HET SEMINAR, BROOKHAVEN NATIONAL LABORATORY

LHC PHYSICS AT NNLO+PS ACCURACY WITH MiNNLO$_{\text{PS}}$

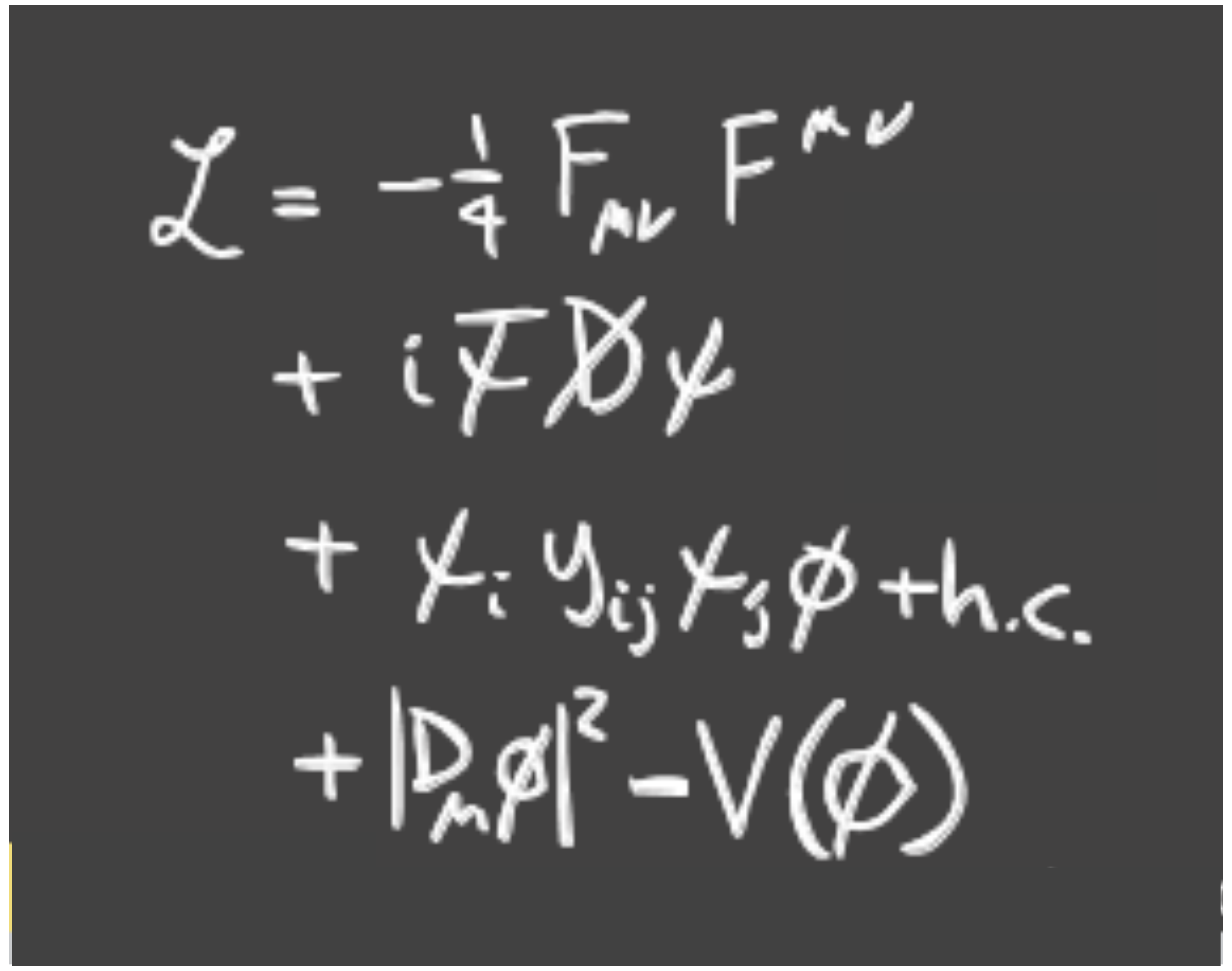
SILVIA ZANOLI - University of Oxford

14th November 2024

1. MOTIVATION

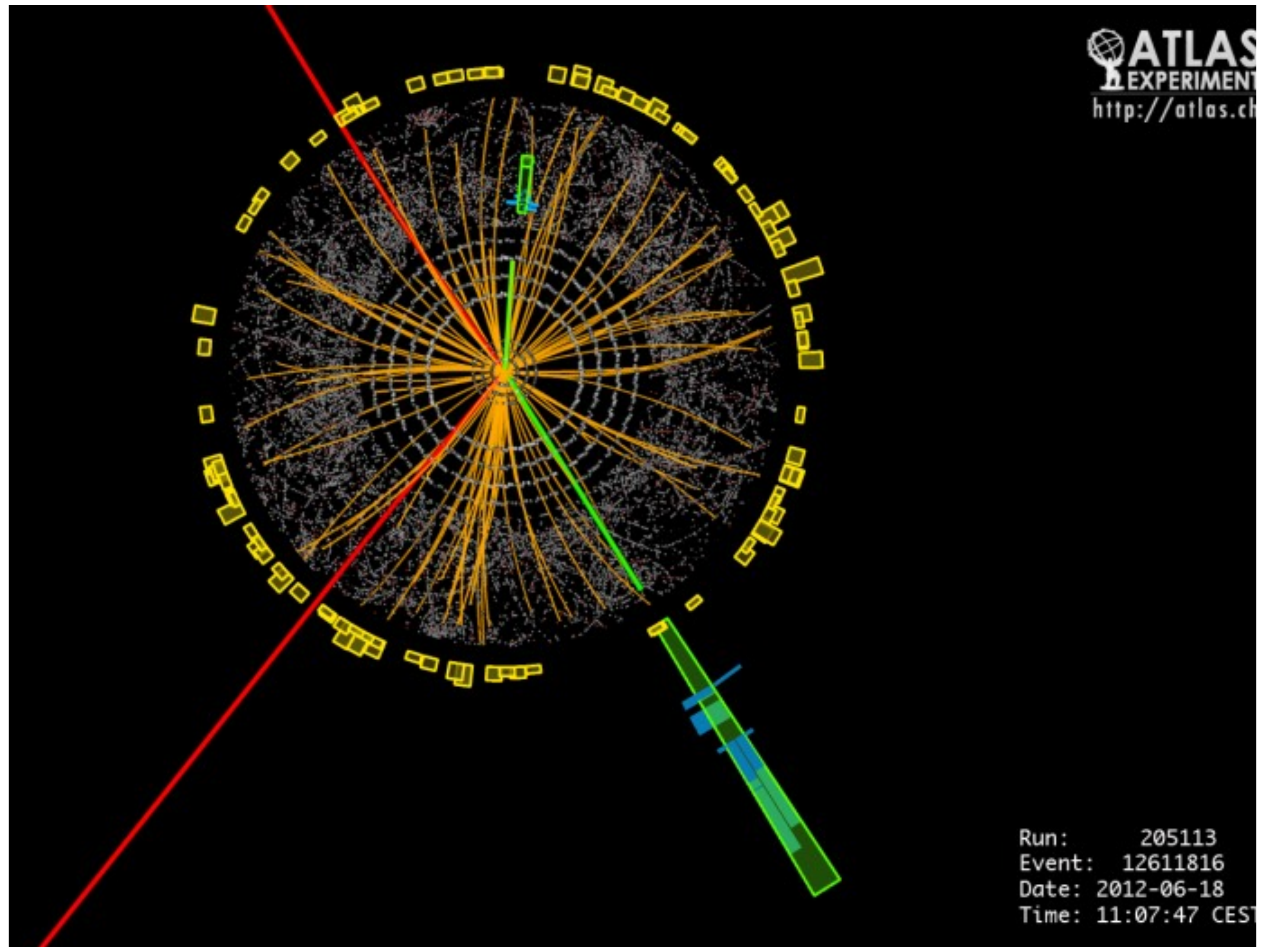
AN AMBITIOUS TASK

THEORY



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

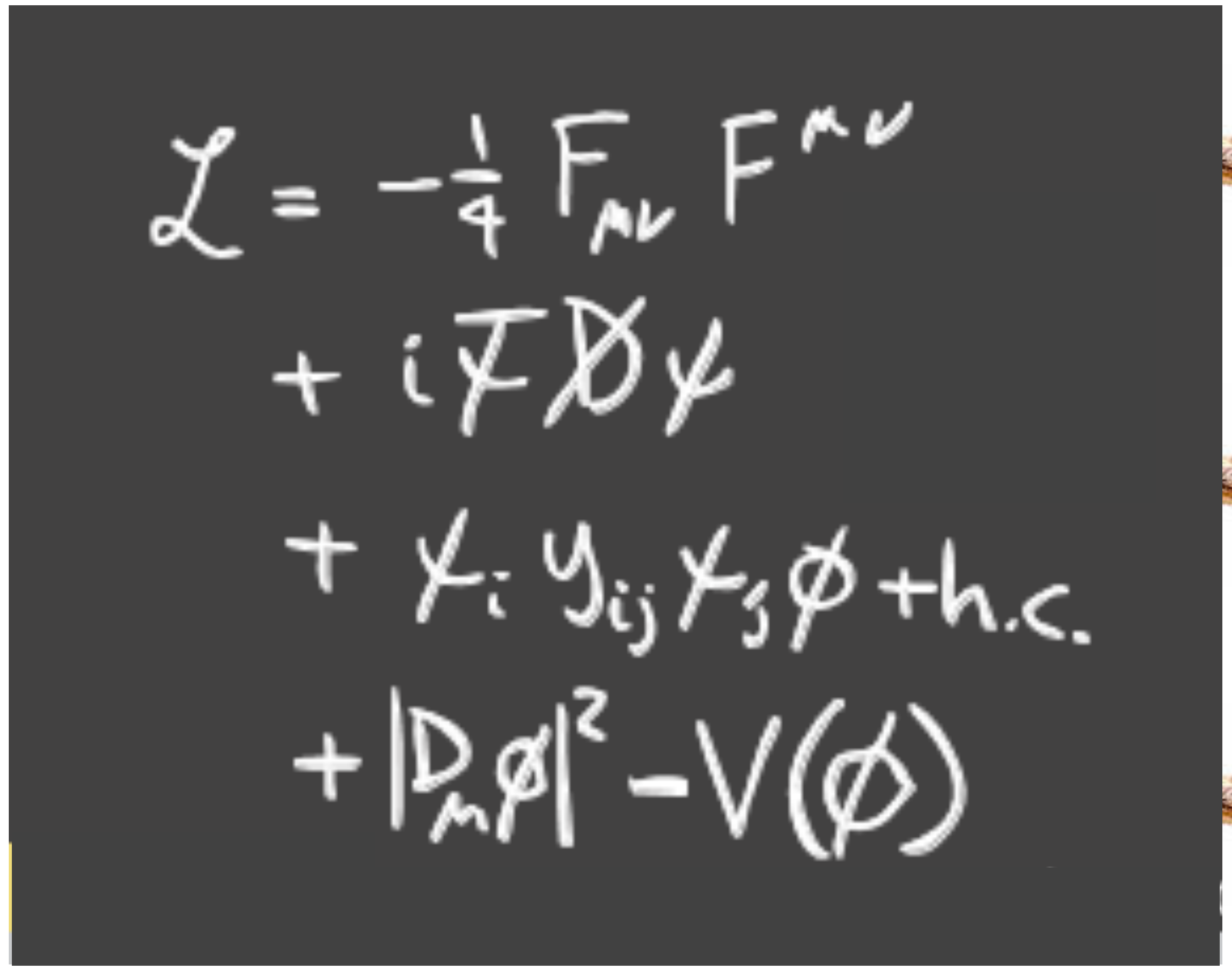
EXPERIMENTAL DATA



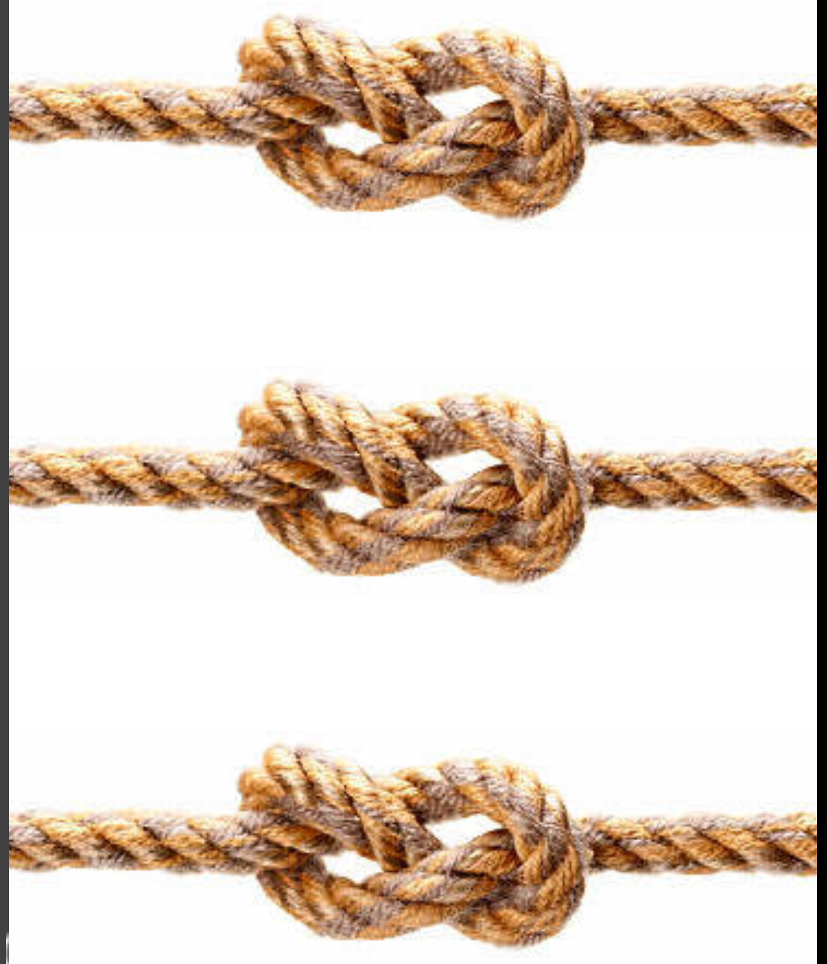
AN AMBITIOUS TASK

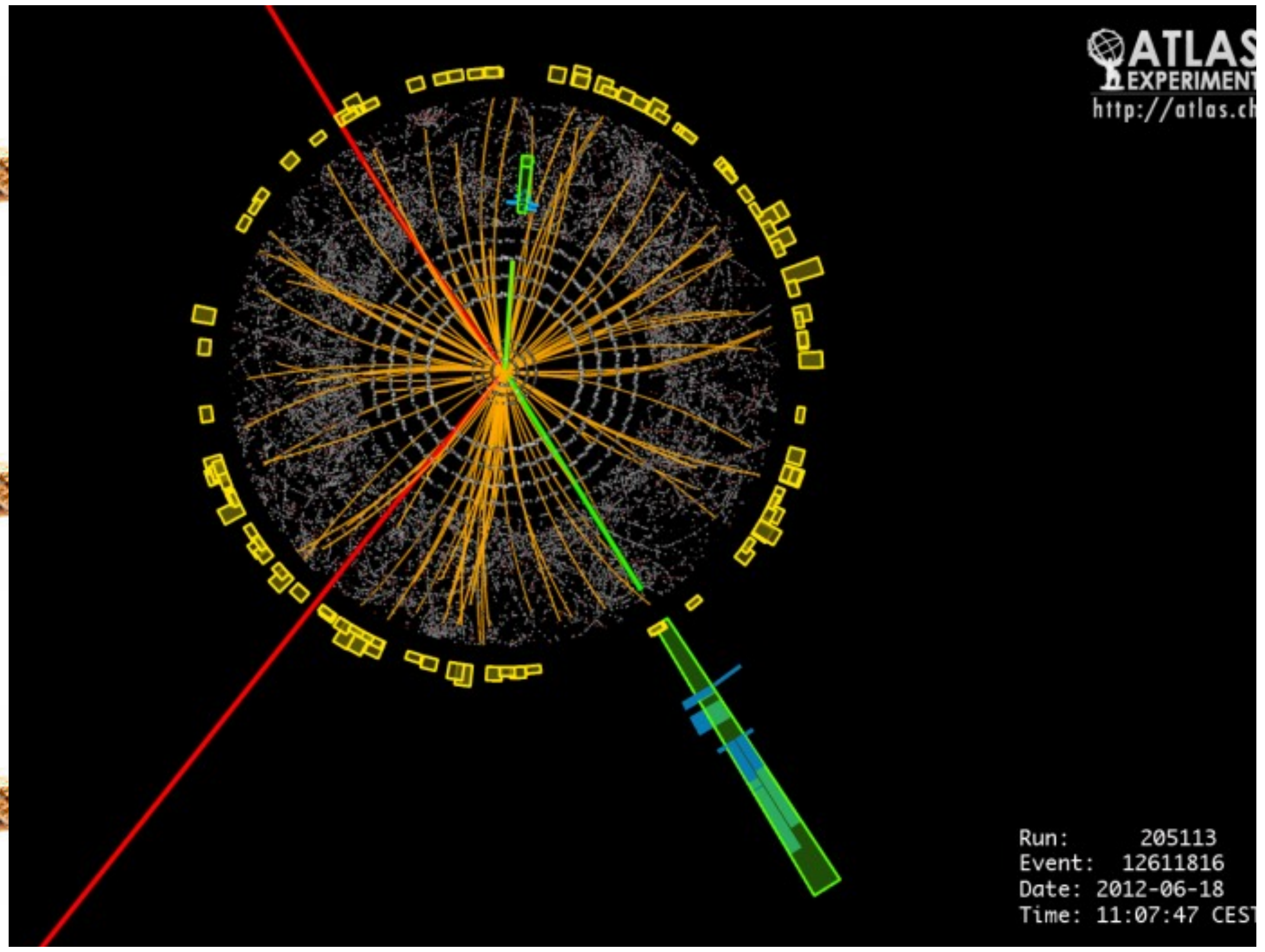
THEORY

EXPERIMENTAL DATA



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$





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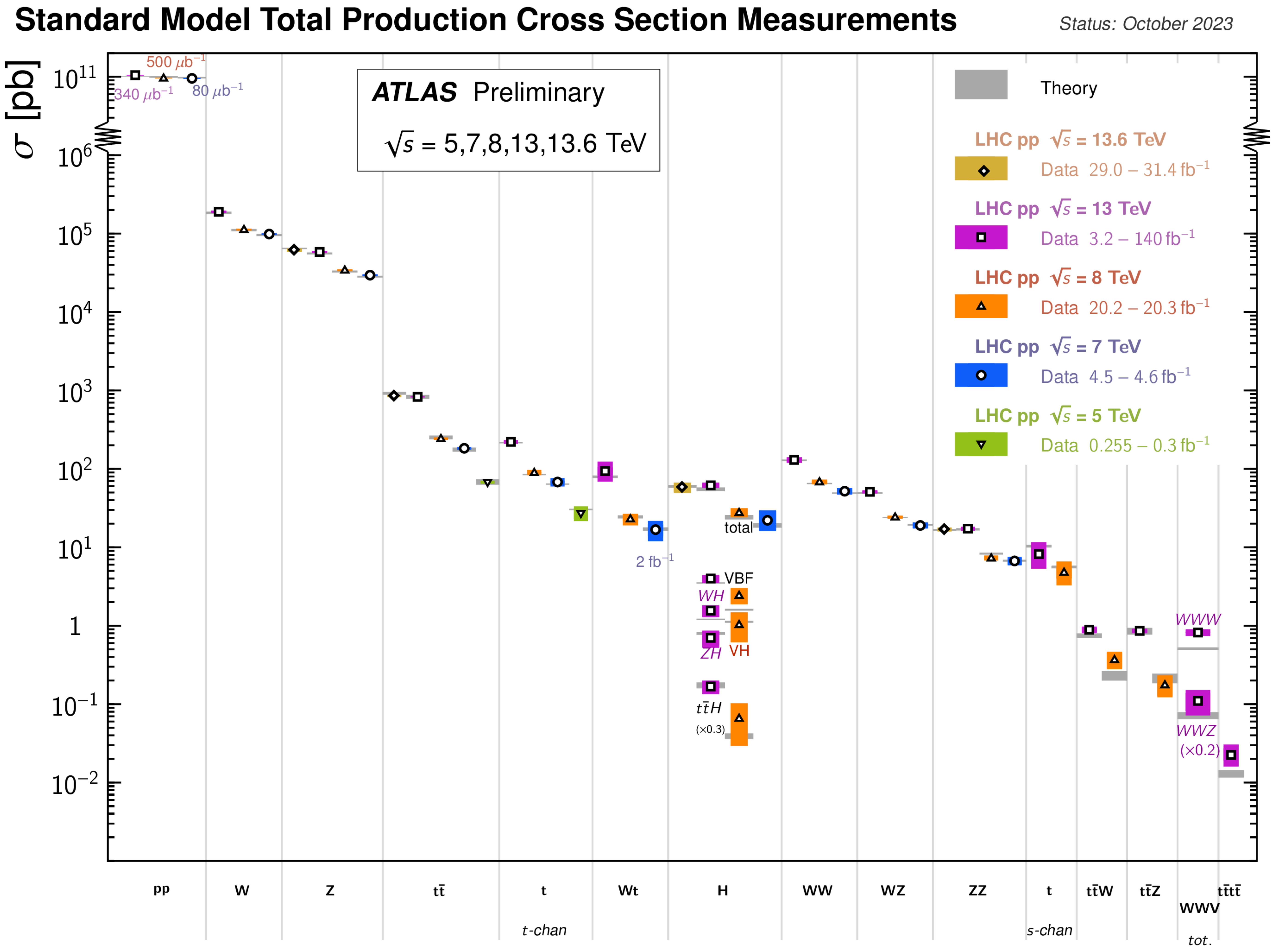
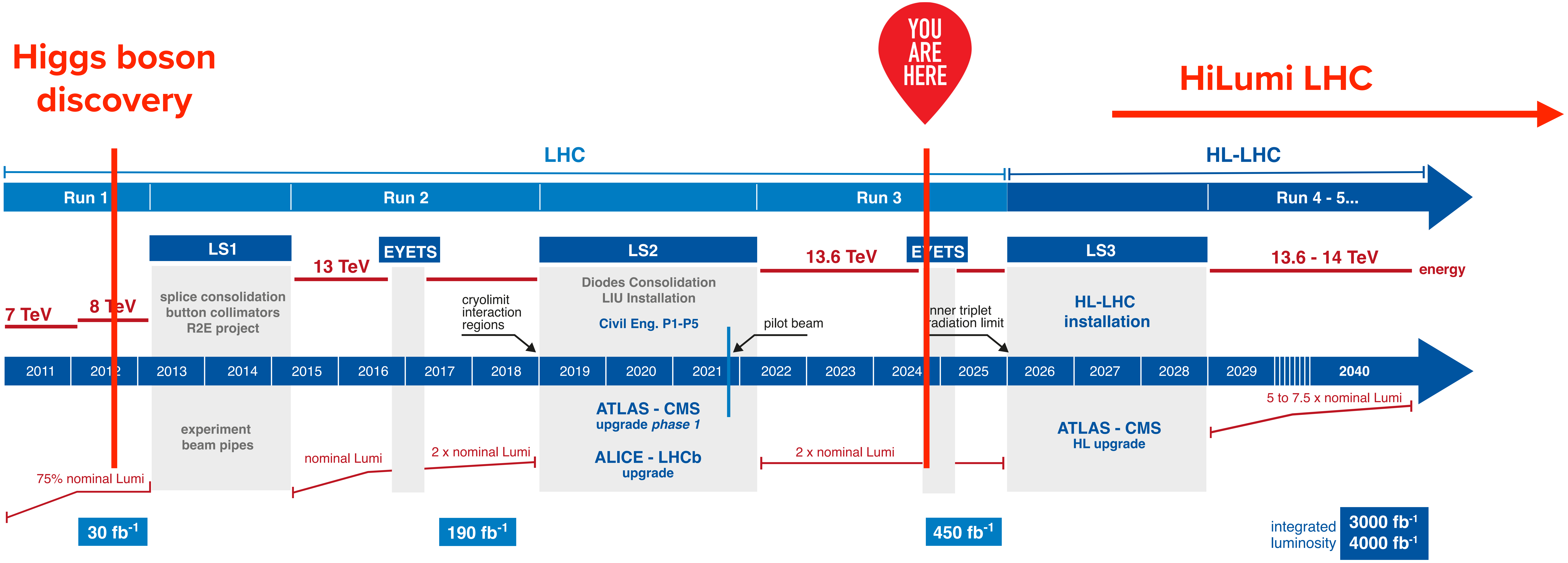
PRECISE AND REALISTIC THEORETICAL PREDICTIONS

THE SUCCESS OF THE STANDARD MODEL



LHC PROGRAMME



Higgs boson discovery

YOU ARE HERE

HiLumi LHC

LHC

HL-LHC

Run 1

Run 2

Run 3

Run 4 - 5...

LS1

splice consolidation
button collimators
R2E project

experiment
beam pipes

EYETS

LS2

Diodes Consolidation
LIU Installation

Civil Eng. P1-P5

ATLAS - CMS
upgrade phase 1

ALICE - LHCb
upgrade

EYETS

LS3

HL-LHC
installation

ATLAS - CMS
HL upgrade

7 TeV

8 TeV

13 TeV

13.6 TeV

13.6 - 14 TeV

energy

cryolimit
interaction
regions

pilot beam

inner triplet
radiation limit

2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2040

75% nominal Lumi

nominal Lumi

2 x nominal Lumi

2 x nominal Lumi

5 to 7.5 x nominal Lumi

30 fb^{-1}

190 fb^{-1}

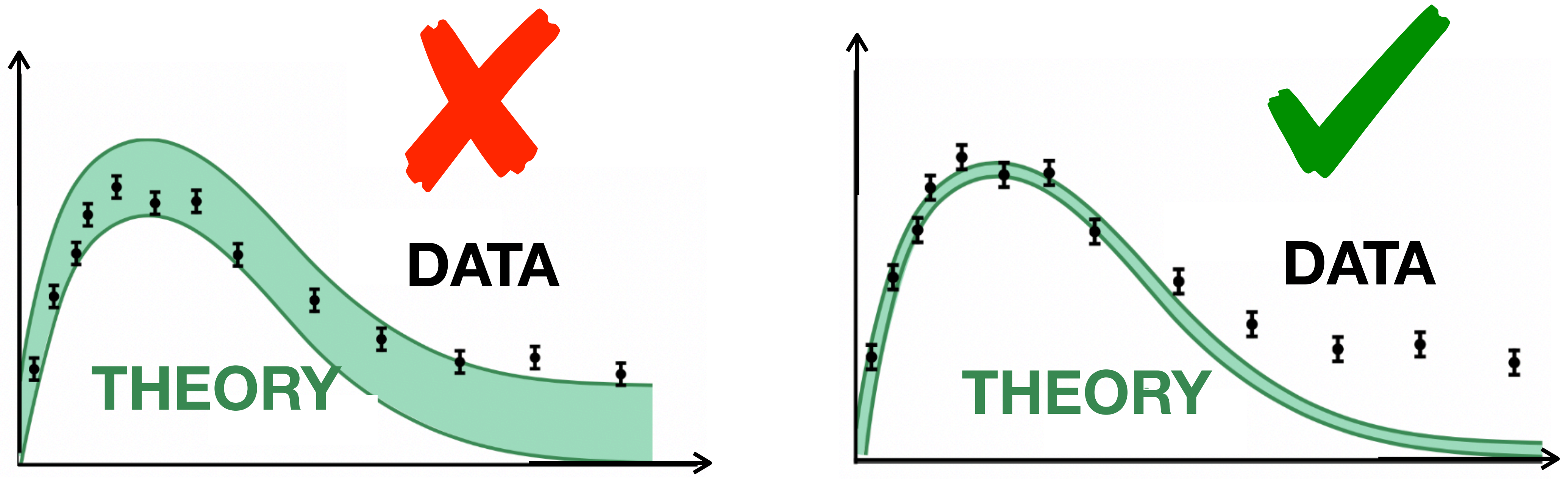
450 fb^{-1}

integrated
luminosity

3000 fb^{-1}
4000 fb^{-1}

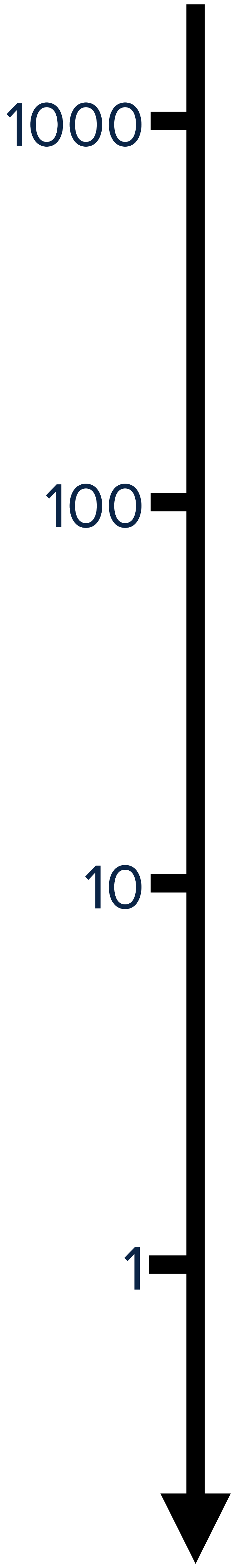
Precision is needed to:

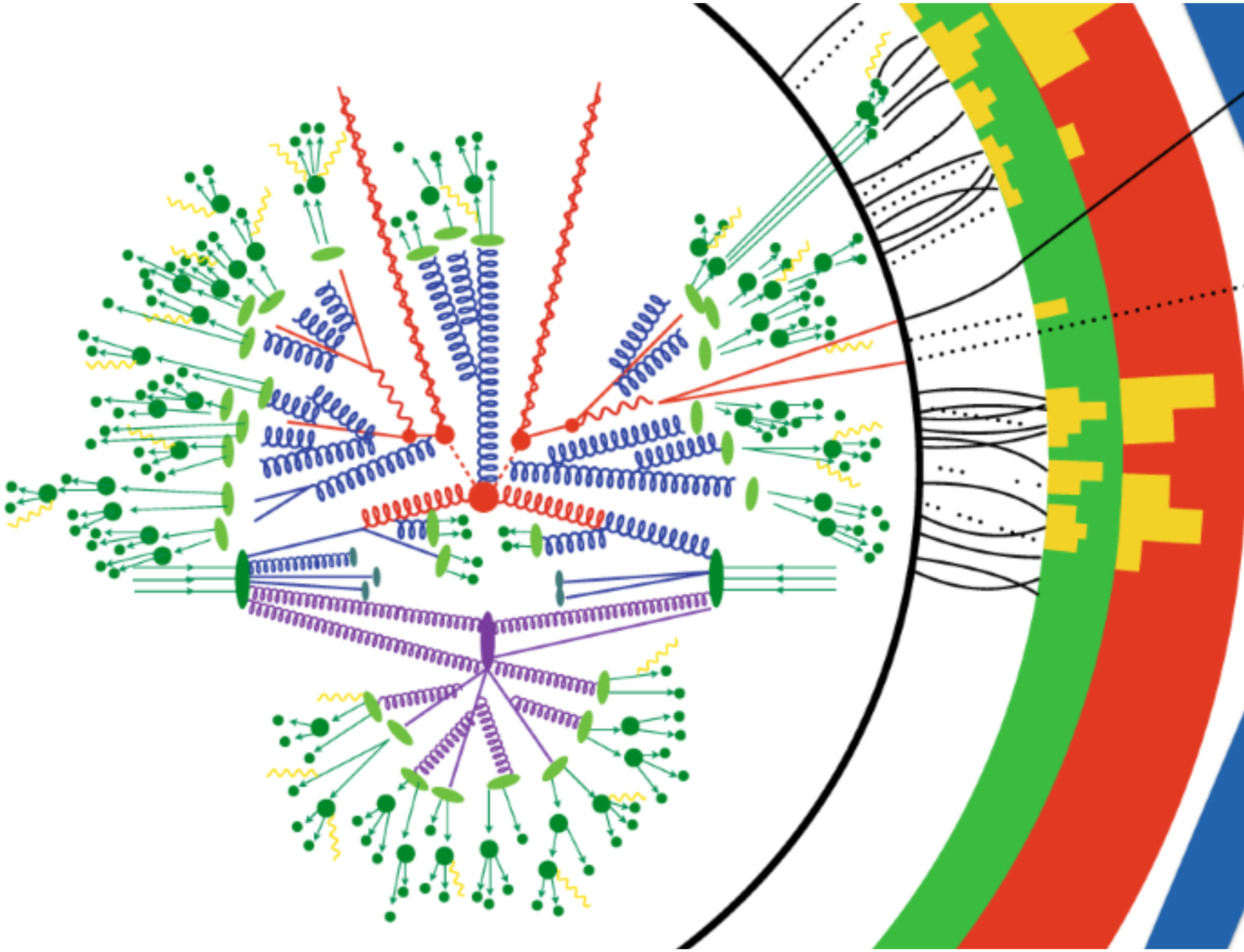
- Study properties of new particles (Higgs boson).
- Test the SM to detect new physics effects.



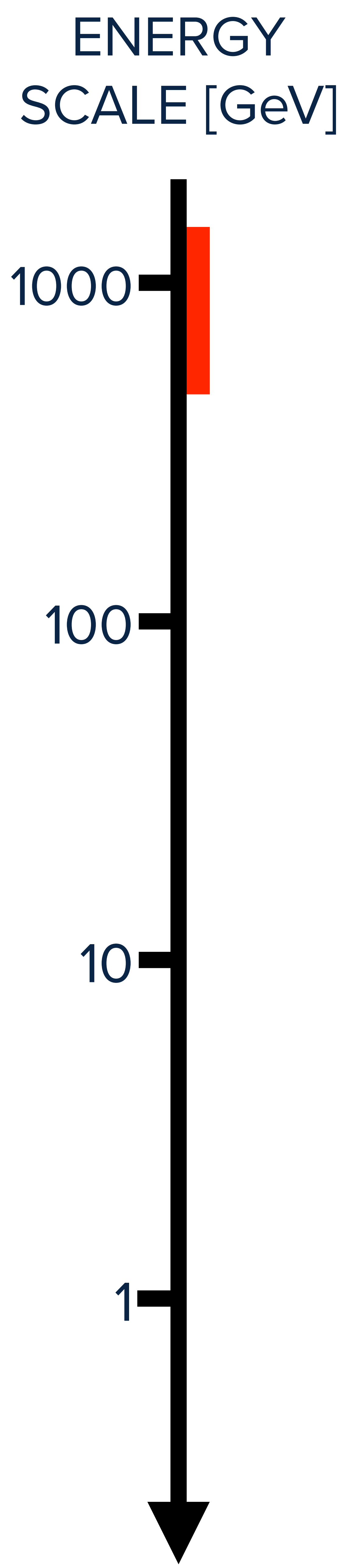
LHC EVENT

ENERGY
SCALE [GeV]

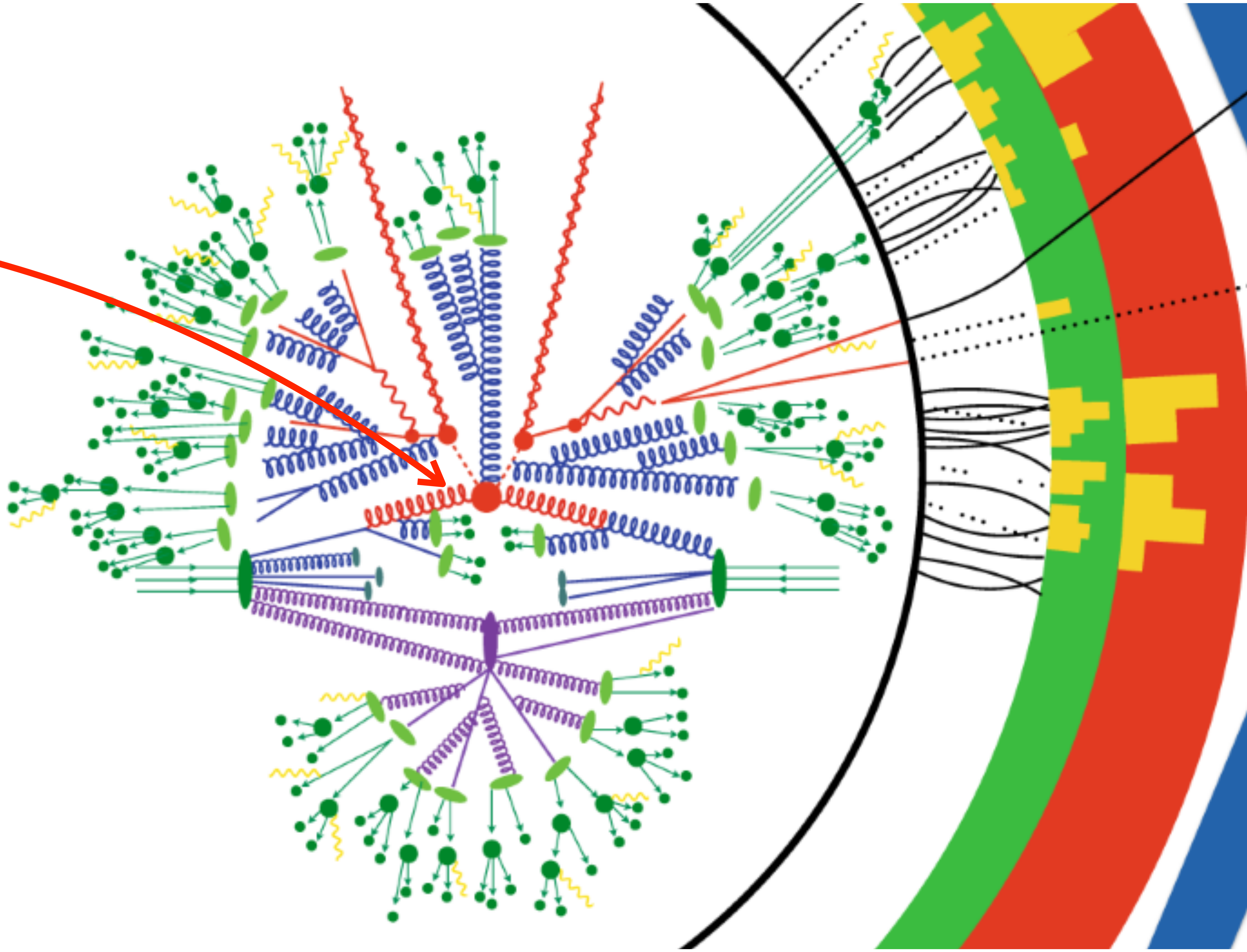




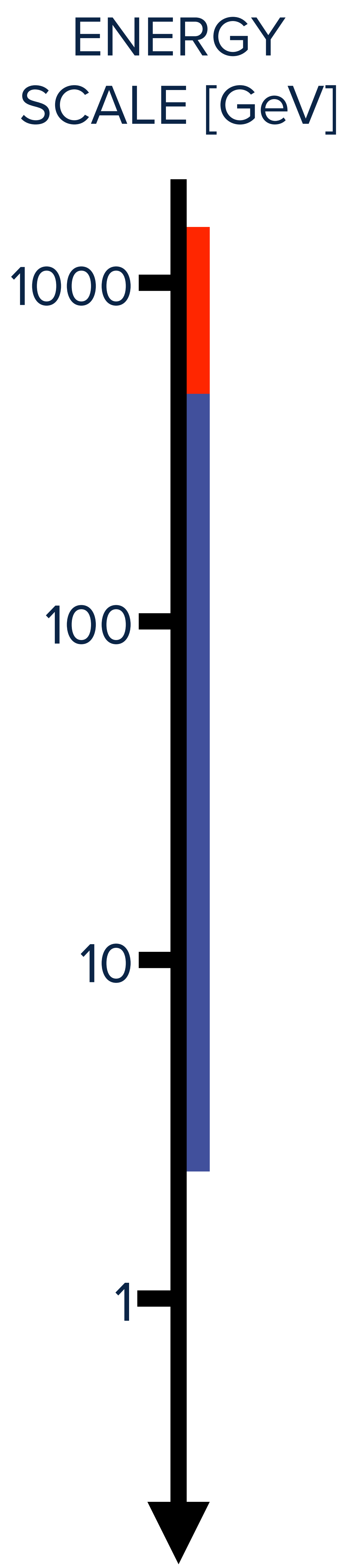
LHC EVENT



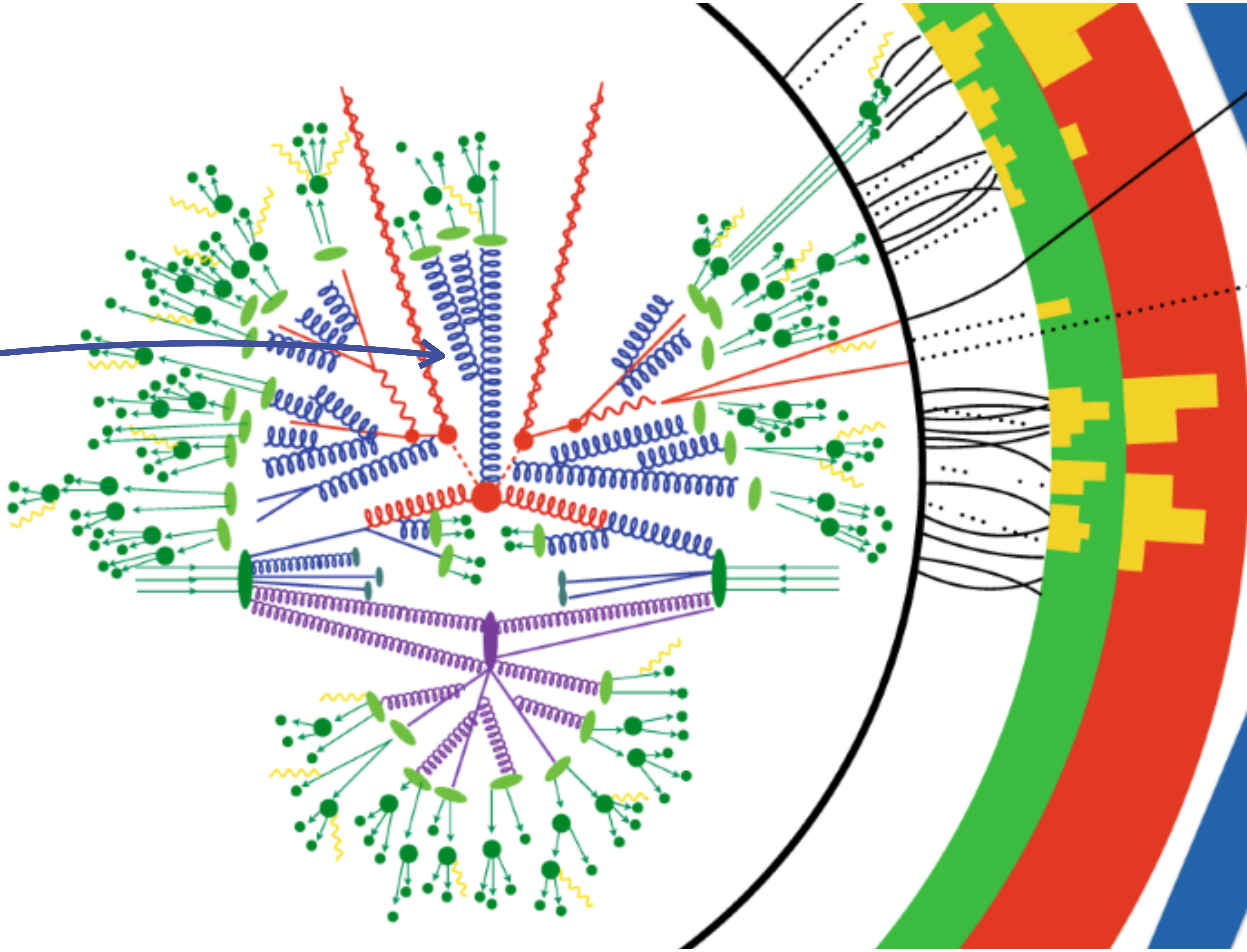
1. HARD SCATTERING



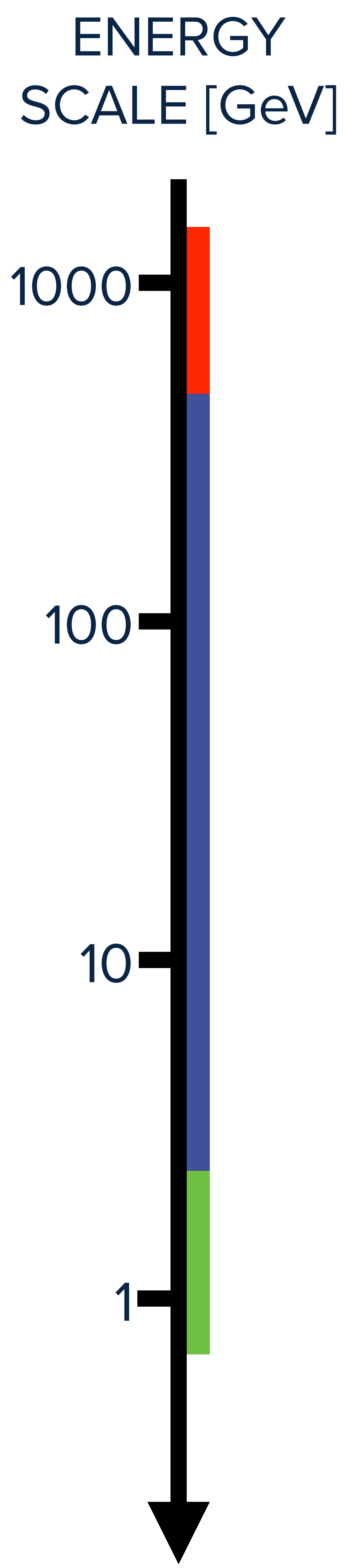
LHC EVENT



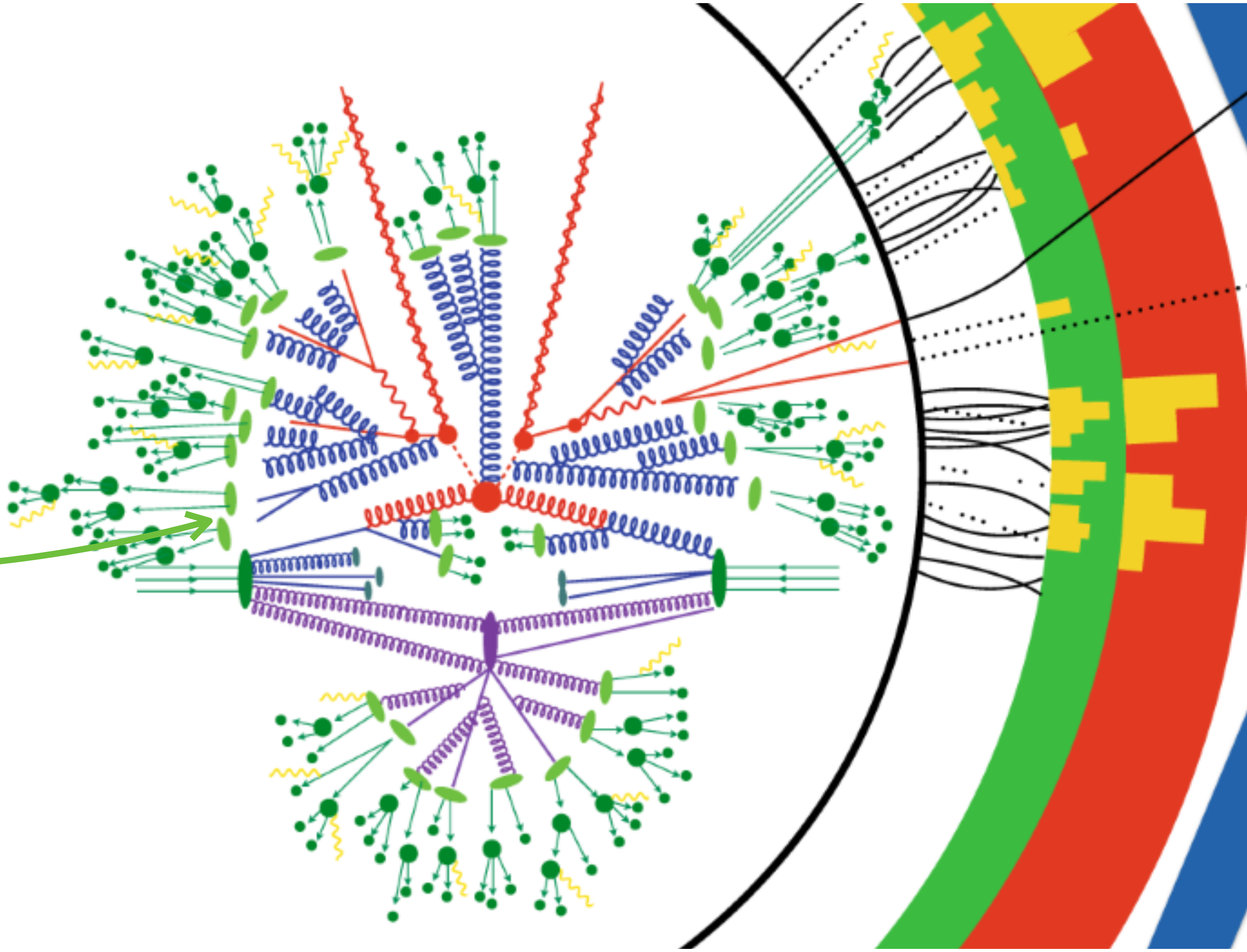
1. HARD SCATTERING
2. PARTON SHOWER



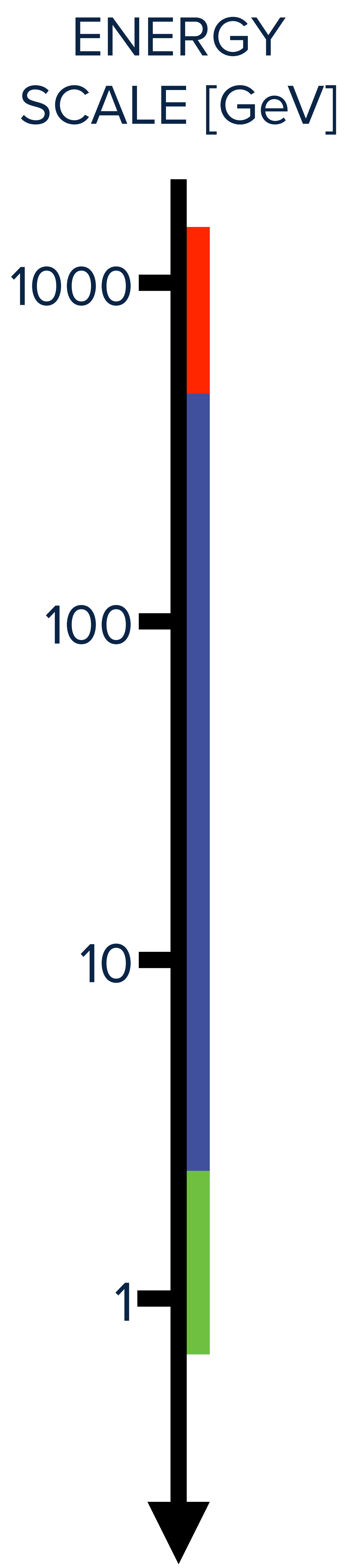
LHC EVENT



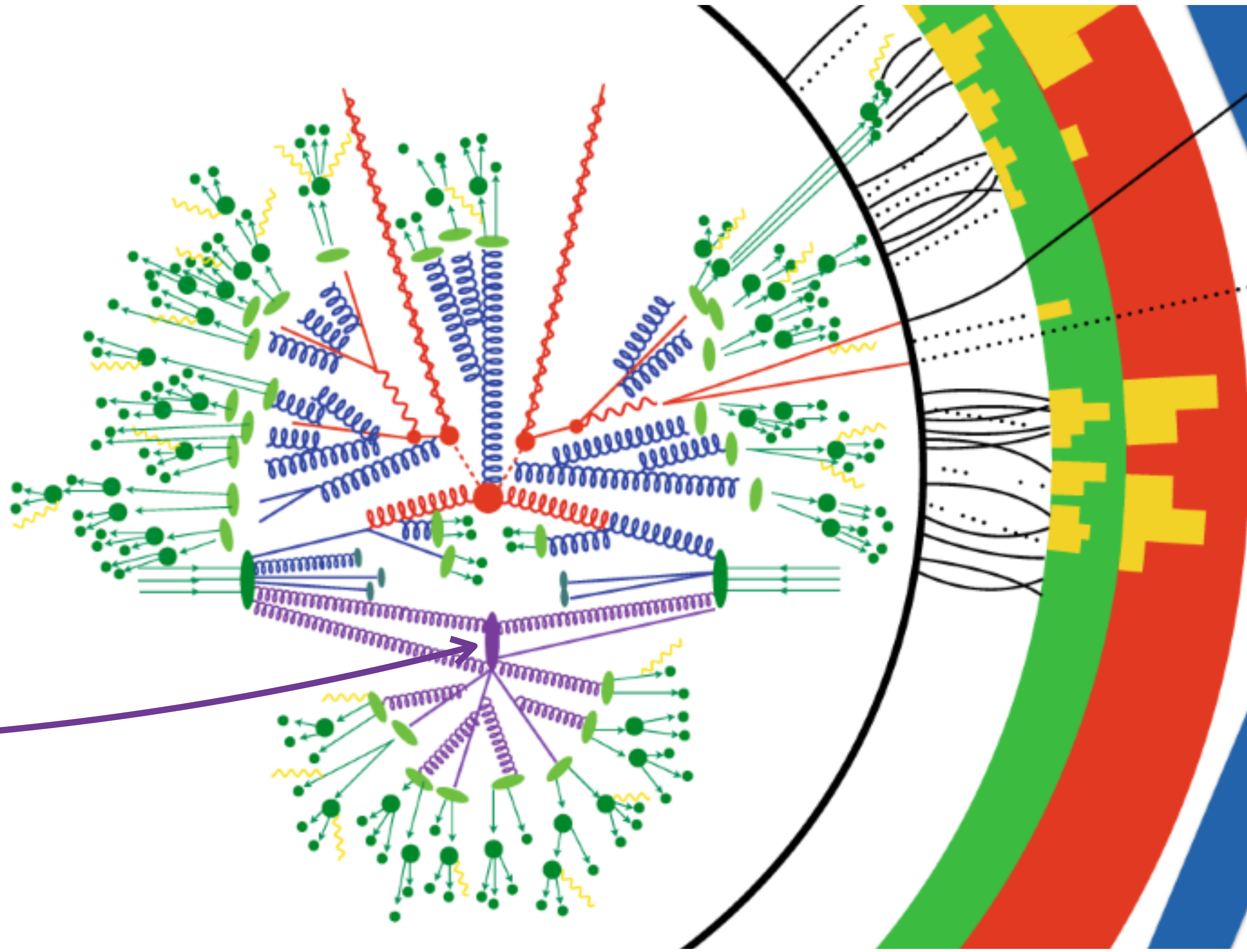
1. HARD SCATTERING
2. PARTON SHOWER
3. HADRONIZATION



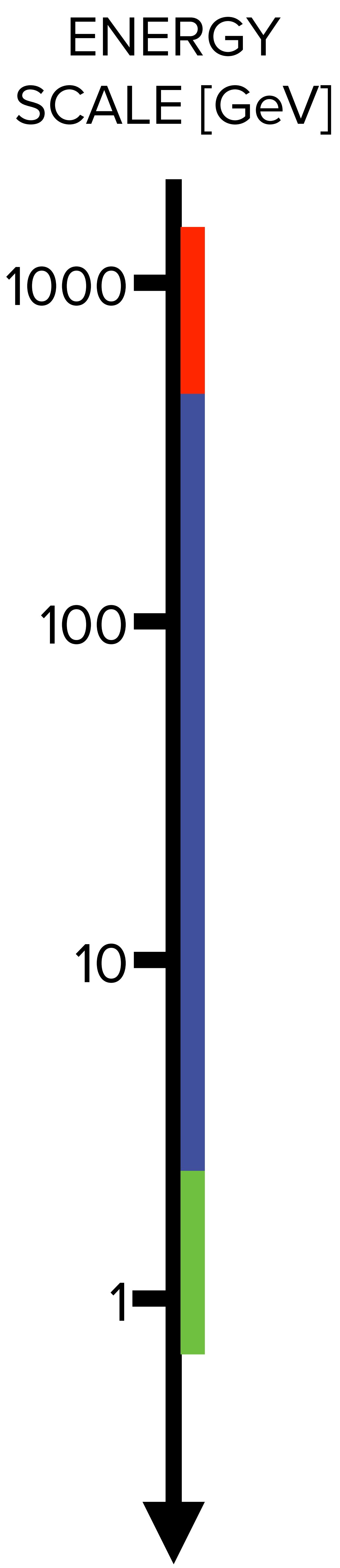
LHC EVENT



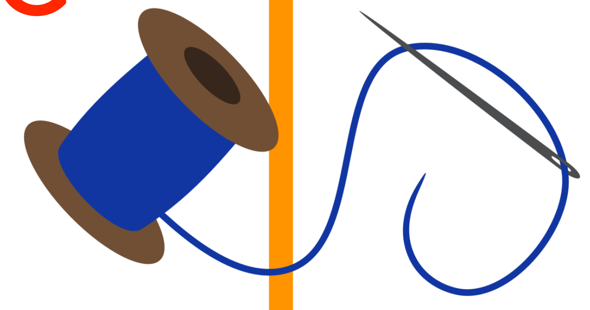
1. HARD SCATTERING
2. PARTON SHOWER
3. HADRONIZATION
4. UNDERLYING EVENT

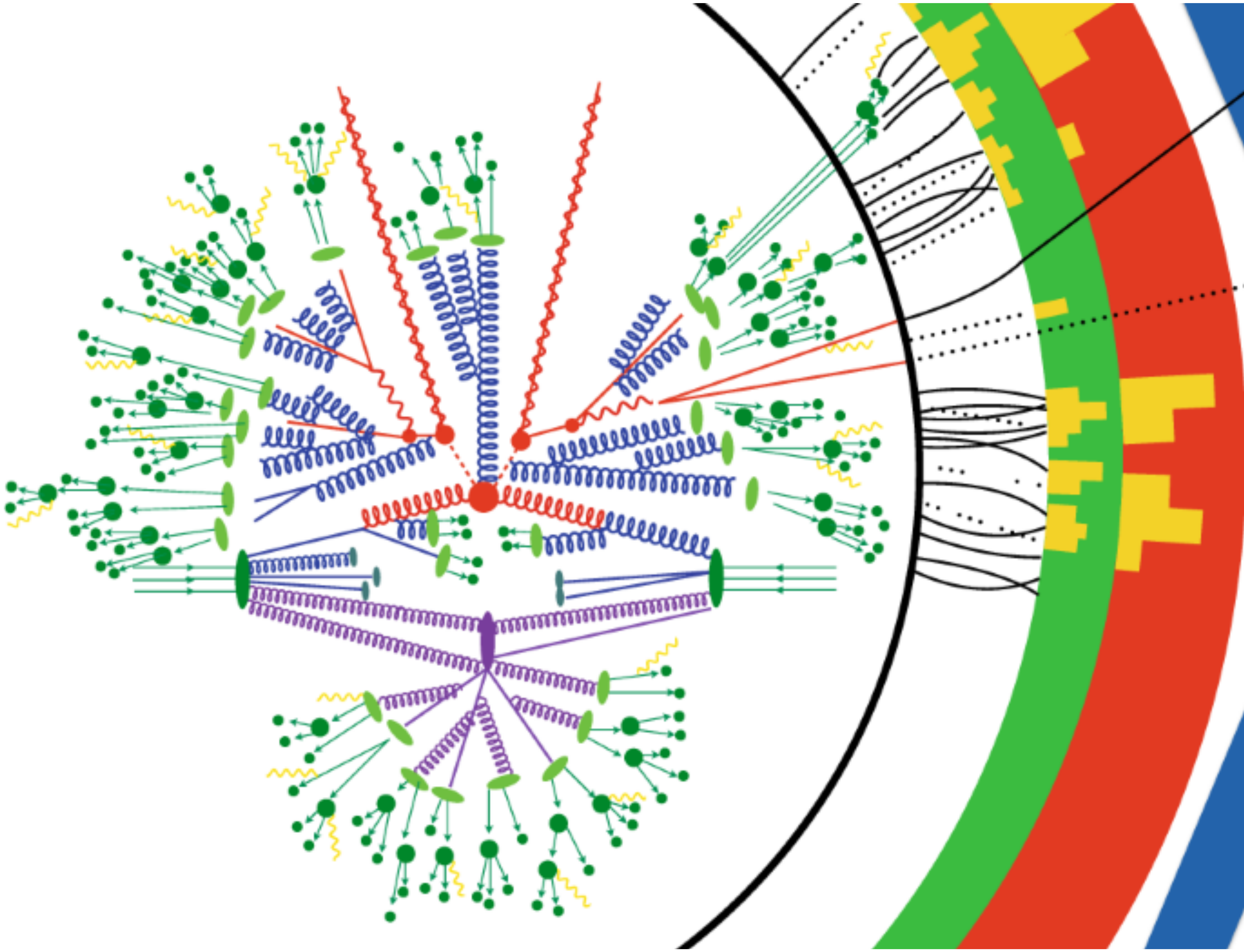


LHC EVENT



1. HARD SCATTERING
2. PARTON SHOWER
3. HADRONIZATION
4. UNDERLYING EVENT



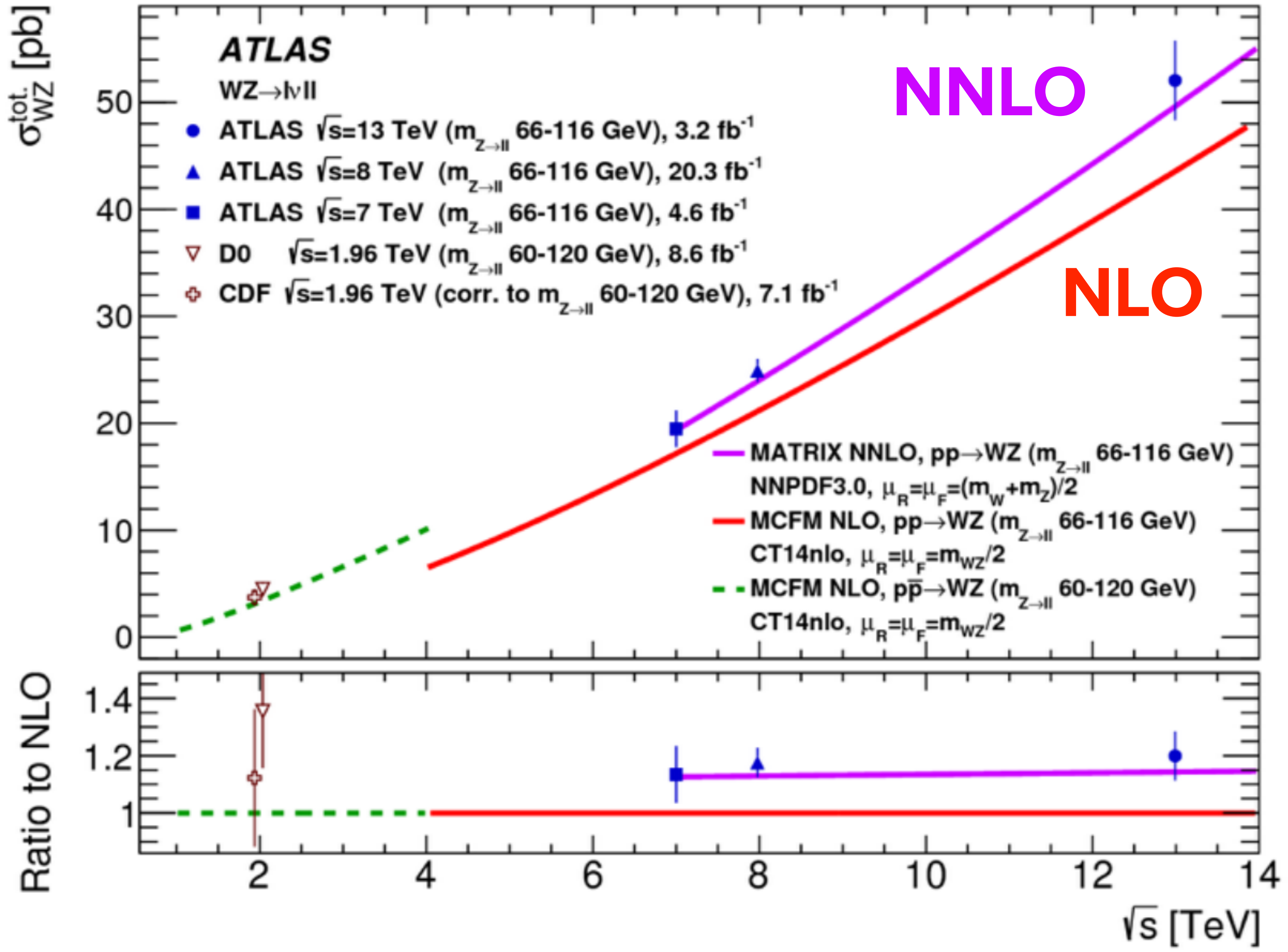


HARD SCATTERING

$\mu \sim Q \gg \Lambda_{QCD}$

Studied with fixed-order calculations. Precision is reached through perturbation theory:

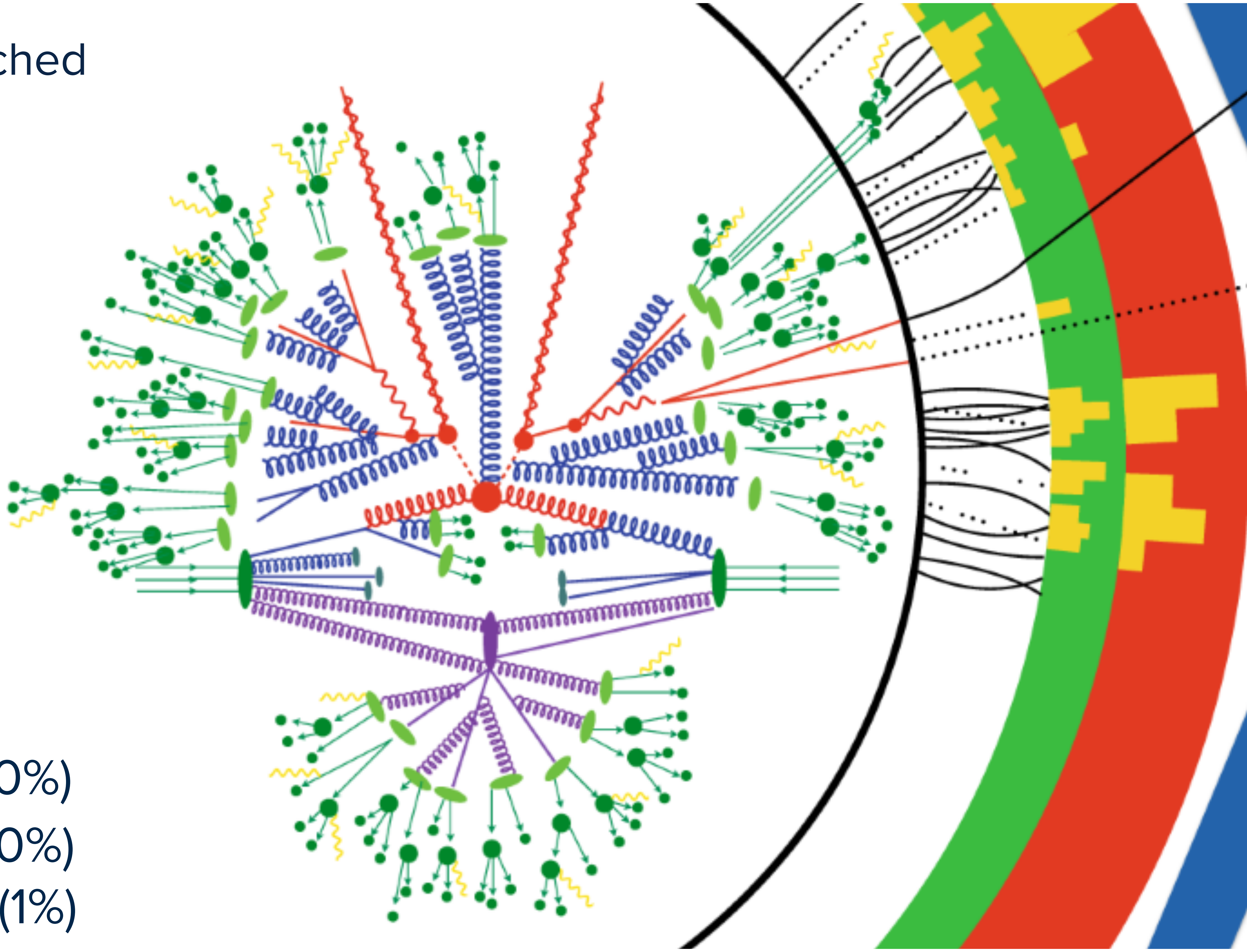
$$\sigma = \sigma_{LO}(1+\alpha_s\delta_{NLO} + \alpha_s^2\delta_{NNLO}+\mathcal{O}(\alpha_s^3))$$



LO → $\mathcal{O}$(100%)

NLO → $\mathcal{O}$(10%)

NNLO → $\mathcal{O}$(1%)



PARTON SHOWER

$\Lambda_{QCD} < \mu < Q$

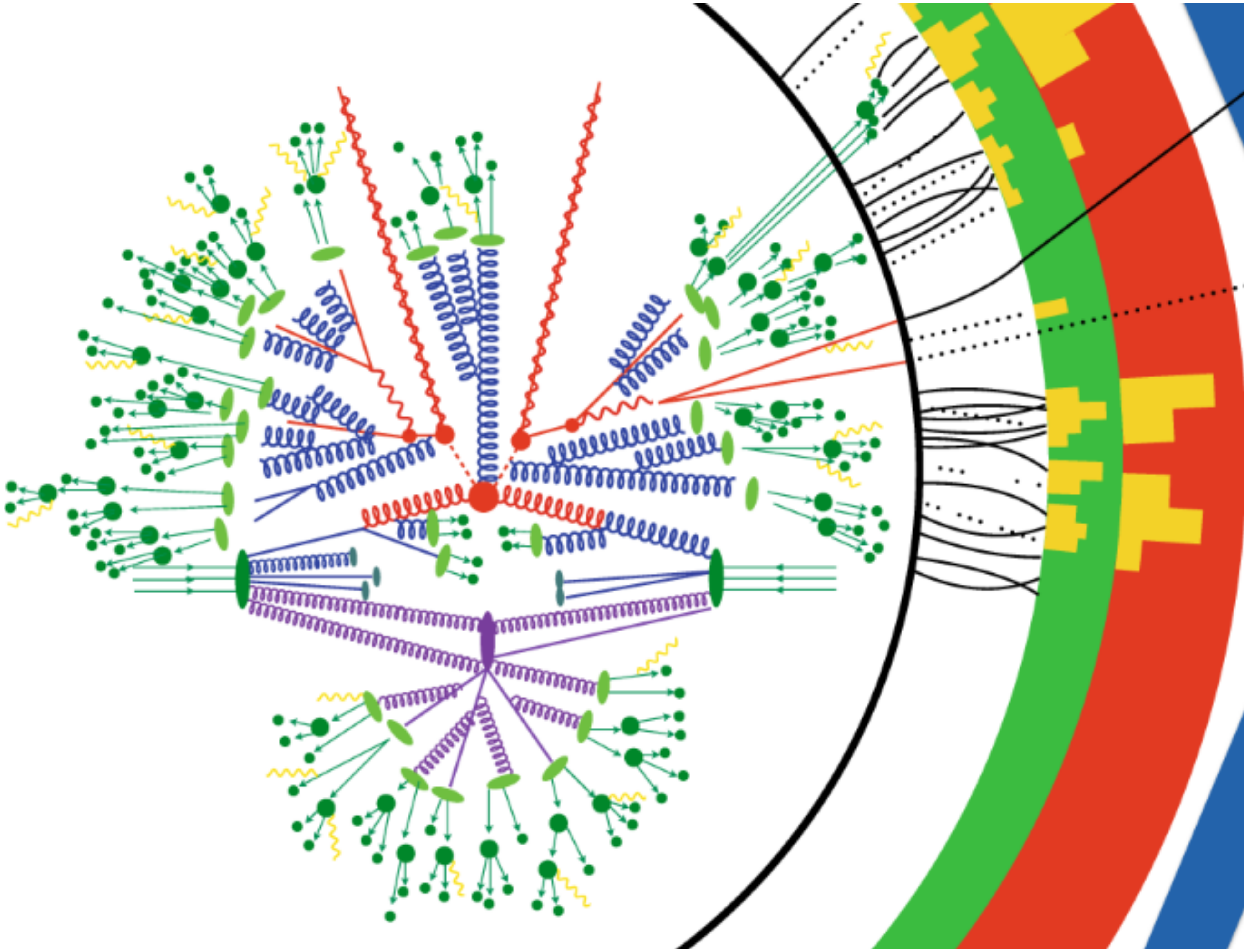
Cascade of particles from the high-energy limit to the detector level. It is constructed starting from the factorization of QCD amplitudes in the infra-red limit:

$$|M_{n+1}|^2 \to |M_n|^2 \cdot K$$

For a specific observable (e.g. event-shape V):

$$\Sigma(V < e^{-|L|}) = \exp\Big(\underbrace{Lg_1(\alpha_s L)}_{\text{LL}} + \underbrace{g_2(\alpha_s L)}_{\text{NLL}} + \underbrace{\alpha_s\, g_3(\alpha_s L)}_{\text{NNLL}} + \dots\Big)$$

Most widely-used showers are only LL accurate.



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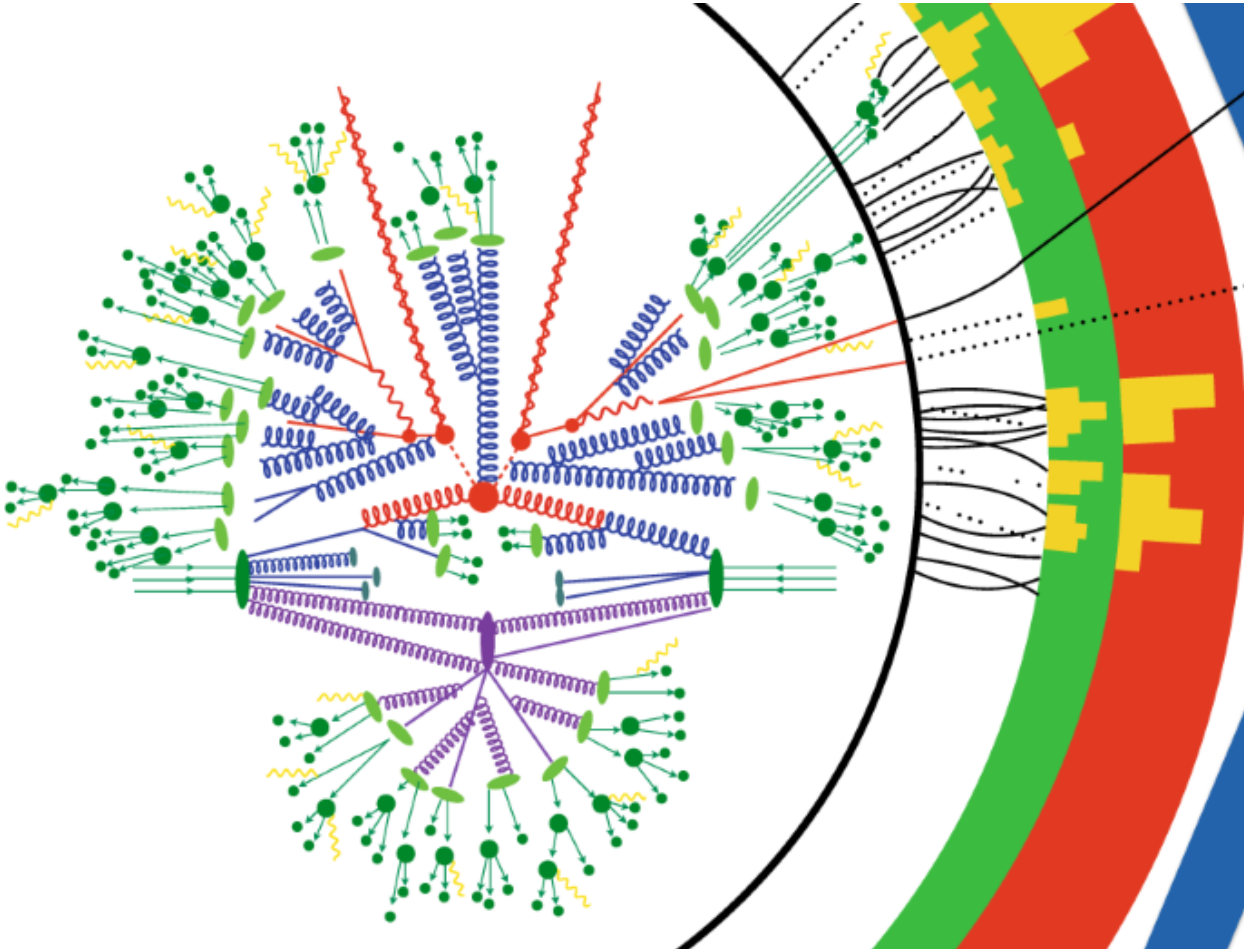
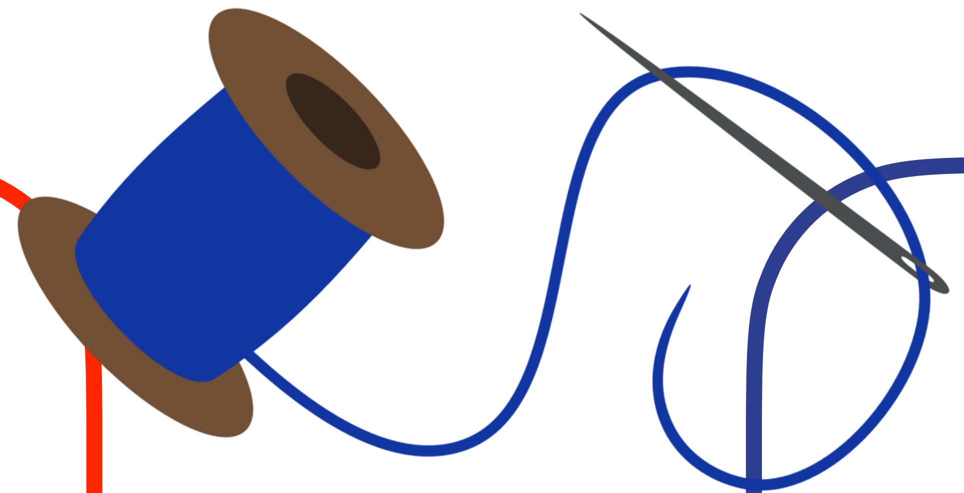
Most widely-used showers are only LL accurate.

Lots of progress done in recent years to improve the accuracy of parton showers (see e.g. Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez ’20). However, LHC phenomenology is not possible with these new tools yet.



MATCHING

COMBINATION OF THE TWO DESCRIPTIONS KEEPING THE BEST FEATURES OF BOTH



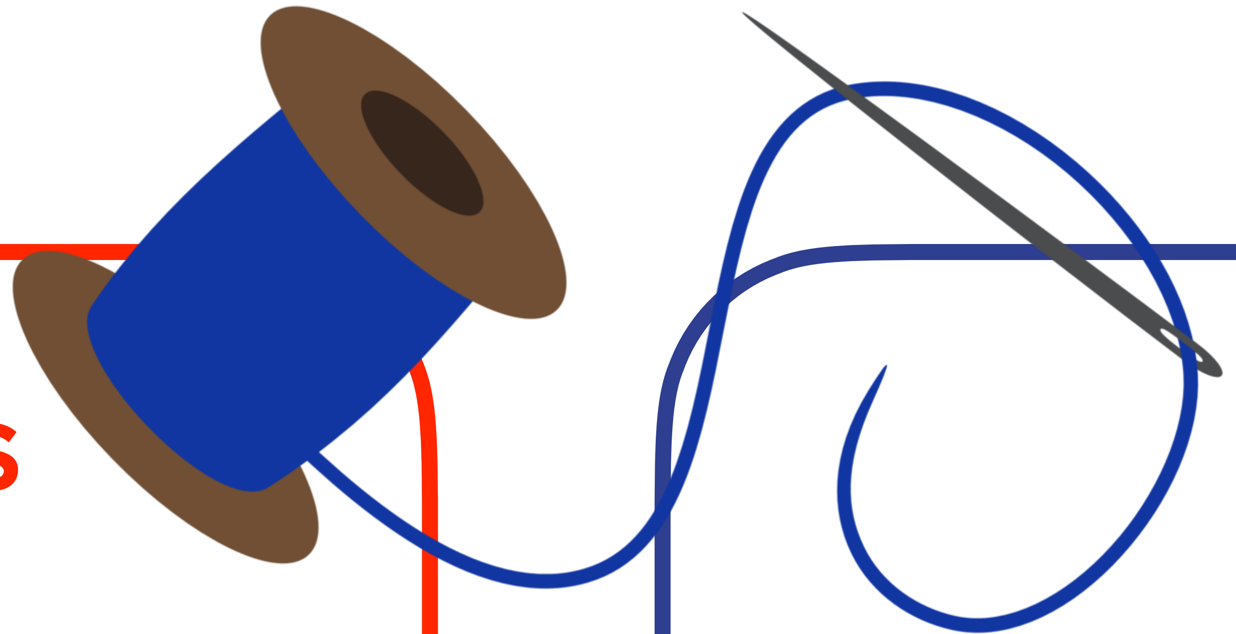
FIXED-ORDER CALCULATIONS

- **Extremely accurate and precise. Systematically improvable accuracy.**
- Non-realistic final state.

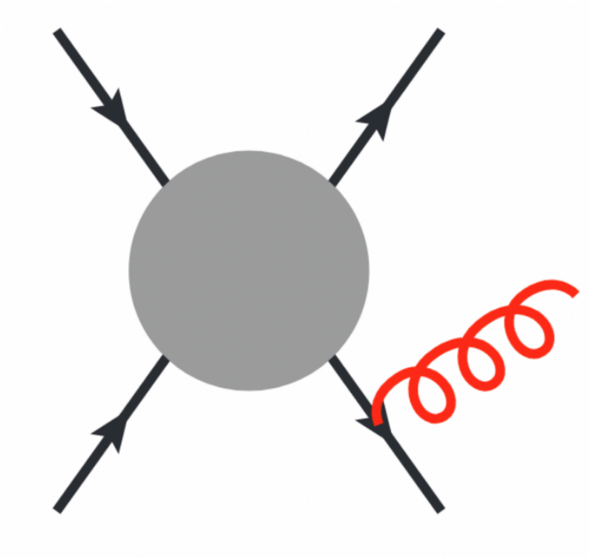
PARTON SHOWER

- **Realistic and fully-differential final states.**
- Difficulties in improving its accuracy (understood only very recently)

WHAT'S THE PROBLEM? (SIMPLE) NLO CASE

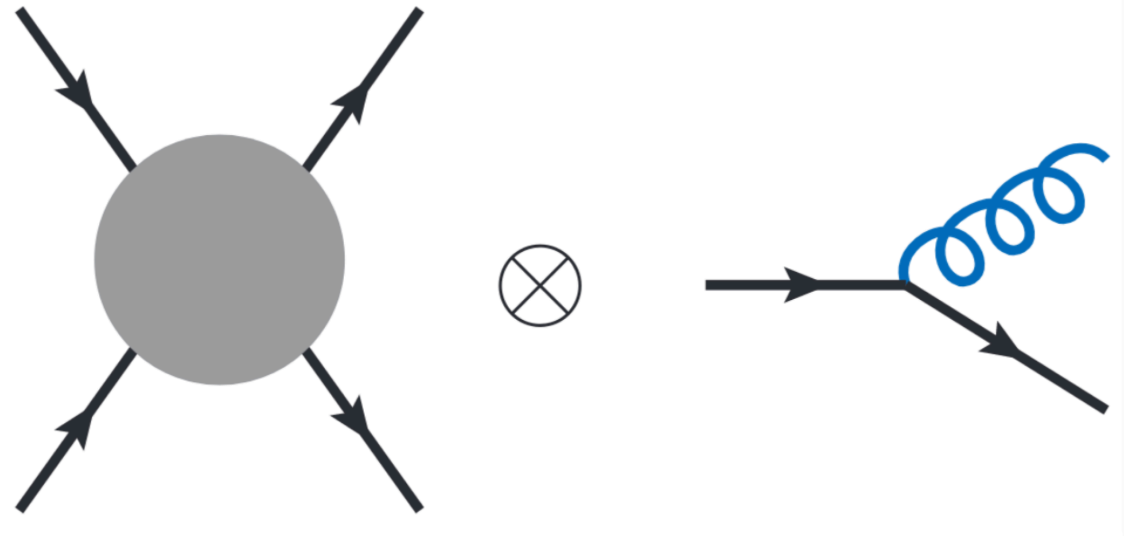


FIXED-ORDER CALCULATIONS



Correct real emission

PARTON SHOWER



Approximate real emission

!! DOUBLE COUNTING !!

MATCHING

✓

NLO+LL$_{PS}$

- A **solved problem** for long time.
- Completely understood and **fully automatized**.
- Two main approaches available: POWHEG [Nason ’04; Frixione, Nason, Oleari ’07; Alioli, Nason, Oleari, Re ’10] and MC@NLO [Frixione, Webber ’02].

WORK IN PROGRESS

NNLO+LL$_{PS}$

- **State-of-the-art** for precision LHC phenomenology.
- Lots of ongoing effort, **many processes already implemented**.
- Two main methods available: MiNNLO$_{PS}$ [Monni, Nason, Re, Wiesemann, Zanderighi ’19] and Geneva [Alioli, Bauer, Berggren,Tackmann,Walsh, Zuberi ’13, + subsequent papers].

2. THE STRATEGY

NLO+PS ACCURACY

- **NLO** accuracy in observables inclusive on QCD radiation (e.g. rapidity distribution).
- **LO** accuracy in 1 jet observables (e.g. transverse momentum of colour singlet).
- The **logarithmic structure of the parton shower** is not spoilt.

F = colour singlet

	F	F+J	F+(>2J)
F@NLO+PS	NLO	LO	PS (LL)
	↓	↓	↓
	$\frac{\mathrm{d}\sigma}{\mathrm{d}y_{\mathrm{F}}}$	$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T,F}}}$	$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T,j_2}}}$

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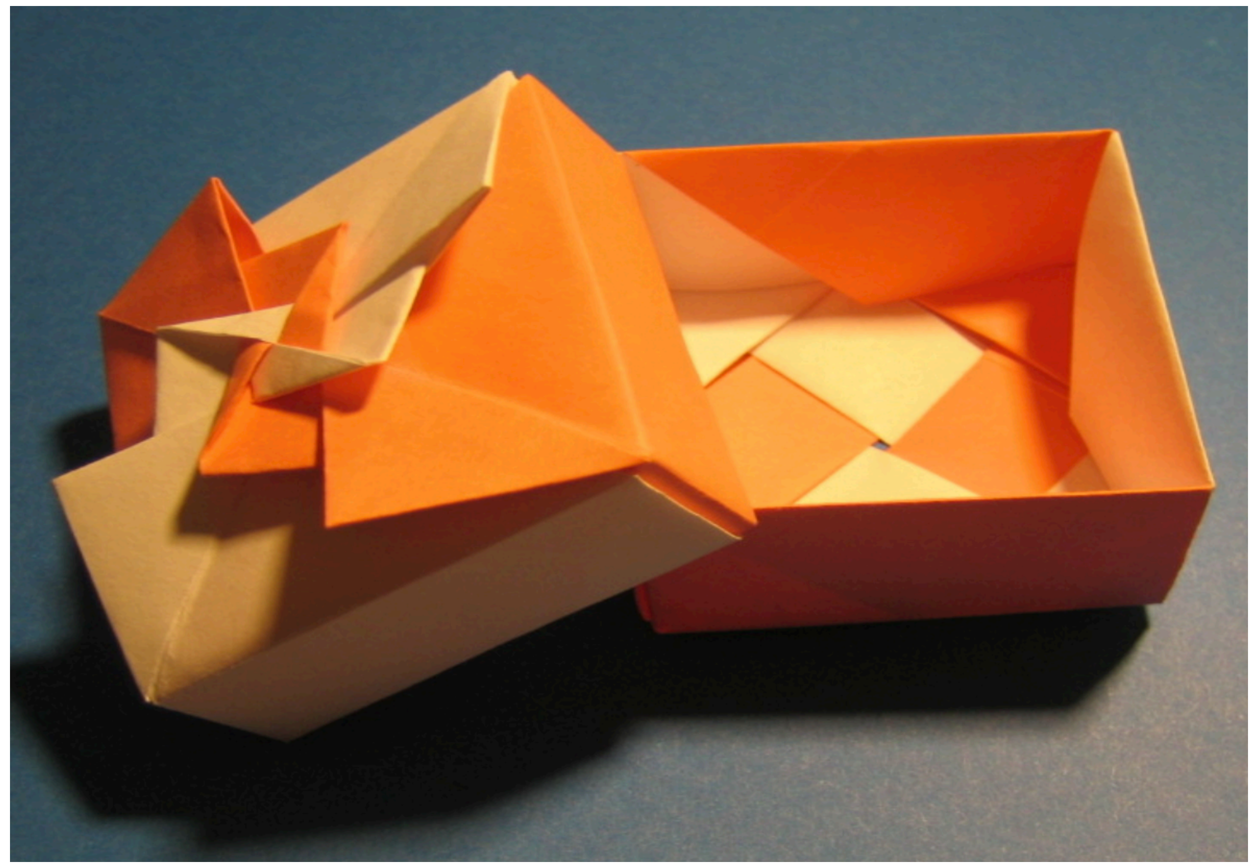
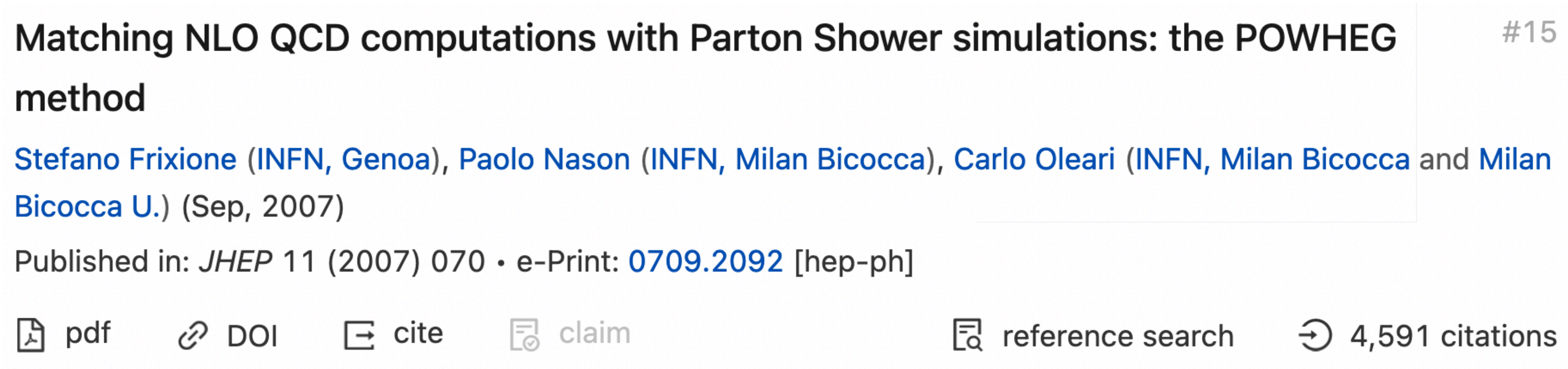
	$\frac{\mathrm{d}\sigma}{\mathrm{d}y_\mathrm{F}}$	$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T,F}}}$	$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T,j_2}}}$

THE POWHEG METHOD





Matching NLO QCD computations with Parton Shower simulations: the POWHEG method

#15

Stefano Frixione (INFN, Genoa), Paolo Nason (INFN, Milan Bicocca), Carlo Oleari (INFN, Milan Bicocca and Milan Bicocca U.) (Sep, 2007)

Published in: *JHEP* 11 (2007) 070 • e-Print: 0709.2092 [hep-ph]

https://powhegbox.mib.infn.it/

[Nason ’04; Frixione, Nason, Oleari ’07; Alioli, Nason, Oleari, Re ’10]

THE POWHEG METHOD

Master Formula

$$d\sigma_{\mathrm{pwg}} = d\Phi_{\mathrm{F}}\, \bar{\mathrm{B}}(\Phi_{\mathrm{F}}) \left\{ \Delta_{\mathrm{pwg}}(\Lambda_{\mathrm{pwg}}) + \int d\Phi_{\mathrm{rad}} \Delta_{\mathrm{pwg}}(p_{\mathrm{T,rad}}) \frac{\mathrm{R}(\Phi_{\mathrm{F}}, \Phi_{\mathrm{rad}})}{\mathrm{B}(\Phi_{\mathrm{F}})} \right\}$$

NLO NORMALIZATION (= xs)

$$\bar{\mathrm{B}}(\Phi_{\mathrm{F}}) = \mathrm{B}(\Phi_{\mathrm{F}}) + \mathrm{V}(\Phi_{\mathrm{F}}) + \int d\Phi_{\mathrm{rad}} \left[\mathrm{R}(\Phi_{\mathrm{FJ}}) - \mathrm{C}(\Phi_{\mathrm{FJ}})\right]$$

FIRST (= hardest) EMISSION
obtained with the correct matrix element R/B

$$\Delta(p_{\mathrm{T}}) = \exp\left\{ - \int d\Phi'_{\mathrm{rad}} \frac{\mathrm{R}(\Phi_{\mathrm{F}}, \Phi'_{\mathrm{rad}})}{\mathrm{B}(\Phi_{\mathrm{F}})} \Theta(p'_{\mathrm{T}} - p_{\mathrm{T}}) \right\}$$

When using a p_T-ordered shower (most common option, like PYTHIA), we apply a p_T-veto: all the emissions produced by the shower must be softer than the first emission produced by POWHEG.

NNLO+PS ACCURACY

F = colour singlet

- **NNLO** accuracy in observables inclusive on QCD radiation (e.g. rapidity distribution).
- **NLO** accuracy in 1 jet observables (e.g. transverse momentum of colour singlet).
- **LO** accuracy in 2 jet observables (e.g. transverse momentum of second leading jet).
- The **logarithmic structure of the parton shower** is not spoilt.

	F	F+J	F+JJ	F+(>3J)
F@NNLO+PS	NNLO	NLO	LO	PS (LL)
	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
	$\frac{d\sigma}{dy_F}$	$\frac{d\sigma}{dp_{T,F}}$	$\frac{d\sigma}{dp_{T,j_2}}$	$\frac{d\sigma}{dp_{T,j_3}}$

NNLO+PS ACCURACY

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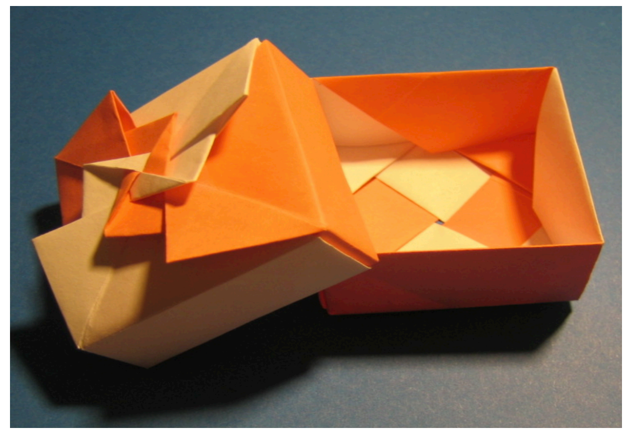
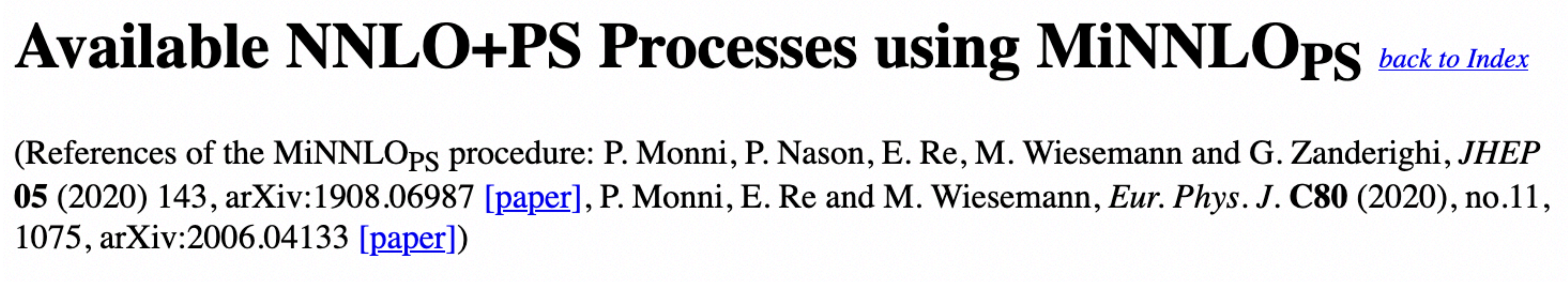
	F	F+J	F+JJ	F+(>3J)
F@NNLO+PS	NNLO	NLO	LO	PS (LL)
	$\downarrow$ $\frac{\mathrm{d}\sigma}{\mathrm{d}y_{\mathrm{F}}}$	$\downarrow$ $\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T,F}}}$	$\downarrow$ $\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T,j_2}}}$	$\downarrow$ $\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T,j_3}}}$

THE MiNNLO$_{\mathrm{PS}}$ METHOD





Available NNLO+PS Processes using MiNNLO$_{\mathrm{PS}}$ *back to Index*

(References of the MiNNLO$_{\mathrm{PS}}$ procedure: P. Monni, P. Nason, E. Re, M. Wiesemann and G. Zanderighi, *JHEP* **05** (2020) 143, arXiv:1908.06987 [paper], P. Monni, E. Re and M. Wiesemann, *Eur. Phys. J.* **C80** (2020), no.11, 1075, arXiv:2006.04133 [paper])

https://powhegbox.mib.infn.it/

[Monni, Nason, Re, Wiesemann, Zanderighi ’19]

THE MiNNLO$_{\text{PS}}$ METHOD

F = colour singlet

Master Formula

$$d\sigma_{F}^{\text{MiNNLO}_{\text{PS}}} = d\Phi_{FJ}\;\bar{B}^{\text{MiNNLO}_{\text{PS}}}(\Phi_{FJ}) \left\{ \Delta_{\text{pwg}}(\Lambda_{\text{pwg}}) + \int d\Phi_{\text{rad}}\,\Delta_{\text{pwg}}(p_{T,\text{rad}}) \frac{R(\Phi_{FJ}, \Phi_{\text{rad}})}{B(\Phi_{FJ})} \right\}$$

NNLO NORMALIZATION (= xs)

SECOND EMISSION
obtained à la POWHEG

THE MiNNLO$_{\text{PS}}$ METHOD

F = colour singlet

Master Formula

$$d\sigma_F^{\text{MiNNLO}_{\text{PS}}} = d\Phi_{\text{FJ}}\ \bar{\text{B}}^{\text{MiNNLO}_{\text{PS}}}(\Phi_{\text{FJ}}) \left\{ \Delta_{\text{pwg}}(\Lambda_{\text{pwg}}) + \int d\Phi_{\text{rad}}\Delta_{\text{pwg}}(p_{\text{T,rad}}) \frac{\text{R}(\Phi_{\text{FJ}}, \Phi_{\text{rad}})}{\text{B}(\Phi_{\text{FJ}})} \right\}$$

NNLO NORMALIZATION (= xs)

SECOND EMISSION
obtained à la POWHEG

$$\bar{\text{B}}^{\text{MiNNLO}_{\text{PS}}}(\Phi_{\text{FJ}}) = \left(\text{B}(\Phi_{\text{FJ}}) \qquad + \text{V}(\Phi_{\text{FJ}}) + \int d\Phi_{\text{rad}}\text{R}(\Phi_{\text{FJJ}}) \qquad \right)$$

Born FJ

⚠ DIVERGENT

Virtual+Real
on F+J

	F	F+J	F+JJ	F+(>3J)
F@NNLO+PS	-	NLO	LO	PS (LL)

NNLO+PS

THE MiNNLO$_{\mathrm{PS}}$ METHOD

F = colour singlet

Master Formula

$$d\sigma_{F}^{\mathrm{MiNNLO_{PS}}} = d\Phi_{FJ}\ \bar{B}^{\mathrm{MiNNLO_{PS}}}(\Phi_{FJ}) \left\{ \Delta_{pwg}(\Lambda_{pwg}) + \int d\Phi_{rad} \Delta_{pwg}(p_{T,rad}) \frac{R(\Phi_{FJ}, \Phi_{rad})}{B(\Phi_{FJ})} \right\}$$

NNLO NORMALIZATION (= xs)

SECOND EMISSION
obtained à la POWHEG

$$\bar{B}^{\mathrm{MiNNLO_{PS}}}(\Phi_{FJ}) = e^{-\tilde{S}(p_T)} \left(B(\Phi_{FJ})\left(1 + \alpha_s \tilde{S}^{(1)}\right) + V(\Phi_{FJ}) + \int d\Phi_{rad} R(\Phi_{FJJ}) \right)$$

Sudakov form factor

$$\tilde{S}(p_T) = \int_{p_T^2}^{Q^2} \frac{dq^2}{q^2}\left[A \log\frac{Q^2}{q^2} + B\right]$$

Born FJ

⚠ DIVERGENT

Correct NLO on F+J

Virtual+Real
on F+J

	F	F+J	F+JJ	F+(>3J)
F@NNLO+PS	NLO	NLO	LO	PS (LL)

THE MiNNLO$_{\mathrm{PS}}$ METHOD

F = colour singlet

Master Formula

$$d\sigma_{\mathrm{F}}^{\mathrm{MiNNLO_{PS}}} = d\Phi_{\mathrm{FJ}}\;\bar{\mathrm{B}}^{\mathrm{MiNNLO_{PS}}}(\Phi_{\mathrm{FJ}}) \left\{ \Delta_{\mathrm{pwg}}(\Lambda_{\mathrm{pwg}}) + \int d\Phi_{\mathrm{rad}}\Delta_{\mathrm{pwg}}(p_{\mathrm{T,rad}})\frac{\mathrm{R}(\Phi_{\mathrm{FJ}},\Phi_{\mathrm{rad}})}{\mathrm{B}(\Phi_{\mathrm{FJ}})} \right\}$$

NNLO NORMALIZATION (= xs)

SECOND EMISSION
obtained à la POWHEG

$$\bar{\mathrm{B}}^{\mathrm{MiNNLO_{PS}}}(\Phi_{\mathrm{FJ}}) = e^{-\tilde{\mathrm{S}}(p_{\mathrm{T}})}\left(\mathrm{B}(\Phi_{\mathrm{FJ}})\left(1+\alpha_s\tilde{\mathrm{S}}^{(1)}\right) + \mathrm{V}(\Phi_{\mathrm{FJ}}) + \int d\Phi_{\mathrm{rad}}\mathrm{R}(\Phi_{\mathrm{FJJ}}) + \left(\mathrm{D}(p_{\mathrm{T}}) - \alpha_s\,\mathrm{D}^{(1)}(p_{\mathrm{T}}) - \alpha_s^2\,\mathrm{D}^{(2)}(p_{\mathrm{T}})\right)\mathscr{F}\right)$$

Sudakov form factor

$$\tilde{S}(p_T) = \int_{p_T^2}^{Q^2}\frac{dq^2}{q^2}\left[A\log\frac{Q^2}{q^2} + B\right]$$

Born FJ

~~DIVERGENT~~

Correct NLO on F+J

Virtual+Real
on F+J

α_s^3 correction
for NNLO normalization

spreading
$\Phi_{\mathrm{F}} \rightarrow \Phi_{\mathrm{FJ}}$

	F	F+J	F+JJ	F+(>3J)
F@NNLO+PS	NNLO	NLO	LO	PS (LL)

THE MiNNLOPS METHOD

$$D(\mathrm{p_T}) \equiv -\frac{\mathrm{d}\tilde{S}(\mathrm{p_T})}{\mathrm{dp_T}}\mathscr{L}(\mathrm{p_T}) + \frac{d\mathscr{L}\mathrm{p_T}}{\mathrm{dp_T}}$$

- Analytic all-order formula:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_\mathrm{F}\mathrm{dp_T}} = \frac{\mathrm{d}\sigma^{\mathrm{sing}}}{\mathrm{d}\Phi_\mathrm{F}\mathrm{dp_T}} + R(\mathrm{p_T}) = \frac{\mathrm{d}}{\mathrm{dp_T}}\left\{e^{-\tilde{S}(\mathrm{p_T})}\mathscr{L}(\mathrm{p_T})\right\} + R(\mathrm{p_T}) = e^{-\tilde{S}(\mathrm{p_T})}\left[D(p_T) + \frac{R(p_T)}{e^{-\tilde{S}(\mathrm{p_T})}}\right]$$

THE MiNNLO$_{\text{PS}}$ METHOD

$$D(\mathrm{p_T}) \equiv -\frac{d\tilde{S}(\mathrm{p_T})}{d\mathrm{p_T}}\mathscr{L}(\mathrm{p_T}) + \frac{d\mathscr{L}\mathrm{p_T}}{d\mathrm{p_T}}$$

- Analytic all-order formula:

$$\frac{d\sigma}{d\Phi_F d\mathrm{p_T}} = \frac{d\sigma^{\text{sing}}}{d\Phi_F d\mathrm{p_T}} + R(\mathrm{p_T}) = \frac{d}{d\mathrm{p_T}}\left\{e^{-\tilde{S}(\mathrm{p_T})}\mathscr{L}(\mathrm{p_T})\right\} + R(\mathrm{p_T}) = e^{-\tilde{S}(\mathrm{p_T})}\left[D(p_T) + \frac{R(p_T)}{e^{-\tilde{S}(\mathrm{p_T})}}\right]$$

- Combine with FJ fixed-order $d\sigma_{FJ}$ and expand up to α_s^3:

$$\int \frac{d\mathrm{p_T}}{\mathrm{p_T}}\alpha_s^m(\mathrm{p_T})\ \ln^n\frac{\mathrm{p_T}}{Q}\ e^{-\tilde{S}(\mathrm{p_T})} \approx \mathcal{O}\left(\alpha_s^{m-\frac{n+1}{2}}\right)$$

$\mu_R = \mu_F = \mathrm{p_T}$

$$d\sigma_F = d\sigma_F^{\text{sing}} + [d\sigma_{FJ}]_{\text{f.o.}} - [d\sigma_F^{\text{sing}}]_{\text{f.o.}} = e^{-\tilde{S}(\mathrm{p_T})}\left\{D + \frac{[d\sigma_{FJ}]_{\text{f.o.}}}{\underbrace{[e^{-\tilde{S}(\mathrm{p_T})}]_{\text{f.o.}}}_{1-\alpha_s\tilde{S}^{(1)}}} - \frac{[d\sigma_F^{\text{sing}}]_{\text{f.o.}}}{\underbrace{[e^{-\tilde{S}(\mathrm{p_T})}]_{\text{f.o.}}}_{-\alpha_s D^{(1)}(\mathrm{p_T}) - \alpha_s^2 D^{(2)}(\mathrm{p_T})}}\right\}$$

NNLO+PS

THE MiNNLO$_{\text{PS}}$ METHOD

$$D(p_T) \equiv -\frac{d\tilde{S}(p_T)}{dp_T}\mathscr{L}(p_T) + \frac{d\mathscr{L}p_T}{dp_T}$$

- Analytic all-order formula:

$$\frac{d\sigma}{d\Phi_F dp_T} = \frac{d\sigma^{\text{sing}}}{d\Phi_F dp_T} + R(p_T) = \frac{d}{dp_T}\left\{e^{-\tilde{S}(p_T)}\mathscr{L}(p_T)\right\} + R(p_T) = e^{-\tilde{S}(p_T)}\left[D(p_T) + \frac{R(p_T)}{e^{-\tilde{S}(p_T)}}\right]$$

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$$d\sigma_F = d\sigma_F^{\text{sing}} + [d\sigma_{FJ}]_{\text{f.o.}} - [d\sigma_F^{\text{sing}}]_{\text{f.o.}} = e^{-\tilde{S}(p_T)}\left\{D + \underbrace{\frac{[d\sigma_{FJ}]_{\text{f.o.}}}{[e^{-\tilde{S}(p_T)}]_{\text{f.o.}}}}_{1-\alpha_s\tilde{S}^{(1)}} - \underbrace{\frac{[d\sigma_F^{\text{sing}}]_{\text{f.o.}}}{[e^{-\tilde{S}(p_T)}]_{\text{f.o.}}}}_{-\alpha_s D^{(1)}(p_T) - \alpha_s^2 D^{(2)}(p_T)}\right\}$$

$$\bar{B}^{\text{MiNNLO}_{\text{PS}}}(\Phi_{FJ}) = e^{-\tilde{S}(p_T)}\left(B(\Phi_{FJ})\left(1+\alpha_s\tilde{S}^{(1)}\right) + V(\Phi_{FJ}) + \int d\Phi_{\text{rad}}R(\Phi_{FJJ}) + \left(D(p_T) - \alpha_s D^{(1)}(p_T) - \alpha_s^2 D^{(2)}(p_T)\right)\mathscr{F}\right)$$

WHAT CAN WE DO WITH MiNNLO$_{\mathrm{PS}}$?

2 → 1 PROCESSES

H [1908.06987, 2407.01354] ✓
Z [1908.06987] ✓
W [2006.04133] ✓
bb→H [2402.04025]

INCLUSION NLO EW

WZ [2208.12660] ✓
Z ongoing

2 → 2 PROCESSES

$Z\gamma$ [2010.10478] ✓
$\gamma\gamma$ [2204.12602] ✓
ZZ [2108.05337] ✓
VH (H→bb) [2112.04168]
(**+SMEFT** [2204.00663])
WW [2103.12077] ✓
WZ [2208.12660] ✓

QQ PRODUCTION

tt [2012.14267, 2112.12135] ✓
bb [2112.04168]

QQF PRODUCTION

bbZ [2404.08598]

✗ EXTENSION TO PROCESSES WITH JETS

[2402.00596]

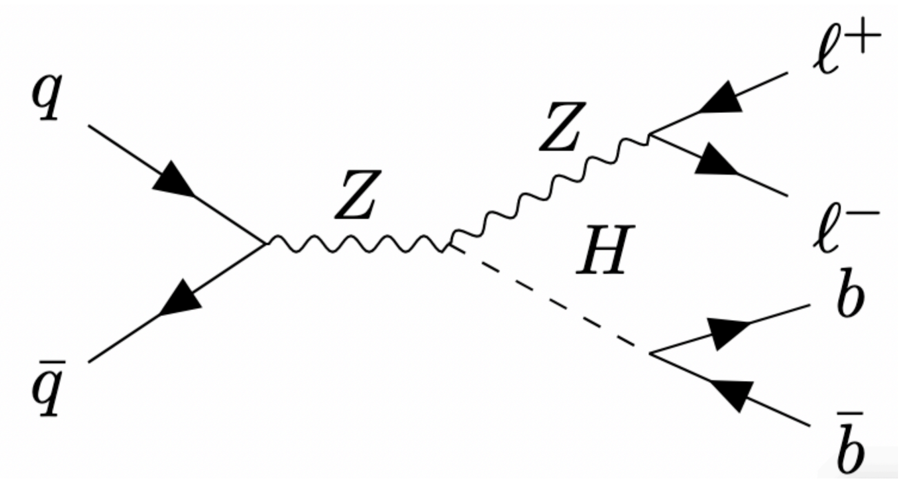
DIFFICULT

✓ = **publicly available at https://powhegbox.mib.infn.it/**

3. PHENOMENOLOGICAL RESULTS

[SZ, Chiesa, Re, Wiesemann, Zanderighi ’21]

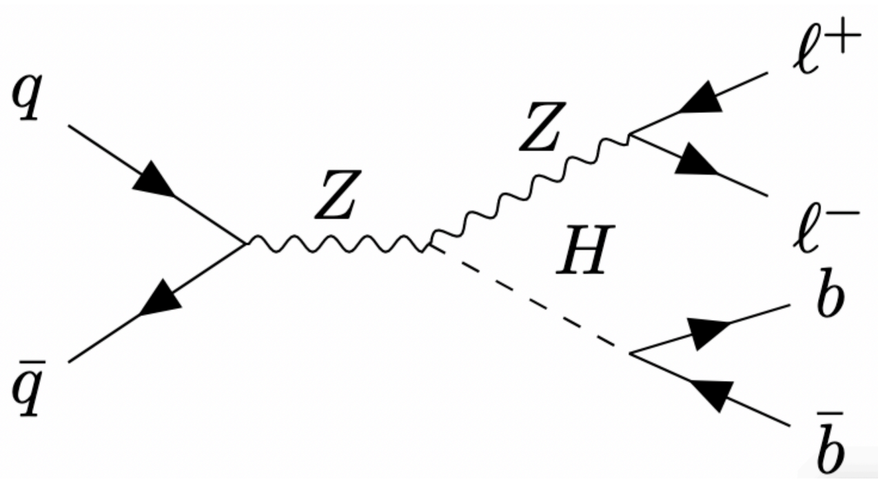
VH x H→bb @ NNLO+PS



- NNLO+PS accuracy in both production and decay.
- Clean channel for H production + largest branching fraction in the decay.

[SZ, Chiesa, Re, Wiesemann, Zanderighi '21]

VH x H→bb @ NNLO+PS



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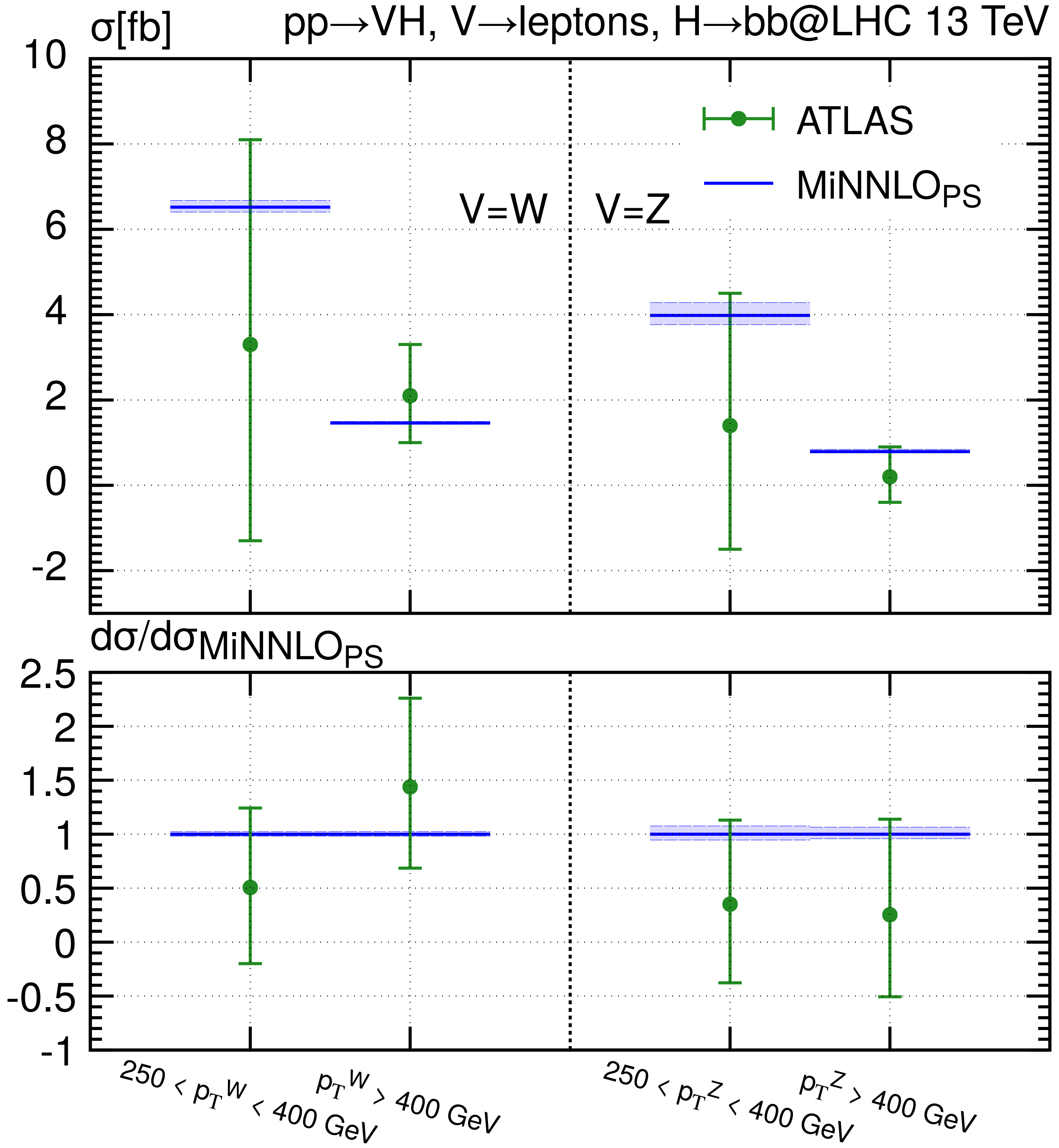
COMPARISON WITH DATA



$pp \to W^\pm H \to \ell^\pm \nu_\ell b\bar{b}$		
σ [fb]	$p_T^W \in$ [250,400] GeV	$p_T^W \in [400, \infty]$ GeV
MiNNLO$_{\rm PS}$	$6.52^{+2.4\%}_{-1.8\%}$	$1.46^{+2.5\%}_{-1.9\%}$
ATLAS [130]	$3.3^{+3.6({\rm Stat.})+3.2({\rm Syst.})}_{-3.4({\rm Stat.})-3.0({\rm Syst.})}$	$2.1^{+1.0({\rm Stat.})+0.6({\rm Syst.})}_{-0.9({\rm Stat.})-0.5({\rm Syst.})}$
$pp \to ZH \to (\ell^+\ell^-, \nu_\ell\bar{\nu}_\ell) b\bar{b}$		
σ [fb]	$p_T^Z \in$ [250,400] GeV	$p_T^Z \in [400, \infty]$ GeV
MiNNLO$_{\rm PS}$	$3.98^{+7.6\%}_{-5.4\%}$	$0.79^{+6.5\%}_{-4.2\%}$
ATLAS [130]	$1.4^{+2.4({\rm Stat.})+1.9({\rm Syst.})}_{-2.3({\rm Stat.})-1.7({\rm Syst.})}$	$0.2^{+0.6({\rm Stat.})+0.3({\rm Syst.})}_{-0.5({\rm Stat.})-0.3({\rm Syst.})}$

[ATLAS 2008.02508]

CROSS SECTIONS

$pp \to W^+ H \to e^+ \nu_e b\bar{b}$		
σ [fb]	`inclusive`	`fiducial-YR`
MiNLO′	$54.04^{+6.6\%}_{-3.6\%}$	$20.13^{+2.3\%}_{-3.1\%}$
MiNNLO$_{\rm PS}$	$57.44^{+1.7\%}_{-0.8\%}$	$21.27^{+1.3\%}_{-1.3\%}$
$pp \to W^- H \to e^- \bar{\nu}_e b\bar{b}$		
σ [fb]	`inclusive`	`fiducial-YR`
MiNLO′	$33.82^{+6.6\%}_{-3.6\%}$	$13.07^{+2.4\%}_{-3.3\%}$
MiNNLO$_{\rm PS}$	$35.87^{+1.5\%}_{-0.7\%}$	$13.77^{+1.5\%}_{-1.6\%}$
$pp \to ZH \to e^+ e^- b\bar{b}$		
σ [fb]	`inclusive`	`fiducial-YR`
MiNLO′	$14.88^{+6.7\%}_{-3.7\%}$	$5.21^{+2.2\%}_{-3.0\%}$
MiNNLO$_{\rm PS}$ (no $gg \to ZH$)	$15.79^{+1.8\%}_{-0.9\%}$	$5.48^{+1.2\%}_{-1.2\%}$
MiNNLO$_{\rm PS}$ (with $gg \to ZH$)	$16.99^{+3.6\%}_{-2.3\%}$	$6.07^{+3.4\%}_{-2.9\%}$

[SZ, Chiesa, Re, Wiesemann, Zanderighi ’21]

VH x H→bb @ NNLO+PS

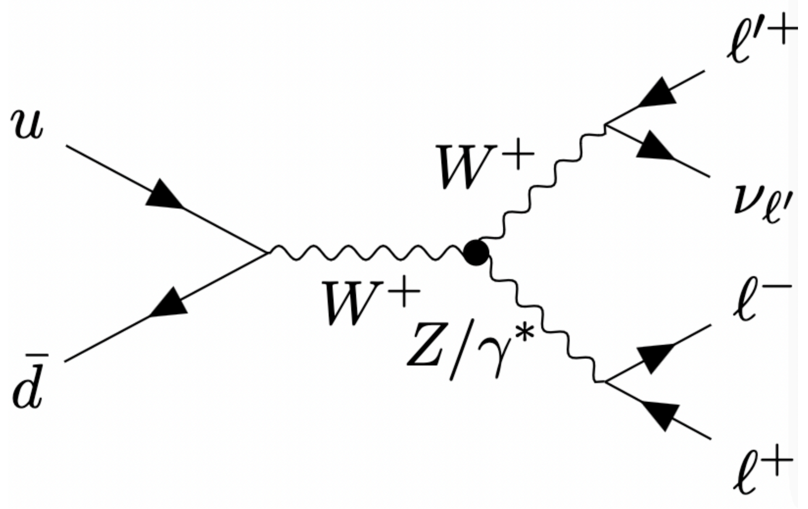
DIFFERENTIAL DISTRIBUTIONS

$$pp \to W^+H \to e^+\nu_e b\bar{b}$$

[Lindert, Lombardi, Wiesemann, Zanderighi, SZ ’22]

WZ @ NNLO$_{\text{QCD}}$+PS & NLO$_{\text{EW}}$+PS

- Direct access to trilinear gauge couplings (BSM searches).
- Clear experimental signature in the leptonic channel.
- Precision physics at % level of accuracy requires inclusion of both QCD and EW effects.



[Lindert, Lombardi, Wiesemann, Zanderighi, SZ ’22]

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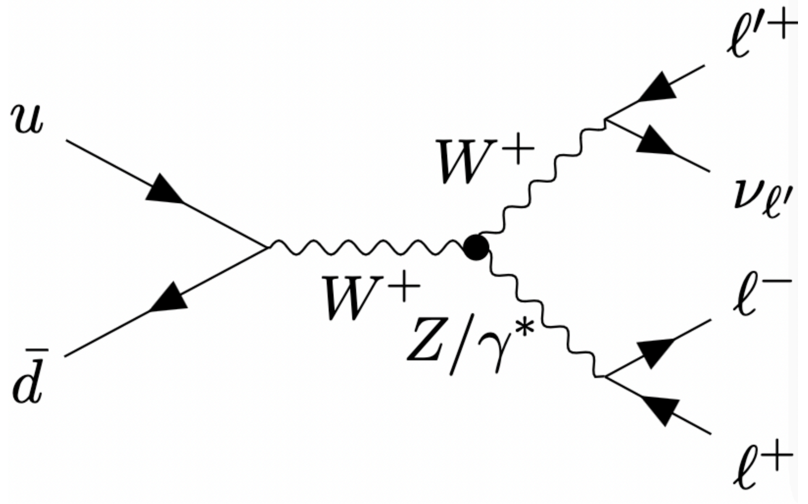


STRATEGY:

1. **Event generation**
   Generate separately NNLO QCD and NLO EW results. The former are obtained with MiNNLOPS, the latter with POWHEG.
2. **Matching with the shower**
   Non trivial treatment of QCD and QED radiation. Treated them separately according to different veto procedures.
3. **A-posteriori recombination**
   Define possible matching schemes (additive/multiplicative) of QCD and EW corrections that do not introduce any double counting.

[Lindert, Lombardi, Wiesemann, Zanderighi, SZ '22]

WZ @ NNLO$_{\text{QCD}}$+PS & NLO$_{\text{EW}}$+PS

ADDITIVE SCHEMES:

1. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} + \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} - \mathrm{LO}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} = \mathrm{NNLO}_{\mathrm{QCD+EW}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}}$
2. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} + \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QED})_{\mathrm{PS}}} - \mathrm{LO}^{(\mathrm{QED})_{\mathrm{PS}}}$
3. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} + \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} - \mathrm{LO}^{(\mathrm{QCD})_{\mathrm{PS}}}$

MULTIPLICATIVE SCHEMES:

4. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} \times \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} / \mathrm{LO}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} = \mathrm{NNLO}_{\mathrm{QCD\times EW}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}}$
5. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} \times \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QED})_{\mathrm{PS}}} / \mathrm{LO}^{(\mathrm{QED})_{\mathrm{PS}}}$
6. $\mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} \times \mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} / \mathrm{LO}^{(\mathrm{QCD})_{\mathrm{PS}}}$
7. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} \times \mathrm{NLO}_{\mathrm{EW}}^{\mathrm{f.o.}} / \mathrm{LO}^{\mathrm{f.o.}}$

NOTATION:

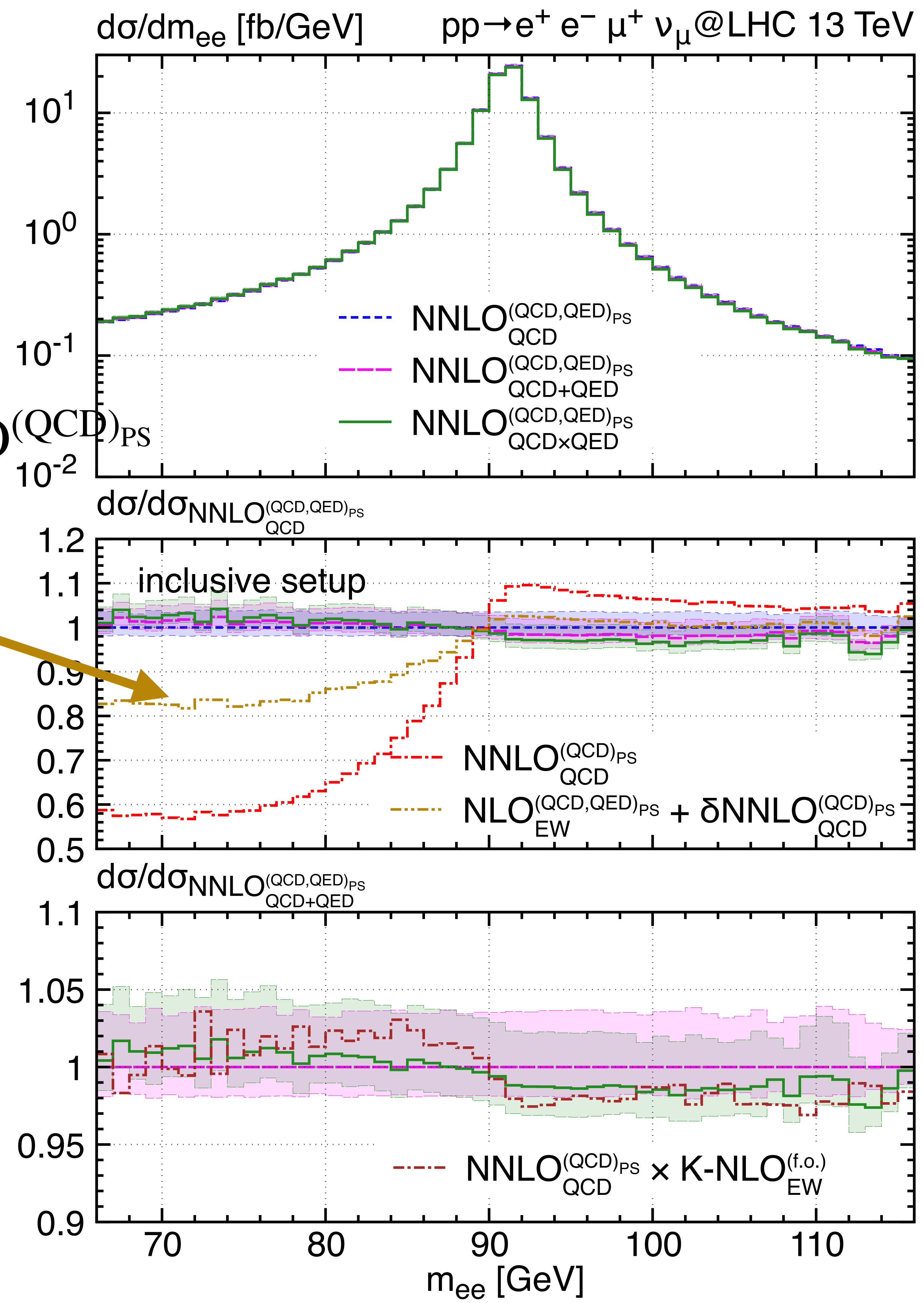
$\mathrm{(N)NLO}_{\mathrm{X}}^{(\mathrm{Y})_{\mathrm{PS}}}$

X = QCD,EW calculation
Y = QCD,QED showers (PY8)

[Lindert, Lombardi, Wiesemann, Zanderighi, SZ ’22]

WZ @ NNLO$_{QCD}$+PS & NLO$_{EW}$+PS

● $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} + \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}} - \mathrm{LO}^{(\mathrm{QCD})_{\mathrm{PS}}}$



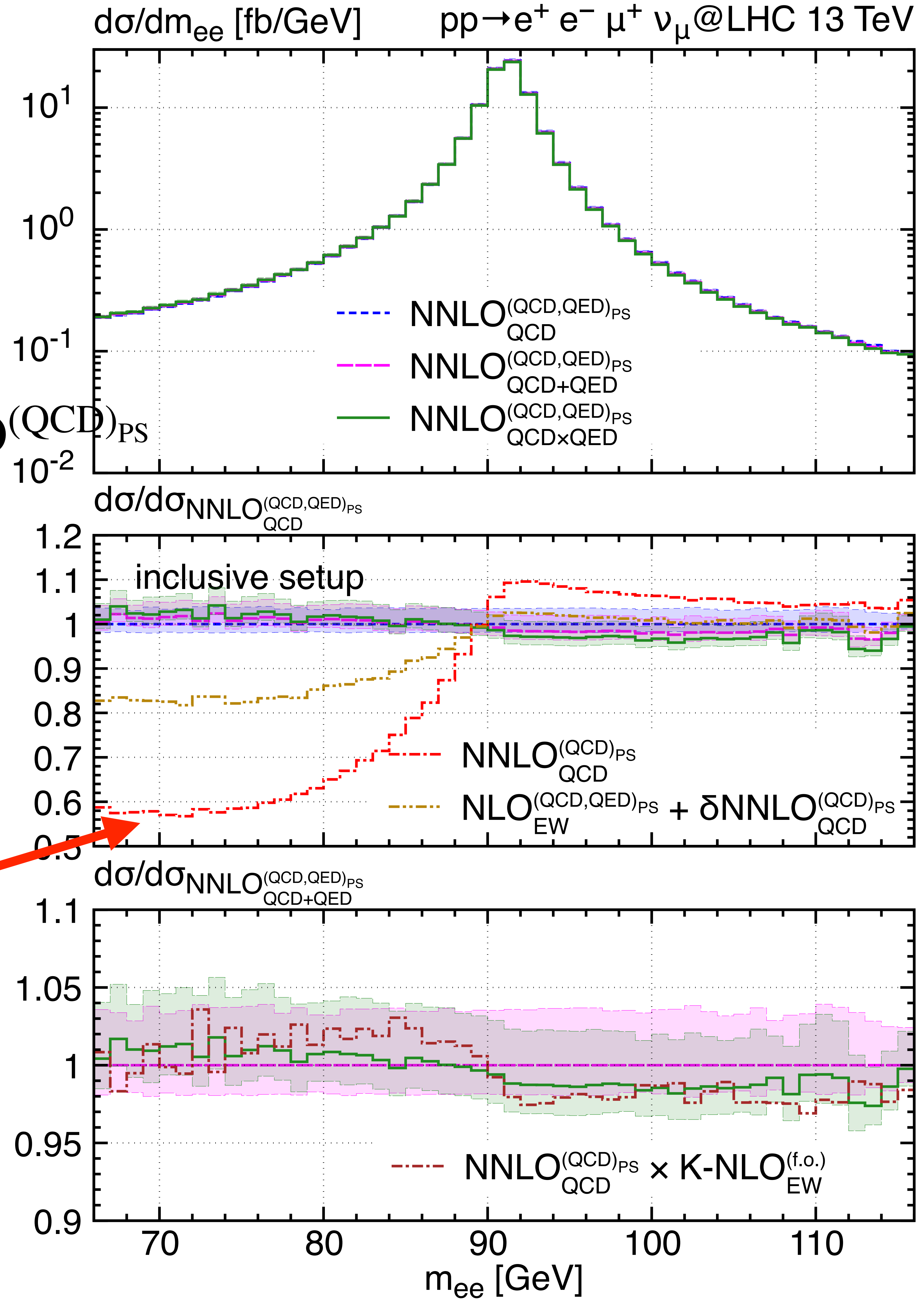
LEGEND:

- ● $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}$
- ● $\mathrm{NNLO}_{\mathrm{QCD+EW}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}$
- ● $\mathrm{NNLO}_{\mathrm{QCD\times EW}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}$
- ● $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}}$
- ● $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} \times \mathrm{K}_{\mathrm{EW}}^{\mathrm{f.o.}}$

[Lindert, Lombardi, Wiesemann, Zanderighi, SZ ’22]

WZ @ $\mathrm{NNLO}_{\mathrm{QCD}}$+PS & $\mathrm{NLO}_{\mathrm{EW}}$+PS

● $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} + \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}} - \mathrm{LO}^{(\mathrm{QCD})_{\mathrm{PS}}}$



● PURE QCD RESULT:

Large effects from missing collinear QED radiations.

LEGEND:

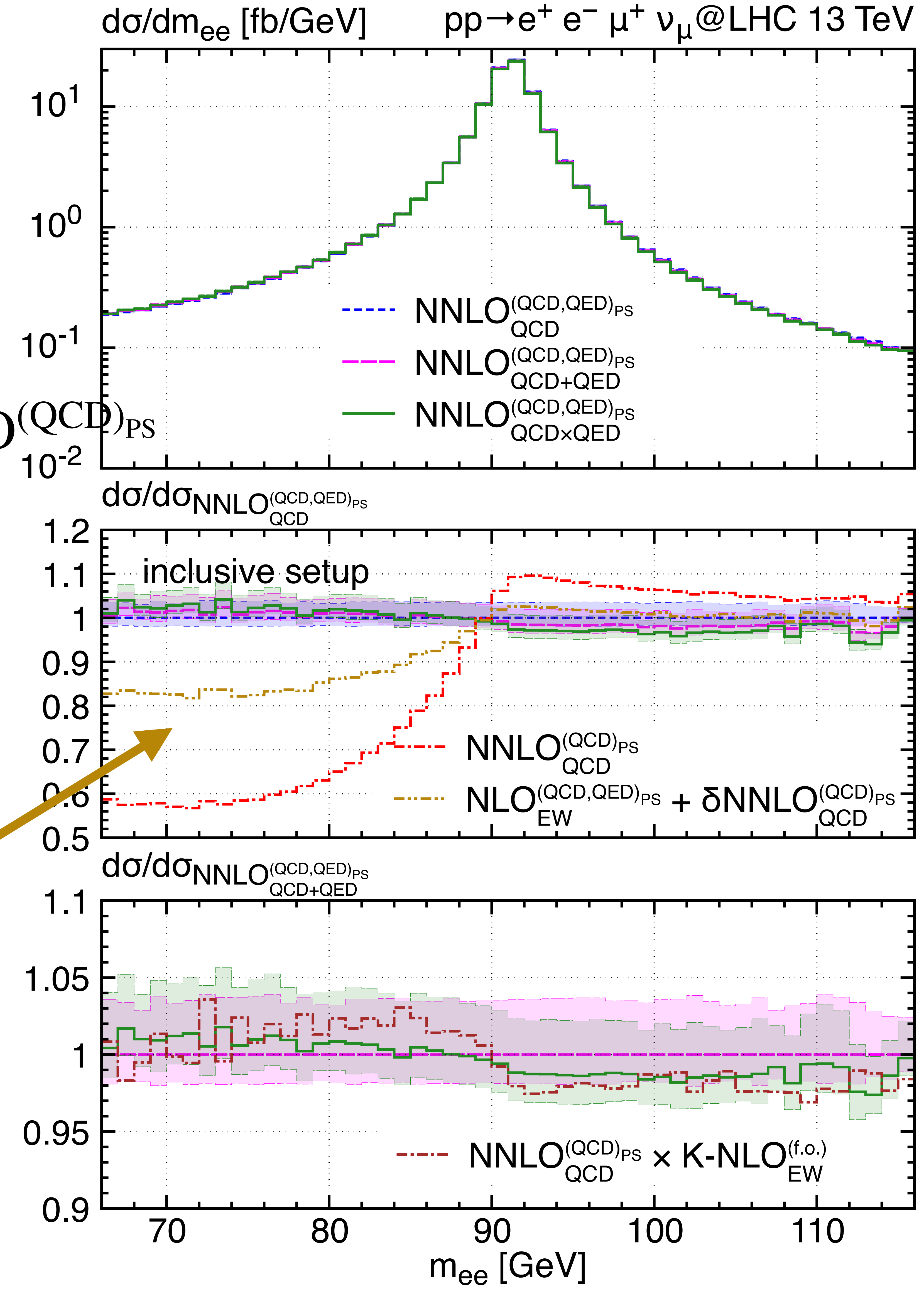
- ● $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}$
- ● $\mathrm{NNLO}_{\mathrm{QCD+EW}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}$
- ● $\mathrm{NNLO}_{\mathrm{QCD\times EW}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}$
- ● $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}}$
- ● $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} \times \mathrm{K}_{\mathrm{EW}}^{\mathrm{f.o.}}$

[Lindert, Lombardi, Wiesemann, Zanderighi, SZ '22]

WZ @ NNLO$_{\mathrm{QCD}}$+PS & NLO$_{\mathrm{EW}}$+PS

● $\mathrm{NNLO}^{(\mathrm{QCD})_{\mathrm{PS}}}_{\mathrm{QCD}} + \cancel{\phantom{\mathrm{NL}}}\mathrm{O}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}_{\mathrm{EW}} - \mathrm{LO}^{(\mathrm{QCD})_{\mathrm{PS}}}$

● misses important QED-QCD effects originating from QED emissions on top of the NNLO calculation.



LEGEND:

- ● $\mathrm{NNLO}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}_{\mathrm{QCD}}$
- ● $\mathrm{NNLO}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}_{\mathrm{QCD+EW}}$
- ● $\mathrm{NNLO}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}_{\mathrm{QCD\times EW}}$
- ● $\mathrm{NNLO}^{(\mathrm{QCD})_{\mathrm{PS}}}_{\mathrm{QCD}}$
- ● $\mathrm{NNLO}^{(\mathrm{QCD})_{\mathrm{PS}}}_{\mathrm{QCD}} \times \mathrm{K}^{\mathrm{f.o.}}_{\mathrm{EW}}$

[Lindert, Lombardi, Wiesemann, Zanderighi, SZ ’22]

WZ @ NNLO$_{\mathrm{QCD}}$+PS & NLO$_{\mathrm{EW}}$+PS

LEGEND:

- ● $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}$
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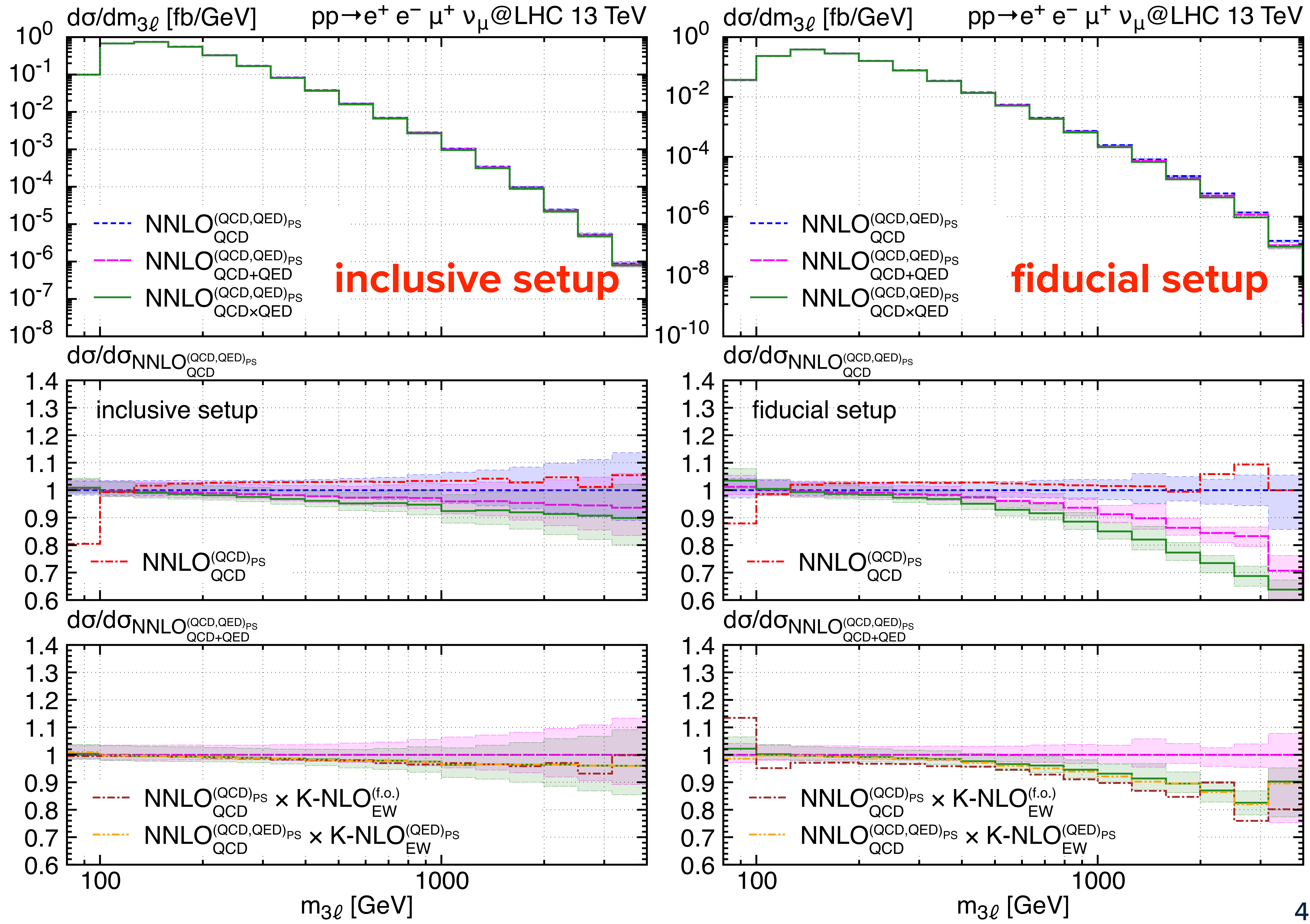

[Lindert, Lombardi, Wiesemann, Zanderighi, SZ ’22]

WZ @ NNLO$_{\text{QCD}}$+PS & NLO$_{\text{EW}}$+PS

LEGEND:

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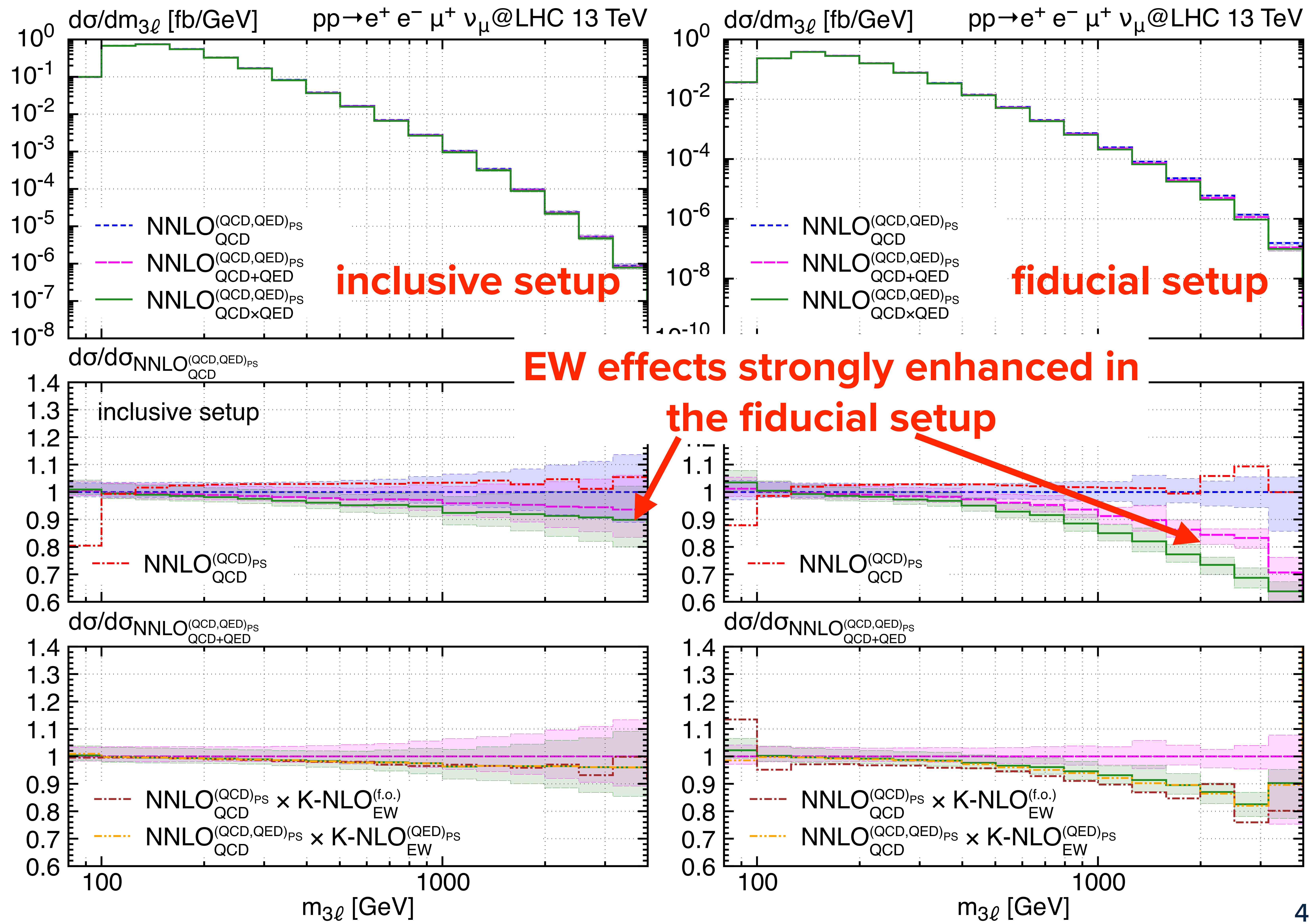


inclusive setup

fiducial setup

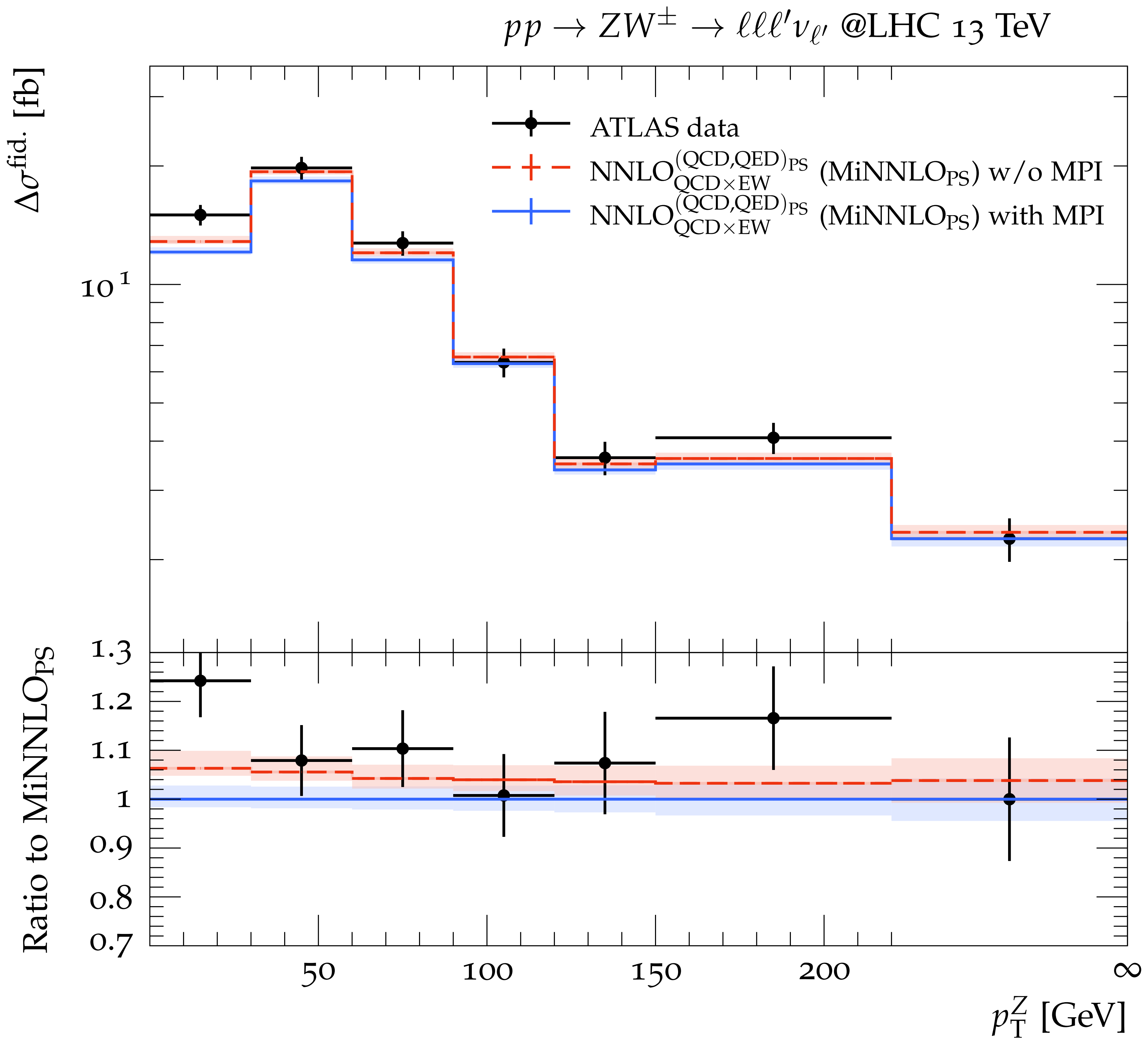
EW effects strongly enhanced in the fiducial setup

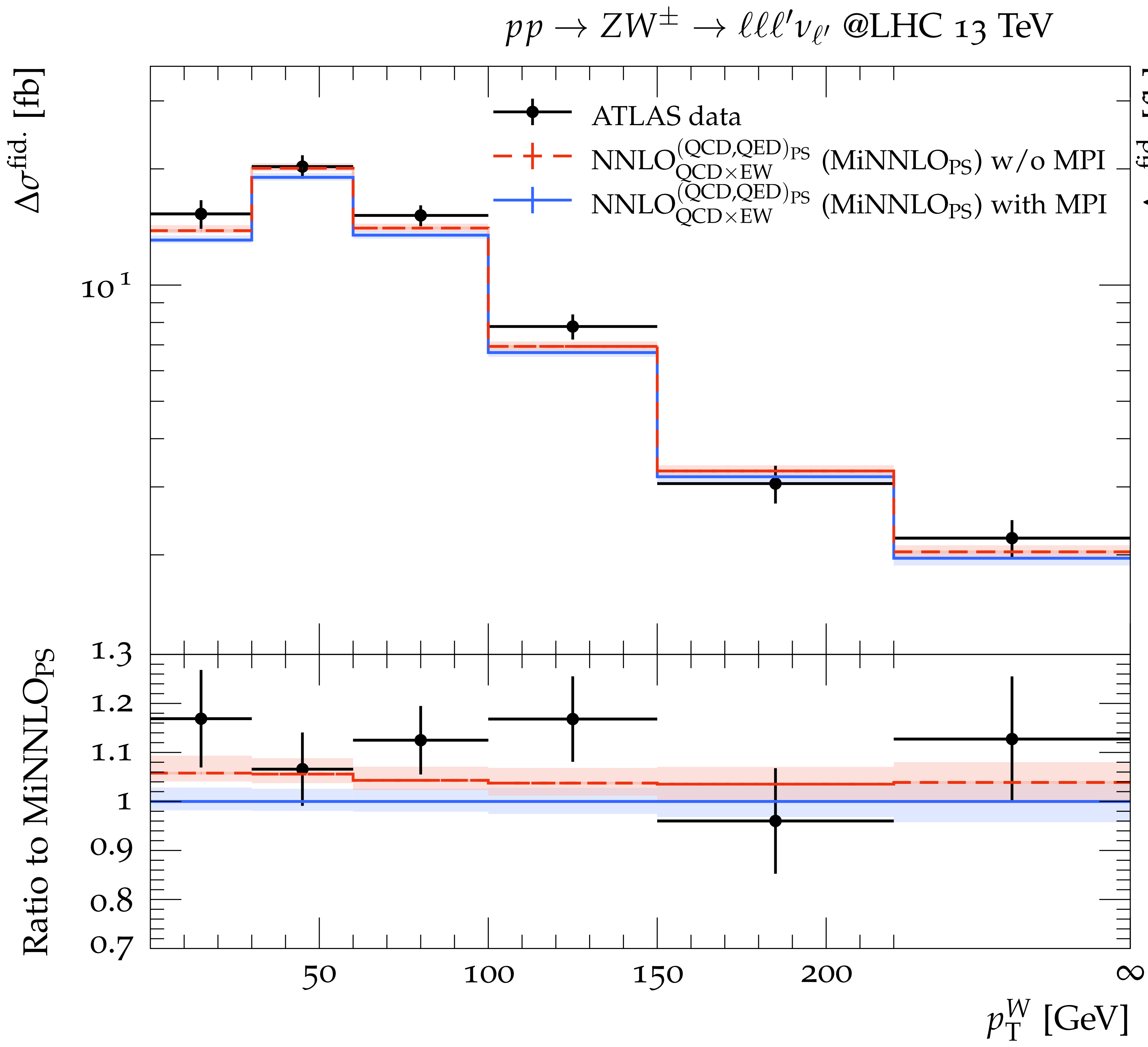
In the inclusive case, Sudakov-logarithms are suppressed in the very forward regions.

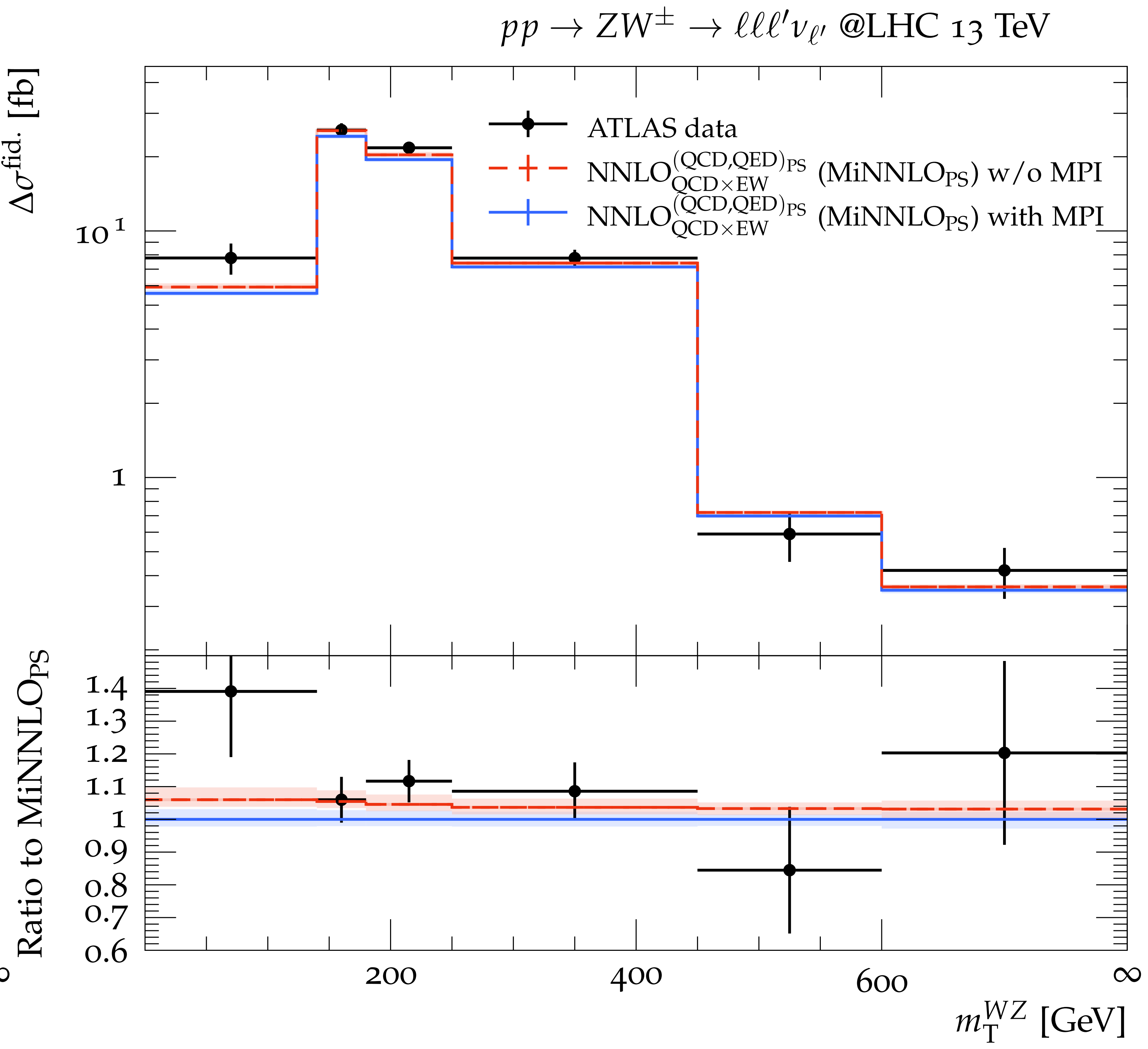
[Lindert, Lombardi, Wiesemann, Zanderighi, SZ ’22]

WZ @ NNLO$_{QCD}$+PS & NLO$_{EW}$+PS

COMPARISON TO DATA







4. CONCLUSIONS

SUMMARY AND OUTLOOKS

- **NNLO+PS** accuracy is the **state-of-the art** for precision physics at the LHC.
- **The MiNNLO$_{\text{PS}}$ method is a powerful framework** to reach this accuracy.
- I presented a selection of interesting phenomenological results obtained with this approach, but many others processes are available here:

https://powhegbox.mib.infn.it/

Many future developments are possible! Currently working on:

- On-the-fly inclusion of NLO EW corrections matched to parton shower.
- Extension to processes with jets.

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Thank you!