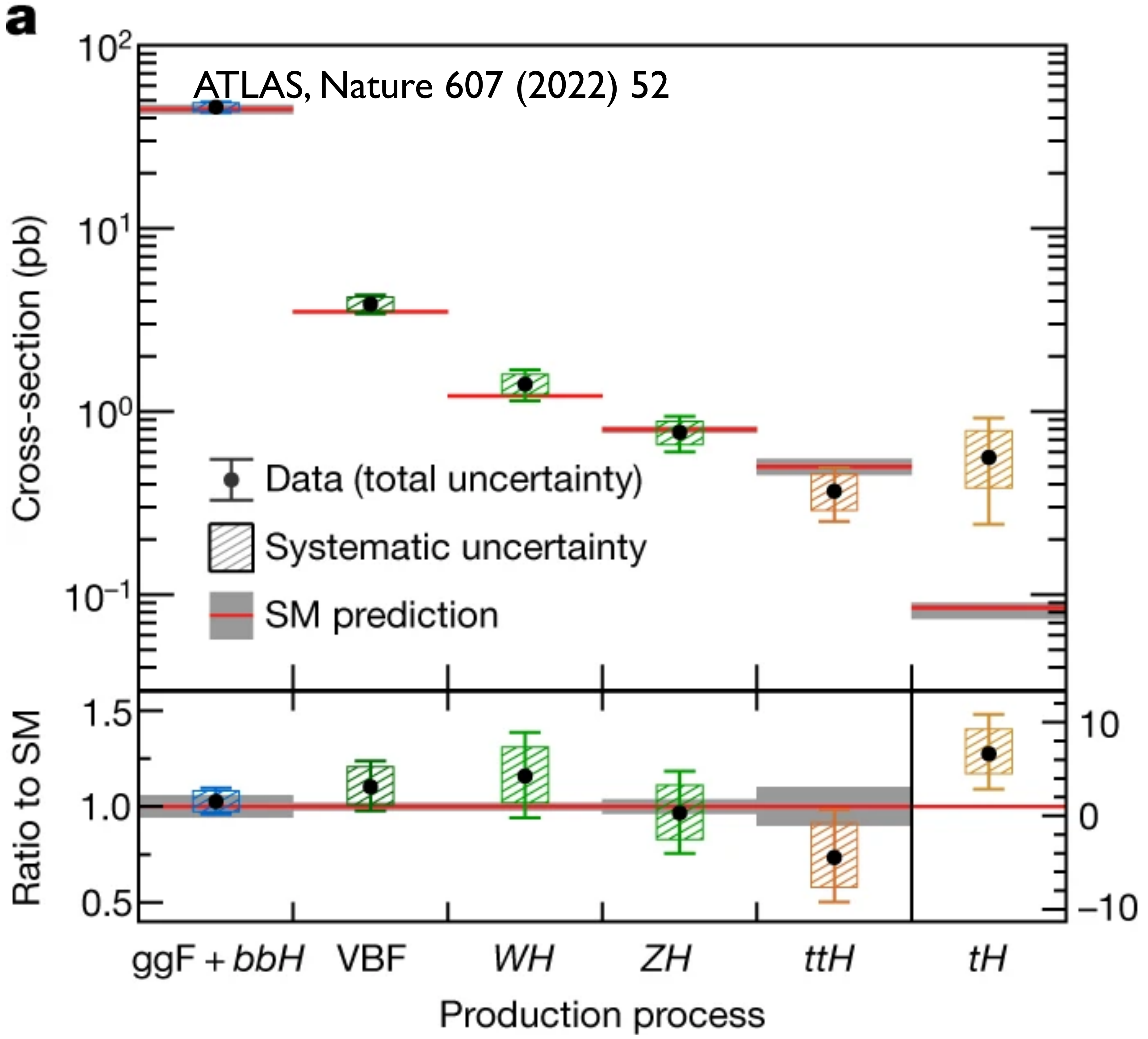
machine-learning powered parameterisation of some of the inputs of the theoretical predictions (e.g. the proton)

Precision is the keyword in any of the options under discussion

When Precision is a crucial tool: deciphering the nature of the Higgs boson

Is the observed scalar particle the Standard Model Higgs boson ?





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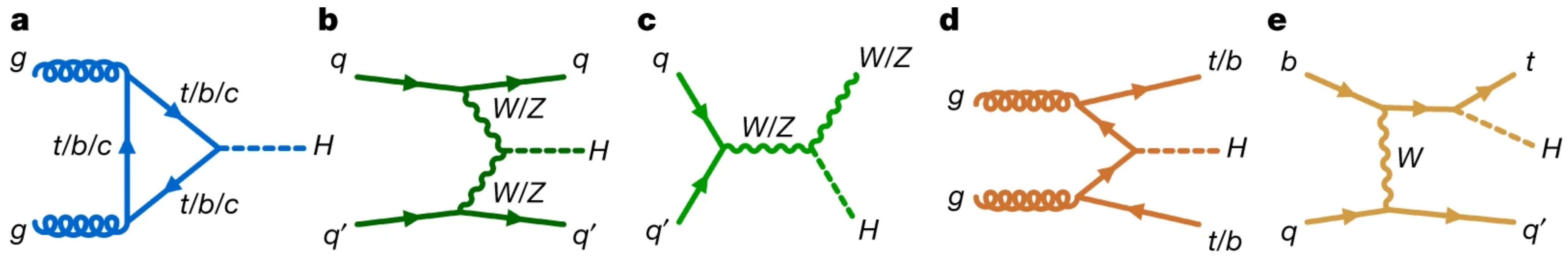
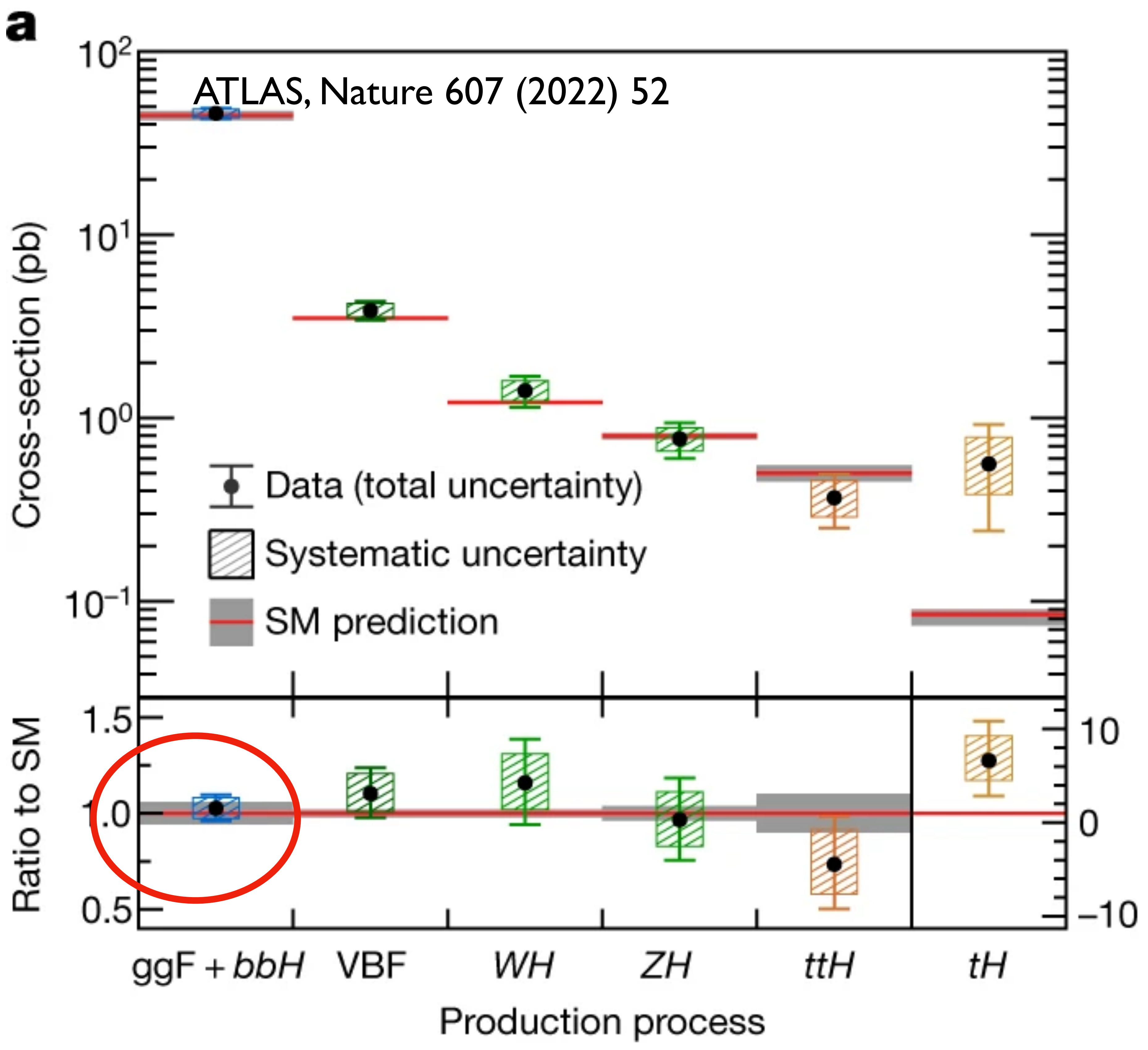
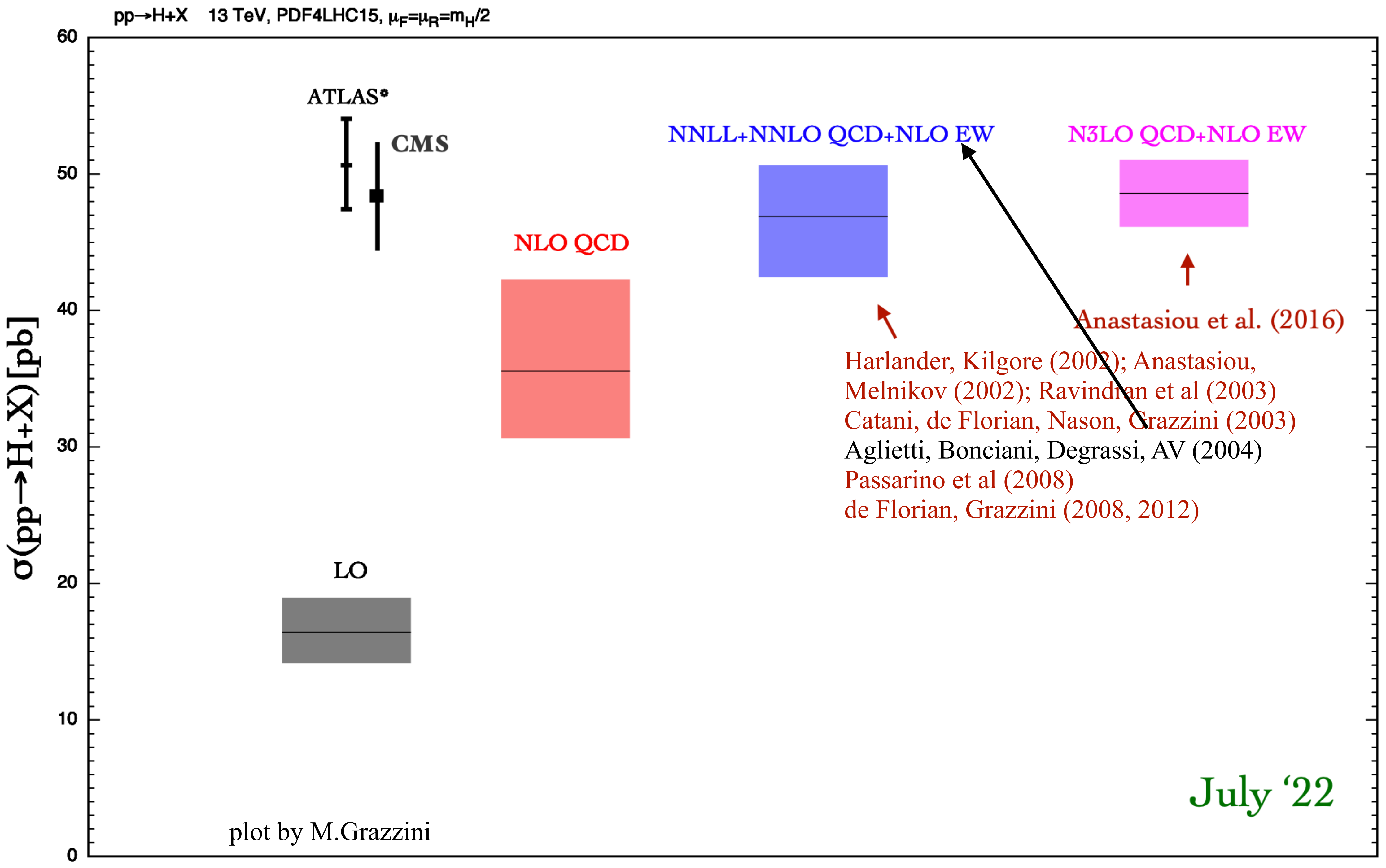




Quantum corrections up to third order needed

for a significant comparison

with the Higgs production cross sections



Motivation: statistical precision from small to large fermion-pair invariant masses

Statistical errors

FCC-ee $\sigma(e^+e^- \to \mu^+\mu^- + X)$

arXiv:2206.08326

sqrt(S) (GeV)	luminosity (ab^{-1})	σ (fb)	% error
91	150	$2.17595\ 10^6$	0.0002
240	5	1870.84 ± 0.612	0.03
365	1,5	787.74 ± 0.725	0.09

LHC and HL-LHC $\sigma(pp \to \mu^+\mu^- + X)$

arXiv:2106.11953

bin range (GeV)	% error 140 fb^{-1}	% error 3 ab^{-1}
91-92	0.03	$6\ 10^{-3}$
120-400	0.1	0.02
400-600	0.6	0.13
600-900	1.4	0.30
900-1300	3.2	0.69

Theoretical systematics

EW input parameters

large QED corrections

increasingly large EW corrections

proton PDFs

increasingly large QCD, QCD-EW and EW corrections

Are we able to reach (at least) the 0.1% precision throughout the whole invariant mass range?

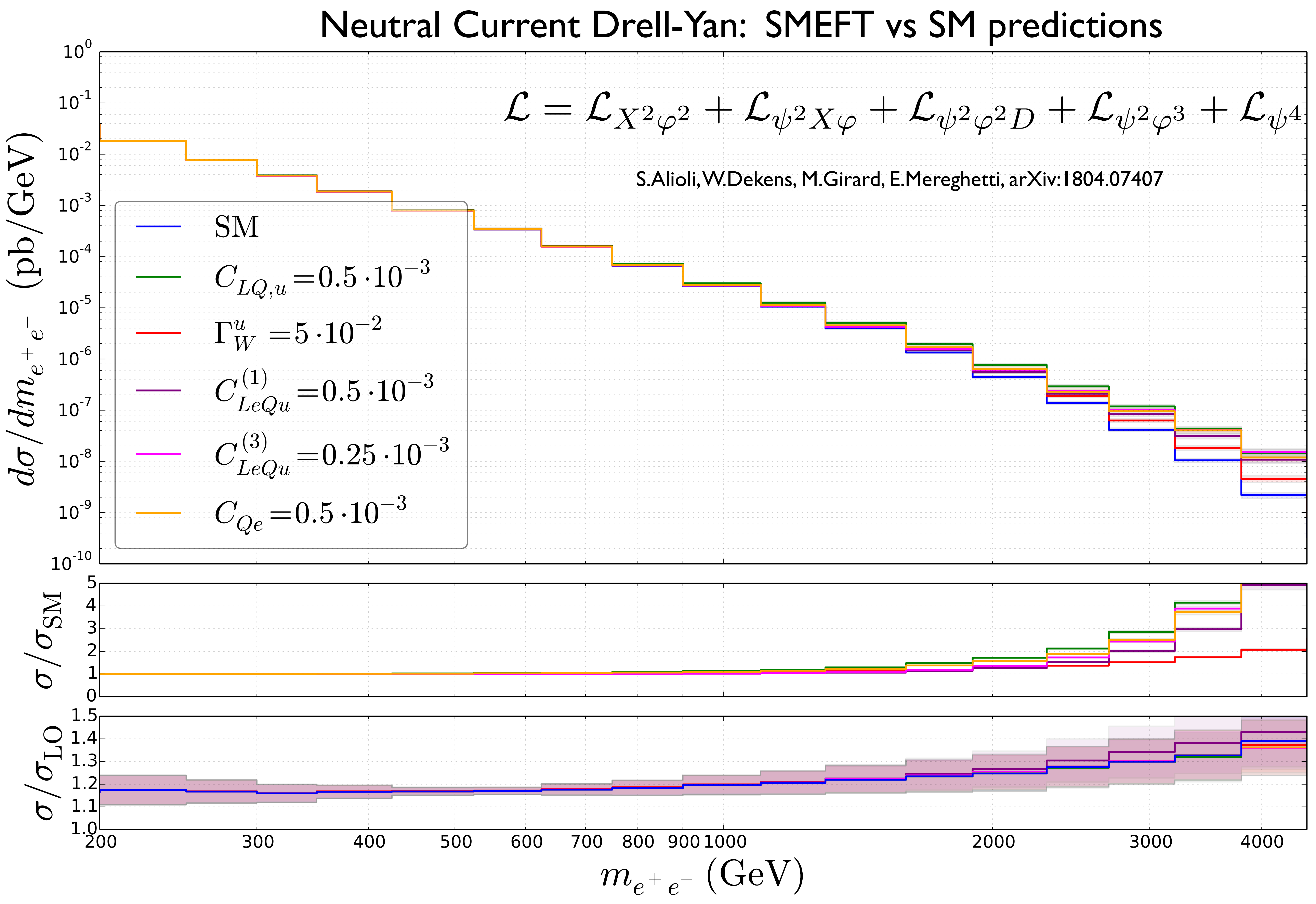
The Drell-Yan case poses the same challenges relevant for FCC-ee

Motivation: impact of higher dimension operators, as a function of the invariant mass

The parameterisation of BSM physics in the SMEFT language can be probed by studying the impact of higher dimension operators as a function of energy.

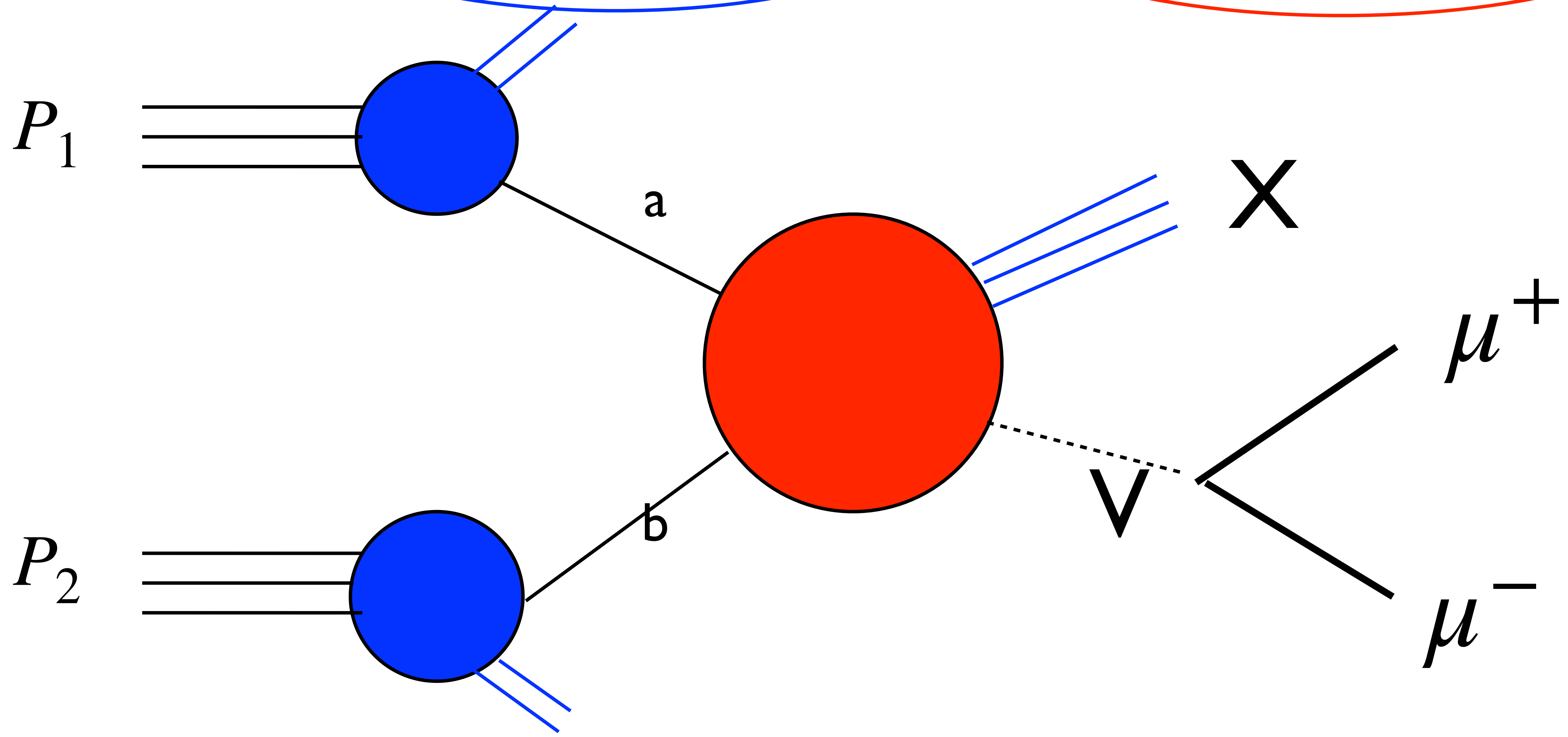
Deviations from the SM prediction require to answer the question "What is the SM?"

→ SM predictions have to be at the same precision level of the data i.e. (sub) per mille level



Factorisation theorems and the cross section in the partonic formalism

$$\sigma(P_1,P_2;m_V)=\sum_{a,b}\int_0^1 dx_1dx_2\, f_{h_1,a}(x_1,M_F)f_{h_2,b}(x_2,M_F)\,\hat\sigma_{ab}(x_1P_1,x_2P_2,\alpha_s(\mu),M_F)$$



Particles $P_{1,2}$ can be protons (→ Drell-Yan @ LHC) or leptons (→ FCC-ee, muon collider)

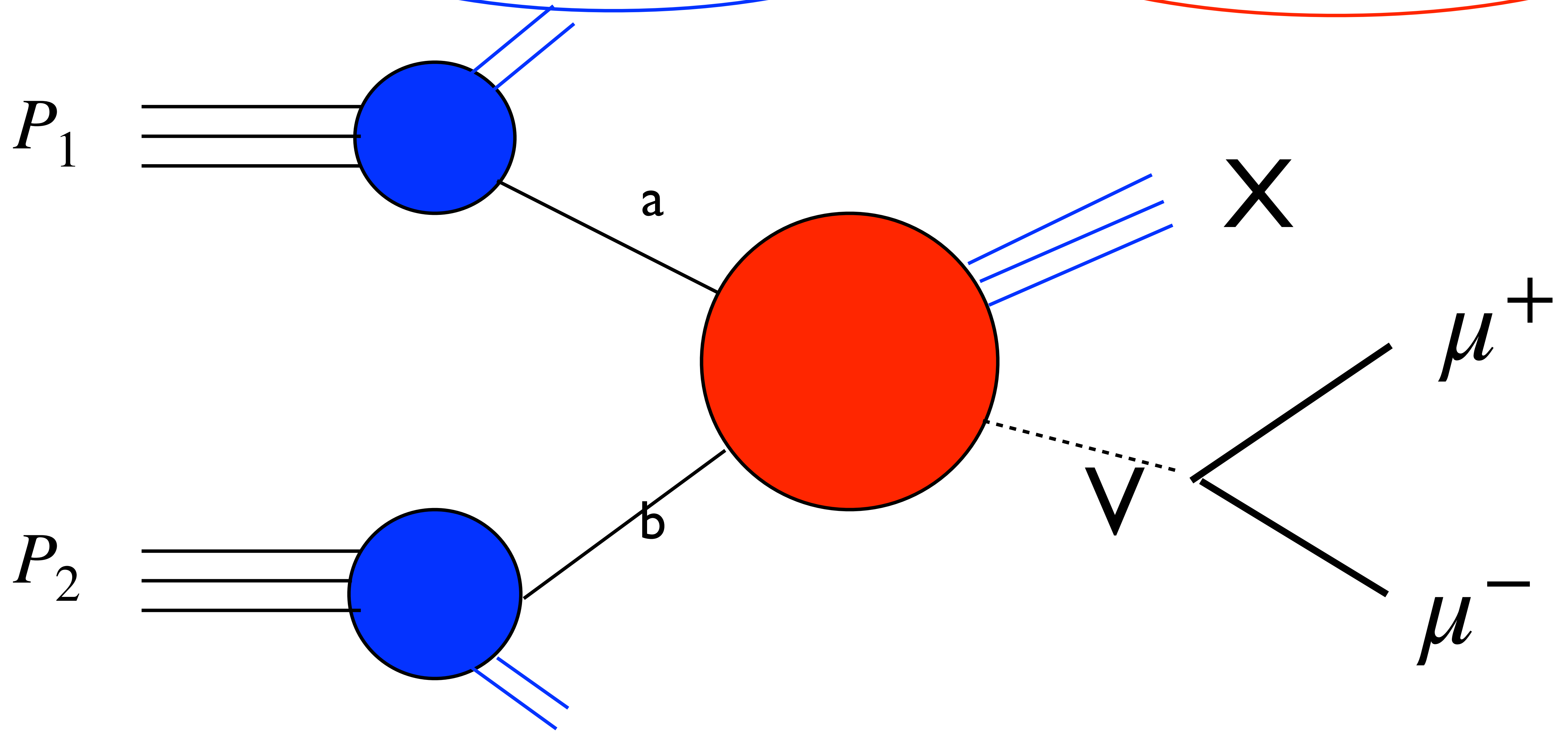
The partonic content of the scattering particles can be expressed in terms of PDFs
proton PDFs: ABM, CT18, MSHT, NNPDF,… lepton PDFs: Frixione et al. arXiv:1911.12040

The partonic scattering can be computed in perturbation theory, in the full QCD+EW theory, exploiting the theoretical progress in QCD, in the understanding of its IR structure

Factorisation theorems guarantee the validity of the above picture up to power correction effects

Factorisation theorems and the cross section in the partonic formalism

$$\sigma(P_1, P_2; m_V) = \sum_{a,b} \int_0^1 dx_1 dx_2 f_{h_1,a}(x_1, M_F) f_{h_2,b}(x_2, M_F) \hat{\sigma}_{ab}(x_1 P_1, x_2 P_2, \alpha_s(\mu), M_F)$$



The partonic scattering requires a combination of:

- fixed-order results → accuracy of the xsec normalisation
- resummation to all order of logarithmically enhanced terms → curing the breakdown of perturbation theory in specific phase-space regions

The matching (removing double countings) is subject to an ambiguity

Milano HEP Theory group

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Stefano Forte
Claudia Frugiuele
Raoul Röntsch
Alessandro Vicini
Marco Zaro

Fixed-order calculations
Resummation
Monte Carlo simulations
Proton/lepton structure
Quantum Computing

Tests of the Standard Model (QCD+EW)
Searches for New Physics (through precision)
Advanced modelling of physical systems

in average we host 3-5 PhD students and 3-4 postdocs

Some theoretical challenges

Advanced simulation and numerical integration

multi particle final states, large phase-spaces, challenges for the numerical integration algorithms

machine-learning can help, reaching 0.01% precision is hard

GPU powering effective at tree-level, studies/discussions in progress at NLO and higher

Cumbersome analytical results in higher orders

the frontier of fixed-order calculations depends on the number of energy scales: external legs + internal masses

the size of analytical amplitudes can reach the GB level → it affects all the steps of the numerical evaluation

new mathematical ideas should support/complement the "brute force" approach

The risk of absorbing New Physics signals in the proton parameterisation

the non-perturbative component of the proton parameterisation is obtained with a fit to collider data

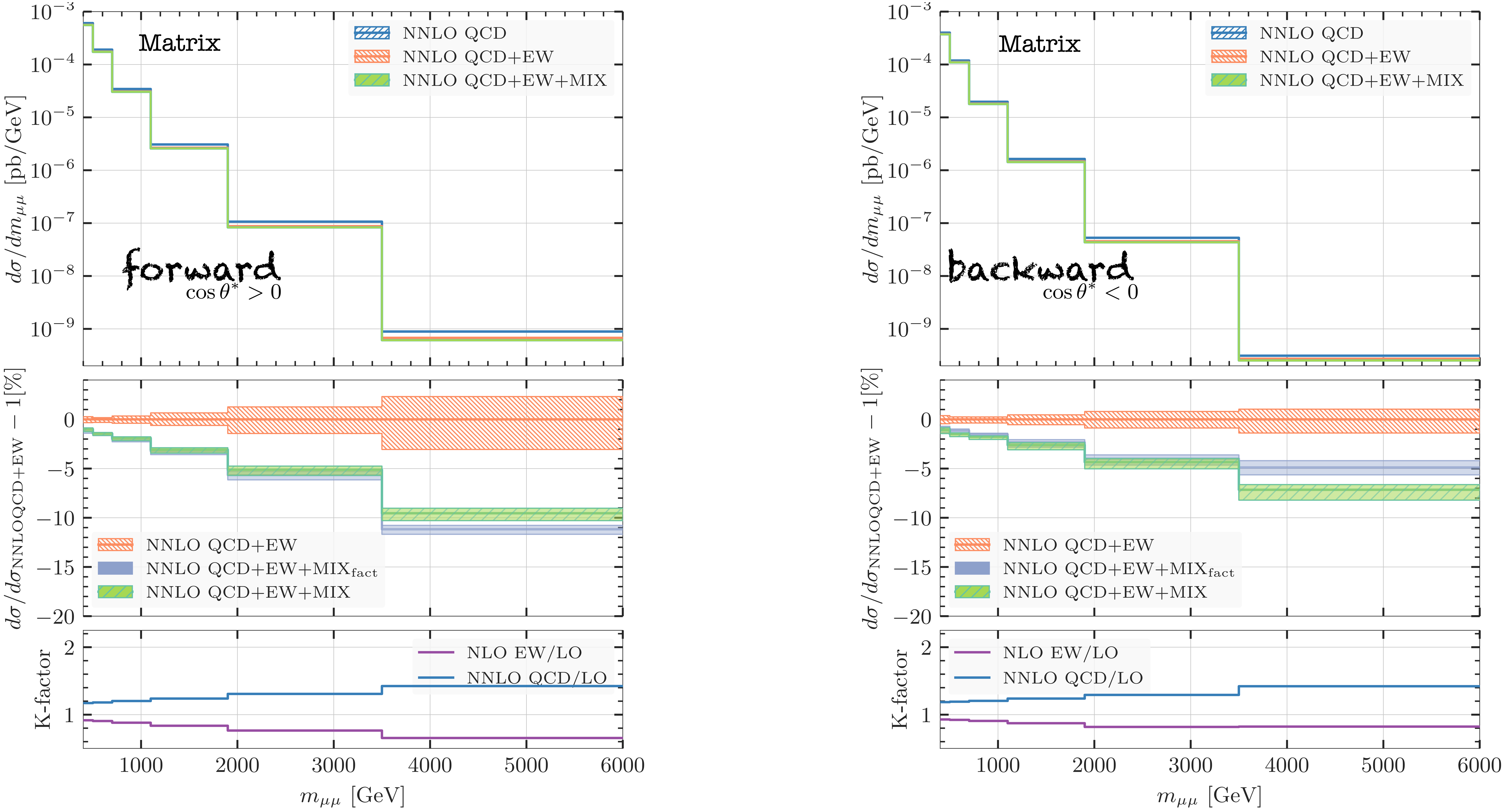
the fit at high mass might inadvertently reabsorb a feeble New Physics signal in the proton PDF

the presence of such a "contamination" may have consequences on the internal consistency of the parameterisation

→ systematic studies of all the parton densities (e.g. antiquark at large-*x*) may help to disentangle the BSM signal

Phenomenology of Neutral Current Drell-Yan including exact NNLO QCD-EW corrections

T.Armadillo, R.Bonciani, L.Buonocore, S.Devoto, M.Grazzini, S.Kallweit, N.Rana, F.Tramontano, AV, arXiv:2106.11953 , Phys.Rev.Lett. 128 (2022) 1, 012002 and work in preparation



Negative mixed NNLO QCD-EW effects (-3% or more) at large invariant masses,

absent in any additive combination → impact on the searches for new physics → impact on PDF determination

Interplay of precision measurements at Z resonance, low-, and high-energy

The very high precision determination of EW parameters at the Z resonance is a cornerstone of the whole precision program but there is more…

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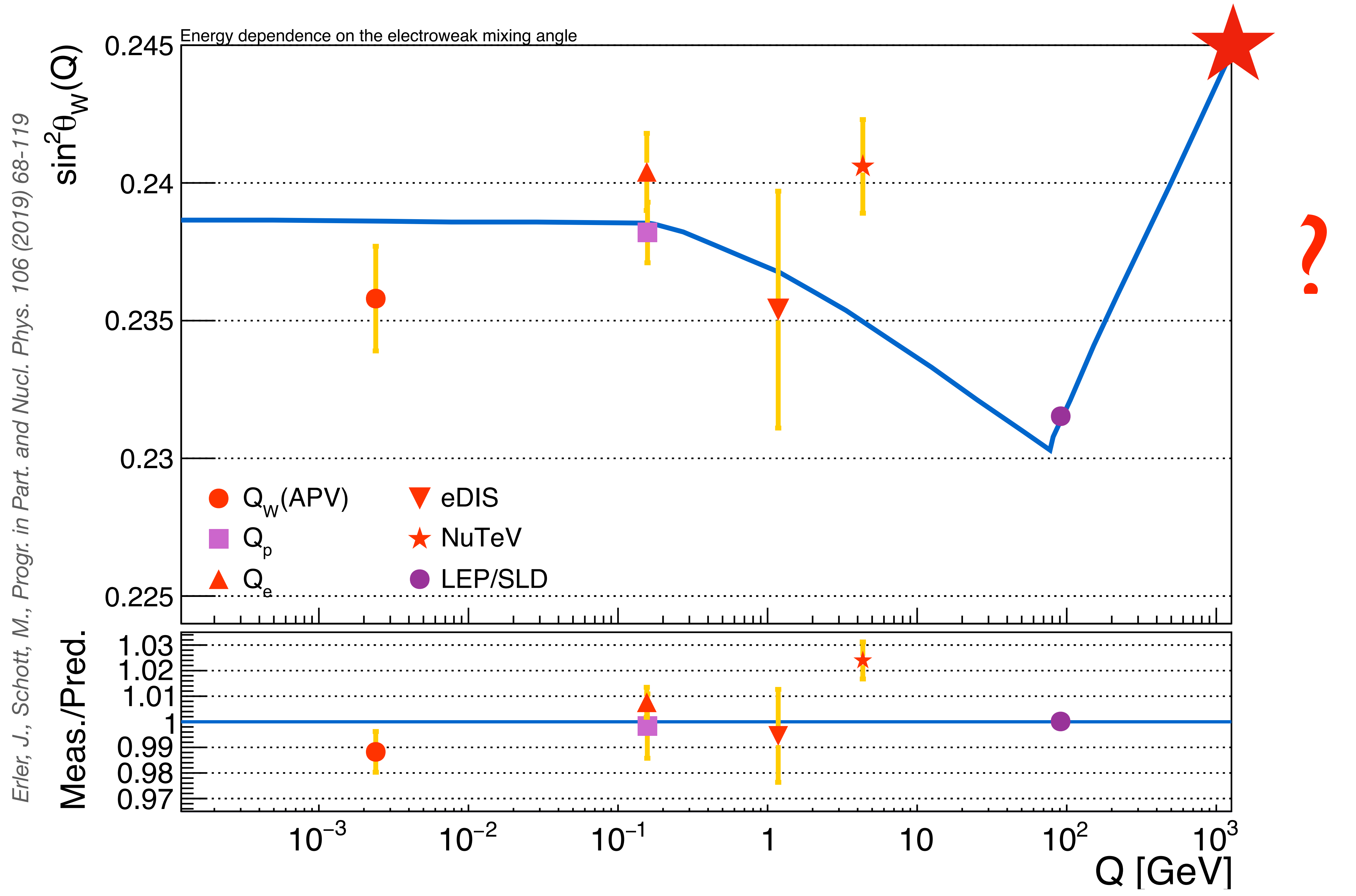
The SM predicts the running of its parameters, like e.g. $\sin^2\hat{\theta}(\mu_R^2)$, with non-trivial features and in turn complementary sensitivity to BSM physics

low-energy (sub-GeV) determinations (P2 in Mainz, Møller at JLab)
high-energy (TeV) determinations (CMS, ATLAS)
offer a stringent test of the SM
complementary to the results at the Z resonance

The running of an MSbar parameter is completely assigned
once boundary and matching conditions are specified



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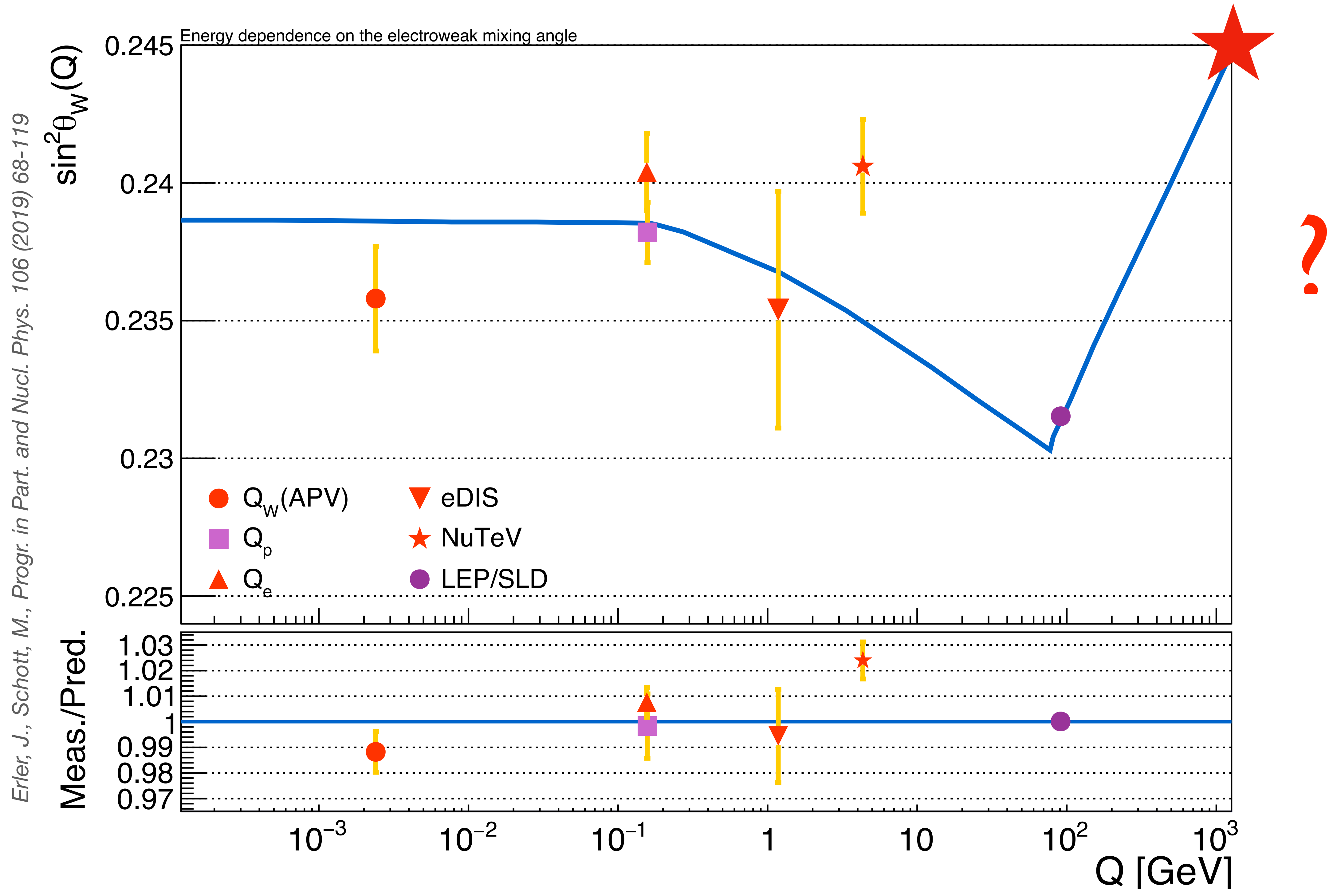

The absence of higher-order SM corrections could fake a BSM signal

in the Effective Field Theory language, missing SM corrections might be compensated by non-vanishing Wilson coefficients

Conclusion

Testing the SM and searching for BSM signals are two complementary perspective
in the interpretation of data at future colliders

The definition of what is the SM and its simulation at 0.01% level are incredible challenges
conceptual, in QFT, mathematical, in numerical simulations

The timescale of several projects is getting longer → impact on the recruiting of postdocs and PhD students

The current progress (=precision) of the LHC physics program has triggered the opening of a new branch of studies
testing the violation of Bell inequalities in several multiparticle final states
⇒ precision can help us to understand the quantum nature of the fundamental interactions