Heavy Flavour production at the LHC with NNLO+PS

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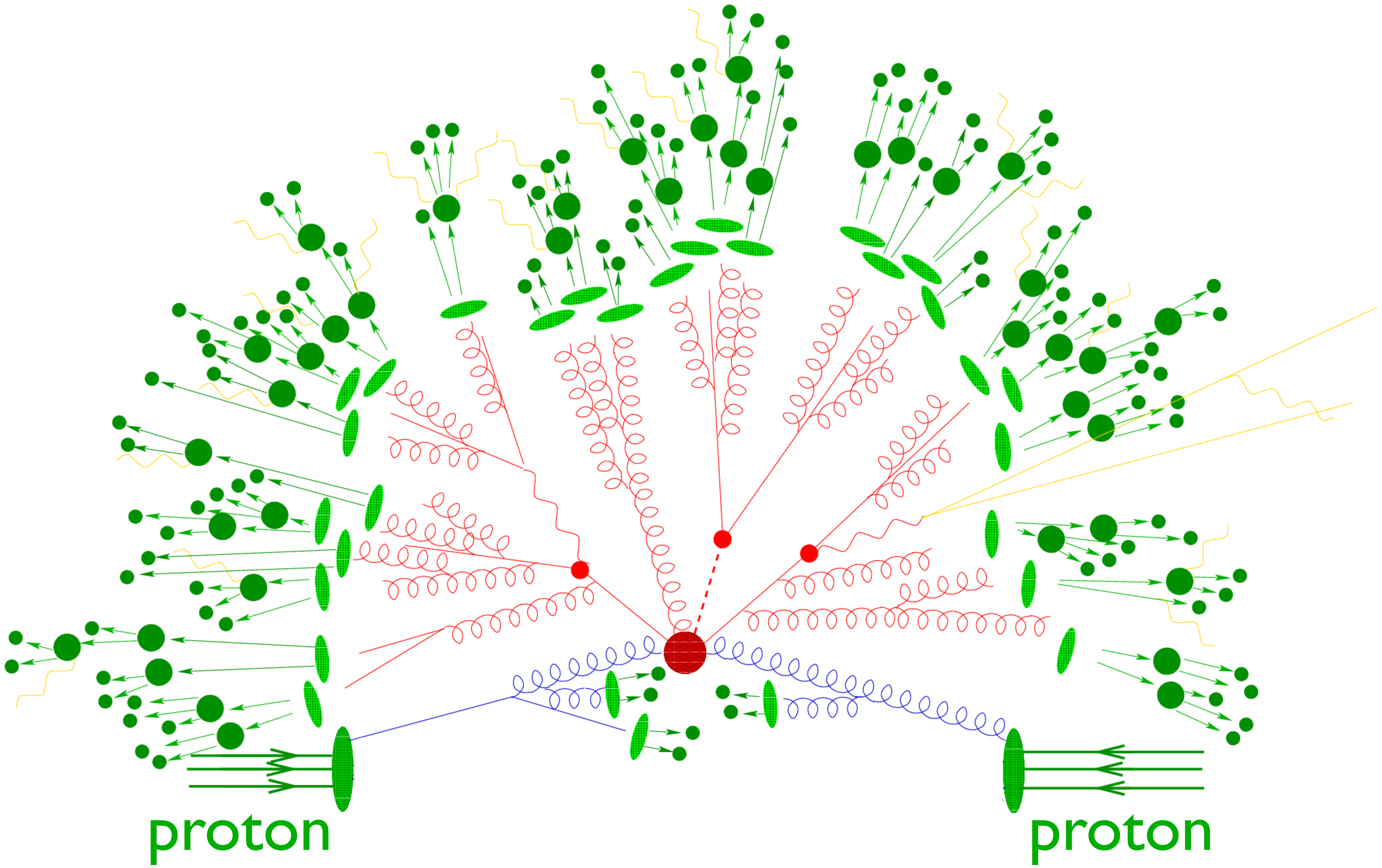
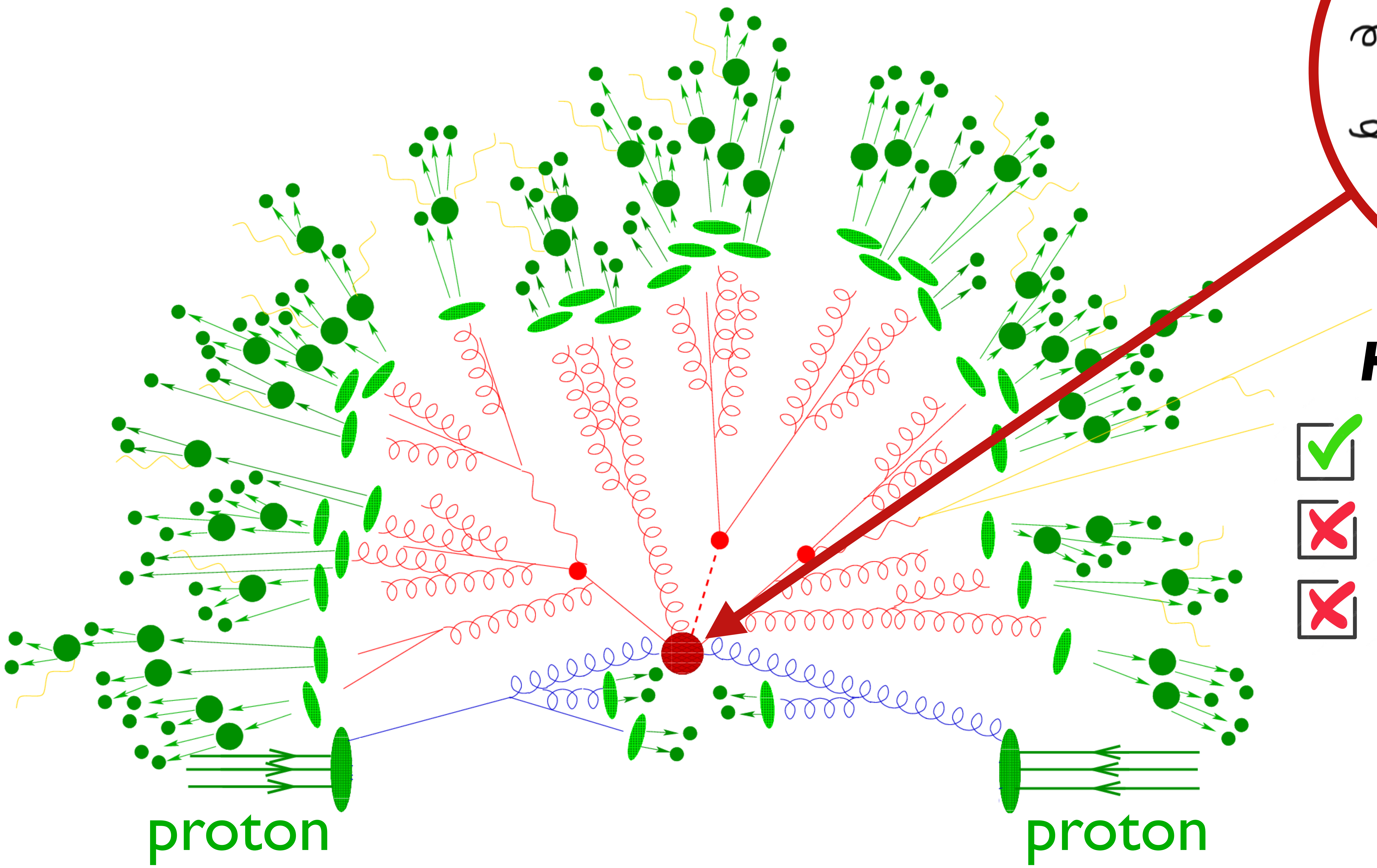
Standard Model at the LHC 2023

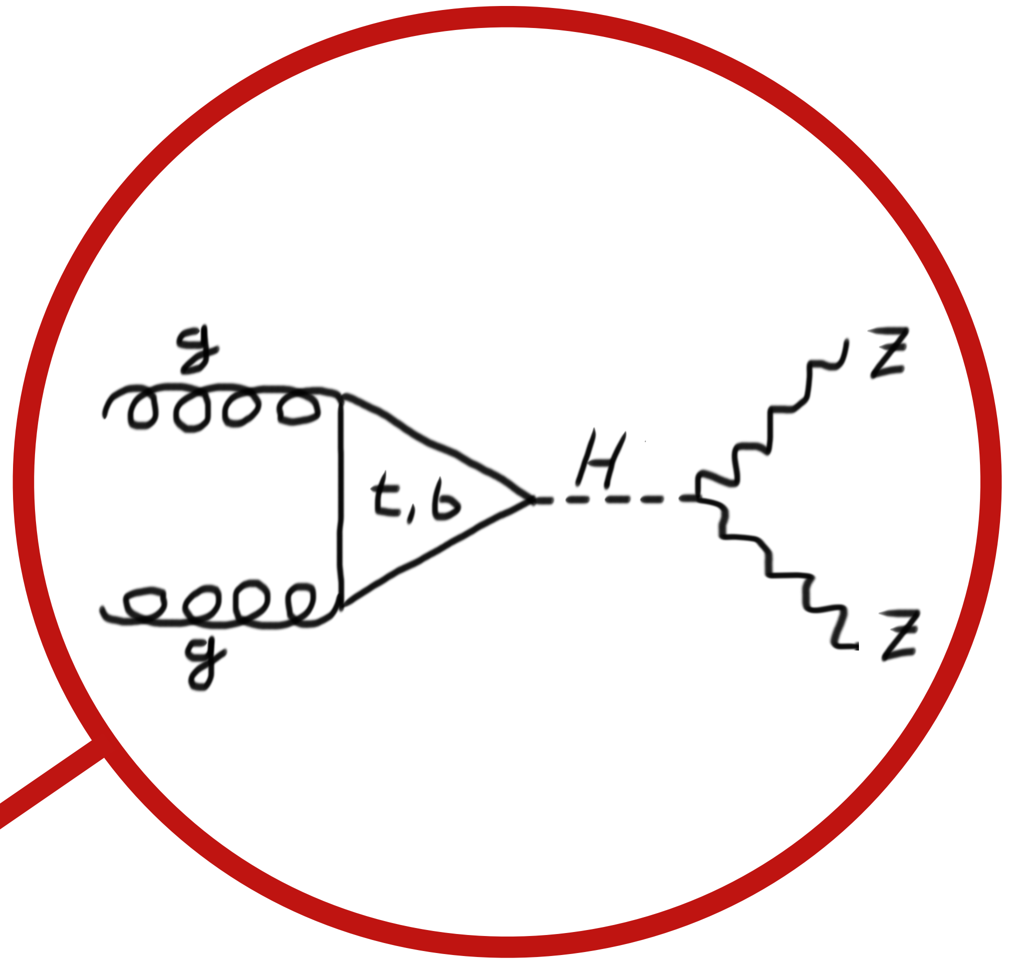
Fermilab (Chicago, USA), July 10-14, 2023

LHC event



LHC event





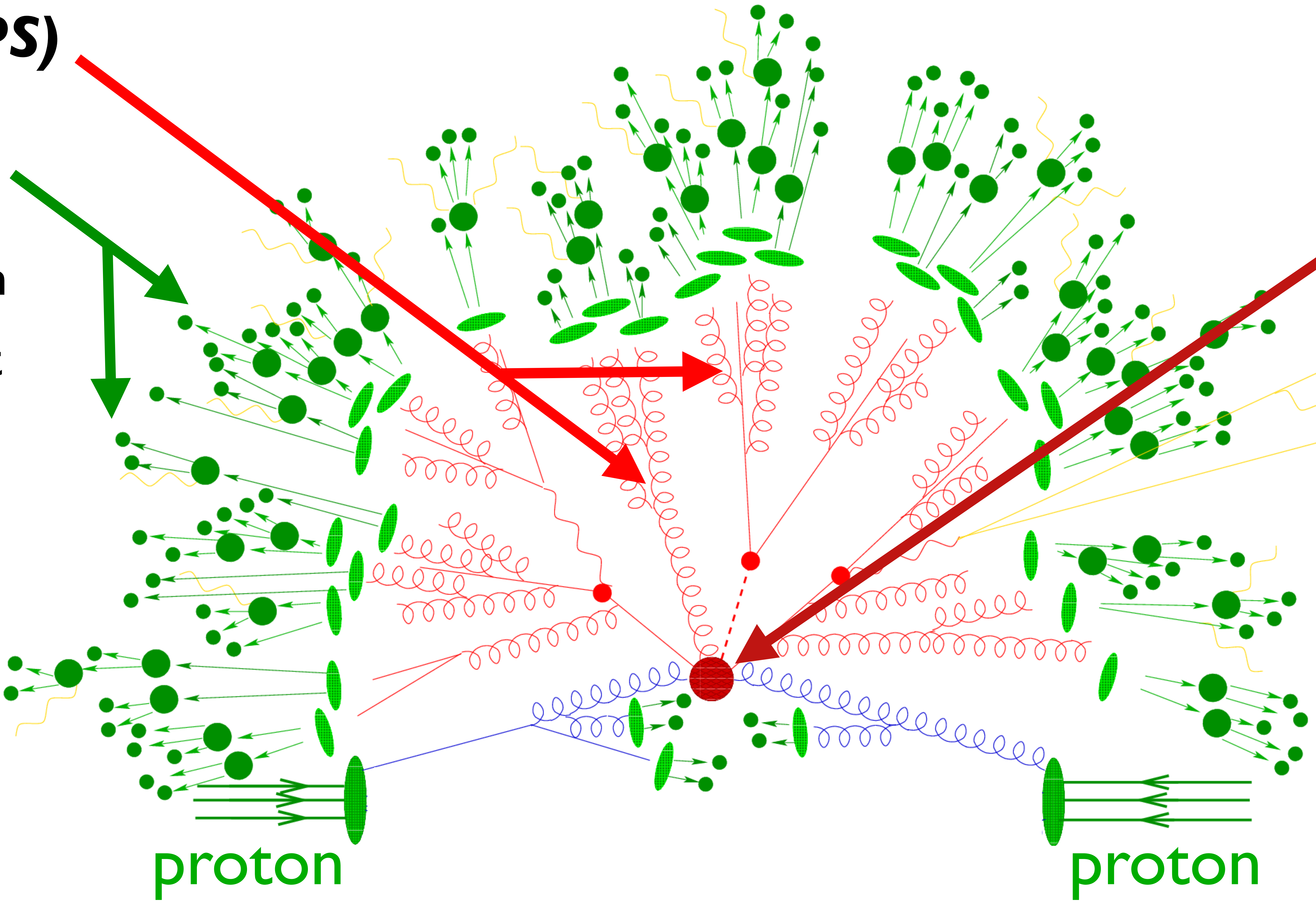
Hard Process

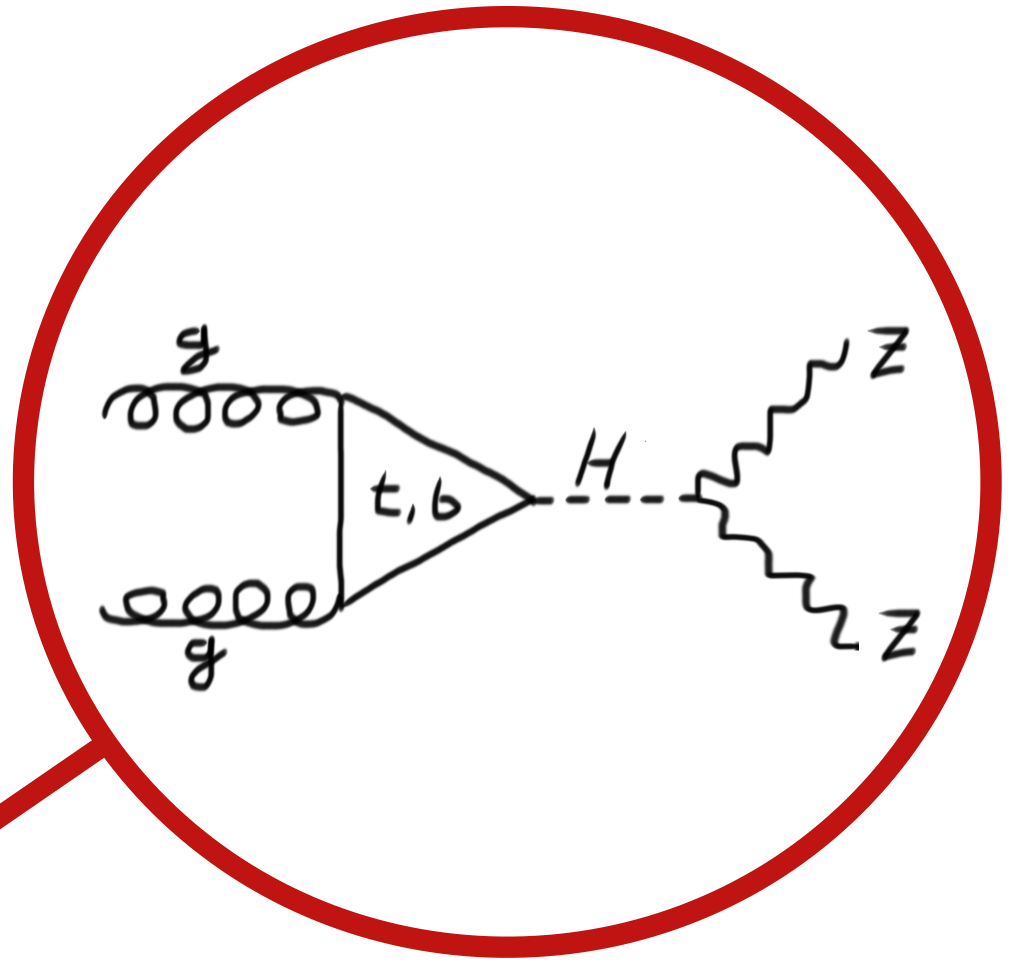
- ☑ N^xLO (high precision)
- ☒ no event
- ☒ no shower accuracy

LHC event

Parton Shower (PS)
+
Hadronization

- ✗ no N^{X}LO precision
- ✓ realistic LHC event
- ✓ shower accuracy (low precision)

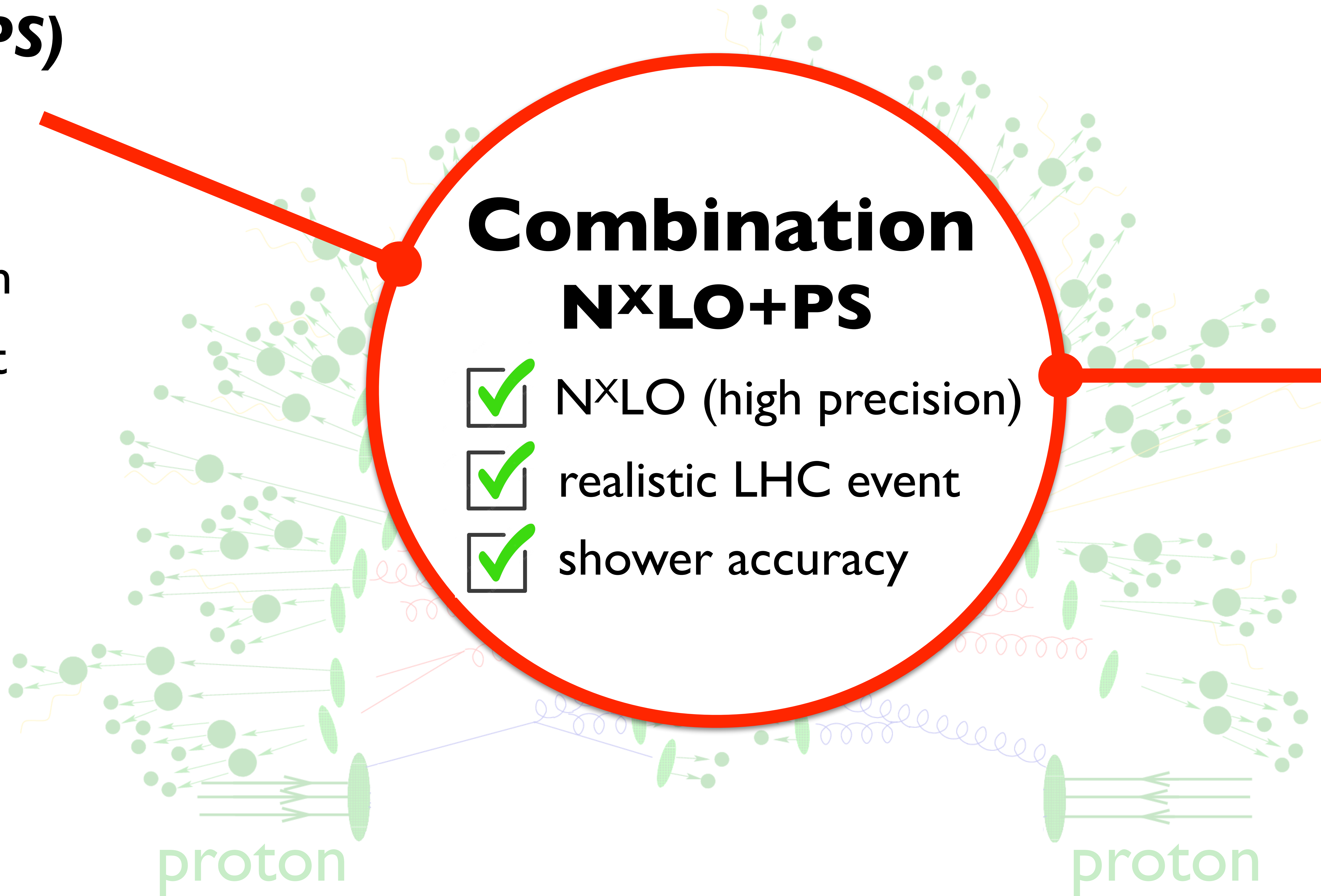




Hard Process

- ✓ N^{X}LO (high precision)
- ✗ no event
- ✗ no shower accuracy

LHC event



Parton Shower (PS)
+
Hadronization

- ☒ no $\mathrm{N}^{x}\mathrm{LO}$ precision
- ☑ realistic LHC event
- ☑ shower accuracy (low precision)

Combination
$\mathrm{N}^{x}\mathrm{LO}$+PS

- ☑ $\mathrm{N}^{x}\mathrm{LO}$ (high precision)
- ☑ realistic LHC event
- ☑ shower accuracy

Hard Process

- ☑ $\mathrm{N}^{x}\mathrm{LO}$ (high precision)
- ☒ no event
- ☒ no shower accuracy

NNLO+PS: What do we want to achieve?

- NNLO accuracy for observables inclusive on radiation. $[d\sigma/dy_F]$
- NLO(LO) accuracy for $F+1(2)$ jet observables (in the hard region). $[d\sigma/dp_{T,j_1}]$
  - appropriate scale choice for each kinematics regime
- resummation from the Parton Shower (PS) $[\sigma(p_{T,j} < p_{T,\mathrm{veto}})]$
- preserve the PS accuracy (leading log - LL)

- possibly, no merging scale required.

	X	X+jet	X+2jets	X+nj (n>2)
XJ (NLO)	—	NLO	LO	—
XJ-MiNLO	NLO	NLO	LO	PS
X@NNLO	NNLO	NLO	LO	—
X@NNLOPS	NNLO	NLO	LO	PS

NNLO+PS methods

NNLOPS: MiNLO+reweighting

[Hamilton, Nason, Oleari, Zanderighi '12, + Re '13], [Karlberg, Re, Zanderighi '14]

- ✦ LL accuracy (+ simple NLL terms) from PS
- ✦ no new unphysical scale (i.e. physically sound)
- ✦ numerically very intensive
- ✦ applied beyond 2→1 processes

Geneva

[Alioli, Bauer, Berggren, Tackmann, Walsh '15 + Zuberi '13]

- ✦ LL accuracy from PS (at most! no NNLL nonesense!)
- ✦ slicing cutoff (missing power corrections)
- ✦ numerical cancellations in slicing parameter
- ✦ applied beyond 2→1 processes

MiNNLO$_{PS}$

[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

- ✦ LL accuracy (+ simple NLL terms) from PS
- ✦ no new unphysical scale (i.e. physically sound)
- ✦ numerically efficient
- ✦ applied beyond 2→1 and even beyond colour singlet

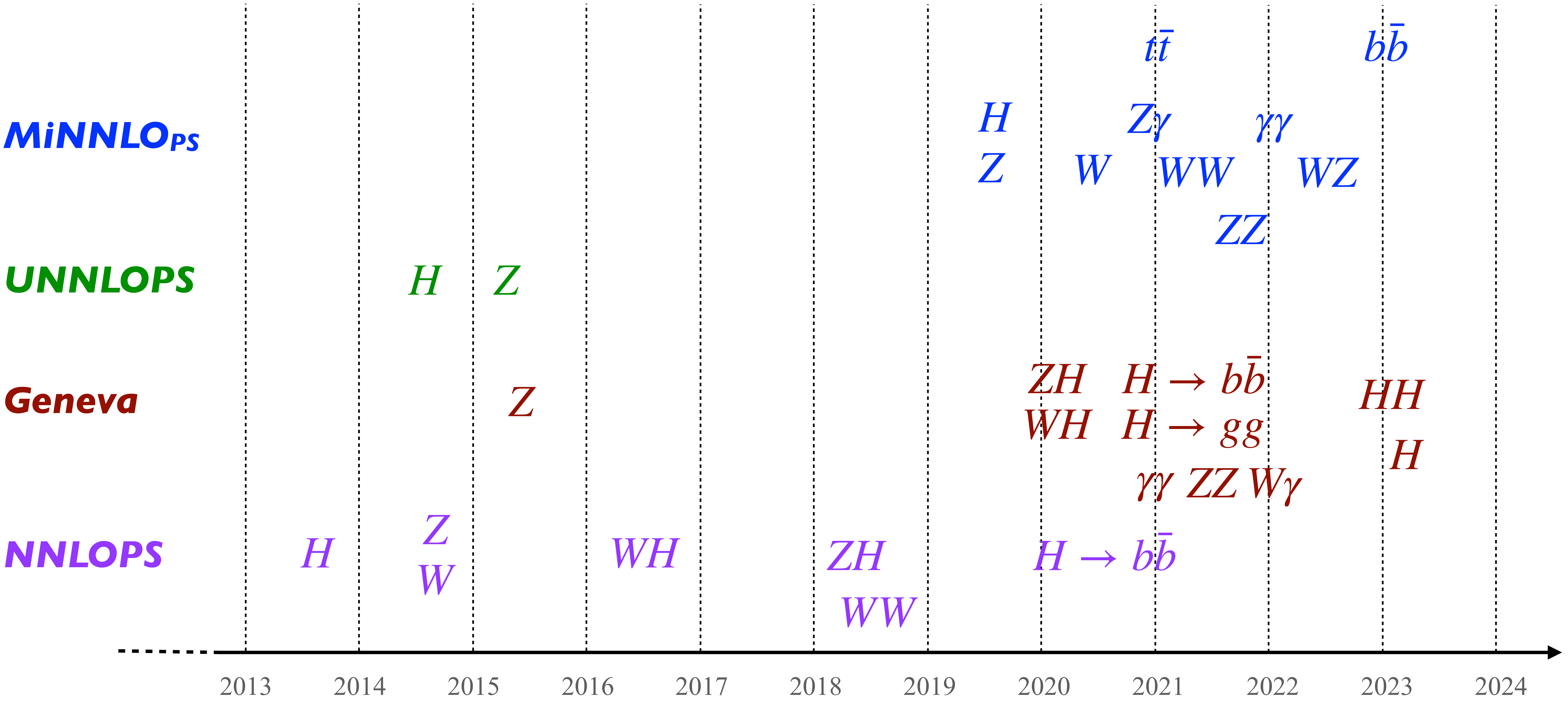
UNNLOPS

[Höche, Prestel '14 '15]

- ✦ extension of UNLOPS merging of event samples
- ✦ two-loop corrections entirely in 0-jet bin
- ✦ only applied to 2→1 processes

there was also some recent progress on NNLO+PS for sector showers [Campbell, Höche, Li, Preuss, Slands '21]

NNLO+PS timeline



NNLO+PS timeline

see also Emanuele Re's talk

MiNNLO$_{PS}$: main idea

[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

- starting equation: $$\frac{d\sigma_F^{res}}{dp_T\, d\Phi_B} = \frac{d}{dp_T}\left\{e^{-S}\mathscr{L}\right\} = e^{-S}\underbrace{\left\{S'\mathscr{L} + \mathscr{L}'\right\}}_{\equiv D}$$ $$\mathscr{L} \sim H\,(C\otimes f)\,(C\otimes f)$$ (symbolically)

- combine with F + jet fixed order $d\sigma_{FJ}$:

$$d\sigma^F = d\sigma_F^{res} + [d\sigma_{FJ}]_{f.o.} - [d\sigma_F^{res}]_{f.o.} = e^{-S}\left\{D + \frac{[d\sigma_{FJ}]_{f.o.}}{\underbrace{[e^{-S}]_{f.o.}}_{1-S^{(1)}\ldots}} \underbrace{-\frac{[d\sigma_F^{res}]_{f.o.}}{[e^{-S}]_{f.o.}}}_{-D^{(1)}-D^{(2)}\ldots}\right\}$$

MiNNLO$_{PS}$: main idea

[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

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- ✦ expanded up to $\alpha_s^3(p_T)$ we have: (resummation scheme: $\mu_R = \mu_F \sim p_T$)

(very symbolic/simplified)

$$d\sigma_F^{\rm MiNNLO} \sim e^{-S}\left\{\underbrace{d\sigma_{FJ}^{(1)}}_{\sim\alpha_s(p_T)}\big(1 + S^{(1)}\big) + \underbrace{d\sigma_{FJ}^{(2)}}_{\sim\alpha_s^2(p_T)} + \underbrace{\big(D - D^{(1)} - D^{(2)}\big)}_{\geq\alpha_s^3(p_T)} + \text{regular}\right\}$$

$\longrightarrow D^{(3)} + \mathcal{O}(\alpha_s^4)$

MiNNLO$_{PS}$: main idea

[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

✦ starting equation:

$$\frac{d\sigma_F^{\text{res}}}{dp_T\, d\Phi_B} = \frac{d}{dp_T}\left\{e^{-S}\mathscr{L}\right\} = e^{-S}\underbrace{\left\{S'\mathscr{L} + \mathscr{L}'\right\}}_{\equiv D}$$

$$\mathscr{L} \sim H\,(C \otimes f)\,(C \otimes f)$$

(symbolically)

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✦ expanded up to $\alpha_s^3(p_T)$ we have: (resummation scheme: $\mu_R = \mu_F \sim p_T$)

MiNLO

$$d\sigma_F^{\text{MiNNLO}} \sim e^{-S}\left\{\underbrace{d\sigma_{FJ}^{(1)}}_{\sim\alpha_s(p_T)}\left(1 + S^{(1)}\right) + \underbrace{d\sigma_{FJ}^{(2)}}_{\sim\alpha_s^2(p_T)} + \underbrace{\left(D - D^{(1)} - D^{(2)}\right)}_{\sim\alpha_s^3(p_T)} + \text{regular}\right\}$$

MiNNLO$_{PS}$: main idea

[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

✦ starting equation:

$$\frac{d\sigma_F^{\rm res}}{dp_T\, d\Phi_B} = \frac{d}{dp_T}\left\{e^{-S}\mathscr{L}\right\} = e^{-S}\underbrace{\left\{S'\mathscr{L} + \mathscr{L}'\right\}}_{\equiv D}$$

$$\mathscr{L} \sim H\,(C\otimes f)\,(C\otimes f)$$

(symbolically)

✦ combine with F + jet fixed order $d\sigma_{FJ}$:

$$d\sigma^F = d\sigma_F^{\rm res} + [d\sigma_{FJ}]_{\rm f.o.} - [d\sigma_F^{\rm res}]_{\rm f.o.} = e^{-S}\left\{D + \frac{[d\sigma_{FJ}]_{\rm f.o.}}{\underbrace{[e^{-S}]_{\rm f.o.}}_{1-S^{(1)}\ldots}} \underbrace{-\frac{[d\sigma_F^{\rm res}]_{\rm f.o.}}{[e^{-S}]_{\rm f.o.}}}_{-D^{(1)}-D^{(2)}\ldots}\right\}$$

✦ expanded up to $\alpha_s^3(p_T)$ we have: (resummation scheme: $\mu_R = \mu_F \sim p_T$)

MiNLO | **NNLO correction**

$$d\sigma_F^{\rm MiNNLO} \sim e^{-S}\left\{\underbrace{d\sigma_{FJ}^{(1)}\left(1+S^{(1)}\right)}_{\sim\alpha_s(p_T)} + \underbrace{d\sigma_{FJ}^{(2)}}_{\sim\alpha_s^2(p_T)} + \underbrace{\left(D - D^{(1)} - D^{(2)}\right)}_{\sim\alpha_s^3(p_T)} + \text{regular}\right\}$$

beyond accuracy

MiNNLO$_{PS}$: master formula

[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

✦ apply idea to POWHEG FJ calculation

$$d\sigma_{FJ} = d\Phi_{FJ}\, \tilde{B}^{FJ} \times \left\{ \Delta_{\rm pwg}(\Lambda_{\rm pwg}) + \int d\Phi_{\rm rad} \Delta_{\rm pwg}(p_{T,\rm rad}) \frac{R_{FJ}}{B_{FJ}} \right\}$$

$$\tilde{B}^{FJ} \sim \left\{ d\sigma_{FJ}^{(1)} + d\sigma_{FJ}^{(2)} \right\}$$

MiNNLO$_{\text{PS}}$: master formula

[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

✦ NNLO+PS by turning POWHEG weight ($\tilde{B}$ function) NNLO accurate:

$$\mathrm{d}\sigma_F^{\mathrm{MiNNLO_{PS}}} = \mathrm{d}\Phi_{FJ}\, \tilde{B}^{\,\mathrm{MiNNLO_{PS}}} \times \left\{ \Delta_{\mathrm{pwg}}(\Lambda_{\mathrm{pwg}}) + \int \mathrm{d}\Phi_{\mathrm{rad}} \Delta_{\mathrm{pwg}}(p_{T,\mathrm{rad}}) \frac{R_{FJ}}{B_{FJ}} \right\}$$

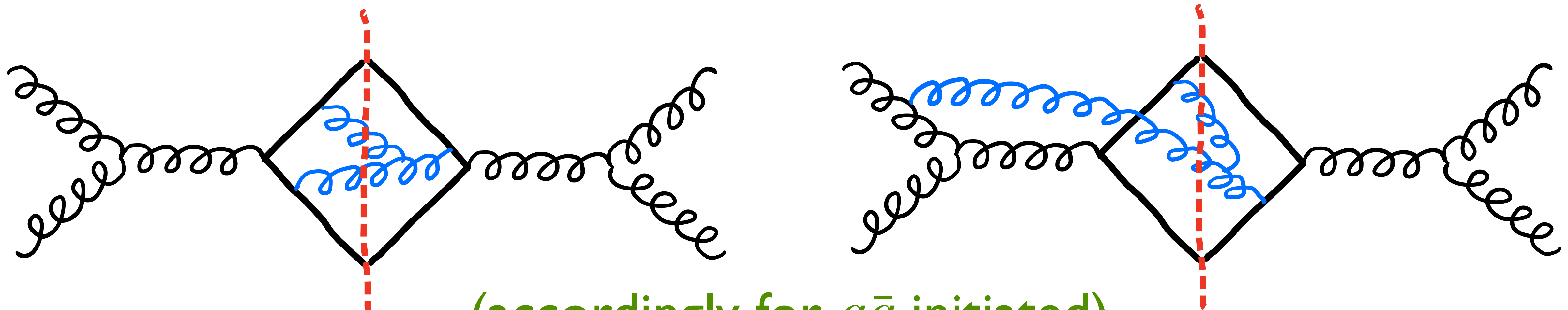
$$\tilde{B}^{\,\mathrm{MiNNLO_{PS}}} \sim e^{-S} \left\{ \mathrm{d}\sigma_{FJ}^{(1)} \big(1 + S^{(1)}\big) + \mathrm{d}\sigma_{FJ}^{(2)} + \big(D - D^{(1)} - D^{(2)}\big) \times F^{\mathrm{corr}} \right\}$$

→ *spreads NNLO corrections in the F + jet phase space*

MiNNLO$_{PS}$: heavy quark production

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]

✦ substantial complication due to final-state radiation and interferences



(accordingly for $q\bar{q}$ initiated)

✦ compare resummation formulas (very schematic):

colour singlet: $$\mathrm{d}\sigma^F_{\mathrm{res}} \sim \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{e^{-S} \quad H \quad (C\otimes f)(C\otimes f)\right\}$$

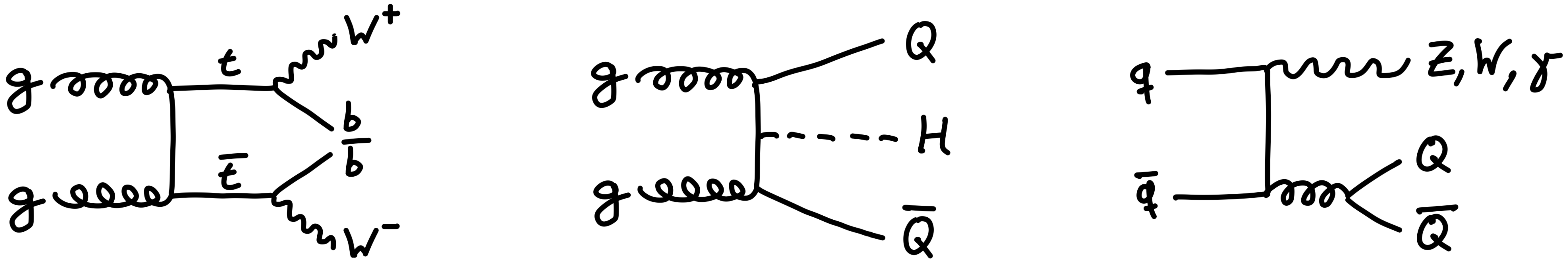
heavy quark pair: $$\mathrm{d}\sigma^F_{\mathrm{res}} \sim \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{e^{-S}\,\mathrm{Tr}(\mathbf{H\Delta})\,(C\otimes f)(C\otimes f)\right\}$$

[Catani, Grazzini, Torre '14]

Δ: operator/matrix in colour space that encodes soft emissions of $t\bar{t}$ and interferences

derived to NNLO in [Catani, Devoto, Grazzini, Mazzitelli, '23]

MiNNLO$_{PS}$: heavy quark + colour singlet production



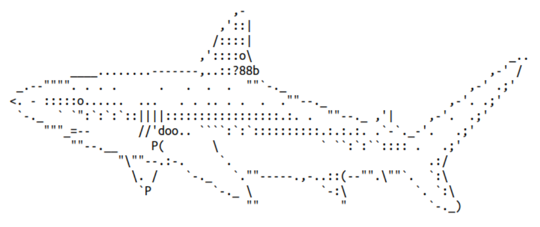
[Mazzitelli, Wiesemann 'work in progress]

✦ same structure of singular/resummed cross section as $Q\bar{Q}$, but need to account for recoil:

colour singlet: $$\mathrm{d}\sigma^F_{\mathrm{res}} \sim \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{e^{-S} \quad H \quad (C\otimes f)(C\otimes f)\right\}$$

heavy quark pair + colour singlet: $$\mathrm{d}\sigma^F_{\mathrm{res}} \sim \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{e^{-S}\,\mathrm{Tr}(\mathbf{H\Delta})\,(C\otimes f)(C\otimes f)\right\}$$

Soft function for Heavy quark production in ARbitrary Kinematics
[Devoto, Mazzitelli 'in preparation]



Results:

top-quark pair production ($t\bar{t}$)

$t\bar{t}$ production

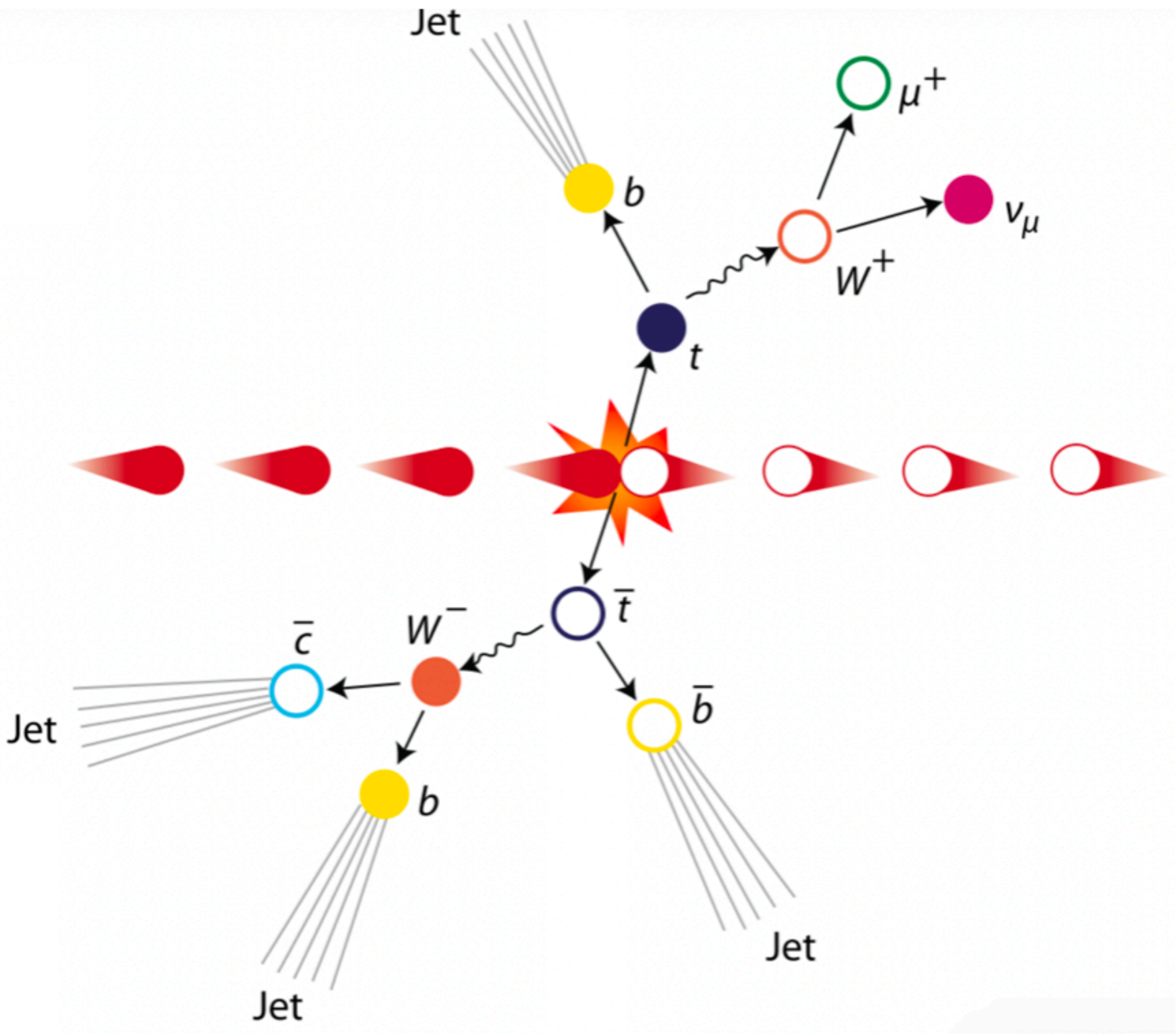
$$t\bar{t} \;\to\; b\bar{b}\,W^-W^+$$

Fully leptonic $\quad W^+W^- \;\to\; l\bar{\nu}_l\,\bar{l}\nu_l$

Semi-leptonic $\quad W^+W^- \;\to\; l\bar{\nu}_l\,q\bar{q}'$

Hadronic $\quad W^+W^- \;\to\; q\bar{q}'q'\bar{q}$

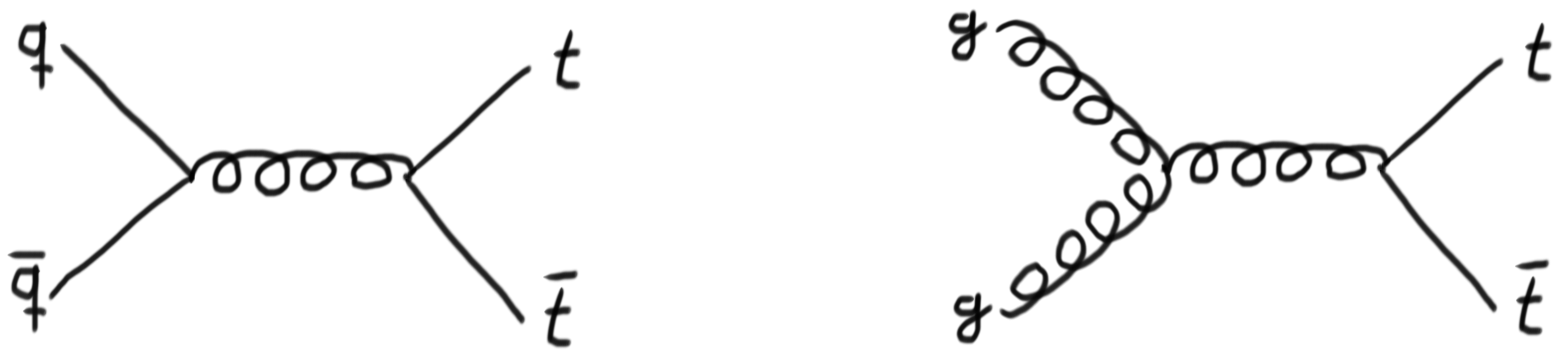
(where $q = \{u, c\}$ and $q' = \{d, s\}$)

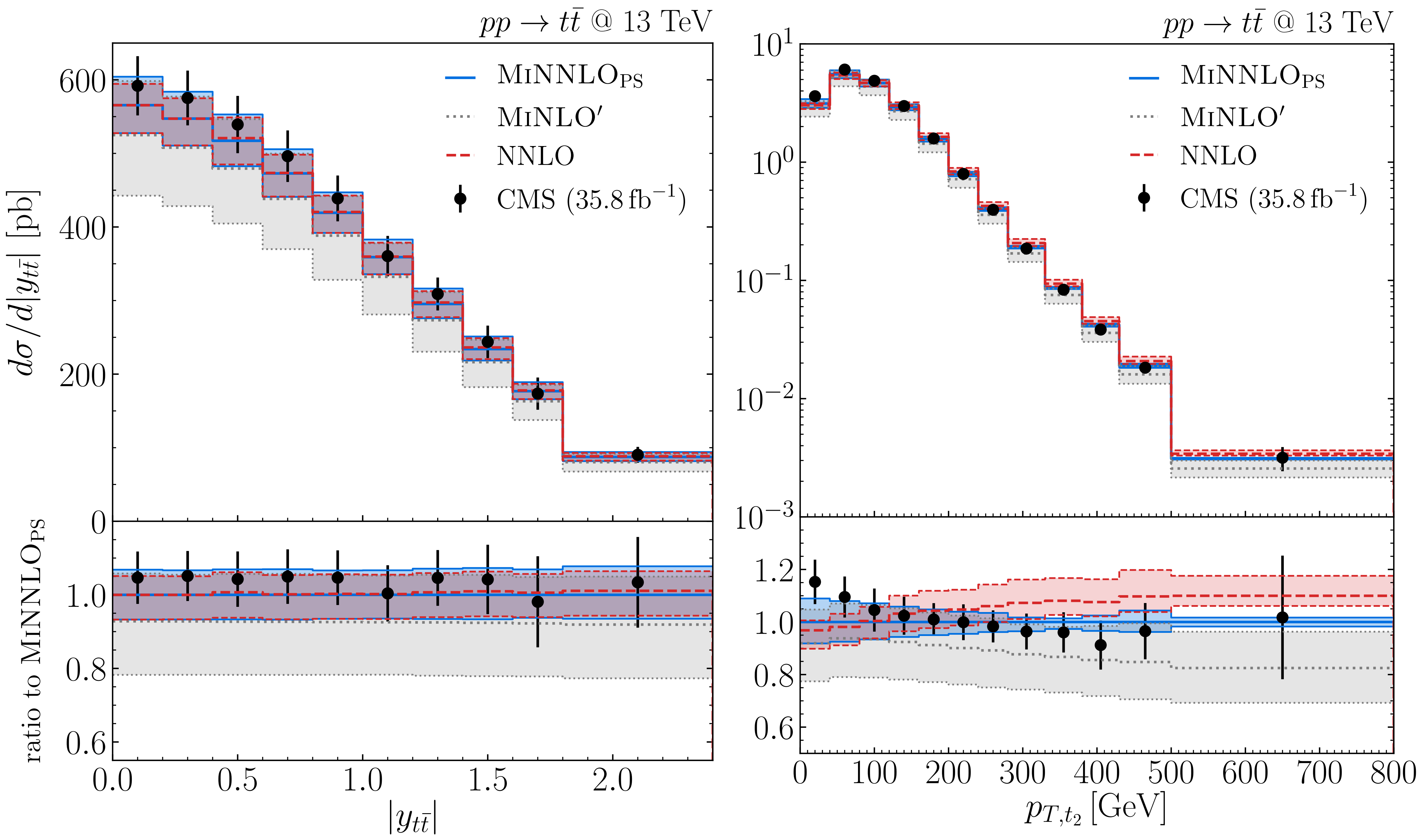


*approximated through a MadSpin-like approach using the full off-shell diagram at LO, keeping spin correlations

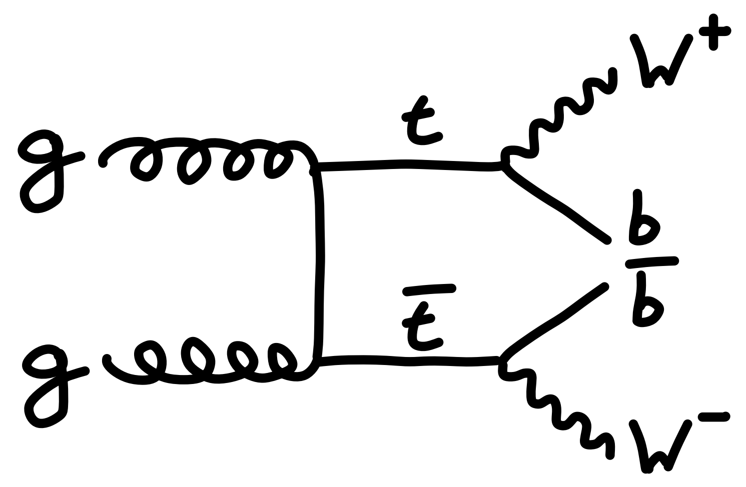
$t\bar{t}$ production

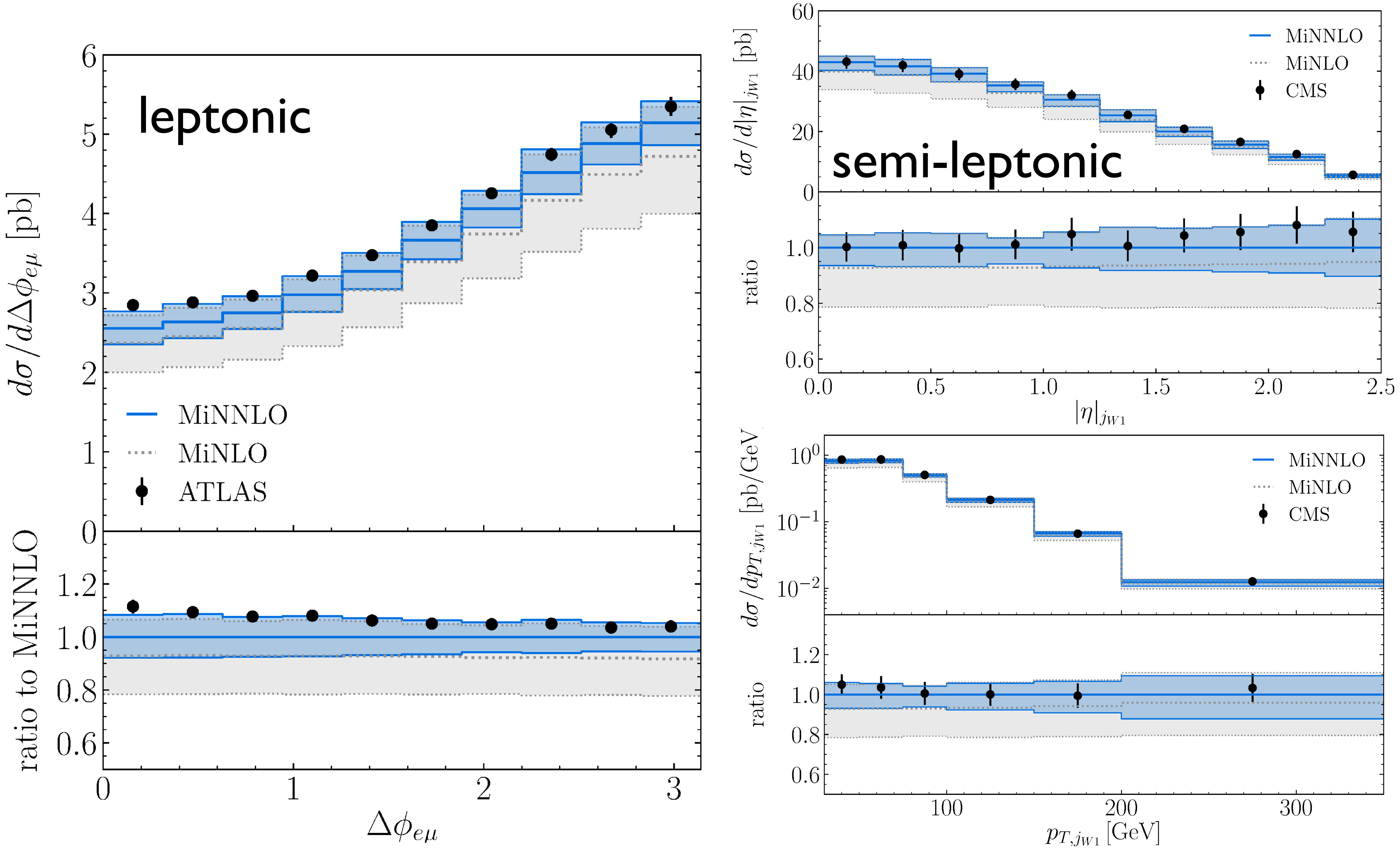
on-shell $t\bar{t}$ production





with off-shell top decays*



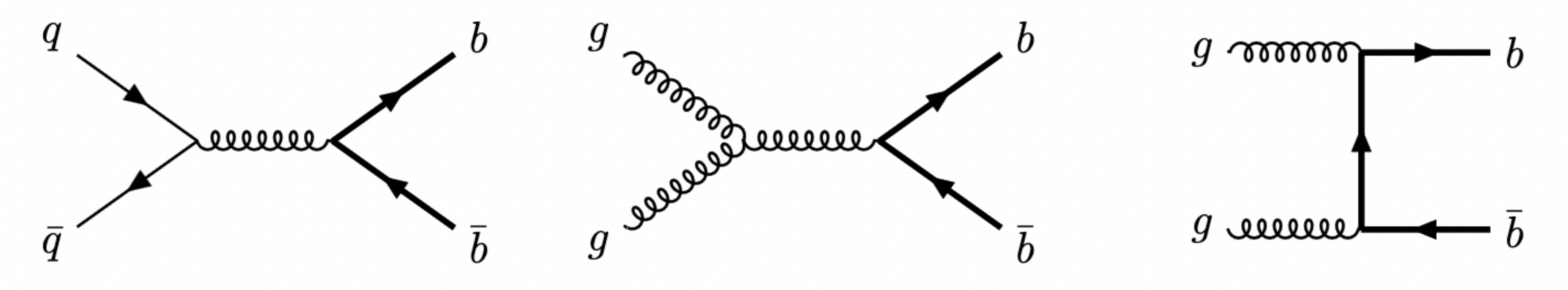


Results:

bottom-quark pair production ($b\bar{b}$)

(B-hadron and b-jet production)

$b\bar{b}$ production



Validation against fixed order results from MATRIX

NLO	MiNLO'	NNLO	MiNNLOps
$348.5(3)^{+27\%}_{-24\%}\ \mu b$	$399.7(5)^{+22\%}_{-21\%}\ \mu b$	$435(2)^{+16\%}_{-15\%}\ \mu b$	$428.7(5)^{+13\%}_{-11\%}\ \mu b$

★ use four-flavour scheme (4FS) with massive bottom quarks

★ NNLO+PS matching important:

→ realistic simulation of B-hadrons (through Pythia8)

→ reliable at high bottom p_T through shower resummation (no FONLL needed)

MiNNLO$_{PS}$: B-hadron production

[Mazzitelli, MW, Zanderighi, Ratti '23]

Comparison to fiducial cross sections from CMS, ATLAS, LHCb

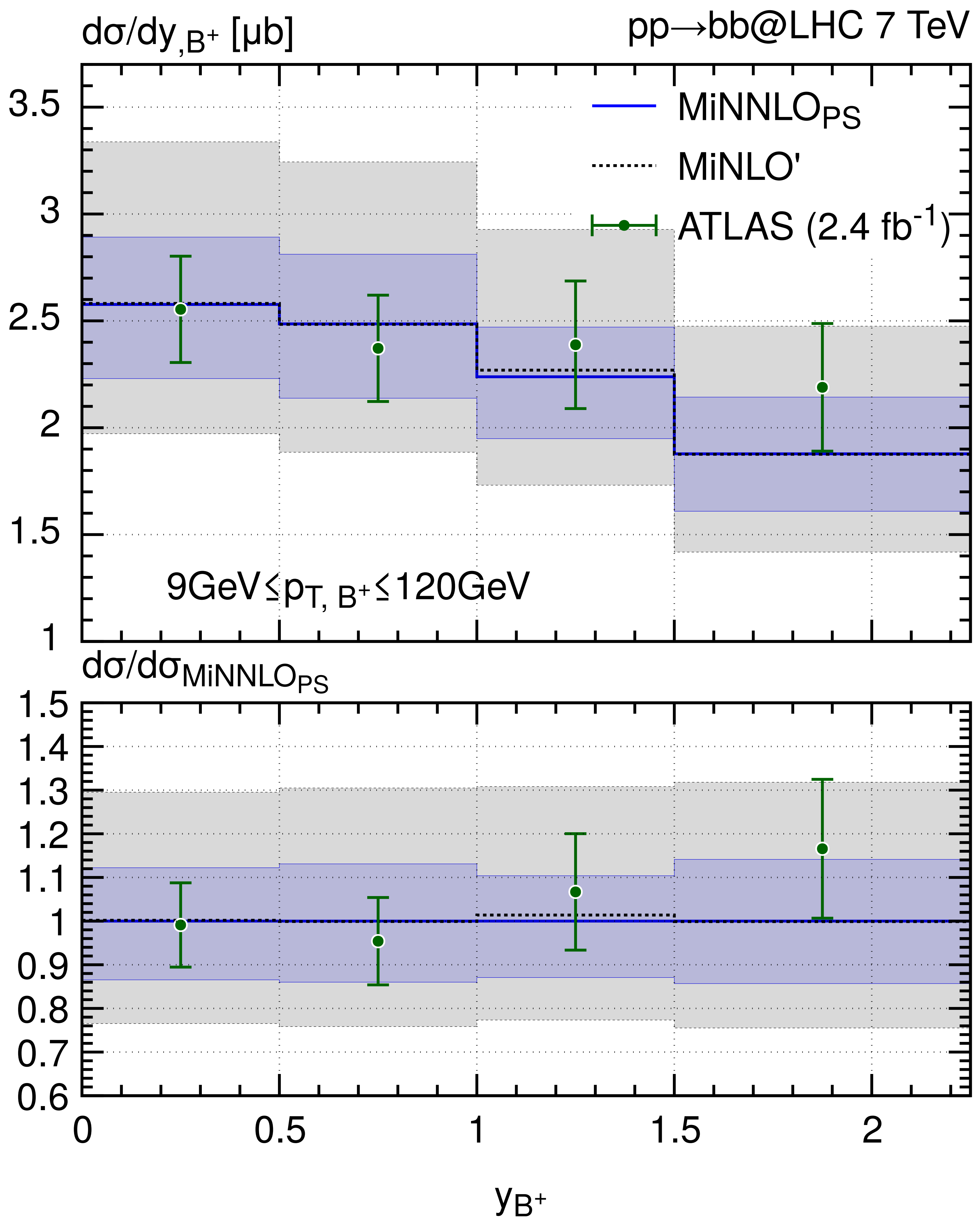
Analysis	Energy	Process	Measured cross section (μb)	MiNNLO$_{PS}$ (μb)
ATLAS	7 TeV	$pp \to B^+ + X$	10.6 ± 0.3(stat) ± 0.7(syst) ± 0.2(lumi) ± 0.4(bf)	$10.17(5)^{+13.3\%}_{-14.0\%}$
CMS	13 TeV	$pp \to B^+ + X$	15.3 ± 0.4(stat) ± 2.1(syst) ± 0.4(lumi)	$11.47(6)^{+11.3\%}_{-13.2\%}$
LHCb-1	7 TeV	$pp \to B^\pm + X$	38.9 ± 0.3(stat) ± 2.5(syst) ± 1.3(bf)	$42.2(1)^{+13.9\%}_{-11.4\%}$
		$pp \to B^0 + X$	38.1 ± 0.6(stat) ± 3.7(syst) ± 4.7(bf)	$42.3(1)^{+14.7\%}_{-11.3\%}$
		$pp \to B_s^0 + X$	10.5 ± 0.2(stat) ± 0.8(syst) ± 1.0(bf)	$9.32(6)^{+13.6\%}_{-11.5\%}$
LHCb-2	7 TeV	$pp \to B^\pm + X$	43.0 ± 0.2(syst) ± 2.5(stat) ± 1.7(bf)	$42.2(1)^{+13.9\%}_{-11.4\%}$
	13 TeV	$pp \to B^\pm + X$	86.6 ± 0.5(stat) ± 5.4(syst) ± 3.4(bf)	$78.5(3)^{+9.0\%}_{-9.3\%}$
LHCb-3	7 TeV	$pp \to B + X$	72.0 ± 0.3(stat) ± 6.8(syst)	$65.3(1)^{+12.6\%}_{-10.5\%}$
	13 TeV	$pp \to B + X$	144 ± 1(stat) ± 21(syst)	$116.2(3)^{+7.6\%}_{-12.3\%}$

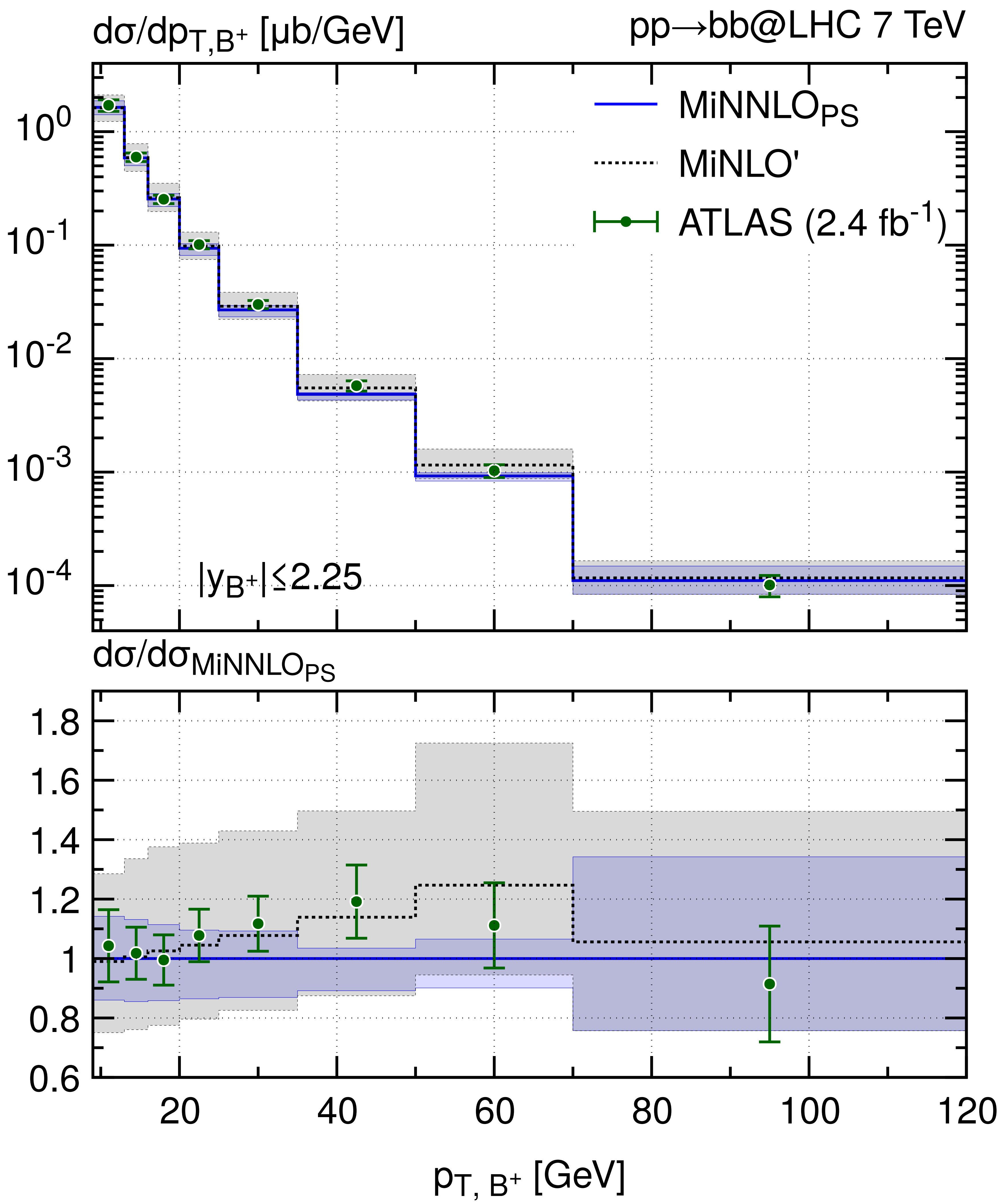
most measurements for B-mesons , but `LHCb-3` includes also all B-baryons

$(B^0, \bar{B}^0, B^+, B^-, B_s^0, \bar{B}_s^0, \ldots)$ $(\Lambda_b^0, \bar{\Lambda}_b^0, \Xi_b^0, \Xi_b^-, \Omega_b^-, \ldots)$

MiNNLO$_{PS}$: B-hadron production

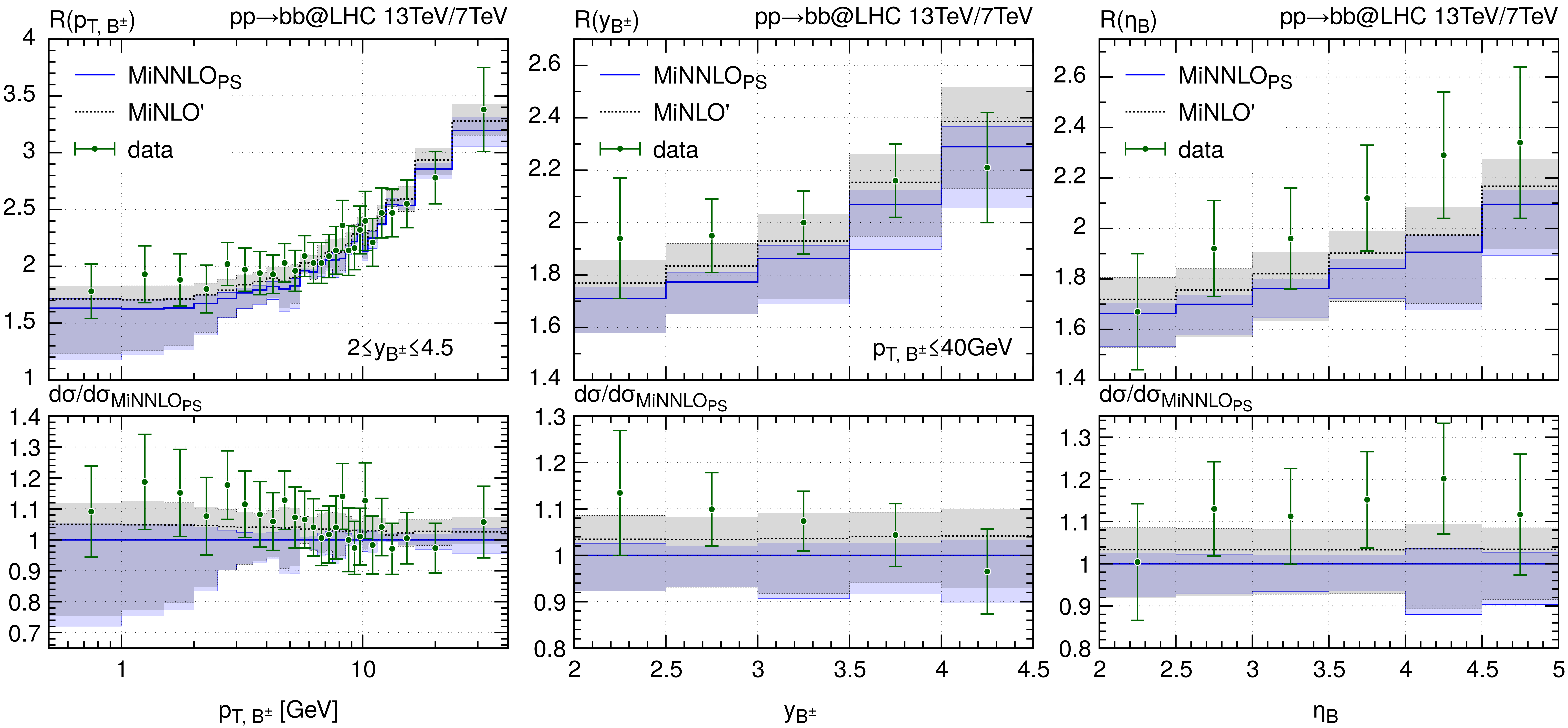
[Mazzitelli, MW, Zanderighi, Ratti '23]





MiNNLO$_{PS}$: B-hadron production

[Mazzitelli, MW, Zanderighi, Ratti '23]



MiNNLO$_{PS}$: b-jet production

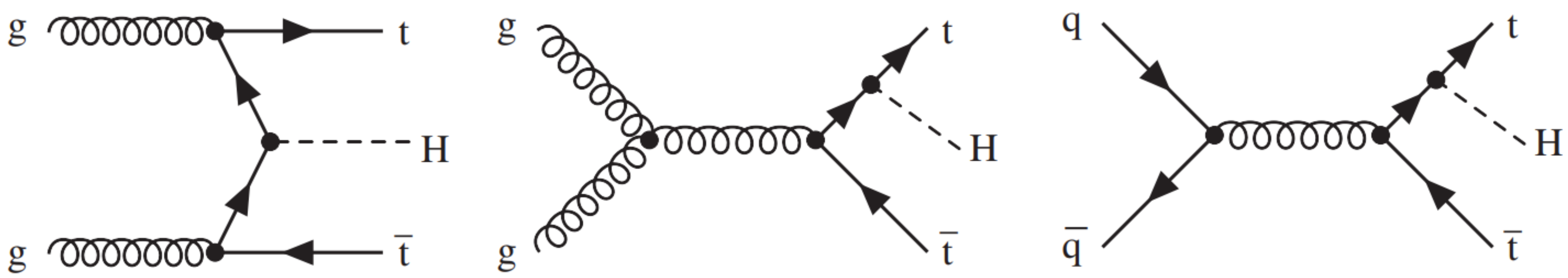
[Gauld, Mazzitelli, MW, Zanderighi, Ratti 'in preparation]

PRELIMINARY

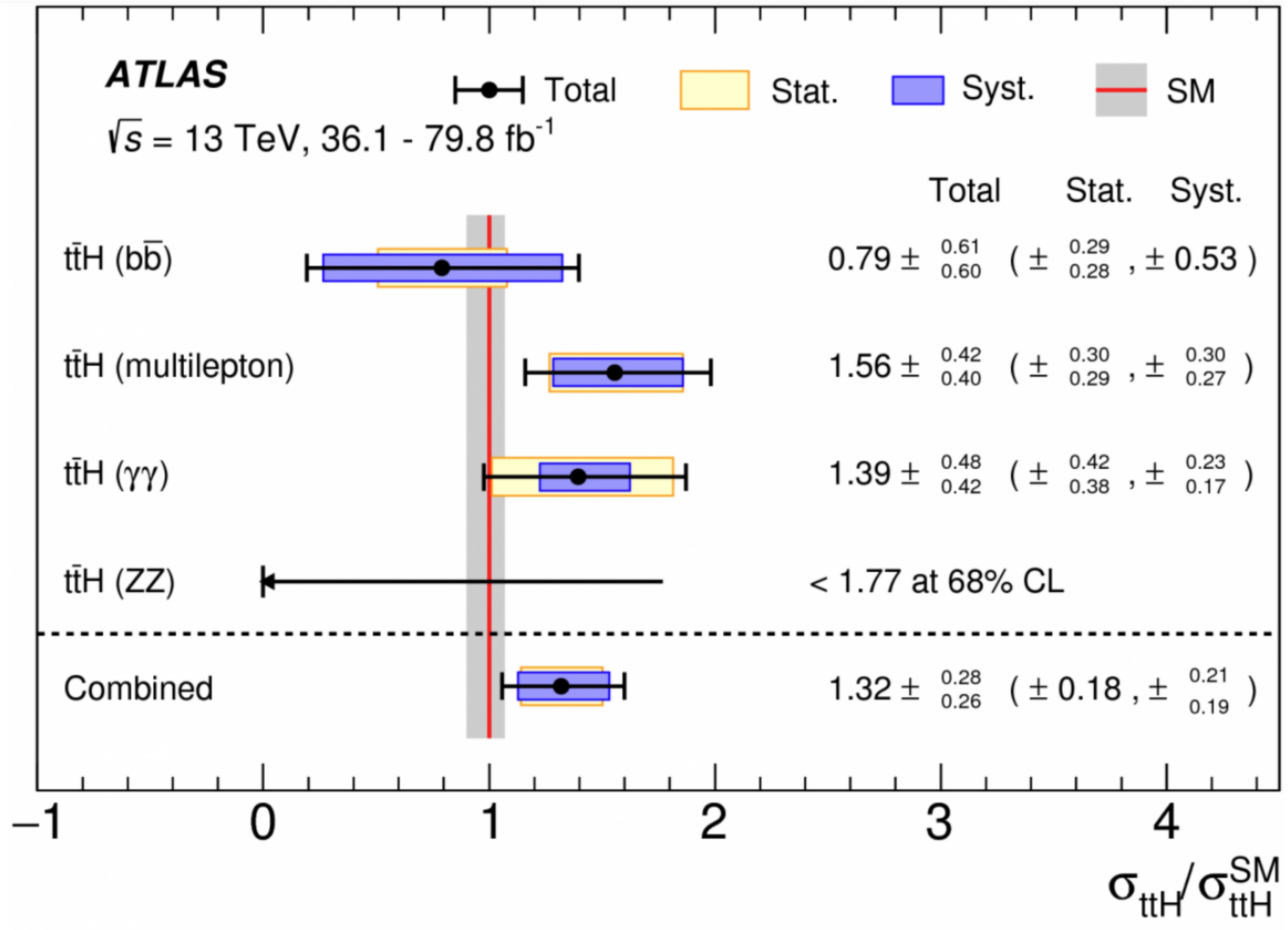
Results:

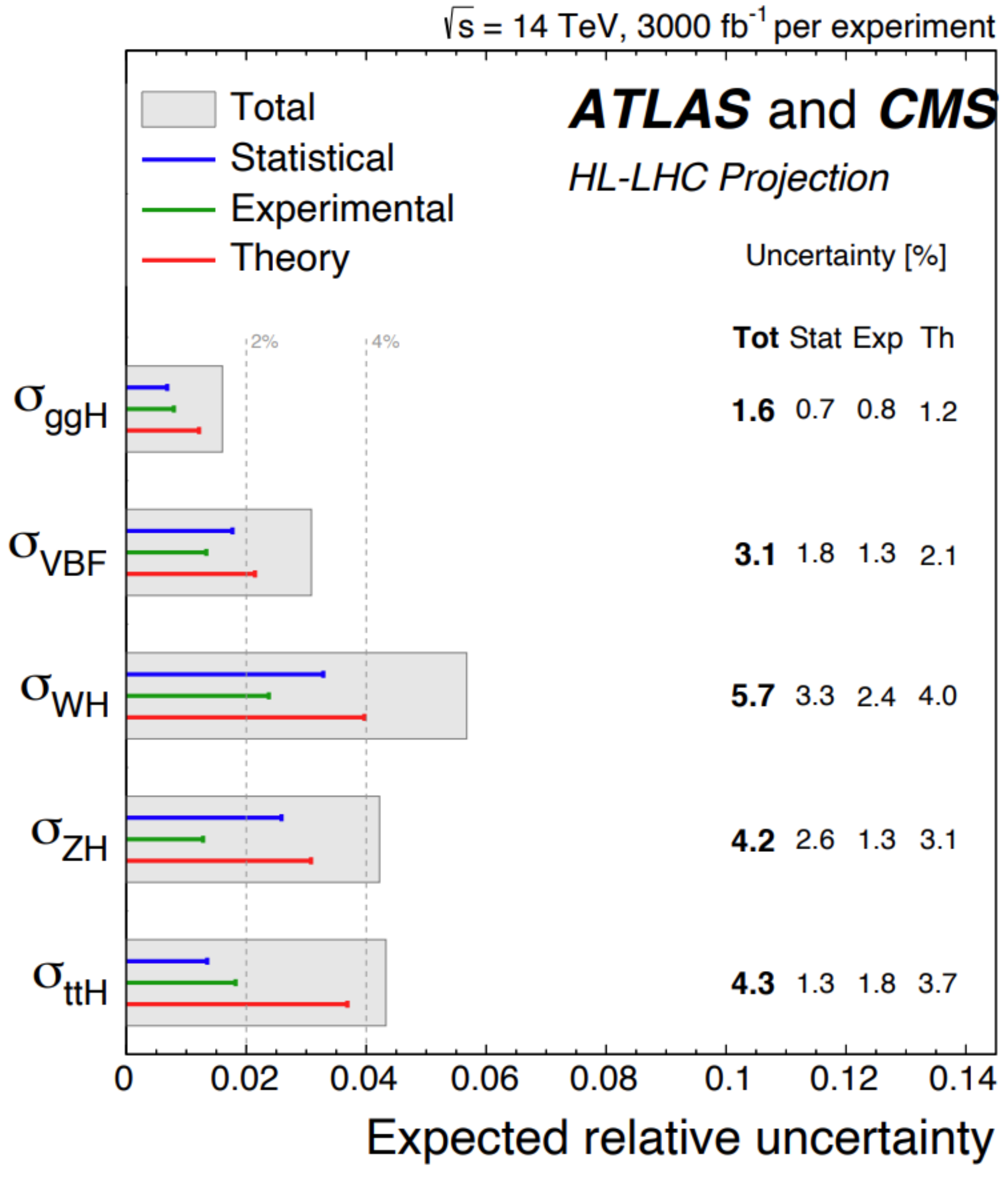
top-quark pair production in association with a Higgs boson ($t\bar{t}H$)

$t\bar{t}H$ production



- ➙ extraction of top Yukawa
- ➙ ttH observed in 2018
  [CMS 1804.02610, ATLAS 1806.00425]
- ➙ today: ~20% uncertainties
- ➙ HL-LHC: ~2% uncertainties



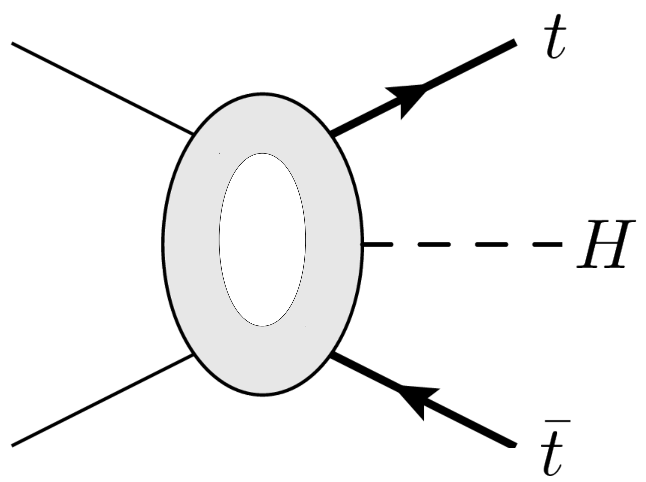


$t\bar{t}H$ production

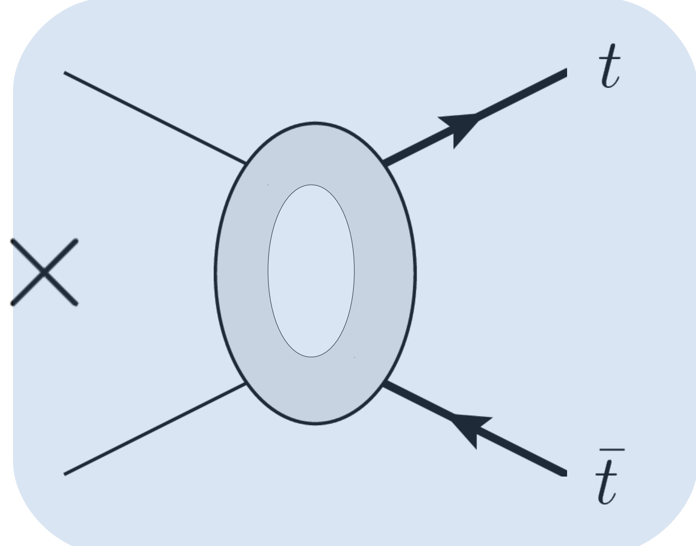
→ Recent (approx.) NNLO calculation for $t\bar{t}H$ production paves the way to build $t\bar{t}H$ NNLO+PS generator
[Catani et al. 2210.04846]

★ $H^{(2)}$ (2-loop amplitudes) has a tiny effect for $t\bar{t}H$ production → setting $H^{(2)} = 0$ is an excellent approximation (valid at sub-percent level)

shown in [Catani et al. 2210.04846] using soft approximation for the Higgs boson



$$\overset{\text{soft}}{\simeq} F\left(\alpha_s, \frac{m_t}{\mu_R}\right) J(p_H) \times$$



$$1 + \frac{\alpha_s}{2\pi}(-4) + \left(\frac{\alpha_s}{2\pi}\right)^2 \left(-\frac{89}{3} - \frac{46}{3}\log\frac{\mu_R^2}{m_t^2}\right) + \dots$$

$$\sum_i \frac{m_t}{v}\frac{m_t}{p_i \cdot p_H}$$

Derived from soft limit of scalar heavy quark form factor, alternatively using Higgs low energy theorems

[Bernreuther et al (2005) Blumlein et al (2017) Fael et al. (2022), Kniehl and Spira (1995)]

Known at two loops from top-pair production at NNLO

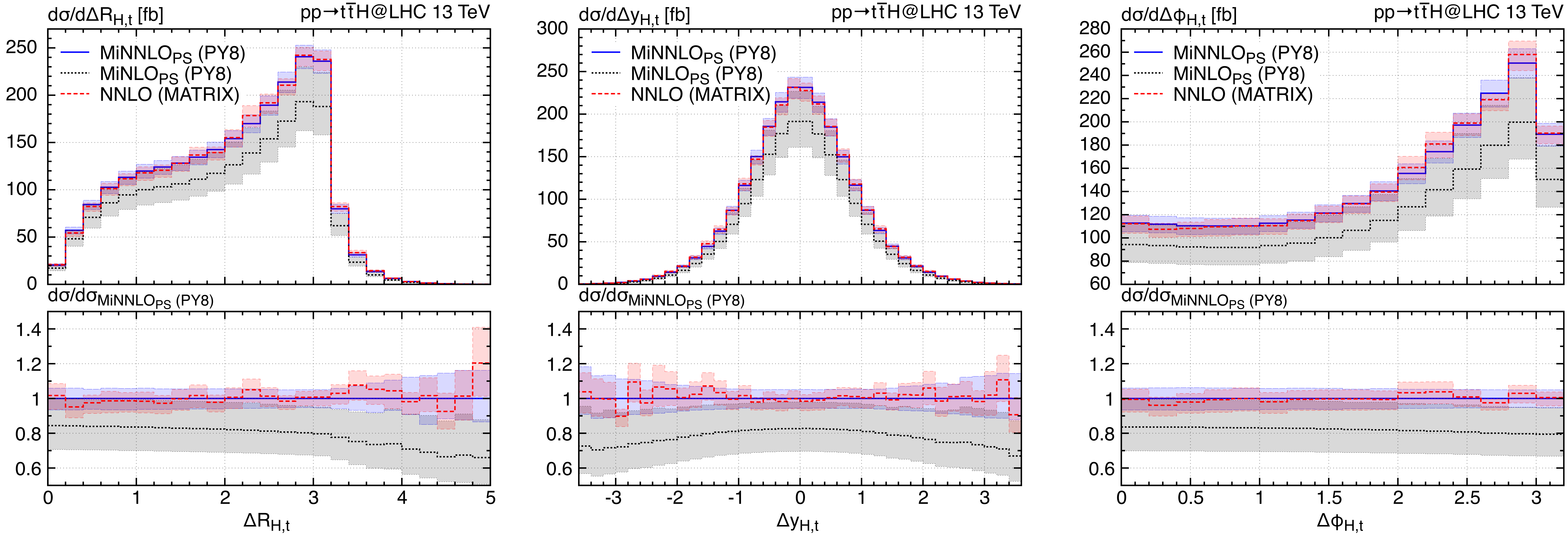
[Baernreuther, Czakon, Fiedler; 1312.6279]

...shamelessly stolen from Javier Mazzitelli's talk at LHCP 2023

MiNNLO$_{PS}$: $t\bar{t}H$ production

[Mazzitelli, MW 'work in progress]

PRELIMINARY



MiNNLO

[Mazzitelli, MW 'work in progress]

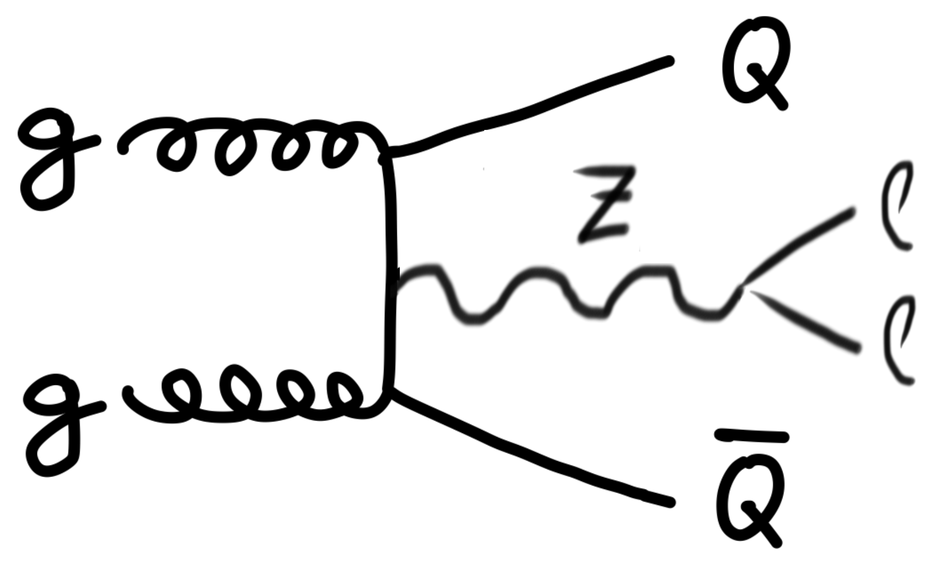
PRELIMINARY

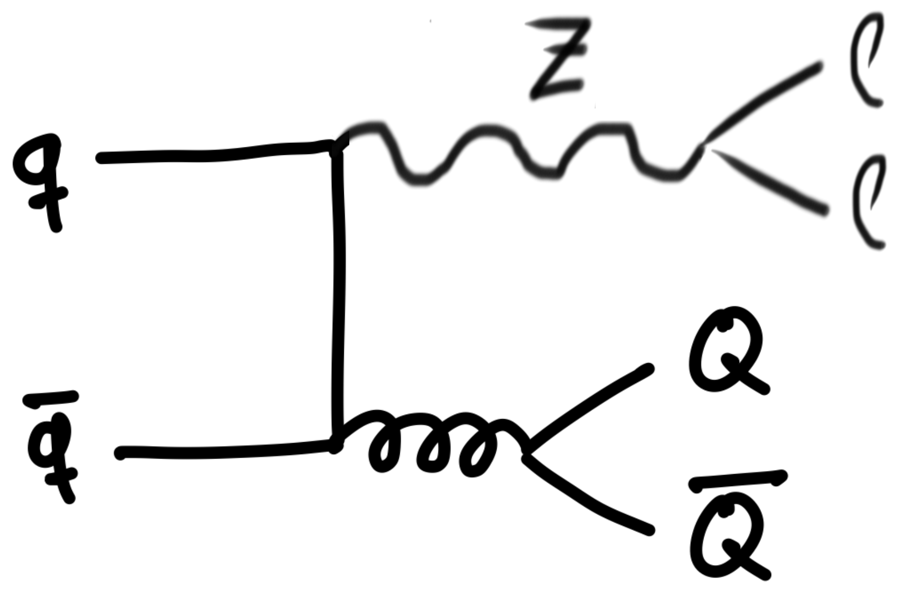
Results:

bottom-quark pair production in association with a Z boson ($b\bar{b}Z$)

MiNNLO$_{PS}$: $b\bar{b}Z$ production

[Mazzitelli, Sotnikov, MW 'work in progress]





★ MiNNLO$_{PS}$ method general for all heavy-quark + colour singlet processes

★ <u>complication:</u>
Z couples to initial-state light quarks and final-state heavy quarks & coupling depends on quark falvour

★ 2-loop amplitude: most complicated ingredient & among most complicated 2-loop computed to date

massless amplitudes at leading colour **+** massification of bottom quarks

➙ based on Pentagon functions
[Chicherin, Sotnikov, Zoia '2110.07541]
& corresponding W+4-parton calculation
[Abreu, Cordero, Ita, Klinkert, Page, Sotnikov '2110.07541]

➙ generates all $\log(m_b)$ terms of the massive 2-loop amplitude (crucial)
[Mitov, Moch 'hep-ph/0612149], see also [2212.04954] for $b\bar{b}W$

MiNNLO$_{PS}$: $b\bar{b}Z$ production

[Mazzitelli, Sotnikov, MW 'work in progress]

PRELIMINARY

	cross section	scale variation	
LO	16.34(1) pb	+23.1%	-17.1%
NLO QCD	33.13(9) pb	+17.1%	-13.8%
MiNLO	25.53(5) pb	+18.9%	-16.4%
MiNNLO (only massif.)	47.0(1)pb	+12.5%	-10.4%
MiNNLO (full 2-loop)	49.3(1)pb	+15.0%	-11.5%

+5% correction from massless 2-loop in LC (without massification)

+49% NNLO correction !

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[Mazzitelli, Sotnikov, MW 'work in progress]

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→ MiNLO/multi-jet merging not suitable due to incomplete α_s^2 correction and large $\log(m_b)$ contribution in 2-loop (leading to miscancellation with $\log(m_b)$ from reals) (only a problem for bottom quarks and processes with $Q \gg m_b$)

Summary

★ NNLO+PS for 2 ➞ 2 available for colour singlet processes

★ First coloured processes at NNLO+PS: Heavy quark pair production ($t\bar{t}$ and $b\bar{b}$)

★ both NNLO corrections and matching to PS crucial, e.g. to describe B hadrons and b-jets

★ First (preliminary) results for QQ+colour singlet processes at NNLO+PS ($t\bar{t}H$ and $b\bar{b}Z$)

Outlook

★ other interesting QQ+colour singlet processes: $b\bar{b}H, t\bar{t}Z, t\bar{t}W, b\bar{b}W, \ldots$

★ new developments also enable off-shell $t\bar{t}$ with full top quark decays at NNLO+PS

★ NNLO+PS for processes with light jets possible (but highly non-trivial)
only 1-jettiness known (but no good observable); k_T^{ness} ? [Buonocore, Grazzini, Haag, Rottoli, Savoini '22]

Summary

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Stay tuned !

Back Up

MiNNLOPS for heavy quarks

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]

$$d\sigma^F_{\rm res} \sim \frac{d}{dp_T}\left\{e^{-S}\,\mathrm{Tr}(\mathbf{H\Delta})\,(C\otimes f)\,(C\otimes f)\right\}$$

$$S = -\int \frac{dq^2}{q^2}\left[\frac{\alpha_s(q)}{2\pi}\left(A^{(1)}\log(M/q)+B^{(1)}\right)+\frac{\alpha_s^2(q)}{(2\pi)^2}\left(A^{(2)}\log(M/q)+B^{(2)}\right)+\ldots\right]$$

'B-type' correction to Sudakov

$$\mathrm{Tr}(\mathbf{H\Delta}) = \langle M|\,\mathbf{\Delta}\,|M\rangle, \quad \mathbf{\Delta} = \mathbf{V}^\dagger\,\mathbf{D}\,\mathbf{V}, \quad \mathbf{V} = \exp\left\{-\int\frac{dq^2}{q^2}\left[\frac{\alpha_s(q)}{2\pi}\mathbf{\Gamma}_{\mathbf{t}}^{(1)}+\frac{\alpha_s^2(q)}{(2\pi)^2}\mathbf{\Gamma}_{\mathbf{t}}^{(2)}\right]\right\}$$

matrix in colour space

MiNNLOPS for heavy quarks

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]

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$$\mathrm{Tr}(\mathbf{H}\boldsymbol{\Delta}) = \langle M|\boldsymbol{\Delta}|M\rangle, \quad \boldsymbol{\Delta} = \mathbf{V}^\dagger\,\mathbf{D}\,\mathbf{V}, \quad \mathbf{V} = \exp\left\{-\int\frac{\mathrm{d}q^2}{q^2}\left[\frac{\alpha_s(q)}{2\pi}\boldsymbol{\Gamma}_{\mathbf{t}}^{(1)}+\frac{\alpha_s^2(q)}{(2\pi)^2}\boldsymbol{\Gamma}_{\mathbf{t}}^{(2)}\right]\right\}$$

✦ approximations keeping NNLO and (N)LL

- azimuthal average with $[\mathbf{D}]_\phi = 1$ ➙ modifies $H \to \overline{H}$ and $(C\otimes f) \to \overline{(C\otimes f)}$ at α_s^2
  see [Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Sargsyan '19]
- $\langle M|\boldsymbol{\Delta}|M\rangle \approx \underbrace{\langle M|M\rangle}_{=H}\frac{\langle M^{(0)}|\boldsymbol{\Delta}|M^{(0)}\rangle}{\langle M^{(0)}|M^{(0)}\rangle}$ ⟵ re-absorb mistake at NNLO in $B^{(2)}$
- expand $\mathbf{V} = \underbrace{\exp\left\{-\int\frac{\mathrm{d}q^2}{q^2}\frac{\alpha_s(q)}{2\pi}\boldsymbol{\Gamma}_{\mathbf{t}}^{(1)}\right\}}_{\equiv\mathbf{V}_{\mathrm{NLL}}}\times\left(1-\int\frac{\mathrm{d}q^2}{q^2}\frac{\alpha_s^2(q)}{(2\pi)^2}\boldsymbol{\Gamma}_{\mathbf{t}}^{(2)}\right)+\mathcal{O}(\mathrm{N^3LL})$

  re-absorb in $B^{(2)}$ coefficient

MiNNLOPS for heavy quarks

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]

$$d\sigma^F_{\rm res} \sim \frac{d}{dp_T}\left\{e^{-S}\,{\rm Tr}(\mathbf{H}\boldsymbol{\Delta})\,(C\otimes f)\,(C\otimes f)\right\}$$

$$S = -\int\frac{dq^2}{q^2}\left[\frac{\alpha_s(q)}{2\pi}\left(A^{(1)}\log(M/q)+B^{(1)}\right)+\frac{\alpha_s^2(q)}{(2\pi)^2}\left(A^{(2)}\log(M/q)+B^{(2)}\right)+\ldots\right]$$

✦ using those approximations (exact up to NNLO & (N)LL) we have:

$$\tilde{B}^{(2)} = B^{(2)} + \frac{\langle M^{(0)}|\boldsymbol{\Gamma}^{(2)\dagger}+\boldsymbol{\Gamma}^{(2)}|M^{(0)}\rangle}{\langle M^{(0)}|M^{(0)}\rangle} + \frac{2\,{\rm Re}\left\{\langle M^{(1)}|\boldsymbol{\Gamma}^{(1)\dagger}+\boldsymbol{\Gamma}^{(1)}|M^{(0)}\rangle\right\}}{\langle M^{(0)}|M^{(0)}\rangle} - \frac{2\,\langle M^{(0)}|\boldsymbol{\Gamma}^{(1)\dagger}+\boldsymbol{\Gamma}^{(1)}|M^{(0)}\rangle\,{\rm Re}\left\{\langle M^{(1)}|M^{(0)}\rangle\right\}}{\langle M^{(0)}|M^{(0)}\rangle^2}$$

and $$e^{-S}\langle M|\boldsymbol{\Delta}|M\rangle = e^{-\tilde{S}}\frac{\langle M^{(0)}|\mathbf{V}^\dagger_{\rm NLL}\mathbf{V}_{\rm NLL}|M^{(0)}\rangle}{\langle M^{(0)}|M^{(0)}\rangle}H + \mathcal{O}(\alpha_s^5)$$

(reminder: $\mathbf{V}_{\rm NLL} \equiv \exp\left\{-\int\frac{dq^2}{q^2}\frac{\alpha_s(q)}{2\pi}\boldsymbol{\Gamma}^{(1)}_{\rm t}\right\}$)

MiNNLOPS for heavy quarks

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]

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use basis $|M^{(0)}\rangle$ where $\boldsymbol{\Gamma}^{(1)}$ diagonal

$$= \sum_{i\in\text{colours}} c_i\,\underbrace{e^{-\tilde{S}+S_i}}_{\equiv\, e^{\bar{S}_i}}$$

eigenvalues of $\mathbf{V}^\dagger_{\rm NLL}\mathbf{V}_{\rm NLL}$ exponent

(reminder: $\mathbf{V}_{\rm NLL} \equiv \exp\left\{-\int\frac{\mathrm{d}q^2}{q^2}\frac{\alpha_s(q)}{2\pi}\boldsymbol{\Gamma}^{(1)}_{\mathbf{t}}\right\}$)

MiNNLOPS for heavy quarks

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]

$$\mathrm{d}\sigma^{F}_{\mathrm{res}} \sim \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{e^{-S}\,\mathrm{Tr}(\mathbf{H}\boldsymbol{\Delta})\,(C\otimes f)\,(C\otimes f)\right\}$$

$$\ldots {}^{(2)} \log(M/q) + B^{(2)}) + \ldots \Big]$$

MiNNLOPS for colour singlets

[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

✦ starting equation:

$$\frac{\mathrm{d}\sigma^{\mathrm{res}}_F}{\mathrm{d}p_T\,\mathrm{d}\Phi_{\mathrm{B}}} = \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{e^{-S}\mathscr{L}\right\} = e^{-S}\underbrace{\left\{S'\mathscr{L} + \mathscr{L}'\right\}}_{\equiv D}$$

$$\mathscr{L} \sim H\,(C\otimes f)\,(C\otimes f)$$

...L) we have:

$$\ldots \boldsymbol{\Gamma}^{(1)\dagger} + \boldsymbol{\Gamma}^{(1)}\,|M^{(0)}\rangle\;\mathrm{Re}\left\{\langle M^{(1)}|M^{(0)}\rangle\right\} \Big/ \langle M^{(0)}|M^{(0)}\rangle^2$$

and $$e^{-S}\langle M|\boldsymbol{\Delta}|M\rangle = \underbrace{e^{-\tilde{S}}\frac{\langle M^{(0)}|\mathbf{V}^{\dagger}_{\mathrm{NLL}}\mathbf{V}_{\mathrm{NLL}}|M^{(0)}\rangle}{\langle M^{(0)}|M^{(0)}\rangle}}\,H + \mathcal{O}(\alpha_s^5)$$

$$= \sum_{i\in\mathrm{colours}} c_i\,\underbrace{e^{-\tilde{S}+S_i}}_{\equiv e^{\bar{S}_i}}$$

simplified to sum of terms with same structure as starting formula for colour singlet case

$$\Rightarrow\;\mathrm{d}\sigma^{F}_{\mathrm{res}} \sim \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{\sum_{i\in\mathrm{colours}} e^{-\bar{S}_i}\,\underbrace{c_i\,\overline{H}\,\overline{(C\otimes f)}\,\overline{(C\otimes f)}}_{\equiv\,\overline{\mathscr{L}}_i}\right\} + \text{terms beyond NNLO \& (N)LL}$$

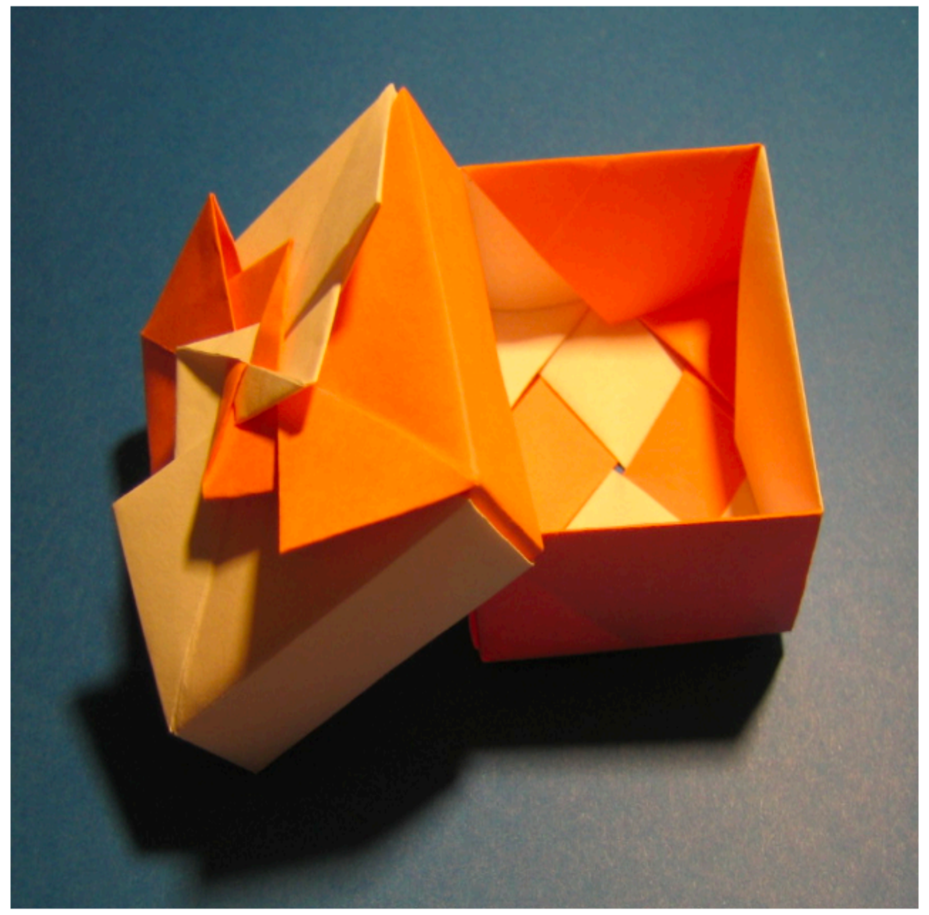
Setup for $t\bar{t}$ MiNNLOPS

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]

- scale setting:
  - overall factor in Born: $\alpha_s^2(m_{t\bar{t}}/2)$
  - MiNNLOPS scales: $\mu_R = \mu_F = \frac{m_{t\bar{t}}}{2}\, e^{-L}, \quad Q = \frac{m_{t\bar{t}}}{2}$
    (no direct correspondence to fixed-order ➙ differences within uncertainties expected)
  - 7-point scale variation
    (including scales in Sudakov ➙ slightly more conservative than in NNLO)
- new modified logarithm: $L = \begin{cases} \log\left(\frac{Q}{p_T}\right) & \text{for } p_T \leq Q/2 \\ 0 & \text{for } p_T \geq Q \end{cases}$
- showered with Pythia8, keeping top quarks stable
- comparison to data unfolded to inclusive phase space [CMS PRD 97 (2018) 112003]

MiNNLO$_{PS}$ generators public in POWHEG BOX

The POWHEG BOX



Project

The POWHEG BOX is a general computer framework for implementing NLO calculations in shower Monte Carlo programs according to the POWHEG method. It is also a library, where previously included processes are made available to the users. It can be interfaced with all modern shower Monte Carlo programs that support the Les Houches Interface for User Generated Processes.

Index:

- Available NLO+PS processes
- NNLOps using MiNNLOps
- Proper references
- Downloads
- Version 2
- Version RES
- Bugs
- Licence
- Contributing Authors

MiNNLO$_{PS}$ for $2 \to 1$ processes (H, Z, W) in POWHEG-BOX-V2
[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

NEW ***Top-quark pair*** *generator now available [Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]*

MiNNLO$_{PS}$ has been extended to $2 \to 2$ colour-singlet processes (built in POWHEG-BOX-RES).

NEW *First implementation of* ***Zγ*** *generator (both $Z \to \ell^+\ell^-$ and $Z \to \bar{\nu}\nu$ + aTGC @NNLO) [Lombardi, MW, Zanderighi '20, '21]*

NEW *New approach to the existing* ***WW*** *generator [Lombardi, MW, Zanderighi '21]*

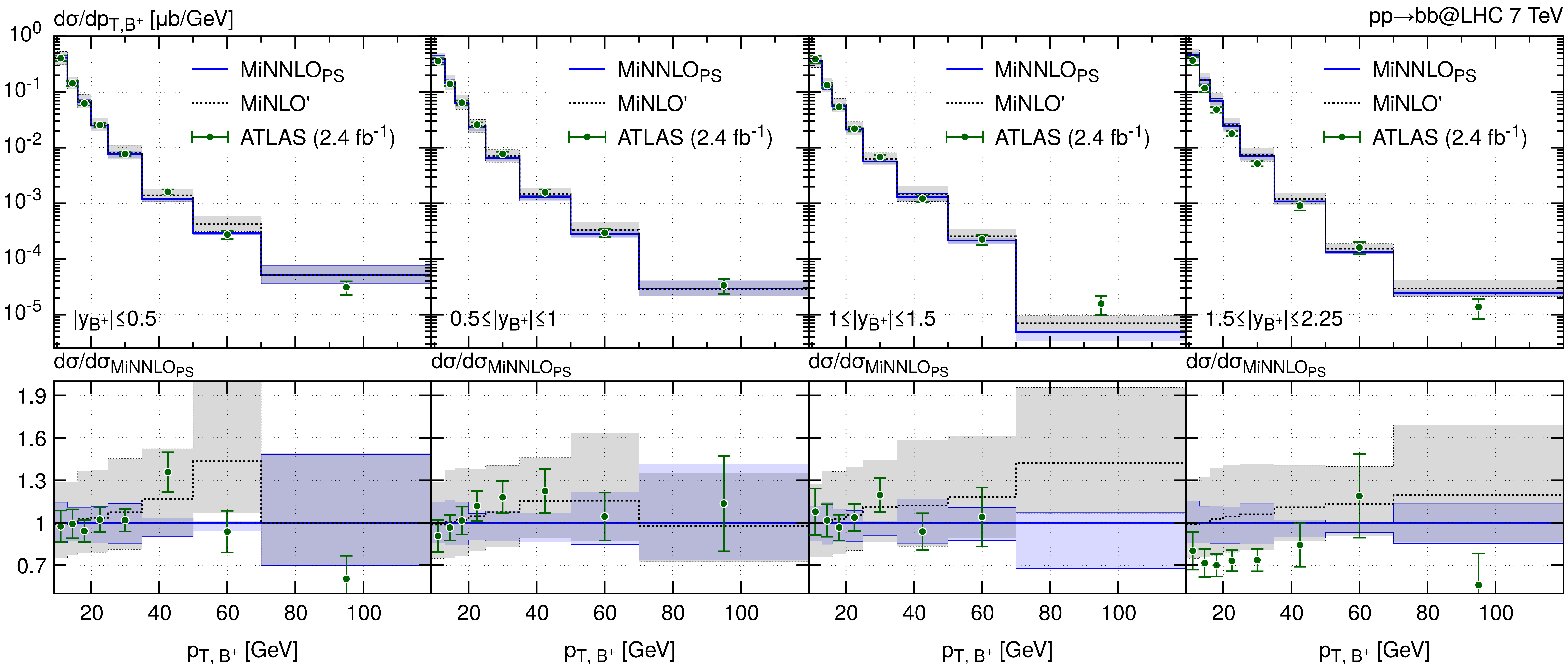
NEW ***ZZ*** *generator with incoherent combination of $\bar{q}q$ and gg channels [Buonocre, Koole, Lombardi, Rottoli, MW, Zanderighi '21]*

NEW ***VH*** *generator interfaced with* ***H→bb*** *decay (t.b.a.) [Zanoli, Chiesa, Re, MW, Zanderighi 'ongoing]*

NEW *More to come …*

MiNNLO$_{PS}$: B-hadron production

[Mazzitelli, MW, Zanderighi, Ratti ’23]



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