Theory Summary

A personal perspective

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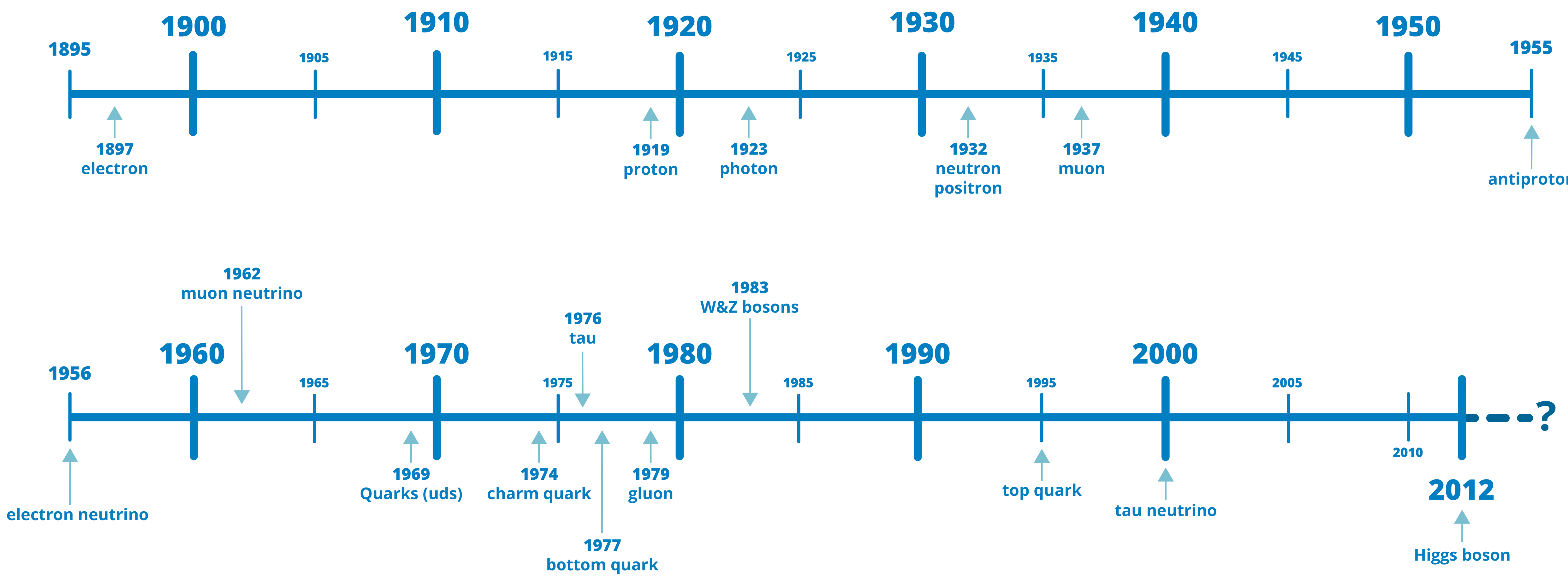
Timeline of particle discoveries

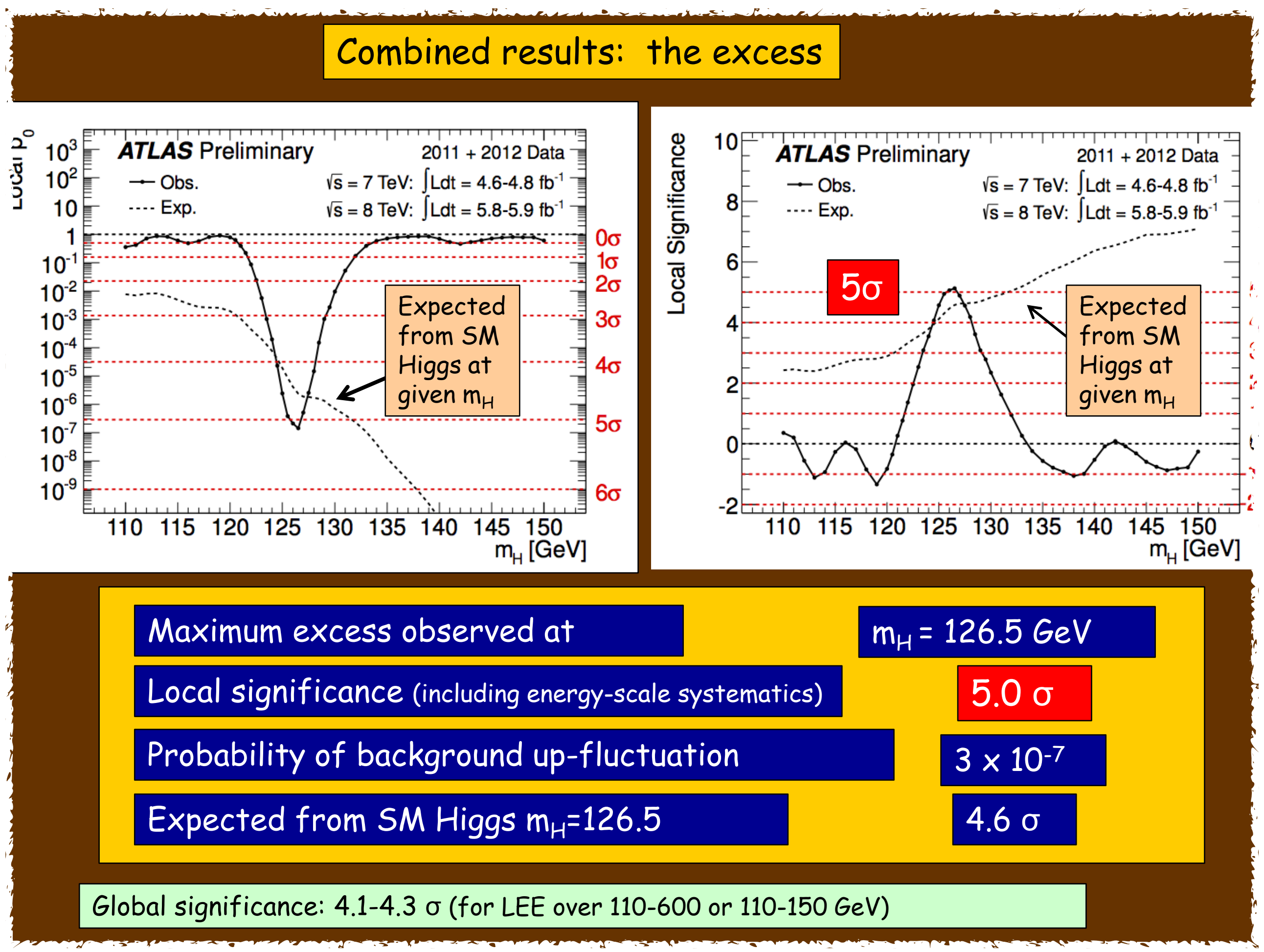
ATLAS EXPERIMENT



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.

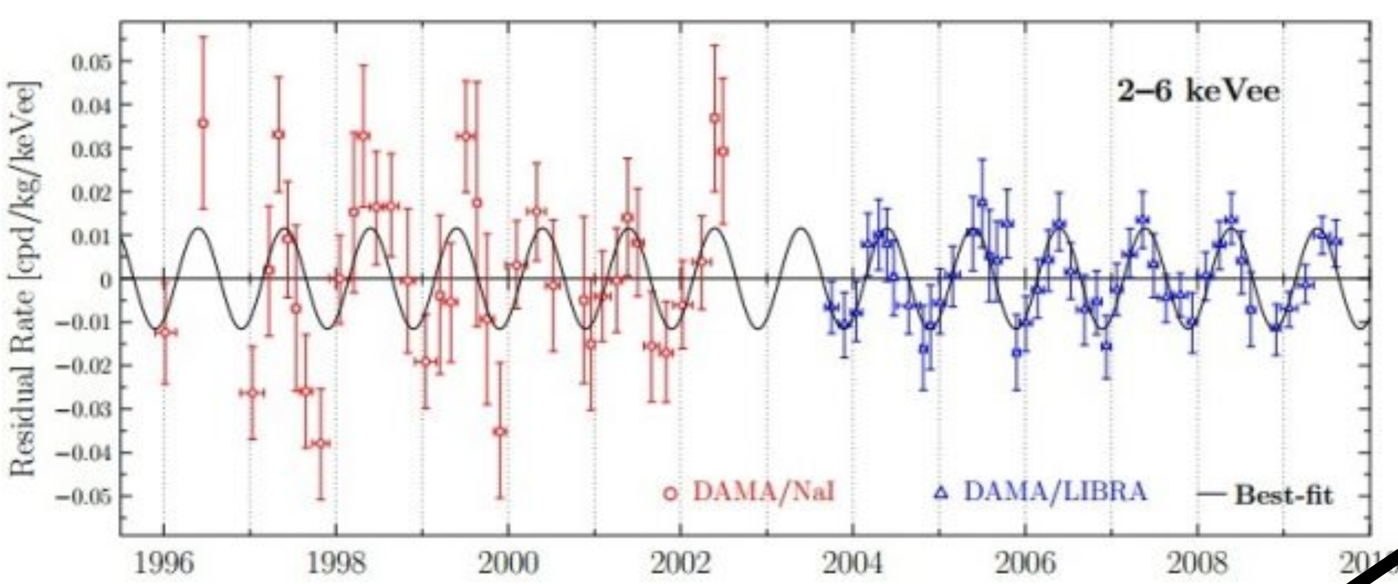
- What stabilises the Higgs mass? ATLAS, CMS …
- What solves the strong CP problem? ADMX, CAST, IAXO …
- What generated the matter-antimatter asymmetry? ALICE, Belle II, Daya Bay, LHCb, NA62, T2K, …
- What is the nature of Dark Matter? LUX, XENON, DarkSide, Super-CDMX …
- What drives the expansion of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

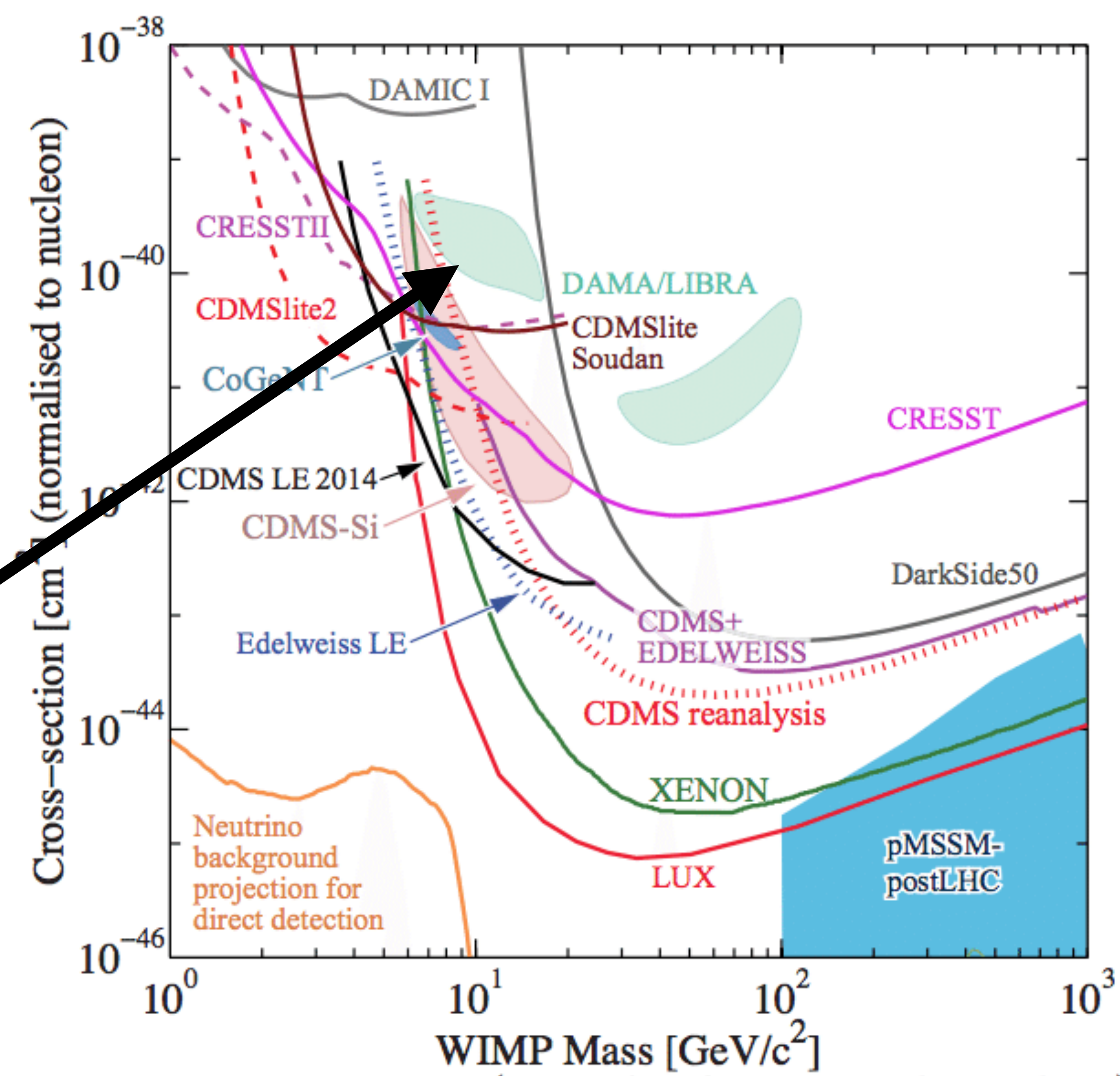
Trying to answer these theory questions has been shaping a very rich and diverse landscape of experimental activities

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

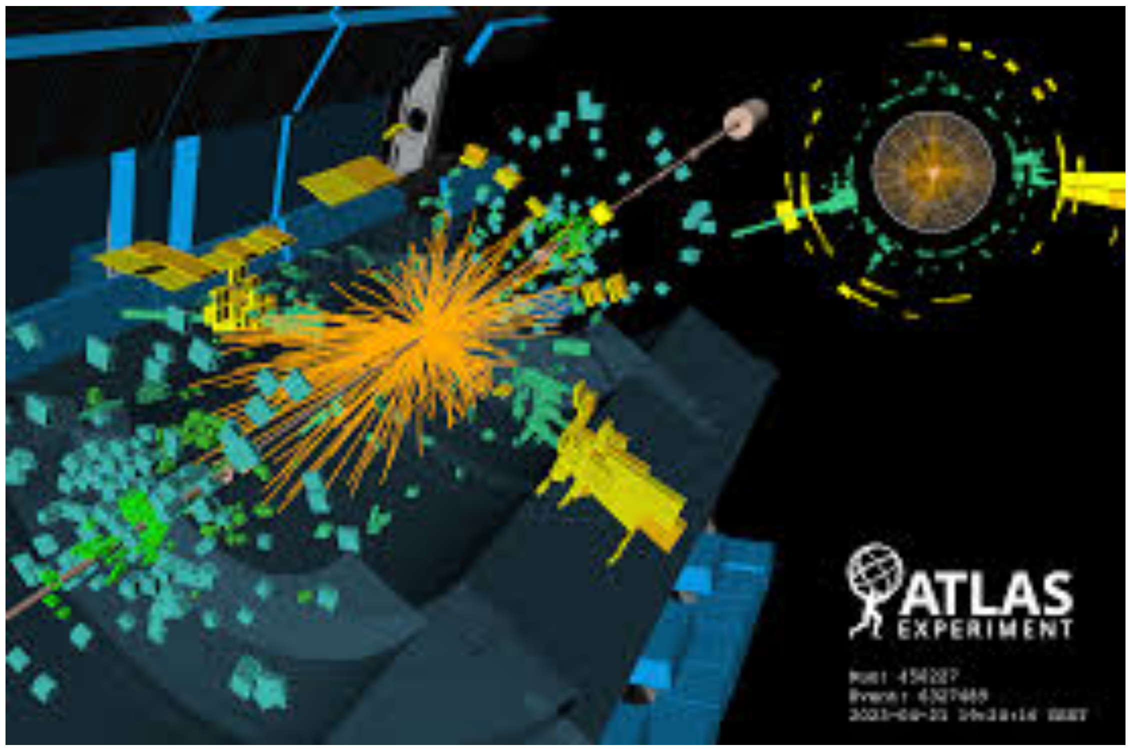
1. Predicting signals and backgrounds $\Rightarrow$ increasing sensitivity to new phenomena
2. Guiding experimental searches $\Rightarrow$ optimising final states and observables
3. Providing a theory interpretation of signals

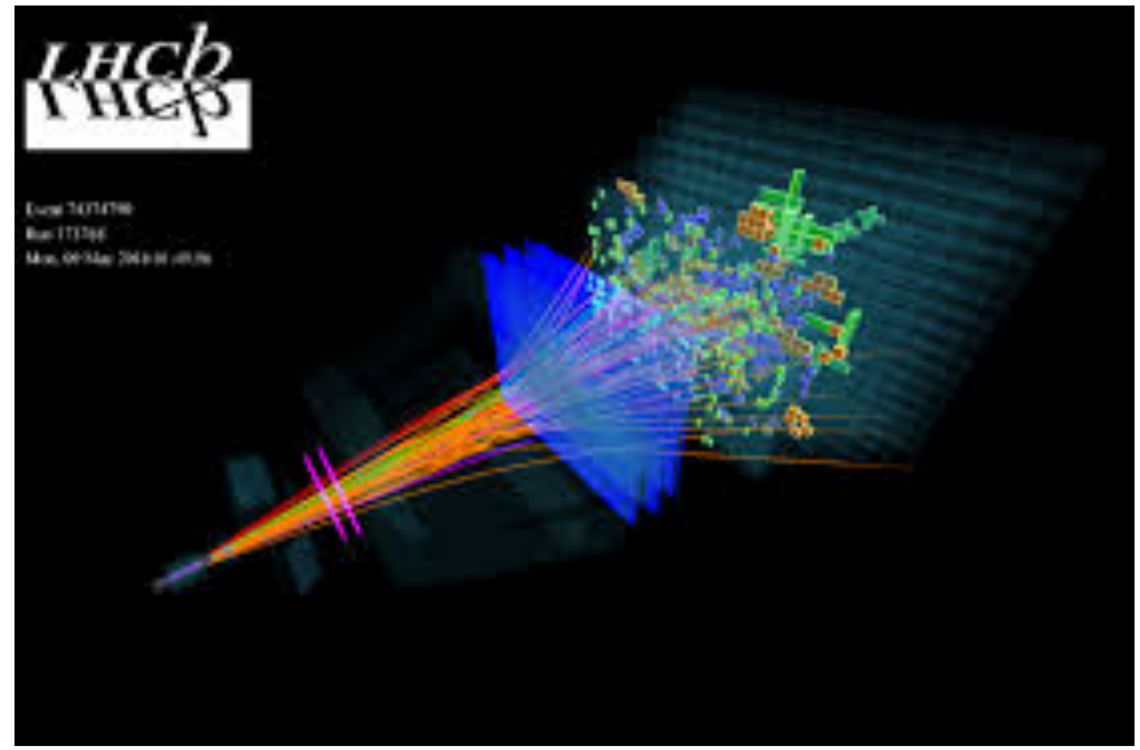
For the future, theory has a crucial in addressing the questions

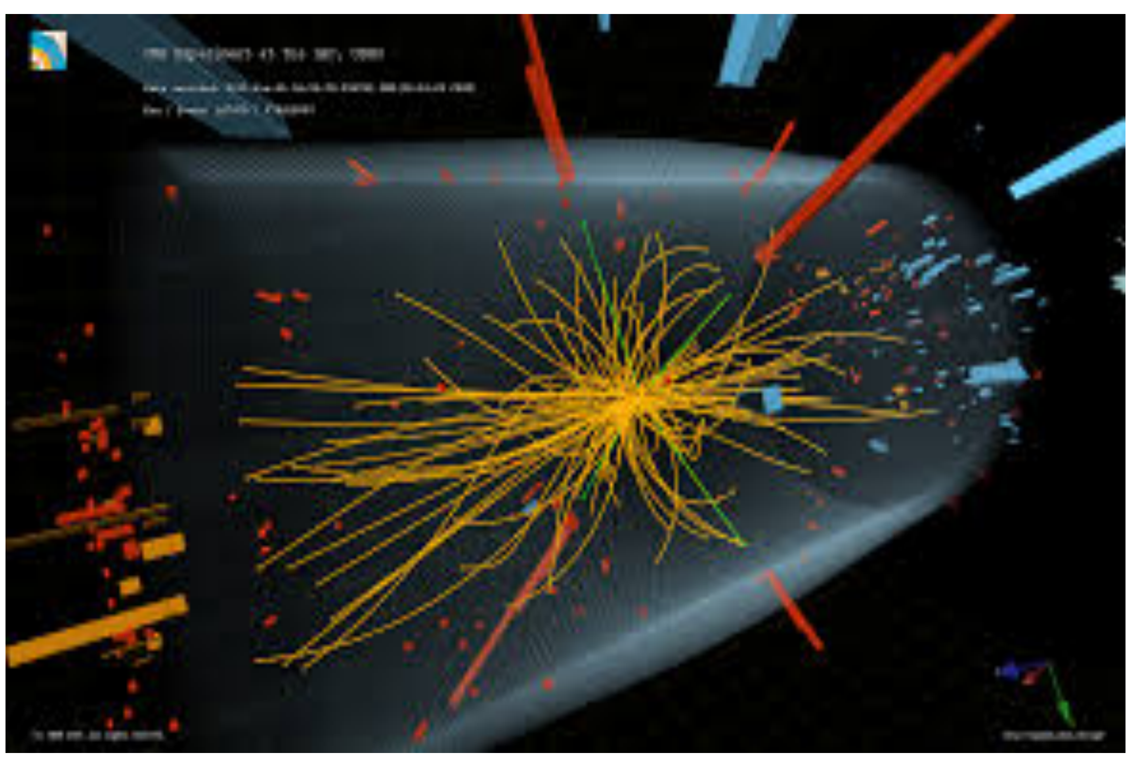
- What should the next collider be?
- Given a collider, what should the requirements of future detectors/experiments be?

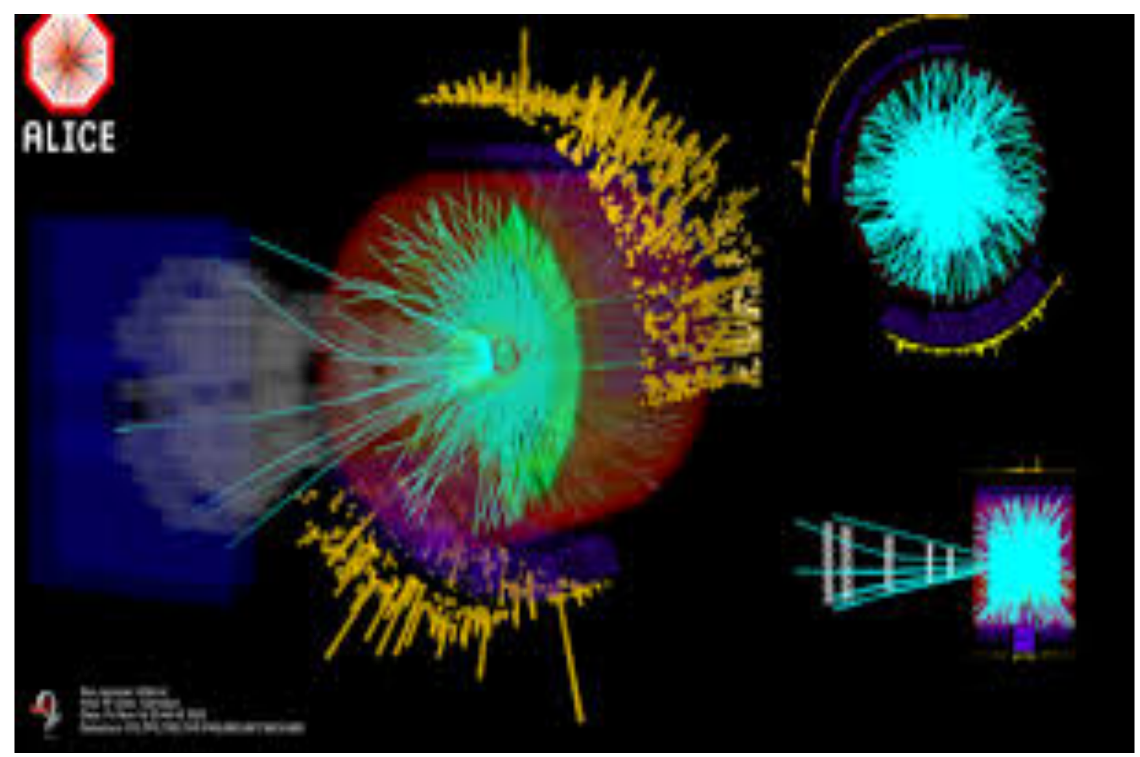
1. Predicting signals and backgrounds
$\Rightarrow$ increasing sensitivity to new physics

Collider events: real world









Theorist point of view

Largely based on factorization

Hard partonic scattering

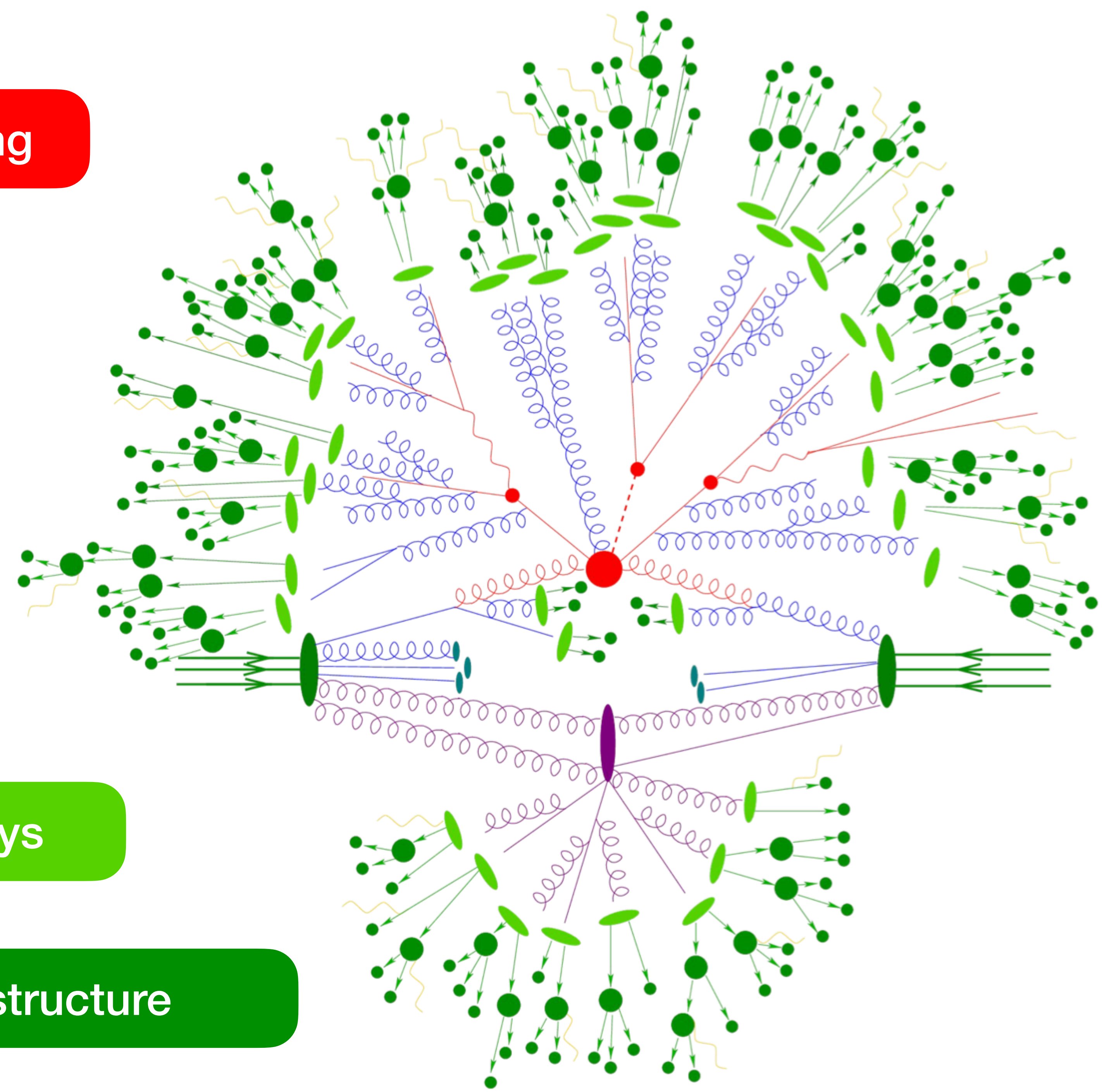
Parton shower

PDFs/underlying event

QED/photons

Hadronization/decays

Jets/substructure



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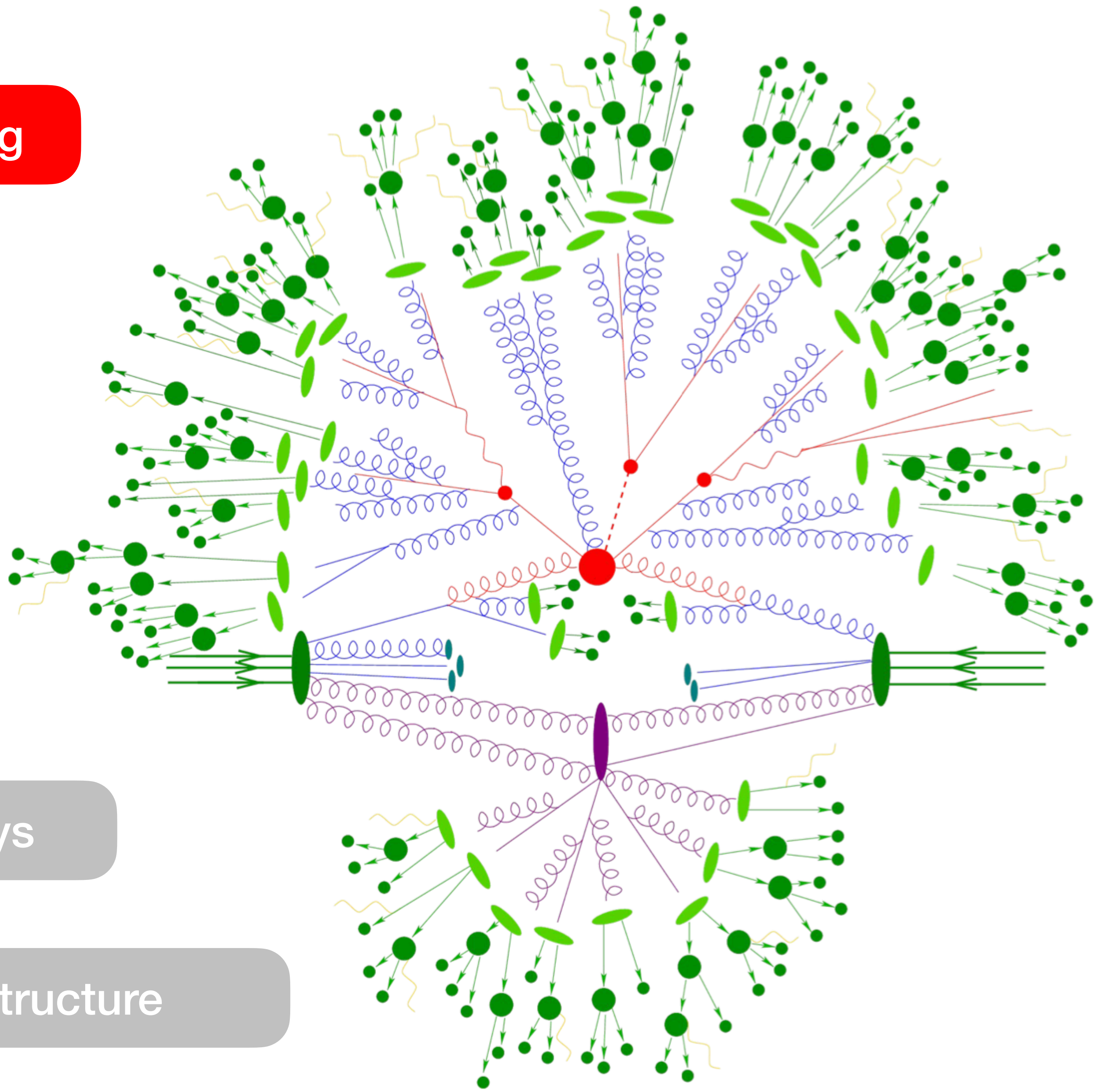
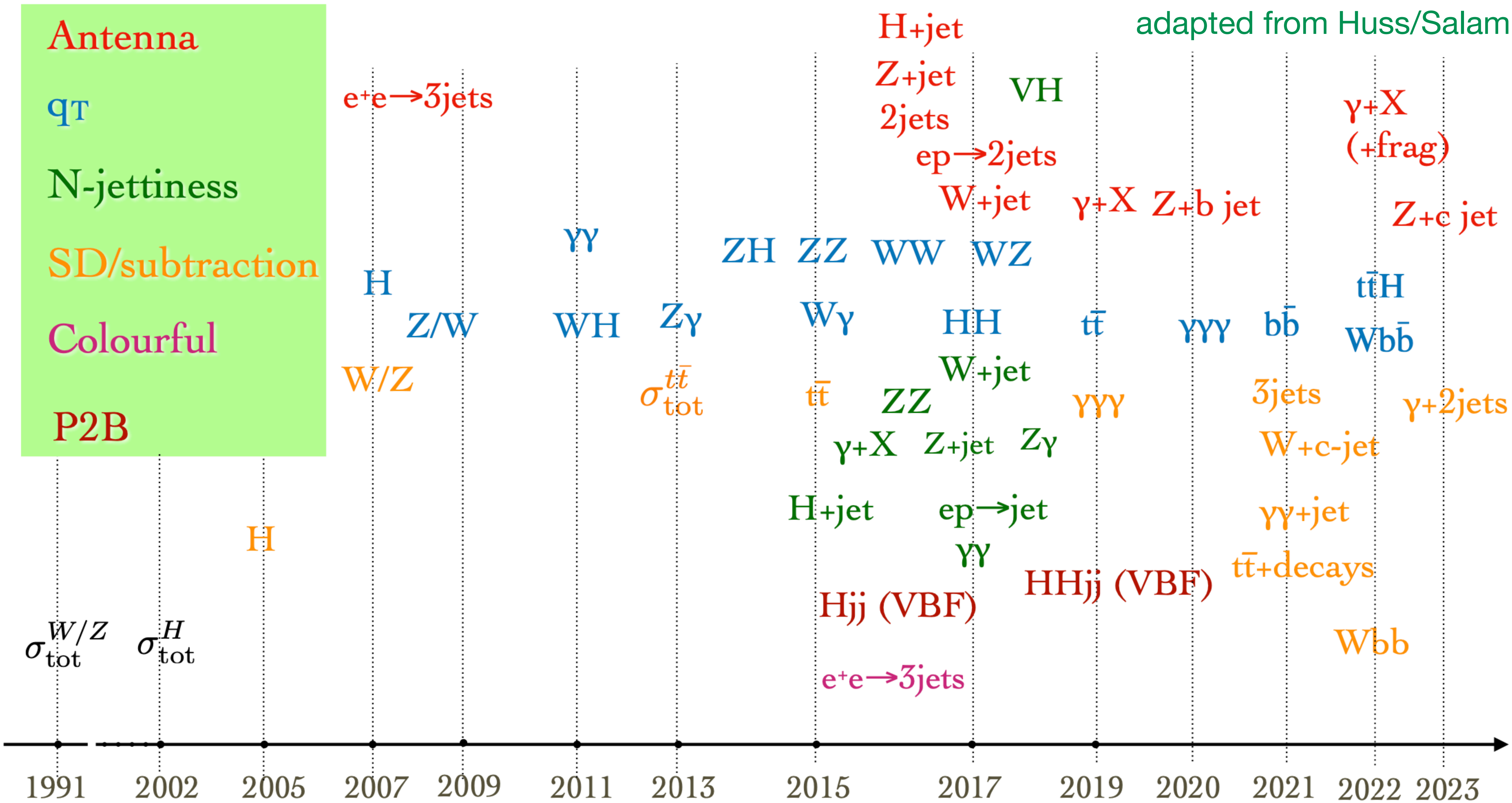


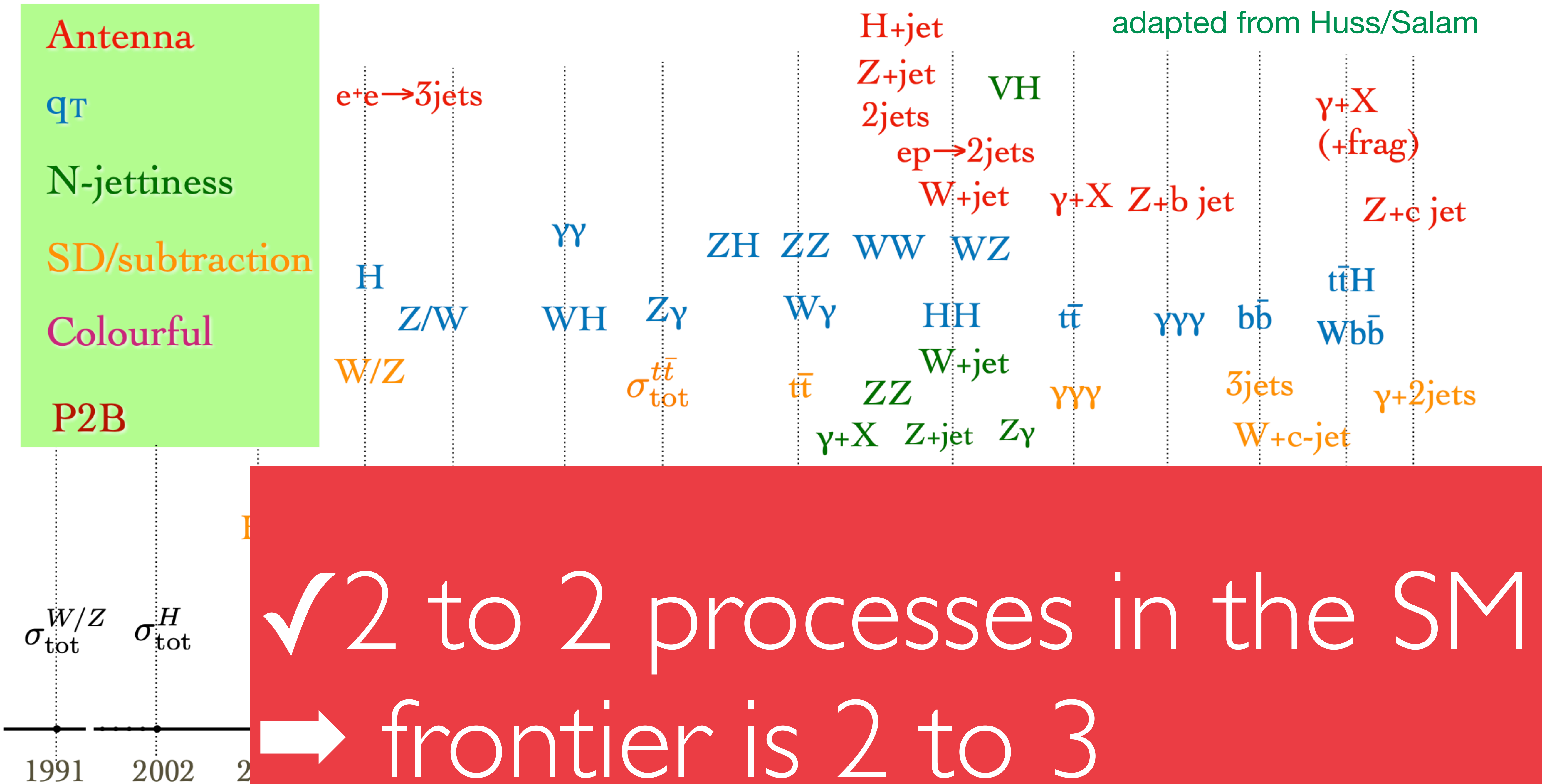
NNLO timeline



Different colour: different way to handle intermediate divergences

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

NNLO timeline



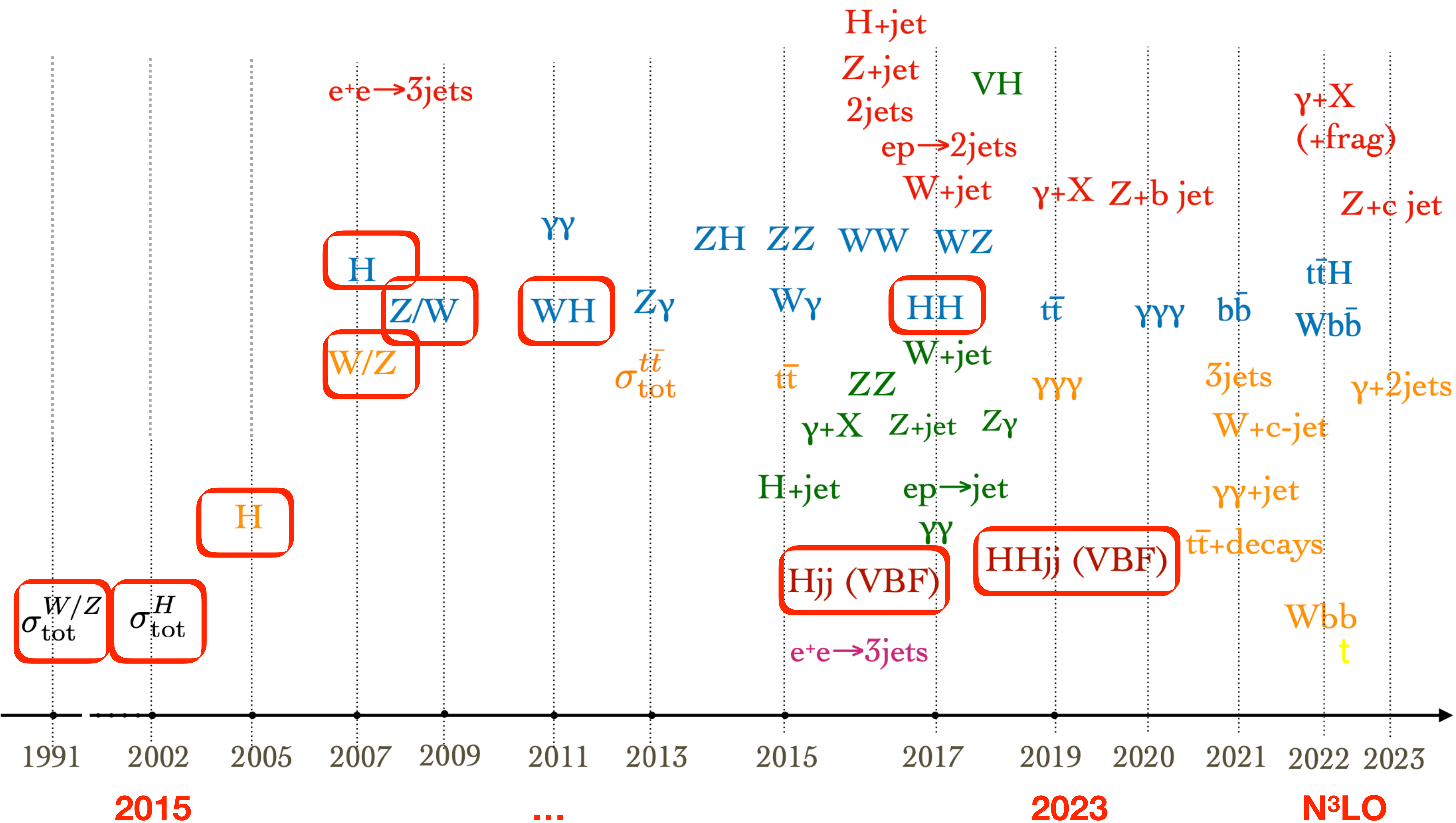
✓2 to 2 processes in the SM

➡ frontier is 2 to 3

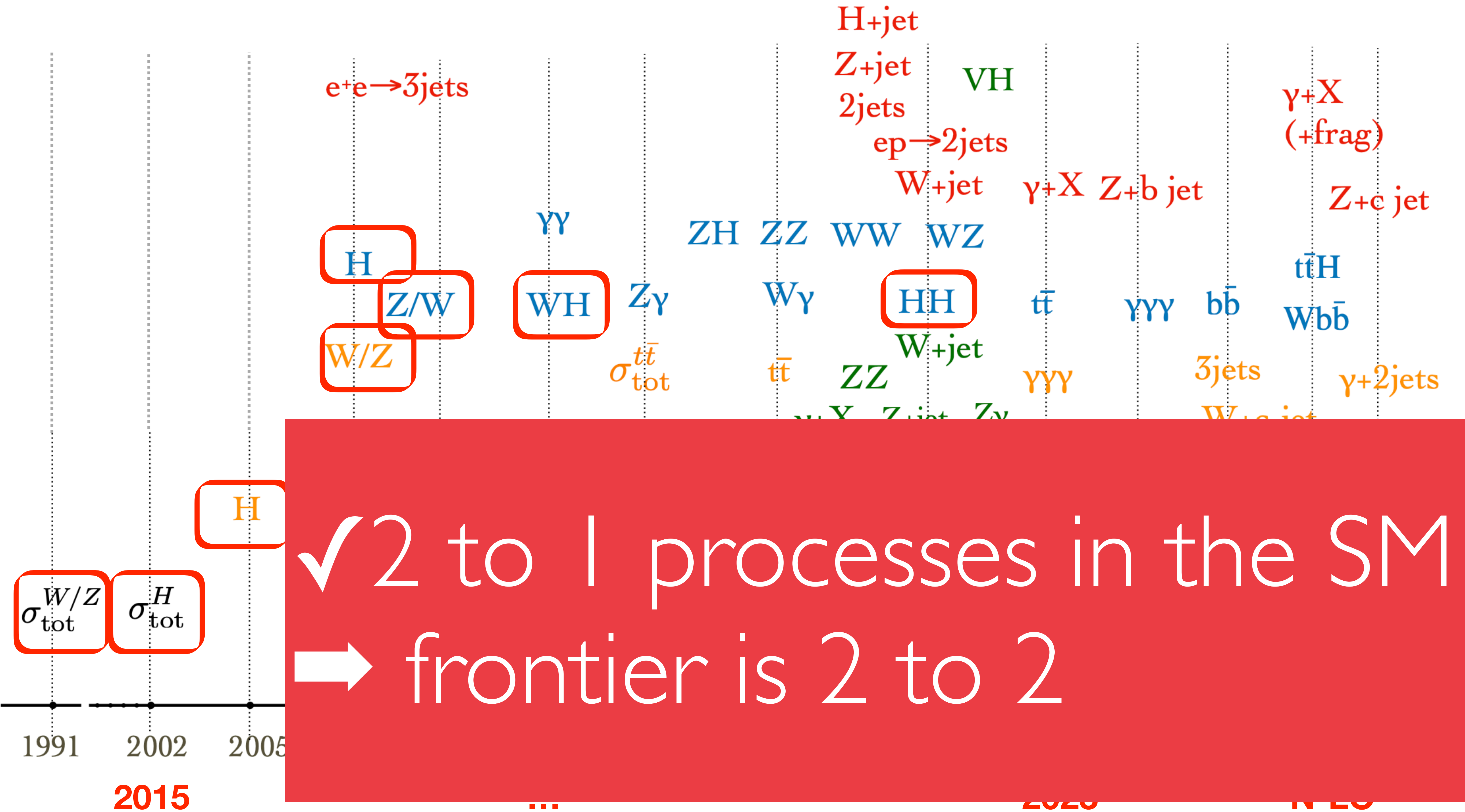
Different colour: c

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

NNLO → N^{3}LO


H+jet
Z+jet
2jets
ep→2jets
W+jet
VH
γ+X
Z+b jet
γ+X
(+frag)
Z+c jet
e+e→3jets
γγ
H
ZH
ZZ
WW
WZ
Z/W
WH
Zγ
Wγ
HH
tt̄
γγγ
bb̄
tt̄H
Wbb̄
W/Z
W+jet
ZZ
γγγ
3jets
γ+2jets
γ+X
Z+jet
Zγ
W+c-jet
H+jet
ep→jet
γγ+jet
H
γγ
tt̄+decays
HHjj (VBF)
Hjj (VBF)
Wbb̄
t
e+e→3jets
1991
2002
2005
2007
2009
2011
2013
2015
2017
2019
2020
2021
2022
2023
2015
...
2023
N3LO

NNLO → N³LO



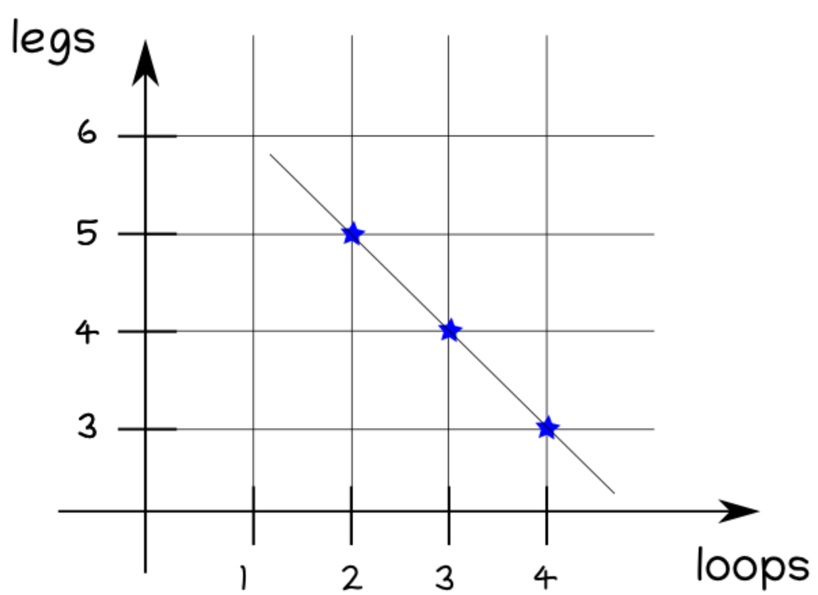
✓2 to 1 processes in the SM

➡ frontier is 2 to 2

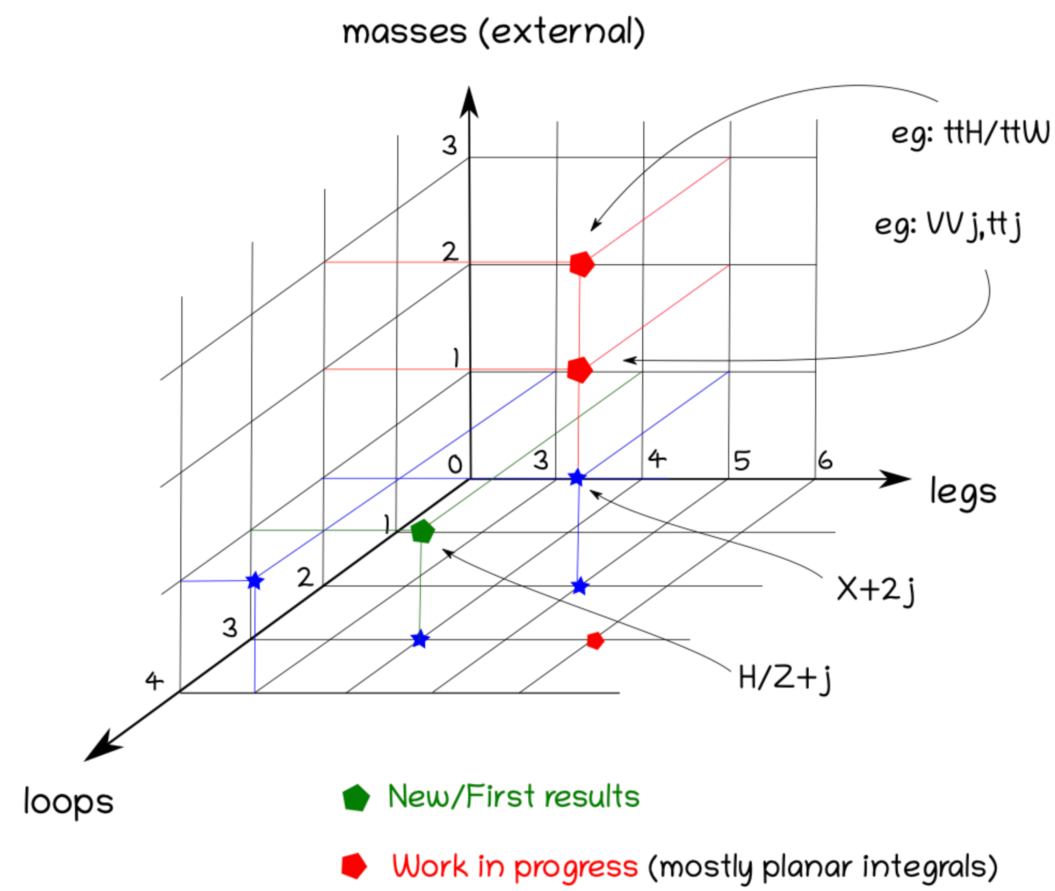
Complexity

Buccione

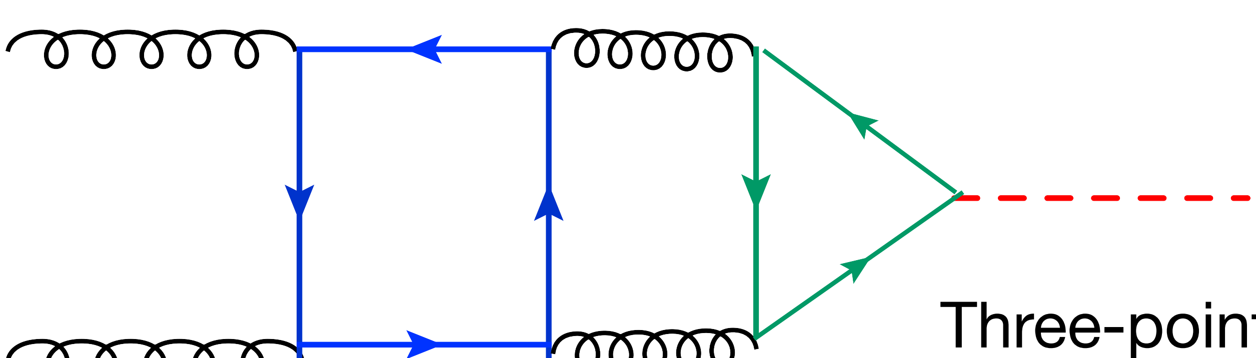
Complexity grows with #loops and #legs.



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 ⇒ Talk by Nieggediedt

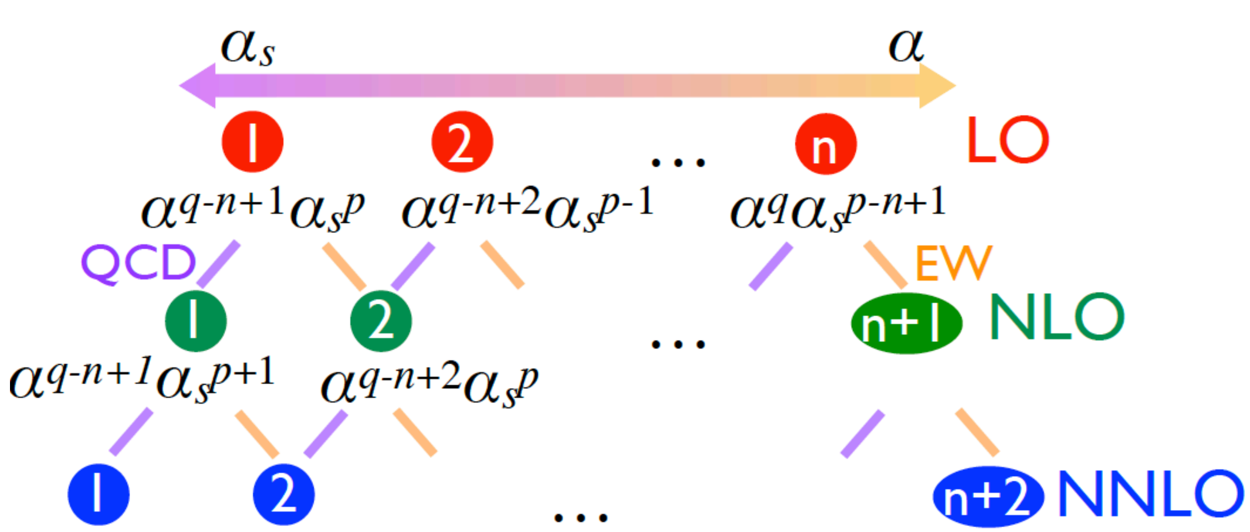
Not just QCD

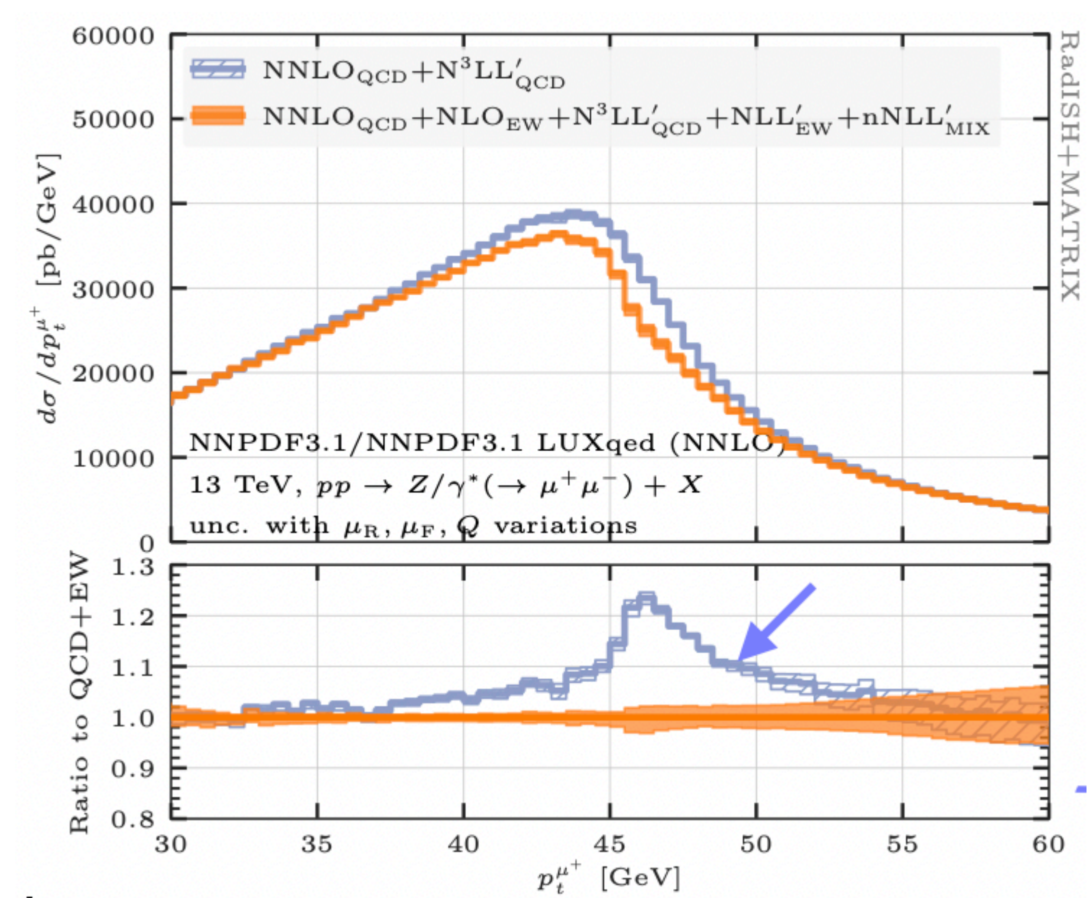
Talks by Bi, Kallweit, Del Pio, Hoppe, Zaro

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, …

Talks by Devoto, Tancredi, Kallweit

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

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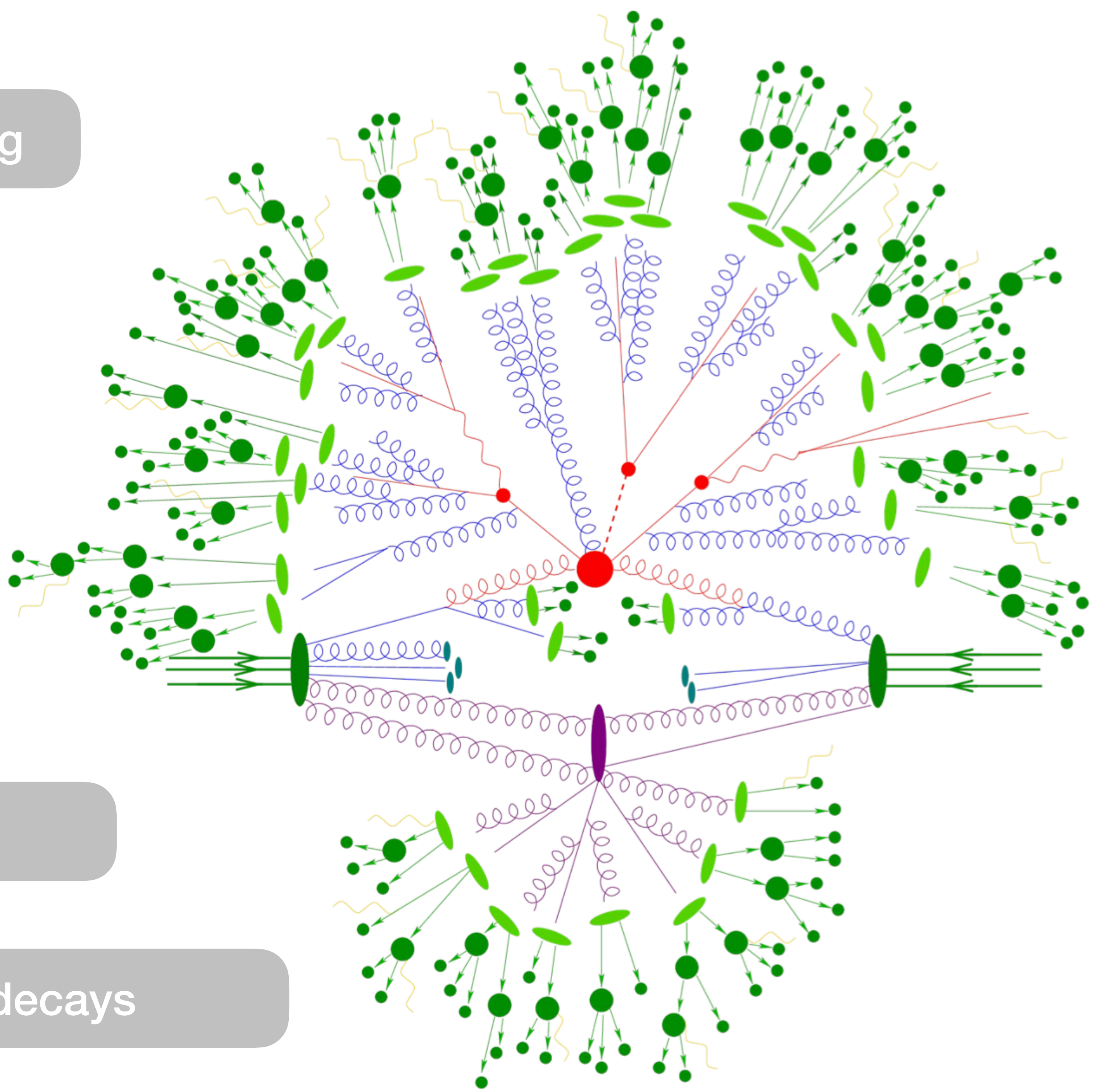
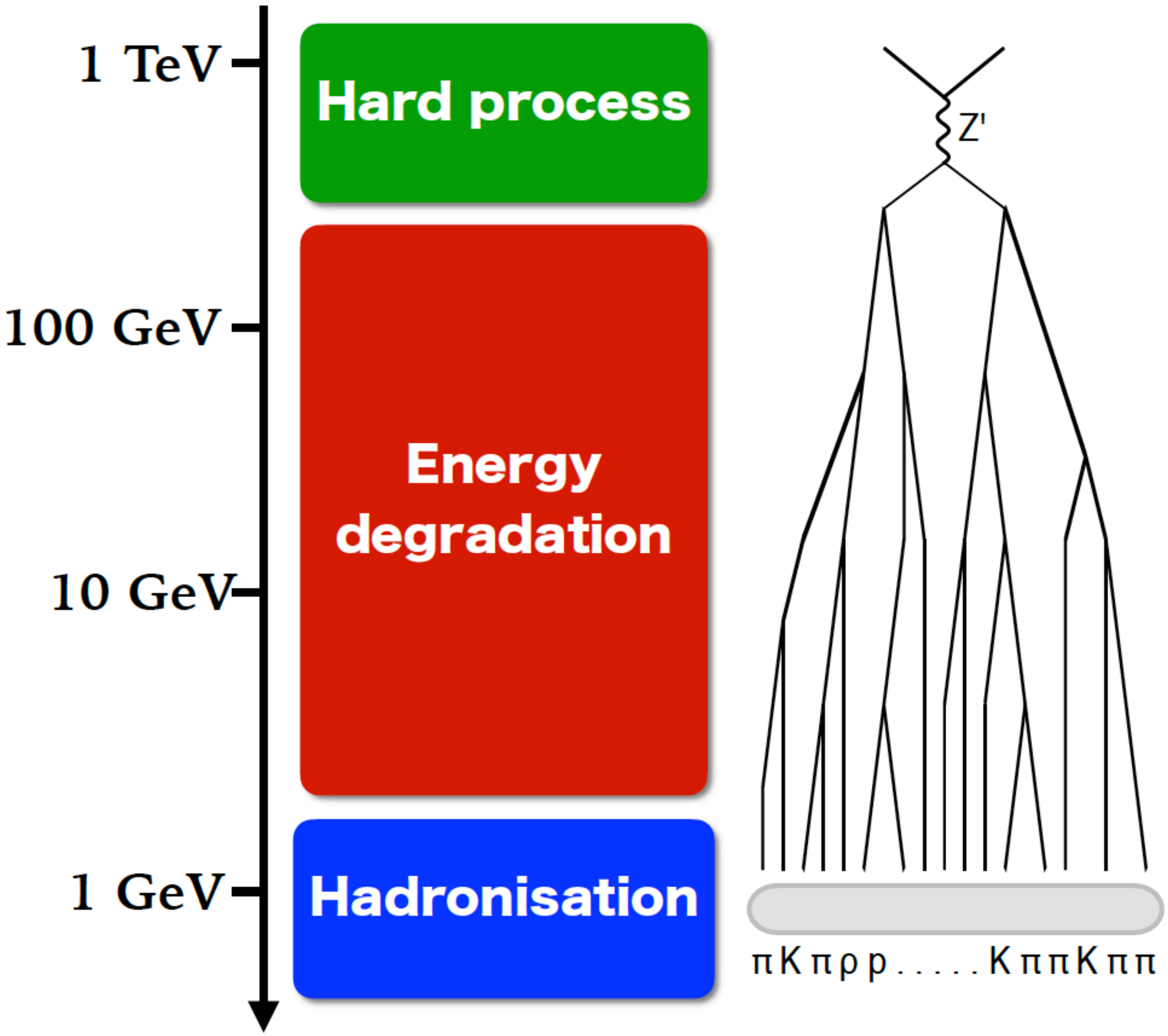
Hadronization

Hadron decays



Parton shower

Talks by Hoppe



from Ravasio/Ferrario

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

Also progress in simulation of Dark Showers

Talk by Scherb

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

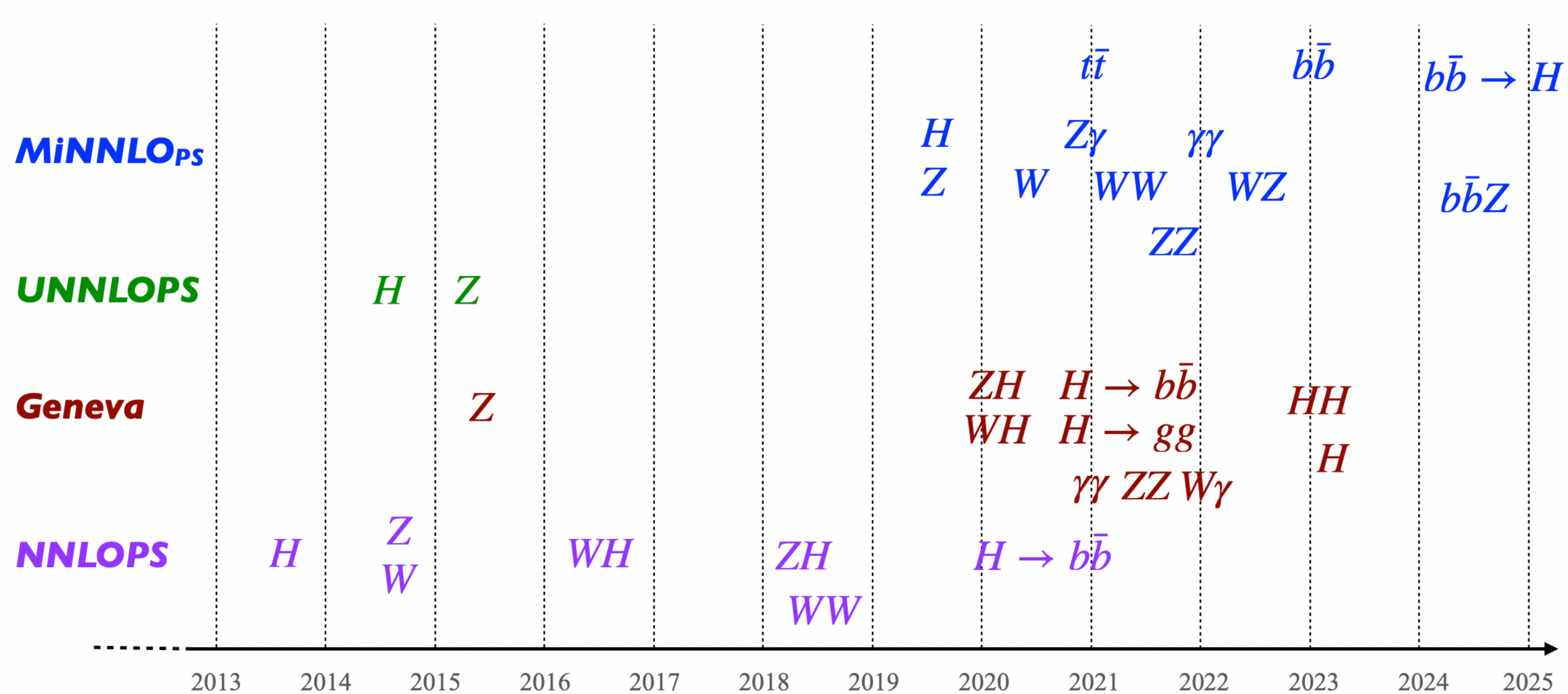
- Improvements in the accuracy of the parton shower
- Numerical procedure to validate the accuracy
- Understanding that some parton showers have lower accuracy
$\Rightarrow$ can be disregarded when assessing theory uncertainties

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

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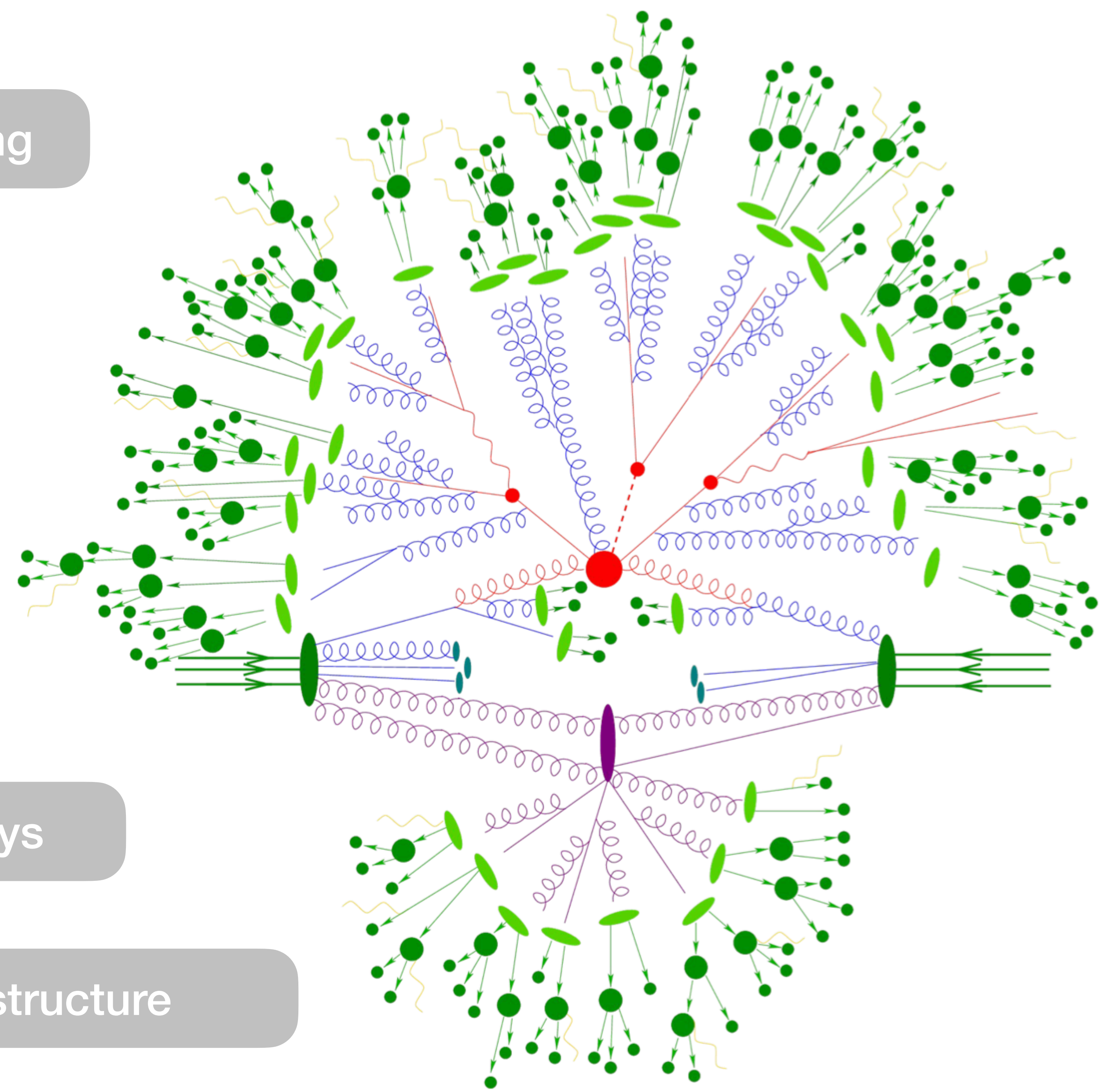
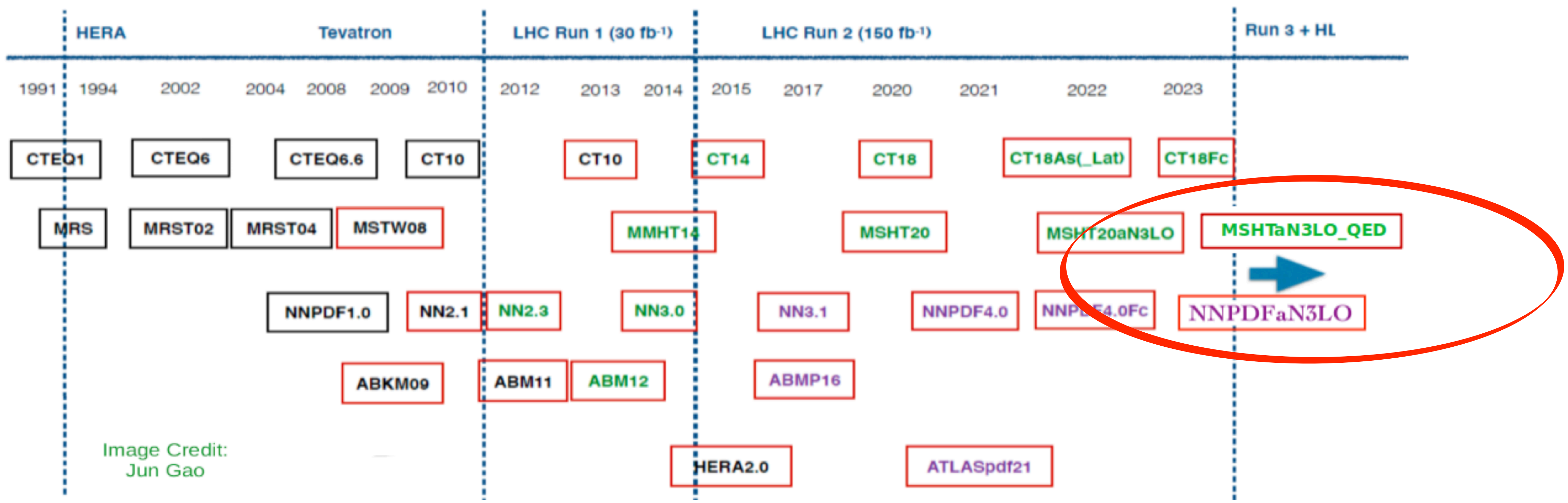


Towards N^{3}LO PDFs

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 ✗

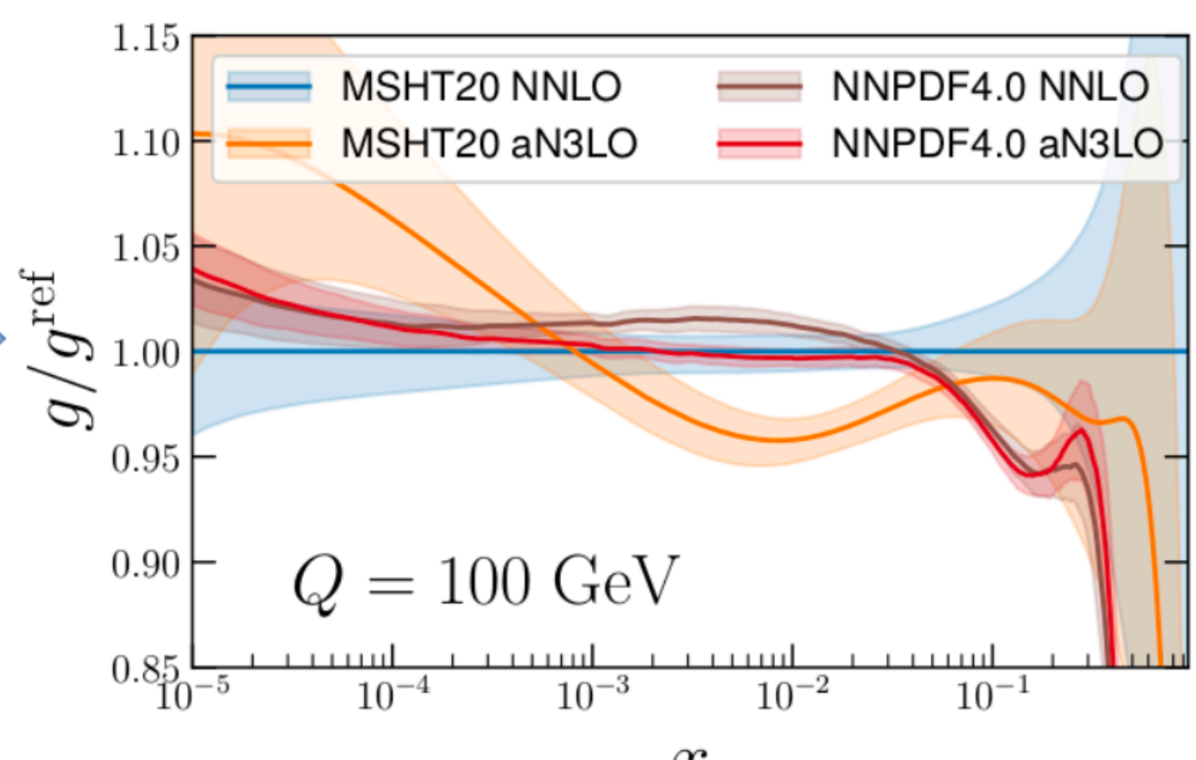
$$F_i\left(x,Q^2\right) = \sum_k C_{i,k} \otimes f_i\left(x,Q^2\right)$$

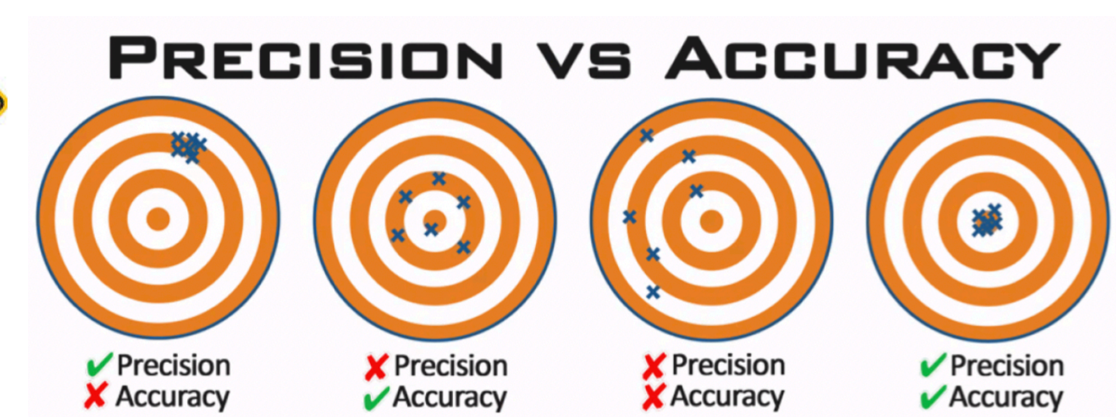
- Hadronic coefficients at N3LO ✗

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)





See also talk by Ubiali

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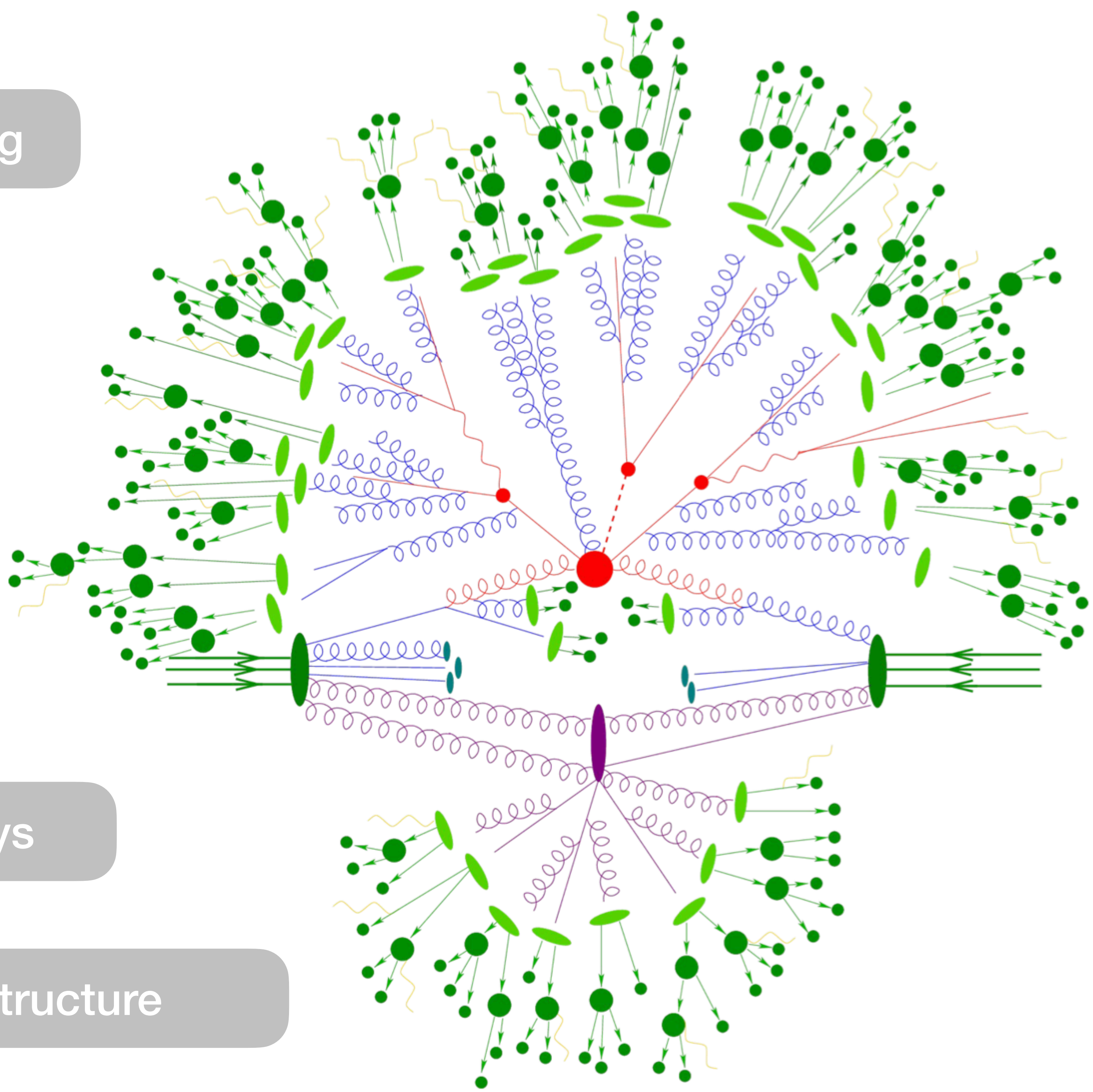
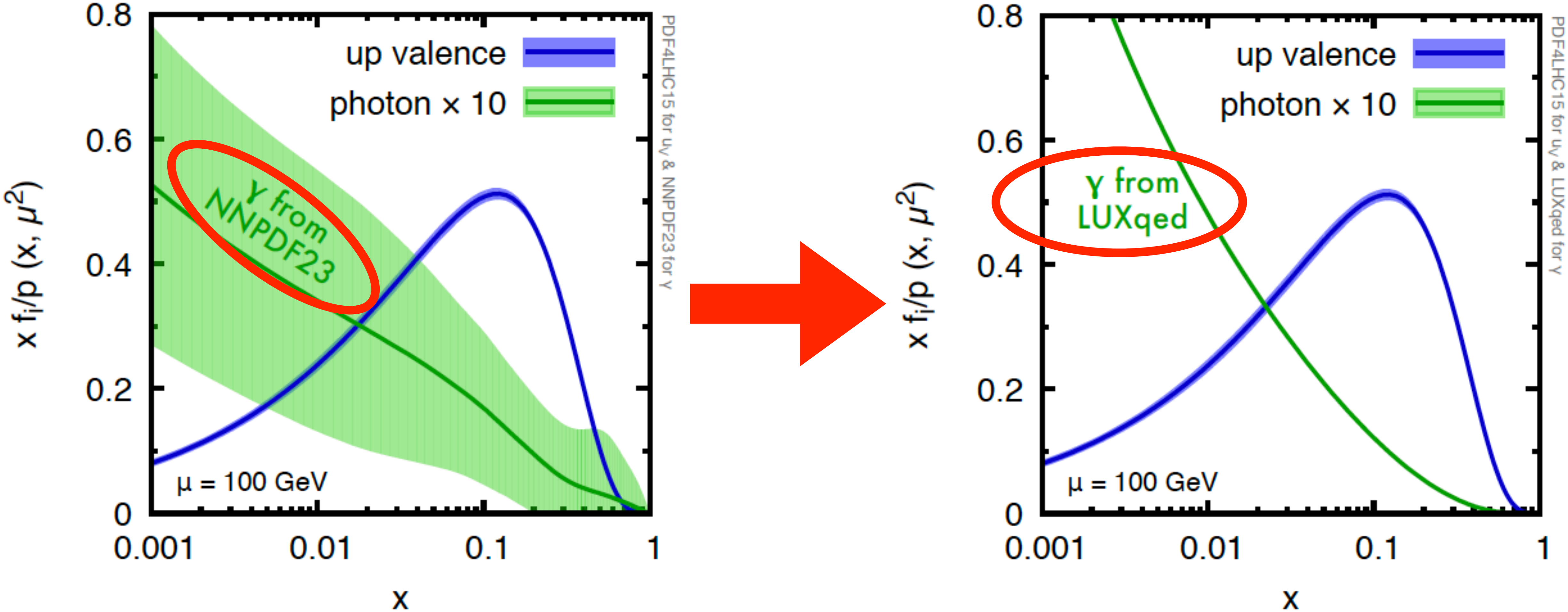


Photon PDF

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

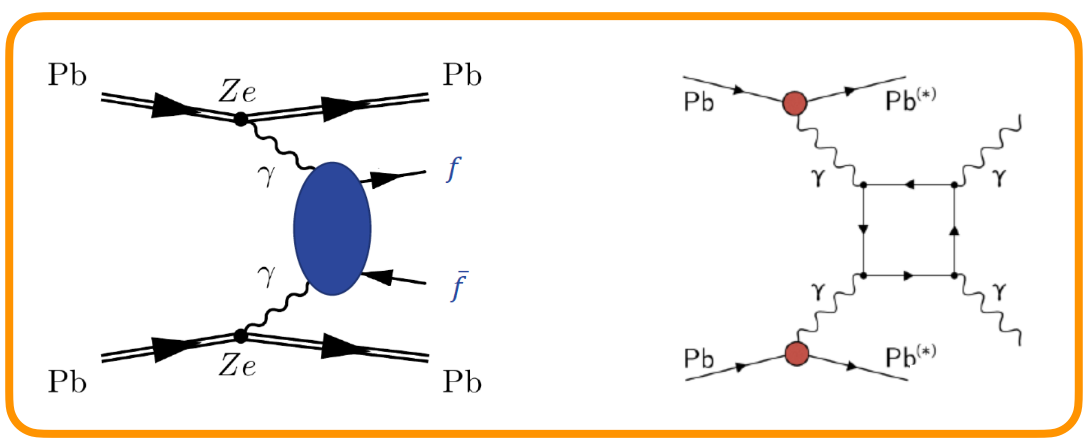
LHC as photon collider

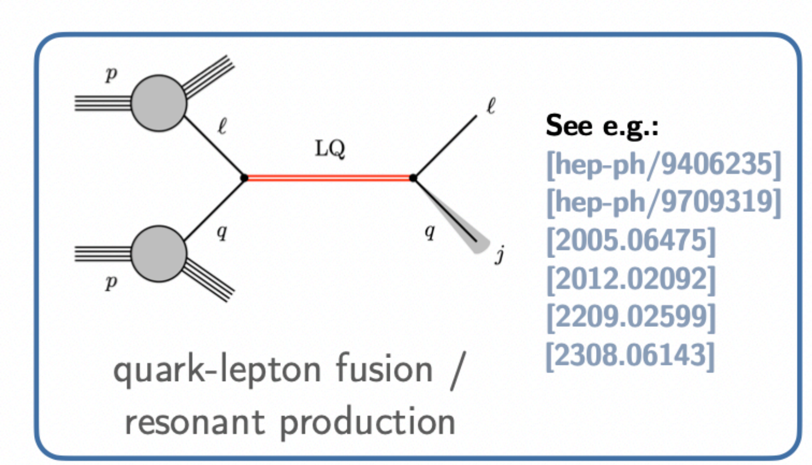
Opens up many new research directions

- 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)

Talk by Lang

Talks by Wilsch and Reimers



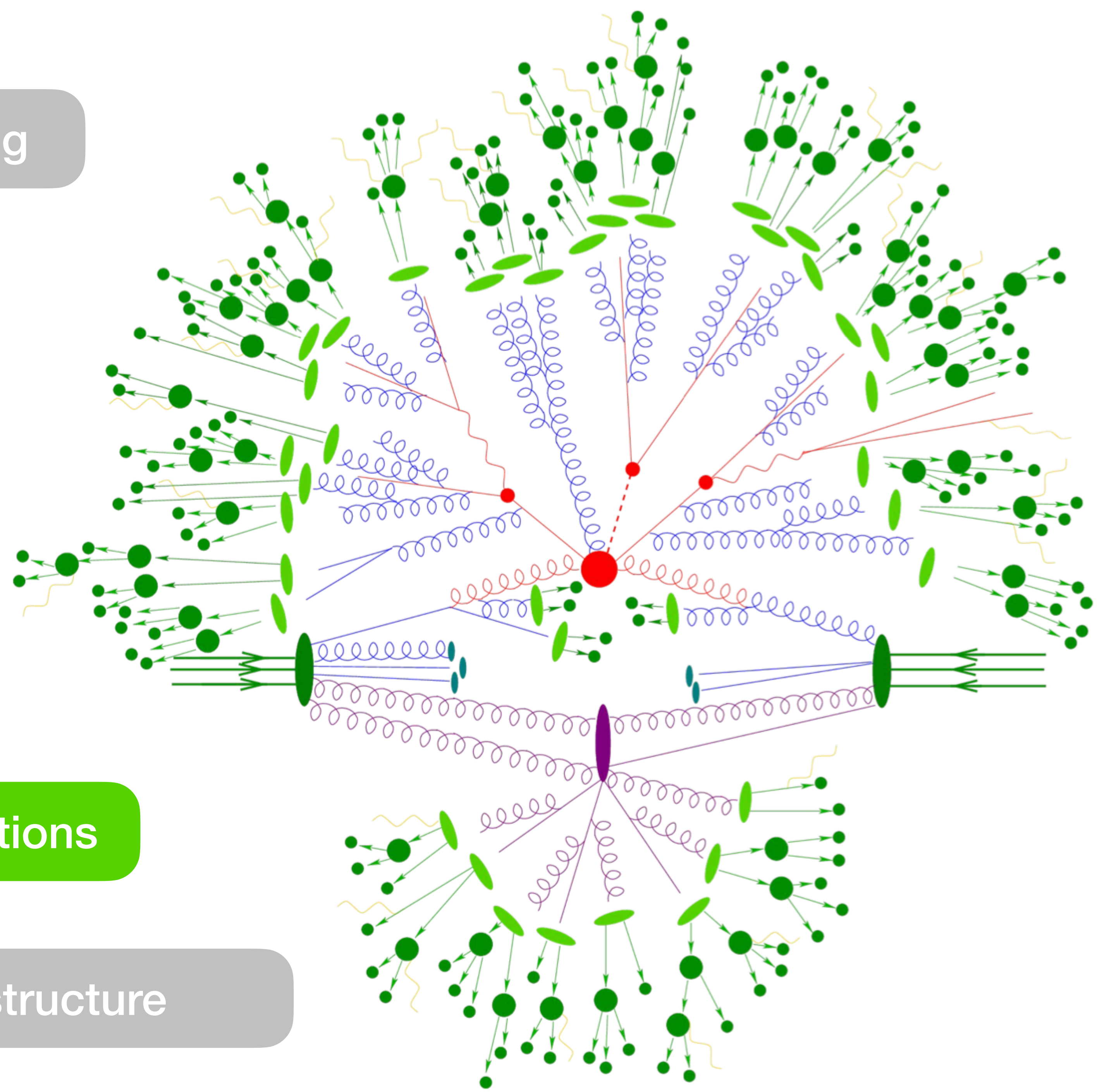


Proof of extraordinary versatility of LHC experiments and of synergy with theory!

Theorist point of view

Largely based on factorization

- Hard partonic scattering
- Parton shower
- PDFs/underlying event
- QED/photons
- **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

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

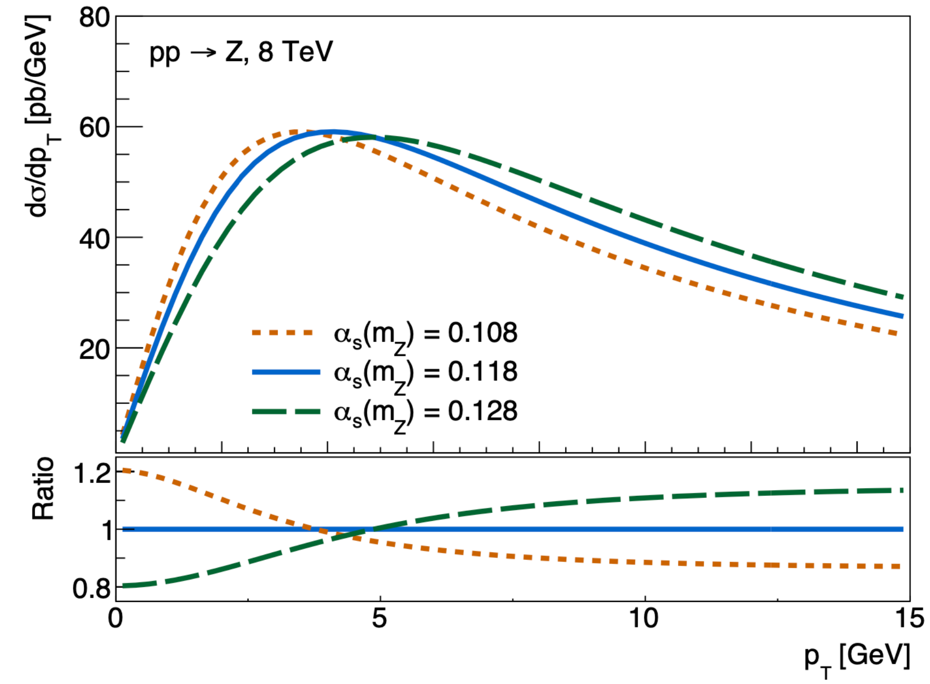
Non-perturbative (NP) power corrections to the factorisation formula

Can become relevant

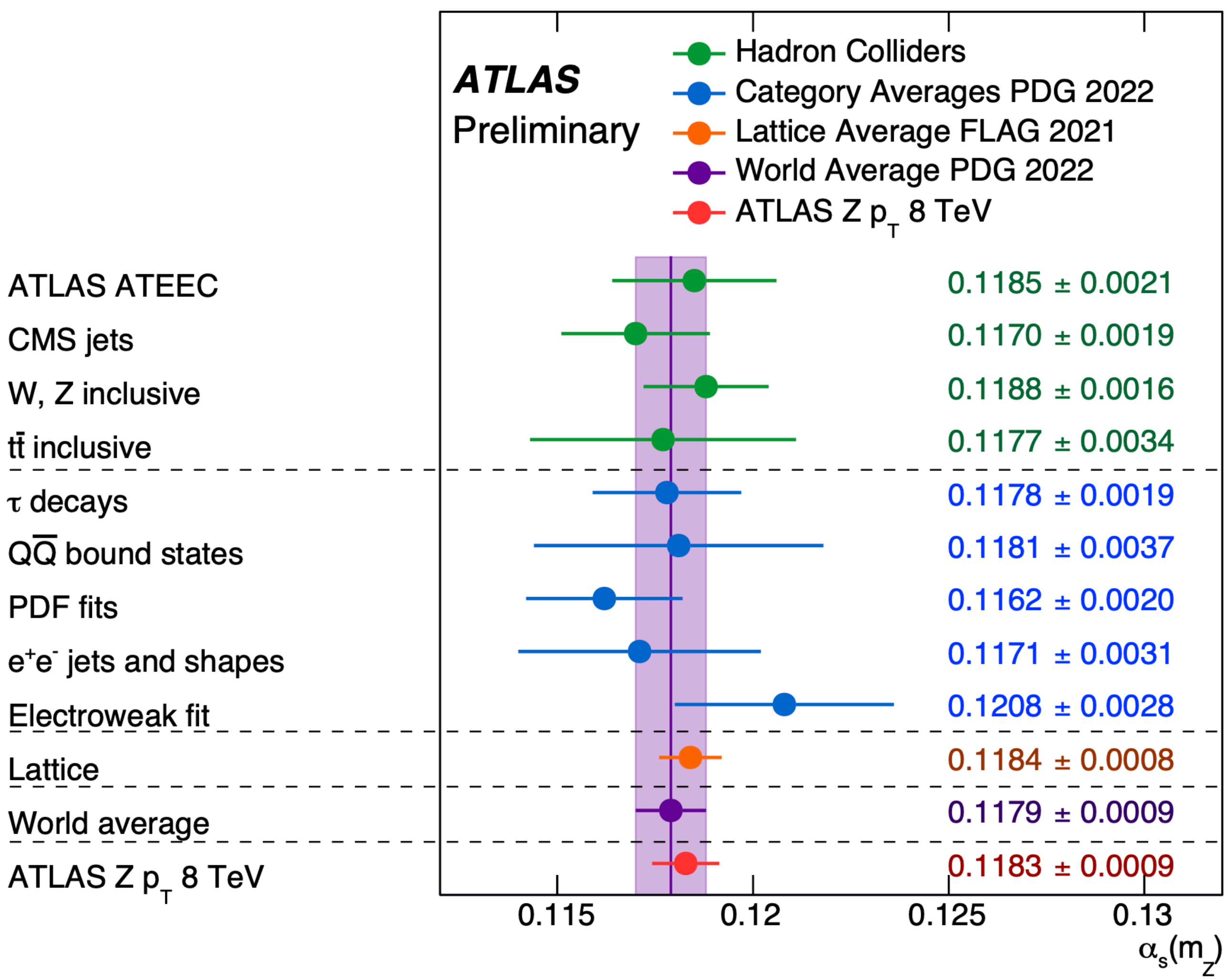
- if n is small, e.g. n=1 (1 GeV/100 GeV ~1%)
- if Q is small, e.g. low transverse momentum
- for ultra-precision measurements

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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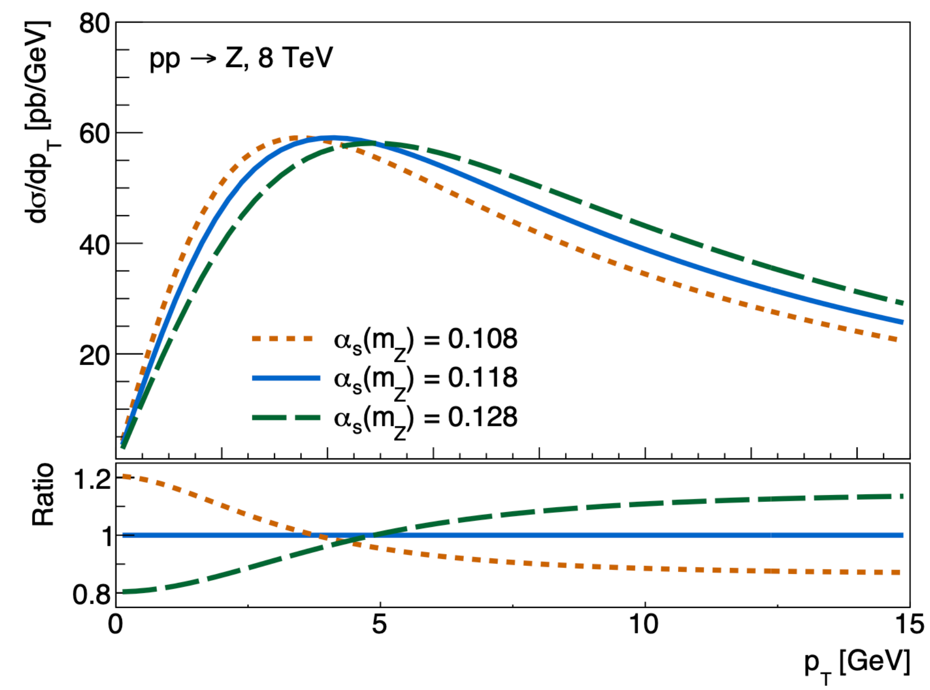

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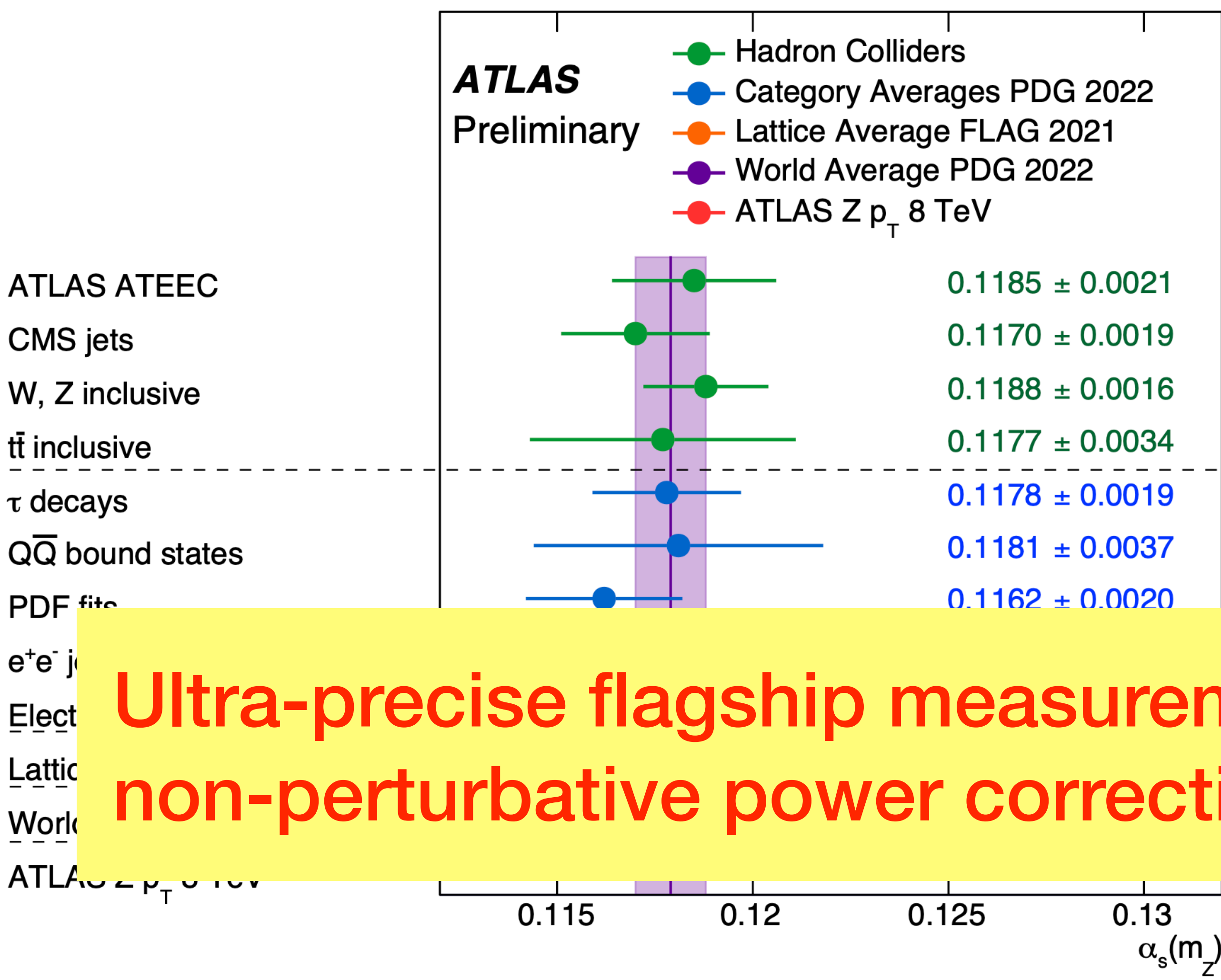


Ultra-precise flagship measurement relies on low p_t where non-perturbative power corrections are more relevant

α_s world average

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

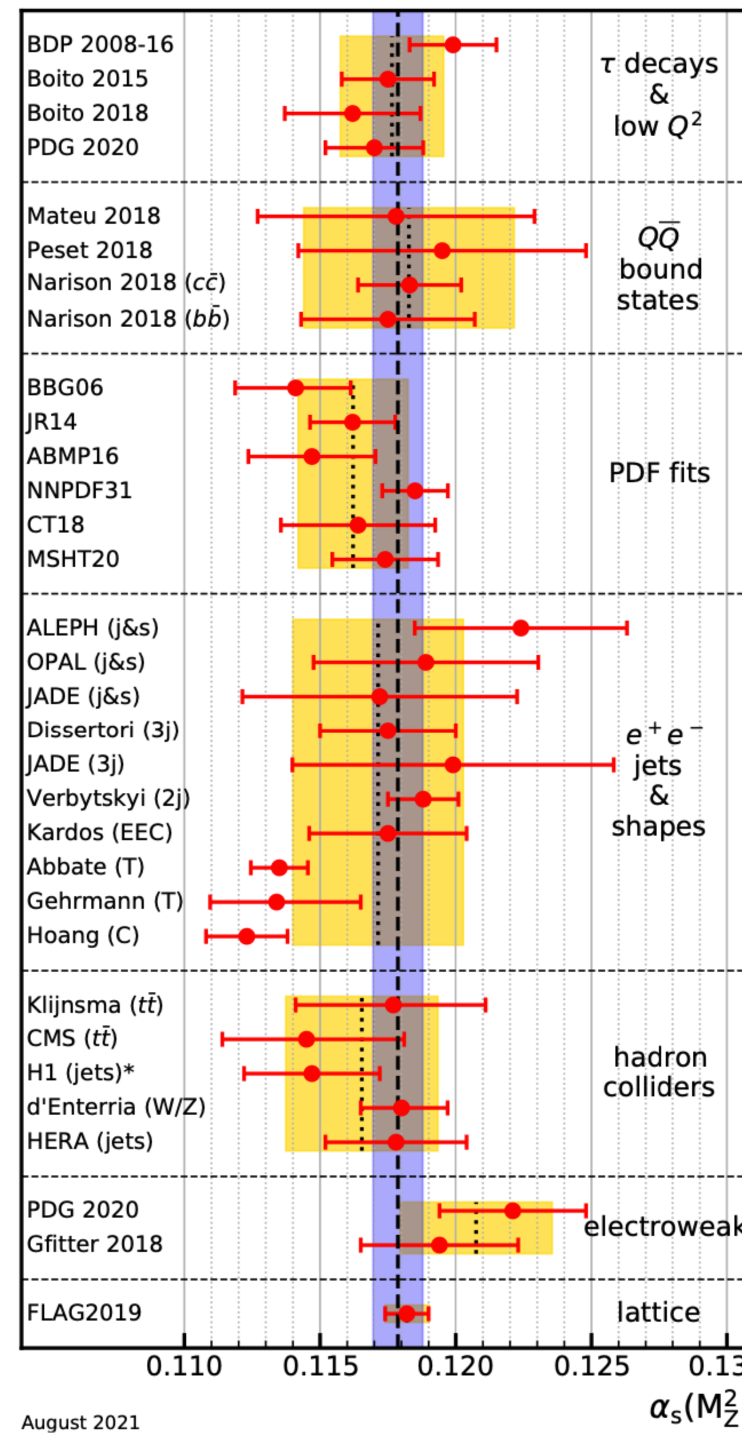
<u>Procedure to compute worlds average in PDG:</u>

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

  ⇒ *the world average of α_s*

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

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

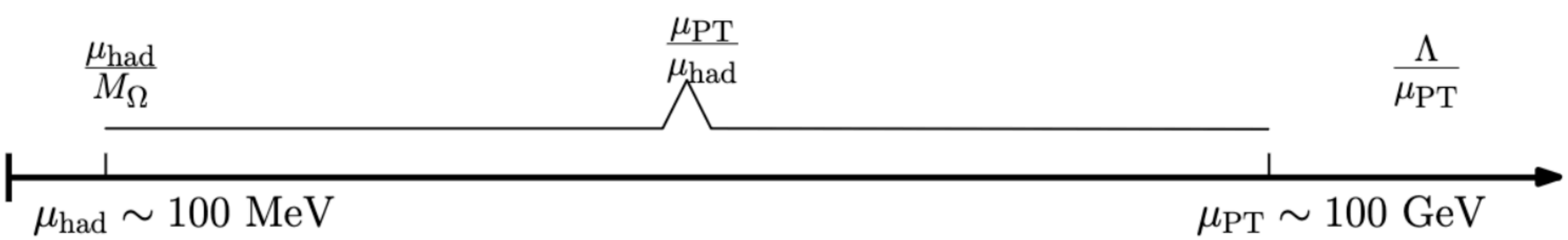


Many ambiguities, choices (e.g. treatment of correlations etc.), subtle aspects involved…

α_s from lattice

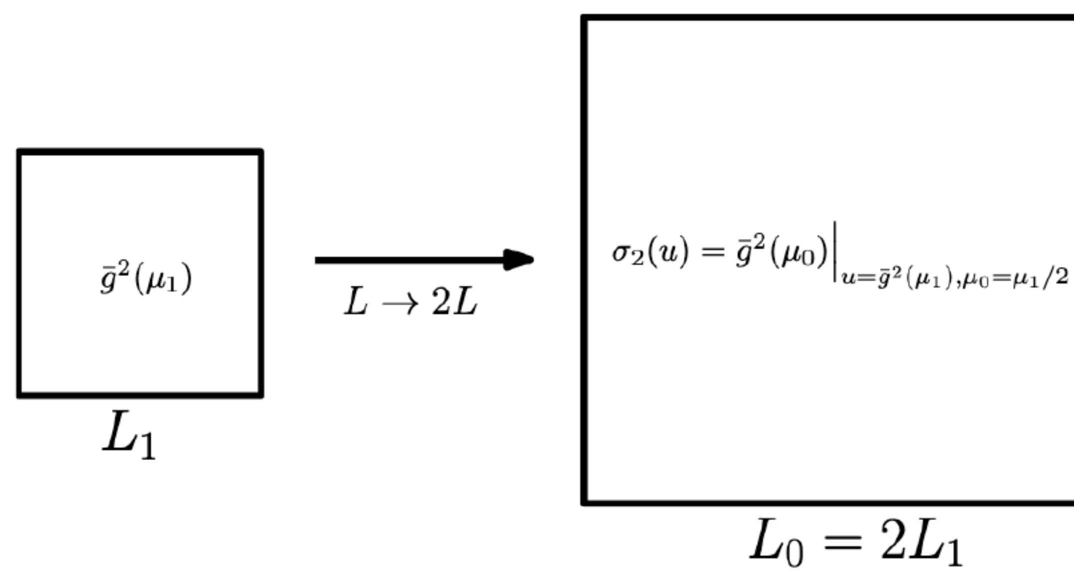
Talk by Del Debbio

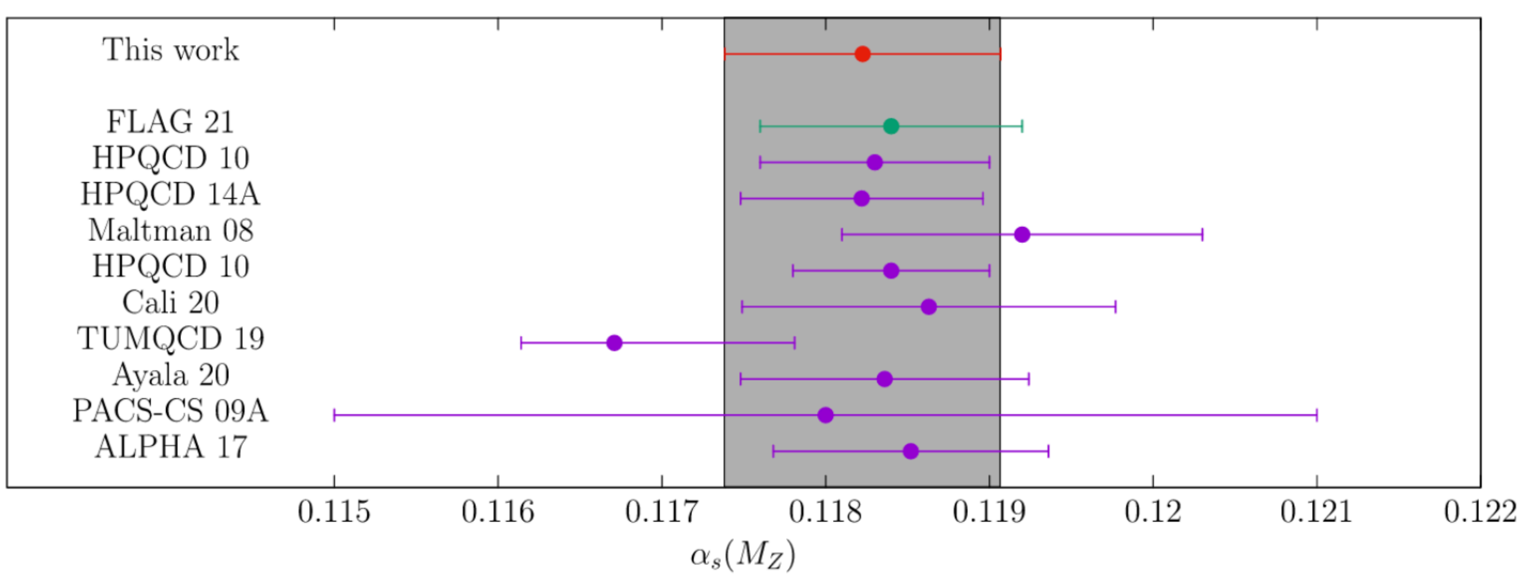
Traditional lattice simulations face multiscale problem



$$\Lambda = M_\Omega^{\rm exp} \times \frac{\mu_{\rm had}}{M_\Omega} \times \frac{\mu_{\rm PT}}{\mu_{\rm had}} \times \frac{\Lambda}{\mu_{\rm PT}}$$

Recent idea: iterative finite size scaling procedure, with step scaling function



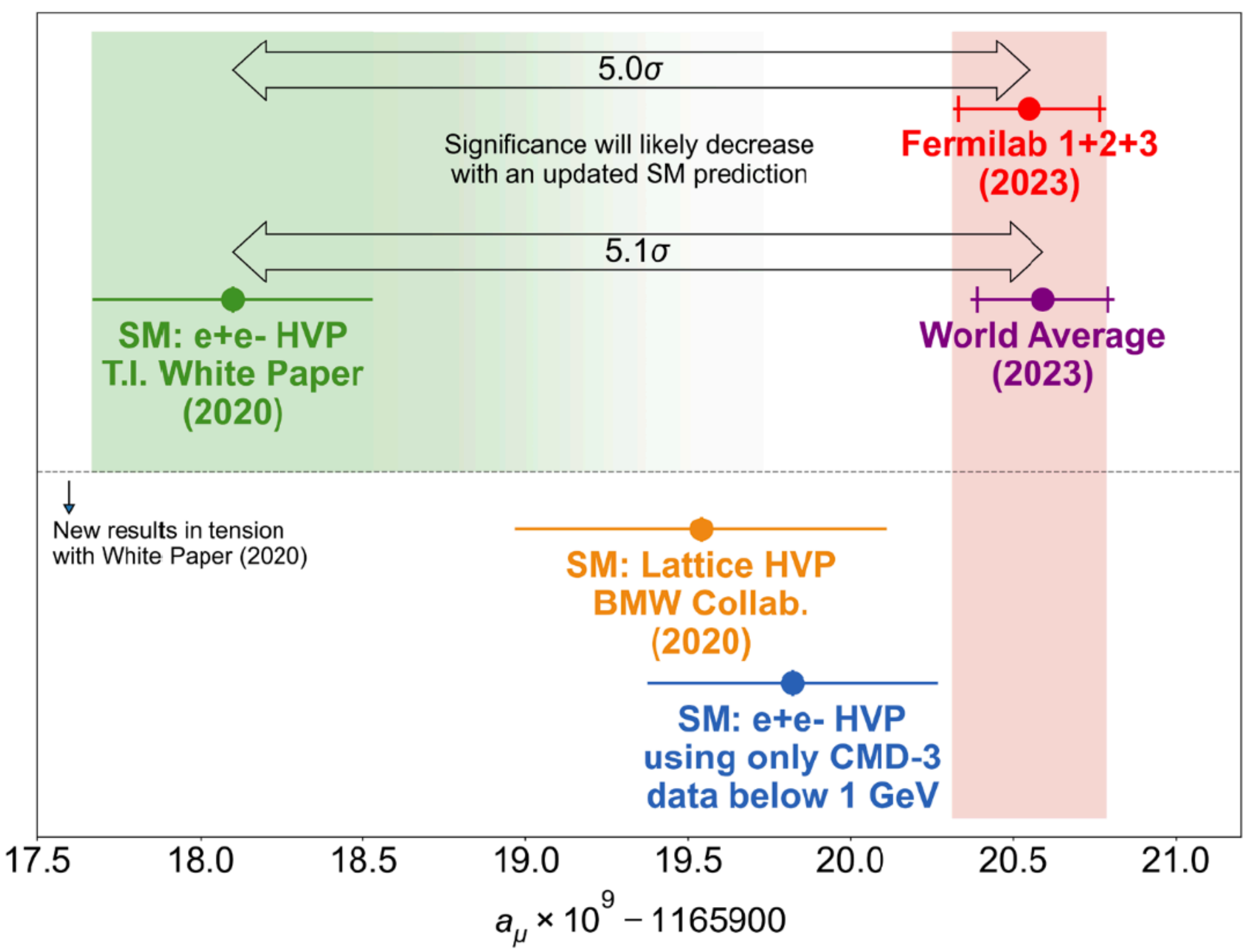


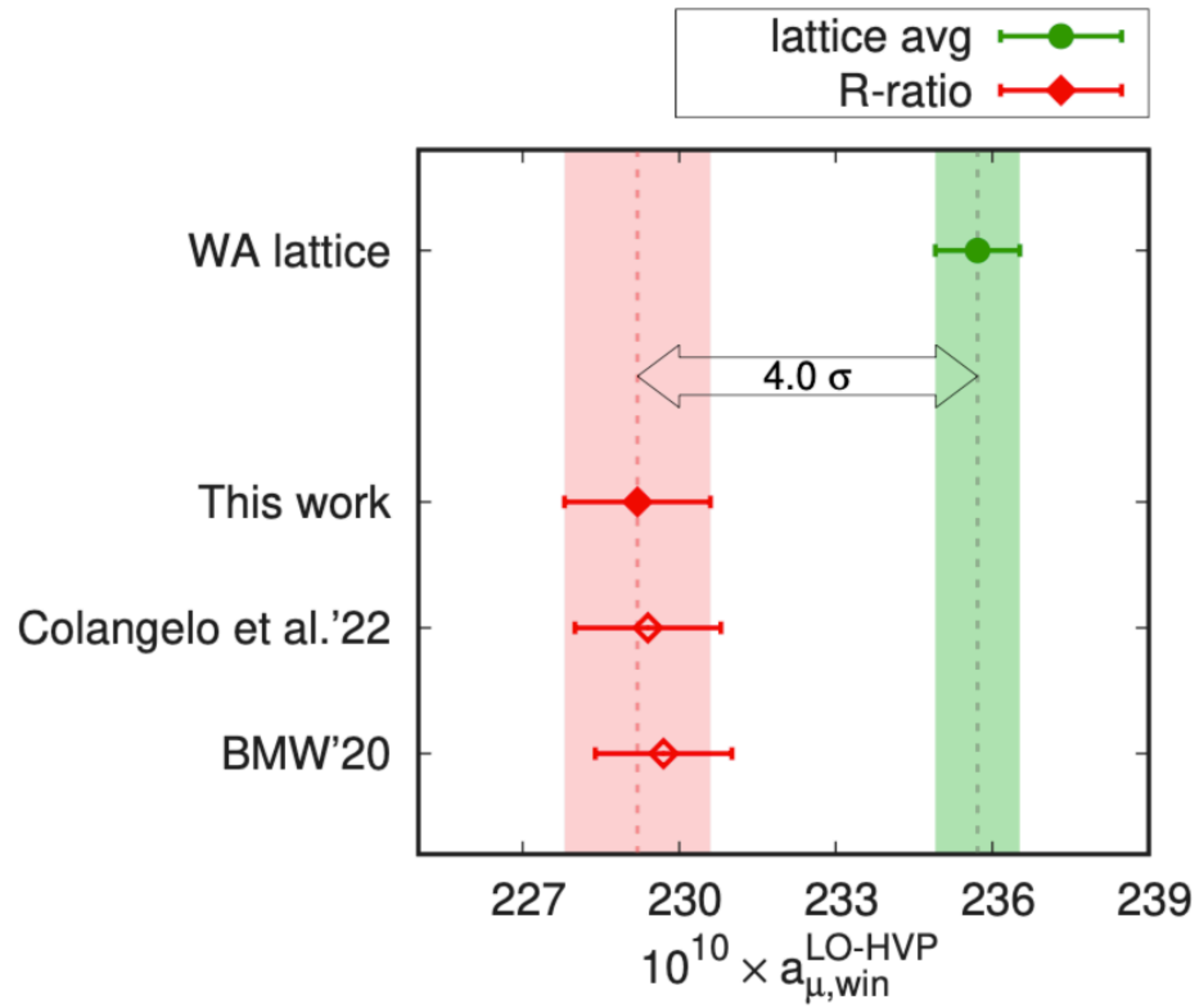
Dominated by statistics, expect improvement soon.

HVP to $(g-2)_\mu$

Talk by Del Debbio

A tension between theory (lattice) and theory (R-ratio)





The devil is in the detail. Work in progress between theory and experiment to clarify this ⇒ something exciting to keep an eye on

2. Guiding experimental searches

$\Rightarrow$ optimising final states and observables

Theorist point of view

Hard partonic scattering

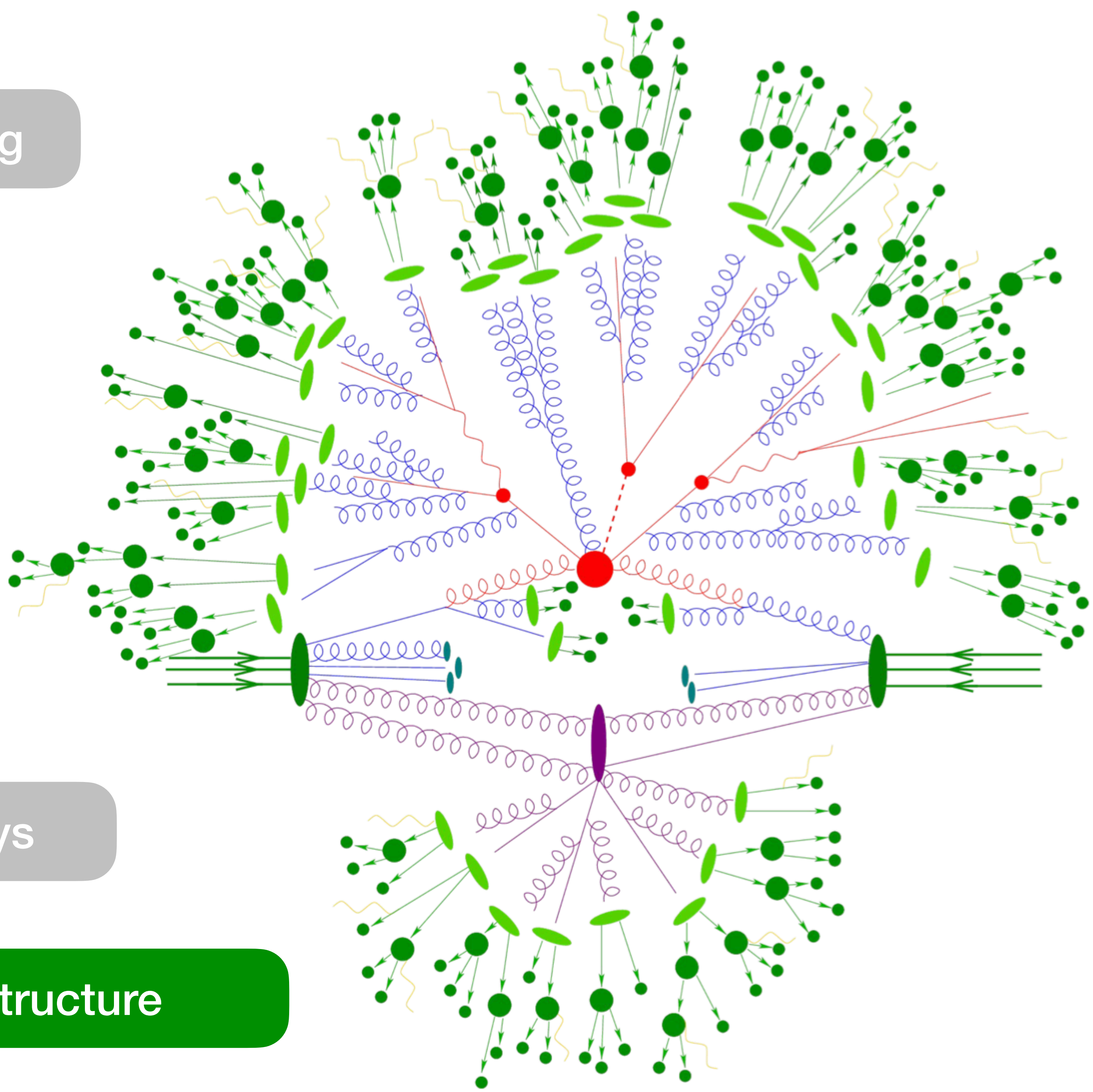
Parton shower

PDFs/underlying event

QED/photons

Hadronization/decays

Jets/substructure



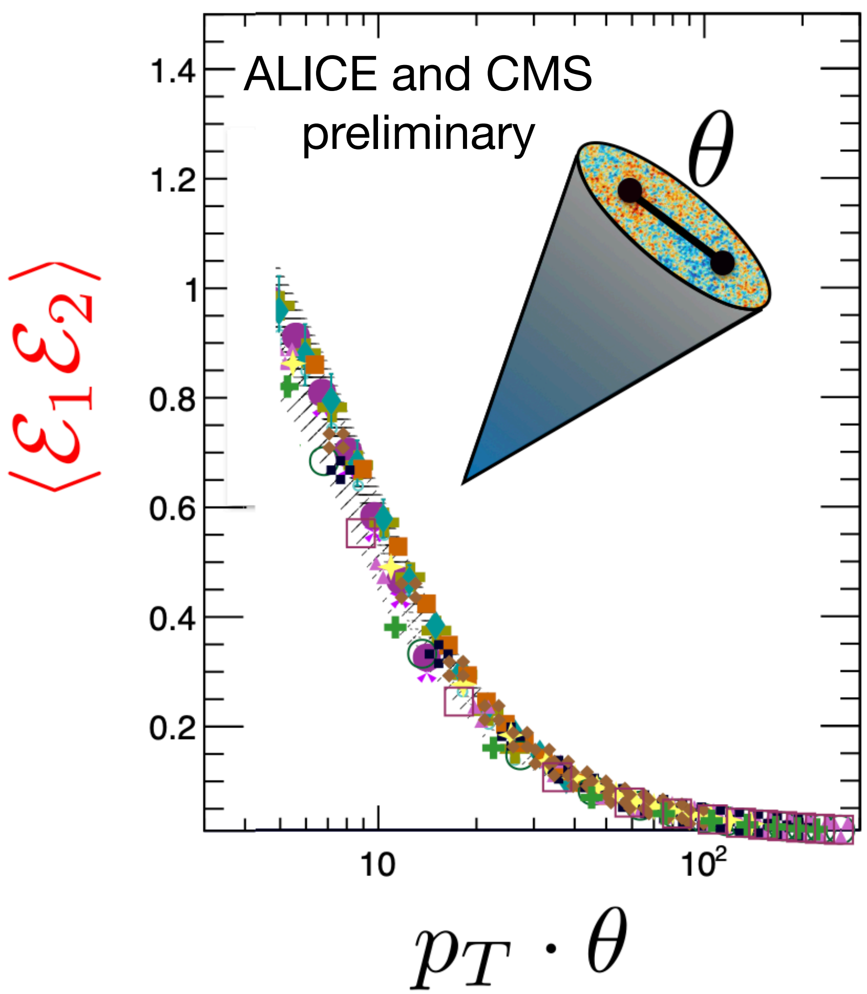
Jet substructure

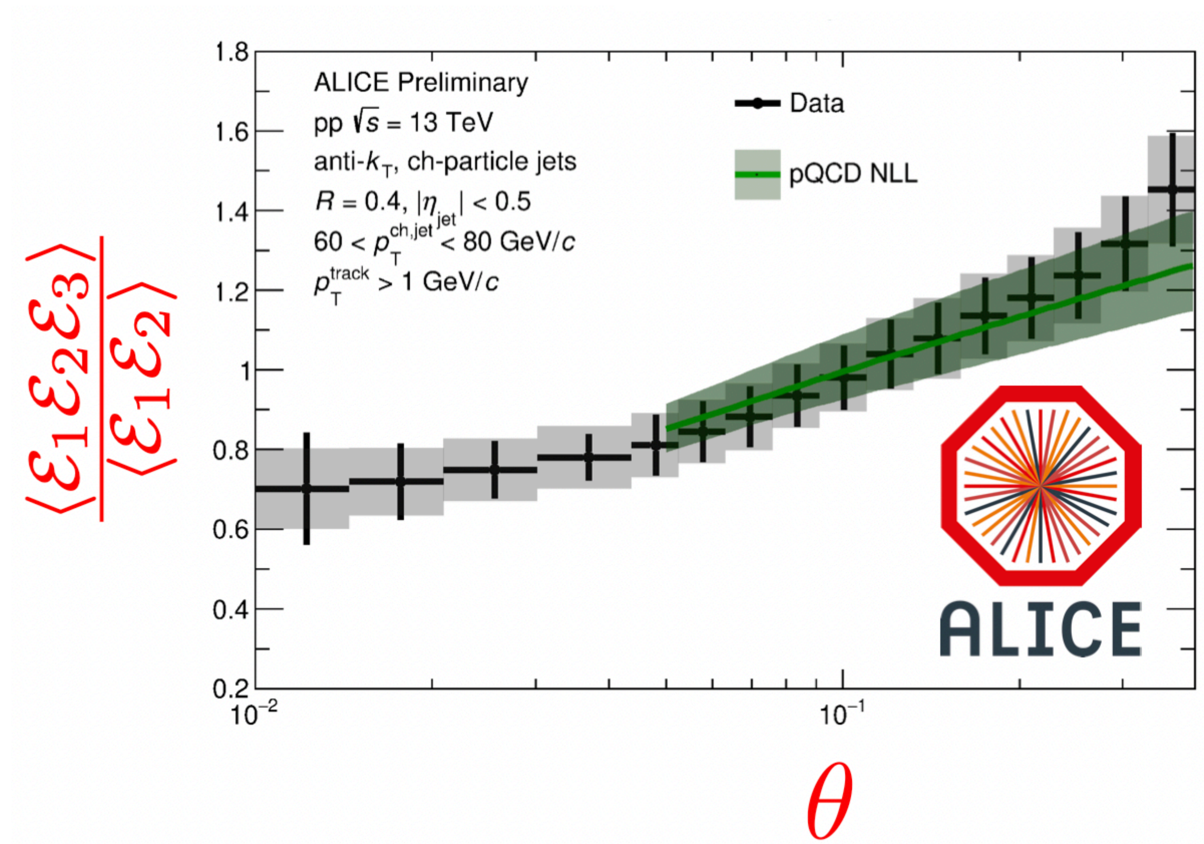
Talk by Caletti, Moult, Nguyen

Insight from formal theory is revolutionising our understand of jets

<u>Example</u>: energy correlators

$$\frac{\langle \mathcal{E}_1 \mathcal{E}_2 \mathcal{E}_3 \rangle}{\langle \mathcal{E}_1 \mathcal{E}_2 \rangle} \sim \frac{\langle \mathbb{O}^{[4]} \rangle}{\langle \mathbb{O}^{[3]} \rangle} \sim \theta^{\gamma(4)-\gamma(3)}$$





Jet substructure as precision science

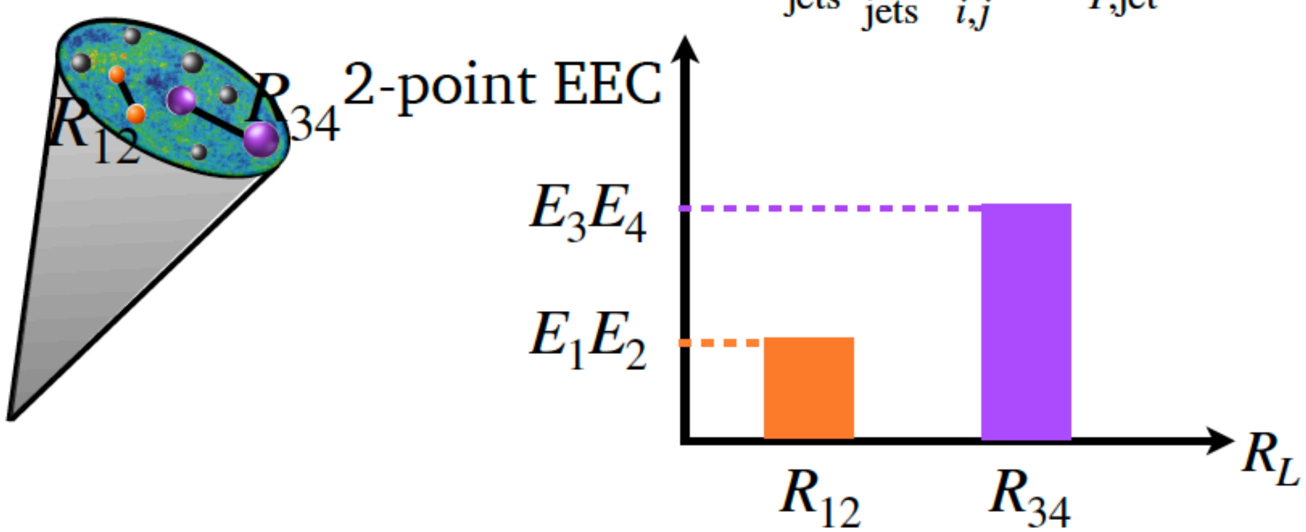
> *The design of good jet algorithms is therefore more a craft than a deductive science.*

Banfi, Salam, Zanderighi (0601139)

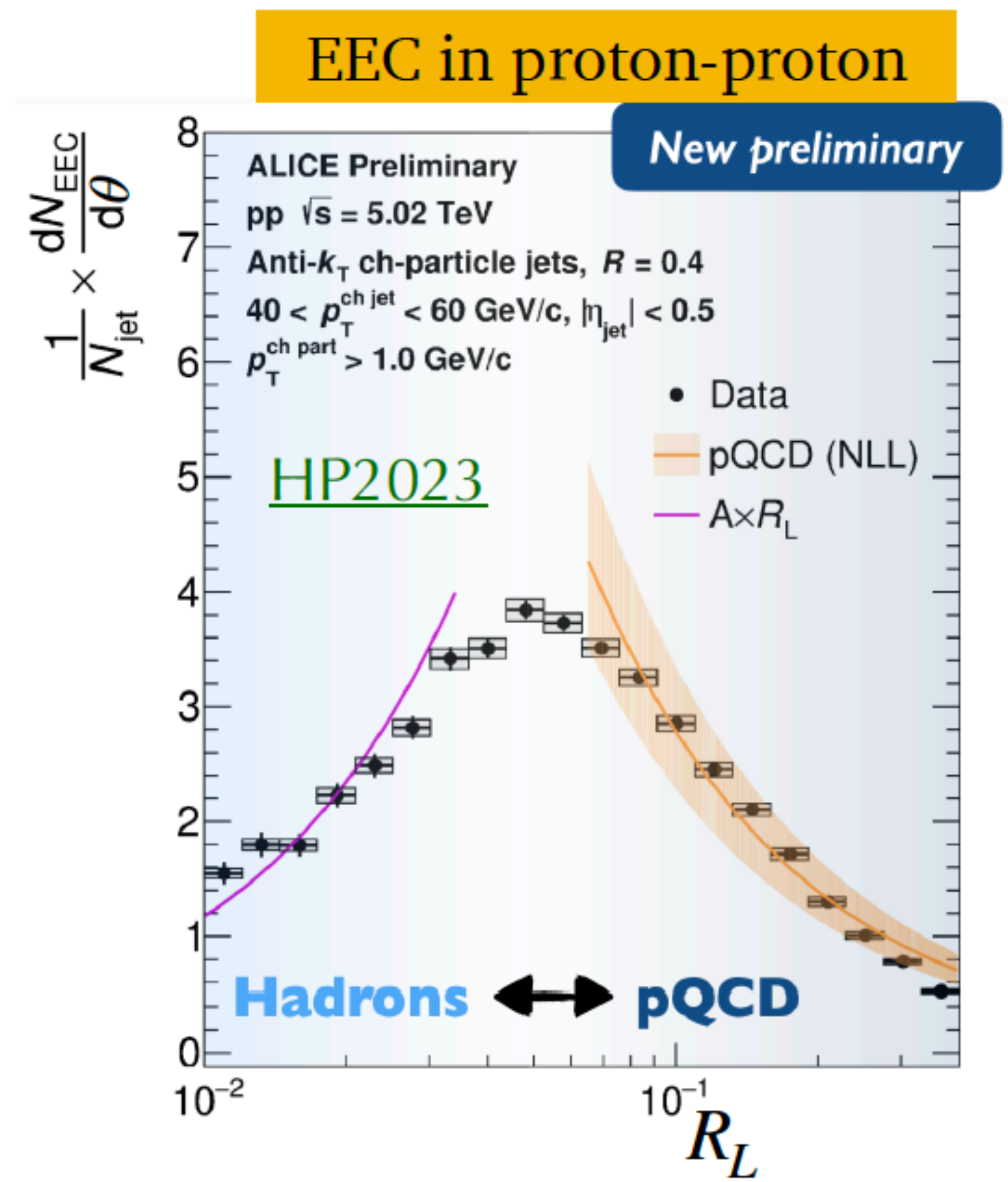
Substructure & jets in medium

Talks by Andres, Barata, Ehlers, Go, Takacs

$$\text{2-point EEC} = \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \sum_{i,j} \frac{P_{T,i} P_{T,j}}{P_{T,\text{jet}}} \delta(R_{ij} - R_L)$$



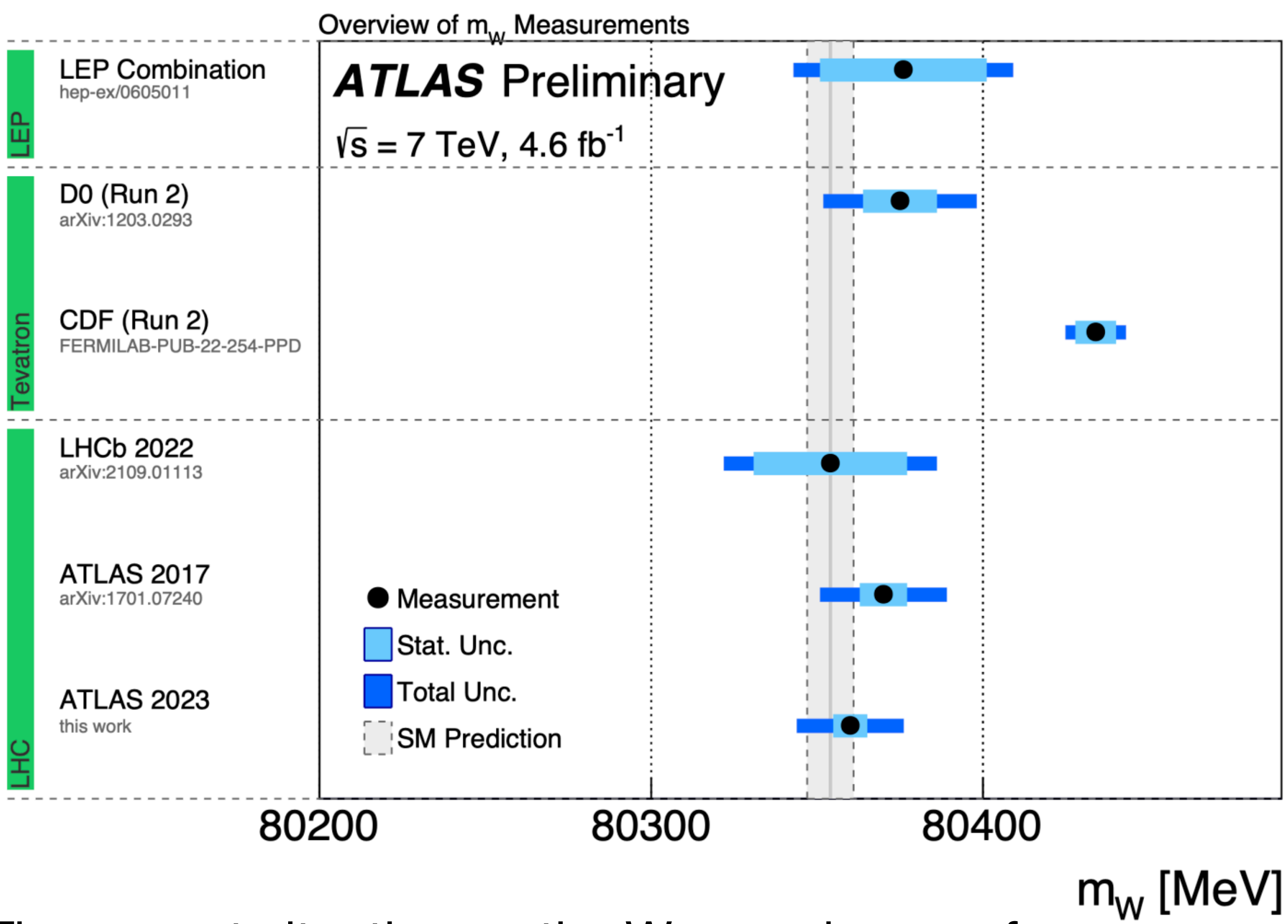
⇒ great candidate for heavy-ion substructure program due to excellent theoretical properties

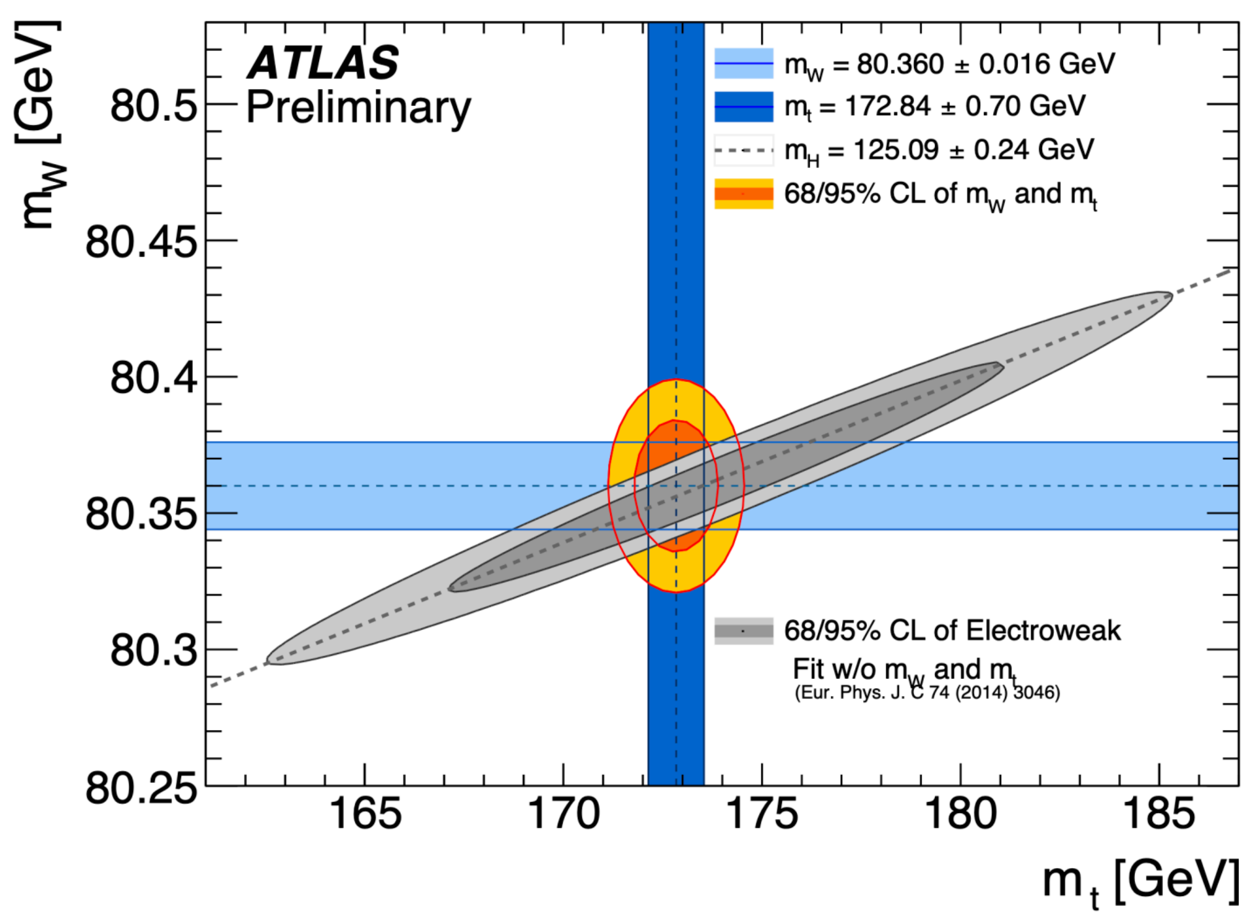


W mass

Talk by Bozzi

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





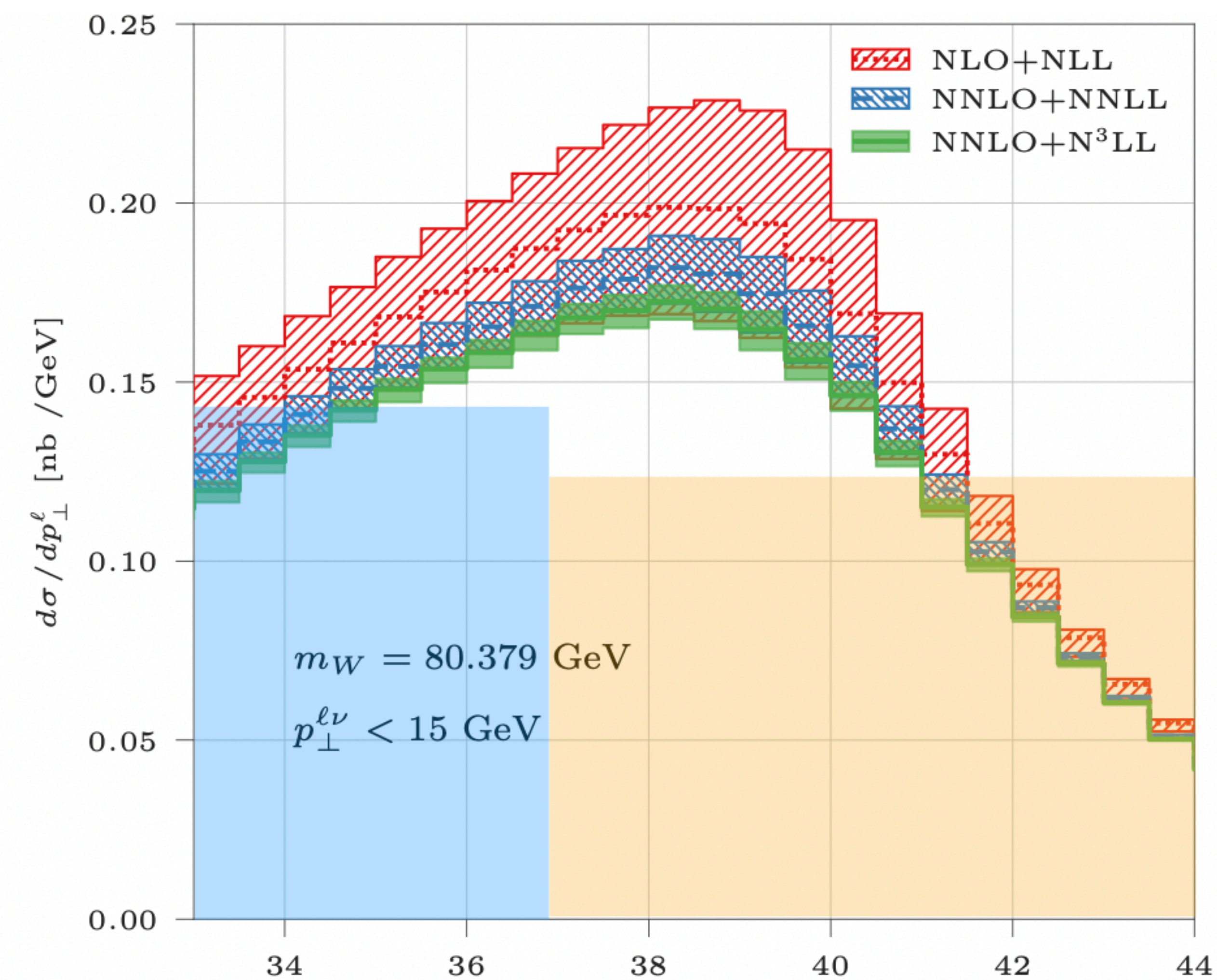
The current situation on the W mass is one of discrepancy between different experiments.

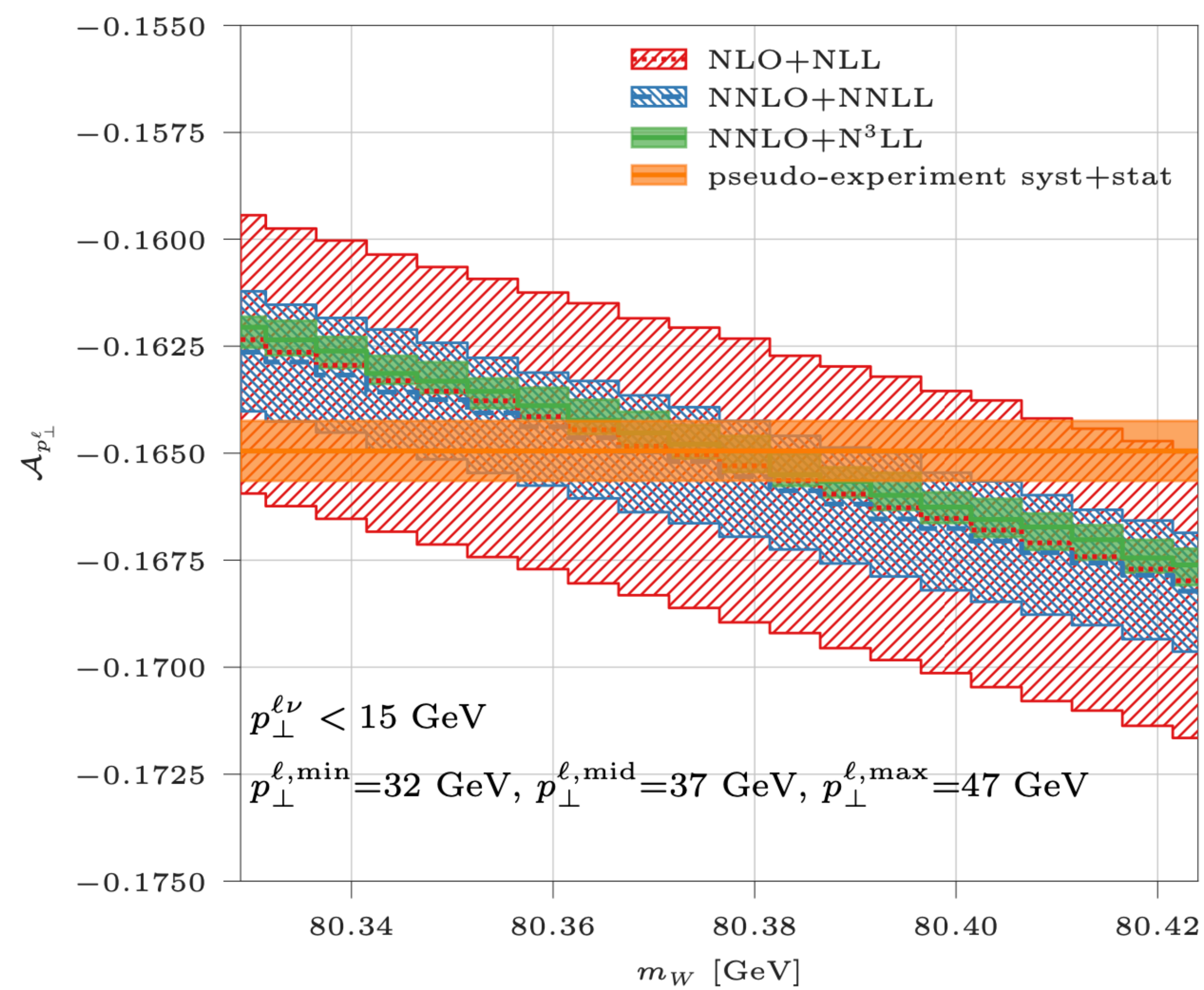
W mass

Talk by Bozzi

New observable: asymmetry around Jakobian peak

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





Effective field theories

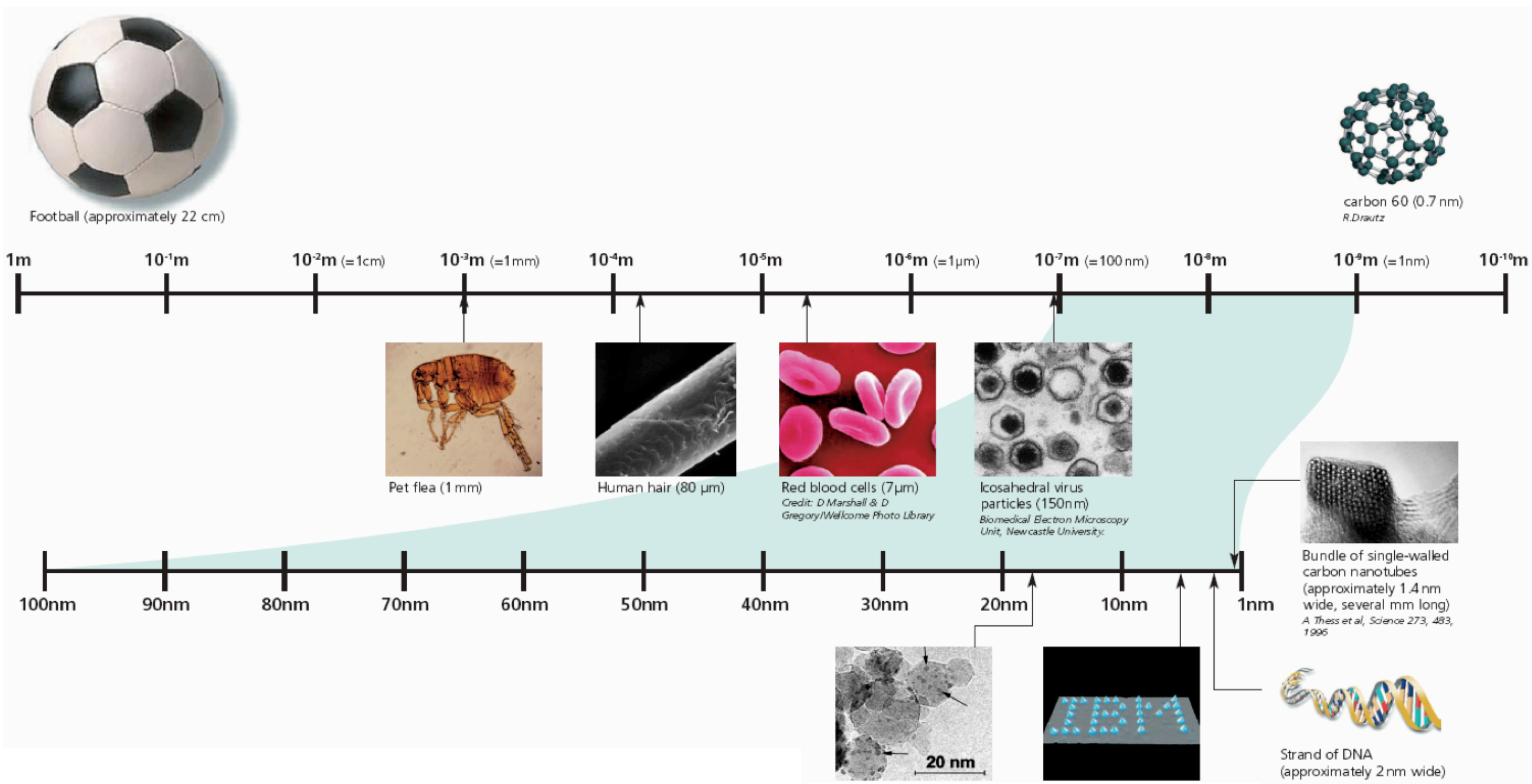
At the LHC

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.

Effective field theories

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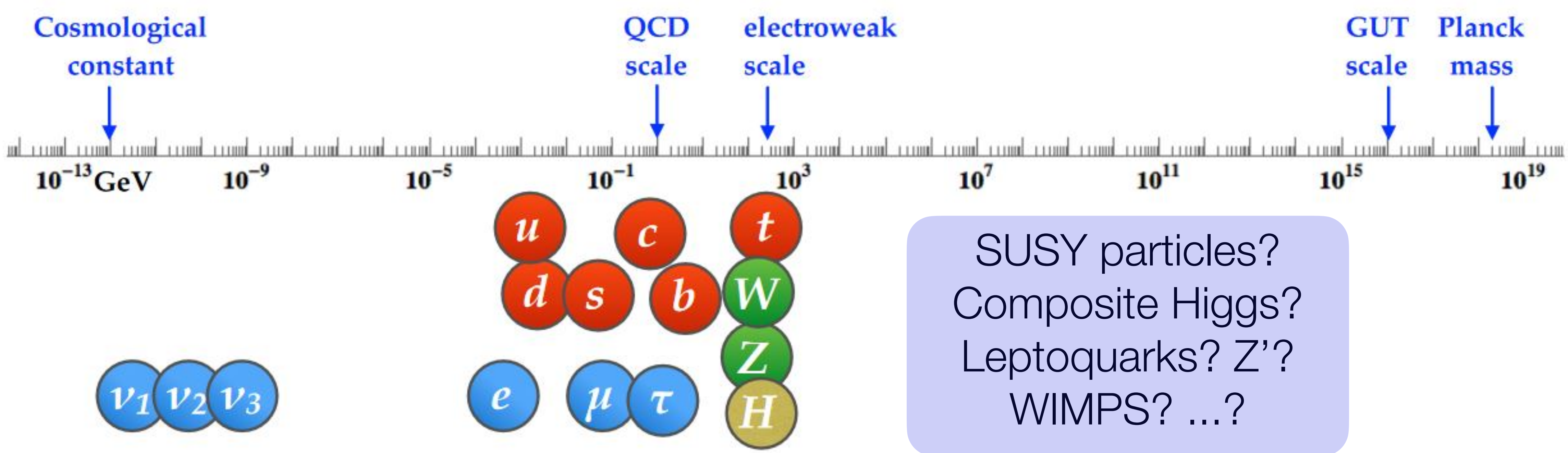


ETFs on one hand allow to achieve precision by neglecting irrelevant details, on the other hand ETFs allow to probe sensitivity to higher scales anticipating possible discoveries.

Effective field theory

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

Talks by Ambrosio, Apyan, Biekoetter, Chatterjee, Callea, Di Noi, Fontes, Lessa, Li, Rodriguez Sachez, Rojo, Thomas, Thomsen, Vitti

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

$\mathcal{C}_i^{(6)}$: 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.

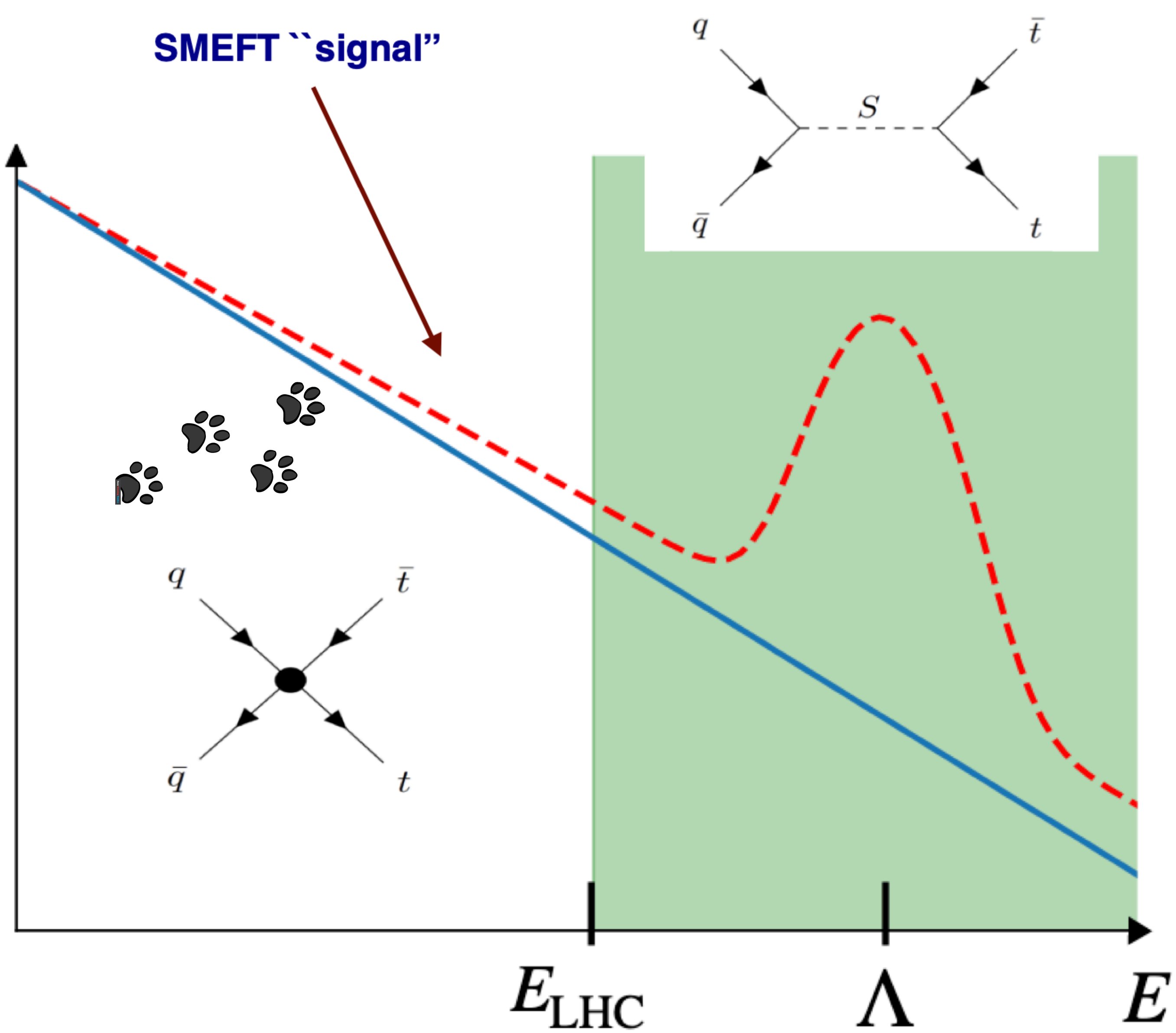
EFT as bridge to a new theory. Many UV theories share the same EFT operators ⇒ calls for automation

HighPT, MATCHMAKEREFT, MATCHETE, SMEFT, SMEFiT

Effective field theory

Targets non-resonant signals, footprint of new physics:

Talk by Rojo



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. $\not{CP}$ 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.)
- $\not{CP}$ terms integrate to 0 in interference terms for CP even observables
- Consideration of beyond-SMEFT EFT frameworks
- jointly fit PDFs and Wilson coefficients

EFT & flavour

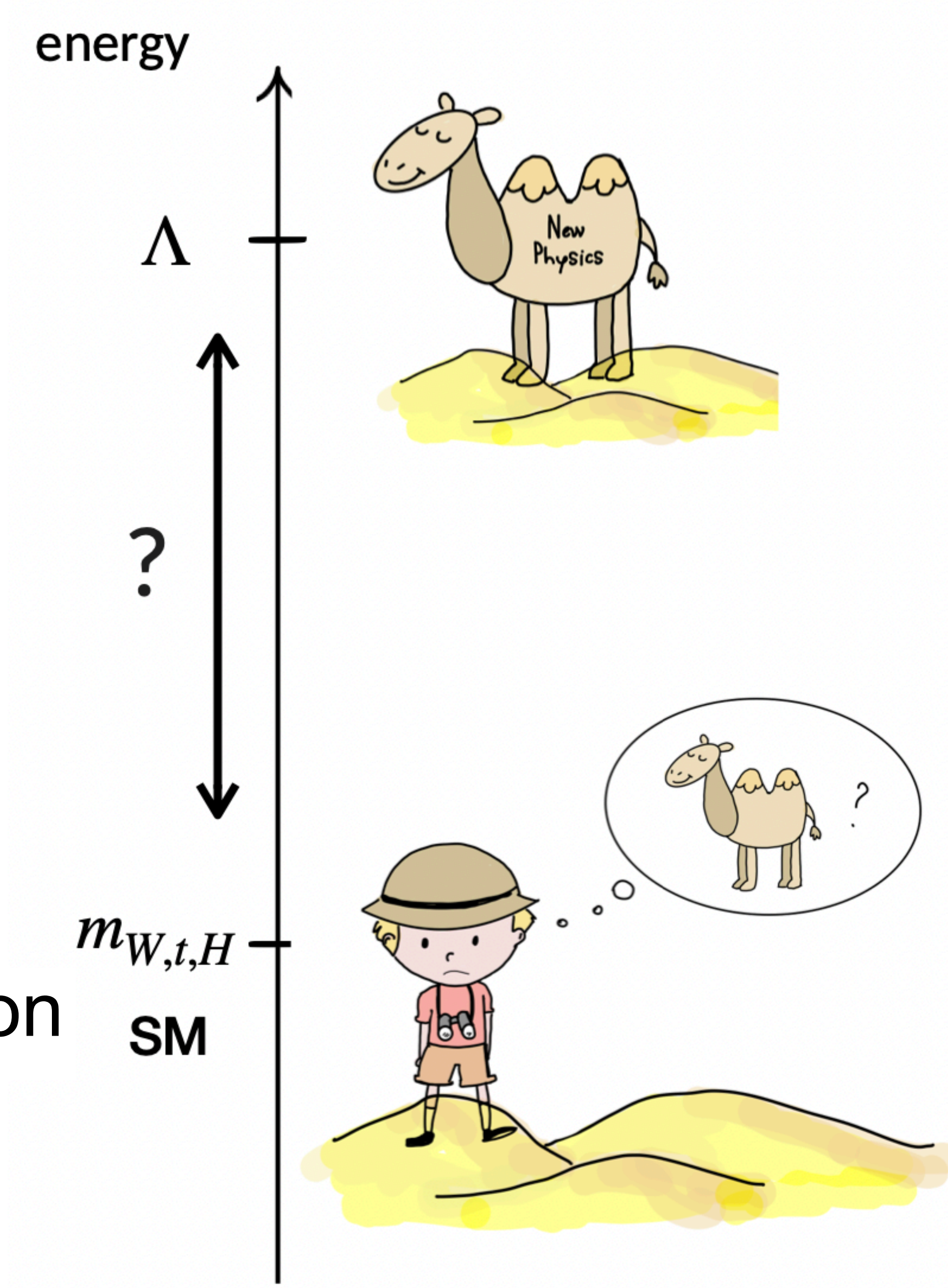
Talk by Cornella

The dream:

from EFT footprints reconstruct UV theory

In flavour sector:

- Use flavour and hierarchy as guide
- Flavour universal NP no longer natural
- NP models distinguishing 3rd generation are motivated targets for future exploration
- FCC-ee can add a lot to FCNC

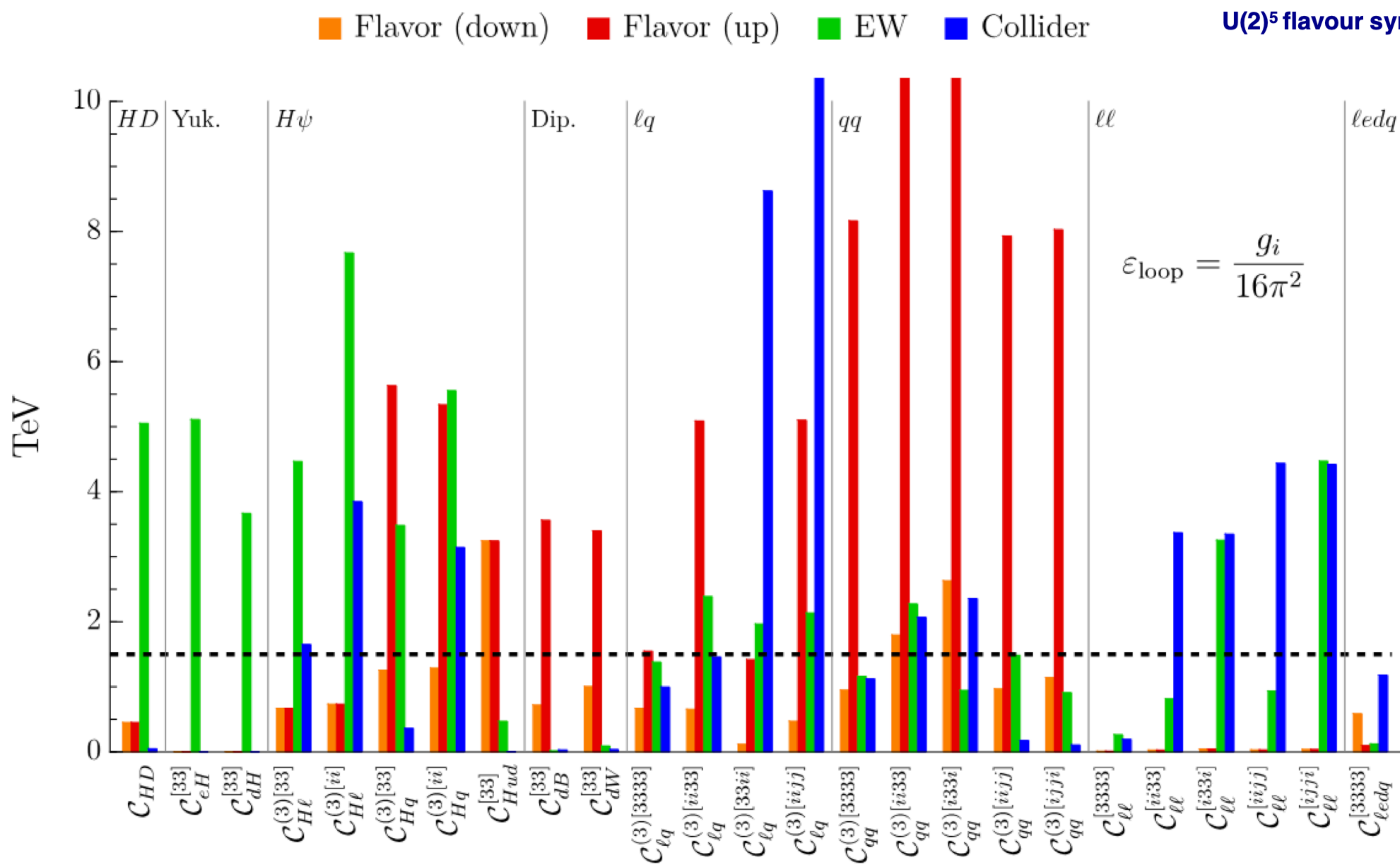


Caveats and prospects

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

Talks by Cornella and Rojo

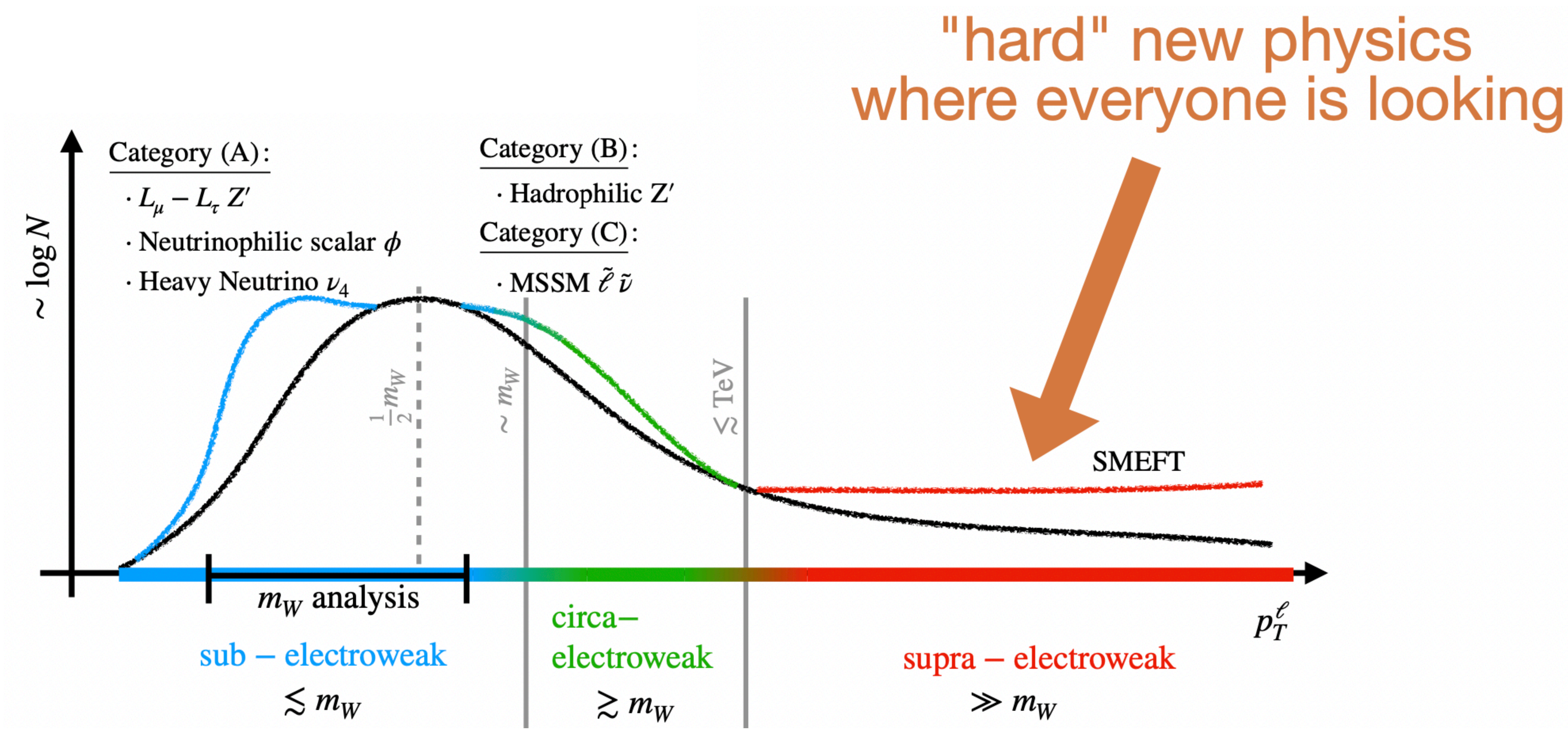
U(2)^5 flavour symmetry



Allwiche
Isidori,
arXiv:2

BSM in the bulk?

Talk by Franceschini, Thamm



Every SM measurement is a new physics search

Every BSM search is a SM measurement

Get rid of this dichotomy in a systematic way?

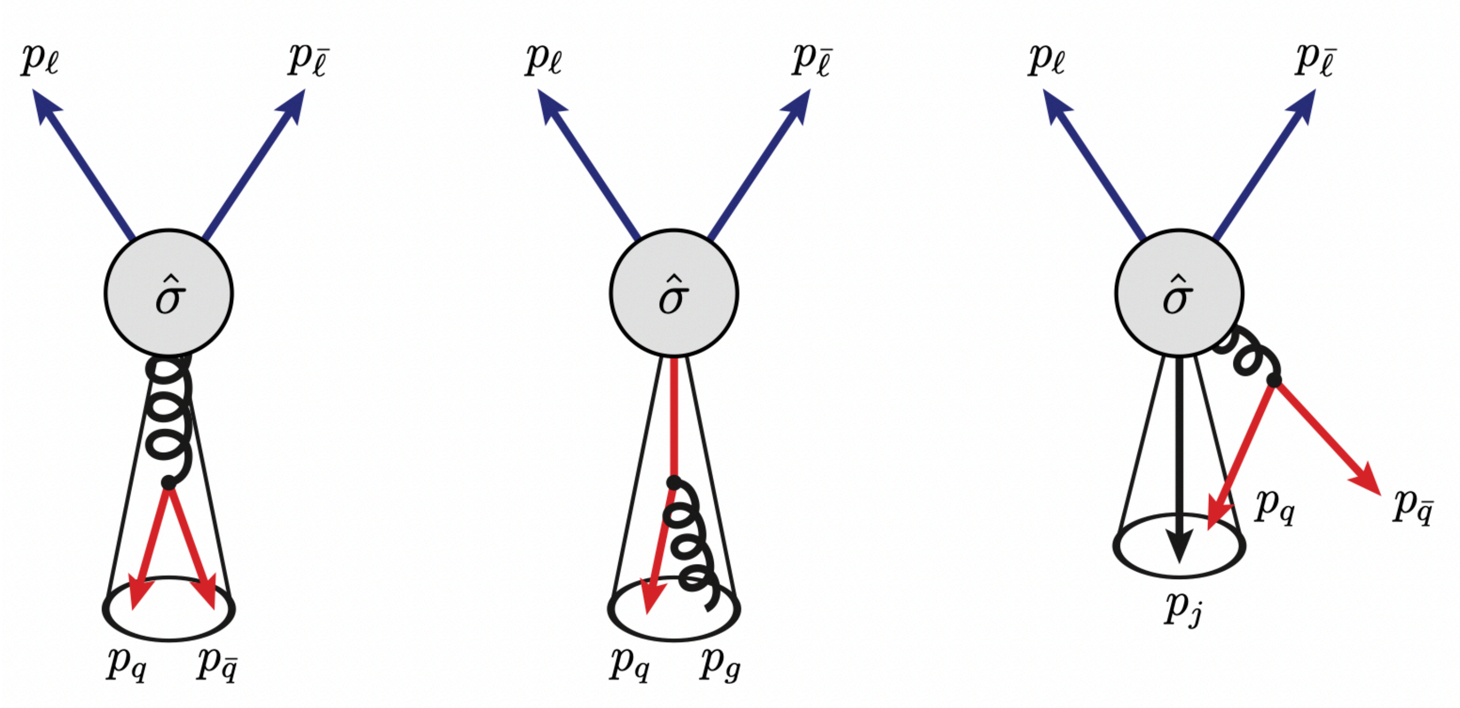
Jet flavour

<u>Example: LHCb charm-jet definition</u>

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

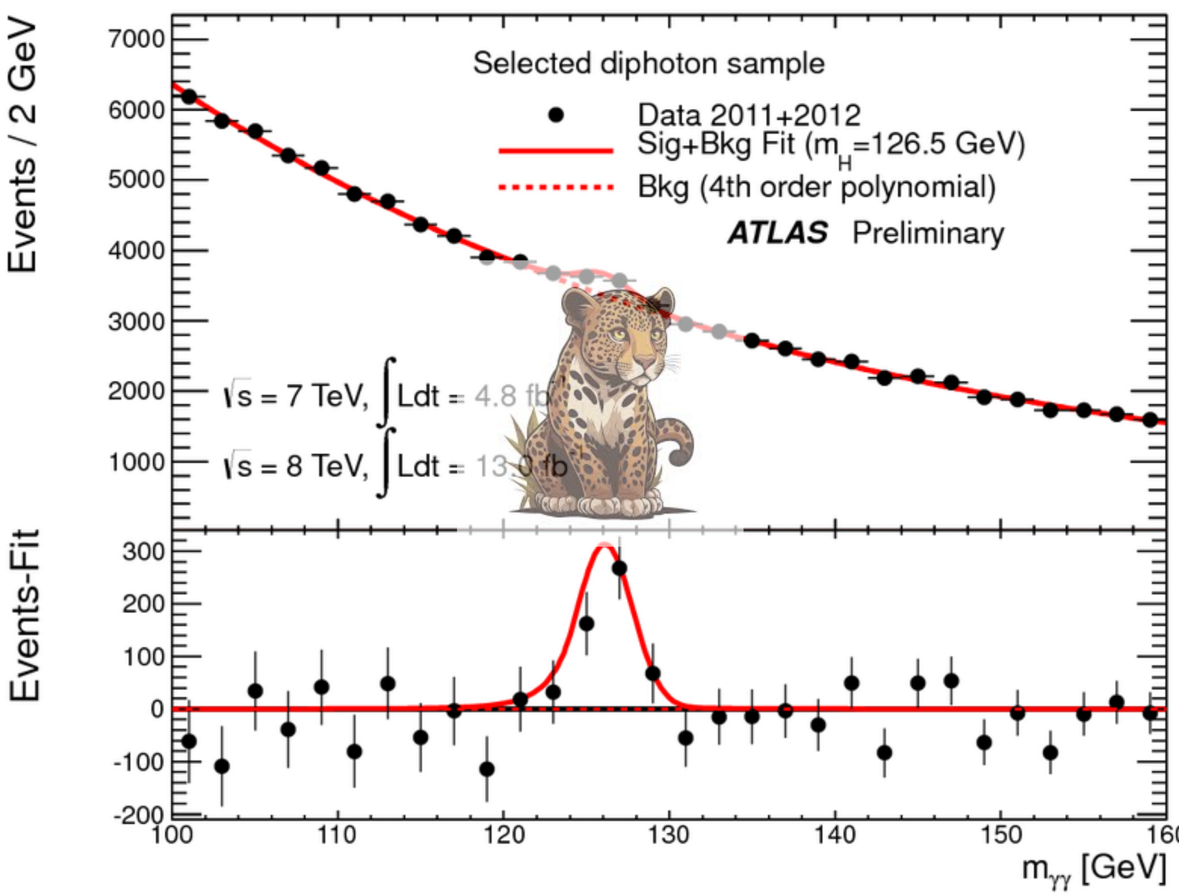
Whether these novel jet definitions will be used in experimental analyses remains to be seen …

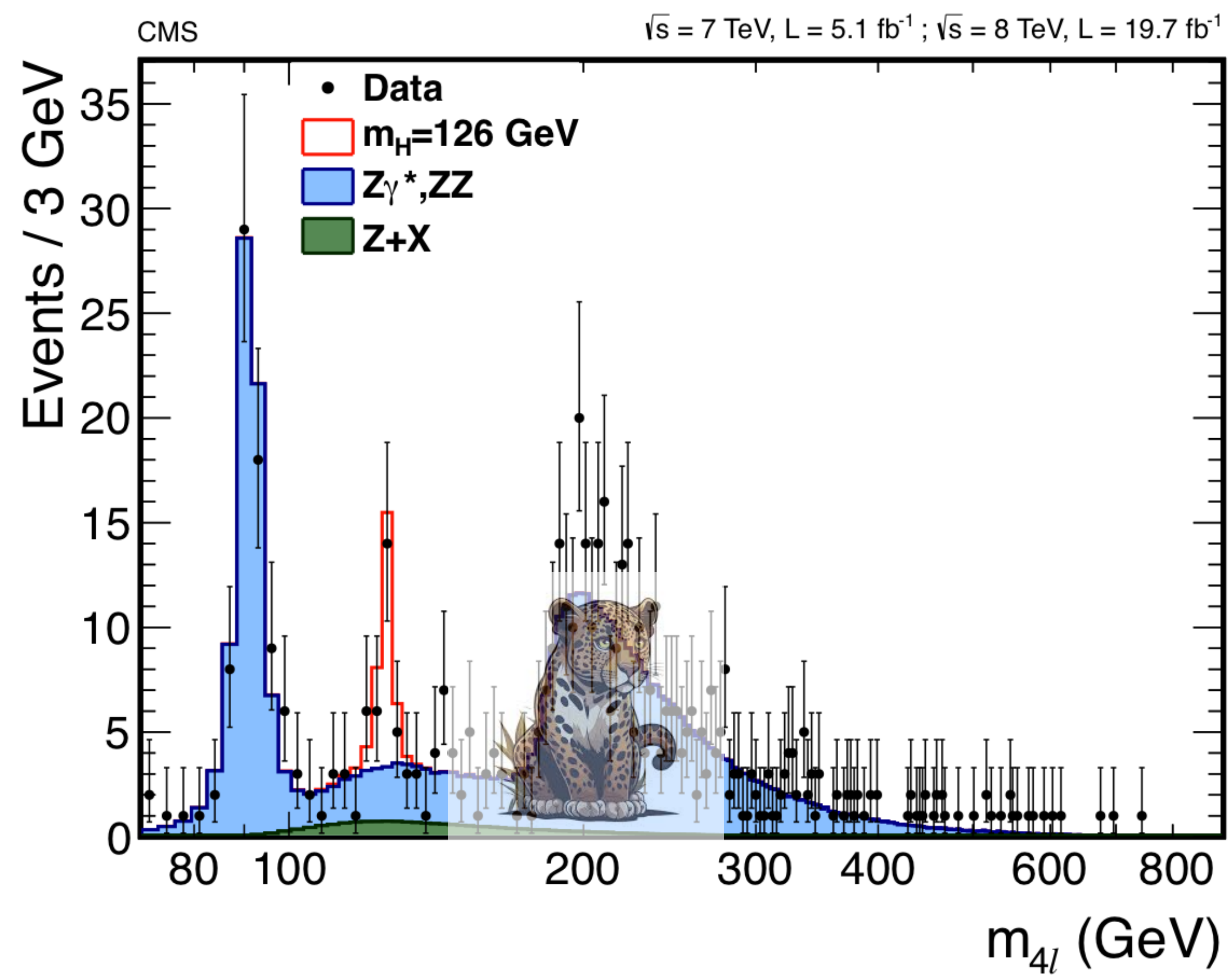
Talk by Caletti, Nguyen, Tancredi

3. Providing a theory interpretation of signals

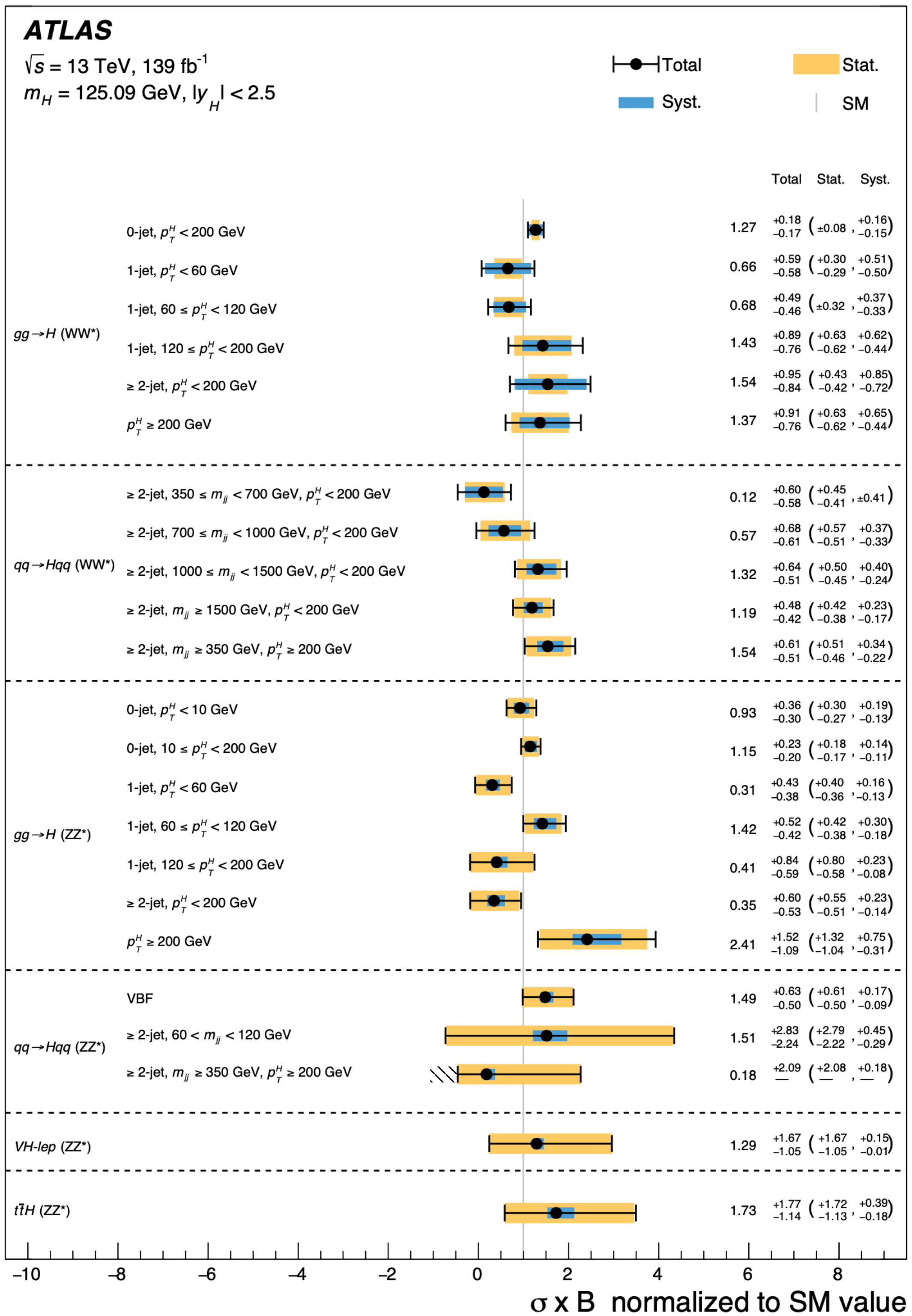
Higgs discovery

Higgs: a theory independent discovery





Higgs discovery



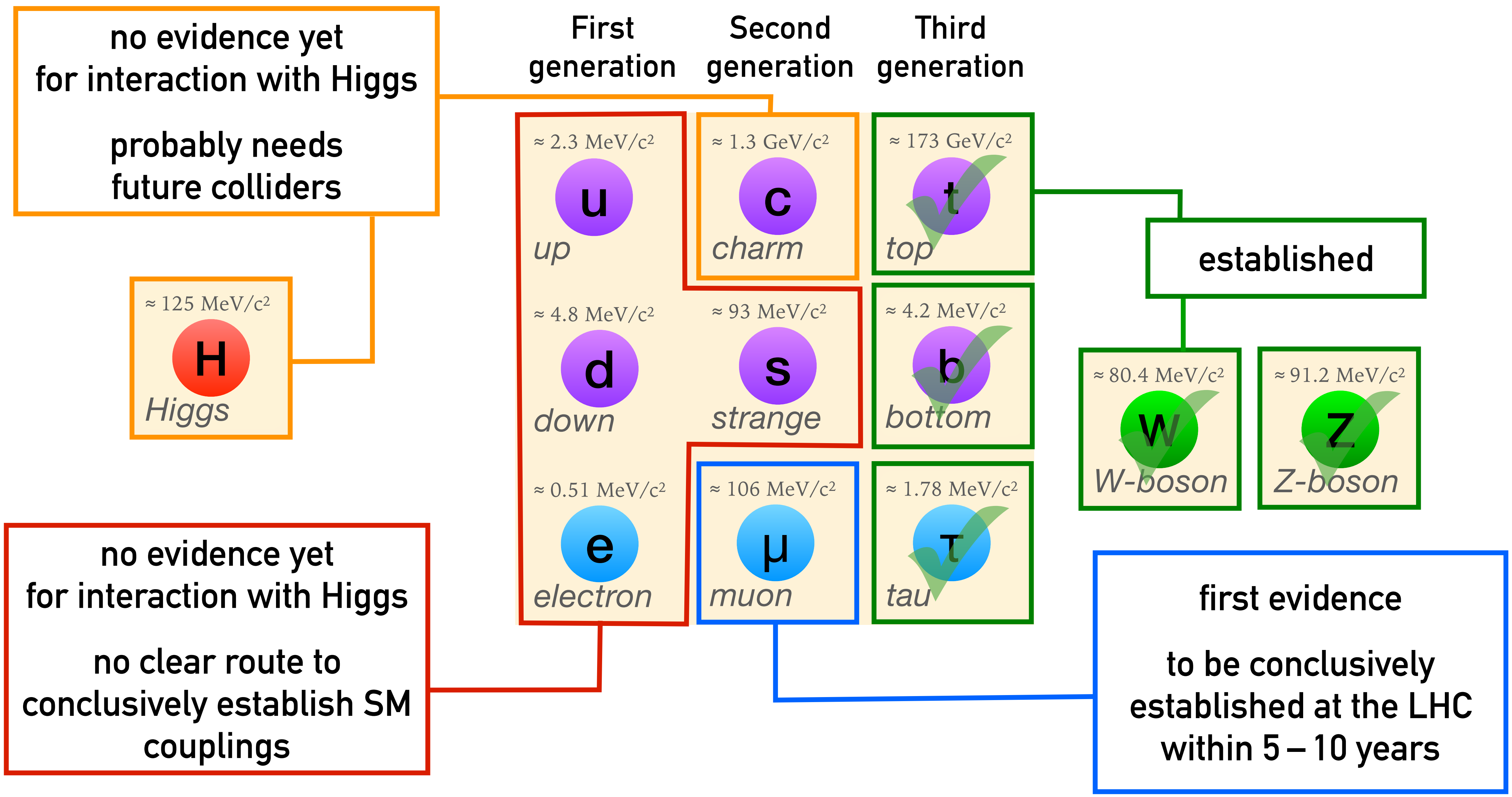
Theory crucial for the interpretation of discoveries

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

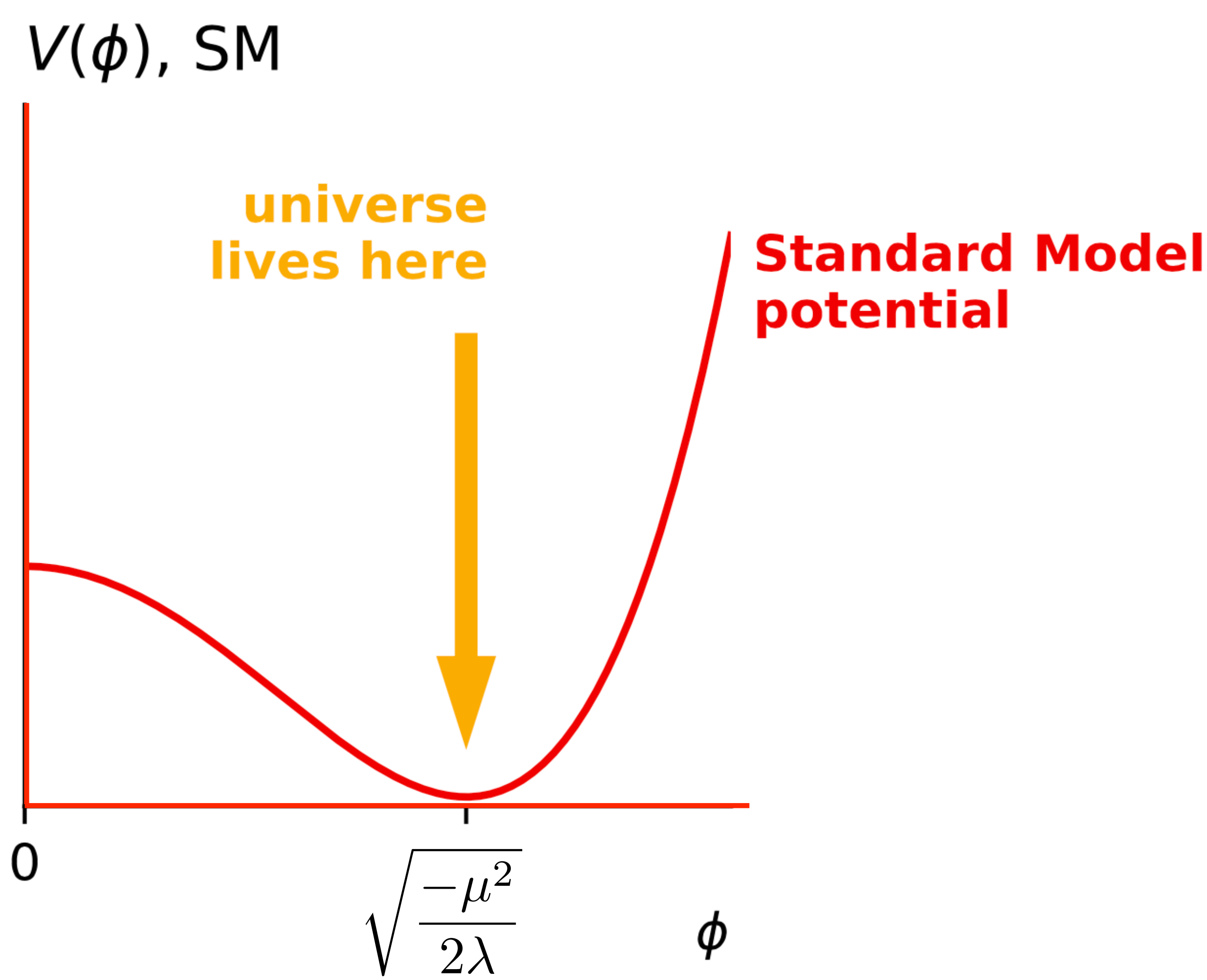
Talks by Dawson, LianTao Wang & Yikon Wang

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



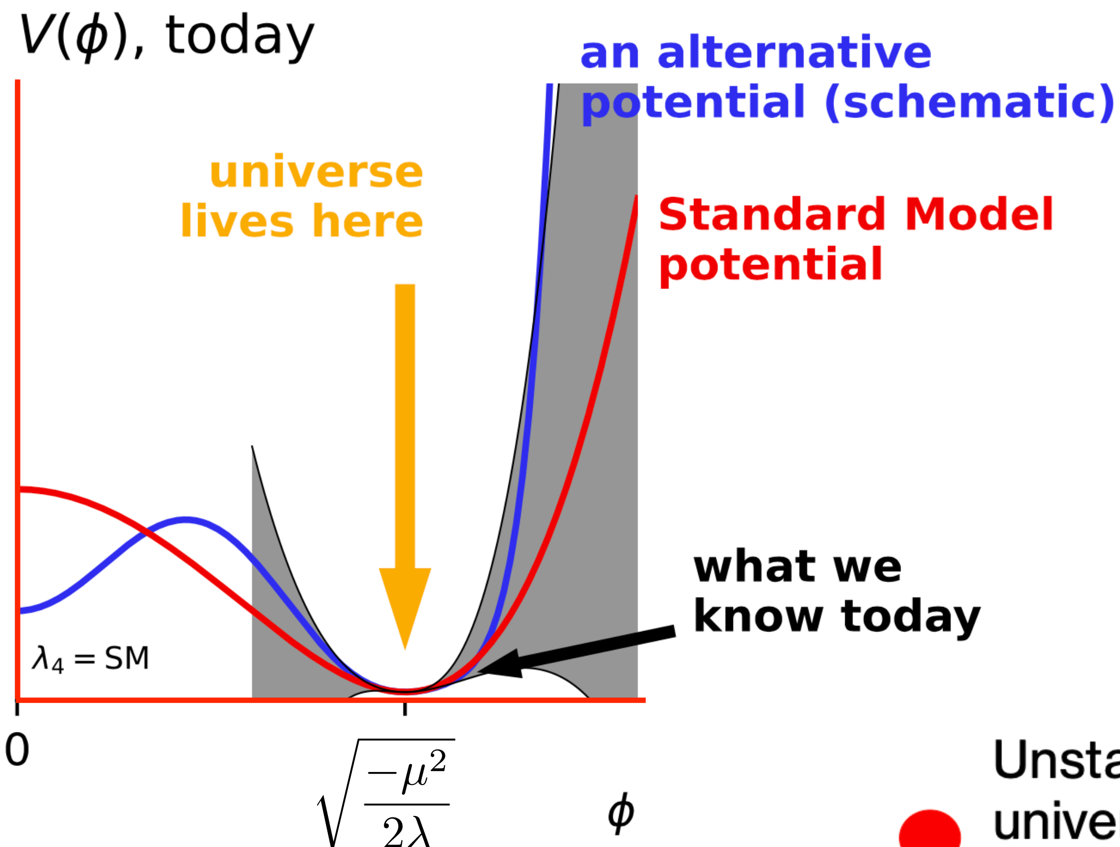
The Higgs boson is responsible for the masses of all particles. Its potential, linked to the Higgs self-coupling, is predicted in the SM, but we have not tested it so far

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

Higgs potential

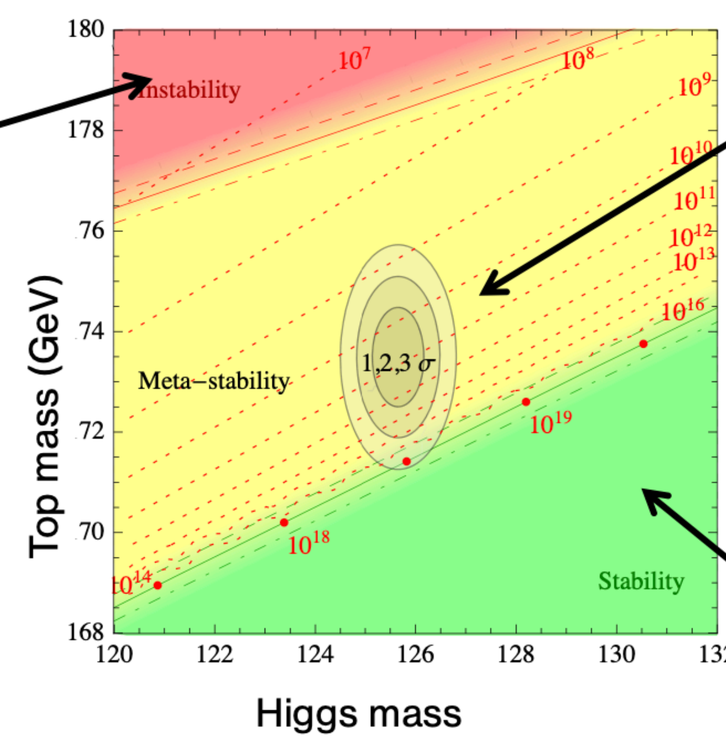
<u>What did we establish so far?</u>

Talks by Dawson, Tancredi, Wang



Unstable universe

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



Our world

Stable universe

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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S. Hossenfelder, 2019

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!