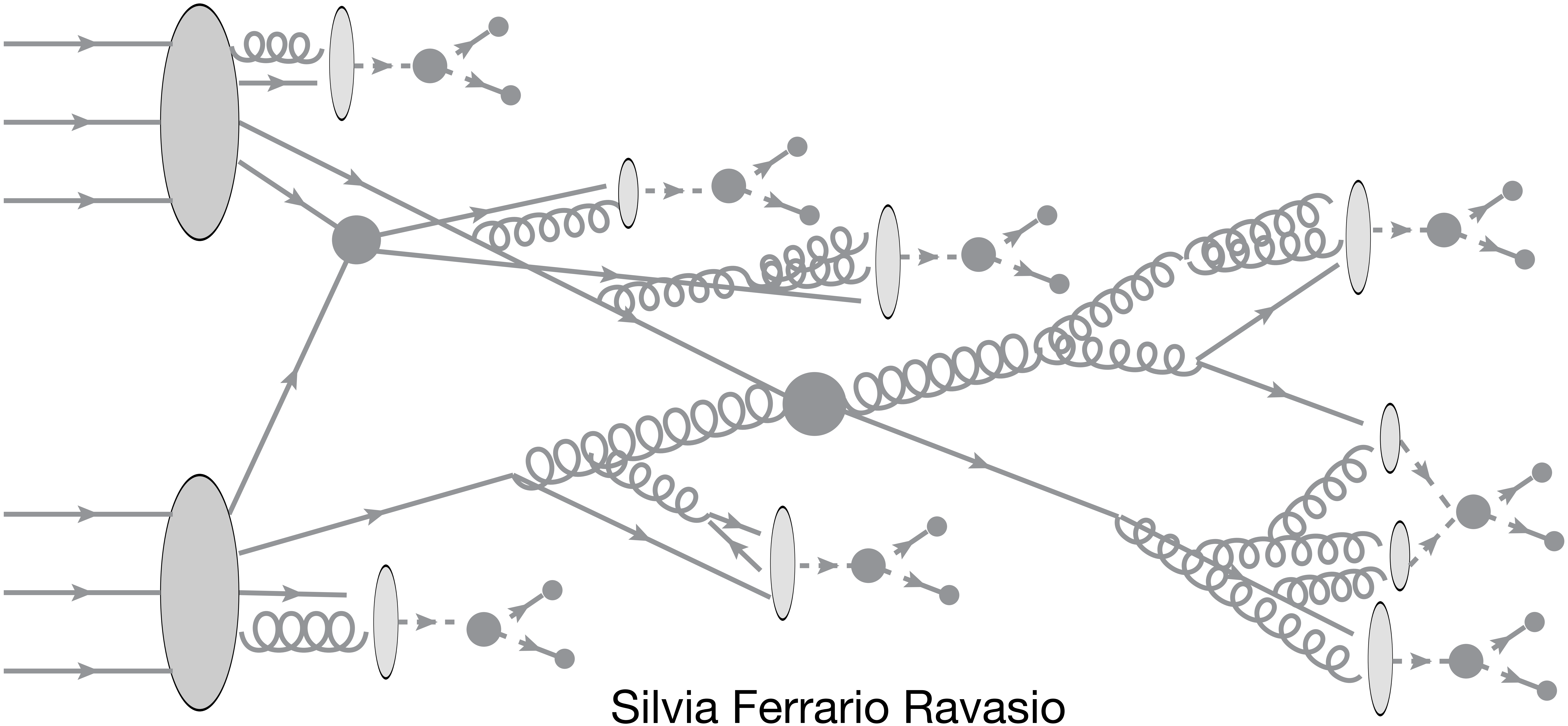
Shower Monte Carlo Event Generators



Silvia Ferrario Ravasio

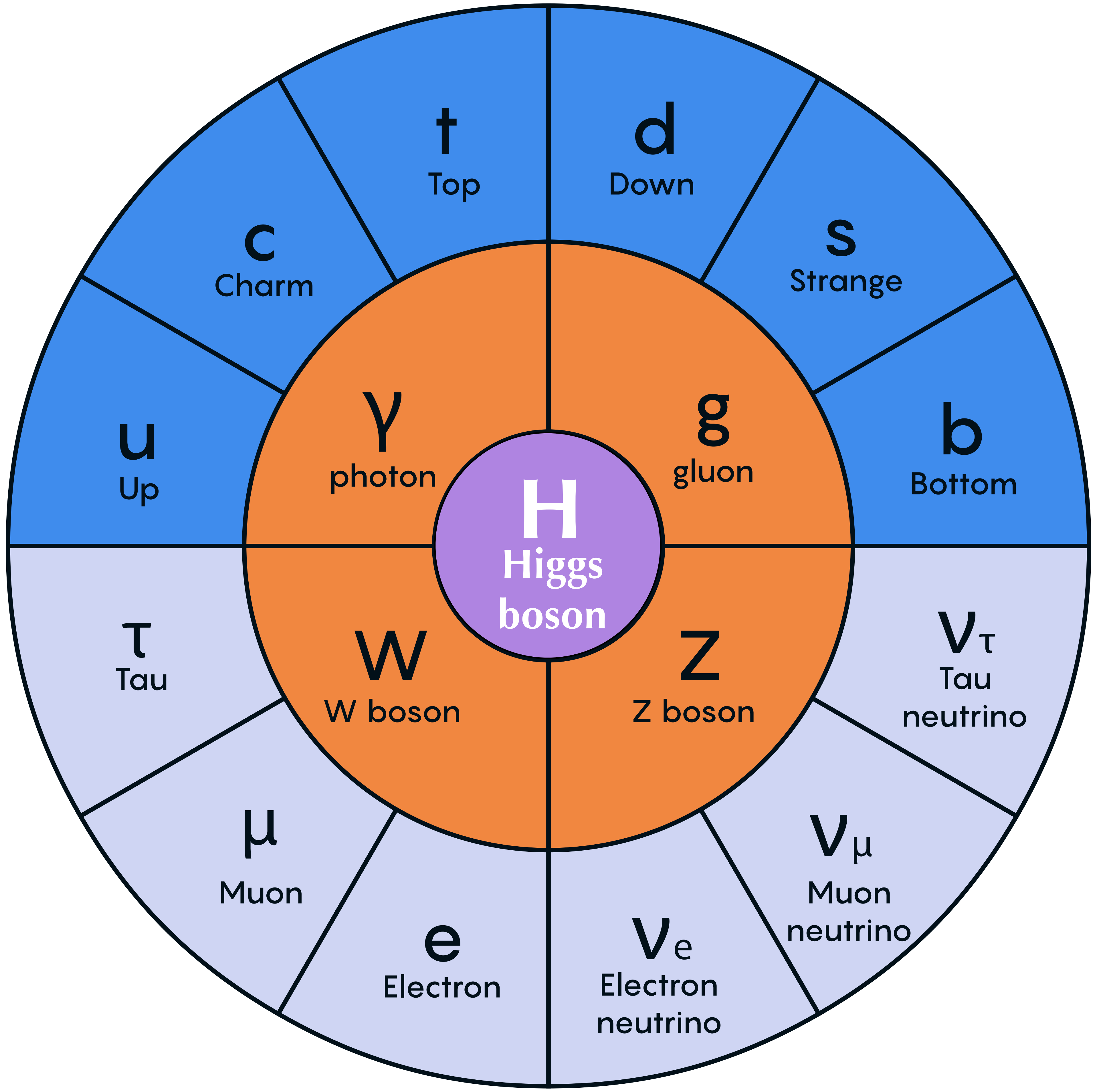
DESY Theory Workshop 2025:

Synergies towards the future Standard Model

23rd September 2025, **DESY, Hamburg (DE)**

The Standard Model of Particle Physics

The **STANDARD MODEL** encapsulates our understanding of the fundamental interactions between elementary particles

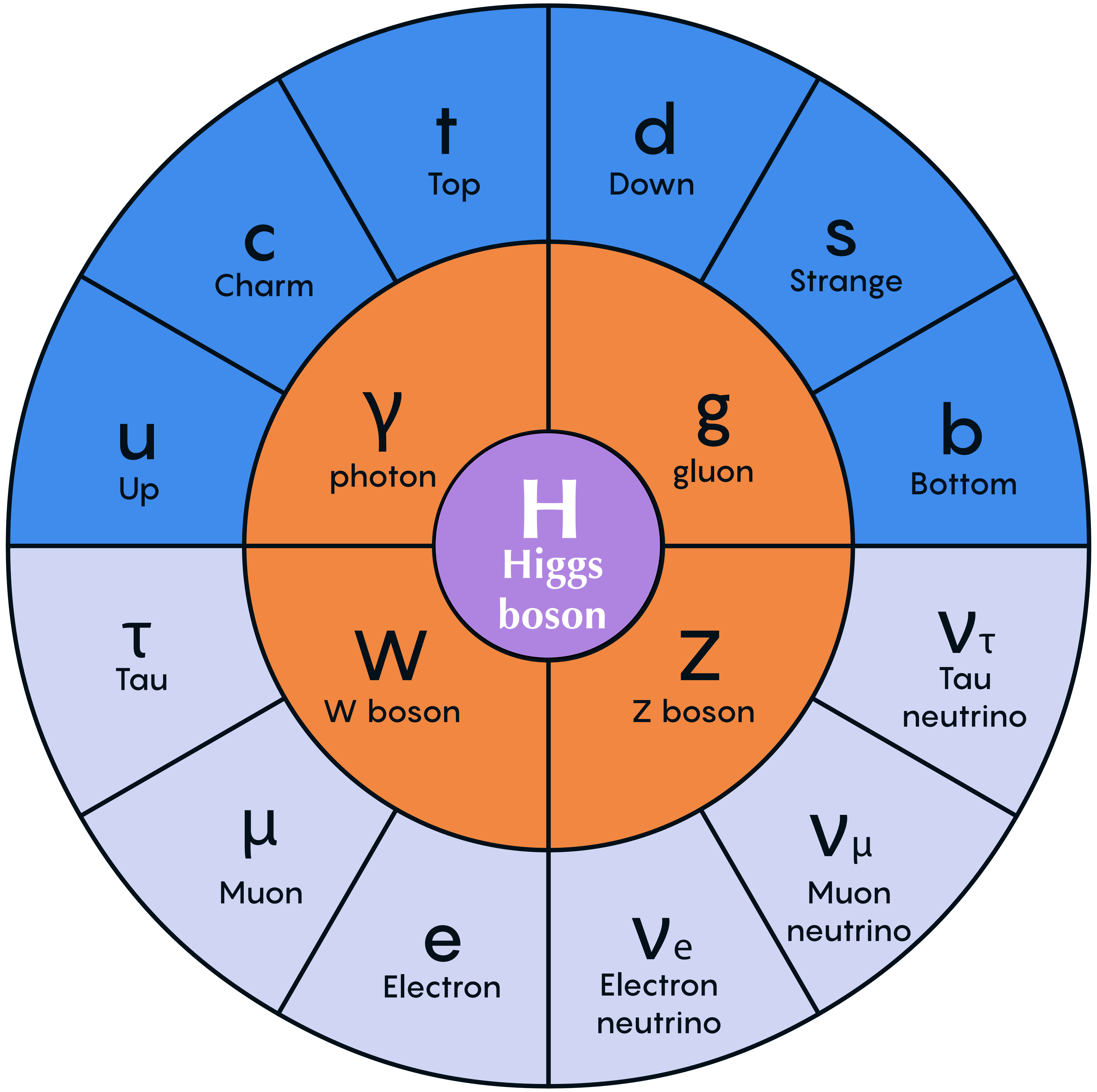


Higgs boson

Last missing piece discovered in 2012

The Standard Model of Particle Physics

The **STANDARD MODEL** encapsulates our understanding of the **fundamental interactions** between **elementary particles**

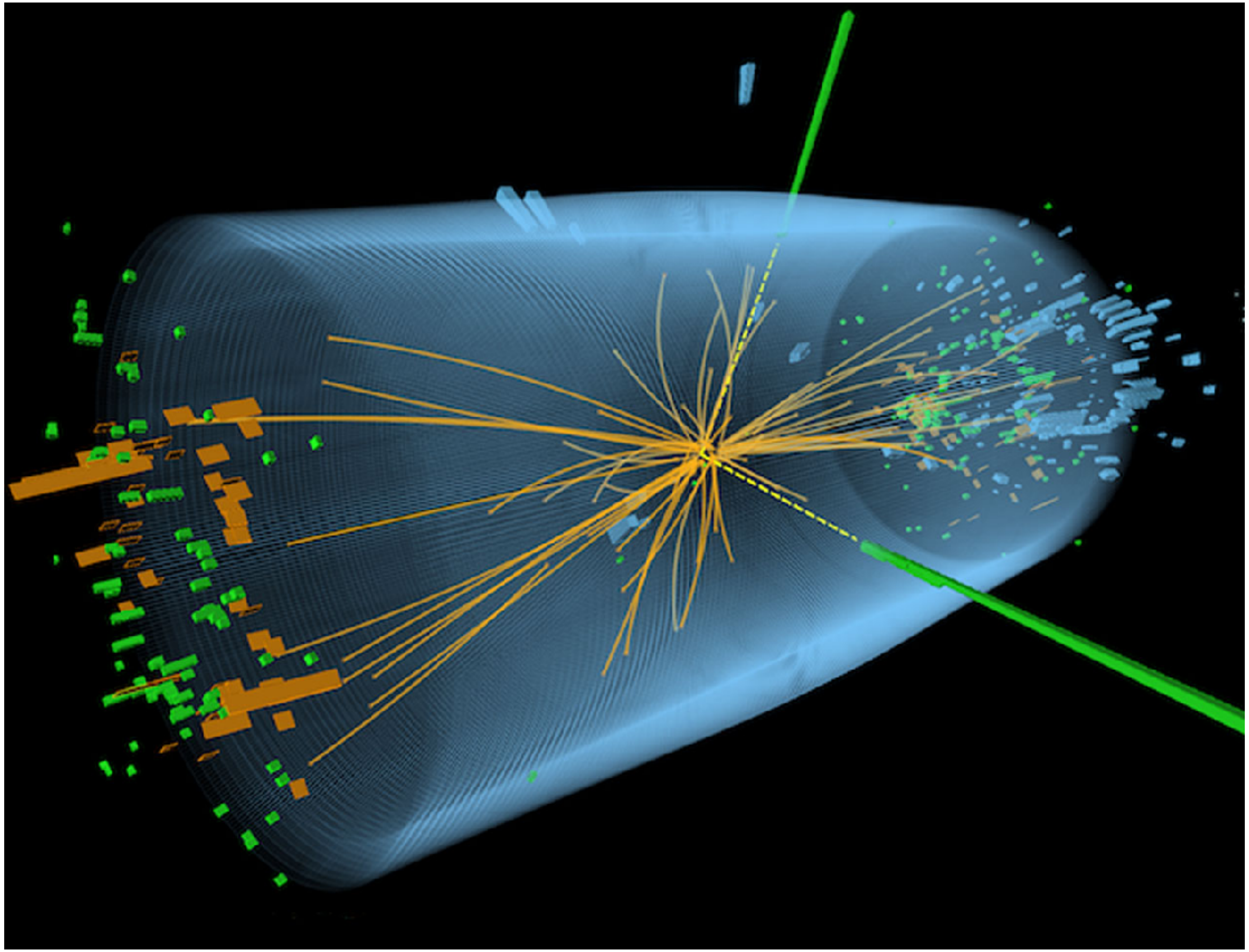


Higgs boson
Last missing piece
discovered in 2012

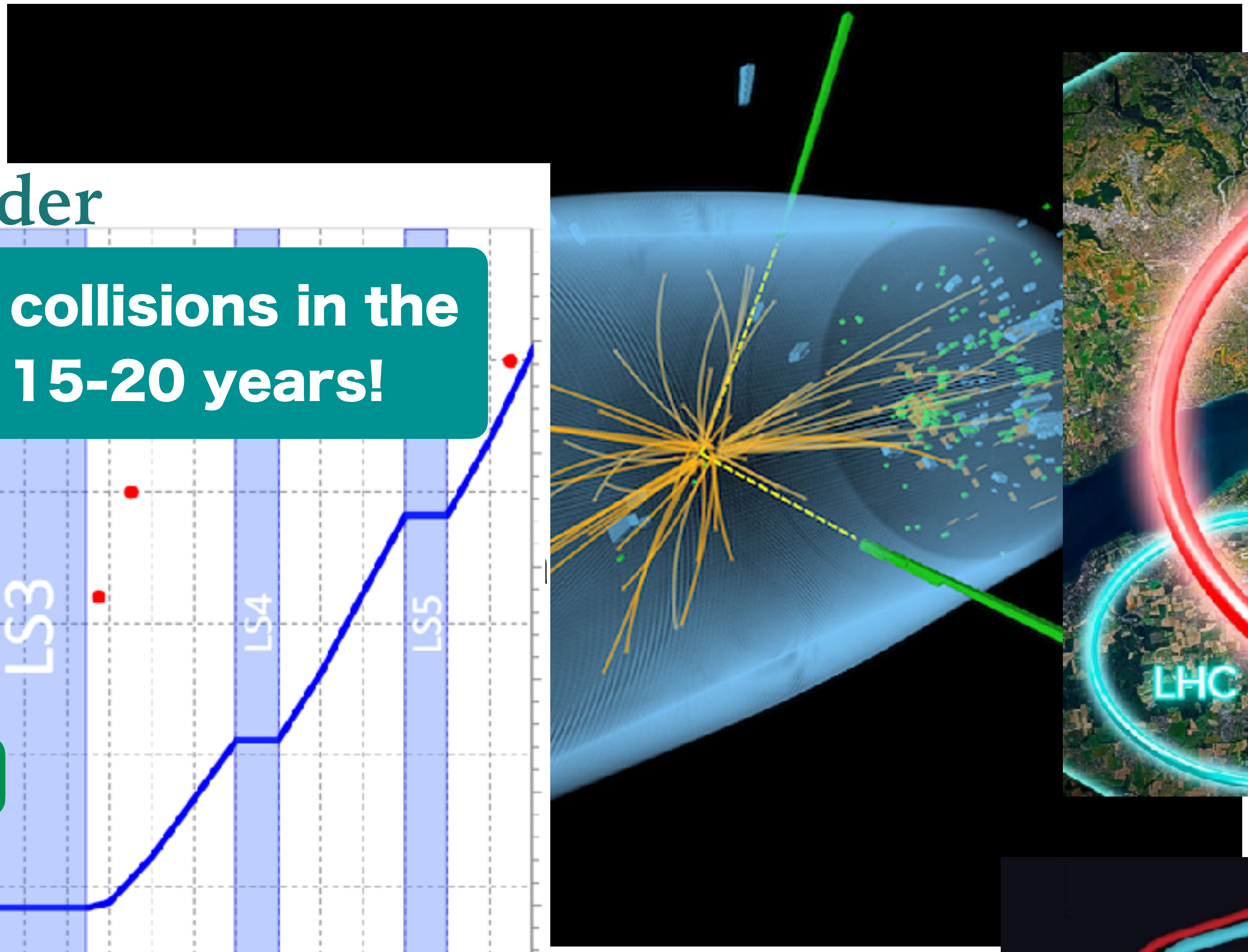
1. **Is the Standard Model complete?**
   No! Dark matter, Gravity, Neutrino Masses, Hieararchy…
2. **Is the Standard Model fully established?**
   No! Most of the **Higgs properties** not yet (precisely) measured; **non-perturbative QCD**

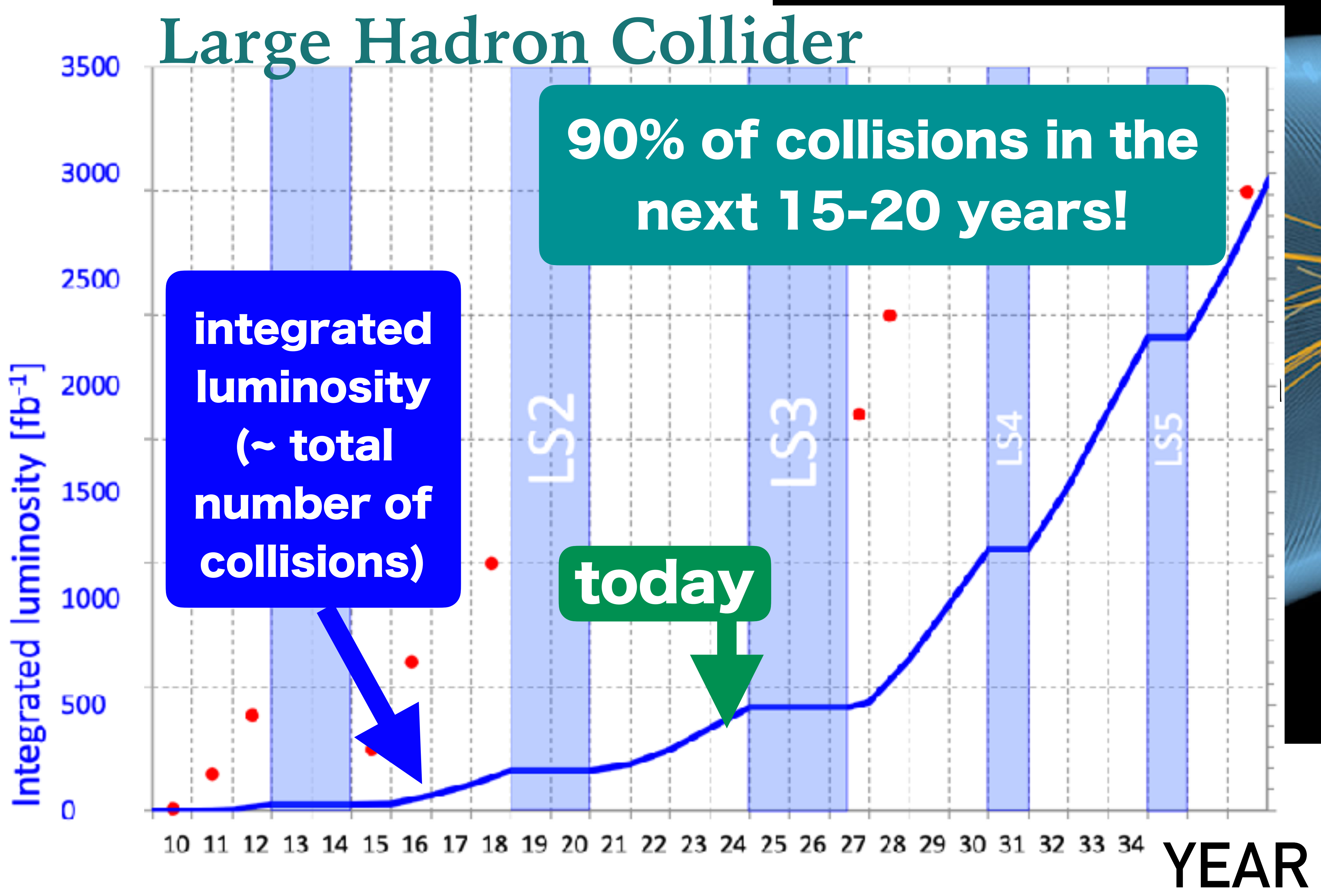
Collider phenomenology

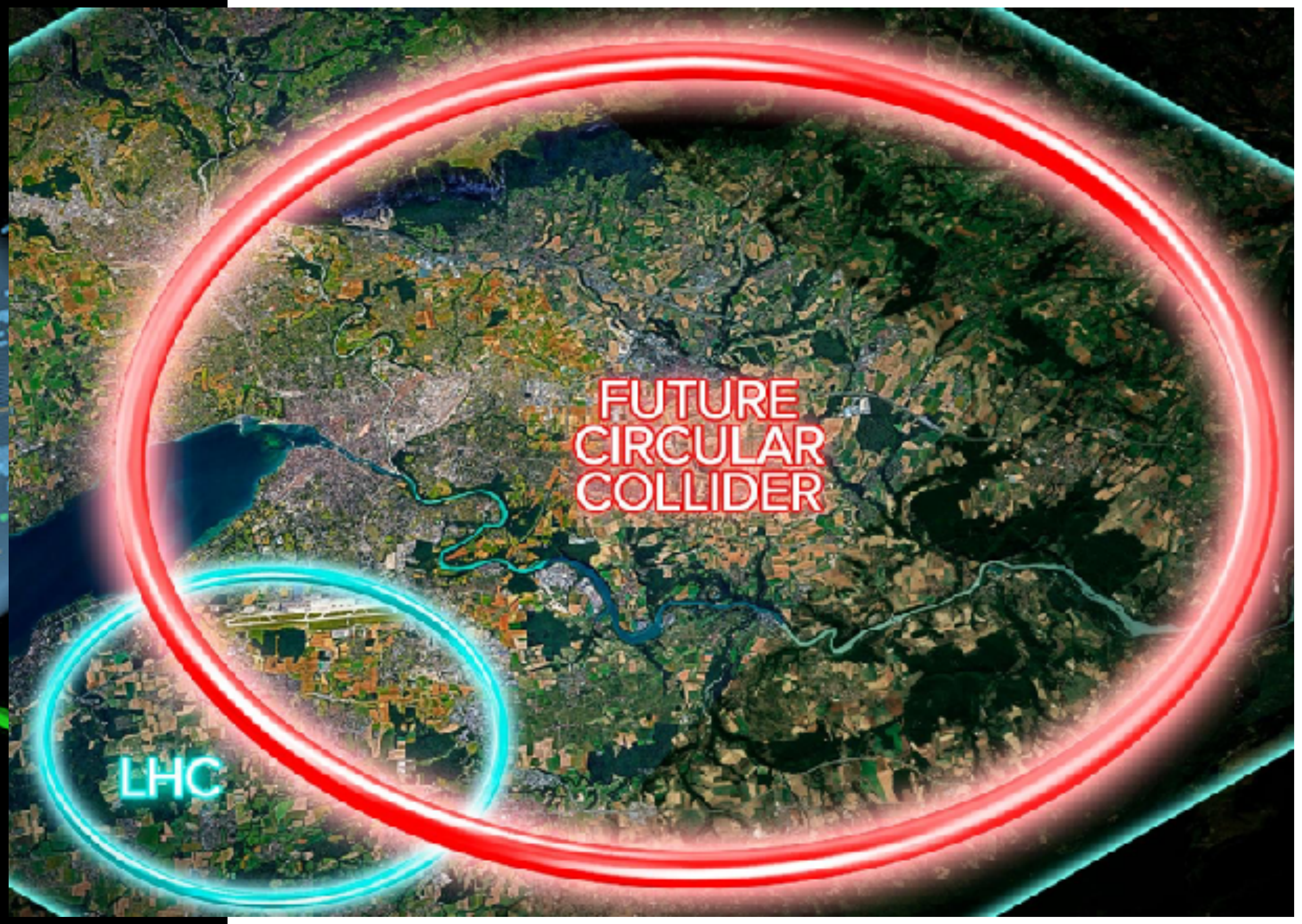
Particle Colliders probe fundamental interactions

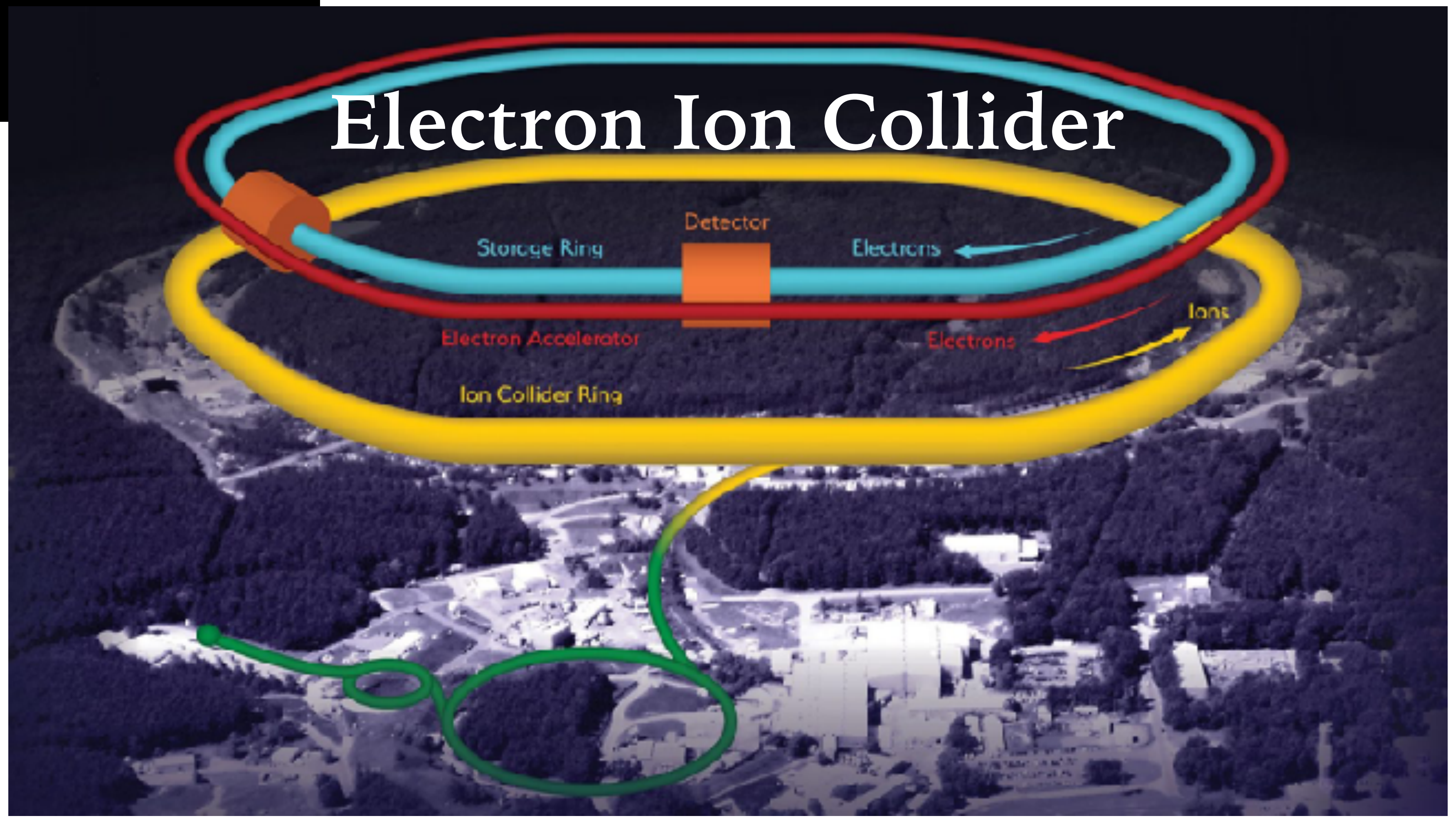


PARTICLE COLLIDERS probe fundamental interactions



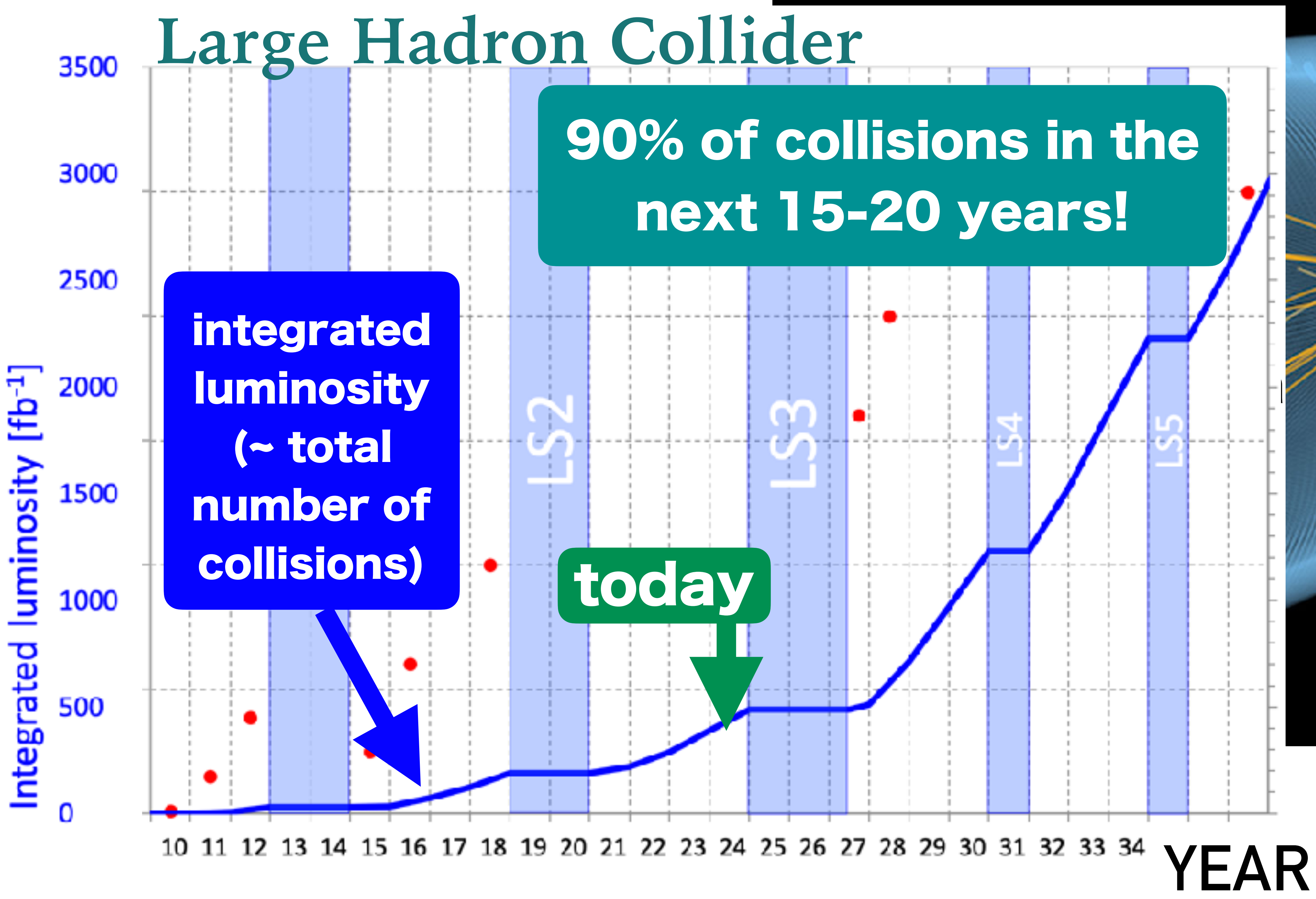


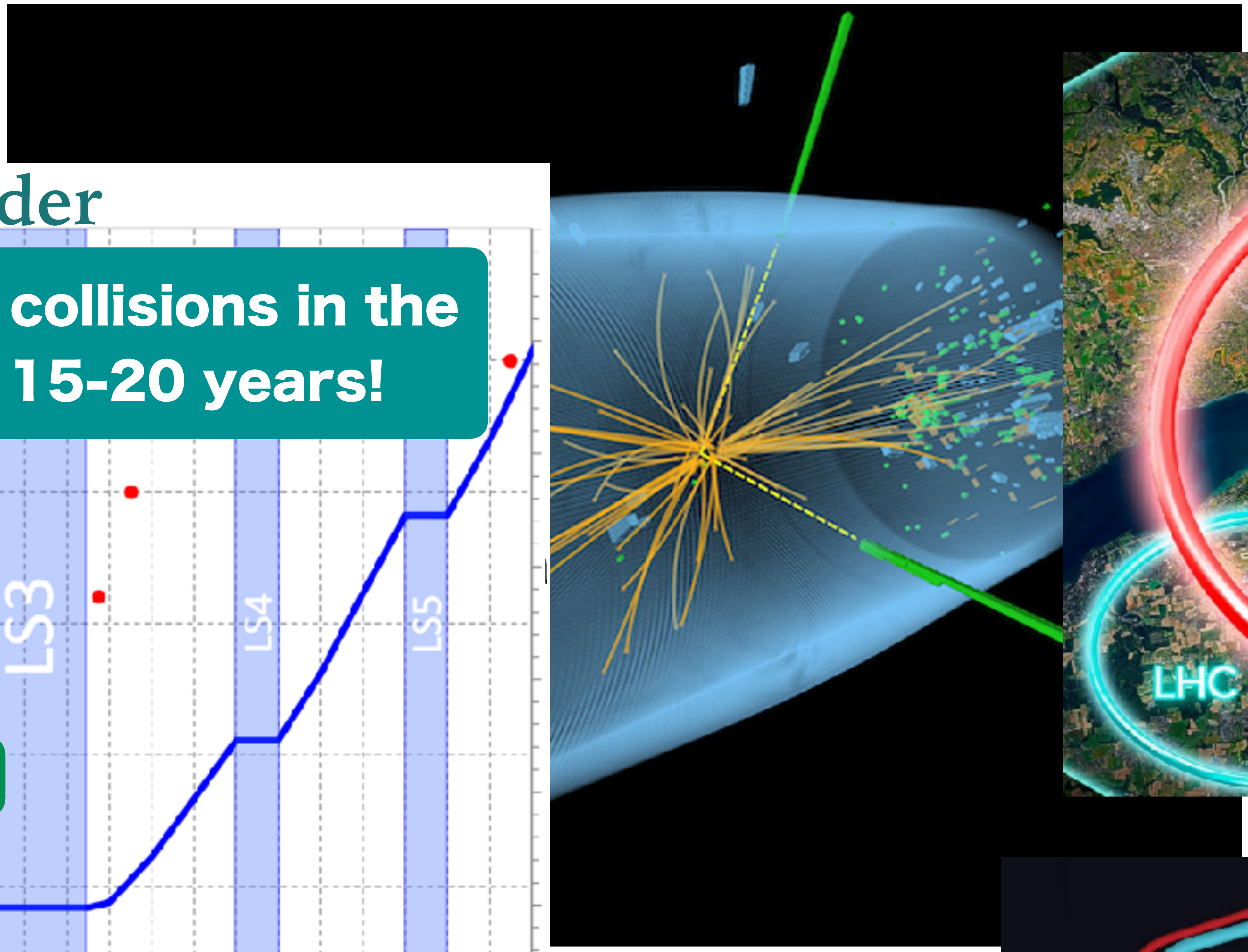


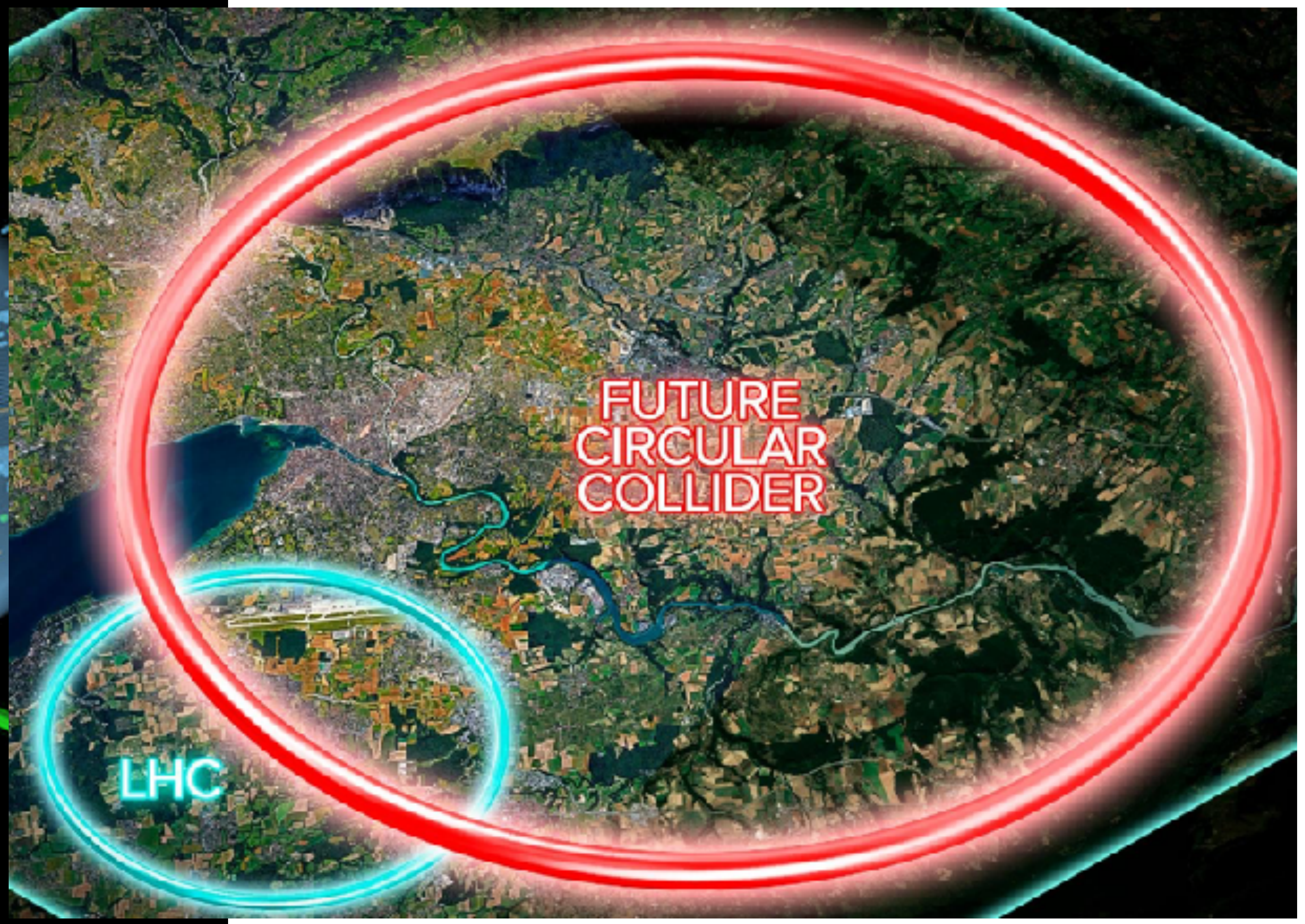


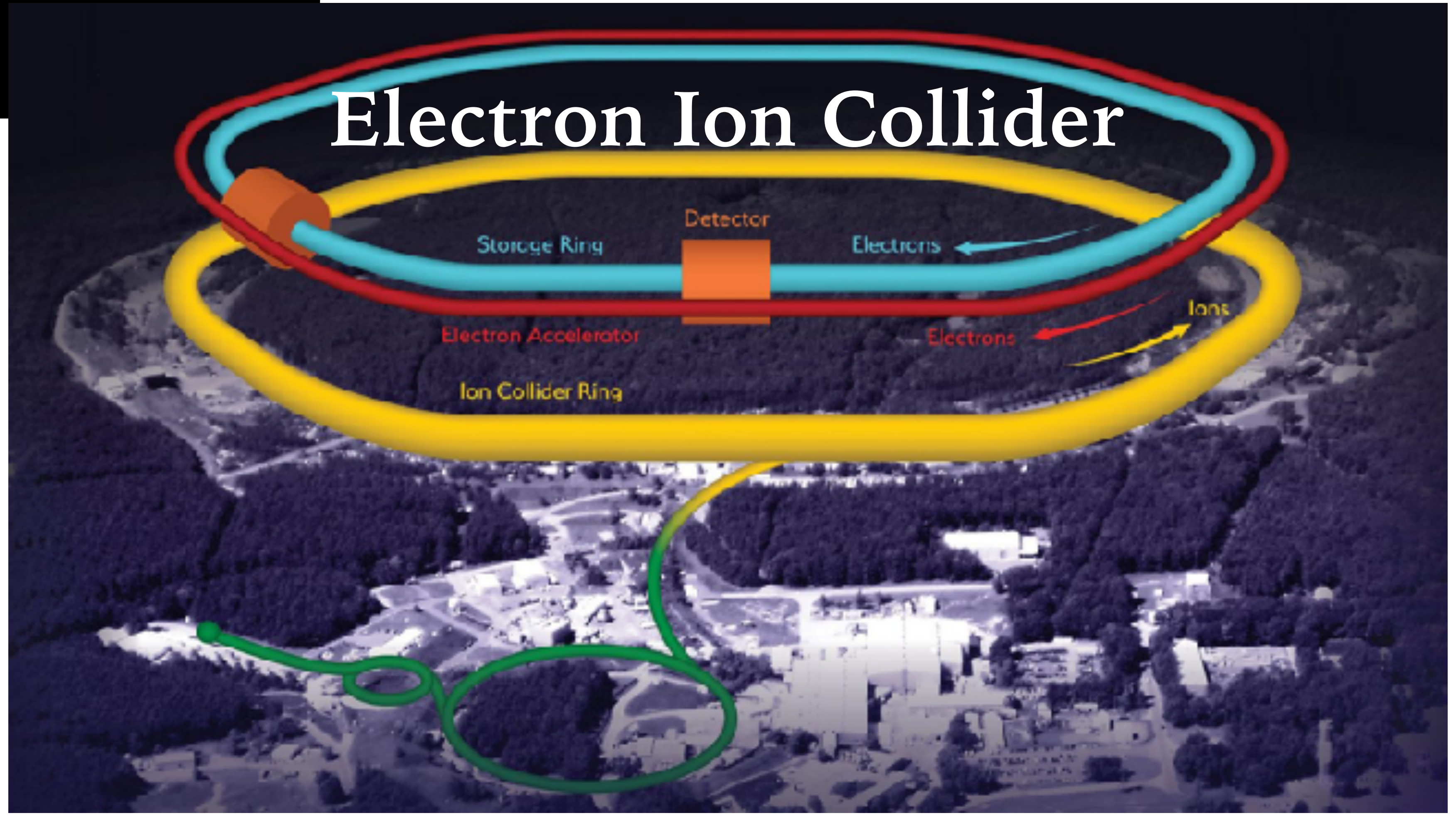
Collider phenomenology

PARTICLE COLLIDERS probe fundamental interactions





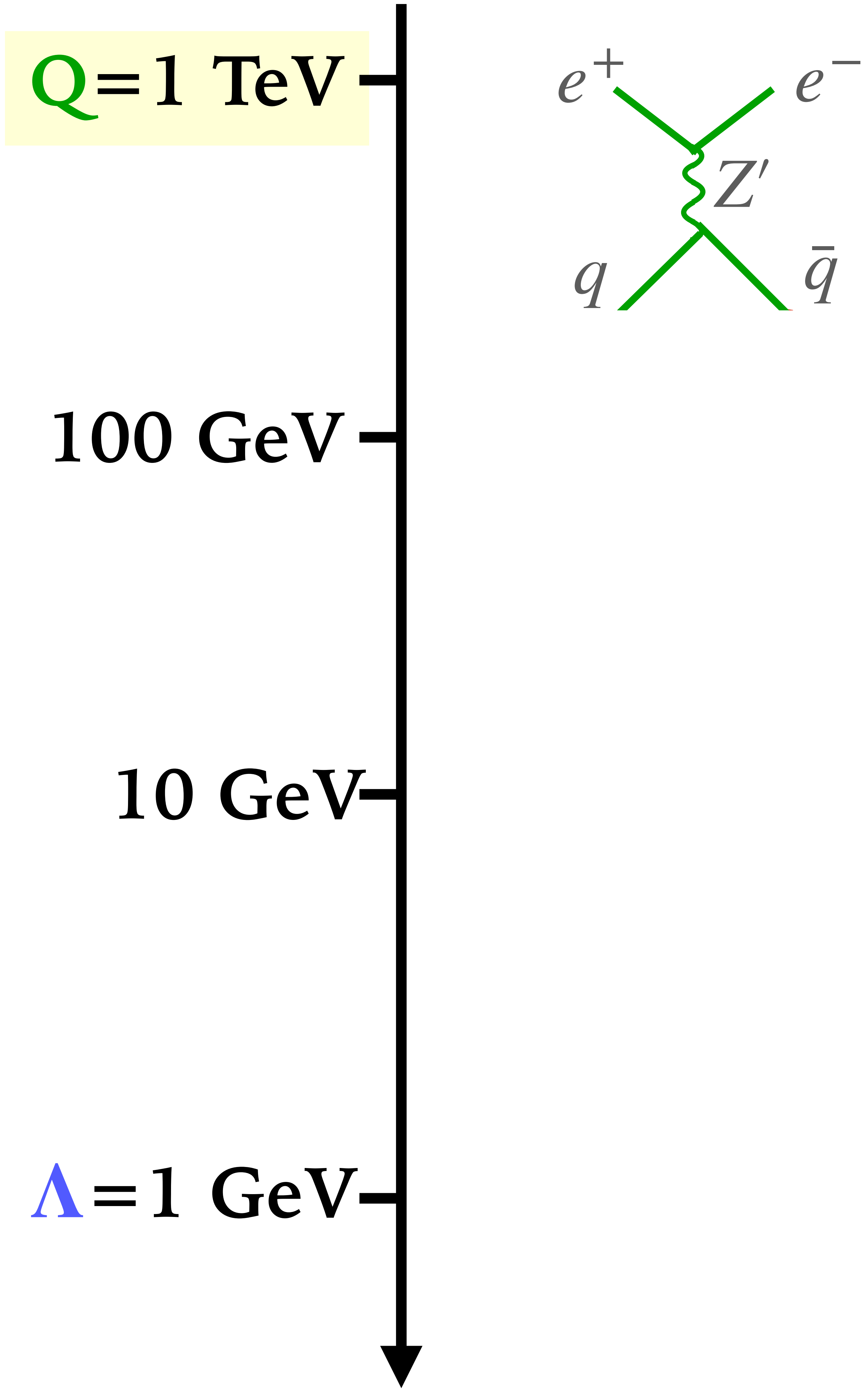




To interpret the data and evaluate the capabilities of future colliders it is paramount to have **accurate theoretical predictions**!

The physics of colliders

Hard process

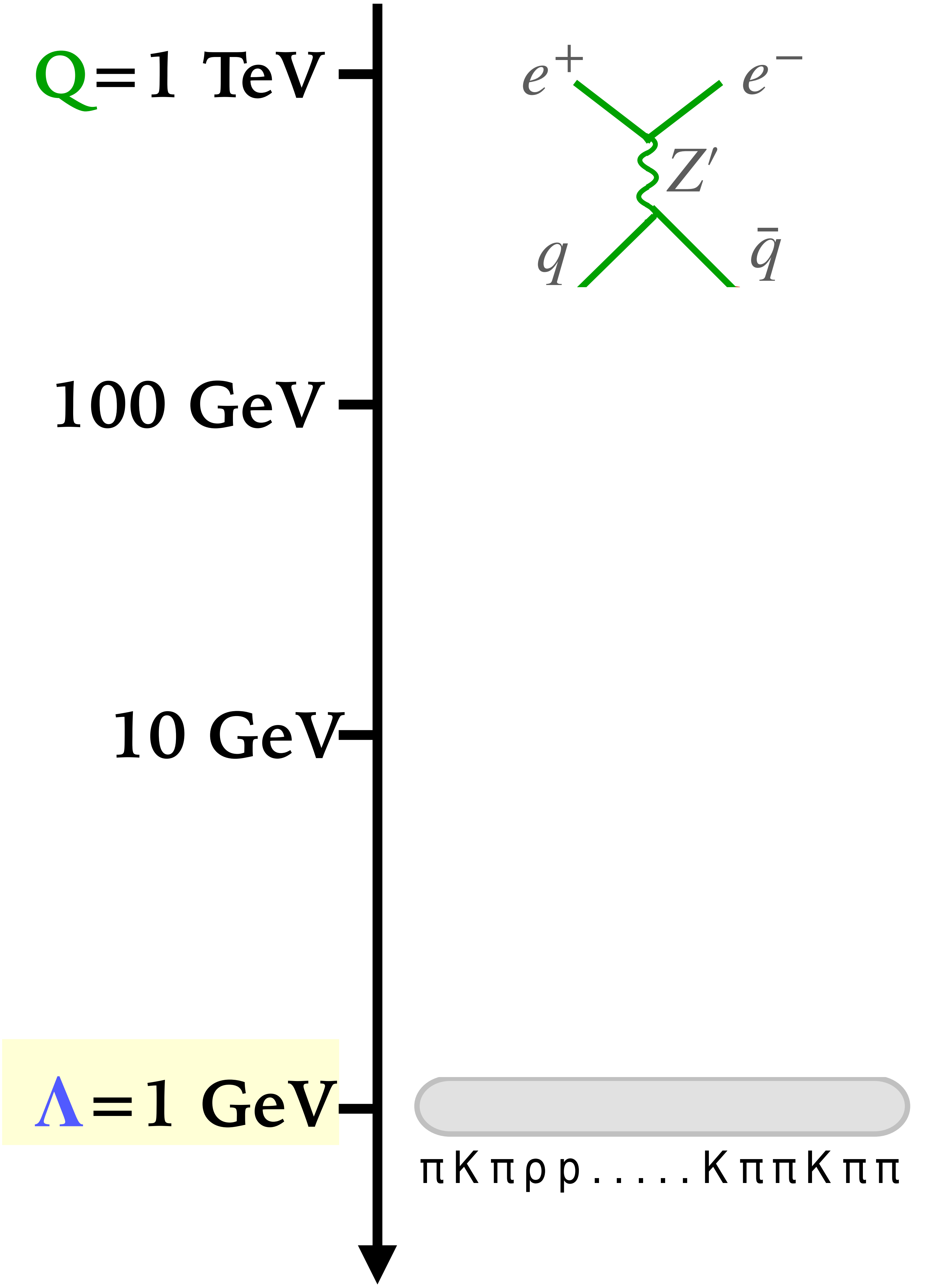


What we are interested in

The physics of colliders

Hard process

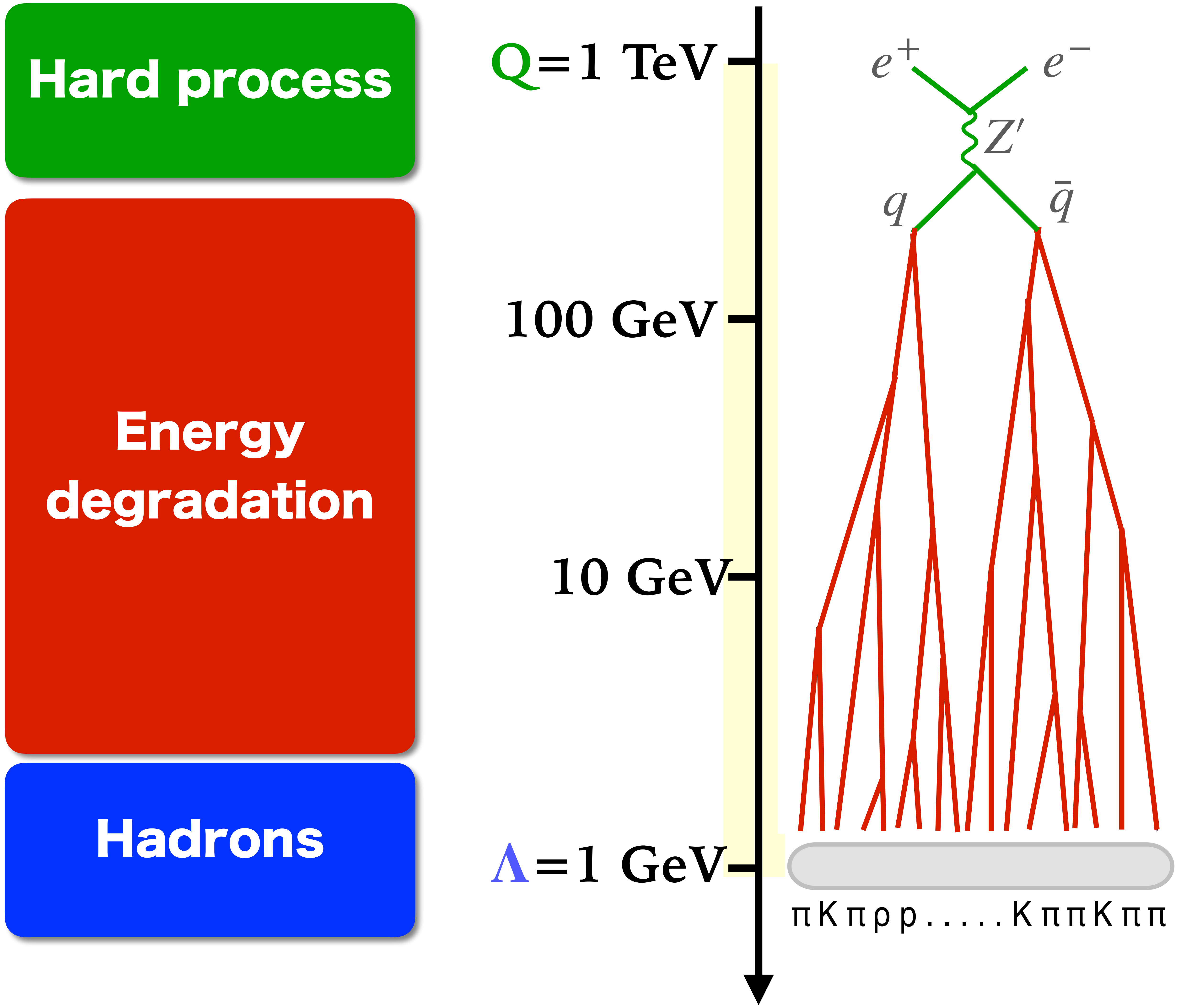
What we are interested in



Hadrons

What is measured

The physics of colliders



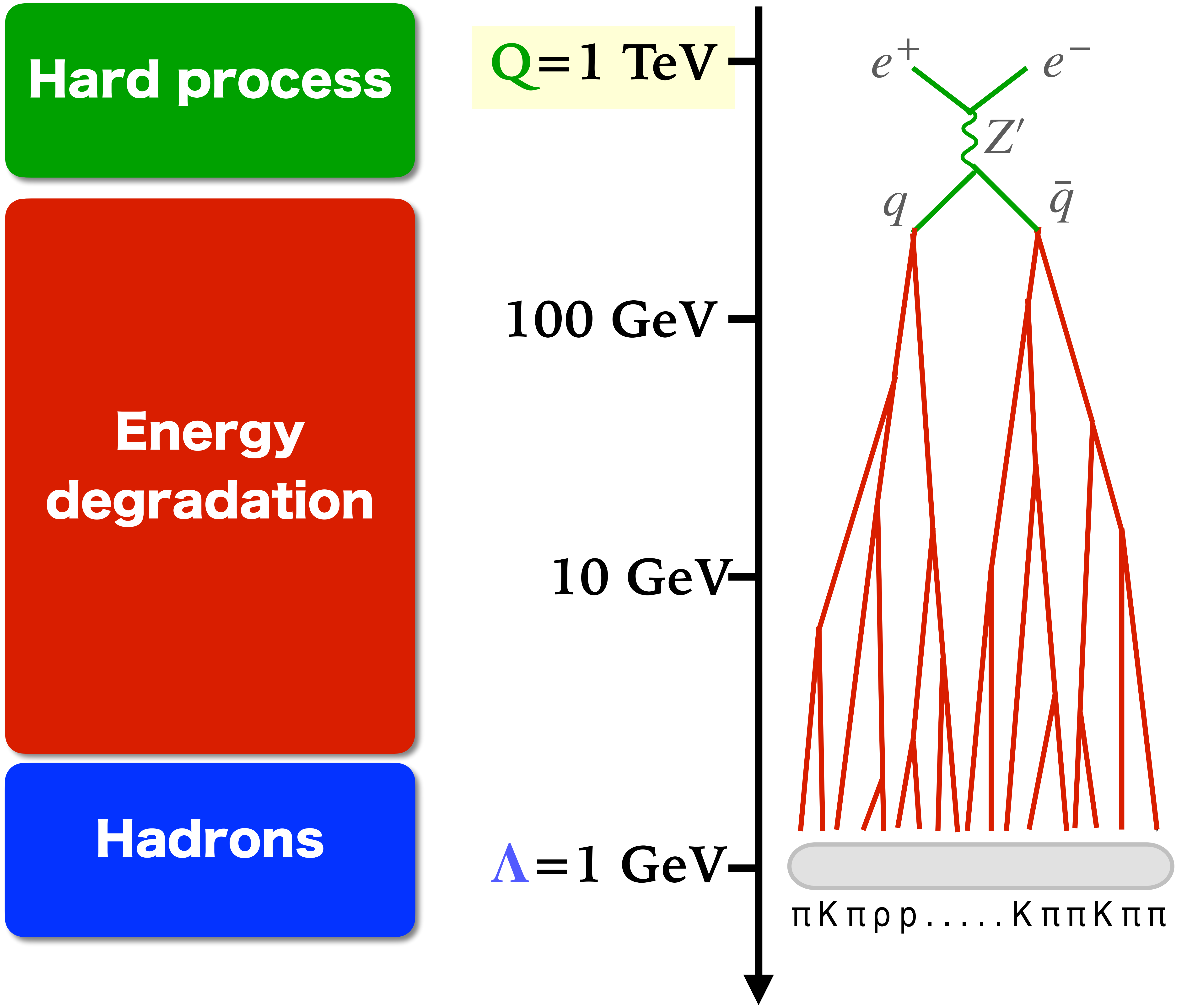
What we are interested in

What happens in between

What is measured

The physics of colliders

Theorists' description



$\alpha_s \ll 1$
Perturbation theory
$\Sigma_{\rm LO} + \alpha_s \Sigma_{\rm NLO} + \ldots$

What we are interested in

What happens in between

What is measured

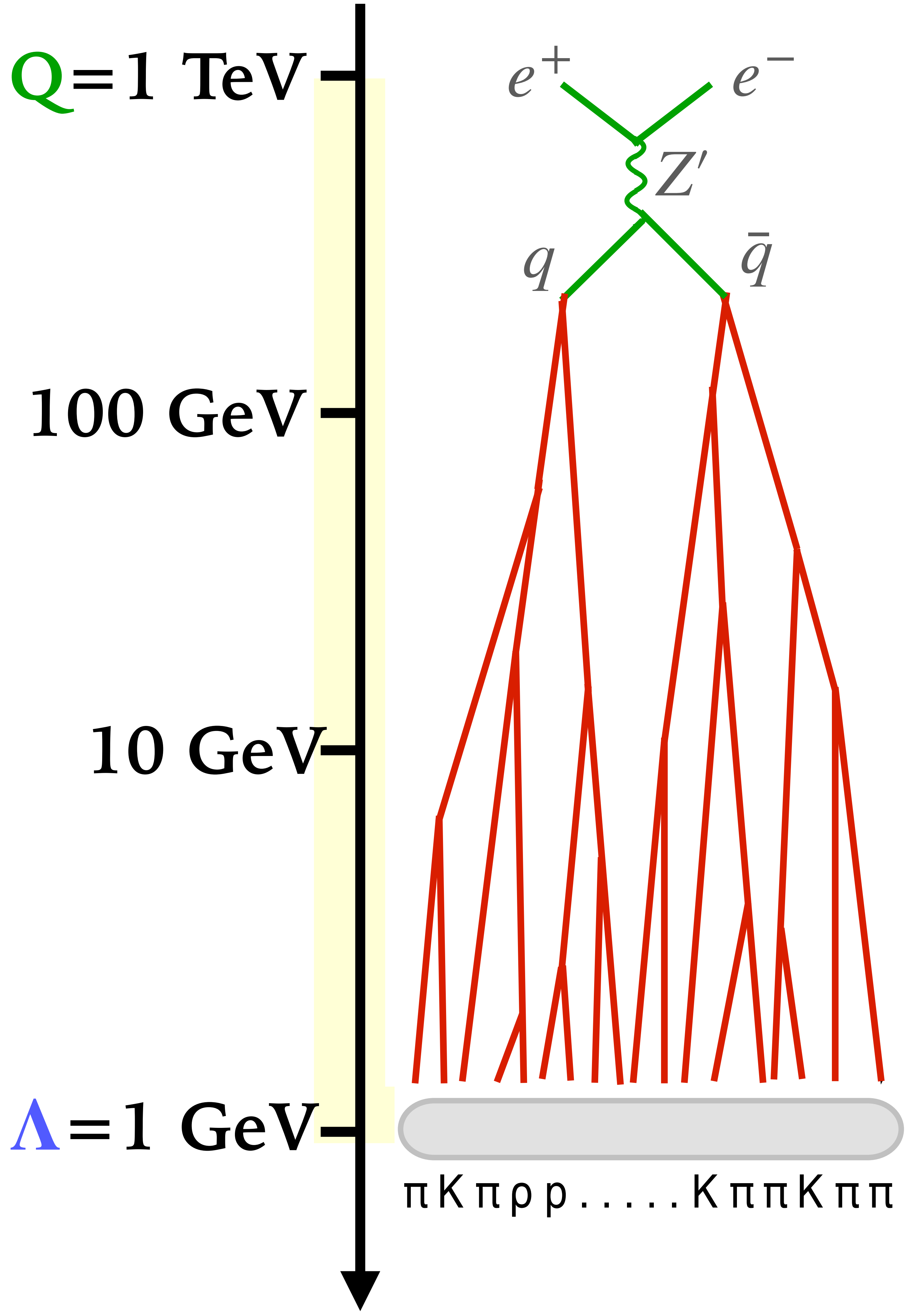
The physics of colliders

Theorists' description

Hard process

Energy degradation

Hadrons



$\alpha_s \ll 1$

Perturbation theory

$\Sigma_{\mathrm{LO}} + \alpha_s \Sigma_{\mathrm{NLO}} + \ldots$

What we are interested in

$L = \ln Q/\Lambda \sim 1/\alpha_s$

all-orders

resummation

Leading Order →

Leading Logarithms

$\mathrm{LL} = (\alpha_s L)^n L$

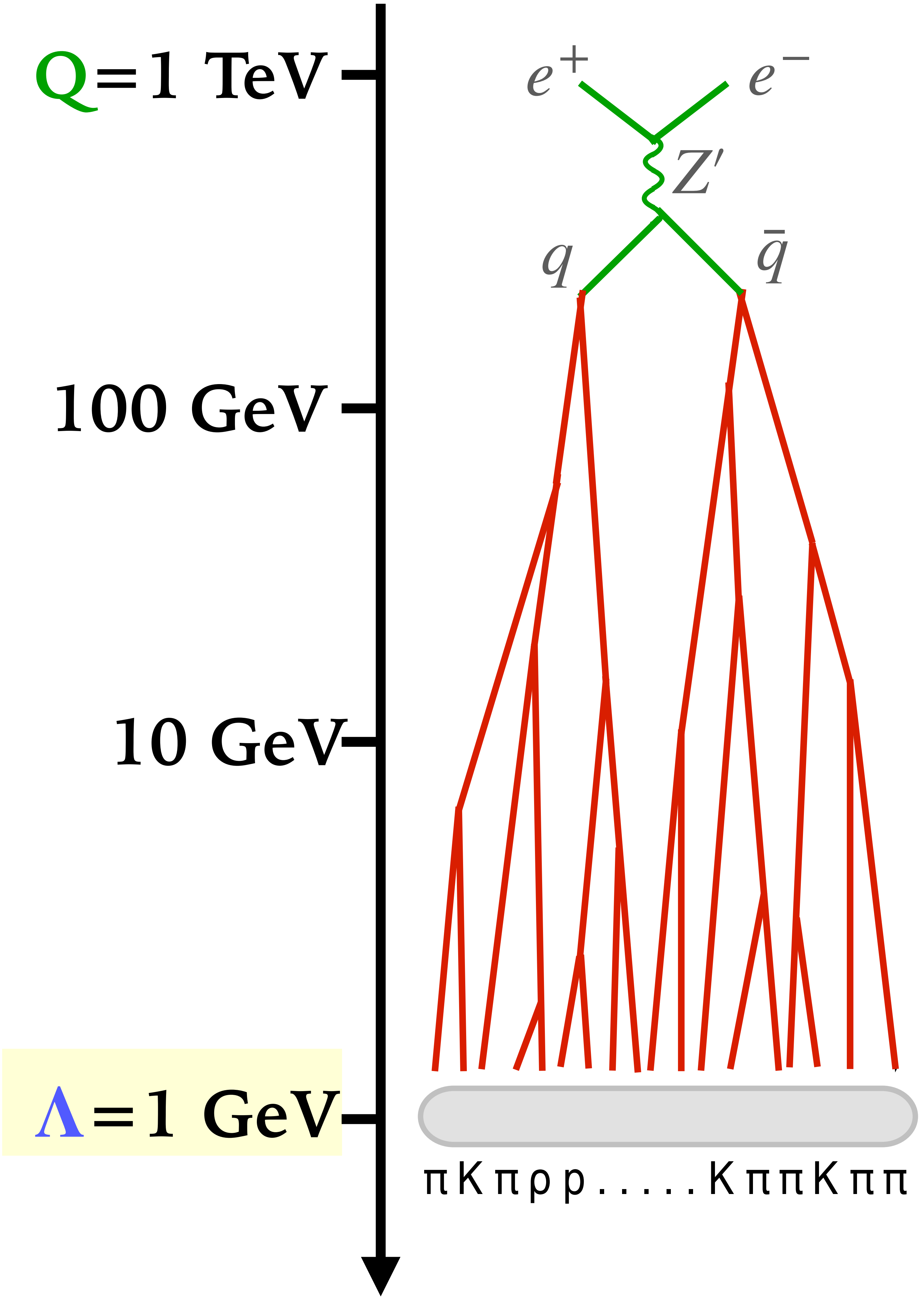
What happens in between

What is measured

The physics of colliders

<u>Theorists' description</u>

Hard process



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Leading Order → Leading Logarithms
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What happens in between

Hadrons

$\alpha_s \gg 1$
Non-perturbative QCD

What is measured

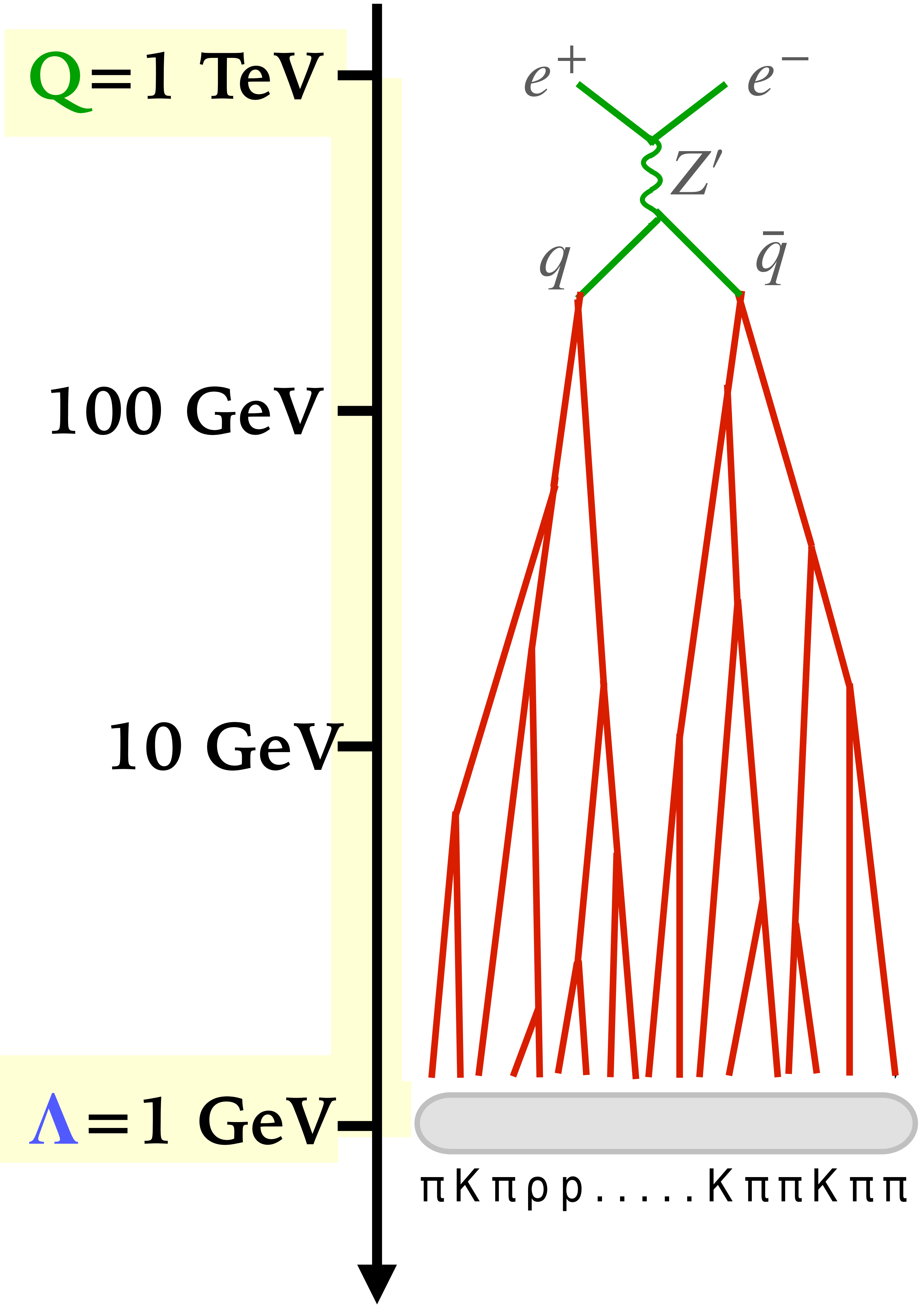
The physics of colliders

Theorists' description

Hard process

Energy degradation

Hadrons



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$\alpha_s \gg 1$
Non-perturbative
QCD

__SHOWER MONTE CARLO__ event generators are the only **theoretical framework** comprising all these ingredients, to produce predictions for arbitrary physical observable!

Default theoretical tool at the LHC!

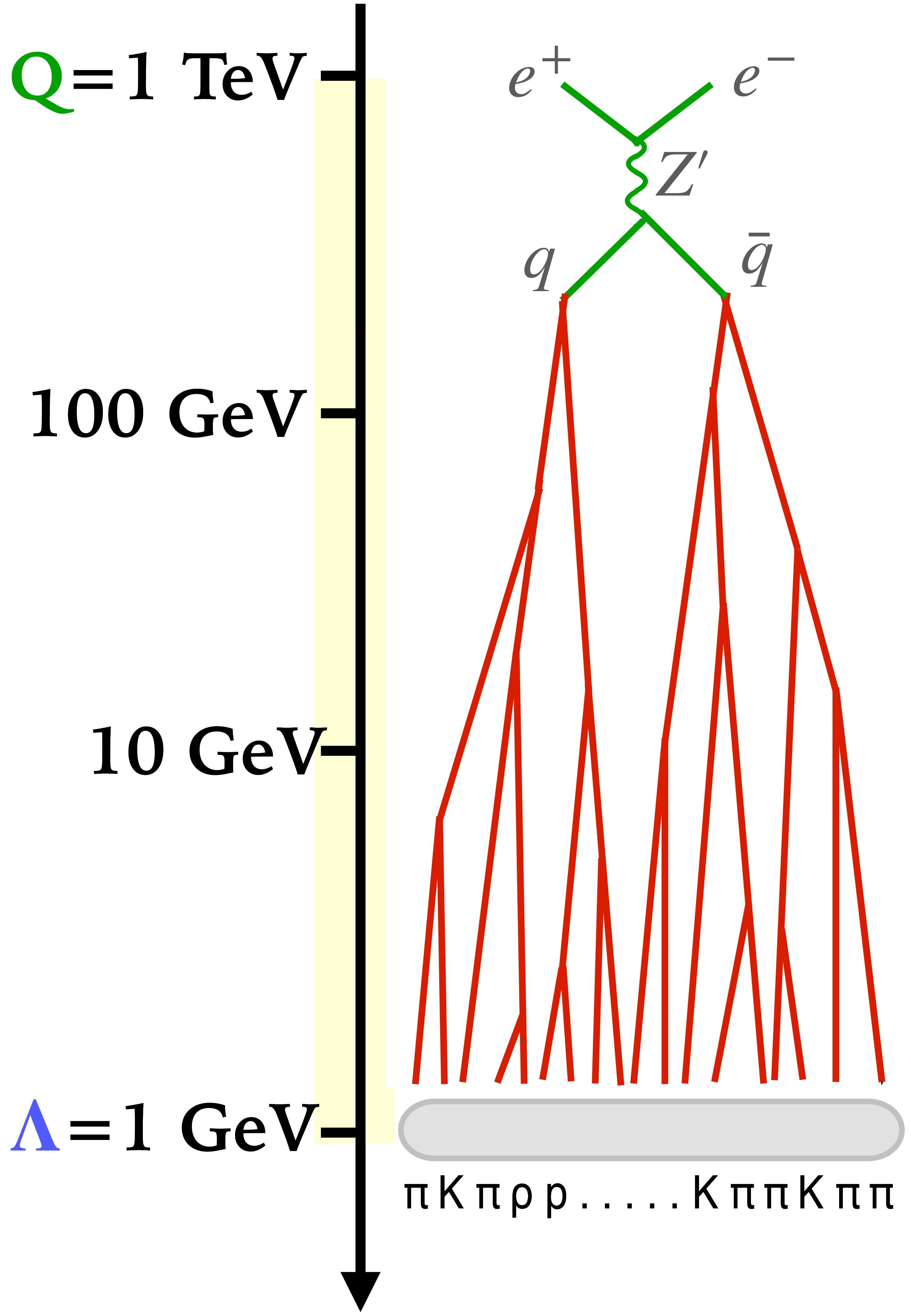
Theorists' description

Hard process

Parton Showers

Energy-degradation of hard partons via an iterated sequence of softer and softer emissions

Hadrons



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$\alpha_s \gg 1$
Non-perturbative QCD

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The physics of colliders — Shower Monte Carlo Event generators

Matching

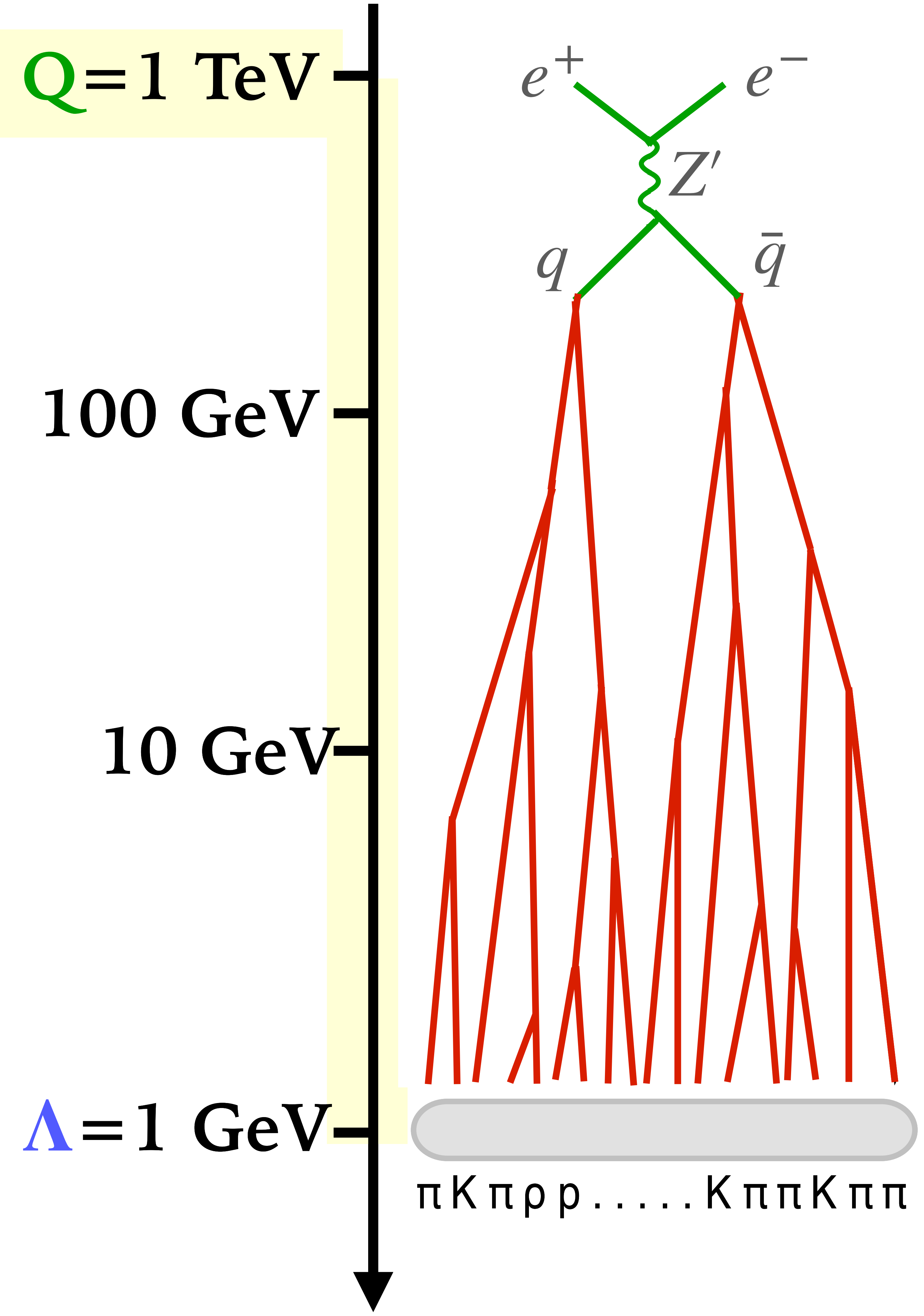
Combining FO with PS avoiding double counting

Parton Showers

Energy-degradation of hard partons via an iterated sequence of softer and softer emissions

Hadrons

Theorists' description



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Matching

Combining FO with PS avoiding double counting

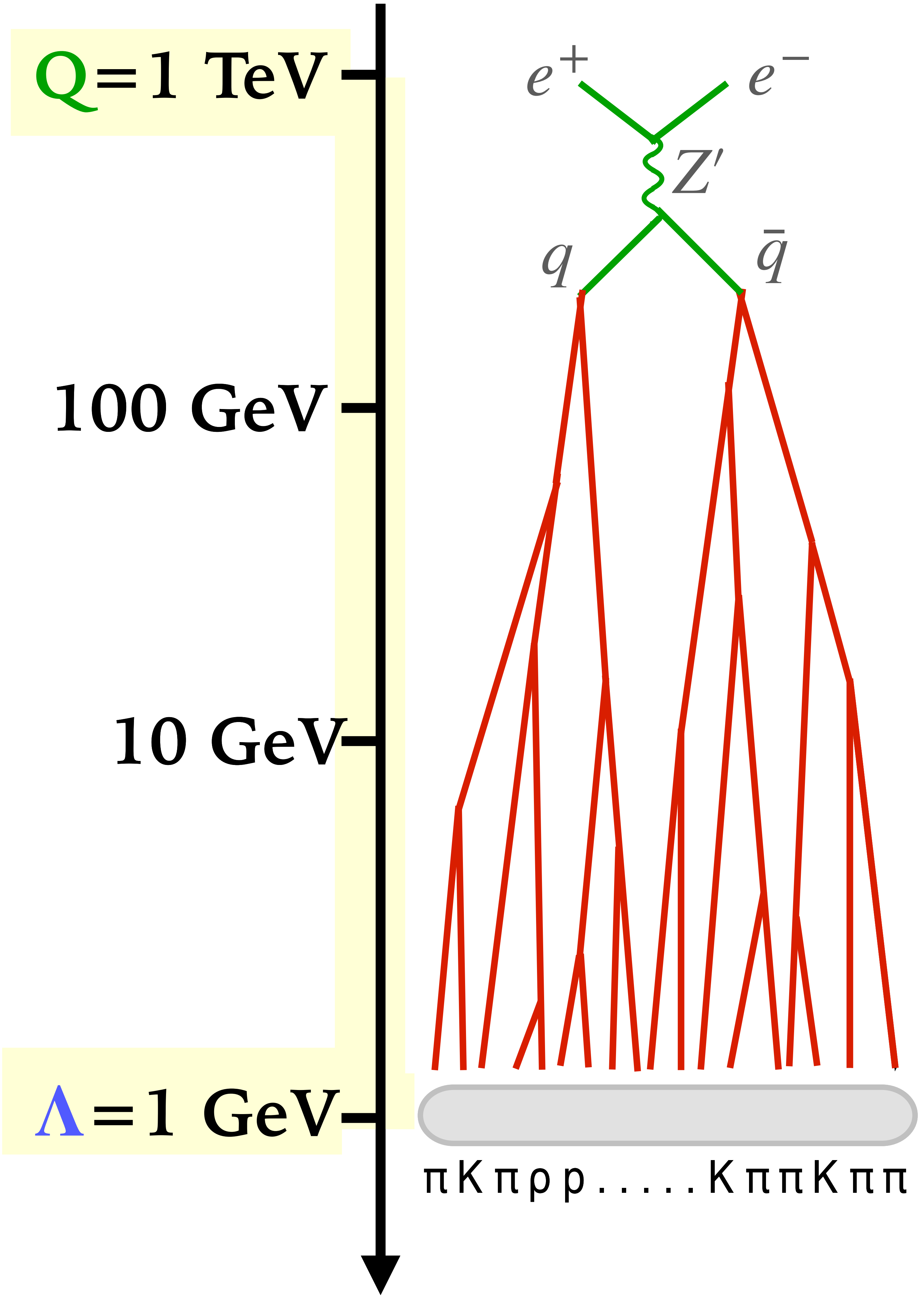
Parton Showers

Energy-degradation of hard partons via an iterated sequence of softer and softer emissions

Soft QCD models

E.g. hadronisation, colour reconnection

Theorists' description



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Shower Monte Carlo Event generators

Pythia8

An introduction to PYTHIA 8.2 — 7,312 citations

Torbjörn Sjöstrand (Lund U., Dept. Theor. Phys.), Stefan Ask (Cambridge U.), Jesper R. Christiansen (Lund U., Dept. Theor. Phys.), Richard Corke (Lund U., Dept. Theor. Phys.), Nishita Desai (U. Heidelberg, ITP) et al. (Oct 11, 2014)

Published in: *Comput.Phys.Commun.* 191 (2015) 159-177 • e-Print: 1410.3012 [hep-ph]

PYTHIA 6.4 Physics and Manual — 13,449 citations

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Sherpa3

Event generation with SHERPA 1.1 — 3,976 citations

T. Gleisberg (SLAC), Stefan. Hoeche (Zurich U.), F. Krauss (Durham U., IPPP), M. Schonherr (Dresden, Tech. U.), S. Schumann (Edinburgh U.) et al. (Nov, 2008)

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Herwig7

Herwig++ Physics and Manual — 3,345 citations

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HERWIG 6: An Event generator for hadron emission reactions with interfering gluons (including supersymmetric processes) — 3,724 citations

Herwig 7.0/Herwig++ 3.0 release note — 1,754 citations

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Madgraph5_aMC@NLO

The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations

J. Alwall (Taiwan, Natl. Taiwan U.), R. Frederix (CERN), S. Frixione (CERN), V. Hirschi (SLAC), F. Maltoni (Louvain U., CP3) et al. (May 1, 2014)

Published in: *JHEP* 07 (2014) 079 • e-Print: 1405.0301 [hep-ph]

9,772 citations

Powheg Box (w MiNNLO)

A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX — 5,068 citations

Simone Alioli (DESY, Zeuthen and INFN, Milan Bicocca), Paolo Nason (INFN, Milan Bicocca), Carlo Oleari (Milan Bicocca U. and INFN, Milan Bicocca), Emanuele Re (Durham U., IPPP and INFN, Milan Bicocca) (Feb, 2010)

Published in: *JHEP* 06 (2010) 043 • e-Print: 1002.2581 [hep-ph]

Matching NLO QCD computations with Parton Shower simulations: the POWHEG method — 5,248 citations

MiNNLO$_{PS}$: a new method to match NNLO QCD to parton showers — 185 citations

Geneva

Combining Higher-Order Resummation with Multiple NLO Calculations and Parton Showers in GENEVA

Simone Alioli (LBL, Berkeley), Christian W. Bauer (LBL, Berkeley), Calvin J. Berggren (LBL, Berkeley), Andrew Hornig (Washington U., Seattle), Frank J. Tackmann (DESY) et al. (Nov, 2012) — 170 citations

Published in: *JHEP* 09 (2013) 120 • e-Print: 1211.7049 [hep-ph]

Matching Fully Differential NNLO Calculations and Parton Showers — 133 citations

Whizard

WHIZARD: Simulating Multi-Particle Processes at LHC and ILC — 996 citations

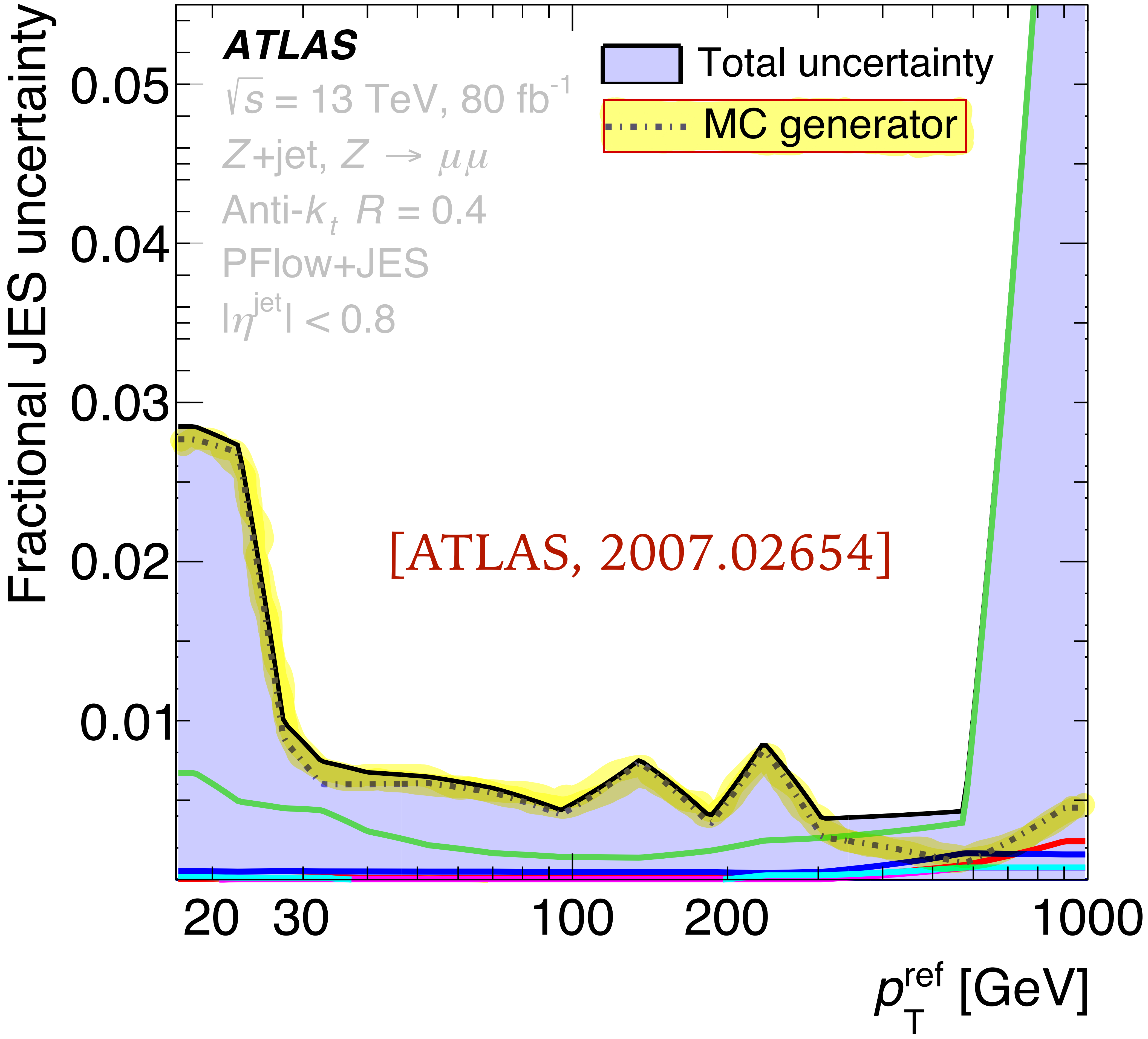
Wolfgang Kilian (Siegen U.), Thorsten Ohl (Wurzburg U.), Jurgen Reuter (Freiburg U.) (Aug, 2007)

Published in: *Eur.Phys.J.C* 71 (2011) 1742 • e-Print: 0708.4233

O'Mega: An Optimizing matrix element generator — 522 citations

Monte Carlo as **limiting factor**: Jet Measurements

Any jet physics analysis ($\mathcal{O}(1k)$ **papers!!**) at colliders requires the **jet energy scale** calibration



Parton shower (and interplay with hadronisation) leading source of systematic uncertainty of Jet Energy Scale

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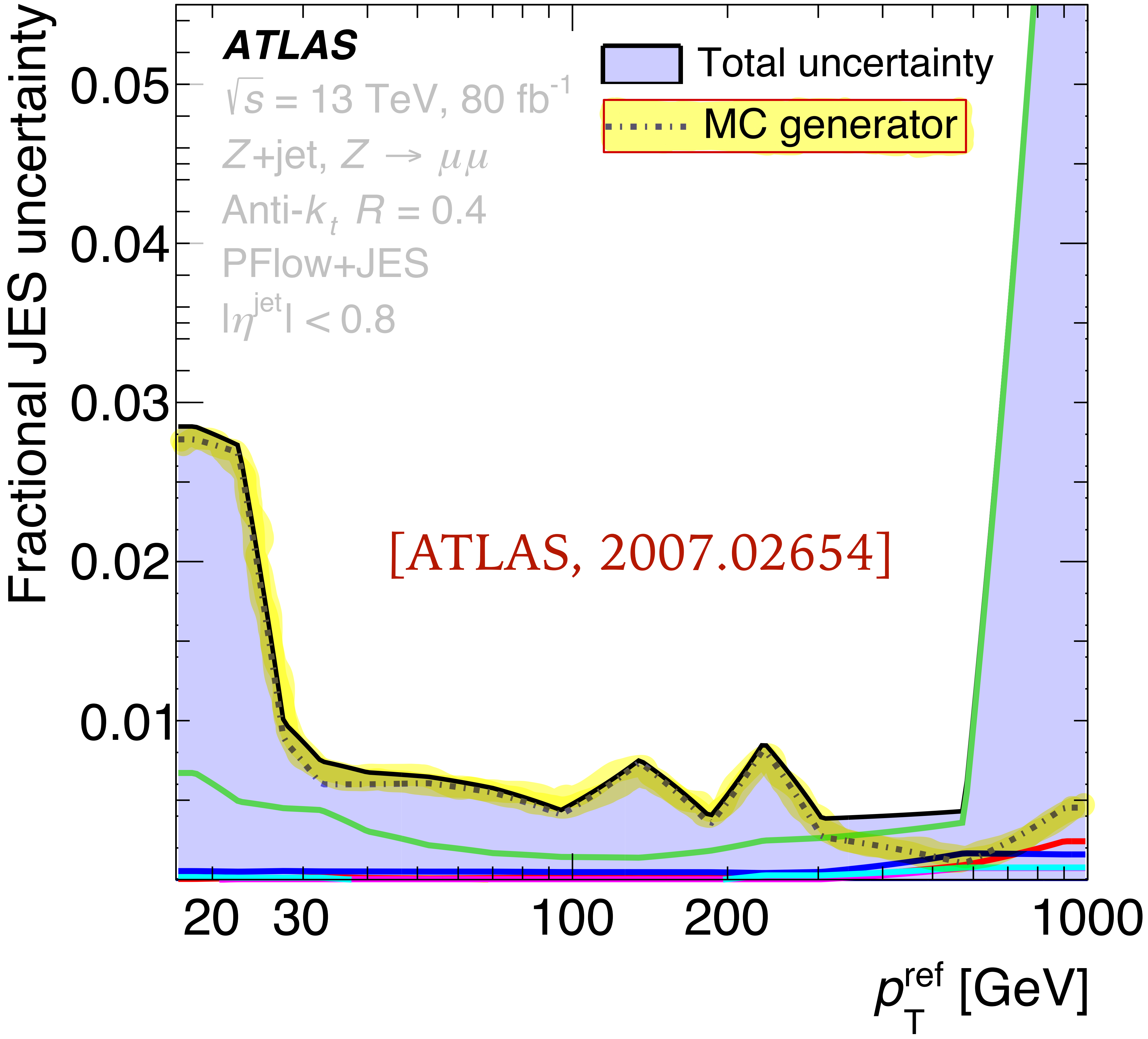


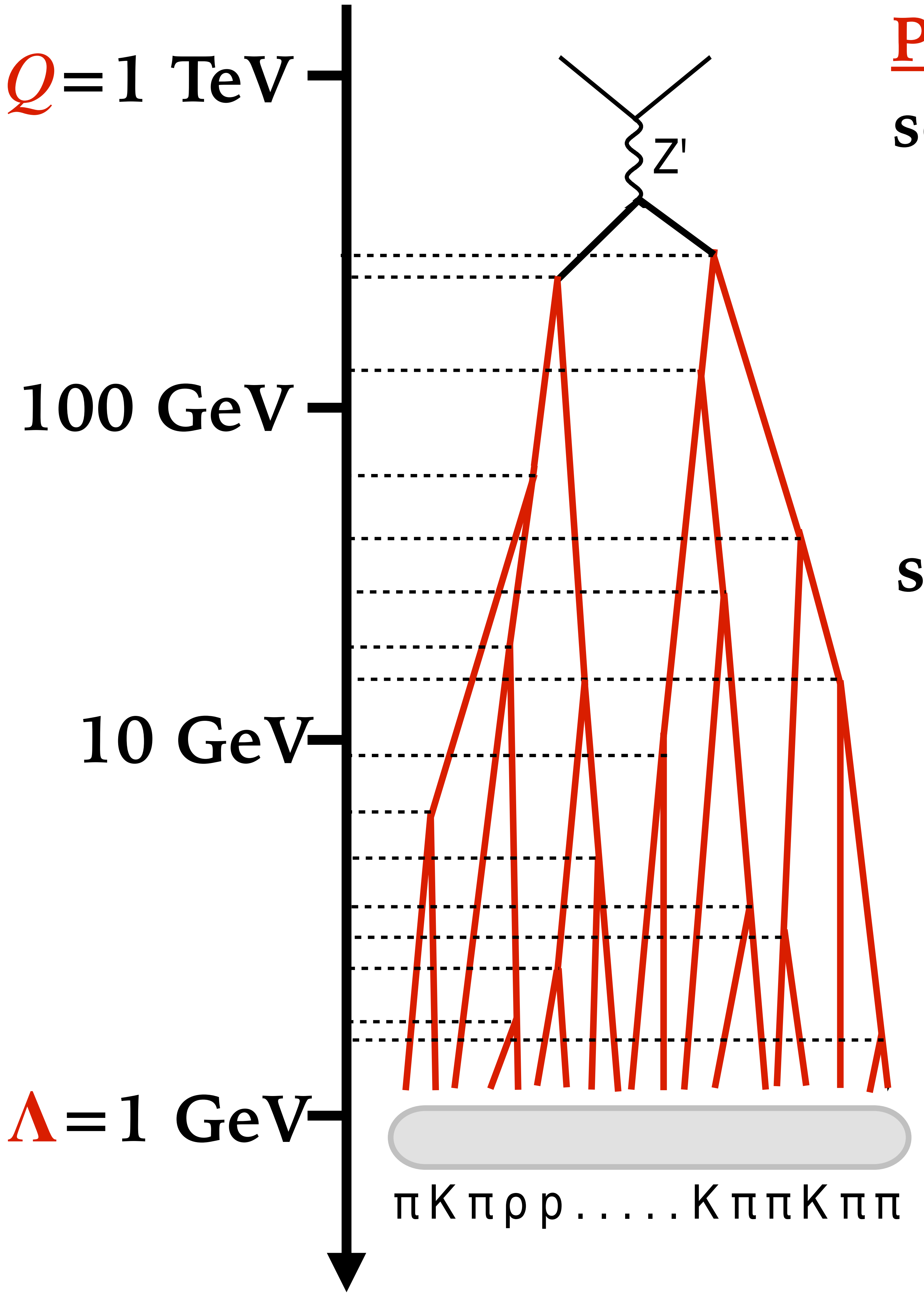
JES largest uncertainty in **top**-mass extractions

Source	Uncertainty [GeV]
Jet energy scale	0.57
Total m_t^{MC} uncertainty	$^{+0.68}_{-0.73}$

[CMS,1812.10505]

Parton shower (and interplay with hadronisation) leading source of systematic uncertainty of Jet Energy Scale

Logarithmically-accurate Parton Showers



Parton showers = energy degradation via an iterated sequence of **softer and softer** emissions

$$L = \ln \frac{Q}{\Lambda} \gg 1$$

simple algorithm to include the **dominant radiative corrections** at all orders for **any observable**!

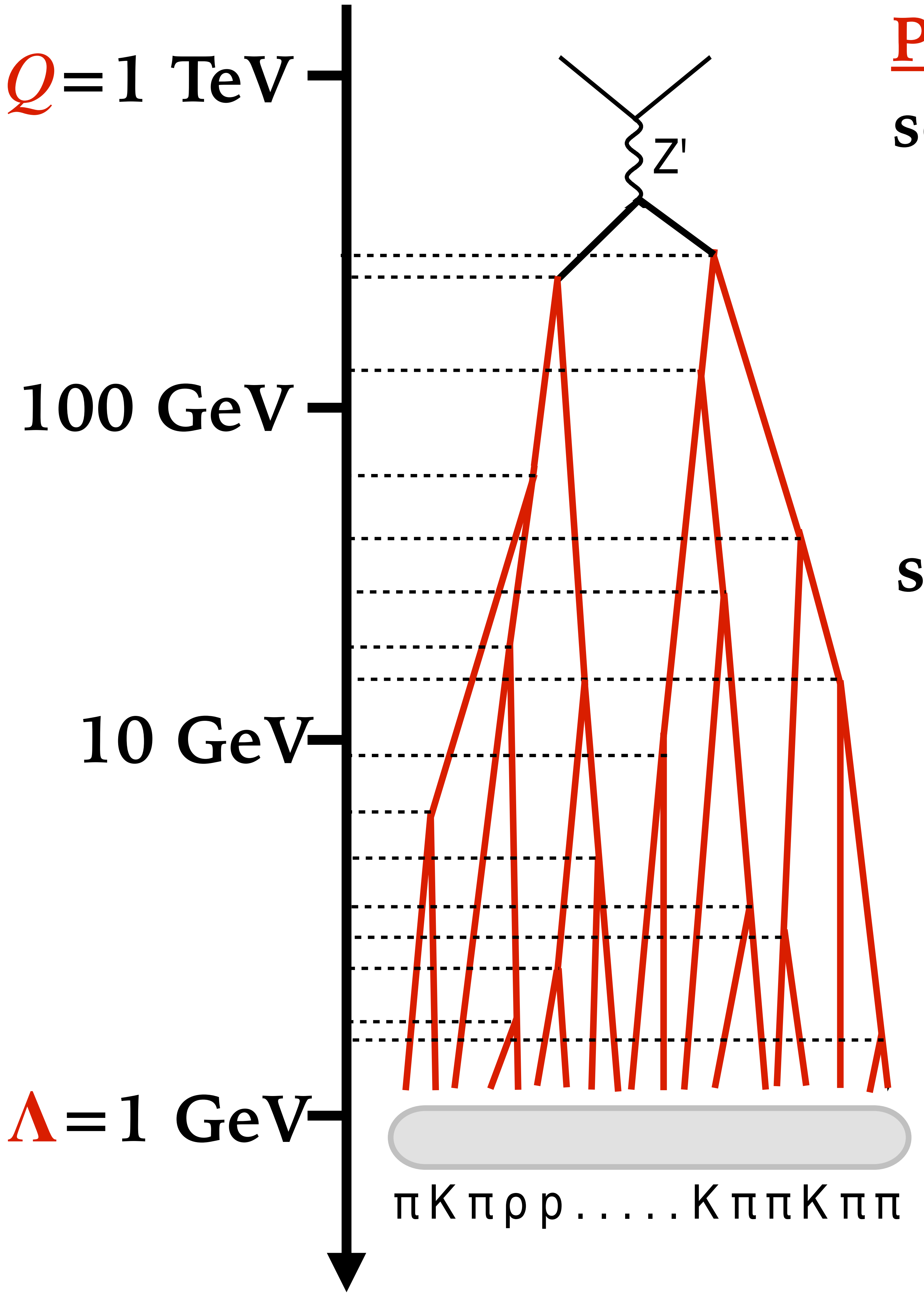
$$\Sigma(O < e^{-L}) = \exp\left(\boxed{-L g_{\mathrm{LL}}(\alpha_s L)} + \ldots\right)$$

LL = leading logs

$\mathcal{O}(\alpha_s L^2)$

$\alpha_s = 0.118$

Logarithmically-accurate Parton Showers



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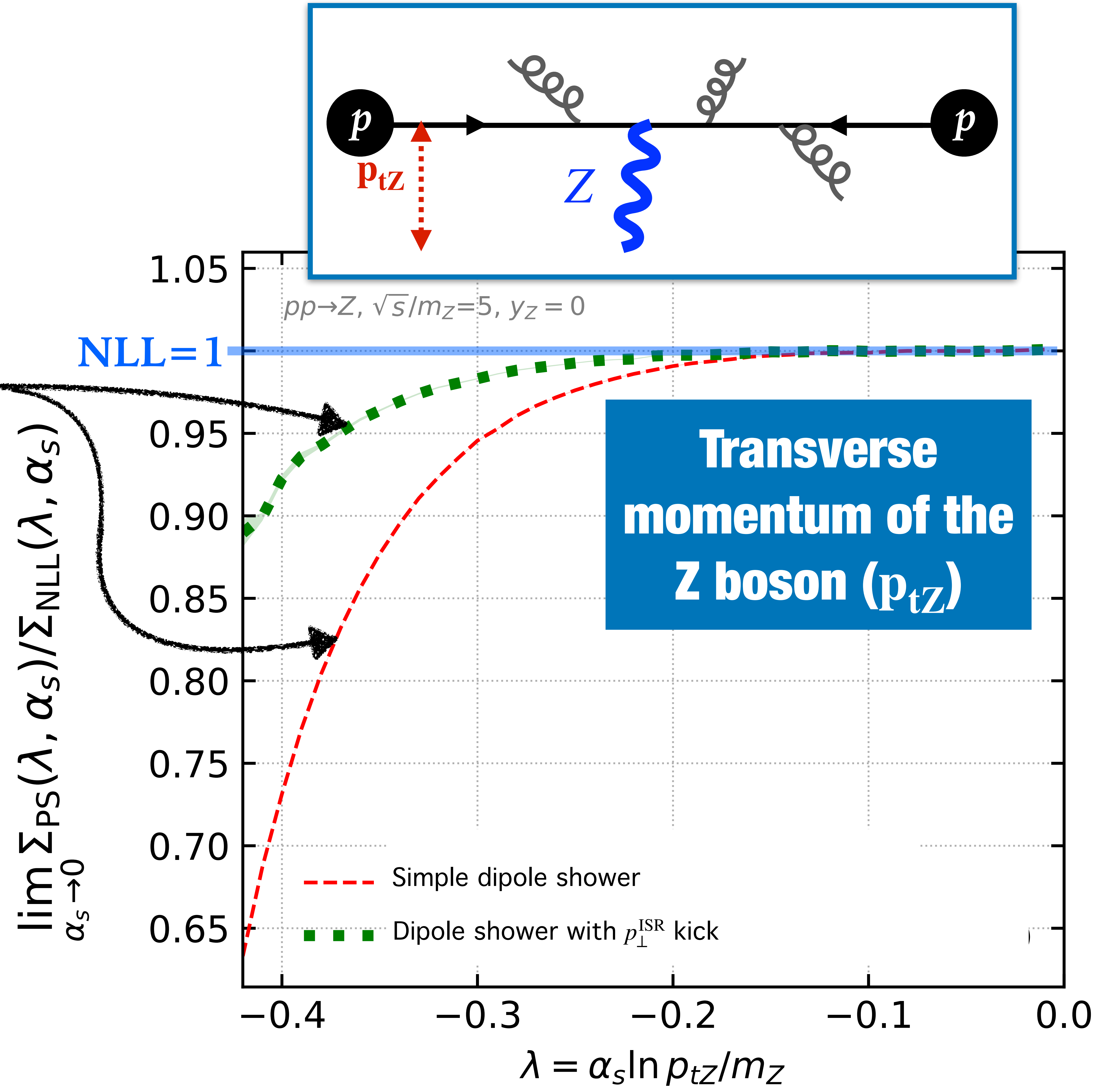
$$\Sigma(O < e^{-L}) = \exp\left(-L g_{\mathrm{LL}}(\alpha_s L) + \boxed{g_{\mathrm{NLL}}(\alpha_s L)} + \ldots\right)$$

$\mathcal{O}(\alpha_s L \times L)$ $\quad$ $\mathcal{O}(\alpha_s L)$ $\quad$ $\alpha_s = 0.118$

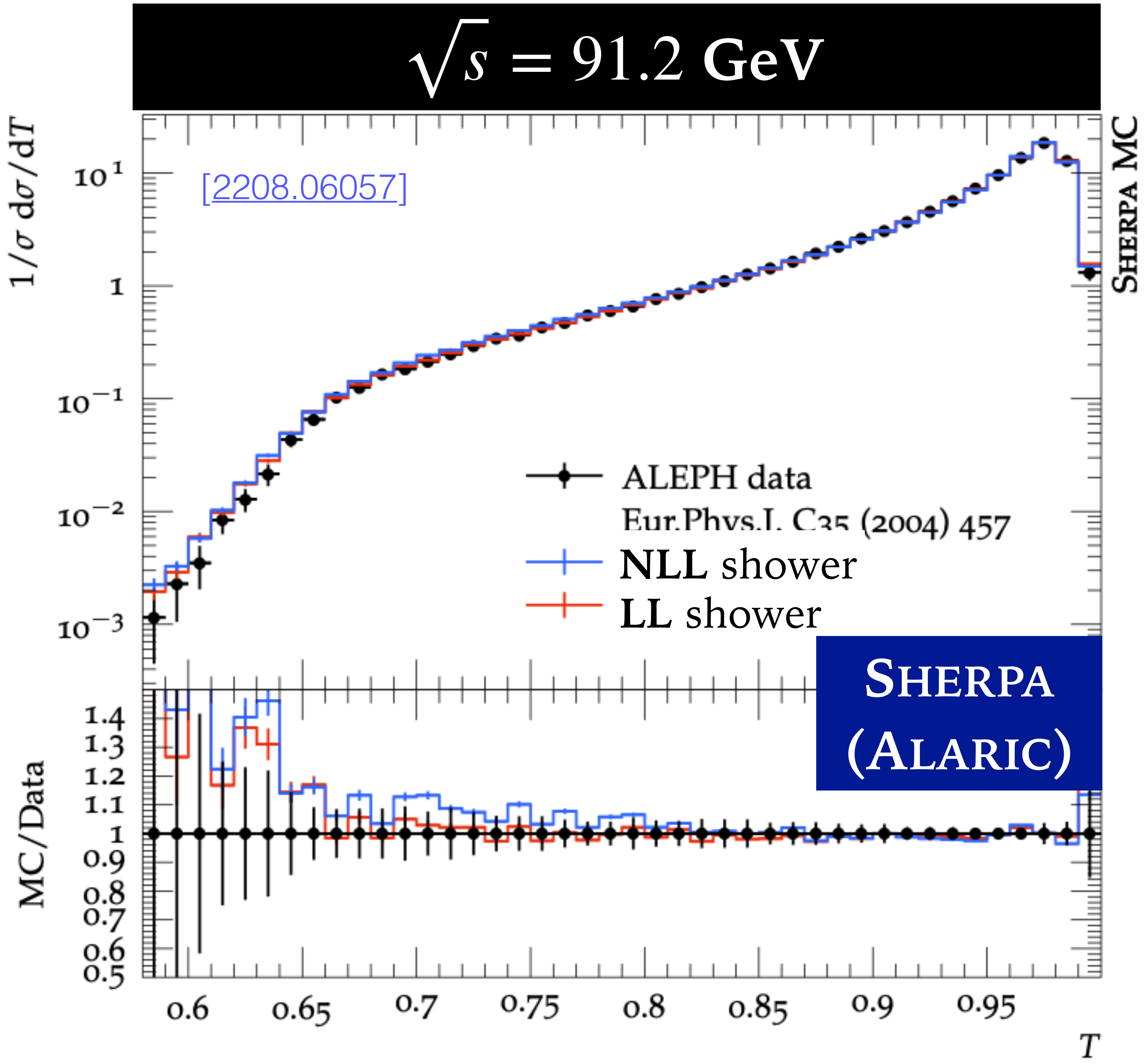
Typically $L \sim 1/\alpha_s$: **Next-To-Leading-Logarithms** are $\mathcal{O}(\mathbf{1})$ and their correct inclusion is imperative!

Logarithmically-accurate Parton Showers

Showers routinely used to interpret LHC data **not NLL!**

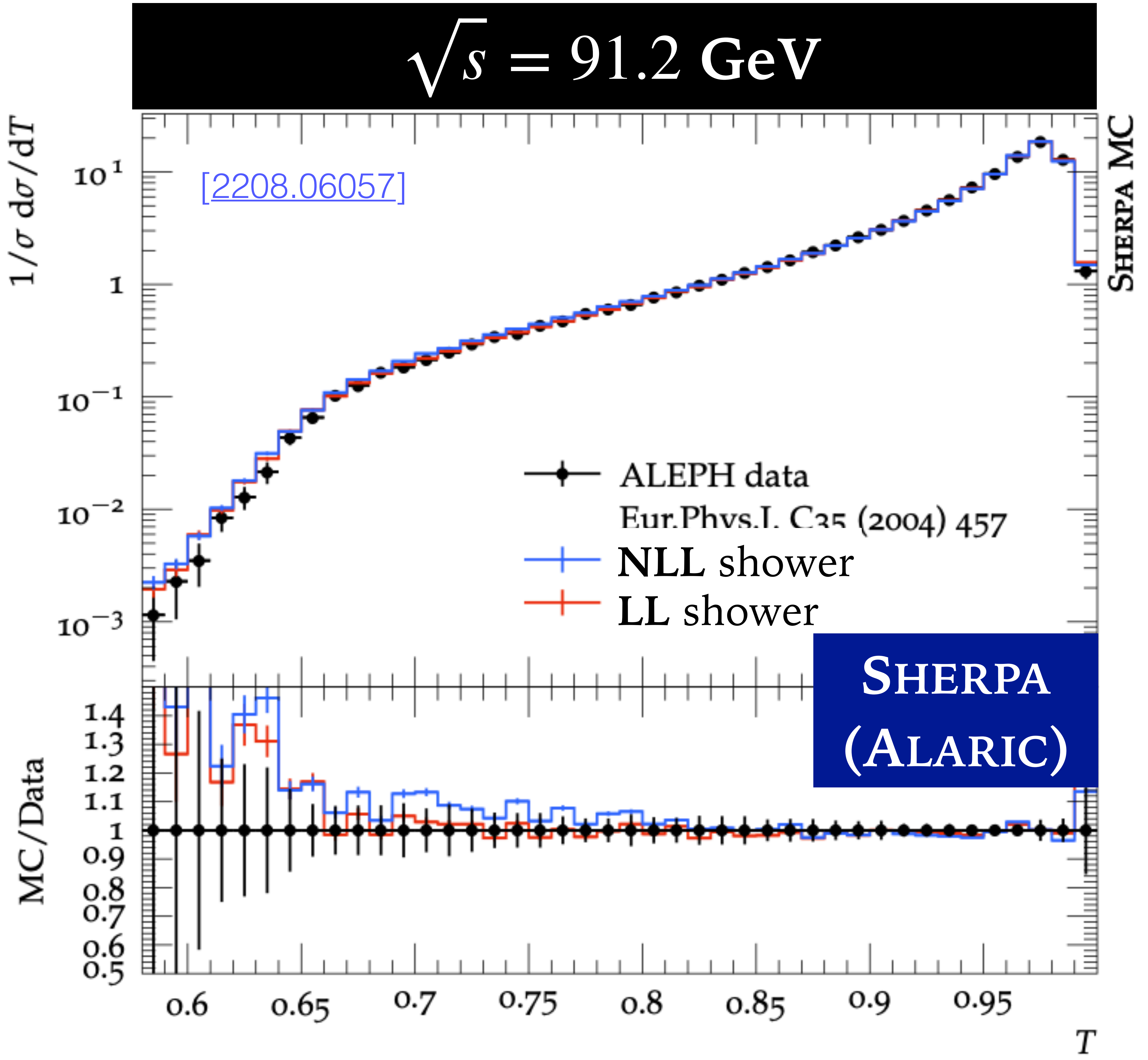


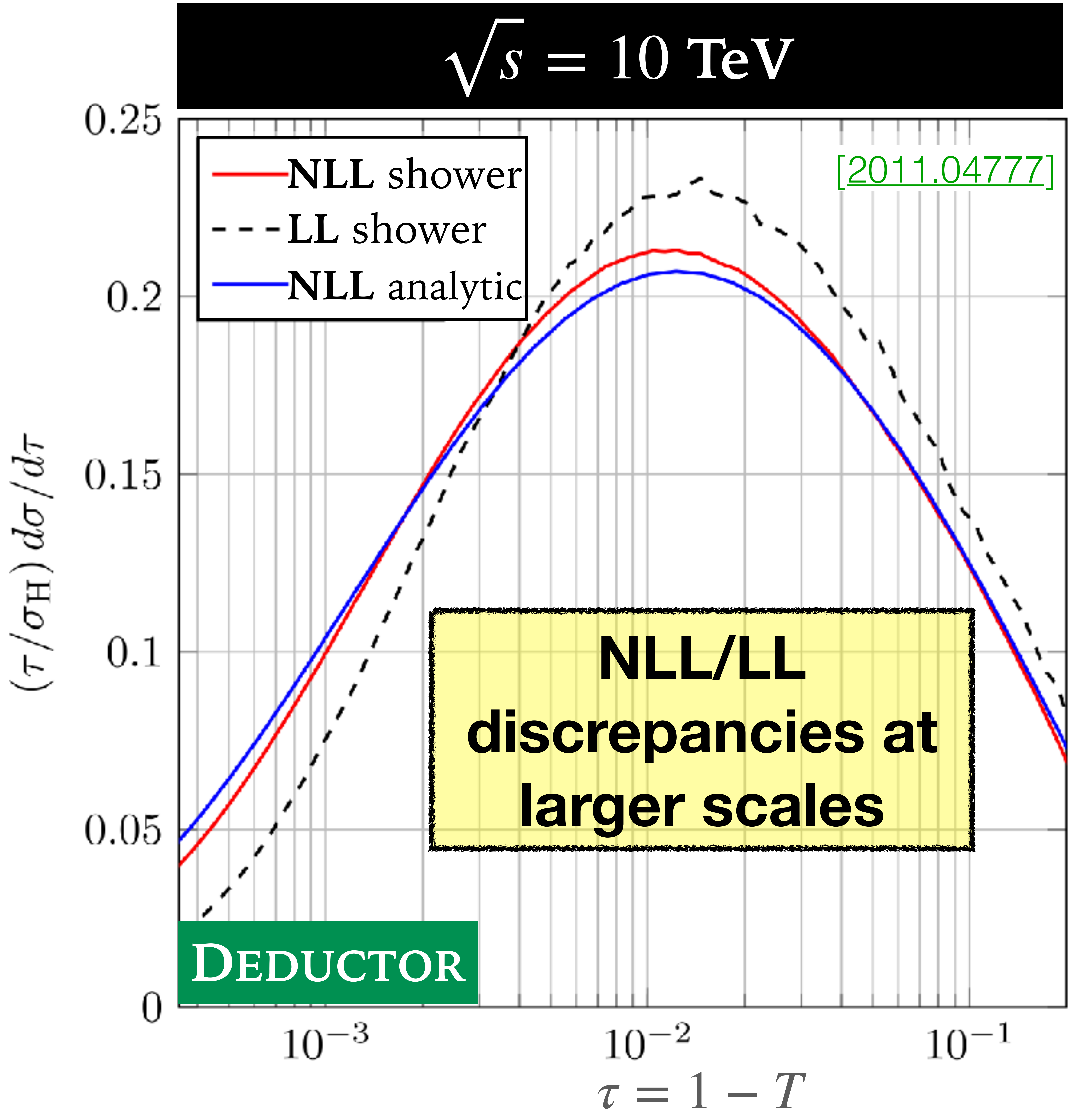
NLL vs LL shower: phenomenological impact



At moderate scales, LL showers behave as NLL ones

NLL vs LL shower: phenomenological impact





NLL showers are becoming a new reality!

Credits to M. van Beekveld

Logarithmic accuracy of parton showers: a fixed-order study
Dasgupta, Dreyer, Hamilton, Monni, Salam [1805.09327]

Parton showers beyond leading logarithmic accuracy
Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez [2002.11114]

Colour and logarithmic accuracy in final-state parton showers
Hamilton, Medves, Salam, Scyboz, Soyez [2011.10054]

Spin correlations in final-state parton showers and jet observables
Karlberg, Salam, Scyboz, Verheyen [2103.16526]

Soft spin correlations in final-sta[te] parton showers
Hamilton, Karlberg, Salam, Scyboz, Verhe[yen] [2111.01161]

PanScales parton showers for hadron collisions: formulation and fixed-order studies
van Beekveld, Ferrario Ravasio, Salam, Soto Ontoso, Soyez, Verheyen [2205.02237]

PanScales

PanScales parton showers for hadron collisions: all-order validation
van Beekveld, Ferrario Ravasio, Hamilton, Salam, Soto Ontoso, Soyez, Verheyen [2207.09467]

Next-to-leading-logarithmic PanScales showers for deep inelastic scattering and vector boson fusion
van Beekveld, Ferrario Ravasio [2305.08645]

Introduction to the PanScales framework, version 0.1
van Beekveld, Dasgupta, El-Menoufi, Ferrario Ravasio, Hamilton, Helliwell, Karlberg, Medves, Monnim Salam, Scyboz, Soto Ontoso, Soyez, Verheyen [2312.13275]

Building a consistent parton shower
Forshaw, Holguin, Plätzer [2003.06400]

Cvolver

Improvements on dipole shower colour
Forshaw, Holguin, Plätzer [2011.15087]

Logarithmic accuracy of angular-ordered parton showers
Bewick, Ferrario Ravasio, Richardson, Seymour [1904.11866]

Herwig

Initial state radiation in the Herwig 7 angular-ordered parton shower
Bewick, Ferrario Ravasio, Richardson, Seymour [2107.04051]

A new approach to color-coherent parton evolution
Herren, Höche, Krauss, Reichelt, Schönherr [2208.06057]

Alaric

New approach to QCD final-state evolution in processes with massive partons
Assi, Höche [2307.00728]

The Alaric parton shower for hadron colliders
Höche, Krauss, Reichelt [2404.14360]

A partitioned dipole-antenna shower with improved transverse recoil
Preuss [2403.19452]

Apollo

Summation of large logarithms by parton showers
Nagy, Soper [2011.04773]

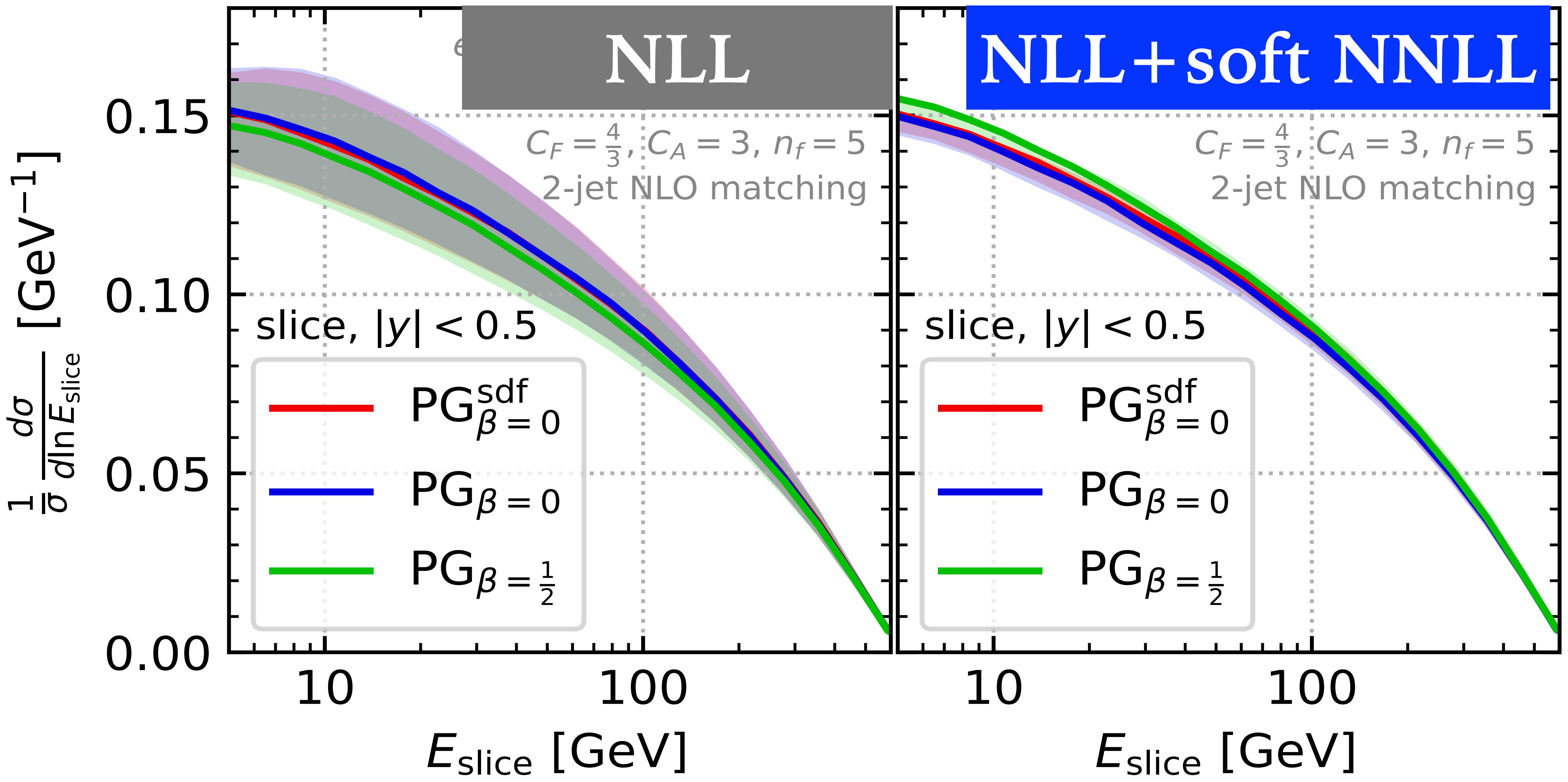
Deductor

Summation by parton showers of large logarithms in electron-positron annihilation
Nagy, Soper [2011.04777]

But also first NNLL shower predictions are starting to appear

NNLL accuracy for observables primarily sensitive to soft emissions

Energy flow in a rapidity slice in e^+e^- @ 1 TeV



SFR, Hamilton, Karlberg, Salam, Scyboz, Soyez [2307.11142]

Better control of the formal accuracy implies reduction / more robust theory uncertainties

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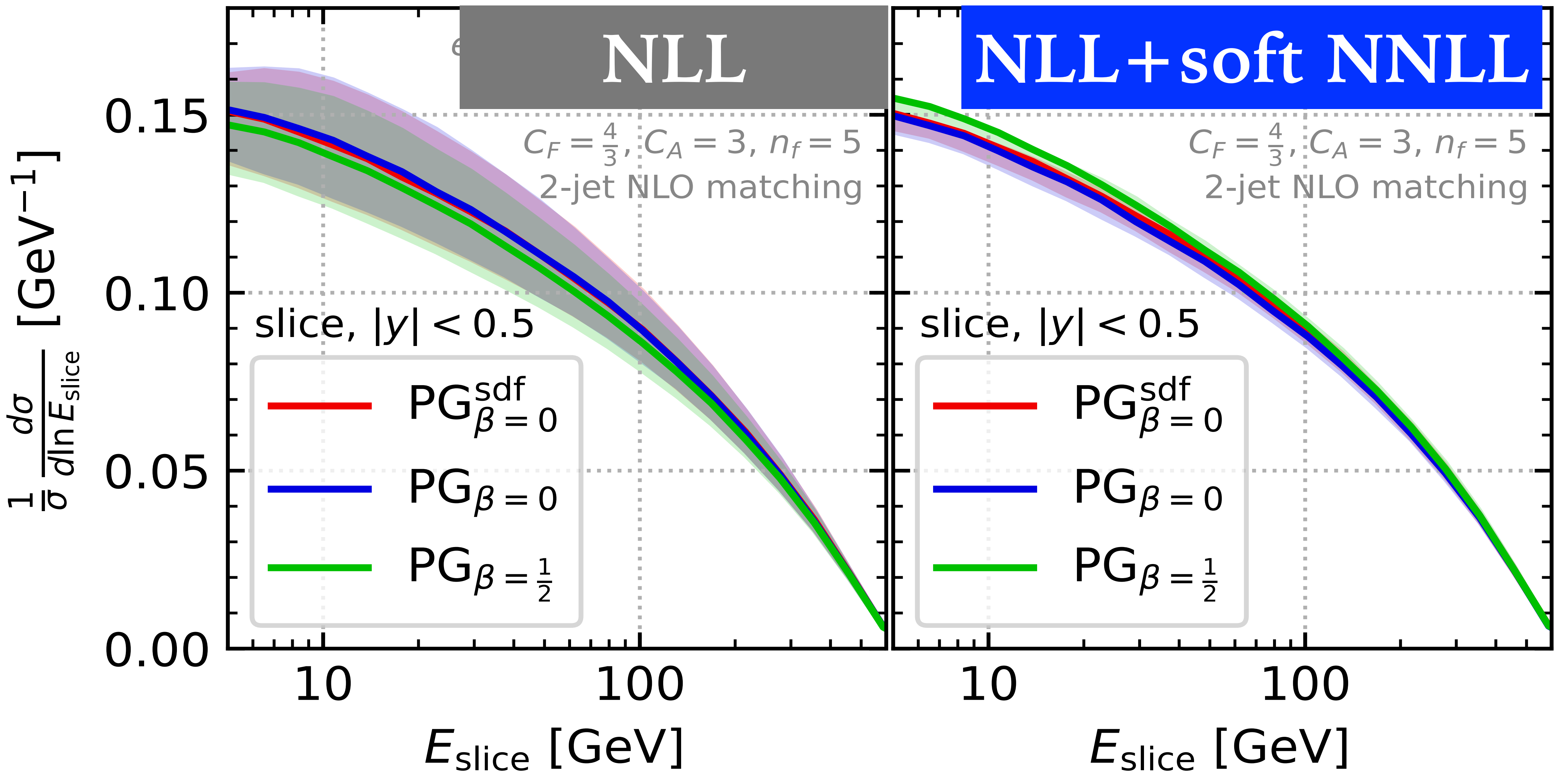
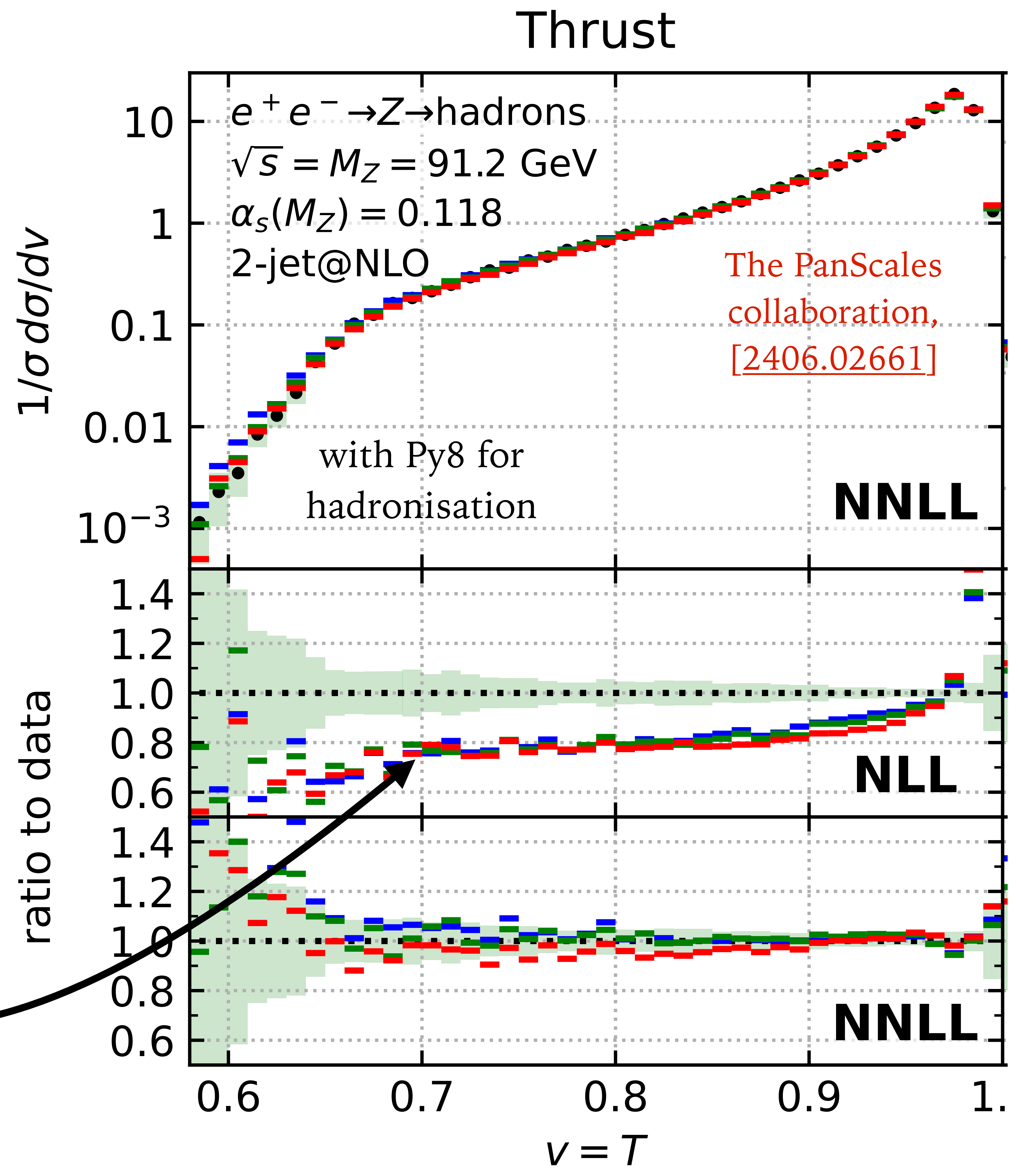


SFR, Hamilton, Karlberg, Salam, Scyboz, Soyez [2307.11142]

NNLL for global event shapes in e^+e^-

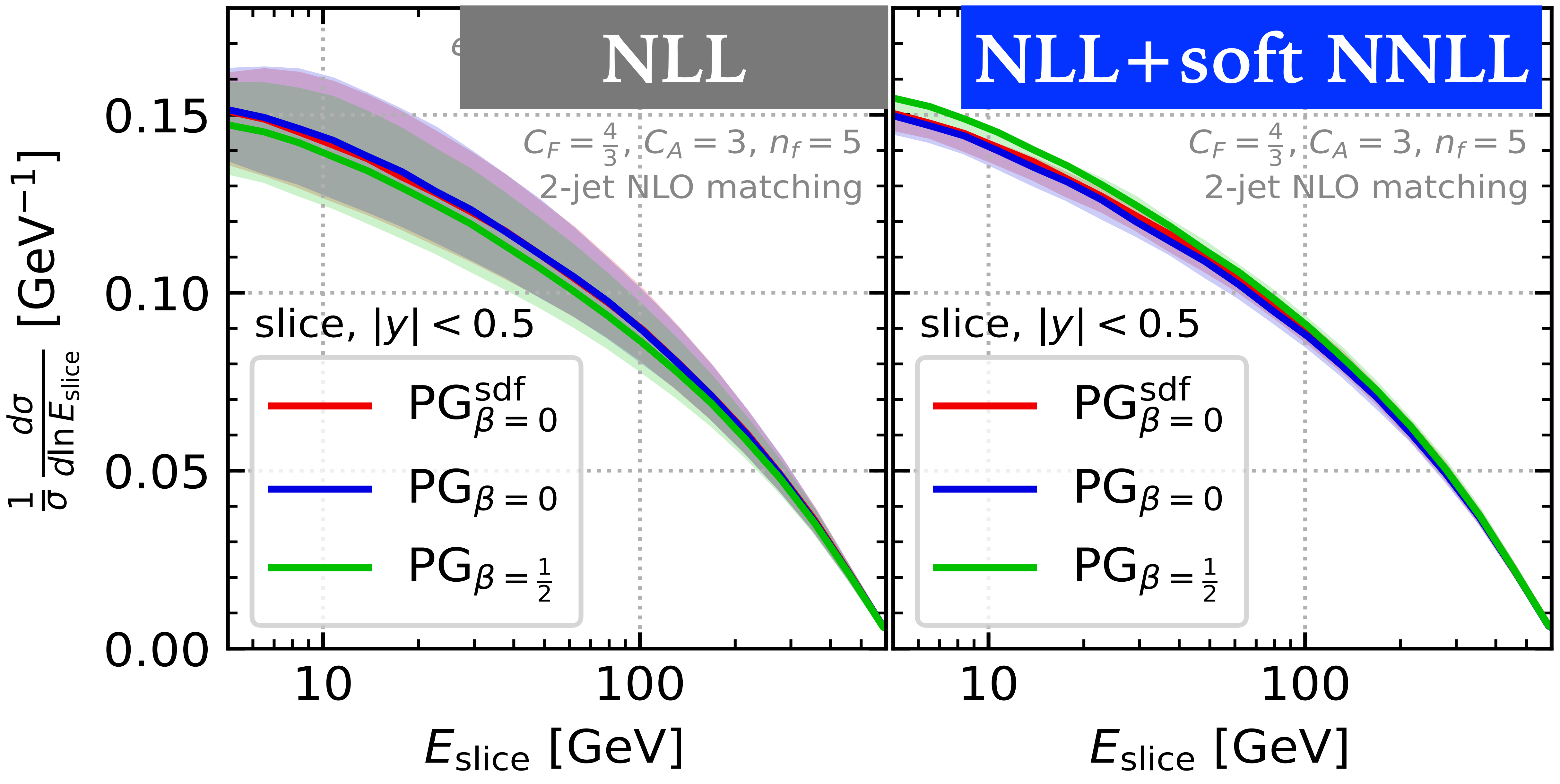


Sherpa: LL vs NLL little difference
PanScales: NLL vs NNLL large difference

But also first NNLL shower predictions are starting to appear

NNLL accuracy for observables primarily sensitive to soft emissions

Energy flow in a rapidity slice in e^+e^- @ 1 TeV

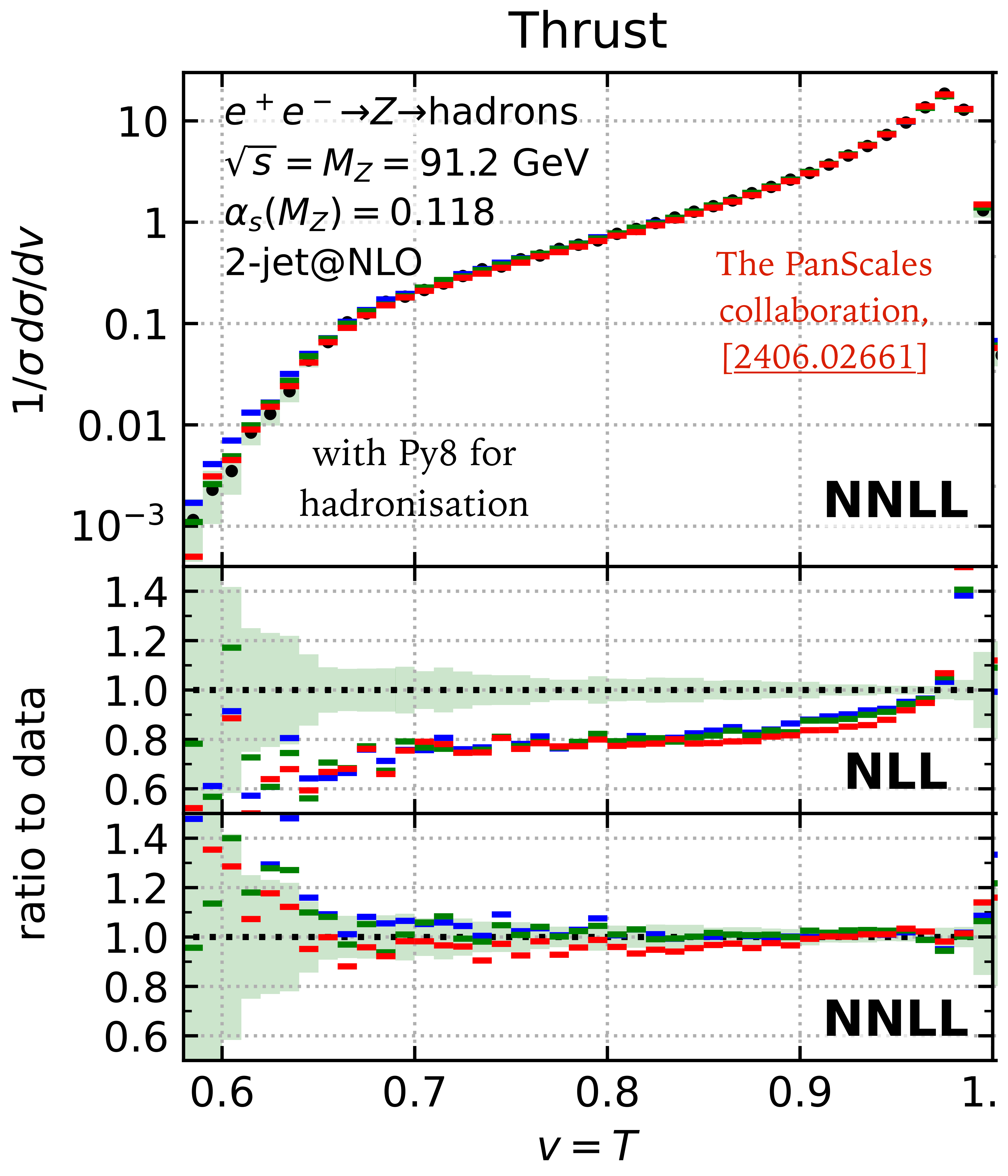


SFR, Hamilton, Karlberg, Salam, Scyboz, Soyez [2307.11142]

NNLL accuracy for collinear quark fragmentation within a toy shower

van Beekveld, Dasgupta, El-Menoufi, Helliwell, Monni, Salam 2409.08316

NNLL for global event shapes in e^+e^-



Amplitude level evolution

- Parton showers are **semi-classical** and do not capture effects stemming from the interference of **amplitudes with different phases**, that can lead e.g. super leading logarithms, colour-coherence factorisation effects, Glauber exchanges

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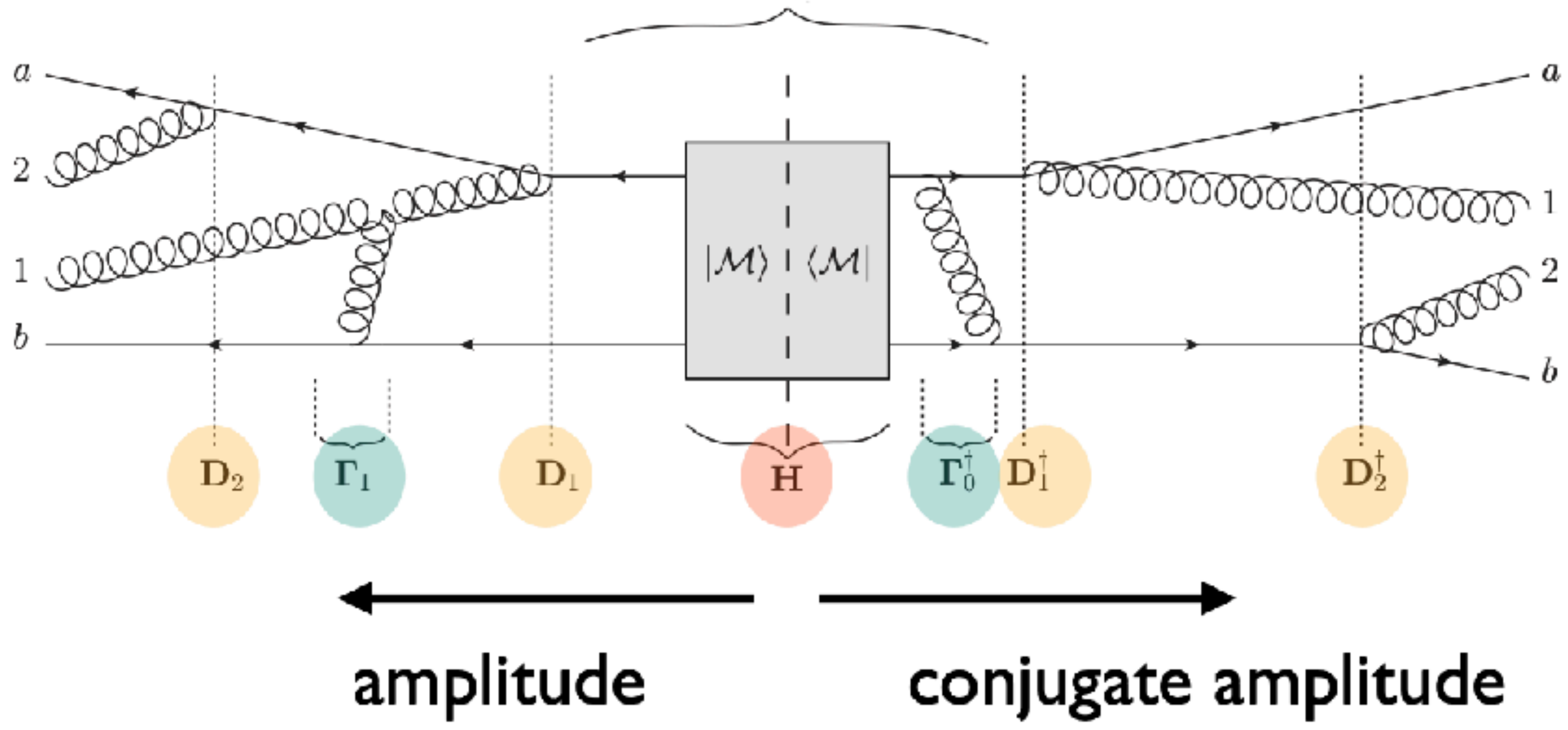
➤ Amplitude-level only concrete solution



CVolver =evolve separately **amplitude** and **conjugate amplitude**: subleading **colour**, **spin** correlations, **Glauber** phases taken into account. Currently limited to **soft** exchanges.
[Martínez, De Angelis, Forshaw, Plätzer, Seymour 1802.08531; Forshaw, Holguin, Plätzer 1905.08686; De Angelis, Forshaw, Plätzer 2007.09648; Plätzer 2210.09178, Forshaw, Plätzer, Torre González 2502.12133 and 2505.13183] + **EW** interactions [Plätzer, Sjodahl 2204.03258]

Deductor =density matrix in **colour** to resum "**nasty soft & Glauber contributions**" [and more]
[Nagy, Soper 0805.0216, 1202.4496, 1401.6364, 1501.00778, 1902.02105, 1905.07176, 1908.11420]

Matching with **NLO** calculations

- **Matching** conventional **LL parton showers** with **NLO calculations** is routinely performed to analyse LHC data.

- NLO matching impreves the description of **inclusive quantities** and **hard jets**

Madgraph5_aMC@NLO

The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations

J. Alwall (Taiwan, Natl. Taiwan U.), R. Frederix (CERN), S. Frixione (CERN), V. Hirschi (SLAC), F. Maltoni (Louvain U., CP3) et al. (May 1, 2014)

Published in: *JHEP* 07 (2014) 079 • e-Print: 1405.0301 [hep-ph]

9,772 citations

Powheg Box

A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX #13 5,068 citations

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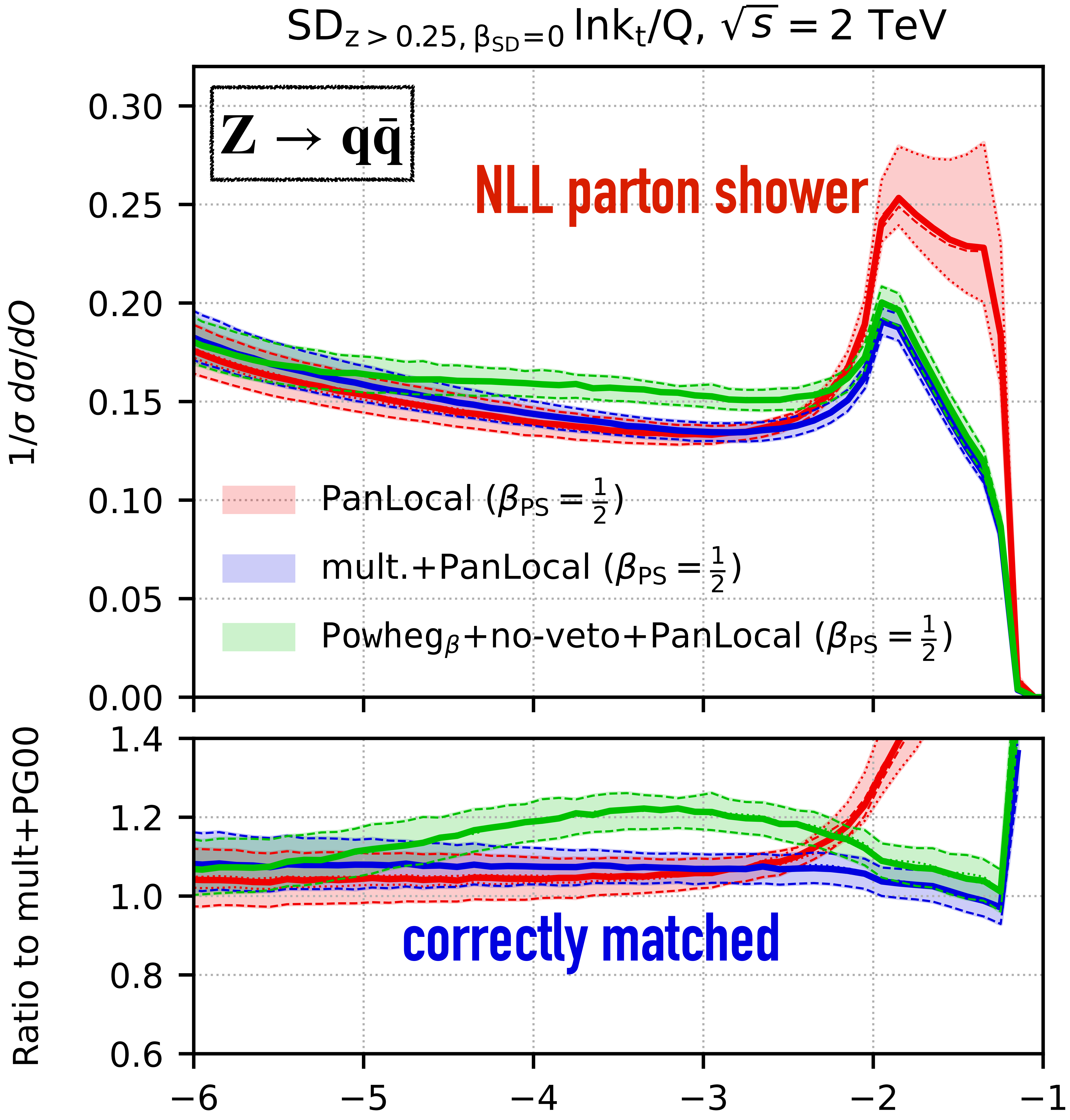
- **What is going to happen with NLL showers?**

Matching and Logarithmic Accuracy

➤ **NLO matching** is necessary for NNLL accuracy

$$\Sigma_{\mathrm{NLO}} = \Sigma_{\mathrm{LO}}(1 + \boxed{\alpha_s \Delta_{\mathrm{NLO}}} + \ldots)$$

$$\Sigma_{\mathrm{NNLL}} = \exp\left(L g_{\mathrm{LL}}(\alpha_s L) + g_{\mathrm{NLL}}(\alpha_s L) + \boxed{\alpha_s g_{\mathrm{NNLL}}(\alpha_s L)}\right)$$



[Hamilton, Karlberg, Salam, Scyboz, Verheyen, 2301.09645]

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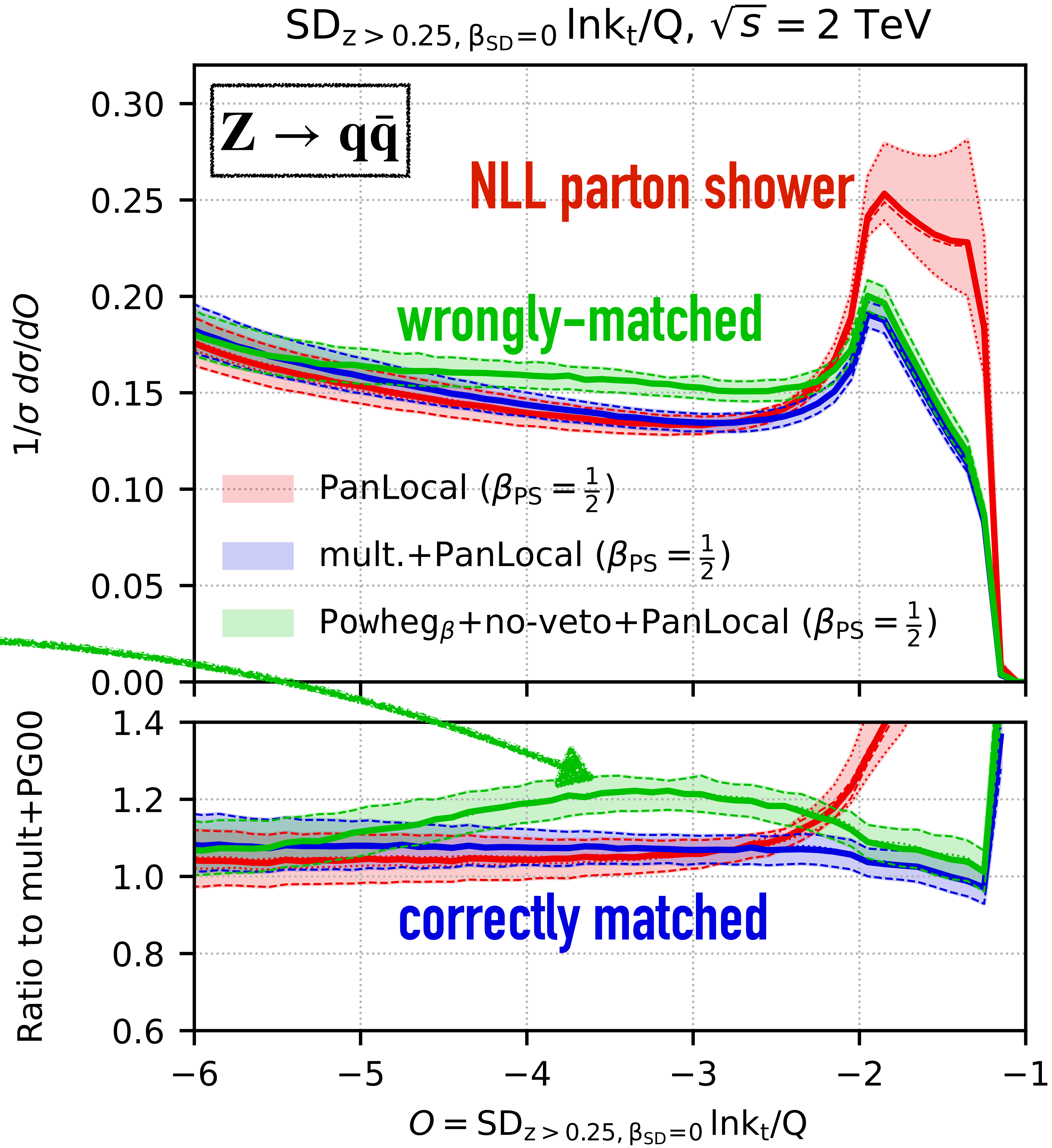
➤ But it could instead **downgrade the NLL accuracy** of the shower

➤ It is necessary to rethink about matching in the context of NLL showers!



[Hamilton, Karlberg, Salam, Scyboz, Verheyen, 2301.09645]

Status of matching with **NLL** showers

➤ PanScales:

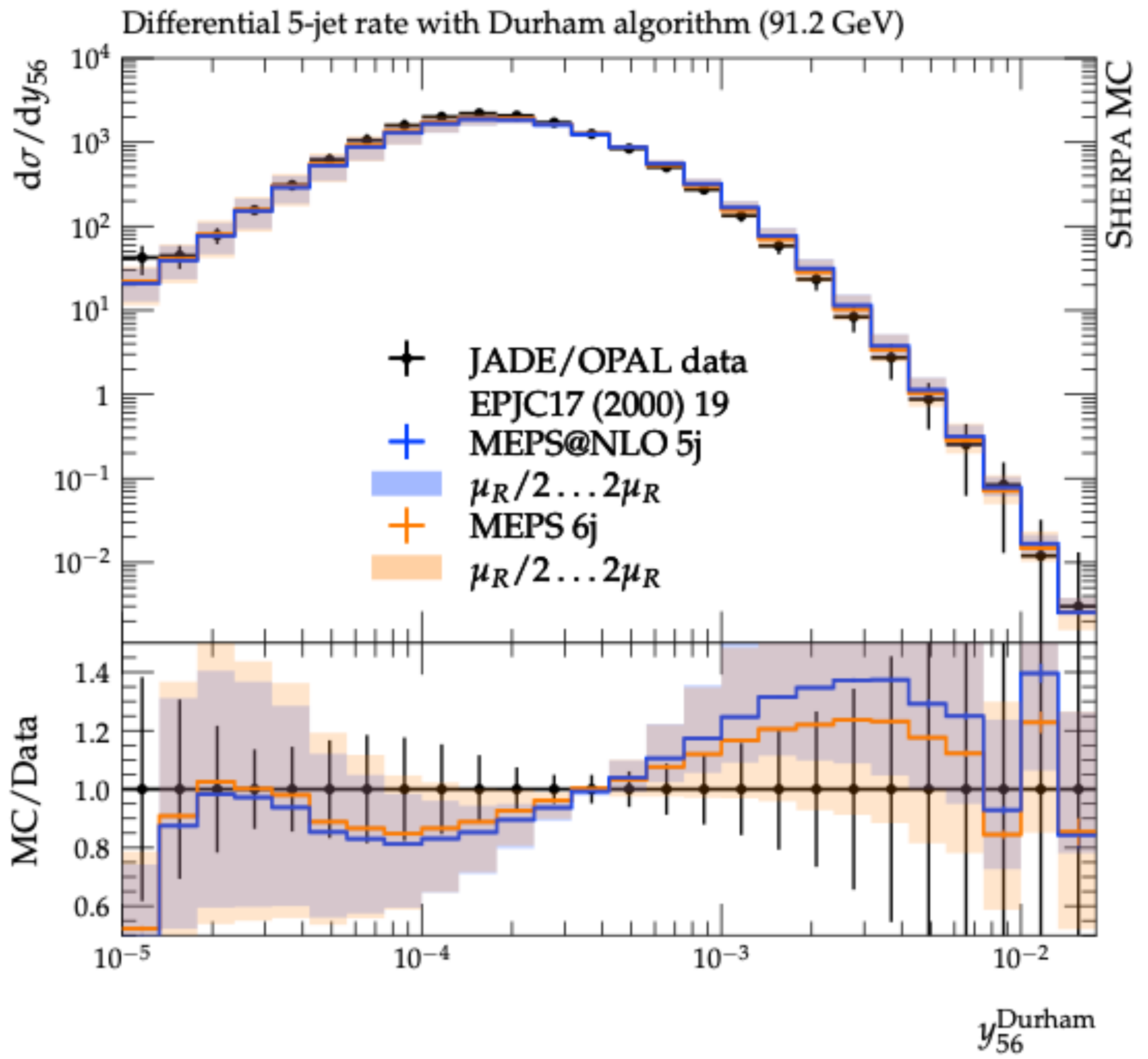
NLO matching for processes with **two-coloured legs** (pp, ep, e^+e^-), with demonstrated Next-to-double logarithmic ($\alpha_s \left(\alpha_s L^2\right)^n$) accuracy for event shapes;
Introduction of a guaranteed positive defined method (**ESME**) and revisitation of **Powheg** method

[Hamilton, Karlberg, Salam, Scyboz, Verheyen, 2301.09645]
[van Beekveld, Ferrario Ravasio, Helliwell et al., 2504.05377]

➤ Alaric:

NLO matching and **multi-jet merging** for e^+e^- (any jet multiplicity);
LO multi-jet merging for pp collisions
Adaptations from **Sherpa-MC@NLO** and **MEPS@(N)LO**

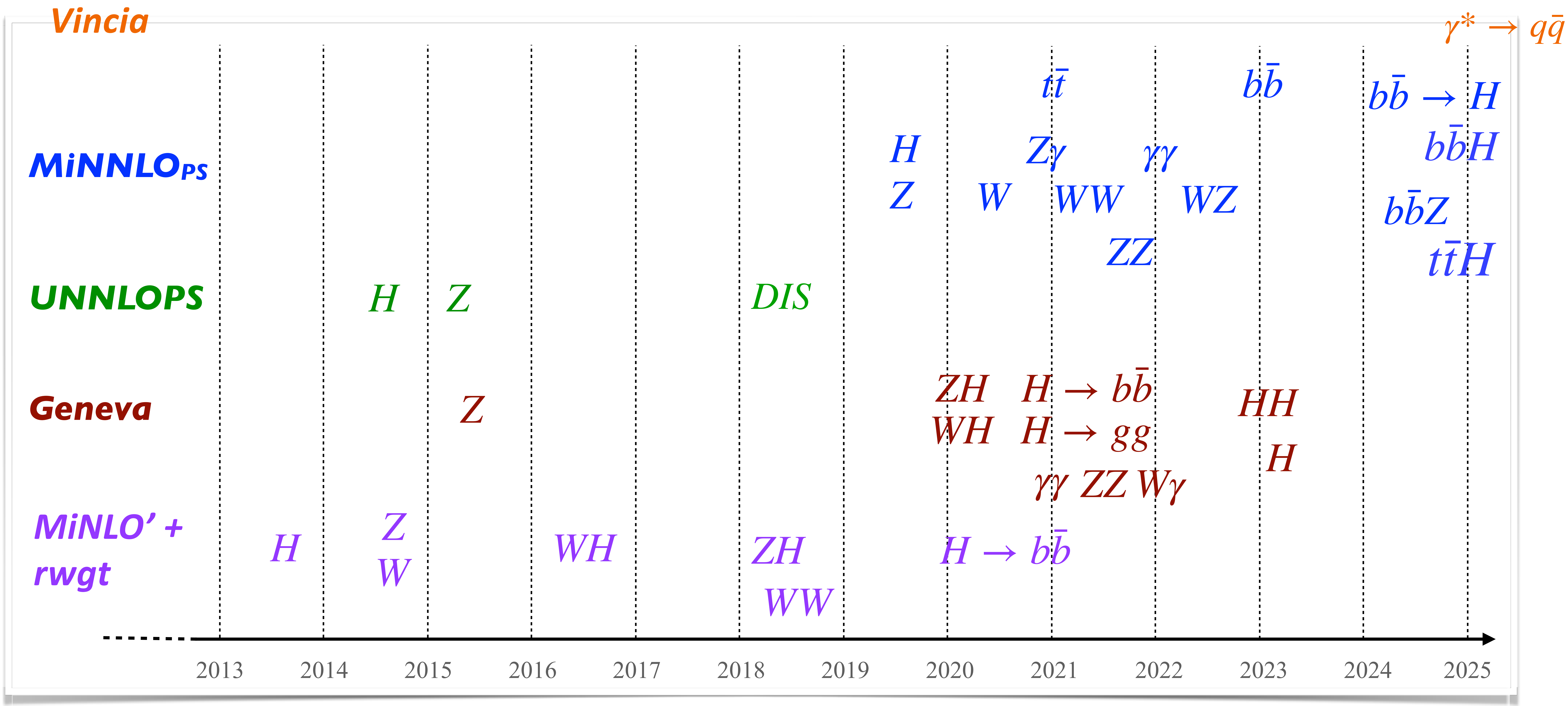
[Hoche, Krauss, Minzinger, Reichelt 2507.22837]
[Hoche, Krauss, Reichelt 2404.14360]



Status of matching with LL showers

Adaptation from M. Weisemann slides at Loopfest 2024

➤ NNLO matching is current fronteer in matching with LL showers



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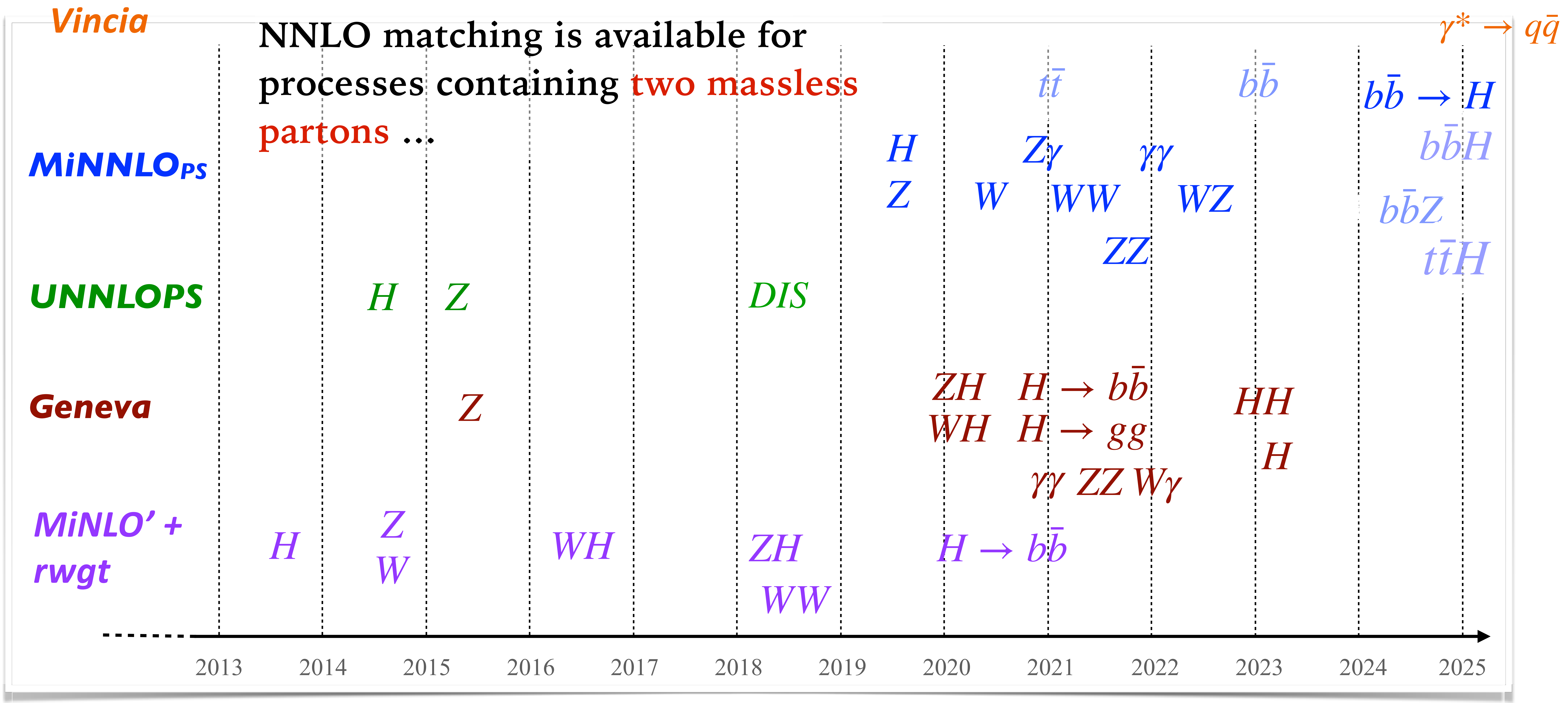

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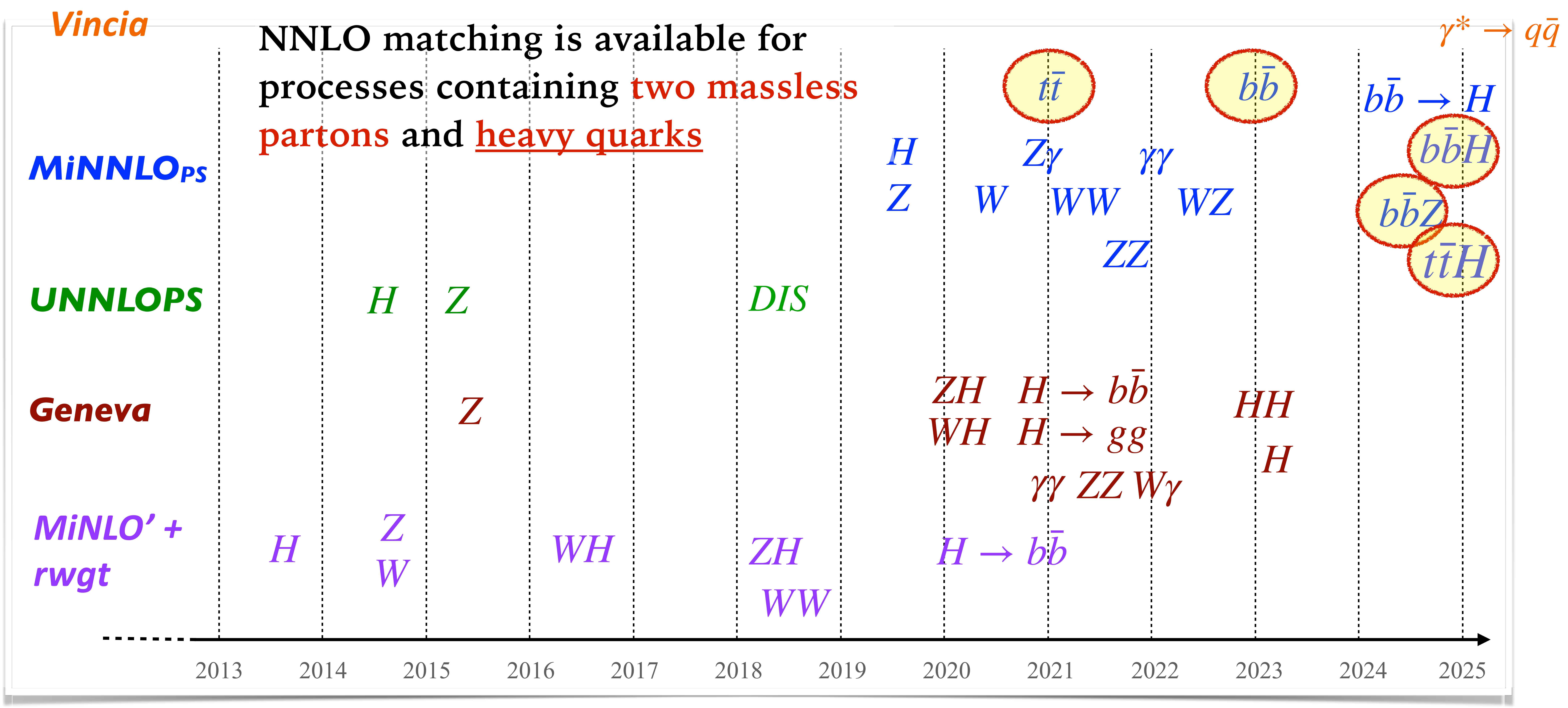
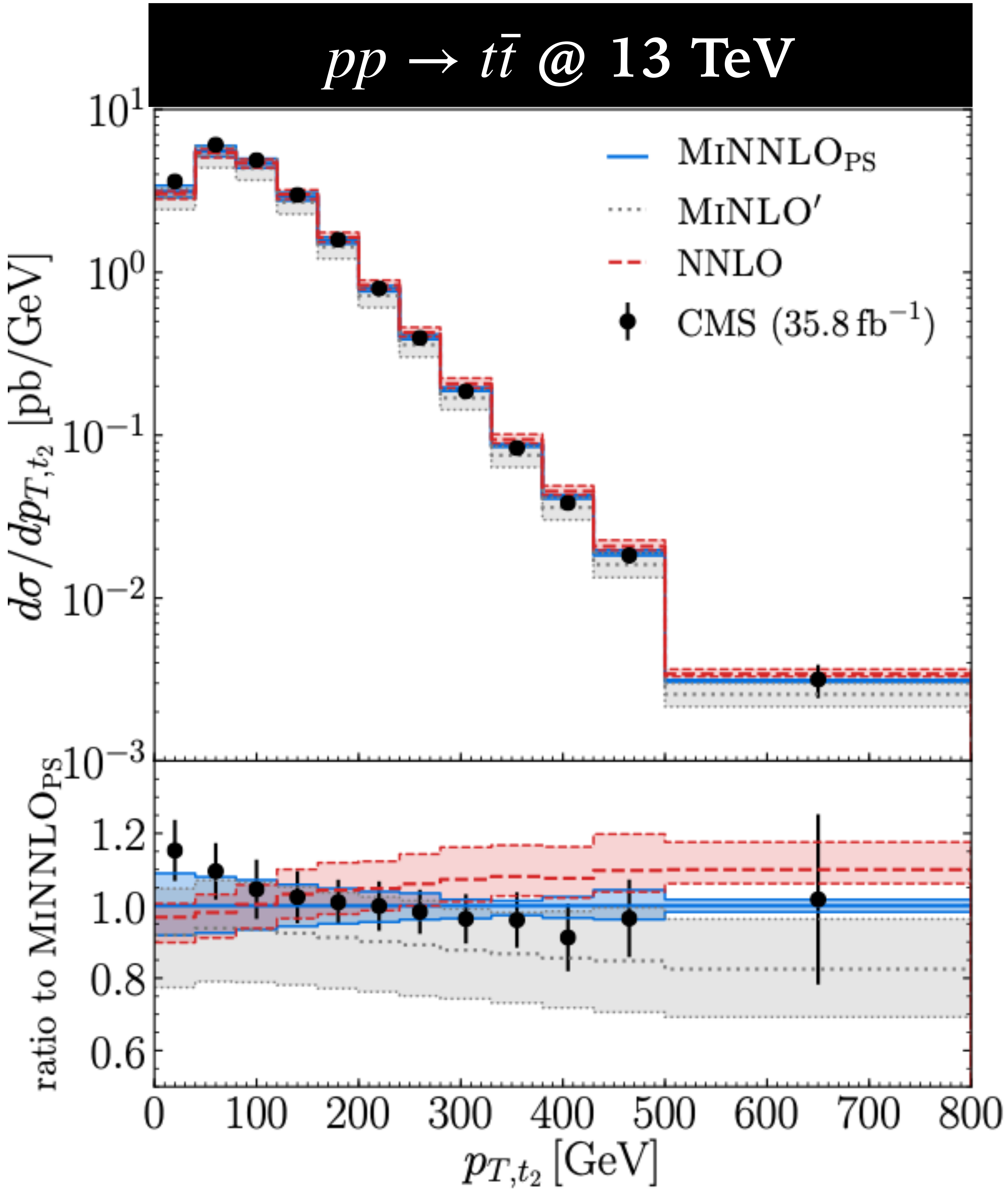
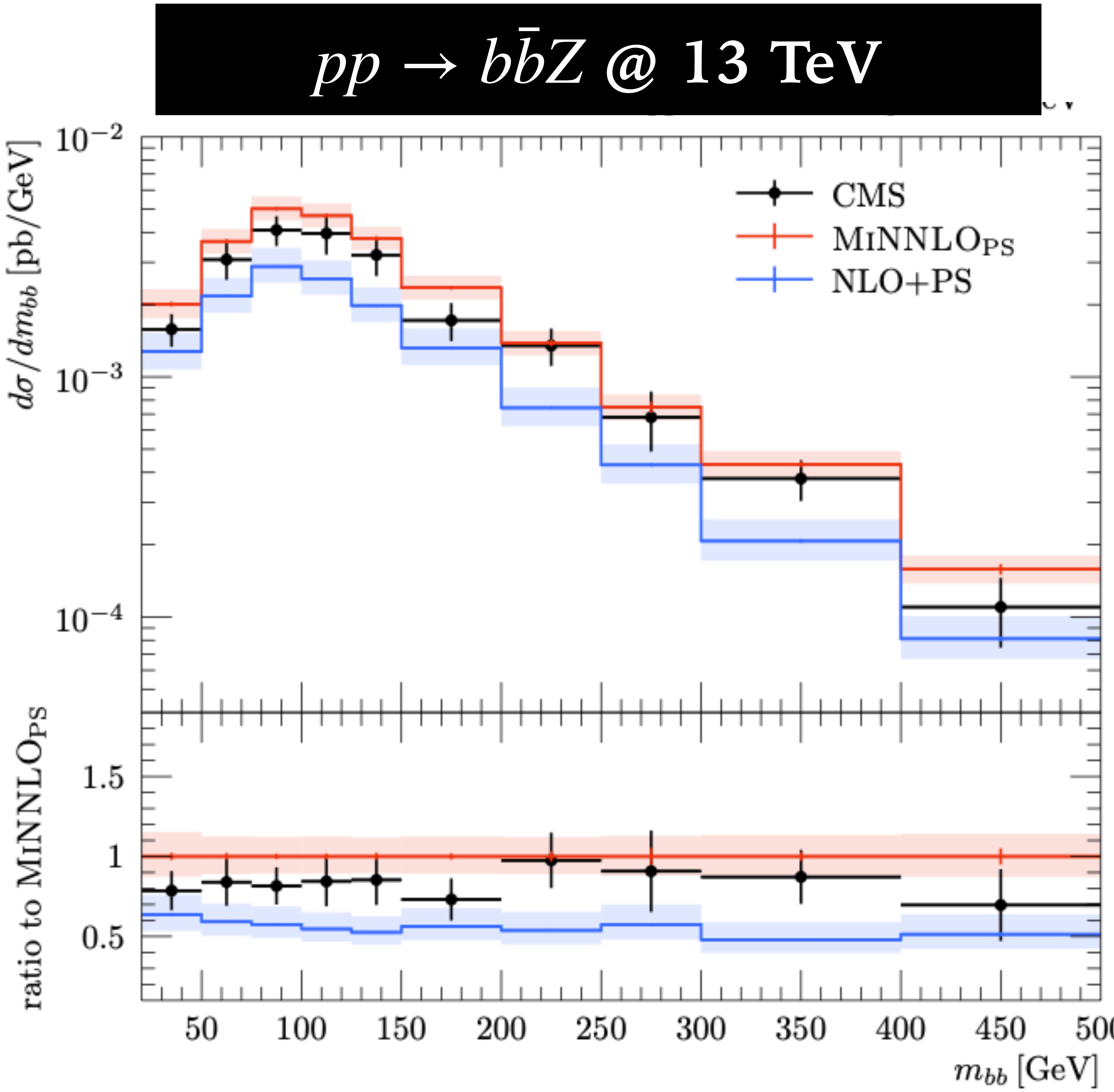


Selected **MiNNLO$_{PS}$** highlights: NNLO matching with **heavy** coloured-final states



[Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi, 2112.12135]

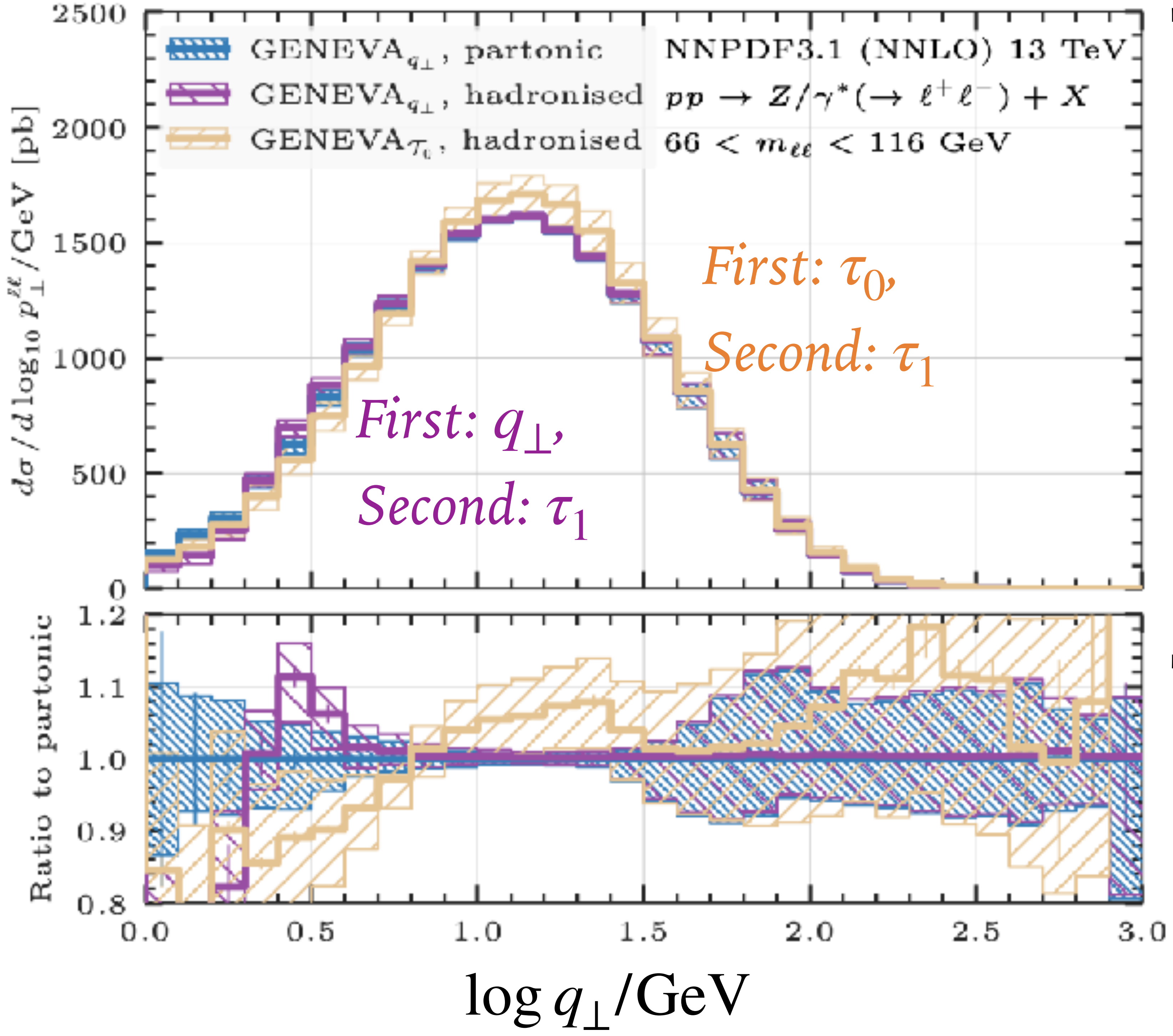


[Mazzitelli, Sotnikov, Wiesemann 2404.08598]

Selected **Geneva** highlights: exploration of several **resolution variables**

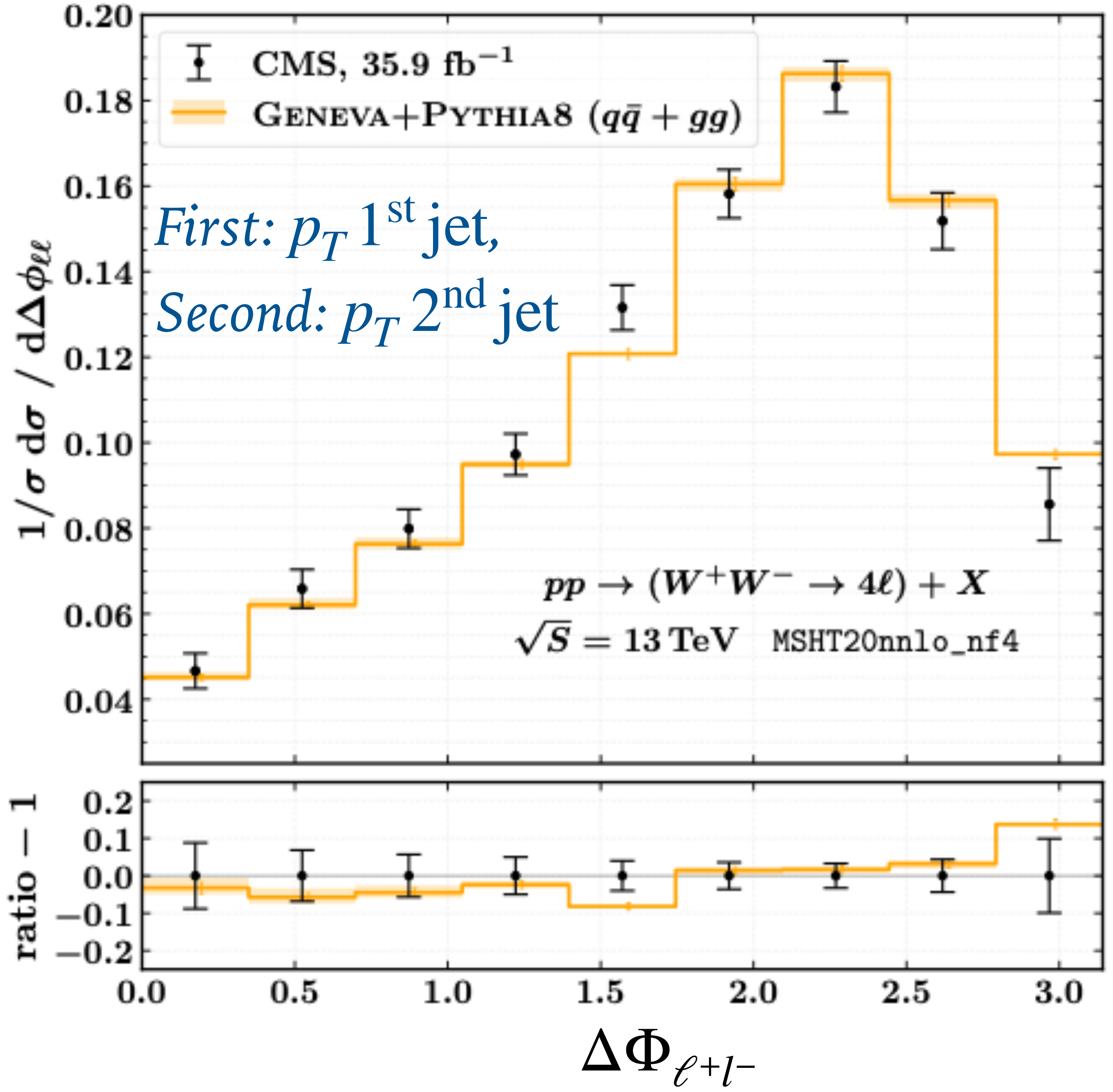
- In the context of matching, the **resolution variable** is used to discriminate emissions described with the **full QCD matrix element**, and those with the **PS approximate** one

$pp \to Z \to \ell^+\ell^-$ @ 13 TeV



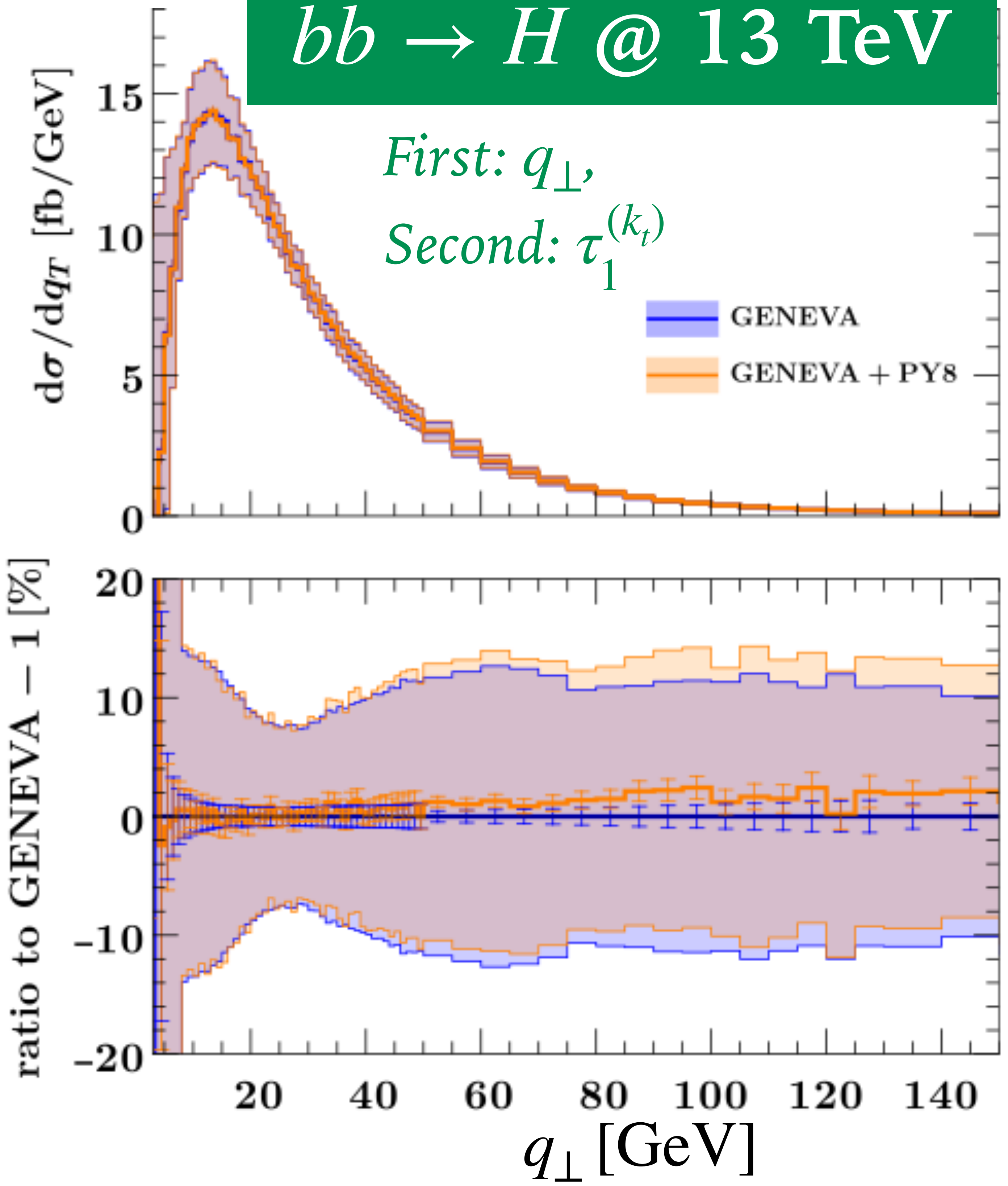
[Alioli et al. 2102.08390]

$pp \to W^+W^- \to \ell^+ l^- \nu_\ell \bar{\nu}_l$ @ 13 TeV



[Gavardi et al., 2308.11577]

$b\bar{b} \to H$ @ 13 TeV



[Gavardi et al., 2505.14773]

- Interplay between resolution variable and **shower accuracy**?

Adding QED and EW interactions in Shower Monte Carlo

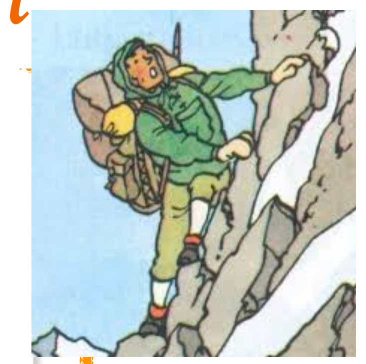
Soft photon resummation

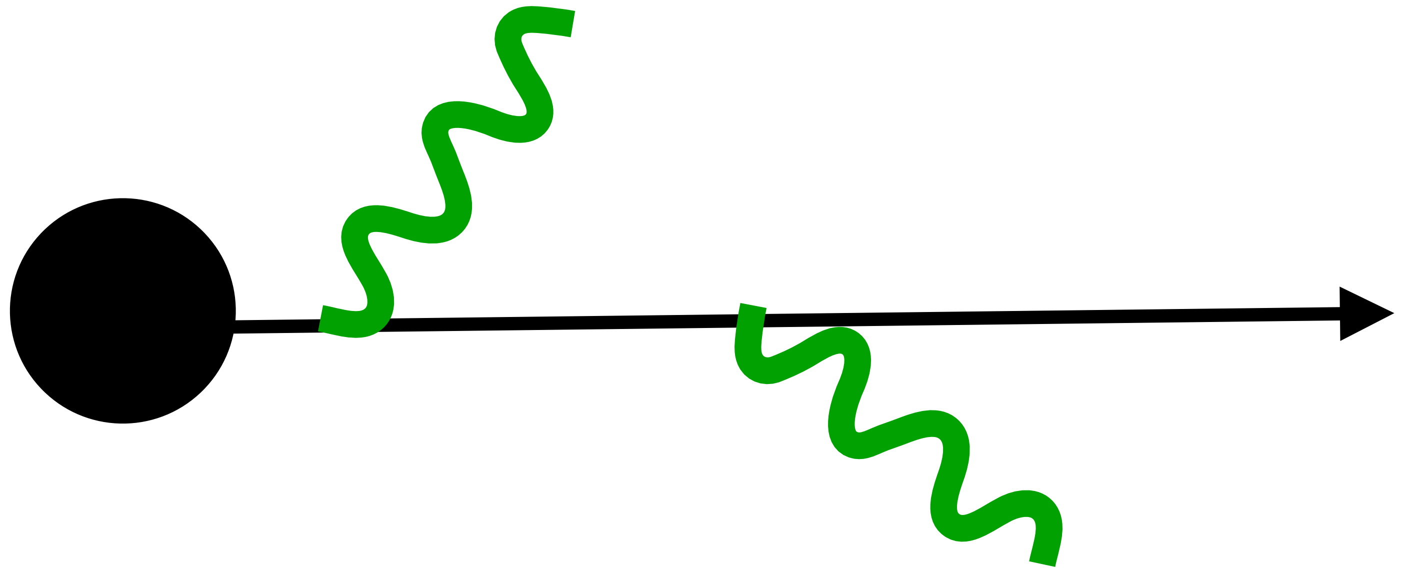
PHOTOS: A Universal Monte Carlo for QED radiative corrections. Version 2.0
Barberio, Was (94)

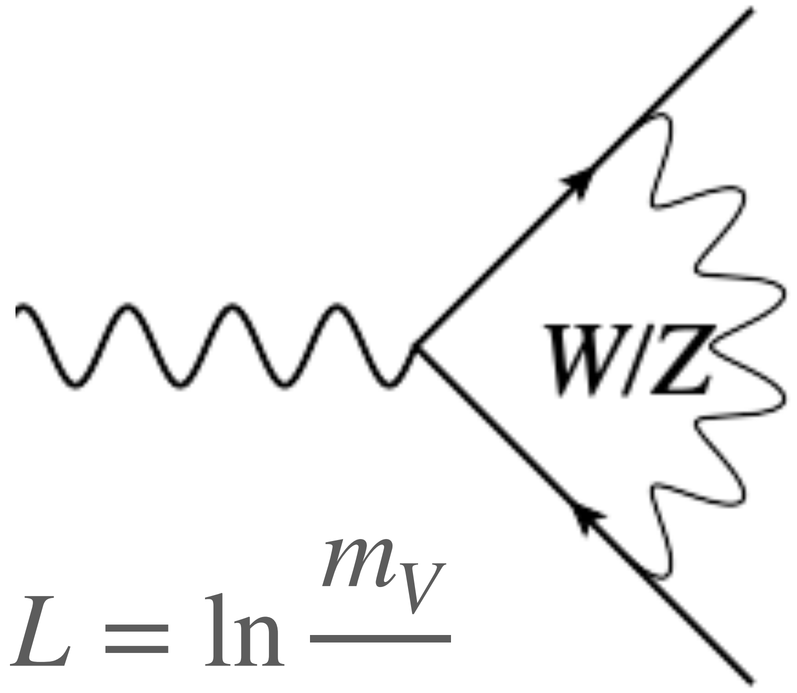
YFS Resummation for Future Lepton-Lepton Colliders in SHERPA
Krauss, Price, Schönherr
[2203.10948]

EW logs resummation

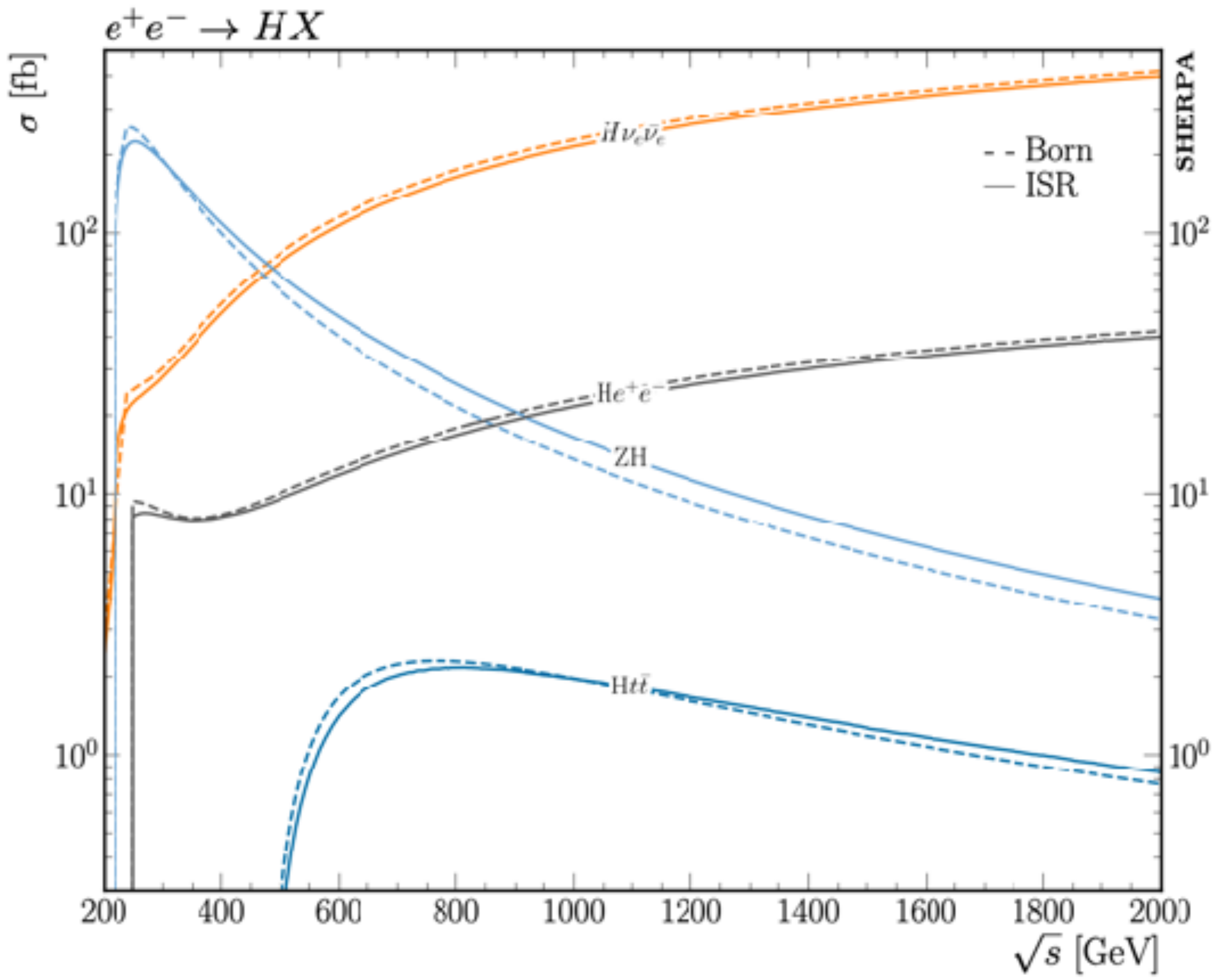
Automated evaluation of electroweak Sudakov logarithms in Sherpa
Bothmann, Napoletano
[2006.14635]







$$L = \ln \frac{m_V}{s}$$



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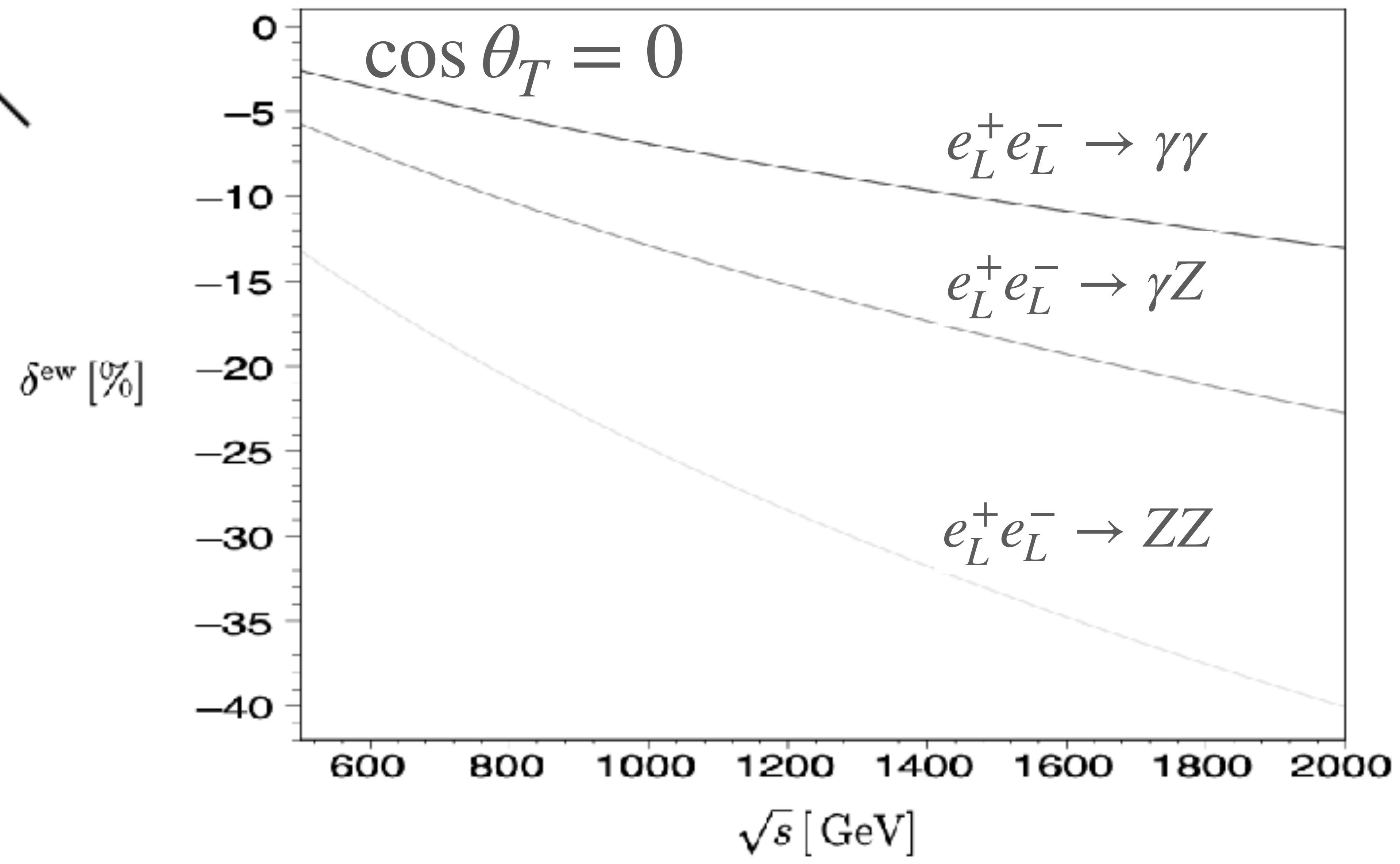

Denner, Pozzorini [hep-ph/0010201]

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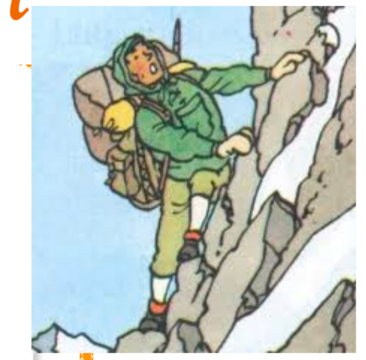

QED ISR (collinear)

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Frixion, Mattelaer, Zaro, Zhao
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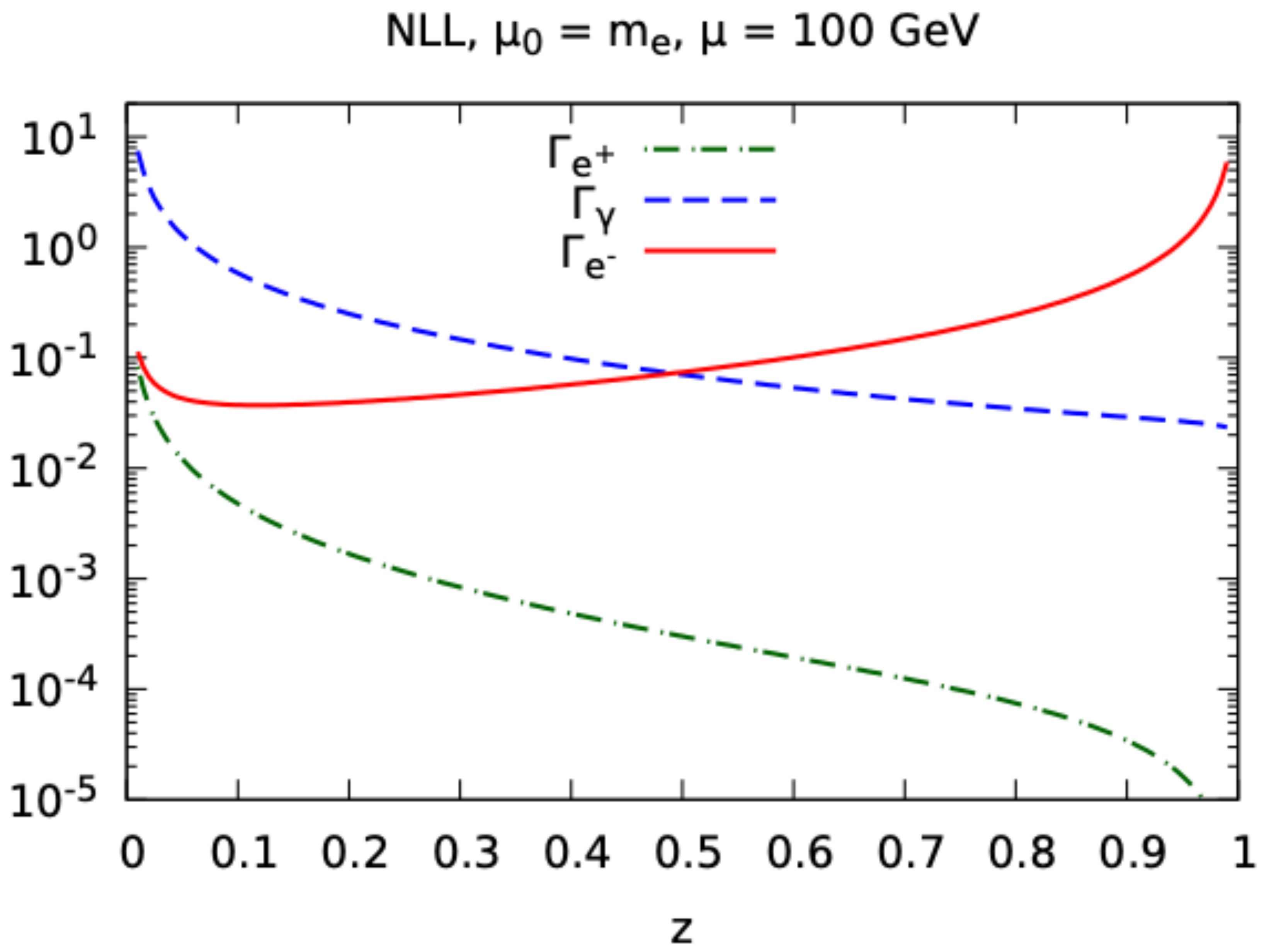

Bertone, Cacciari, Frixione, Stagnitto, 1911.12040

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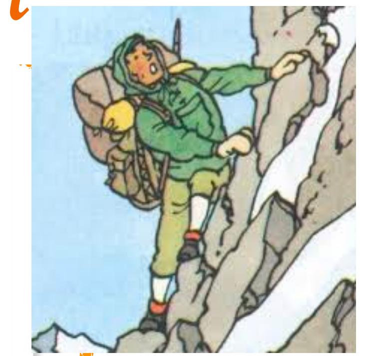

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Interleaved QED/EW and QCD PS

Implementation of angularly ordered electroweak parton shower in Herwig 7
Masouminia, Richardson [2108.10817]

Herwig 7 release notes
(QED shower) Bellm et al,
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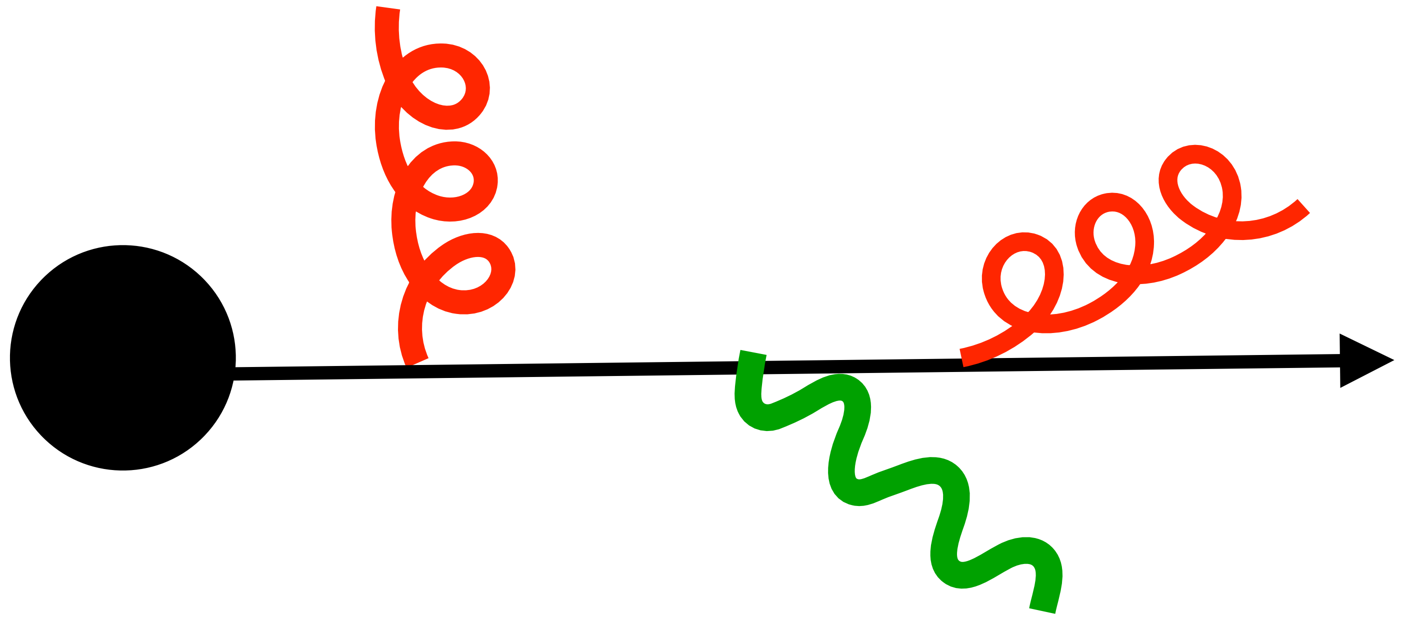
Multipole photon radiation in the Vincia parton shower
Verheyen, Skands [2002.04939]

Interleaved resonance decays and electroweak radiation in the Vincia parton shower
Brooks, Skands, Verheyen
[2108.10786]



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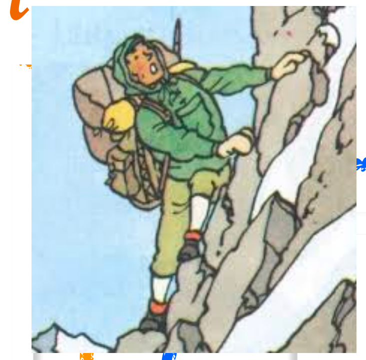

Matching with fixed order

An automated subtraction of NLO EW infrared divergences
(Sherpa) Schönherr [1712.07975]

The automation of next-to-leading order electroweak calculations
(MG5) Frederix, Frixione, Hirschi, Pagani, Shao, Zaro [1804.10017]

Implementation of electroweak corrections in the POWHEG BOX: single W production
Barze, Montagna, Nason, Nicrosini, Piccinini [1202.0465]

$W^{\pm}Z$ production at NNLO QCD and NLO EW matched to parton showers with MiNNLO$_{PS}$
Lindert, Lombardi, Wiesemann, Zanderighi, Zanoli [2208.12660]

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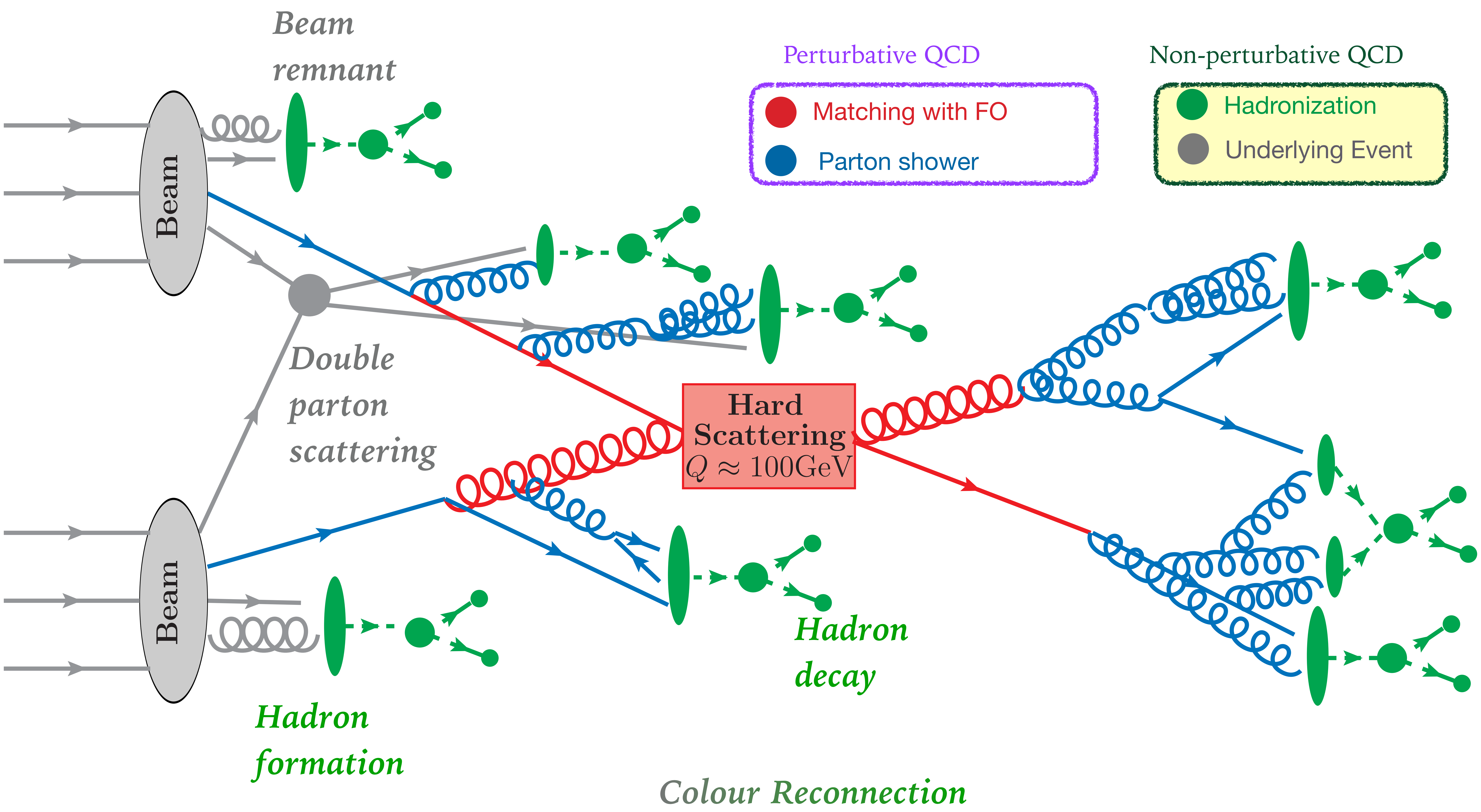
The landscape of **non-perturbative** physics

➤ **Phenomenological models** to describe complex non-perturbative aspects



Hadronisation: selected developments

- **Phenomenological models** to describe complex non-perturbative aspects
- To augment the predictivity of these models, one should try to include as much as possible **constraints from first-priciples physics / analytic knowledge**, and not just from data

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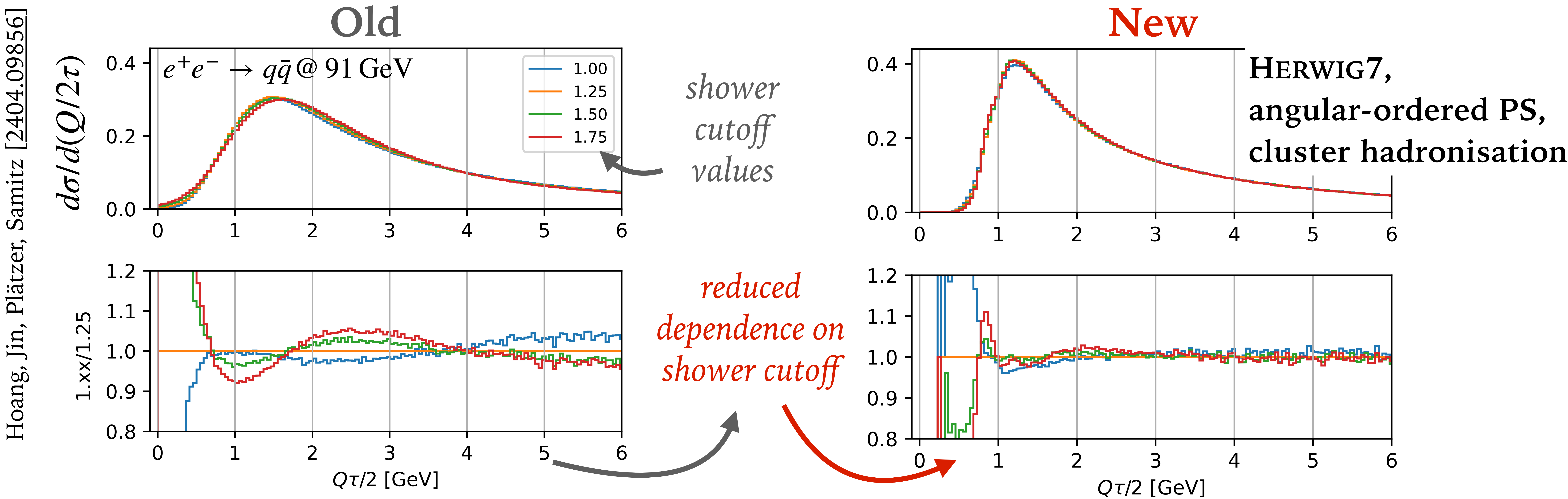
Shower cutoff scale as a factorisation scale and use QCD factorisation to impose constraints on hadronisation corrections



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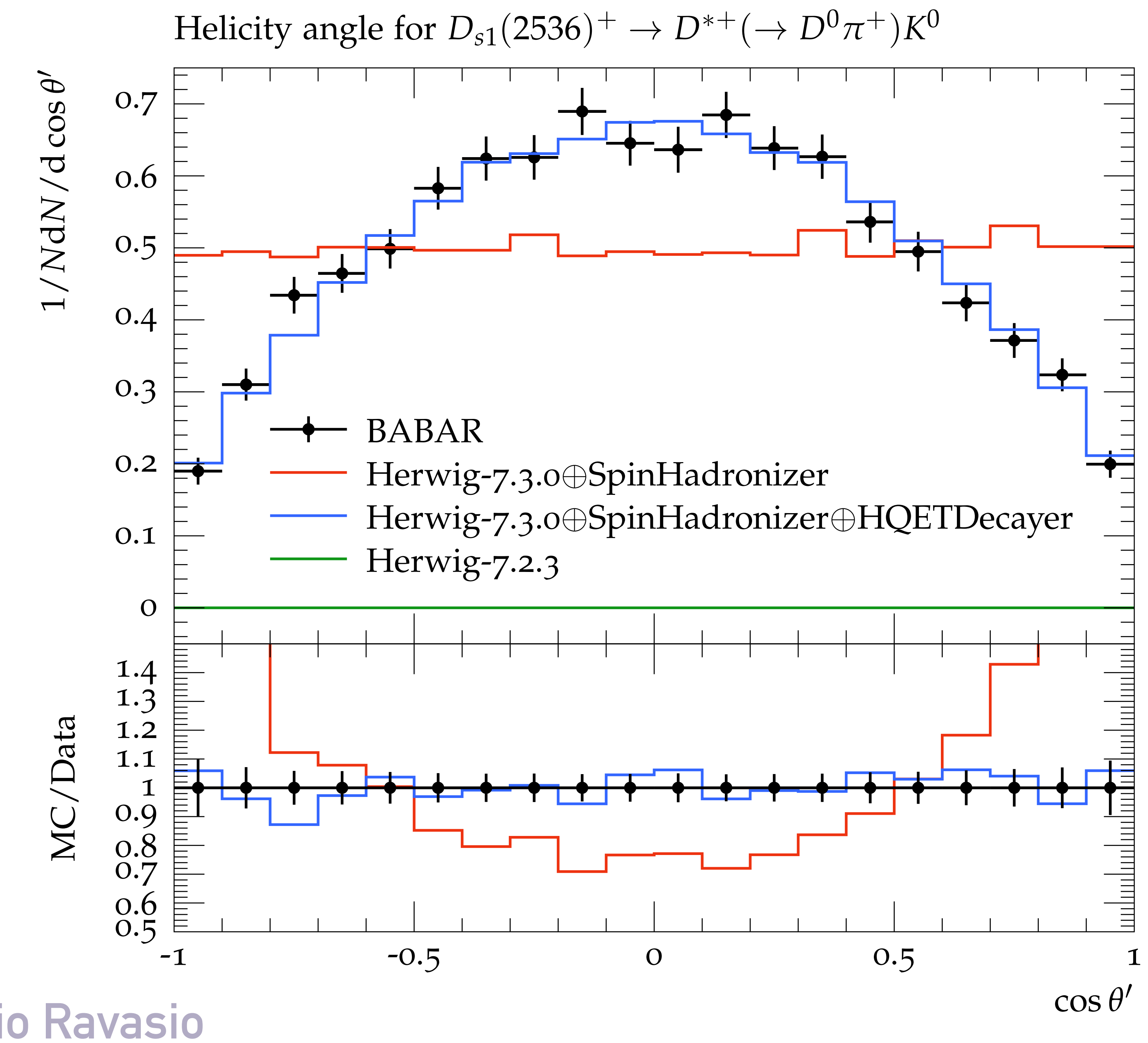
Shower cutoff scale as a factorisation scale and use QCD factorisation to impose constraints on hadronisation corrections

Use analytic matrix elements to model the decay of unstable hadrons

Masoumini, Richardson [2312.02757]



HERWIG7, cluster hadronisation

SpinHadronizer

Hadrons inherit from the helicity information of the pardons that form them: gets the right mean value

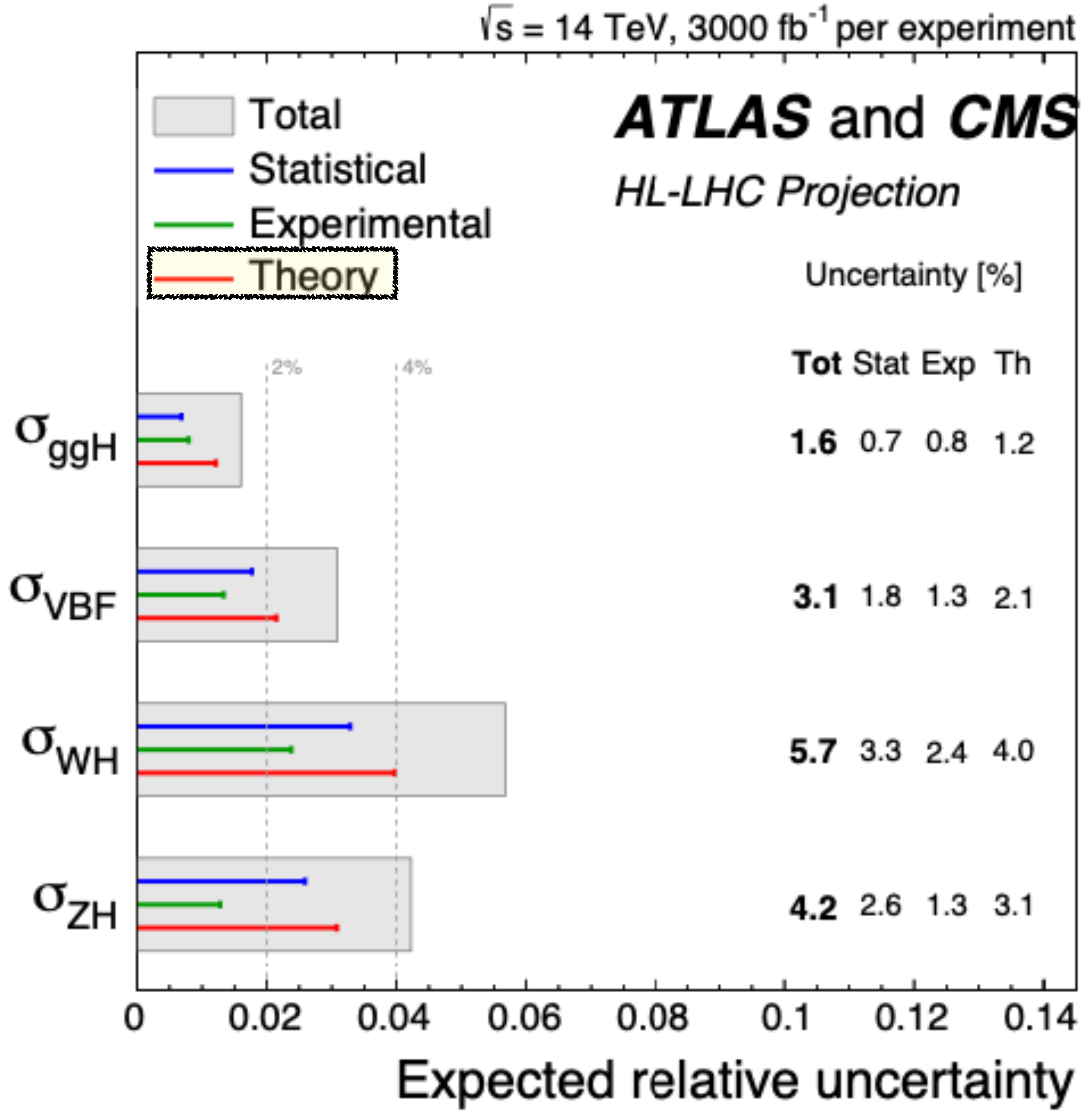
+HQETDecayer

Decay the hadrons using MEs from HQET

For incorporation of quark spin effects in the **string hadronisation** model, see e.g. Kerbizi, Lönnblad, Martin [2407.07706]

Conclusions and outlook

- **Shower Monte Carlo** event generators are **crucial** for exploiting collider experiments
- They capture all physics aspects spanning from **multi-TeV** to few **MeV** physics
- High-lumi LHC and prospected new colliders require **improving** all the components of Shower Monte Carlo Event Generators
  - **Parton showers** formal accuracy is rapidly improving
  - **Matching** with fixed-order has been active area for research in the past 20 years, but we are still far from a NNLO+PS revolution
  - **QED** and **EW** interactions: important for % physics at LHC, paramount for 0.1% physics at lepton colliders
  - Find theory-inspired contains to improve **soft-physics models**
  - Make it all numerically **efficient**

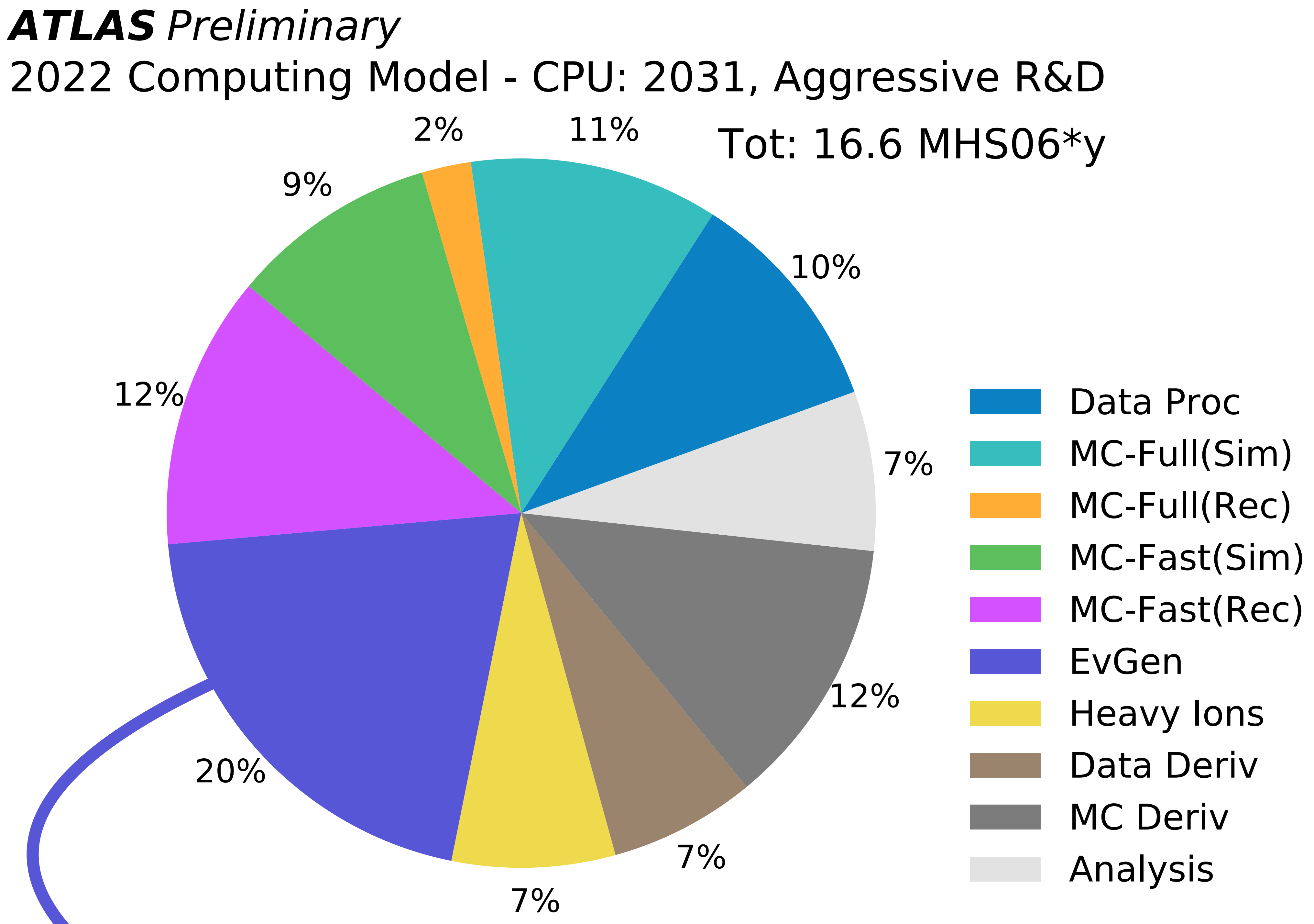


[1902.00134]

Backup

Computational efficiency

[CERN-LHCC-2022-005]



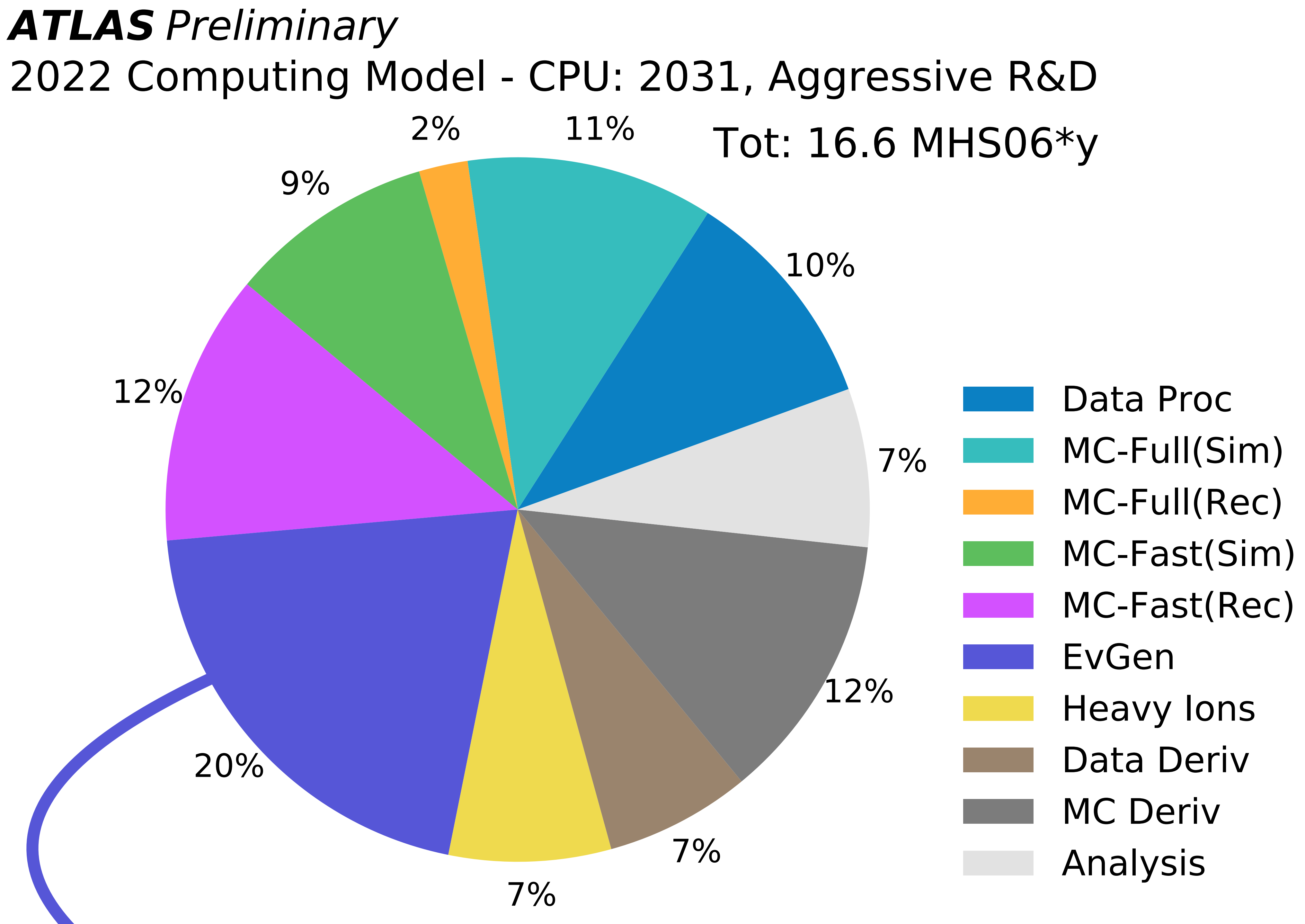
SMC runtime: large runtime lead to MC uncertainties dominating measuremens

e.g. ATLAS $V + h \to b\bar{b}/c\bar{c}$

CMS $V + h \to b\bar{b}$

Computational efficiency

[CERN-LHCC-2022-005]



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Requiring that a sample with a **fraction f negative-weight** events has the same relative error as one without, one needs to generate

$$c = \frac{1}{(1-2f)^2}$$ more events

$pp \to e^+e^-$	6.9% (1.3)
$pp \to e^+\nu_e$	7.2% (1.4)
$pp \to H$	10.4% (1.6)
$pp \to Hb\bar{b}$	40.3% (27)
$pp \to W^+j$	21.7% (3.1)
$pp \to W^+t\bar{t}$	16.2% (2.2)
$pp \to t\bar{t}$	23.0% (3.4)

Frederix, Frixione, Prestel, Torrielli 2002.12716

Matching and merging plague: negative weights

- A large fraction of **negative weights** renders a SMC inefficient (and not suited for **machine learining** applications!)

General methods to reduce the fraction of negative weights

Powheg: Nason hep-ph/0409146
MC@NLO improvements: Frederix, Frixione, Prestel, Torrielli 2002.12716; Danziger, Höhe, Siegert 2110.15211

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Fully positive matching (atm for simple processes only)

KrkNLO: Jadach, Placzek, Sapeta, Siódmok, Skrzypek 1503.06849; Jadach, Nail, Placzek, Sapeta, Siódmok, Skrzypek 1607.06799; Sarmah, Siódmok, Whitehead 2409.16417
ESME: van Beekveld , Ferrario Ravasio, Helliwell Karlberg, Salam, Scyboz, Soto-Ontoso, Soyez, Zanoli 2504.05377