Theory Introduction

A personal perspective

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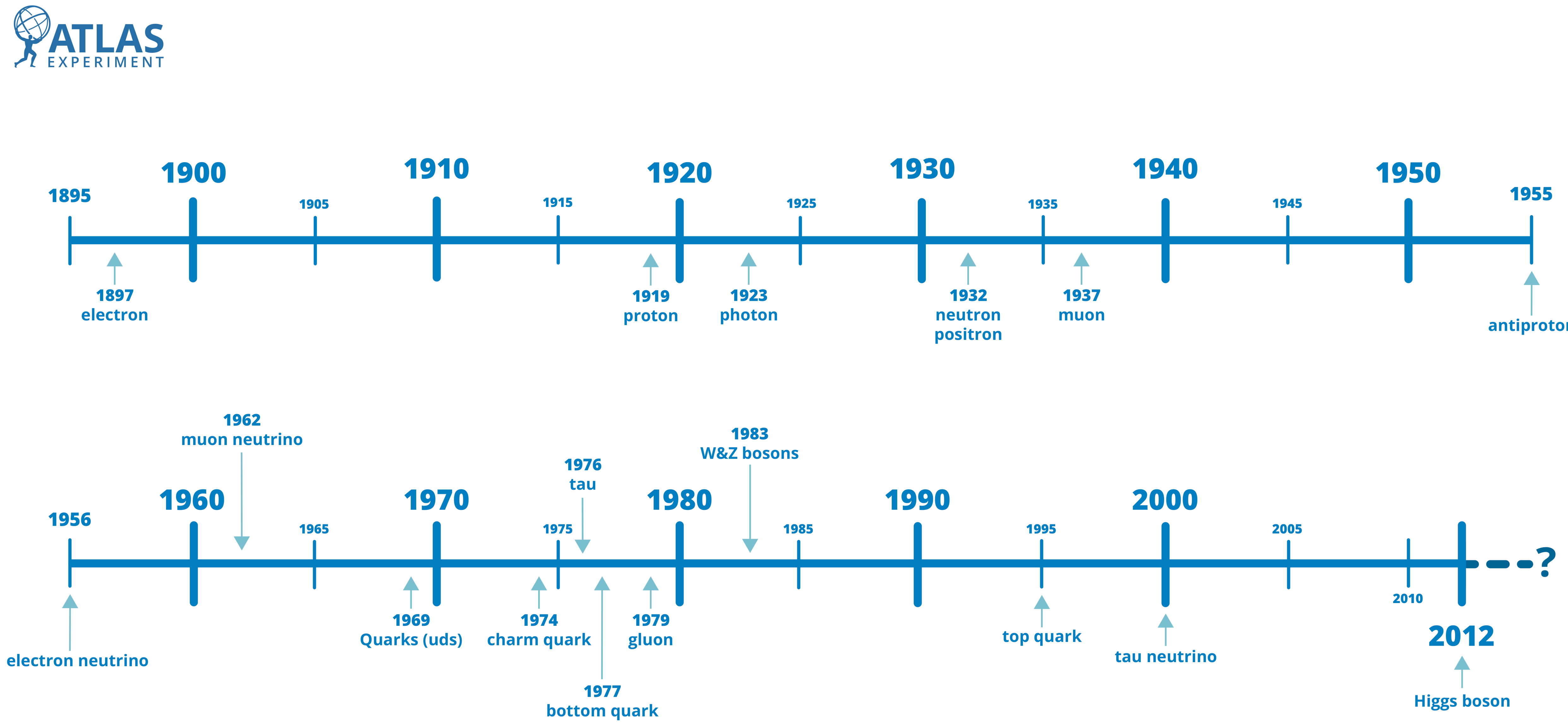
Boost 2024 — 16th International Workshop on Boosted Object phenomenology, Reconstruction, Measurements, and Searches at Colliders
Genova, July 2024

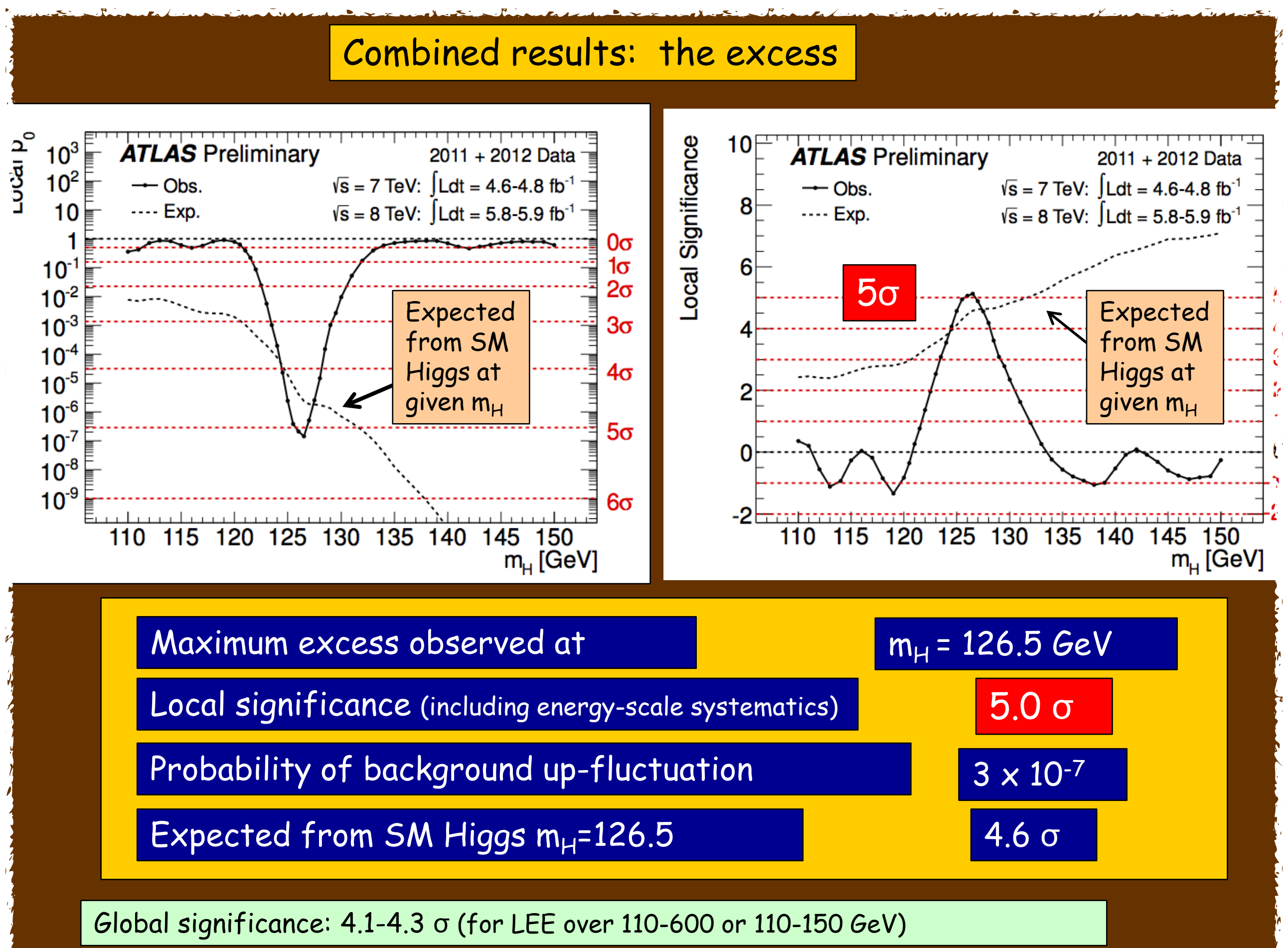
Timeline of particle discoveries



Over the last 150 years, new particles have been continually discovered, marking a triumph for particle physics made possible by the increasing support and investment in collider machines

Turning point

The discovery of the Higgs boson is a turning point. We have now a self-consistent theory that can be extrapolated to very high energies. Any new discovery of a new particle will mark the start of a new era



CERN, 4th July 2012

Other key discoveries

Discoveries are not just about new particles

A selection of other groundbreaking discoveries

- Dark matter (1930)
- Cosmic microwave background radiation (1965)
- Observational evidence for black holes (1971)
- Accelerating Universe aka dark energy (1990)
- Neutrino oscillations (1998)
- Detection of gravitational waves (2015)
- …

Many of these discoveries arose from observation, rather than being prompted by the need to address specific theoretical questions

Observational

Structural

Problems

Phenomena unaccounted for in the SM

Matter-antimatter asymmetry

Dark matter Dark energy

Why is $\theta < 10^{-10}$? $\mathcal{L} \supset \theta G_{\mu\nu}\tilde{G}^{\mu\nu}$

Axions?

Accidental symmetries and violations

Proton decay

Parity violation

Lack of calculability/stability

Flavour mass hierarchy

EW hierarchy problem

Structure of the Standard Model (SM)

Why 3 generations? Gravity?

Why $SU(3) \times SU(2) \times U(1)$?

Key theory questions

The role of theory in guiding experimental endeavours through fundamental questions remains undisputed.

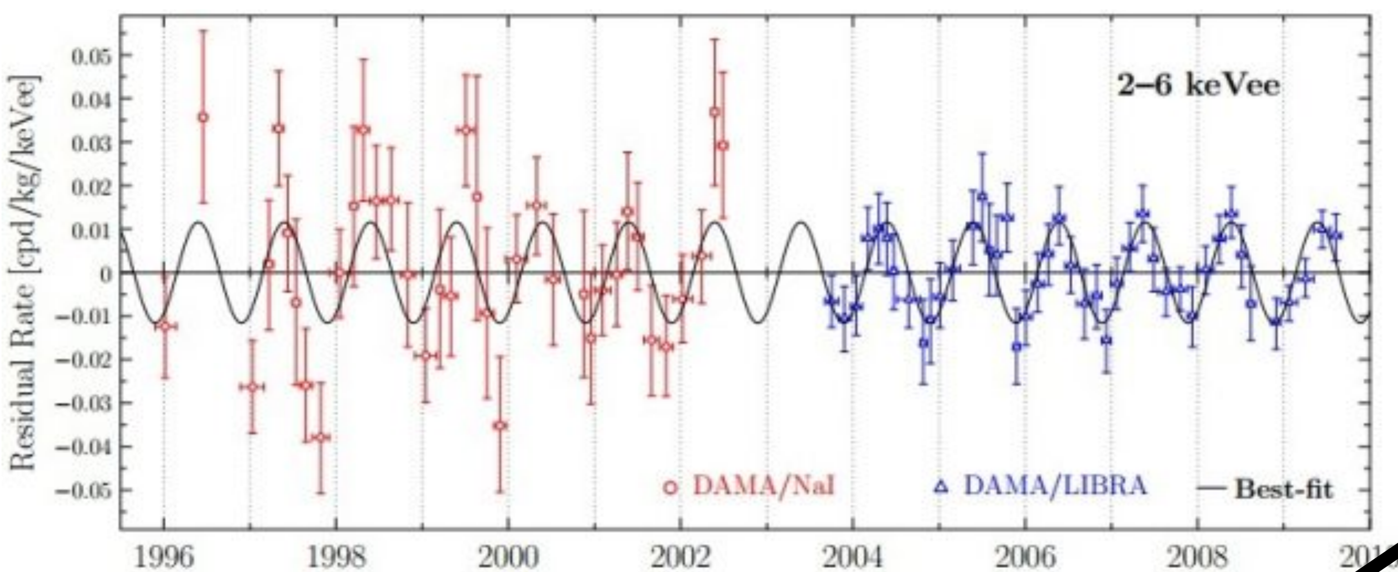
- What stabilises the Higgs mass? ATLAS, CMS …
- What solves the strong CP problem? ADMX, CAST, IAXO …
- What generated the matter-antimatter asymmetry? ALICE, Belle II, Daya Bay, LHCb, NA62, T2K, …
- What is the nature of Dark Matter? LUX, XENON, DarkSide, Super-CDMX …
- What drives the expansion of the universe? Hubble, Planck, DES, LSST …
- Is there something behind the hierarchical flavour structure? Belle II, Daya Bay, KOTO, LHCb, Mu2e, NA62, T2K, …
- …

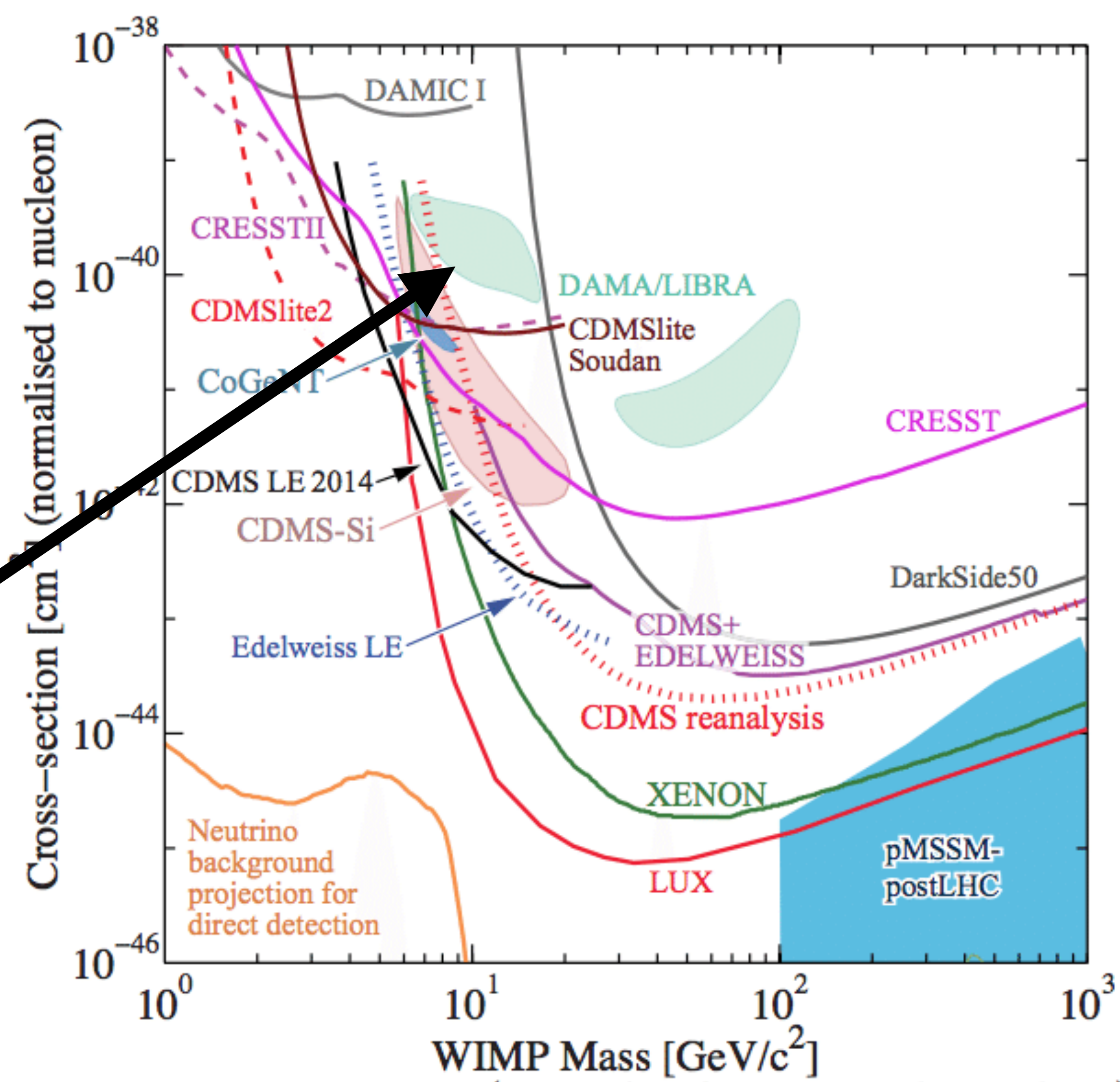
Trying to answer these theory questions has been shaping a very rich and diverse landscape of experimental activities

Experimental richness

In this landscape, the importance of diversification and redundancy in experimental activities can not be understated.

<u>Example: DAMA/LIBRA</u>





Annual modulation due to earth moving in Dark Matter background
Significance: 9-12 σ

But excluded by many other experiments

LHC & future colliders

Compared to many other experiments, colliders are multi-purpose machines. This partially lifts the responsibility of theorists to guide experimental searches

At the LHC theory plays a crucial role in

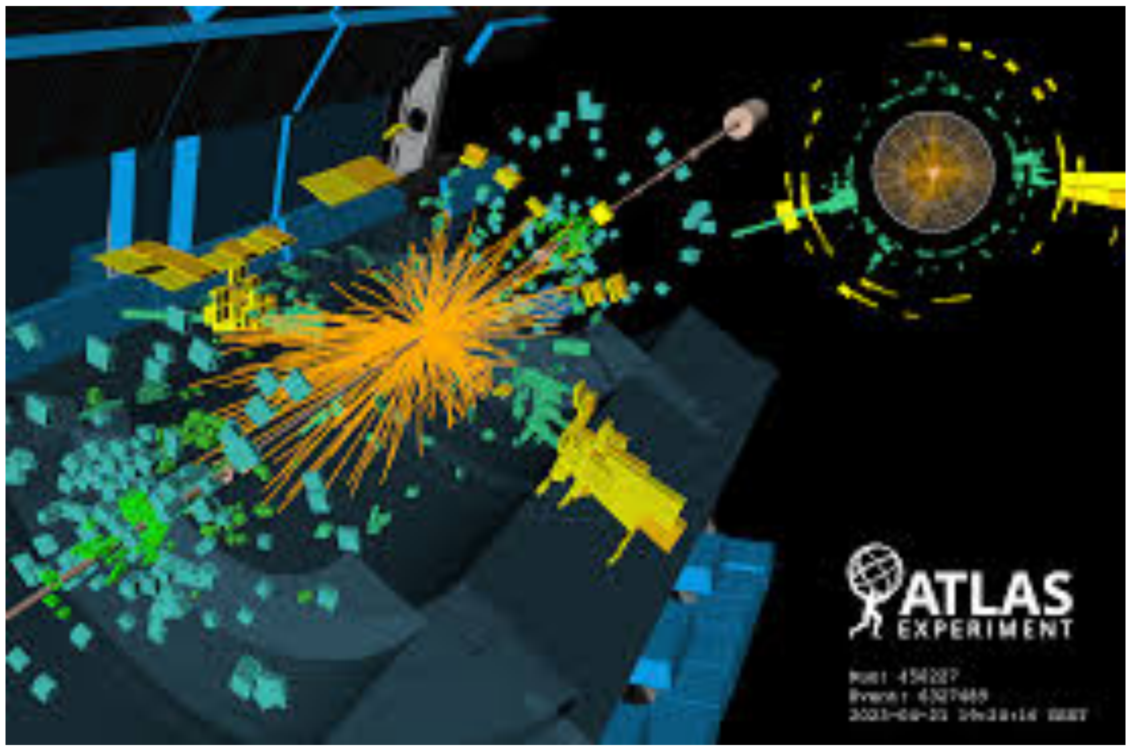
1. Predicting signals and backgrounds ⇒ increasing sensitivity to new phenomena
2. Guiding experimental searches ⇒ optimising final states and observables
3. Providing a theory interpretation of signals

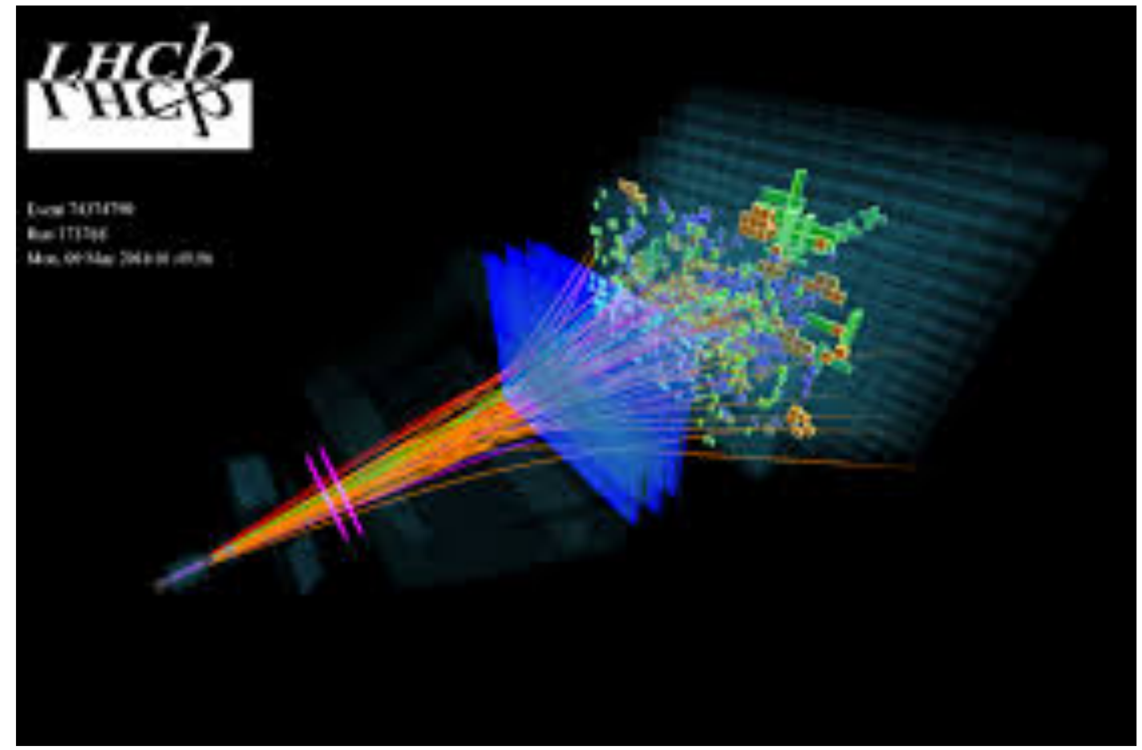
For the future, theory has a crucial in addressing the questions

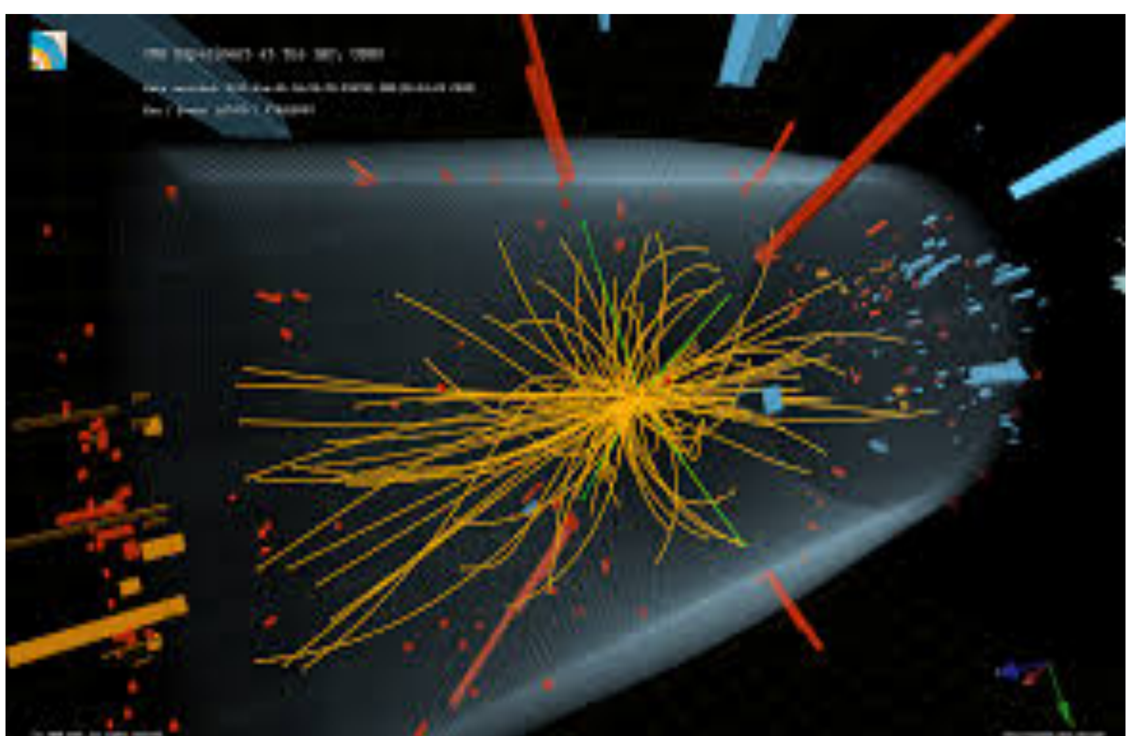
- What should the next collider be?
- Given a collider, what should the requirements of future detectors/experiments be?

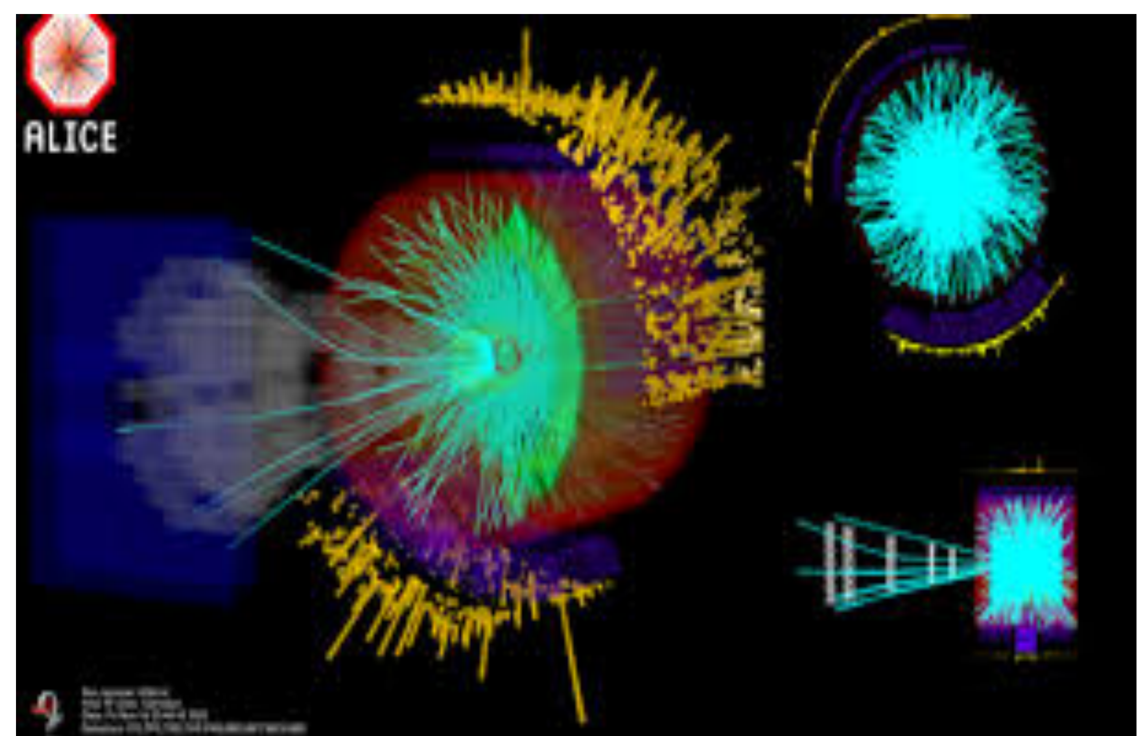
1. Predicting signals and backgrounds
$\Rightarrow$ increasing sensitivity to new physics

Collider events: real world









Theorist point of view

Largely based on factorization

Hard partonic scattering

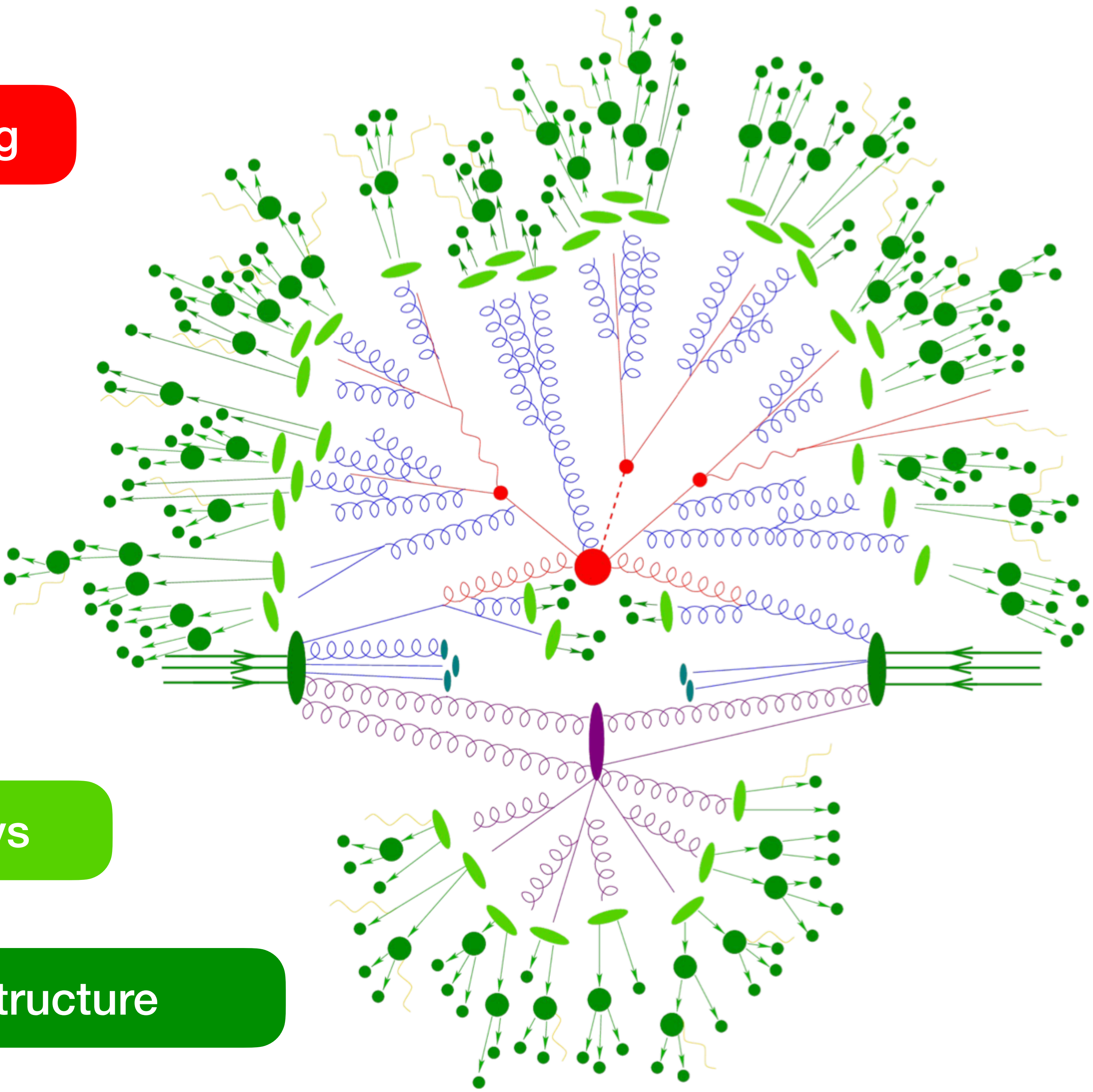
Parton shower

PDFs/underlying event

QED/photons

Hadronization/decays

Jets/substructure



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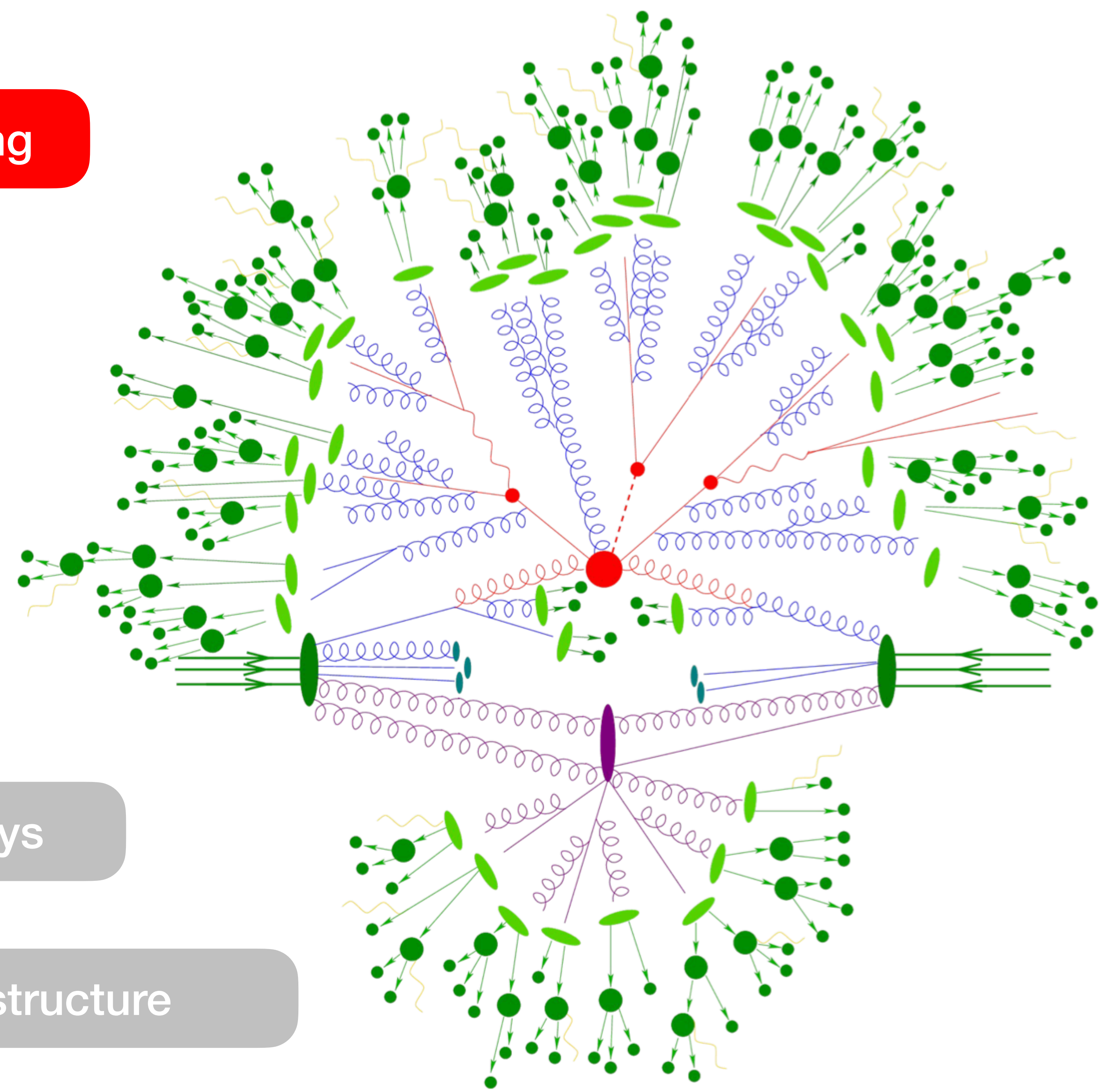
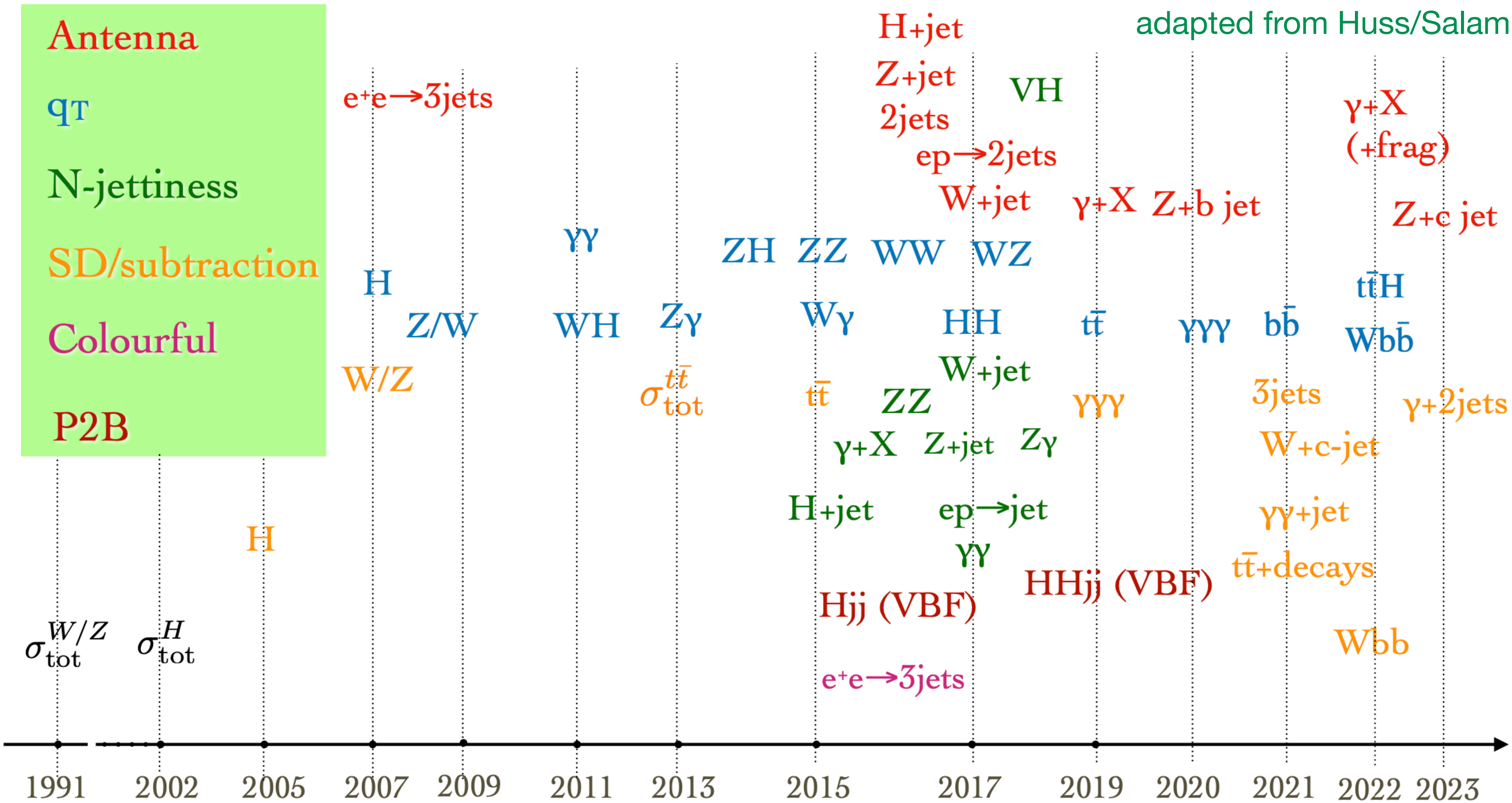


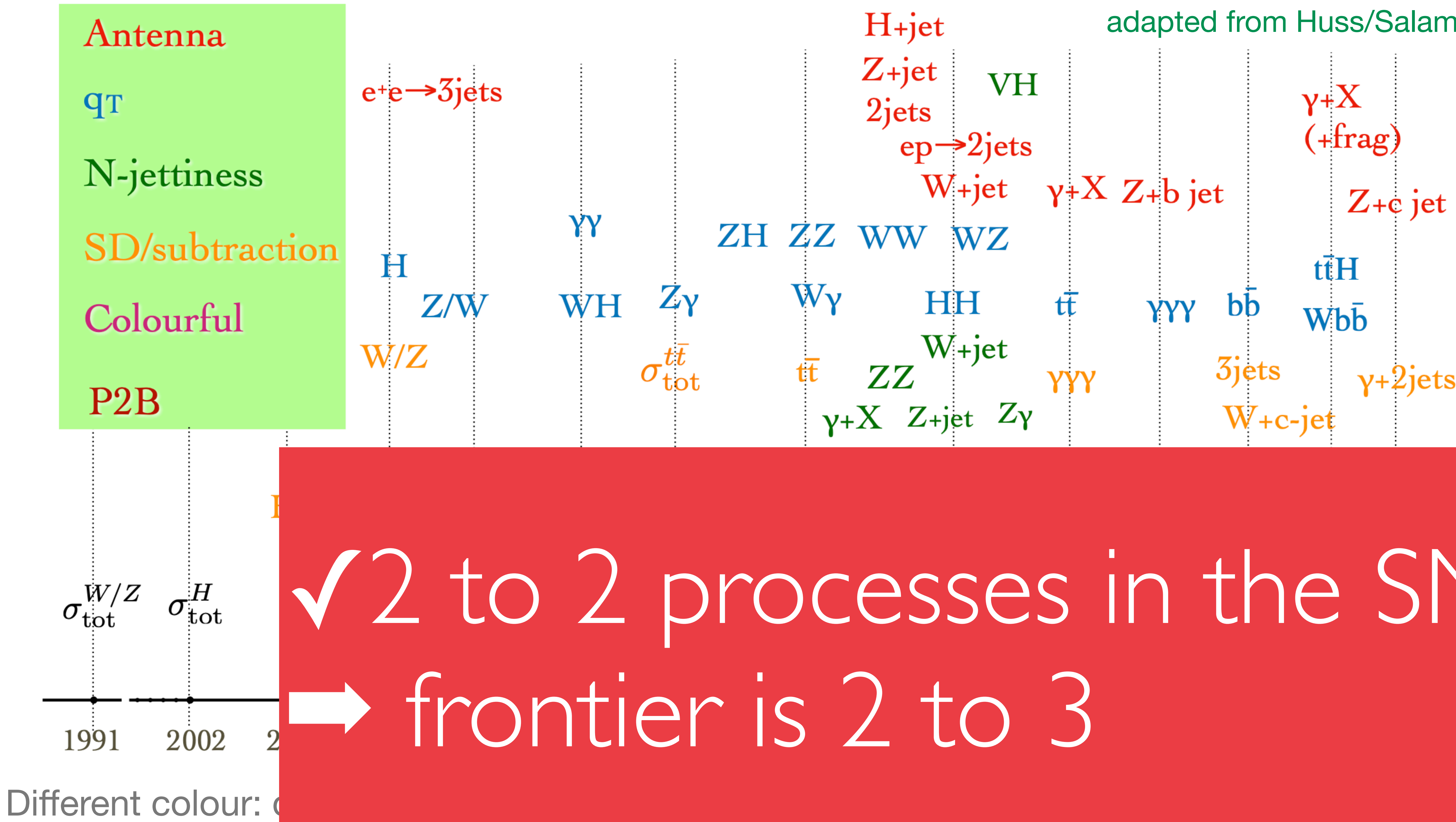
NNLO timeline



Different colour: different way to handle intermediate divergences

The dream is to have NNLO fully automated for generic processes [Sotnikov]

NNLO timeline

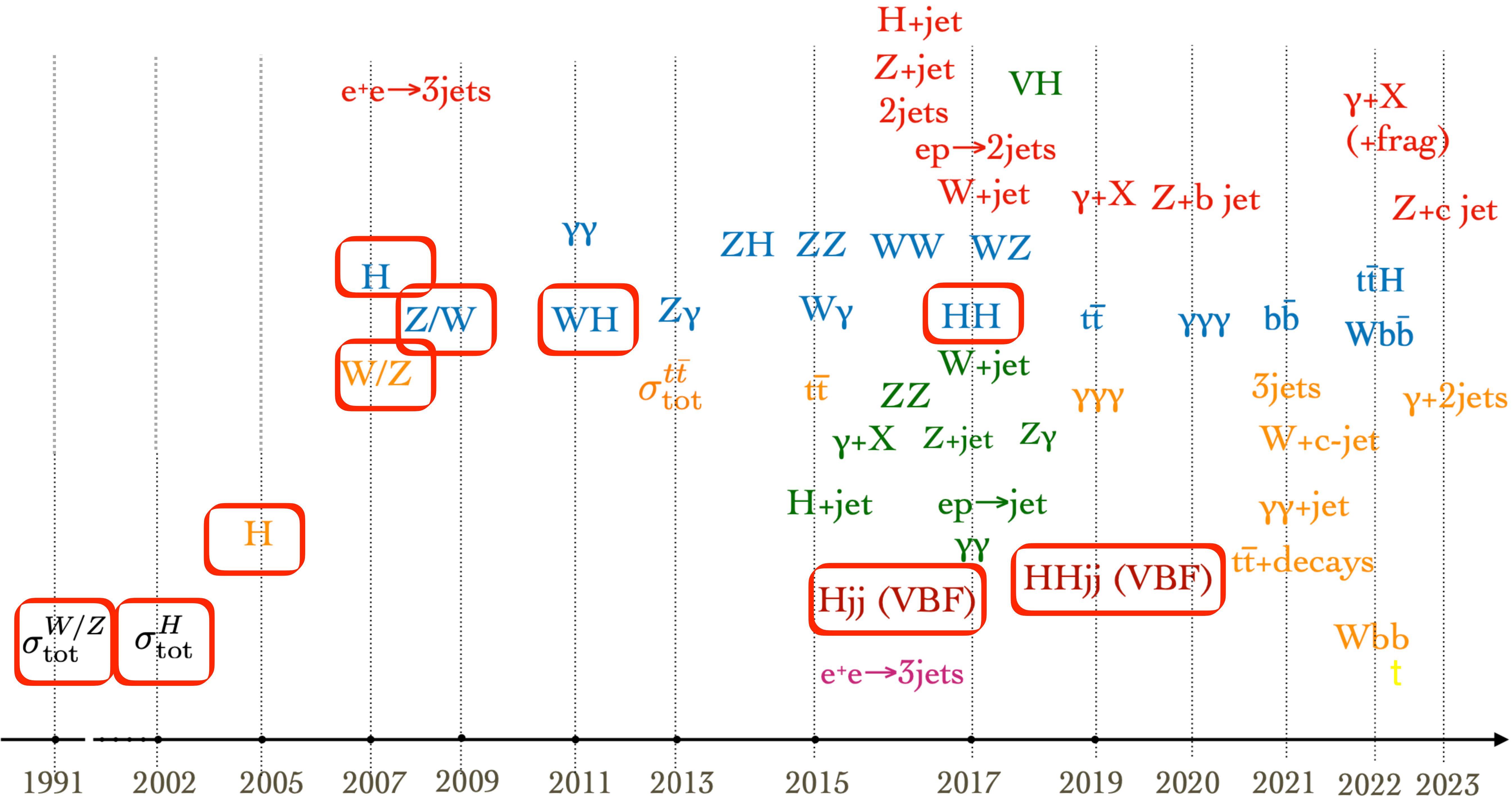


✓2 to 2 processes in the SM

➡ frontier is 2 to 3

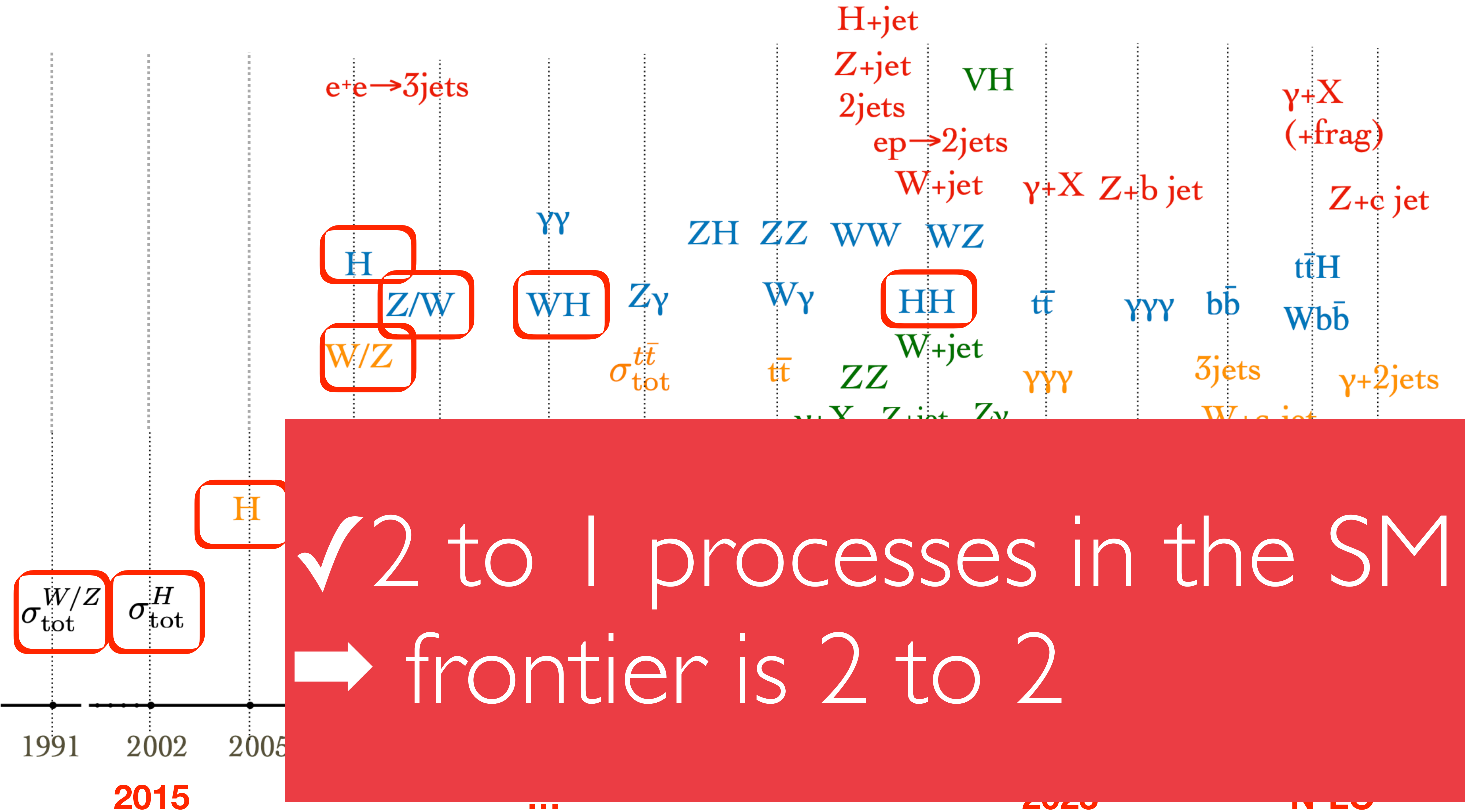
The dream is to have NNLO fully automated for generic processes [Sotnikov]

NNLO → N³LO



2015 ... **2023** **N³LO**

NNLO → N³LO



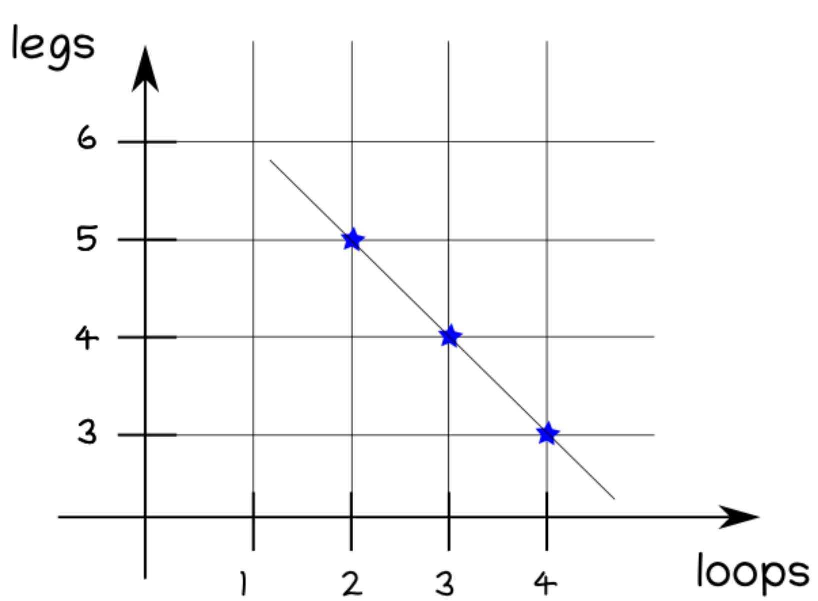
✓2 to 1 processes in the SM

➡ frontier is 2 to 2

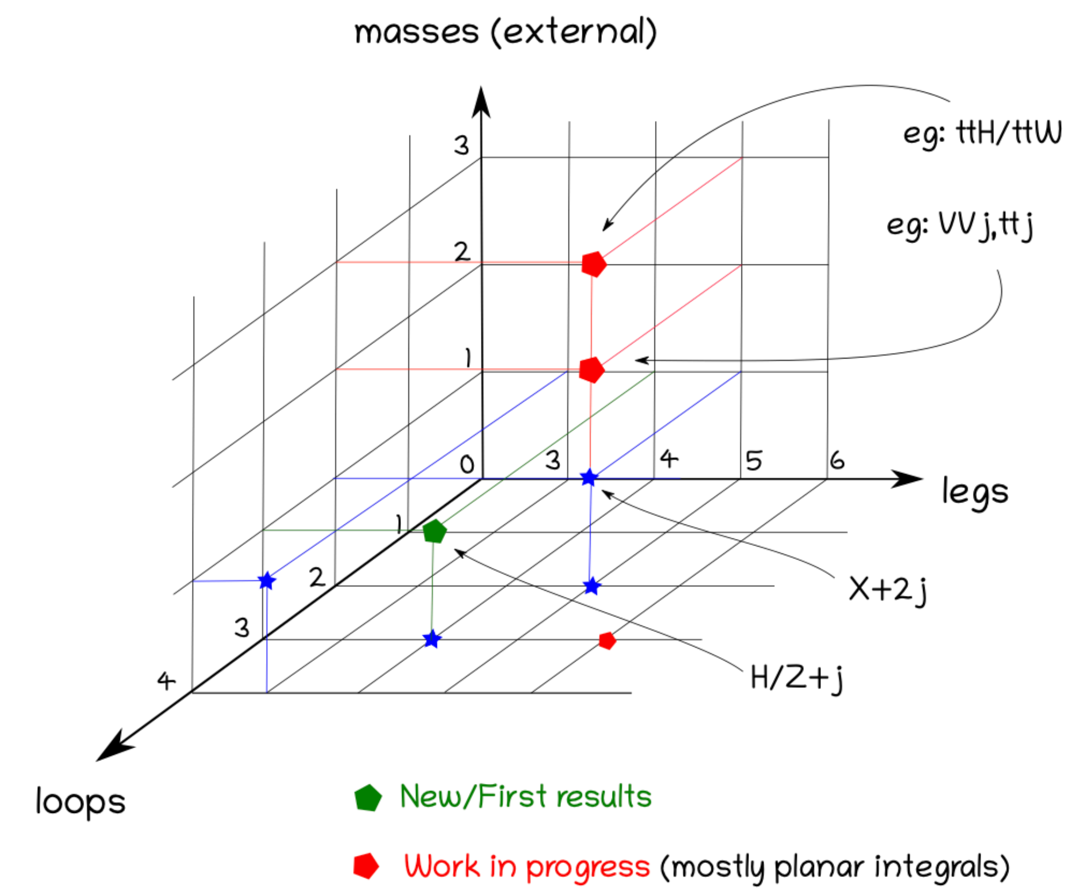
Complexity

From Buccione

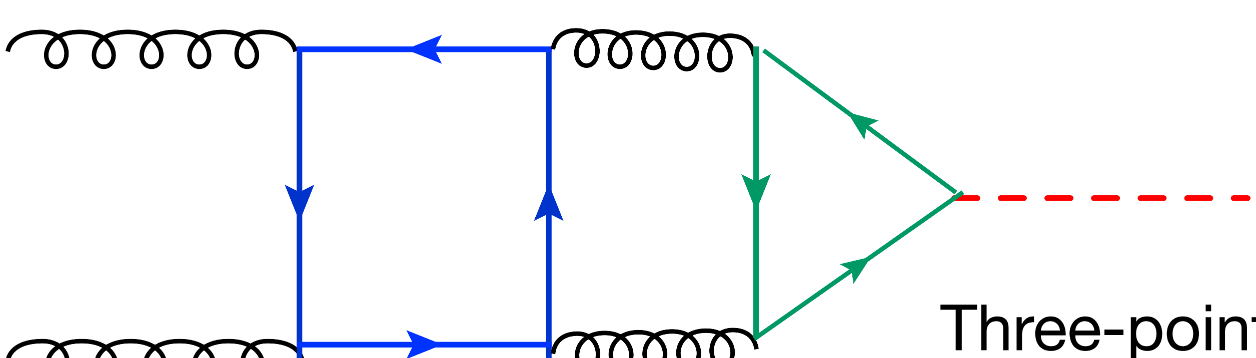
Complexity grows with #loops and #legs.



Masses add an extra dimension (and level of complexity) to the problem



<u>Example:</u> NNLO correction to Higgs



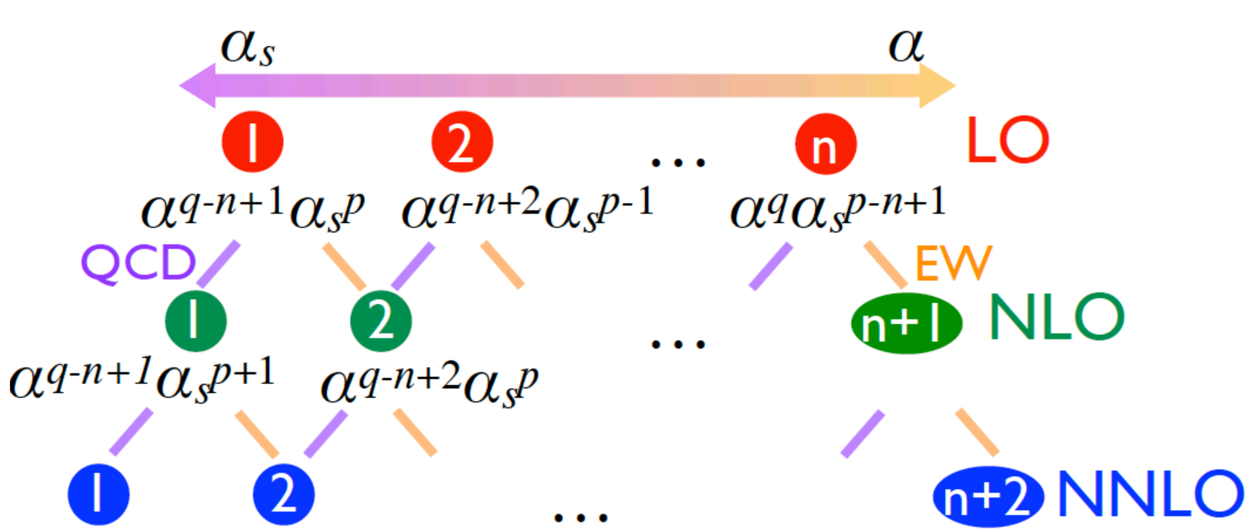
Three-point function (3-legs) with 3 loops and 3 masses

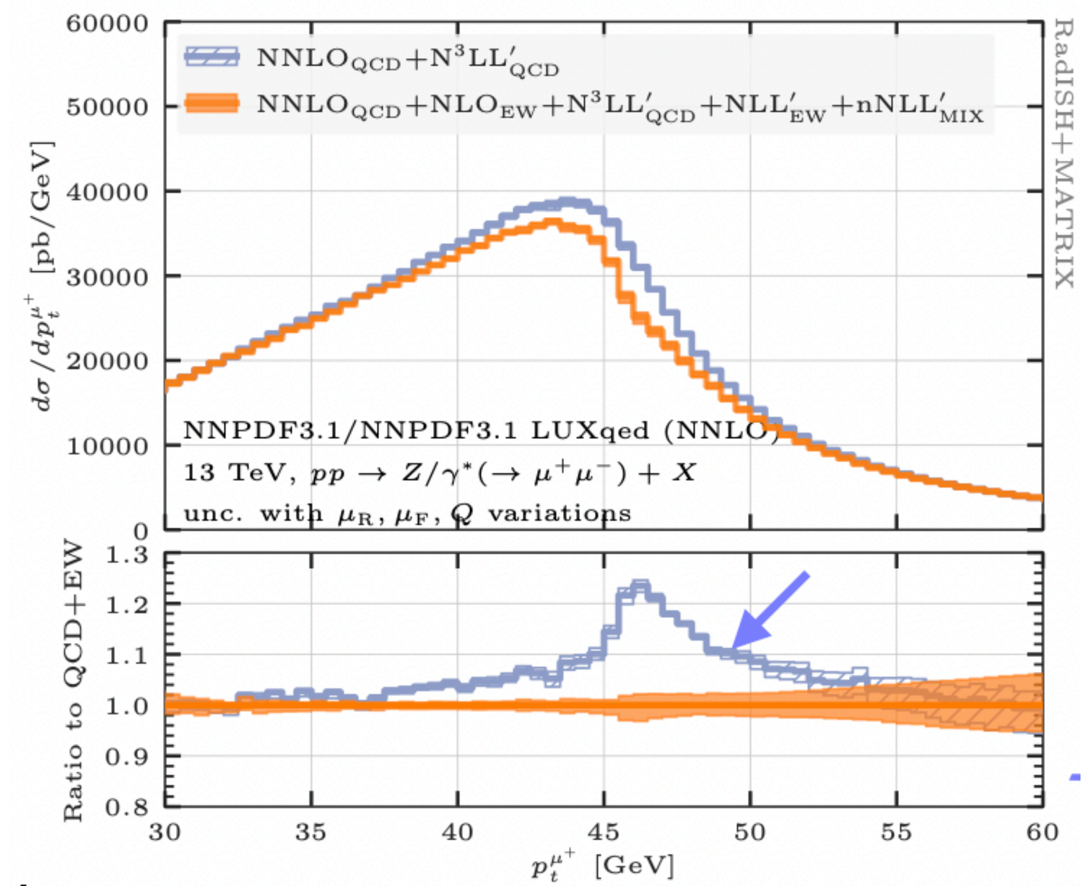
Not just QCD

Several mechanisms can enhance electroweak effects (not just %)

EW Sudakov logarithms, couplings, radiative return, kinematics, …

Field moving EW beyond NLO (mixed QCD-EW, Sudakov logs, QED resummation…)





Matching of EW to parton shower at NLO still open problem

Hard partonic scattering

Progress beyond expectations ⇒ remarkable success of theorists

- Progress not due to cranking old machinery but driven by new ideas and developments of new formal developments

Differential equations, symbols, alphabets, finite fields method, functional reconstruction, …

- Strong synergies with formal mathematics

Many calculations eagerly awaited and in sight in the next five years

NNLO for ttH, Wbb, ttbb, …; N^3LO for dibosons, …

In the meantime, very clever approximations help reduce theory uncertainties together with solid validation methods

massification procedures, soft “boson” approximation, expansions …

pQCD well on track to keep up with experimental precision

Theorist point of view

Hard partonic scattering

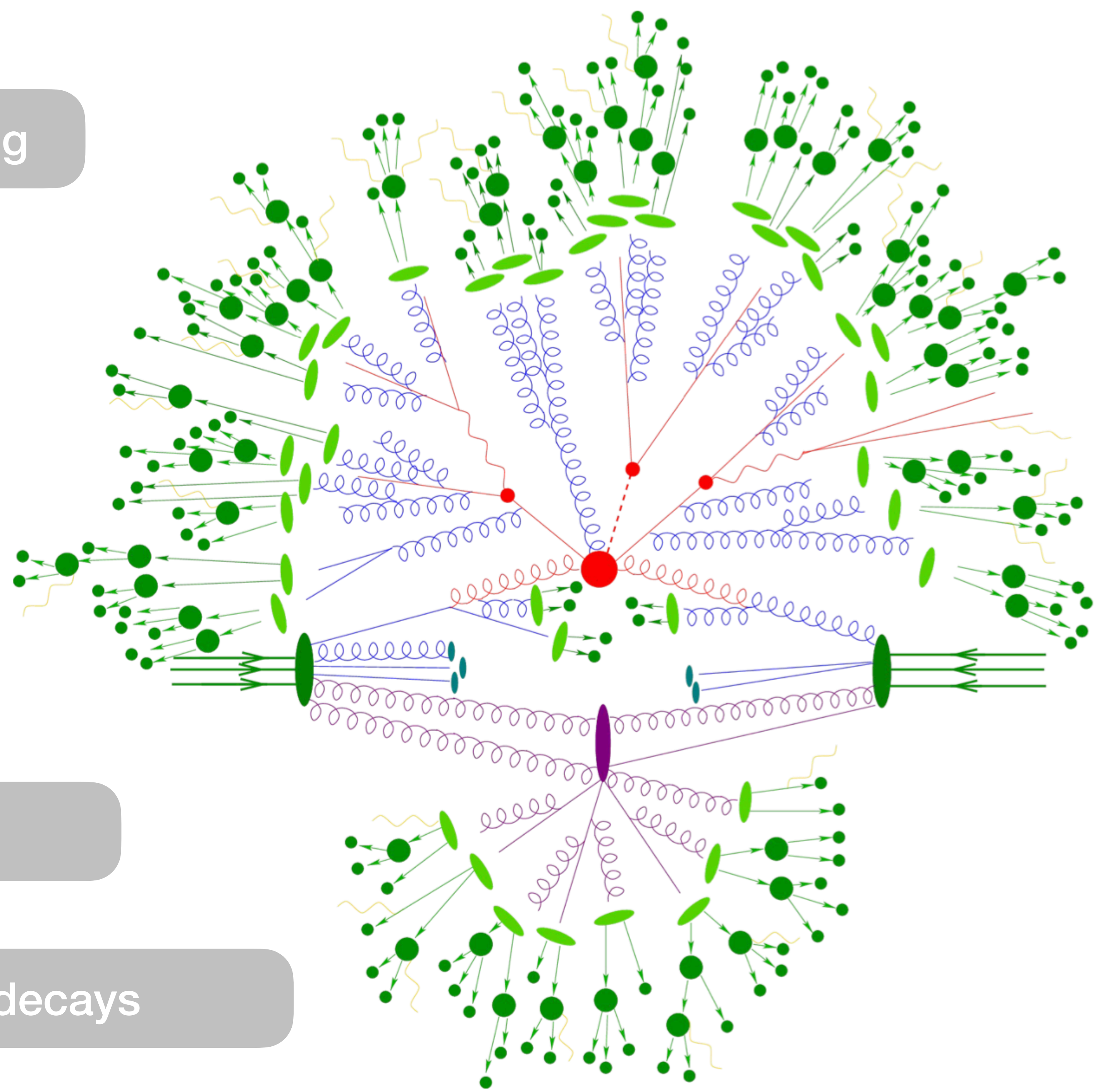
Parton shower

PDFs/underlying event

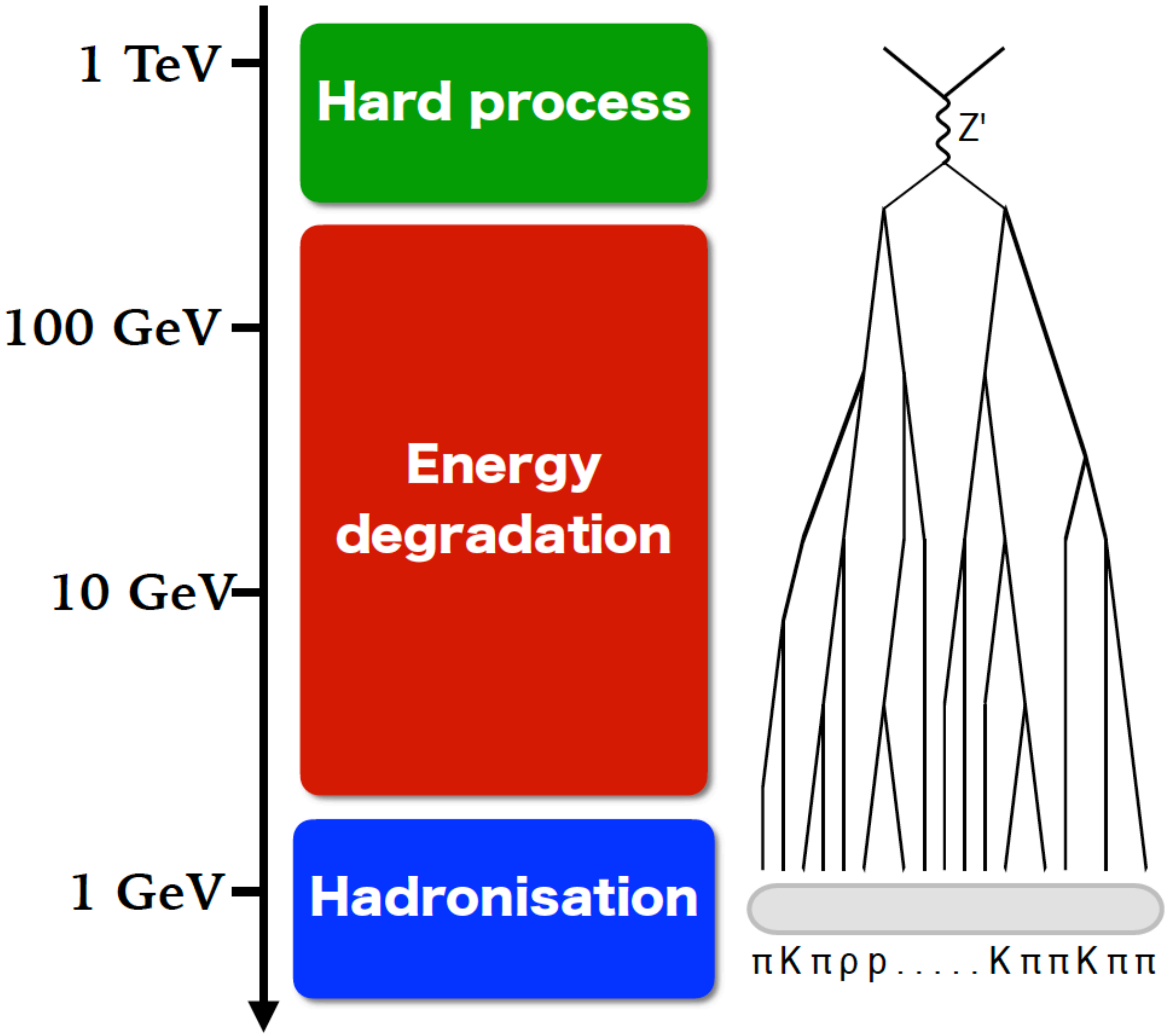
QED/photons

Hadronization

Hadron decays



Parton shower



from Ravasio-Ferrario

<u>Parton shower:</u>
Energy degradation of particles from the hard collision, producing more particles during evolution

Modern parton showers

Parton showers are ubiquitous at the LHC

Modelling QCD processes, event simulation, background estimates, unfolding, detector simulation, …

The development of parton shower has seen a dramatic change in recent years. Key new elements of modern parton showers include

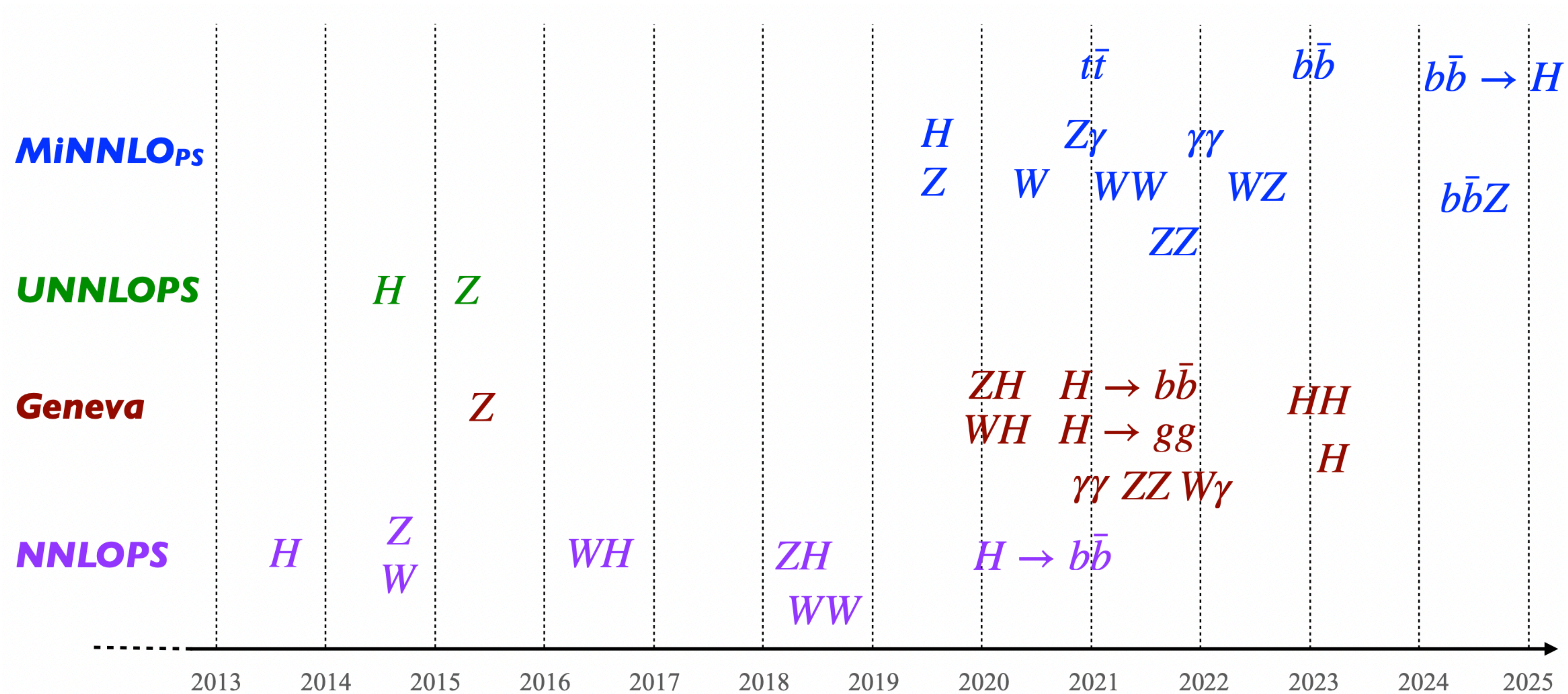
- Improvements in the accuracy of the parton shower
- Numerical procedure to validate the accuracy
- Understanding that some parton showers have lower accuracy
  $\Rightarrow$ can be disregarded when assessing theory uncertainties

ALARIC, DEDUCTOR, PANSCALES, HERWIG7 …

A revolution in parton shower developments is ongoing. Will be crucial for Run 3, HL-LHC and FCC.

Parton shower matching

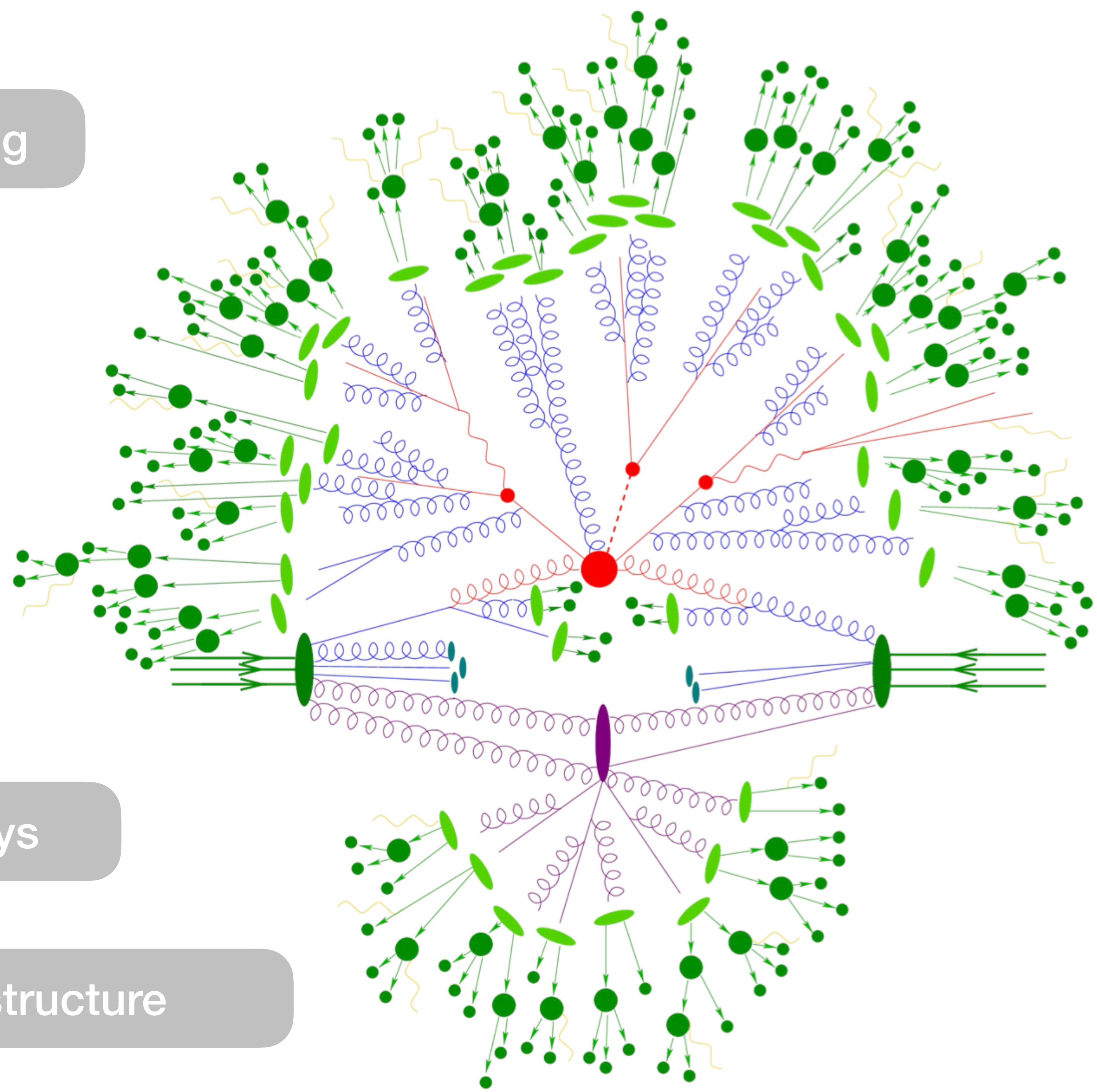
Different methods developed. NNLOPS with leading logarithmic accuracy in the shower well understood



Not yet clear how to preserve accuracy of more accurate showers in the matching

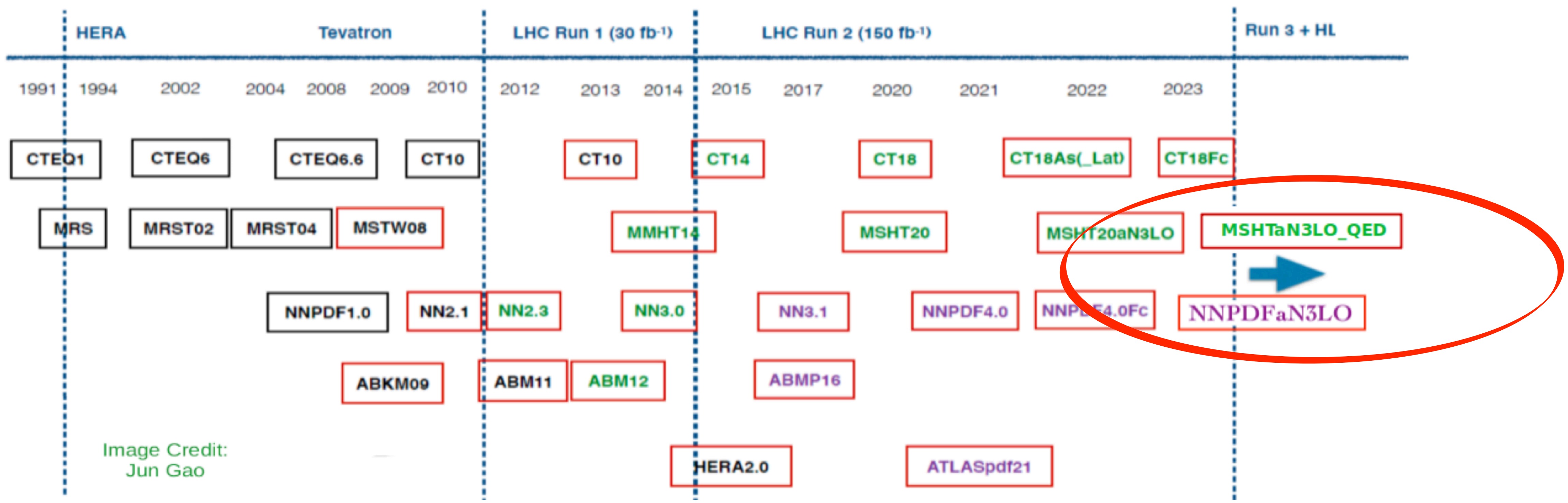
Theorist point of view

- Hard partonic scattering
- Parton shower
- **PDFs/underlying event**
- QED/photons
- Hadronization/decays
- Jets/substructure



Towards N^{3}LO PDFs

First approximate N^{3}LO PDFs are available:



Yet, many ingredients for N^{3}LO accurate PDFs are missing:

- Splitting functions ✗

$$\mu^2 \frac{df_i}{d\mu^2} = P_{ij}\left(\mu^2\right) \otimes f_i\left(\mu^2\right)$$

- VFNS matching conditions ✓

$$f_i^{(n_f+1)}\left(x,\mu^2\right) = A_{ij}\left(x,\alpha_s\right) \otimes f_i^{(n_f)}\left(x,\mu^2\right)$$

- DIS **massless** partonic coefficients ✓

  DIS **massive** partonic coefficients ✗

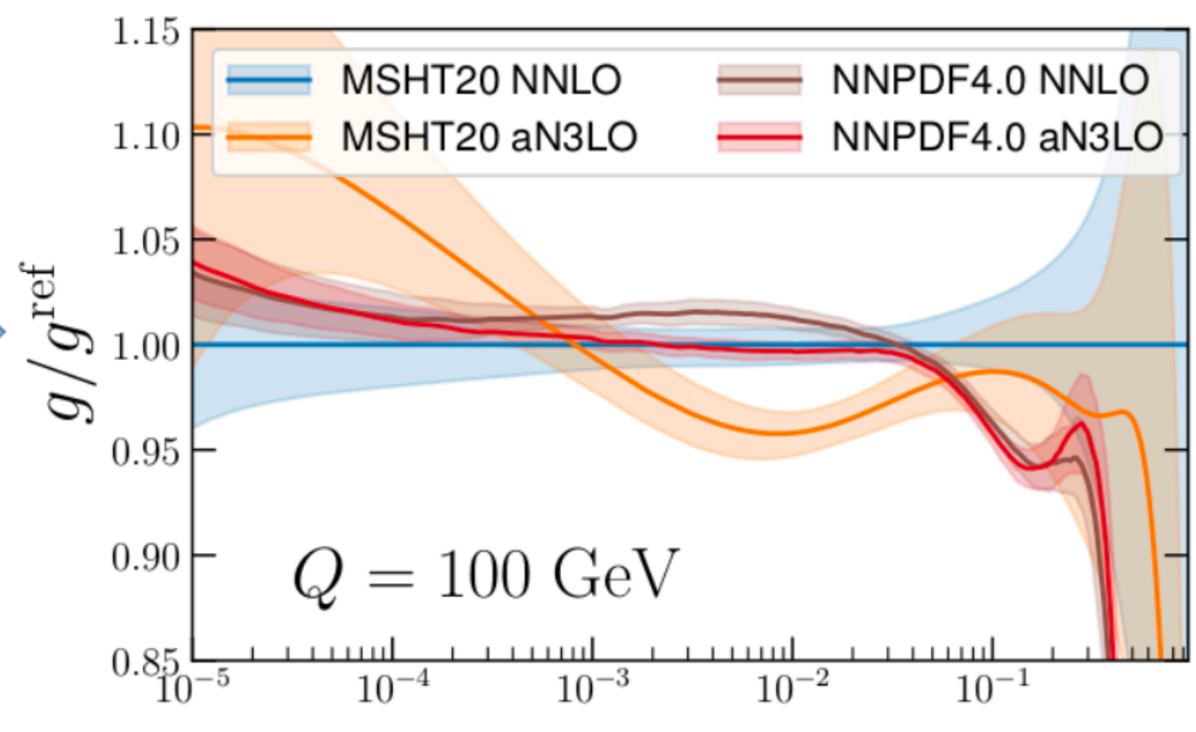
$$F_i\left(x,Q^2\right) = \sum_k C_{i,k} \otimes f_i\left(x,Q^2\right)$$

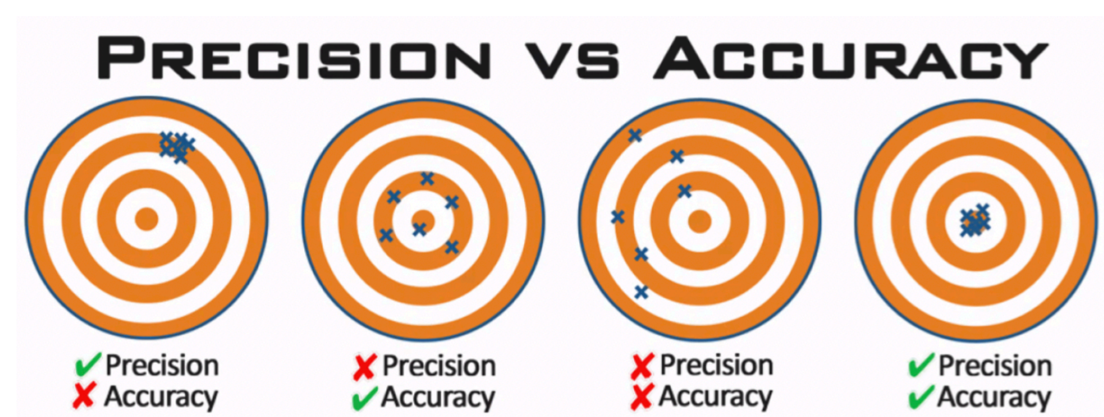
- Hadronic coefficients at N3LO ✗

Towards N^{3}LO PDFs

Similarities	Differences
Include available N3LO info at time of publication	Own approximations used for each piece
Include theoretical uncertainties for missing pieces	Different methodology for theory uncertainty.

Largest differences in gluon PDFs (several percent in Higgs region)





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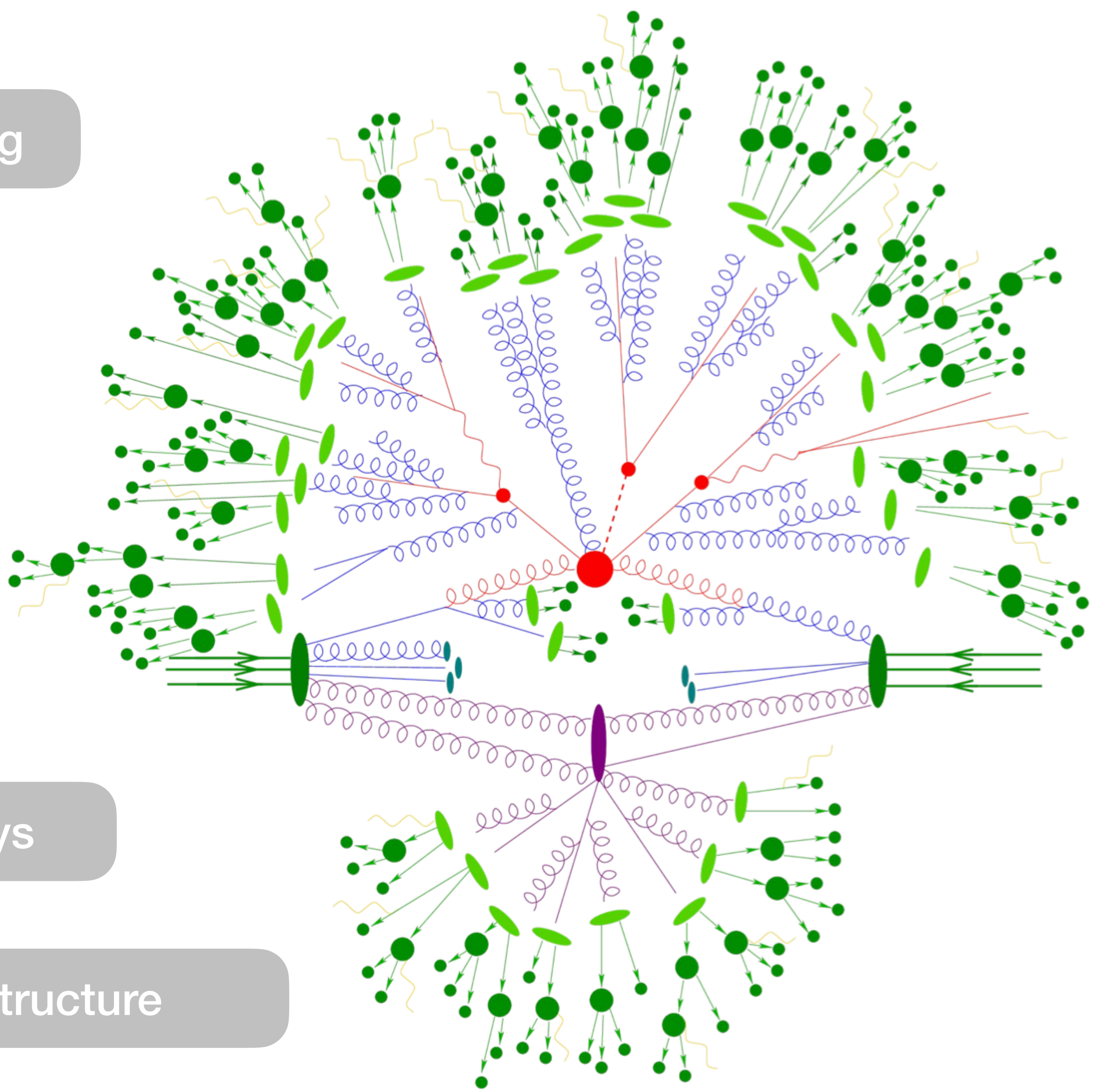
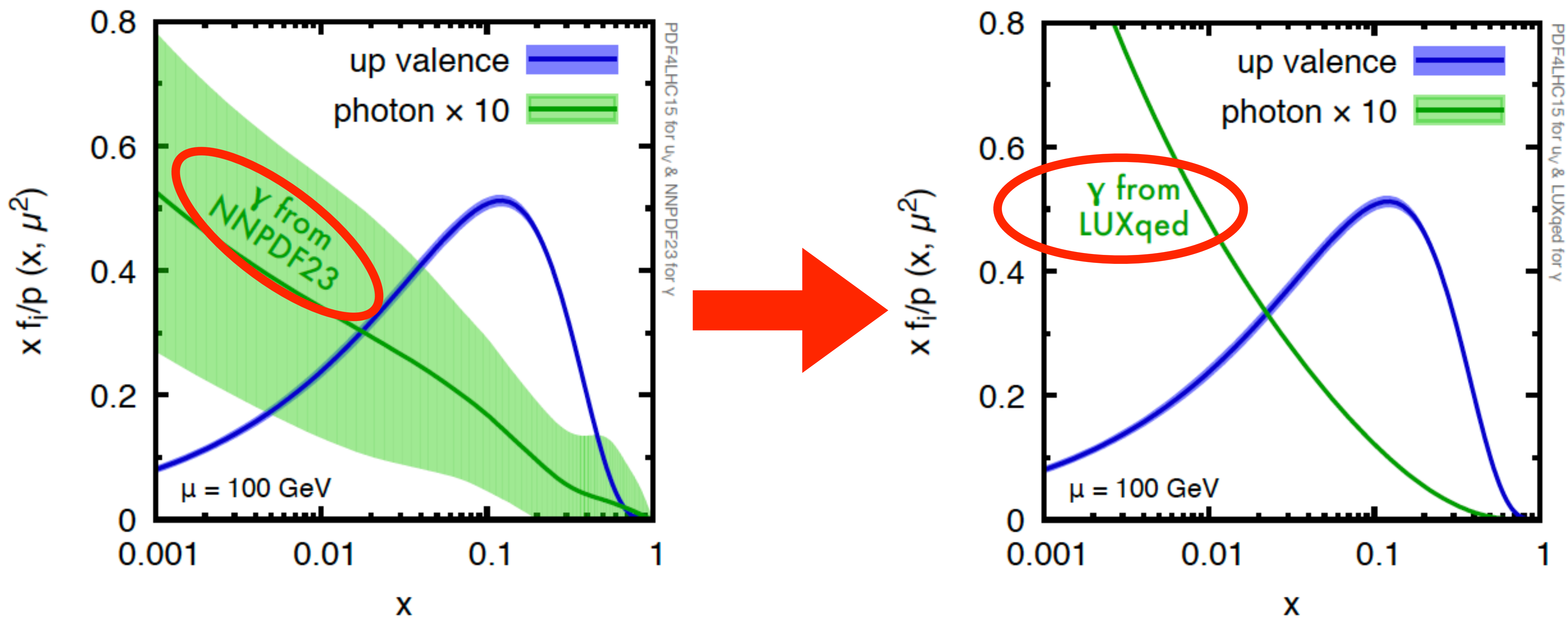


Photon PDF

Because of QED effects, photons (and leptons) can be found in protons

Thinking outside the box, it was possible to reduce the uncertainty on the photon PDF from 100% to about 1%

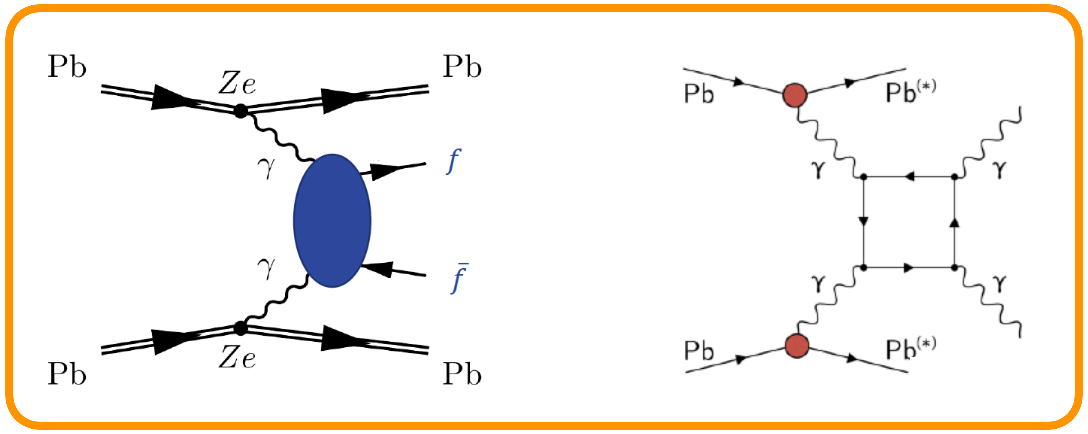


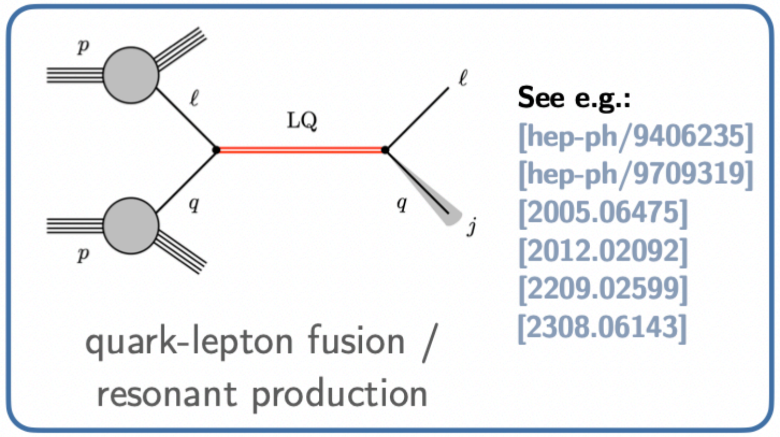
Photon became the best known parton in the proton

LHC as photon collider

Opens up many new research directions

- LHC as a photon collider ⇒ photon-induced dilepton production
- Photo-nuclear reactions, including vector-meson production
- Photon-photon induced processes in Heavy Ion collisions
- LHC as photon collider also for BSM searches
- Leptons in the protons ⇒ new search channel for leptoquarks (resonant LQ production)





Proof of extraordinary versatility of LHC experiments and of synergy with theory!

Theorist point of view

Largely based on factorization

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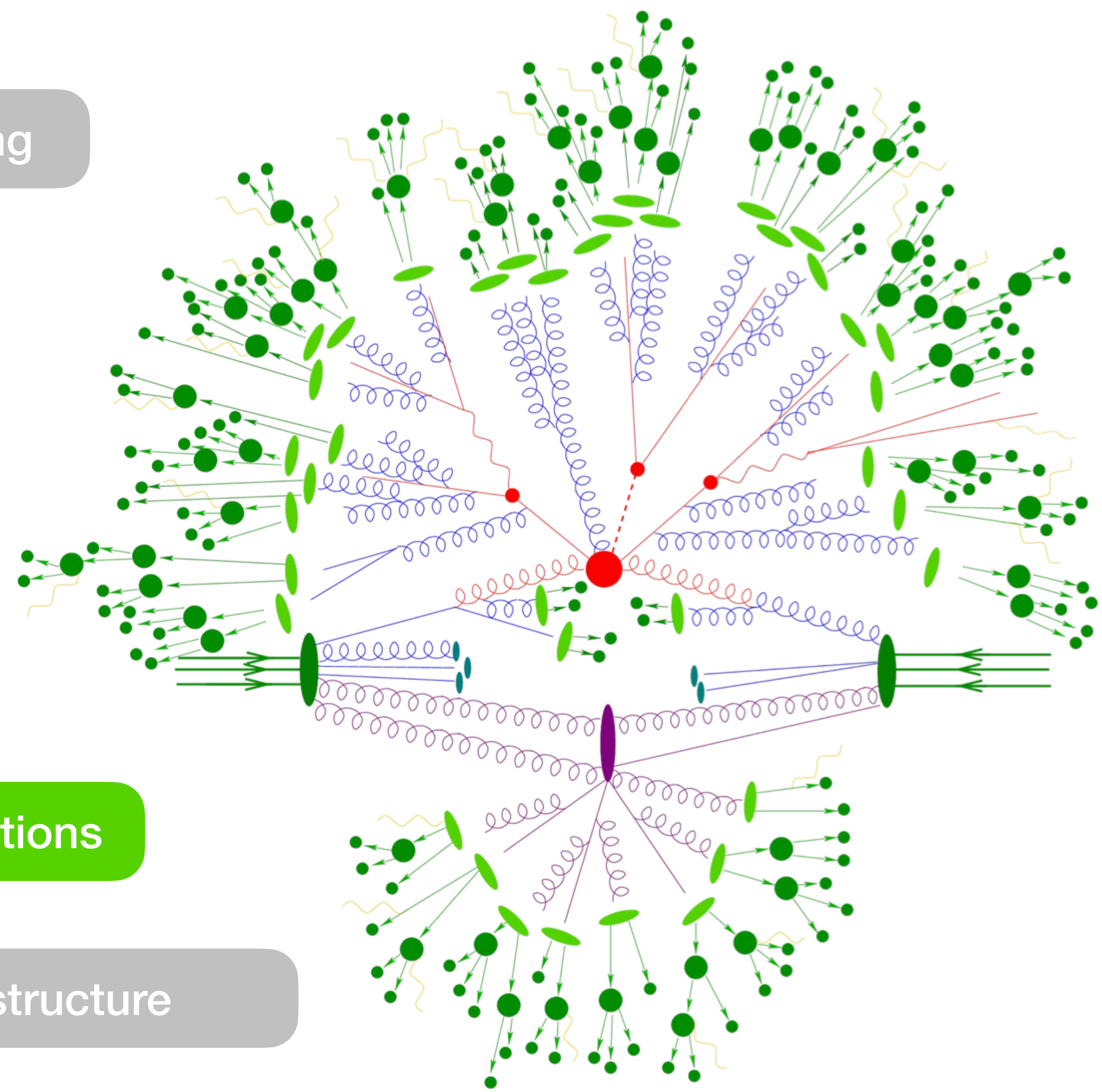
Non perturbative power corrections

Jets/substructure



Theory master formula

Factorisation implies the following form of hadronic cross sections

$$d\sigma_{\mathrm{PP}\to\mathrm{final}} = \sum_{\mathrm{i,j,final}} \int dx_1 dx_2 d\Phi_{\mathrm{final}} f_i(x_1,\mu_F^2) f_j(x_2,\mu_F^2) \frac{d\hat{\sigma}_{\mathrm{ij}\to\mathrm{final}}}{d\Phi_{\mathrm{final}}} \Theta_{\mathrm{cuts}}$$

Parton distributions functions
Extracted from data at various experiments/energies. PDFs are universal and their evolution is perturbative (LO, NLO, NNLO, …)

Partonic cross sections
Expansion in the coupling constants (LO, NLO, NNLO, …), also including enhanced all-order terms (LL, NLL, NNLL, …)

Theory master formula

Factorisation implies the following form of hadronic cross sections

$$d\sigma_{\mathrm{PP}\to\mathrm{final}} = \sum_{\mathrm{i,j,final}} \int dx_1 dx_2 d\Phi_{\mathrm{final}} f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \frac{d\hat{\sigma}_{\mathrm{ij}\to\mathrm{final}}}{d\Phi_{\mathrm{final}}} \Theta_{\mathrm{cuts}} \left(1 + \mathcal{O}(\Lambda_{\mathrm{NP}}^n / Q^n)\right)$$

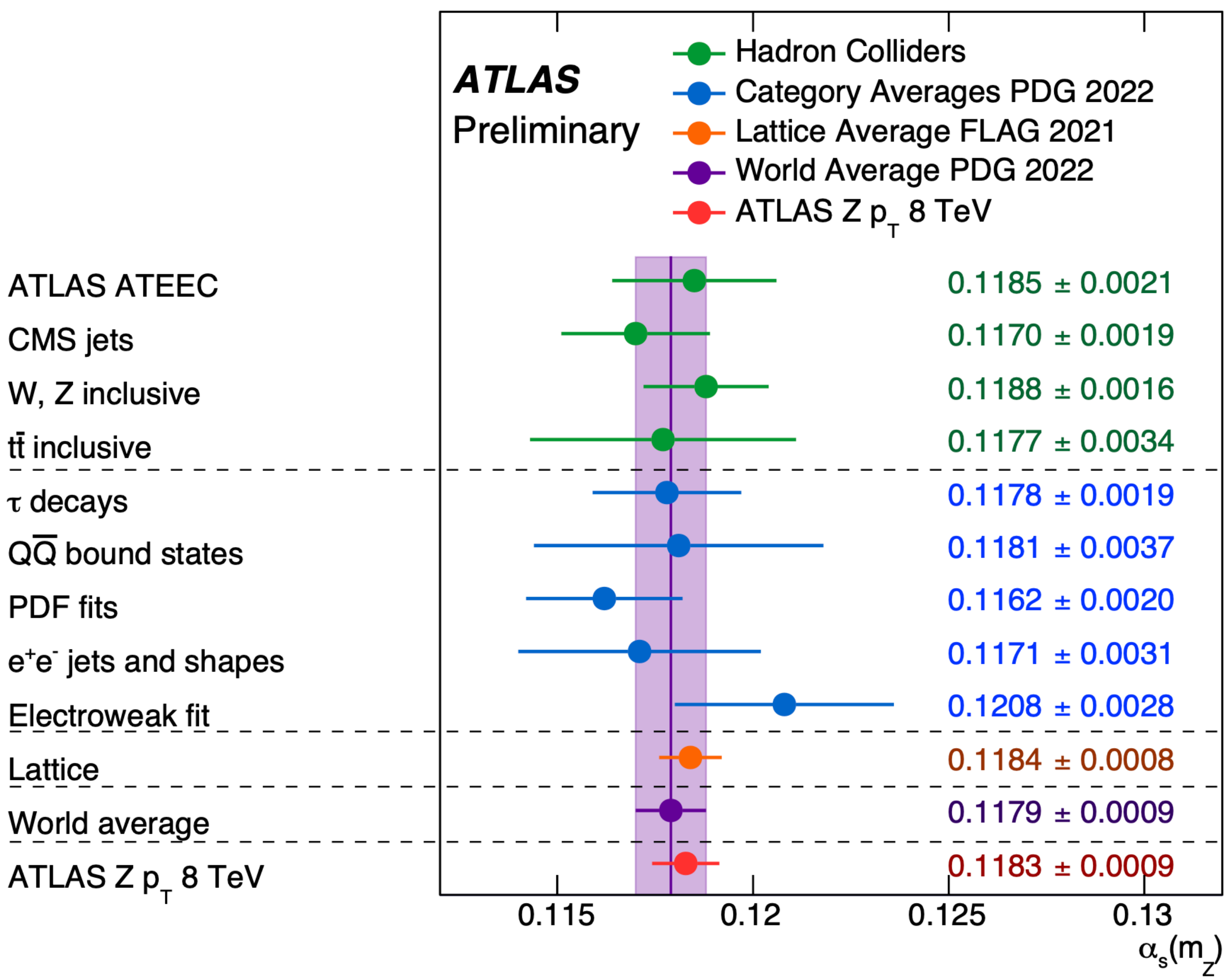
Non-perturbative (NP) power corrections to the factorisation formula

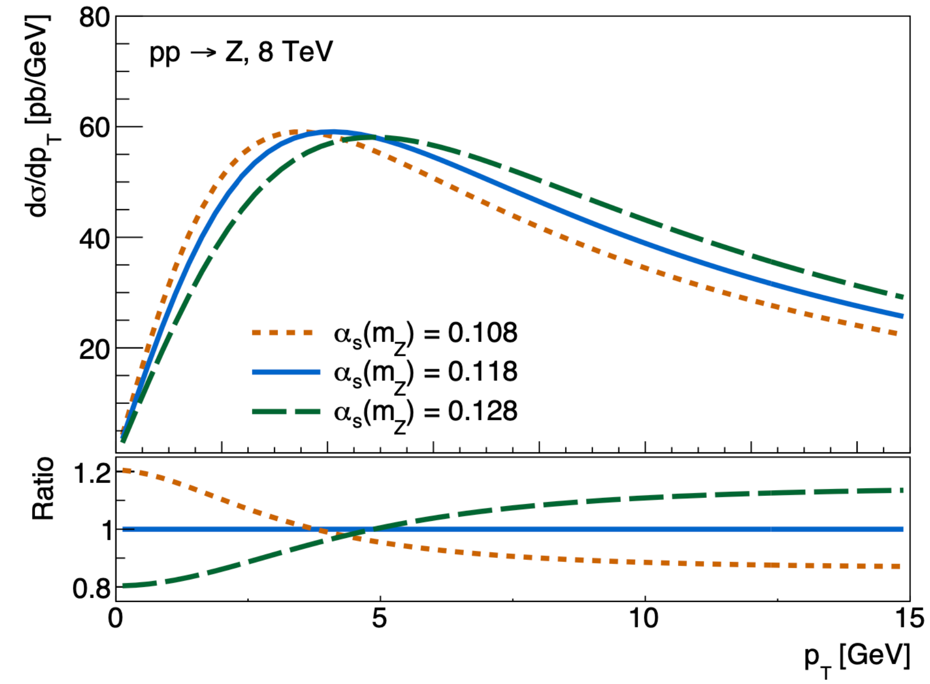
Can become relevant

- if n is small, e.g. n=1 (1 GeV/100 GeV ~1%)
- if Q is small, e.g. low transverse momentum
- for ultra-precision measurements

α_s from $p_{t,Z}$

E.g. $p_{t,Z}$ close to the Sudakov peak used recently by ATLAS to extract α_s with high precision





$$\alpha_s(m_Z) = 0.11828^{+0.00084}_{-0.00088}$$

Experimental uncertainty	+0.00044	-0.00044
PDF uncertainty	+0.00051	-0.00051
Scale variations uncertainties	+0.00042	-0.00042
Matching to fixed order	0	-0.00008
Non-perturbative model	+0.00012	-0.00020
Flavour model	+0.00021	-0.00029
QED ISR	+0.00014	-0.00014
N4LL approximation	+0.00004	-0.00004
Total	+0.00084	-0.00088

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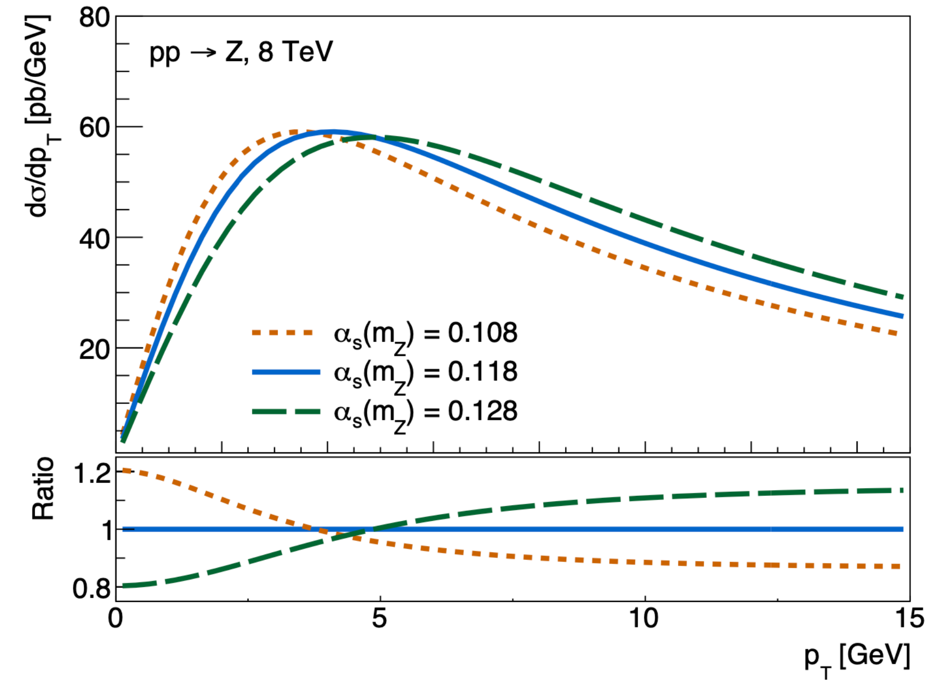

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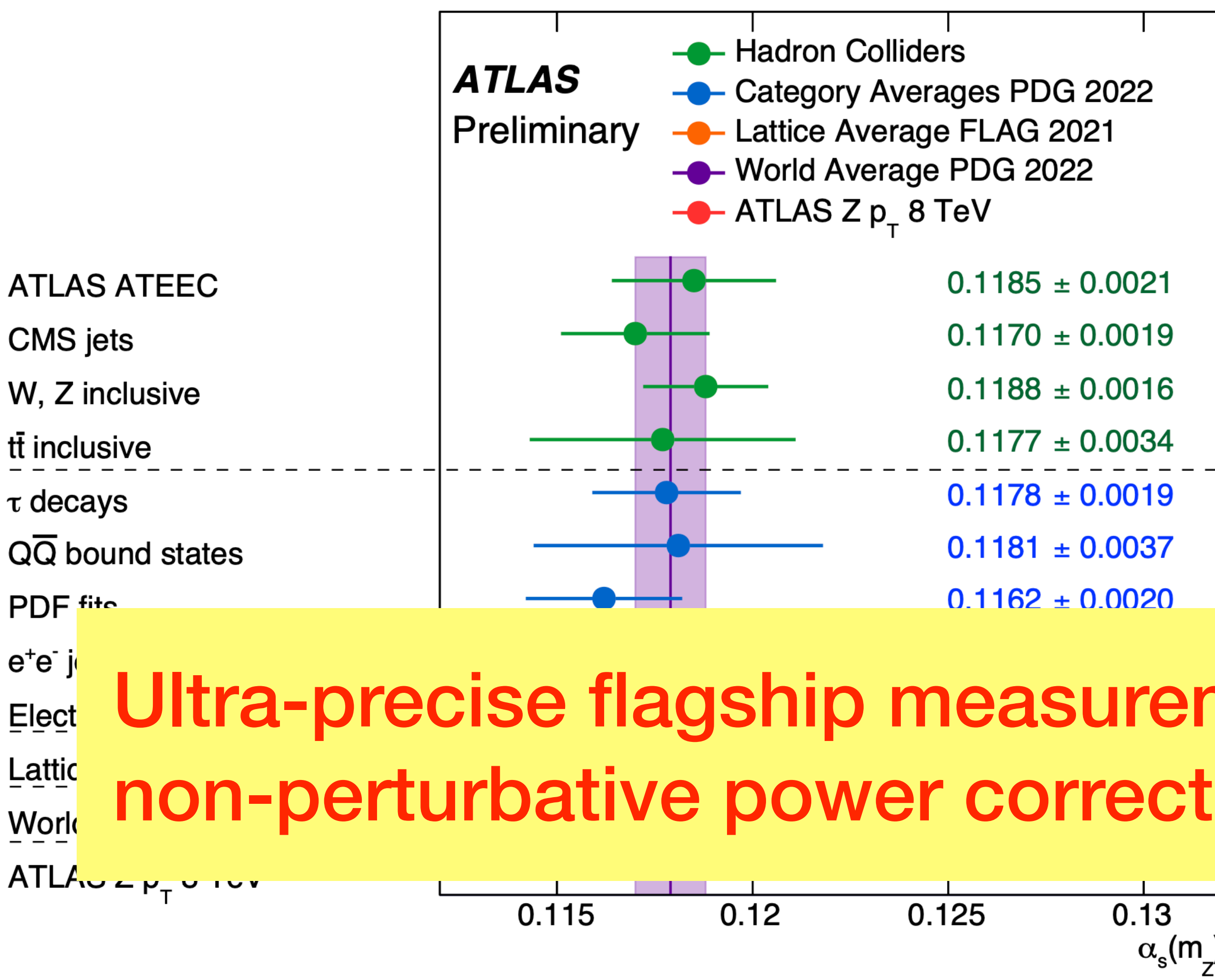


Ultra-precise flagship measurement relies on low p_t where non-perturbative power corrections are more relevant

α_s world average

Uncertainty on α_s (and PDF) can be the dominant source of uncertainty

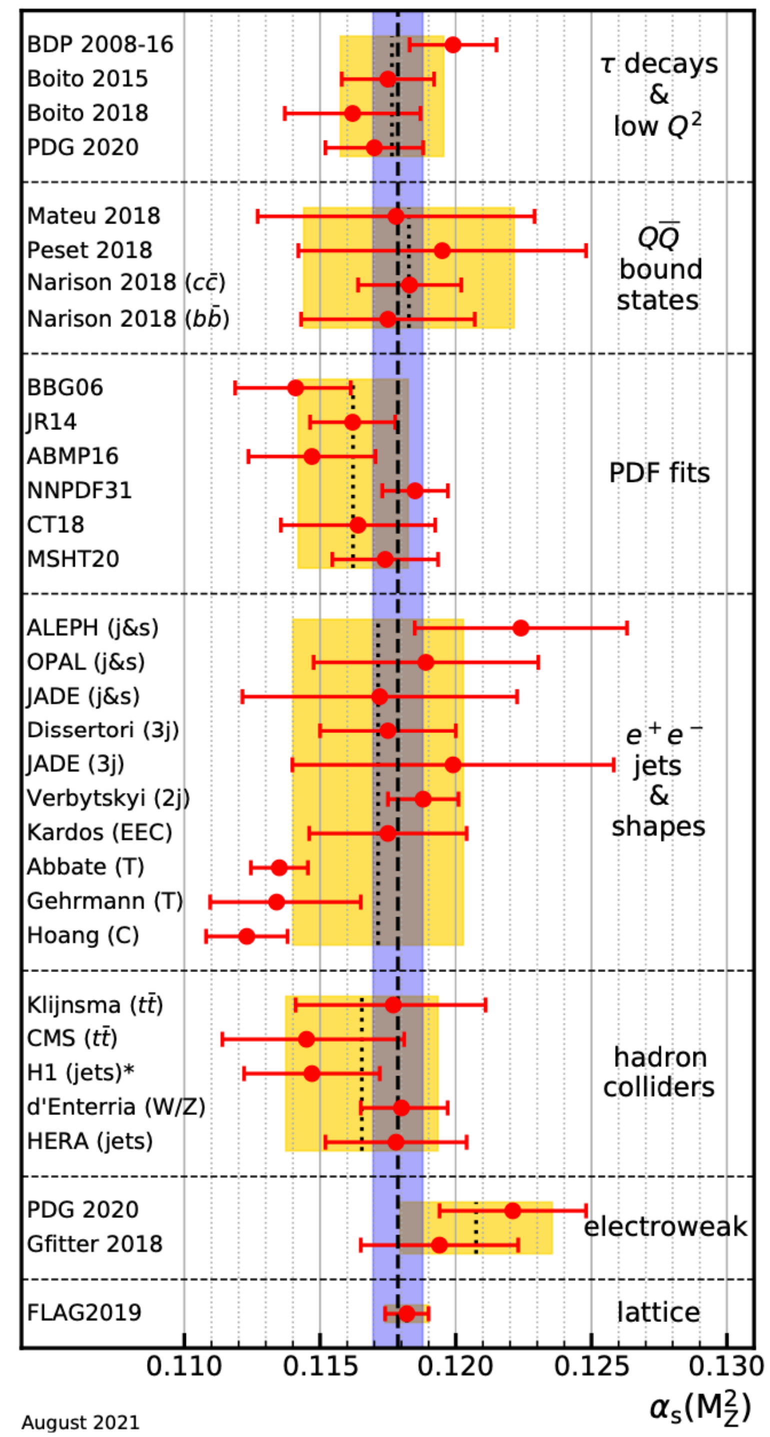
<u>Procedure to compute worlds average in PDG:</u>

- subdivide observables in categories
- provide an average for each category
- provide an average of all categories

  ⇒ *the world average of α_s*

$$\alpha_s(M_Z^2) = 0.1179 \pm 0.0009$$

$$\alpha_s(M_Z^2) = 0.1182 \pm 0.0008\,, \qquad \text{(lattice)}$$
$$\alpha_s(M_Z^2) = 0.1176 \pm 0.0010\,, \qquad \text{(without lattice)}$$



Many ambiguities, choices (e.g. treatment of correlations etc.), subtle aspects involved…

2. Guiding experimental searches
$\Rightarrow$ optimising final states and observables

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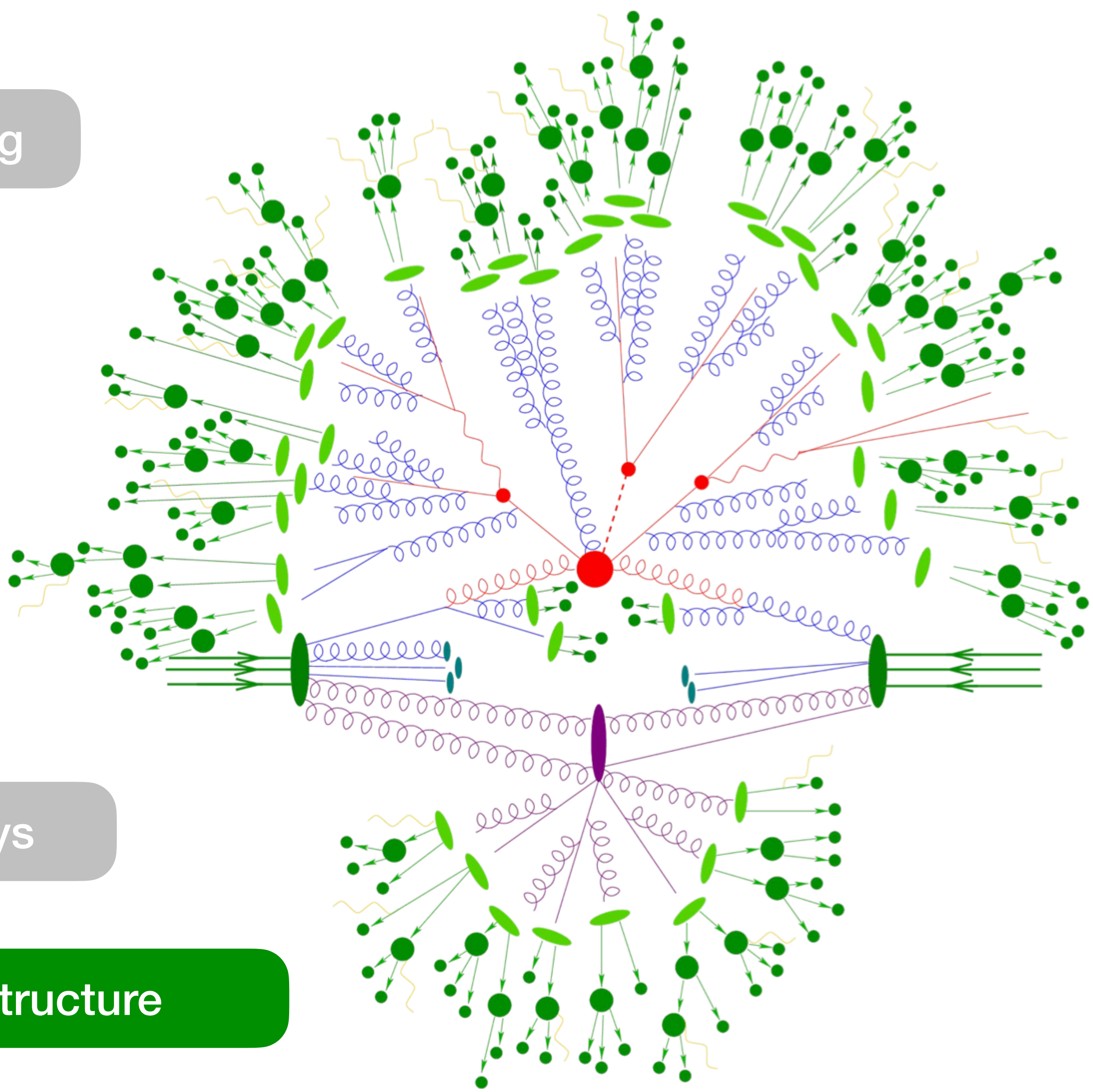

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29 July 2024 to 2 August 2024
Genova, Italy
Europe/Rome timezone

Enter your search term

New techniques for reconstructing and calibrating hadronic objects with ATLAS	Magda Diamantopoulou	Palazzo Ducale, Genova, Italy	14:00 - 14:20
Jet performance and PU mitigation techniques	Nurfikri Norjoharuddeen	Palazzo Ducale, Genova, Italy	14:20 - 14:40
Classifying hadronic objects in ATLAS with ML/AI algorithms	Robert Les	Palazzo Ducale, Genova, Italy	14:40 - 15:00
Identification of Lorentz-boosted jets in the CMS experiment	Donato Troiano	Palazzo Ducale, Genova, Italy	15:00 - 15:20
Flavour Tagging with Graph Neural Network with the ATLAS Detector	NEELAM KUMARI	Palazzo Ducale, Genova, Italy	15:20 - 15:40
Searches with exotic jet substructure techniques	Simon Rothman	Palazzo Ducale, Genova, Italy	15:40 - 16:00
Coffee break		Palazzo Ducale, Genova, Italy	16:00 - 16:20
Triggering Jets in Run 3 with the ATLAS Global Feature Extractor	Cecilia Tosciri	Palazzo Ducale, Genova, Italy	16:20 - 16:40
AI-based event classification with CMS	Chen Zhou	Palazzo Ducale, Genova, Italy	16:40 - 17:00
OmniLearn: A Method to Simultaneously Facilitate All Jet Physics Tasks	Vinicius Mikuni	Palazzo Ducale, Genova, Italy	17:00 - 17:20
A multi-task Large Language Model for jets	Humberto Reyes-Gonzalez	Palazzo Ducale, Genova, Italy	17:20 - 17:40

What can kernel methods offer to HEP?	Lorenzo Rosasco	Palazzo Ducale, Genova, Italy	14:00 - 14:40
Accelerating resonance searches via signature-oriented pre-training	Congqiao Li	Palazzo Ducale, Genova, Italy	14:40 - 15:00
Streamlined jet tagging network assisted by jet prong structure	MIHOKO NOJIRI	Palazzo Ducale, Genova, Italy	15:00 - 15:20
Efficient machine learning for model-independent tests	Dr Marco Letizia	Palazzo Ducale, Genova, Italy	15:20 - 15:40
SPECTER: Efficient Evaluation of the Spectral EMD	Rikab Gambhir	Palazzo Ducale, Genova, Italy	15:40 - 16:00
Coffee break		Palazzo Ducale, Genova, Italy	16:00 - 16:20
NNLL results for the relation of the top quark mass parameter in Monte Carlo generators and the pole mass.	Aditya Pathak et al.		
An approach to pin down the top quark mass parameter in MC event generators	Andre Hoang	Palazzo Ducale, Genova, Italy	16:40 - 17:00
Using the W as a Standard Candle to Reach the top	Aditya Pathak	Palazzo Ducale, Genova, Italy	17:00 - 17:20
Determination of Higgs boson properties and searches for new resonances using highly boosted objects with the ATLA...	Kunlin Ran		
Top-quark jet substructure measured with the ATLAS detector	mario campanelli	Palazzo Ducale, Genova, Italy	17:40 - 18:00
How to Unfold Top Decays	Sofia Palacios Schweitzer	Palazzo Ducale, Genova, Italy	18:00 - 18:20

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Searches for Higgs boson production through decays of heavy resonances	Suman Chatterjee	Palazzo Ducale, Genova, Italy	09:20 - 09:40
Probing the Supersymmetric Standard Model at the Large Hadron Collider through Vector Boson Fusion Processes and	Umar Sohail Qureshi		
Search for heavy BSM particles in final states with boosted top quarks or W bosons at CMS	Alberto Orso Maria Iorio	Palazzo Ducale, Genova, Italy	10:00 - 10:20
Searches for new physics using unsupervised machine learning for anomaly detection in $\sqrt{s}$ = 13 TeV pp colli...	Benjamin Michael Wynne		
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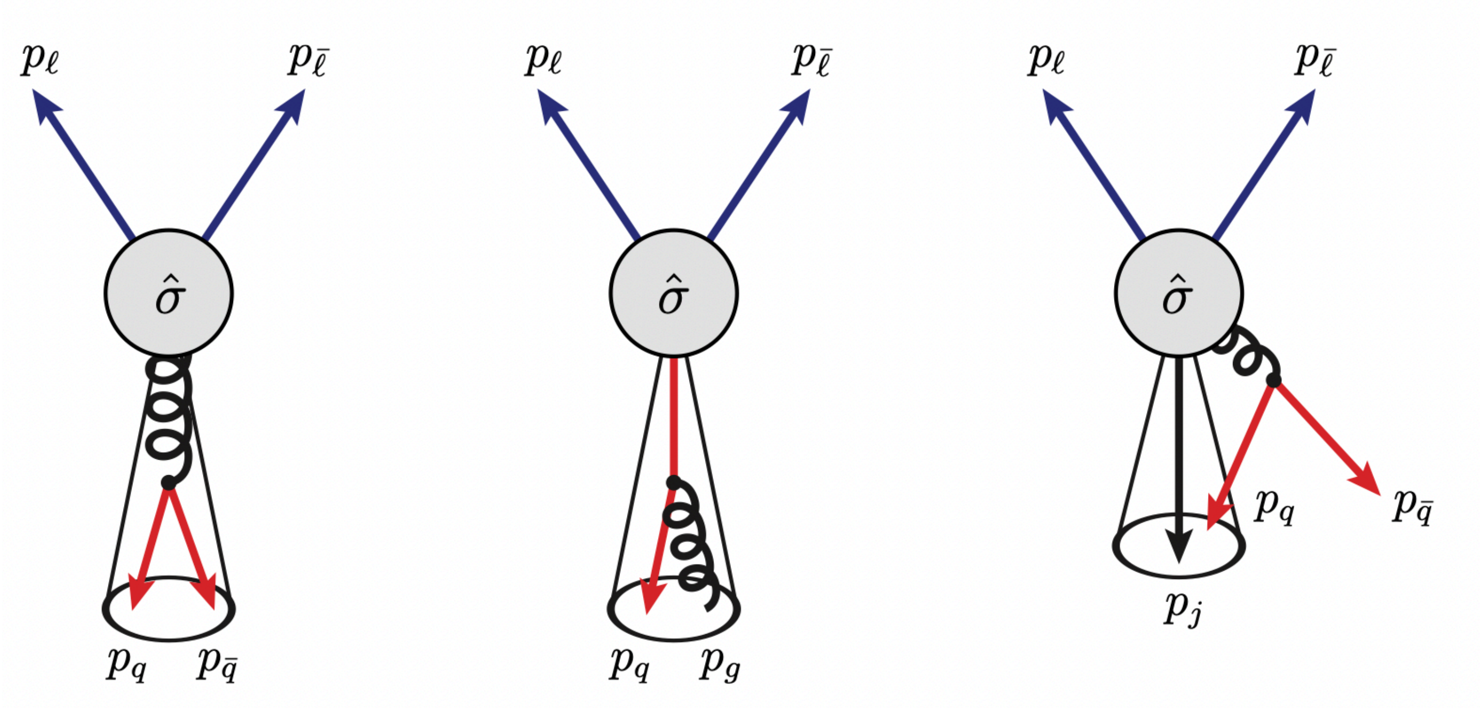
Jet flavour

Example: LHCb charm-jet definition

LHCb 2109.08084

- reconstruct jets with anti-k_t algorithm
- require that the leading jet passes fiducial cuts
- the leading jet is considered a charm jet if there is at least one c-hadron satisfying $p_{t,\text{c-hadron}} > 5$ GeV and $\Delta R(\text{jet,c-hadron}) < 0.5$

This definition is infrared and collinear unsafe when applied to massless charm



Jet flavour

Old proposal: based on k_t algorithm — Banfi, Salam, GZ ’06

Recent proposals:

Practical jet flavour through NNLO — Caletti et al. ’22

Infrared-safe flavoured anti-k_t jets — Czakon et al. ’22

A dress of flavour to suit any jets — Gauld et al. ’22

Flavoured jets with exact anti-k_t kinematics — Caola et al. ’23

Goals

- anti-k_t like kinematics
- infrared-safe to all orders
- flavour information, e.g. for jet-substructure
- experimentally feasible

Whether these novel jet definitions will be used in experimental analyses remains to be seen …

Effective field theories

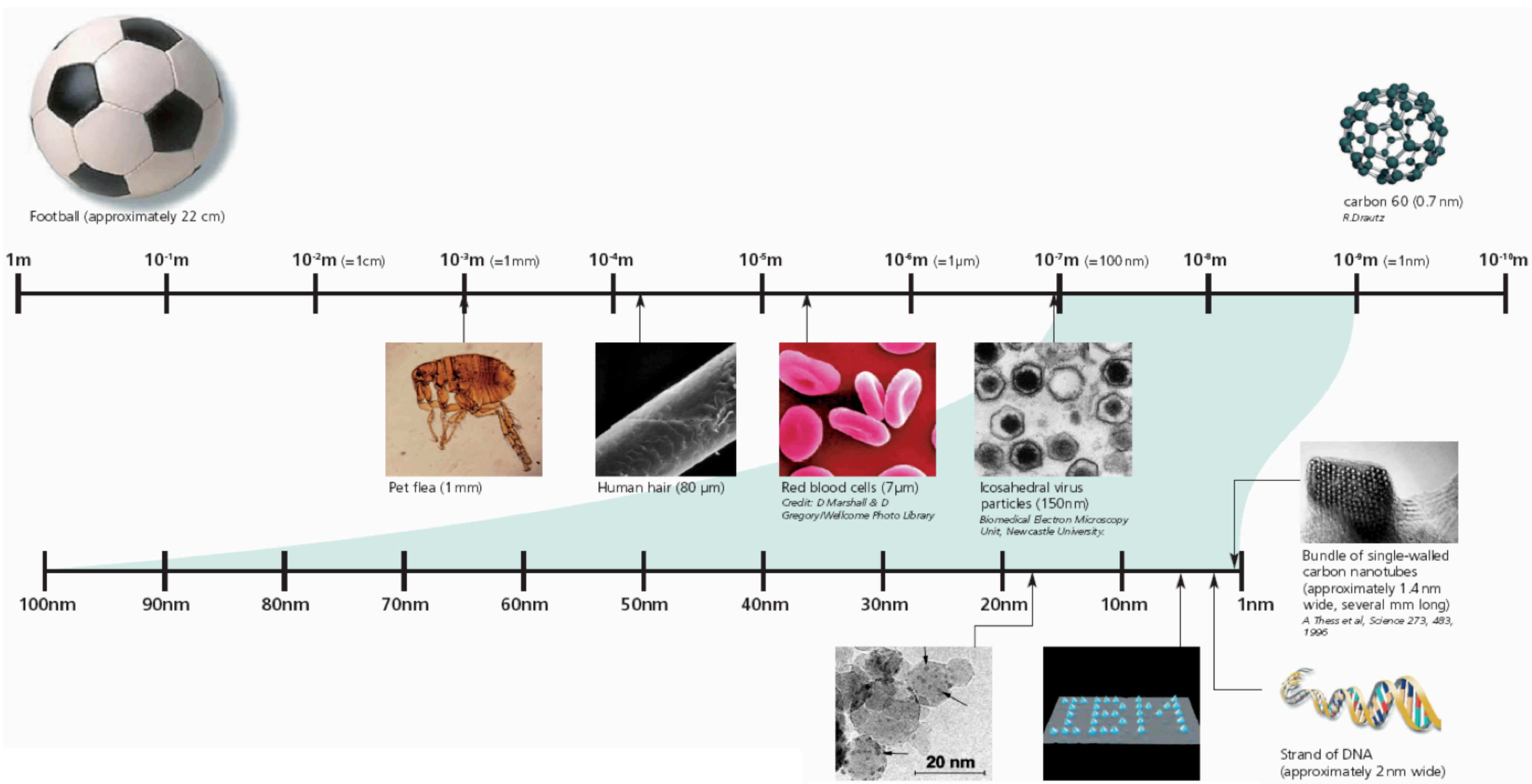
At the LHC

In ~~football~~ as in watchmaking, talent and elegance mean nothing without rigour and precision.

Lionel Messi

Effective field theories

The physical idea behind EFTs, scale separation, is ubiquitous:



ETFs on one hand allow to achieve precision by neglecting irrelevant details, on the other hand ETFs allow to probe sensitivity to higher scales anticipating possible discoveries.

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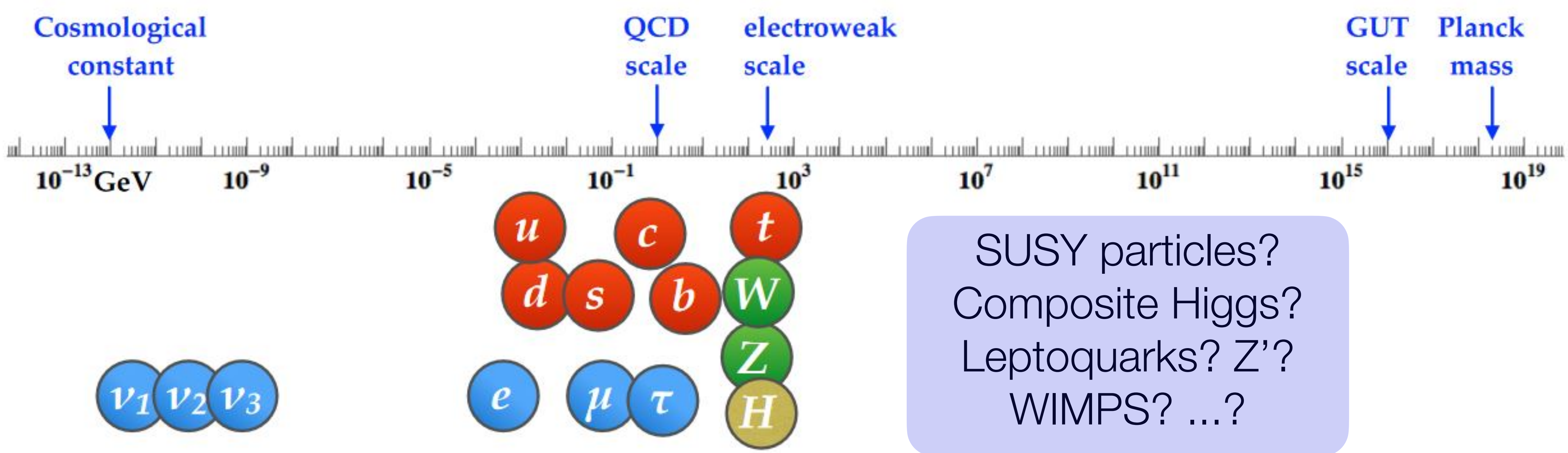

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Effective field theory

<u>SMEFT:</u> integrate out unknown, heavy states

$$\mathcal{L} \approx \mathcal{L}_{\text{SM}}^{D=4} + \sum_{i=1}^{2499} \frac{C_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(D=6)}$$

$\mathcal{C}_i^{(6)}$: UV Wilson coefficients

$\mathcal{O}_i^{(D=6)}$: IR sensitive operators

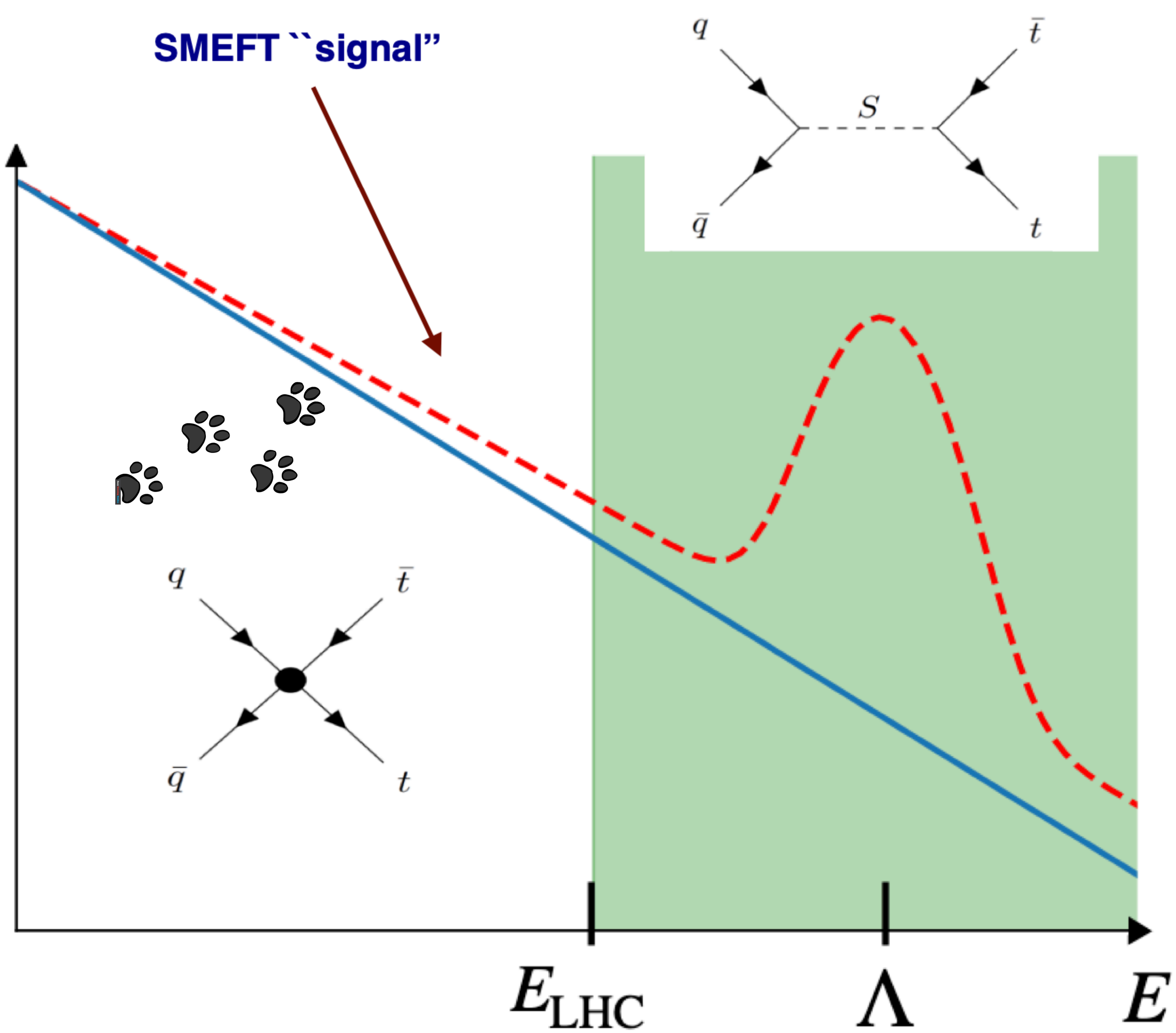
# of relevant operators reduced using symmetries and kinematic suppressions. Still, lots of data needed to break degeneracies.

EFT as bridge to a new theory. Many UV theories share the same EFT operators ⇒ calls for automation

HighPT, MATCHMAKEREFT, MATCHETE, SMEFT, SMEFiT

Effective field theory

Targets non-resonant signals, footprint of new physics:



Most interesting: new Lorentz structures, helicity selection rules, interferences …

Effective field theory

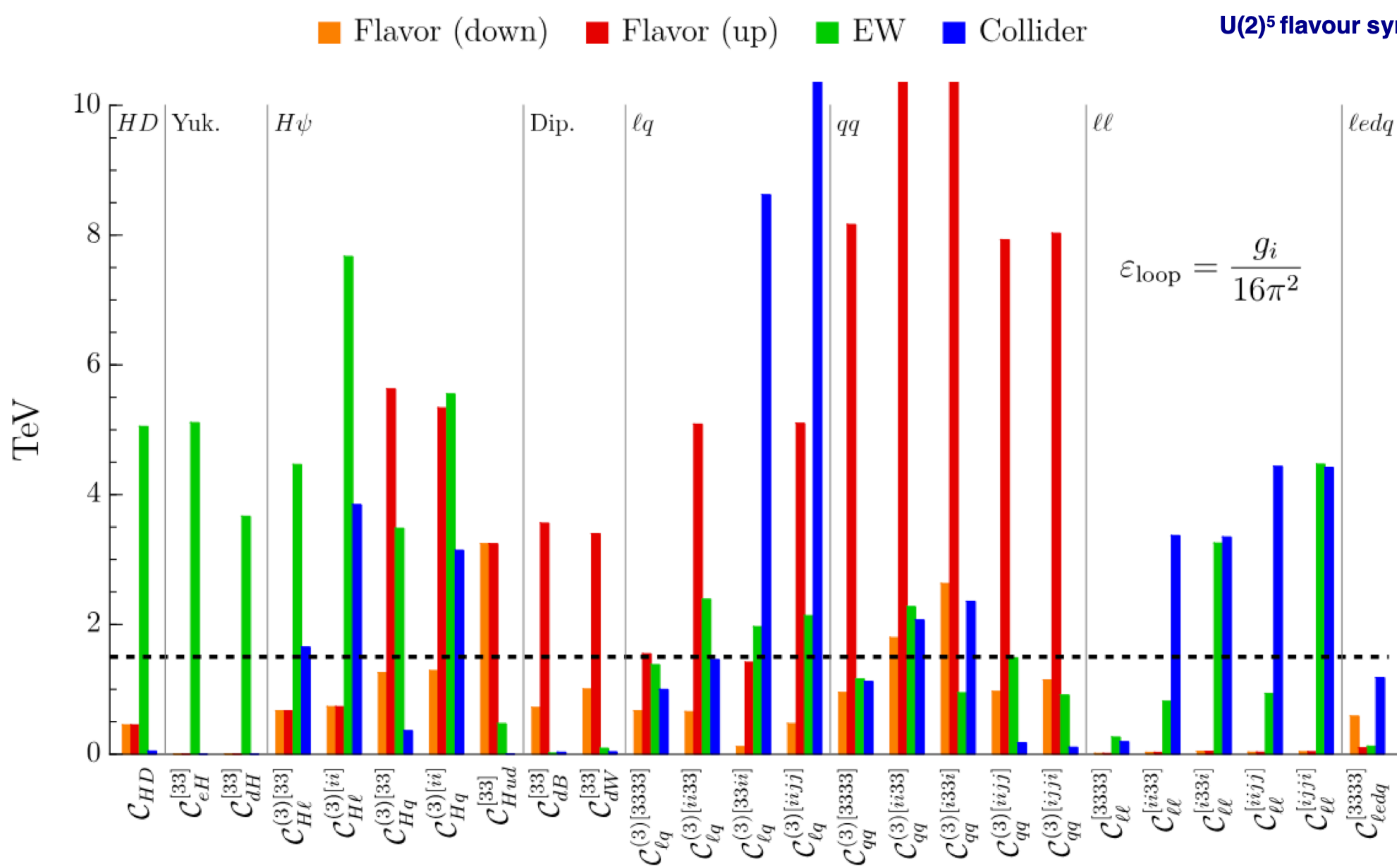
Many theory issues to be addressed:

- Assumptions about flavor & other symmetries (e.g. $\not{C}P$ in Higgs sector)
- Definition of representative scenarios and benchmarks
- Relevance of dimension-eight contributions and applicability of EFT to high p_t processes
- EFT validity, flat directions and correlations
- Dependence on input schemes
- Theory constraints (unitarity, positivity, etc.)
- $\not{C}P$ terms integrate to 0 in interference terms for CP even observables
- Consideration of beyond-SMEFT EFT frameworks
- jointly fit PDFs and Wilson coefficients

Caveats and prospects

Complementarity of flavour, EW and high-p_t colliders, and great potential of Tera-Z machine (e.g. FCC-ee)

U(2)⁵ flavour symmetry

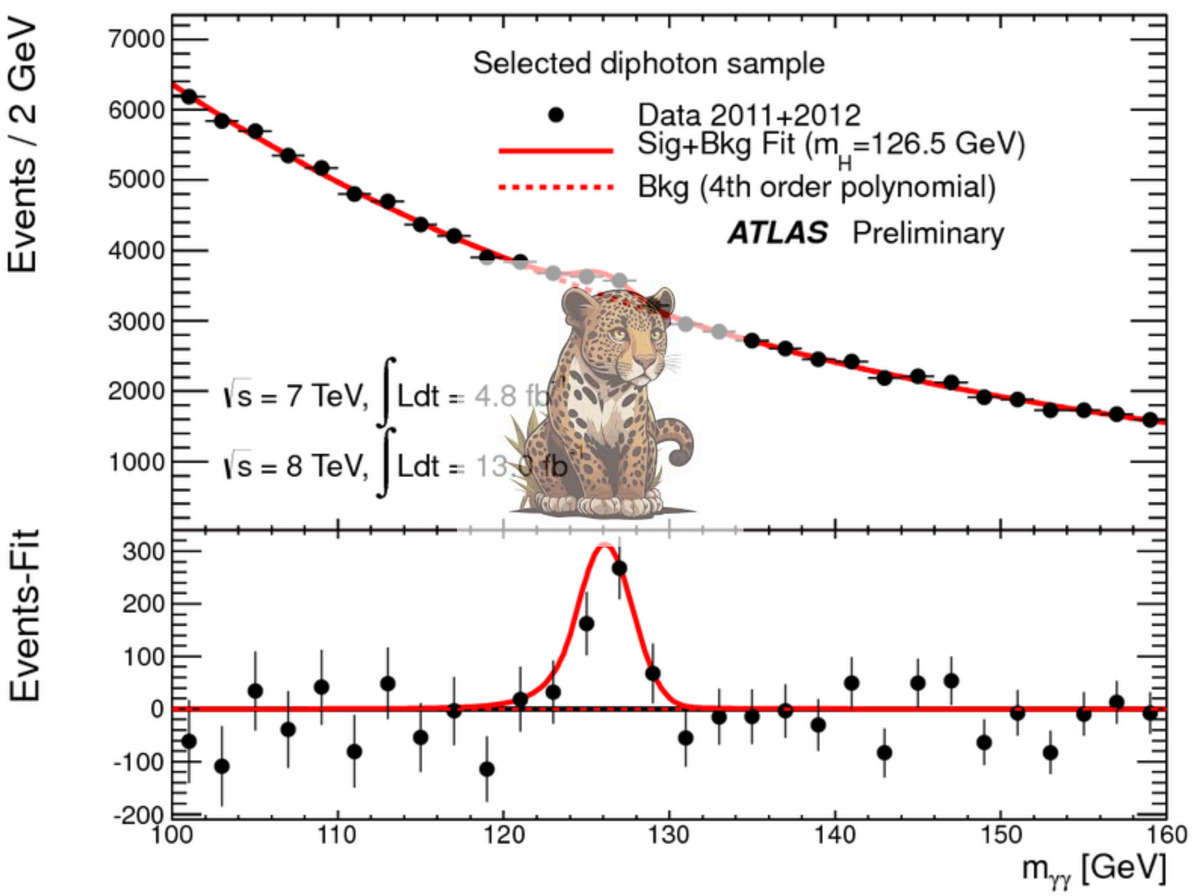


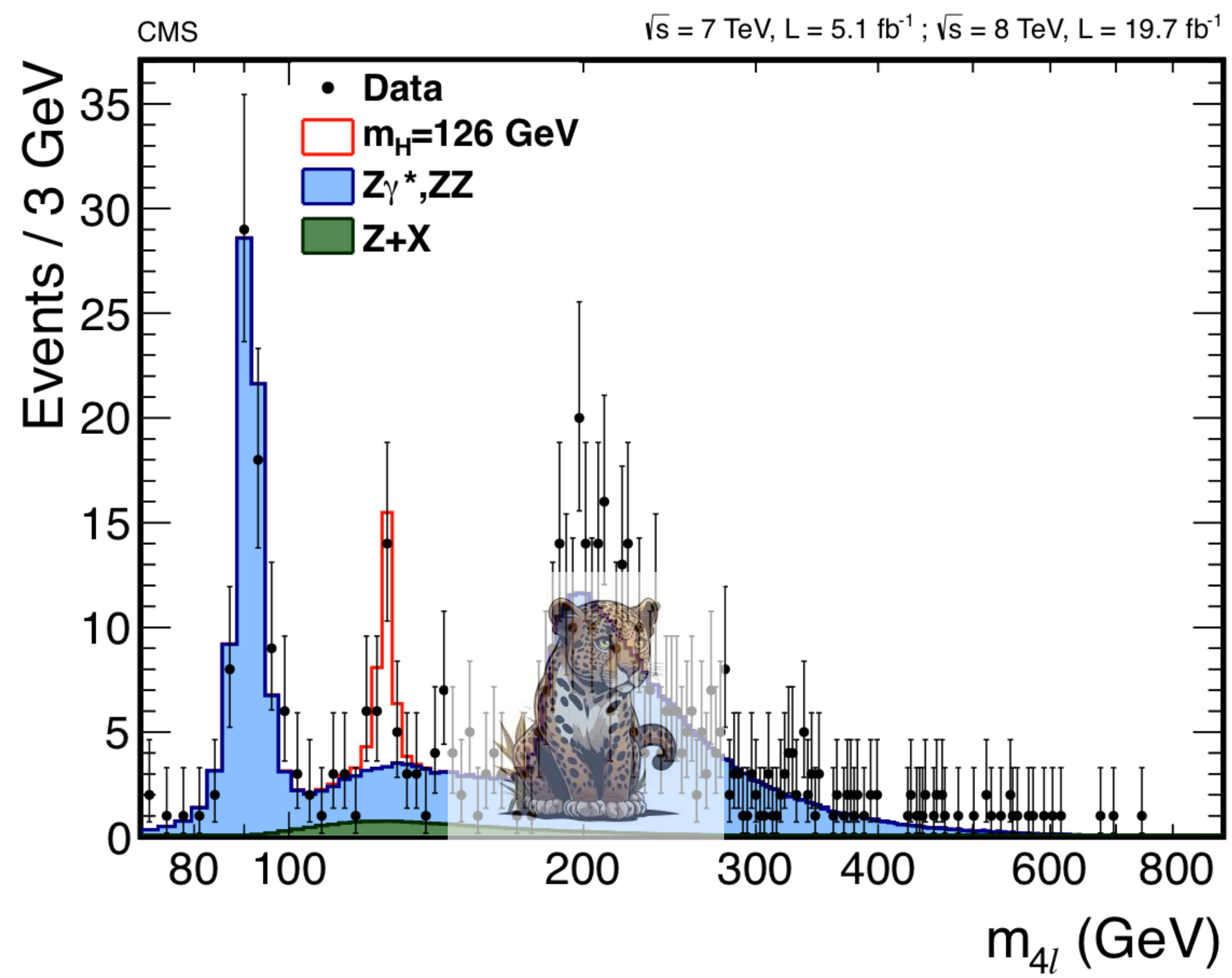
Allwiche
Isidori,
arXiv:2

3. Providing a theory interpretation of signals

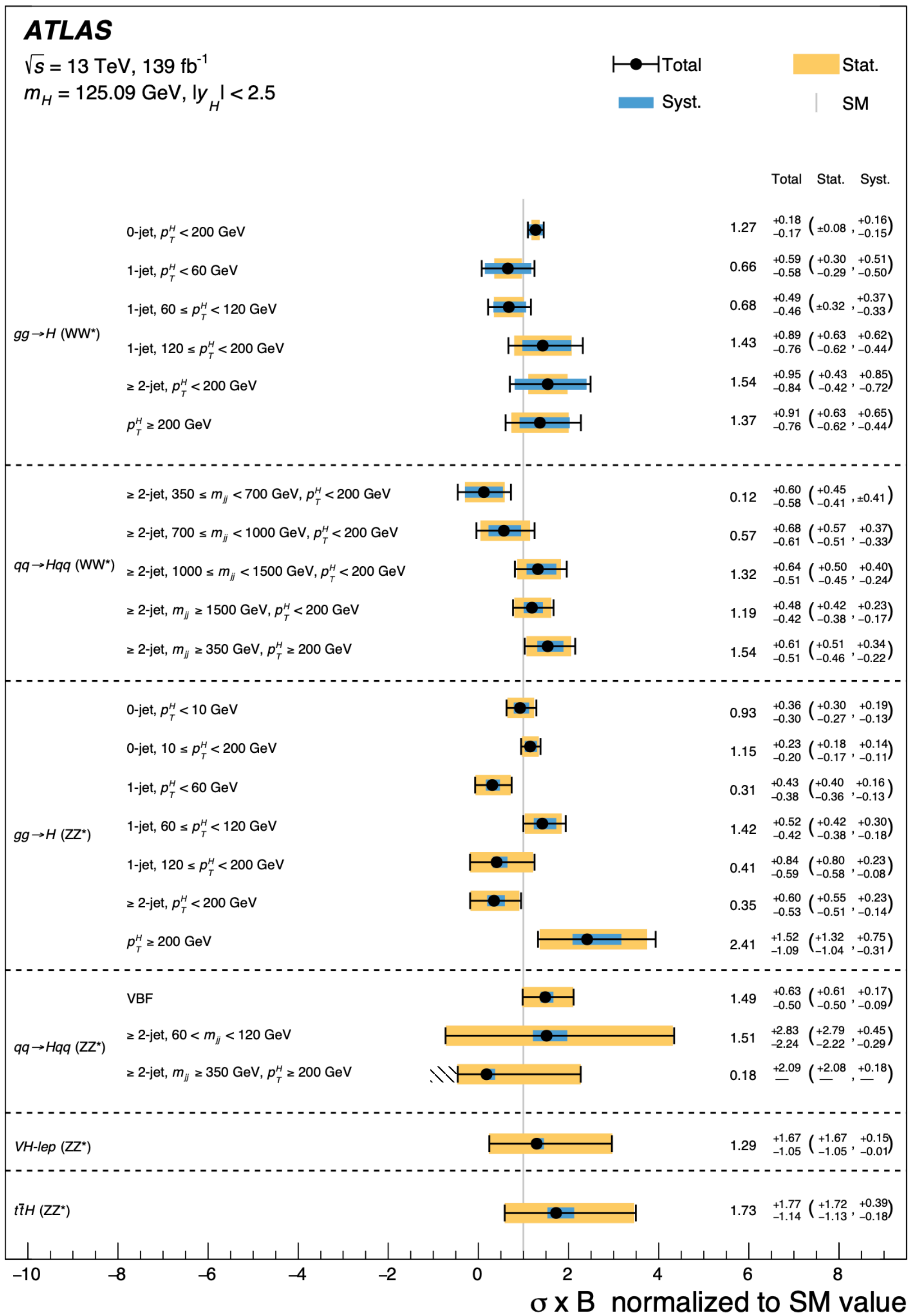
Higgs discovery

Higgs: a theory independent discovery





Higgs discovery



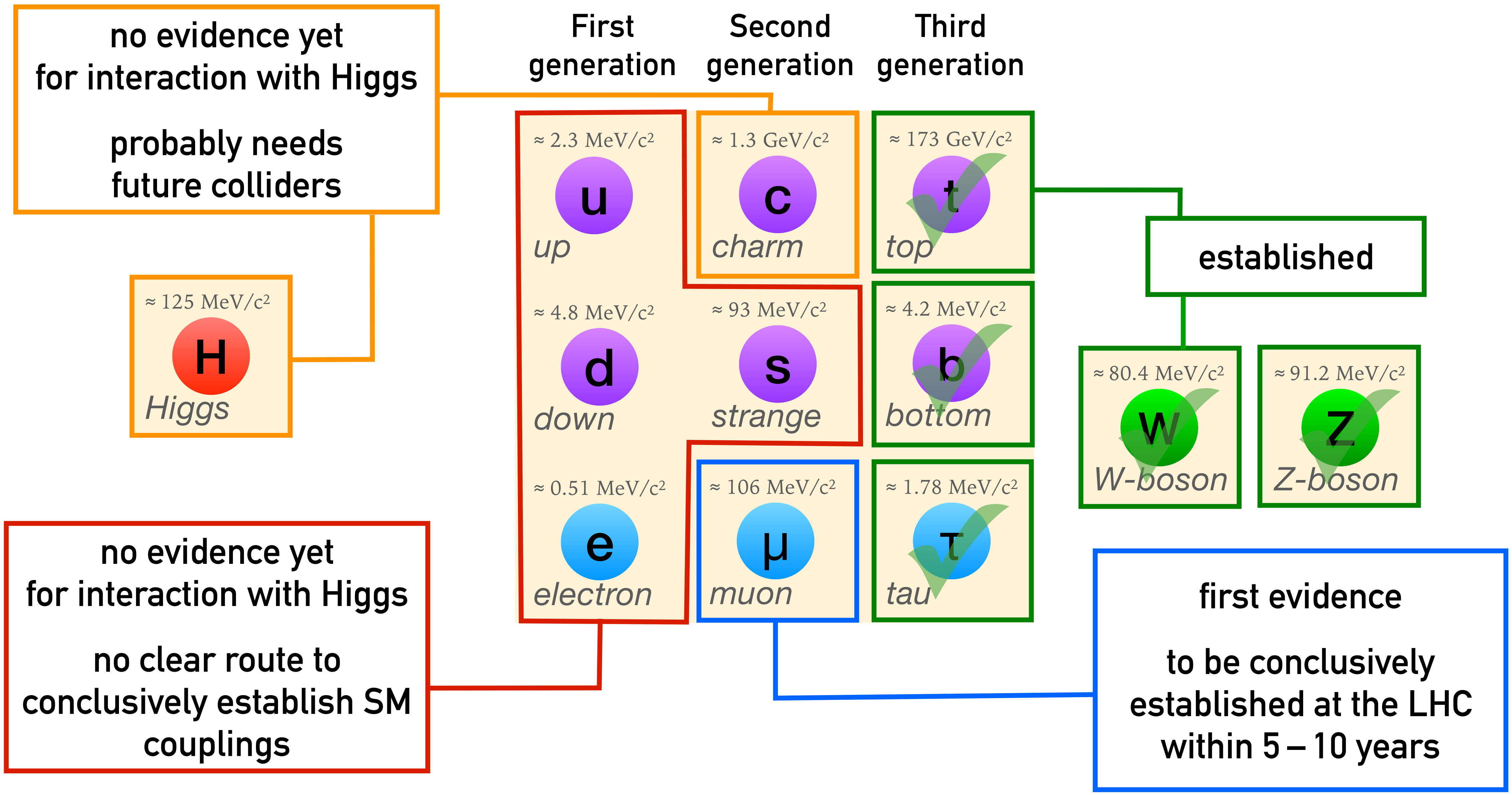
Theory crucial for the interpretation of discoveries

Charting the Higgs sector

- 5-20% accuracy in many production/ decay channels
- Exploring the Yukawa interaction
- First constraints on the Higgs potential

Higgs interactions

Status and prospects of our knowledge of Higgs interactions with known particles



Nature, 2022

Higgs and New Physics

Seeds of New Physics in the Higgs Lagrangian:

$$\mathcal{L}(\phi) = (D_\mu \phi)^\dagger (D^\mu \phi) - \mu_0^2 |\phi|^2 + \lambda |\phi|^4 + Y_{ij} \bar{\psi}_L^i \psi_R^j \phi$$

Gauge invariant mass generation of gauge bosons in the SM

The Higgs mass terms. Connected to the naturalness problem

The Higgs quartic self-interaction. Connected to the question of the stability of the potential

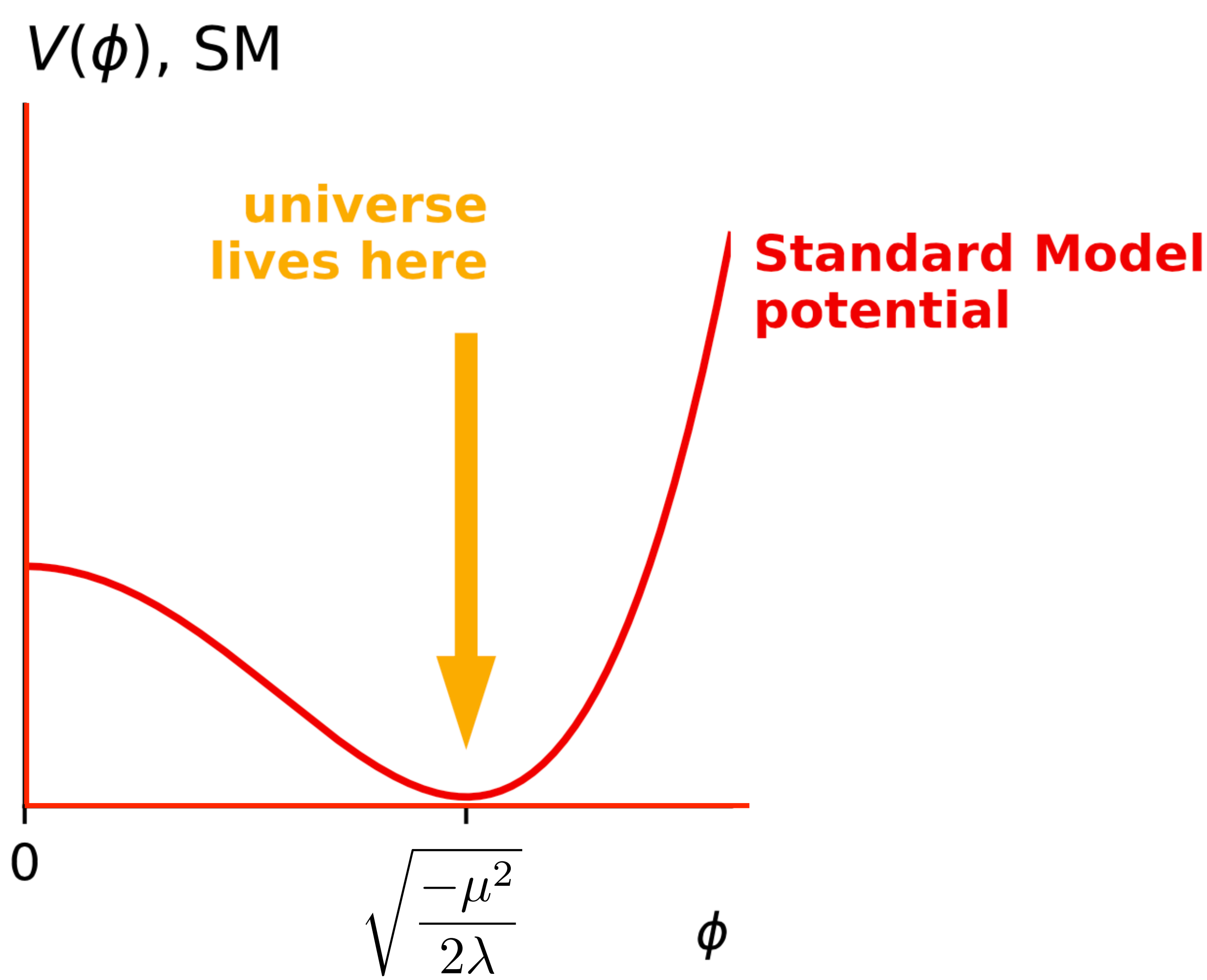
Yukawas give mass to fermions. Connected to flavour/CP problem

Higgs potential

$$V(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4$$

Theorist's assumption

the cornerstone of the SM, also connects with the stability of the universe

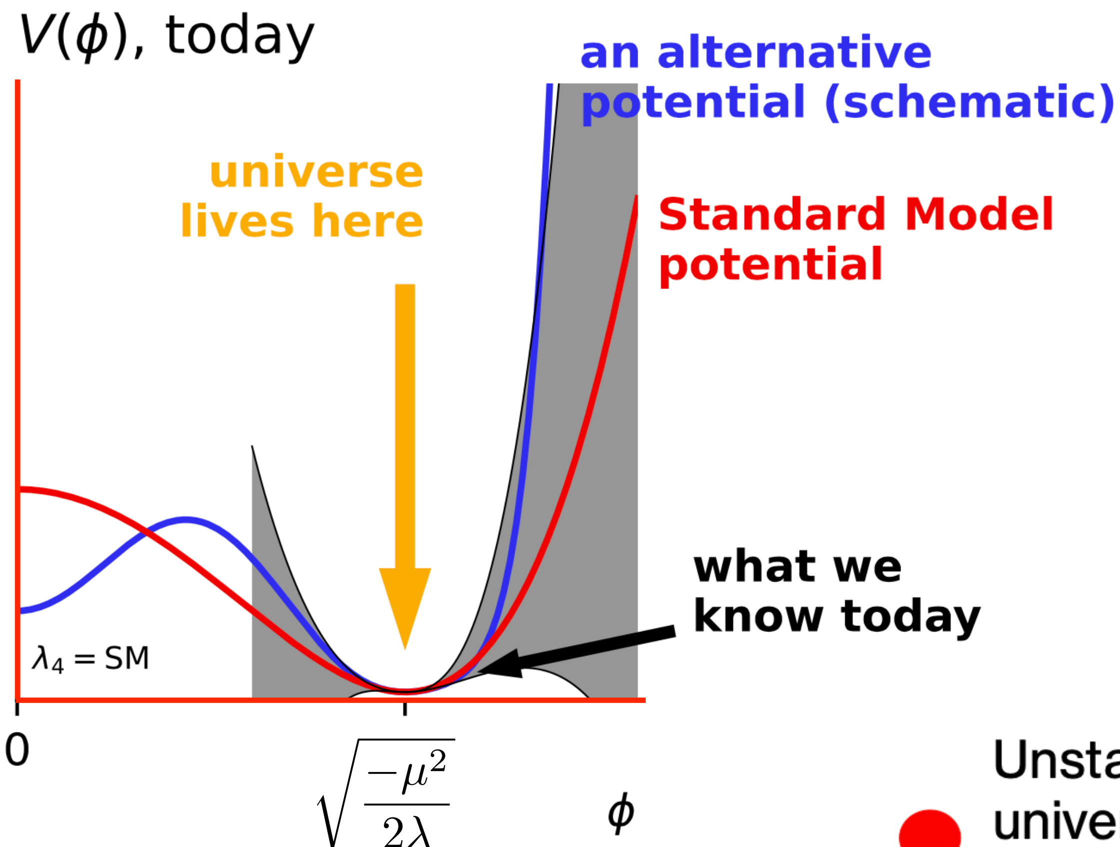


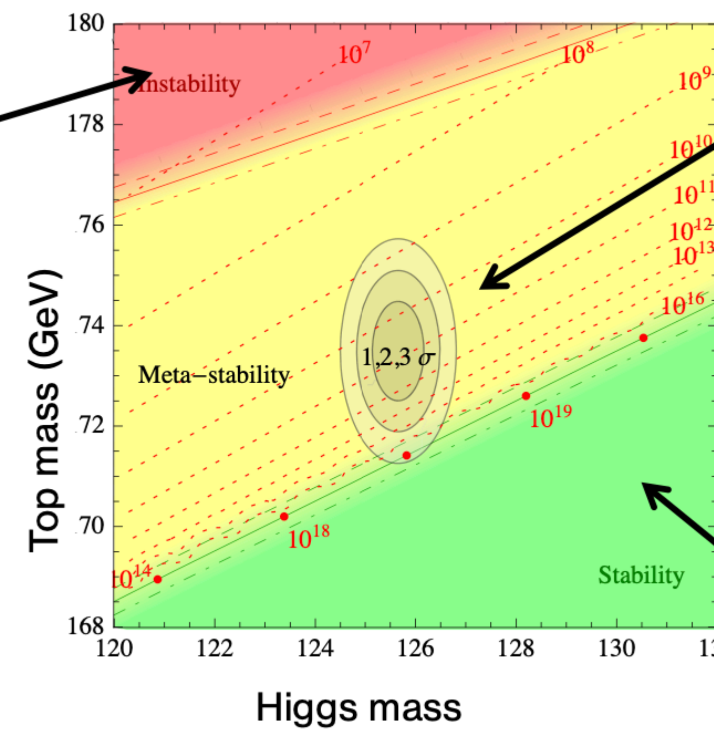
The Higgs boson is responsible for the masses of all particles. Its potential, linked to the Higgs self-coupling, is predicted in the SM, but we have not tested it so far

Establishing this assumption is a big answerable question, a guaranteed pay-off

Higgs potential

What did we establish so far?





Whether or not the Higgs potential is unstable depends sensitively on precision measurements of M_t

Conclusions

- Remarkable progress from the theory side

  New ideas, new tools, record-breaking calculations, new observables, …

  Theorists are keeping up well with amazing experimental efforts

- So far, we have beautiful agreement between theory predictions and experimental data, marking a remarkable success of the SM

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When is the precision reached good enough?

When is it the time to stop?

Conclusions

But now, with the Higgs-boson found in 2012, their theory - the "standard model of particle physics" - is complete. It's fine. There's nothing missing. ***All Pokemon caught.***

S. Hossenfelder, 2019

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The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote. ***Our future discoveries must be looked for in the sixth place of decimals.***

Albert A. Michelson, 1894

Conclusions

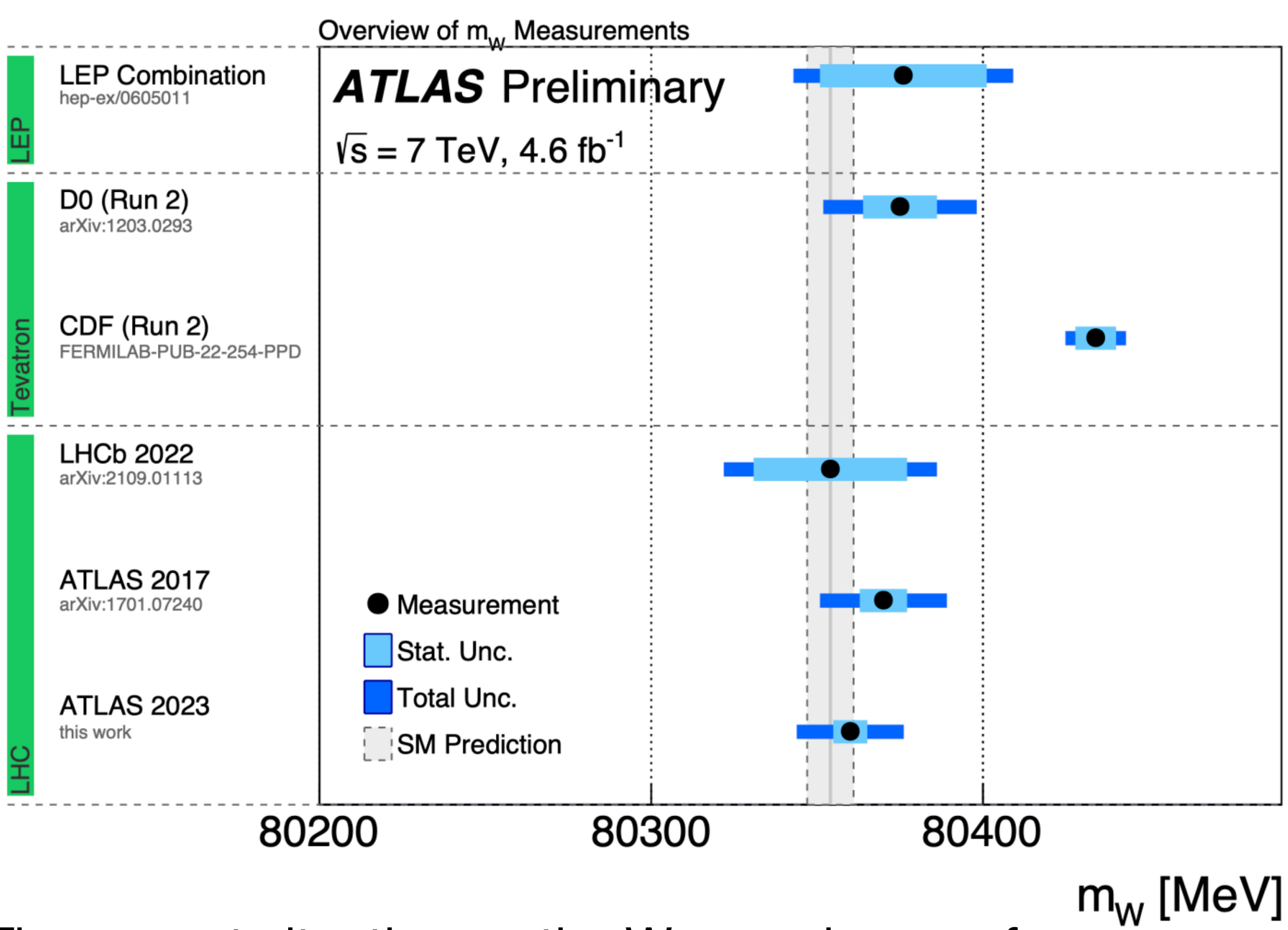
Maybe we caught all pokemons, but the game is far from over. We are getting ready to play the next level.

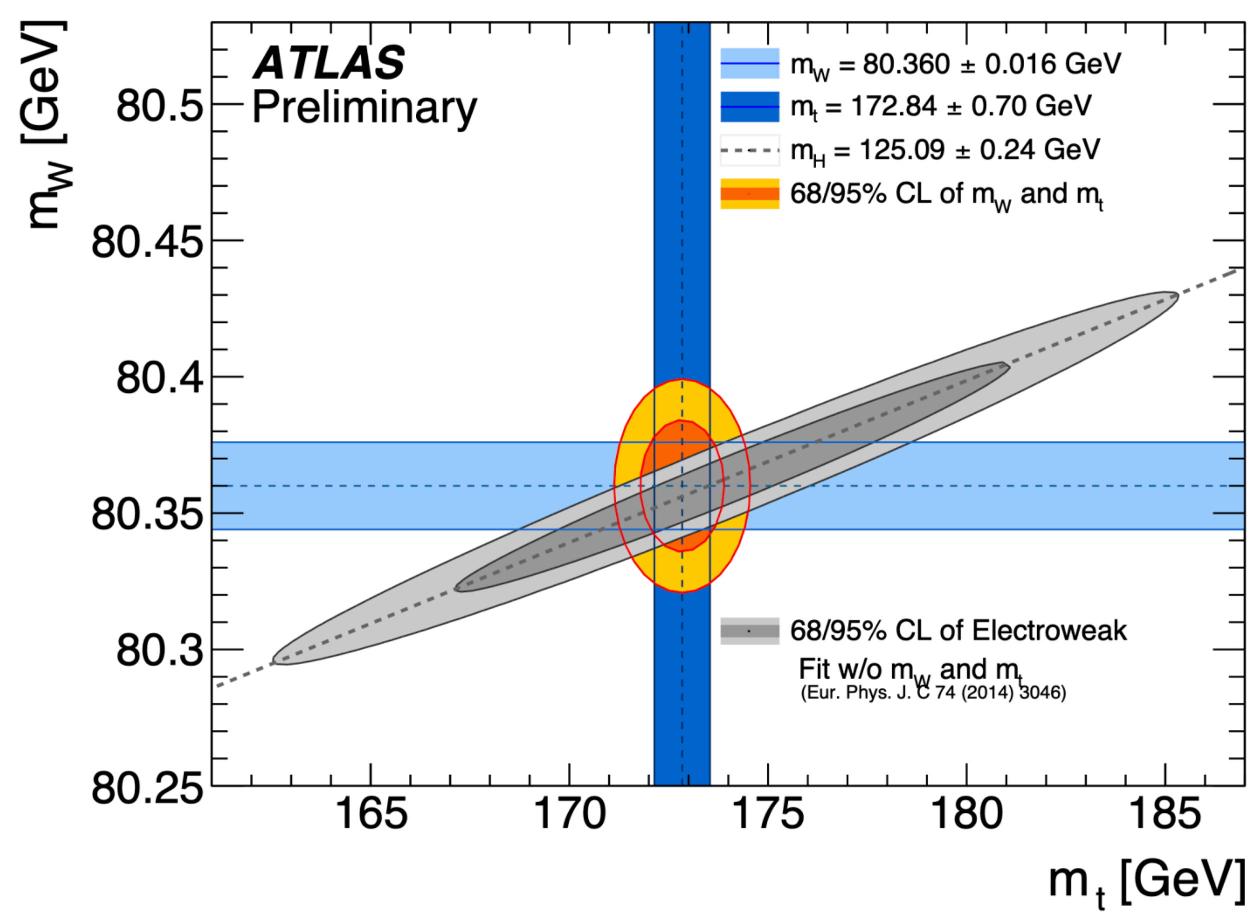
Colliders, i.e. high-energy controlled experimental setups, are the best bet to address a varied of fundamental questions.

We face deep, fundamental questions. Answering them will require to think big, act bold, work hard and be patient!

W mass

Extraction of W mass to the current level of precision without precision theory predictions unimaginable





The current situation on the W mass is one of discrepancy between different experiments.

New observables for W mass

Asymmetry around Jakobian peak

$$\mathcal{A}_{p_\perp^\ell}(p_\perp^{\ell,\mathrm{min}}, p_\perp^{\ell,\mathrm{mid}}, p_\perp^{\ell,\mathrm{max}}) \equiv \frac{L_{p_\perp^\ell} - U_{p_\perp^\ell}}{L_{p_\perp^\ell} + U_{p_\perp^\ell}}$$