Precision Physics in the LHC Era

Phenomenology Symposium 2026

University of Pittsburgh

Federico Buccioni

LHC in the Precision Physics Era

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Why precision? Why at the LHC?

(sounds fairly obvious) the LHC is a lab, it carries out experiments:

we prepare the initial state, repeat the experiments billions of times, calibrate the conditions, systematically improve detectors and theory…

→ we test hypotheses and investigate **Particle Physics** at the **highest possible energies** in a **controlled environment**

After the 2012 Higgs boson discovery the SM is complete…

the **particle content**, **yes**! Can we say the same about the **interactions**? I would say NO

The **LHC** "naturally" entered a **precision phase**:

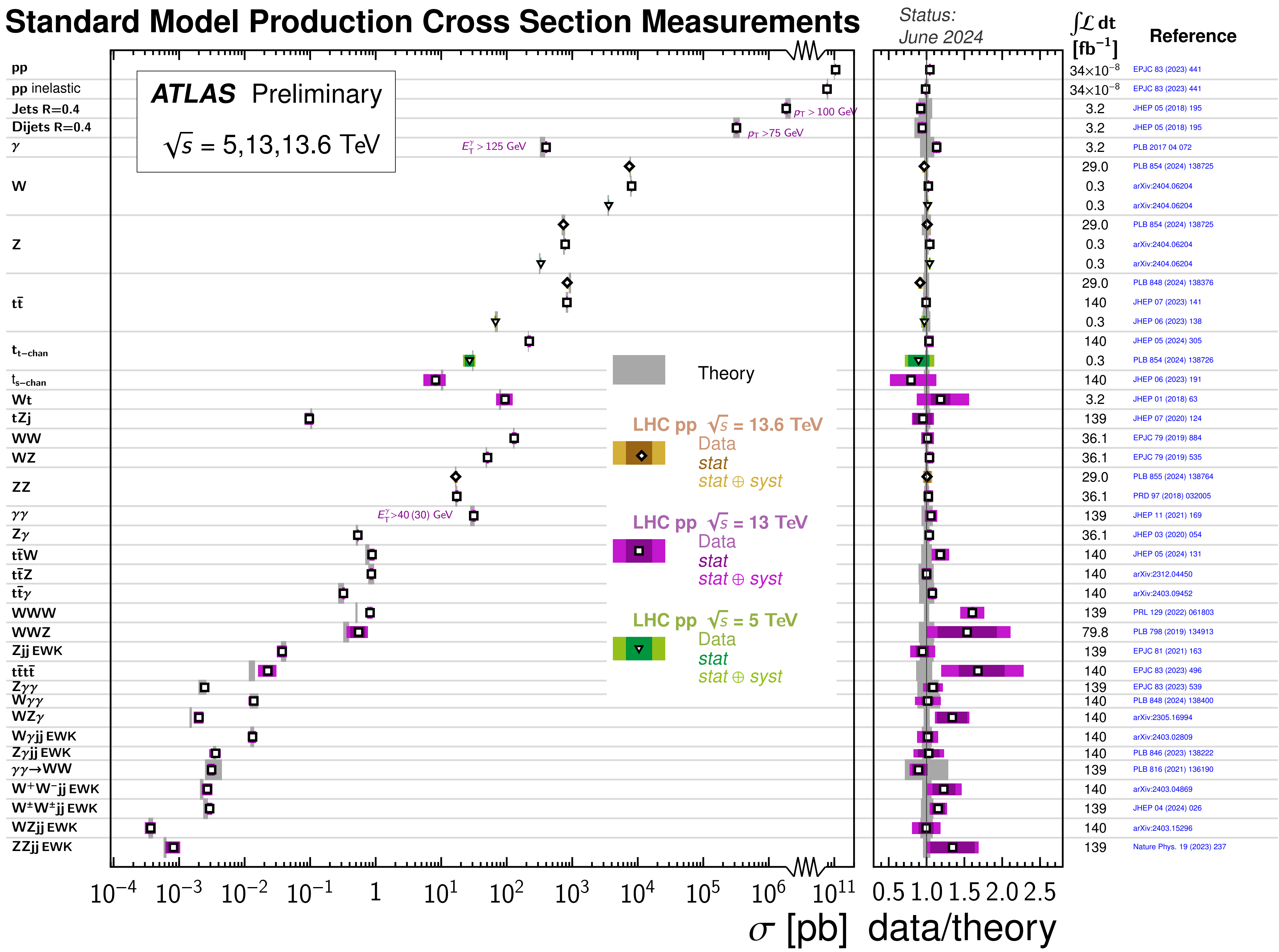
- parts of the SM are still largely unexplored (mostly the Higgs sector)
- the SM is a predictive theory in many respects: precision is intrinsic
- New Physics is very heavy (beyond what we probed) or interacts very weekly with the SM…or both

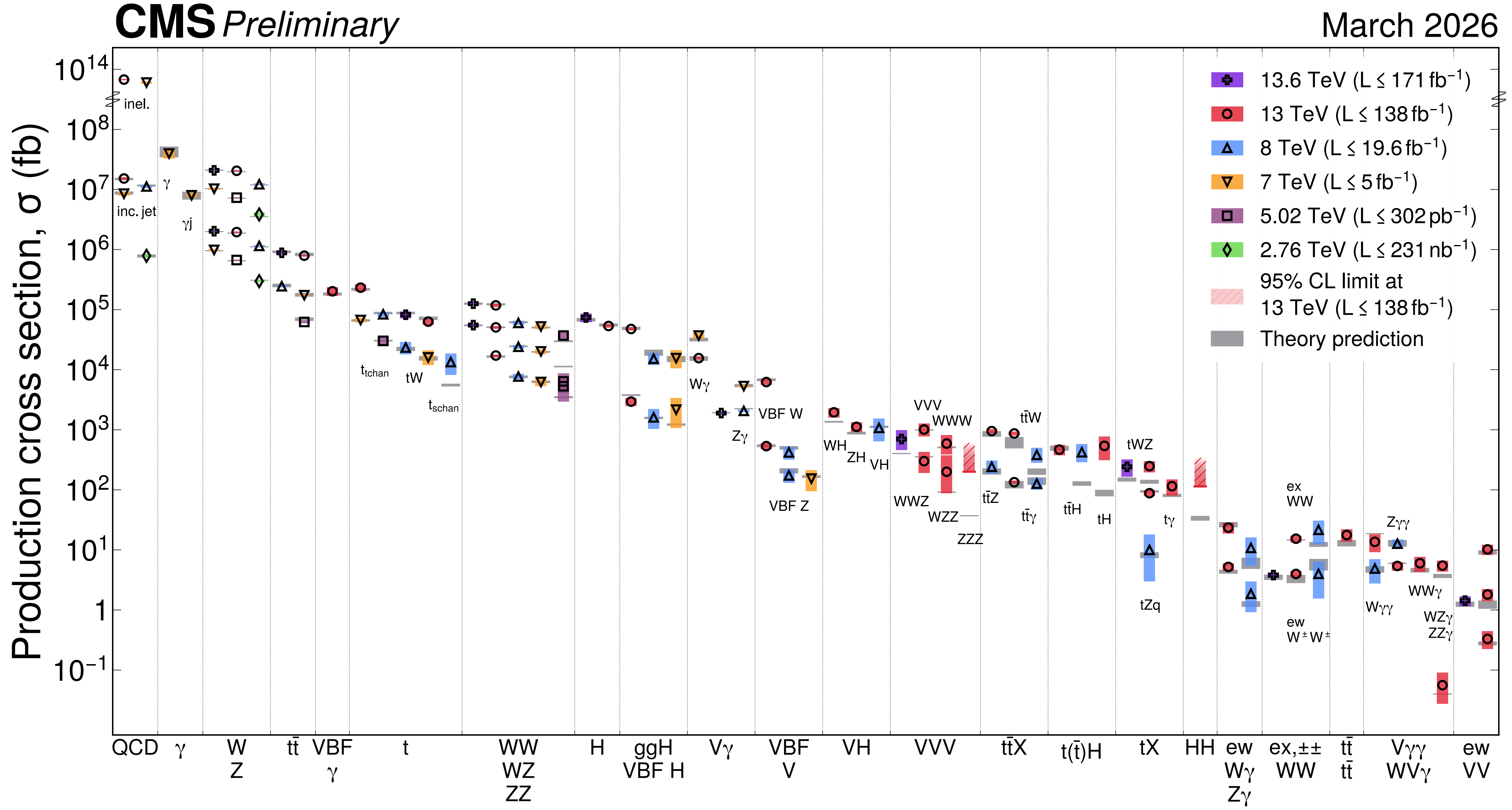
→ precision offers a way → Is the SM the theory of Nature in the multi-TeV region?

Disclaimer: selection of topics might reflect personal bias [precision SM]

LHC: vast and diverse research campaign

LHC measures rates (XS) spanning 15 orders of magnitude!





final-state signatures involve jets (flavoured and not), leptons, photons

aiming at studying all corners of the SM (and beyond)!

Extreme task for SM precision theorists! Challenges of very different origin

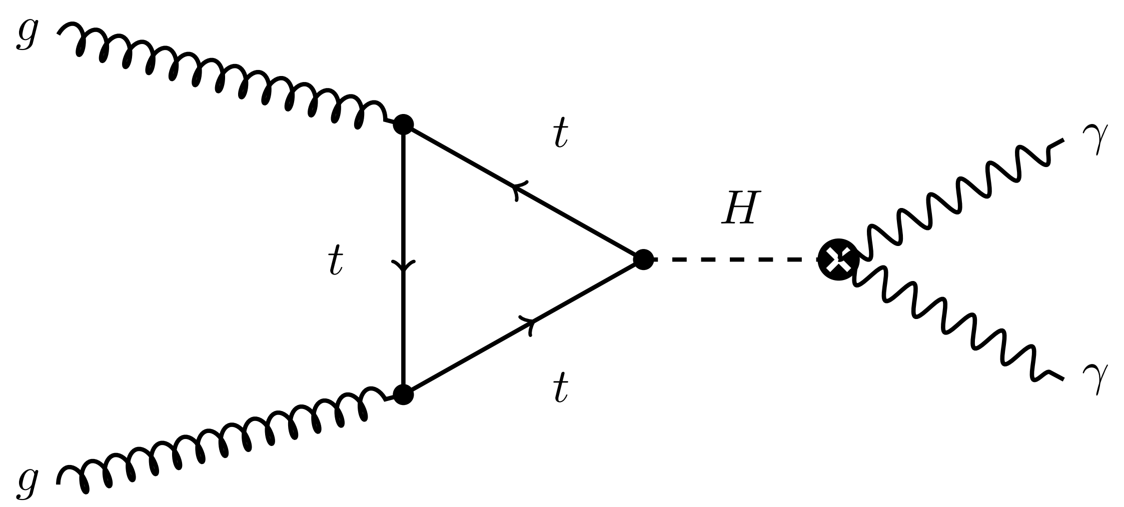
daily struggle:

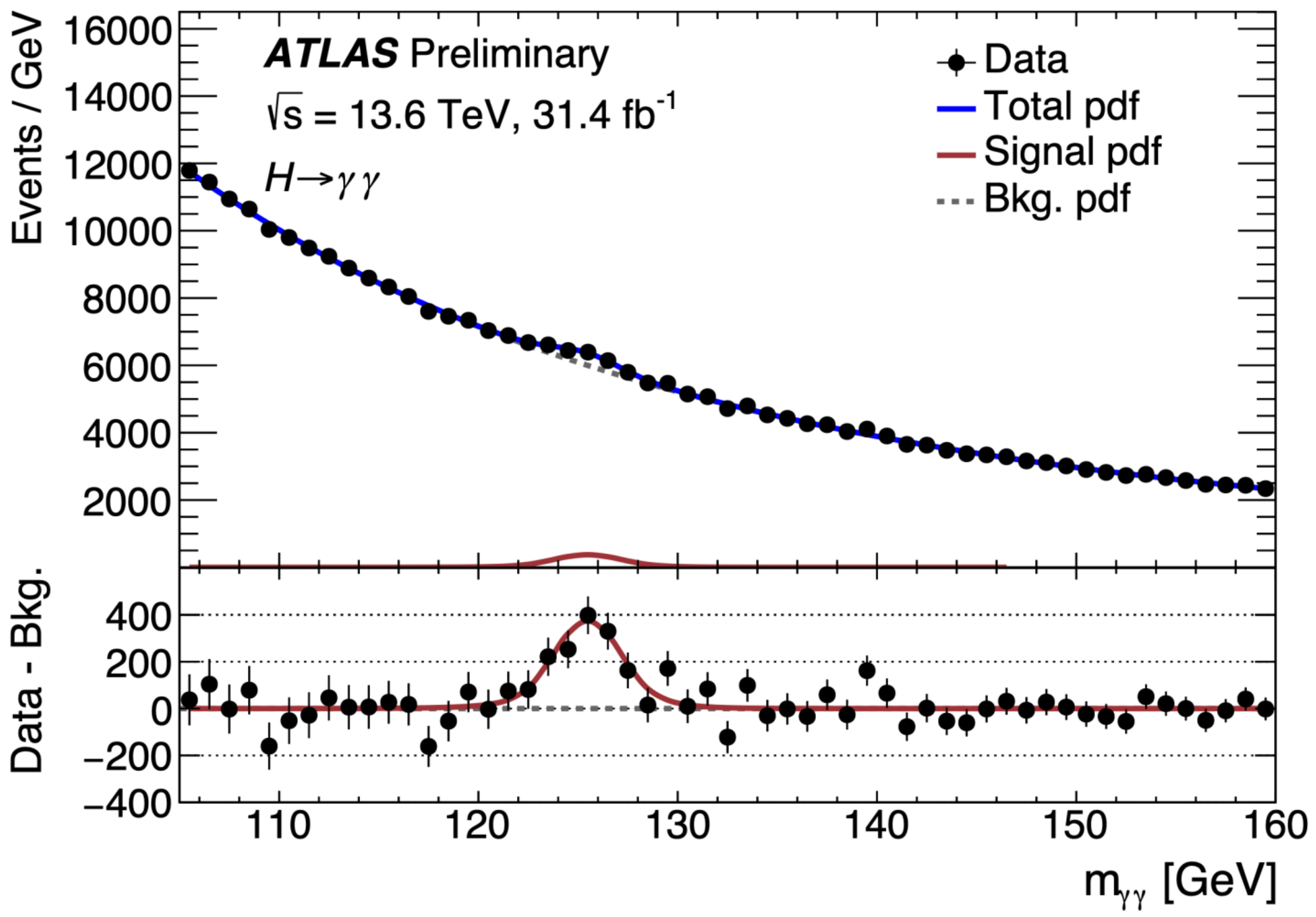
$\delta_{\rm exp}$ vs $\delta_{\rm th}$

Indirect → direct discoveries at the LHC

H production mechanism at LHC: gg fusion

mediated by a loop of top quarks





indirect

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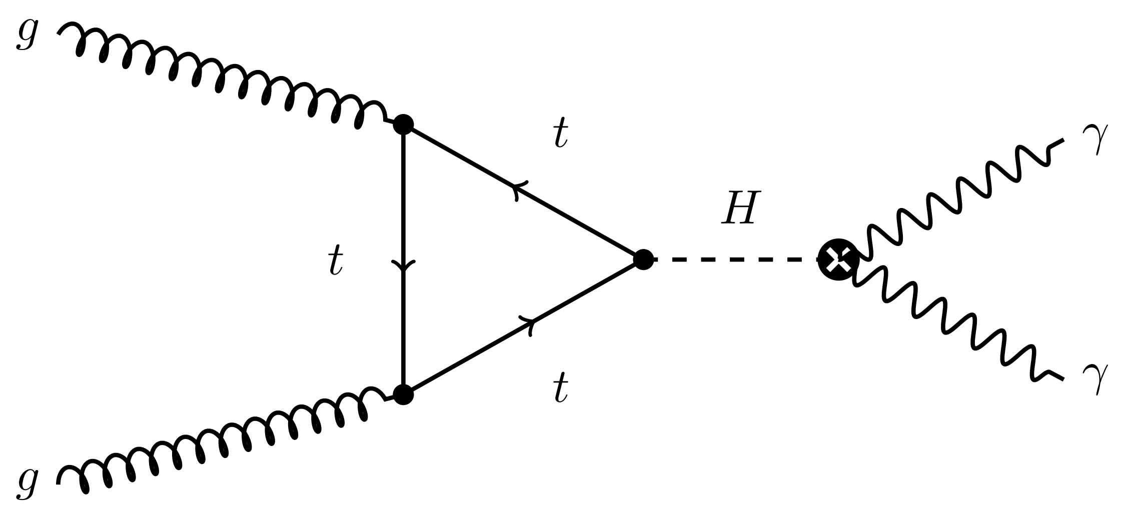
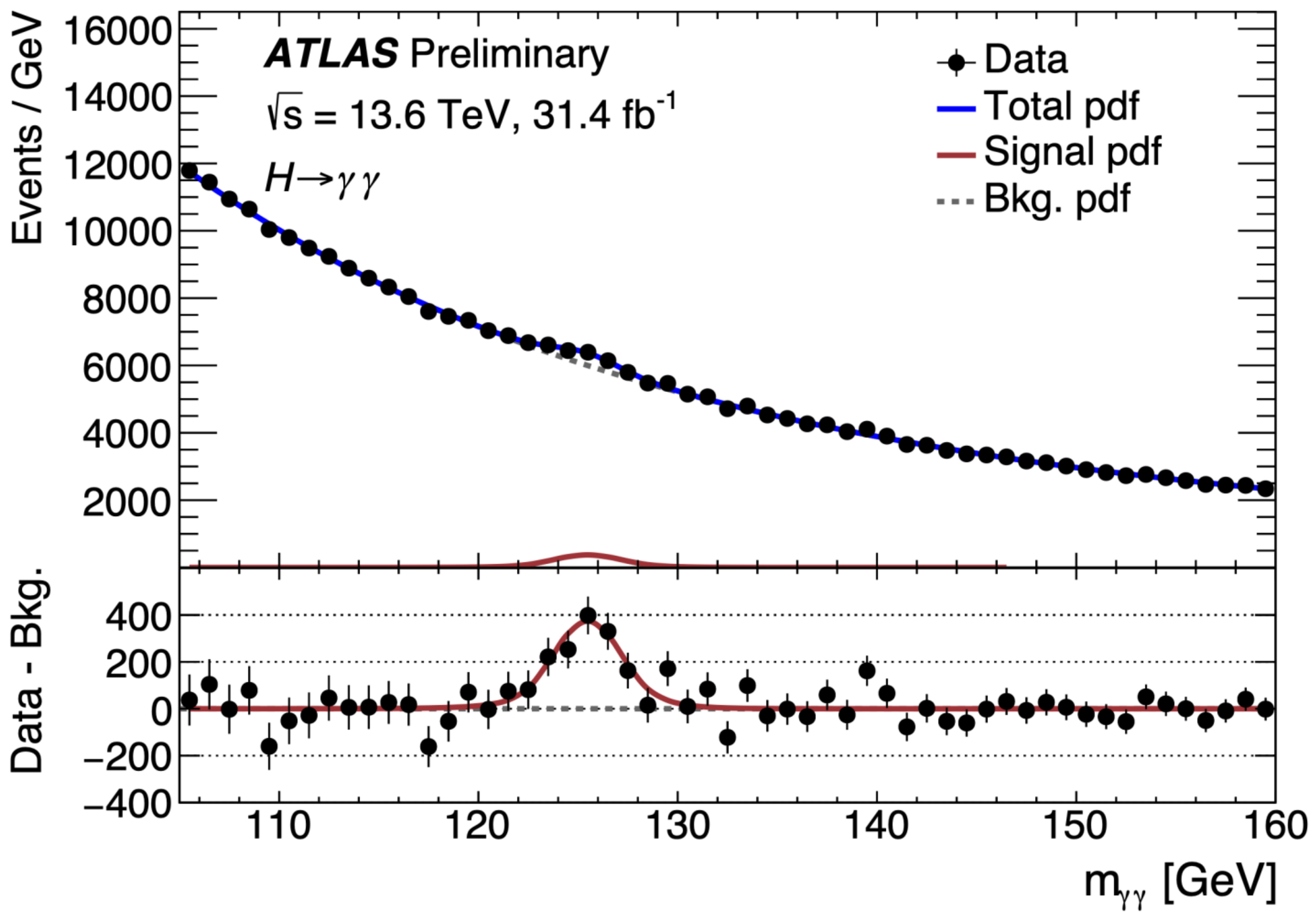




indirect

12/2009

[Plehn, Salam, Spannowsky 0910.5472]

Last but not least, the associated production of a top quark with a Higgs boson at the LHC has a long history, usually in combination with a Higgs decay to bottoms. quotes a significance of 1.8 to 2.2σ for 30 fb^{-1}. Due to a (too) low signal-to-background ratio $S/B \sim 1/9$ this channel might not reach a 5σ significance for any luminosity. The main problems are the combinatorial background of bottom jets and the lack of a truly distinctive kinematic feature of the Higgs decay jets.

Observation of $t\bar{t}$H production

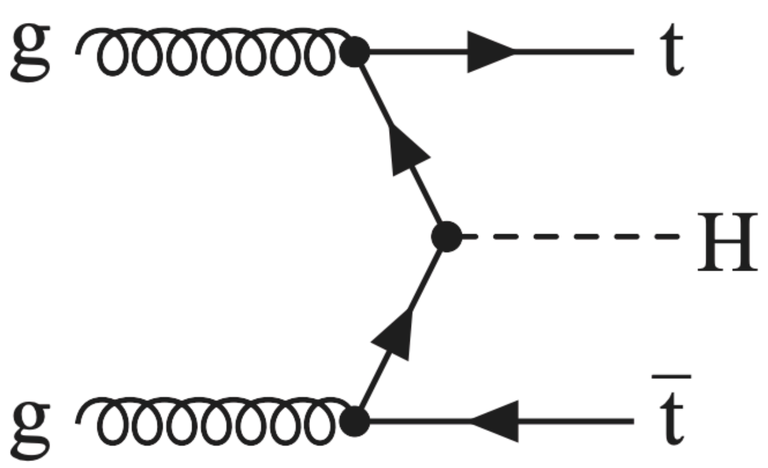
5.2 σ The CMS Collaboration* 06/2018

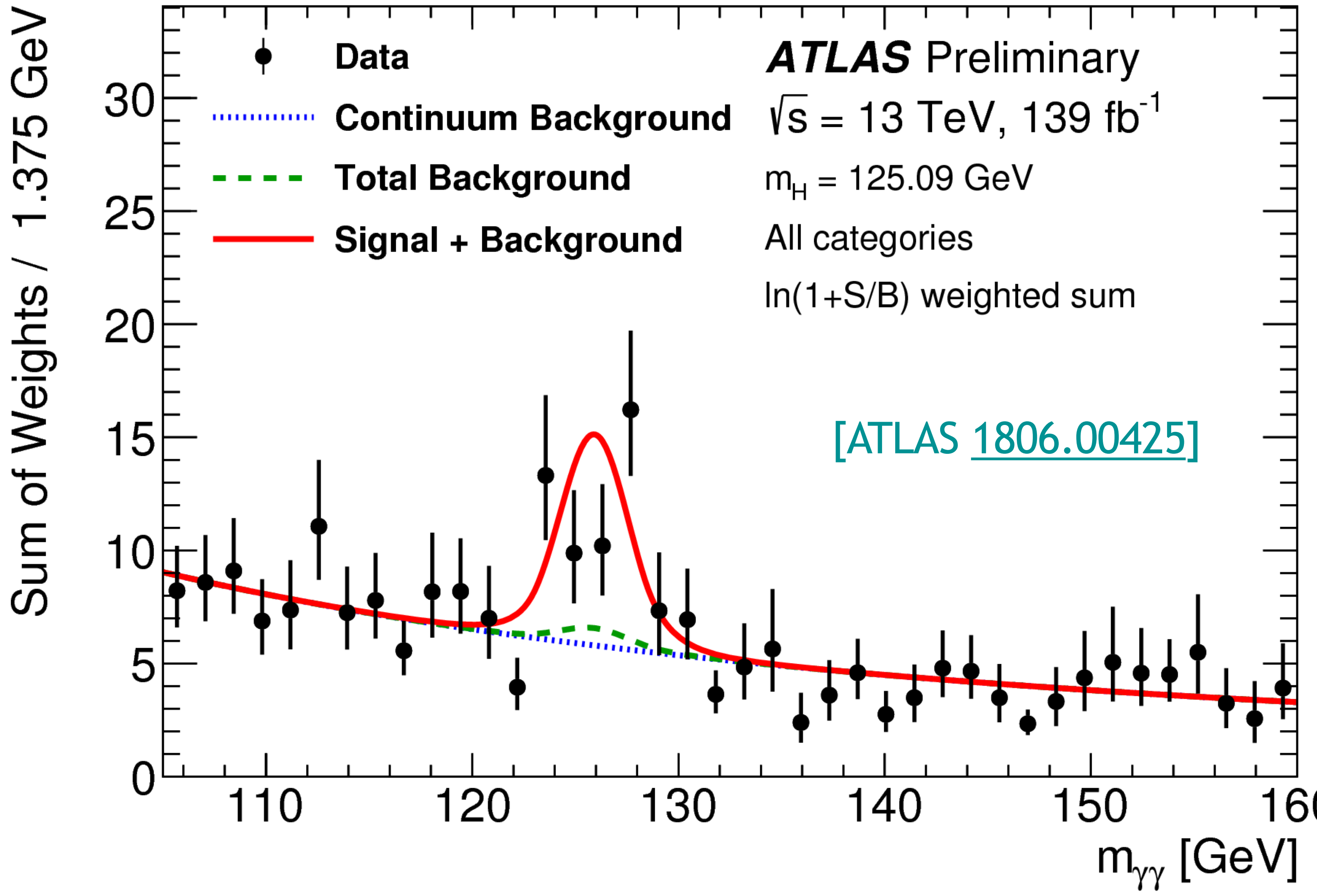
Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector

6.3 σ 08/2018

associated ttH production

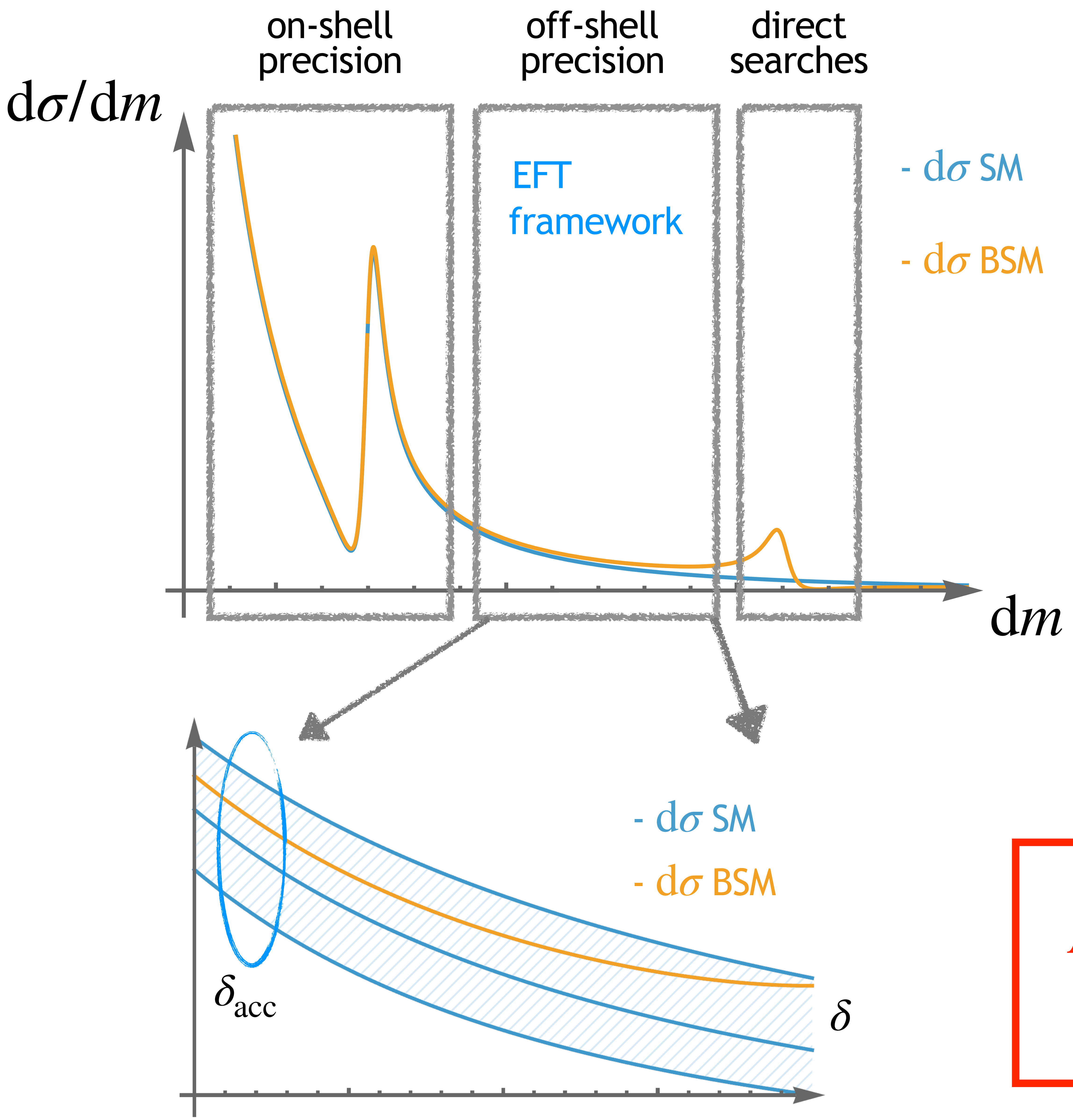
direct access to Yukawa





direct

The energy and precision frontier



$$\mathscr{L}_{\rm eff} \simeq \mathscr{L}_{\rm SM} + \frac{c}{\Lambda^2}\mathscr{O}^{(d=6)} + \dots$$

truncate at dim=6

$$\mathscr{A}_{\rm eff} = \mathscr{A}_{\rm SM} + c\frac{E^2}{\Lambda^2}\mathscr{A}_{\mathscr{O}}$$

acc ~ our knowledge

$$d\sigma_{\rm eff} = d\sigma_{\rm SM}(1+\delta) \quad \text{vs} \quad d\sigma_{\rm meas} = d\sigma_{\rm SM}(1+\delta_{\rm acc})$$

$$\delta_{\rm acc} \gtrsim \delta \qquad \delta_{\rm acc} \gtrsim \frac{E^2}{\Lambda^2}$$

(assuming $c \sim 1$)

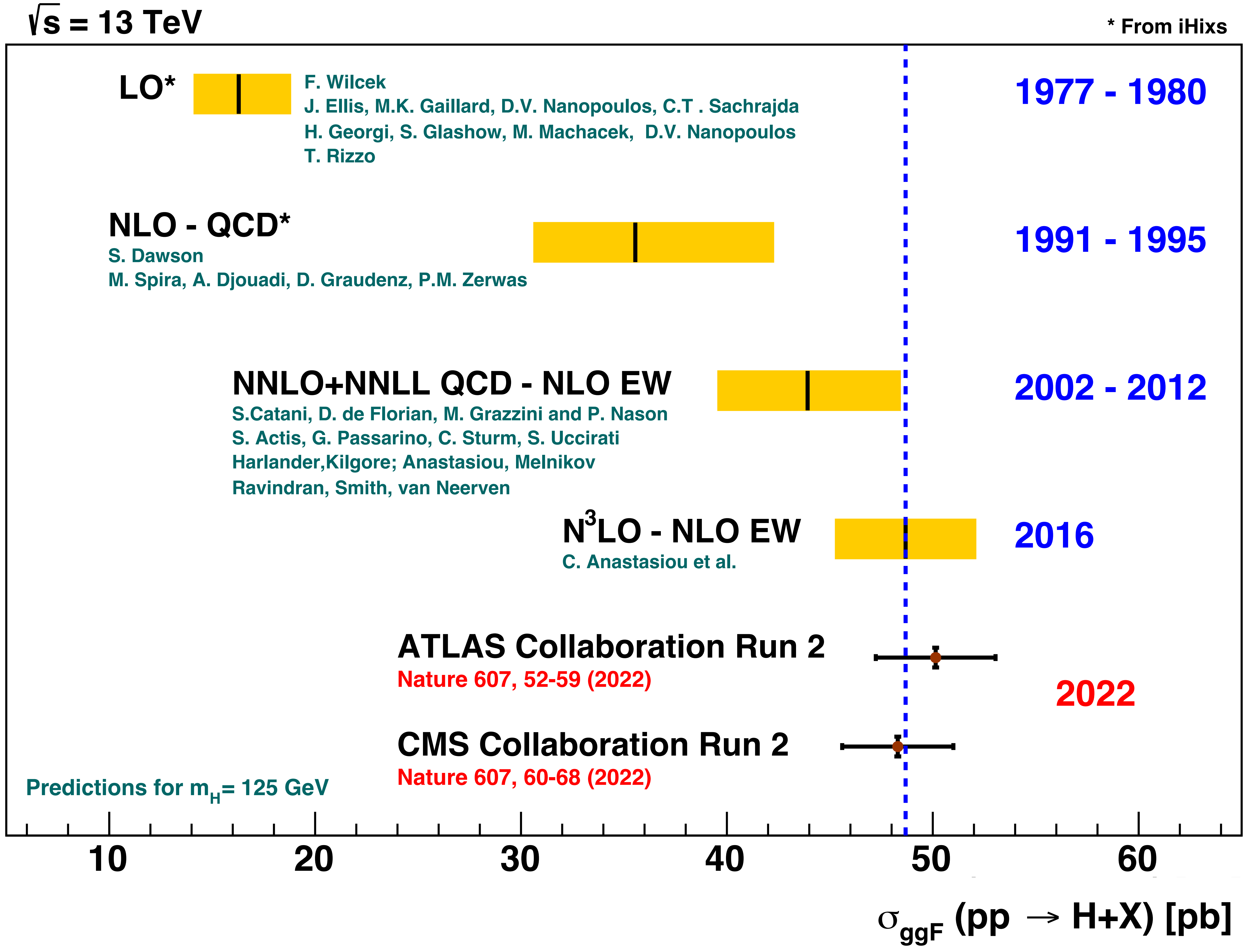
$$\Lambda \gtrsim \frac{E}{\sqrt{\delta_{\rm acc}}}$$

$E \sim 1\,\text{TeV}$ + $\delta_{\rm acc} \sim 1\,\%$

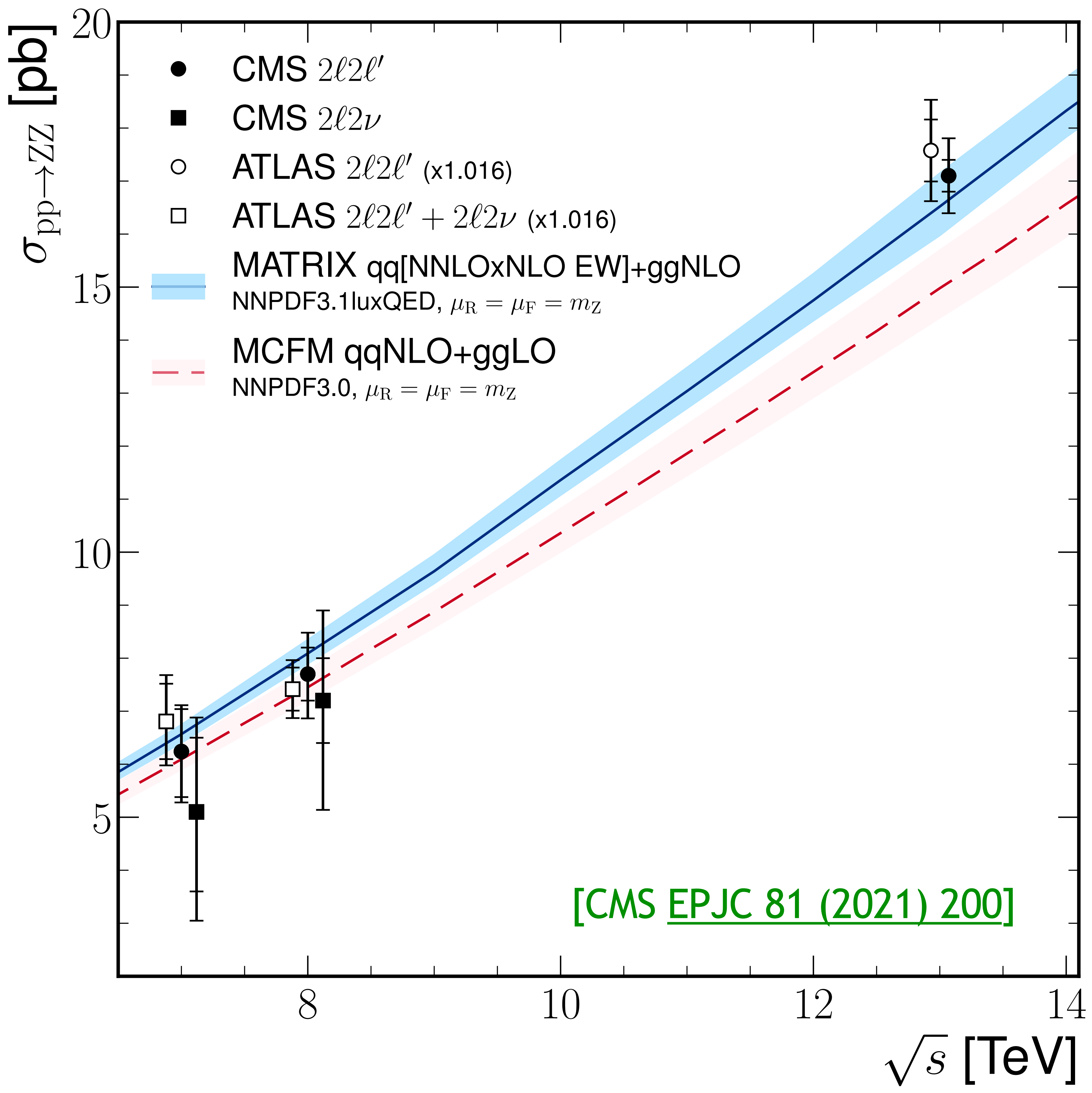
$\Lambda \geq 10\,\text{TeV}$

(off-shell precision)

Theory predictions better be under control



Higgs-boson production



di-boson production

Role of precise theory predictions

"data-theory" (dis)agreement paradigm ⟷ input for meaningful interpretation of the data

prediction vs *extraction*

Theory uncertainties:

intrinsic (eg missing higher orders)

parametric (eg input parameters)

but there's more…

(Ex a) Electroweak Precision Observables (EWPOs)

(Ex b) How to robustly estimate intrinsic theory uncertainties?

(Ex c) Fit from data, eg PDFs, hadronisation models

(Ex d) Calibration/Interpretation of XS measurements

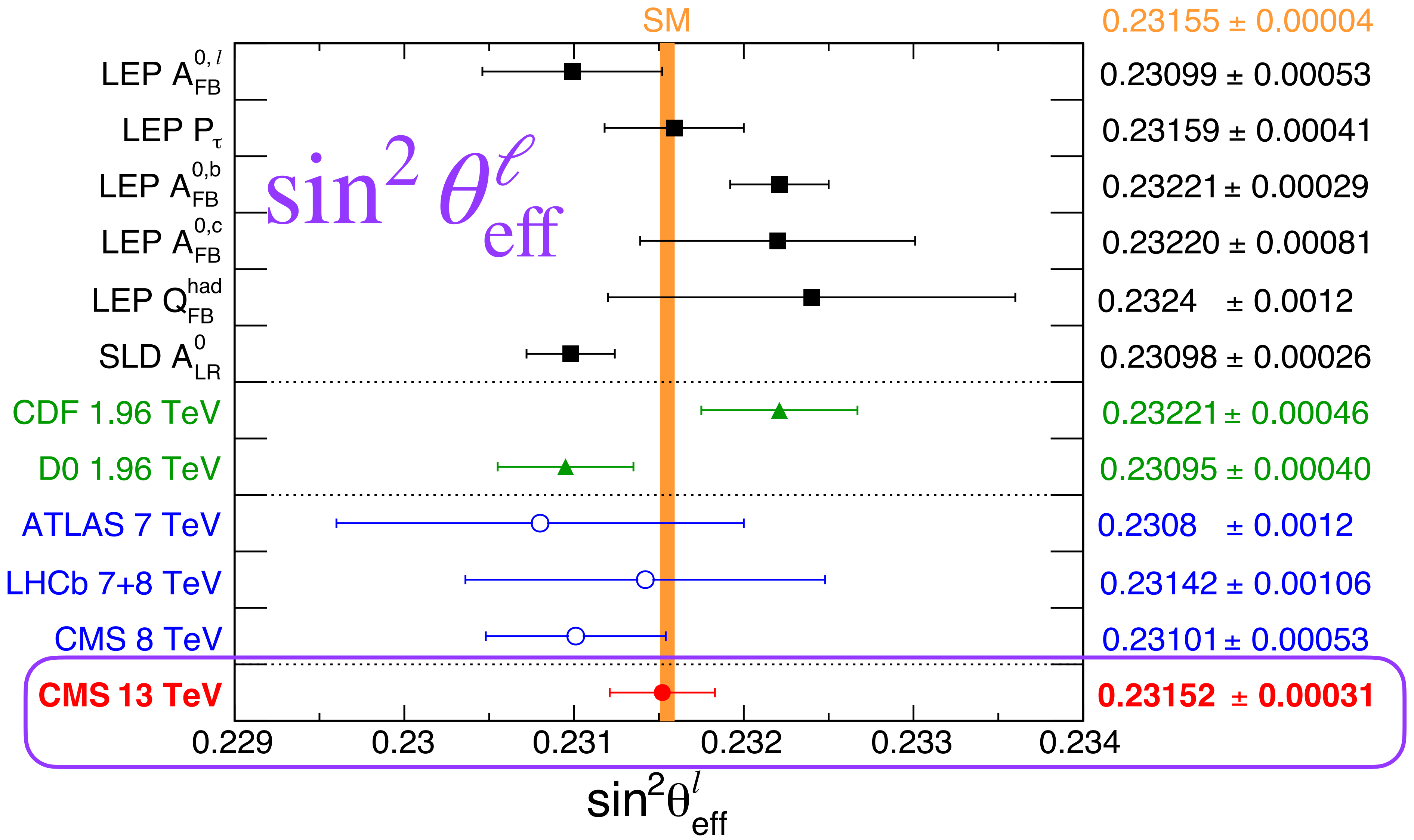
Delicate relation:

real observables ⟷ "pseudo observables"

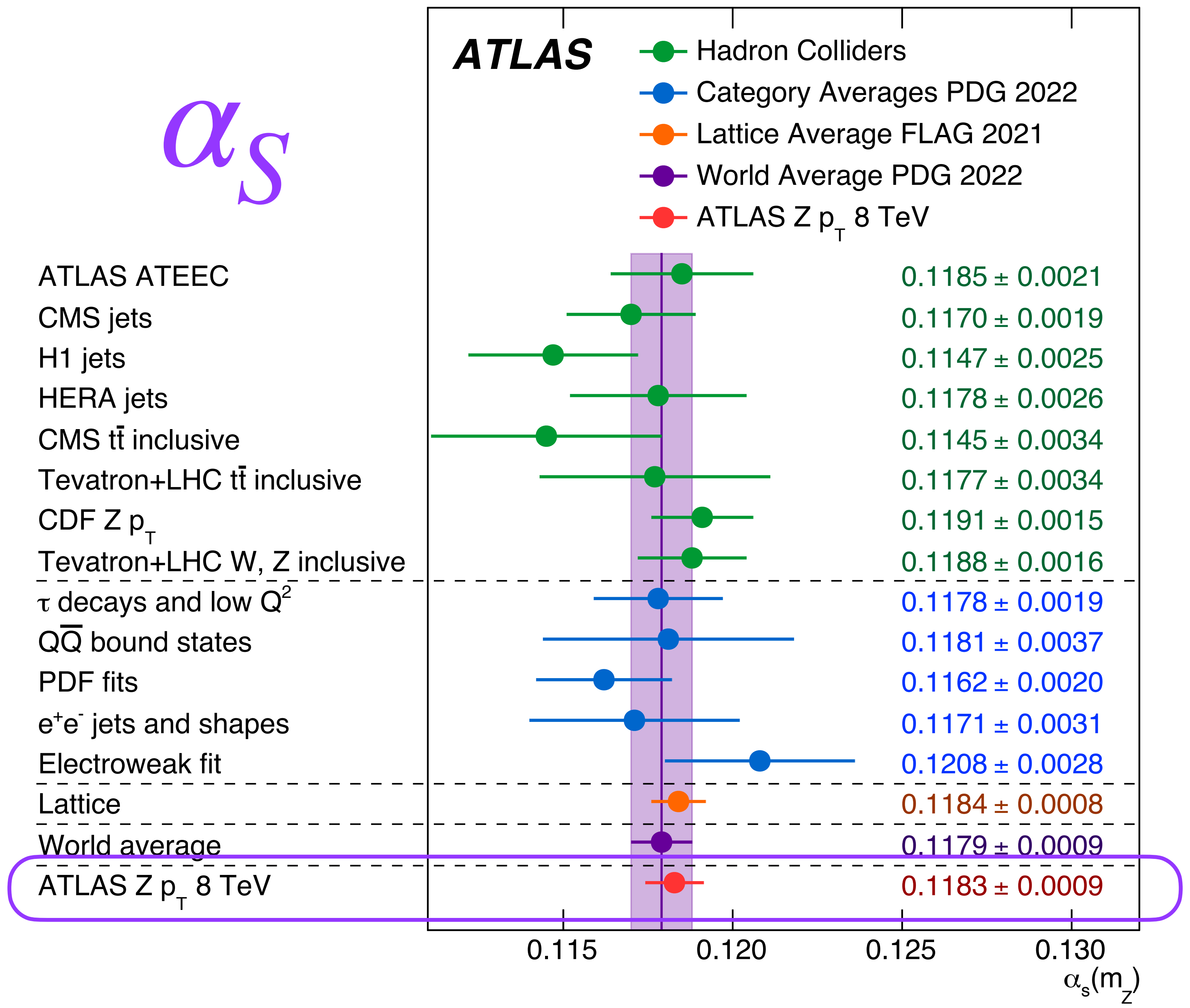
critically hinges on accurate theory simulations

Why the obsession with ultra precise SM parameters?

[CMS 2408.07622]



[ATLAS 2309.12986]



extracted from data on **differential distributions**

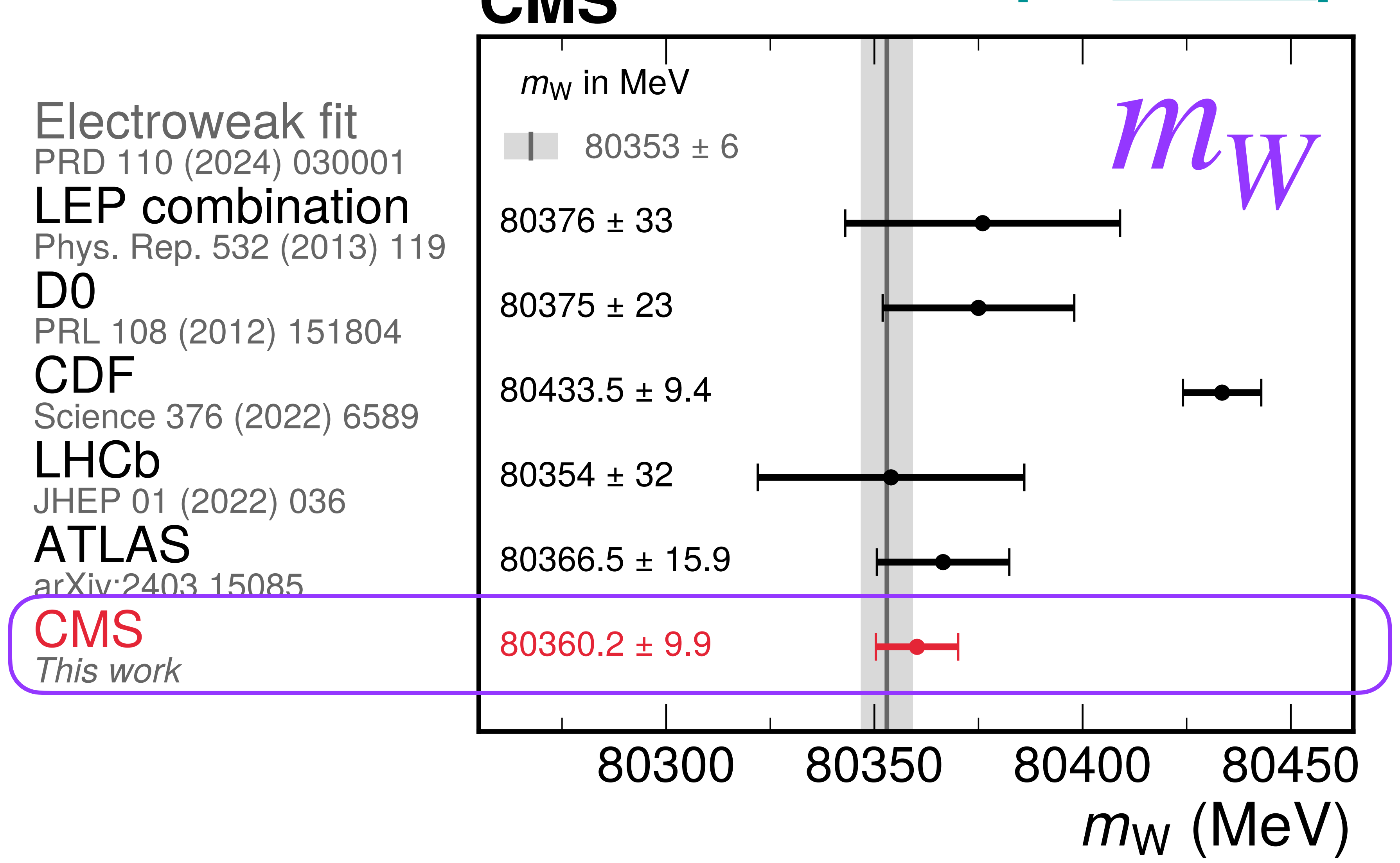
↓

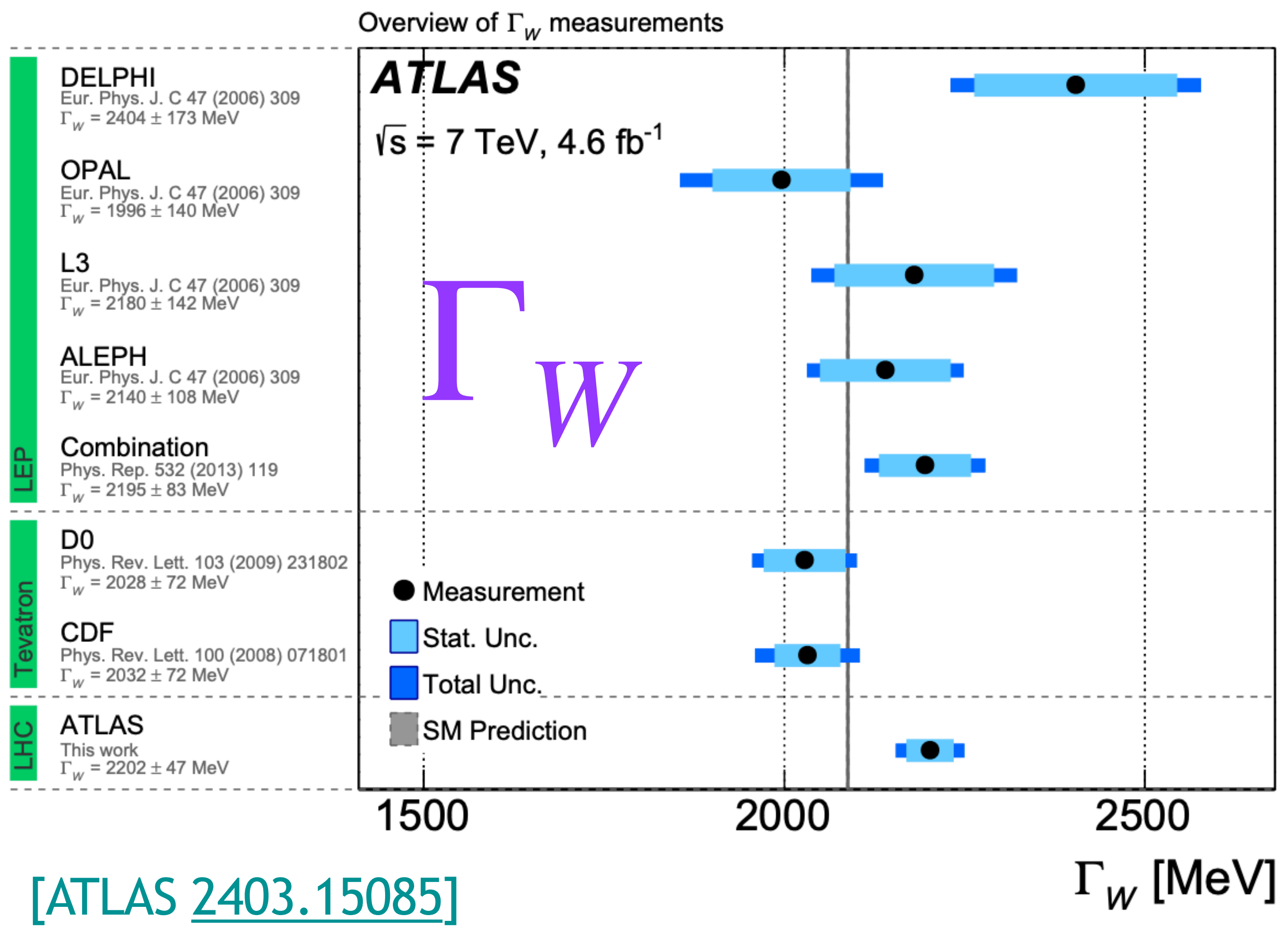
procedure relies on theory predictions

↓

exquisite control required in **disparate regions of phase space**

[CMS 2412.13872]





[ATLAS 2403.15085]

Special role played by the **Drell-Yan (DY) process**

CCDY (γ^*, Z) and NCDY $(W^\pm)$

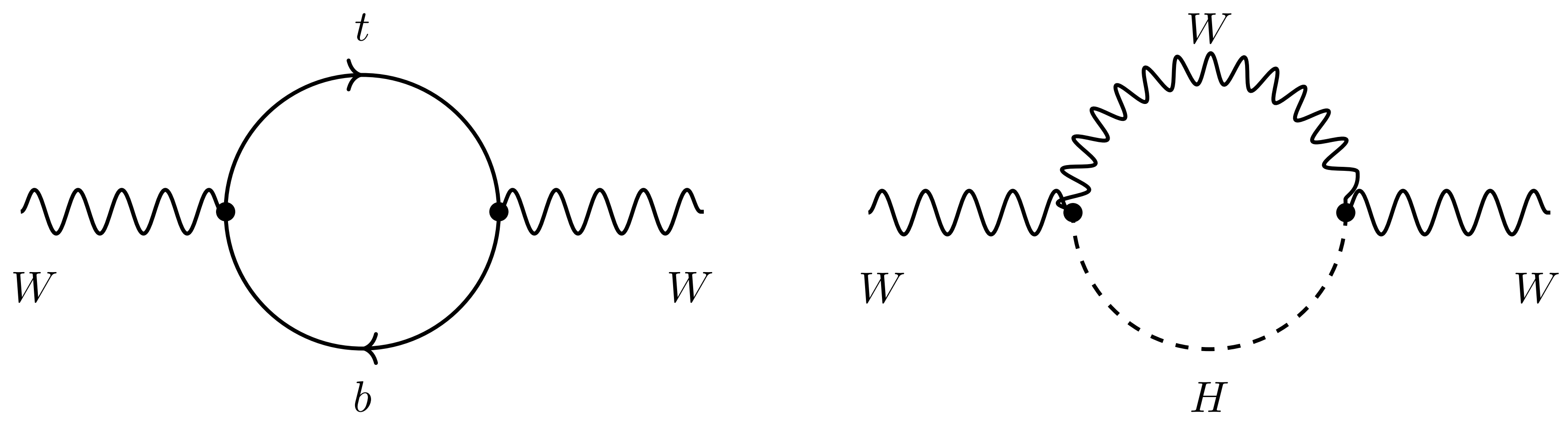
LHC stress-testing the SM at the quantum level

with the Higgs boson discovery, the SM is an **over constrained theory** (nowadays: the **Higgs mass** is a **precision parameter**!)

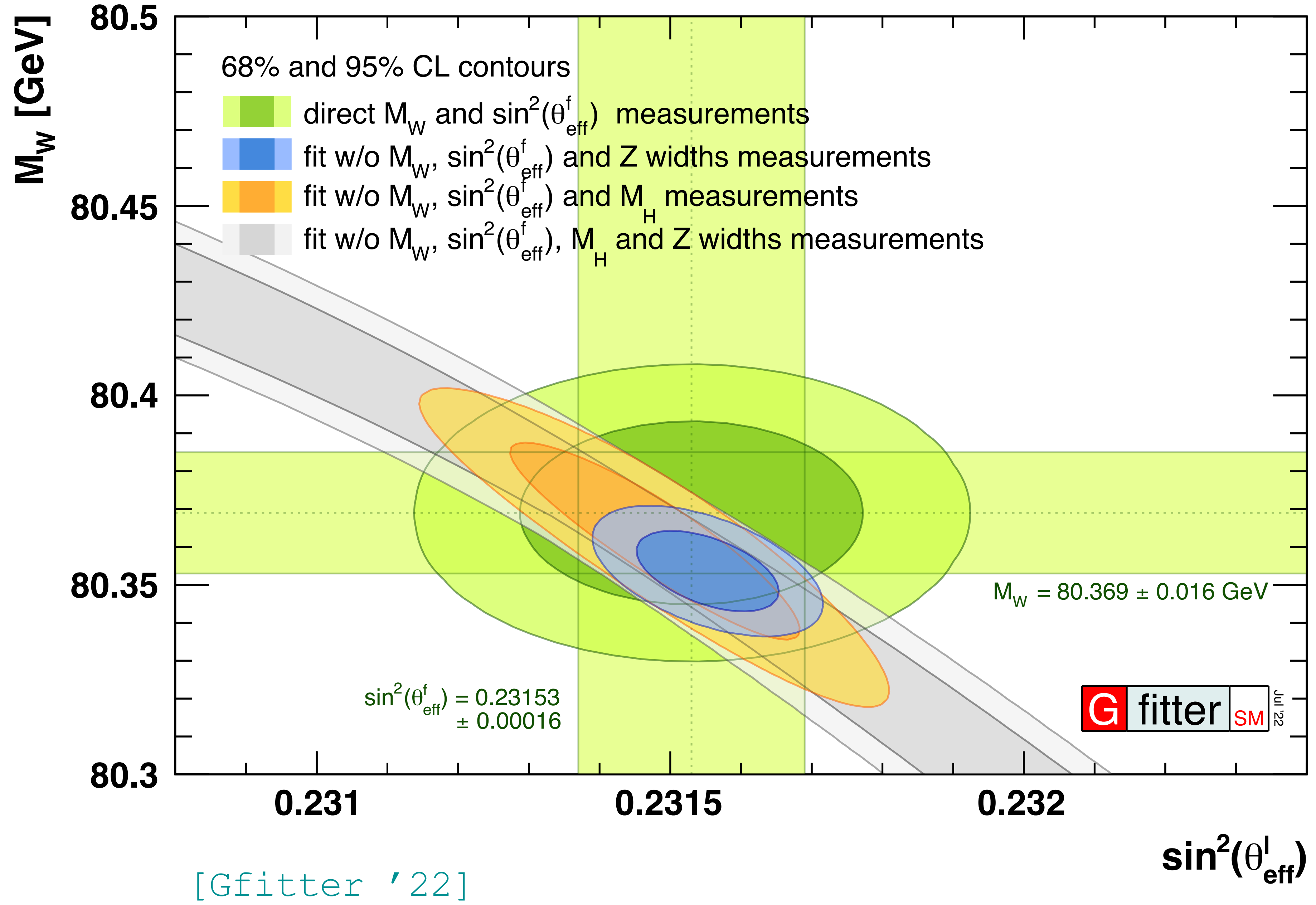
m_W and $\sin^2\theta^\ell_{\rm eff}$ are **predictions of the SM**: related to m_H and m_t via loop (quantum) corrections

$m_W = 80.349 \pm 0.007$ GeV [Gfitter '22]

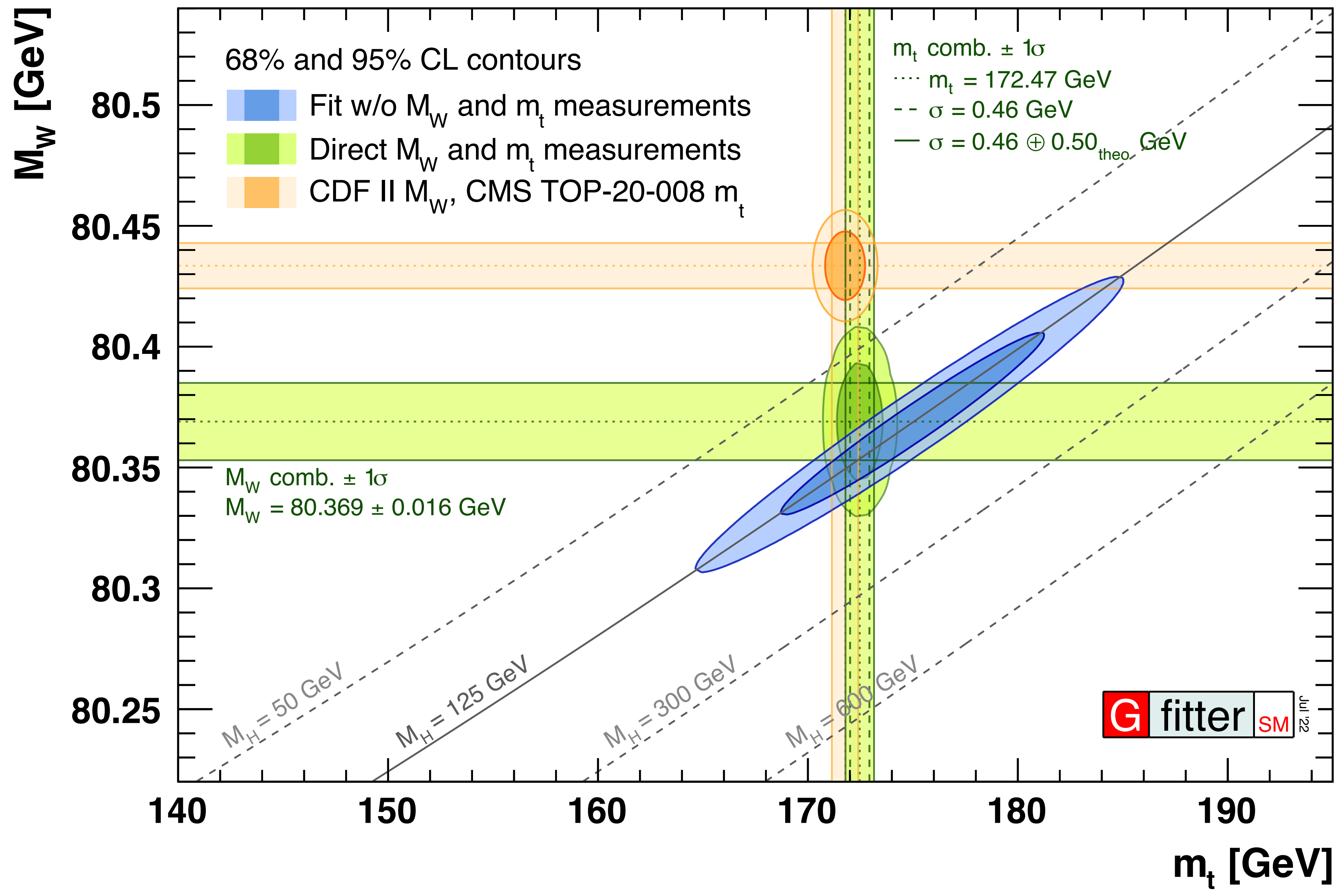
$\sin^2\theta^\ell_{\rm eff} = 0.23154 \pm 0.00006$ [Gfitter '22]



TH state of the art 2-loop EW [Awramik et al hep-ph/0311148], [Dubovyk et al 1906.08815]



[Gfitter '22]

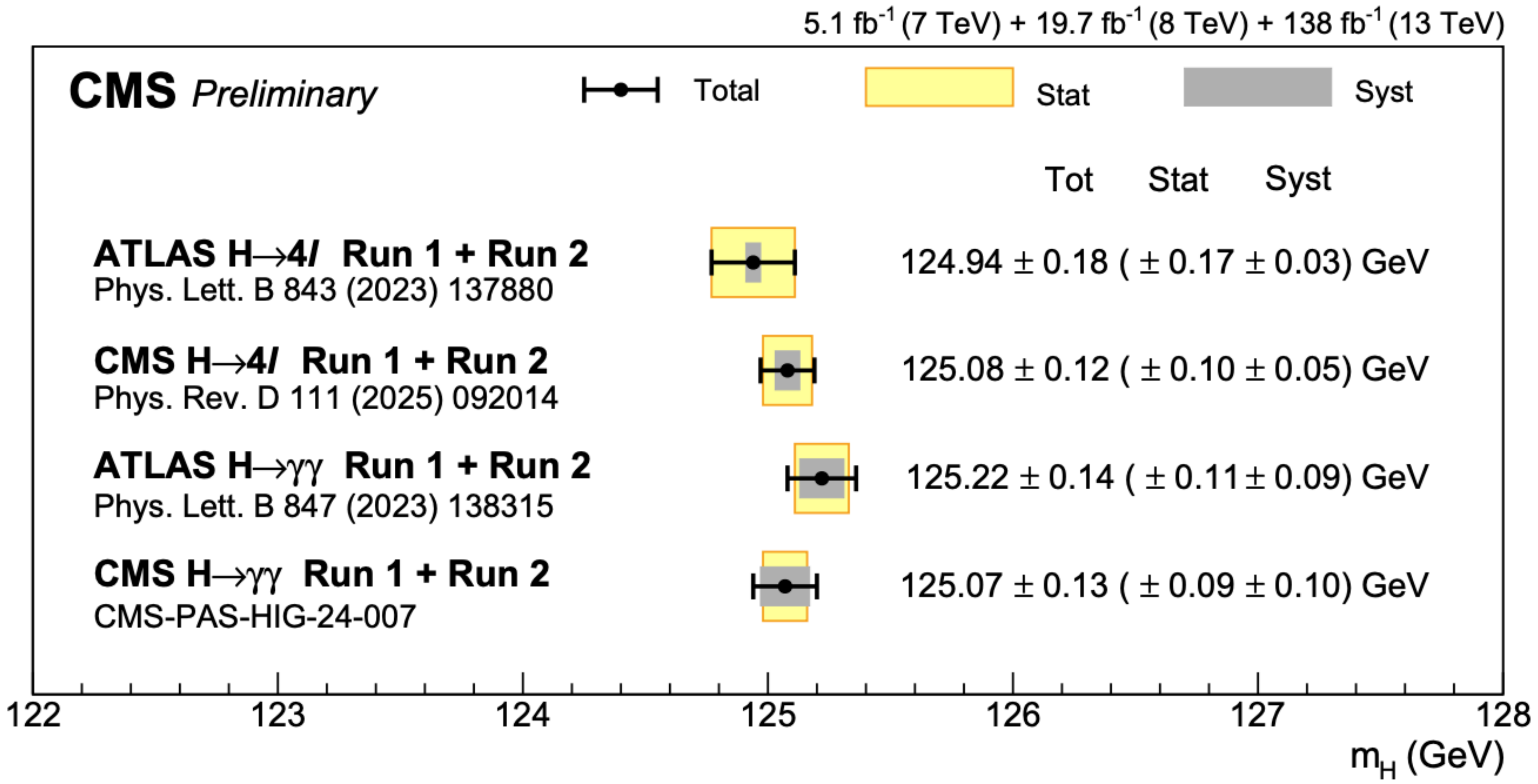


Higgs precision physics

Higgs mass (and width) entering the precision era

measurements in both $\gamma\gamma$ and $Z^*Z \to 4\ell$ channels

Combination of Run 1 + 2



CMS [PAS HIG-24-007]

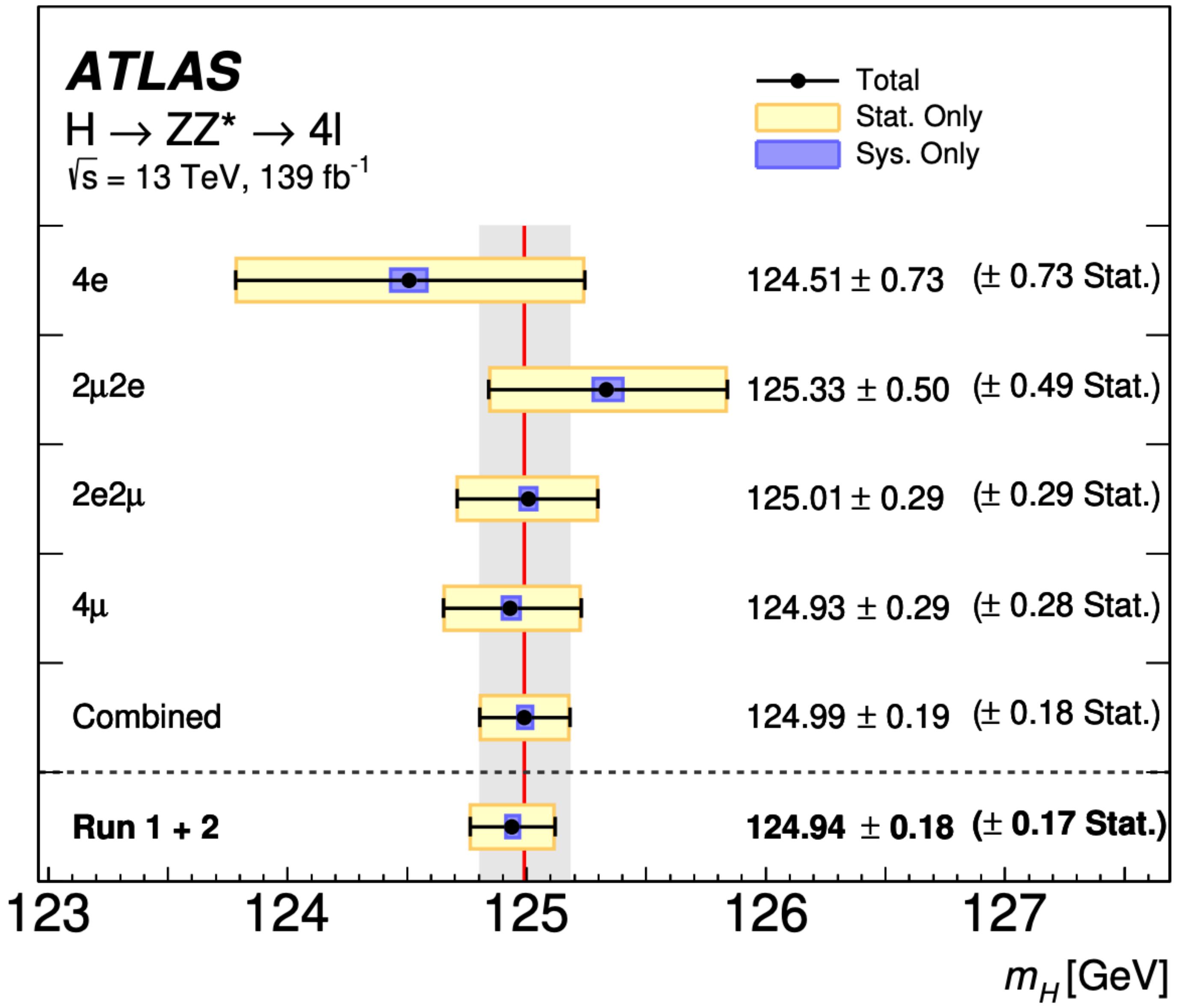
$m_H(\gamma\gamma) = 125.07 \pm 0.09(\text{stat}) \pm 0.10(\text{syst.})\,\text{GeV}$

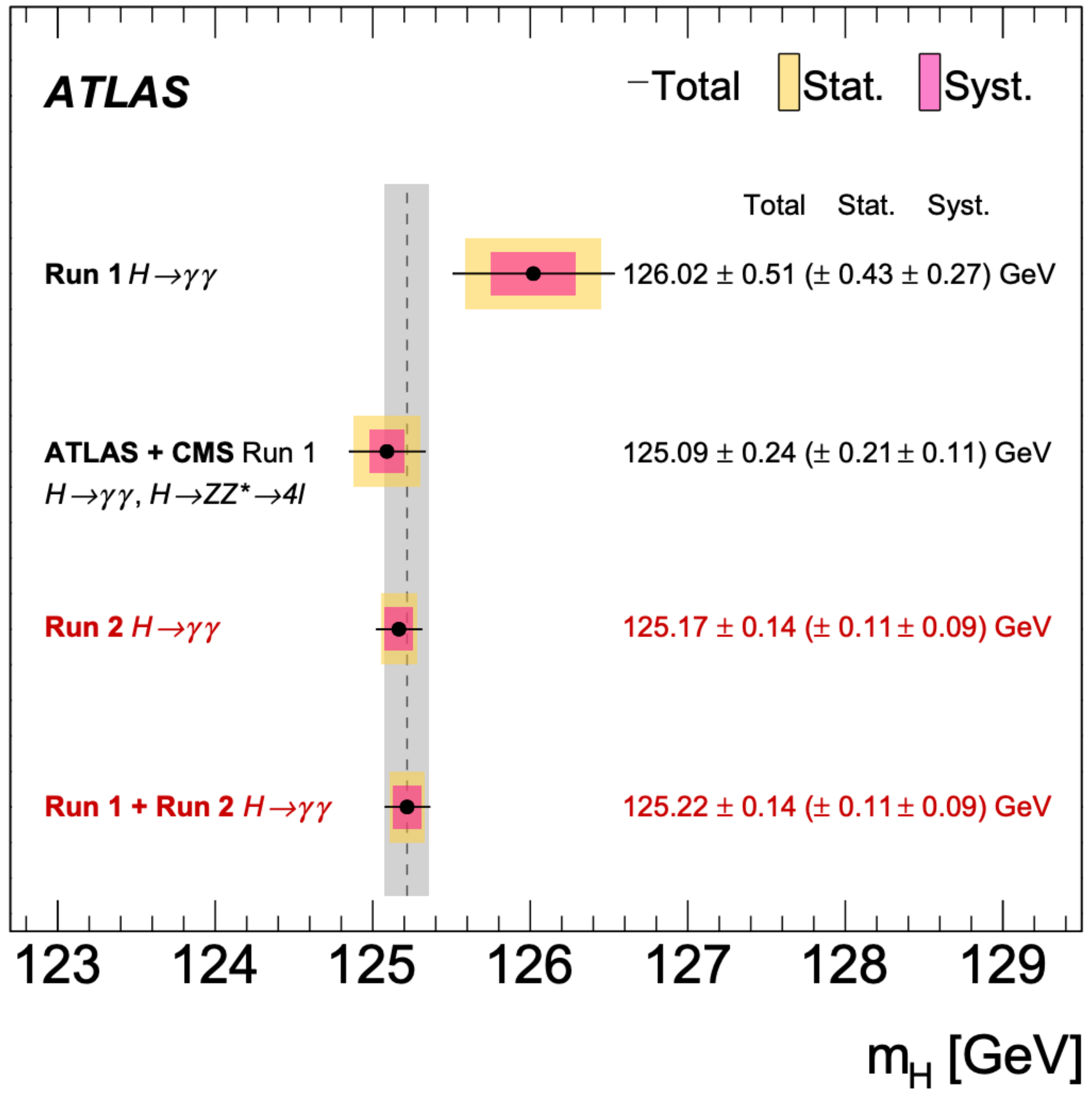
CMS [2409.13663]

$m_H(4\ell) = 125.08 \pm 0.10(\text{stat}) \pm 0.05(\text{syst.})\,\text{GeV}$

ATLAS [2207.00320]

$m_H(4\ell) = 124.99 \pm 0.18(\text{stat}) \pm 0.04(\text{syst.})\,\text{GeV}$





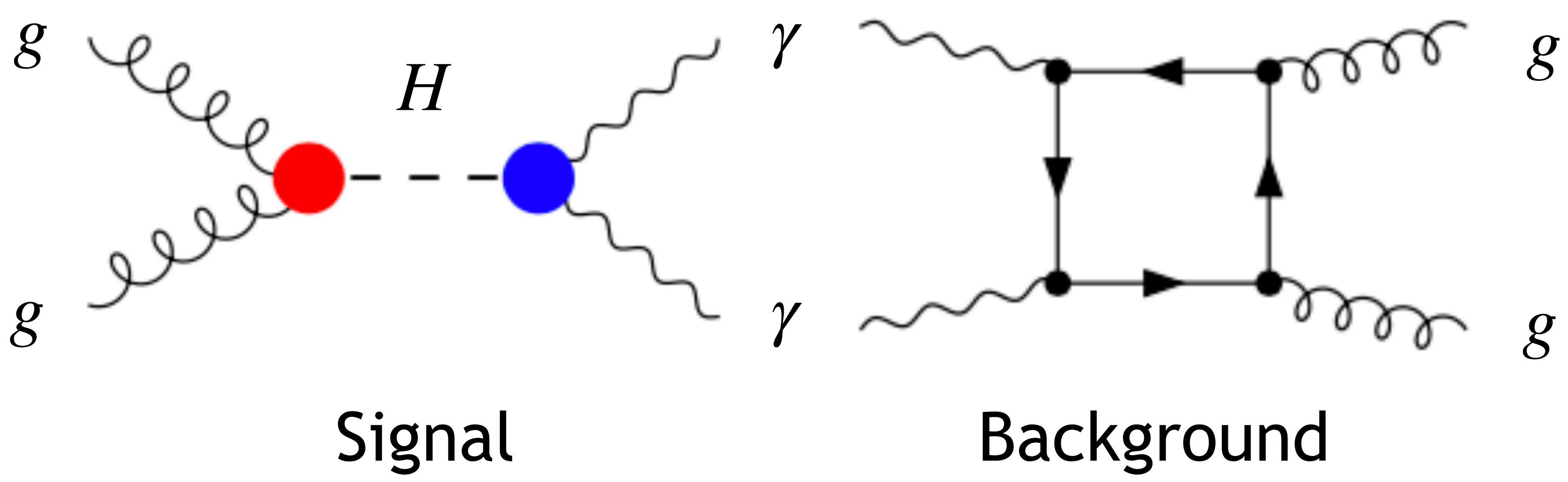
ATLAS [2308.07216]

$m_H(\gamma\gamma) = 125.22 \pm 0.11(\text{stat}) \pm 0.09(\text{syst.})\,\text{GeV}$

Higgs precision physics (subtle effects)

$|i\rangle = |gg\rangle$

$|f\rangle = |\gamma\gamma\rangle$



$$\mathcal{M}_{gg\to\gamma\gamma} = \frac{\mathcal{M}_{\rm sig}}{m_{\gamma\gamma}^2 - m_H^2 + i\Gamma_H m_h} + \mathcal{M}_{\rm bkg}$$

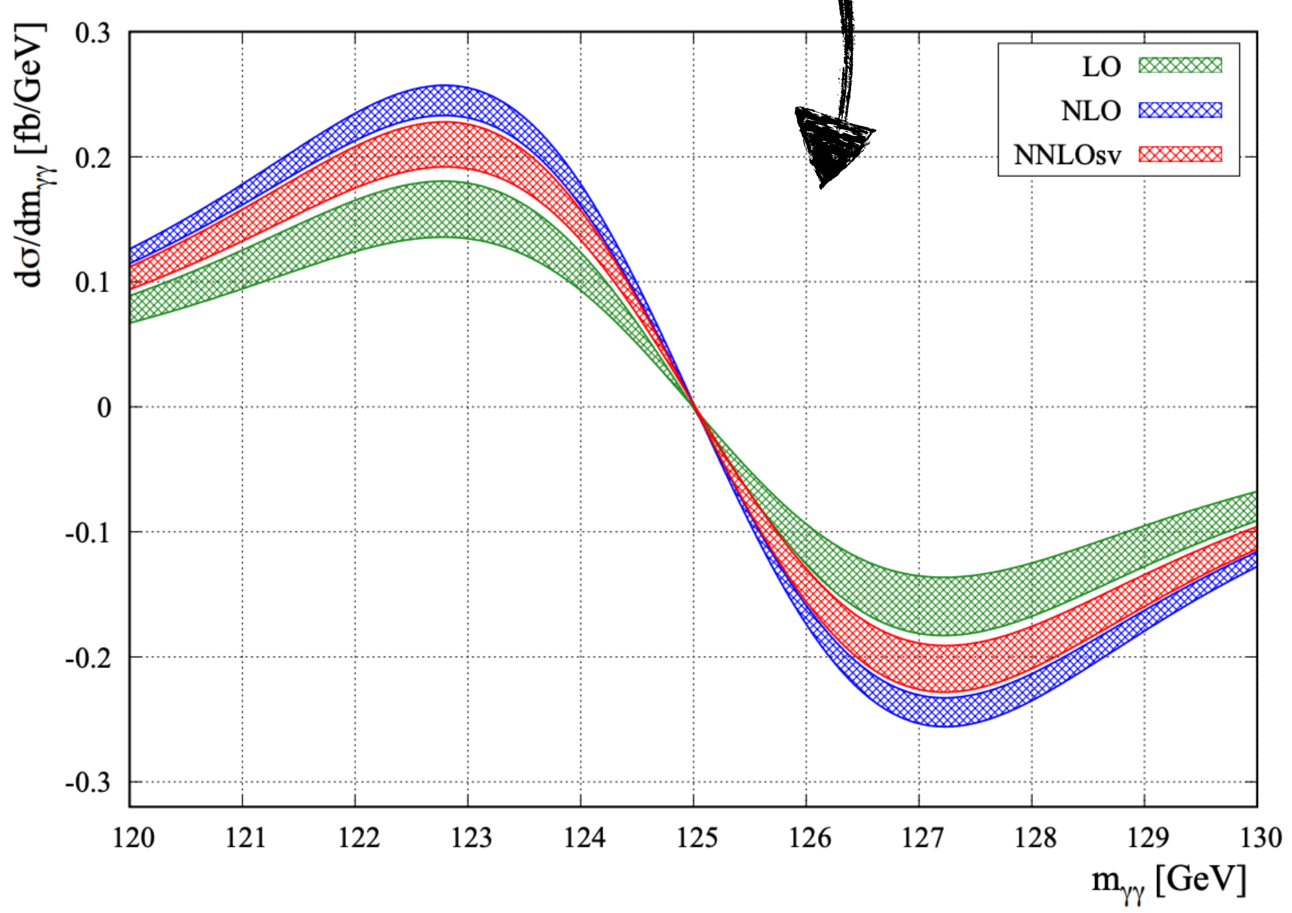
same happens in ZZ , but weaker effect; in $\gamma\gamma$ |B/S| larger due to loop induced $H \to \gamma\gamma$ decay!

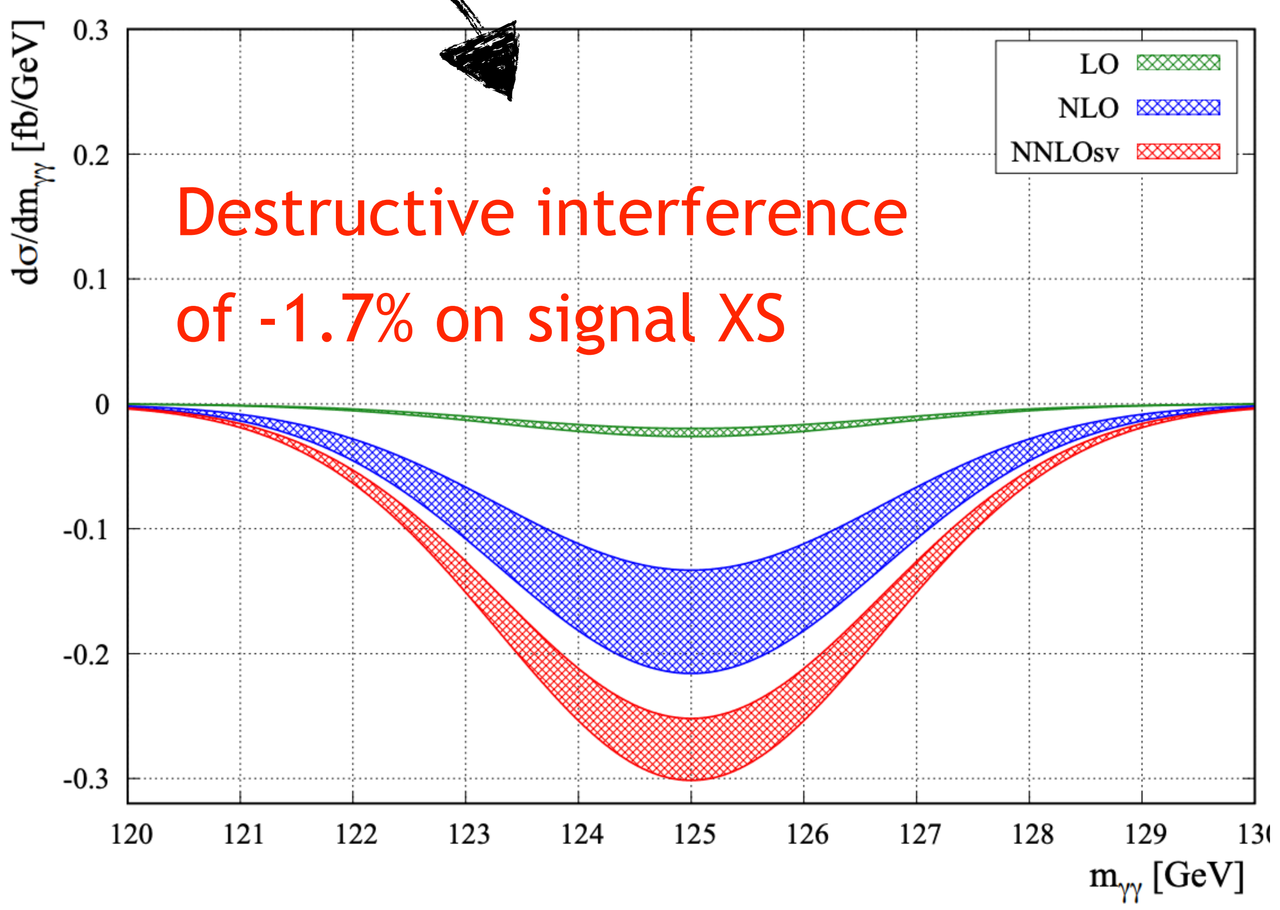
$$|\mathcal{M}_{gg\to\gamma\gamma}|^2 = |\mathcal{M}_{\rm sig}|^2 + |\mathcal{M}_{\rm bkg}|^2 + \frac{2m_{\gamma\gamma}^2}{(m_{\gamma\gamma}^2 - m_H^2)^2 + \Gamma_H^2 m_H^2}\left[(m_{\gamma\gamma}^2 - m_H^2) \times ReI + \Gamma_H m_H \times ImI\right]$$

This effect (*interferometry*) proposed to put bounds on Γ_H

[Martin 1208.1533], [Dixon, Li 1305.3854], [Campbell, Carena, Harnik, Liu 1704.08259]

Impact of higher order QCD effects [Bargiela, FB et al 2212.06287]





Q: Are such effects detectable? Are they relevant?
Can they inform us on something interesting?

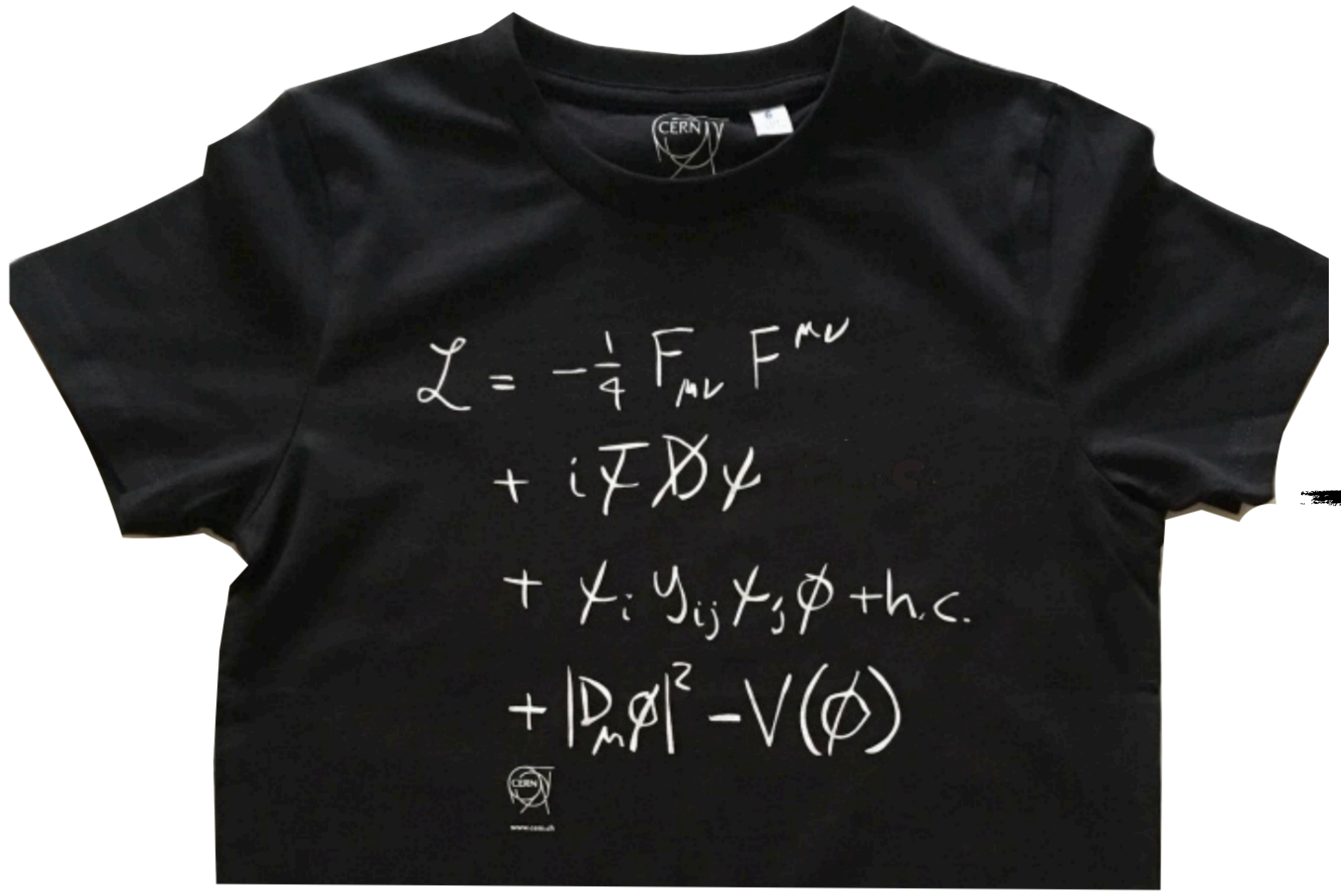
A: given the current and projected accuracy at LHC

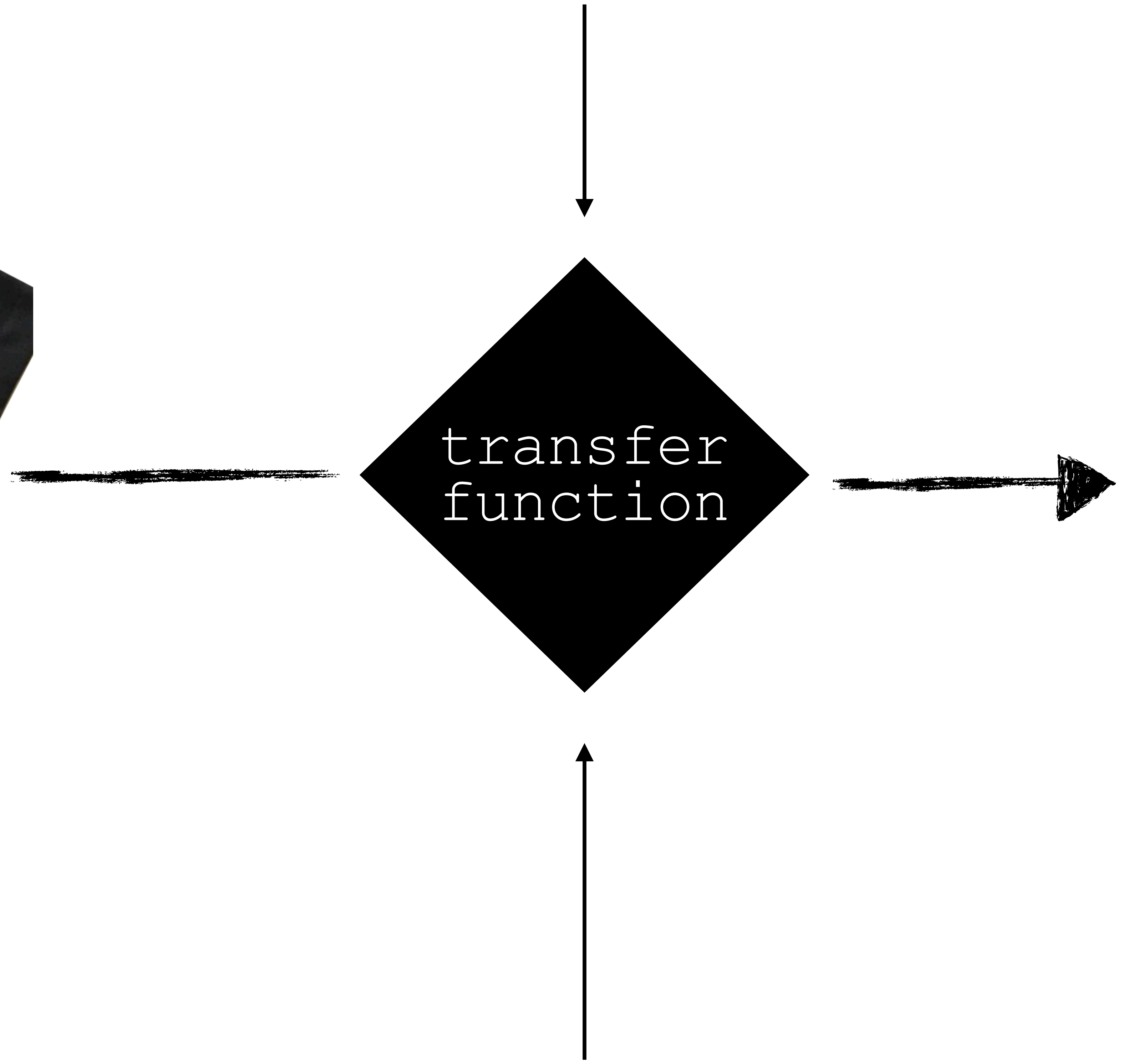
"Yes": not science fiction any more

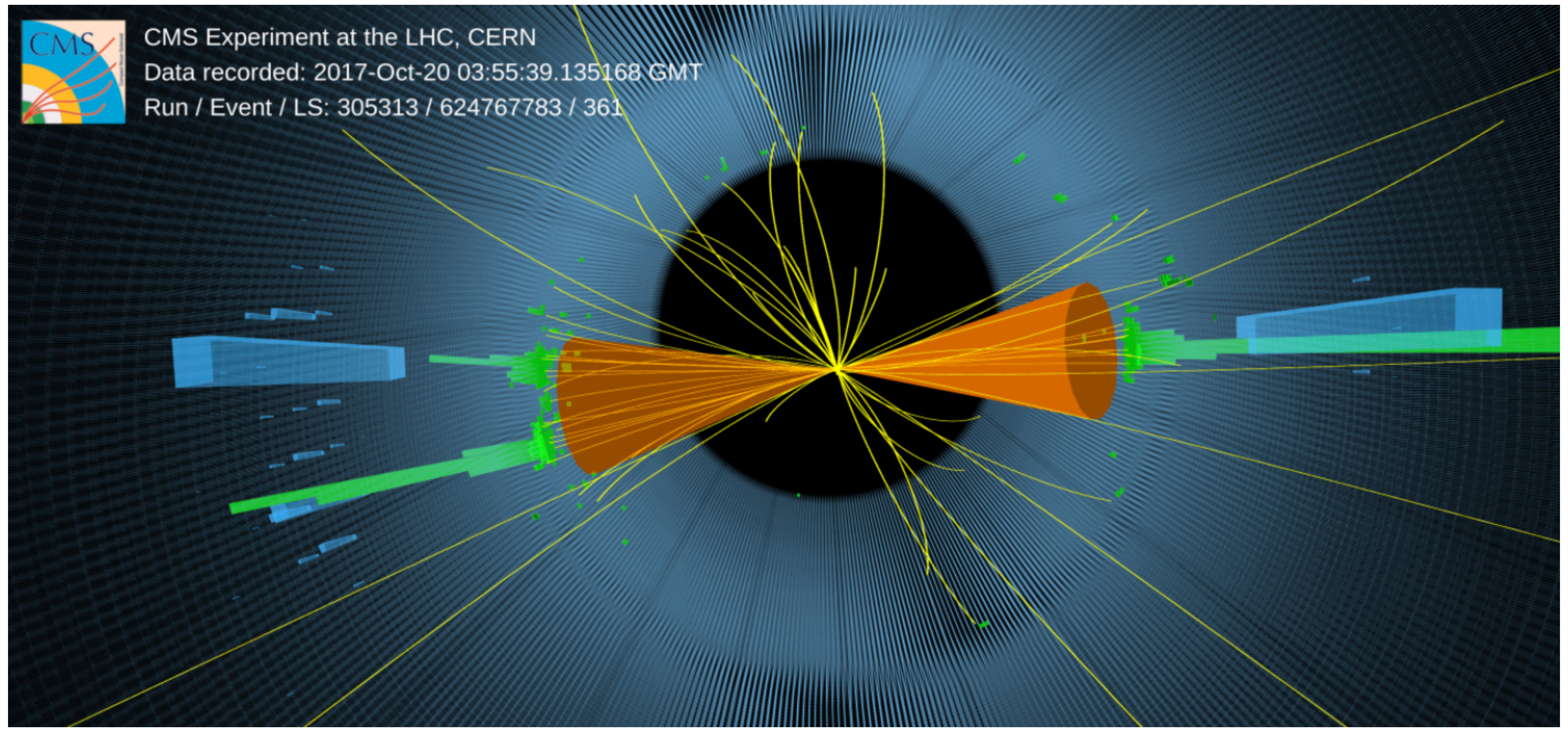
How do we get there?

interplay of many ingredients: *divide et impera*

as precise as the least precise component







Given a “simple” set of rules

first principle calculations (systematically improvable, though extremely complex)

evolution equations

however: often still relying on modelling for several aspects (when theory framework not robust)

(calculations ~ predictions ~ simulations)

Precise theory predictions

scope, status and challenges

Inherent challenge in describing collider events

protons

O(1 GeV)

↓

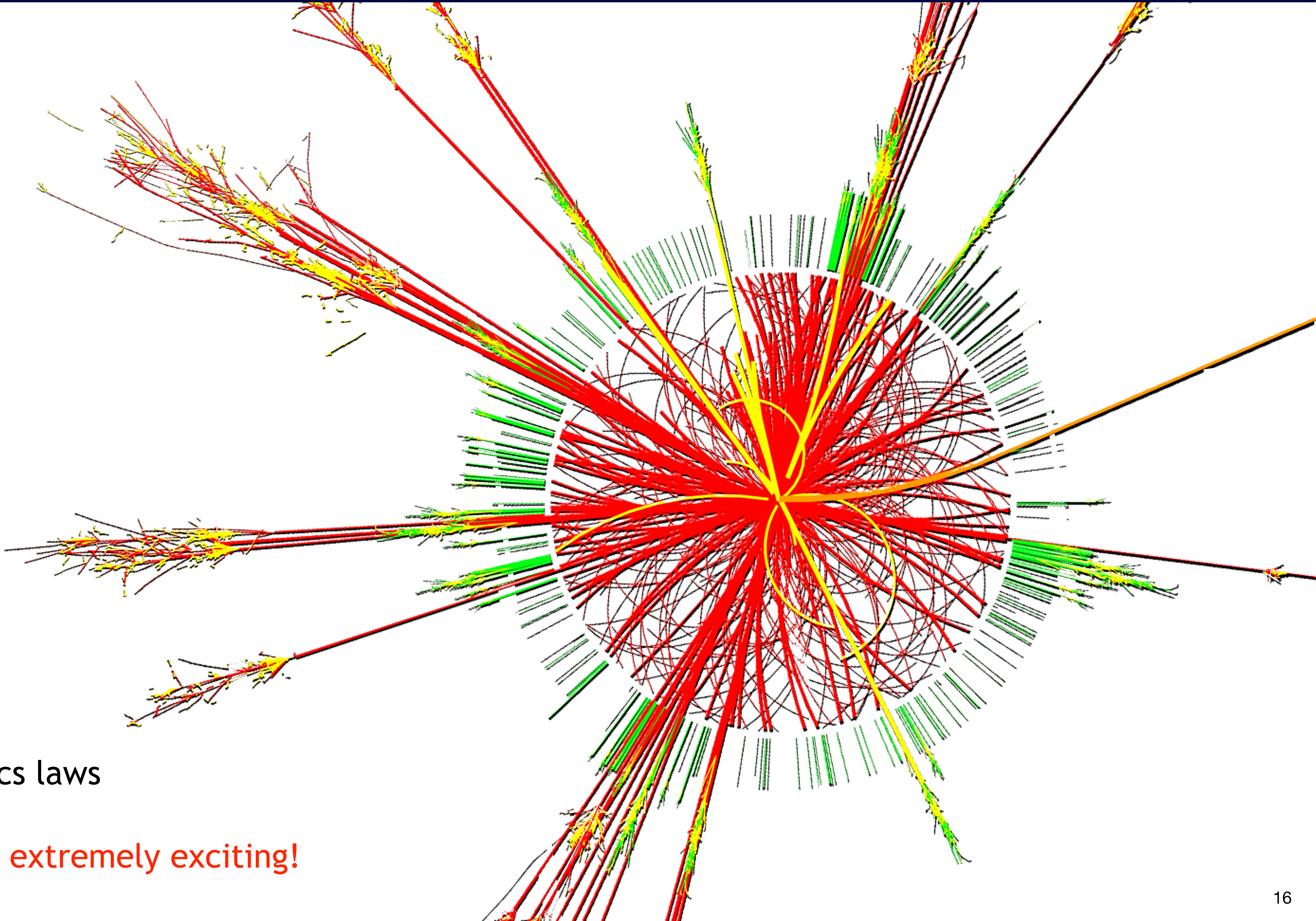
(partonic) hard process

O(1 TeV) jets

↓

hadronisation phase

O(100 MeV)



- in principle:

  using a minimal set of Physics laws

- in practice: a lot harder, but extremely exciting!

Some “simple” guiding principles

Some “simple” guiding principles

$Q \gg \Lambda_{\text{QCD}}$ $Q \gg m_q$

perturbative regime

$\left(\frac{\alpha_s}{2\pi}\right)^n$ $\left(\frac{\alpha}{2\pi}\right)^\ell$

QCD EW

going $n \to n+1$ enormous jump in complexity
(typically 10/20 years)

- $\ell = 2$ only for a couple of examples
- $n = 3$ for a handful of (simplest) reactions

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$Q \gtrsim m_b$

mass effects

$$\ln^k\left(\frac{m_b}{Q}\right) \qquad \left(\frac{m_b}{Q}\right)^k$$

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mass contributions: additional scales in the problem

$$m_b \sim 4\,\mathrm{GeV},\ Q \sim 90\,\mathrm{GeV} \ \Rightarrow m_b/Q \sim 4.5\,\%$$

also related: heavy-flavour identification

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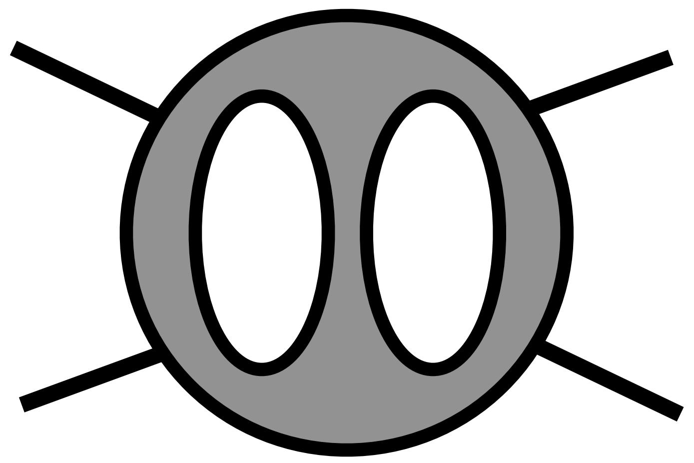
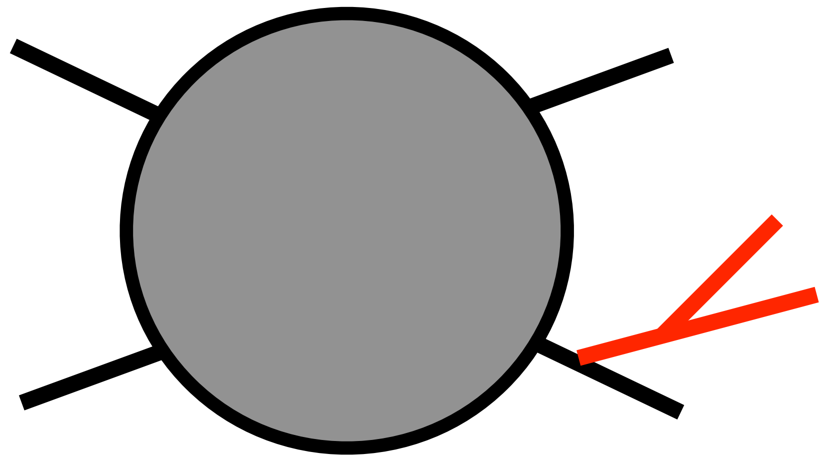
higher- (fixed-) order calculations



virtual/loop corrections



real corrections

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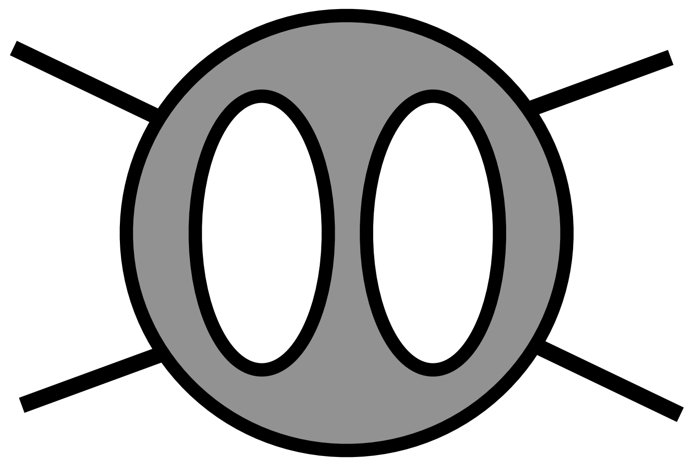

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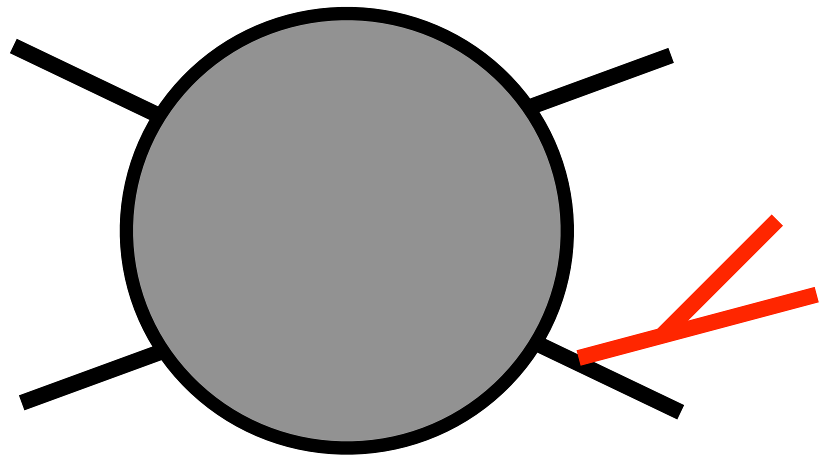

real corrections

ratio of disparate scales (eg $q_\perp/Q \ll 1$)

all-orders resummation needed

- achieving demanded accuracy highly complex

in special kinematic configurations

$$\alpha_{(s)}^n \ln^k(x), \quad x \ll 1$$

logarithmically enhanced terms

resummation

Some “simple” guiding principles

$\Lambda_{\text{QCD}} \sim 300\,\text{MeV}$

$Q \sim m_Z \sim 91\,\text{GeV}$

$\longrightarrow \quad \frac{\Lambda_{\text{QCD}}}{Q} \sim 0.3\,\%$

describing the non-perturbative regime is a daunting but great conceptual challenge

$$\mathrm{d}\sigma \sim \mathrm{d}\sigma^{(P)} + \mathrm{d}\sigma^{(NP)} \qquad \mathrm{d}\sigma^{(NP)} \sim \left(\frac{\Lambda_{\text{QCD}}}{Q}\right)^p$$

- reliable hadronisation models are at the foundation of many analysis

$Q \sim \Lambda_{\text{QCD}}$

non-perturbative phys.

$\left(\Lambda_{\text{QCD}}/Q\right)^p$

$p = ?$

power-correct.

hadronisation

Some “simple” guiding principles

$Q \gg \Lambda_{\rm QCD} \quad Q \gg m_q$

perturbative regime

$\left(\frac{\alpha_s}{2\pi}\right)^n$ $\left(\frac{\alpha}{2\pi}\right)^\ell$

QCD EW

$Q \gtrsim m_b$

mass effects

$\ln^k\left(\frac{m_b}{Q}\right) \quad \left(\frac{m_b}{Q}\right)^k$

$Q \sim \Lambda_{\rm QCD}$

non-perturbative phys.

$\left(\Lambda_{\rm QCD}/Q\right)^p$

$p = ?$

power-correct.

hadronisation

actually a very complex and exciting mosaic

in special kinematic configurations

$\alpha_{(s)}^n \ln^k(x), \quad x \ll 1$

logarithmically enhanced terms

Theory predictions: ideal and real-life scenarios

Ideal SM precision theorist scenario:

- “count” experiments: observables as inclusive as possible (cross sections)
- observables defined at large-Q (minimise non-perturbative effects) with minimal IR sensitivity

perturbation theory works best

Theory predictions: ideal and real-life scenarios

Ideal SM precision theorist scenario:

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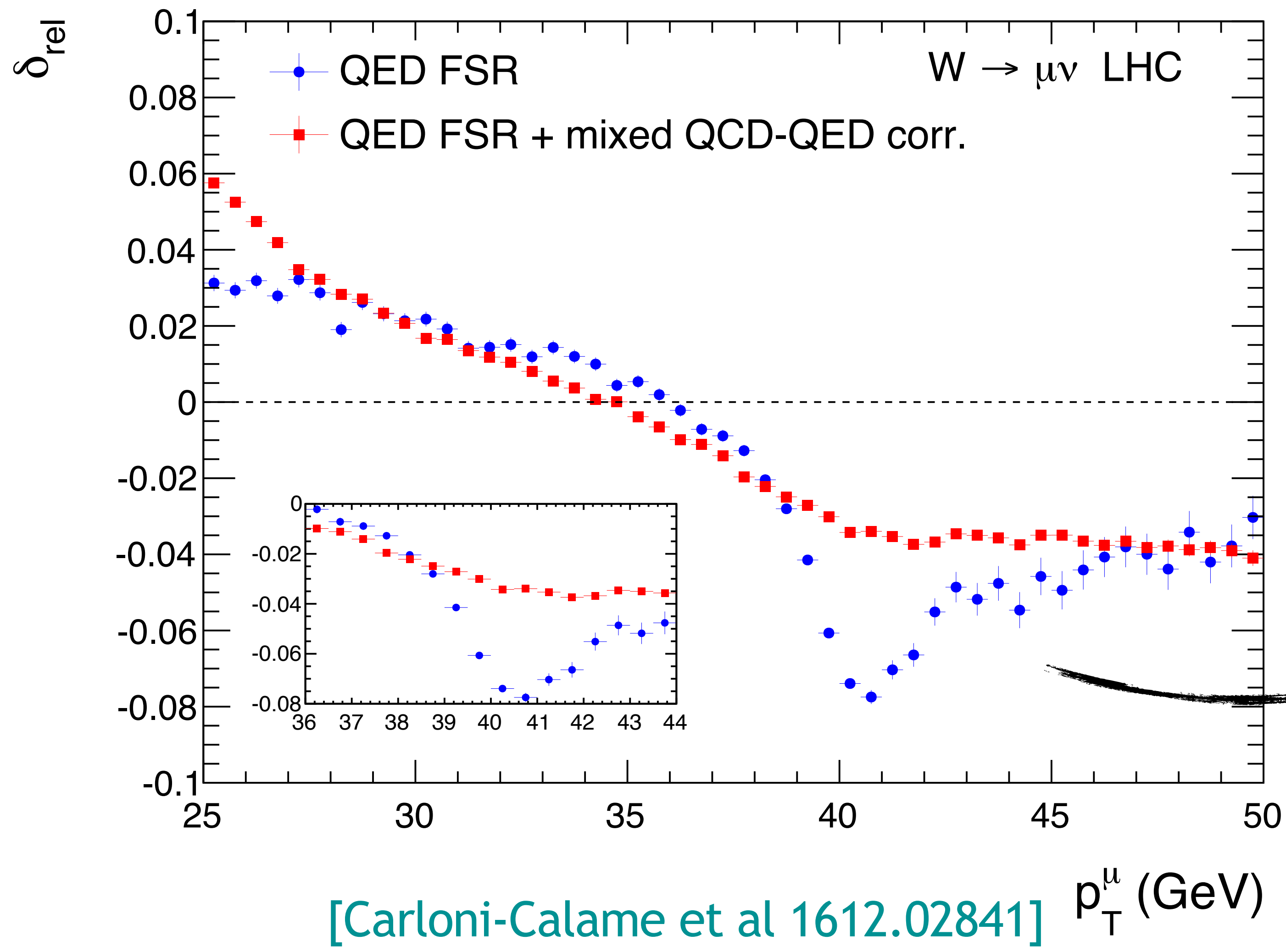
- observables defined at **large-Q** (minimise non-perturbative effects) with **minimal IR sensitivity**

perturbation theory works best

In real life:

most interesting Physics info extracted from distributions… and often in **extremely delicate regions from TH point of view**

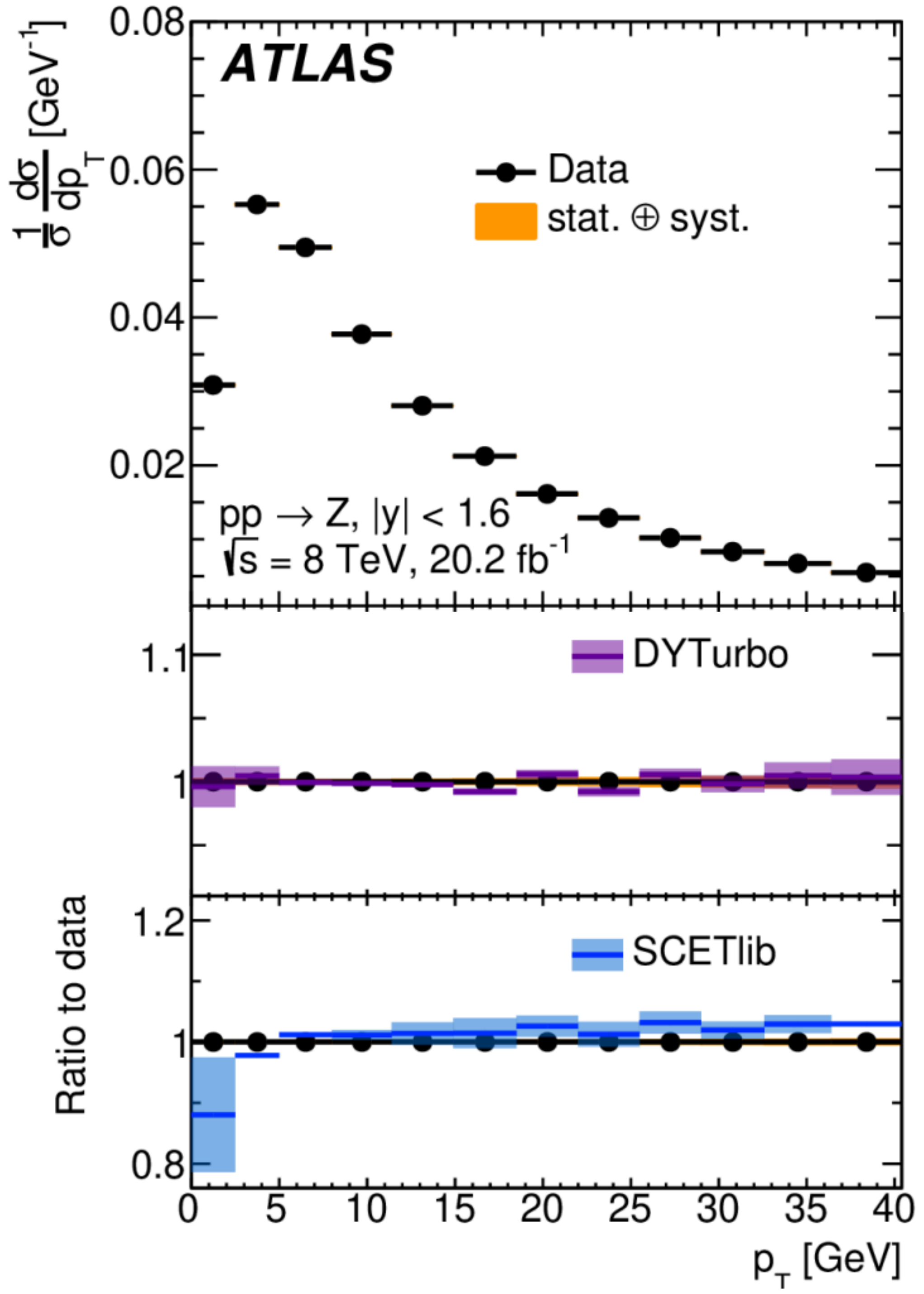


[Carloni-Calame et al 1612.02841]

Experiments: control on the shape at ‰ level

IS QCD radiation + FS QED radiation

strong shape distortion around Jacobian peak



Issue 1:

dominated by low-p_T region, $q_T/m_Z \ll 1$

resummation indispensable

Issue 2:

$$\Lambda \sim 1\,\text{GeV},\ Q \sim 100\,\text{GeV}$$

$$\delta_{\text{exp}} \sim 0.3\,\%$$

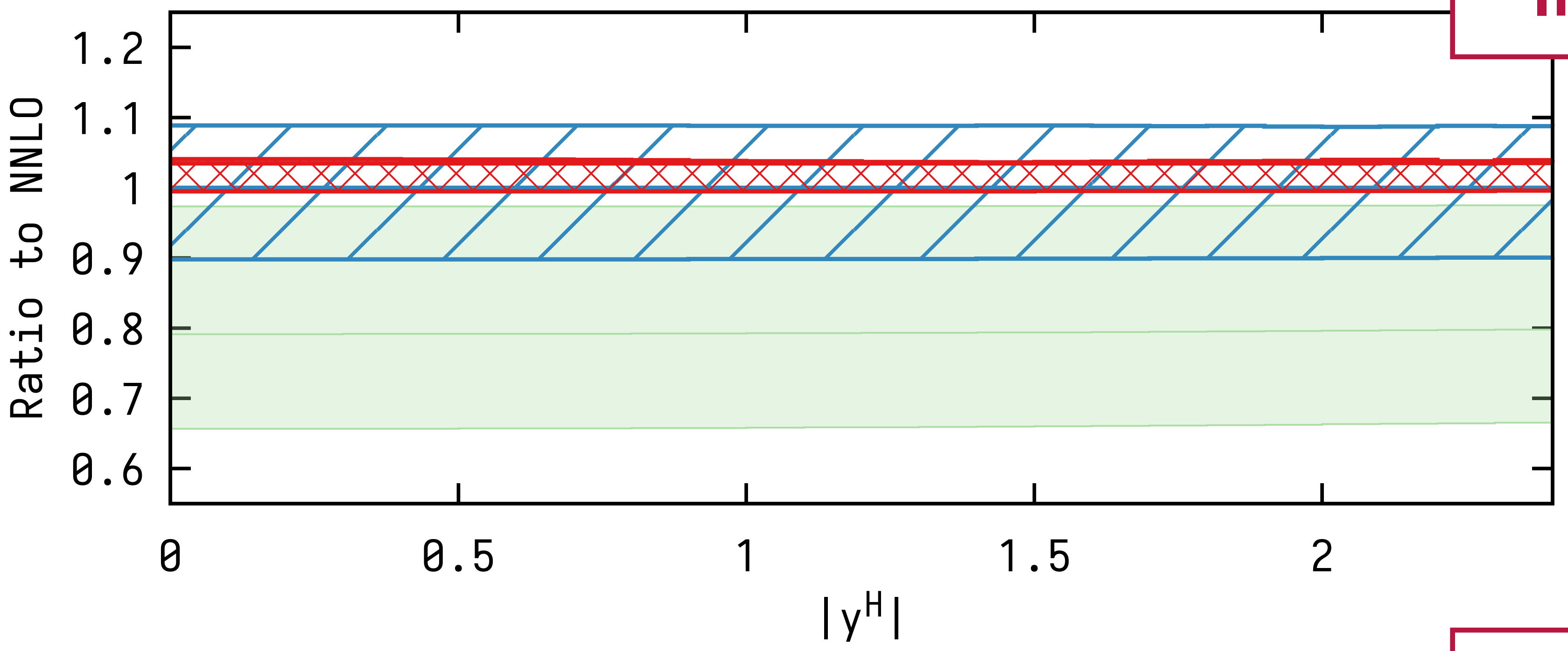
$$p = 1,\ (\Lambda/Q) \sim 1\,\%\ ; \quad p = 2,\ (\Lambda/Q) \sim 0.01\,\%$$

$p \geq 2$ [Ferrario-Ravasio et al 2011.14114]

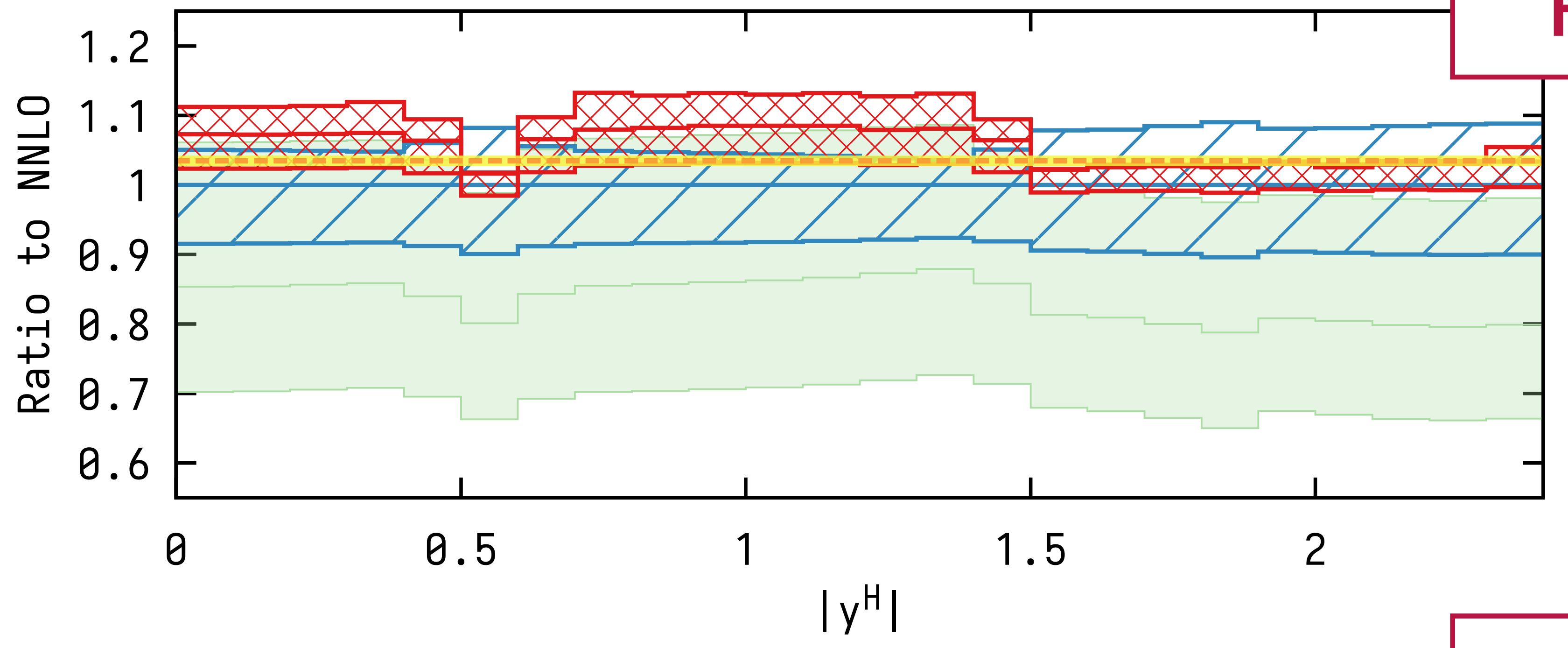
TH-EXP: very delicate interplay

Example: Higgs @ N3LO QCD [Chen et al 2102.07607]

Inclusive



Fiducial

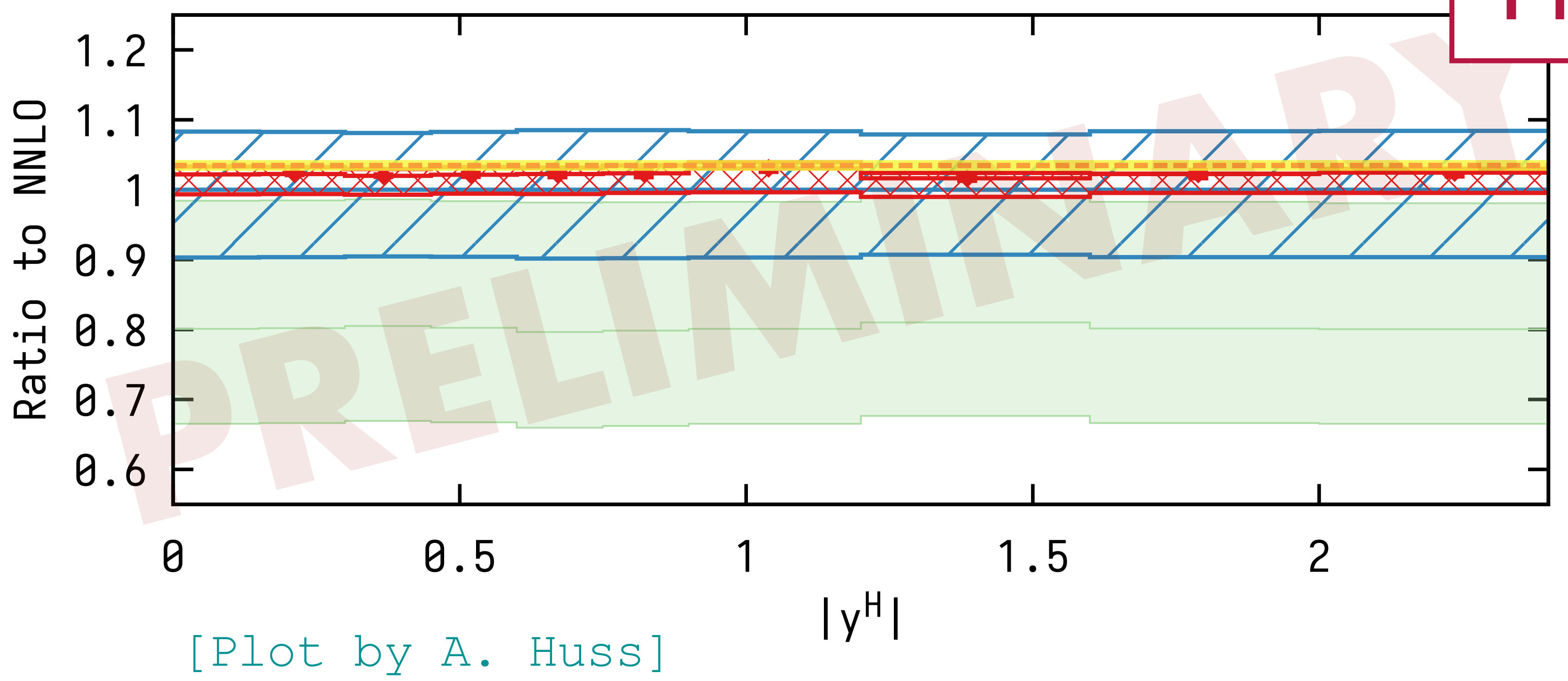


ATLAS

$p_{T,\gamma_+} > 0.35\, m_H$

$p_{T,\gamma_-} > 0.25\, m_H$

Product cuts



$\sqrt{p_{T,\gamma_-} p_{T,\gamma_+}} > 0.35\, m_H$

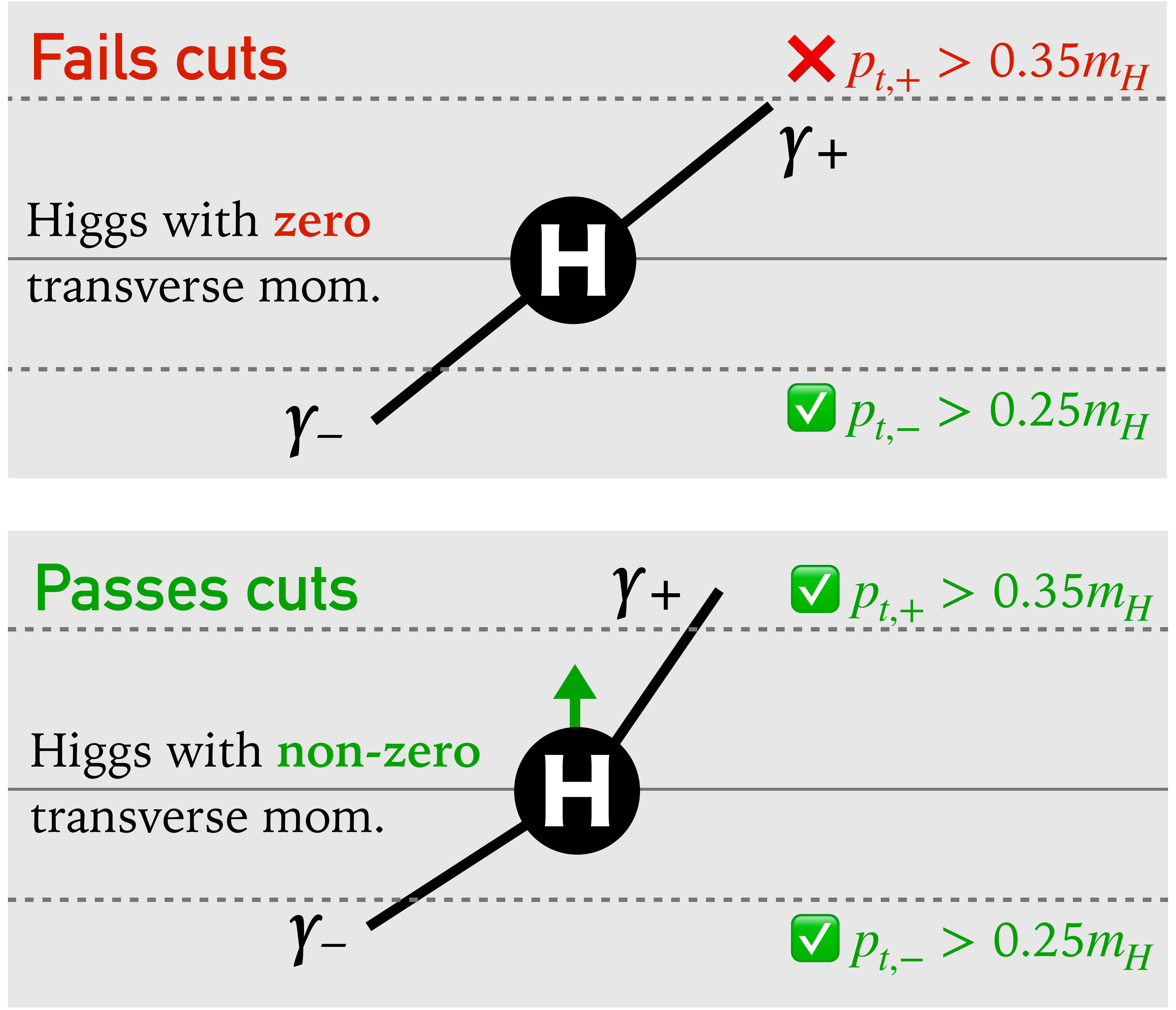
$p_{T,\gamma_-} > 0.25\, m_H$

[Plot by A. Huss]

IR sensitivity in cuts [Frixione, Ridolfi hep-ph/9707345], [Ebert, Tackmann 1911.08486]

Linear acceptance in $q_T \to 0$

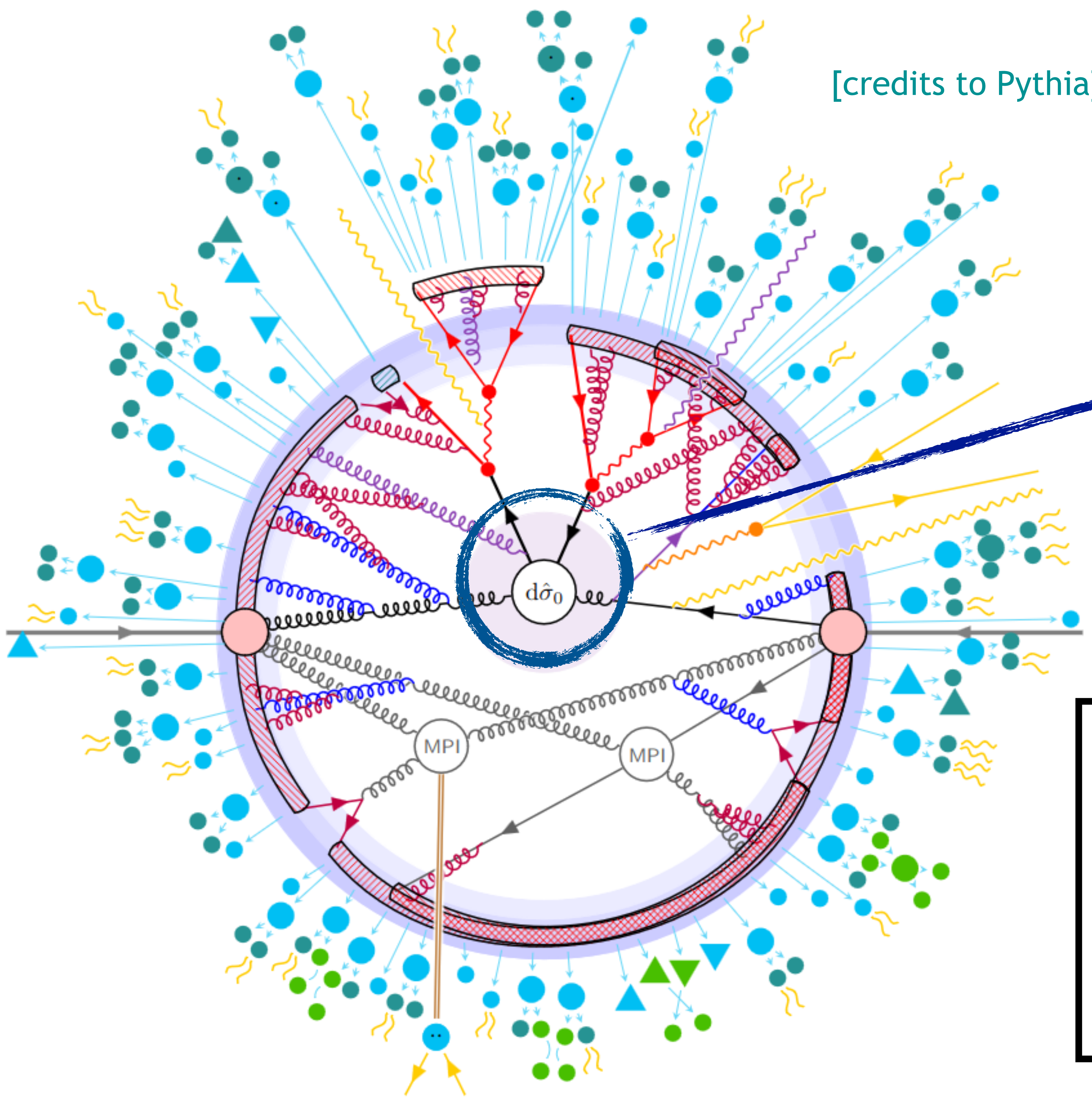
lingo: “fiducial power corrections” (factorial growth)



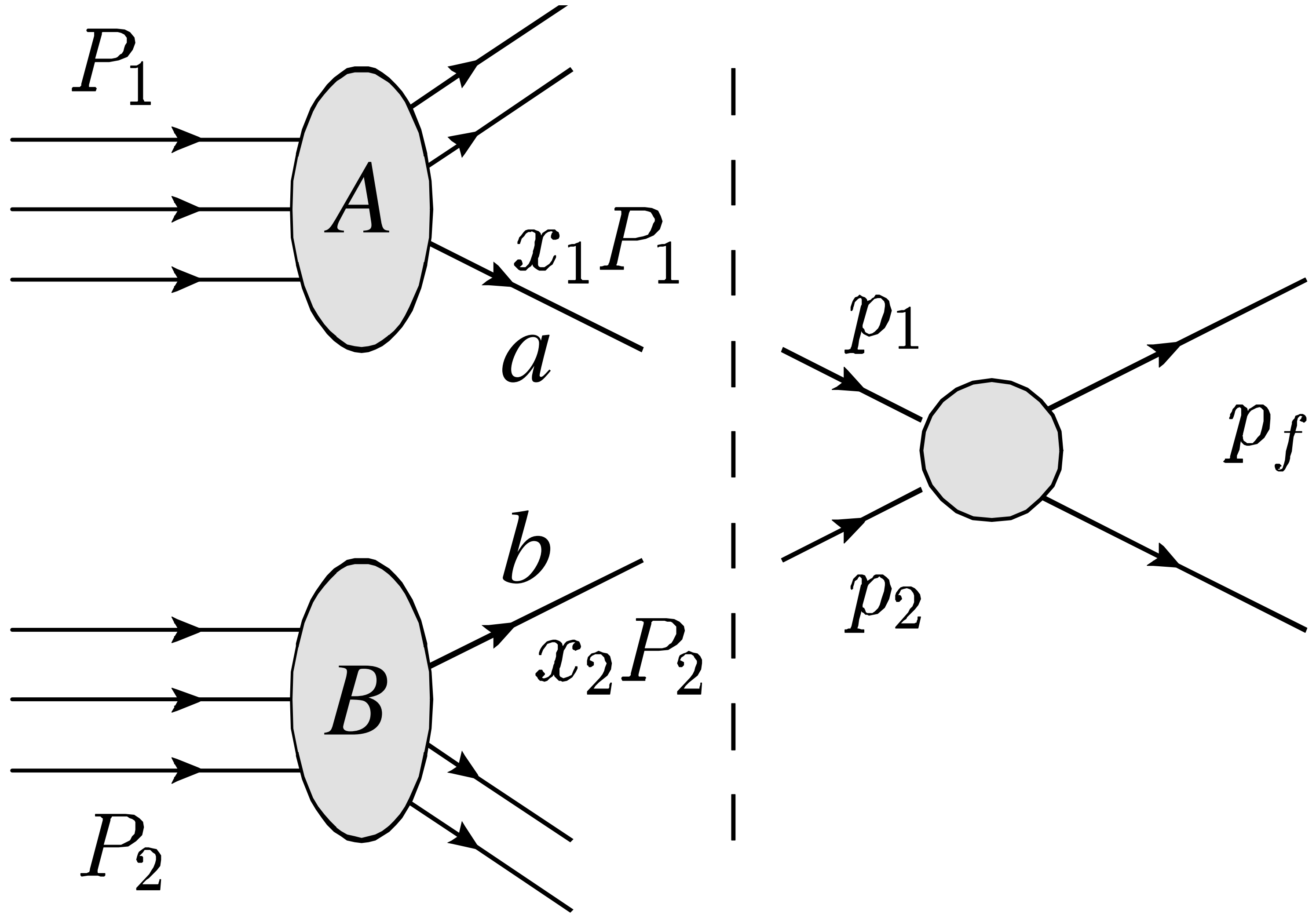
[Sketch by F. Caola at Aspen '26]

- cured via q_T resummation [Ebert et al 2006.11382]
- remove linear correction via product cuts [Salam, Slade 2106.08329]

Hadronic cross sections: the master formula



[credits to Pythia]



The master formula

$$\frac{d\sigma_{AB\to X}}{dO} = \sum_{ab}\int_0^1 dx_1 dx_2\, f_{a,A}(x_1,\mu)\, f_{b,B}(x_2,\mu)\, \frac{d\hat{\sigma}_{ab\to X}(x_1,x_2,\mu)}{dO} + \mathcal{O}\left(\frac{\Lambda^p_{QCD}}{Q^p}\right)$$

parton distribution functions (PDFs)
(long distance, non-perturbative)

hard scattering
(short distance, perturbation theory)

non-perturbative physics
(power corrections)

Fixed-order perturbation theory

QCD

$\alpha_s(m_Z) \simeq 0.118 \sim 10\,\%$

EW

$\alpha(m_Z) \simeq 1/128 \simeq 1\,\%$

at typical LHC energy scales simultaneous expansion in α and α_s

$$d\sigma = d\sigma^{(0,0)} + \alpha_s d\sigma^{(1,0)} + \alpha\, d\sigma^{(0,1)} + \alpha_s^2 d\sigma^{(2,0)} + \alpha\alpha_s d\sigma^{(1,1)} + \alpha^2 d\sigma^{(0,2)} + \alpha_s^3 d\sigma^{(3,0)}$$

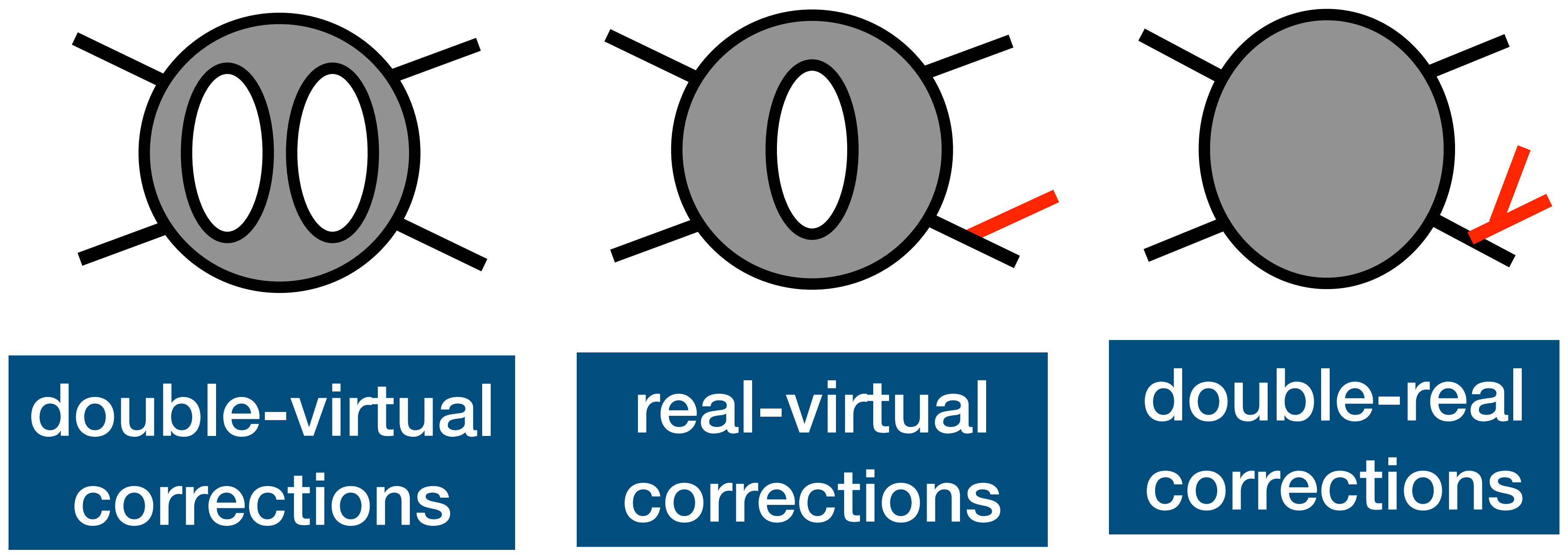
- $d\sigma^{(0,0)}$ → Leading Order (LO)
- $\alpha_s d\sigma^{(1,0)}$ → Next-to-Leading Order (NLO) QCD
- $\alpha\, d\sigma^{(0,1)}$ → NLO EW
- $\alpha_s^2 d\sigma^{(2,0)}$ → Next-to-Next-to-Leading Order (NNLO) QCD
- $\alpha\alpha_s d\sigma^{(1,1)}$ → Mixed QCDxEW → only the “simplest” reactions
- $\alpha^2 d\sigma^{(0,2)}$ → NNLO EW → No (full) LHC process described with this accuracy yet
- $\alpha_s^3 d\sigma^{(3,0)}$ → N3LO QCD → only for simplest processes

(first $2 \to 2$ just few weeks ago)

$\alpha_s^2 \sim \alpha_W$

Scattering amplitudes

Scattering amplitudes (in loop expansion) are at the core of perturbative methods



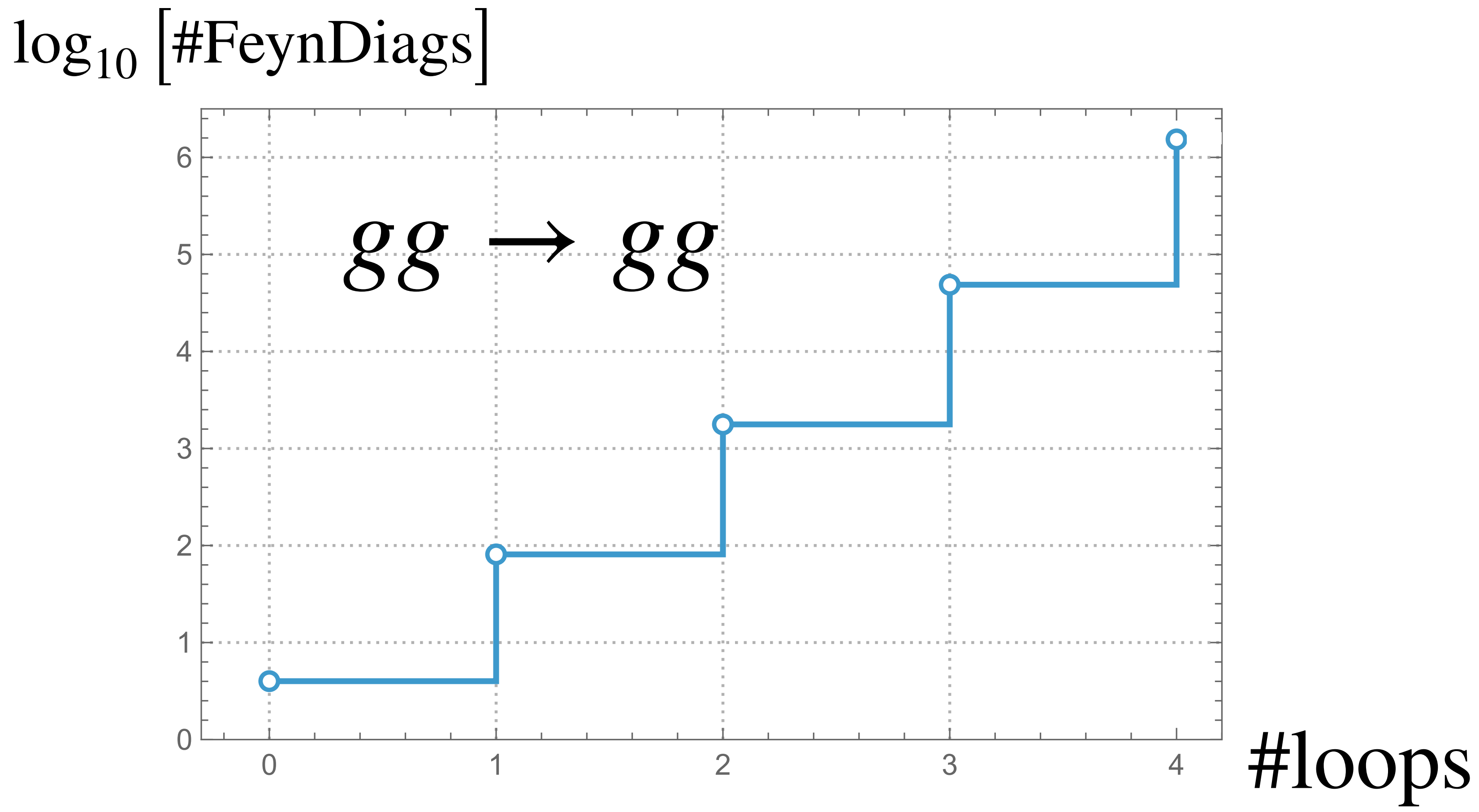
at a given fixed order N in perturbation theory (at LO $N = 0$):

#loops + #extra-emissions = N

Example: at NNLO corrections for m-particle production

a) 2-loop $(m+2)$-point amplitudes, b) 1-loop $(m+3)$-point amplitudes, c) 0-loop $(m+4)$-point amplitudes

- tree-level and 1-loop calculations are fully automated
- beyond 1-loop: still case by case calculation

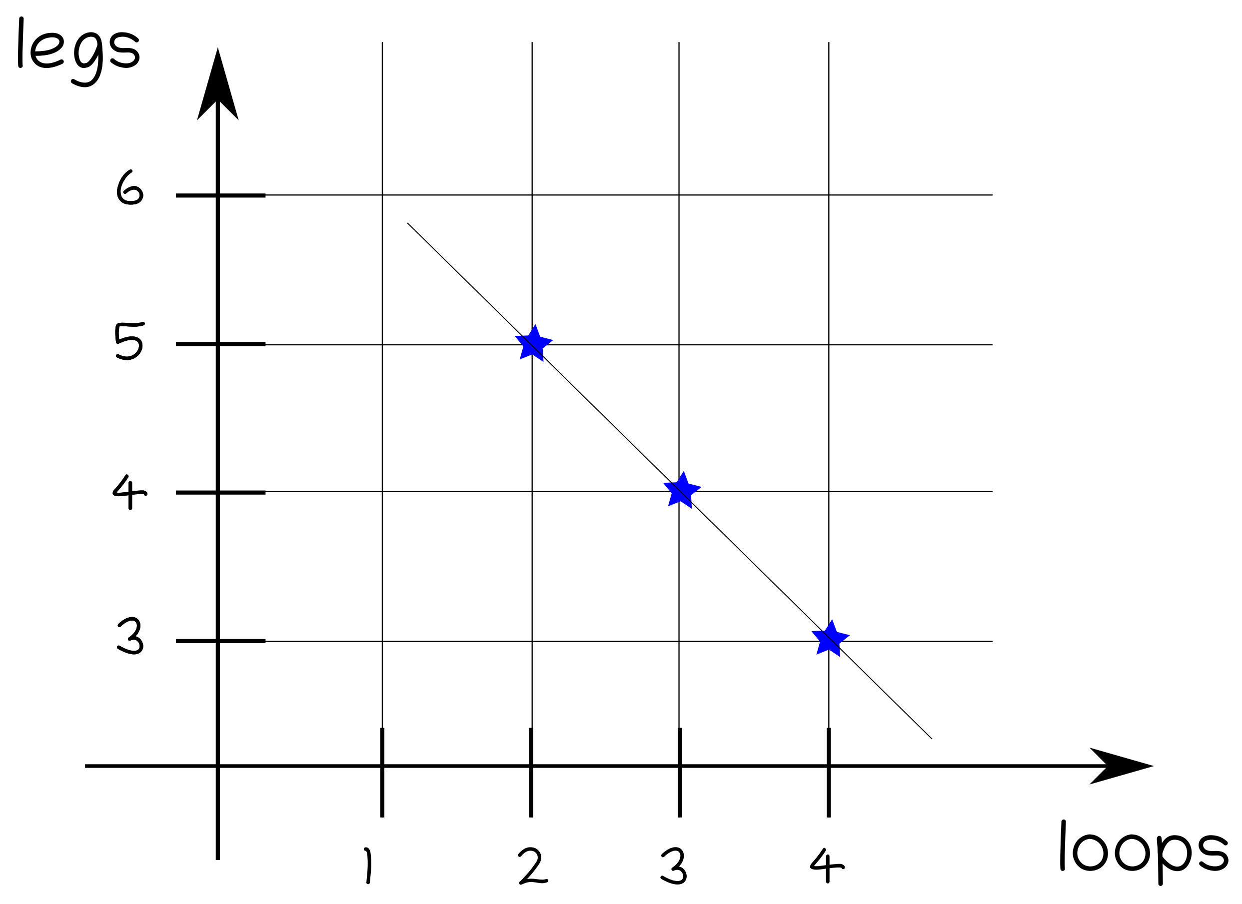


complexity increases dramatically with the loop order and the external particles (legs~scales)

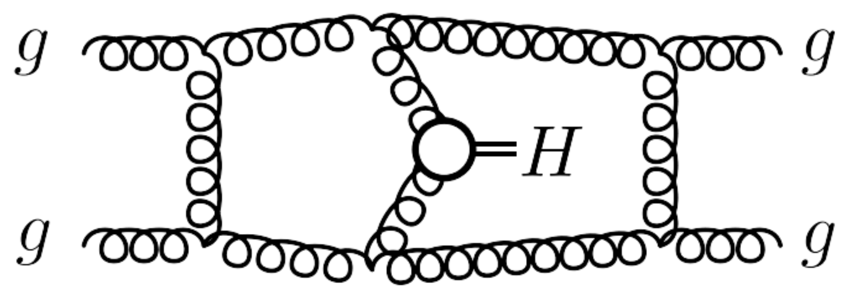
- encode the short-distance dynamics (**high momentum transfer**)
- need to be evaluated in **unresolved regions: large separation of scales**

Scattering amplitudes

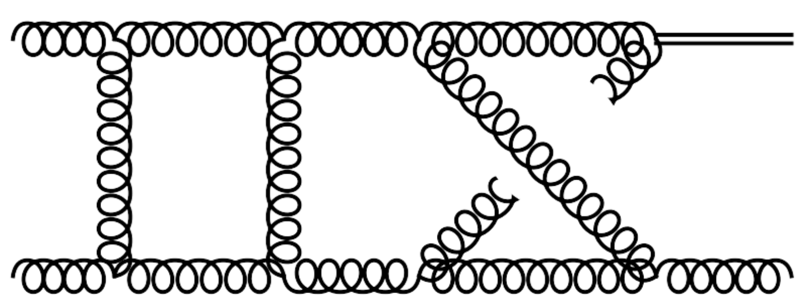
State of the art in massless QCD: $n_{\text{loops}} + n_{\text{legs}} = 7$



(some full, mostly partial) results for 2-loop $2 \to 3$ scattering with external masses
eg 5 days ago: H+4g at large N_c [De Laurentis et al 2605.04009]



Large-N_c results for 3-loop $2 \to 2$ with one external mass
see eg. [Gehrmann et al 2307.15405],[Chen et al 2504.06490]

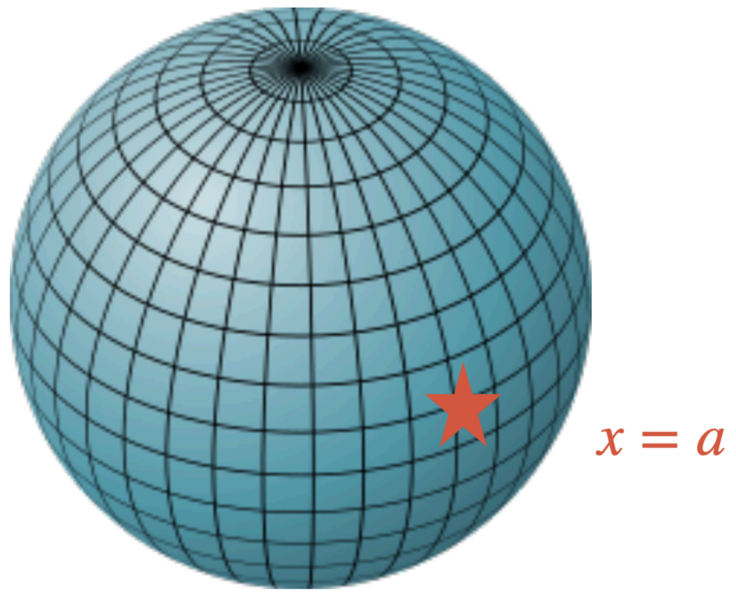


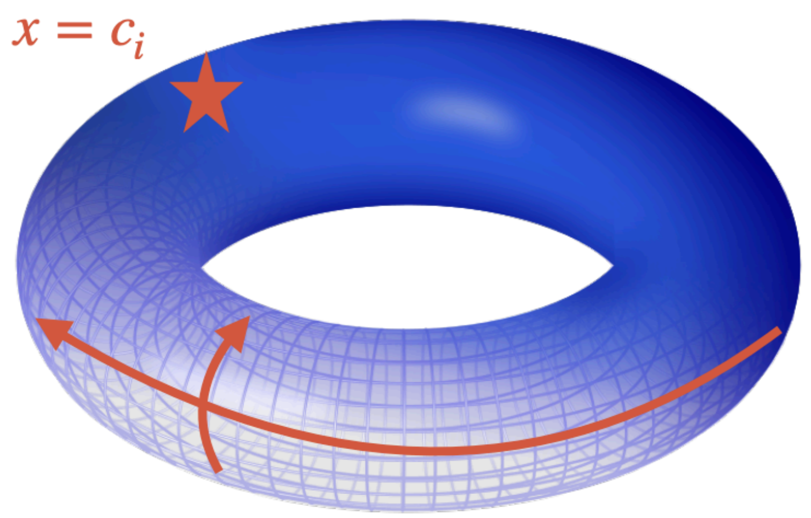
QCD:

- sadly, not as nice as symmetric theories, eg $\mathcal{N} = 4\,\text{sYM}$ → final result ~ "simple", but much obscured at intermediate steps
- even worse with massive particles, eg top quark: **algebraic complexity** + **mathematical structure** (elliptic and beyond)

EW:

- massive particles (Z, W, H, t) everywhere, in loops and in legs:
  geometry of the problem changes drastically from $1 \to 2$ loops

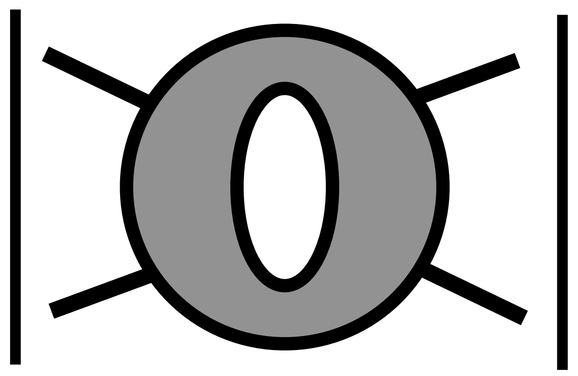


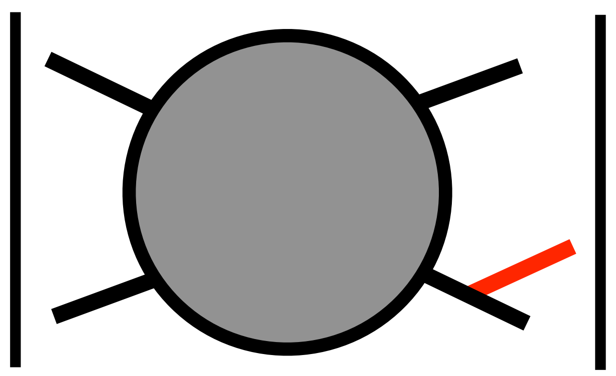


partial/preliminary contributions [Freitas, Song, Xie 2305.16547] [Freitas, Wallace 2512.15700]

Differential XS and infrared (IR) dynamics

$$\mathrm{d}\sigma^{\mathrm{NLO}} = \int_\Lambda \mathrm{d}\Phi_m \left| \quad \right|^2 + \int_\Lambda \mathrm{d}\Phi_{m+1} \left| \quad \right|^2 = \text{fin}$$





$-\infty$ explicit in loop calculation

$+\infty$ phase-space integration over unresolved (IR) divergent regions

problem: how to regulate (and *subtract*) IR divergences from real emissions?

Slicing methods:

$$\int_0^1 \mathrm{d}x \frac{f(x)}{x^{1+\epsilon}} = \lim_{r\to 0}\left(\int_r^1 \mathrm{d}x \frac{f(x)}{x} + \int_0^r \mathrm{d}x \frac{f(x)}{x^{1+\epsilon}} \right)$$

→ computed from factorisation formulae in soft/collinear regimes → power series in r (most times only leading power known)

Local subtraction methods:

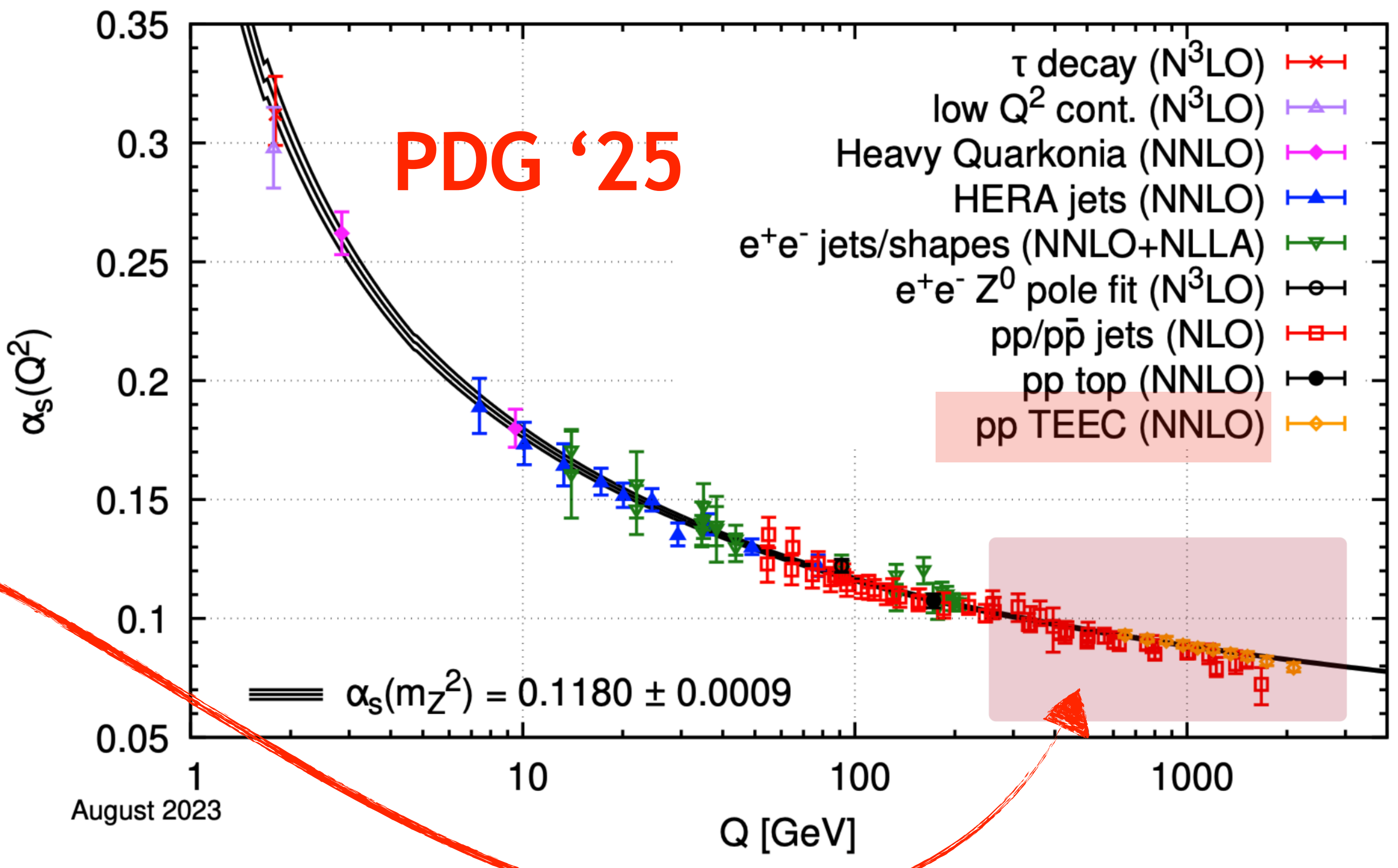
$$\int_0^1 \mathrm{d}x \frac{f(x)}{x^{1+\epsilon}} = \int_0^1 \mathrm{d}x \frac{f(x)-f(0)}{x} + \int_0^1 \mathrm{d}x \frac{f(0)}{x^{1+\epsilon}}$$

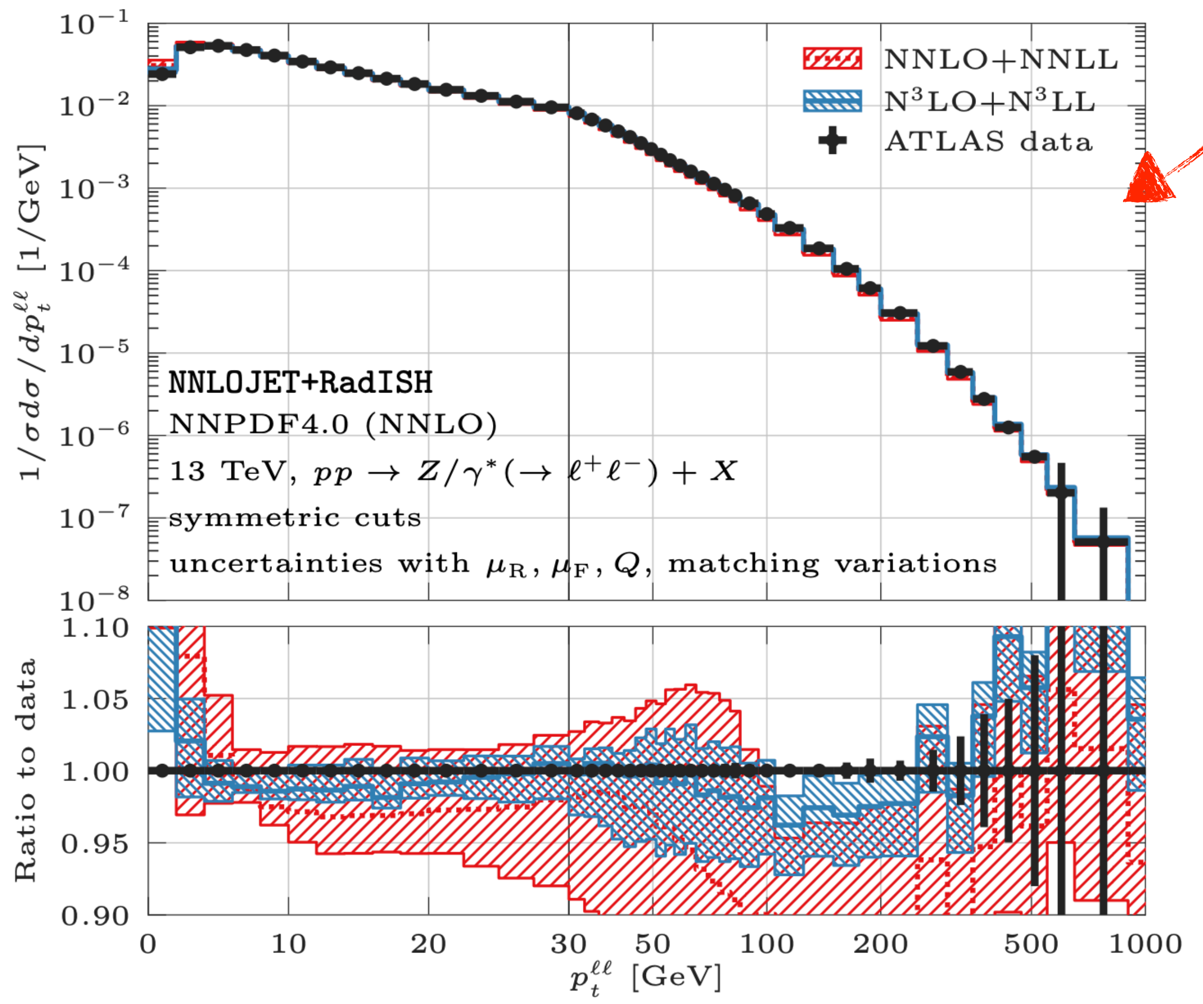
→ $-\frac{1}{\epsilon} f(0)$ → explicit divergence, cancelled against loop

Challenges in dealing with the IR

[Table courtesy of F. Caola, Aspen '26]

	Higgs/DY	H+j/Higgs p_t	jjj
NNLO local	1 CPU hours	100k CPU hours	100M CPU hours
NNLO slicing	400 CPU hours	> 100k CPU hours	x
N^3LO local	200k CPU hours	x	x
N^3LO slicing	5M CPU hours	x	x



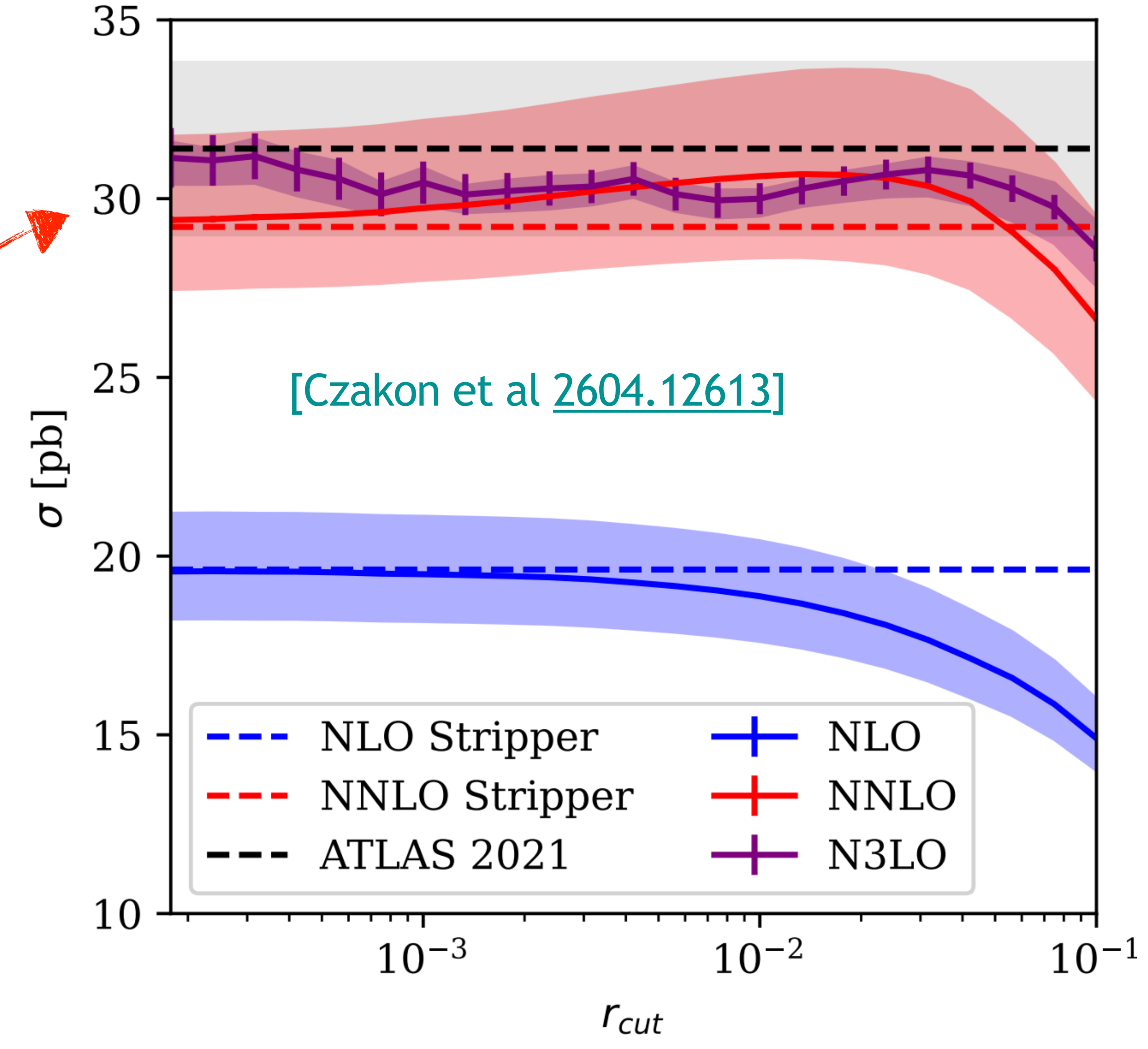


- (as discussed) used to extract most precise $\alpha_s(m_Z)$ value at colliders
- ideally we'd also use this to fit PDFs

[Chen et al 2203.01565]

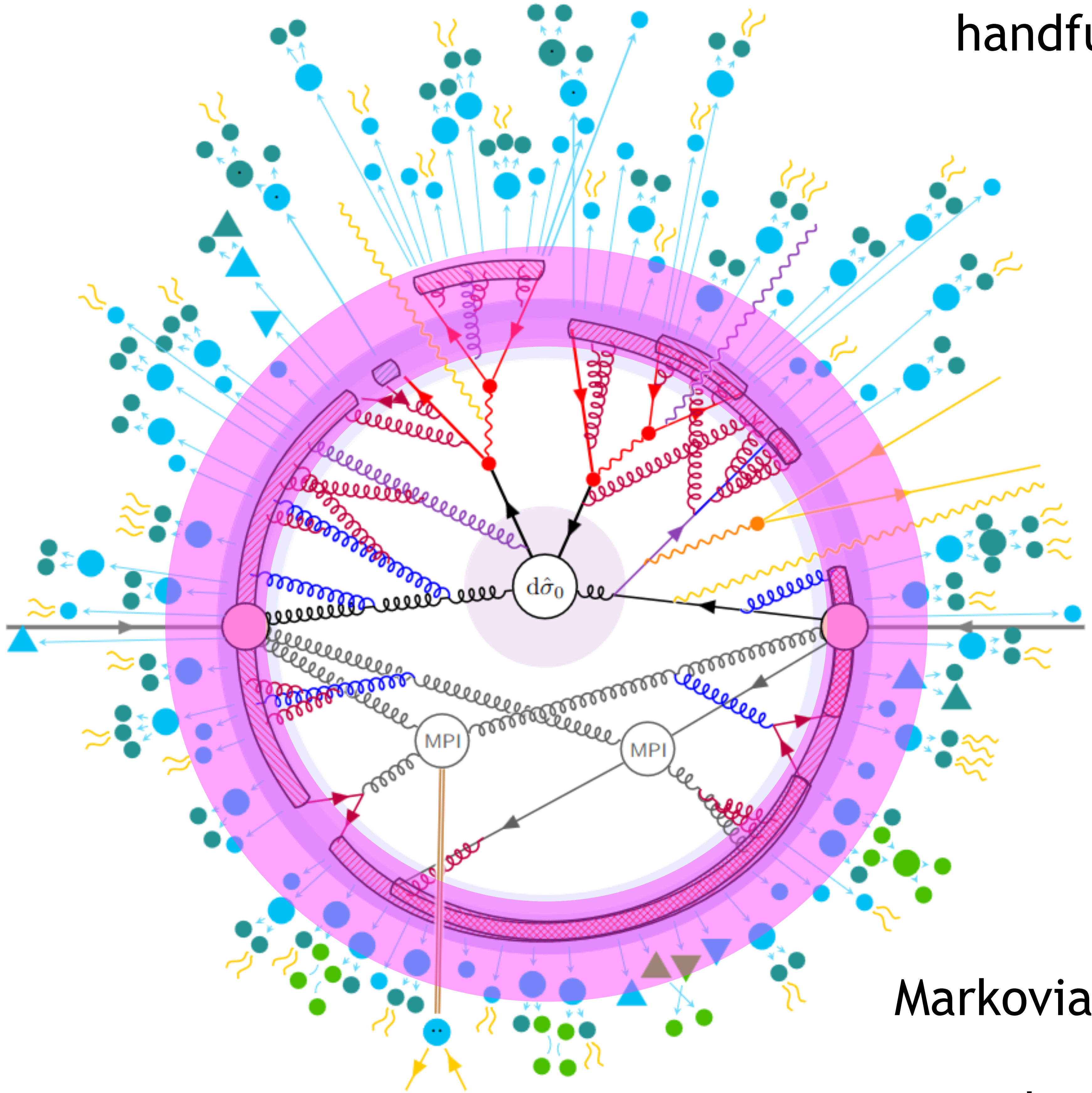
New: $\gamma\gamma$ at N3LO QCD

[slicing ~ 8.5 M hours]



Towards the non-perturbative regime

leaving the perturbative regime → evolve down to confinement regime



handful of particles at fixed order → hundreds of baryons/mesons + photons, leptons etc

Parton Shower Monte Carlo Generators (PSMCs)

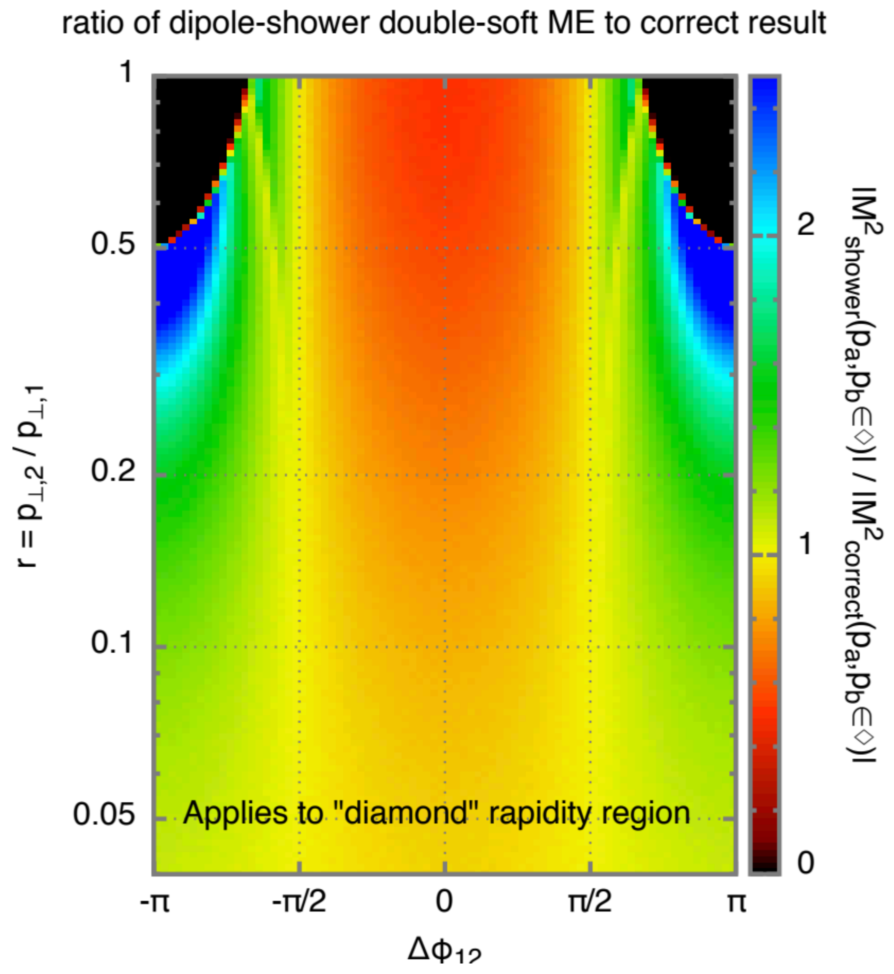
PSMCs at the heart of arguably any analysis (present and future colliders)

Pithya **Herwig** **Sherpa** + **Powheg box** **Madgraph**

Markovian process: evolution according to some ordering down to non-pert. scale

- evolution at large N_c, no spin correlations ~ classical evolution
- how to preserve perturbative and logarithmic accuracy? how to assess accuracy in general?
- how much non-perturbative/**hadronisation models** under control?

PSMCs: recent developments



New spring for PSMCs ~ 2020

impossibility to gain high log. accuracy in certain classes of showers algorithms [Dasgupta et al 1805.09327]

triggered a whole new research program

Some new (and old) questions:

I. Formal (logarithmic) accuracy

II. Matching to higher-order calculations (log-accuracy compliant)

III. Electroweak corrections

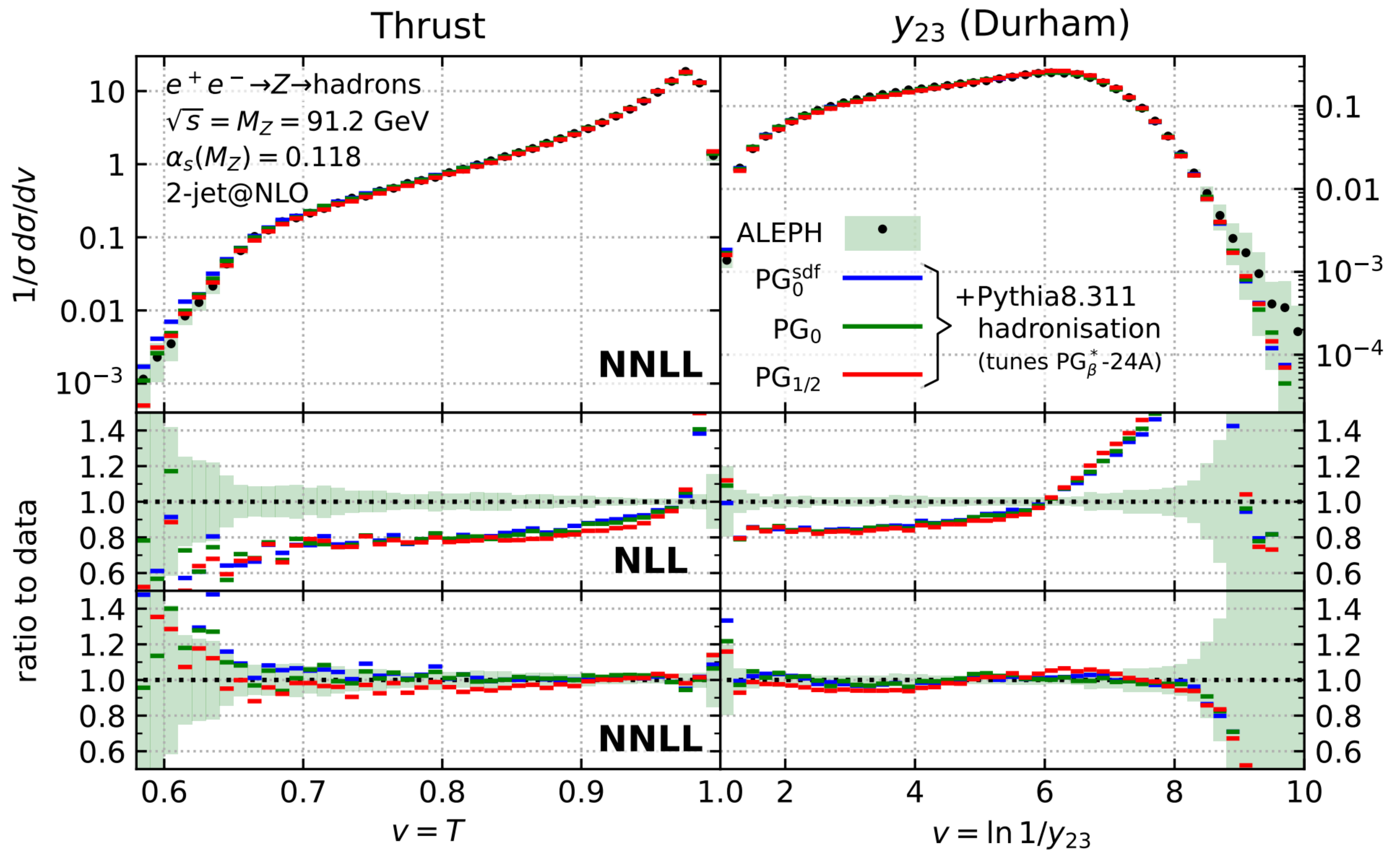
QCD + QED showers, resonance-aware showers

IV. Possible alternative avenues/rethinking

eg. amplitudes/colour evolution [see eg Forshaw et al 2502.12133]

V. Theory uncertainties

Extrapolation from fiducial to inclusive (typically in much better control)



Recent milestone result: NNLL accurate PS for e+e- [van Beekveld et al. 2406.02661]

Work in progress for pp collisions (colour singlet first)

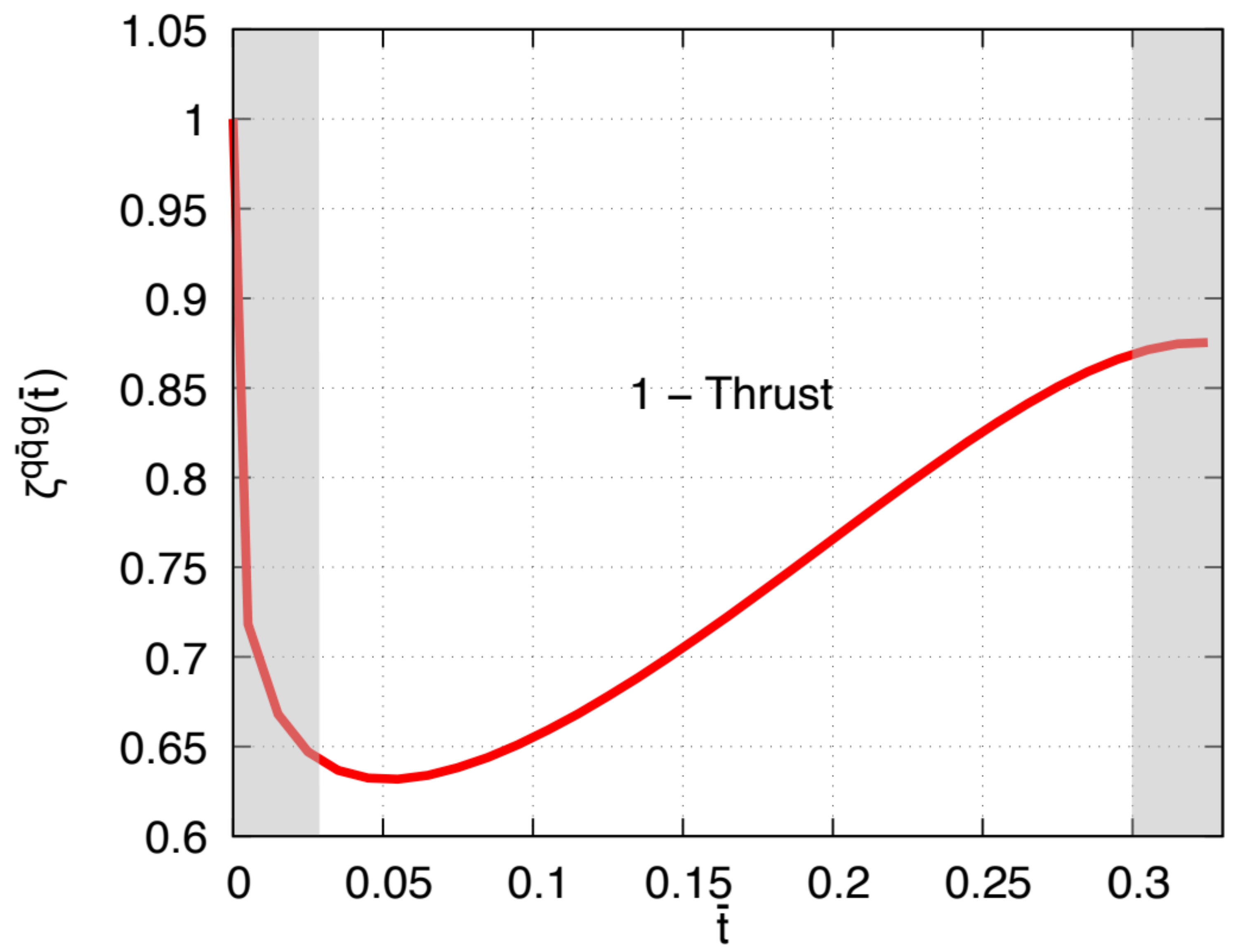
Questions in non-perturbative QCD

All-order infrared/non-perturbative ambiguities (potentially) plague several precision measurements/extractions

- the **top-quark pole mass** suffers from a non-perturbative ambiguity from infrared renormalons $\mathcal{O}$(hundreds MeV)
- α_s **extraction from event shapes** (in lepton colliders) in regions highly sensitive to non-perturbative effects
- α_s **extraction at LHC** from Z transverse momentum (q_T) at very low q_T
- **precision jet Physics** at future (even present!) colliders due to hadronisation models (encoded in PSMCs)

Quantified as power corrections: $\left(\frac{\Lambda_{\rm QCD}}{Q}\right)^p$

old results (models) typically derived in simple scenarios (then extrapolated)



recent analytical investigations (based on models):

- linear ($p = 1$) power corrections in shape observables + don't obey extrapolation [Caola et al 2204.02247]
- anomalous scaling of linear power corrections [Farren-Colloty et al 2507.18696]

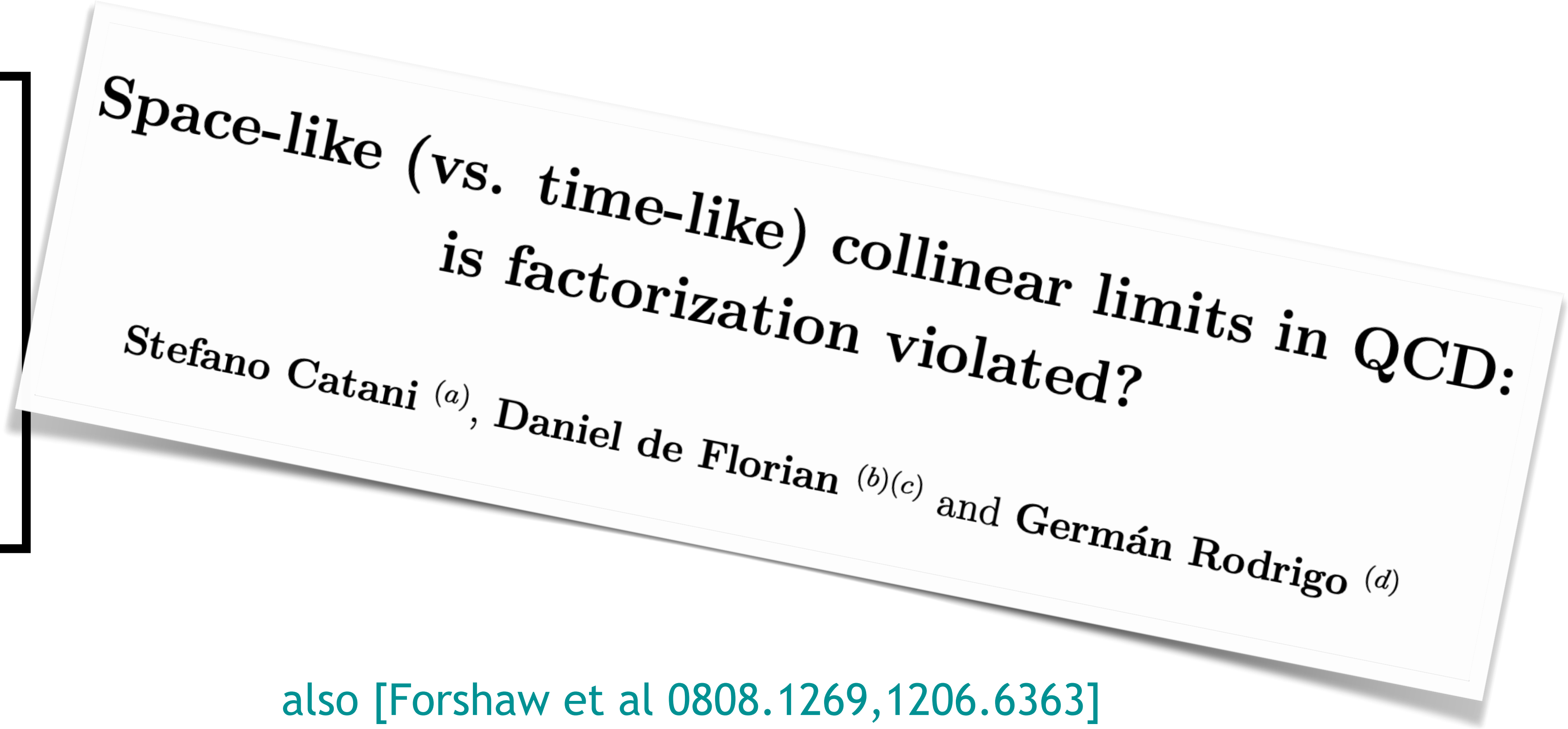
“New phenomena” (and questions) in QCD

Extreme precision poses **profound questions about the basic infrastructure**

The master formula

$$\frac{d\sigma_{AB\to X}}{dO} = \sum_{ab}\int_0^1 dx_1 dx_2\, f_{a,A}(x_1,\mu) f_{b,B}(x_2,\mu)\, \frac{d\hat{\sigma}_{ab\to X}(x_1,x_2,\mu)}{dO} + \mathcal{O}\left(\frac{\Lambda^p_{\rm QCD}}{Q^p}\right)$$

proved only for DIS and inclusive Drell-Yan


Space-like (vs. time-like) collinear limits in QCD: is factorization violated?

Stefano Catani [(a)], Daniel de Florian [(b)(c)] and Germán Rodrigo [(d)]

also [Forshaw et al 0808.1269,1206.6363]

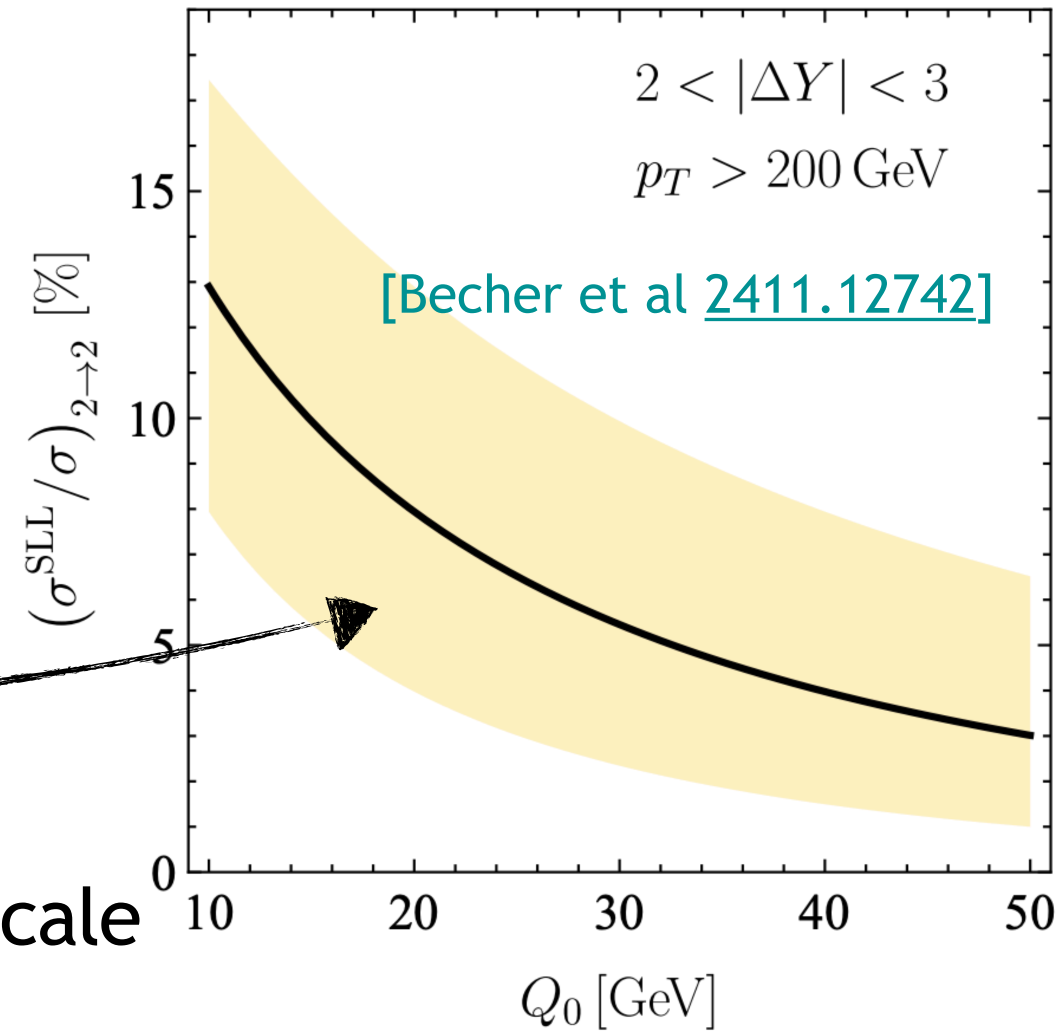
Factorisation violating effects: start at **third order** in QCD in jet cross-sections

origin: Coloumb/Glauber (soft-virtual) gluons **destroy** a fundamental property of QCD: **colour coherence**

time-like vs space-like collinear dynamics: complex phases ~ $i\pi$ → **only there in pp collisions** (LHC)

great community effort in making sure the infrastructure is robust!

at observable level: onset of “*super-leading logarithms*”. Are these effects relevant?



$Q_0 \sim$ jet-veto scale

Concluding remarks

Many topics not covered in this talk

- PDFs and their impact on precision measurements
- resummation: where important, methods and state of the art
- new generation of numerical methods for multi-loop calculations
- “new observables”, eg energy-energy correlators (EEC)
- flavoured jets tagging
- Higgs boson width
- Vector boson scattering and multi-boson production
- analyses of polarised vector bosons
- evidence (or not) of top anti-top bound state (*toponium*)
- lattice determination of SM parameters and precision “observables”

and so many more…

Summary

- the LHC entered a precision phase → further enhanced in the upcoming High-Lumi phase
- investigation of unexplored sectors of the SM (second-generation Yukawas + Higgs potential)
- bounds on the next energy scale and search for indirect signs of new Physics

This program can succeed only if quality of theory predictions and exp. measurements simultaneously improve

→ after all this progress, theory is often the weaker link

Theory predictions: often not just add another loop or another "*N*"

- even asking "what can theorists compute?" and "what can experimentalists measure?" are non-trivial questions
- challenges have very different origins: cover several order of magnitudes across a broad phase space
- there are "new phenomena" and unsolved problems even in QCD

QCD, but actually the whole SM

Quantum Chromodynamics —
The perfect Yang–Mills gauge field theory*

David Gross
University of California, Santa Barbara, CA 93106, USA

Over the many years after the completion of the standard model, there have been extraordinary impressive tests of quantum chromodynamics as well as impressive calculations. The calculation of the running of the coupling has now been carried out to many loop orders and George Sterman, who will talk about the application of perturbative QCD to LHC physics, correct George?

George Sterman: Something like that.

David Gross: Something like that. These calculations and their comparison with experiment are absolutely essential. At the LHC we look for new physics, but new physics is bound to be rare — typically one new interesting event per billion old and boring events. In order to pick out one new event out of a billion events, you must understand those one billion events with enormous accuracy. The technology of calculating within QCD is just totally amazing. In another experimental develop-

Extra slides

(naive) Perturbation theory

SM perturbative expansion: QCD + EW corrections

simple power counting:

$\alpha_s \sim 0.1 \quad \alpha_W \sim 1/137 \sim 0.01 \quad \alpha_s^2 \sim \alpha_W$

$$\hat{\sigma}_{ab\to X} = \hat{\sigma}^{(0,0)}_{ab\to X} \longrightarrow \text{LO prediction}$$

$$+ \alpha_s\, \delta\hat{\sigma}^{(1,0)}_{ab\to X} + \alpha_s^2\, \delta\hat{\sigma}^{(2,0)}_{ab\to X} + \alpha_s^3\, \delta\hat{\sigma}^{(3,0)}_{ab\to X} + \cdots \longrightarrow \text{higher-order QCD corrections}$$

$$+ \alpha_W\, \delta\hat{\sigma}^{(0,1)}_{ab\to X} + \alpha_s \alpha_W\, \delta\hat{\sigma}^{(1,1)}_{ab\to X} + \cdots \longrightarrow \text{higher-order EW + QCDxEW}$$

(too) naively: $\longrightarrow$ $\mathcal{O}(10\%)$ $\mathcal{O}(\text{few}\%)$ $\mathcal{O}(\lesssim 1\%)$

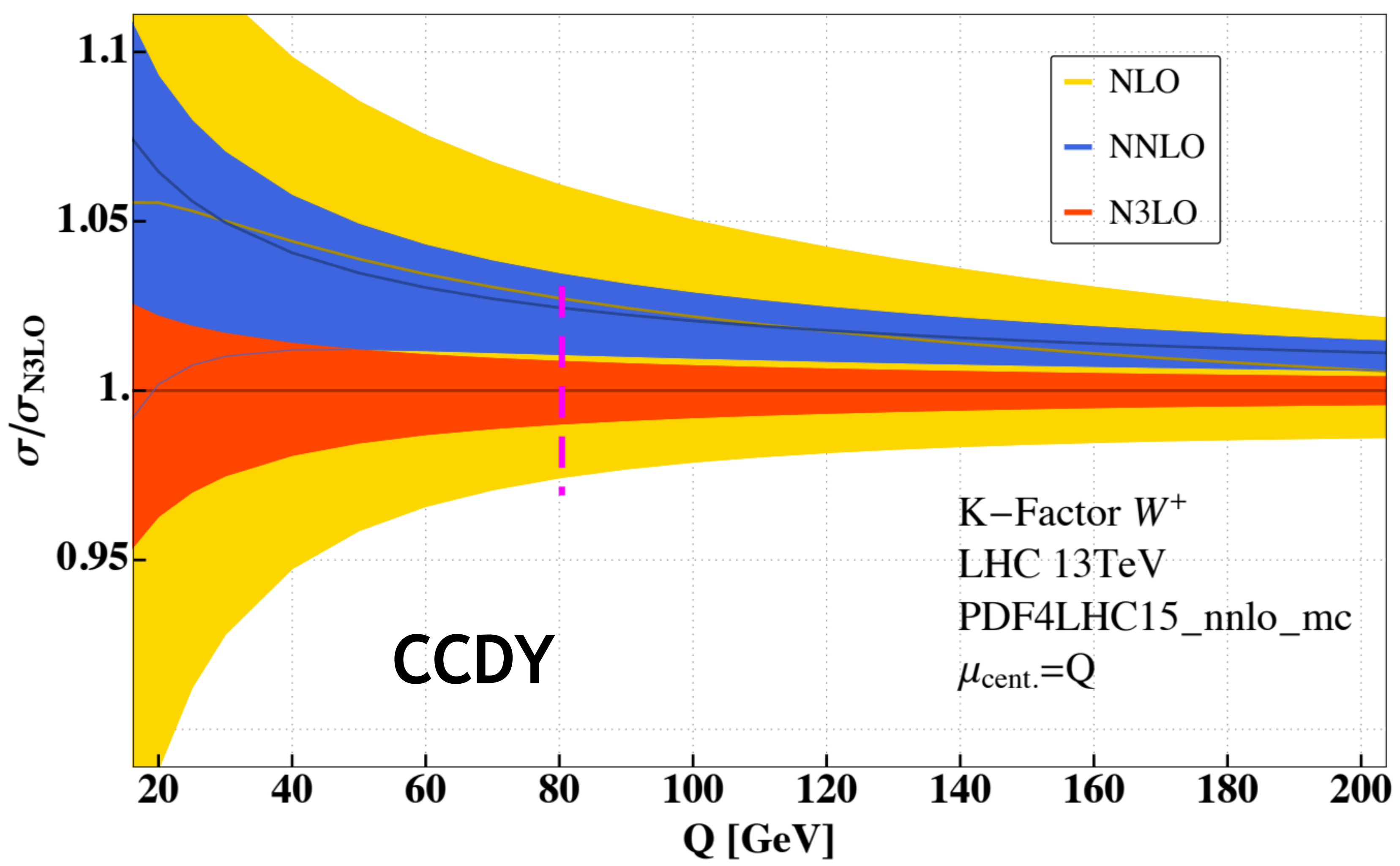
practically this is **never the case**
(even for inclusive observables)

Ex: **NCDY XS**

[FB et al 2203.11237]

σ[fb]	$\sigma^{(0,0)}$	$\delta\sigma^{(1,0)}$	$\delta\sigma^{(0,1)}$	$\delta\sigma^{(2,0)}$	$\delta\sigma^{(1,1)}$
$q\bar{q}$	1561.42	340.31	−49.907	44.60	−14.78
$\gamma\gamma$	59.645		3.166		
qg		0.060		−32.66	2.07
$q\gamma$			−0.305		−0.227
$g\gamma$					0.2668
gg				1.934	

$|\delta^{(2,0)}| \sim |\delta^{(1,1)}|$



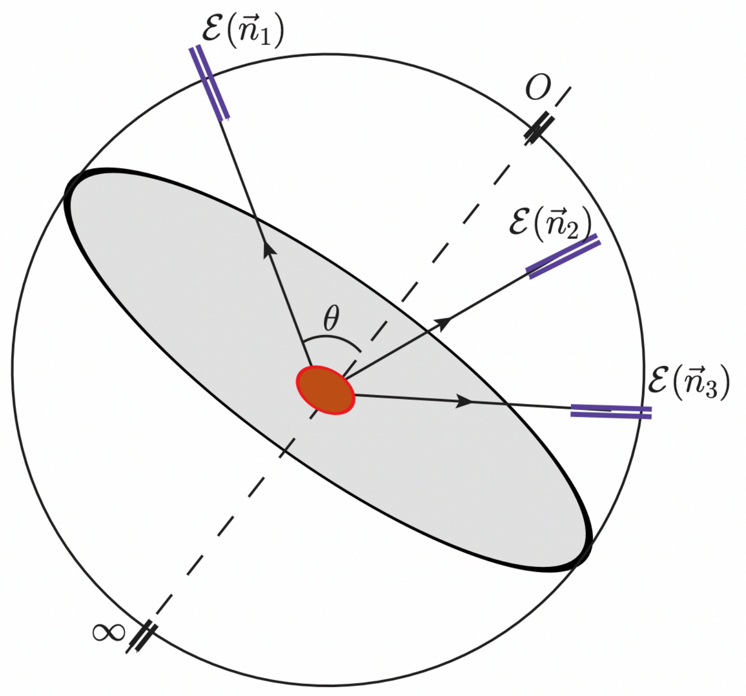
$|\delta^{(2,0)}| \sim |\delta^{(3,0)}|$

NNLO and N3LO predictions do not overlap

“New” avenues to QCD across all regimes

Emergence of **novel ideas**, inspired by **formal QFT/CFTs**

energy flow operator (~ “**detector operators**”)

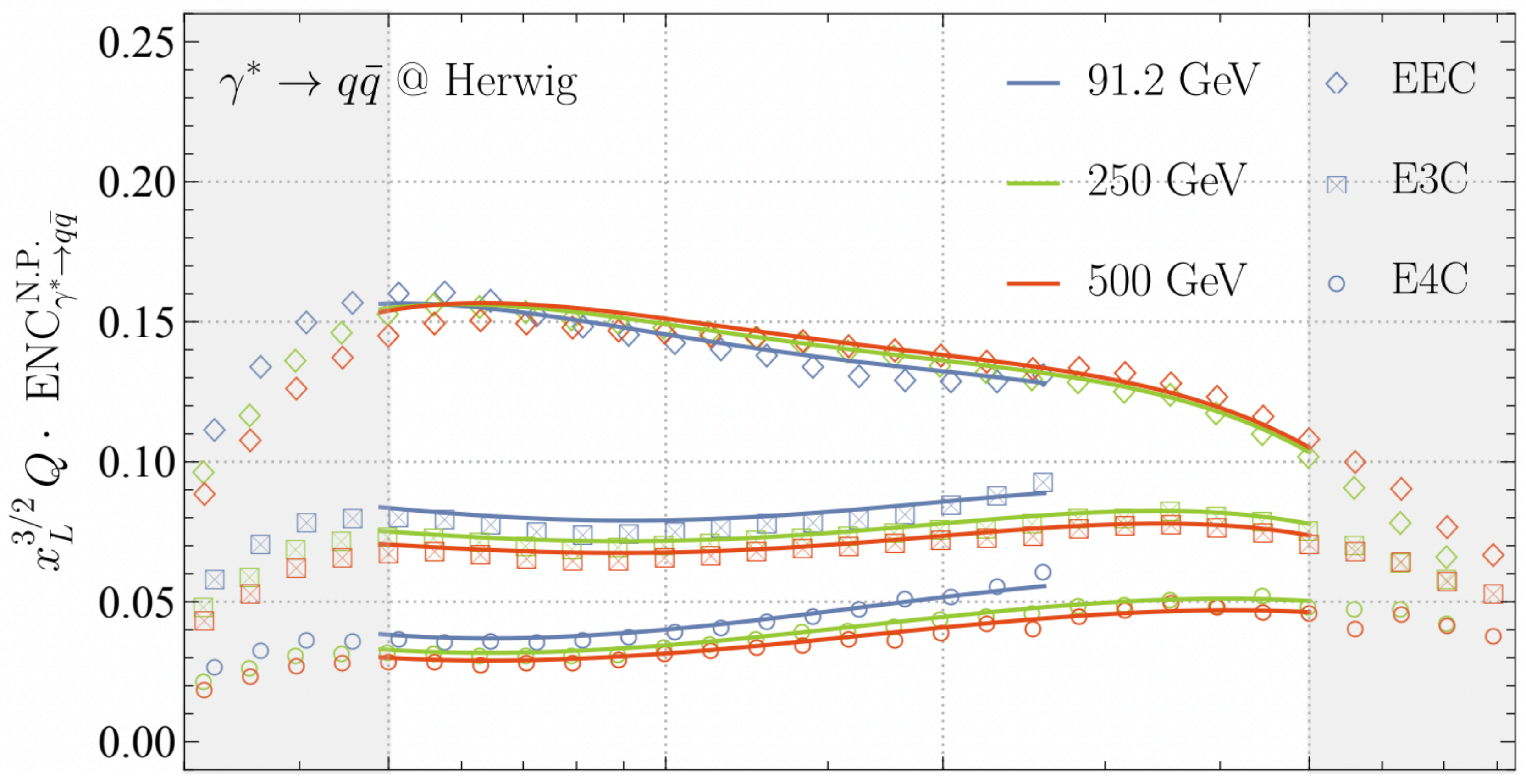


$$\mathcal{E}(\hat{n}) = \lim_{r\to\infty} \int_0^\infty dt\, r^2 n_i T_{0i}(t, r\hat{n})$$

detector operator observables via **light-ray OPE**

in the **collinear limit**

$$\lim_{n_1\to n_2} \mathcal{E}(n_1)\mathcal{E}(n_2) = \frac{1}{x_L}\vec{C}\cdot\vec{\mathbb{O}}^{[J=3]}_{\tau=2}(n_2) + \frac{\Lambda_{\rm QCD}}{x_L^{3/2}}\vec{D}\cdot\vec{\mathbb{O}}^{[J=2]}_{\tau=2}(n_2) + \ldots$$



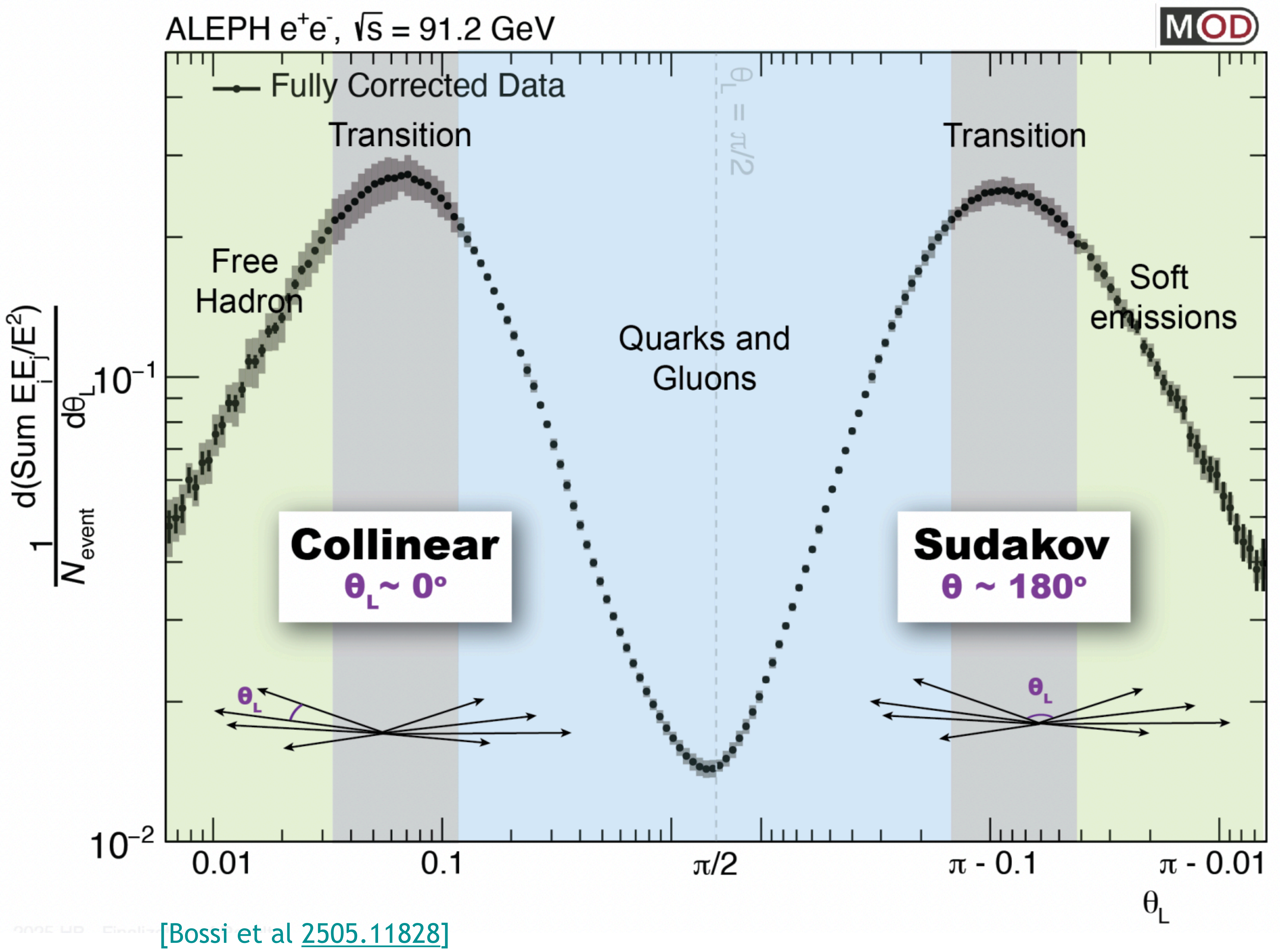
Scaling violation in power corrections to energy correlators

[Chen et al 2406.06668]

analytic vs Monte Carlo predictions

Measurement of EEC with archived ALEPH data

$$\mathrm{EEC}(\theta_L) = \sum_{i,j=1}^{n} \int d\sigma \frac{E_i E_j}{E^2} \delta(\theta_{ij} - \theta_L)$$



[Bossi et al 2505.11828]