QCD for LHC

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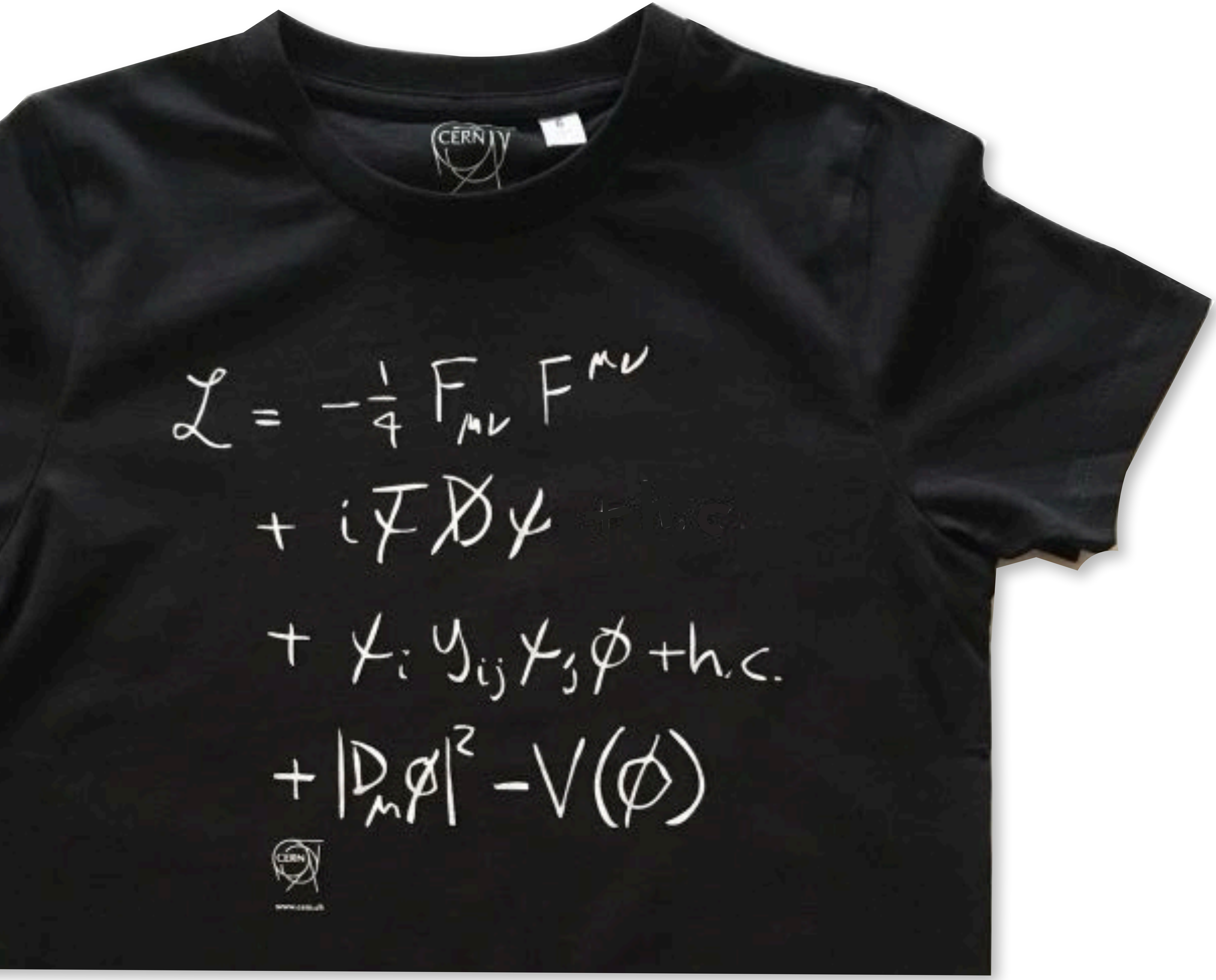
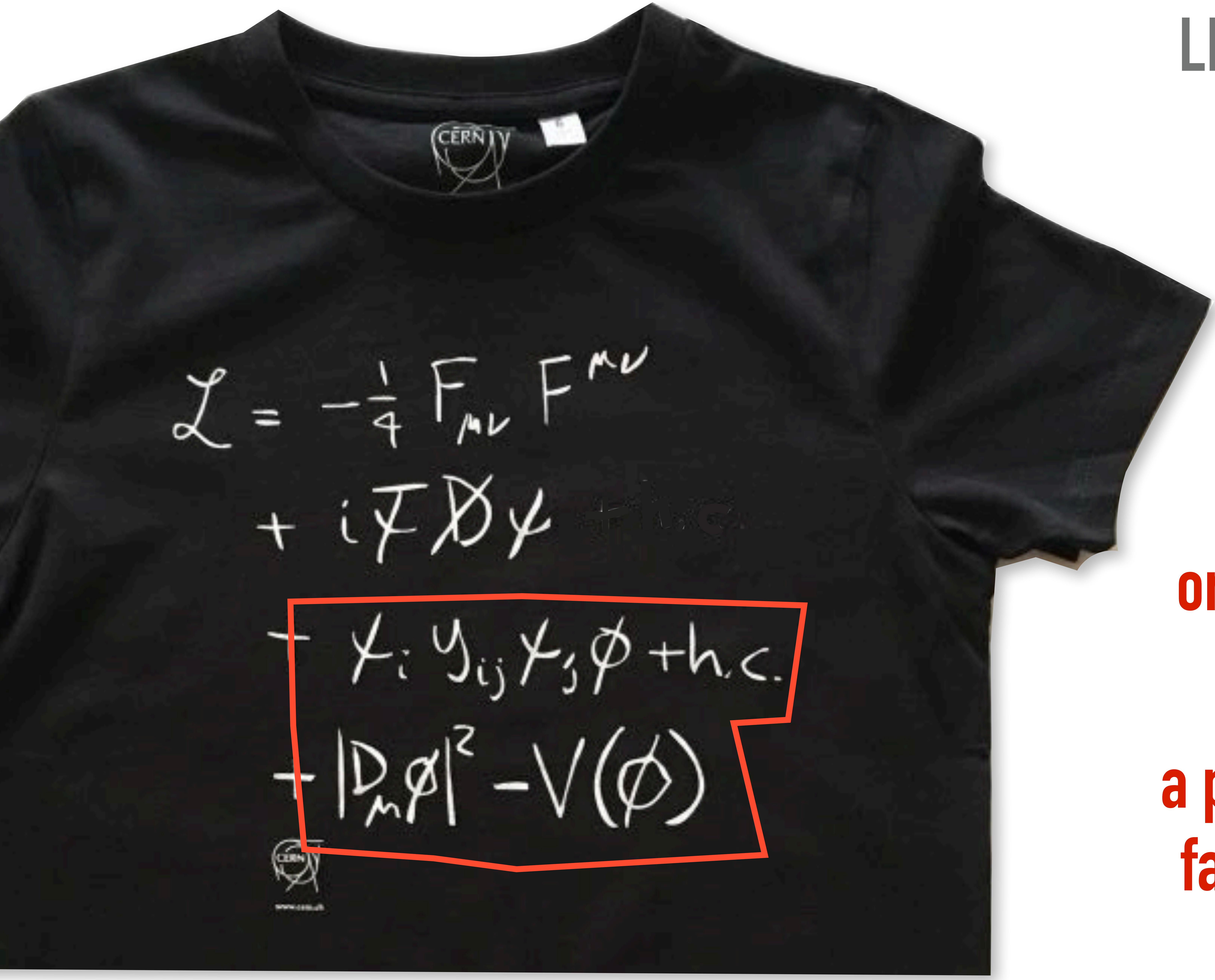
International School of Subnuclear physics
57th course, In Search of the Unexpected
Erice, June 2019

what are we trying to learn at the LHC?



what is the underlying Lagrangian of particle physics?



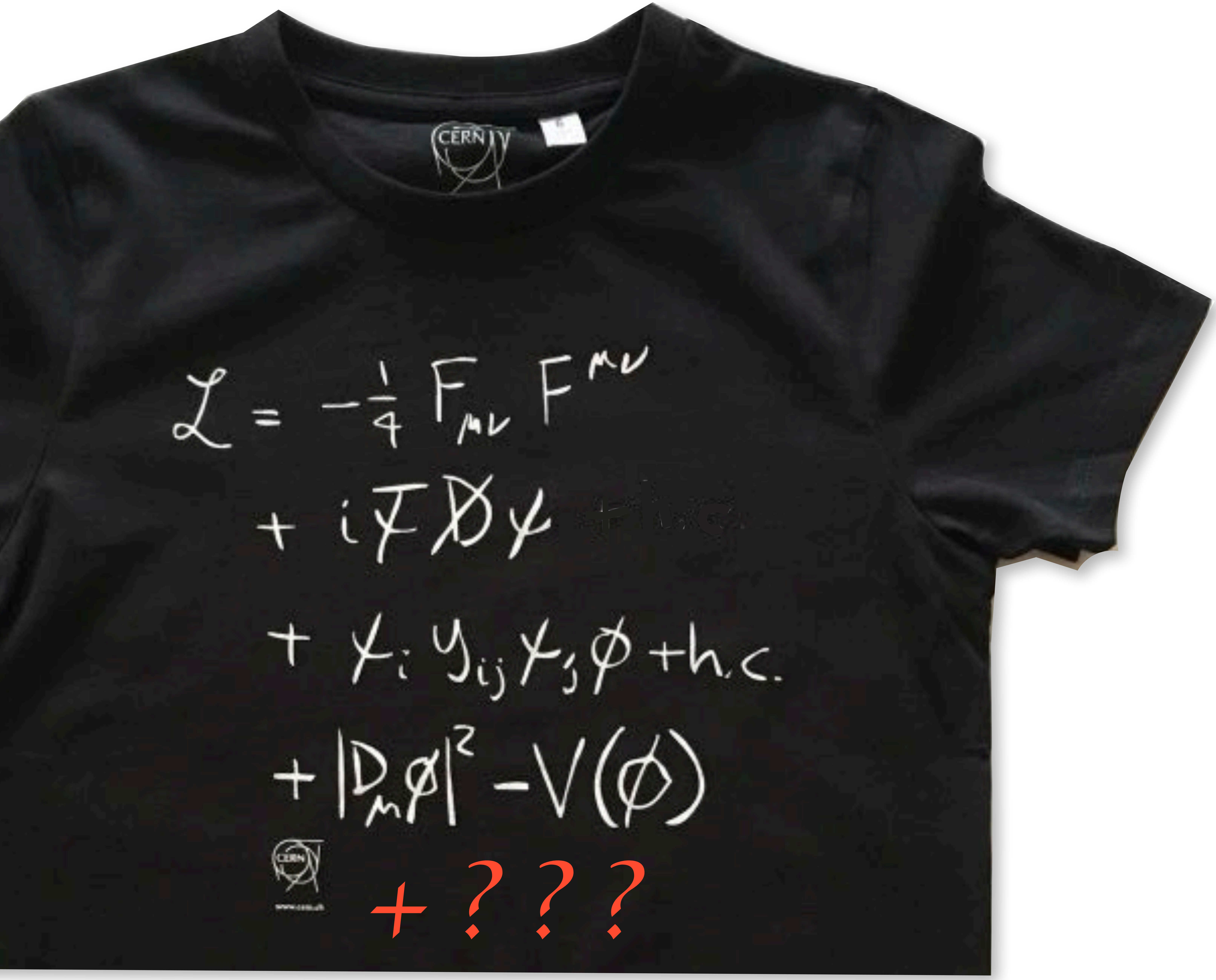
LHC is first machine to directly access Higgs sector

Is it the minimal version hypothesised in the SM?

origin of mass for W/Z

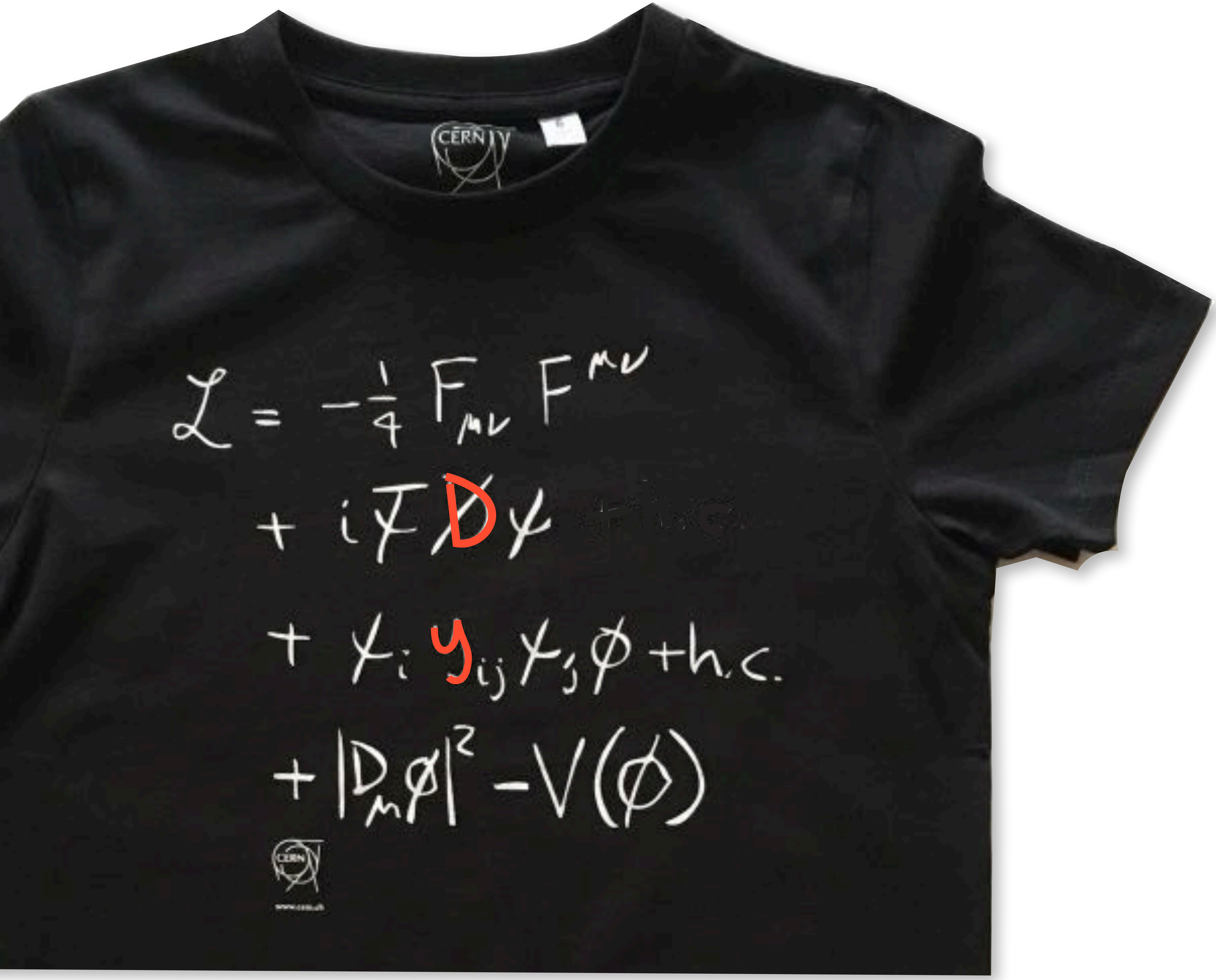
origin of mass for fermions via Yukawa couplings

a potential $V(\varphi)$ that is theorists' favourite toy (φ^4), but yet to be confirmed in nature



Is there anything else at the ~TeV scale?

If not, then many people worry about fine tuning



what are the values of the parameters of the SM?

couplings

(esp. strong coupling)

masses

(e.g. top & W masses)

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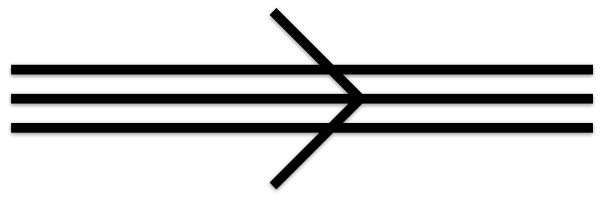
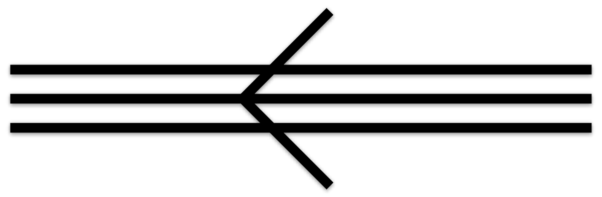
$$\frac{M_h}{\text{GeV}} > 124.2 - \frac{190}{\log_{10}^2 \frac{T_{\text{RH}}}{\text{GeV}}} + 2.0\left(\frac{M_t}{\text{GeV}} - 173.34\right) - 0.6\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.$$

arXiv:1505.04825

A proton-proton collision: INITIAL STATE

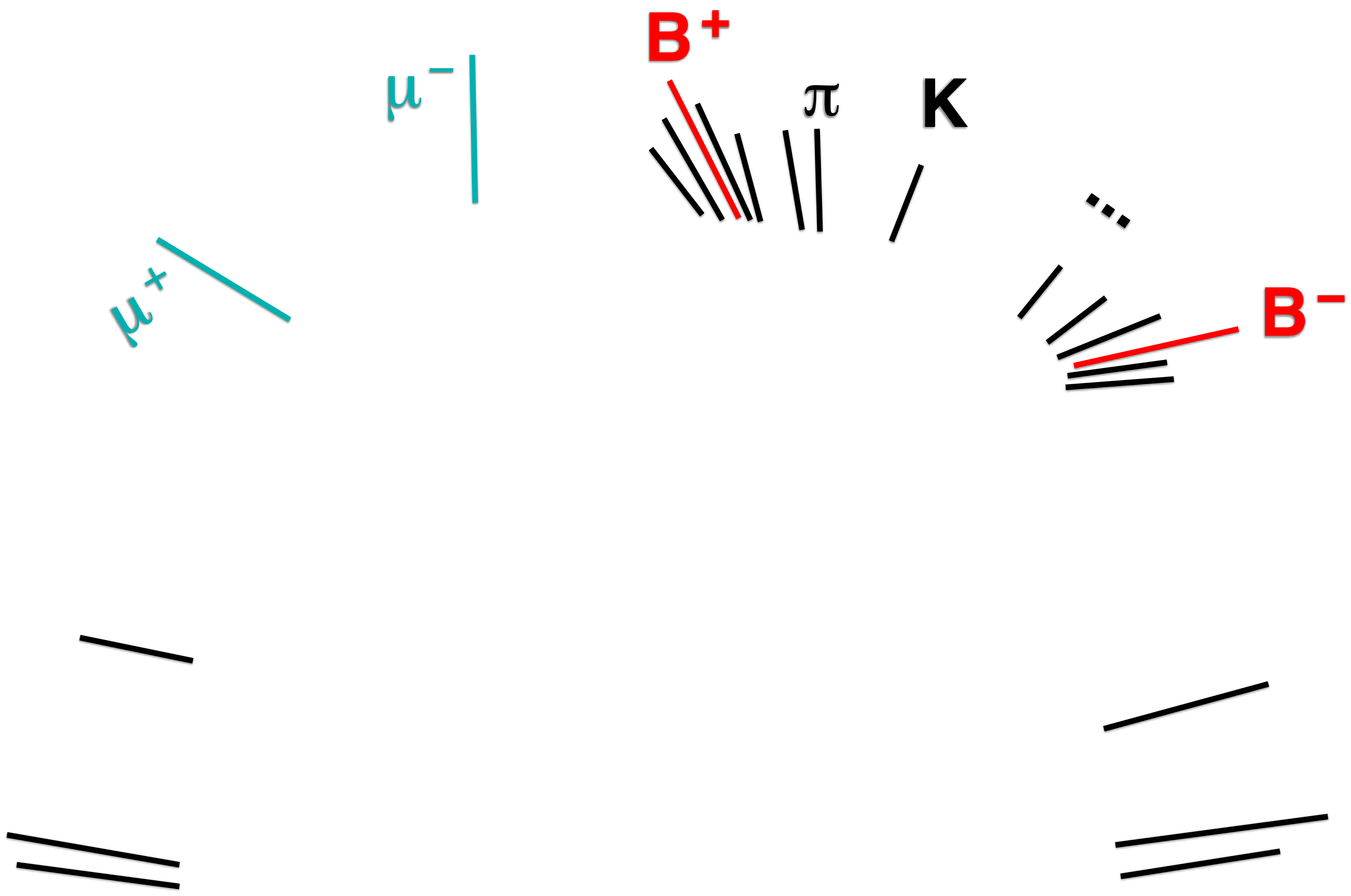


proton



proton

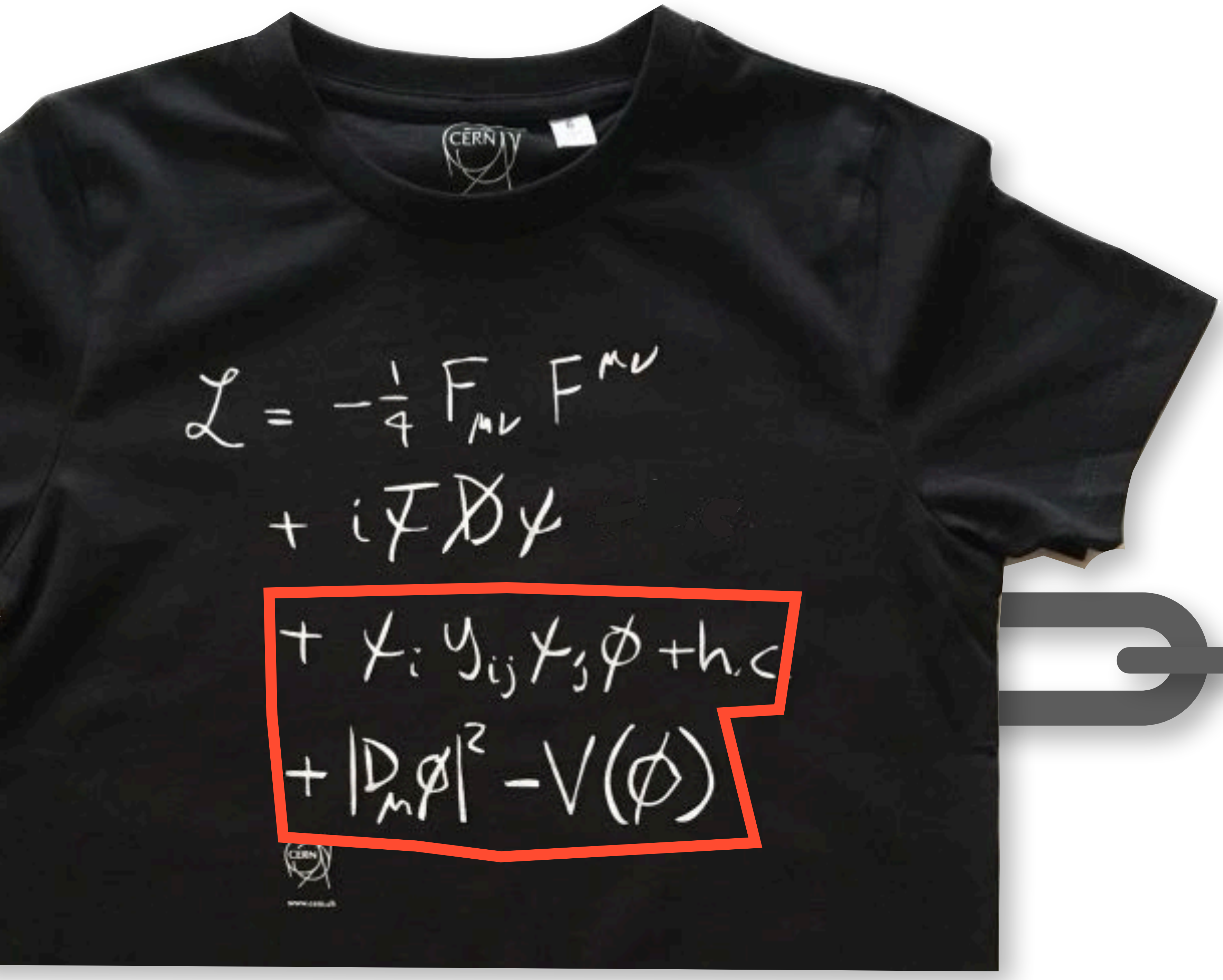
A proton-proton collision: FINAL STATE



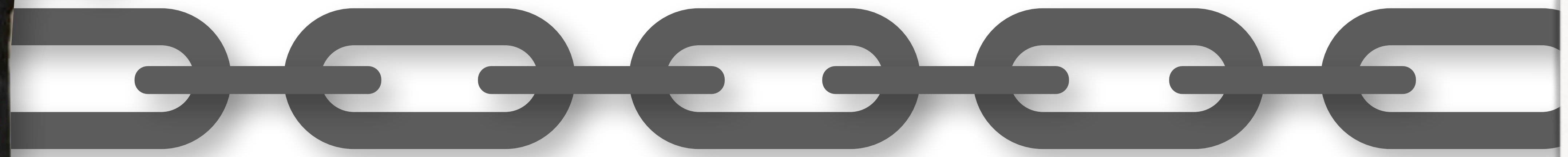
(actual final-state multiplicity ~ several hundred hadrons)

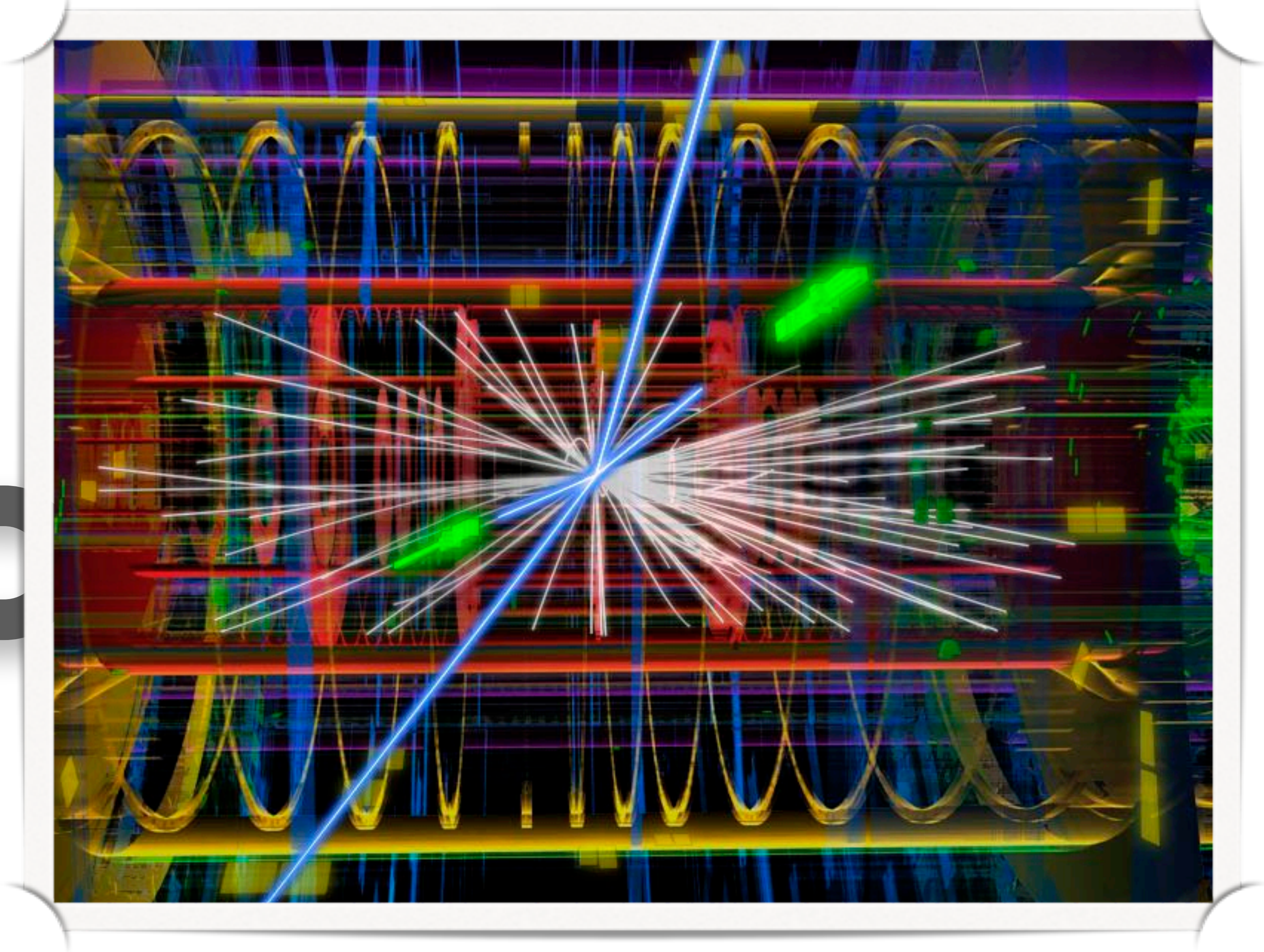
UNDERLYING THEORY

EXPERIMENTAL DATA



how do you make quantitative connection?



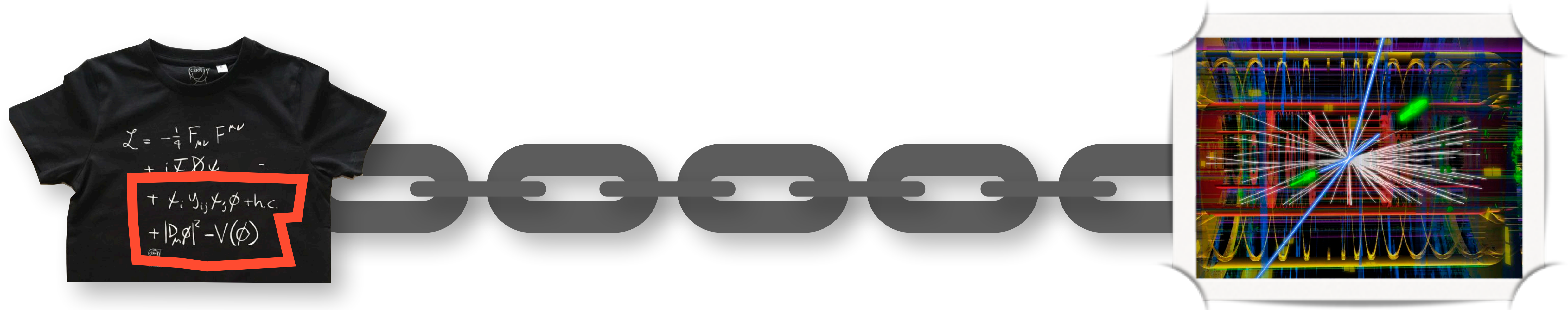


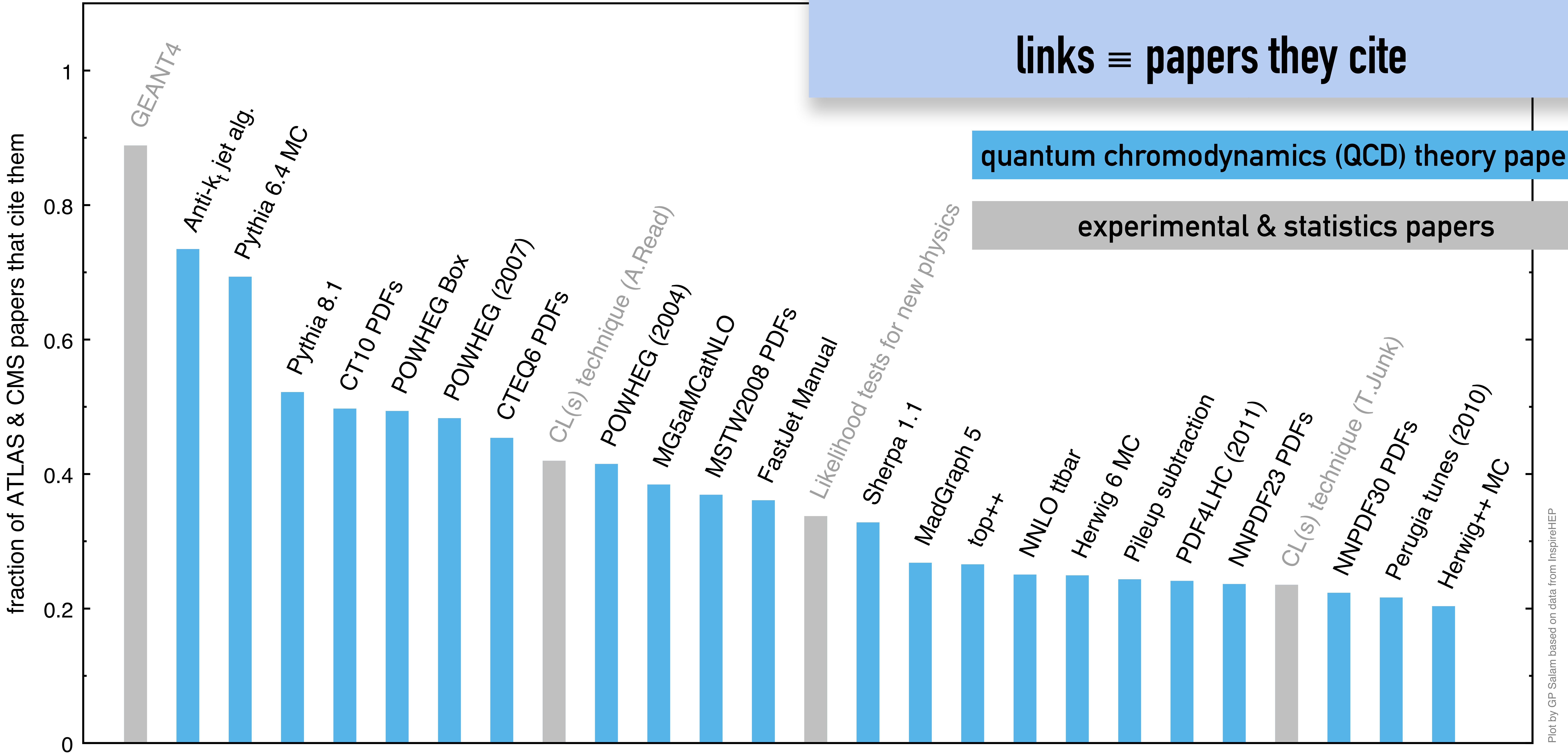
through a chain of experimental and theoretical links

What are the links?

ATLAS and CMS (big LHC expts.) have written ~1000 articles since 2014

links ≡ papers they cite





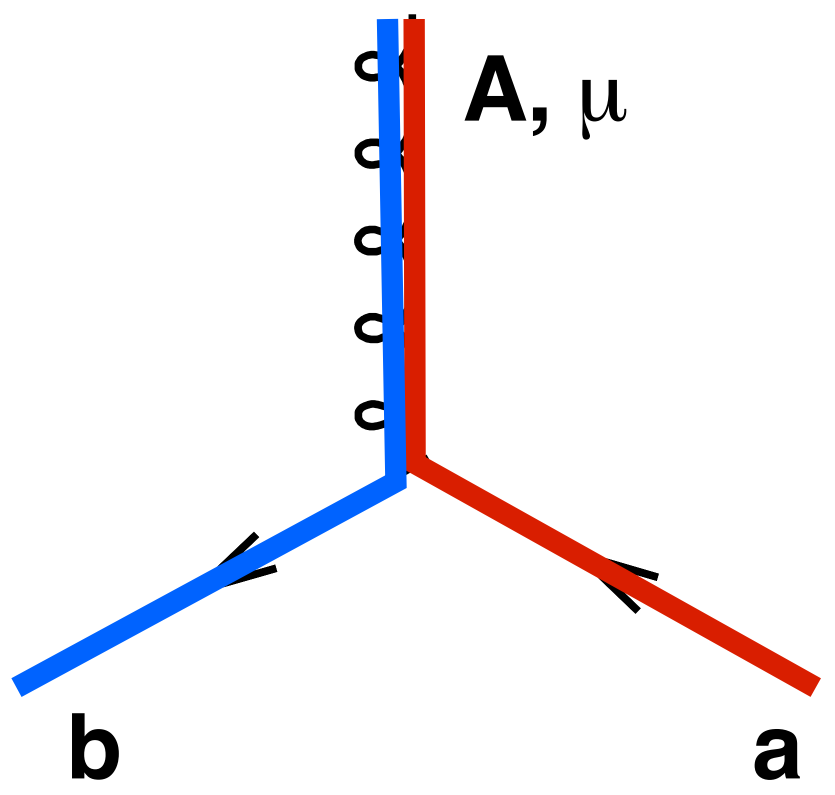
this lecture: 7 small parts

1. structure of QCD Lagrangian
2. a master formula
3. the strong coupling
4. parton distribution functions
5. fixed order calculations
6. Monte Carlo event generators
7. jets

the QCD lagrangian

and lattice QCD

quantum chromodynamics (QCD)



Quarks — 3 colours: $\psi_a = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{pmatrix}$

Quark part of Lagrangian:

$$\mathcal{L}_q = \bar{\psi}_a(i\gamma^\mu\partial_\mu\delta_{ab} - g_s\gamma^\mu t^C_{ab}\mathcal{A}^C_\mu - m)\psi_b$$

$SU(3)$ local gauge symmetry $\leftrightarrow$ 8 $(= 3^2 - 1)$ generators $t^1_{ab} \dots t^8_{ab}$ corresponding to 8 gluons $\mathcal{A}^1_\mu \dots \mathcal{A}^8_\mu$.

A representation is: $t^A = \frac{1}{2}\lambda^A$,

$$\lambda^1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda^2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda^3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda^4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix},$$

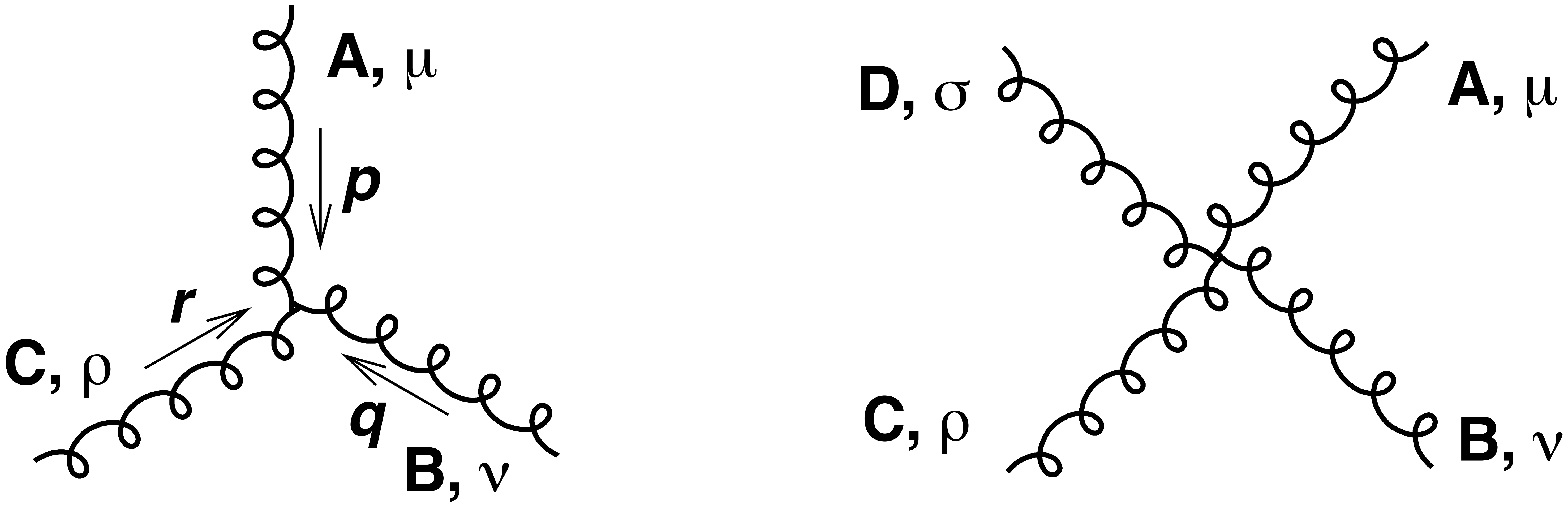
$$\lambda^5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}, \lambda^6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \lambda^7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix}, \lambda^8 = \begin{pmatrix} \frac{1}{\sqrt{3}} & 0 & 0 \\ 0 & \frac{1}{\sqrt{3}} & 0 \\ 0 & 0 & \frac{-2}{\sqrt{3}} \end{pmatrix},$$

quantum chromodynamics (QCD)

Field tensor: $F^A_{\mu\nu} = \partial_\mu \mathcal{A}^A_\nu - \partial_\nu \mathcal{A}^A_\nu - g_s f_{ABC} \mathcal{A}^B_\mu \mathcal{A}^C_\nu$ $\quad [t^A, t^B] = i f_{ABC} t^C$

f_{ABC} are structure constants of $SU(3)$ (antisymmetric in all indices — $SU(2)$ equivalent was ϵ^{ABC}). Needed for gauge invariance of gluon part of Lagrangian:

$$\mathcal{L}_G = -\frac{1}{4} F^{\mu\nu}_A F^{A\,\mu\nu}$$



quantum chromodynamics (QCD)

The only complete solution uses **lattice QCD**

- put all quark & gluon fields on a 4d lattice (NB: imaginary time)
- Figure out most likely configurations (Monte Carlo sampling)

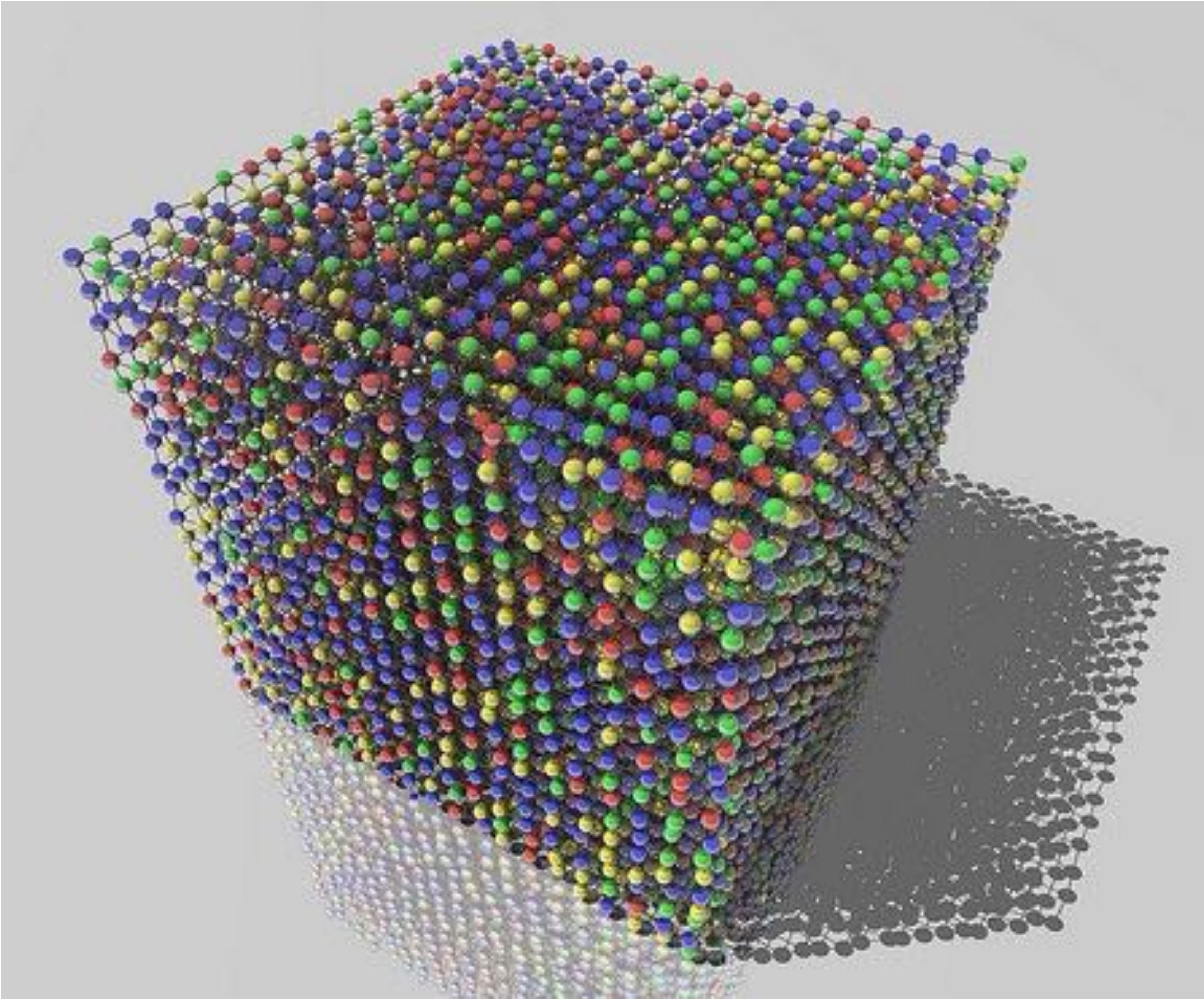


image credit fdecomite [flickr]

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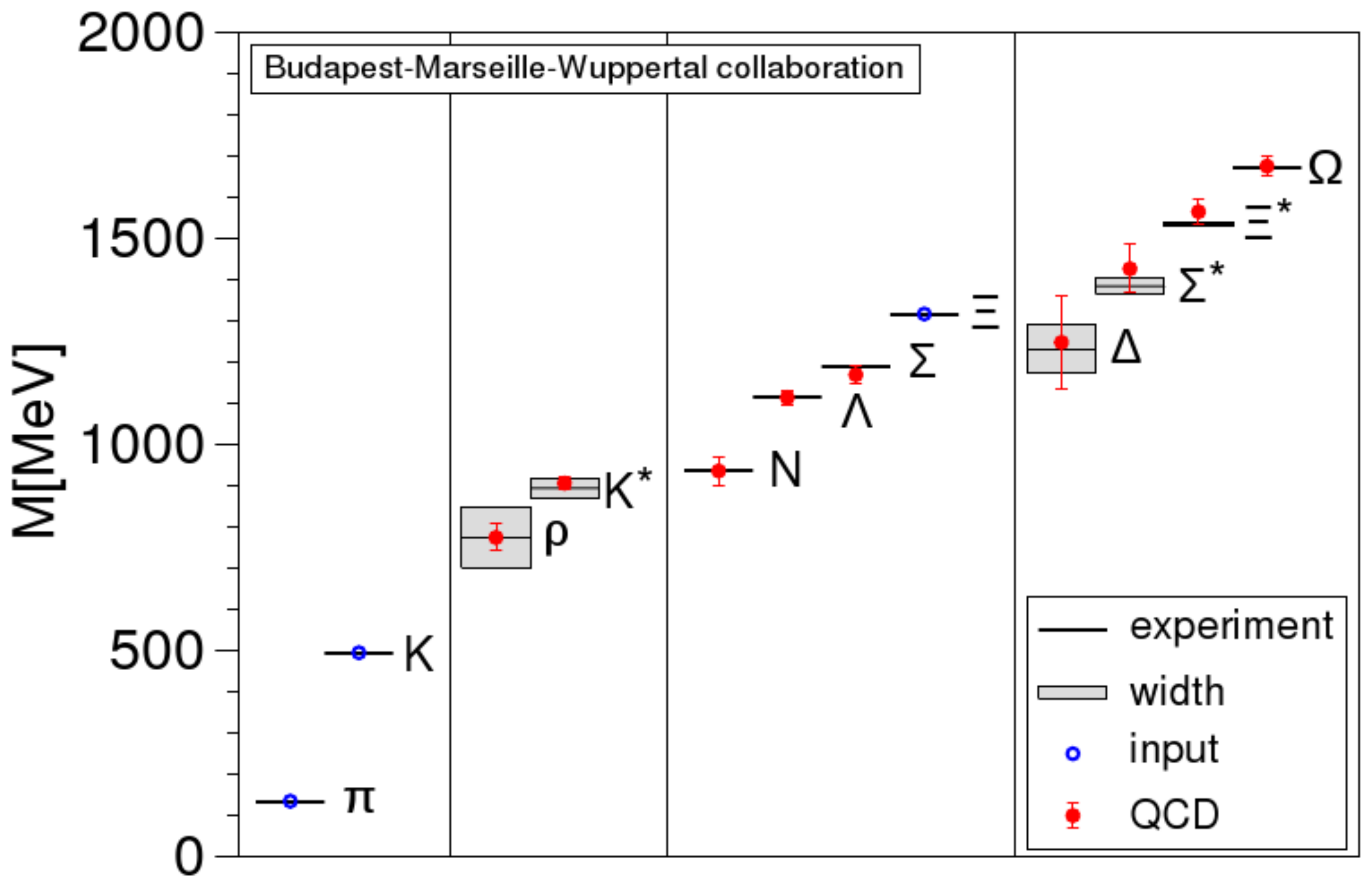
hadron spectrum from lattice QCD



Durr et al, arXiv:0906.3599

For LHC reactions, lattice would have to

- ➤ Resolve smallest length scales (2 TeV ~ 10^{-4} fm)
- ➤ Contain whole reaction (pion formed on timescale ~ 1fm, with boost of 10^4 — i.e. 10^4 fm)

That implies 10^8 nodes in each dimension, i.e. 10^{32} nodes — **inconceivable**

the strong coupling, α_s

it feeds into everything else in collider QCD

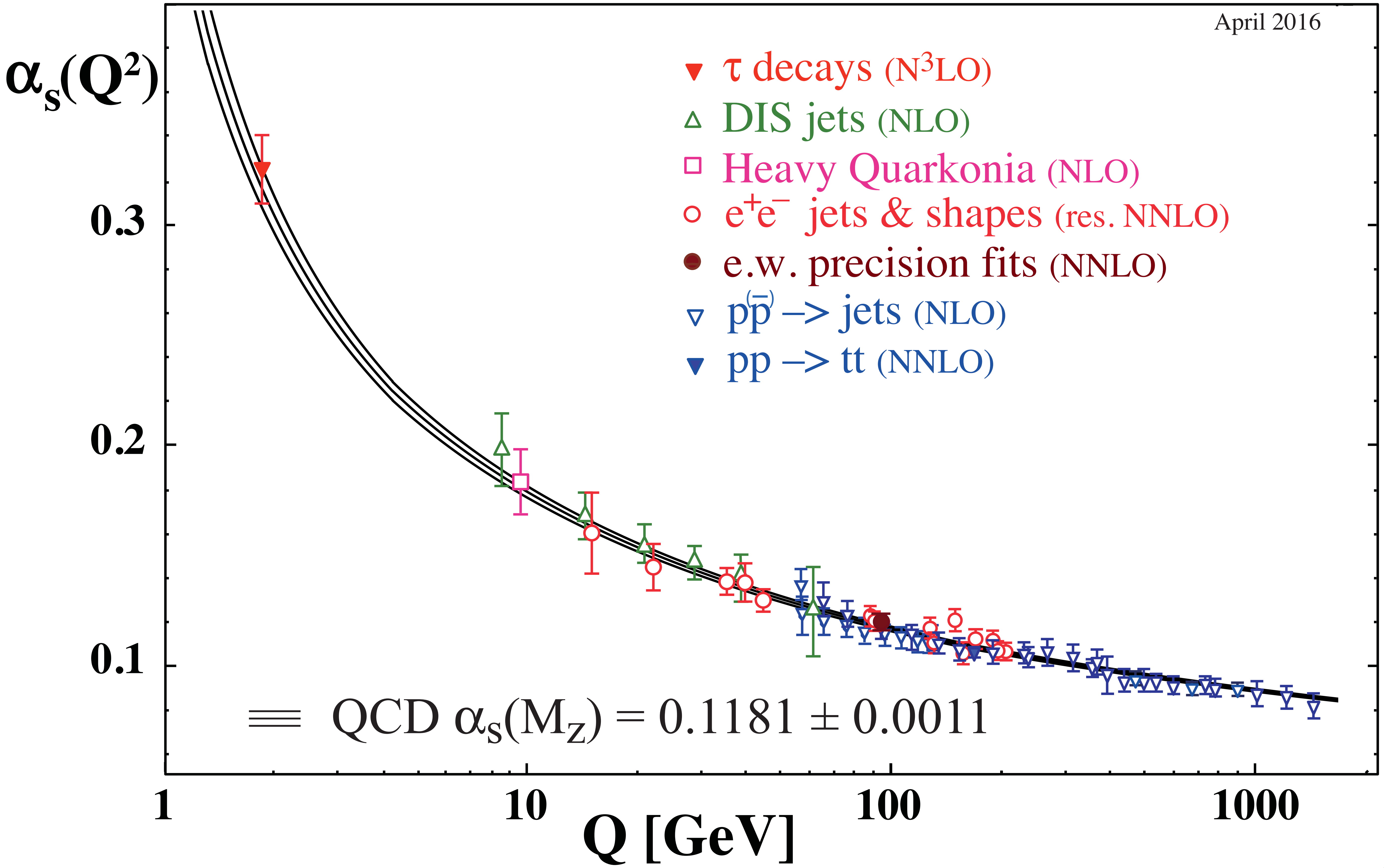
for more info see arXiv:1712.05165, arXiv:1902.08191

All couplings run: the QCD coupling runs fastest

$$\text{Solve} \quad Q^2 \frac{d\alpha_s}{dQ^2} \simeq -b_0 \alpha_s^2 \;\Rightarrow\; \alpha_s(Q^2) \simeq \frac{\alpha_s(Q_0^2)}{1 + b_0 \alpha_s(Q_0^2) \ln \frac{Q^2}{Q_0^2}} = \frac{1}{b_0 \ln \frac{Q^2}{\Lambda^2}}$$

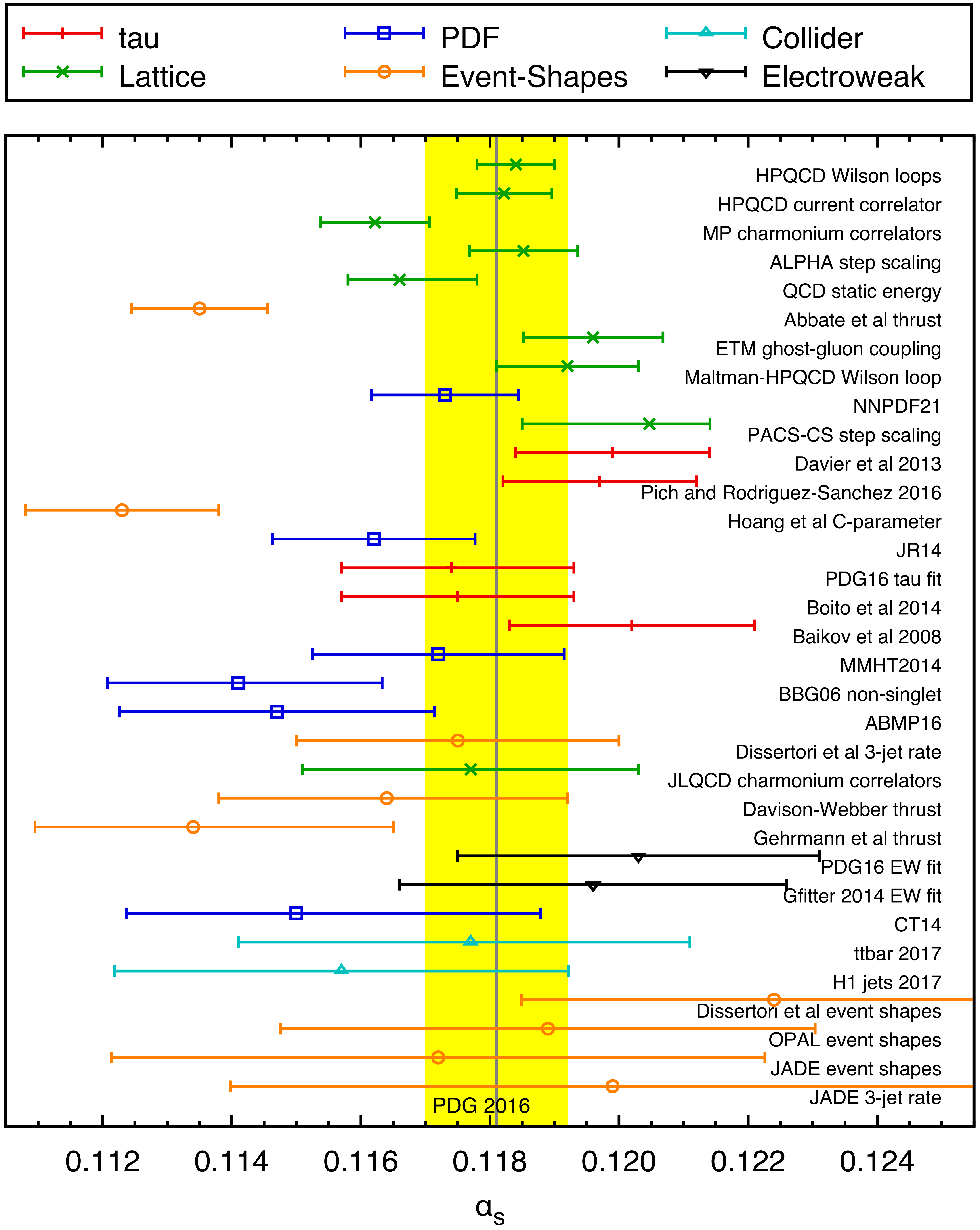
$\Lambda \simeq 0.2$ GeV (aka Λ_{QCD}) is the fundamental scale of QCD, at which perturbative coupling blows up.

- it sets the mass scale for most hadrons
- perturbation theory only valid for $Q \gg \Lambda$, where α_s is small



PDG World Average:

$\alpha_s(M_Z) = 0.1181 \pm 0.0011$ (0.9%)



strong-coupling determinations

Bethke, Dissertori & GPS in PDG '16

- Most consistent set of independent determinations is from lattice
- Two determinations with smallest errors are from same group (HPQCD, 1004.4285, 1408.4169)
  $\alpha_s(M_Z) = 0.1183 \pm 0.0007$ (0.6%) [heavy-quark correlators]
  $\alpha_s(M_Z) = 0.1183 \pm 0.0007$ (0.6%) [Wilson loops]
- Many determinations quote small uncertainties ($\lesssim$1%). Most are disputed!
- Most robust is perhaps ALPHA lattice result
  $\alpha_s(M_Z) = 0.1185 \pm 0.00084$ (0.7%)
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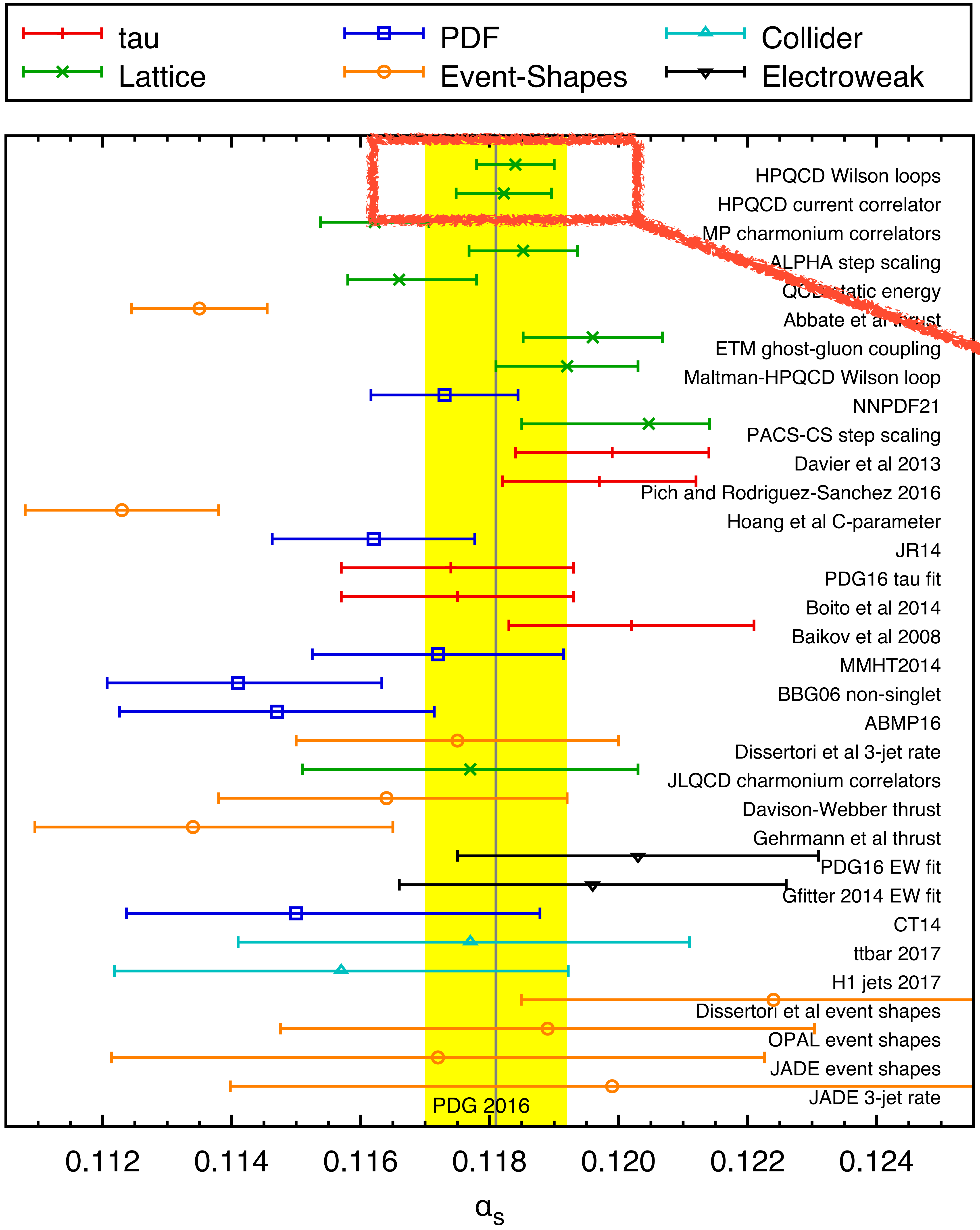
strong-coupling determinations



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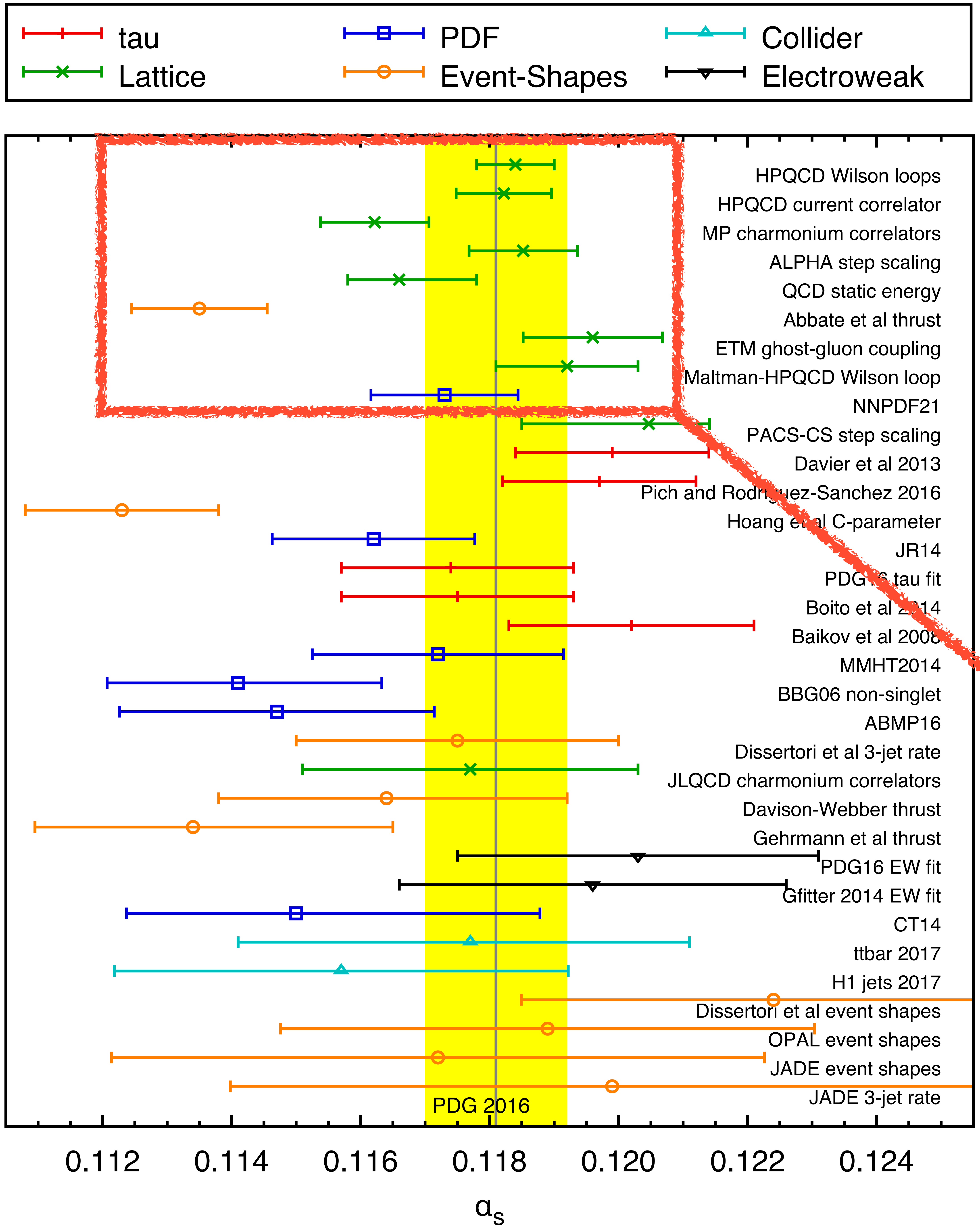

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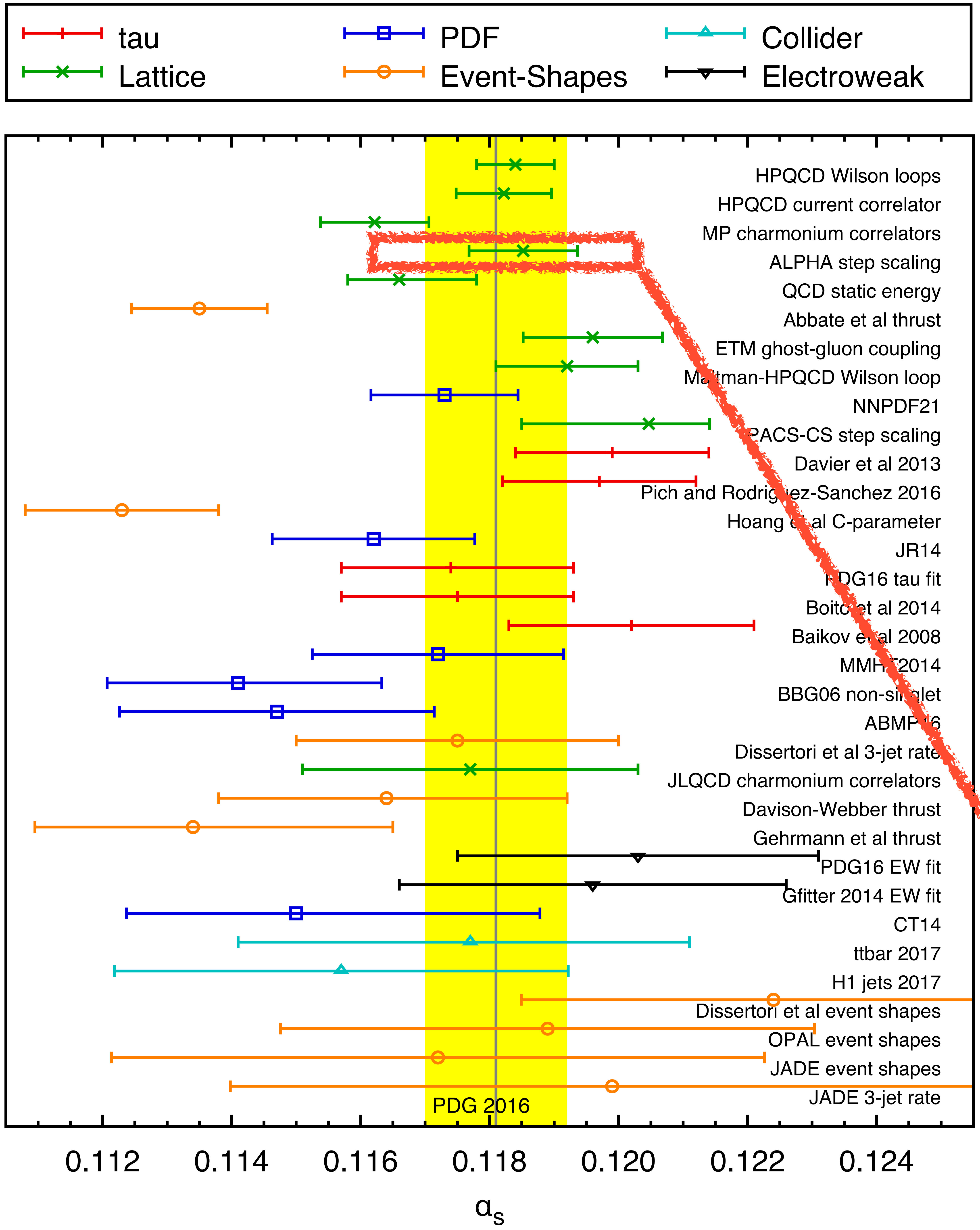

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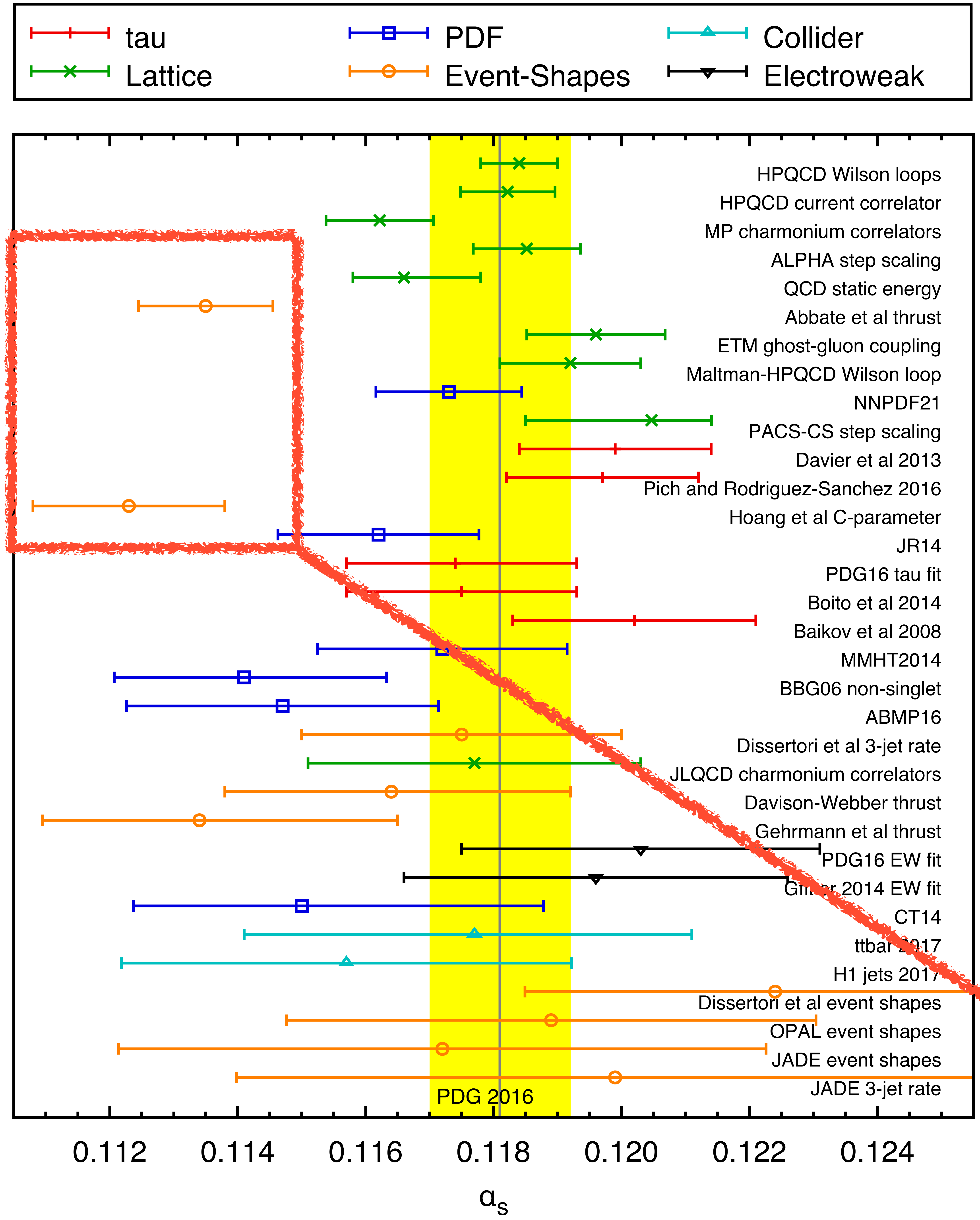

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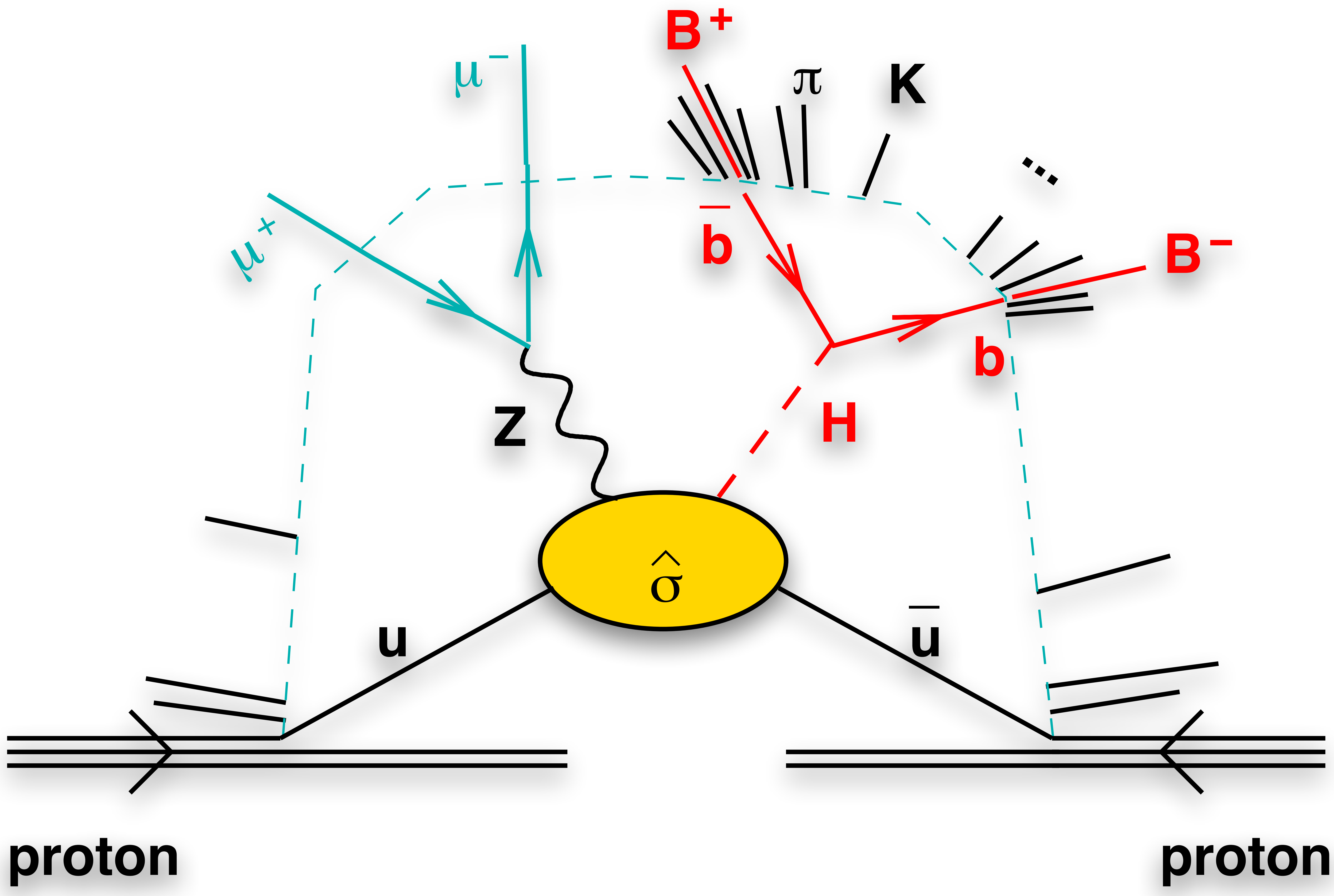
factorisation

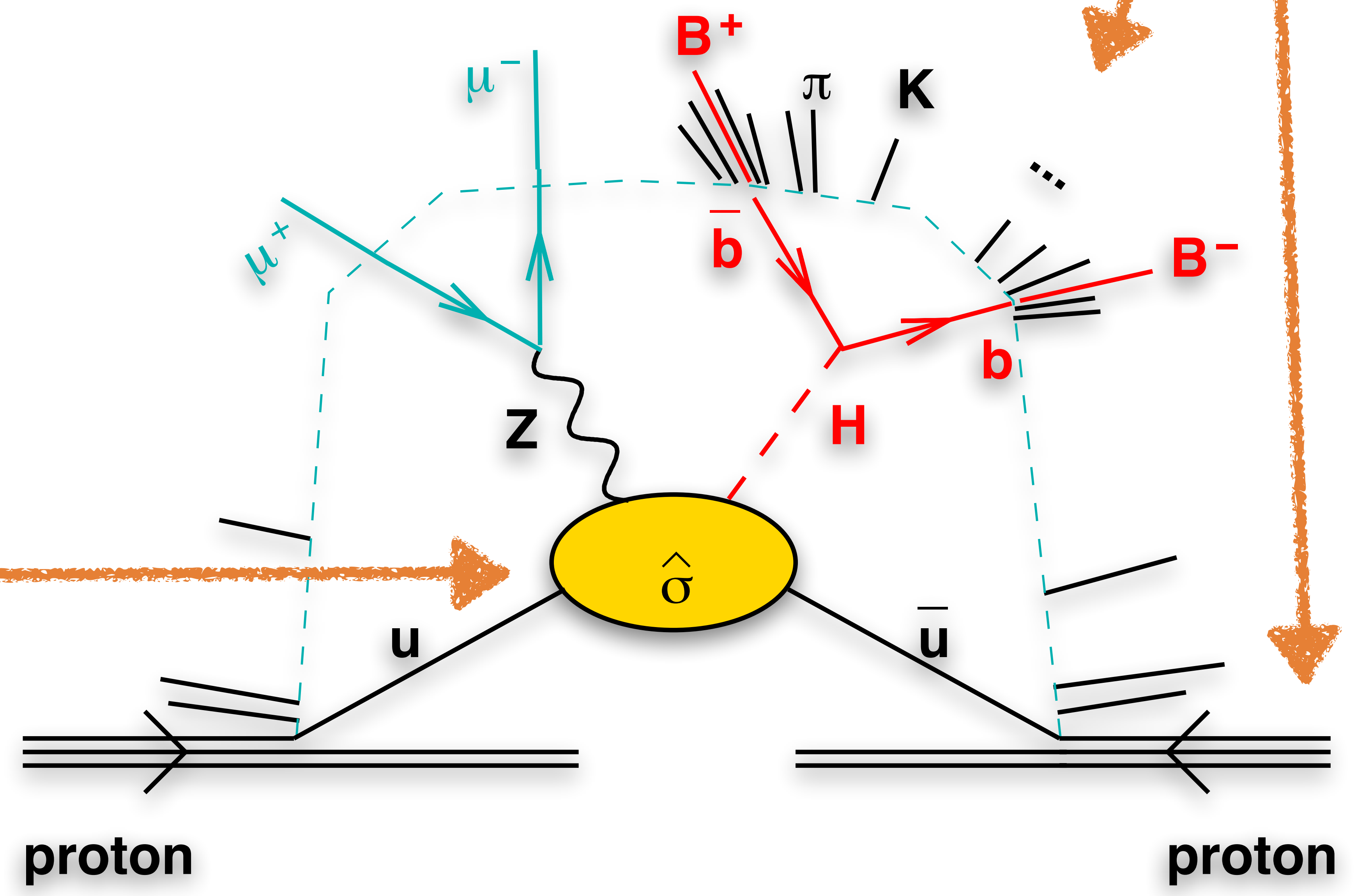
and perturbative expansions

a proton–proton collision: FILLING IN THE PICTURE



Why is simplification "allowed"? key idea #1 FACTORISATION

- Proton's dynamics occurs on timescale O(1–10^4 fm/c)
  Final-state hadron dynamics occurs on timescale O(1–10^4 fm/c)
- Production of Higgs, Z (and other "**hard processes**") occurs on timescale $1/M_H \sim 1/125$ GeV ~ 0.002 fm/c



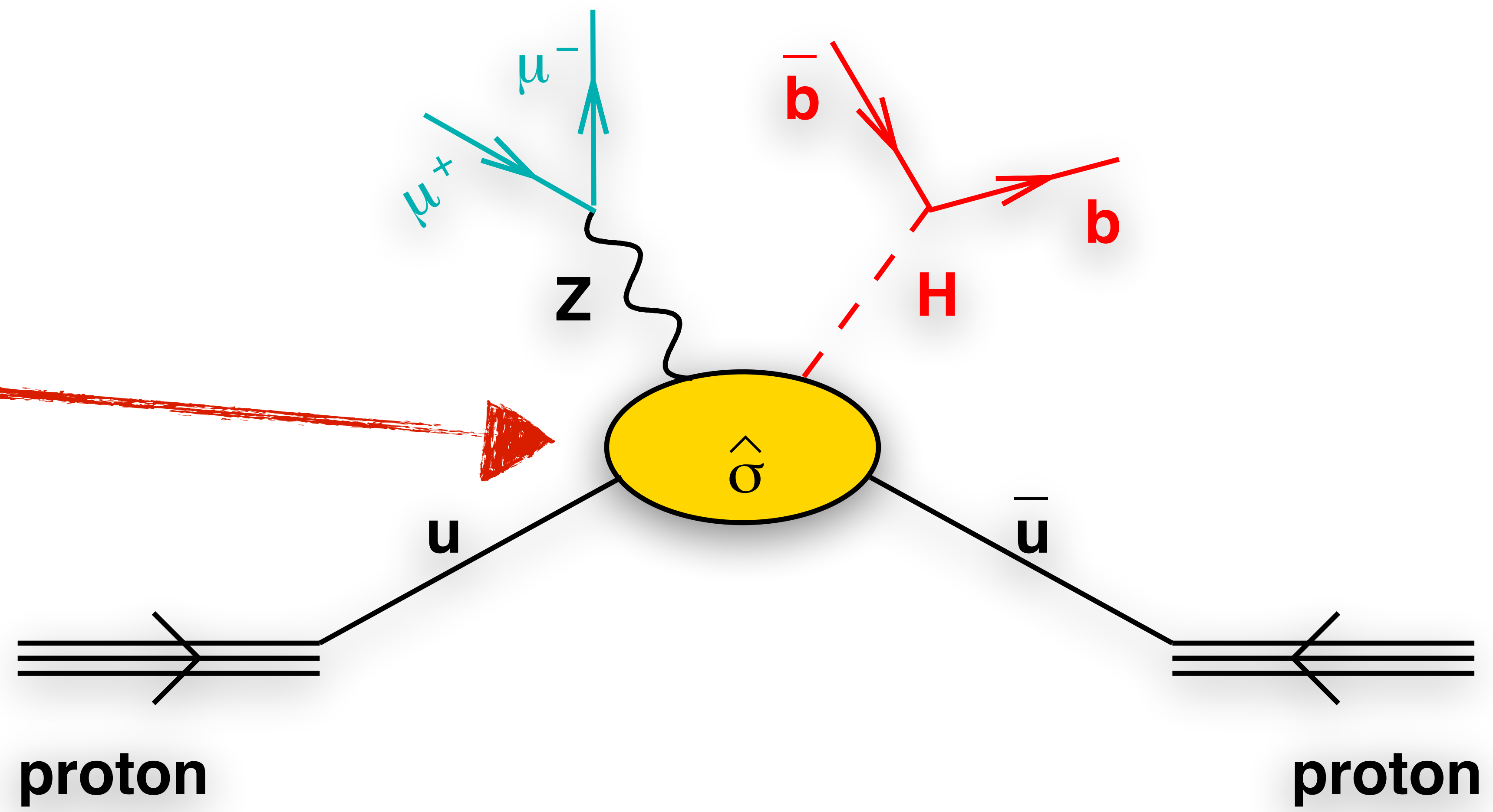
That means we can separate — **"factorise"** — the hard process, i.e. treat it as independent from all the hadronic dynamics

Why is simplification "allowed"? key idea #2 USE PERTURBATION THEORY

- On timescales $1/M_H \sim 1/125$ GeV ~ 0.002 fm you can take advantage of **asymptotic freedom**
- i.e. you can write results in terms of an expansion in the (*not so*) strong coupling constant $\alpha_s(125 \text{ GeV}) \sim 0.11$

$$\hat{\sigma} = \hat{\sigma}_0 (1 + c_1 \alpha_s + c_2 \alpha_s^2 + \cdots)$$

LO
(Leading Order)



Why is simplification "allowed"? key idea #2 short-distance QCD corrections are perturbative

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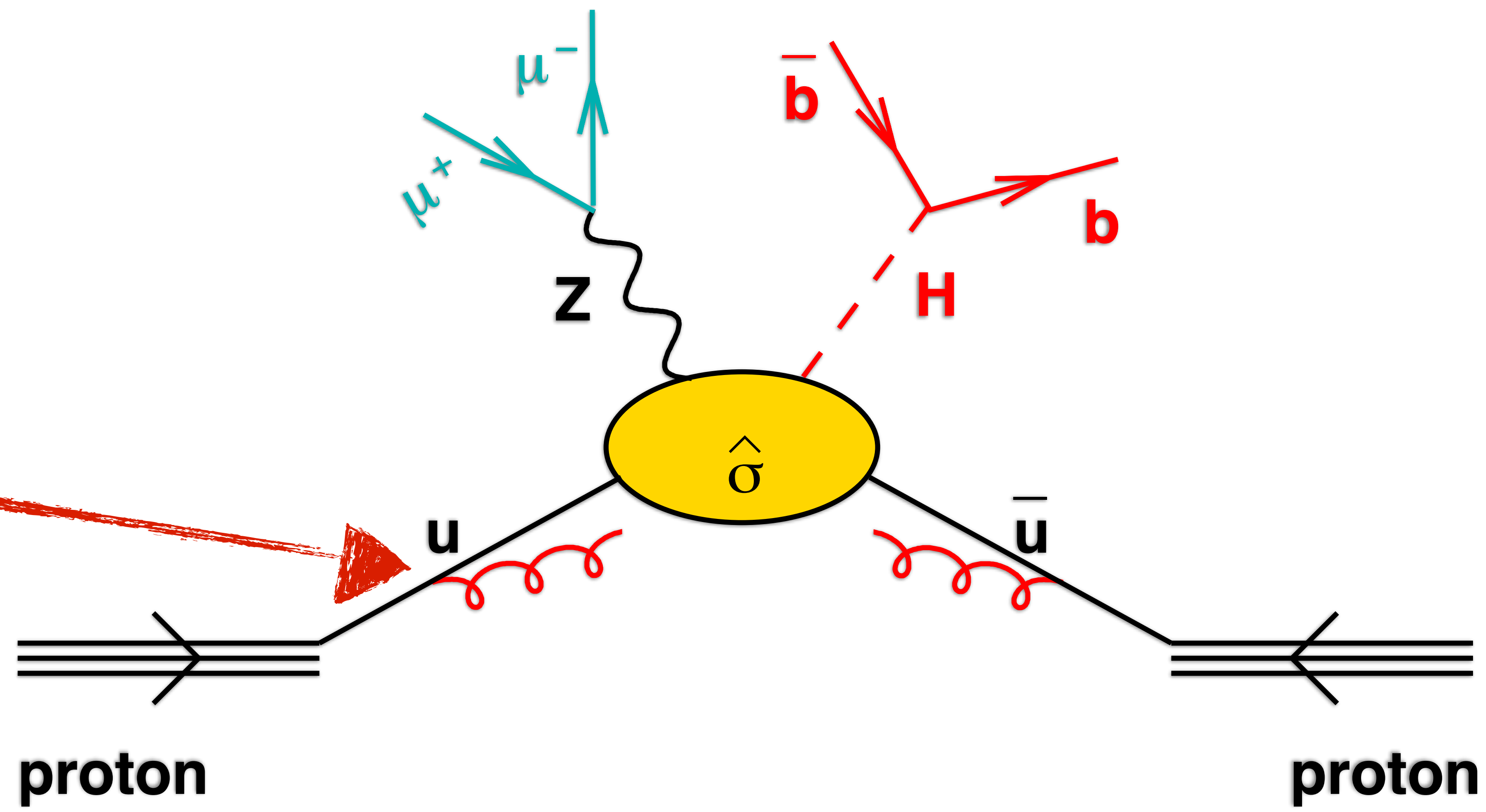
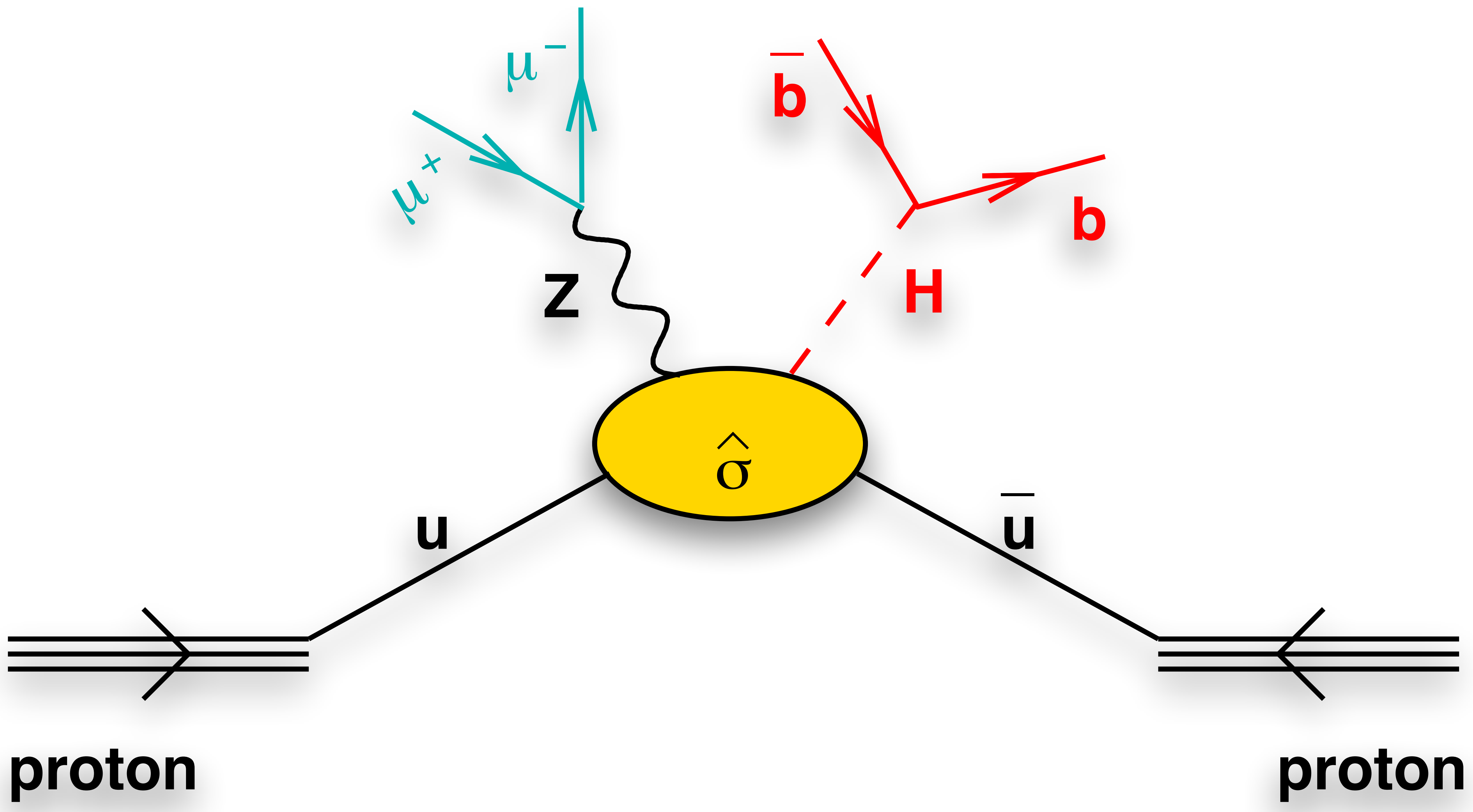
NNLO
(Next-to-next-to-Leading Order)



the master equation

$$\sigma\left(h_1 h_2 \to ZH + X\right) = \sum_{n=0}^{\infty} \alpha_s^n\left(\mu_R^2\right) \sum_{i,j} \int dx_1 dx_2\, f_{i/h_1}\left(x_1, \mu_F^2\right) f_{j/h_2}\left(x_2, \mu_F^2\right)$$

$$\times\, \hat{\sigma}^{(n)}_{ij\to ZH+X}\left(x_1 x_2 s, \mu_R^2, \mu_F^2\right) + \mathcal{O}\left(\frac{\Lambda^2}{M_W^4}\right),$$



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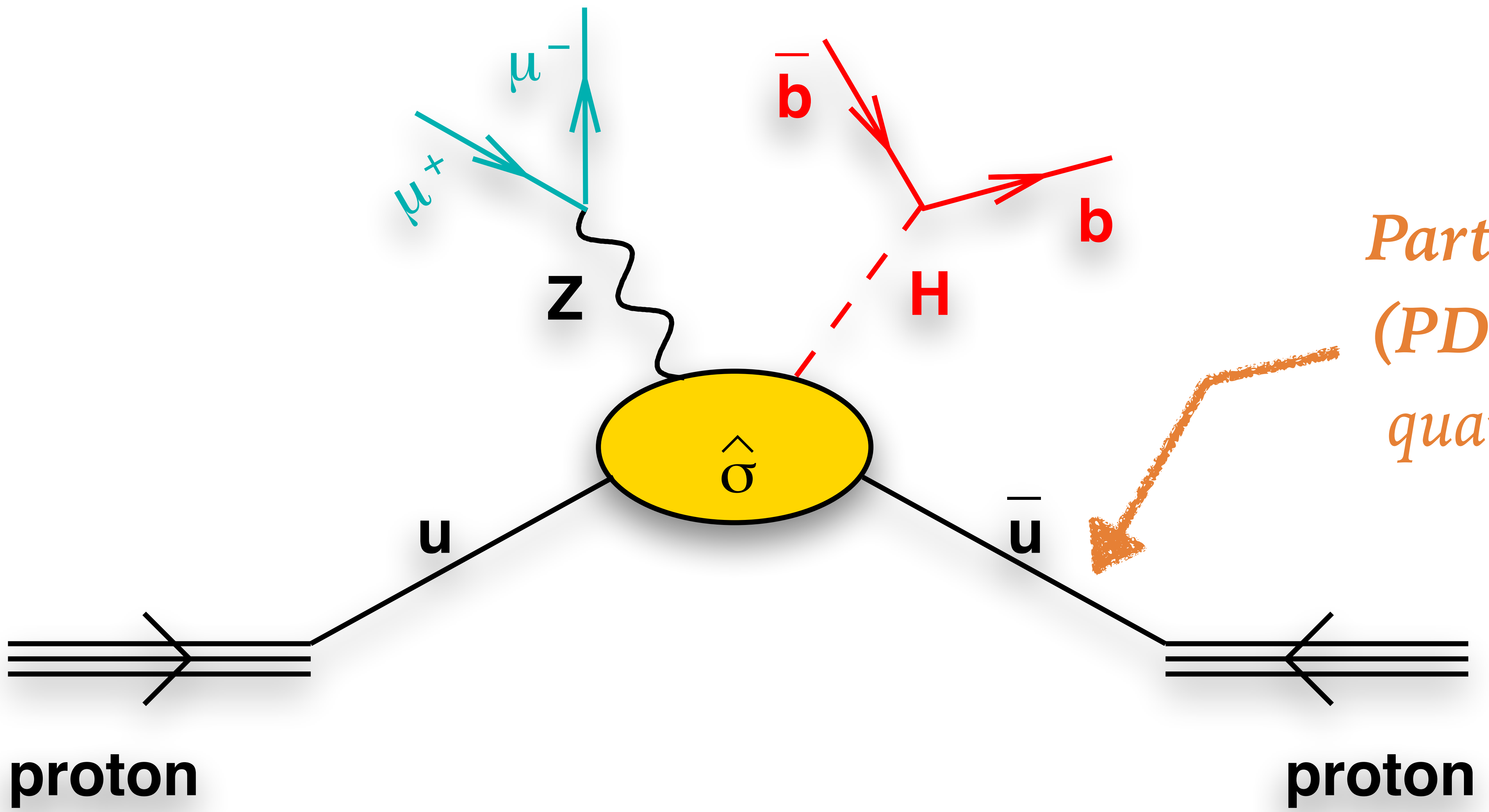

Parton distribution function (PDF): e.g. number of up anti-quarks carrying fraction x_2 of proton's momentum

the master equation

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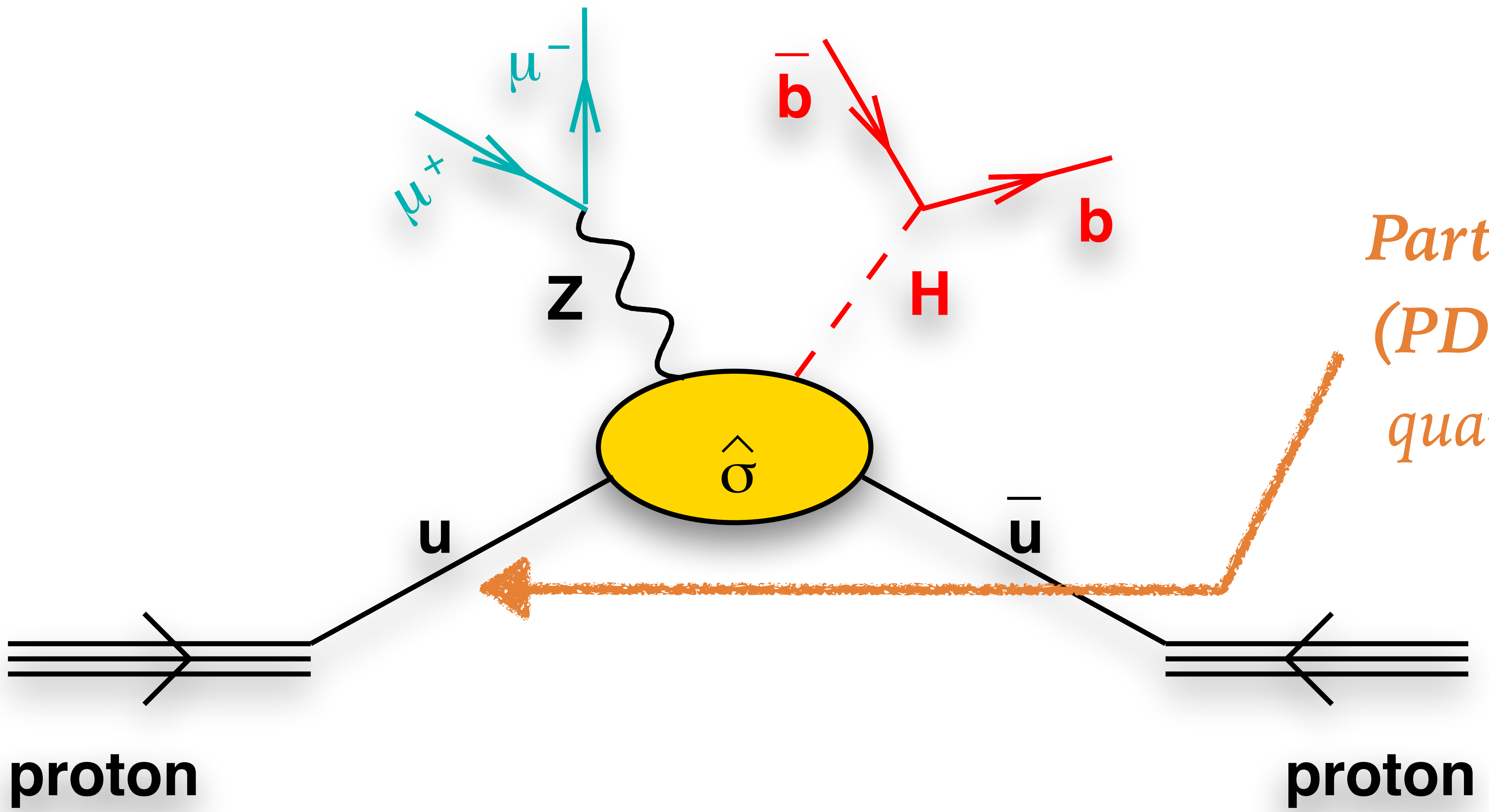

Parton distribution function (PDF): e.g. number of up quarks carrying fraction x_1 of proton's momentum

the master equation

Perturbative sum over powers of the strong coupling: typically we use first 2-4 orders

$$\sigma\left(h_1 h_2 \to ZH + X\right) = \sum_{n=0}^{\infty} \alpha_s^n\left(\mu_R^2\right) \sum_{i,j} \int dx_1 dx_2\, f_{i/h_1}\left(x_1, \mu_F^2\right) f_{j/h_2}\left(x_2, \mu_F^2\right)$$

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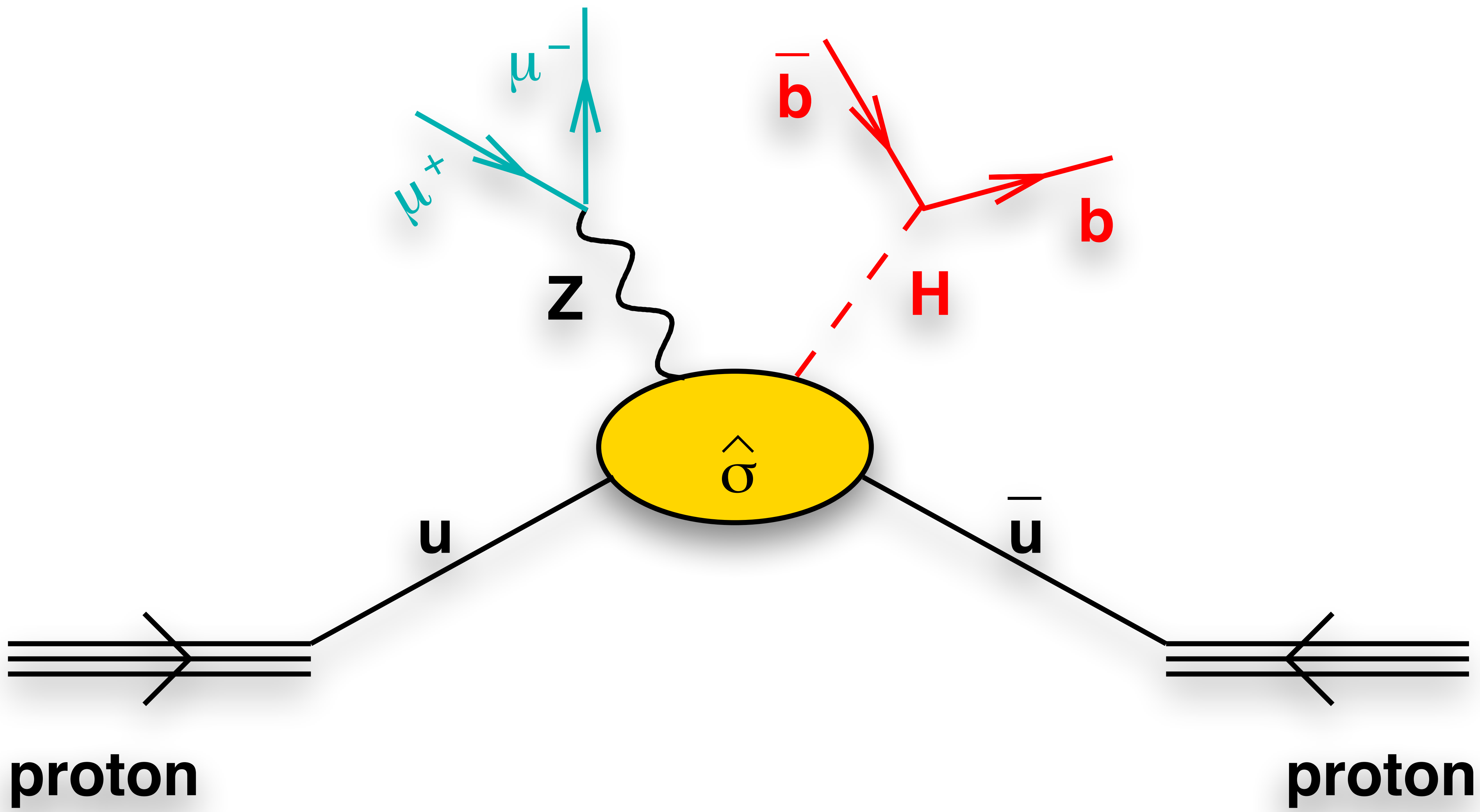

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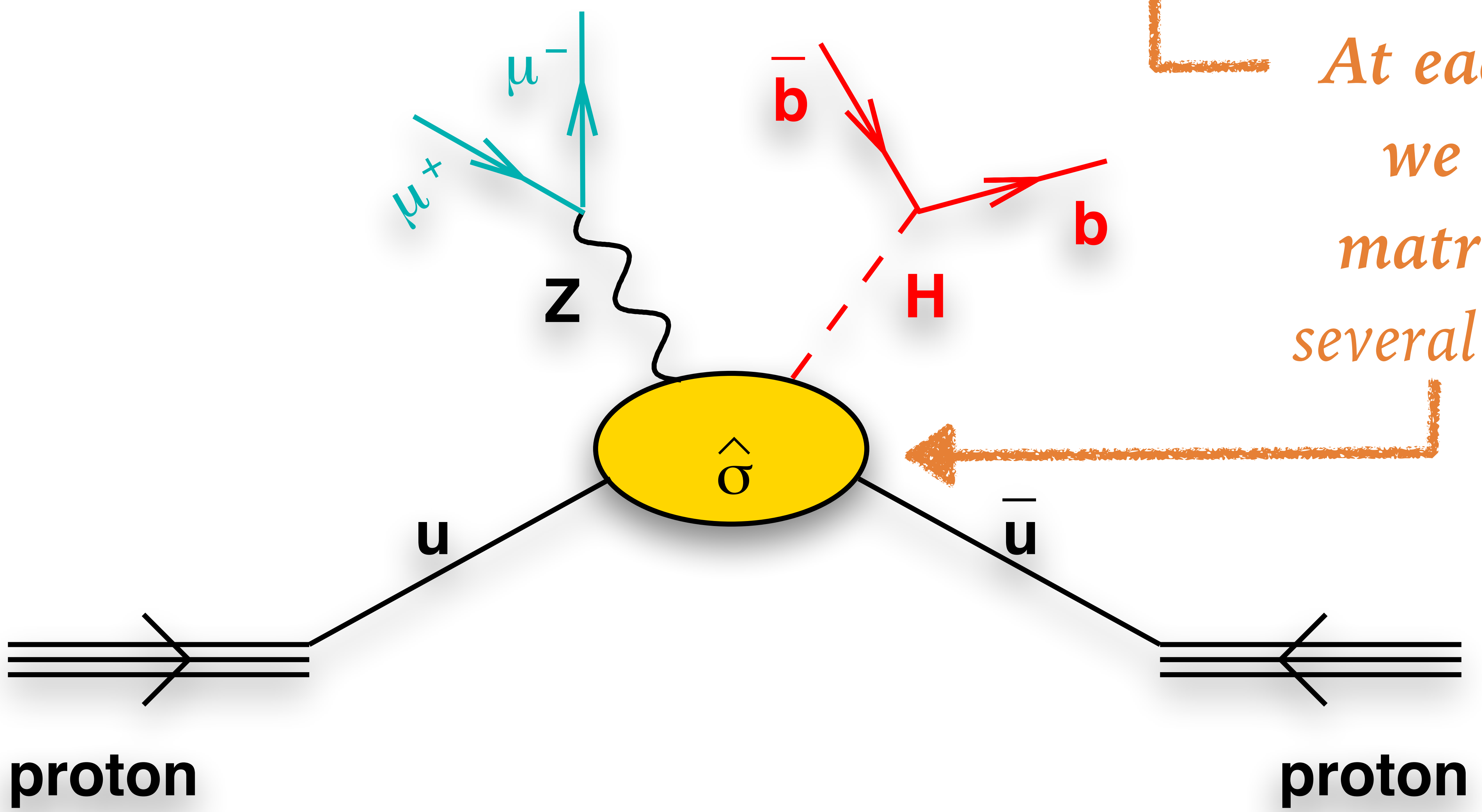
At each perturbative order n we have a specific "hard matrix element" (sometimes several for different subprocesses)



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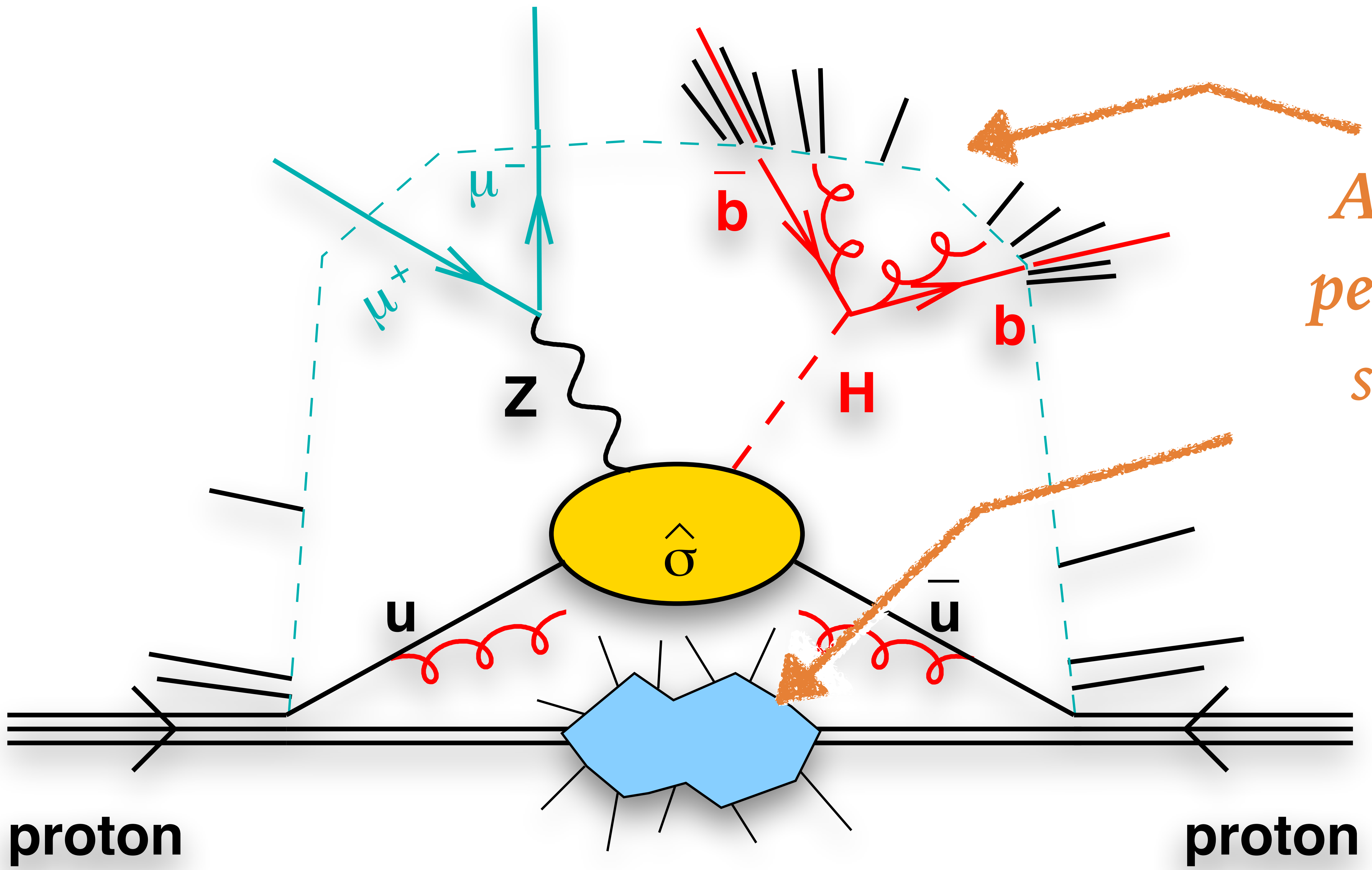
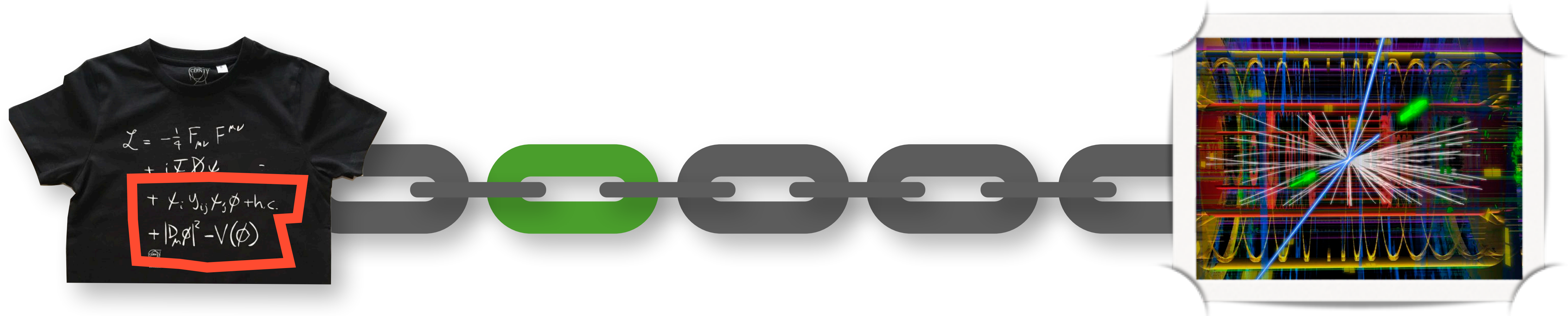


Additional corrections from non-perturbative effects: higher "twist", suppressed by powers of QCD scale (Λ) / hard scale

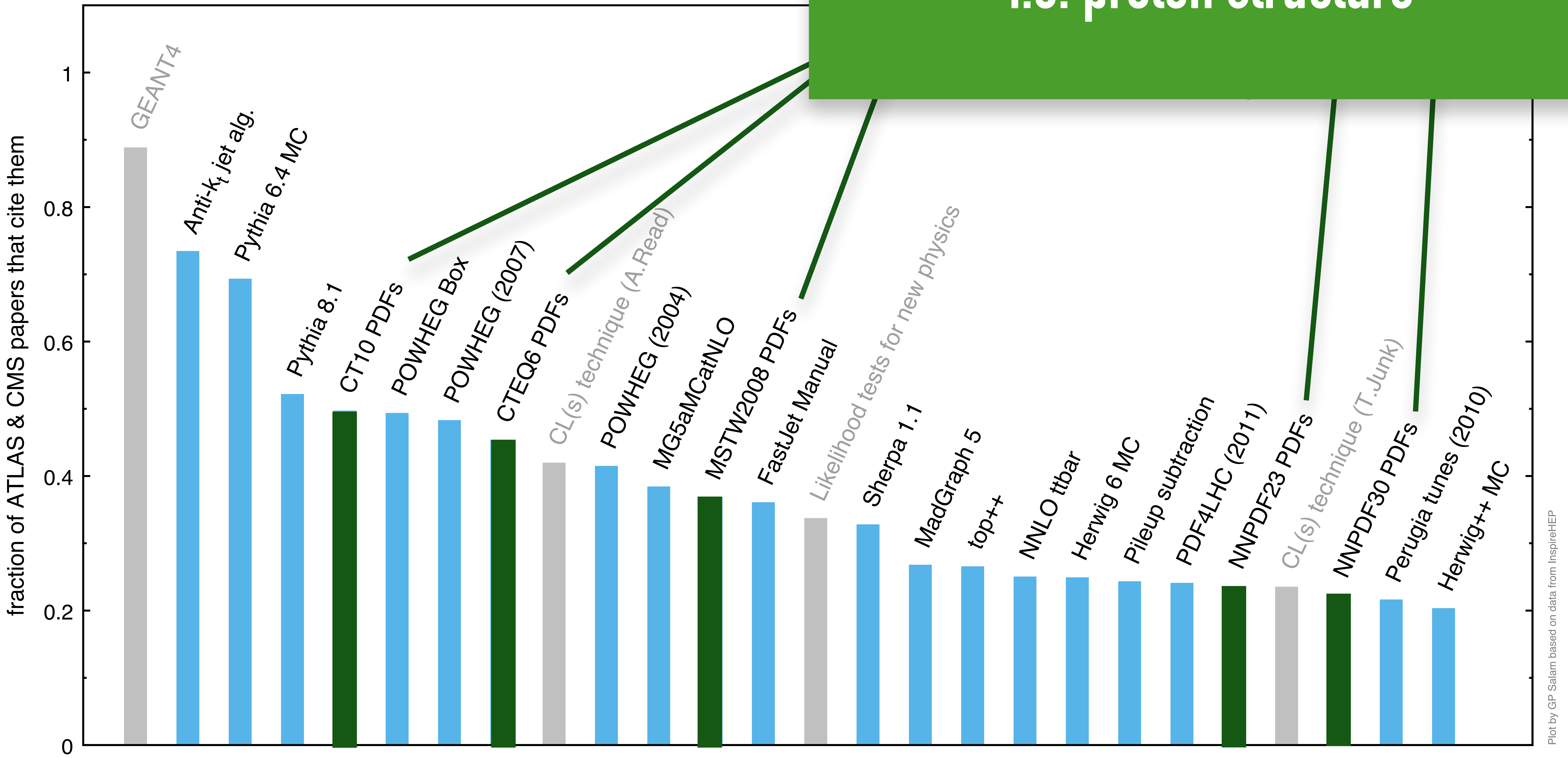
parton distribution functions (PDFs)

For visualisations of PDFs and related quantities,
a good place to start is

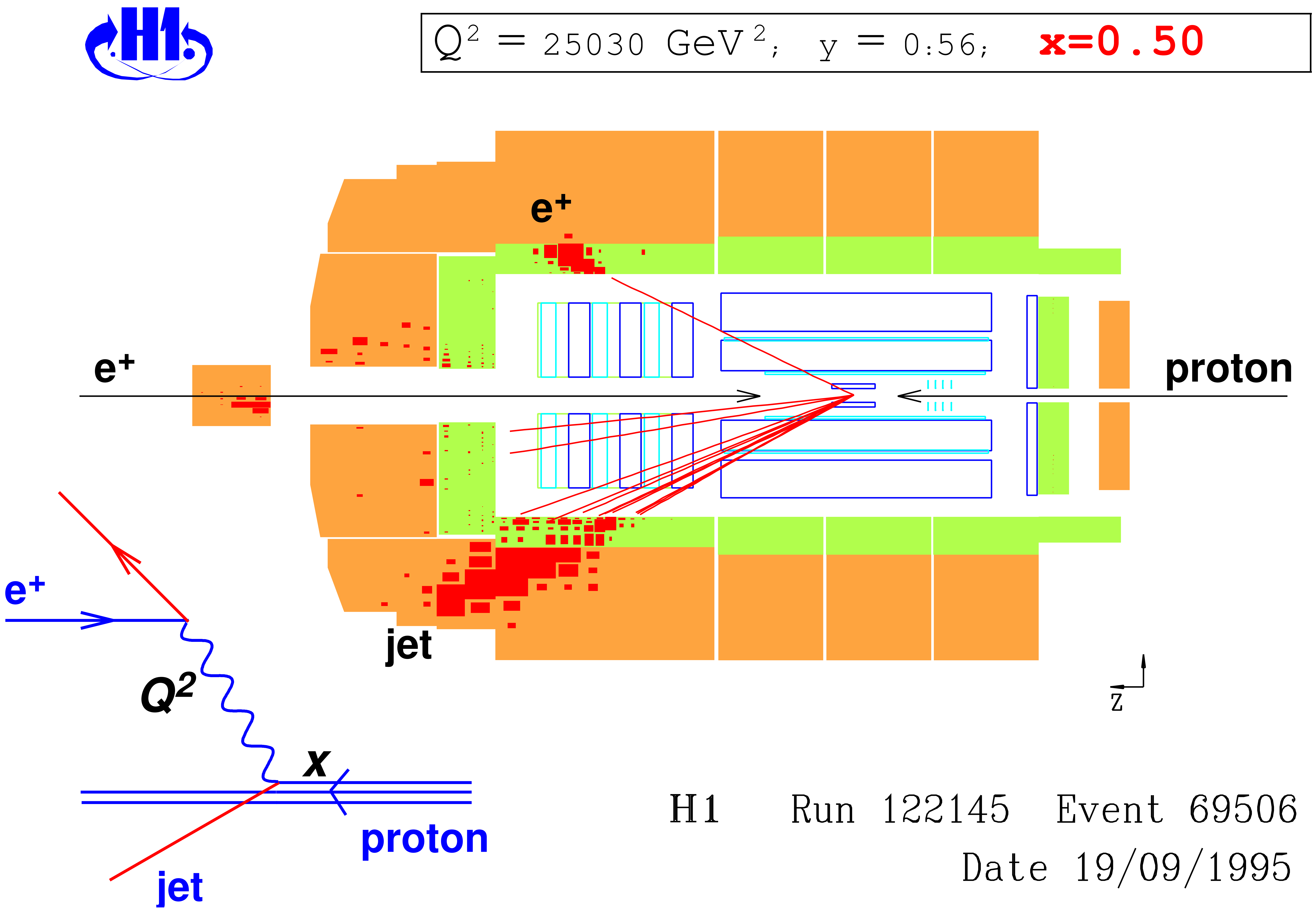
http://apfel.mi.infn.it/ (ApfelWeb)



knowing what goes into a collision
i.e. proton structure



Deep Inelastic Scattering — the simpler context to determine PDFs



two major kinematic variables:

x ≃ longitudinal momentum fraction of struct quark

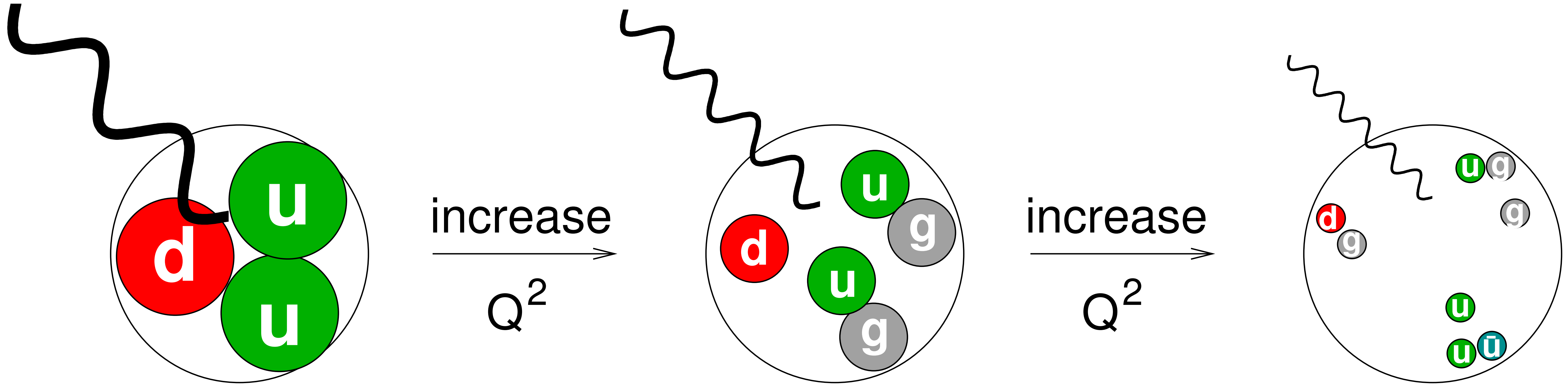
Q^2 ≃ photon virtuality → transverse resolution at which is probes proton structure

Parton distribution and DGLAP

- Write up-quark distribution in proton as

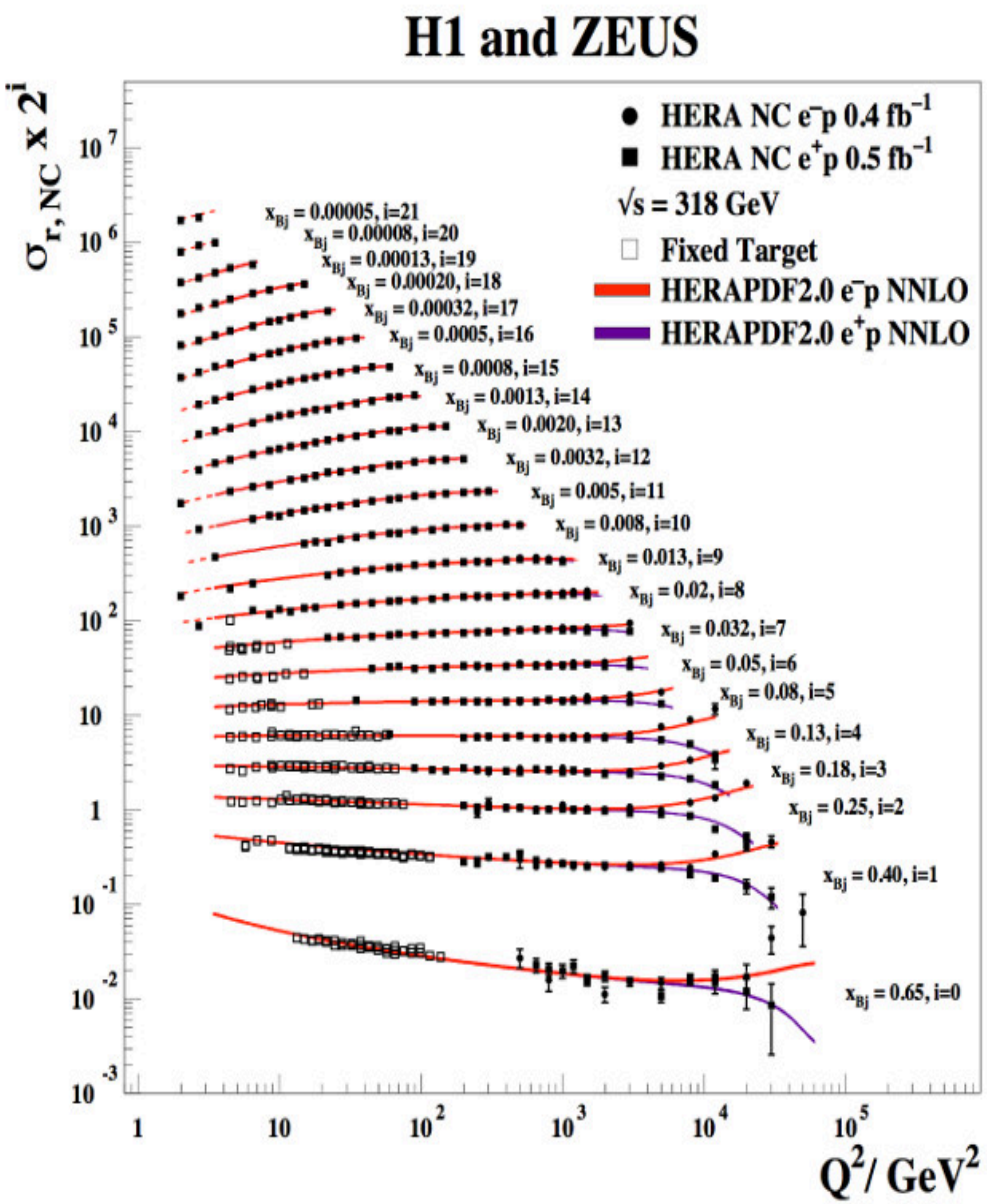
$$f_{u/p}(x, \mu_F^2)$$

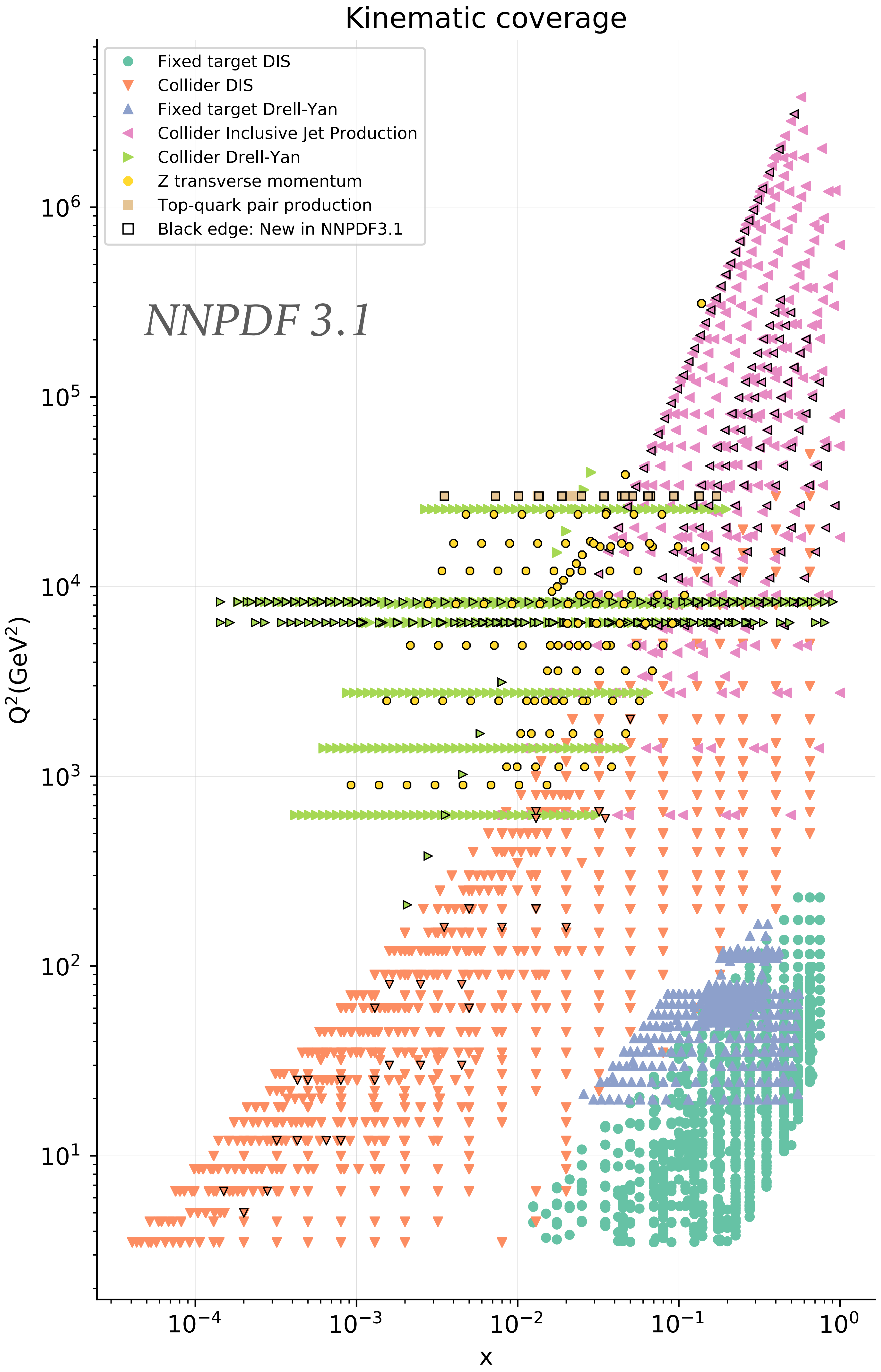
- μ_F is the **factorisation scale** — a bit like the renormalisation scale (μ_R) for the running coupling.
- As you vary the factorisation scale, the parton distributions evolve with a renormalisation-group type equation



Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equations

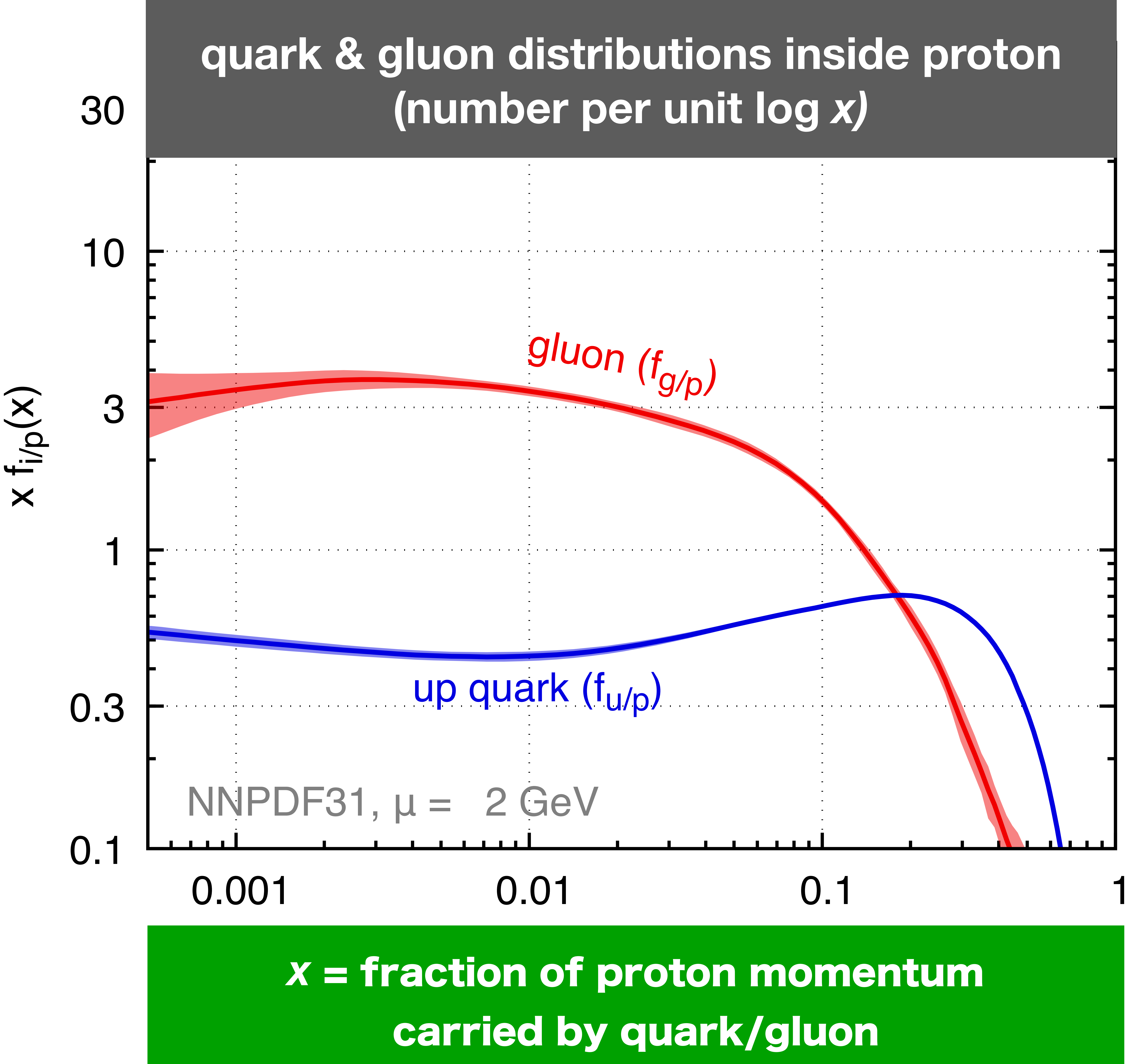
Today's PDF fits





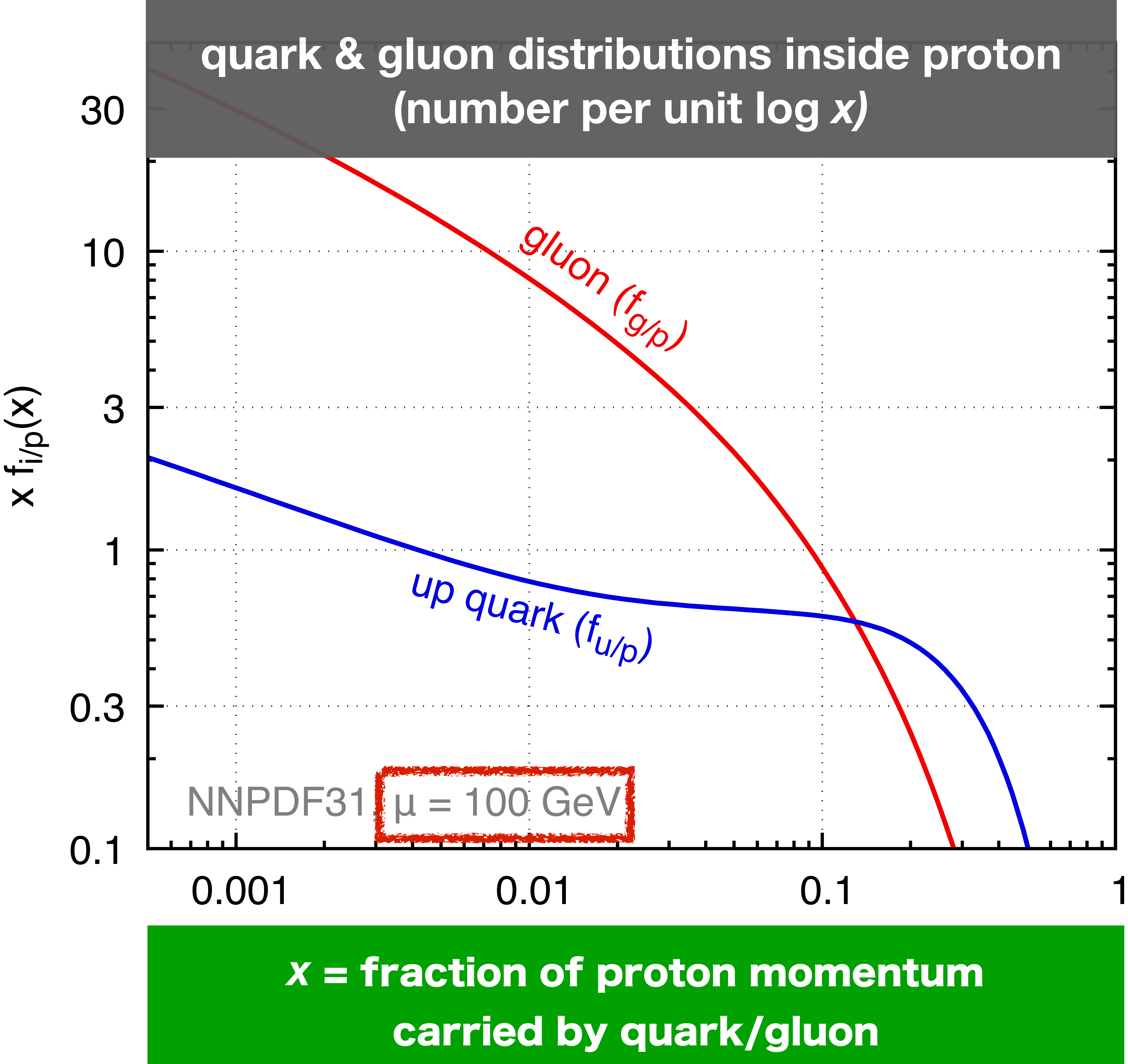
Today's PDF fits

- LHC EW physics probes $x \sim m_H/\sqrt{s} \sim 0.01$
- gluon distribution is ~ 10× larger than (up) quark distribution



Today's PDF fits

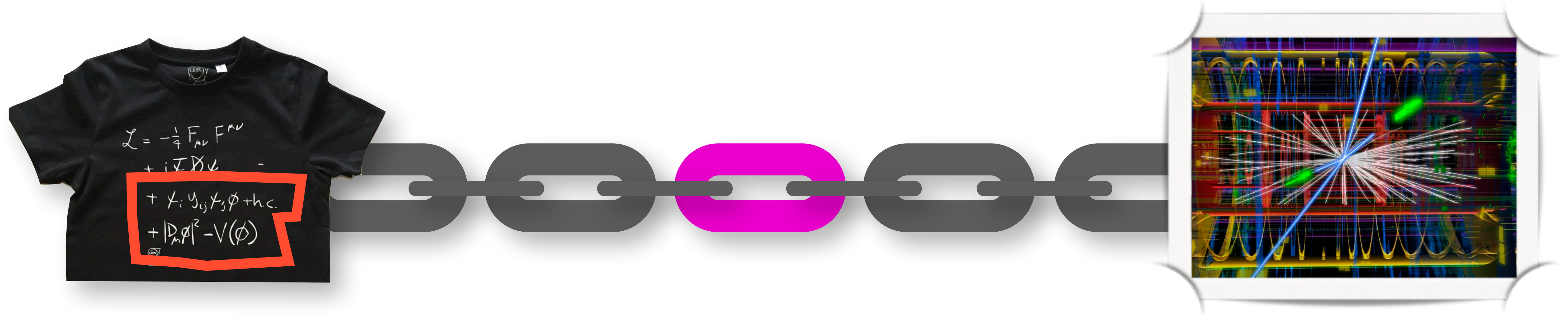
- LHC EW physics probes $x \sim m_{\mathrm{H}}/\sqrt{s} \sim 0.01$
- gluon distribution is ~ 10× larger than (up) quark distribution
- viewing proton at scales from 2 GeV to 100 GeV, DGLAP evolution modifies PDFs by ~ ×2–10



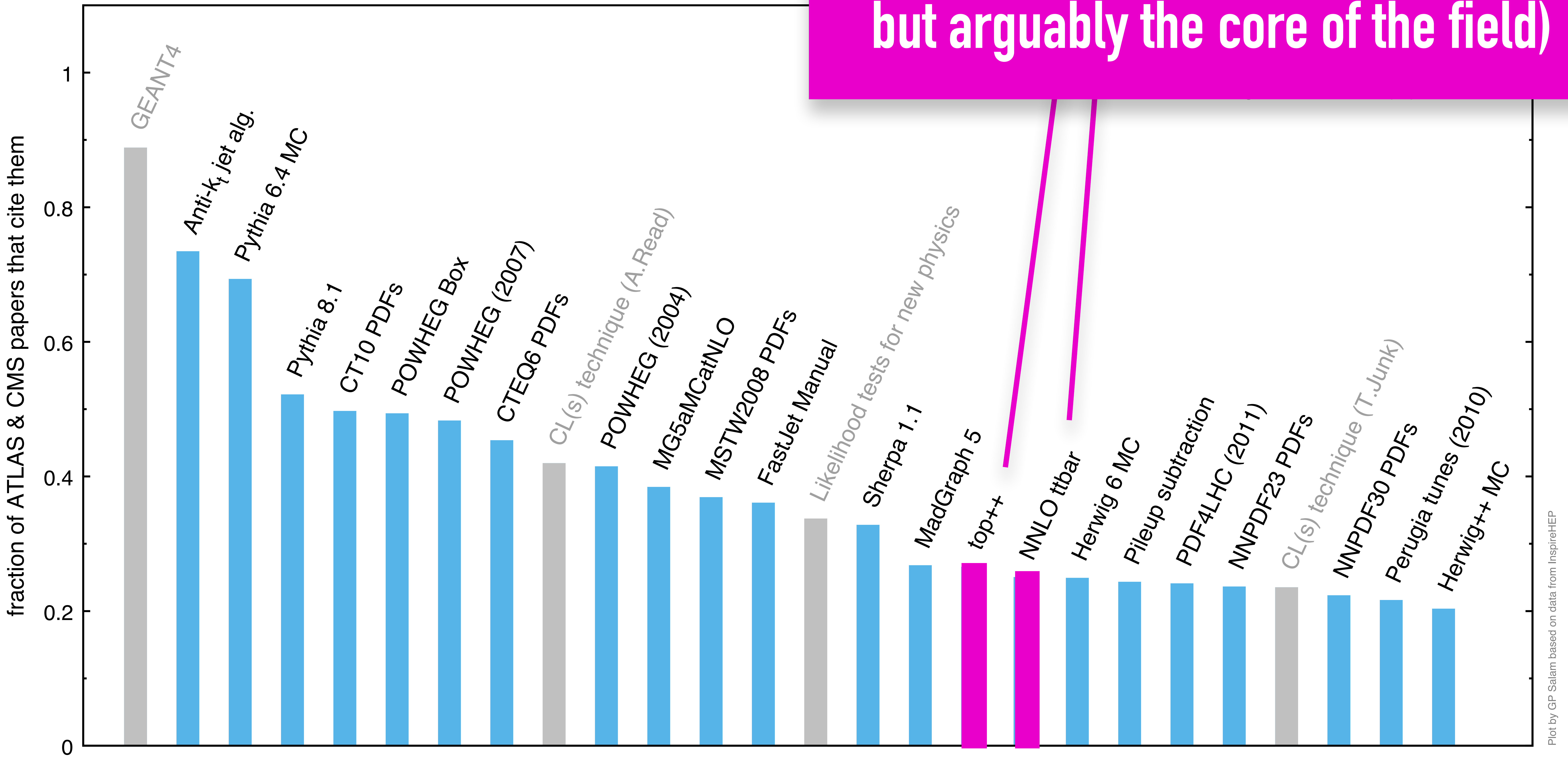
fixed-order calculations

$$\sigma \sim \sigma_2 \alpha_s^2 + \sigma_3 \alpha_s^3 + \sigma_4 \alpha_s^4 + \sigma_5 \alpha_s^5 + \cdots$$

LO NLO NNLO N3LO



fixed order calculations (only modestly represented in plot, but arguably the core of the field)

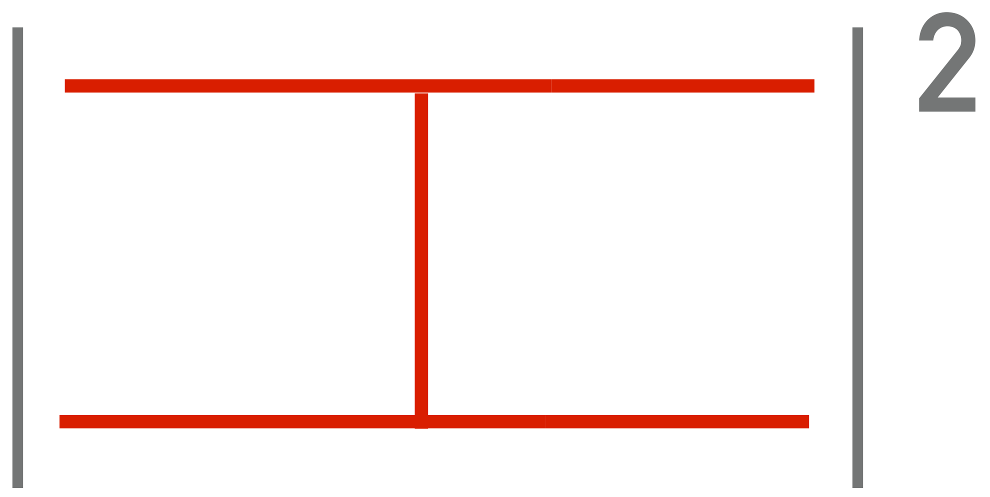


Ingredients for a calculation (generic 2→2 process)

LO

Tree

2→2

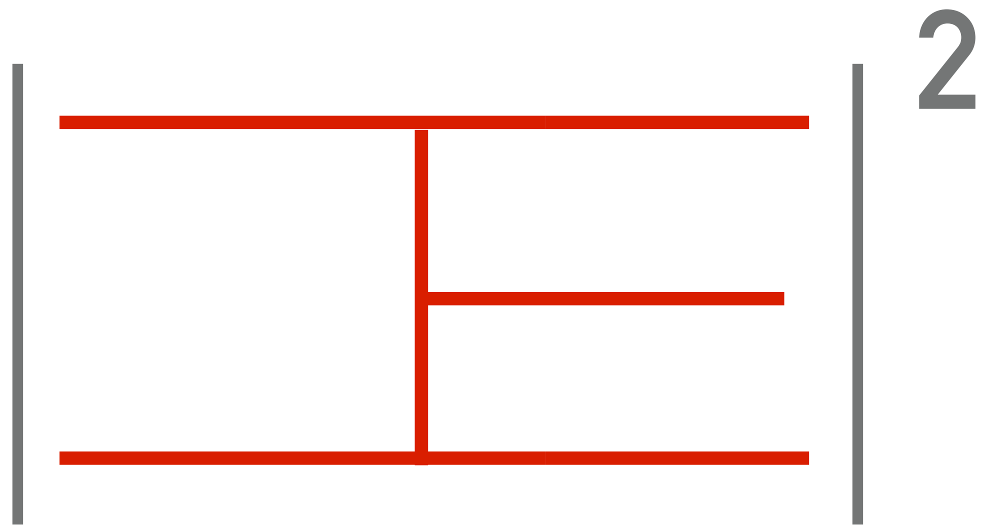


to illustrate the concepts, we don't care what the particles are — just draw lines

NLO

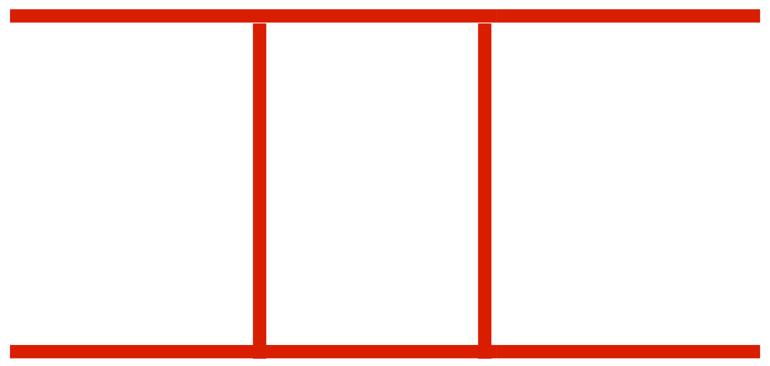
Tree

2→3

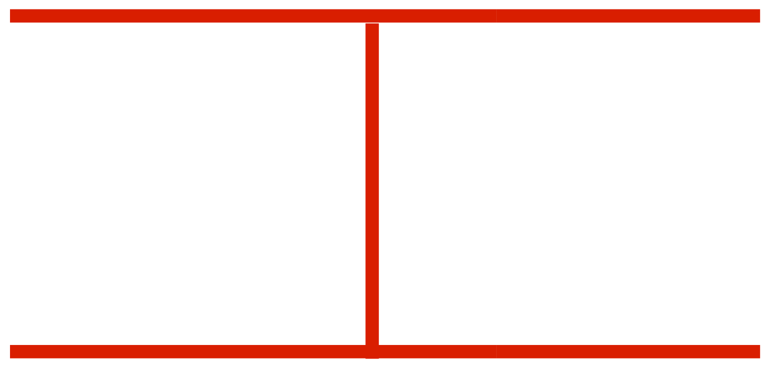


1-loop

2→2



$\times$

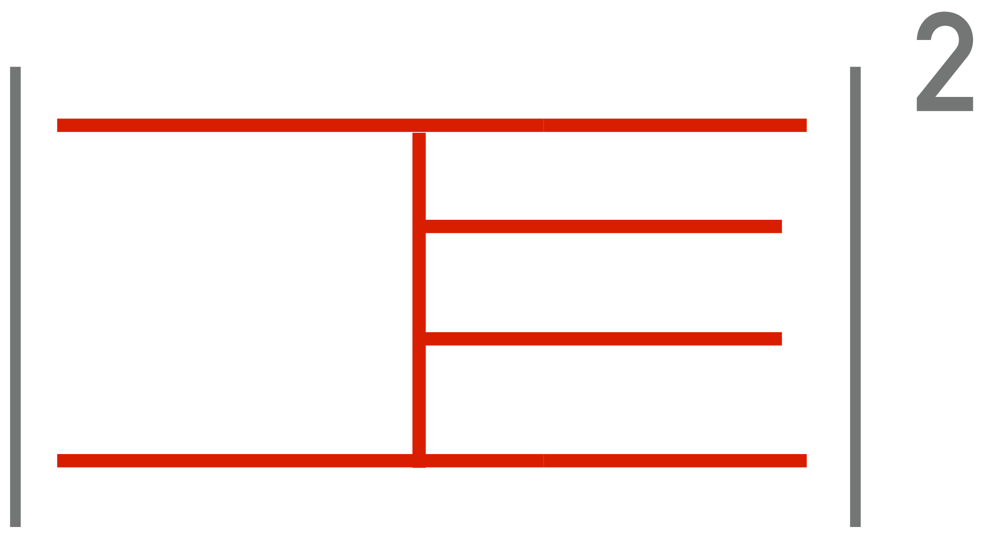


$+$ *complex conj.*

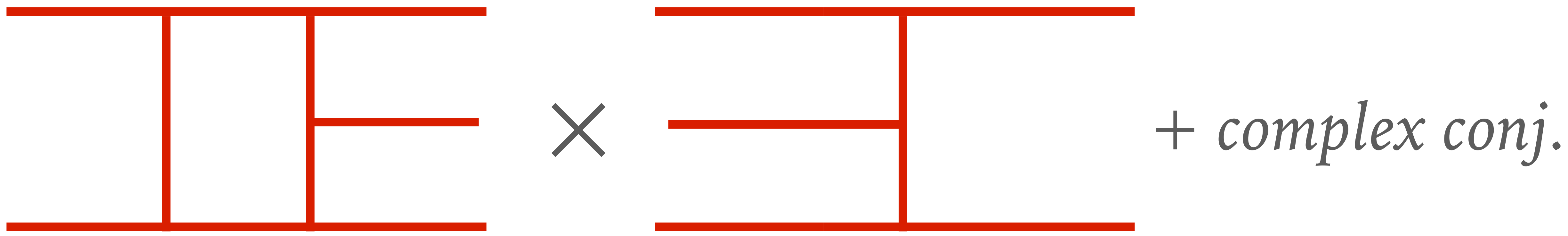
Ingredients for a calculation (generic 2→2 process)

NNLO

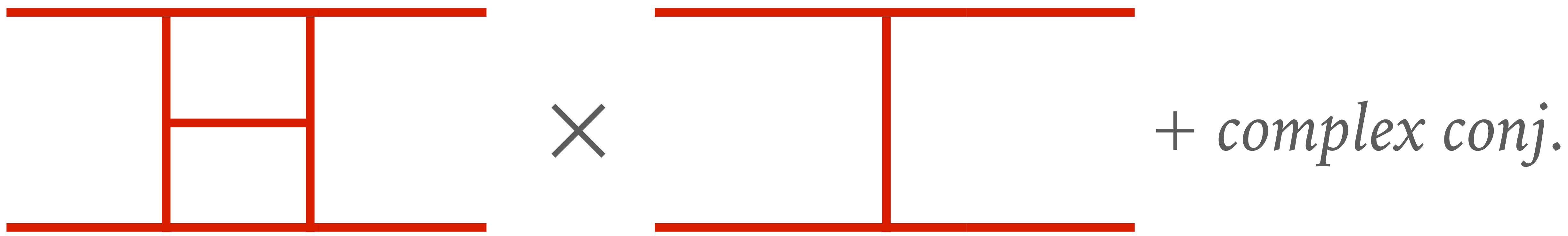
Tree
2→4



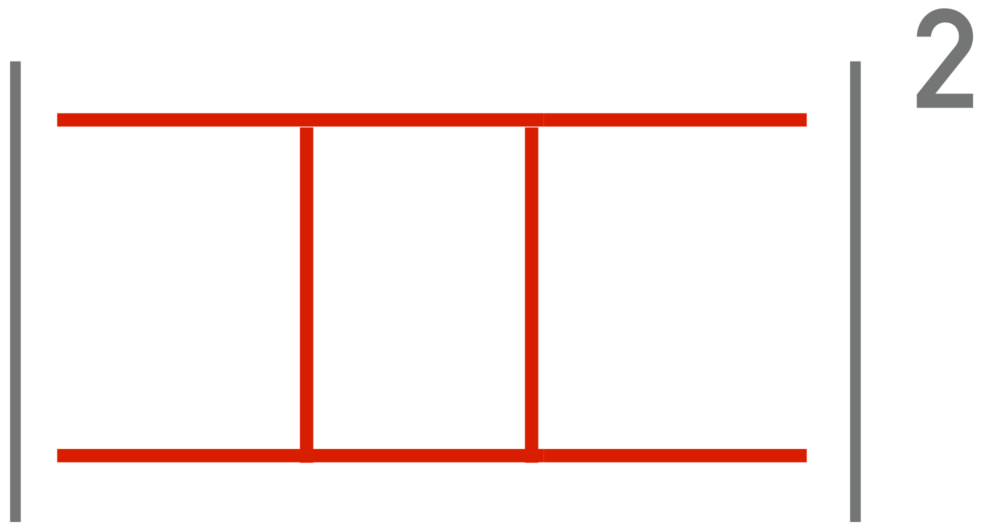
1-loop
2→3



2-loop
2→2

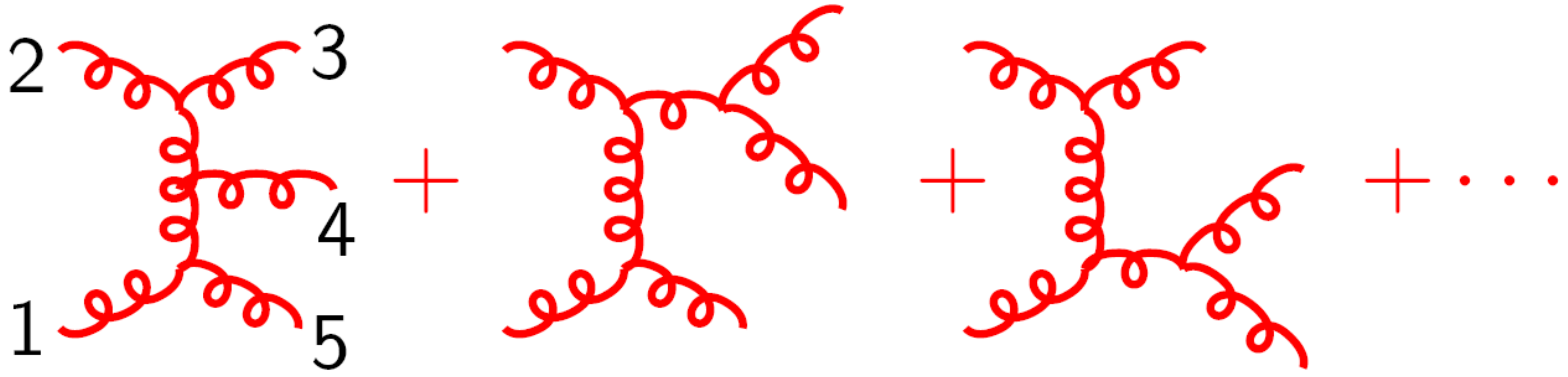


1-loop
2→2



doing better than Feynman diagrams to calculate individual terms

slide adapted from Fabrizio Caola



+ 22 similar terms

```
amp =

    + F(CiE1,Ci2,CiE4)*F(CiE2,Ci2,CiXX)*F(CiE3,CiE5,CiXX) * (
       - e1.e3*e2.e5*e4.p1*s14^-1
       - 1/2*e1.e3*e2.e5*e4.p4*s14^-1
       - 1/2*e1.e4*e2.e3*e5.p1*s14^-1
       + 1/2*e1.e4*e2.e3*e5.p4*s14^-1
       + 1/2*e1.e4*e2.e5*e3.p1*s14^-1
       - 1/2*e1.e4*e2.e5*e3.p4*s14^-1
       + e1.e5*e2.e3*e4.p1*s14^-1
       + 1/2*e1.e5*e2.e3*e4.p4*s14^-1
       - 1/2*e1.p1*e2.e3*e4.e5*s14^-1
       + 1/2*e1.p1*e2.e5*e3.e4*s14^-1
       - e1.p4*e2.e3*e4.e5*s14^-1
       + e1.p4*e2.e5*e3.e4*s14^-1
       )

    + F(CiE1,Ci2,CiE4)*F(CiE2,Ci2,Ci4)*F(CiE3,CiE5,Ci4) * (
       - 2*e1.e2*e3.e5*e4.p1*p1.p3*s14^-1*s124^-1
       - 2*e1.e2*e3.e5*e4.p1*p1.p4*s14^-1*s124^-1
       + 2*e1.e2*e3.e5*e4.p1*p2.p3*s14^-1*s124^-1
       - 2*e1.e2*e3.e5*e4.p1*p3.p4*s14^-1*s124^-1
       - e1.e2*e3.e5*e4.p4*p1.p3*s14^-1*s124^-1
       - e1.e2*e3.e5*e4.p4*p1.p4*s14^-1*s124^-1
       + e1.e2*e3.e5*e4.p4*p2.p3*s14^-1*s124^-1
       - e1.e2*e3.e5*e4.p4*p3.p4*s14^-1*s124^-1
       + e1.e2*e3.p1*e4.p1*e5.p1*s14^-1*s124^-1
       - 3*e1.e2*e3.p1*e4.p1*e5.p2*s14^-1*s124^-1
       + e1.e2*e3.p1*e4.p1*e5.p3*s14^-1*s124^-1
       + e1.e2*e3.p1*e4.p1*e5.p4*s14^-1*s124^-1
       + 1/2*e1.e2*e3.p1*e4.p4*e5.p1*s14^-1*s124^-1
       - 3/2*e1.e2*e3.p1*e4.p4*e5.p2*s14^-1*s124^-1
       + 1/2*e1.e2*e3.p1*e4.p4*e5.p3*s14^-1*s124^-1
       + 1/2*e1.e2*e3.p1*e4.p4*e5.p4*s14^-1*s124^-1
       + 3*e1.e2*e3.p2*e4.p1*e5.p1*s14^-1*s124^-1
```

=

Massive simplification!

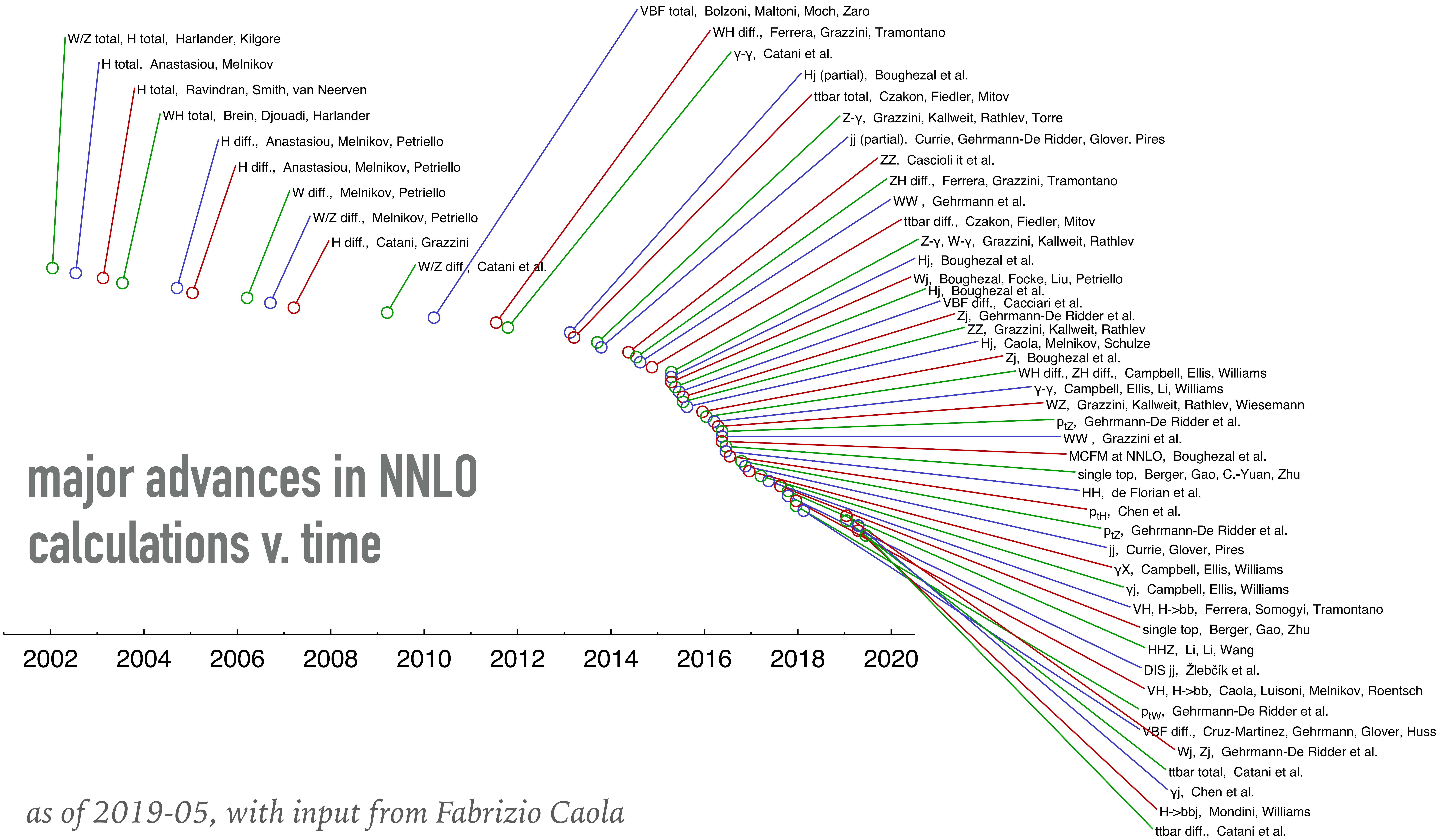
$$A_5^{\rm tree}(1^\pm, 2^+, 3^+, 4^+, 5^+) = 0$$

$$A_5^{\rm tree}(1^-, 2^-, 3^+, 4^+, 5^+) = i\frac{\langle 12\rangle^4}{\langle 12\rangle\langle 23\rangle\langle 34\rangle\langle 45\rangle\langle 51\rangle}$$

$$A_5^{\rm tree}(1^-, 2^+, 3^-, 4^+, 5^+) = i\frac{\langle 13\rangle^4}{\langle 12\rangle\langle 23\rangle\langle 34\rangle\langle 45\rangle\langle 51\rangle}$$

mathematically equivalent

major advances in NNLO calculations v. time



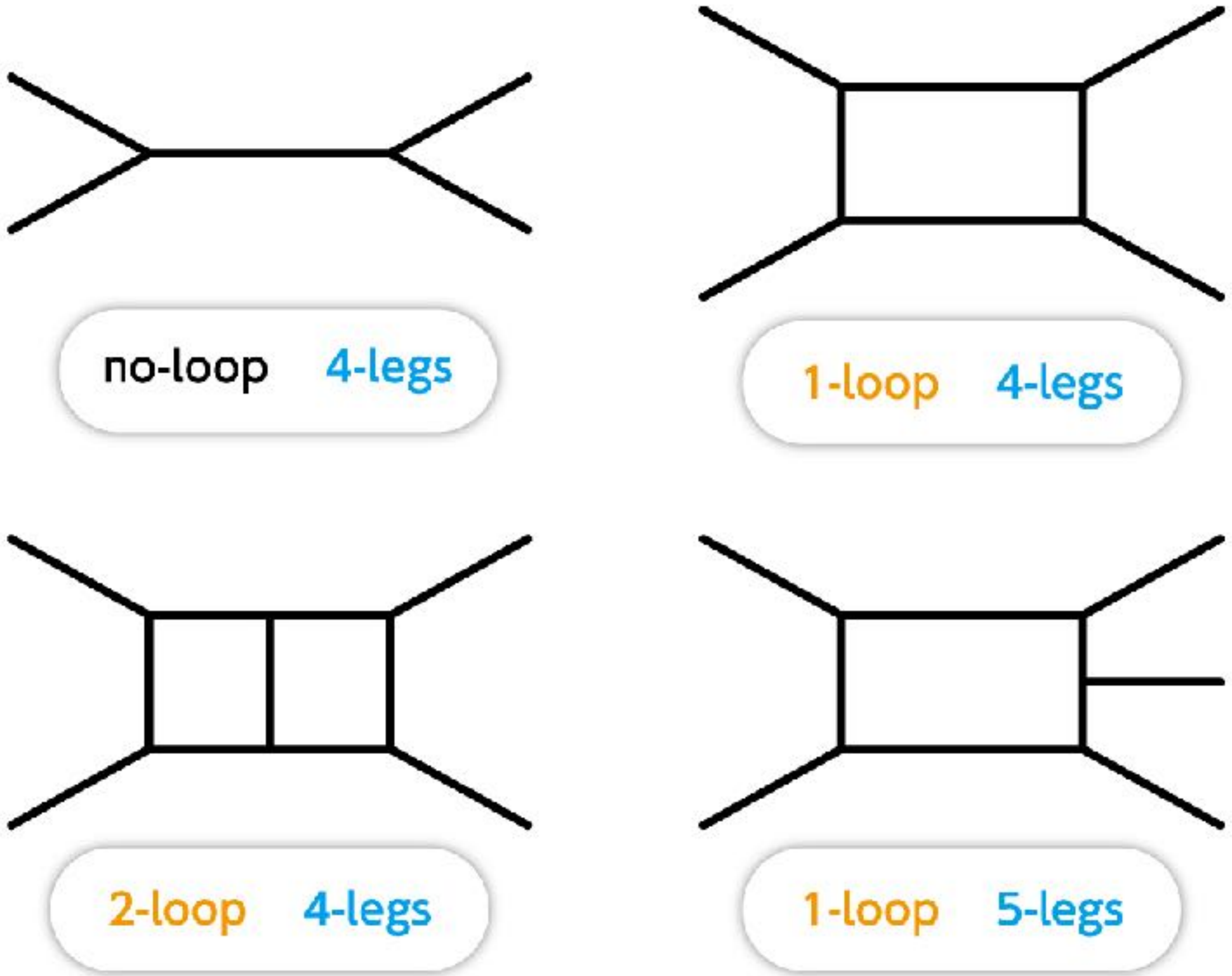
as of 2019-05, with input from Fabrizio Caola

Higher precision needs more legs & more loops

Analytic Form of the Planar Two-Loop Five-Parton Scattering Amplitudes in QCD

S. Abreu,[a] J. Dormans,[b] F. Febres Cordero,[b,c] H. Ita,[b] B. Page,[d] and V. Sotnikov[b]

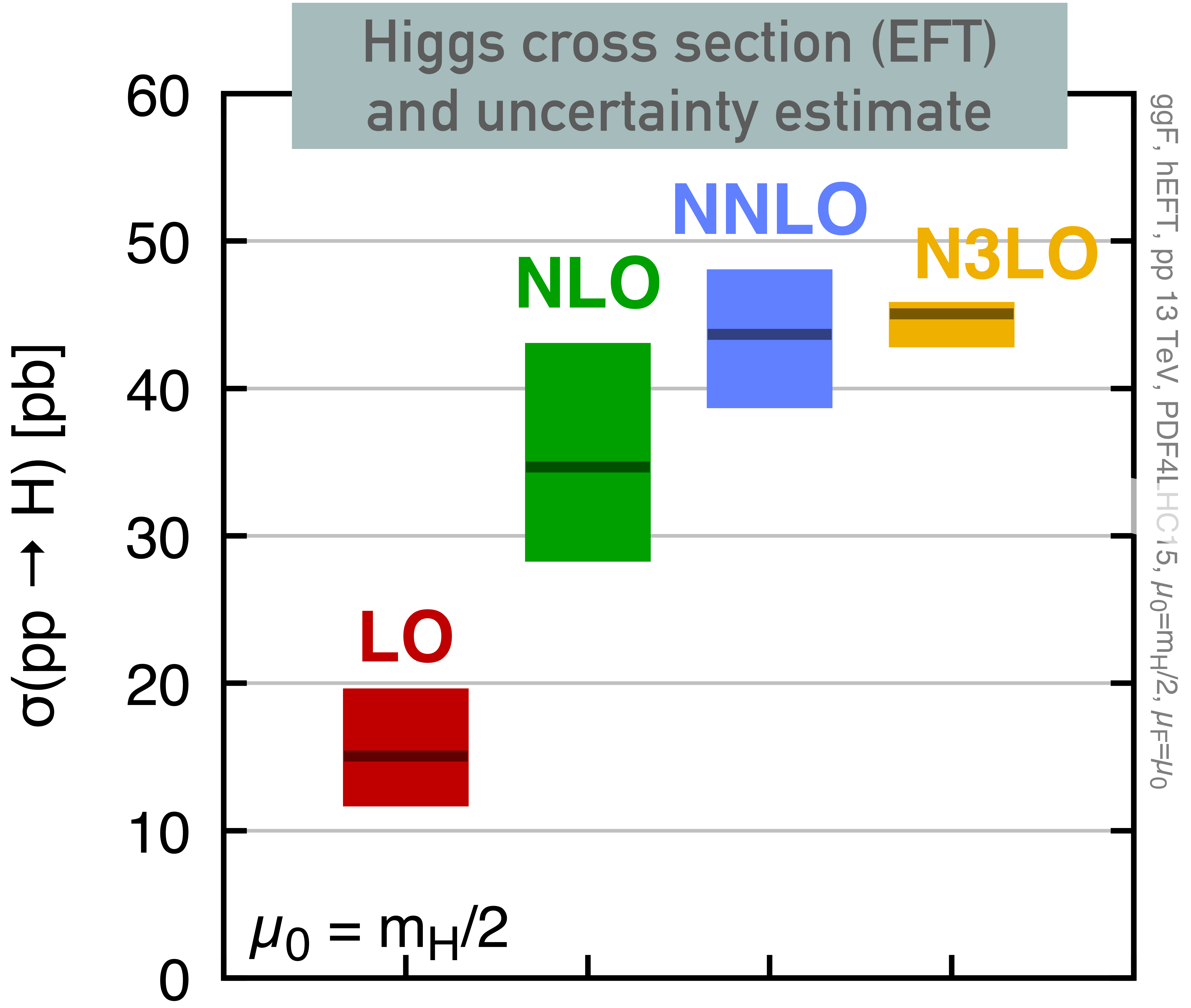
ABSTRACT: We present the analytic form of all leading-color two-loop five-parton helicity amplitudes in QCD. The results are analytically reconstructed from exact numerical evaluations over finite fields. Combining a judicious choice of variables with a new approach to the treatment of particle states in D dimensions for the numerical evaluation of amplitudes, we obtain the analytic expressions with a modest computational effort. Their systematic simplification using multivariate partial-fraction decomposition leads to a particularly compact form. Our results provide all two-loop amplitudes required for the calculation of next-to-next-to-leading order QCD corrections to the production of three jets at hadron colliders in the leading-color approximation.



Order in perturbation theory: $\alpha_s^{n_{\text{legs}}+n_{\text{loops}}-2}$

Image: adapted from Kaori Kurokawa

perturbative series for Higgs production (gg → H)



results from arXiv:1503.06056

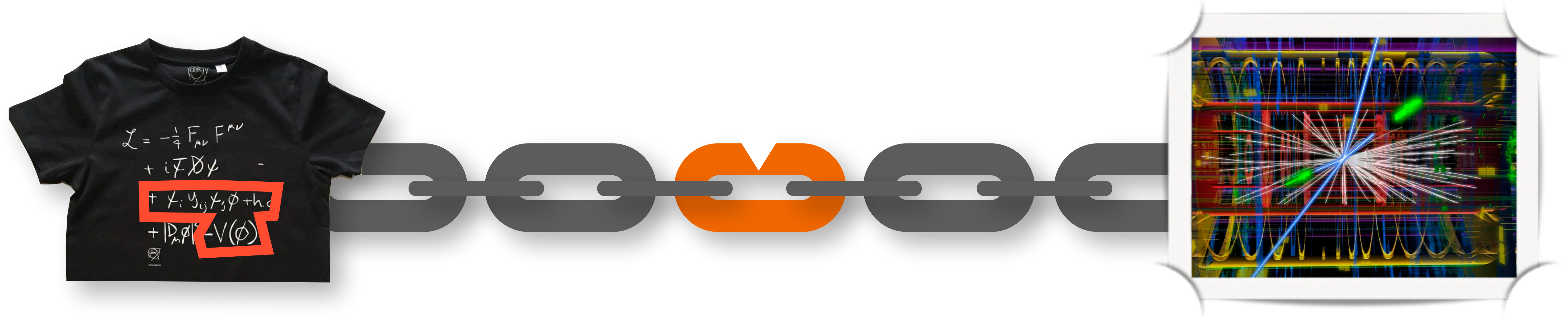
even though $\alpha_S(m_H) \simeq 0.11$, perturturbative series requires a number of orders in order to start converging

a similar phenomenon holds for almost all hadron collider cross sections (though not usually quite this bad)

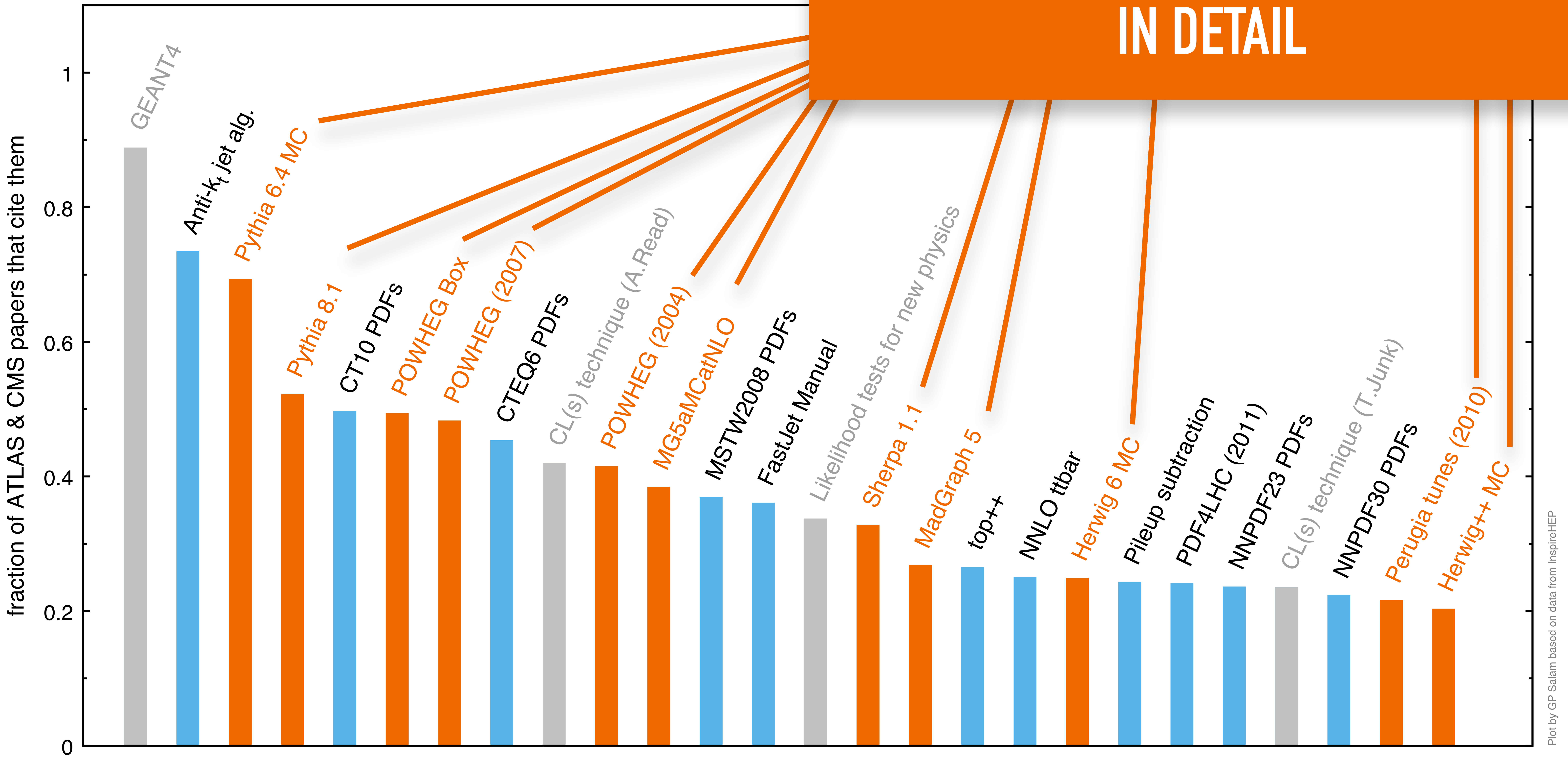
NB: here, only the renorm. scale $\mu (\equiv \mu_R)$ has been varied to estimate uncertainty. In real life you need to change renorm. and factorisation (μ_F) scales.

Monte Carlo event generators

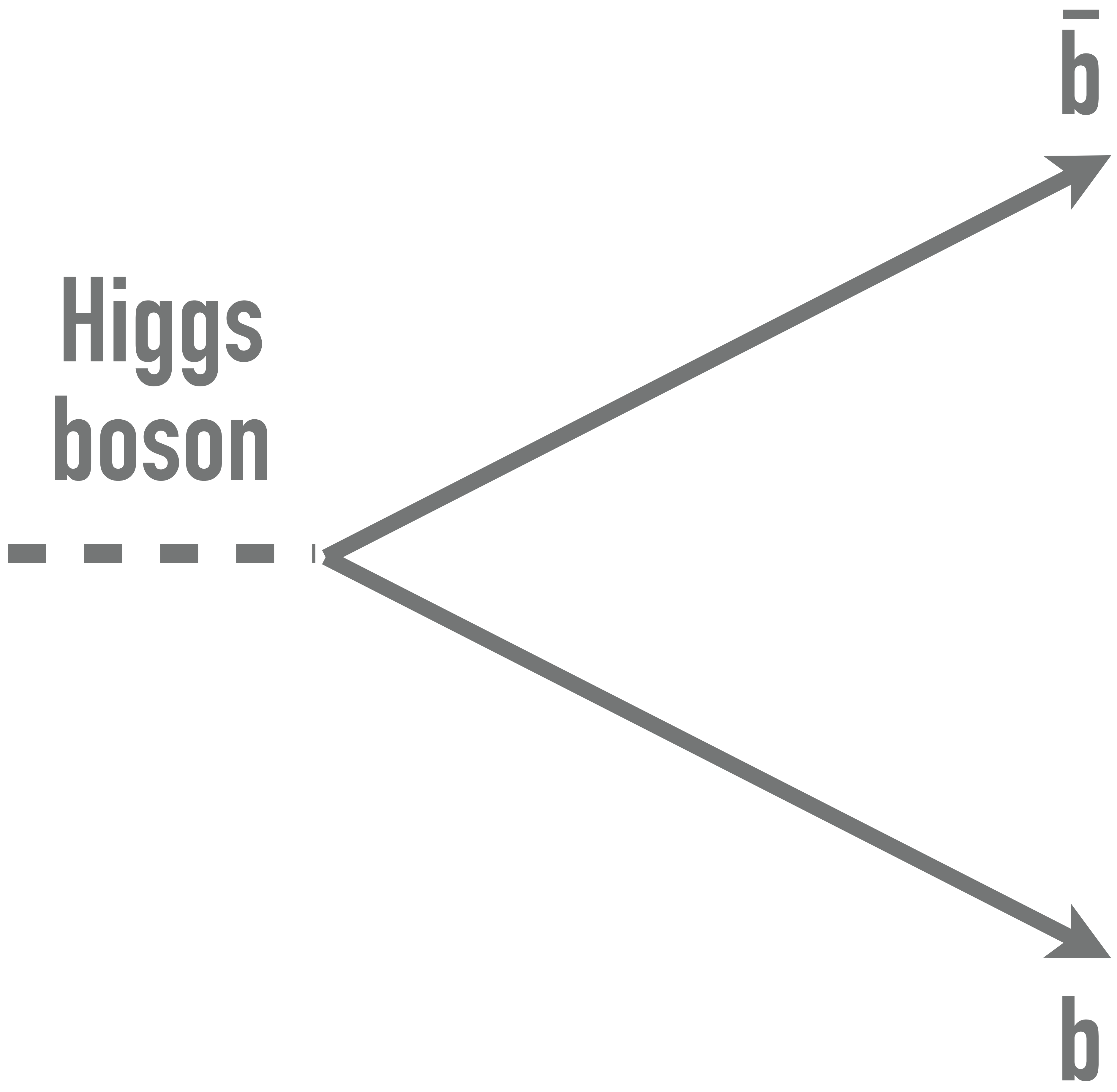
see e.g. arXiv:1202.1251, PDG review

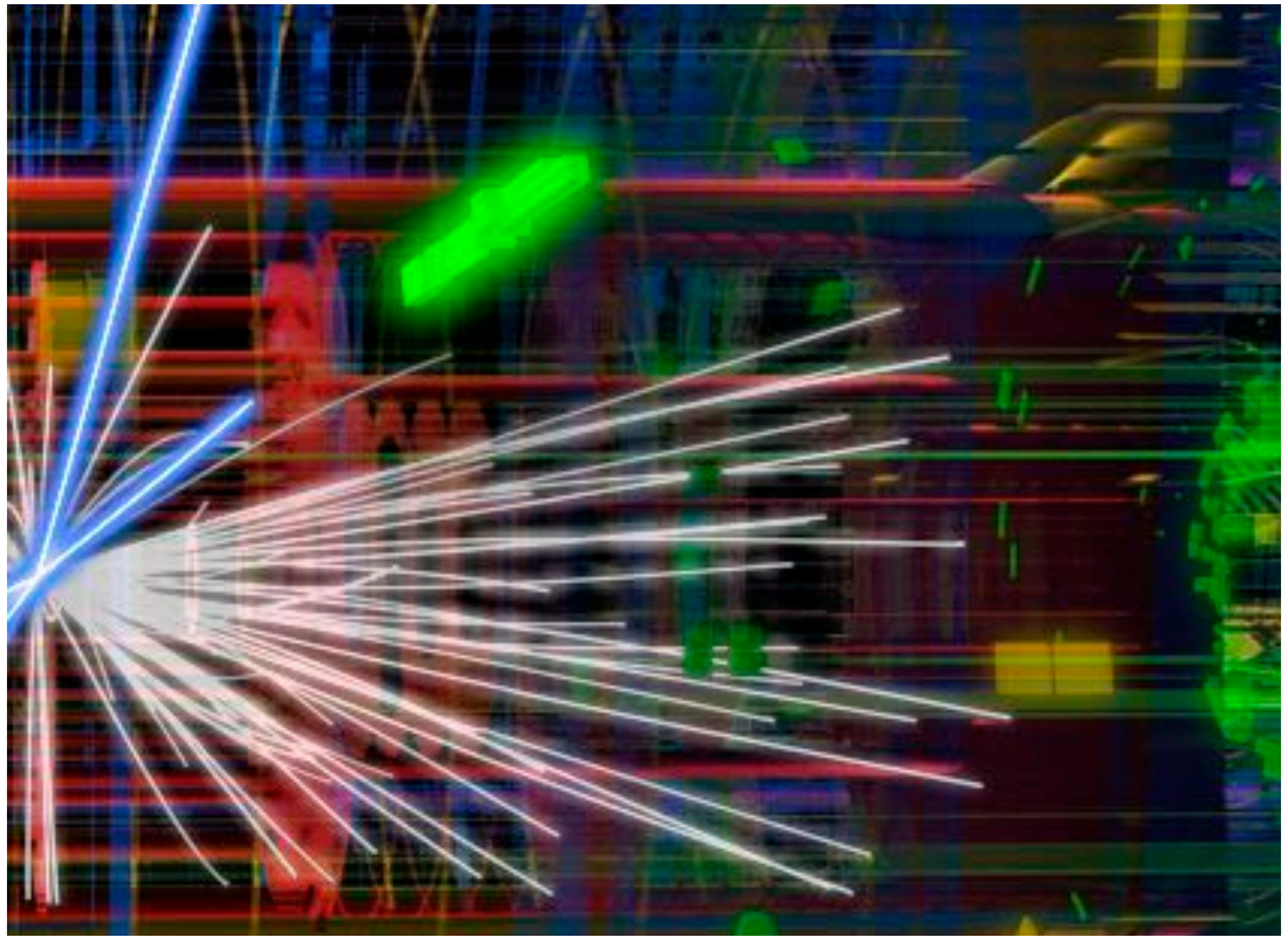


predicting what collider events look like IN DETAIL

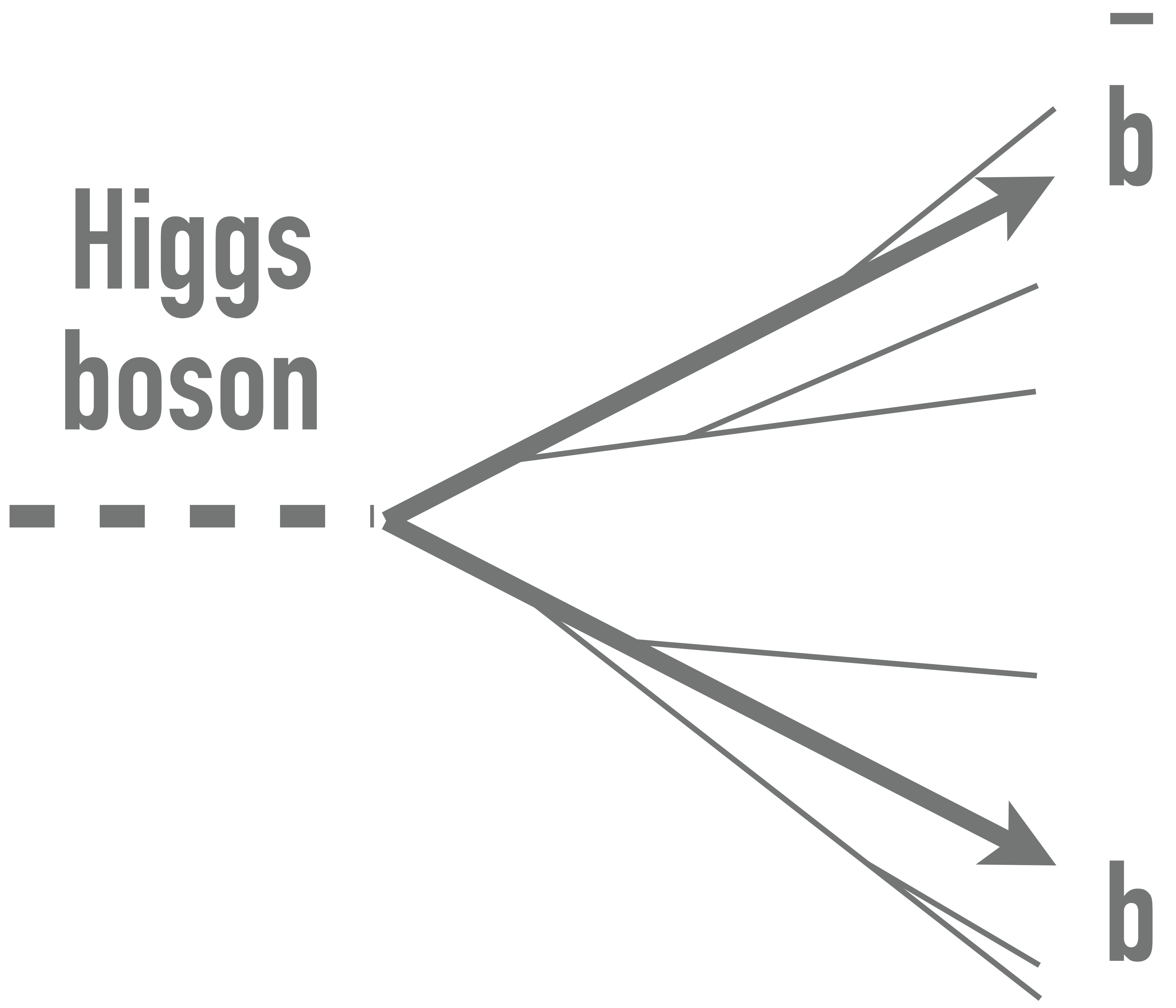


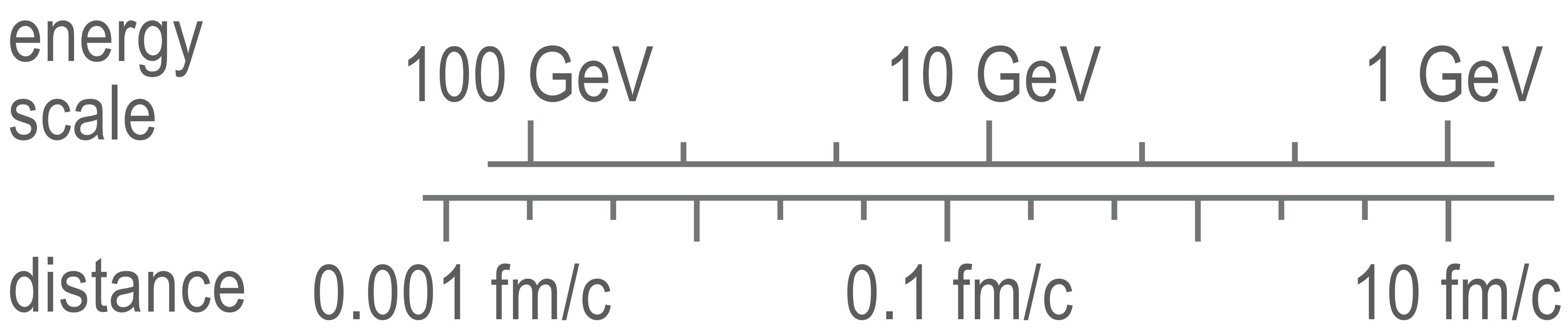
QCD Parton Shower [parton = quark or gluon]

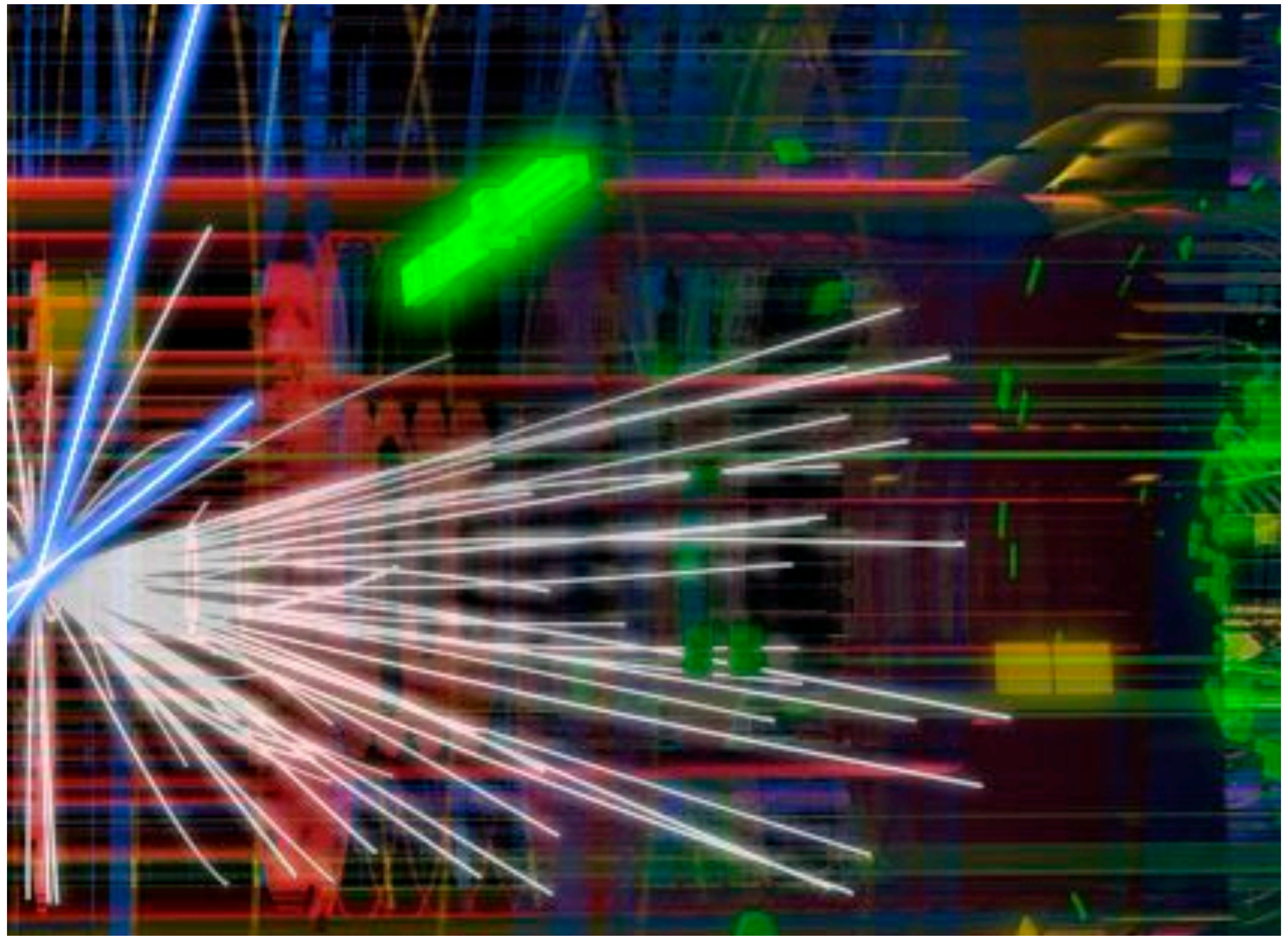




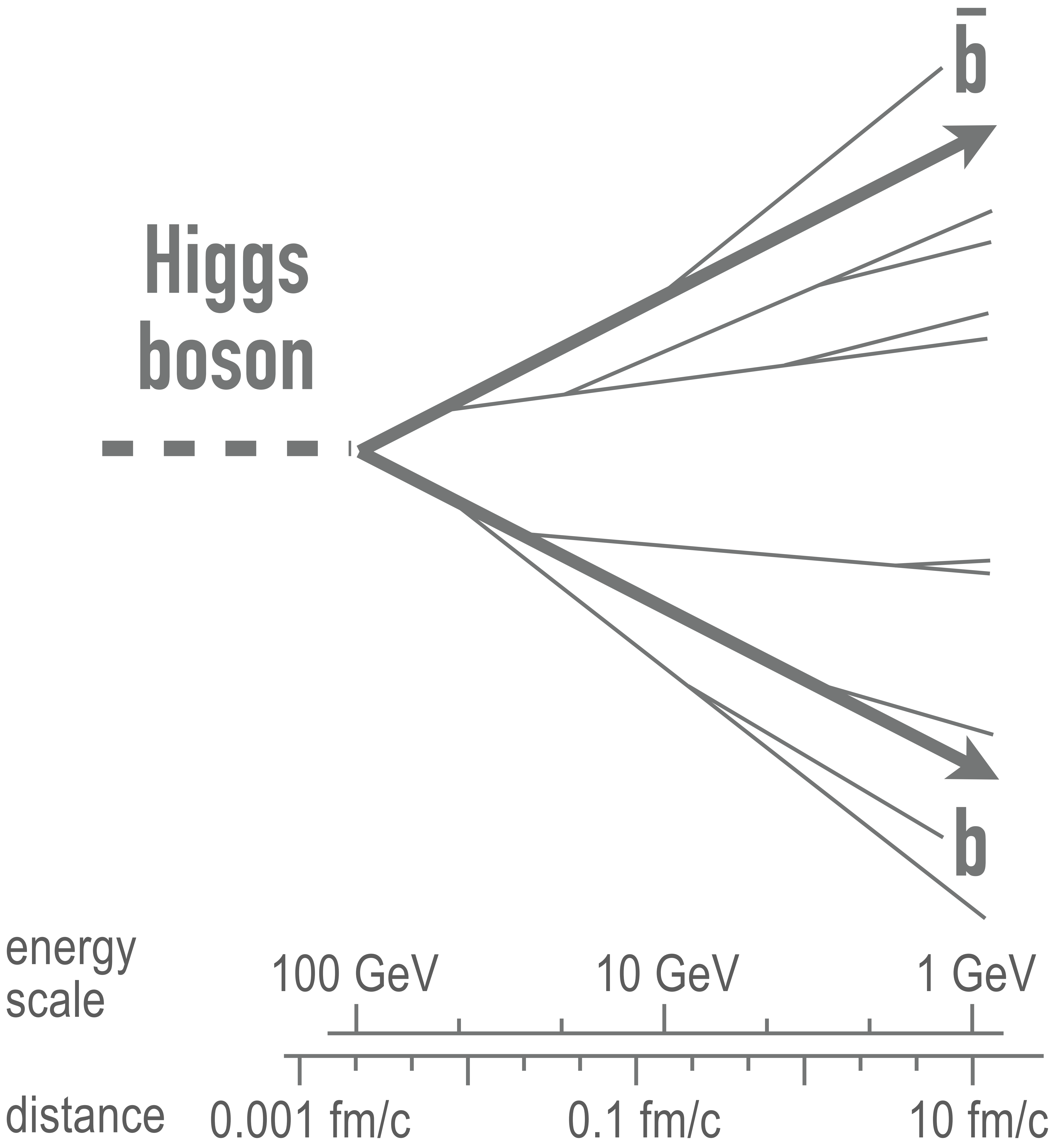
QCD Parton Shower [parton = quark or gluon]







QCD Parton Shower [parton = quark or gluon]



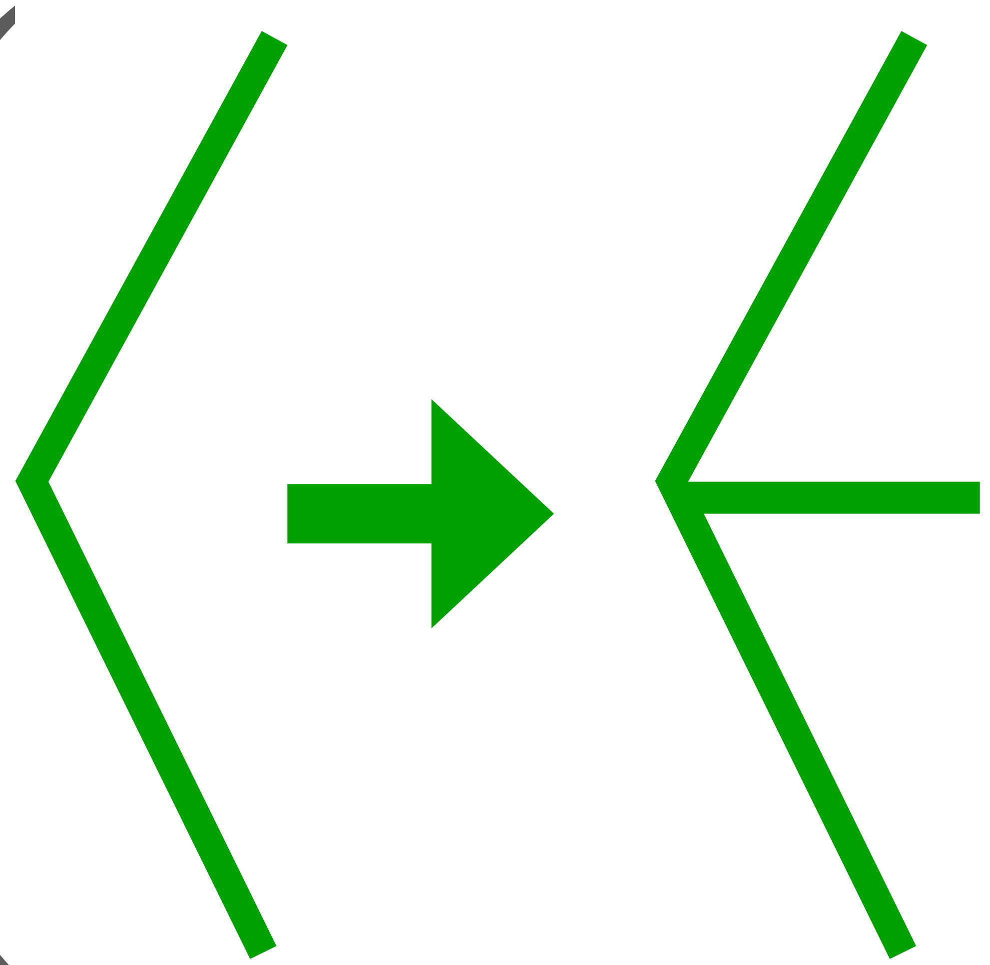
Pattern of branching usually simulated with a **Monte Carlo Parton Shower algorithm**

Experiments **always compare data to Monte Carlo simulations** to establish fundamental hypotheses

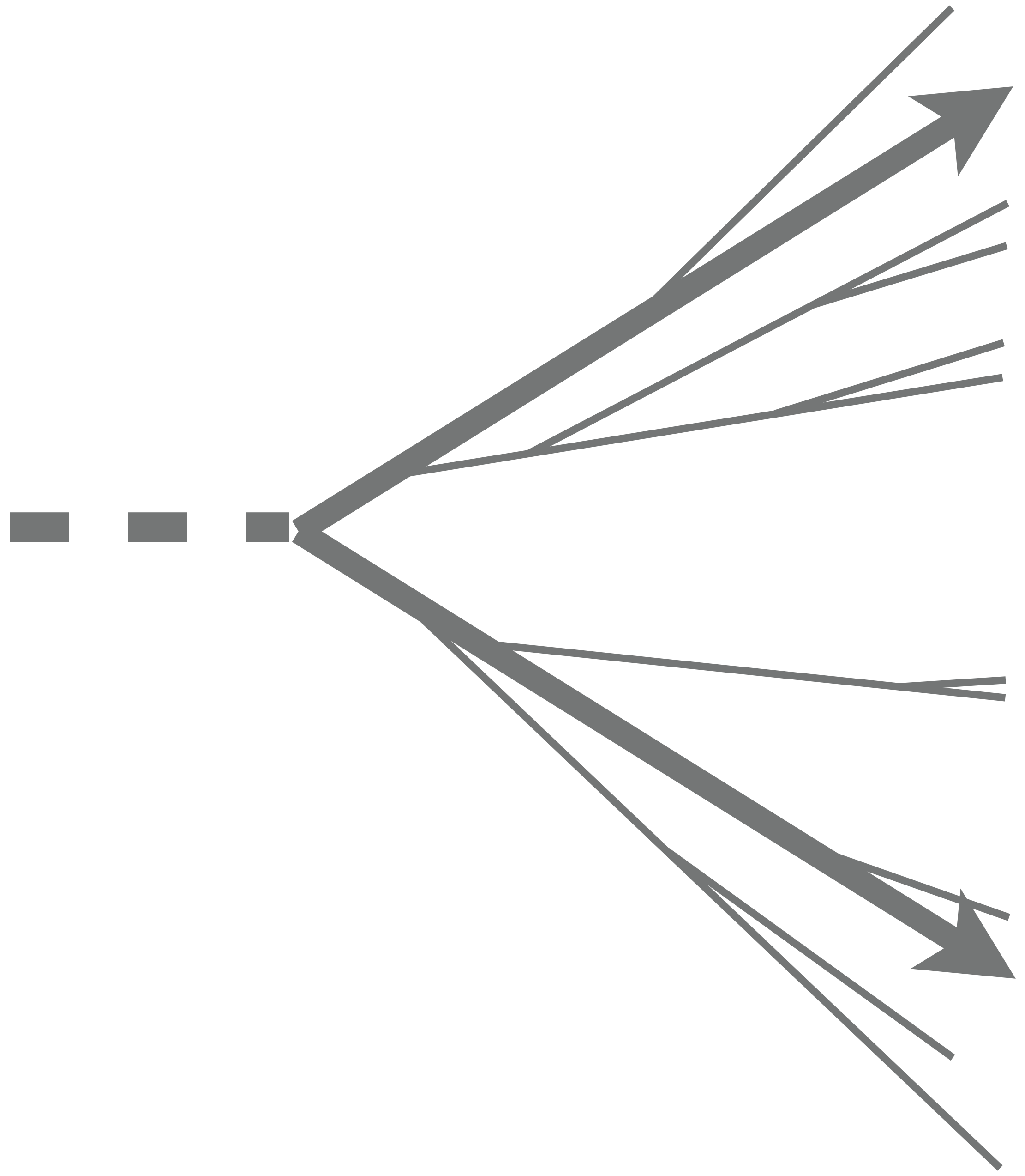
Robustness & accuracy of multi-scale properties of these simulations is one of the open questions of the field

At its simplest: the perturbative part of event generators

$$\sum_{n=0}^{\infty}\prod_{i=1}^{n}\Bigg($$



$$\Bigg) =$$



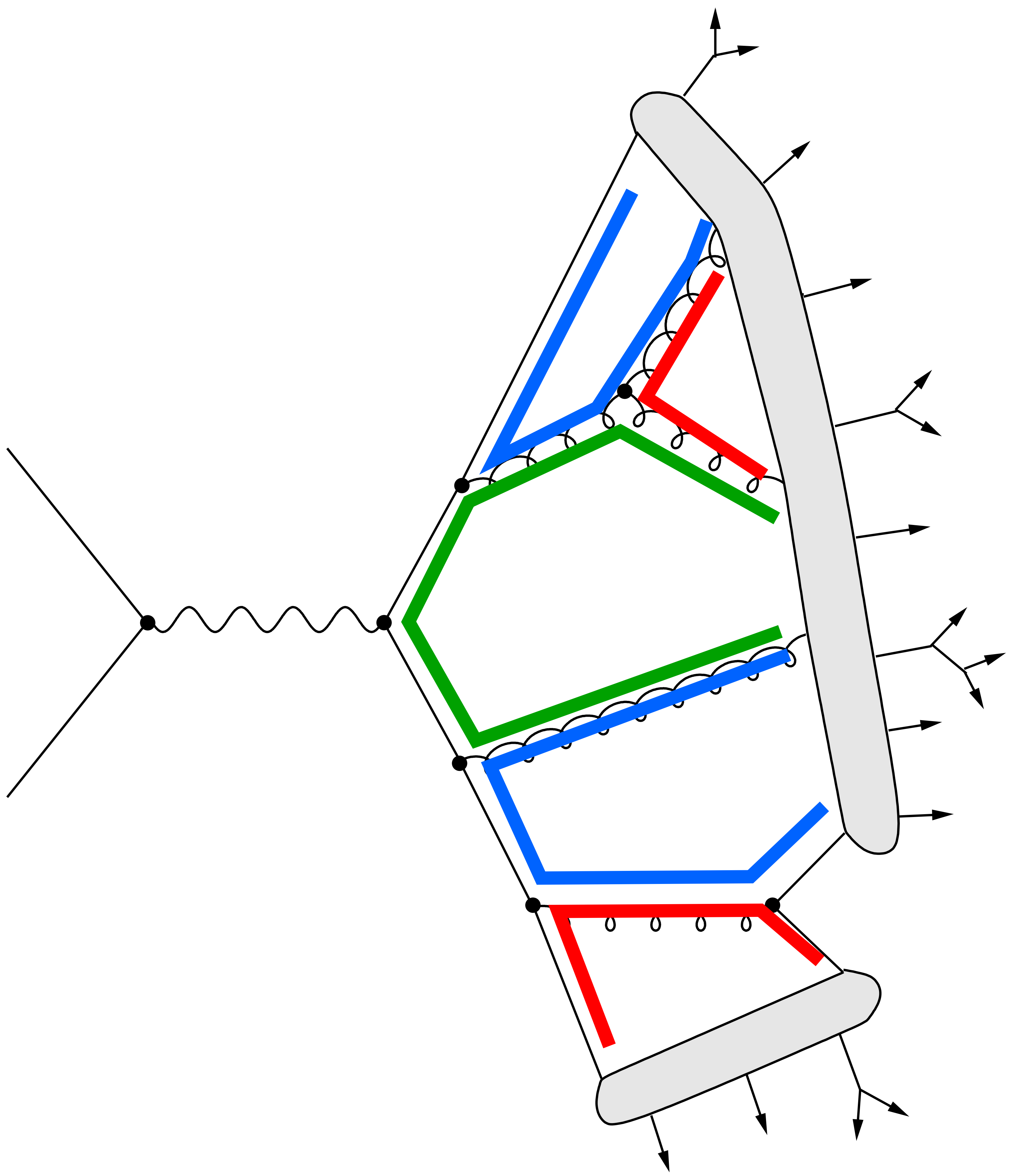
iteration of 2→3 (or 1→2) splitting kernel

in what sense does it give the right answer when you ask arbitrary questions about the final state?

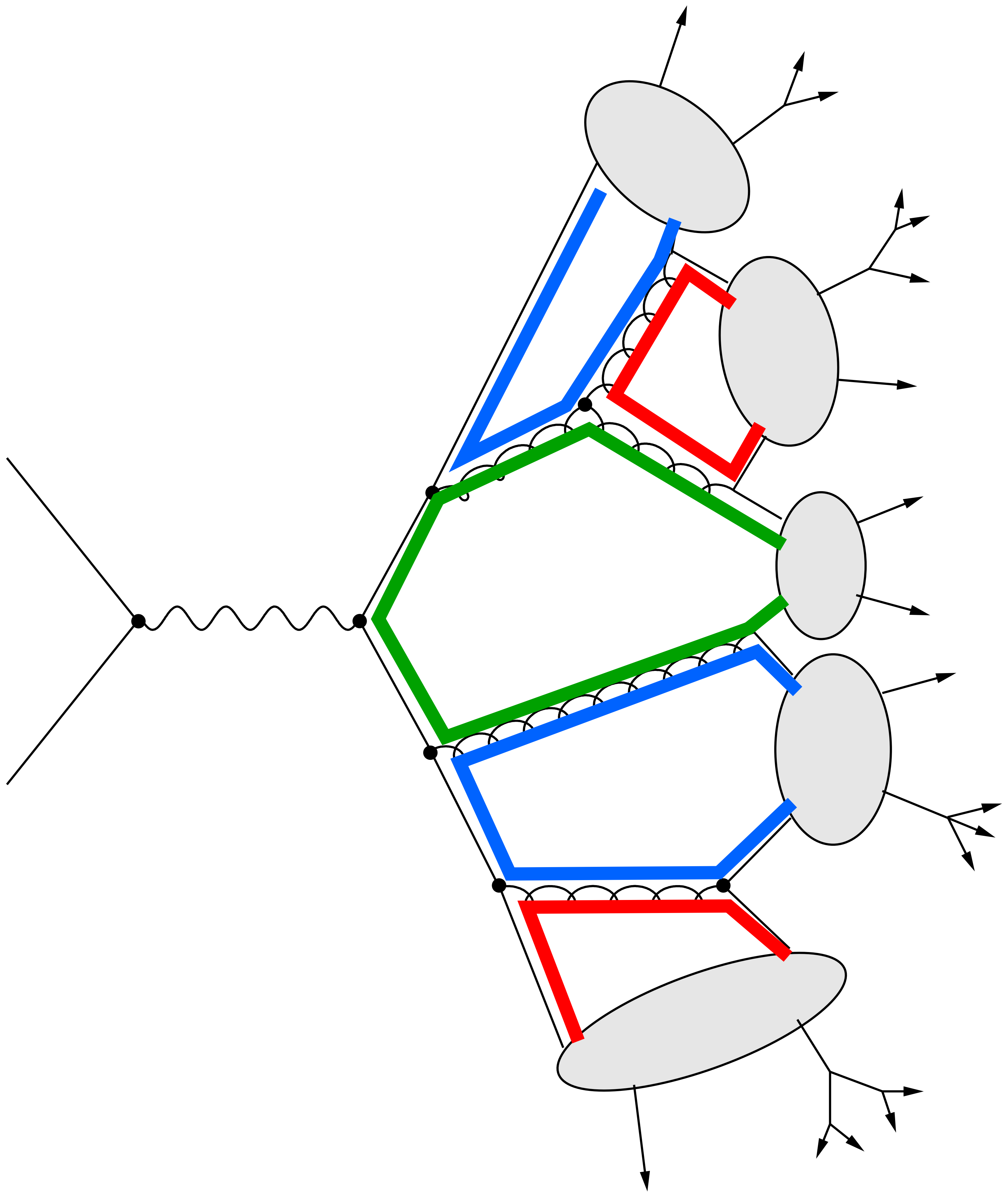
cf. arXiv:1805.09327

parton–hadron transition ("**hadronisation**") can, today, only be modelled

reorganise coloured partons into colour-singlet hadrons



String Fragmentation
(Pythia and friends)

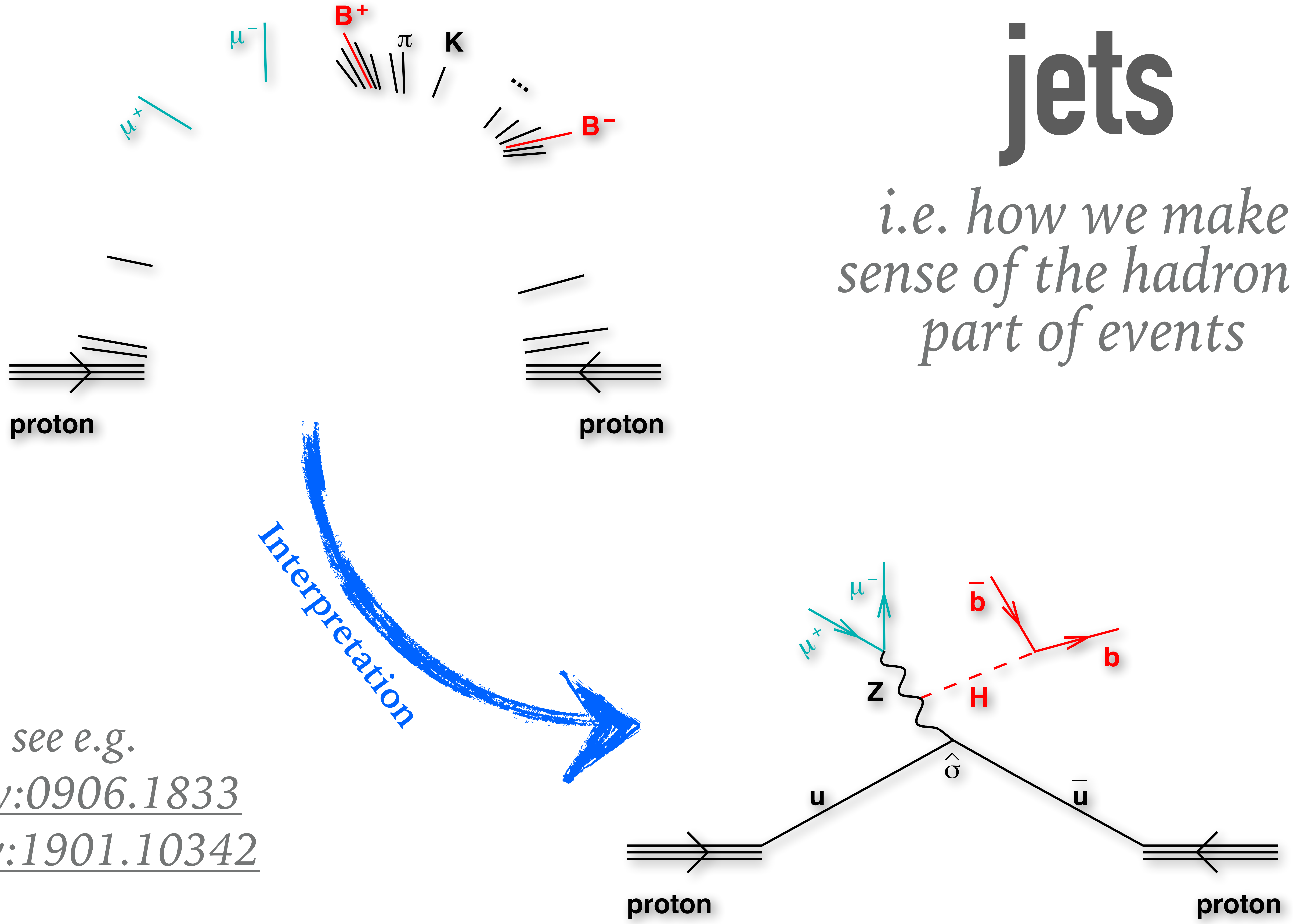


Cluster Fragmentation
(Herwig) (& Sherpa)

Pictures from ESW book

jets

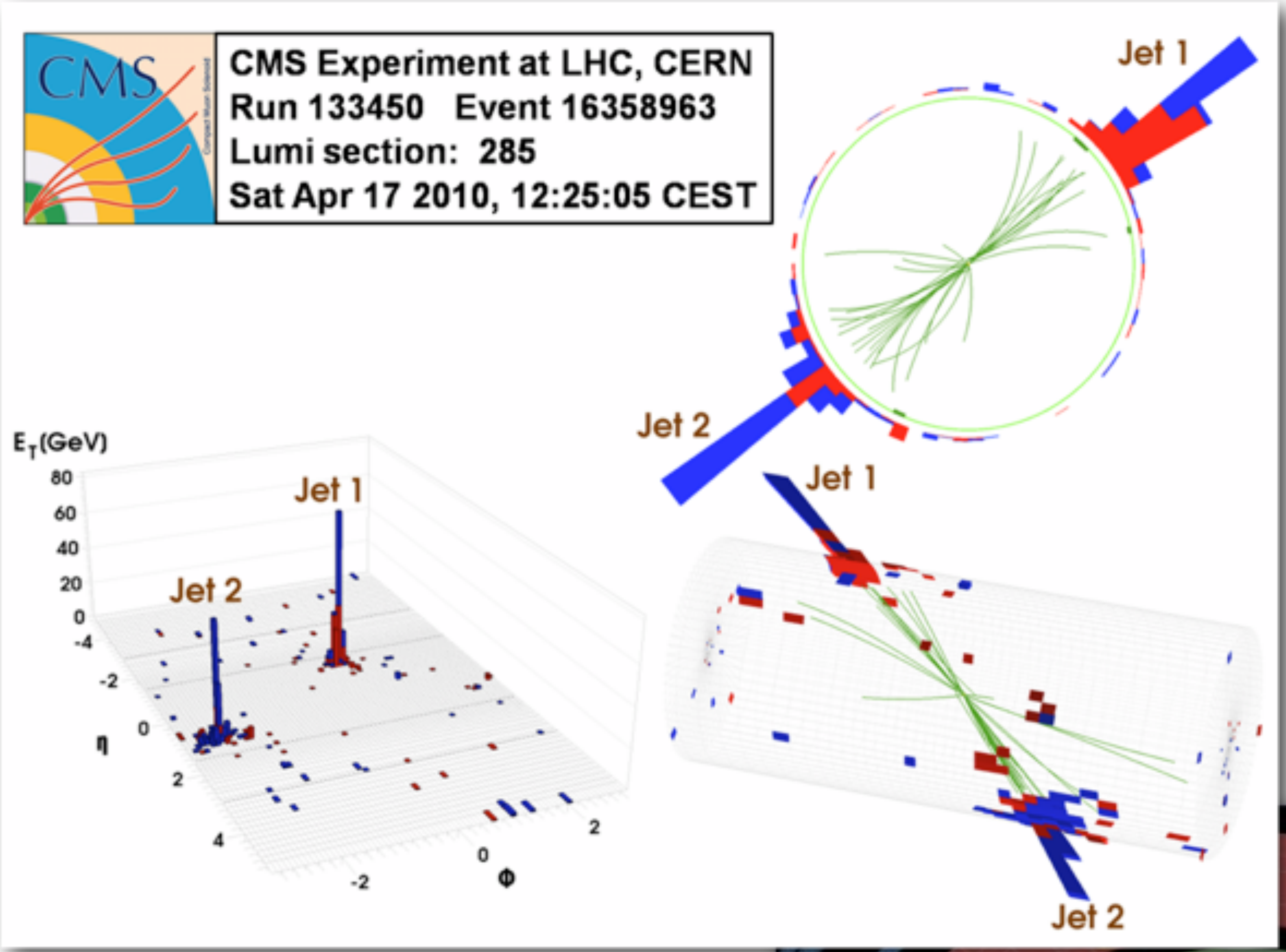
i.e. how we make sense of the hadronic part of events

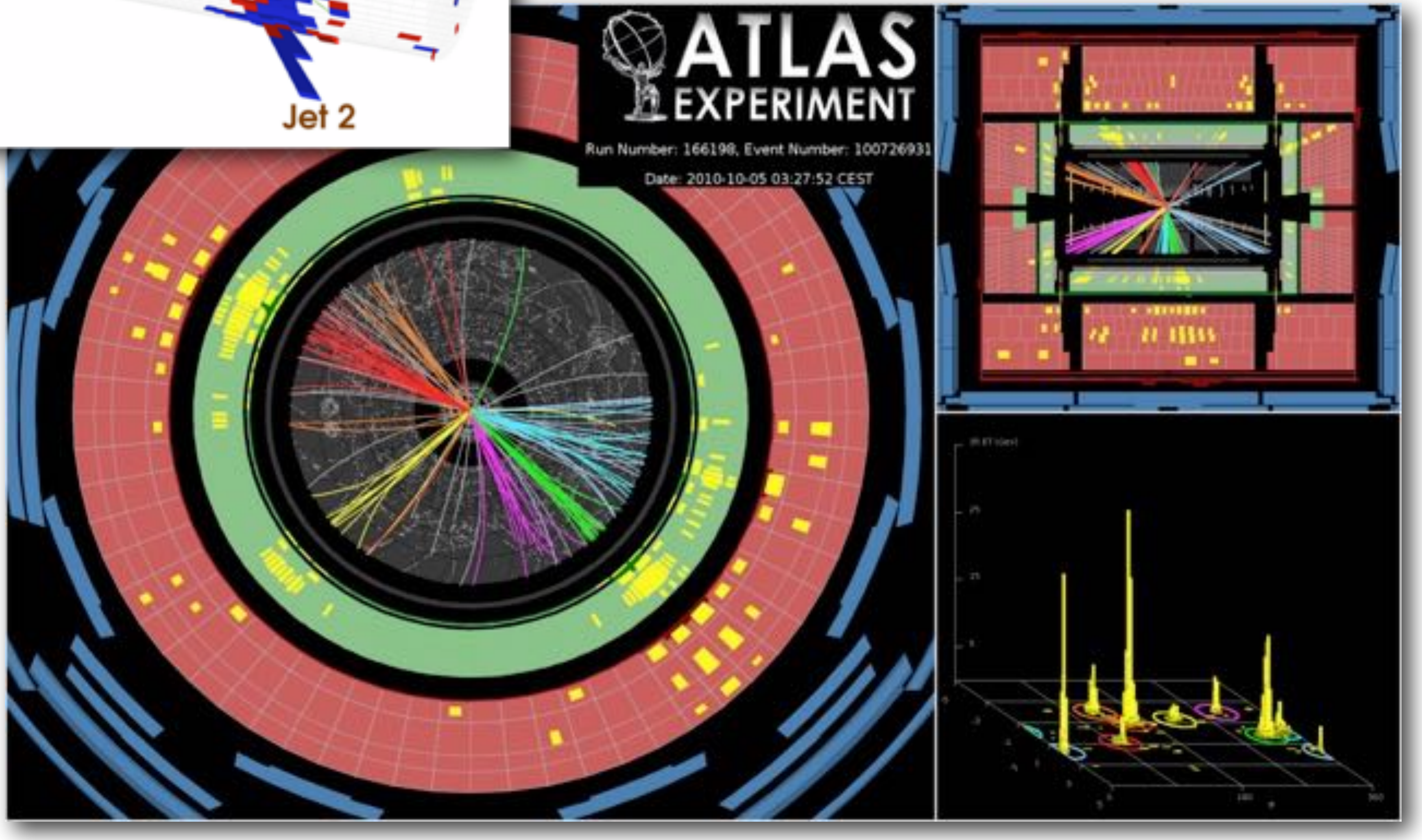


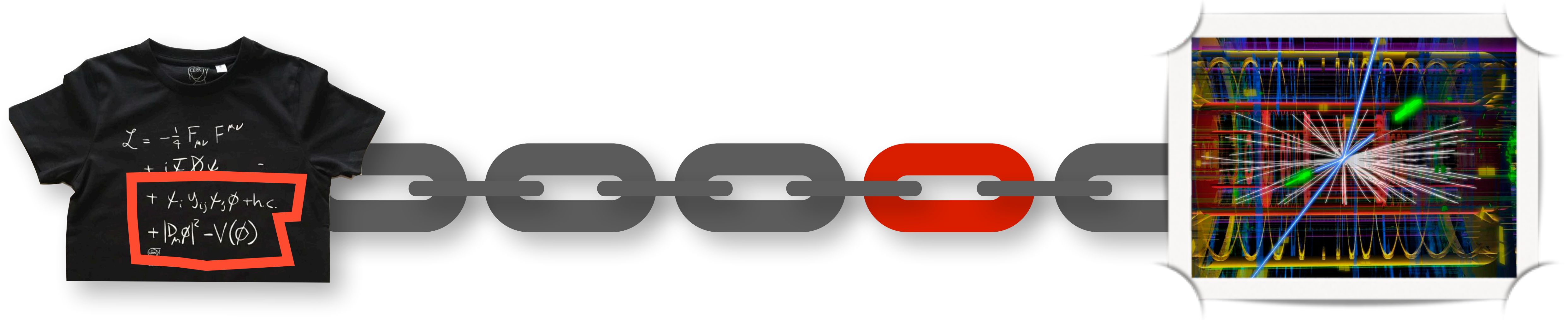
see e.g.
arXiv:0906.1833
arXiv:1901.10342

jets

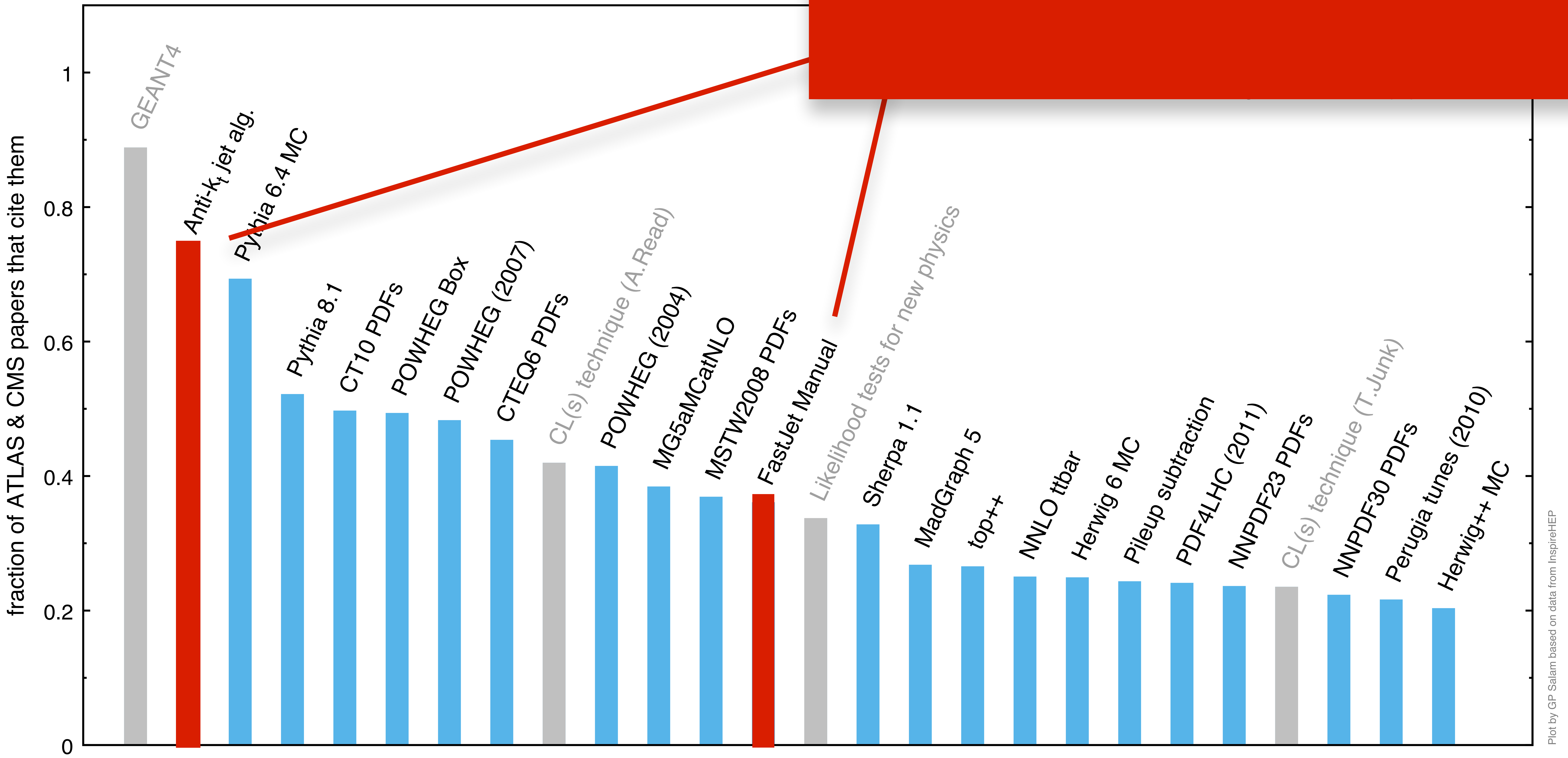
i.e. how we make sense of the hadronic part of events



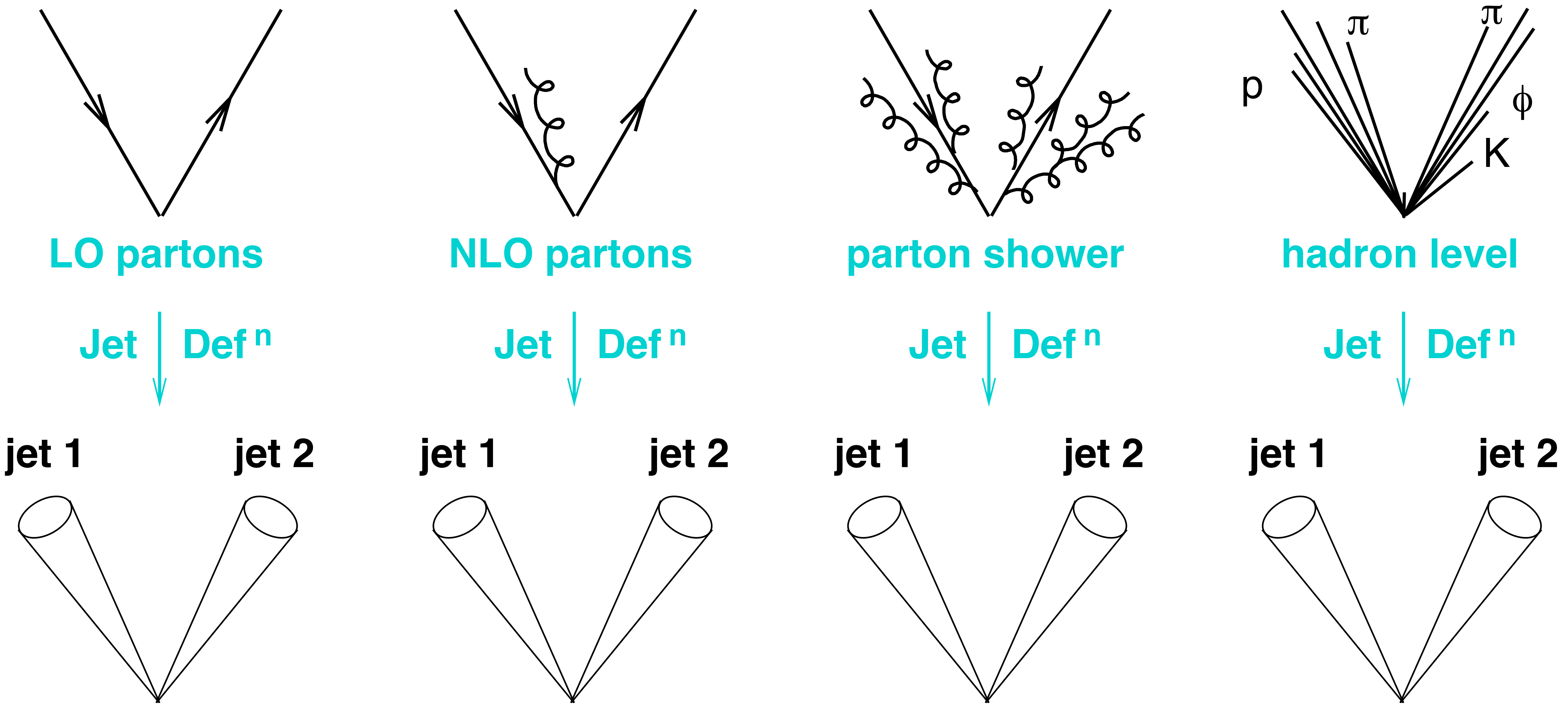




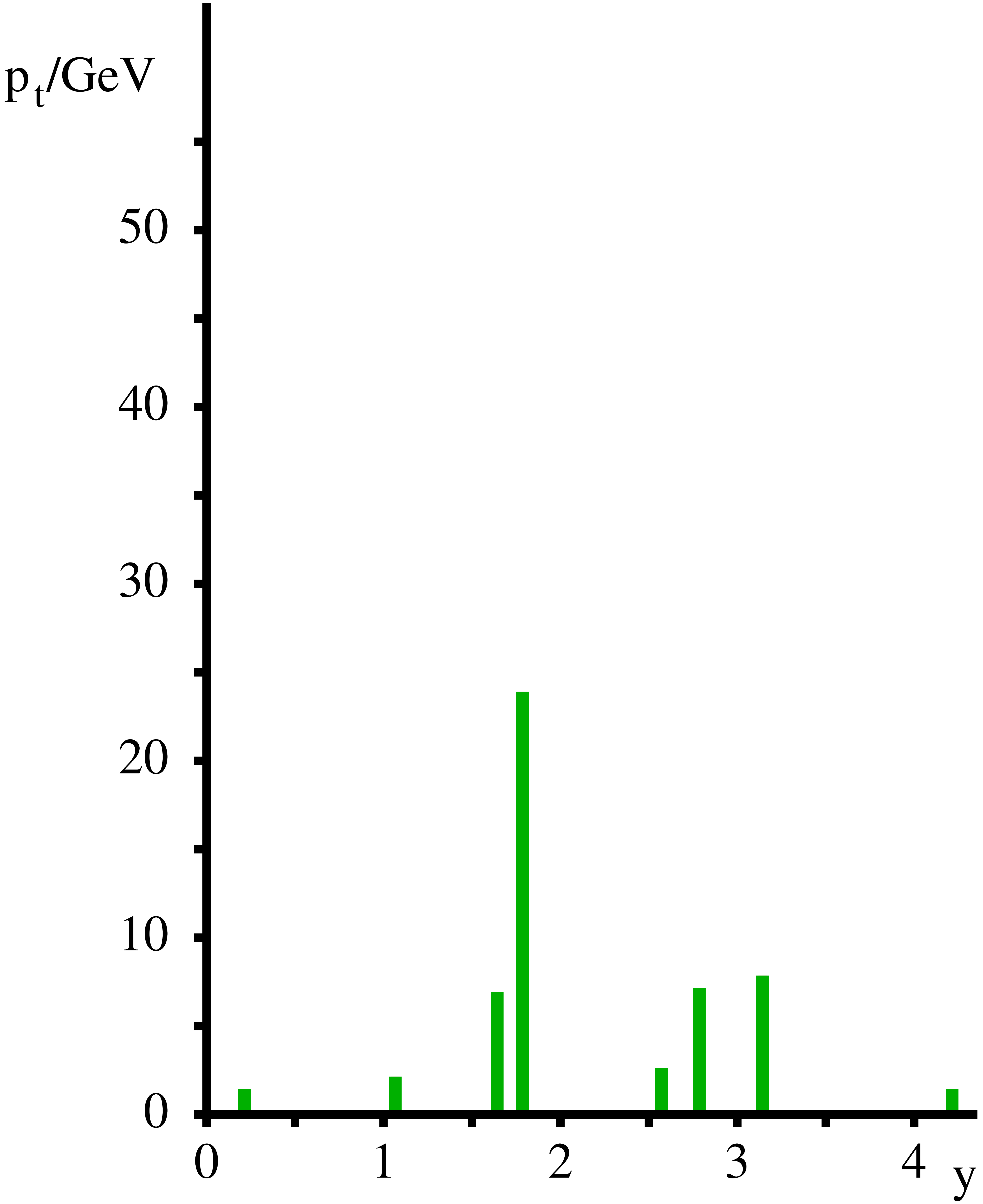
jets: organising event information



what should a jet definition achieve? A projection to a simple picture of energy flow

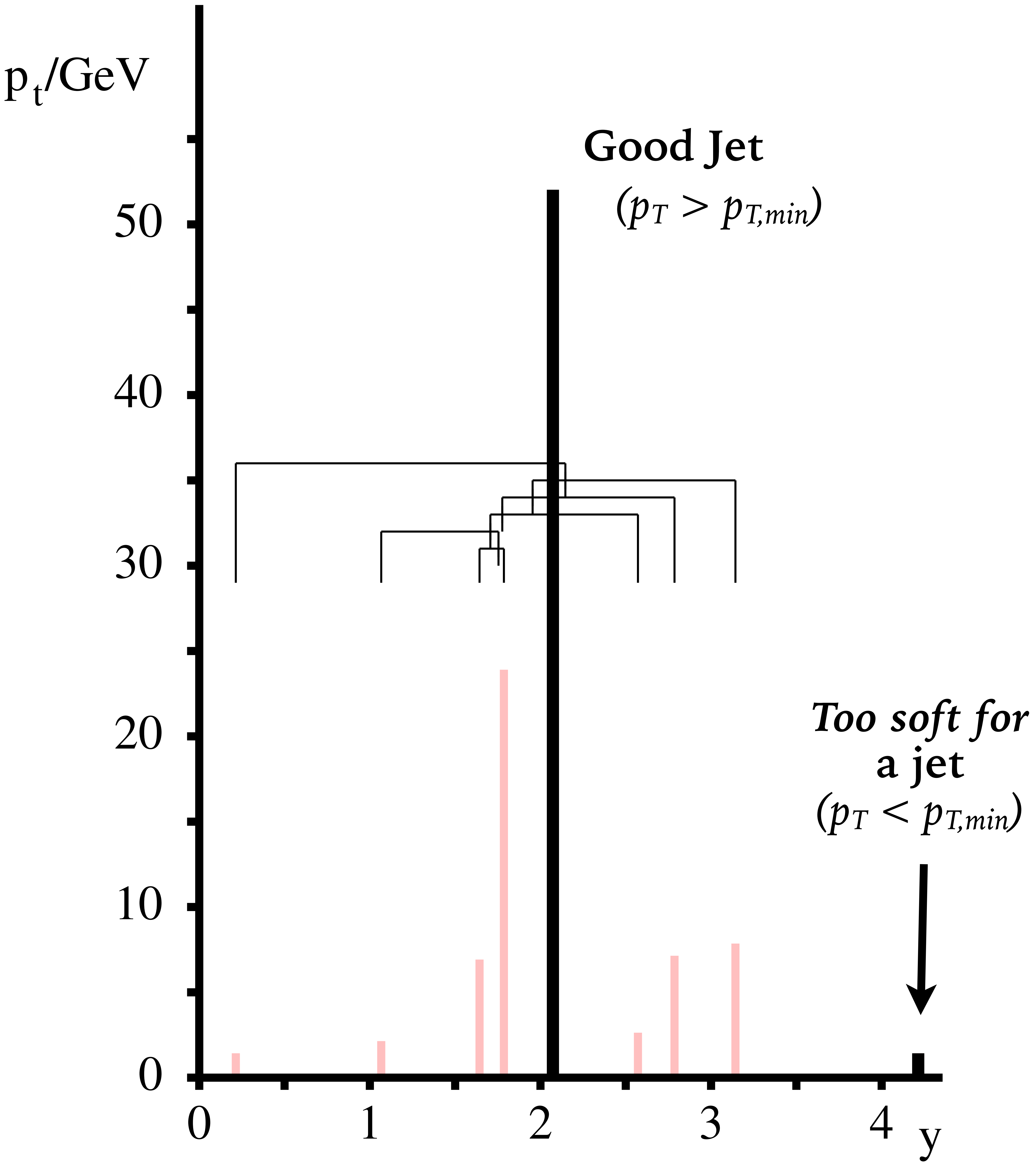


projection to jets should be resilient to QCD effects



anti-k_t jet algorithm

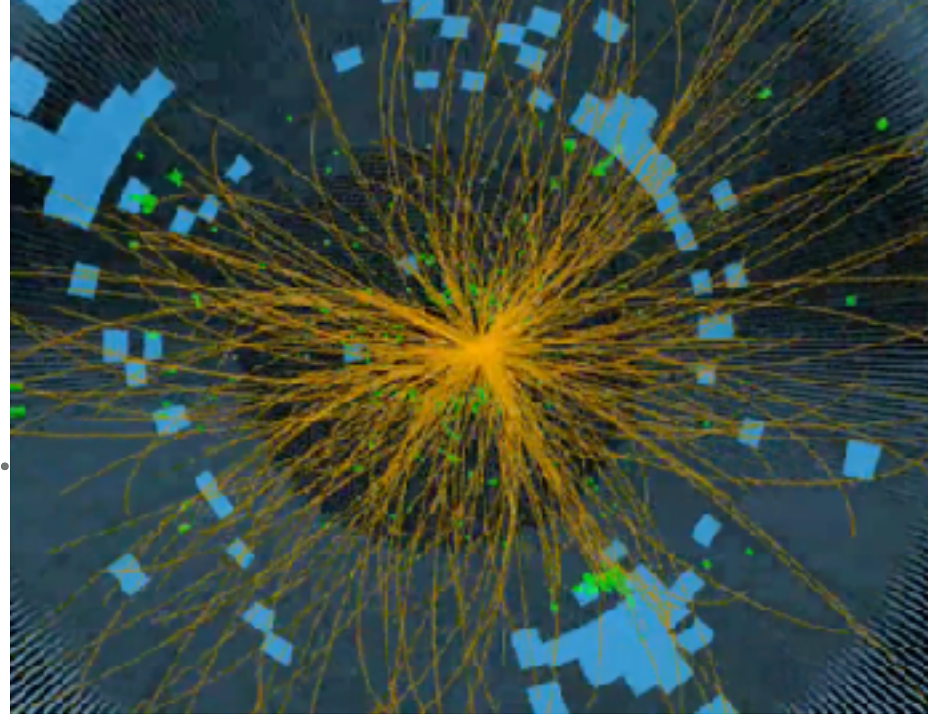
- successive recombination of closest pair of particles (with some distance measure)
- parameter for reach in angle (R)
- parameter for minimum energy of jet ($p_{t,min}$)

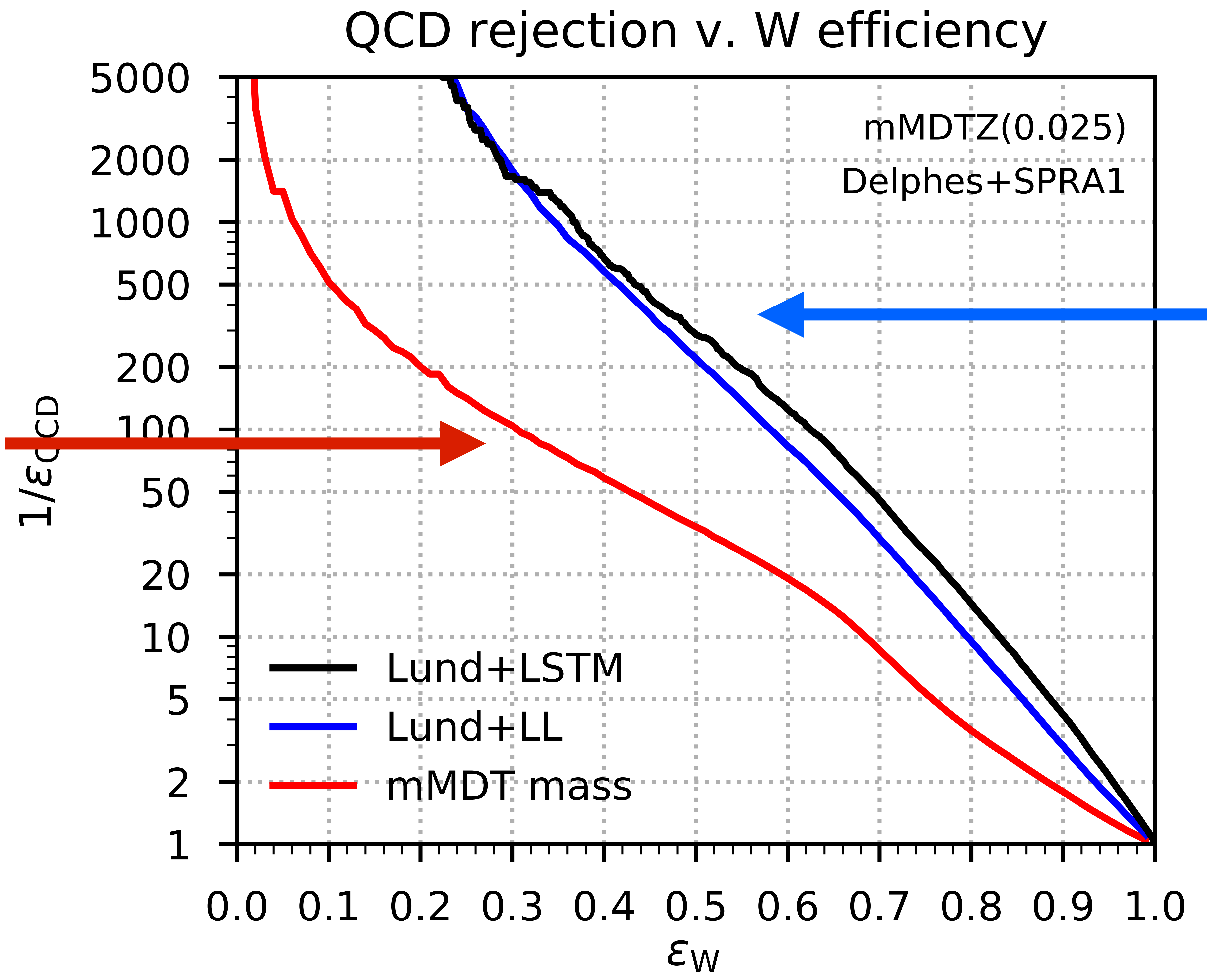


anti-k_t jet algorithm

- successive recombination of closest pair of particles (with some distance measure)
- parameter for reach in angle (R)
- parameter for minimum energy of jet ($p_{t,min}$)

using full event information: jet substructure for W tagging





QCD rejection with just jet mass

QCD rejection with use of full jet substructure

5–10x better

taken from Dreyer, GPS & Soyez '18

For identifying spatial clusters, we have implemented both centroid-linkage hierarchical clustering using FastJet […]

Via the qSR software, FastJet can analyze a typical super-resolution dataset within a few seconds. By storing the full tree structure, the user can quickly re-cluster data and compare the resulting clusters at varying characteristic sizes.

Cold Spring Harbor Laboratory

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New Results

qSR: A software for quantitative analysis of single molecule and super-resolution data

J. Owen Andrews, Arjun Narayanan, Jan-Hendrik Spille, Won-Ki Cho, Jesse D. Thaler, Ibrahim I. Cisse

doi: https://doi.org/10.1101/146241

Abstract | Info/History | Metrics | Data Supplements | Preview PDF

Abstract

We present a software for quantitative analysis of single molecule based super-resolution data. The software serves as an open-source platform integrating multiple algorithms for rigorous spatial and temporal characterizations of protein clusters in super-resolution data of living, or fixed cells.

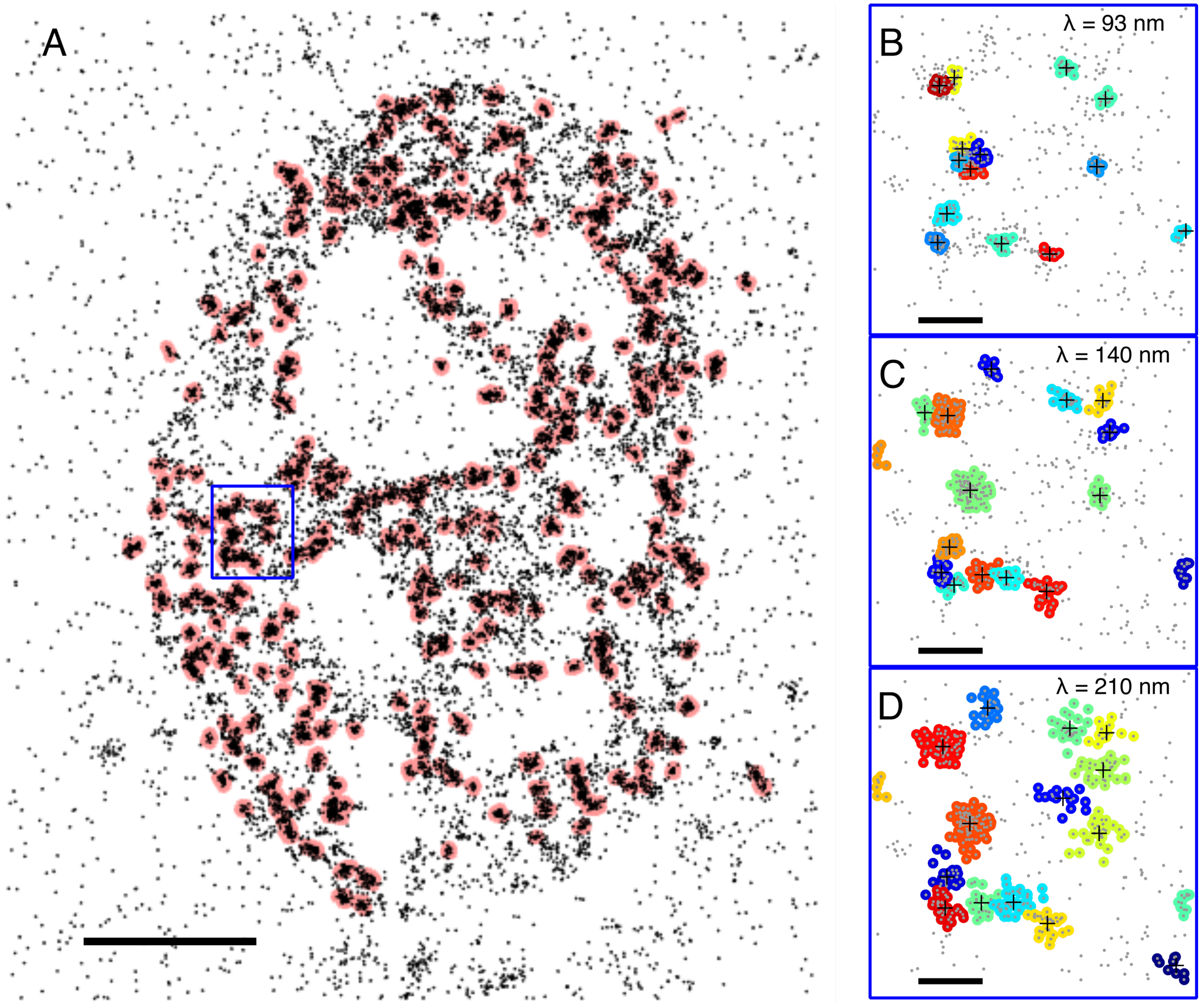


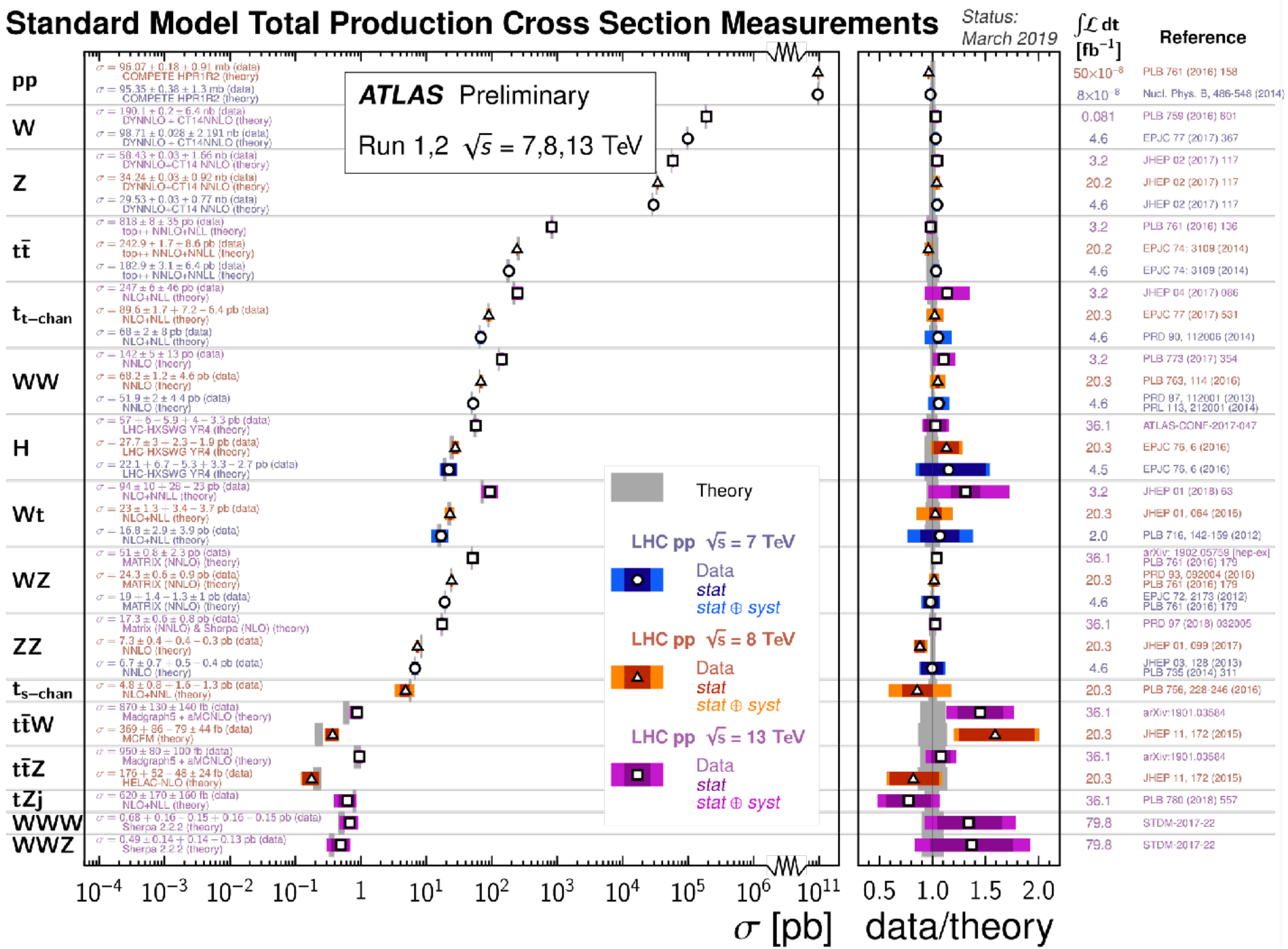
Figure S6: FastJet hierarchical clustering. (A) FastJet clusters found with a length scale of 140nm. (B-D) Zoomed in view of the region in the blue box from A. The clusters were generated by cutting the tree with a length scale of 93 nm, 140 nm, and 210 nm respectively. The black + signs mark the centroids of each cluster. Scale Bars – A: 5 μm B - D: 500 nm

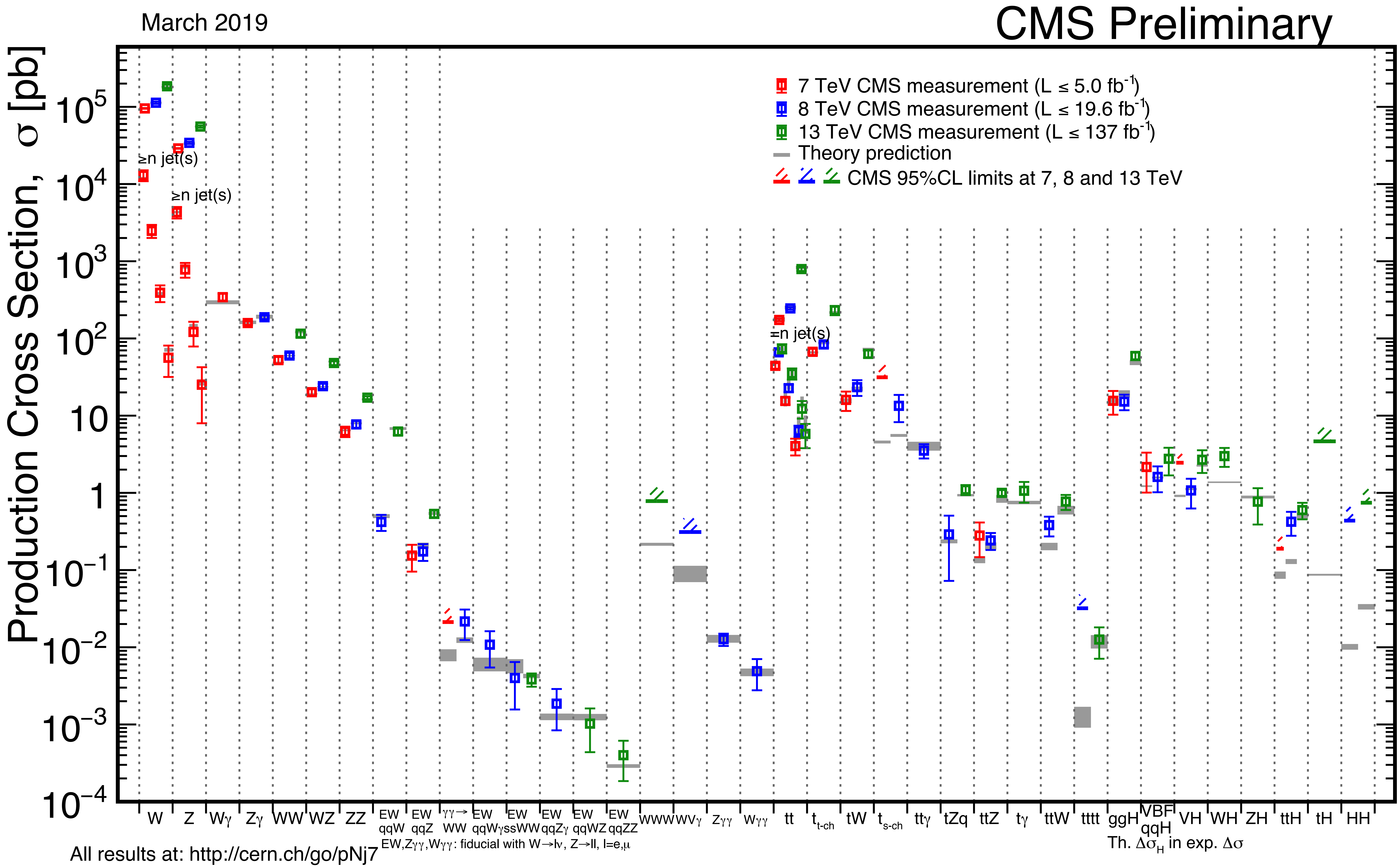
closing

does it work?

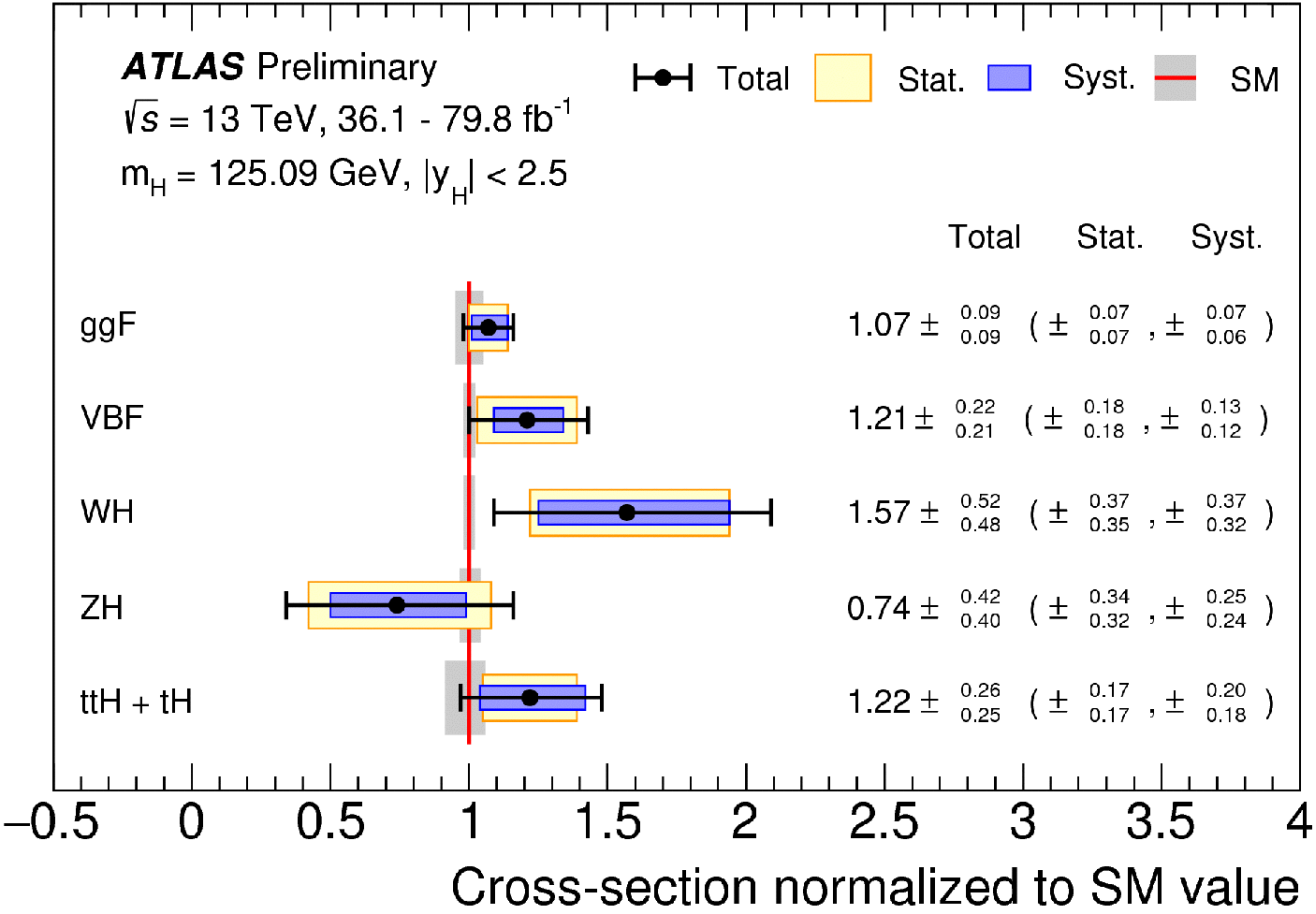
does it work sufficiently well?

vast array of LHC data agrees with QCD predictions

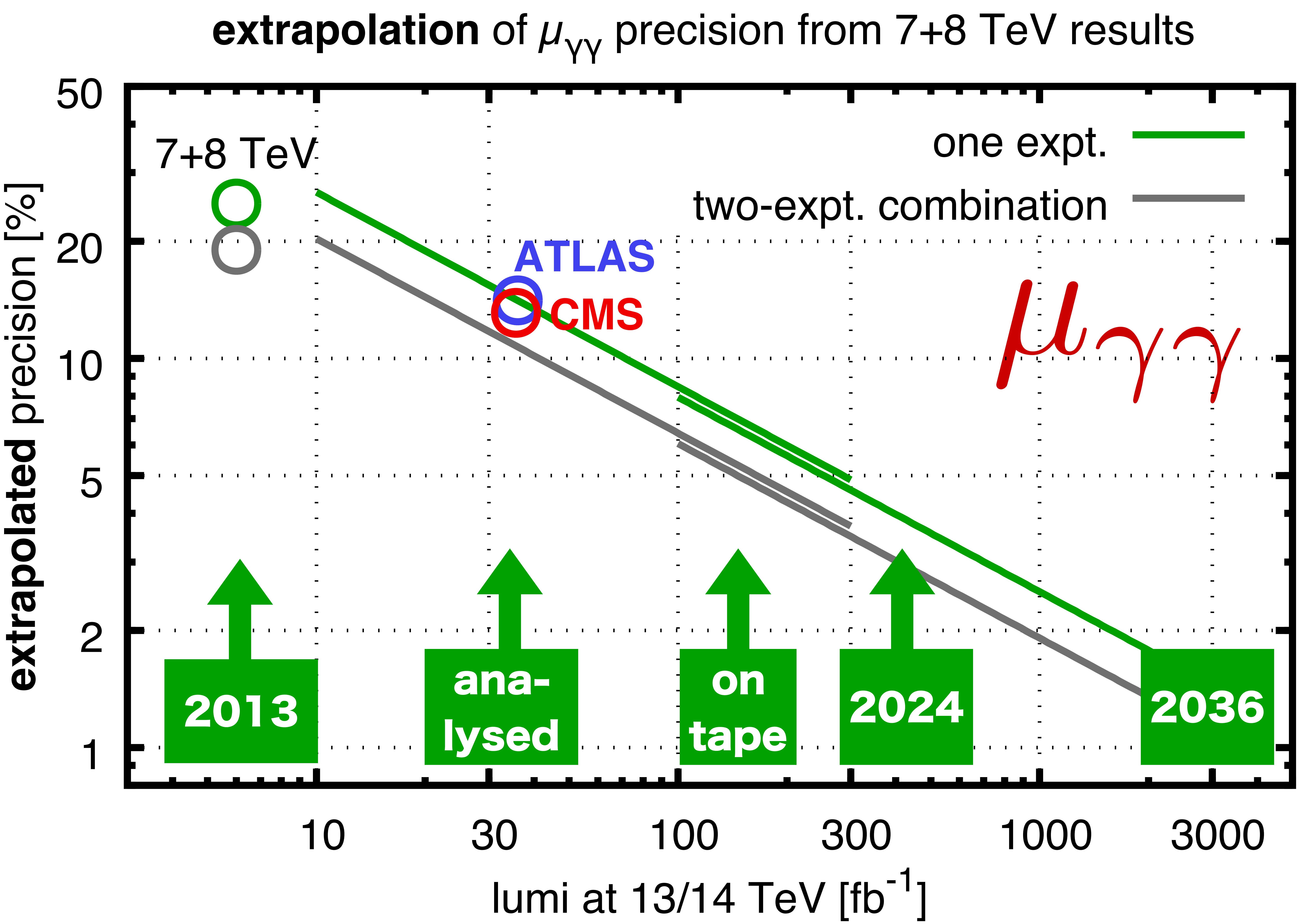



March 2019
CMS Preliminary
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
13 TeV CMS measurement (L ≤ 137 fb-1)
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
≥n jet(s)
≥n jet(s)
=n jet(s)
W Z Wγ Zγ WW WZ ZZ EW qqW EW qqZ γγ→WW EW qqWγ EW ssWW EW qqZγ EW qqWZ EW qqZZ WWW WVγ Zγγ Wγγ tt t t-ch tW t s-ch ttγ tZq ttZ tγ ttW tttt ggH VBF qqH VH WH ZH ttH tH HH
EW,Zγγ,Wγγ: fiducial with W→lν, Z→ll, l=e,μ
Th. ΔσH in exp. Δσ
All results at: http://cern.ch/go/pNj7

Higgs cross-sections v. QCD theory



Higgs precision (H → γγ) : optimistic estimate v. luminosity & time

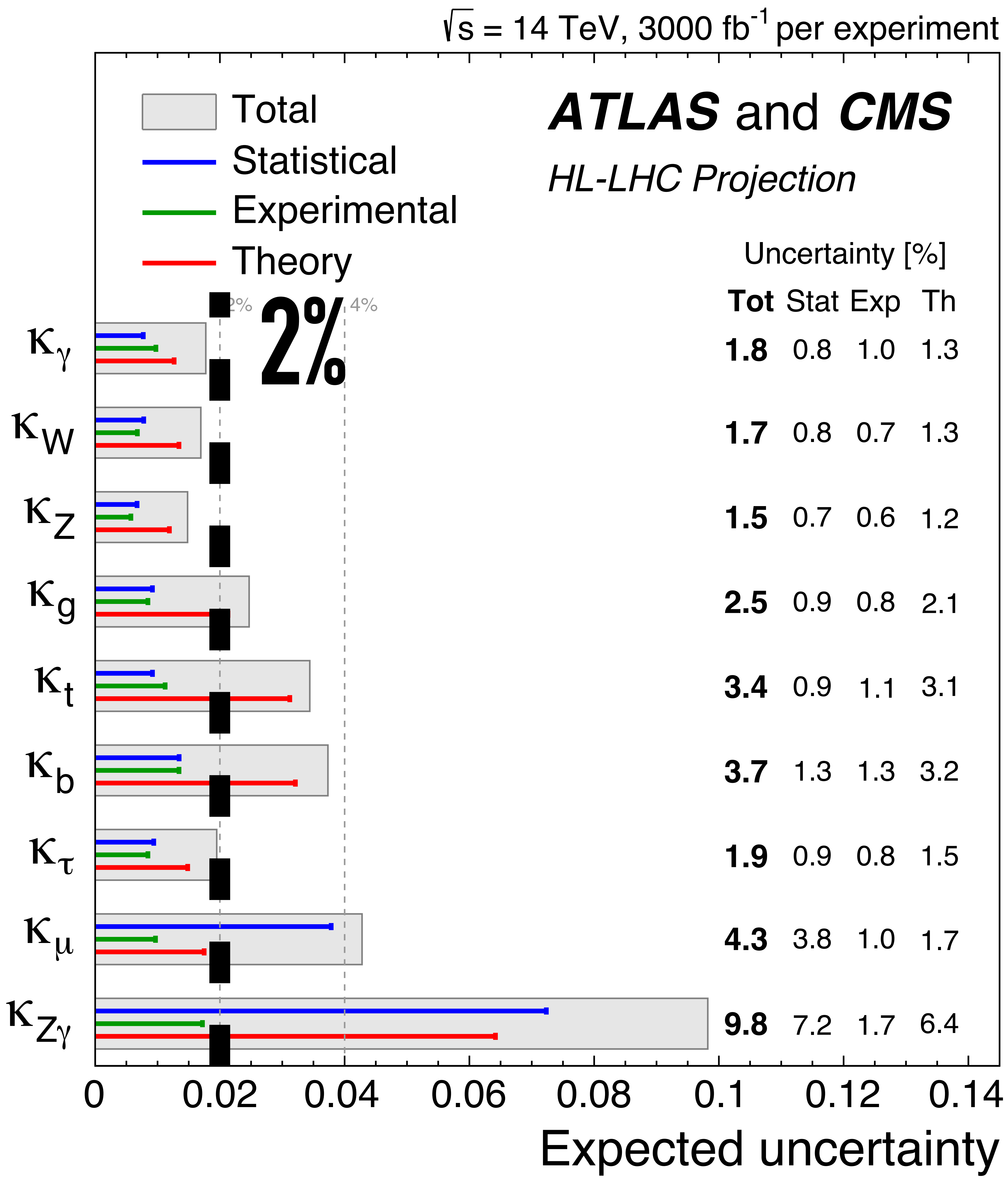


Today, Higgs coupling precisions are in the 10-20% range.

The LHC has the statistical potential to take Higgs physics from "observation" to 1–2% precision

1 fb^{-1} = 10^{14} collisions

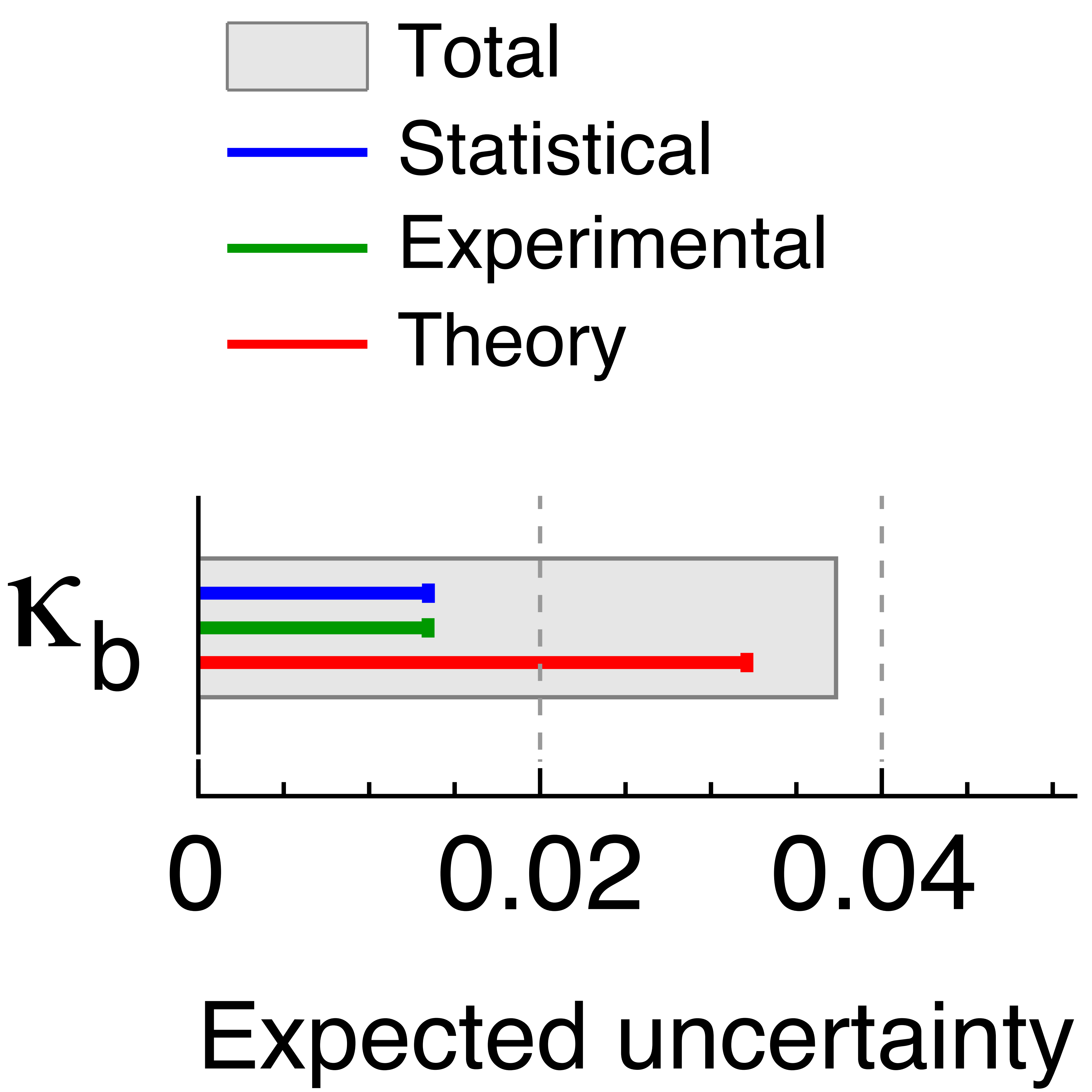
HL-LHC official Higgs coupling projections (by ~2036)



We wouldn't consider electromagnetism established (textbook level) if we only knew it to 10%

HL-LHC can deliver 1–2% for a range of couplings

HL-LHC official Higgs coupling projections (by ~2036)



We wouldn't consider electromagnetism established (textbook level) if we only knew it to 10%

HL-LHC can deliver 1–2% for a range of couplings

if theoretical interpretations can be made sufficiently accurate

theory (QCD) uncertainty dominates, even with an assumption of ×2 improvement by 2030s

can we ensure that QCD is up to the task?