Calculational challenges for high-energy colliders

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Université catholique de Louvain
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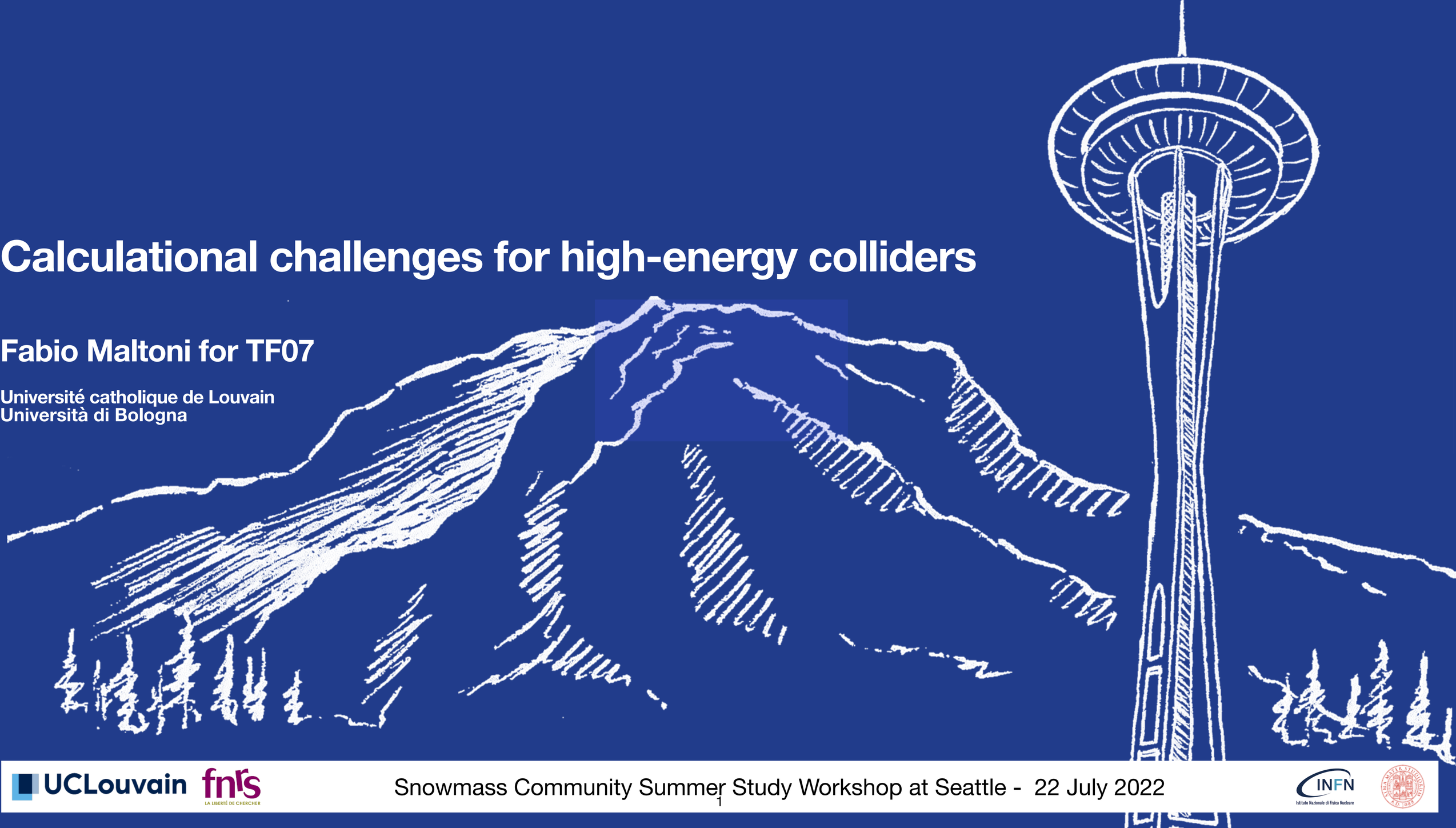
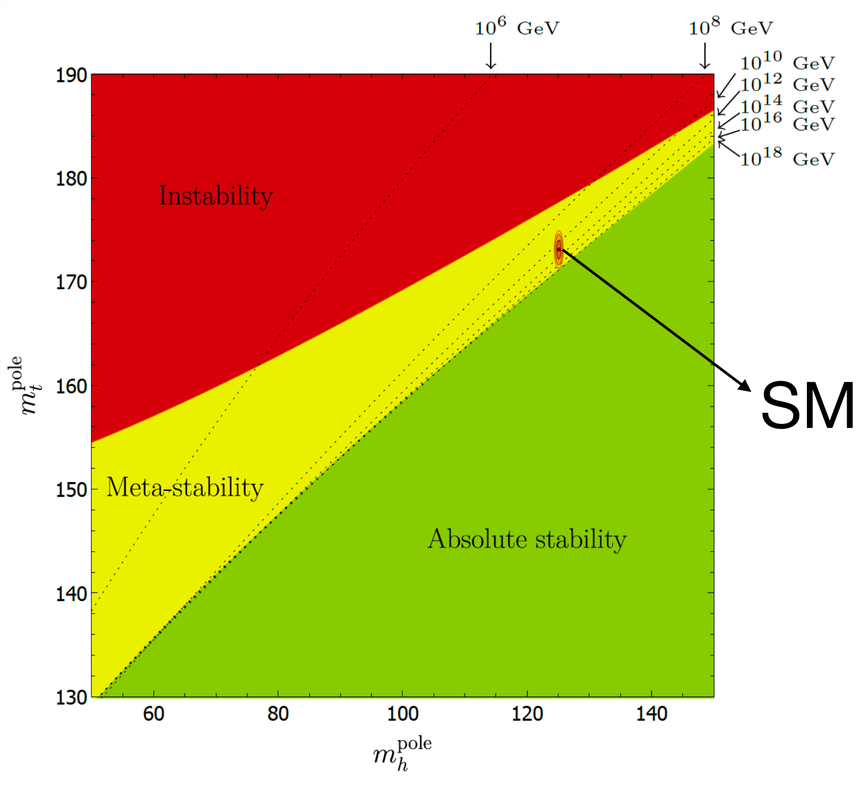


Where do we stand?

$$\mathscr{L}^{(4)}_{SM} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi} i \not{D} \psi + (y_{ij}\bar{\psi}^i_L \phi \psi^j_R + \mathrm{h.c.}) + |D_\mu \phi|^2 - V(\phi)$$



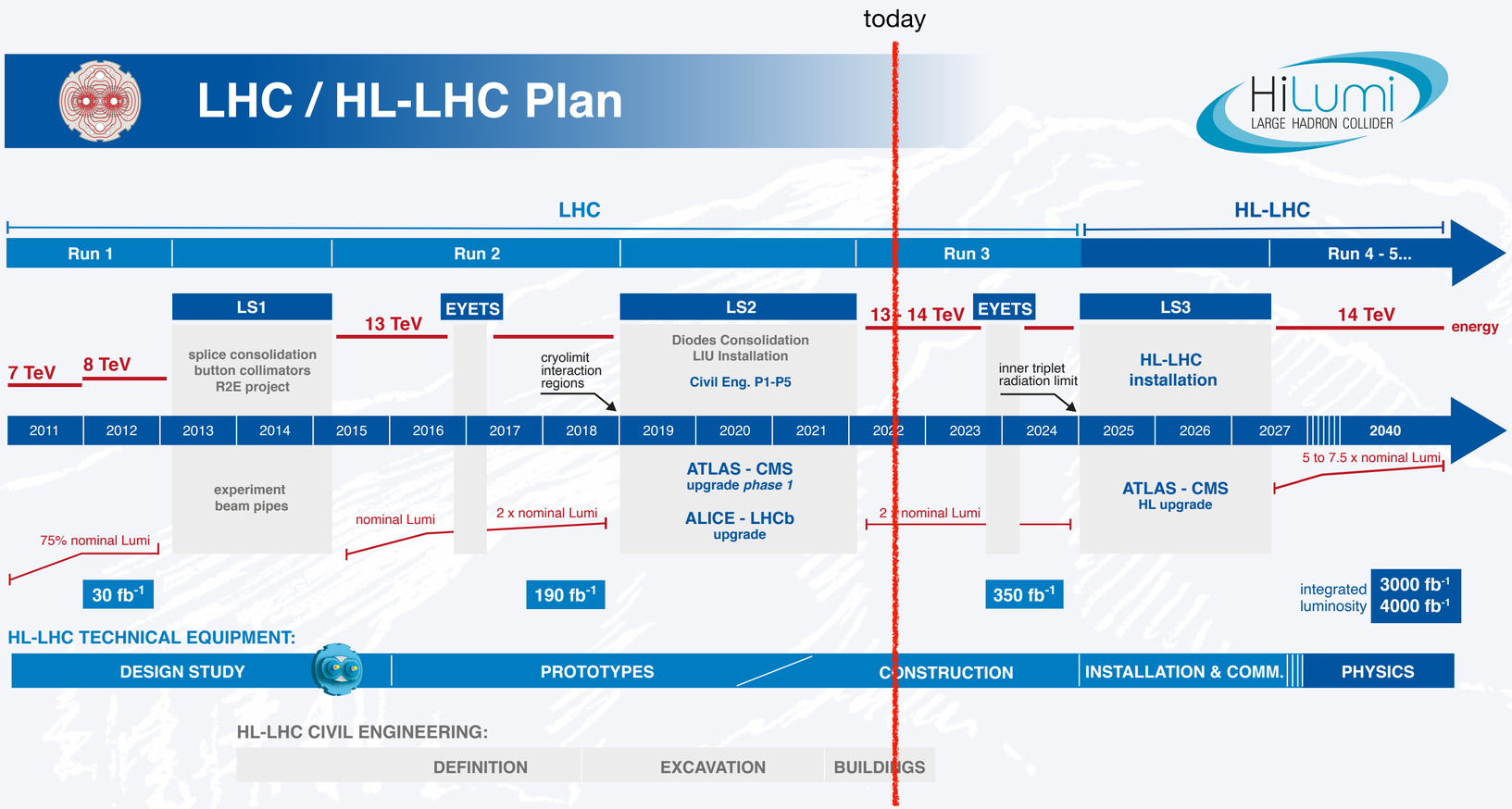
[Andreassen et al. 1707.08124]

- $SU(3)_c$ x $SU(2)_L$ x $U(1)_Y$ gauge symmetries.
- Matter is organised in chiral multiplets of the fund. representation.
- The SU(2) x U(1) symmetry is spontaneously broken to $U(1)_{EM}$.
- Yukawa interactions lead to fermion masses, mixing and CP violation.
- Matter+gauge group => Anomaly free
- Renormalisable = valid to “arbitrary” high scales.
- A number of accidental symmetries seen in Nature.
- Neutrino masses can be accommodated in two distinct ways.

CC#1: Determine the SM parameters in terms of underlying UV dynamics, and in particular the Higgs mass is out of control.

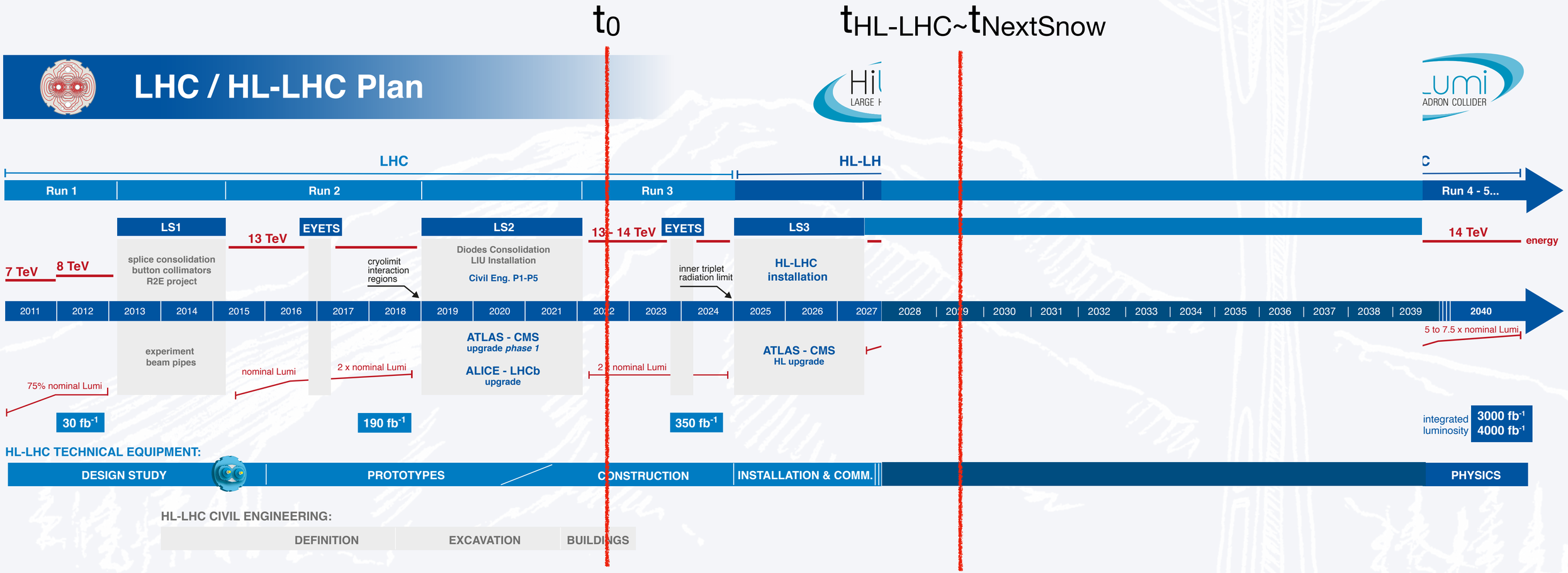
Where do we stand?

The LHC reference frame and unit of time



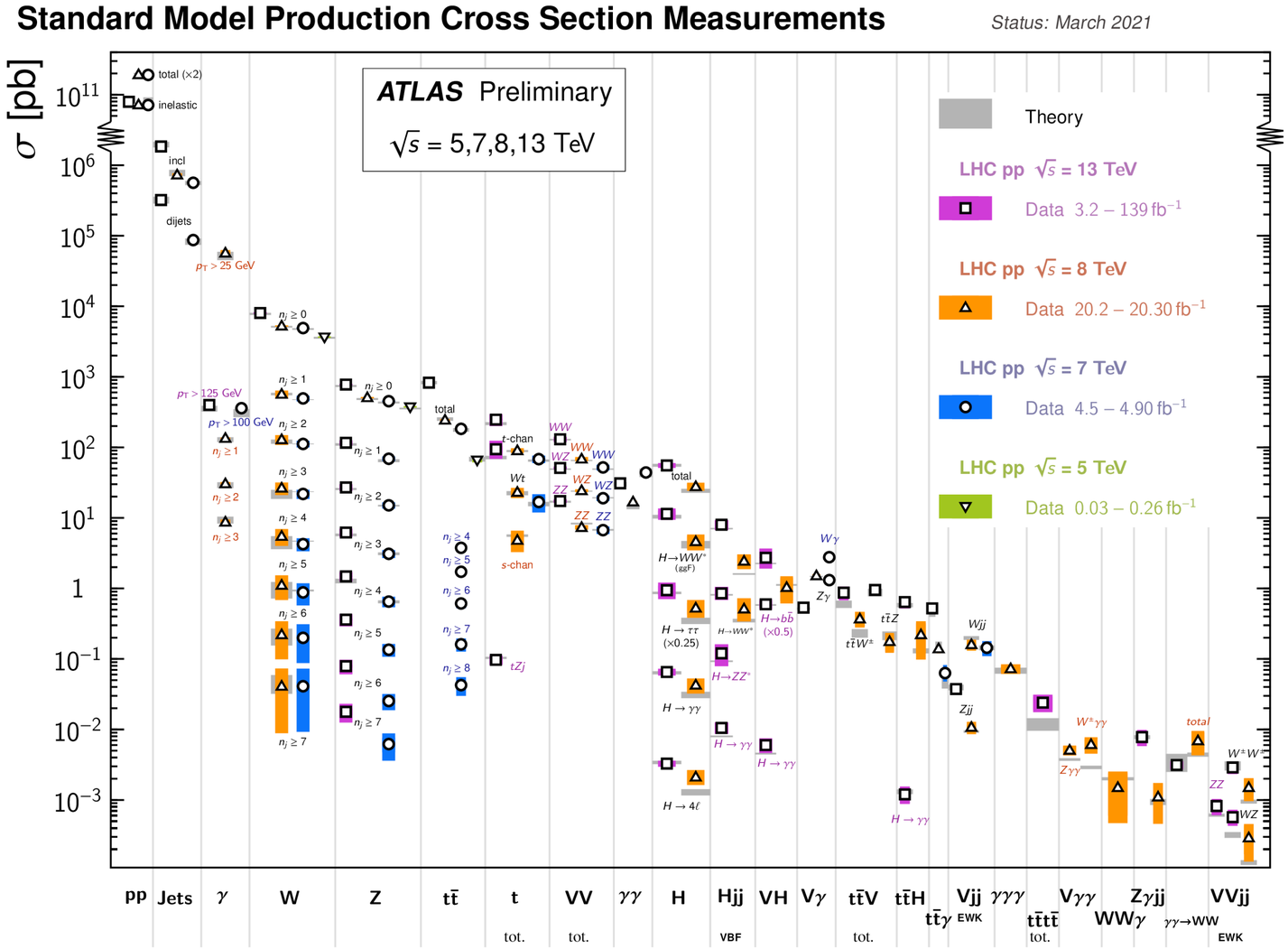
Where do we stand?

The LHC reference frame and unit of time

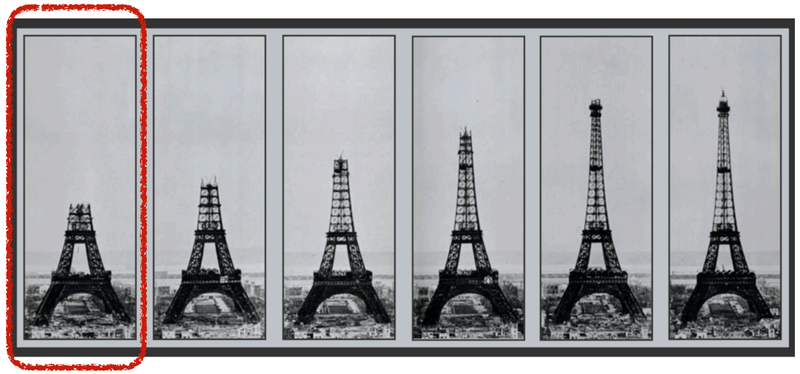


We are at 1/3 of our adventure with 1/20 of the expected data

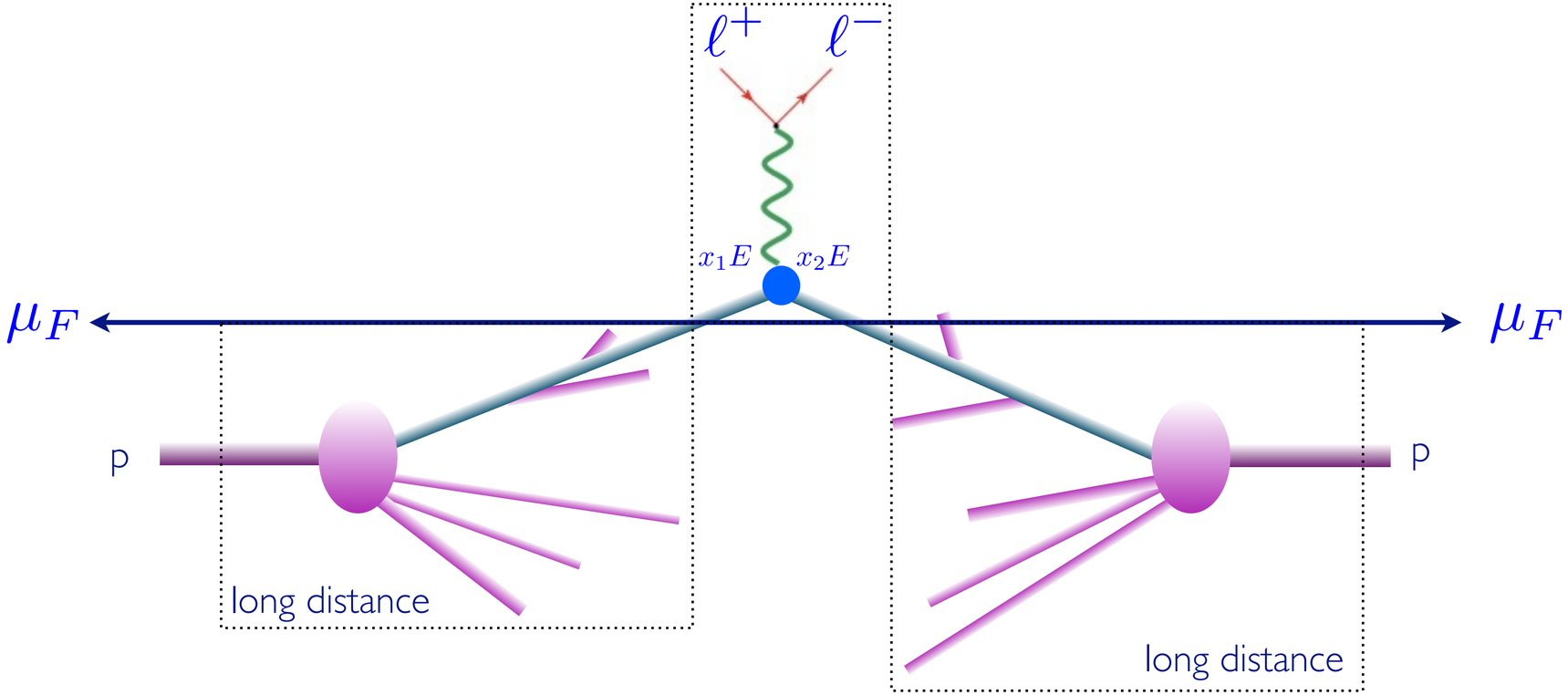
Where do we stand?



- Tangible results of an amazing experimental effort over a 10+ year span, accessing a wide range of final states, each with very different challenges.
- Theory predictions seem adeguate. (The key role of MCs is hidden in this plot).
- Comparison with SM predictions shows that we have the necessary theoretical and experimental control to move onto the next phase.



LHC master formula



$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab\to X}(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2})$$

Measure (& evolve <u>perturbatively</u>)

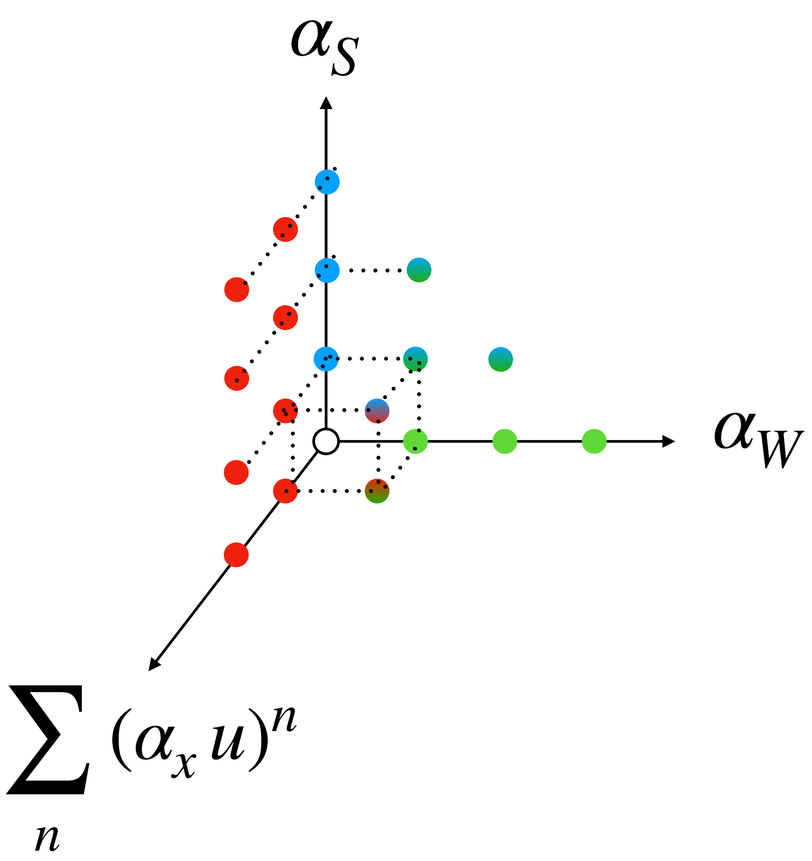
Compute <u>perturbatively</u>

Precision calculations for the LHC

The path

"Rules of thumb at the LHC":

- Predictions must be calculated at least to **NLO QCD** to control the central value at 10-20%.
- **N2LO QCD** provides control at 5% level and on the uncertainties stabilizing the perturbative expansion.
- **N2LO QCD** is expected to be of the **same order** as **NLO EW** $\alpha_S^2 \sim \alpha_W$**, yet EW** corrections grow large and negative at high energies (Sudakov logs).
- **N3LO QCD** is the frontier of precision aiming ~1% of MHO uncertainties.
- **Resummation** Universal, all-order terms that are potentially large for some observables (logs or 1PI loops for propagators) need to be resummed. They might refer to global or non-global observables. Resummation leads to mprovements in precision and accuracy.



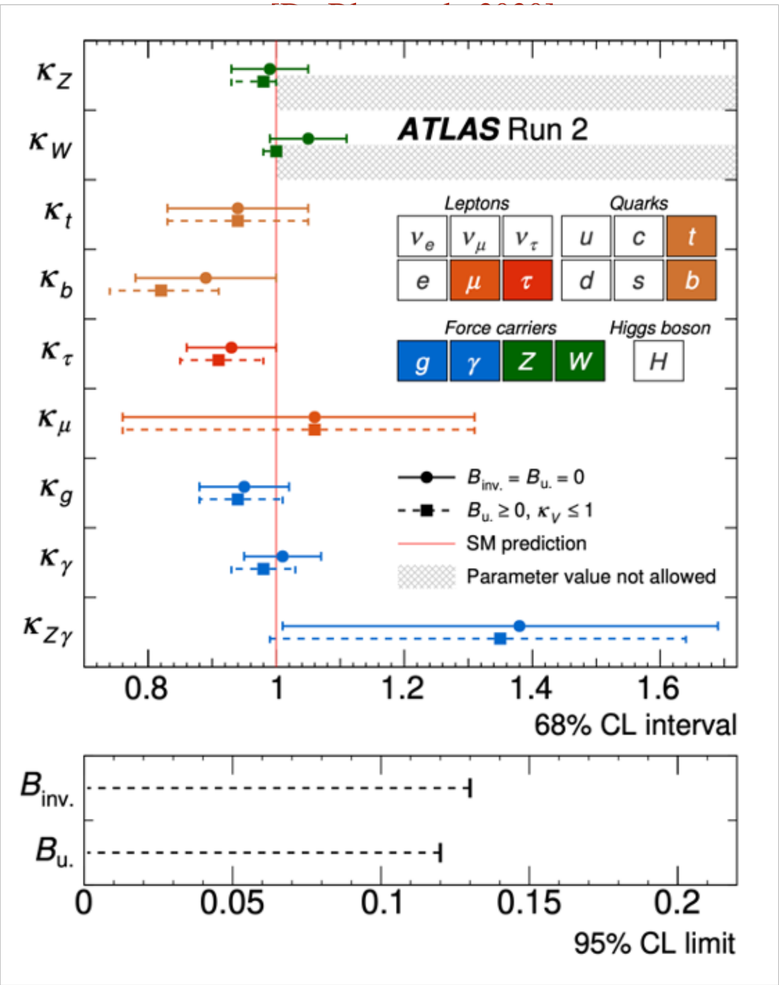
The precision goal

Edwin 1990

Edwin 2022

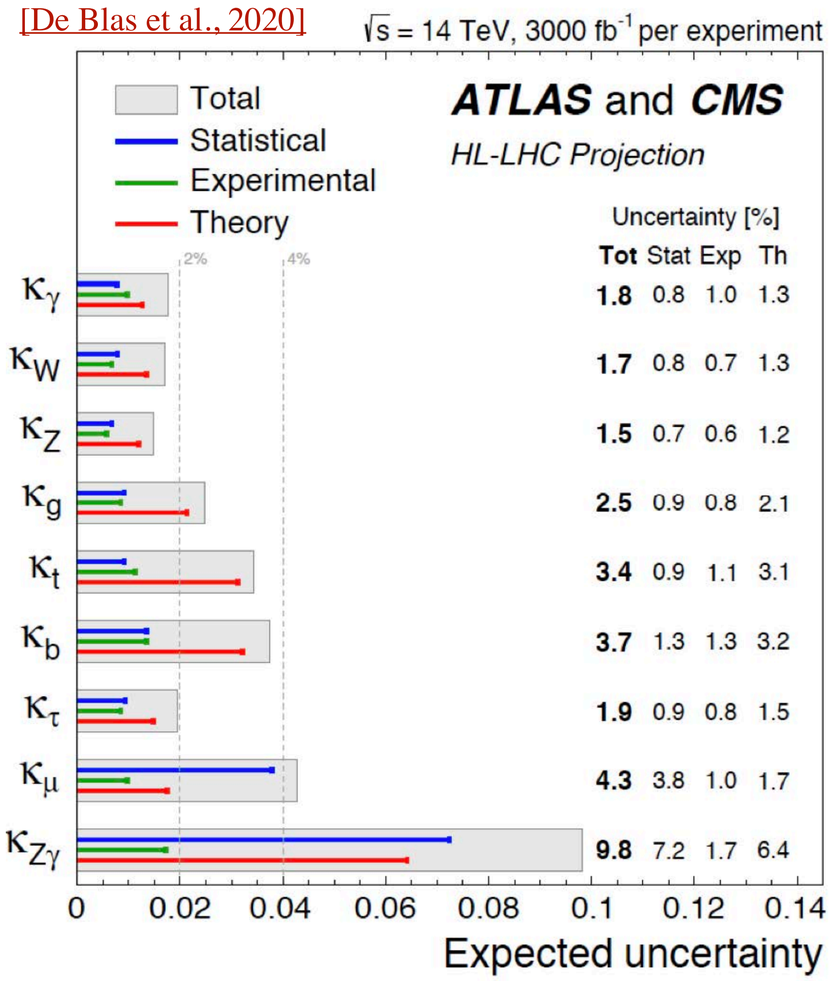
HL-LHC projections

Higgs couplings



10-20% → 2-4%

[De Blas et al., 2020]



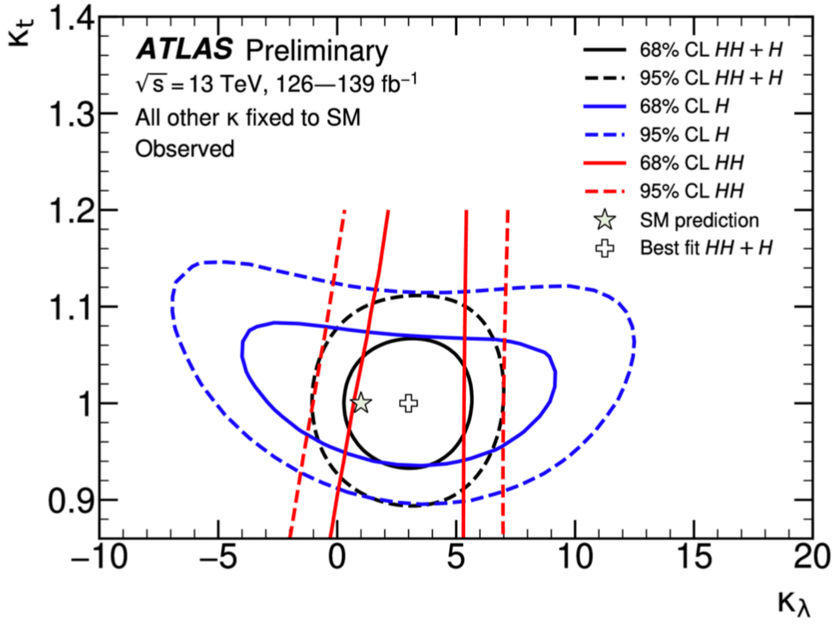
$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM} \kappa_i^2 \cdot \Gamma_f^{SM} \kappa_f^2}{\Gamma_H^{SM} \kappa_H^2} \quad \to \quad \mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

HL-LHC projections

Higgs couplings

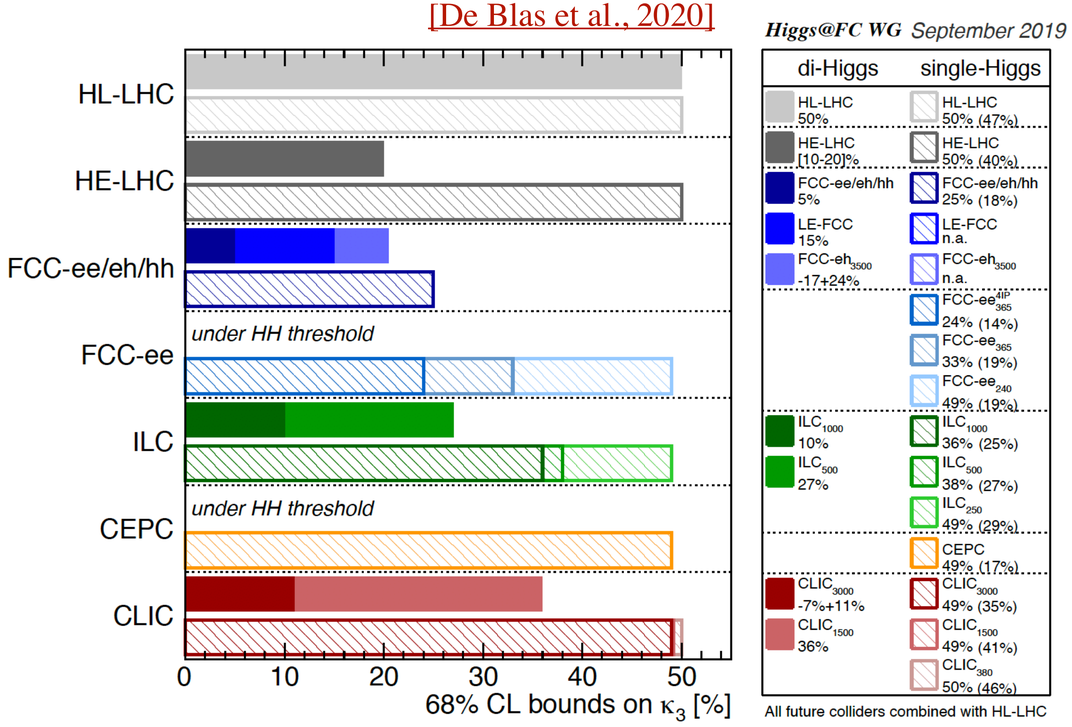
Now

[ATLAS, 2022]



Future

[De Blas et al., 2020]

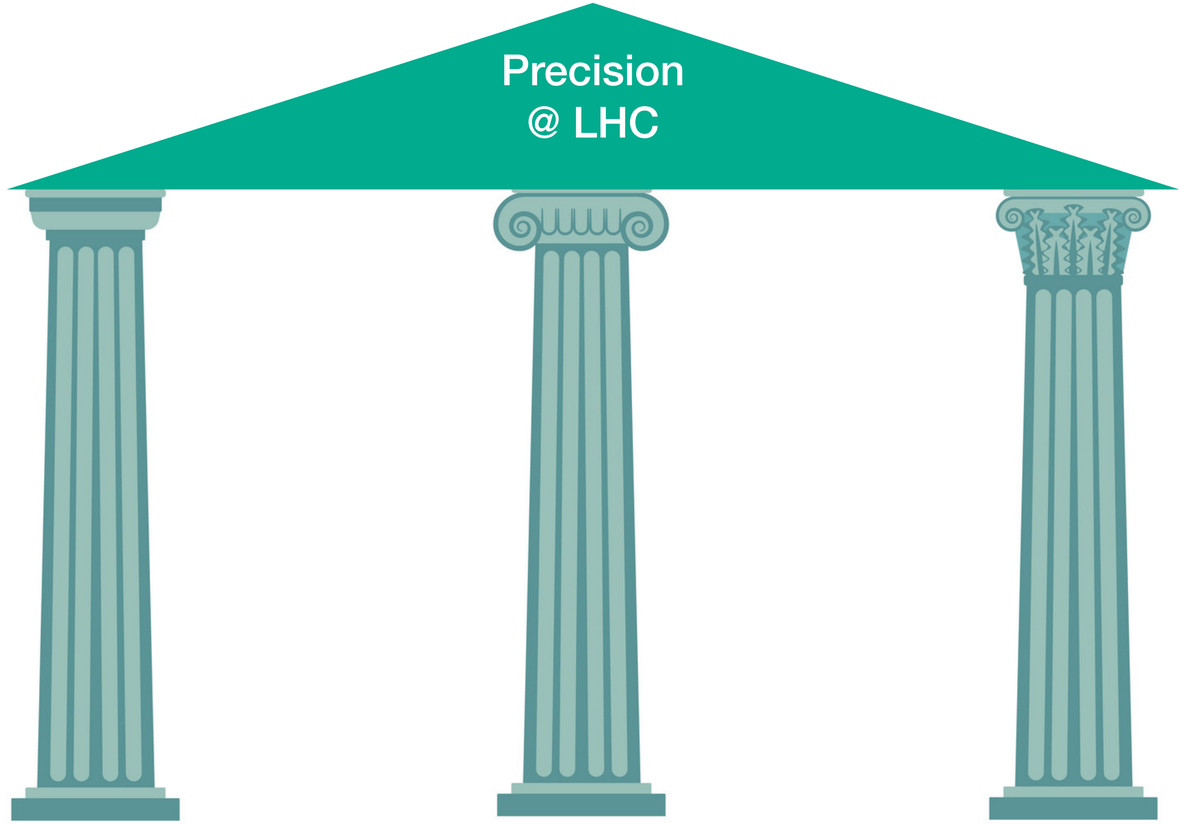


Currently limits on k_λ from H and HH are comparable and will stay so at the HL-LHC.

Borderline sensitivity to say something about EW baryogenesis…

Precision calculations for the LHC

Status



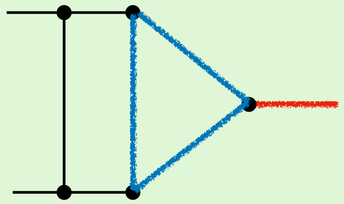
Fixed Order
LO, NLO,…
QCD EW

Resummation
LL, NLL,…
Parton Showers

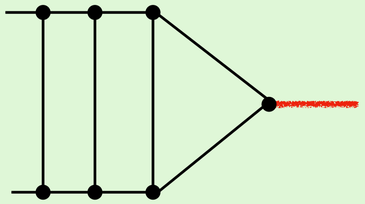
PDF's
LO,NLO,..Evolution
Fits

The multi-loop frontier

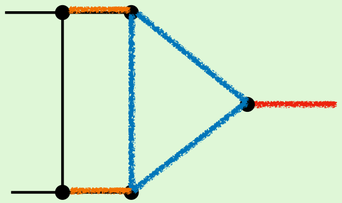
DONE



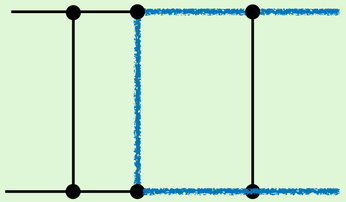
H,Z,W at $N2LO_{QCD}$



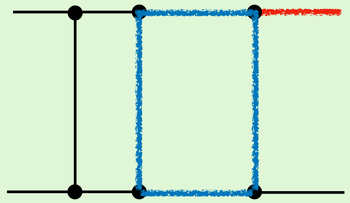
H,Z,W at N3LO



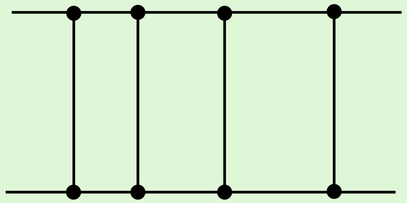
H,Z,W at $NLO2_{EWxQCD}$



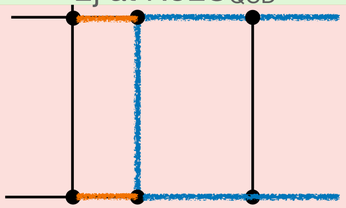
tt at $N2LO_{QCD}$



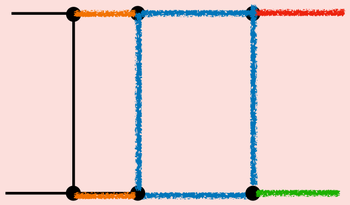
H+j at NLO_{QCD}



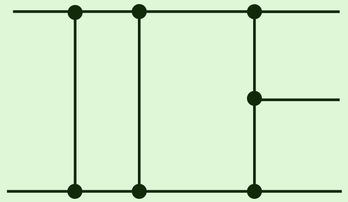
2j at $N3LO_{QCD}$



tt at $NLO2_{EWxQCD}$

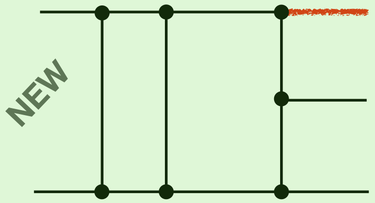


ZH at $N2LO_{EW}$

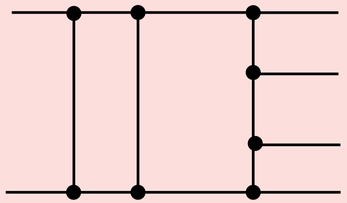


3j at $N2LO_{QCD}$

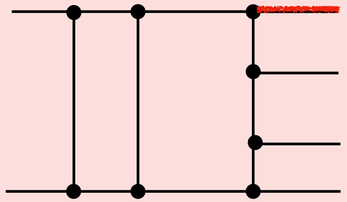
NEW



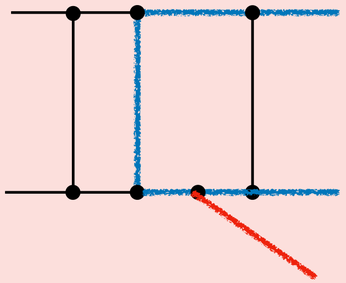
Vbb at $N2LO_{QCD}$



4j at $N2LO_{QCD}$

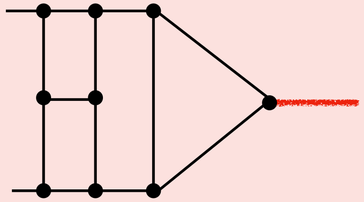


V+3j at $N2LO_{QCD}$



ttH at $N2LO_{QCD}$

As of 22 July 2022.
FAST MOVING FRONTIER



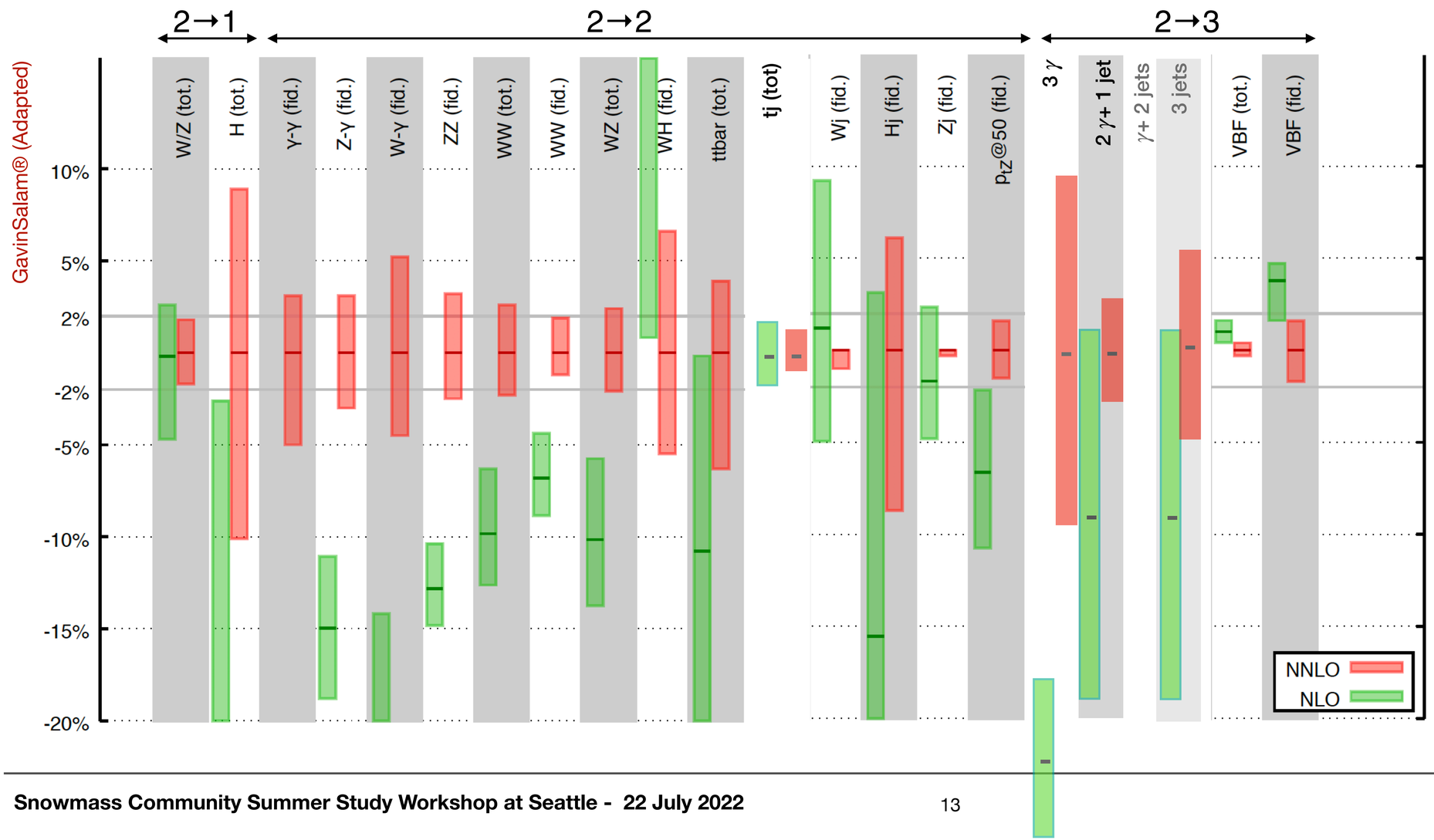
H,Z,W at $N4LO_{QCD}$

* The more # of loops/legs/scales (colors) the more difficult.
* Only Z,W,H 2 to 1 production known at N3LO
* EWxQCD corrections very limited
* EW N2LO still to be explored
* Need a subtraction method to turn to IR safe observables

TO DO

Precision calculations for the LHC

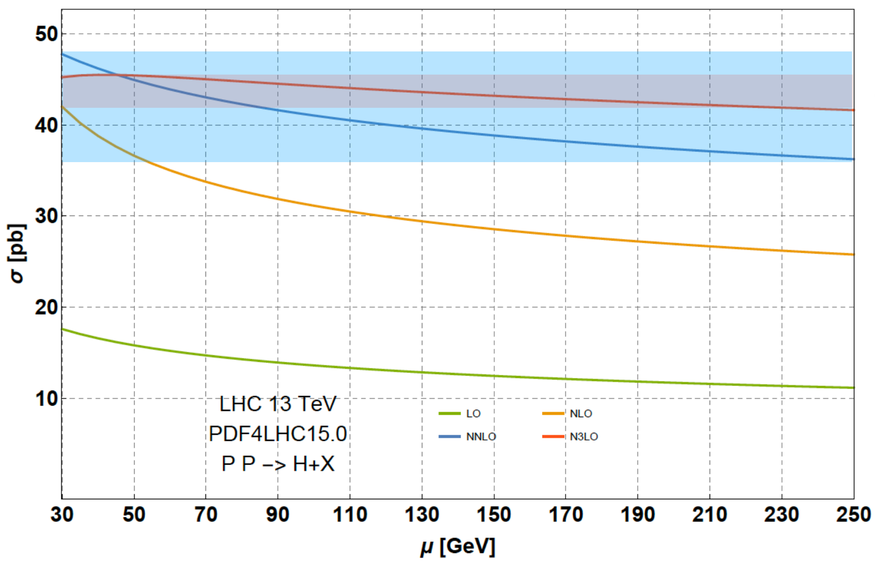
Status: Fixed Order



- NNLO brings us in the few percent arena
- Several NNLO computations move the central value out of the NLO uncertainties
- The 2→3 wall broken

Precision calculations for the LHC

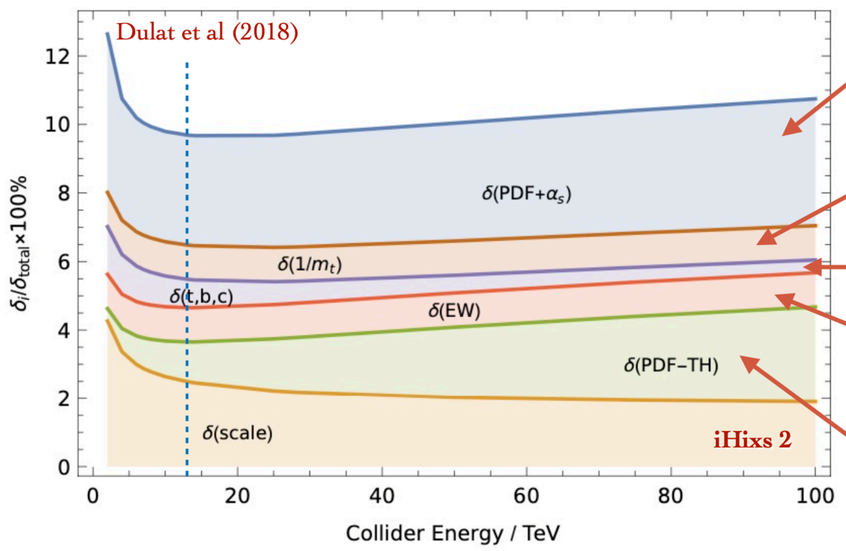
N3LO revolution



<5%

ggF known at N^{3}LO in HEFT ~ 1-2% uncertainty

$\alpha_s = 0.118 \pm 0.001 \rightarrow \mathcal{O}(2\%)$ uncertainty on x-section



Exact top mass dependence

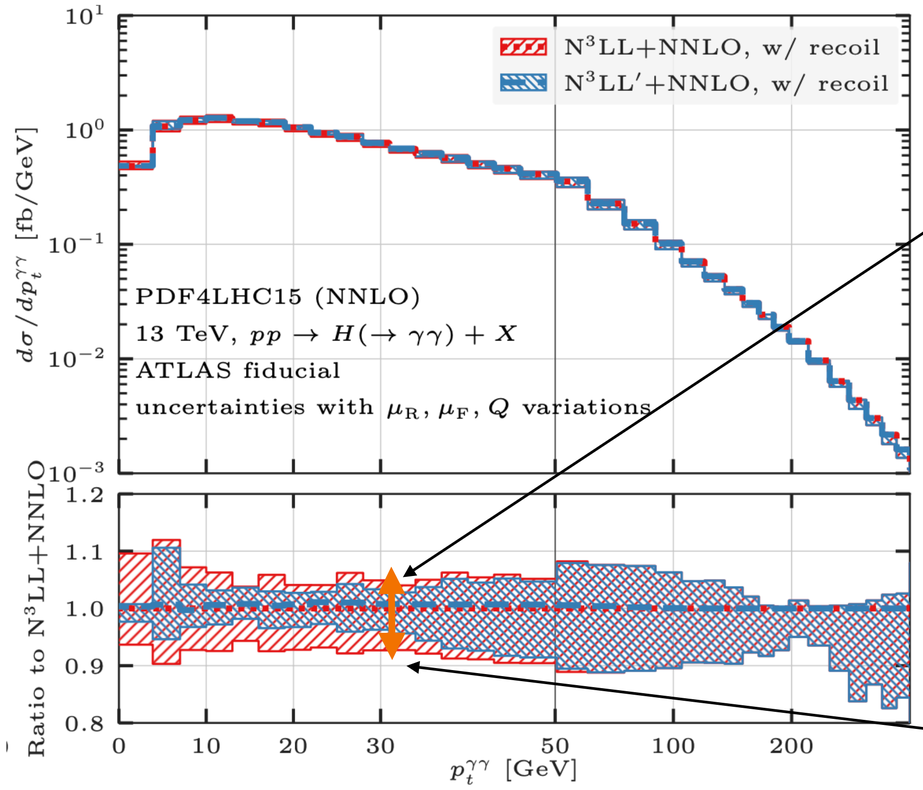
Bottom mass contribution

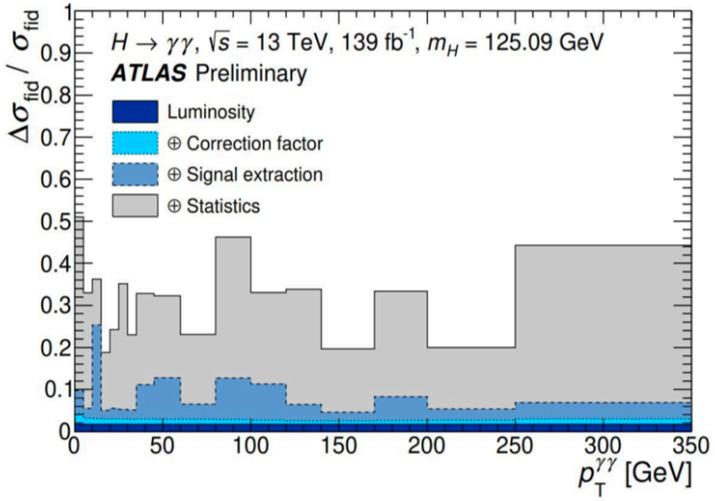
QCD+EW mixed contributions

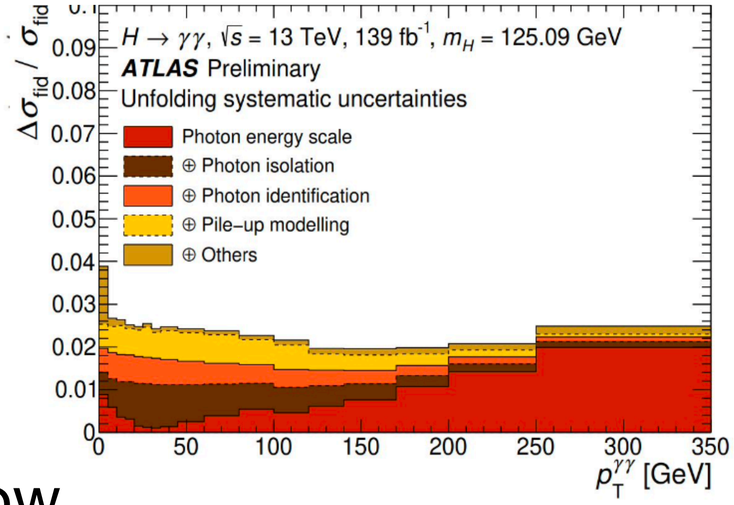
requires N^{3}LO PDFs

Precision calculations for the LHC

N3LO : good for the moment





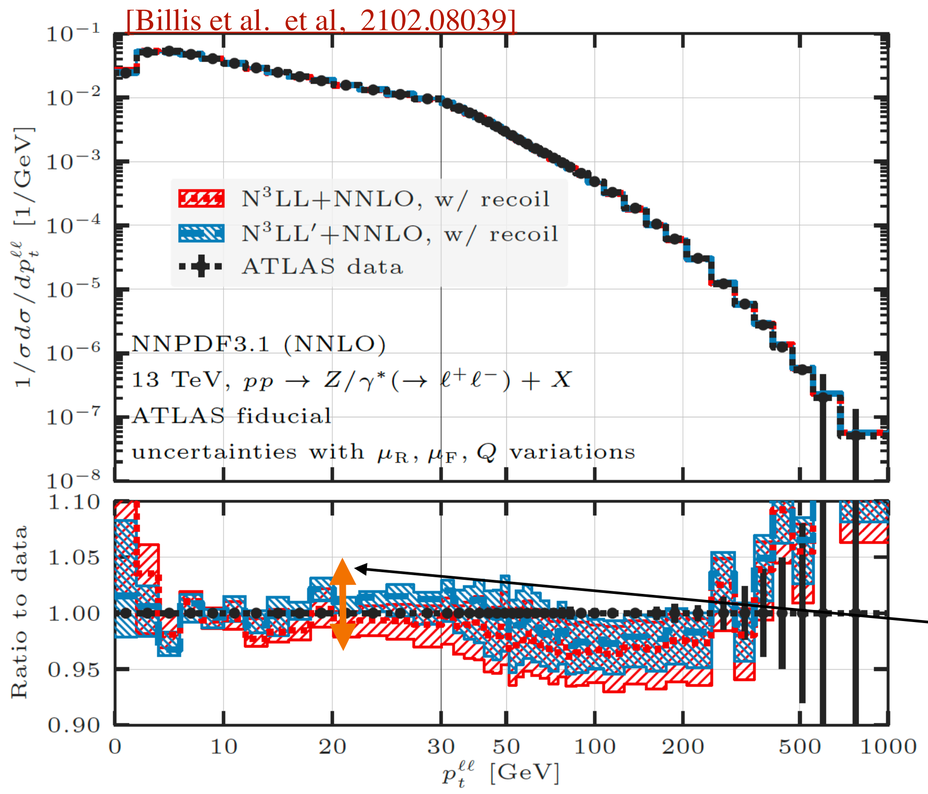


TH and EXP are comparable now….

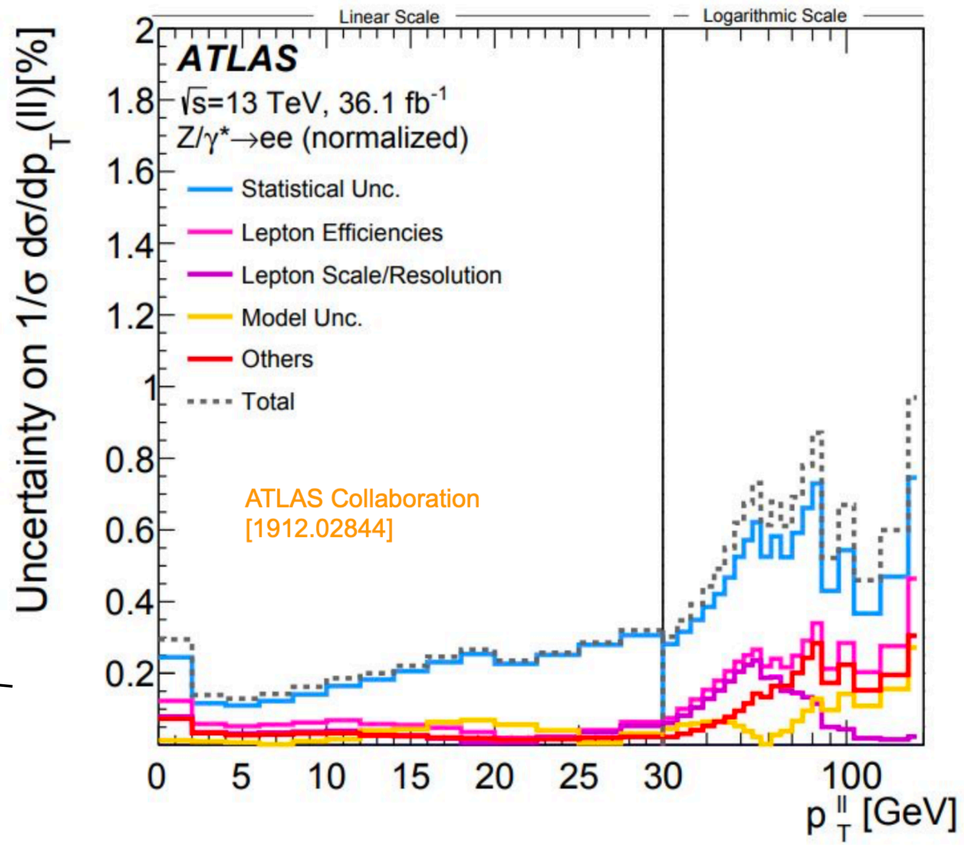
Contribution to: 2022 Snowmass Summer Study e-Print: 2203.06730 [hep-ph]
Contribution to: 2022 Snowmass Summer Study: e-Print:2203.07907 [hep-ph]

Precision calculations for the LHC

N3LO : already not enough



Resummation improves the stability of the cross section predictions even in presence of cut-induced log effects.

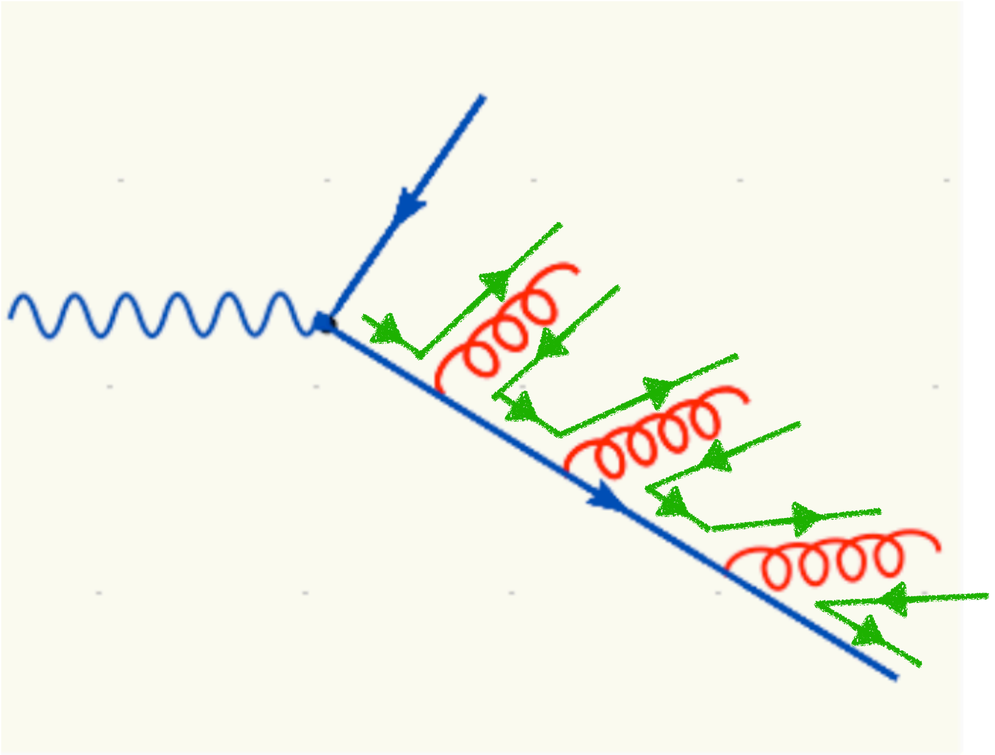


EXP (way) better than TH already now!!

Contribution to: 2022 Snowmass Summer Study: e-Print:2203.12557 [hep-ph]
Contribution to: 2022 Snowmass Summer Study, e-Print: 2203.06799 [hep-ph]

Precision calculations for the LHC

Fully exclusive simulations



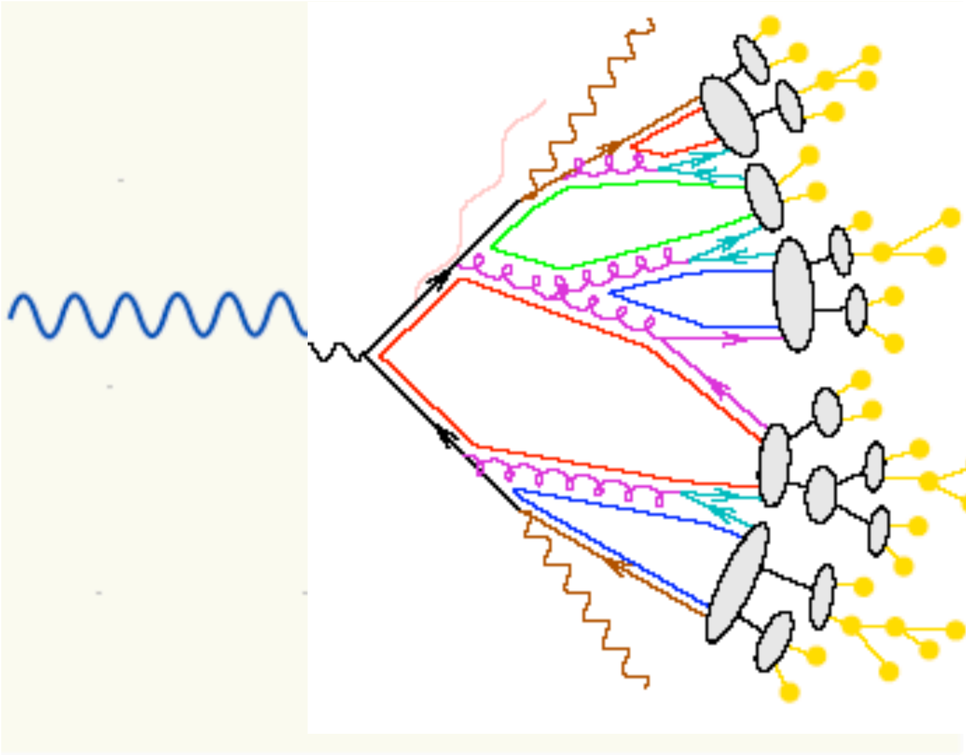
In QCD every gluon emission creates a new dipole with a smaller opening. Angular ordering of the soft radiation. Finally leading to color-connected cluster of low virtuality that can fragment into hadrons. DGLAP resummation+angular ordering allows collinear and soft resummation.

Gavin Salam ICHEP 2022

Contribution to: 2022 Snowmass Summer Study: e-Print:2203.12557 [hep-ph]
Contribution to: 2022 Snowmass Summer Study, e-Print: 2203.06799 [hep-ph]

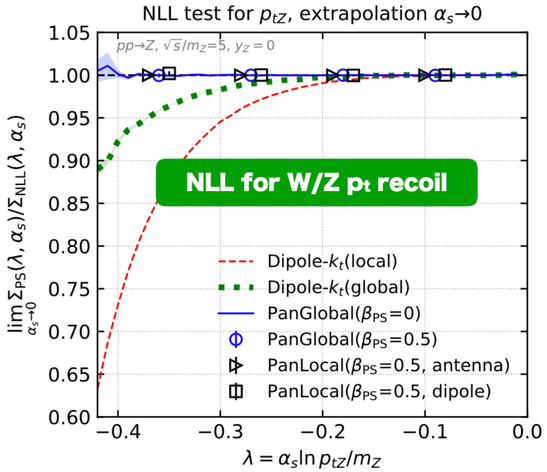
Precision calculations for the LHC

Fully exclusive simulations



In QCD every gluon emission creates a new dipole with a smaller opening. Angular ordering of the soft radiation. Finally leading to color-connected cluster of low virtuality that can fragment into hadrons. DGLAP resummation+angular ordering allows collinear and soft resummation.

All current PS implementations are formally at LL accuracy (with several improvements towards NLL). Moving them to NLL has been proven a formidable challenge. Needs to account subheading effects in the logs and in color.



and much more, e.g.

- conceptually, practically simple soft spin correlations (Hamilton, Karlberg, GPS, Scyboz, Verheyen 2111.01161)
- calculations for steps beyond NLL
  - collinear splitting: Dasgupta, El Menoufi@ICHEP, 2109.07496;
  - subleading non-global logs: Banfi, Dreyer, Monni, 2111.02413; NNDL
  - multiplicity at NNDL: Medves@ICHEP, Soto-Ontoso, Soyez, 2111.02413
- phenomenological use (a year or two away)

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[M. Dasgupta et al. 2002.11114] [K. Hamilton et al. 2011.10054]

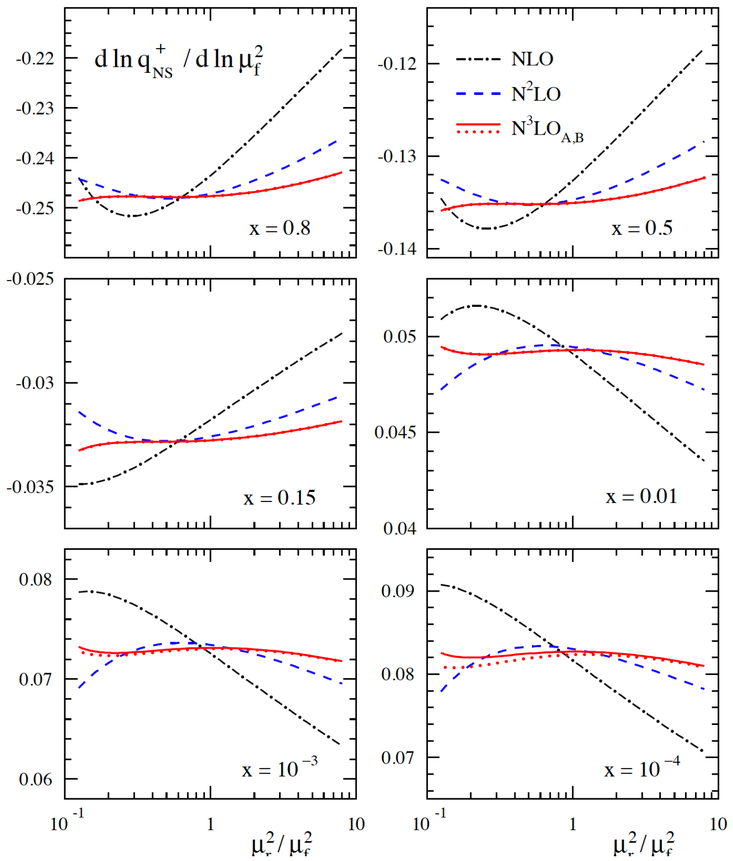
Systematic explorations are on-going and very promising.

[Nagy and Soper 2011.04773, 2011.04777]

[Forshaw et al. 2003.06400]

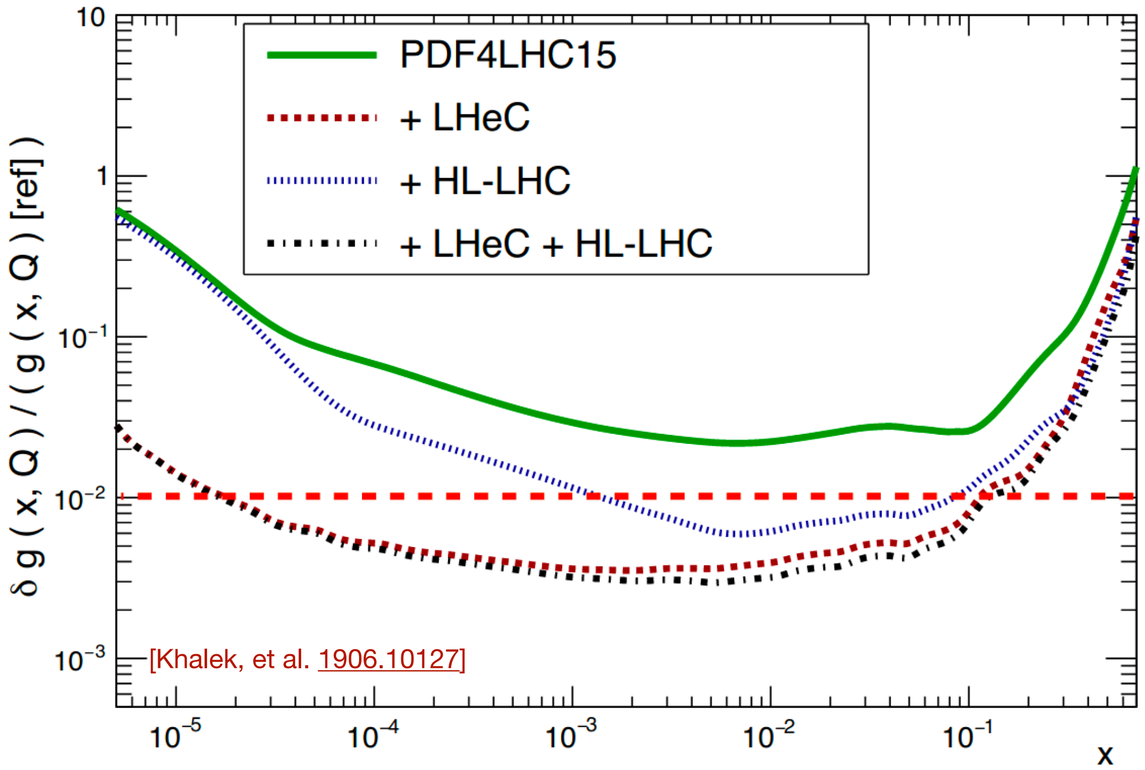
Precision calculations for the LHC

Status: PDF's



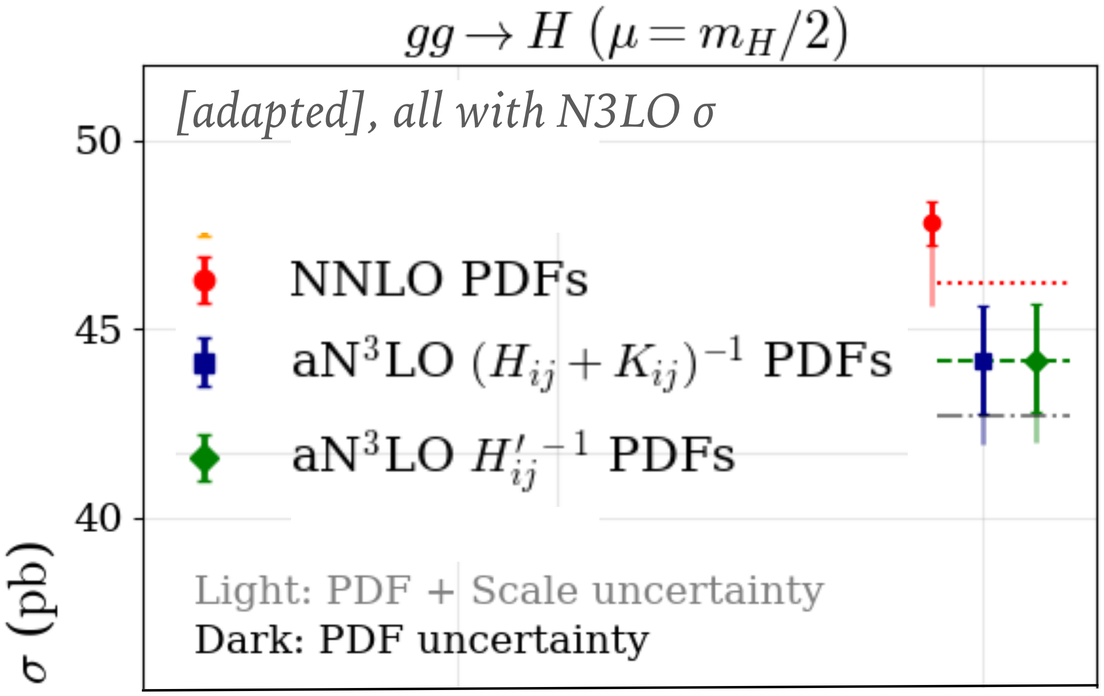
[Moch et al. , 1707.08315]

- Complete N3LO PDF's evolution not available yet. Non-singlet evolution available at 4 loops already.
- Error budget with many sources. MHO uncertainties yet to be included in the final assessment.
- Reaching 1% will be very challenging.
- Room for a breakthrough from lattice?



Precision calculations for the LHC

Status: PDF @ N3LO



[J. McGowan et al 2207.04738]

σ order	PDF order	σ (pb) + $\Delta\sigma_+ - \Delta\sigma_-$ (%)
		PDF uncertainties
N^{3}LO	aN^{3}LO (no theory unc.)	44.164 + 3.03% - 3.13%
	aN^{3}LO $(H_{ij} + K_{ij})$	44.164 + 3.34% - 3.15%
	aN^{3}LO (H'_{ij})	44.164 + 3.43% - 3.07%
	NNLO	47.817 + 1.17% - 1.22%

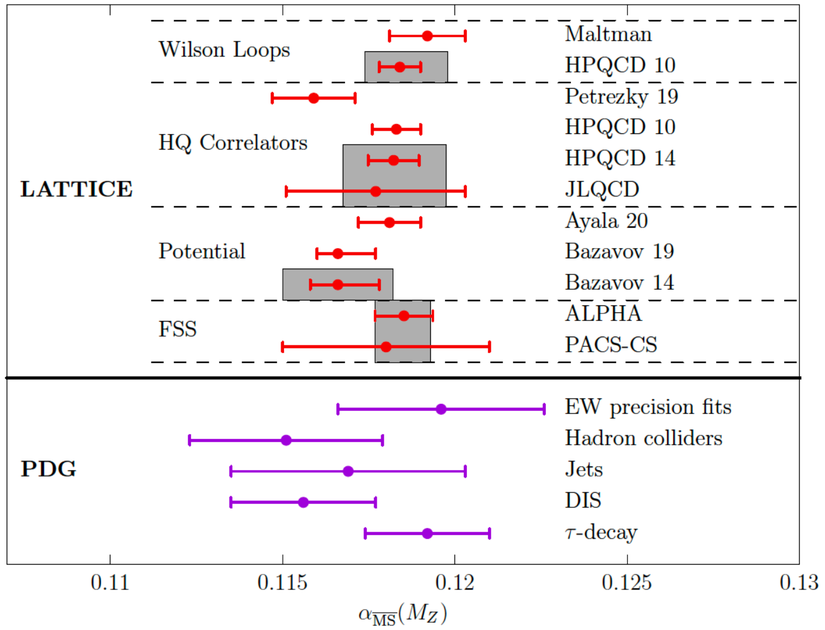
- Includes approximations and data-driven fits to N3LO parts that are current unwon
- Sizeable decrease in Higgs cross sections (~8%)
- Leads to a larger uncertainties in the PDF

Contribution to: 2022 Snowmass Summer Study e-Print: 2203.08271 [hep-ph]
Contribution to: 2022 Snowmass Summer Study e-Print: 2203.13923 [hep-ph]

The lattice frontier

α_S and PDF's

Lattice determinations of the strong coupling [Del Debbio and A. Ramos e-Print: 2101.04762]

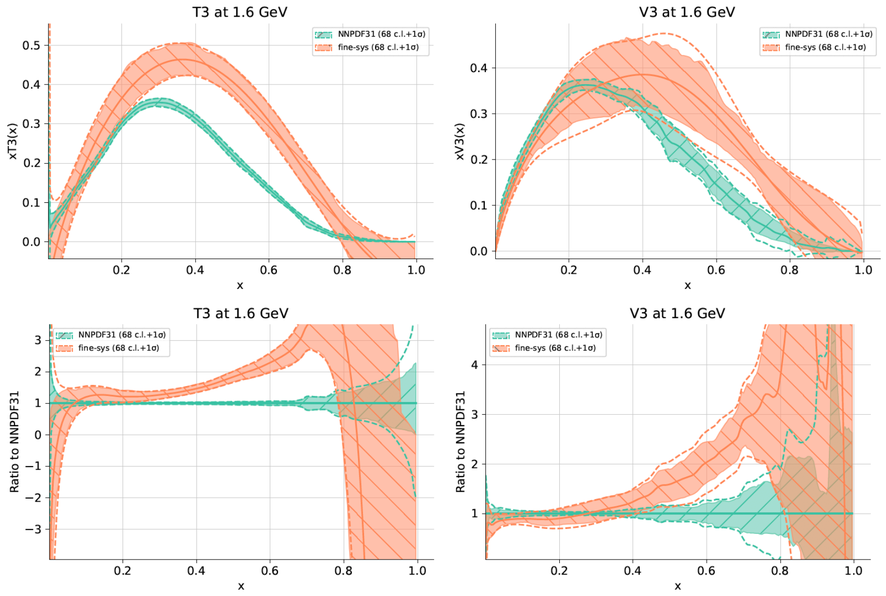


$$P(Q) = \sum_{k=0}^{n} c_k(s)\alpha_{\overline{\rm MS}}^k(\mu) + \mathcal{O}(\alpha_{\overline{\rm MS}}^{n+1}(\mu)) + \mathcal{O}\left(\frac{\Lambda^p}{Q^p}\right), \qquad (s = \mu/Q).$$

MHO PC

Using Lattice QCD, one can combine input from well-measured QCD quantities -- like for example the proton mass, or a meson decay constant -- with the perturbative expansion of a short distance observable that does not need to be directly observable (like the quark anti-quark force). The advantage of this approach is that the experimental input comes from the hadron spectrum with a negligible uncertainty.

Parton Distribution Functions from Ioffe Time Pseudodistributions from Lattice Calculations: Approaching the Physical Point [Bálint Joó et al. : 2004.01687]
Neural-network analysis of Parton Distribution Functions from Ioffe-time pseudodistributions [L. Del Debbio et al. 2010.03996]



$V_3(x) = u(x) - \bar{u}(x) - [d(x) - \bar{d}(x)]$
$T_3(x) = u(x) - \bar{u}(x) + [d(x) - \bar{d}(x)]$

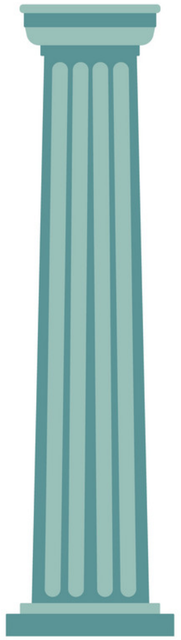
$$\mathfrak{M}(\nu, z_3^2) = \int_{-1}^{1} dx\, C(x\nu, \mu^2 z_3^2)\, f(x, \mu^2) + \mathcal{O}(z_3^2\Lambda^2)$$

$$C(\xi, \mu^2 z_3^2) = e^{i\xi} - \frac{\alpha_s}{2\pi} C_F \int_0^1 dw \left[\frac{1+w^2}{1-w}\log\left(z_3^2\mu^2\frac{e^{2\gamma_E+1}}{4}\right) + 4\frac{\log(1-w)}{1-w} - 2(1-w)\right]_+ e^{i\xi w} + \mathcal{O}(\alpha_s^2)$$

This formula allows to relate collinear PDFs to quantities which are computable in lattice QCD simulations, through a factorized expression similar to those relating collinear PDFs to physical cross sections.It can be used in a fitting framework, to extract PDFs from lattice data, performing the same kind of analysis which is usually done when considering experimental data.

Precision calculations for the LHC

CC#2 : Reach the 1% goal by the start of the HL-LHC

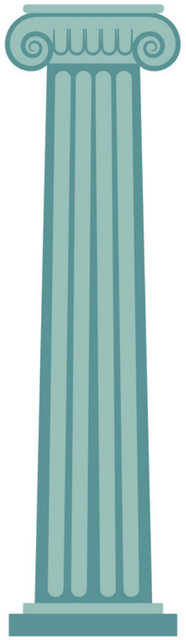


Fixed Order

LO, NLO,…

QCD/EW

- Very fast progress in conceptual as well as technical aspects.
- Tight and consolidated community, with high momentum.
- Considering the status of 20 years ago seems clear that NNLO will be completed and N3LO will start to become available for 2→2 (see 3-loop $q\bar{q} \to \gamma\gamma$ results)
- Mixed QCD-EW being included.

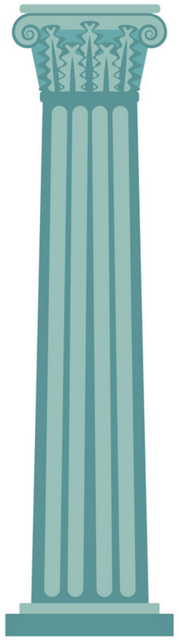


Resum

LL, NLL,…

PS

- A variety of approaches available, both analytical and numerical.
- Analytically historically matching the FO accuracy.
- NNLO+PS will be the new standard. (N3LO+PS already being explored)
- Having a NLL and beyond PS, is being explored now. To be seen.
- Not clear whether one can reach 1%.



PDF's

LO,NLO,..

Fits

- Complete N3LO PDF's evolution not available yet.
- PDF determination from fitting large set of data. Final quality depends on measurements.
- Error budget with many sources. MHO uncertainties yet to be included in the final assessment.
- Reaching 1% will be very challenging.
- Room for a breakthrough from lattice.

Precision calculations for the LHC

What about New Physics?

- Precision predictions for popular (SUSY) BSM scenarios have been made available over the years.
- As the BSM options proliferate, automatic methods to compute at least NLO corrections have been used.
- In any case, the generic rationale is that they are not needed for discovery (don’t change the sensitivity) but only in the limit setting.
- Are there significant exceptions?

Searching for new interactions with an EFT

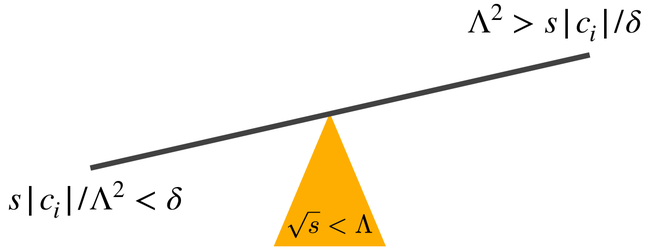
A simple approach

One can satisfy all the previous requirements, by building an EFT on top of the SM that respects the gauge symmetries:

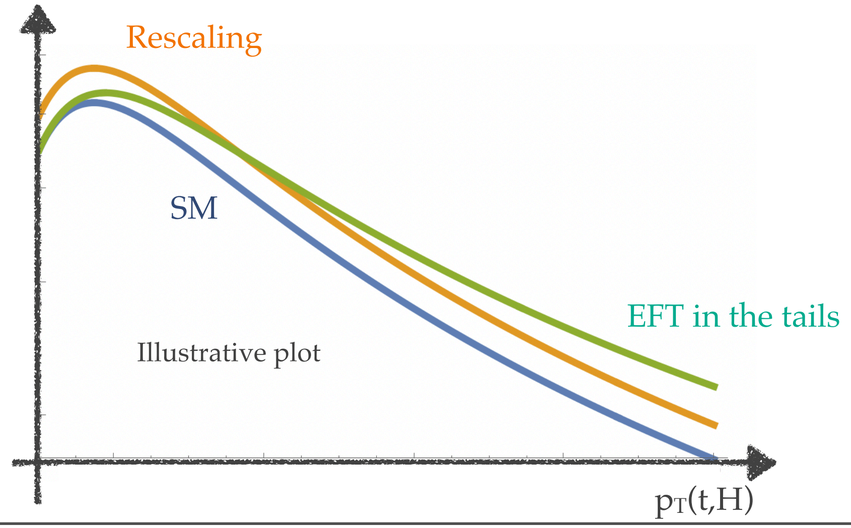
$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \dots$$

With the "only" assumption that all new states are heavier than energy probed by the experiment $\sqrt{s} < \Lambda$.

The theory is renormalizable order by order in $1/\Lambda$, perturbative computations can be consistently performed at any order, and the theory is predictive, i.e., well defined patterns of deviations are allowed, that can be further limited by adding assumptions from the UV. Operators can lead to larger effects at high energy (for different reasons).



Energy helps precision



* Sufficiently weakly interacting states may also exist without spoiling the EFT.

Restyling the SM

SM 1967

SM(EFT) 2020

Searching for new interactions with an EFT

Interpretation needs precision

The master equation of an EFT approach has three key elements:

$$\Delta \mathrm{Obs}_n = \mathrm{Obs}_n^{\mathrm{EXP}} - \mathrm{Obs}_n^{\mathrm{SM}} = \frac{1}{\Lambda^2} \sum_i a_{n,i}^{(6)}(\mu)\, c_i^{(6)}(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Most precise EFT predictions

Most precise SM predictions for observables:
NLO, NNLO, N3LO…

Most precise/accurate experimental measurements with uncertainties and correlations

Searching for new interactions with an EFT

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Most precise EFT predictions

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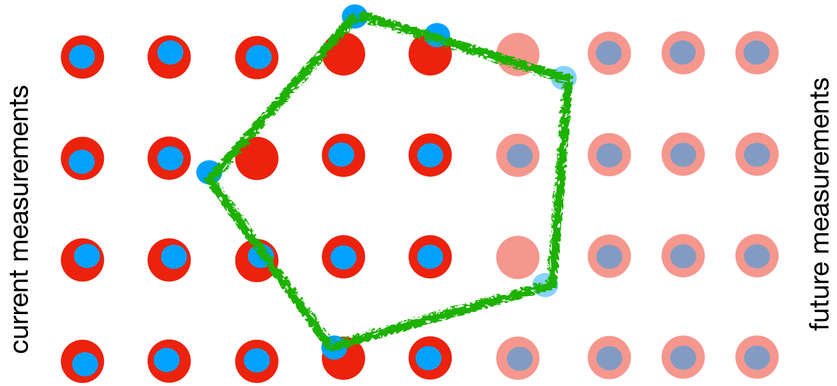
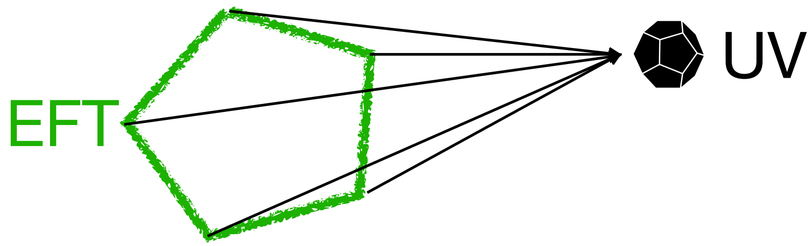


⇒ increased NP Sensitivity

⇒ increased UV identification power

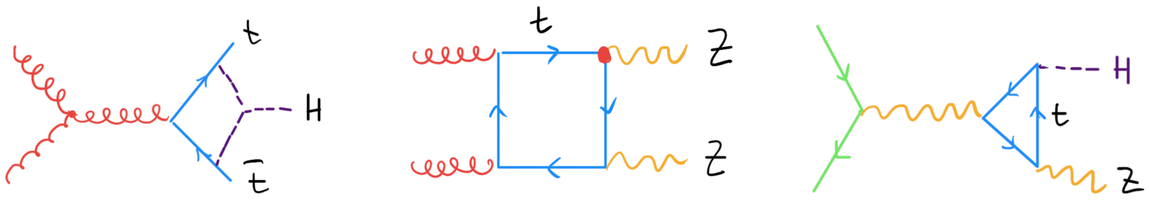


Searching for new interactions with an EFT

Progress in SMEFT at 1-loop level

1-loop accuracy allows:

- Unveil the SMEFT structure (mixing)
- K-factors (accuracy)
- Scale uncertainties (precision)
- Exploit loop sensitivity:



"same strategy" as in SM@dim4

RGE
· Anomalous dimension matrix [Jenkins, Manohar and Trott, 2013,2014,2014]

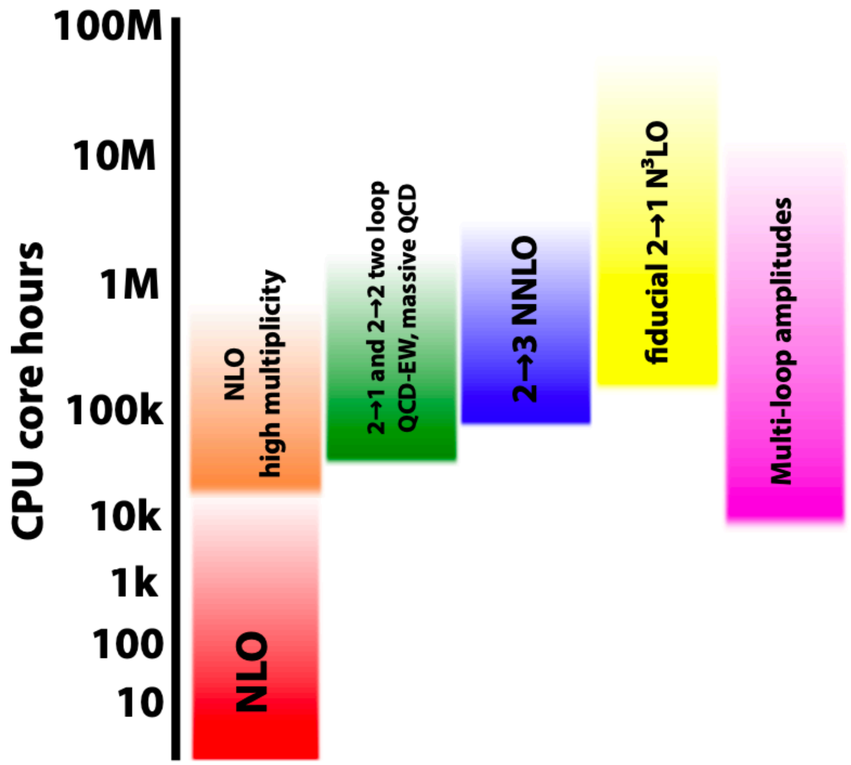
Production
· pp→jj (4F) [Gao, Li, Wang, Zhu, Yuan, 2011]
· pp→tt (4F) [Shao, Li, Wang, Gao, Zhang, Zhu, 2011]
· pp →VV [Dixon, Kunszt, Signer ,1999] [Melia, Nason, Röntsch, Zanderighi ,2011] [Baglio, Dawson, Lewis ,2017,2018,2019][Chiesa et al., 2018]
· top FCNCs [Degrande, FM, Wang, Zhang ,2014] [Durieux, FM, Zhang ,2014]
· pp →tt (chromo) [Franzosi, Zhang ,2015]
· pp →tj [Zhang ,2016] [de Beurs, Laenen, Vreeswijk, Vryonidou ,2018]
· pp → ttZ [Rontsch and Schulze,2015] [Bylund, FM, Tsinikos, Vryonidou, Zhang ,2016]
· pp → ttH [FM, Vryonidou, Zhang ,2016]
· pp →HV,Hjj [Greljo, Isidori, Lindert, Marzocca, 2015][Degrande, Fuks, Mawatari, Mimasu, Sanz ,2016], [Alioli, Dekens, Girard, Mereghetti ,2018]
· pp→H [Grazzini, Ilnicka, Spira, Wiesemann ,2016] [Deutschmann, Duhr, FM, Vryonidou ,2017]
· pp → tZj,tHj [Degrande, FM, Mimasu, Vryonidou, Zhang ,2018]
· pp → jets [Hirschi, FM, Tsinikos, Vryonidou ,2018]
· pp → VVV [Degrande, Durieux, FM, Mimasu, Vryonidou, Zhang, 20xx]
· gg → ZH,Hj,HH [Bylund, FM, Tsinikos, Vryonidou, Zhang ,2016]
· Higgs self-couplings [McCullough, 2014][Degrassi, Giardino, FM, Pagani, Shivaji, Zhao, 2016-2018][Borowka et al. 2019][FM,Pagani, Zhao, 2019]
· EW loops in tt [Kuhn et al.,1305.5773], [Martini 1911.11244]
· EW top loops in Higgs & EW [Vryonidou, Zhang ,2018][Durieux, Gu, Vryonidou, Zhang ,2018] [Boselli et al. 2019]
· Drell-Yan (EW corrections) [Dawson and Giardino, 2021]

Decay
· Top [Zhang ,2014] [Boughezal, Chen, Petriello, Wiegand ,2019]
· h → VV [Hartmann, Trott ,2015] [Ghezzi, Gomez-Ambrosio, Passarino, Uccirati ,2015, 2015] [Dawson, Giardino ,2018,2018][Dedes, et al. ,2018] [Dedes, Suxho, Trifyllis ,2019]
· h → ff [Gauld, Pecjak, Scott ,2016] [Cullen, Pecjak, Scott ,2019][Cullen, Pecjak, ,2020]
· Z,W [Hartmann, Shepherd, Trott ,2016] [Dawson, Ismail, Giardino ,2018,2018,2019]

EWPO
· EWPO [Zhang, Greiner, Willenbrock '12] [Dawson, Giardino ,2020]

Precision calculations for the LHC

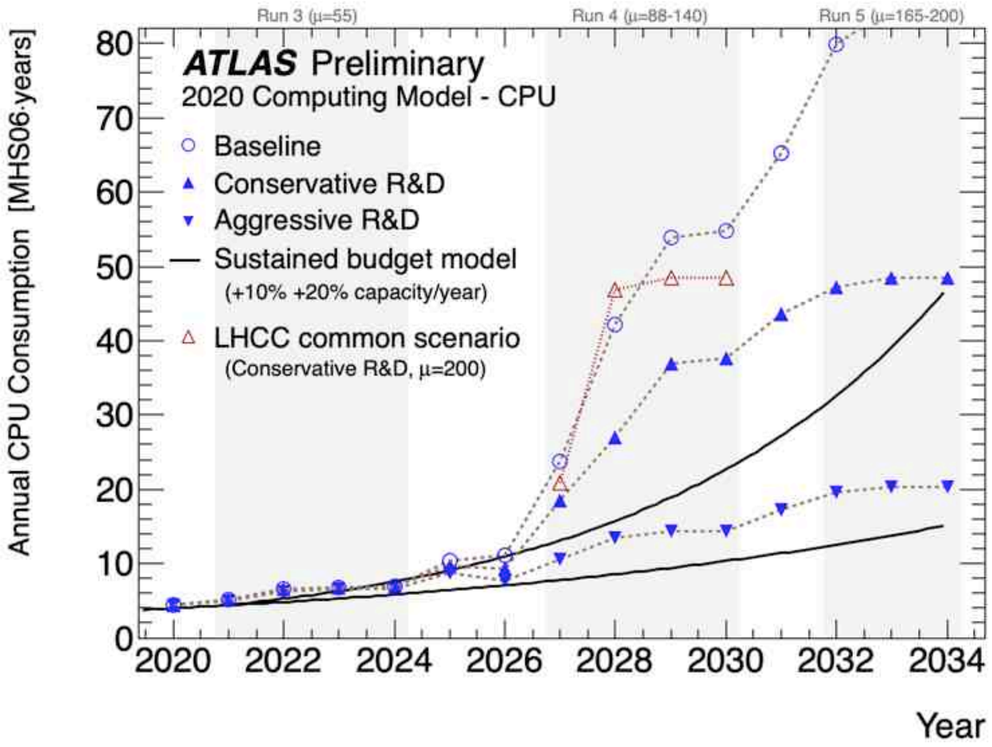
Computing needs

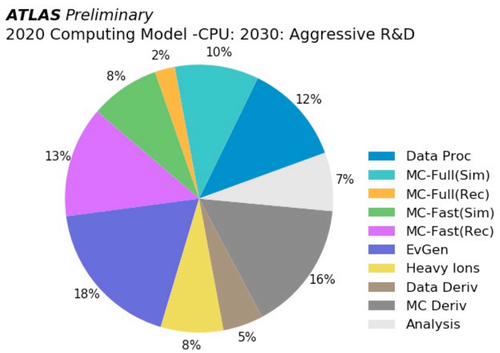


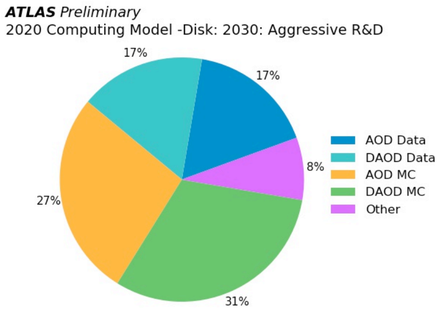
Higher precision ⇒ more computing and (memory) storage

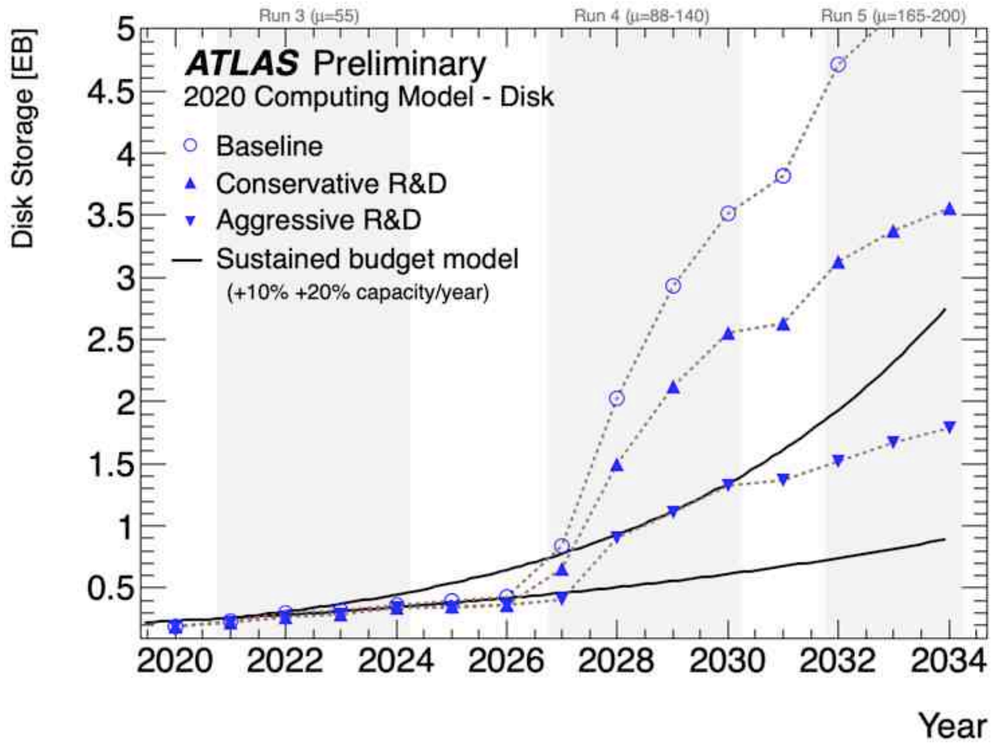
Precision calculations for the LHC

Computing needs







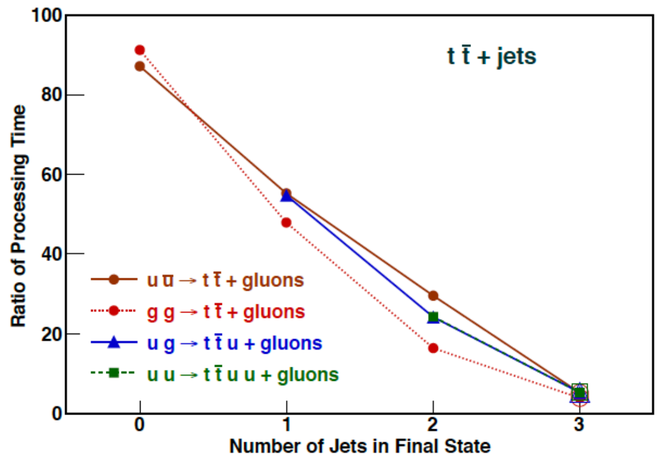


CC#3: develop tools that can provide all the necessary predictions/simulations within the planned computing and storage resources.

Computational opportunities

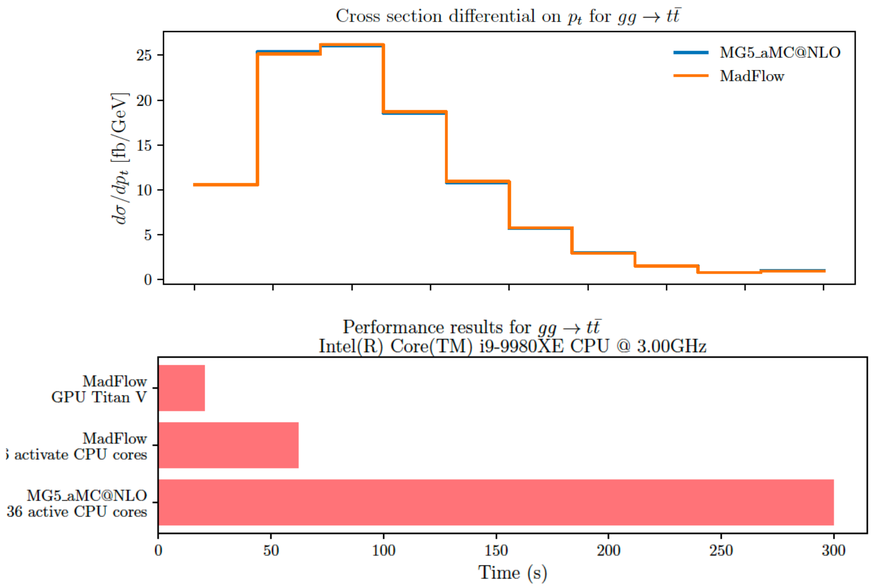
New architectures

MadGraph on GPUs 2013



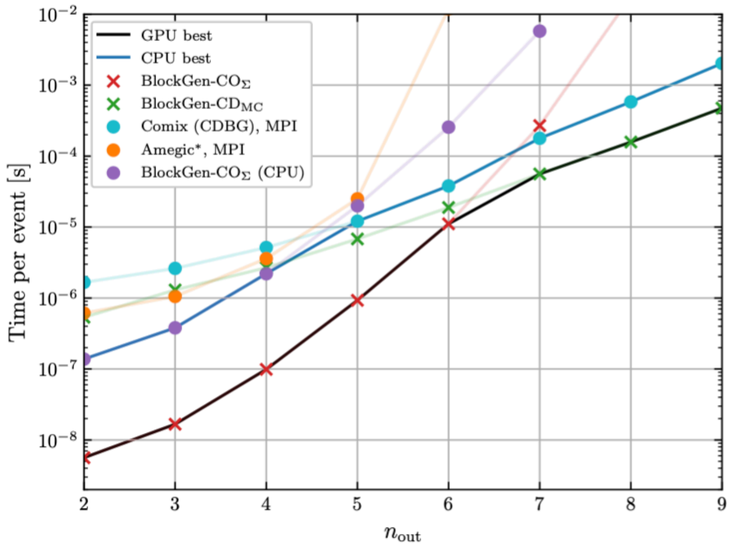
[Hagiwara et al. , 1305.0708]

MadGraph



[S. Carrazza et al. , 2105.10529]

Comix/Amegic on GPUs



[E. Bothmann, et al. 2106.06507]

Proof of principle implementation based on CUDA and first GPUs. Memory constraints, large color matrices → huge gains but scaling with # extra partons bad…

Modern approach based on new architectures,

Computational opportunities

Machine Learning techniques

A survey of machine learning-based physics event generation

[Y. Alanazi, et al. 2106.00643]

Understanding Event-Generation Networks via Uncertainties

[M. Bellagente et al 2104.04543]

Phase Space Sampling and Inference from Weighted Events with Autoregressive Flows

[B. Stienen et al. , 2011.13445]

i-flow: High-dimensional Integration and Sampling with Normalizing Flows

[Christina Gao et al. 2001.05486]

How to GAN Event Unweighting

[M. Backes et al. : 2012.07873]

Generative Networks for LHC events

[Anja Butter and Plehn 2008.08558]

Invertible Networks or Partons to Detector and Back Again

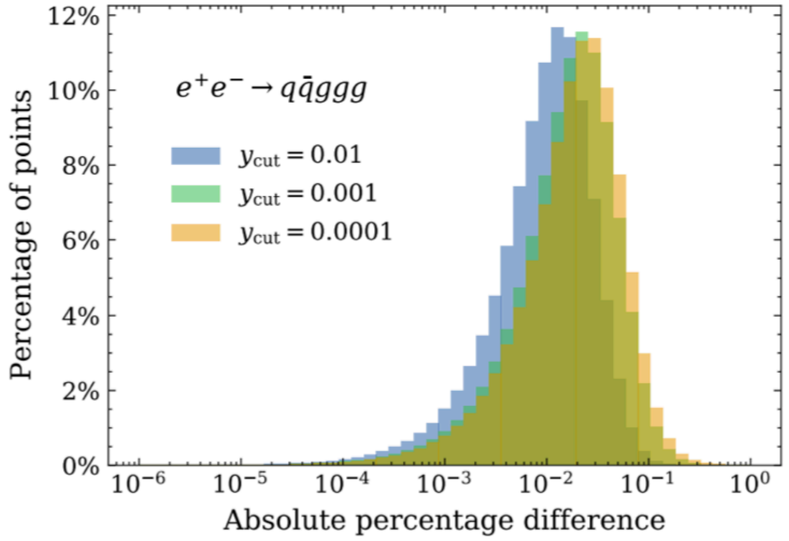
[M. Bellagente et al. e-Print: 2006.06685]

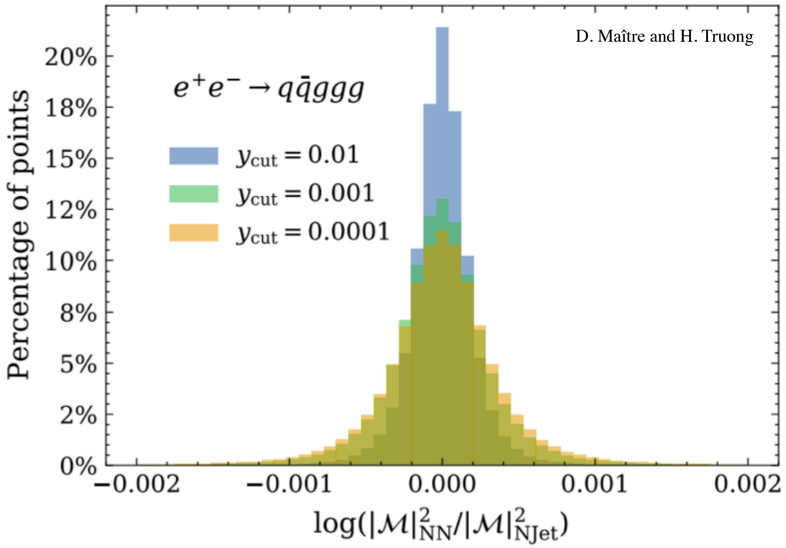
How to GAN away Detector Effects

[M. Bellagente et al, 1912.00477]

How to GAN LHC Events

Anja Butter et al. 1907.03764 [hep-ph]





Impressive progress in the exploration of different methods and in identifying the most relevant questions in last few years!

- Can the ML-MC go beyond the statistical precision of the training event samples?
- Can they faithfully reproduce the physics?
- Can they provide new physics insights?

Computational opportunities

Quantum Computing

Growing interest in quantum computations for HEP:

Quantum Algorithm for High Energy Physics Simulations
[C. W. Bauer et al. 1904.03196]

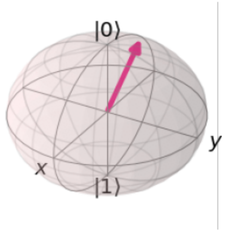
Quantum Algorithms for Jet Clustering
Annie Y. Wei et al. 1908.08949 [hep-ph]

Towards a quantum computing algorithm for helicity amplitudes and parton showers
Khadeejah Bepari et al. 2010.00046 [hep-ph]

Determining the proton content with a quantum computer
Adrián Pérez-Salinas et al. 2011.13934

Simulating collider physics on quantum computers using effective field theories
C. W. Bauer et al. 2102.05044 [hep-ph]

Quantum algorithm for Feynman loop integrals
Selomit Ramírez-Uribe et al. 2105.08703

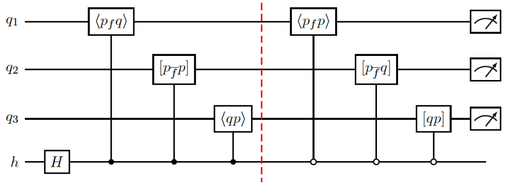


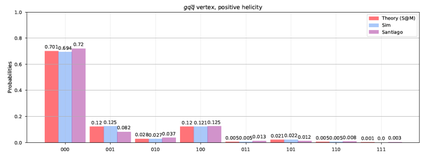
$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle = \begin{pmatrix}\cos\frac{\theta}{2}\\ \sin\frac{\theta}{2}e^{i\phi}\end{pmatrix},$$

(a) $|p\rangle^{\dot{a}}$

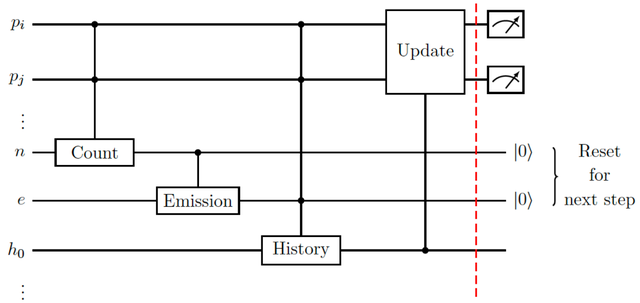
sum over helicities

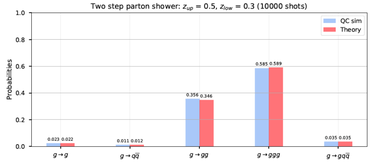
$$\mathcal{M}_+ = -\sqrt{2}\frac{\langle p_f q\rangle[p_{\bar{f}} p]}{\langle qp\rangle}, \qquad \mathcal{M}_- = -\sqrt{2}\frac{\langle p_f p\rangle[p_{\bar{f}} q]}{[qp]}.$$





sum over PS histories





Computational opportunities

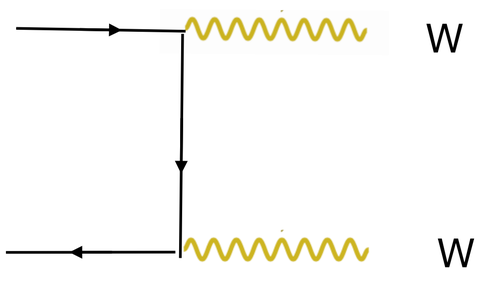
Considerations

- Serious computational bottleneck ahead of us for HL-LHC
- Many really new ideas being explored
- Having an ambitious objective to estimate the gap might help:

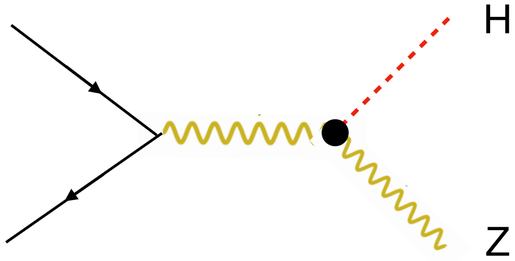
Achieve real-time event simulation

Precision calculations for EW.H.T factories

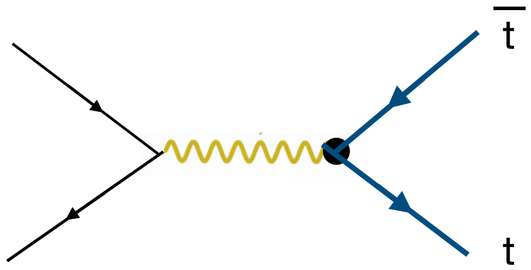
The workhorses



Known at NLO in EW with W decays. In order to determine mW at 1 MeV needs to be known at the subpermill level. NNLO EW computation involves many scales. In addition an EFT treatment of the W threshold is necessary.



Workhorse for H studies. Known at NLO in EW with Z decays. NNLO correct. Gives access to trilinear and top-Yukawa at one loop and quadrilinear Higgs self-couplings and others at two loops.



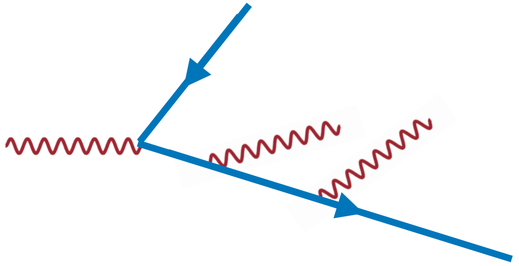
Known at N3LO in the NRQCD EFT approach at threshold for top mass and width determination. NLO QCD corrections for the 2->6 known. NNLO EW corrections are not known.

In addition ISR effects, collinear and soft need to be included.

Contribution to: 2022 Snowmass Summer Study: e-Print:2203.12557 [hep-ph]
Contribution to: 2022 Snowmass Summer Study, e-Print: 2203.06799 [hep-ph]

Precision calculations for EW.H.T factories

QED showers



In QED the charges are scalars. No flows! -Qi * Qj can be negative emission of a photon is independent from the others and the dipole does not change. Interleaving with the much more probable QCD radiation in the case of quarks is a challenge.

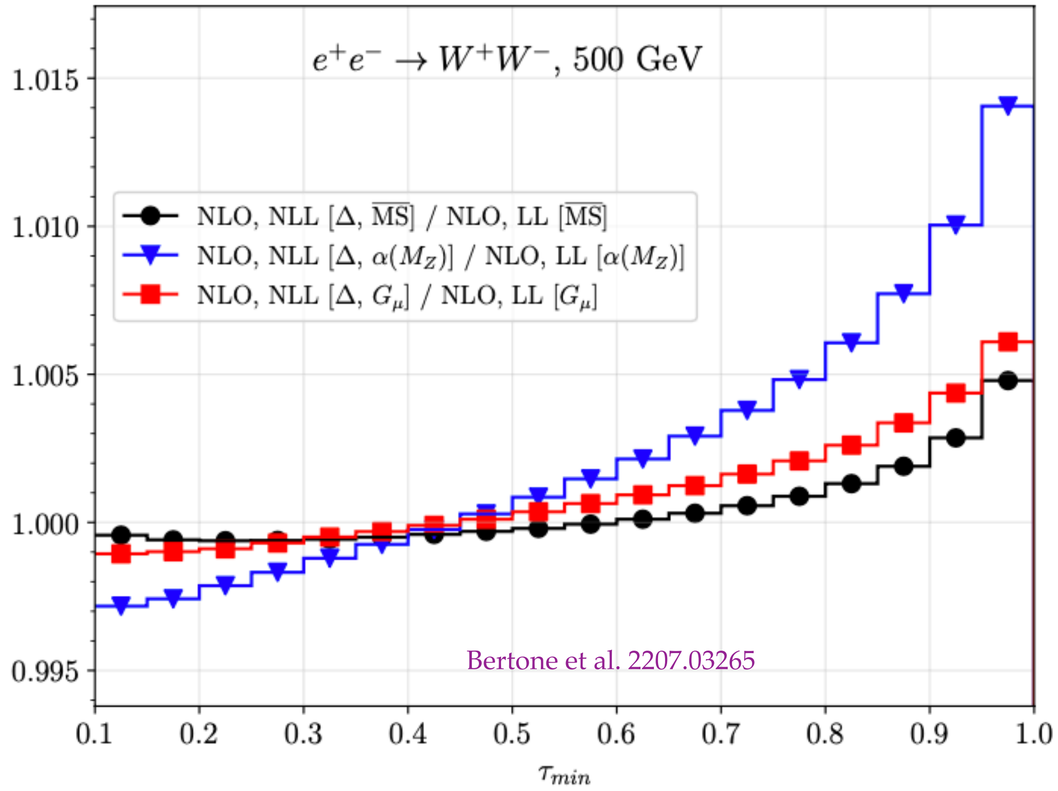
However, YFS Soft resummation provides a way to resum soft contributions

$$\mathrm{d}\sigma = \sum_{n_\gamma=0}^{\infty} \frac{1}{n_\gamma!} \mathrm{d}\Phi_Q \left[\prod_{i=1}^{n_\gamma} \mathrm{d}\Phi_i^\gamma\right] (2\pi)^4 \delta^4\left(\sum_{\text{in}} q_{\text{in}} - \sum_{\text{out}} q_{\text{out}} - \sum_{i=1}^{n_\gamma} k_i\right) \left| \sum_{n_\gamma^V=0}^{\infty} \mathcal{M}_{n_\gamma}^{n_\gamma^V+\frac{1}{2}n_\gamma} \right|^2 .$$

$$\mathrm{d}\sigma = \sum_{n_\gamma=0}^{\infty} \frac{e^{Y(\Omega)}}{n_\gamma!} \mathrm{d}\Phi_Q \left[\prod_{i=1}^{n_\gamma} \mathrm{d}\Phi_i^\gamma \, \tilde{S}(k_i)\right] \left(\tilde{\beta}_0 + \sum_{j=1}^{n_\gamma} \frac{\tilde{\beta}_1(k_j)}{\tilde{S}(k_j)} + \sum_{\substack{j,k=1 \\ j<k}}^{n_\gamma} \frac{\tilde{\beta}_2(k_j,k_k)}{\tilde{S}(k_j)\,\tilde{S}(k_k)} + \cdots\right)$$

Collinear effects captured through the residuals. Improvements necessary to also have γ to fermions splitting included at order α^2.

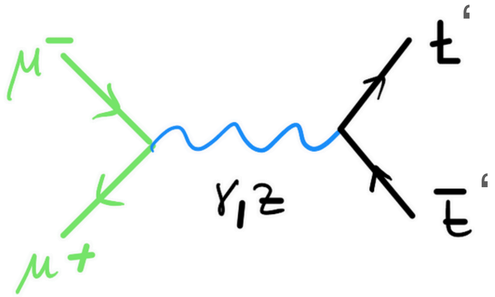
NLO+NLL vs NLO+LL



Multi-TeV lepton colliders

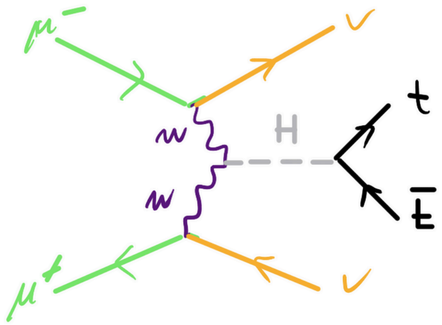
The essentials

O(10) TeV lepton-lepton collider energy allows to have **two colliders in one**:



$$\sigma_s \sim \frac{1}{s}$$

$$\sigma_s \sim \frac{1}{M^2} \log^n \frac{s}{M}$$



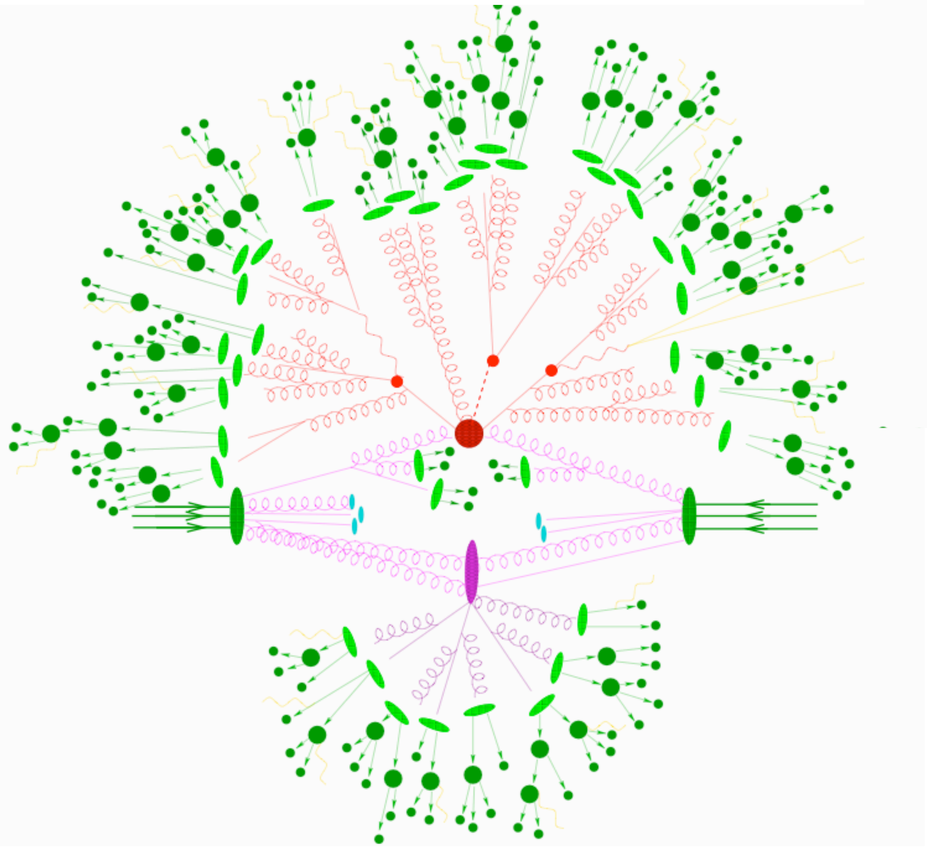
Discovery

Measurements

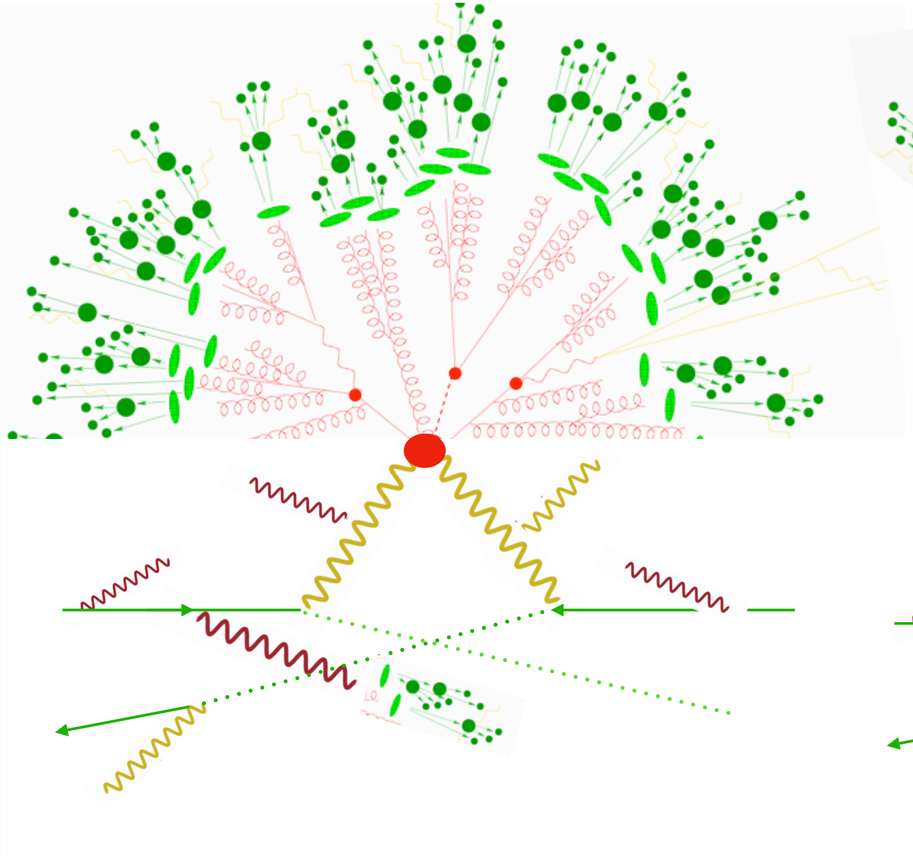
A completely new regime opening for a multi-TeV muon collider

Different physics being probed in the two channels

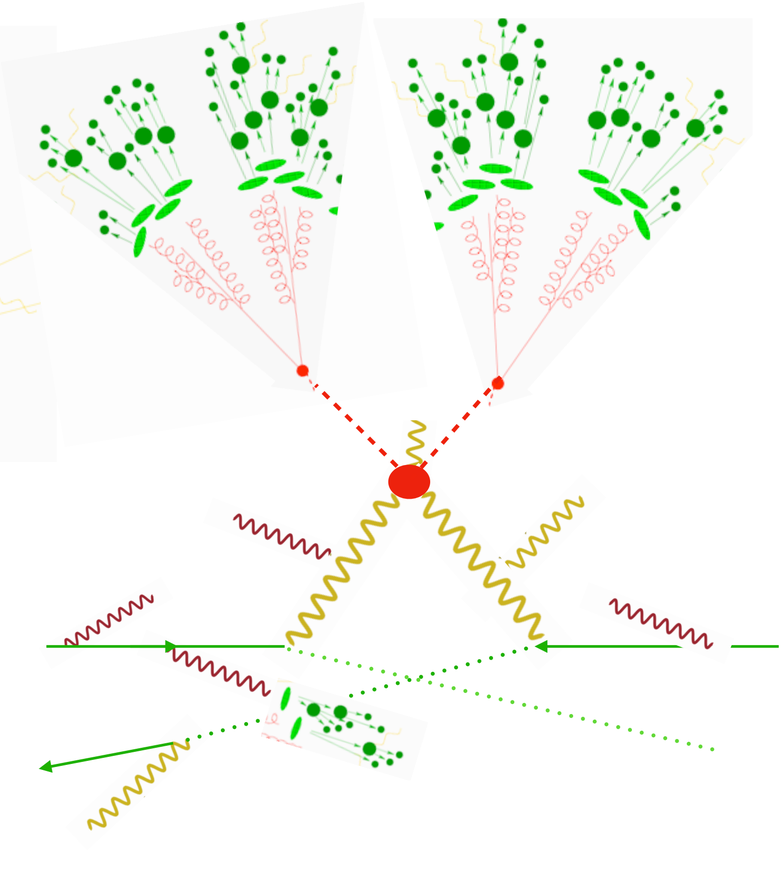
How events look in a multi-TeV lepton collider?



tth production at the LHC
(Fully hadronic)



tth production at the muC 100 TeV



HH→4b production at a multi-TeV muC

In a muon collider gluons and quarks first appear at scales of order 100 GeV in the decays of W,Z,H (from either initial state or final state radiation) or from photon splitting. Multijet final states are of EW origin.

Precision calculations for multi-TeV lepton colliders

EW resummation

$$f_B(z,\mu^2) = \sum_A \int_z^1 \frac{d\xi}{\xi} f_A(\xi) \int_{m^2}^{\mu^2} d\mathscr{P}_{A\to B+C}(z/\xi, k_T^2)$$

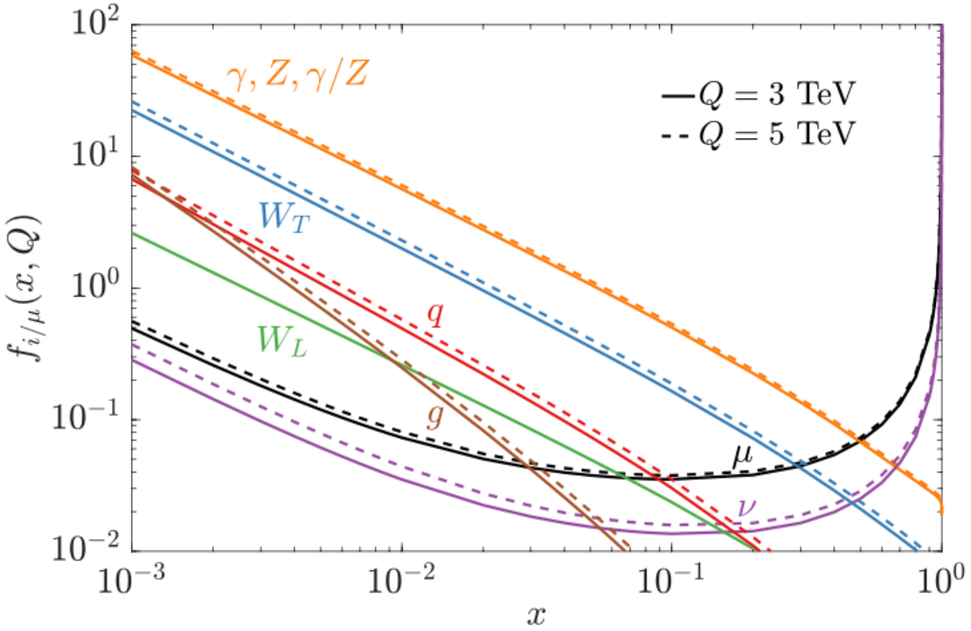
$$\frac{\partial f_B(z,\mu^2)}{\partial \mu^2} = \sum_A \int_z^1 \frac{d\xi}{\xi} \frac{d\mathscr{P}_{A\to B+C}(z/\xi,\mu^2)}{dz dk_T^2} f_A(\xi,\mu^2)$$

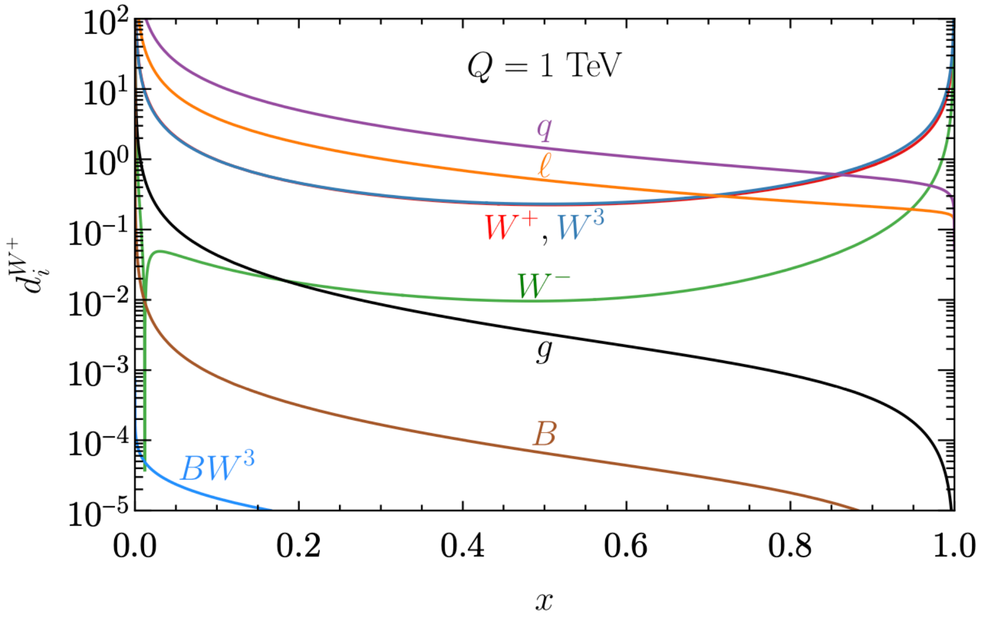
Han, Ma, Xie arXiv:2007.14300v4. 2103.09844

$$\Delta_A(t) = \exp\left[-\sum_B \int_{t_0}^t \int dz \mathscr{P}_{A\to B+C}(z)\right],$$

$$f_A(x,t) = \Delta_A(t) f_A(x,t_0) + \int_{t_0}^t \frac{dt'}{t'} \frac{\Delta(t)}{\Delta(t')} \int \frac{dz}{z} \mathscr{P}_{A\to B+C}(z) f_A(x/z,t')$$

Han, Ma, Xie rXiv:2203.11129v1





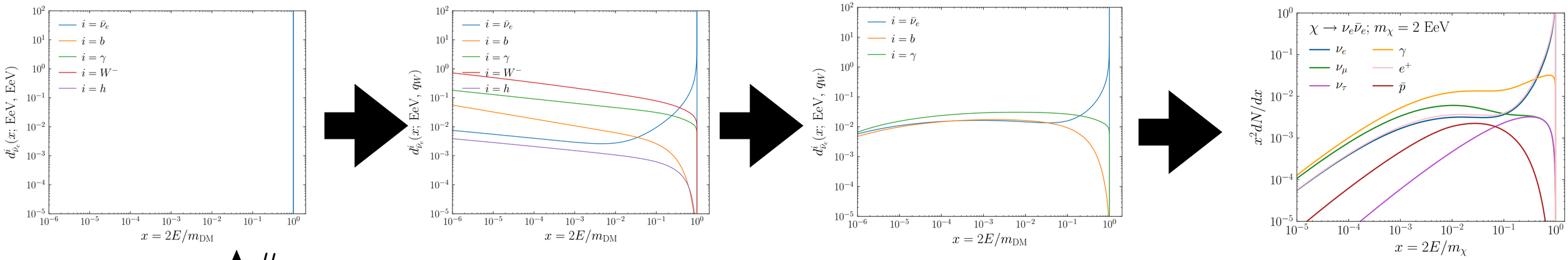
Some comments here

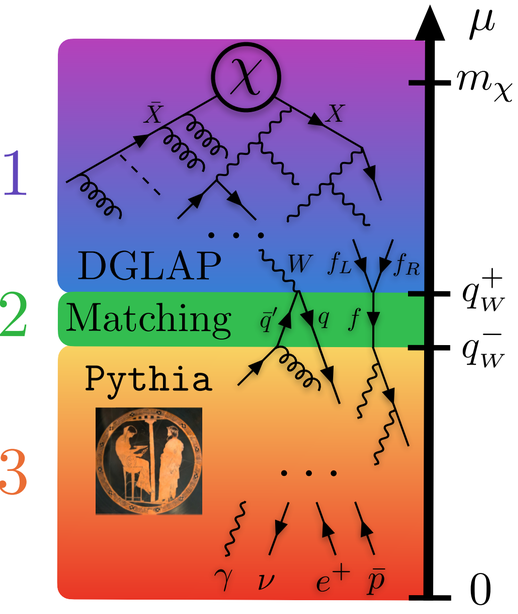
Contribution to:2022 Snowmass Summer Study e-Print: 2203.07256 [hep-ph]
Contribution to:2022 Snowmass Summer Study e-Print: 2203.06799 [hep-ph]

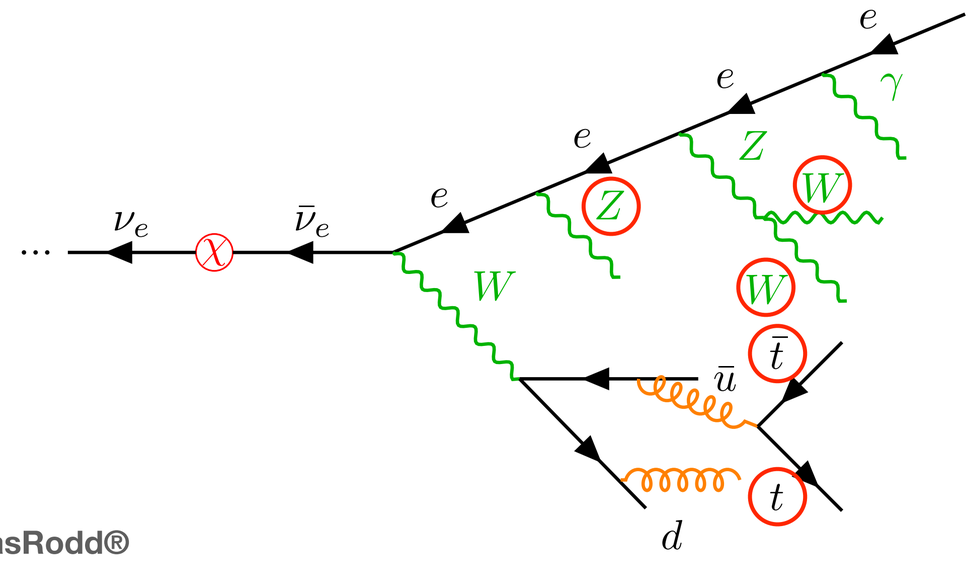
Precision calculations for multi-TeV lepton colliders

EW showers

At very high energies, E>>v, SU(2) x U(1) is restored and evolution through EW radiation will take place. The non-abelian nature of SU(2) will make a shower look more like QCD. One the scales are down to ~v EWSB effects will start to become important again.







NicolasRodd®

Evolution (EW double logs and polarisation):

- [Christiansen, Sjostrand 1401.5238]
- [Christiansen, Prestel 1510.01517]
- [Chen, Han, Tweedie 1611.00788]
- [Manohar, Waalewijn 1802.08687]
- [Bauer, Provasoli, Webber 1806.10157]
- [Bauer, Webber 1808.08831]
- [Kleiss, Verheyen, 2002.09248]
- [Bauer, Rodd, Webber 2007.15001]
- [Masouminia, Richardson, 2108.10817]
- [Brooks, Skands, Verheyen 2108.10786v2]

Computational challenges for high-energy colliders

Summary

#1: Determine the SM parameters in terms of underlying UV dynamics, and in particular the Higgs mass, which is out of control.

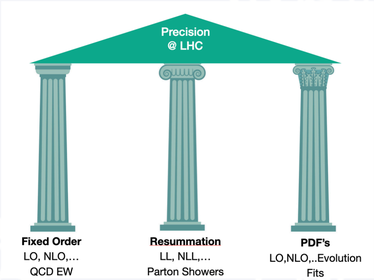
#2: Reach the 1% goal for TH predictions for pp collisions by the start of the HL-LHC.

#3: Develop MC tools that can provide all the necessary predictions/simulations within the planned computing and storage resources.

#4: Bring the TH predictions for HTE factories to the level (0.1-0.01%) necessary for perspective studies.

#5: Achieve understanding and precision predictions for SM (EW) phenomena at very high energy.

Our deep motivation



Data + computational complexity to be tamed. New technologies (ML, Quantum, GPU) to the rescue

Catch up with 20-year of TH developments after LEP

Cover physics of the SM at 100 TeV scales

Precision calculations for the HL-LHC

Goals	ETA wrt $t_{HL\text{-}LHC}$
NLO_{QCD} x NLO_{EW}	Before
NNLO EW for 2 → 2	Well before
$NNLO_{QCD}$ for (any) 2 → 3	Well before
PDF at N3LO	By
$N3LO_{QCD}$ for main 2 → 2 (loops+subtraction)	Unknown
$N4LO_{QCD}$ for candles	Unknown

Precision showering

Goals	ETA wrt to $t_{HL\text{-}LHC}$
NLL accuracy for QCD observables at pp collisions and implementation	Before
NNLO+NLL accuracy for QCD observables at hadron colliders	Before
NLO+LL with QCD+QED shower for any collider	Well before
NNLO+NLL accuracy with QCD+QED	At
LL EW Shower + Matching/merging	Well Before
NNLO+NLL Shower for lepton colliders	After