QCD CORRECTIONS FOR SM PROCESSES

SM – techniques, calculations & phenomenology WG

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CERN

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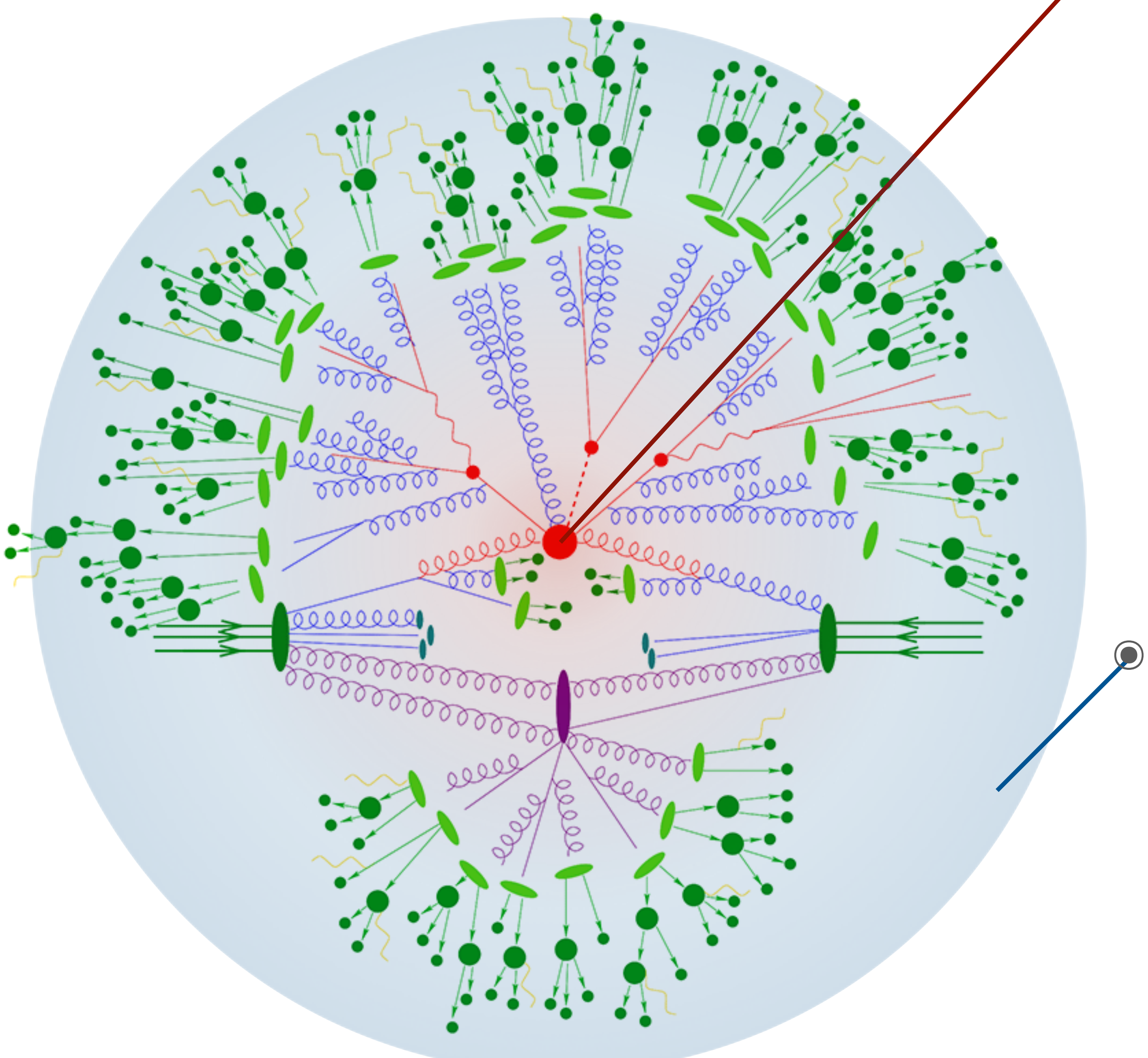
Disclaimer

- *impossible to cover everything*
- *personal selection of recent results*
- *highlight some potentially interesting topics*
  (more at: https://phystev.cnrs.fr/wiki/2021:topics)
- *QCD, but dedicated talks:*

  Higgs, PDF & jets, substructure, MC, …

SCATTERING REACTIONS @ LHC!



Short distance "hard"

- high scales: 10^2—10^3 GeV

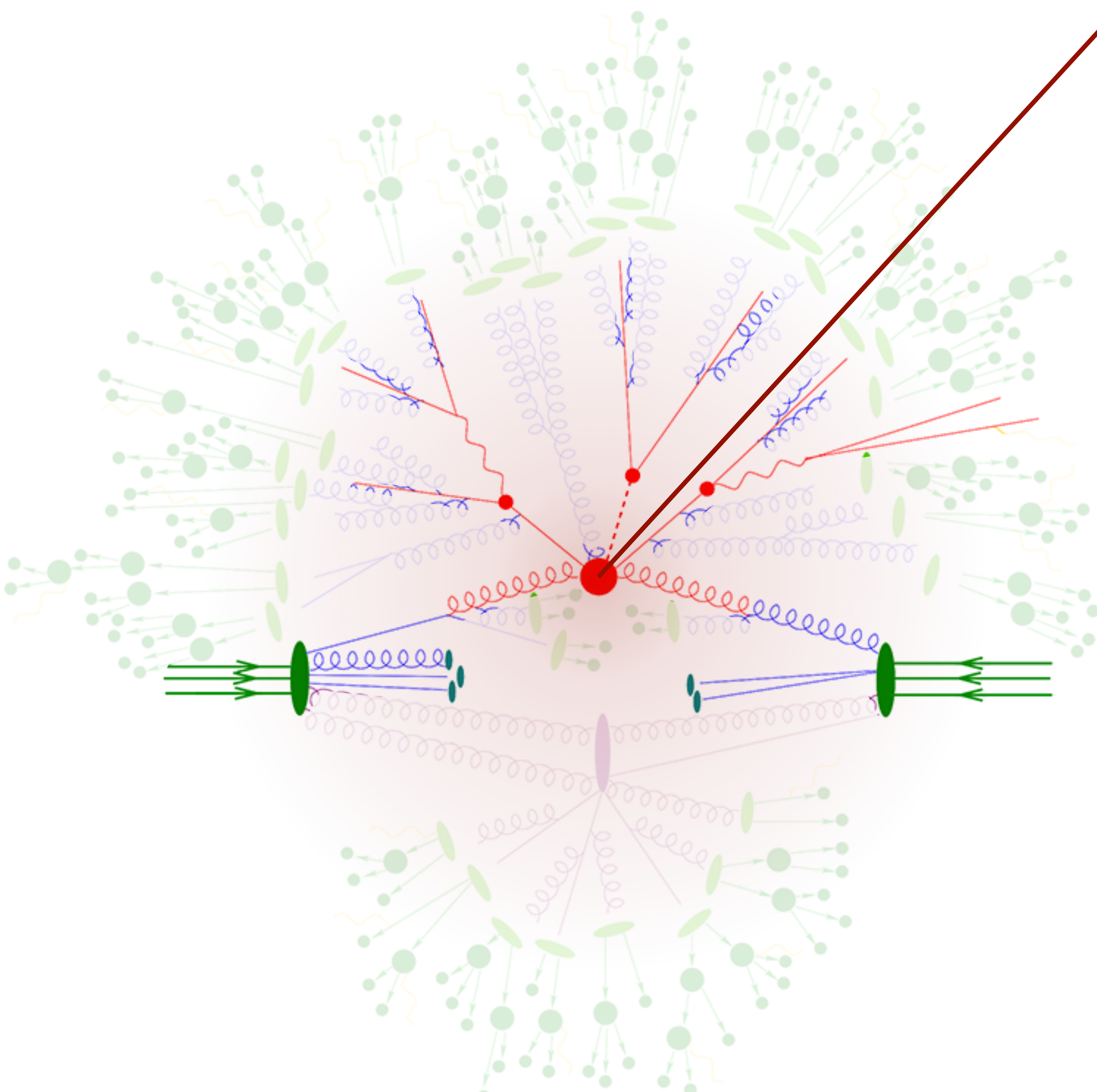
evolution towards a physical observable state

Long distance "soft"

- low scales: $\mathcal{O}$(few GeV)

{Tools & MC}

Scattering Reactions @ LHC!



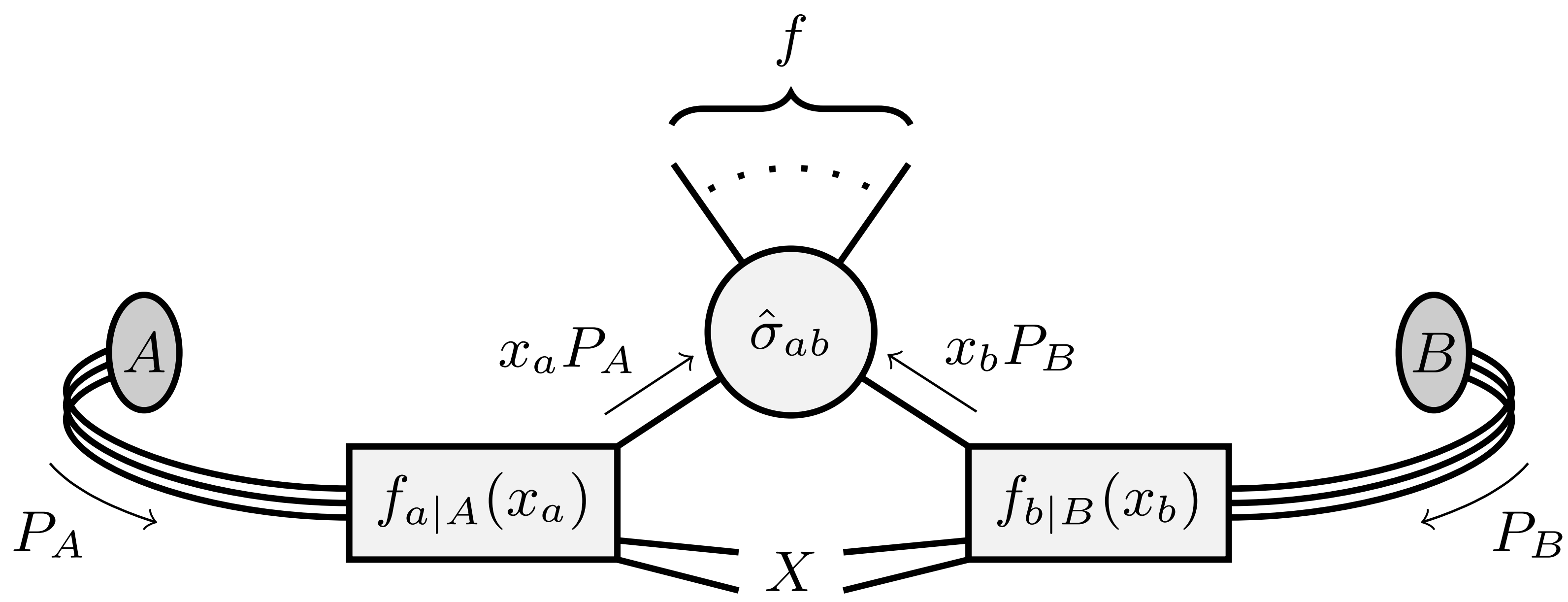
- **Short distance** "hard"
  - high scales: 10^2—10^3 GeV

$$\sigma = \sigma_0 \times \left(1 + \alpha_s + \alpha_s^2 + \alpha_s^3 + \ldots\right)$$

fixed order: LO NLO NNLO N³LO ...

- **Long distance** "soft"
  - low scales: $\mathcal{O}$(few GeV)

The Master Formula.



$$\sigma_{AB} = \sum_{ab} \int_0^1 \mathrm{d}x_a \int_0^1 \mathrm{d}x_b \; f_{a|A}(x_a) \; f_{b|B}(x_b) \; \hat{\sigma}_{ab}(x_a, x_b) \; \left(1 + \mathcal{O}(\Lambda_{\mathrm{QCD}}/Q)\right)$$

parton distribution functions (PDFs)
(non-perturbative, universal)

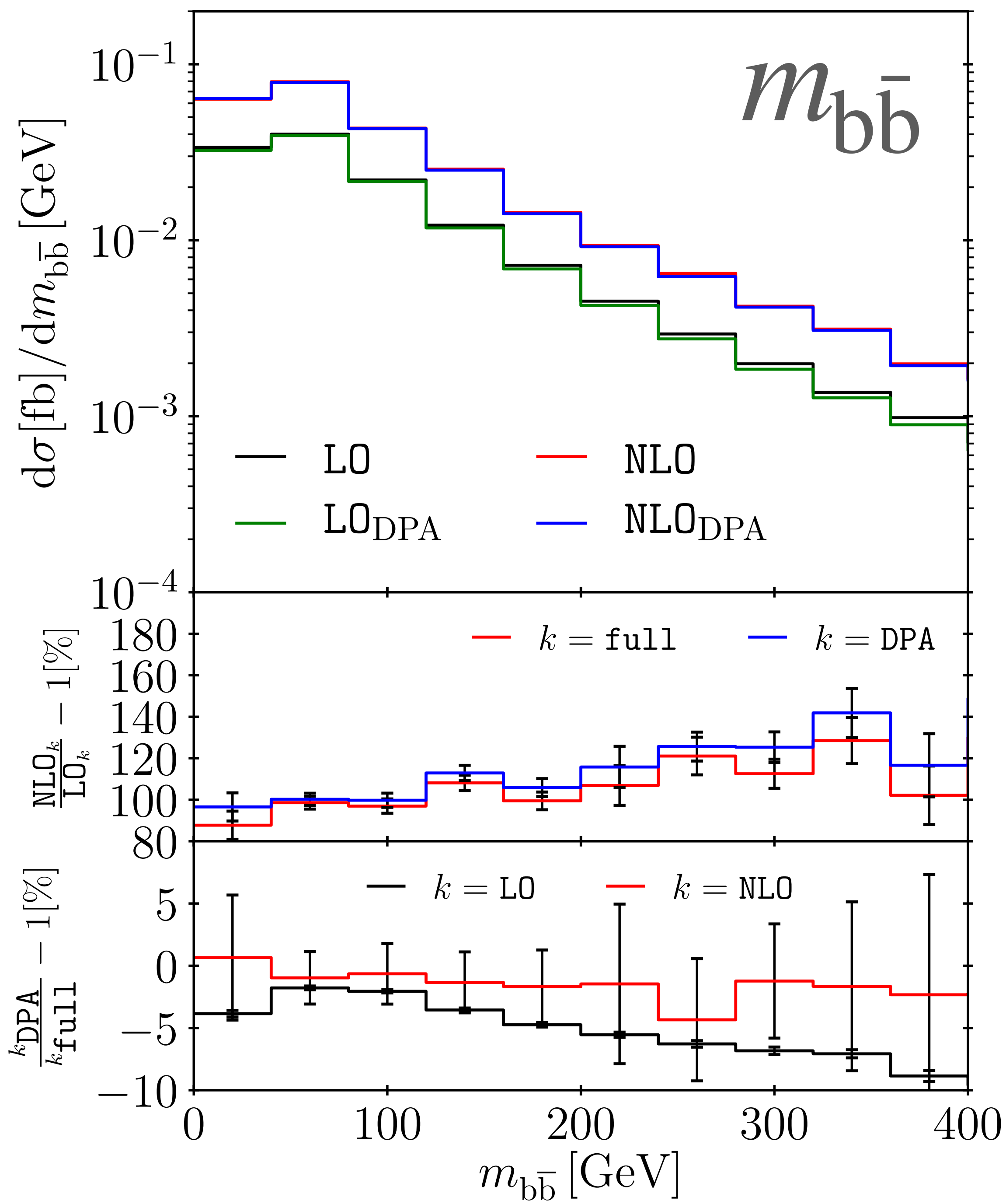
hard scattering
(perturbation theory)

non-perturbative effects
(power suppressed)
ultimately, limiting factor?

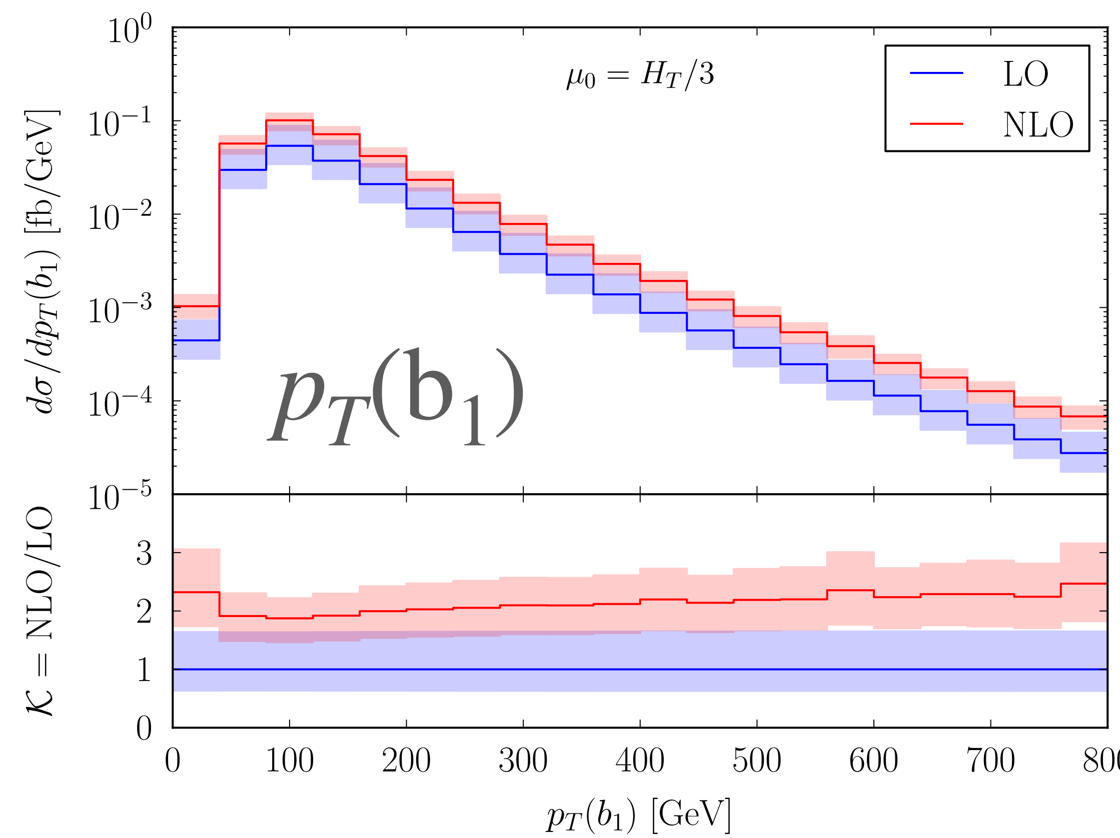
NLO — Pushing the Limits*

➤ 2 → 8 (6 coloured particles): $pp \to \mu^- \bar{\nu}_\mu e^+ \nu_e b\,\bar{b}\,b\,\bar{b}$ (off-shell $t\bar{t}b\bar{b}$)

[Denner, Lang, Pellen '20]



[Bevilacqua, Bi, Hartanto, Kraus, Lupattellib, Worek '21]

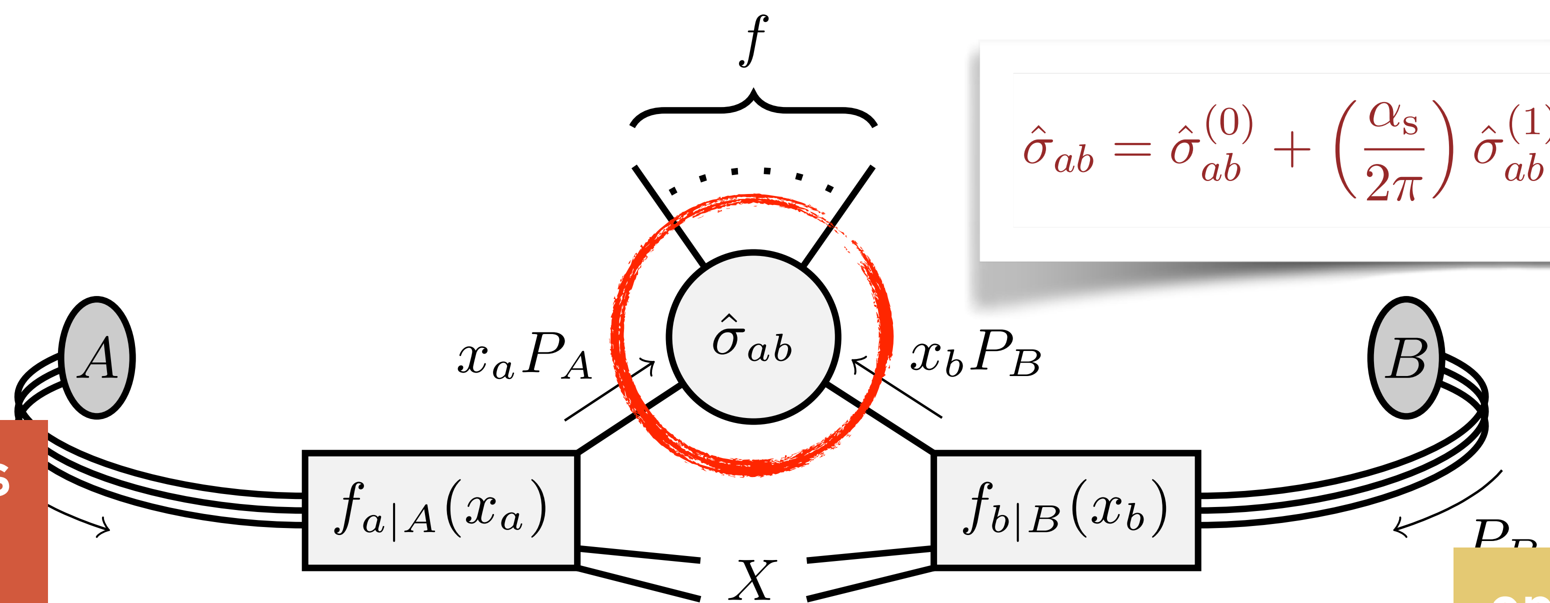


- large **NLO** corr. & impact on shape
- full v.s. on-shell: 5 - 10 %

* *another frontier: NLO loop-induced* **{S. Jones}**

NNLO — Bottle Necks

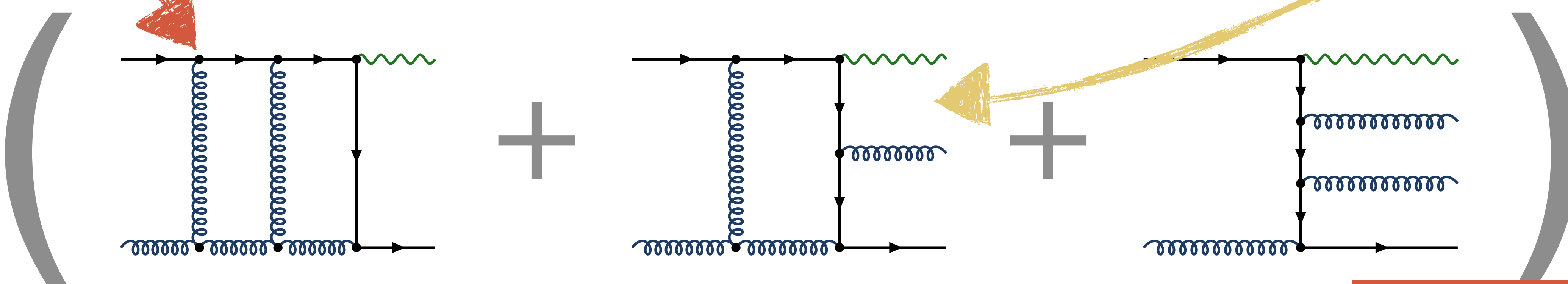
$$\hat{\sigma}_{ab} = \hat{\sigma}_{ab}^{(0)} + \left(\frac{\alpha_s}{2\pi}\right)\hat{\sigma}_{ab}^{(1)} + \left(\frac{\alpha_s}{2\pi}\right)^2 \hat{\sigma}_{ab}^{(2)} + \ldots$$



two-loop amplitudes
(new class of functions, combinatoric & algebraic complexity)

one-loop amplitudes
(evaluation in singular & unstable regions)

next-to-next-to-leading order (NNLO)



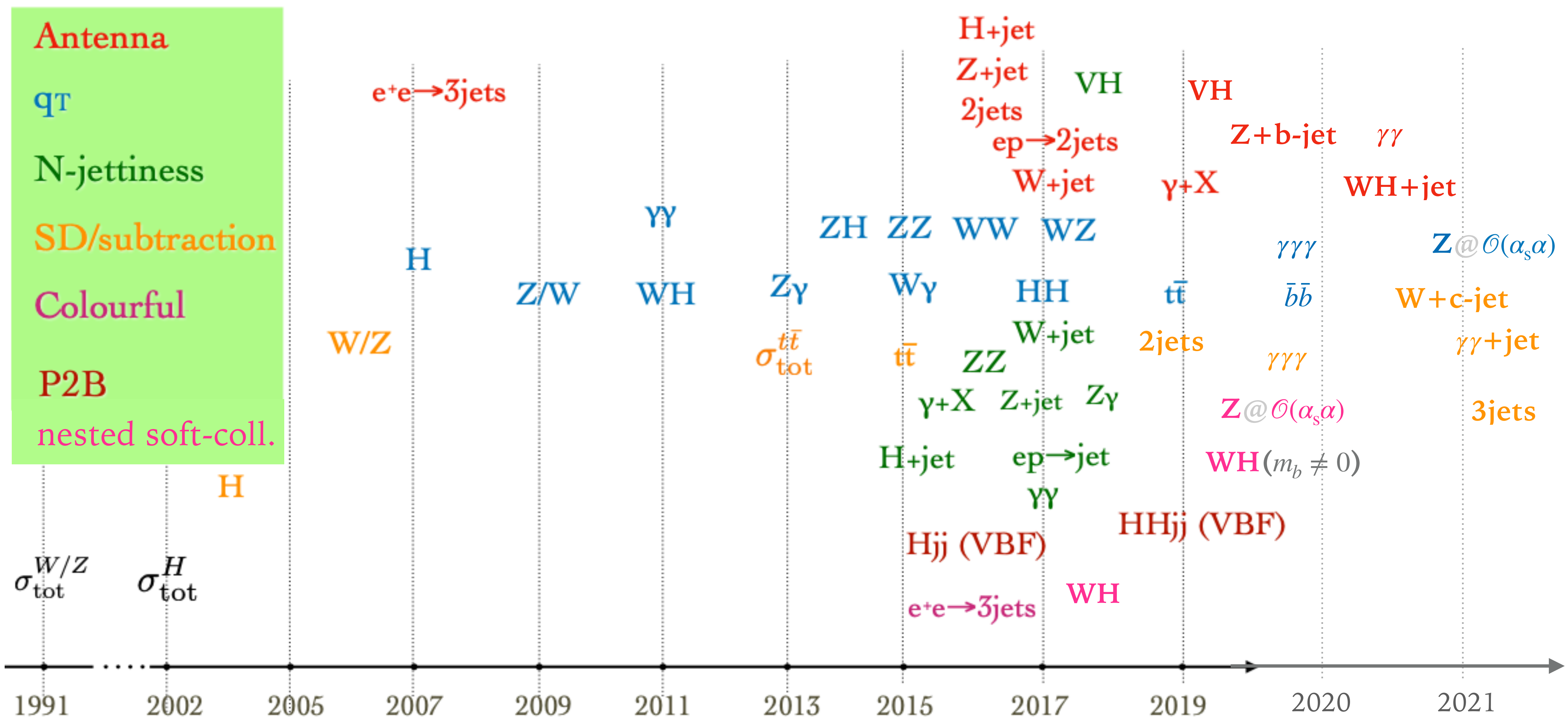
"double virtual" *"real-virtual"* *"double real"*

infrared singularities

IR subtraction
(involved IR structure, numerical stability, construction)

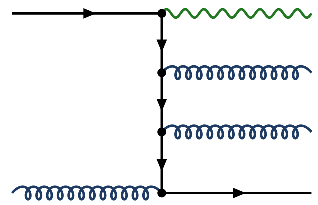
Timeline for NNLO

- Remarkable progress in the development of methods to perform NNLO computations!

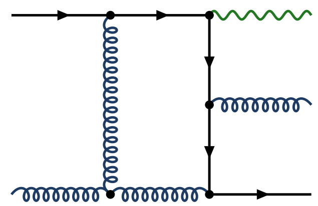


[based on slide by M. Grazzini; QCD@LHC 2019]

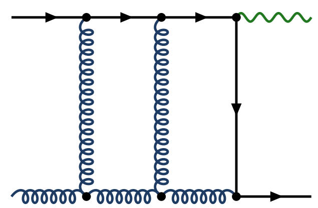
$$\sigma_{\text{NNLO}} = \int_{\Phi_{Z+3}} \mathrm{d}\sigma^{\text{RR}}_{\text{NNLO}}$$



$$+ \int_{\Phi_{Z+2}} \mathrm{d}\sigma^{\text{RV}}_{\text{NNLO}}$$



$$+ \int_{\Phi_{Z+1}} \mathrm{d}\sigma^{\text{VV}}_{\text{NNLO}}$$



$\sum$ finite

- in general: measurement function
  - fiducial cross sections
  - differential distributions
  - reconstruction (jets, γ, …)

  } $\mathcal{F}^{(n)}_{\text{obs}}$

➡ massage expression to render intermediate objects finite
(suitable for MC integration)

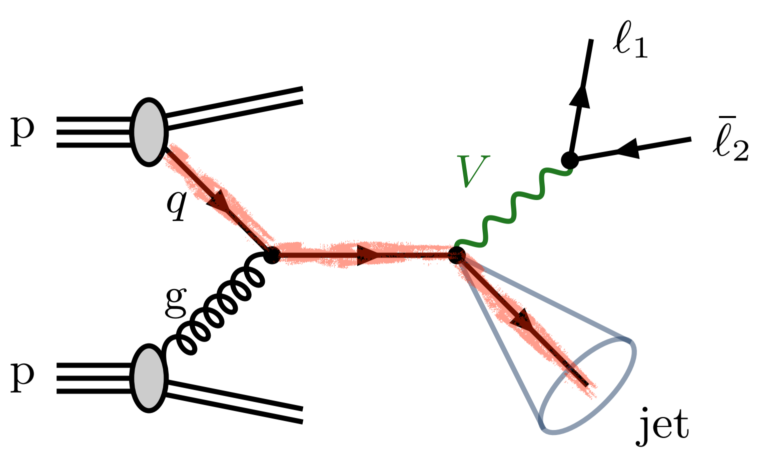
Different Methods*

- Antenna [Gehrmann–De Ridder, Gehrmann, Glover '05]
- CoLorFul [Del Duca, Somogyi, Trocsanyi '05]
- qT-subtraction [Catani, Grazzini '07; MATRIX]
- STRIPPER (sector-improved residues) [Czakon '10]
- nested soft-collinear [Caola, Melnikov, Röntsch '17]
- N-jettiness [Gaunt, Stahlhofen, Tackmann, Walsh '15] [Boughezal, Focke, Liu, Petriello '15; MCFM]
- Projection-to-Born [Cacciari, et al. '15]
- Geometric, Local analytical Sectors
  [Herzog '18] [Magnea et al. '18]

* *Subtraction & Slicing*

V + jet Production @ NNLO QCD with Flavour

NNLO QCD now well-established with 2 independent calculations:



- Z+jet:
  - Antenna: [Gehrmann-De Ridder, Gehrmann, Glover, AH, Morgan '15]
  - N-jettiness: [Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello '15]
- W+jet:
  - N-jettiness: [Boughezal, Liu, Petriello '15]
  - Antenna: [Gehrmann-De Ridder, Gehrmann, Glover, AH, Walker '17]
- γ+jet:
  - N-jettiness: [Campbell, Ellis, Williams '16]
  - Antenna: [Chen, Gehrmann, Glover, Höfer, AH '19]

… now comes in different flavours:

- Z+b-jet
  [Gauld, Gehrmann-De Ridder, Glover, AH, Majer '20]
- W+c-jet
  [Czakon, Mitov, Pellen, Poncelet '20]

- identify flavour of a jet ("tag")
  - ⇝ test of perturbative QCD
  - ⇝ flavour structure of protons
- $m_q \equiv 0 \Leftrightarrow$ IR unsafe with anti-k_T

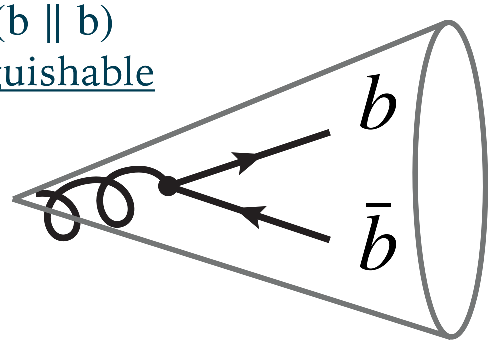
Flavour Tagging & IR Safety

anti-k_T used in experiment

- $m_b \neq 0$ (4FS): finite, but sensitive to $\ln(Q^2/m_b^2)$
- $m_b \equiv 0$ (5FS): divergent

1. Collinear (NLO)

g ↔ (b || $\bar{\text{b}}$)
indistinguishable

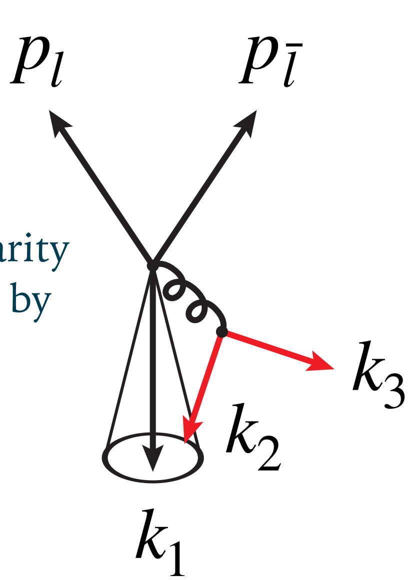


⇝ assign tag using: b ↔ + 1 & $\bar{\text{b}}$ ↔ − 1

(alternatively reject even tags)

2. Soft (NNLO)

$E_g \to 0$ singularity
not protected by
$E_g \geq 2m_q$



⇝ modify the clustering: flavour-k_T [Banfi, Salam, Zanderighi '06]

$$d_{ij} = \frac{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}{R^2} \begin{cases} \max(k_{ti}, k_{tj})^\alpha \min(k_{ti}, k_{tj})^{2-\alpha} & \text{softer of } i, j \text{ is flavoured,} \\ \min(k_{ti}, k_{tj})^\alpha & \text{softer of } i, j \text{ is unflavoured,} \end{cases}$$

Flavour Tagging & IR Safety

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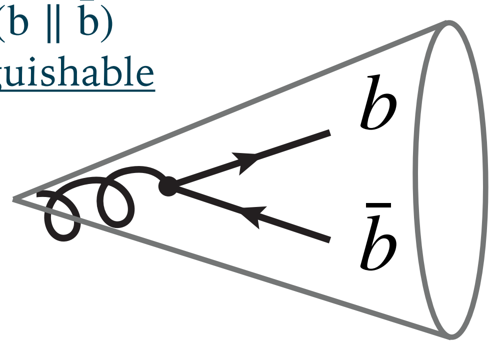

issue for any fixed-order & jet algo!

⇝ assign tag using: $\text{b} \leftrightarrow +1$ & $\bar{\text{b}} \leftrightarrow -1$

(alternatively reject even tags)

2. Soft (NNLO)

$E_g \to 0$ singularity
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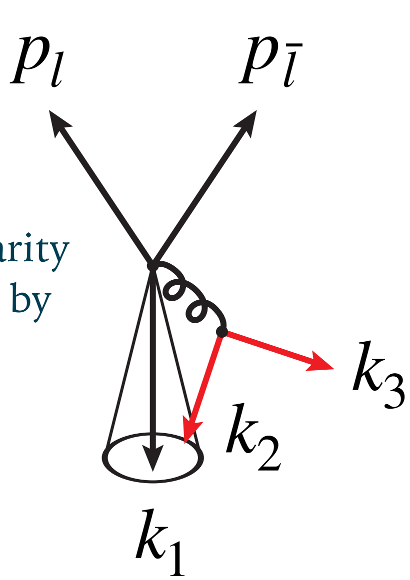

mismatch to experiment!

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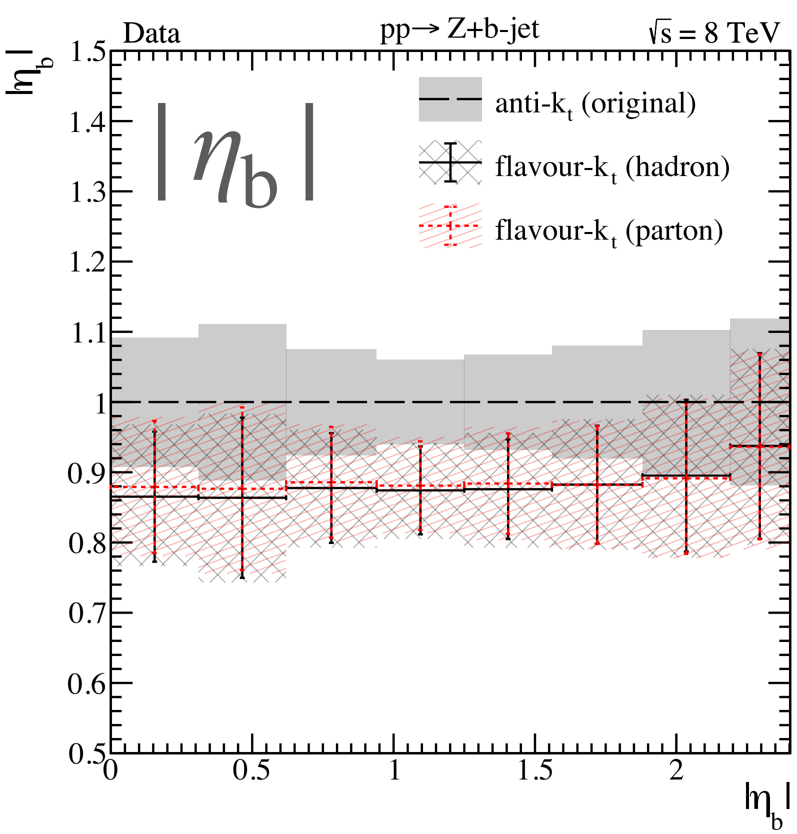
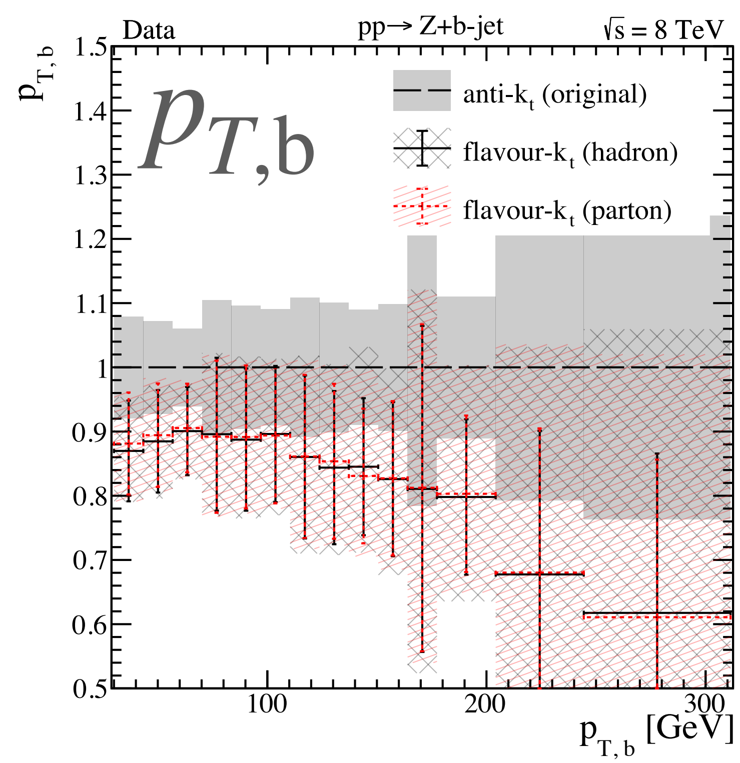
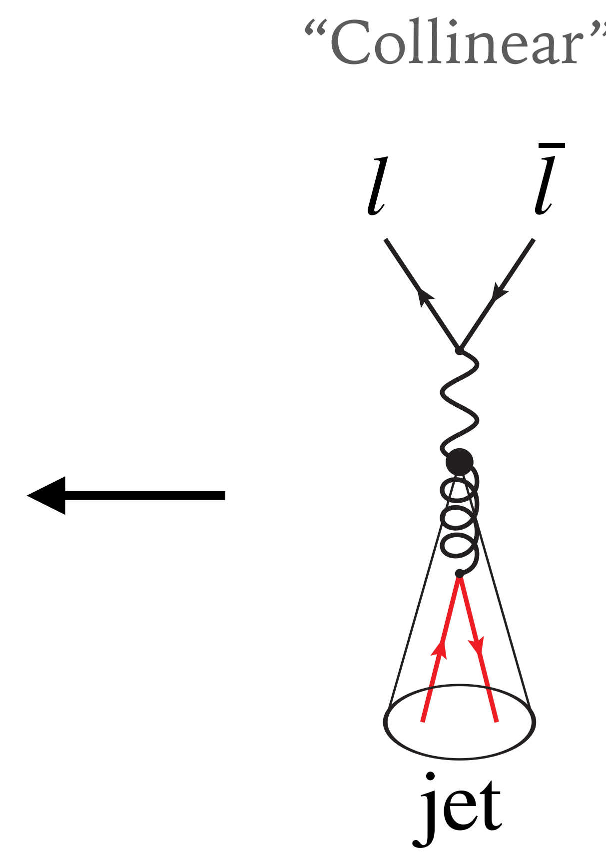
Flavour Tagging — TH v.s. EXP

- ➤ Unfolding ~10% sizeable for Z+b-jet (larger @ high-p_T)
  - ⇝ mainly "background subtraction"







- ◉ flavour-k_T in experiment? At least resolve the collinear? How reliable is NLO+PS?
- ◉ alternatives to flavour-k_T? Can substructure techniques help (soft drop, …)?

Top Quark Pairs @ NNLO with the $\overline{\text{MS}}$ Mass

[Catani, Devoto, Grazzini, Kallweit, Mazzitelli '20]

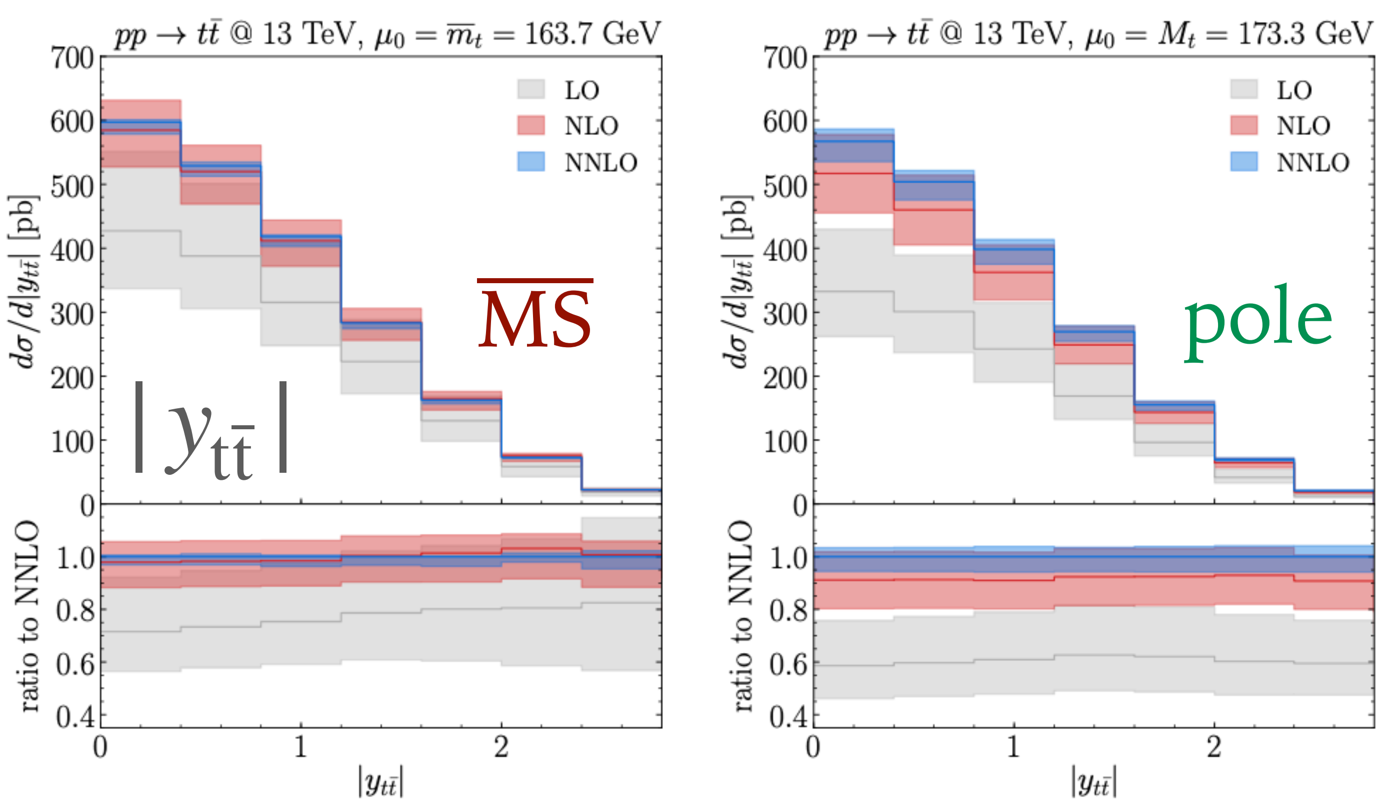
- relation between the pole mass and the $\overline{\text{MS}}$ mass:

$$M_{\rm t} = m_{\rm t}(\mu_m)\, d_m(m_{\rm t}(\mu_m), \mu_m) = m_{\rm t}(\mu_m)\left(1 + \alpha_{\rm s}\, d^{(1)}(\mu_m) + \ldots\right)$$

- formal replacement $(M_{\rm t} \to m_{\rm t}(\mu_m))$ & expand $\Rightarrow$ $\overline{\text{MS}}$ cross section:

$$\bar{\sigma}(\alpha_{\rm S}(\mu_R), \mu_R, \mu_F; \mu_m, m_t(\mu_m); X) = \sigma(\alpha_{\rm S}(\mu_R), \mu_R, \mu_F; M_t = m_t(\mu_m)\, d(m_t(\mu_m), \mu_m); X)$$

new scale μ_m ⇝ 15-point scale variation



- good perturbative behaviour
- difference between schemes reduce at higher orders

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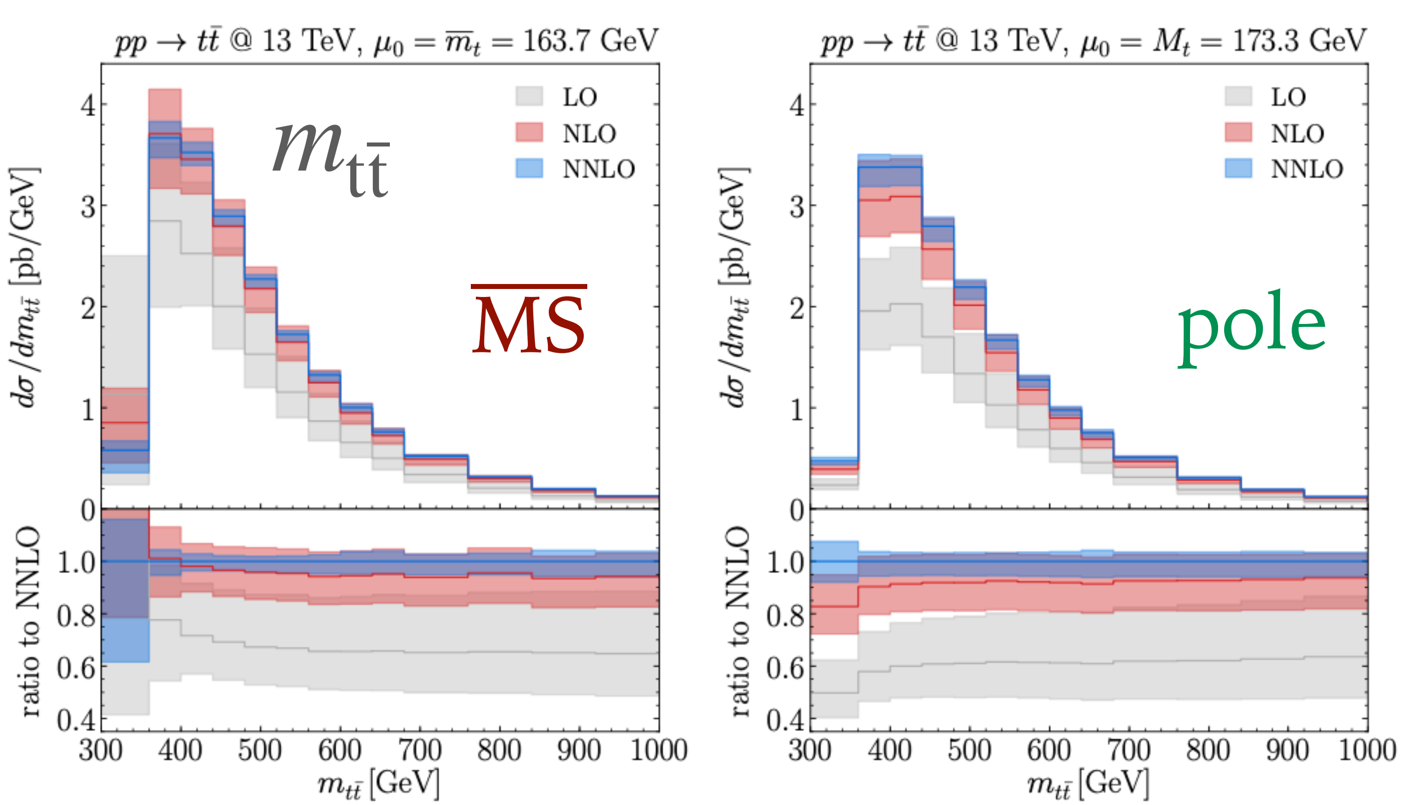

- caution: threshold region
  ⇝ large K-factor & uncertainties

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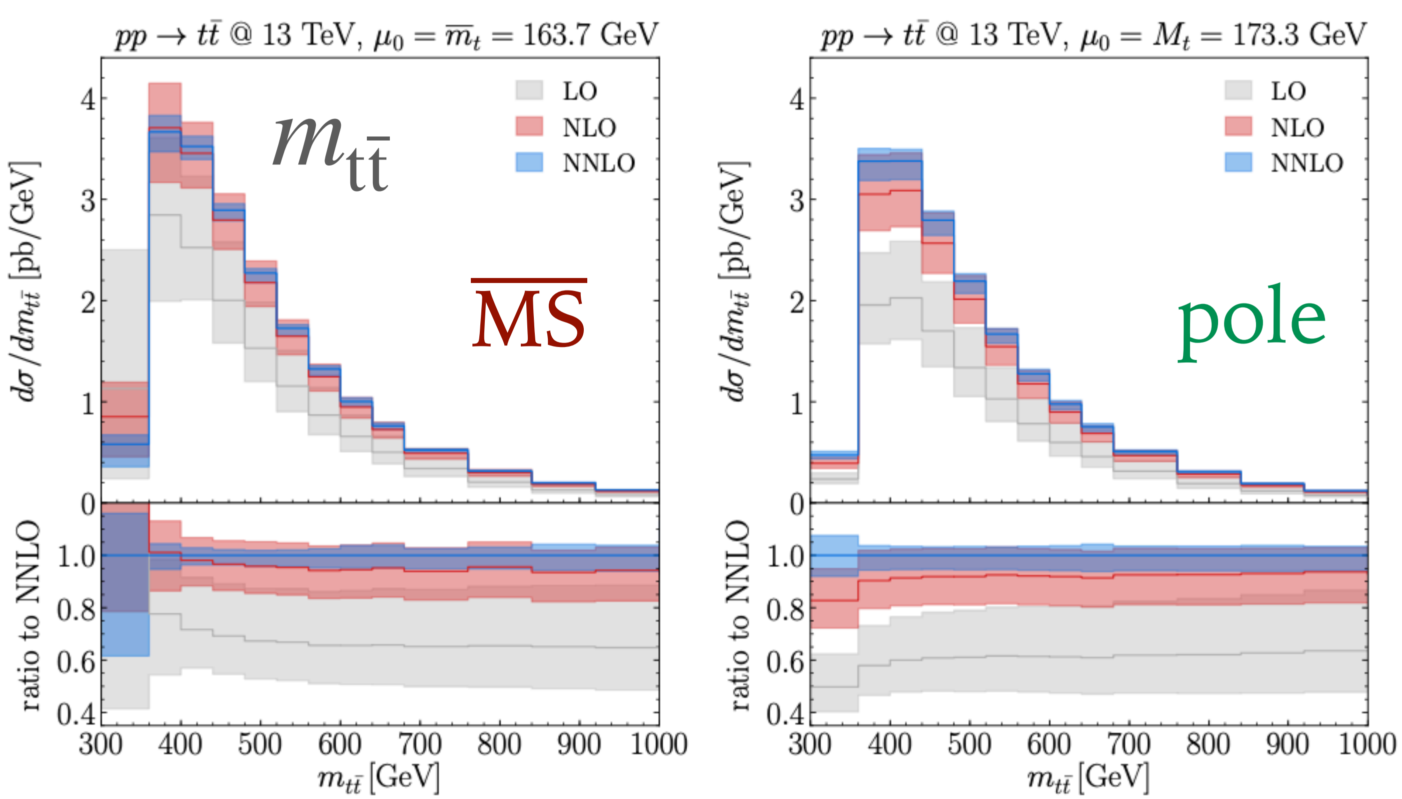


- caution: threshold region
  ⇝ large K-factor & uncertainties

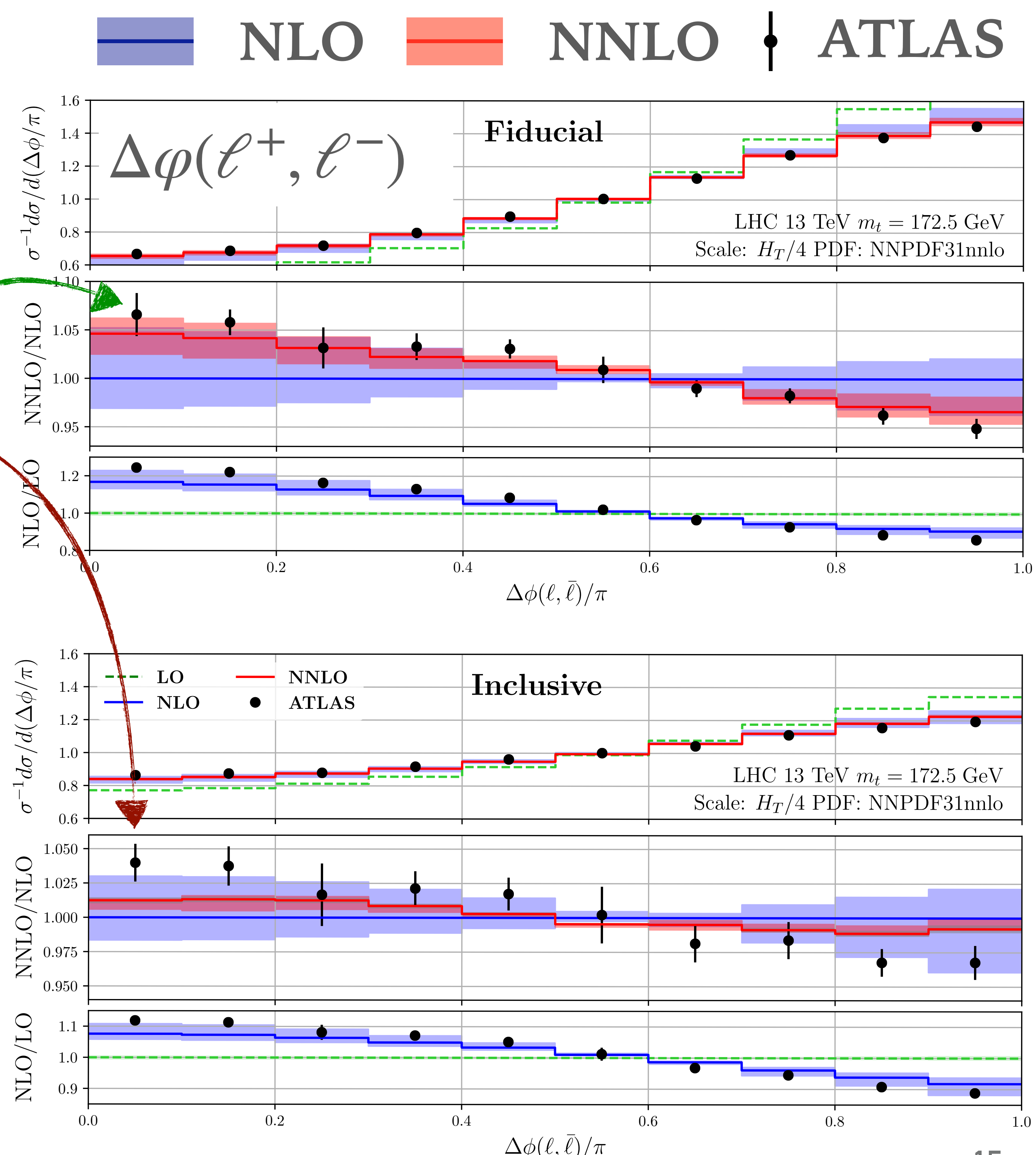
- difference between $\overline{\text{MS}}$ & pole mass extraction?
- running-mass effects found to be small

Top Quark Spin Correlation at NNLO

[Behring, Czakon, Mitov, Papanastasiou, Poncelet `19]

- leptons carry spin information of the tops
- fiducial: good agreement
- inclusive: some tension
- possible sources:
  - ✓ scale choice, m_t, PDF, finite width, EW corrections
  - ? extrapolation ⇝ need better understanding of modelling?
- full spin density matrix

[Czakon, Mitov, Poncelet '20]



TOP QUARK SPIN CORRELATION AT NNLO

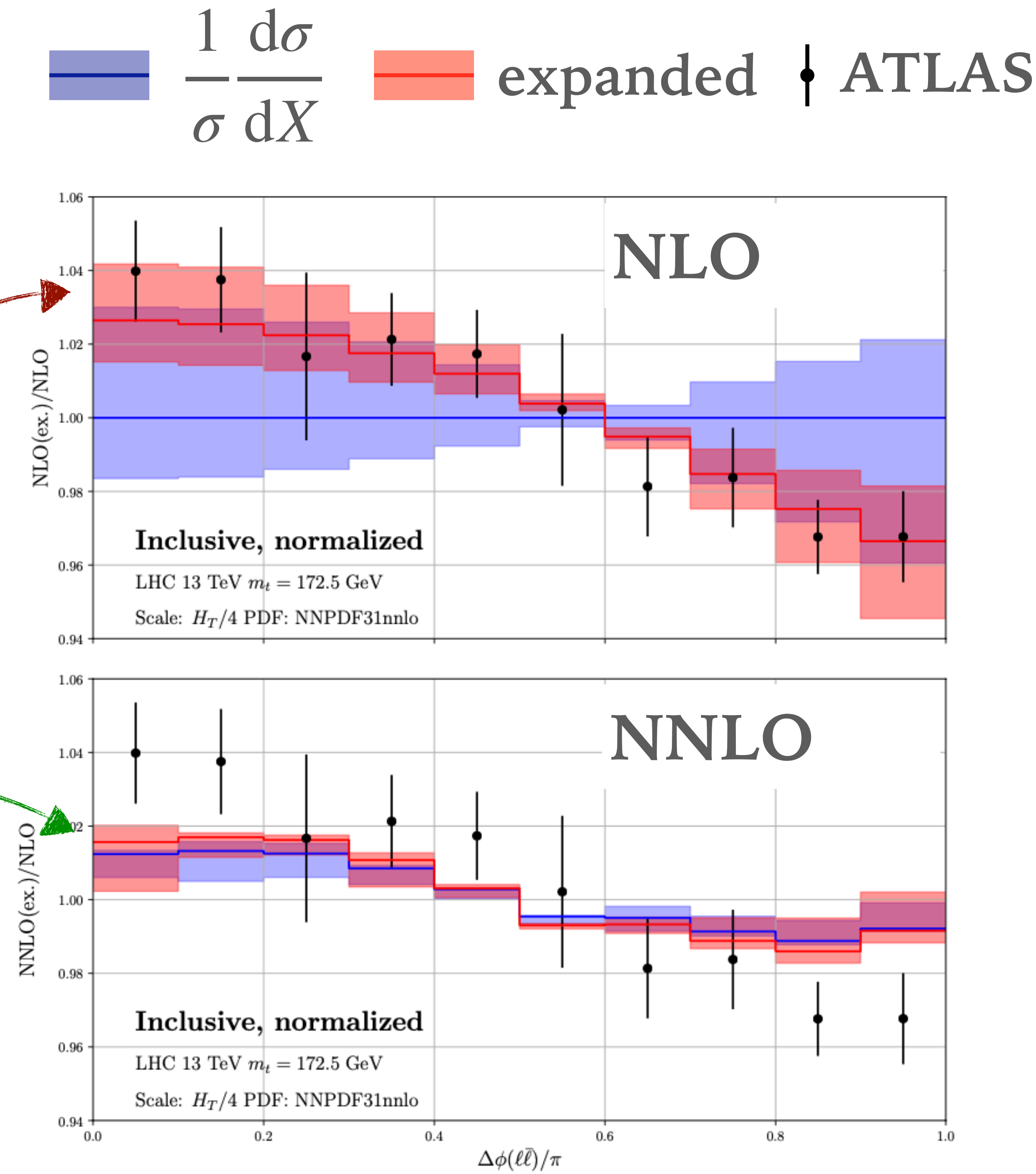
[Czakon, Mitov, Poncelet '20]

- choice in expanding the ratio:

$$R \equiv \frac{1}{\sigma}\frac{d\sigma}{dX} = R^{(0)} + \alpha_s R^{(1)} + \alpha_s^2 R^{(2)} \ldots$$

(formally equivalent)

- fake "agreement" at NLO
  - difference $\sim$ NLO uncertainty!
- both agree @ NNLO
  - predictions robust
  - tension persists in "inclusive"

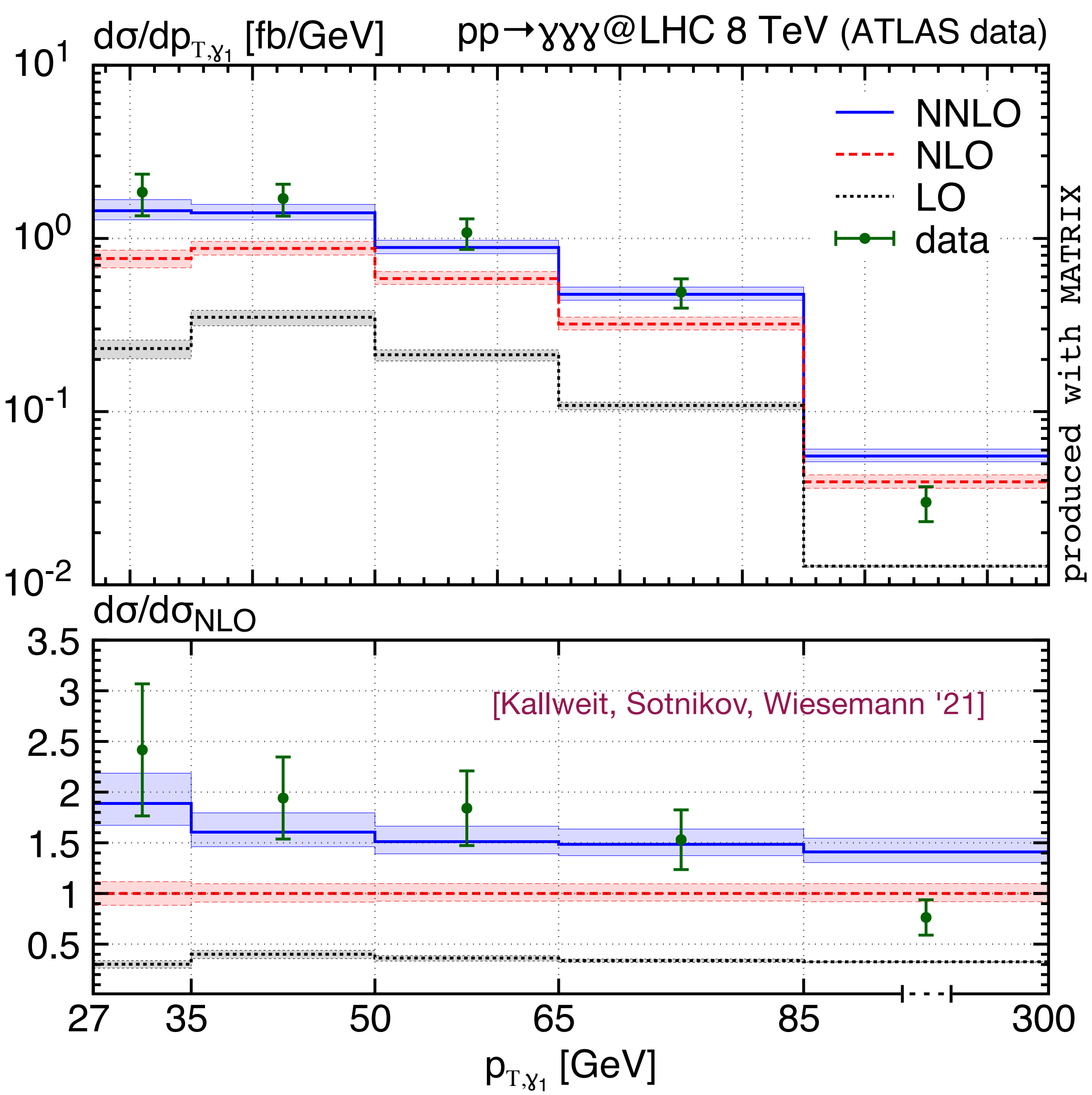


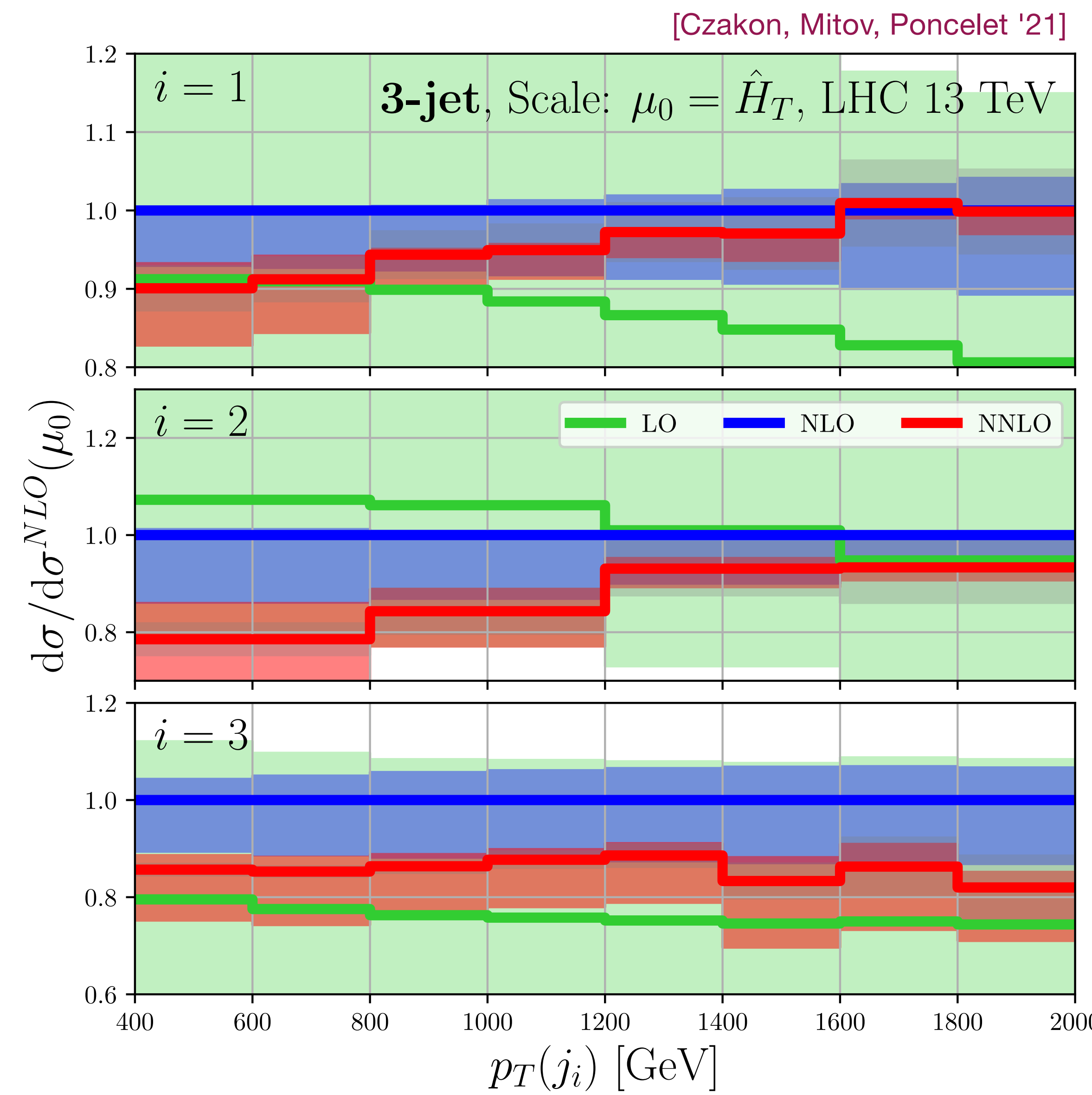
The 2 → 3 Frontier

➤ First results with massless external states:

LH '17 wishlist

$pp \to 3\,\text{jets}$	NLO_{QCD}	$\text{N}^2\text{LO}_{\text{QCD}}$





$pp \to \gamma\gamma\gamma$

$pp \to 3\,\text{jets}$

* *see also:* [Chawdhry, Czakon, Mitov, Poncelet '19]

THE $2 \to 3$ FRONTIER

➤ First results with massless external states:

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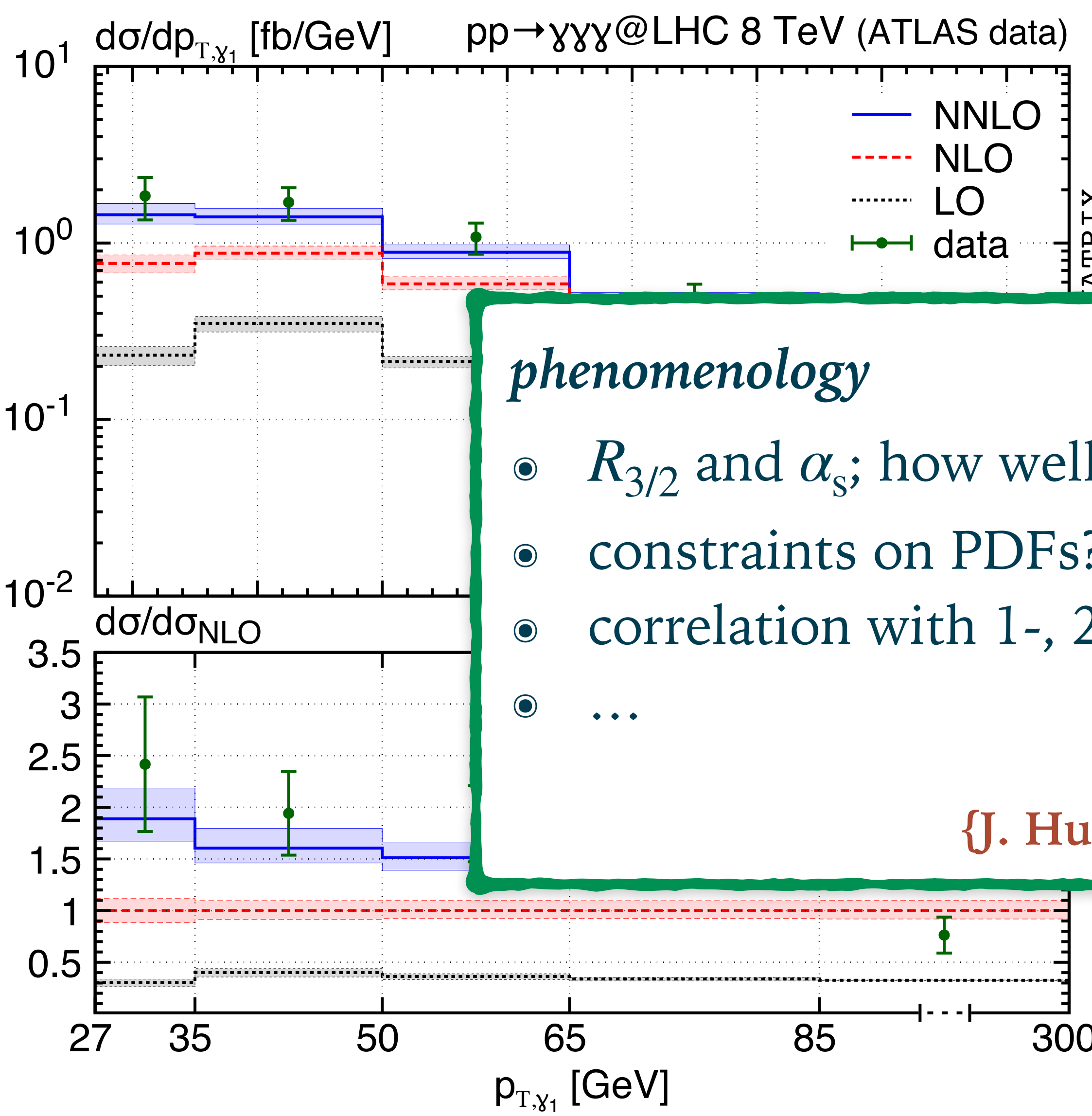


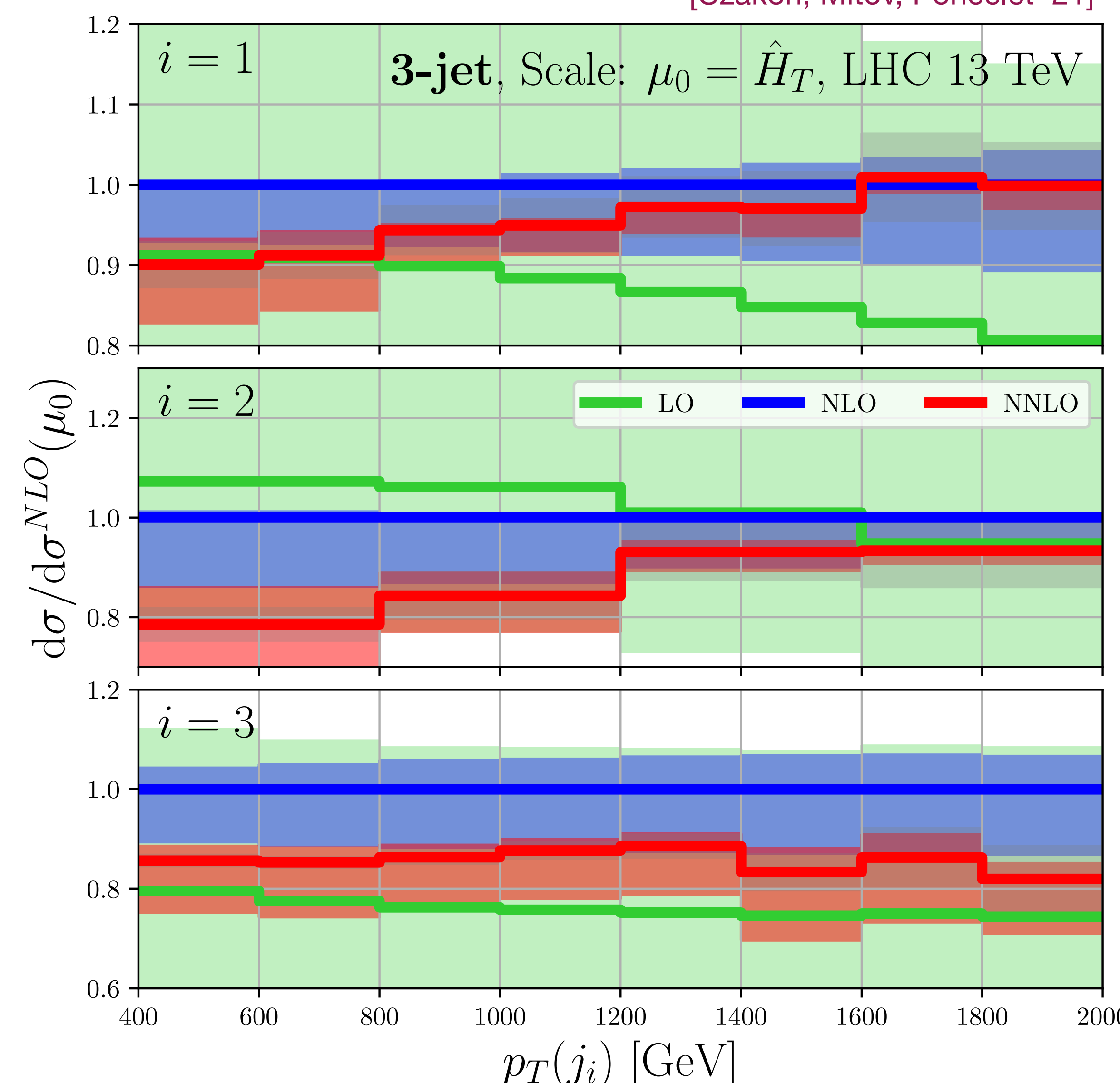
phenomenology

- $R_{3/2}$ and α_s; how well?
- constraints on PDFs?
- correlation with 1-, 2-jet?
- …

{J. Huston}

$pp \to \gamma\gamma\gamma$

[Czakon, Mitov, Poncelet '21]



$pp \to 3\,\text{jets}$

* *see also:* [Chawdhry, Czakon, Mitov, Poncelet '19]

Two-Loop Amplitudes

- What we can do: $2 \to 1$, 2 (also masses), 3 (massless)
- $2 \to 3$ amplitudes ready for phenomenology
  - $\mathrm{pp} \to \gamma\,\gamma\,\gamma$: (LC) [Abreu, Page, Pascual, Sotnikov '20] [Chawdhry, Czakon, Mitov, Poncelet '20]
  - $\mathrm{pp} \to \gamma\,\gamma\,j$: (LC) [Chawdhry, Czakon, Mitov, Poncelet '21] [Agarwal, Buccioni, von Manteuffel, Tancredi '21] (full) [Agarwal, Buccioni, von Manteuffel, Tancredi '21]
  - $\mathrm{pp} \to j\,j\,j$: (LC) [Abreu, Febres Cordero, Ita, Page, Sotnikov '21]
- 5-point with one external mass
  - (planar) [Abreu, Ita, Moriello, Page, Tschernow, Zeng '20] [Papadopoulos, Tommasini, Wever '15] [Canko, Papadopoulos, Syrrakos '20] $(W b\bar{b})$ [Badger, Bayu, Zoia '21]

soon within reach?

- $\mathrm{pp} \to \mathrm{Z/W^{\pm}/H} + j\,j$
- …

NNLO Short Summary

- fully differential NNLO: the new standard for $2 \to 2$ (towards $2 \to 3$)

- These calculations are …

… very complex

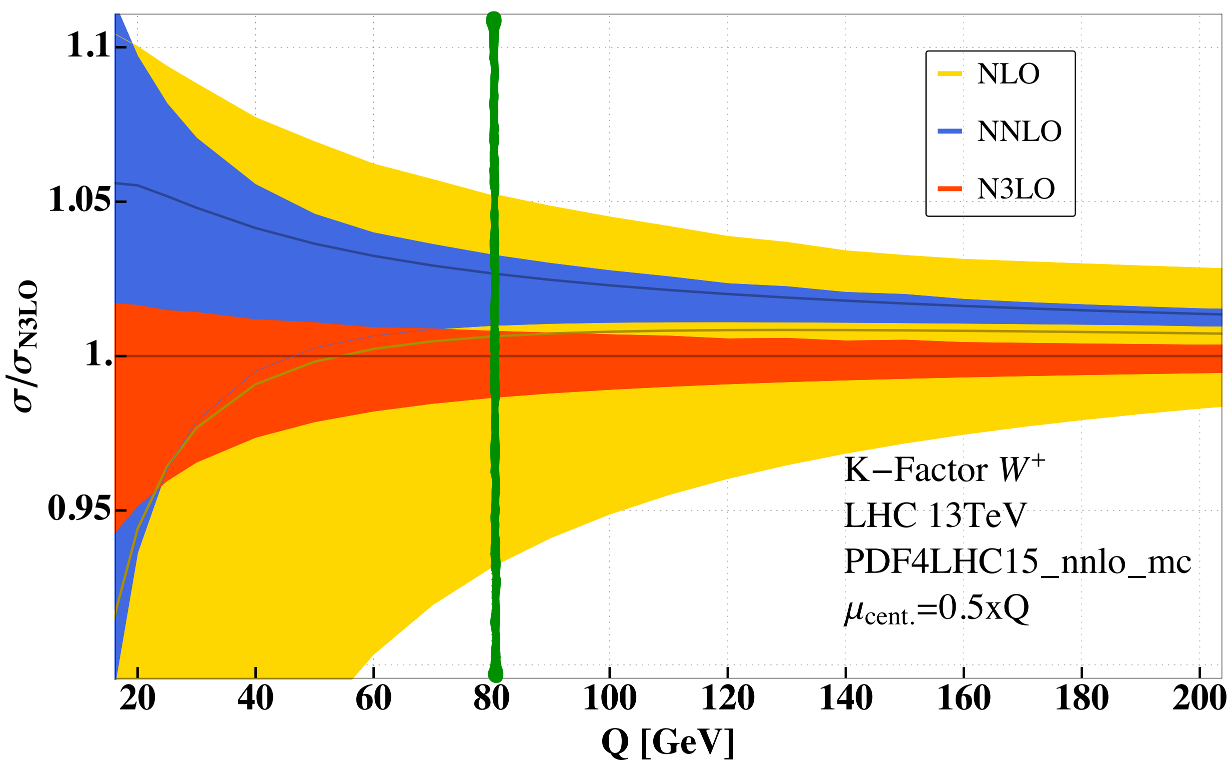
- ⇝ independent methods and/or implementation
- ⇝ validation & benchmark: Drell-Yan (sizeable differences) [Alekhin, Kardos, Moch, Trócsányi '21]
- ⇝ challenges for code releases: usability, quality assurance, …

… CPU-cost intensive

- ⇝ prohibitive for e.g. PDF & α_s fits
- ⇝ fast interpolation grids: APPLfast [APPLgrid, fastNLO, NNLOJET '19]
- ⇝ n-Tuples [LH '15, '17, '19]

N^{3}LO — INCLUSIVE

H [Anastasiou et al. '15] [Mistlberger '18], H(VBF) [Dreyer, Karlberg '16], HH(VBF) [Dreyer, Karlberg '18], DY [Duhr, Dulat, Mistlberger '20]



[Duhr, Dulat, Mistlberger '20]

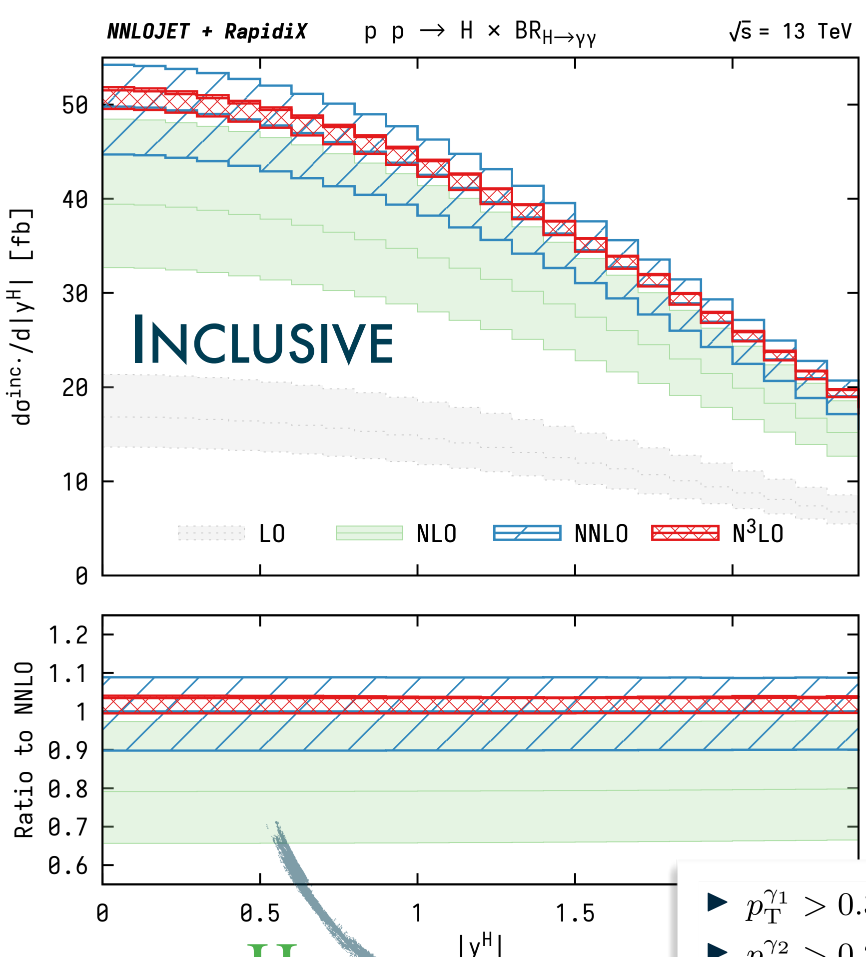
Q/GeV	$K^{\text{N}^3\text{LO}}_{\text{QCD}}$	δ(scale)	δ(PDF+α_S)	δ(PDF-TH)	$\frac{\sigma^{(0)}_{Z+\gamma^*}}{\sigma^{(0)}_{\gamma^*}}$
30	0.952	$^{+1.5\%}_{-2.5\%}$	$\pm4.1\%$	$\pm2.7\%$	1.01
50	0.966	$^{+1.1\%}_{-1.6\%}$	$\pm3.2\%$	$\pm2.5\%$	1.09
70	0.973	$^{+0.89\%}_{-1.1\%}$	$\pm2.7\%$	$\pm2.4\%$	2.16
90	0.978	$^{+0.75\%}_{-0.89\%}$	$\pm2.5\%$	$\pm2.4\%$	415
110	0.981	$^{+0.65\%}_{-0.73\%}$	$\pm2.3\%$	$\pm2.3\%$	7.4
130	0.983	$^{+0.57\%}_{-0.63\%}$	$\pm2.2\%$	$\pm2.2\%$	3.5
150	0.985	$^{+0.50\%}_{-0.54\%}$	$\pm2.2\%$	$\pm2.2\%$	2.6

- **NNLO** $\rightarrow$ **N^{3}LO**:
  $\leftrightarrow$ outside & similar size band?!

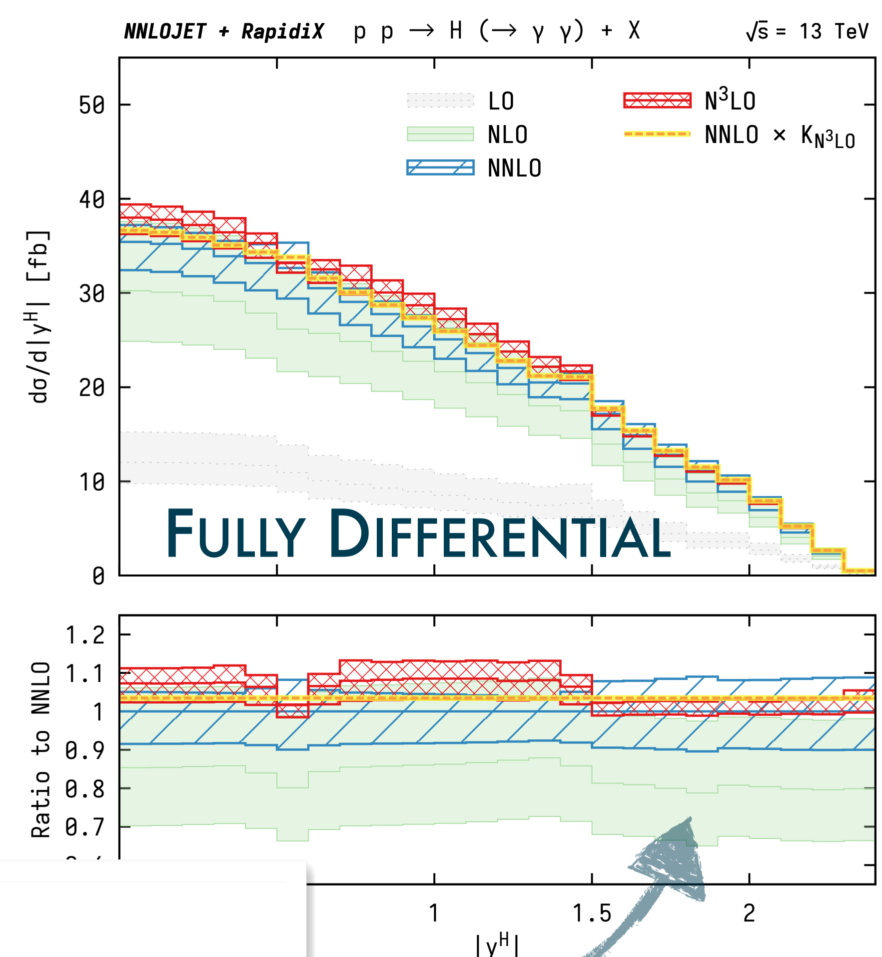
- Missing N^{3}LO **PDFs!**
- Do we need to worry about fitting h.o. corrections?

N^{3}LO — Going Differential

DIS [Currie, Gehrmann, Glover, AH, Niehues, Vogt, Walker], $H[y^H]$ [Cieri, et al. '18, Dulat, Mistlberger, Pelloni '18], $H \to bb$ [Mondini, Schiavi, Williams '19],
H [Chen, Gehrmann, Glover, AH, Mistlberger, Pelloni '21], $H[\sigma^{\text{fid.}}]$ [Billis, et al. '21], $DY[\sigma^{\text{fid.}}]$ [Cieri, et al. '21]



$$\frac{d\sigma^{pp\to H}}{dY}$$



[Chen, Gehrmann, Glover, AH, Mistlberger, Pelloni '21]

- $p_T^{\gamma_1} > 0.35 \cdot m_{\gamma\gamma}$
- $p_T^{\gamma_2} > 0.25 \cdot m_{\gamma\gamma}$
- $|y^\gamma| < 2.37$
- reject $1.37 < |y^\gamma| < 1.52$ (barrel-endcap)
- *photon isolation* in $\Delta R < 0.2$
  $\hookrightarrow \sum_{\Delta R_{i\gamma} < 0.2} p_{T,i} < 0.05 \cdot E_T^\gamma$

$$d\sigma^{pp\to H}$$

N^{3}LO — Going Differential

What is next?

- Drell-Yan !
- $pp \to \gamma\gamma$.

  ingredients:

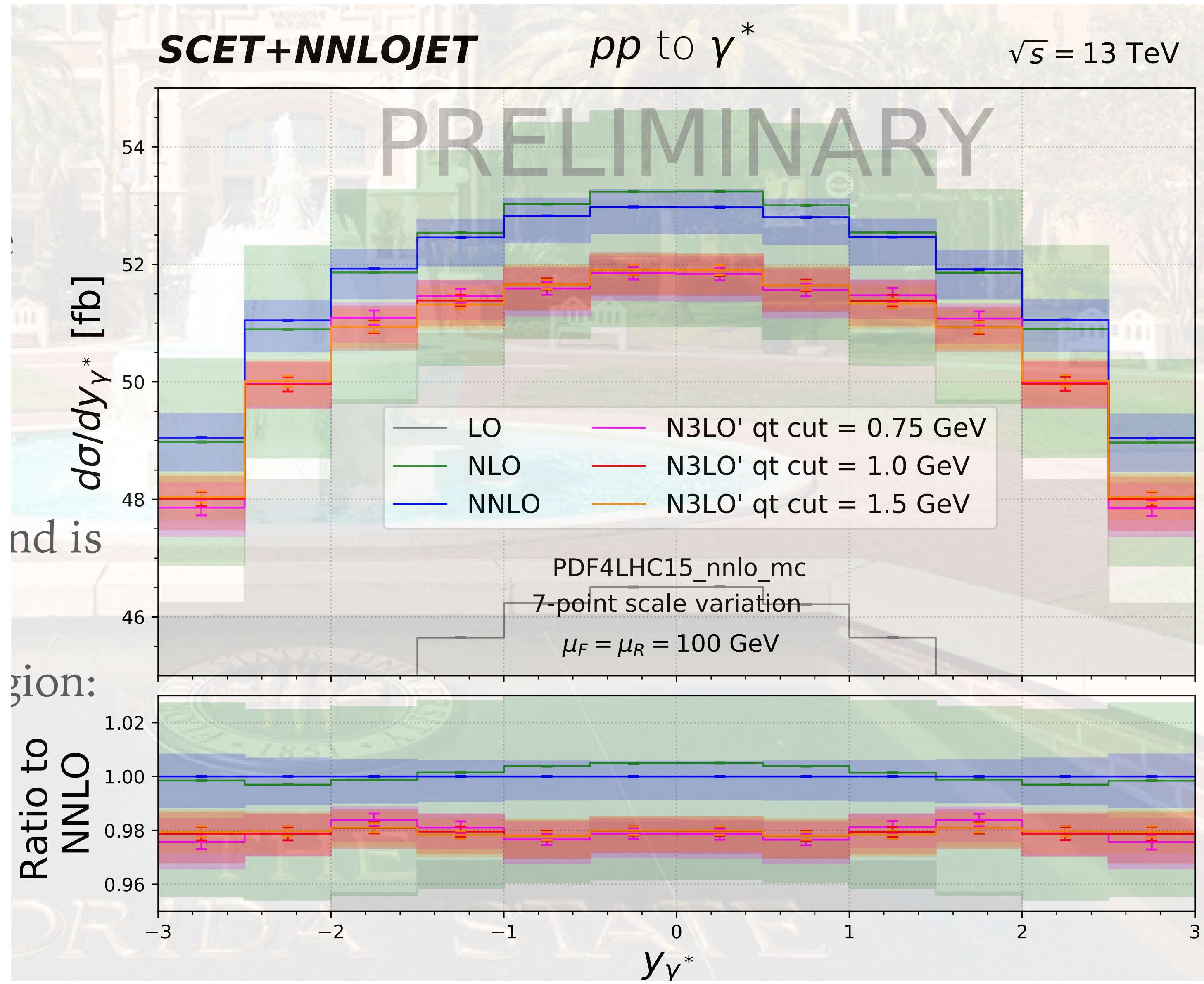
  q_T subtraction

  $pp \to \gamma\gamma j$ @ NNLO

  $pp \to \gamma\gamma$ @ 3-loops

  [Caola, von Manteuffel, Tancredi '20]
- … ?

[talk by X. Chen — Radcor LoopFest 2021]

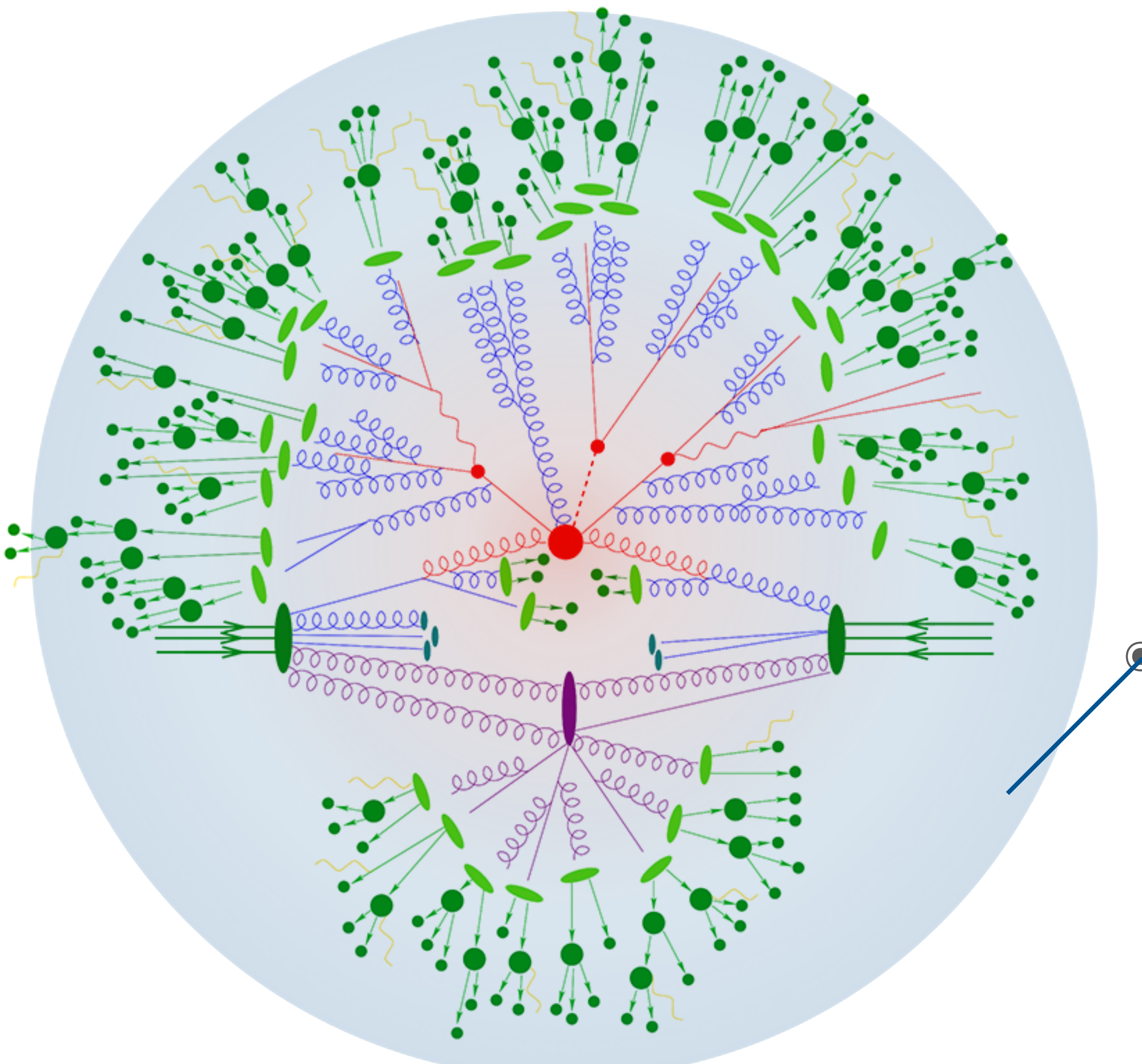


dY

▸ *photon isolation* in $\Delta R < 0.2$

$\hookrightarrow \sum_{\Delta R_{i\gamma} < 0.2} p_{T,i} < 0.05 \cdot E_T^\gamma$

Scattering Reactions @ LHC!



- **Short distance** "hard"
  - high scales: 10^2—10^3 GeV

$$\sigma = \sigma_0 \times \left(1 + \alpha_s + \alpha_s^2 + \alpha_s^3 + \ldots\right)$$

fixed order: LO NLO NNLO N³LO ...

large logs L!

- **Long distance** "soft"
  - low scales: $\mathcal{O}$(few GeV)

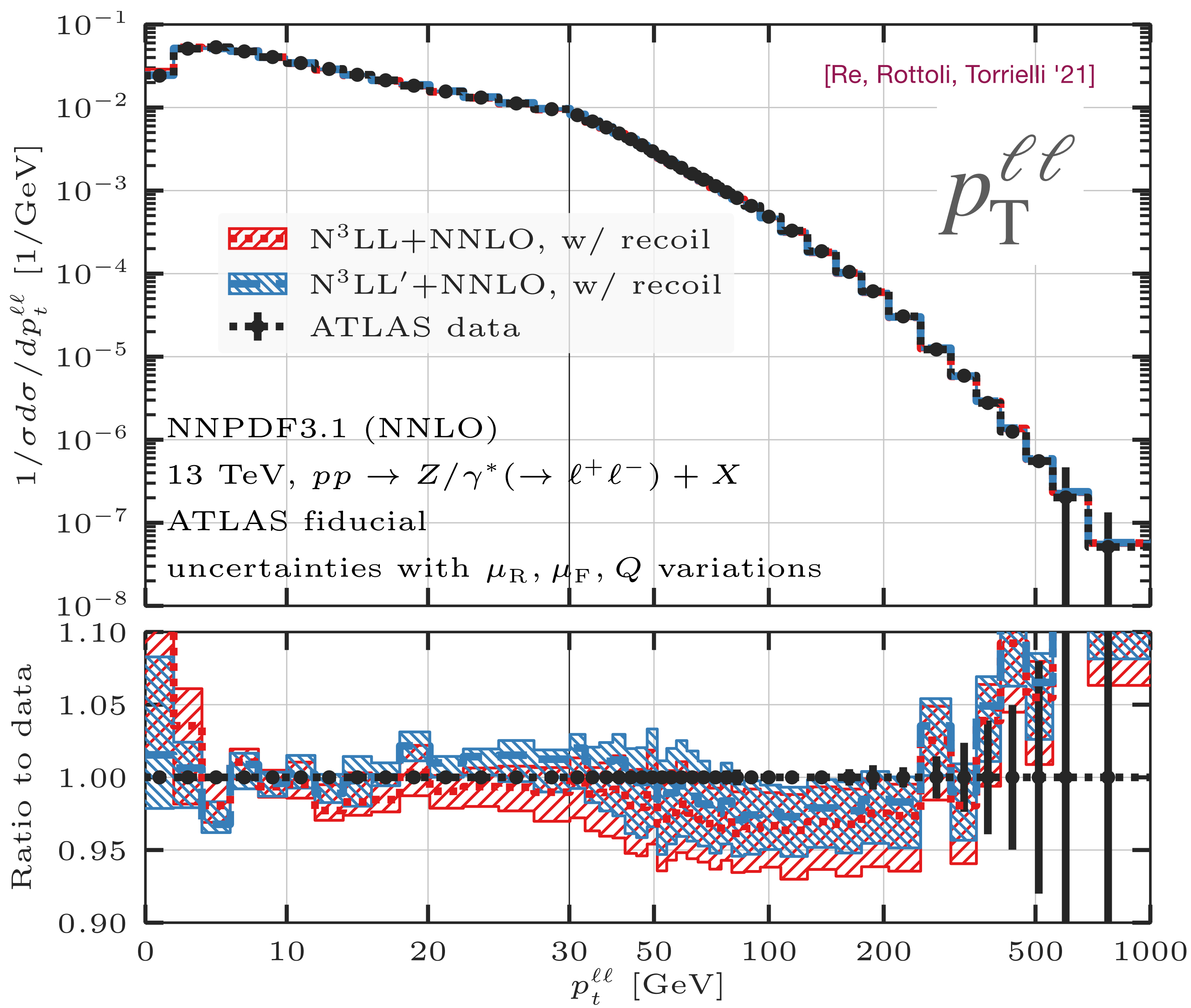
$$\sigma = \sigma_0 \cdot \exp\left(\alpha_s^n L^{n+1} + \alpha_s^n L^n + \alpha_s^n L^{n-1} + \ldots\right)$$

resummation: LL NLL NNLL ...

q_T Distribution @ N3LL'

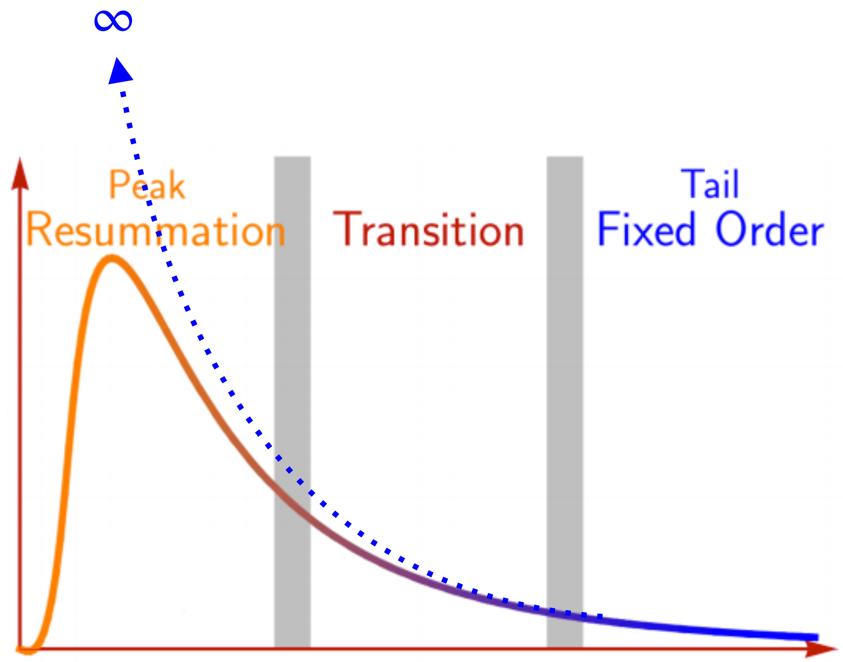
[Becher, Neumann '20; Billis et al. '21; Carmada et al. '21; Re et al. '21]

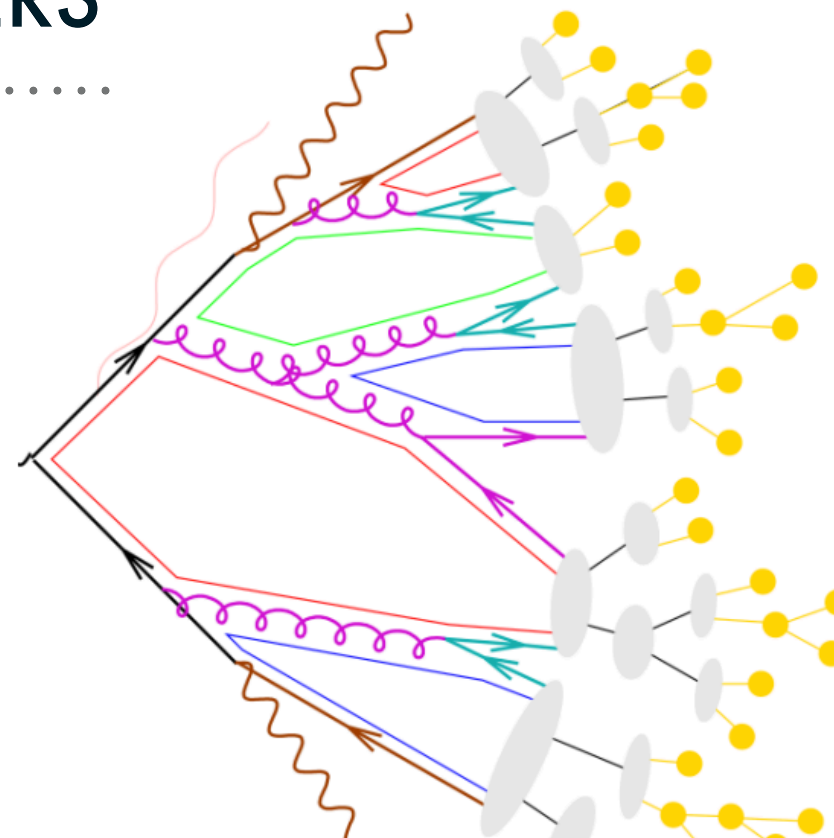
- N3LL' = supplement N3LL with all constant terms of $\mathcal{O}(\alpha_s^3)$
  - ⇝ predict N3LO fiducial cross section [Billis, Dehnadi, Ebert, Michel, Tackmann '21] [Camarda, Cieri, Ferrera '21]



- N3LL'+NNLO improved description of **data** w.r.t **N3LL+NNLO**
- linear power corrections ↔ recoil [Ebert, Tackmann '19]
  (±1-2 % after matching to NNLO)
- reduced uncertainties few-% level across $p_T^{\ell\ell}$

Resummation & Parton Showers





{substructure}

Resummation

inclusive (analytic), tailored to specific observable with high logarithmic accuracy

- q_T N3LL(')
  [Becher, Neumann '20; Billis et al. '21; Carmada et al. '21; Re et al. '21]
- NLL non-global logs
  [Banfi, Dreyer, Monni '21]
- …

Parton Showers (PS)

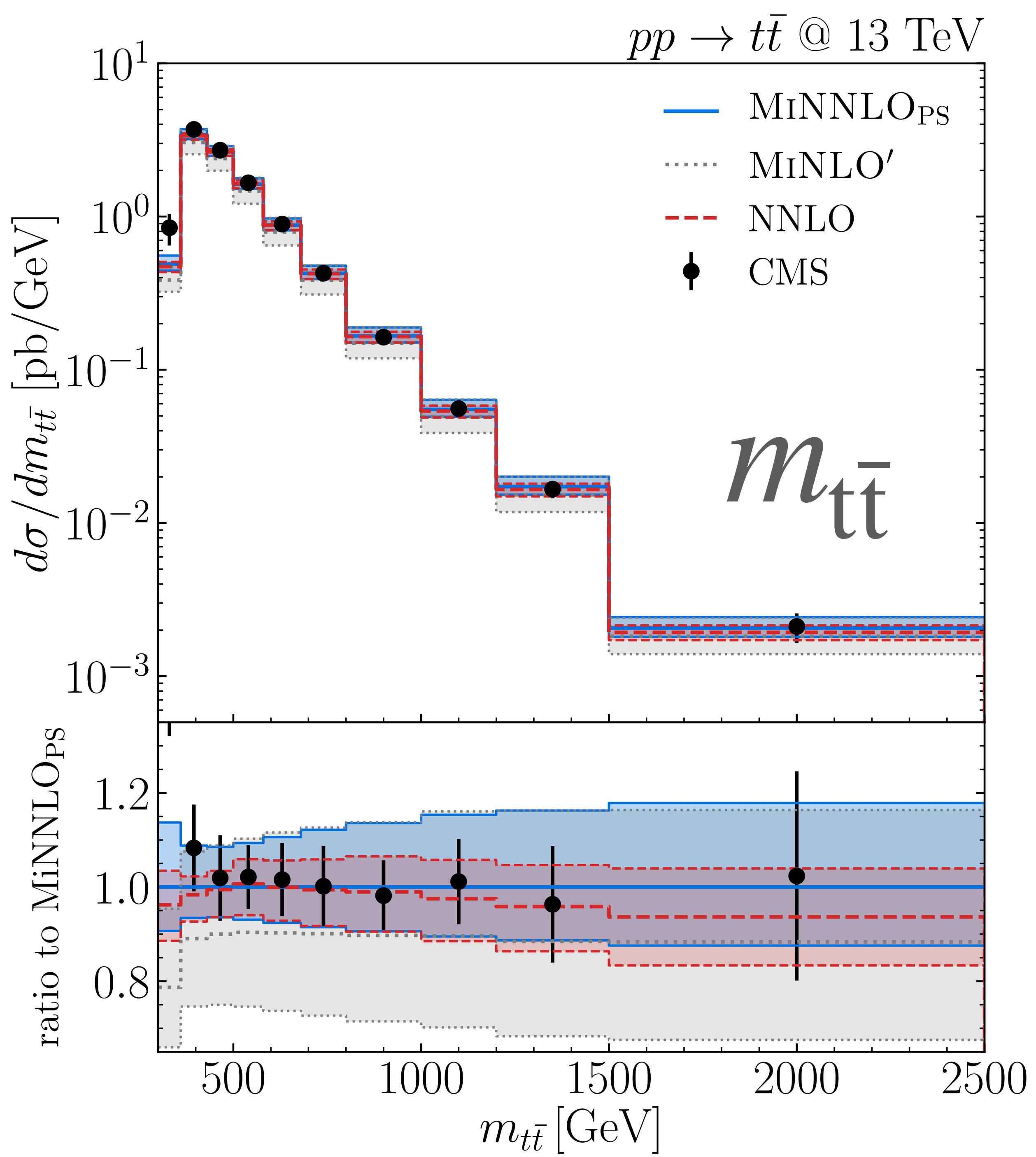
exclusive (MC algorithm), general purpose + non-pertubative models

{Tools & MC}

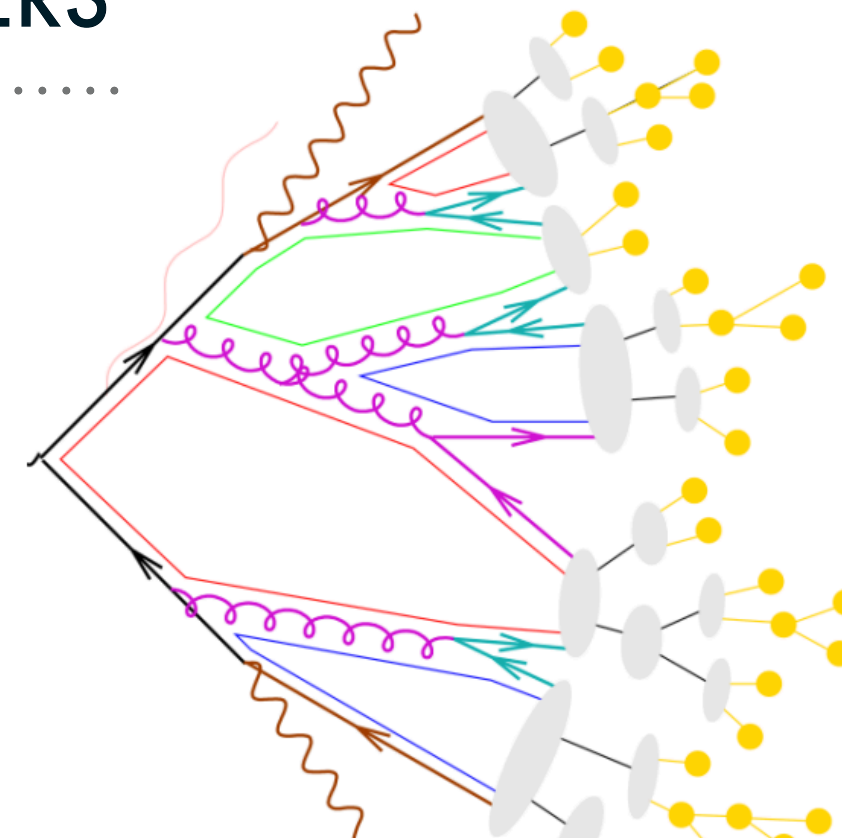
- NNLO + PS: NNLOPS [Hamilton, et al. '12,...] UNNLOPS [Höche, Li, Prestel '14,...] / [Plätzer '12] Geneva [Alioli, Bauer, et al. '13,...] MiNNLOPS [Monni, Nason, Re, Wiesemann, Zanderighi '19,...]

RESUMMATION & PARTON SHOWERS

[Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi '21]



- first NNLO+PS with coloured final state



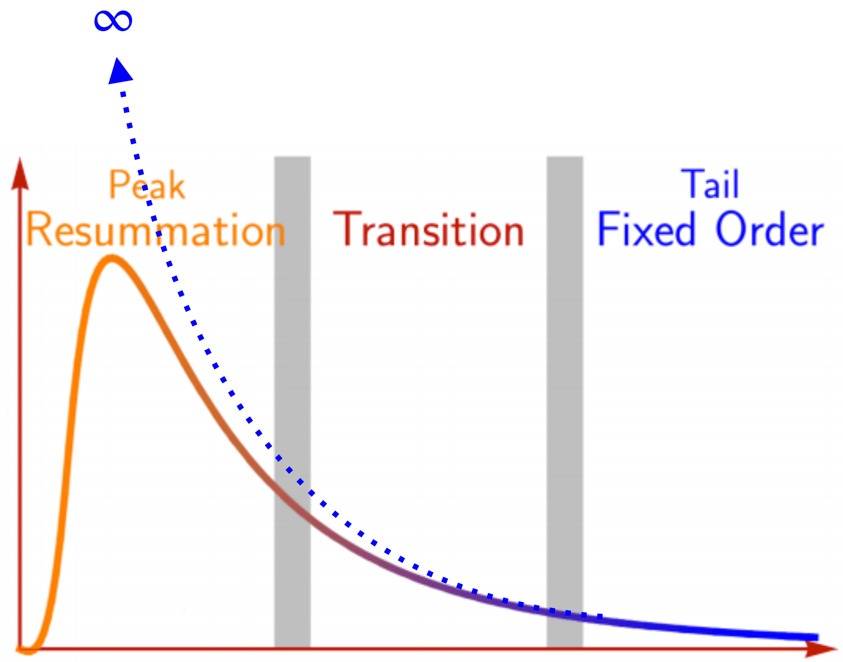
Parton Showers (PS)

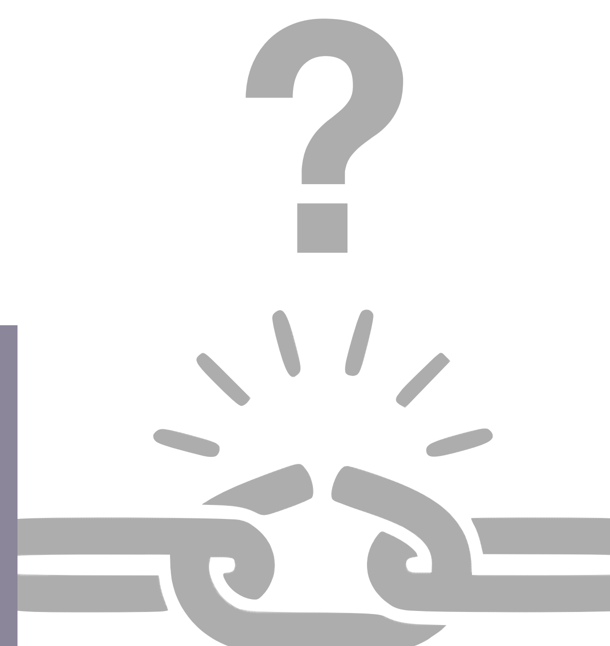
exclusive (MC algorithm),
general purpose
+ non-pertubative models

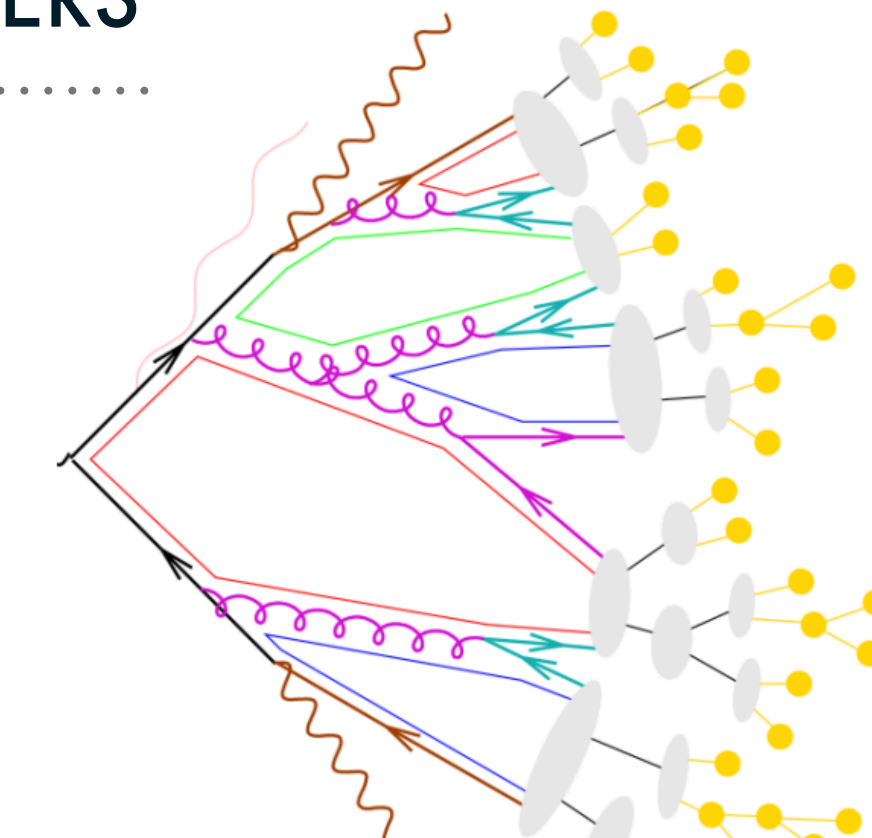
{Tools & MC}

- NNLO + PS: NNLOPS [Hamilton, et al. '12,...] UNNLOPS [Höche, Li, Prestel '14,...] / [Plätzer '12] Geneva [Alioli, Bauer, et al. '13,...] MiNNLOPS [Monni, Nason, Re, Wiesemann, Zanderighi '19,...]

Resummation & Parton Showers







Resummation

inclusive (analytic), tailored to specific observable with high logarithmic accuracy

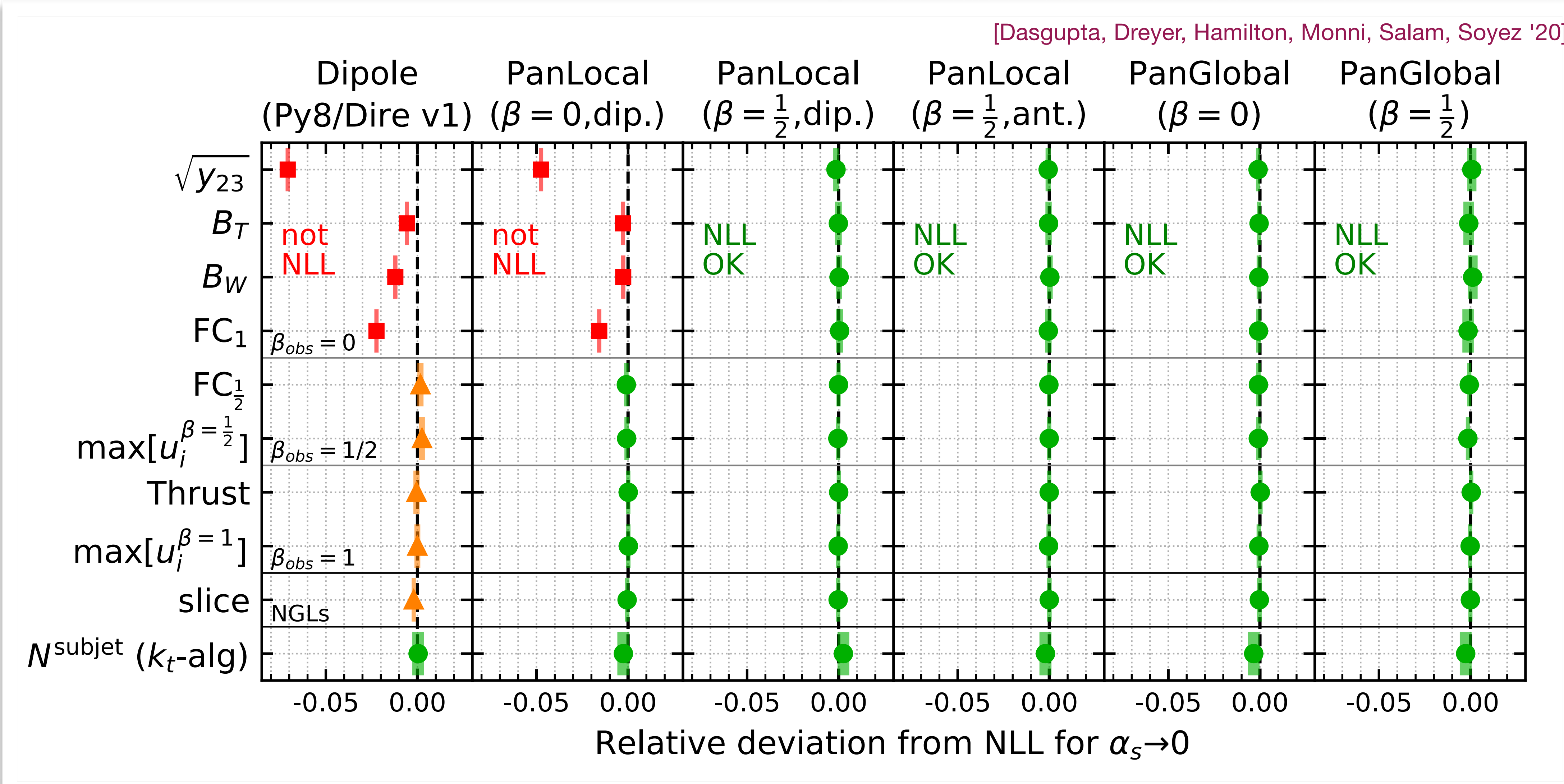
Parton Showers (PS)

exclusive (MC algorithm), general purpose + non-pertubative models

- What is the (logarithmic) accuracy of parton showers?
- Is it (N)LL? For what observable(s)?
- crucial to understand ⇝ design new PS [Forshaw, Holguin, Plätzer '20] [Nagy, Soper '19] [...] [Dasgupta, et a. '20; Hamilton, et al. '20; Karlberg, et al. '21]

INVESTIGATING SHOWER ACCURACY*

➤ Compare PS to NLL observables: $\alpha_s \to 0$ for fixed $\alpha_s L$



◉ Is this observables set "complete"? How to extend it for pp?

◉ Can this test be adopted by other groups?

* *see also:* [Nagy, Soper, '20]

Theory uncertainties pt. 1

- increasingly urgent to have more robust uncertainty estimates
  - e.g. for theory uncertainties in PDF fits

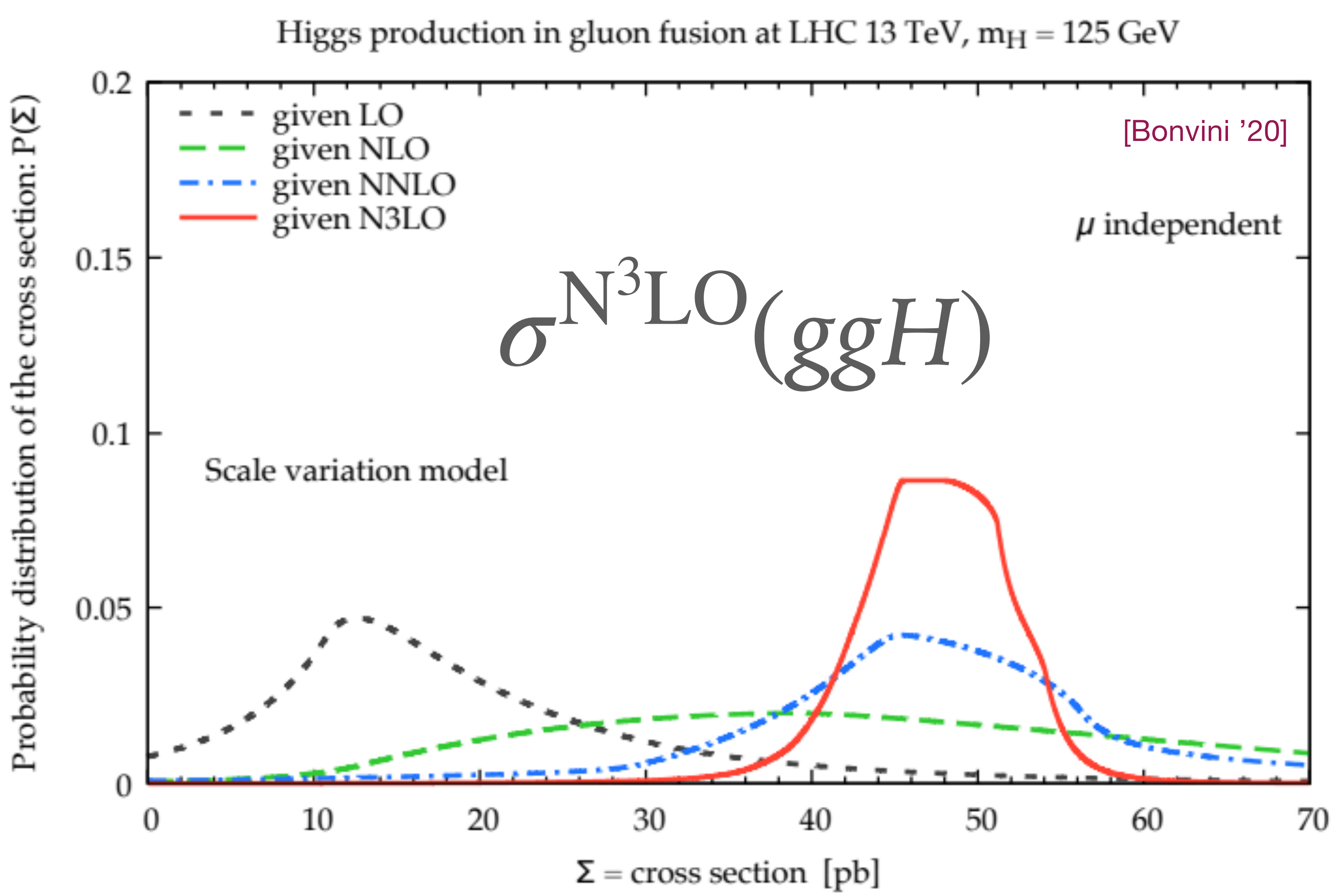
- scale ambiguities in jets ($p_{T,j}$ v.s. $\hat{H}_T$)
- scales in ratios:
  - top spin correlation (to expand or not @ NLO)
  - $p_T(Z)$ / $p_T(W)$ (correlate: very small residual uncertainties)
  - ang. coefficients A_i (un-correlate in the *same process*)
- nuisance parameters in p_T res.

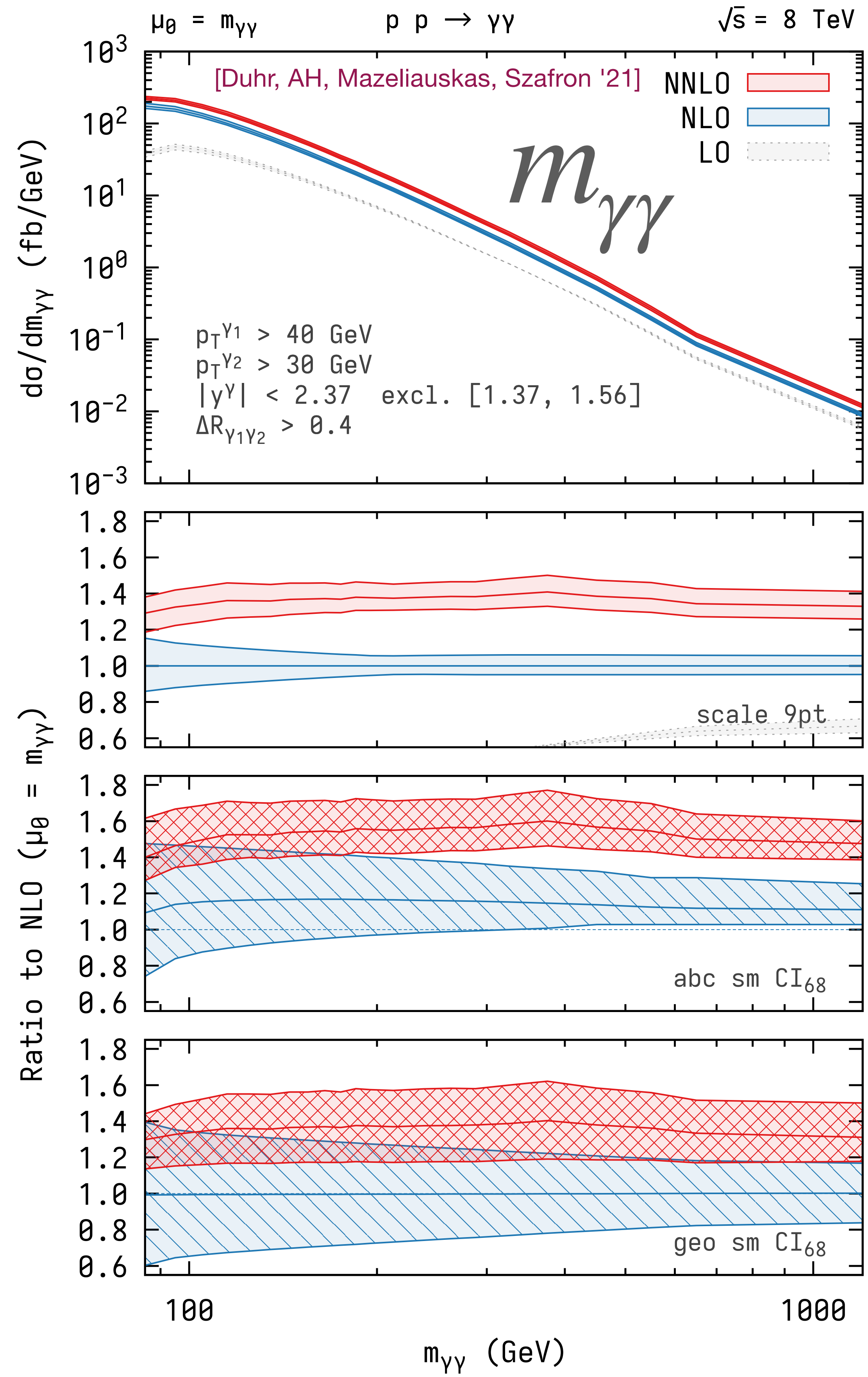
THEORY UNCERTAINTIES PT.2

➤ alternative approaches

⇝ statistical interpretation?

Bayesian model [Cacciari, Houdeau '11]





◉ PDF ↔ model and priors

◉ treatment of correlations?

Final remarks.

- **Remarkable progress** in precision calculations:
  - $2 \to 8$ @ NLO, $2 \to 3$ @ NNLO, $2 \to 1$ @ N^3LO
- still many **issues & challenges** $\Rightarrow$ discussions sessions!
- More topics to consider: https://phystev.cnrs.fr/wiki/2021:topics
  - mixed QCD-EW corrections.
  - $p_T(Z)$—in the world of per-cent precision
    - ➡ m_b effects, QED ISR, NP effects, …
  - wishlist: what is needed for HL-LC, 100 TeV, EIC?
  - … **your ideas!**

Enjoy (virtual) Les Houches!