

# Multiscale dynamics of particle collisions

Pier Francesco Monni  
CERN

**Guido Altarelli Award - June 11 2020**

# LHC's open questions in 2020

## **Is new physics within reach of the LHC ?**

New physics (NP) is clearly elusive. Most likely scenario: consistent pattern of deviations in complementary measurements is necessary to diagnose genuine presence of NP. Finding small deviations from the SM **requires a precise theory control over exclusive observables in remote corners of phase space**

# LHC's open questions in 2020

## **Is new physics within reach of the LHC ?**

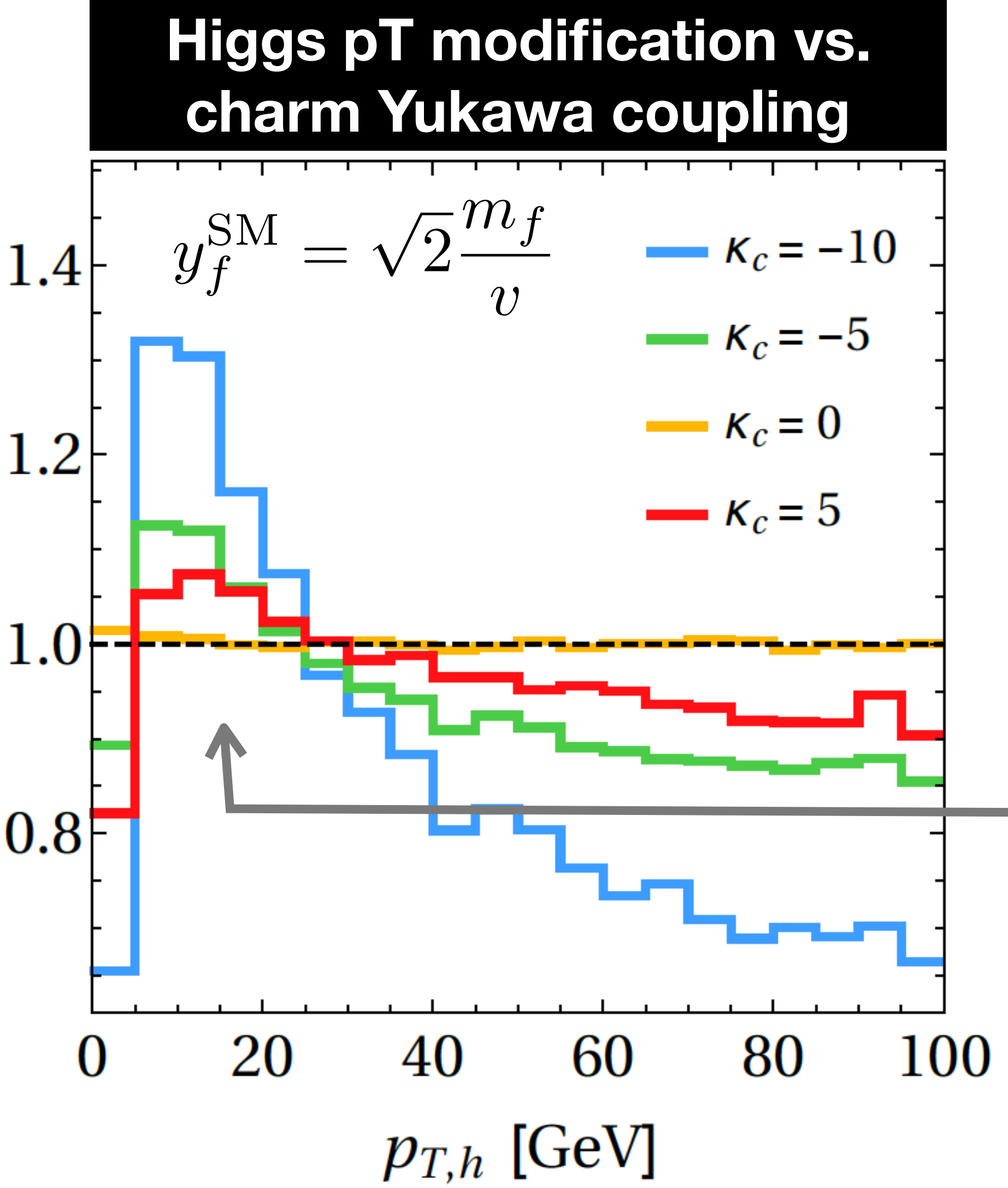
New physics (NP) is clearly elusive. Most likely scenario: consistent pattern of deviations in complementary measurements is necessary to diagnose genuine presence of NP. Finding small deviations from the SM **requires a precise theory control over exclusive observables in remote corners of phase space**

## **Is the Higgs sector really the SM one ?**

Understanding this particle with % accuracy is not like any other precision test of the SM, small details can open a gate to NP scenarios (e.g. composite Higgs, additional scalars, ...). Unlike in the first question, we already have the Higgs and we must explore it: **most information ciphered in differential distributions**

# An example: Higgs Yukawa couplings to 2<sup>nd</sup> generation

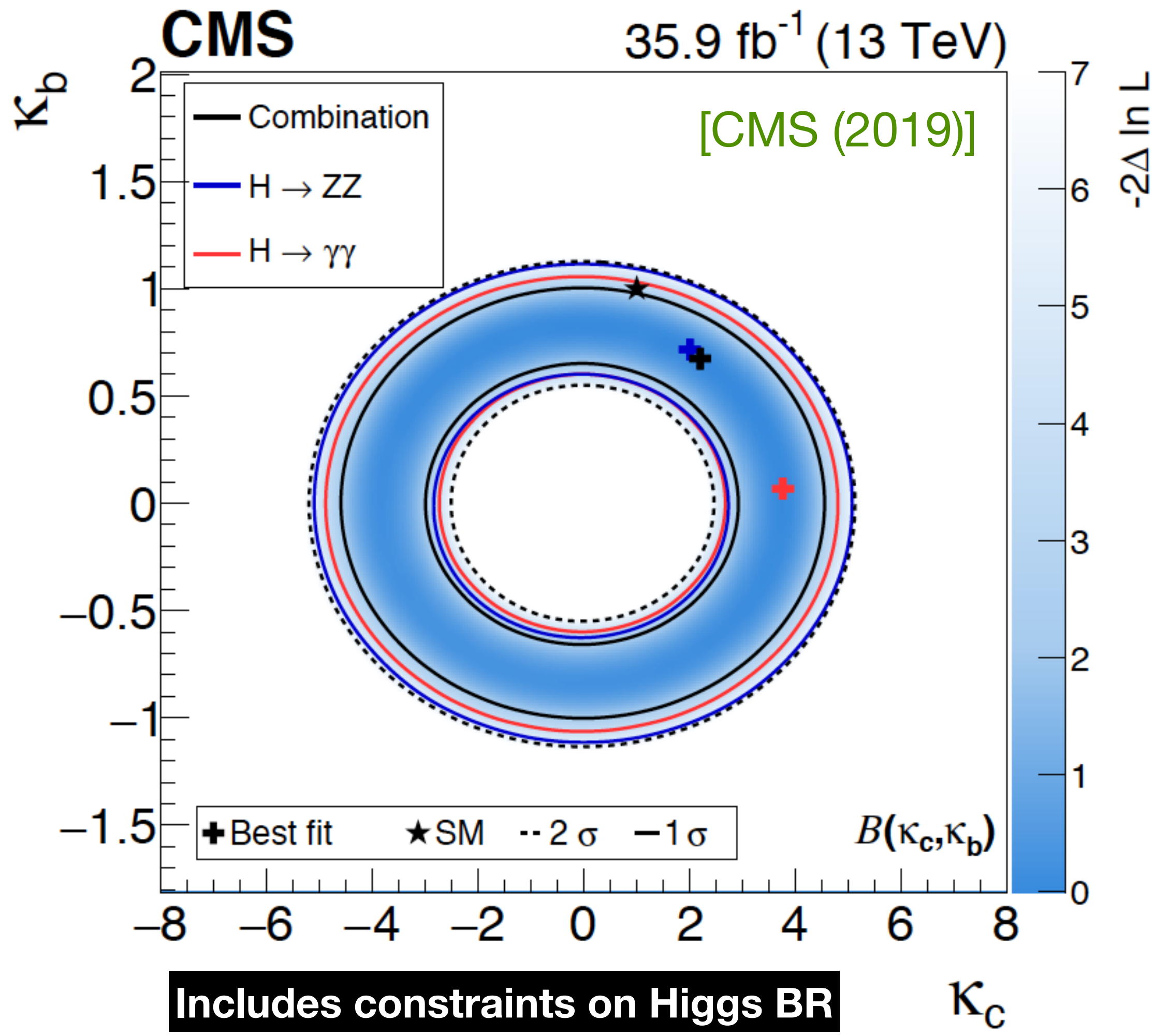
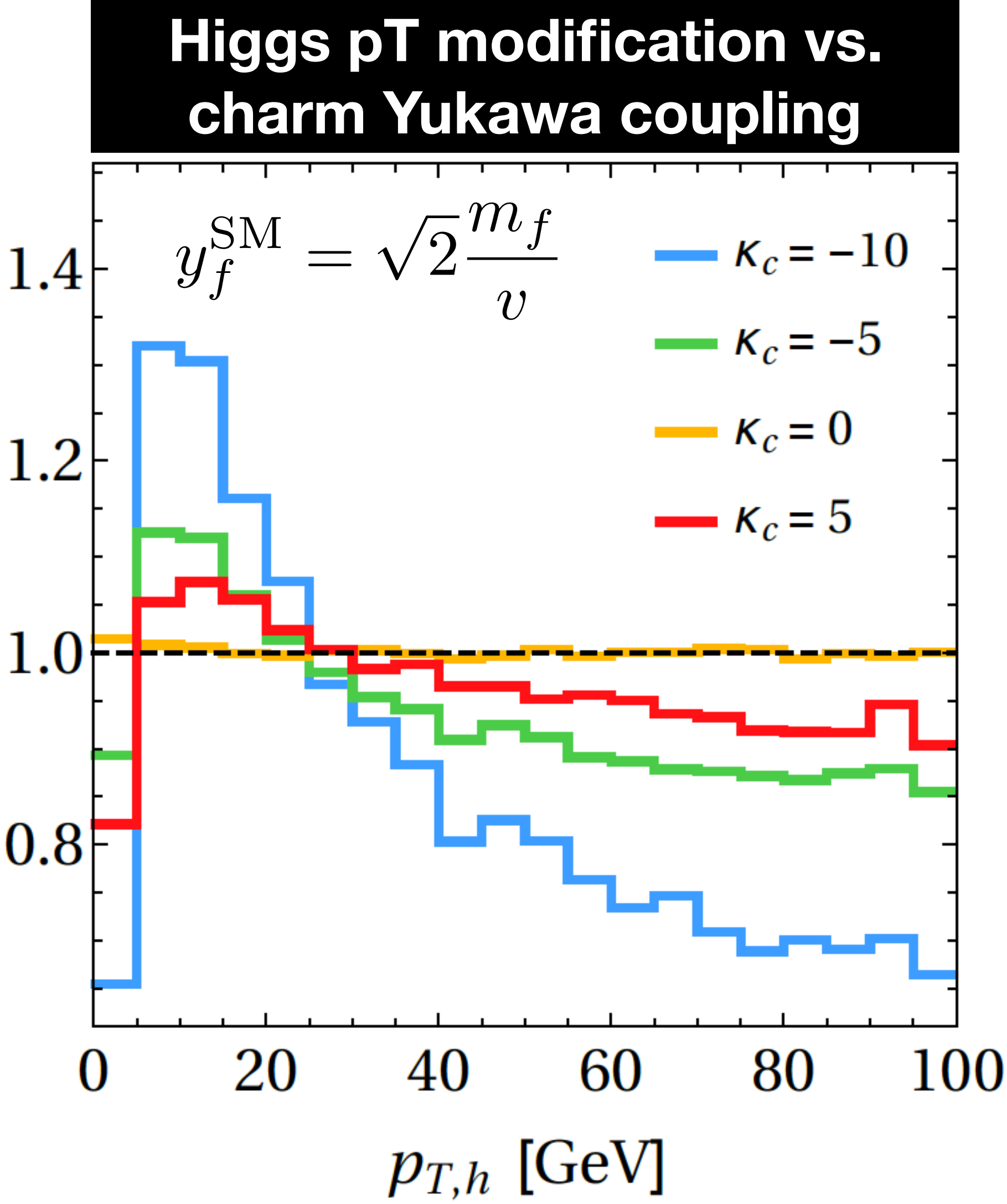
[Bishara, Haisch, PM, Re (2016)]  
see also [Soreq, Zhu, Zupan (2016)]



Shape distortions are maximized at small  $p_T$ .  
Close to bottom/charm thresholds.  
**[Reminder: we're after small deviations (few x SM), precise TH necessary!]**

# An example: Higgs Yukawa couplings to 2<sup>nd</sup> generation

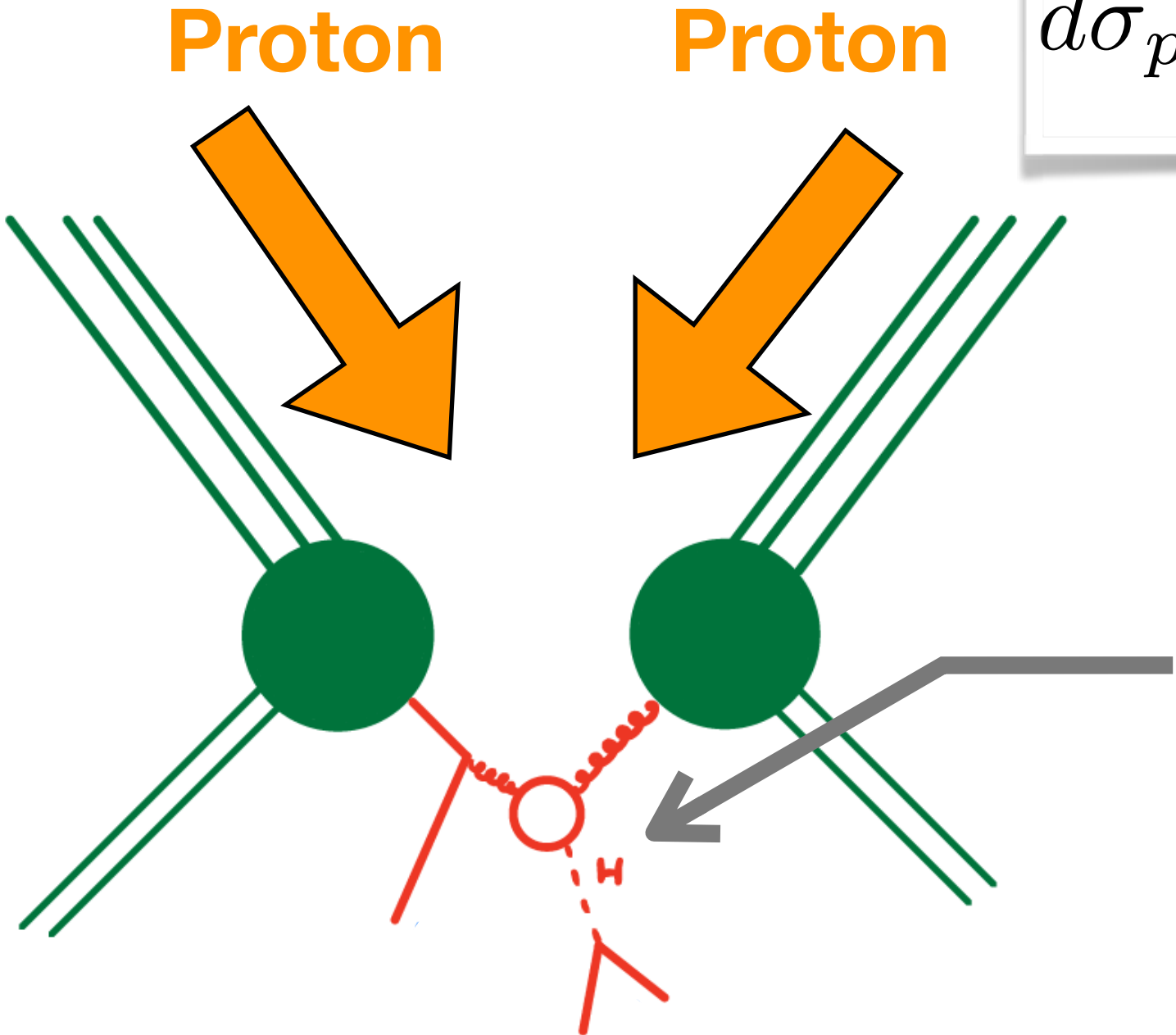
[Bishara, Haisch, PM, Re (2016)]  
 see also [Soreq, Zhu, Zupan (2016)]



# A successful approach

$$d\sigma_{pp \rightarrow H+X} = f_i(x_1, \mu^2) \otimes d\hat{\sigma}_{ij \rightarrow H+X} \otimes f_j(x_2, \mu^2) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{Q}\right)$$

[Collins, Soper, Sterman (1985)]

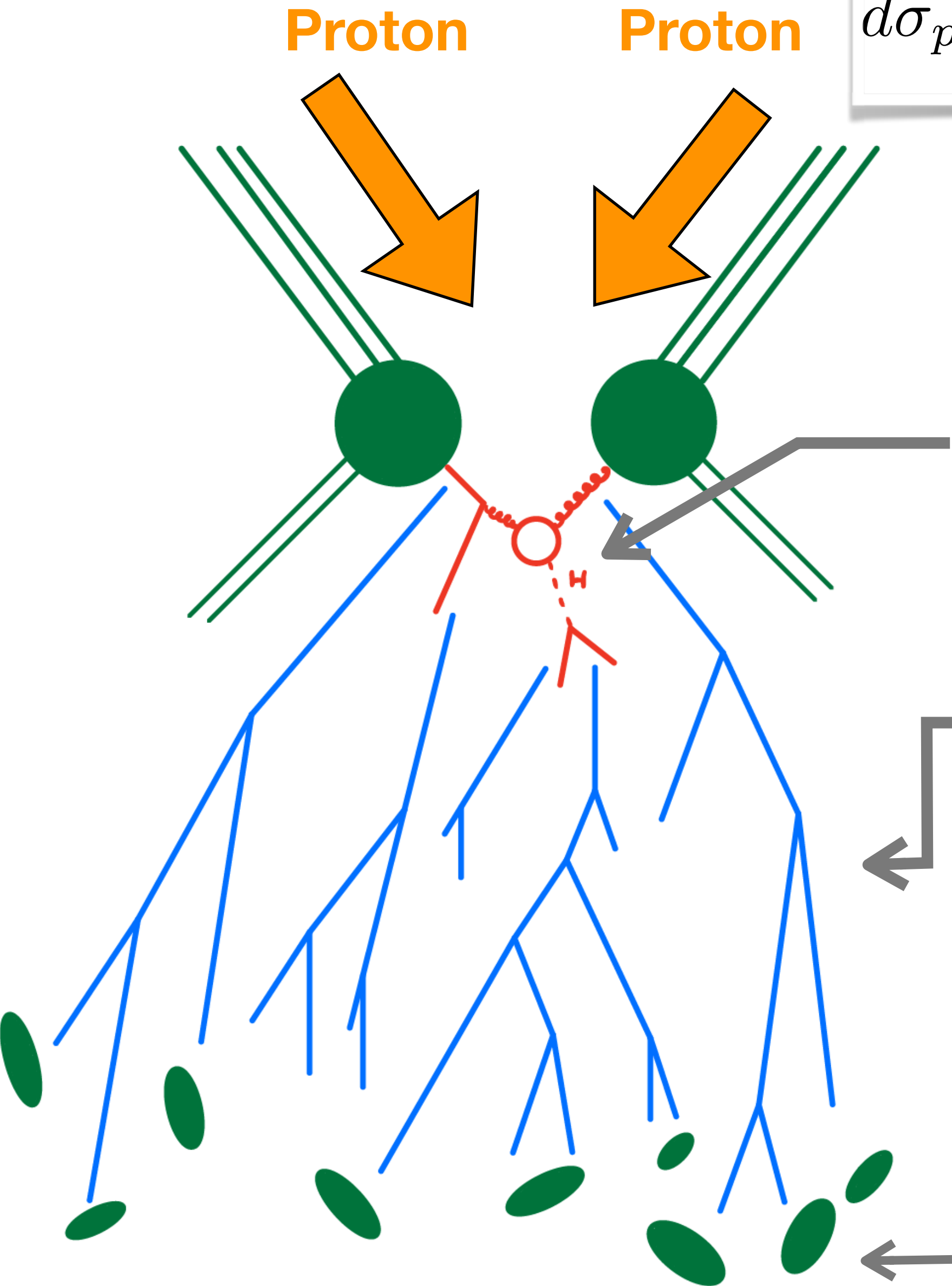


Hard collision ( $\sim 10^2 - 10^3$  GeV):  
standard perturbation theory

# A successful approach

$$d\sigma_{pp \rightarrow H+X} = f_i(x_1, \mu^2) \otimes d\hat{\sigma}_{ij \rightarrow H+X} \otimes f_j(x_2, \mu^2) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{Q}\right)$$

[Collins, Soper, Sterman (1985)]



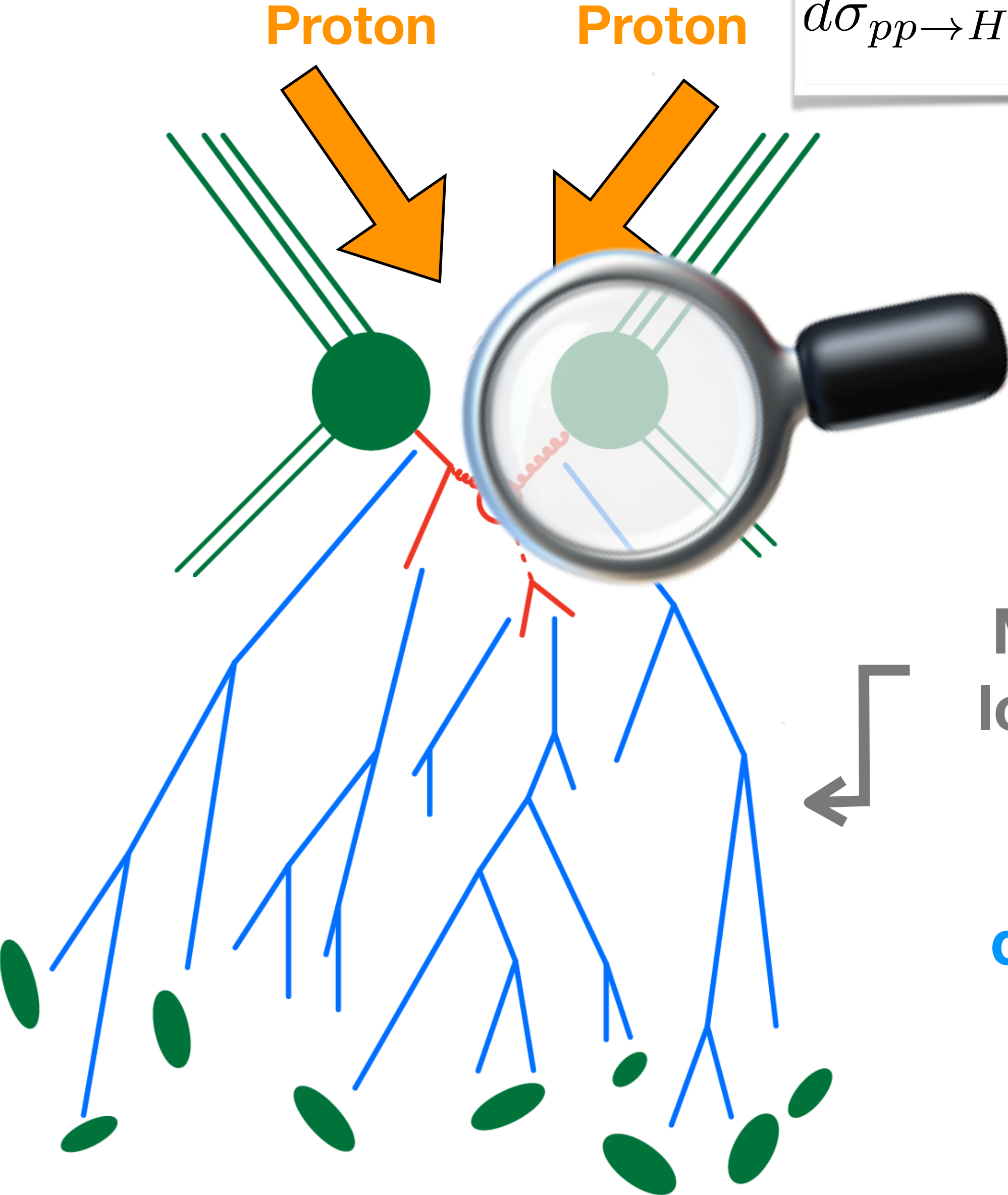
**Hard collision ( $\sim 10^2 - 10^3$  GeV):  
standard perturbation theory**

**Multi-scale evolution: large  
logarithms of ratio of scales  
must be resummed**

**Hadronic scales ( $\sim 1$  GeV)**

# A successful approach

$$d\sigma_{pp \rightarrow H+X} = f_i(x_1, \mu^2) \otimes d\hat{\sigma}_{ij \rightarrow H+X} \otimes f_j(x_2, \mu^2) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{Q}\right)$$



Multi-scale evolution: large logarithms of ratio of scales must be resummed

**E.g. evolution of parton densities with energy scale**

# ASYMPTOTIC FREEDOM IN PARTON LANGUAGE

[Altarelli, Parisi (1977)]  
[Gribov, Lipatov (1972)]  
[Dokshitzer (1977)]

G. ALTARELLI \*

*Laboratoire de Physique Théorique de l'École Normale Supérieure \*\* , Paris, France*

G. PARISI \*\*\*

*Institut des Hautes Etudes Scientifiques, Bures-sur-Yvette, France*

In the leading logarithmic approximation, the results can again be phrased in the parton language by assigning a well determined  $Q^2$  dependence to the parton densities. In spite of the relative simplicity of the final results, their derivation, although theoretically rigorous, is somewhat abstract and formal, being formulated in the language of renormalization group equations for the coefficient functions of the local operators which appear in the light cone expansion for the product of two currents.

In this paper we show that an alternative derivation of all results of current interest for the  $Q^2$  behaviour of deep inelastic structure functions is possible. In this approach all stages of the calculation refer to parton concepts and offer a very illuminating physical interpretation of the scaling violations. In our opinion the present

# The *dual* interpretation of DGLAP equations

- ▶ Crucial observations:
  - ▶ Long distance physics can be factorized and summed to all perturbative orders
  - ▶ Fine details of the scattering (e.g. density of partons) depend on **evolution (resolution) scale**

## RG evolution of operators matrix elements

Inclusive evolution of parton densities with the resolution scale at which the hadron (proton) is probed

$$\frac{dq^i(x, t)}{dt} = \frac{\alpha(t)}{2\pi} \int_x^1 \frac{dy}{y} \left[ \sum_{j=1}^{2f} q^j(y, t) P_{q^i q^j} \left( \frac{x}{y} \right) + G(y, t) P_{q^i G} \left( \frac{x}{y} \right) \right]$$

$$\frac{dG(x, t)}{dt} = \frac{\alpha(t)}{2\pi} \int_x^1 \frac{dy}{y} \left[ \sum_{j=1}^{2f} q^j(y, t) P_{G q^j} \left( \frac{x}{y} \right) + G(y, t) P_{GG} \left( \frac{x}{y} \right) \right]$$

[Altarelli, Parisi (1977)]

# The *dual* interpretation of DGLAP equations

- ▶ **Crucial observations:**
  - ▶ Long distance physics can be factorized and summed to all perturbative orders
  - ▶ Fine details of the scattering (e.g. density of partons) depend on **evolution (resolution) scale**

**RG evolution of operators matrix elements**

Inclusive evolution of parton densities with the resolution scale at which the hadron (proton) is probed

$$\frac{dq^i(x, t)}{dt} = \frac{\alpha(t)}{2\pi} \int_x^1 \frac{dy}{y} \left[ \sum_{j=1}^{2f} q^j(y, t) P_{q^i q^j} \left( \frac{x}{y} \right) + G(y, t) P_{q^i G} \left( \frac{x}{y} \right) \right]$$

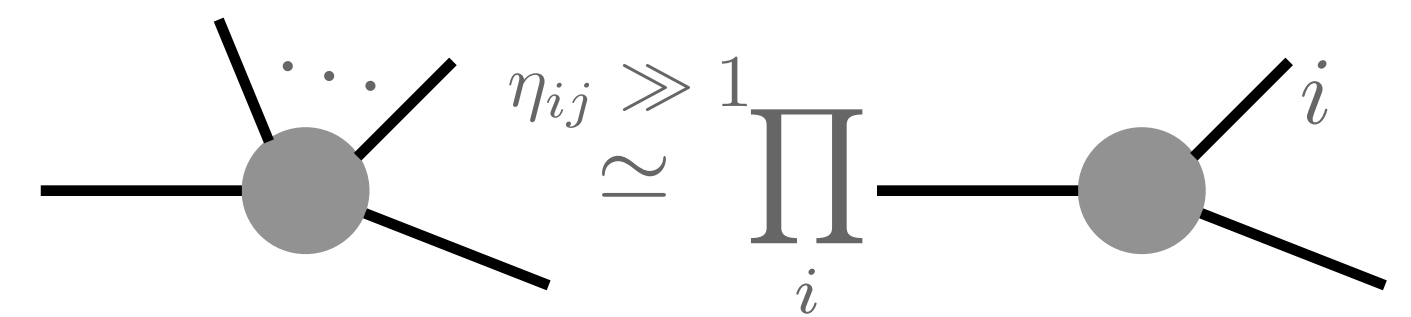
$$\frac{dG(x, t)}{dt} = \frac{\alpha(t)}{2\pi} \int_x^1 \frac{dy}{y} \left[ \sum_{j=1}^{2f} q^j(y, t) P_{G q^j} \left( \frac{x}{y} \right) + G(y, t) P_{GG} \left( \frac{x}{y} \right) \right]$$

[Altarelli, Parisi (1977)]



**Iterative structure of multi particle amplitudes in collinear limit**

Physics is described by iterating a finite set of fundamental building blocks. Exclusive description via a *Parton Shower* picture



# A change in the language of resummations

- ▶ This correspondence is far reaching, and allows one to address more complex questions than the evolution of parton densities e.g. What is the particle multiplicity distribution in collider events (within a jet alg.) ? What is the  $p_T$  distribution of a Drell-Yan pair ? ...
- ▶ Today, resummation for collider observables is often formulated in the modern language of Effective Field Theory. **Can we aim at a more exclusive understanding of all-order dynamics that can be systematically extended to higher logarithmic orders ?**

**Factorization and RG evolution of operators MEs**

e.g. Z boson  $p_T$  spectrum

$$d\sigma \sim \mathcal{H} \mathcal{B} \otimes \mathcal{B} \otimes S$$

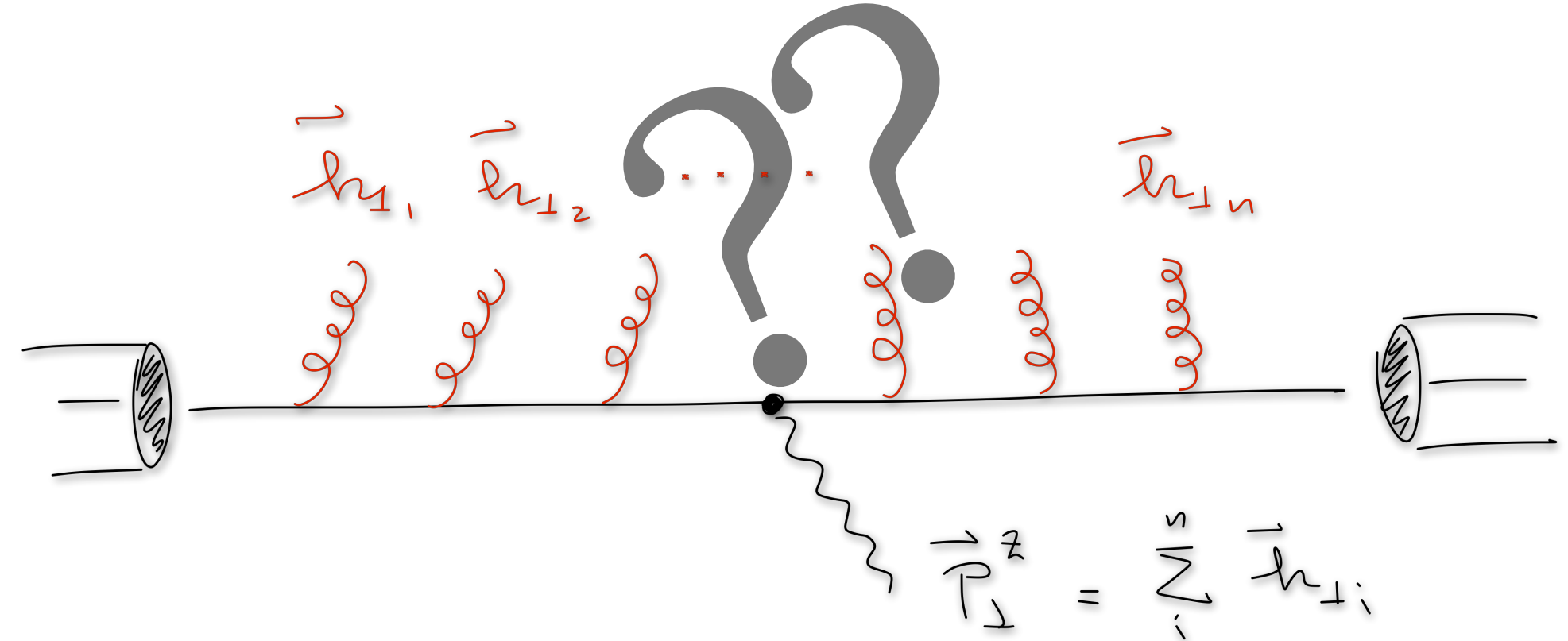
Matching coefficient

MEs of EFT fields

[each ingredient obeys RG evolution]



**Resummation via iteration of fundamental (squared) amplitudes**



# A change in the language of resummations

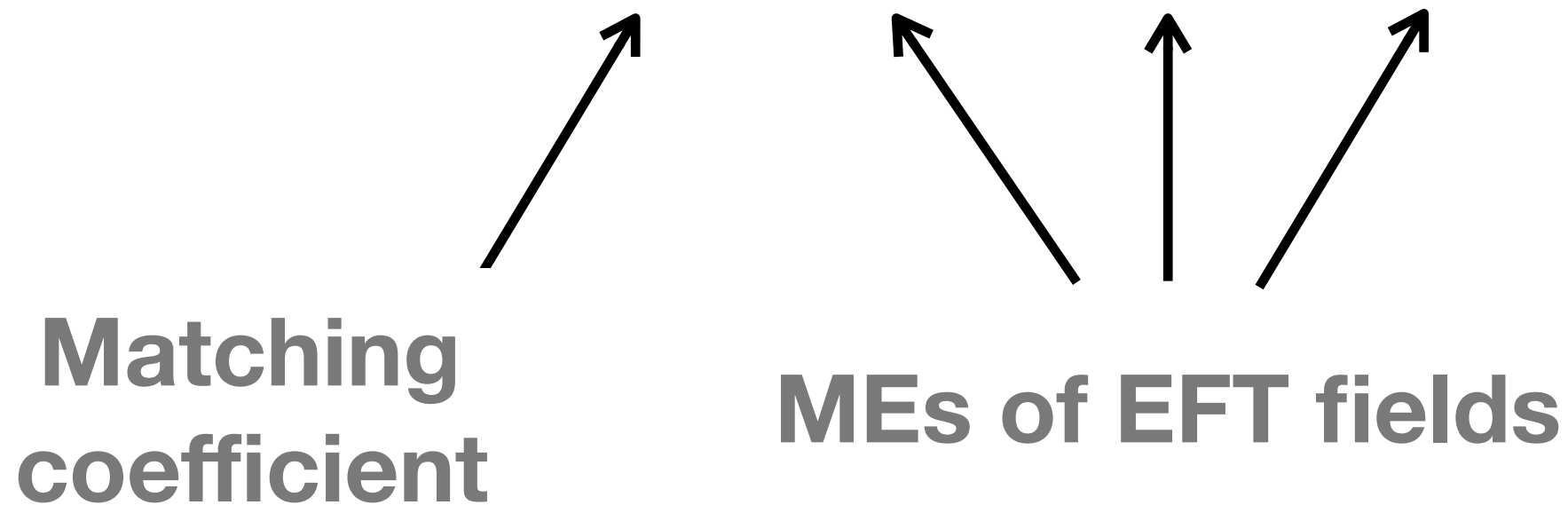
- ▶ This correspondence is far reaching, and allows one to address more complex questions than the evolution of parton densities e.g. What is the particle multiplicity distribution in collider events (within a jet alg.) ? What is the  $p_T$  distribution of a Drell-Yan pair ? ...
- ▶ Today, resummation for collider observables is often formulated in the modern language of Effective Field Theory. **Can we aim at a more exclusive understanding of all-order dynamics that can be systematically extended to higher logarithmic orders ?**

**Factorization and RG evolution of operators MEs**

**Resummation via iteration of fundamental (squared) amplitudes**

e.g. Z boson  $p_T$  spectrum

$$d\sigma \sim \mathcal{H} \mathcal{B} \otimes \mathcal{B} \otimes S$$



A general method requires:

- ▶ Identifying hierarchical structure of squared amplitudes
- ▶ Handle subtraction of infrared singularities locally at all orders

[each ingredient obeys RG evolution]

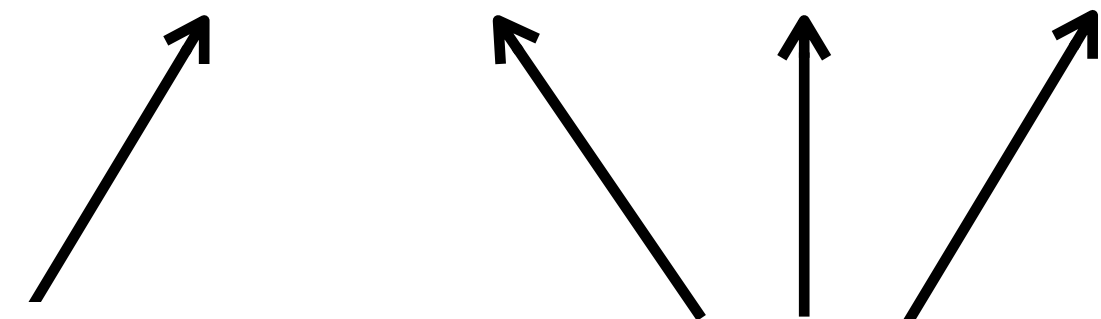
# A change in the language of resummations

- ▶ This correspondence is far reaching, and allows one to address more complex questions than the evolution of parton densities e.g. What is the particle multiplicity distribution in collider events (within a jet alg.) ? What is the  $p_T$  distribution of a Drell-Yan pair ? ...
- ▶ Today, resummation for collider observables is often formulated in the modern language of Effective Field Theory. **Can we aim at a more exclusive understanding of all-order dynamics that can be systematically extended to higher logarithmic orders ?**

**Factorization and RG evolution of operators MEs**

e.g. Z boson  $p_T$  spectrum

$$d\sigma \sim \mathcal{H} \mathcal{B} \otimes \mathcal{B} \otimes S$$



Matching coefficient

MEs of EFT fields

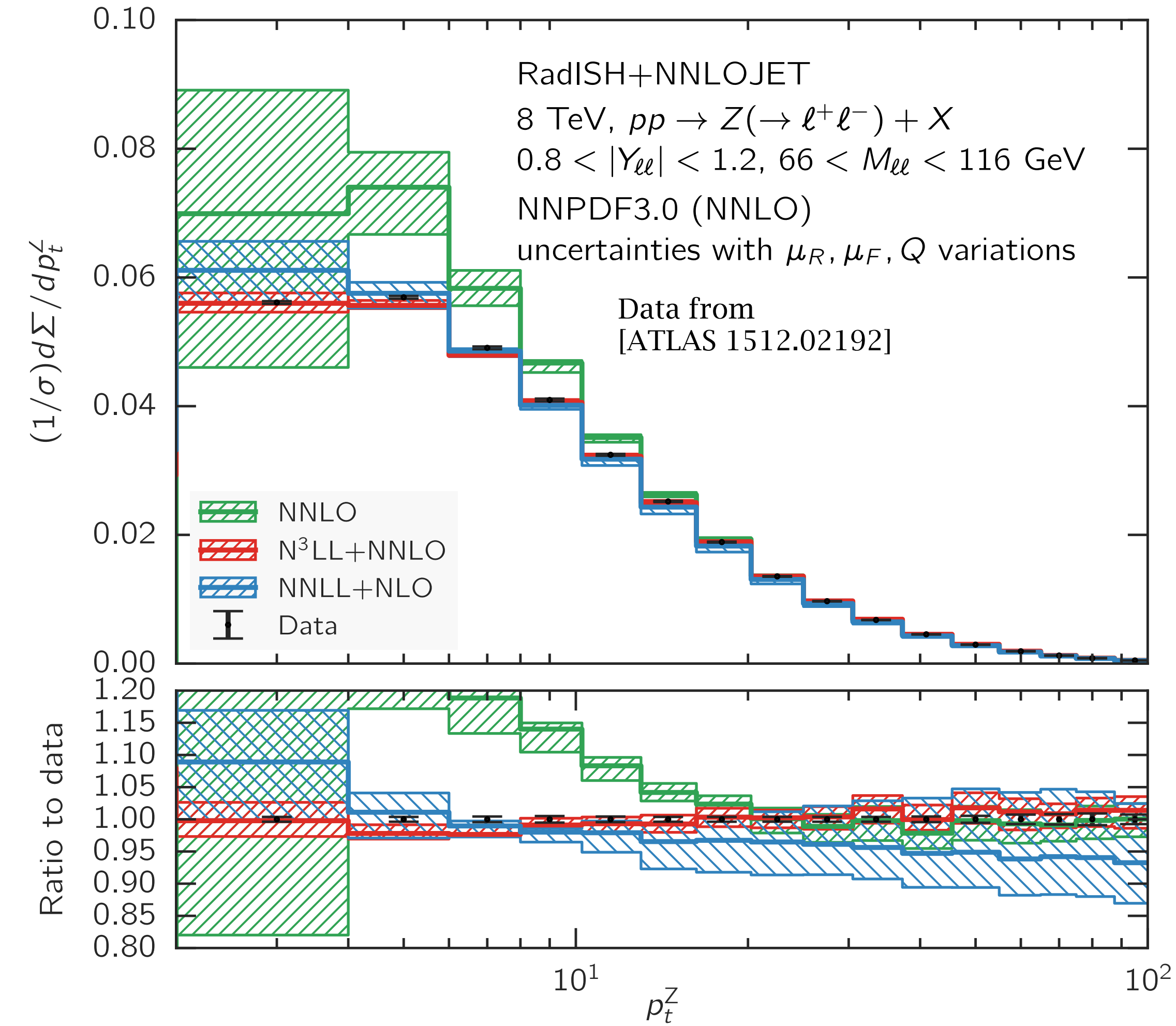
[each ingredient obeys RG evolution]



**Resummation via iteration of fundamental (squared) amplitudes**

Pioneering work at NLL by [Banfi, Salam, Zanderighi (2001-2004)]  
 Formulation at NNLL and N<sup>3</sup>LL across the years with many collaborators  
 [Banfi, PM, Salam, Zanderighi (2012);  
 Banfi, McAslan, PM, Zanderighi (2015);  
 PM, Re, Torrielli (2016);  
 Bizon, PM, Re, Rottoli, Torrielli (2017-2018);  
 Banfi, El-Menoufi, PM (2018), ...]

# Drell Yan $p_T$ spectrum at the LHC

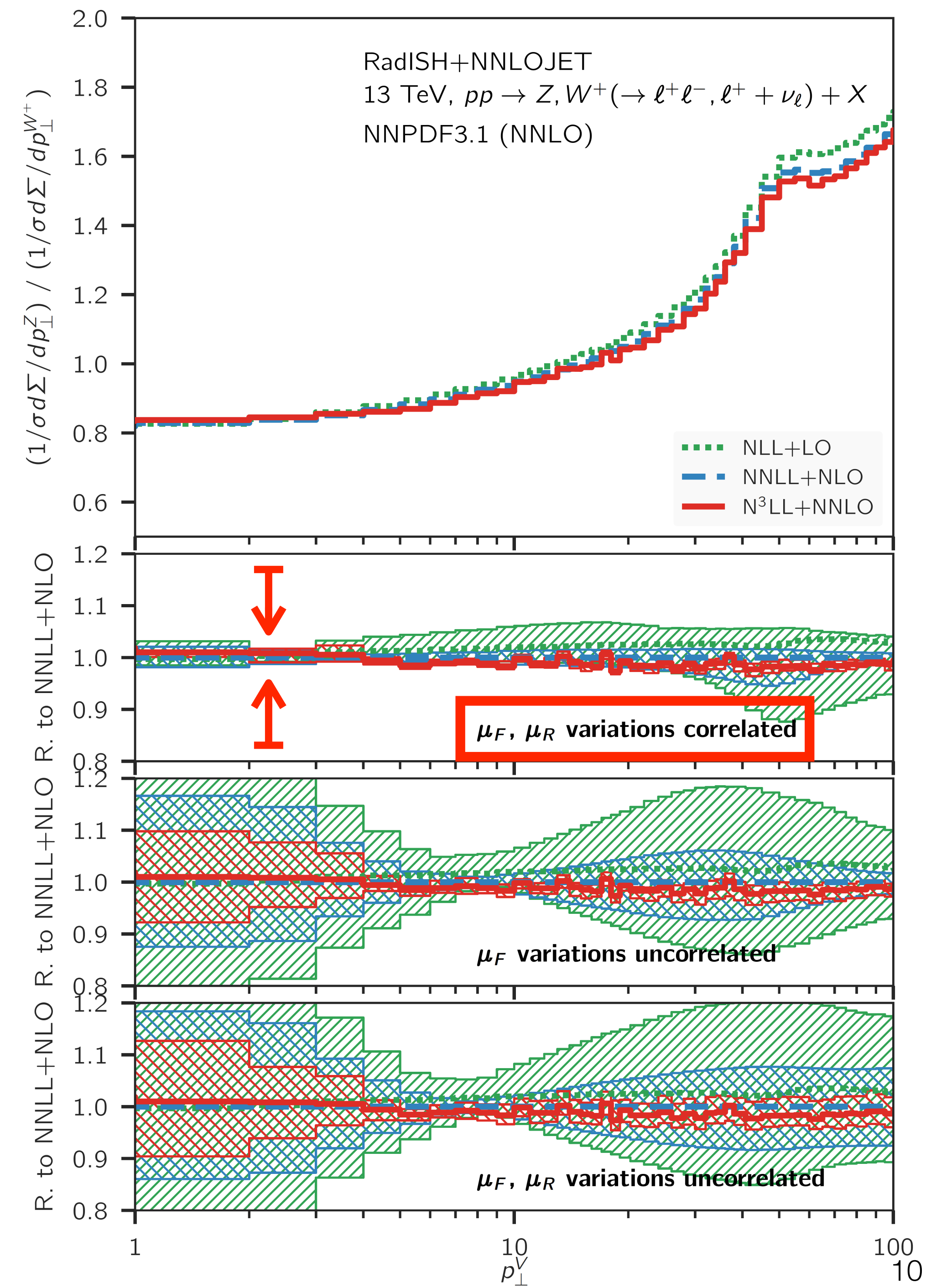


**Fiducial  $N^3LL+NNLO$  necessary  
for accurate description of data  
[2-3% theory uncertainty]**

[Bizon, Chen, Gehrmann, Gehrmann, Glover, Huss, PM, Re, Rottoli, Torrielli (2018)]

# Drell Yan $p_T$ spectrum at the LHC

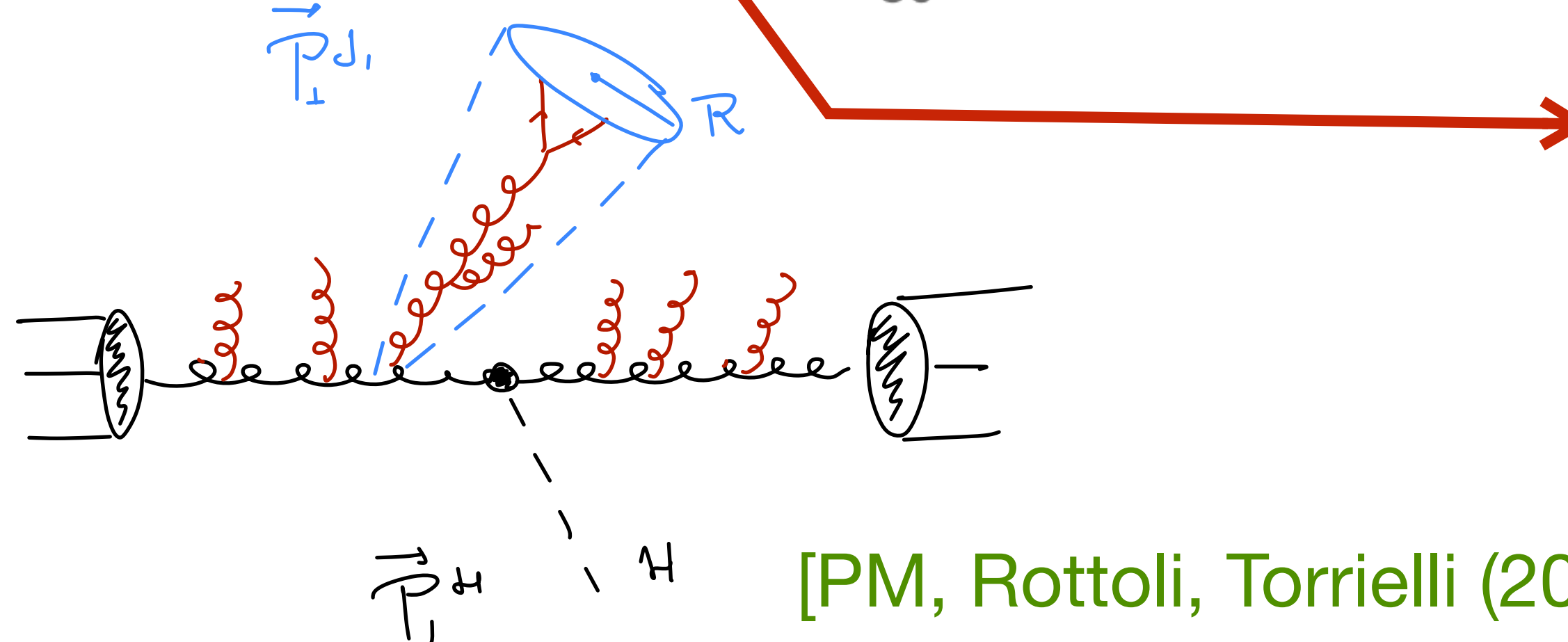
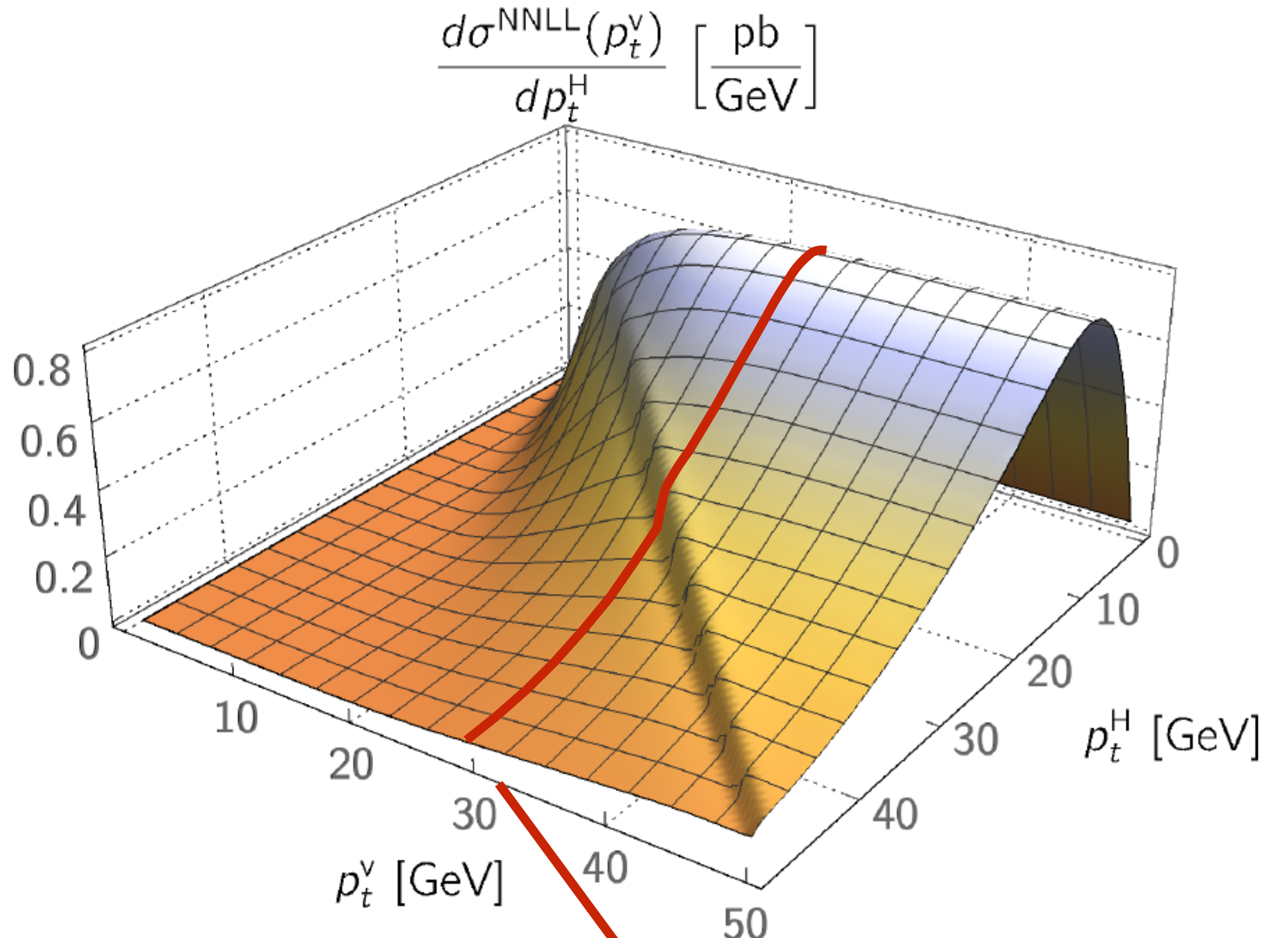
**W spectrum unmeasurable, must crucially rely on theory calculation of Z/W  $p_T$  ratio. N<sup>3</sup>LL+NNLO theory necessary for ~% control**



[Beware: other sources of uncertainty absent here, e.g. NP corrections, PDFs, bottom quarks, ...]

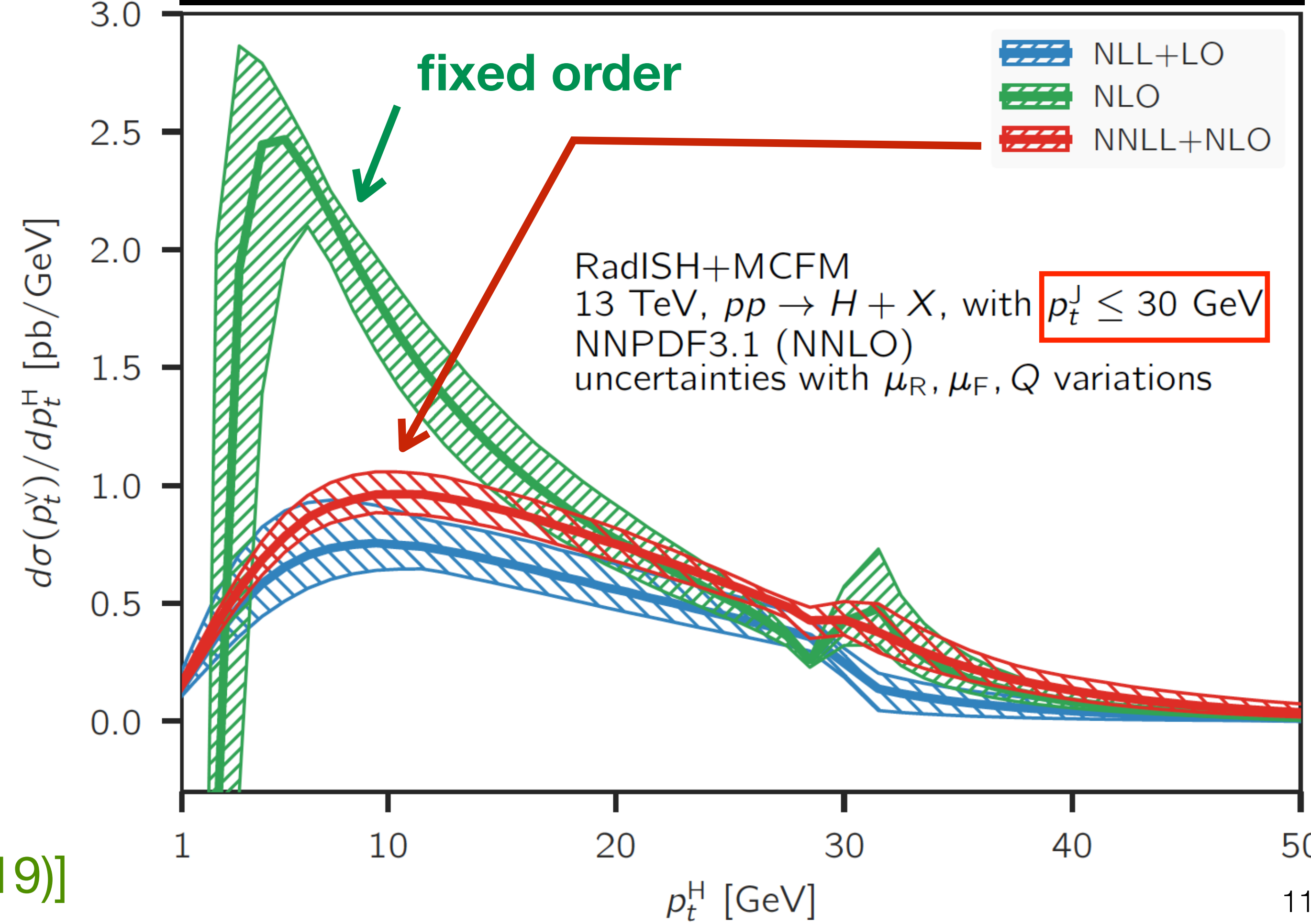
[Bizon, Gehrmann, Gehrmann, Glover, Huss, PM, Re, Rottoli, Torrielli, Walker (2019)]

# Deciphering the Higgs boson with 2-D resummation



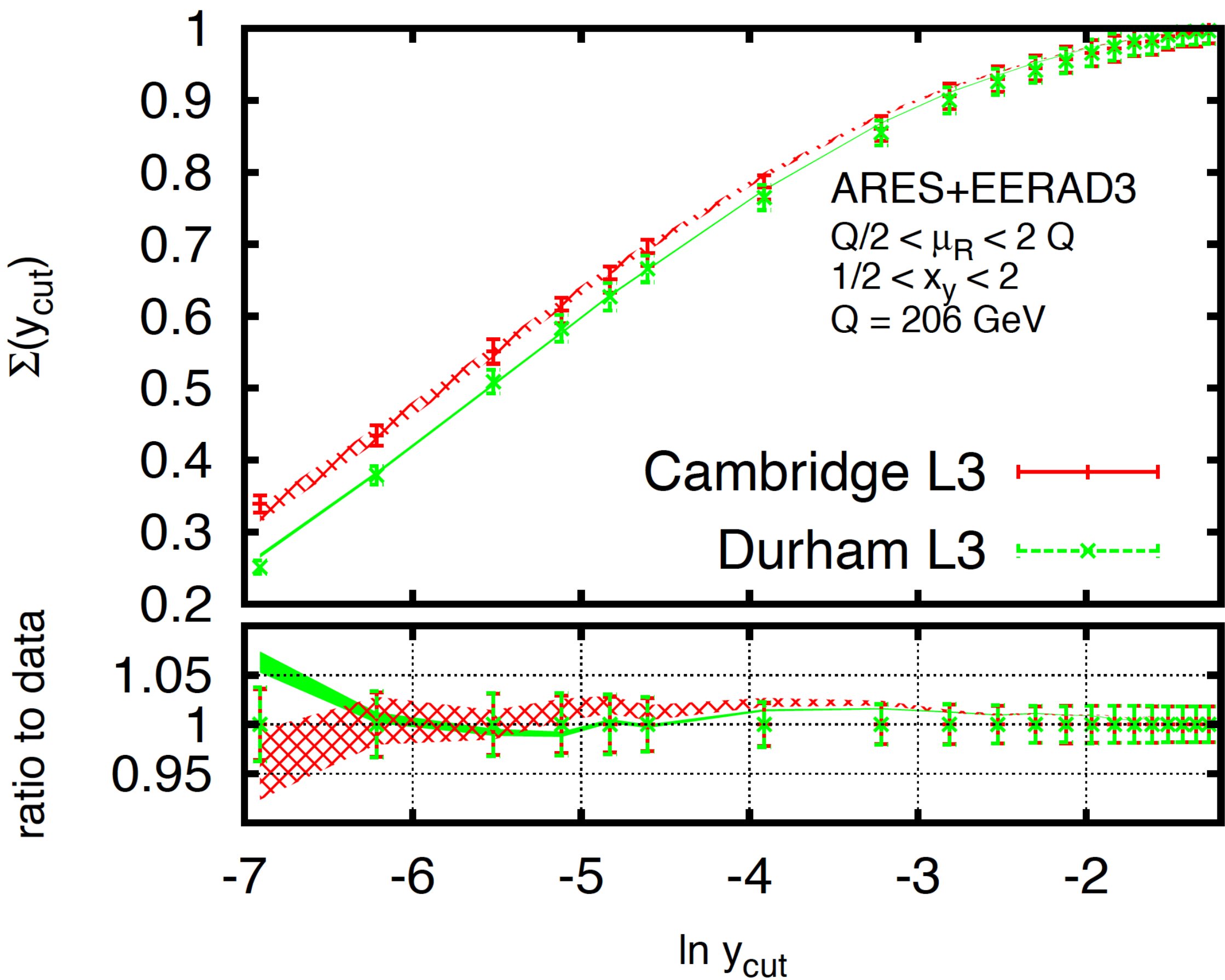
[PM, Rottoli, Torrielli (2019)]

**Double differential NNLL resummation for Higgs and leading-jet  $p_T$  [e.g. Higgs  $p_T$  in 0-jet bin]**

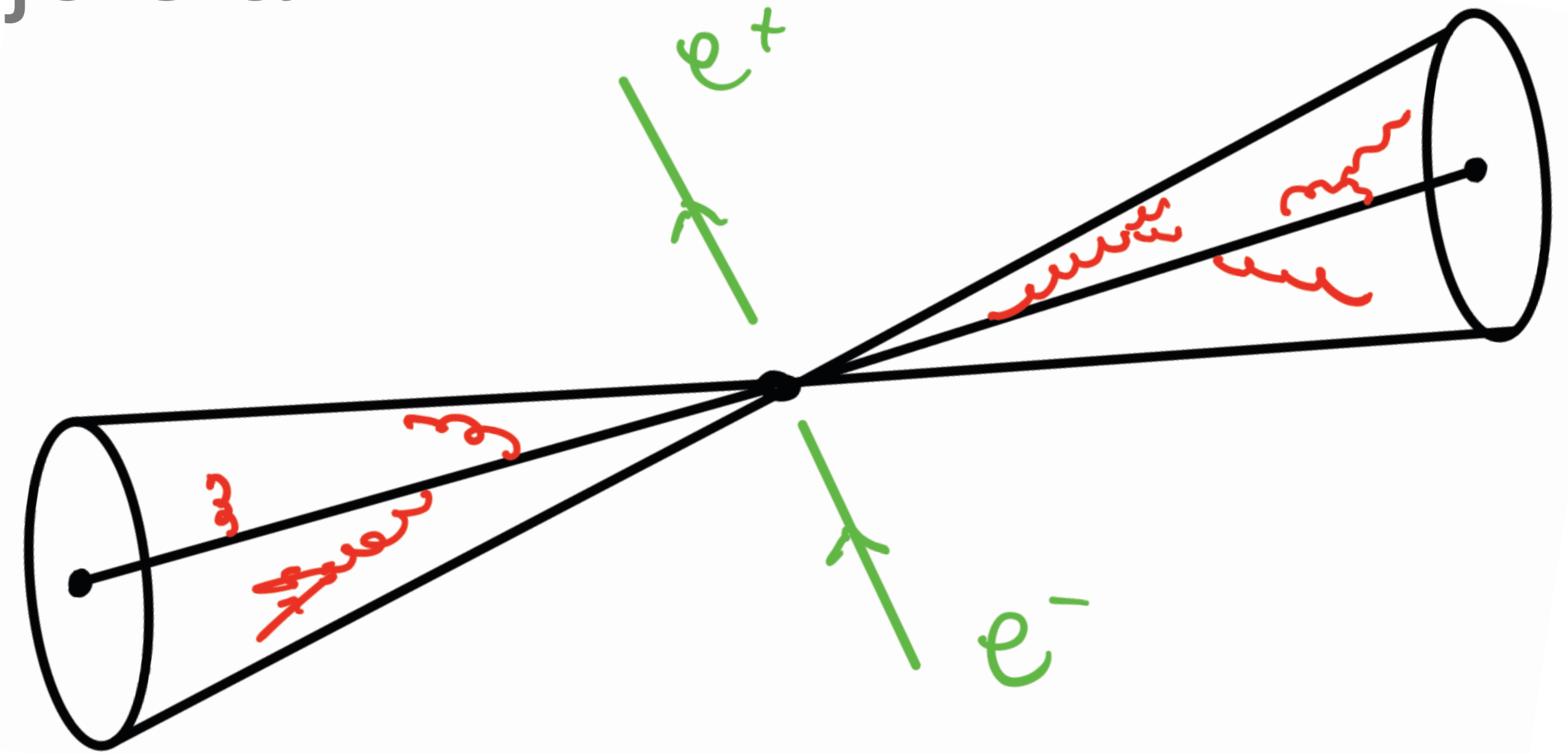


# Beyond LHC: $\alpha_s$ from $e^+e^- \rightarrow 2$ jets at LEP

Jet rates allow for precise fits of  $\alpha_s$ , but feature a complex logarithmic structure

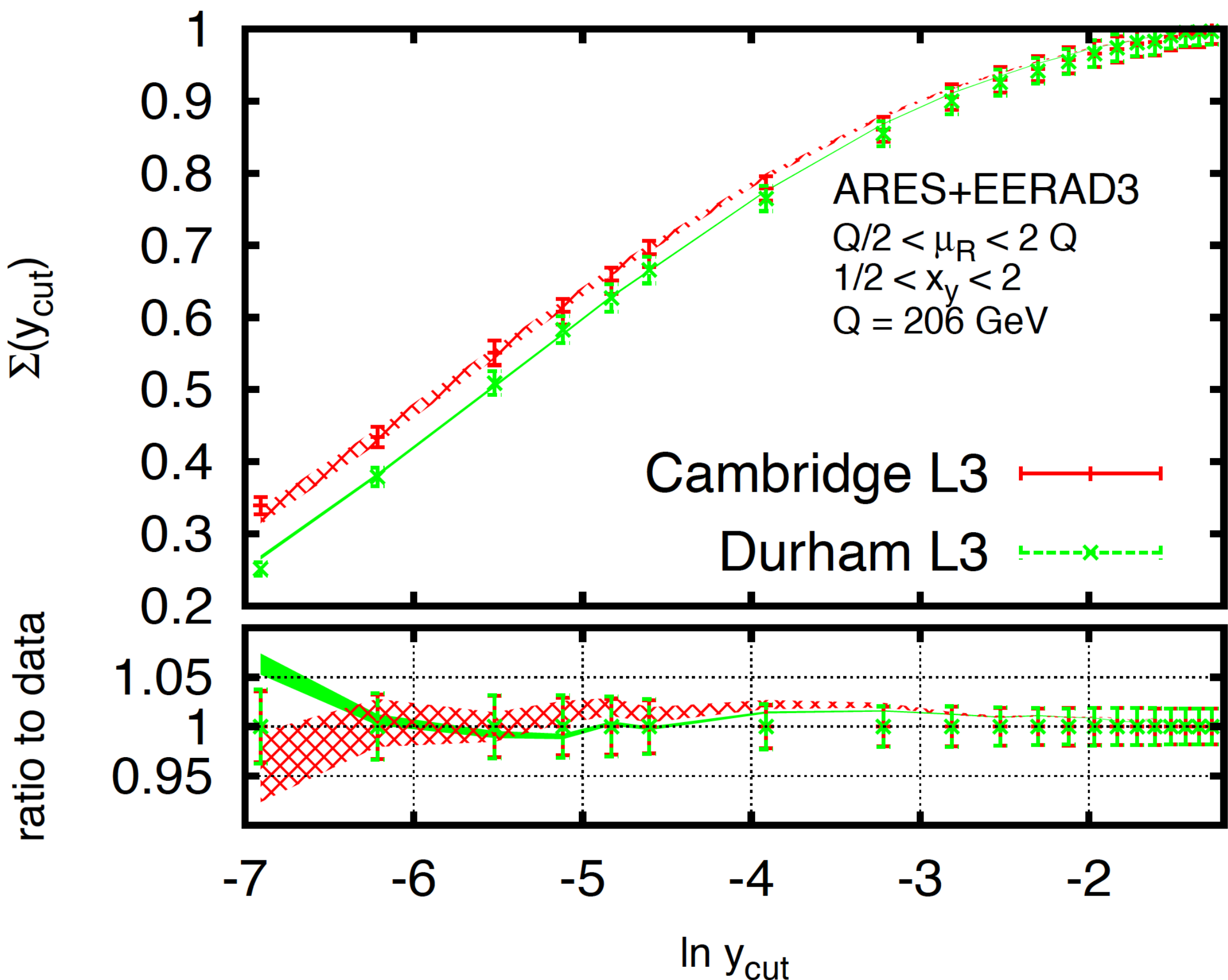


[Banfi, McAslan, PM, Zanderighi (2016)]

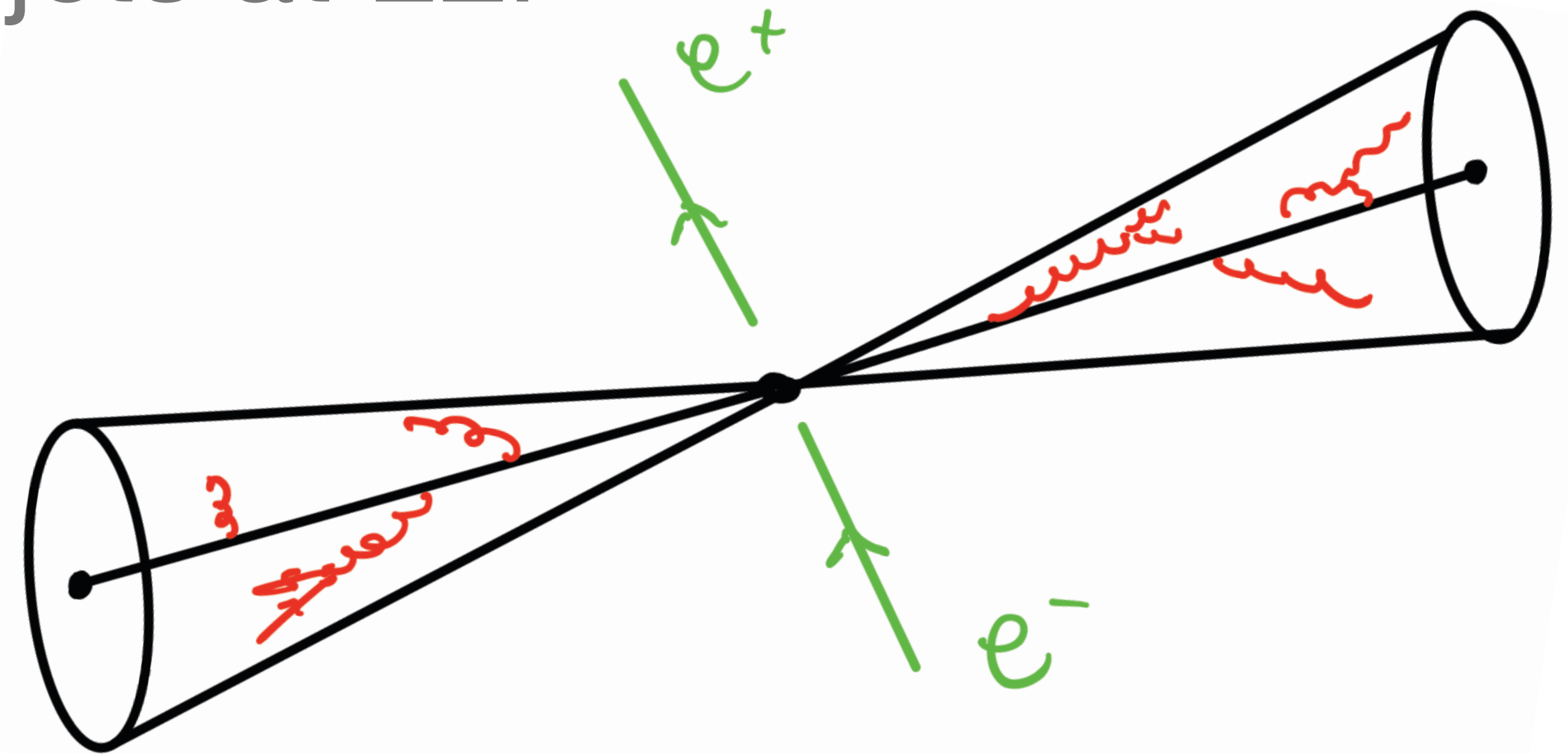


# Beyond LHC: $\alpha_s$ from $e^+e^- \rightarrow 2$ jets at LEP

Jet rates allow for precise fits of  $\alpha_s$ , but feature a complex logarithmic structure



[Banfi, McAslan, PM, Zanderighi (2016)]



**Calculation at NNLL+N<sup>3</sup>LO  
allows fit of  $\alpha_s$  with % precision**

$$\alpha_s(M_Z) = 0.11881 \pm 0.00063 \text{ (exp.)} \pm 0.00101 \text{ (hadr.)} \\ \pm 0.00045 \text{ (ren.)} \pm 0.00034 \text{ (res.)}$$

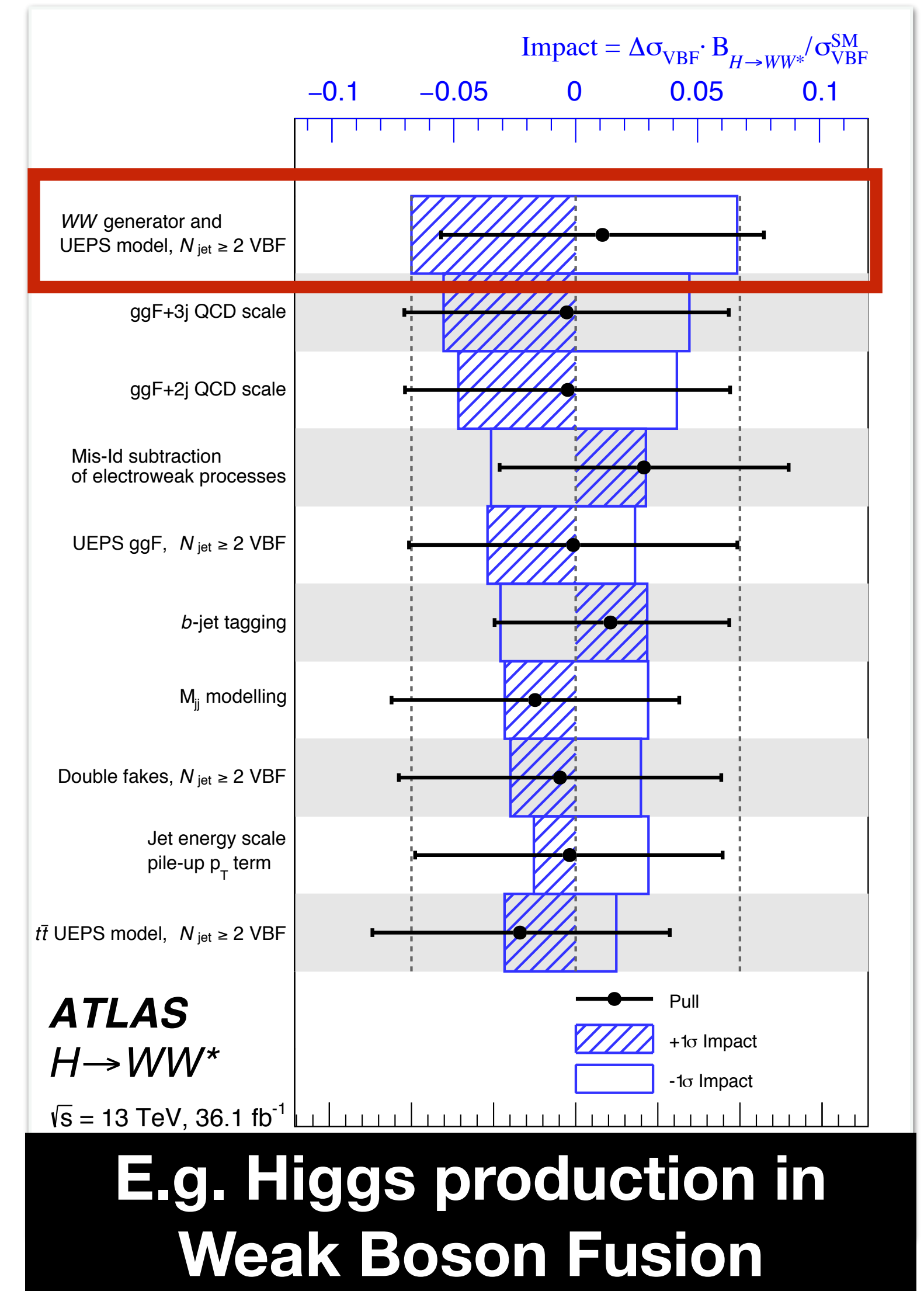
[Verbytskyi, Banfi, Kardos, PM, Kluth, Somogyi, Szor, Trocsanyi, Tulipant, Zanderighi (2019)]

# An old stubborn problem: parton showers

- ▶ Main TH/EXP bridge for decades [Pioneering work by Sjostrand (1985)]
- ▶ Exclusive events (crucial also for ML training & calibration)
- ▶ Today commonly among the dominant systematics

**Should be accurate across many observables:**

Currently limited at leading logarithmic accuracy  
[i.e. potentially missing  $O(\alpha_s L \sim 1) \sim \text{LO}$  effects]



[ATLAS (PLB 2019)]

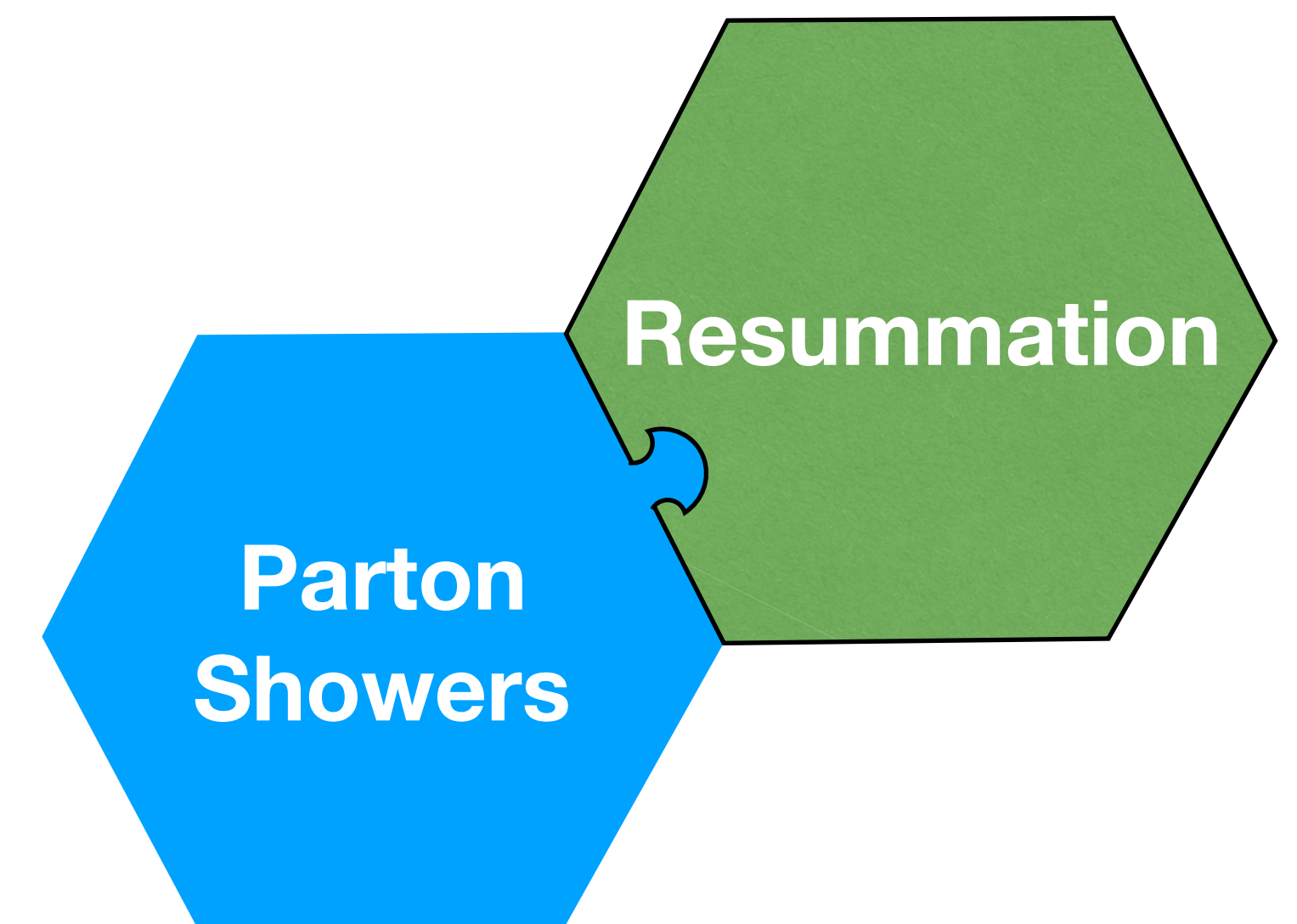
# An old stubborn problem: parton showers

- Main TH/EXP bridge for decades [Pioneering work by Sjostrand (1985)]
- Exclusive events (crucial also for ML training & calibration)
- Today commonly among the dominant systematics

## Elements of the PS can be constrained by QCD & resummation

- Reproduce multi particle (squared) amplitudes in relevant kinematic regimes
- Reproduce analytic resummations for multiscale problems

Important step towards a solid & systematic connection between these two fields



[Dasgupta, Dreyer, Hamilton, PM, Salam (2018)]

[Dasgupta, Dreyer, Hamilton, PM, Salam, Soyez (2020)]

# Designing NLL parton showers: accuracy test

**Relative deviation from exact NLL  
[in proper kinematic limits]**

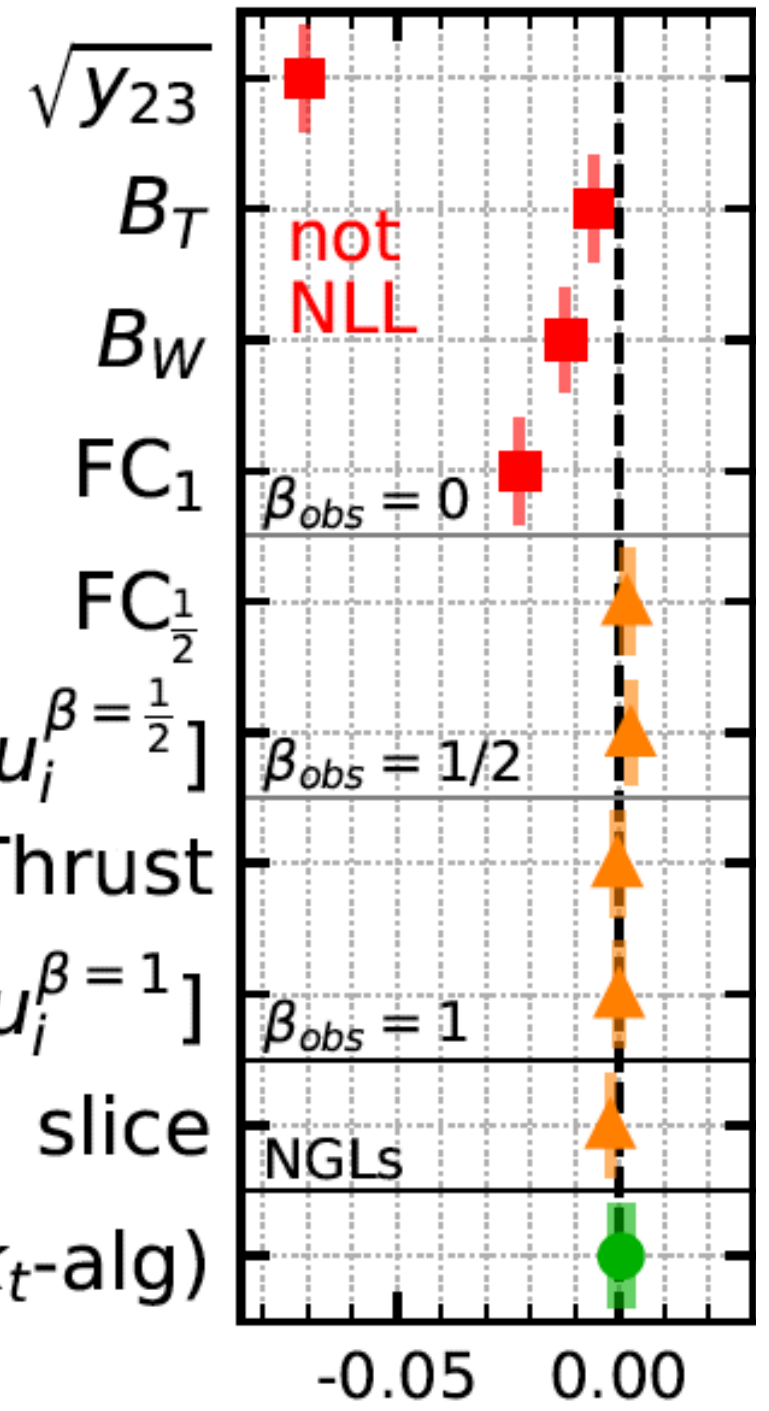
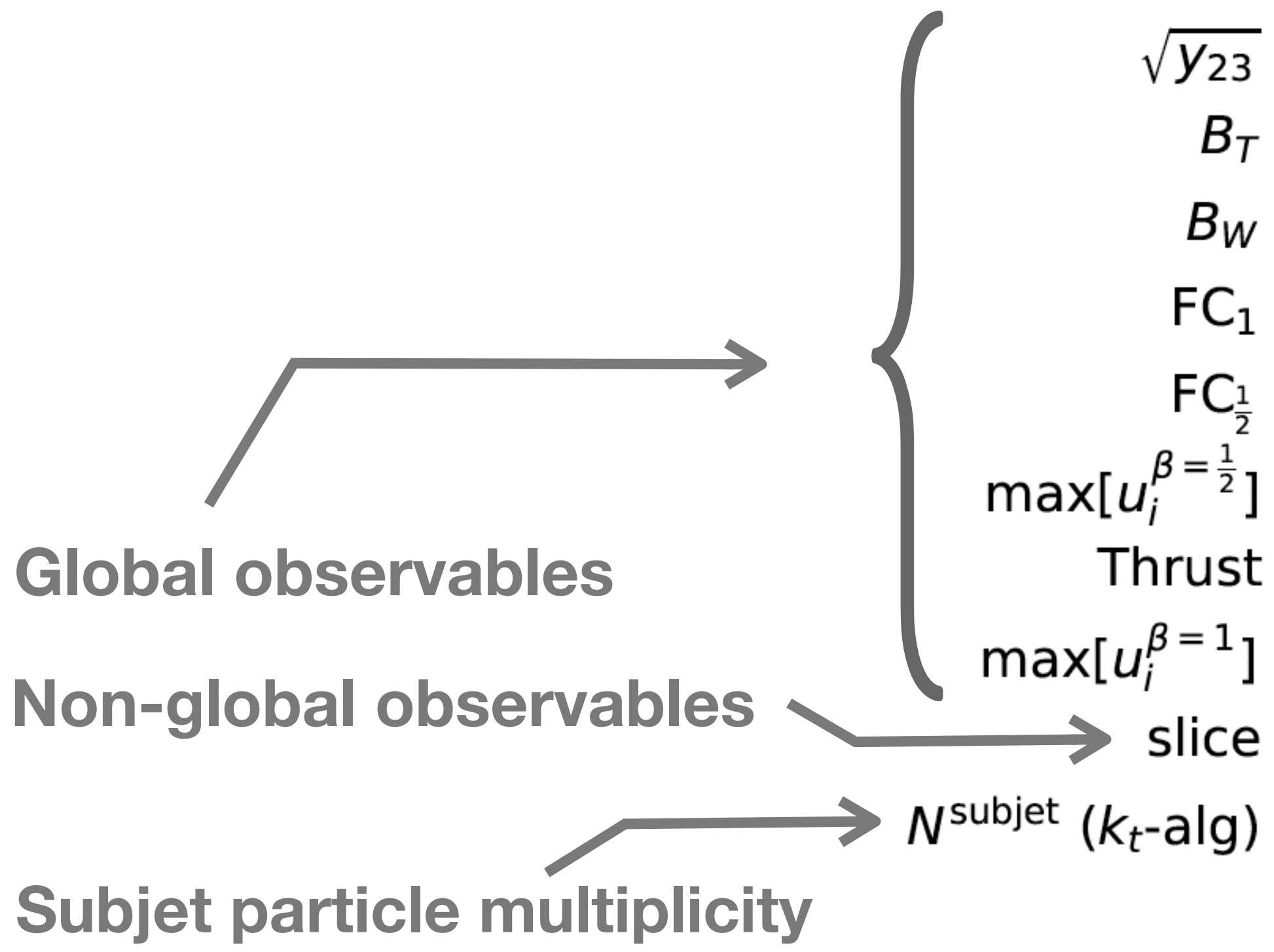


[Sjostrand et al. '15]  
[Hoeche, Prestel '15]

Dipole  
(Py8/Dire)

One crucial innovation is the possibility to test quantitatively the perturbative (logarithmic) accuracy of a parton shower algorithm.

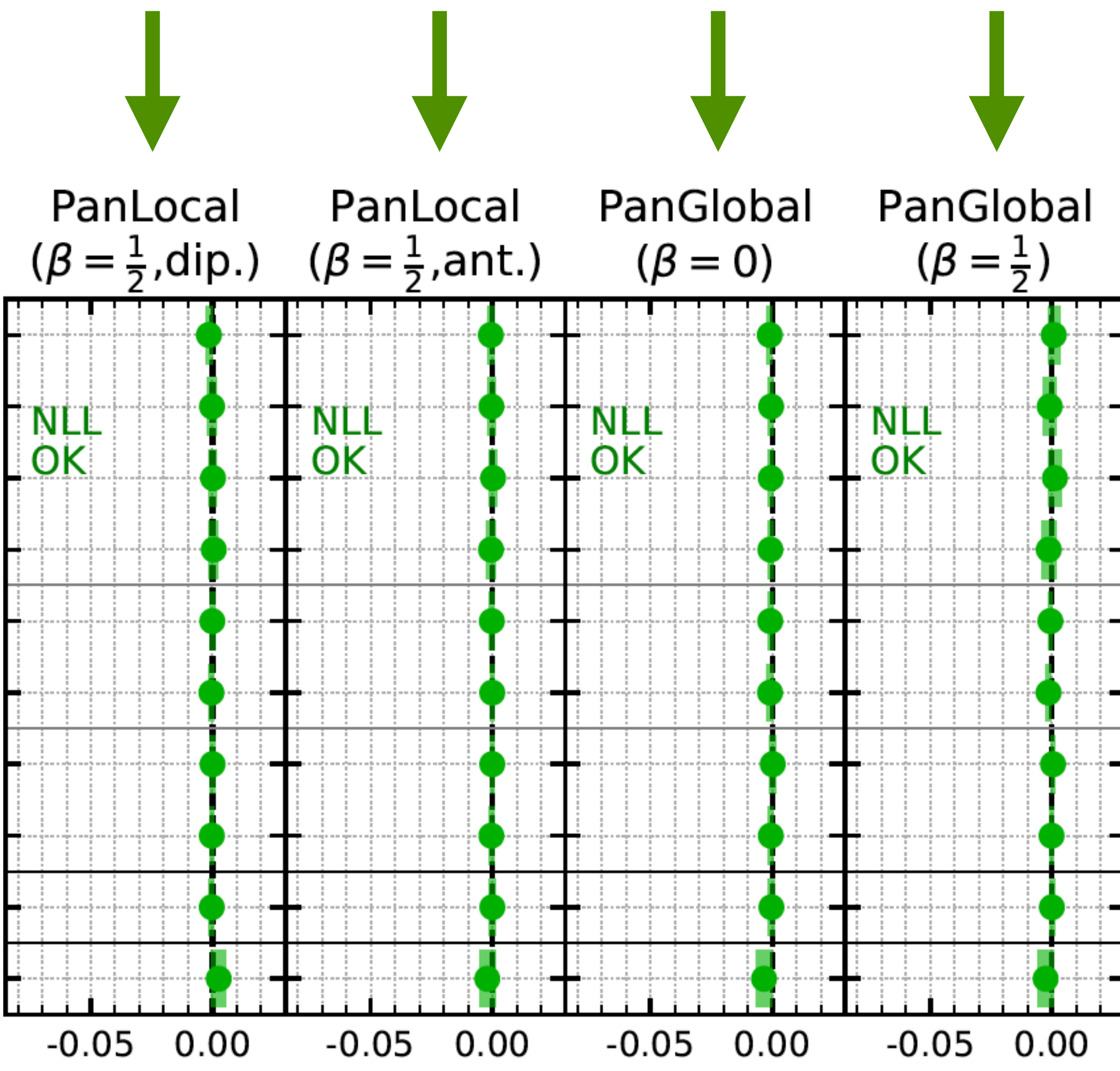
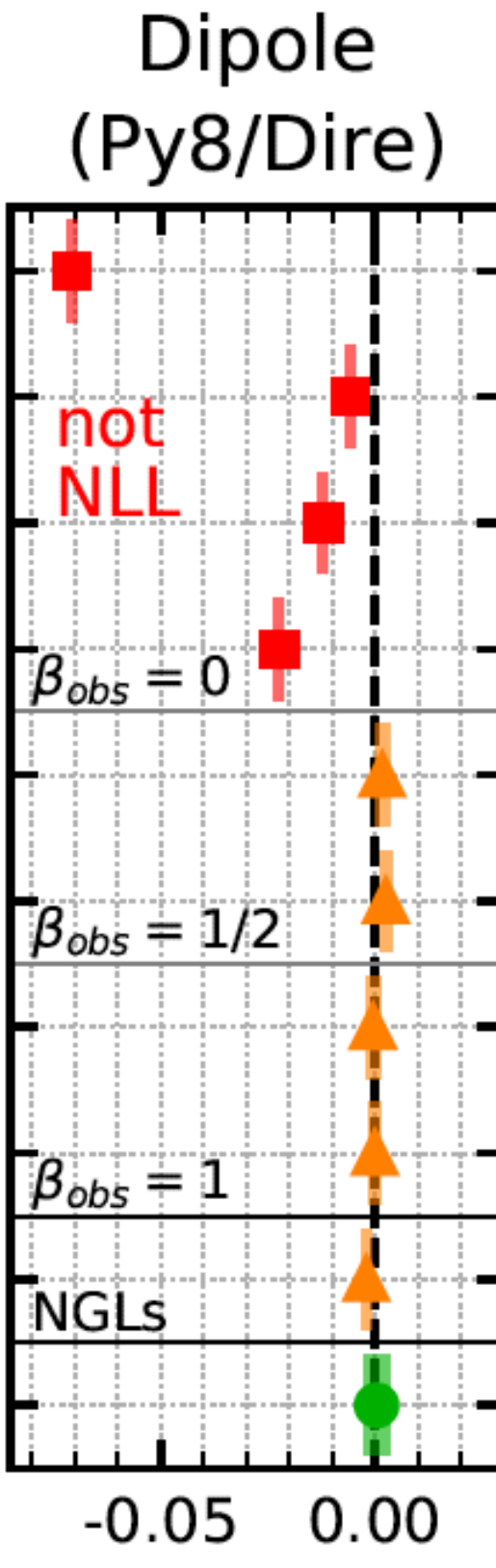
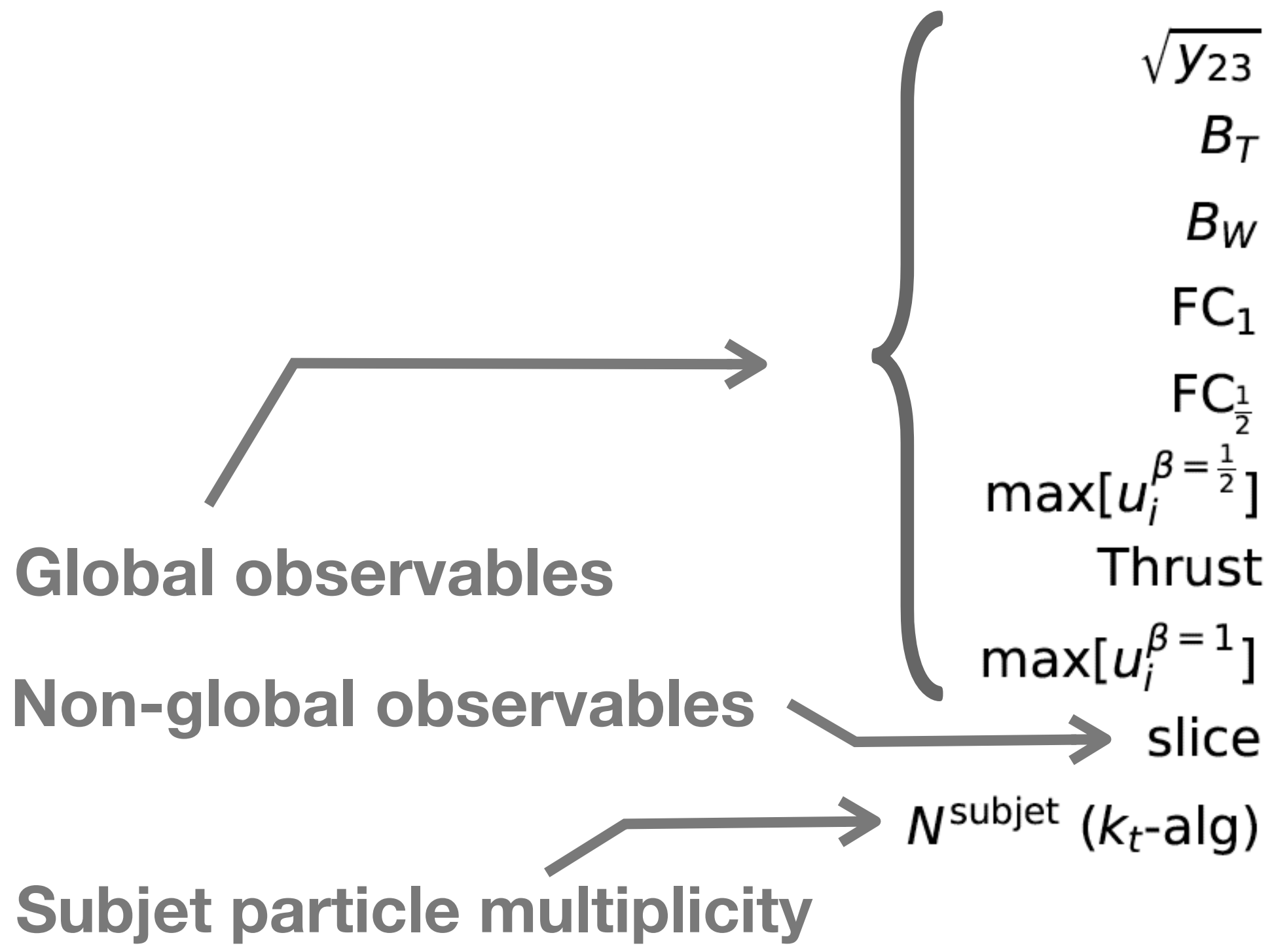
The second is the ability to formulate new solutions with higher-order accuracy ...



Orange triangles indicate spurious terms at fixed order, yielding small effects when resummed

# Designing NLL parton showers: accuracy test

**Relative deviation from exact NLL  
[in proper kinematic limits]**



**The new showers are NLL  
for all observables !**

[Dasgupta, Dreyer, Hamilton, PM, Salam (2018)]  
[Dasgupta, Dreyer, Hamilton, PM, Salam, Soyez (2020)]

# Acknowledgments

- ▶ **The whole field is deeply grateful to Guido Altarelli for his foundational contributions to QCD, which today constitutes the core component of our tool set for decoding the laws of nature at particle colliders**
- ▶ **Many thanks to the Selection Committee, Centro Fermi, The European Physical Journal, and World Scientific for this award**
- ▶ **My special thanks go to my many collaborators, and to my academic mentors Gavin Salam, Giulia Zanderighi and Thomas Gehrmann for their guidance and support, and for patiently walking me through this beautiful field and inspiring my interest in high energy physics**
- ▶ **Finally, thank you all for your time today**