

QCD THEORY FOR COLLIDERS

XXIX International Symposium on Lepton Photon Interactions at High Energies

LP²I9

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Lepton Photon 2019 — Toronto, August 8th 2019

DISCLAIMER

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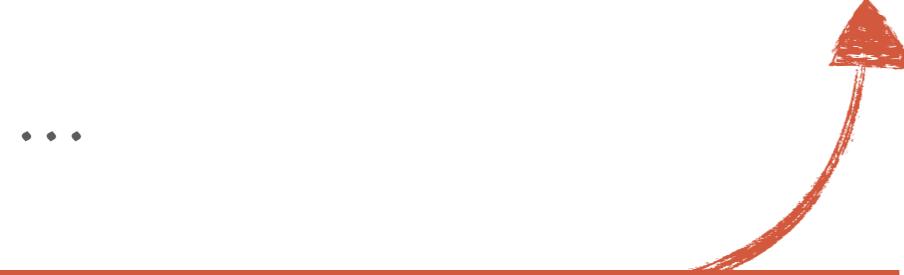
- *tremendous progress in QCD calculations*
- *impossible to cover everything*
- *personal selection of recent results*
- *highlight trends and future directions*

FOCUS: PRECISION QCD

WHY PRECISION?

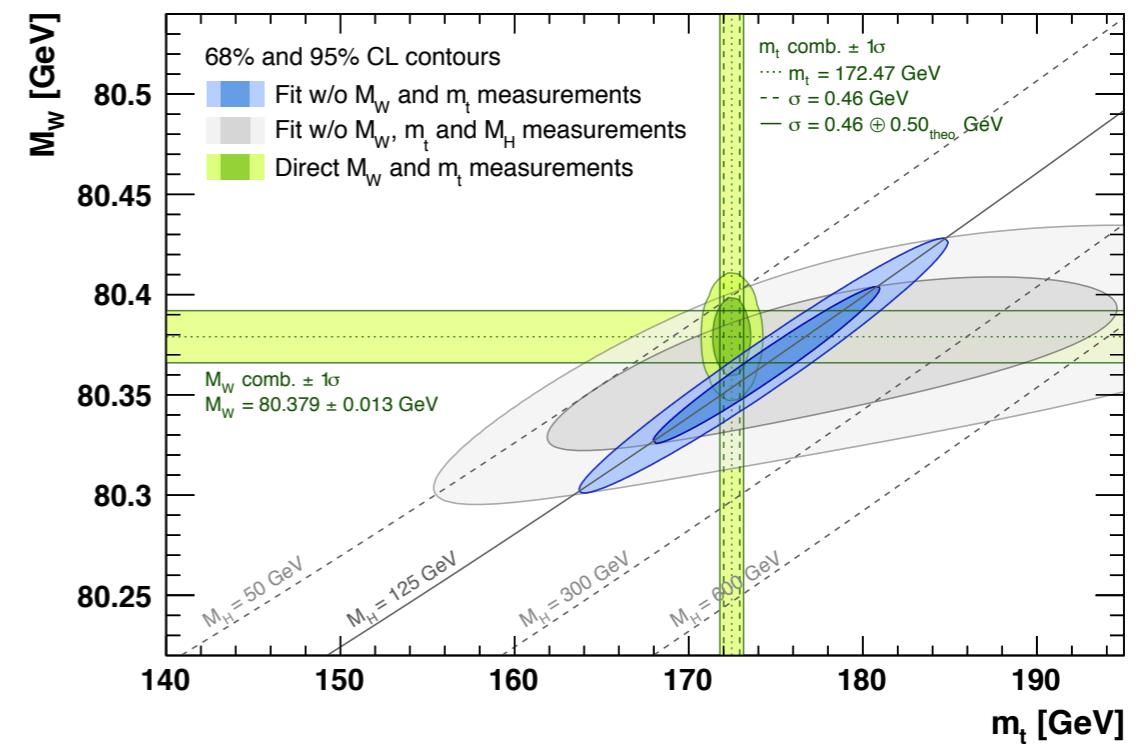
NEW PHYSICS — HIDING IN SMALL & SUBTLE EFFECTS?

- *interaction weak*
- *wide resonance*
- *too heavy*
- *shape distortion*
- *challenging signature*
- ...



requires solid understanding
and control of SM backgrounds

PRECISION MEASUREMENTS & INDIRECT SEARCHES



- constrained system
- self consistent?

A grey circle containing a red question mark, with two green wavy lines extending from its sides, symbolizing the search for consistency in the theory.

precision theory
for
“standard candles”

QUANTUM CHROMODYNAMICS

$$\mathcal{L} = \frac{1}{4g^2} G_{\mu\nu}^\alpha G_{\mu\nu}^\alpha + \sum_j \bar{q}_j (i\gamma^\mu D_\mu + m_j) q_j$$

where $G_{\mu\nu}^\alpha = \partial_\mu A_\nu^\alpha - \partial_\nu A_\mu^\alpha + i f_{bc}^{~a} A_\mu^b A_\nu^c$

and $D_\mu = \partial_\mu + i t^a A_\mu^a$

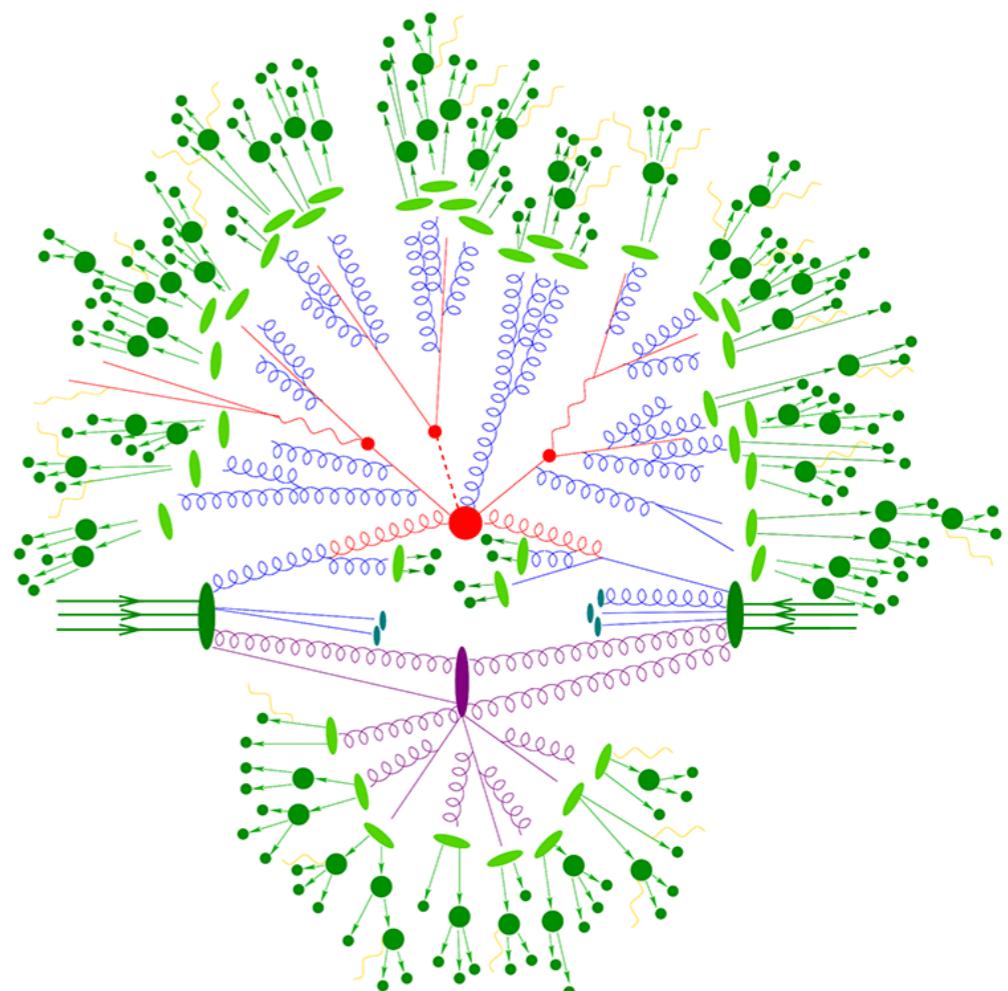
That's it!

“

Quantum chromodynamics is conceptually simple.
Its realization in nature, however,
is usually very complex.
But not always.

-Frank Wilczek

- QCD: strongly coupled



QCD @ HIGH MOMENTUM TRANSFER

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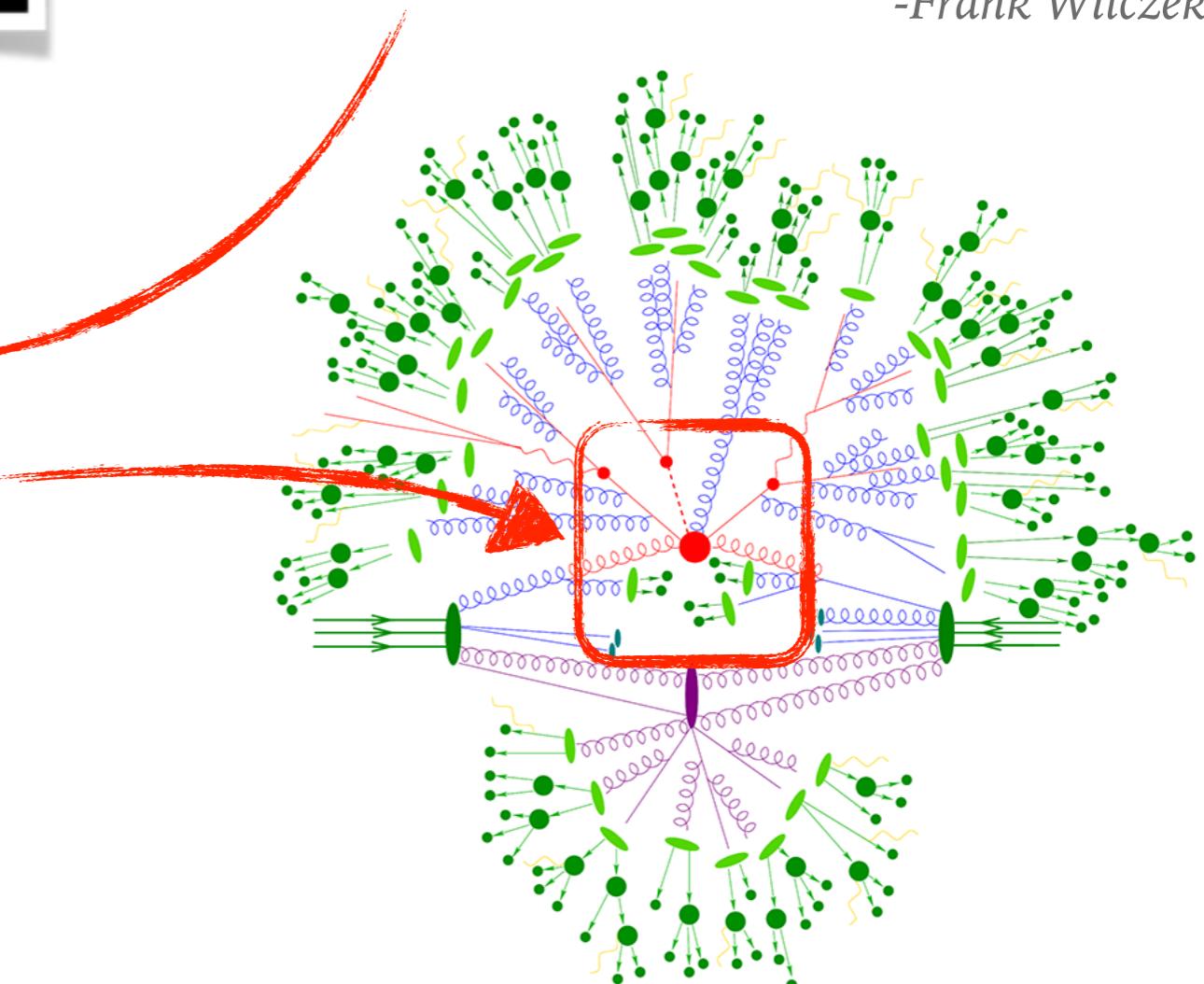
and $D_\mu \equiv \partial_\mu + i t^a A_\mu^a$

That's it!

- QCD: strongly coupled
- simplifications @ high momentum transfer
 1. *asymptotic freedom*
 2. *factorization*

“ Quantum chromodynamics is conceptually simple. Its realization in nature, however, is usually very complex. **But not always.**

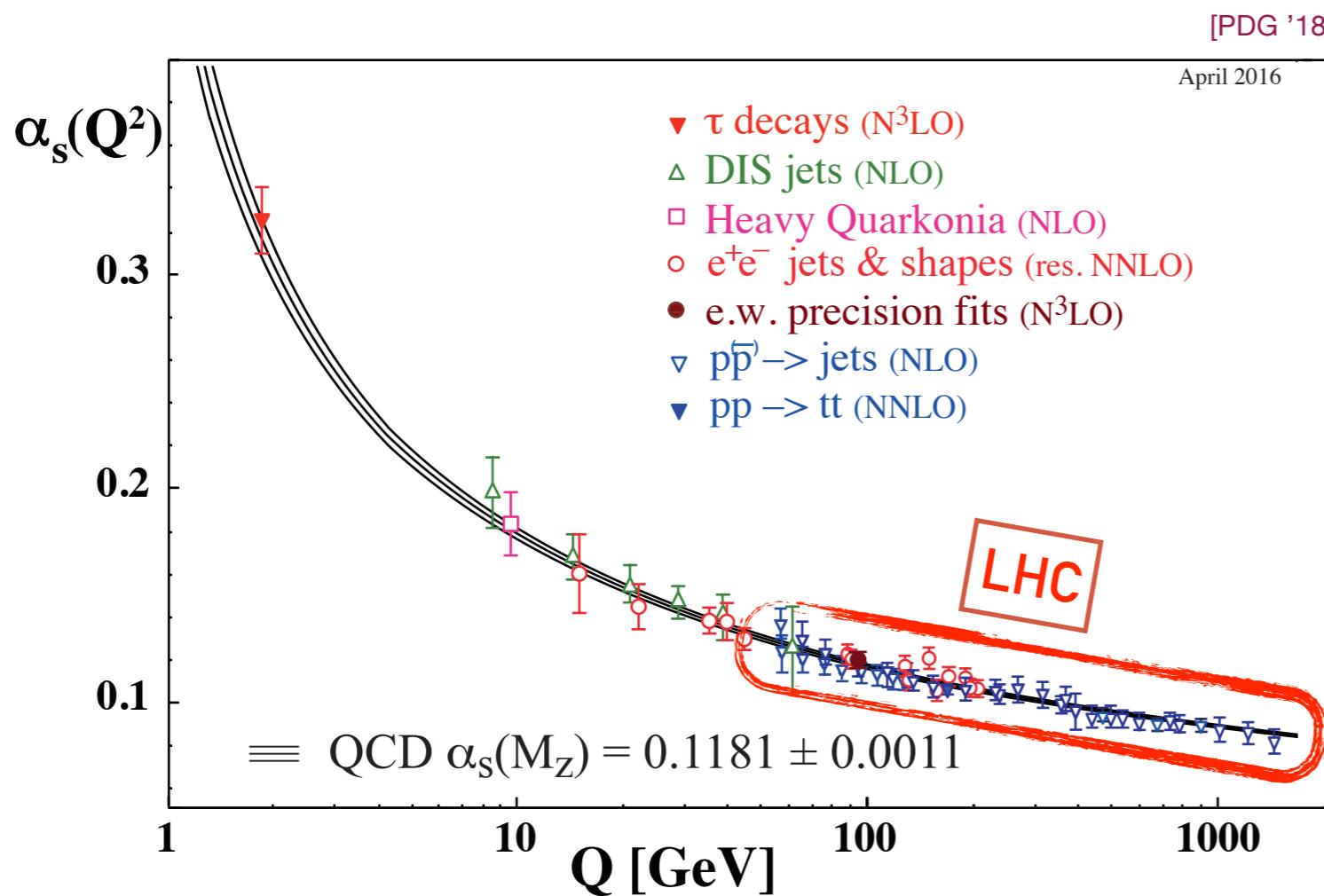
-Frank Wilczek



1. ASYMPTOTIC FREEDOM

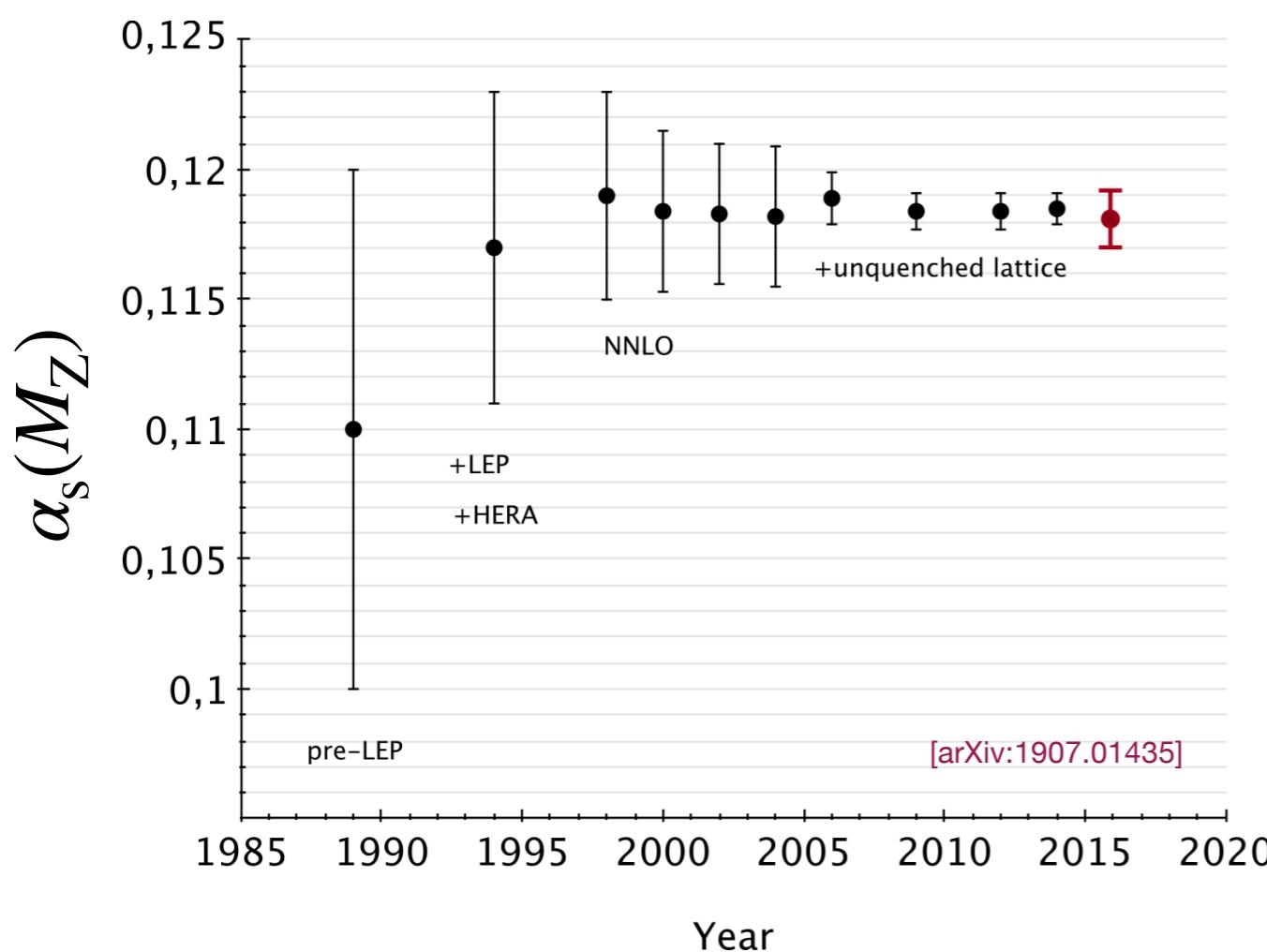
The strong coupling runs

$$Q^2 \frac{d\alpha_s}{dQ^2} = \beta(\alpha_s), \quad \beta(\alpha_s) = -\alpha_s^2(b_0 + b_1\alpha_s + \dots)$$



- known to 5-loops (b_4)
[Baikov, Chetyrkin, Kühn '17]
[Luthe et al. '16] [Herzog et al. '17]
- single free parameter in $m_q \rightarrow 0$ limit
- validation across three orders in magnitude!
- perturbative @ high scales

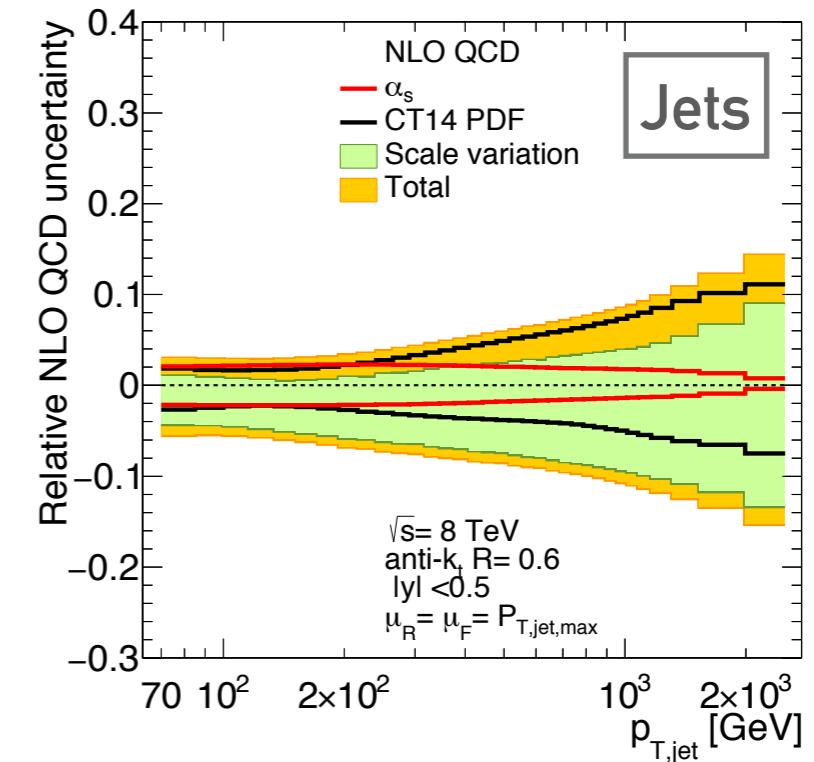
1. ASYMPTOTIC FREEDOM — STRONG COUPLING



$$\alpha_s(M_Z) = 0.1181 \pm 0.0011$$

- least precisely known ($\sim 1\%$) of all fundamental couplings
- **sub-%**: lattice(?), Giga/Tera-Z, ...

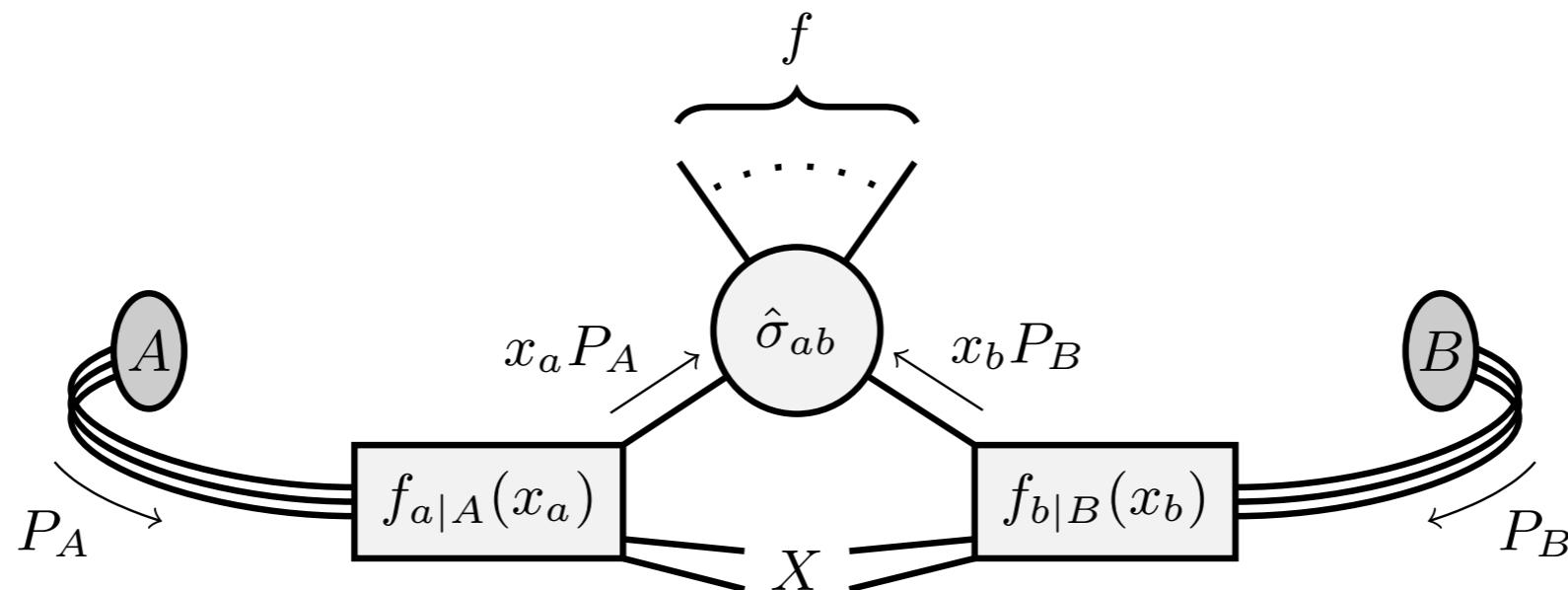
impacts virtually all processes at the LHC



Higgs

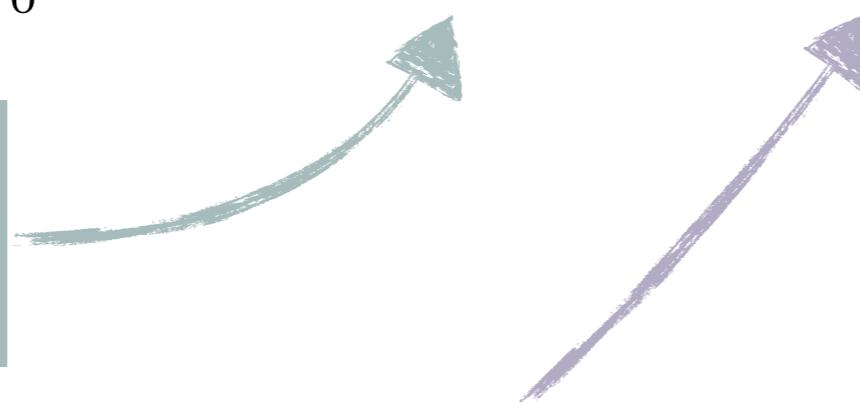
Process	$\sigma (\text{pb})$	$\delta \alpha_s (\%)$	PDF + $\alpha_s (\%)$	Scale (%)
ggH	49.87	± 3.7	-6.2 +7.4	-2.61 + 0.32
tH	0.611	± 3.0	± 8.9	-9.3 + 5.9
Channel	$M_H [\text{GeV}]$	$\delta \alpha_s (\%)$	Δm_b	Δm_c
H \rightarrow c \bar{c}	126	± 7.1	$\pm 0.1\%$	$\pm 2.3\%$
H \rightarrow gg	126	± 4.1	$\pm 0.1\%$	$\pm 0\%$

2. FACTORIZATION



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

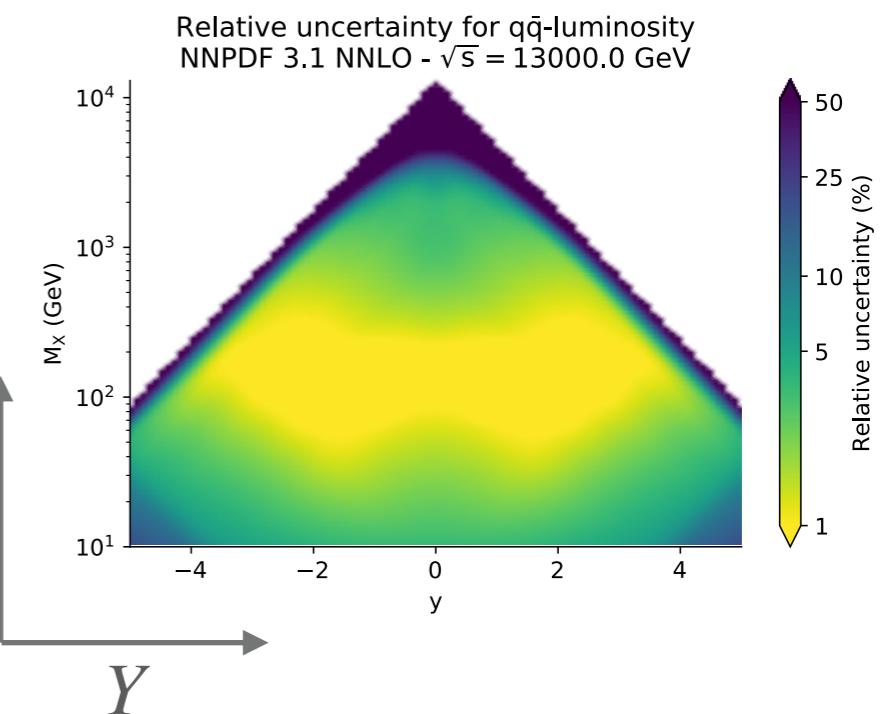
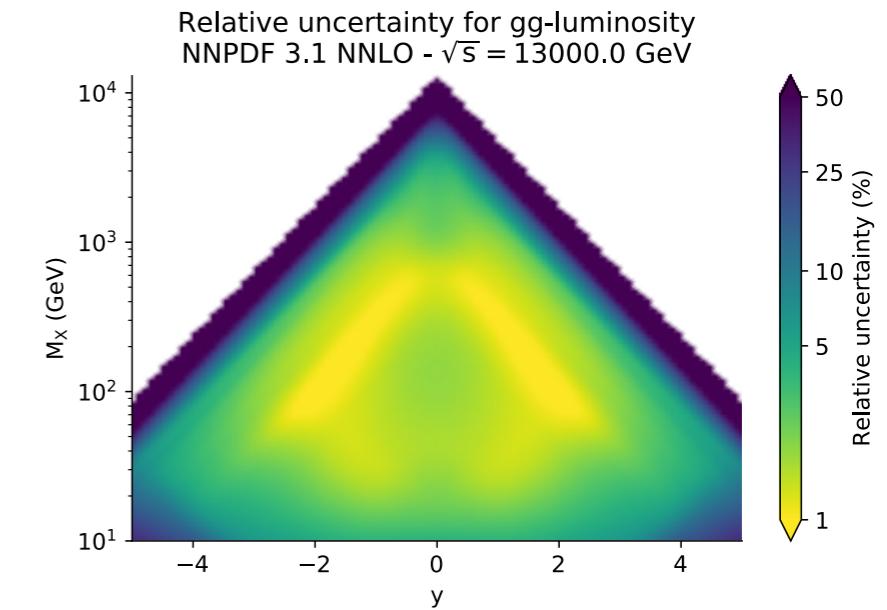
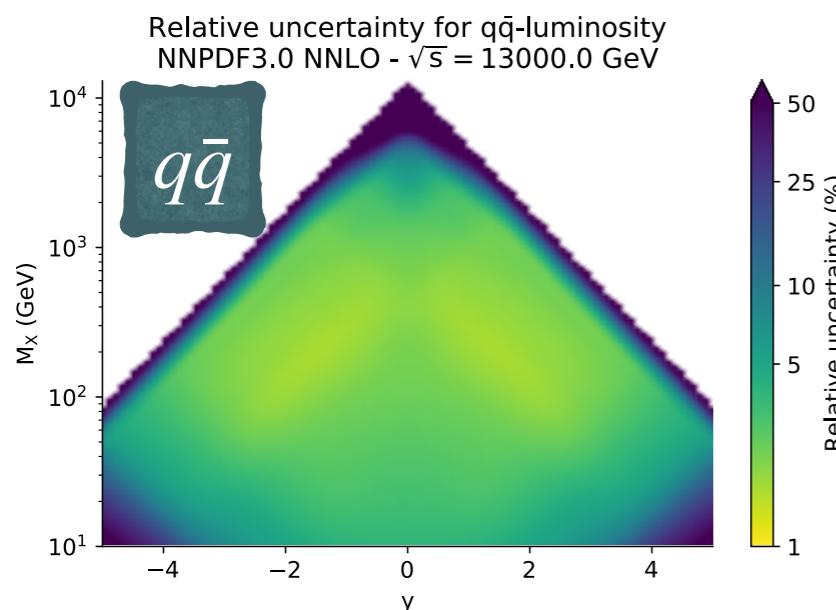
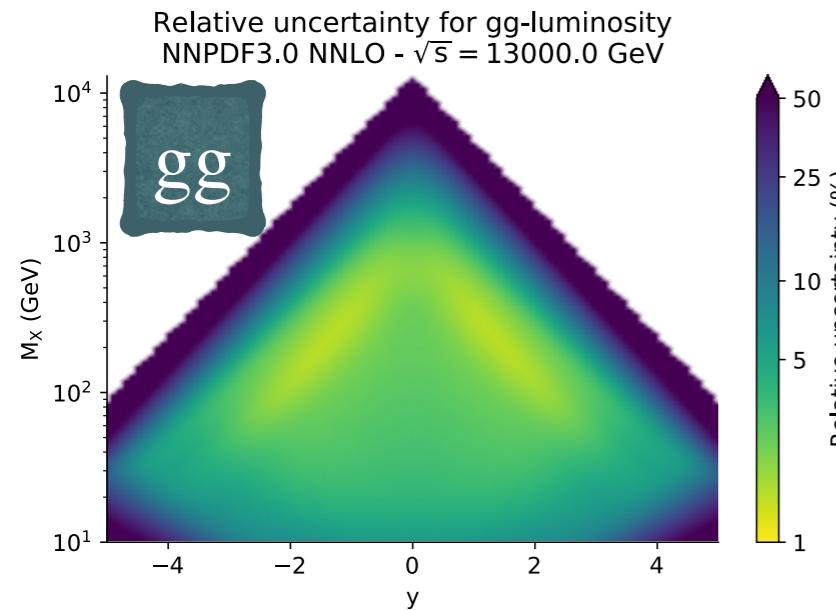
parton distribution functions
(non-perturbative, universal)



hard scattering
(perturbation theory)

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

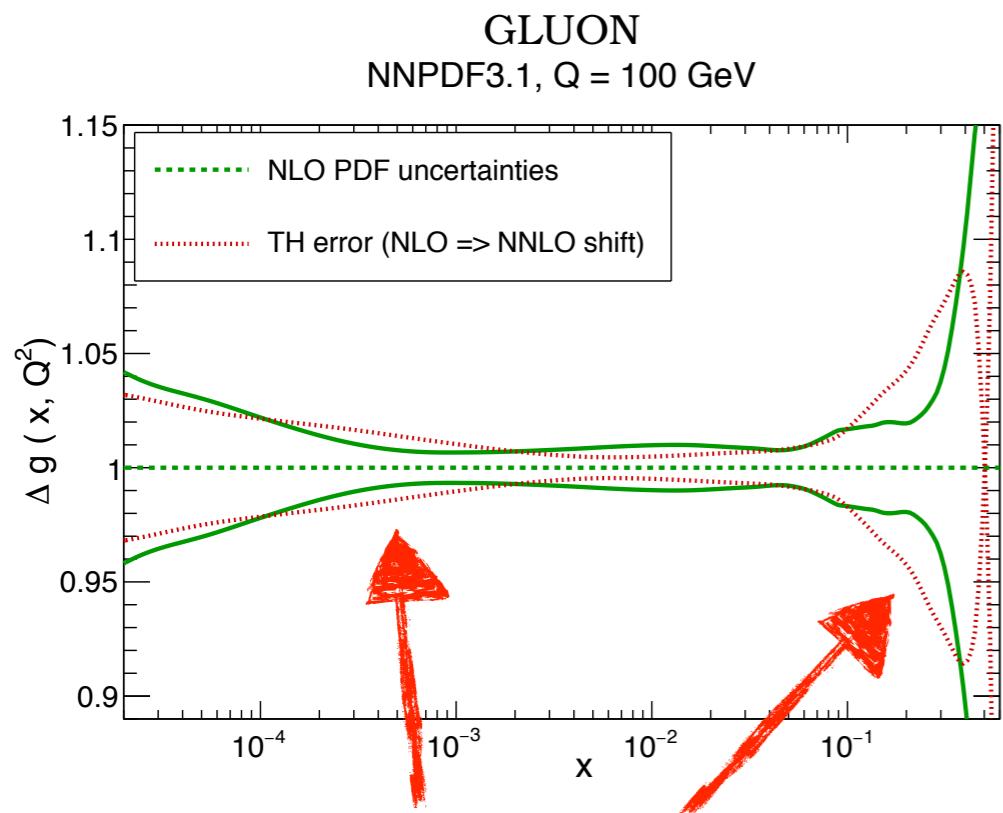
2. FACTORIZATION — PARTON DISTRIBUTION FUNCTIONS



- uncertainties $\sim 1\text{-}2\%$ at central rapidity & $100 \text{ GeV} \lesssim M_x \lesssim 1 \text{ TeV}$

2. FACTORIZATION — PDFs & MHOU

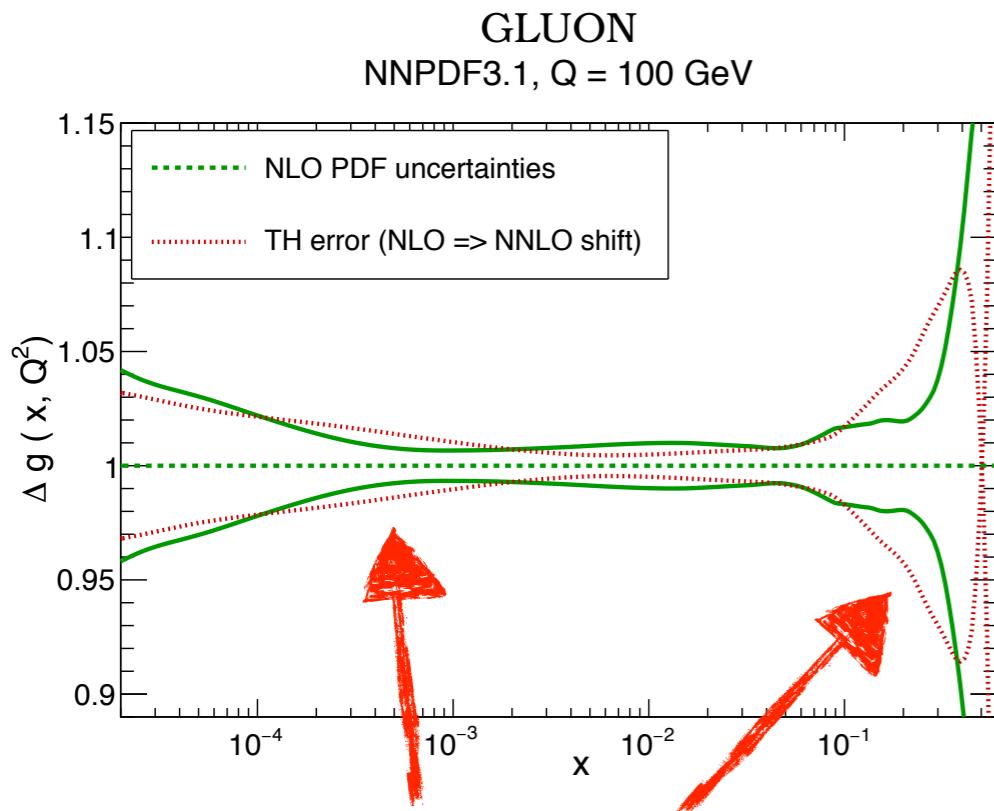
[NNPDF '19]



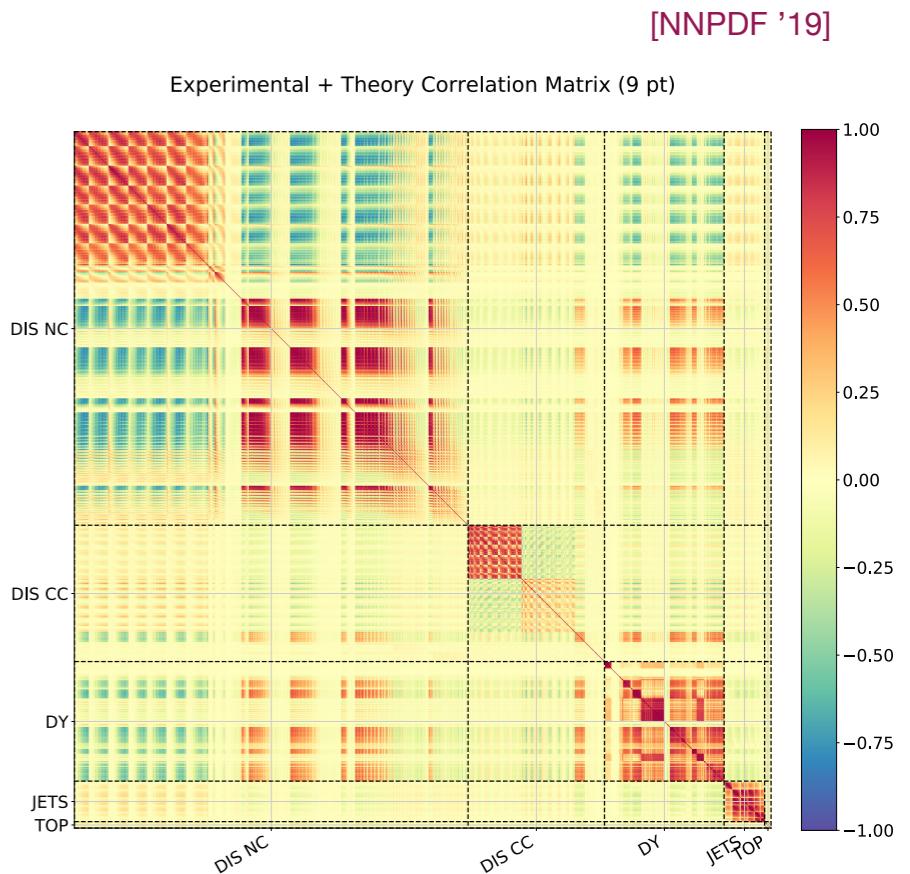
- missing higher order uncertainties (MHOU) not included in PDF fits
- becoming more and more **urgent**

[Harland-Lang, Thorne '19] [NNPDF '19]

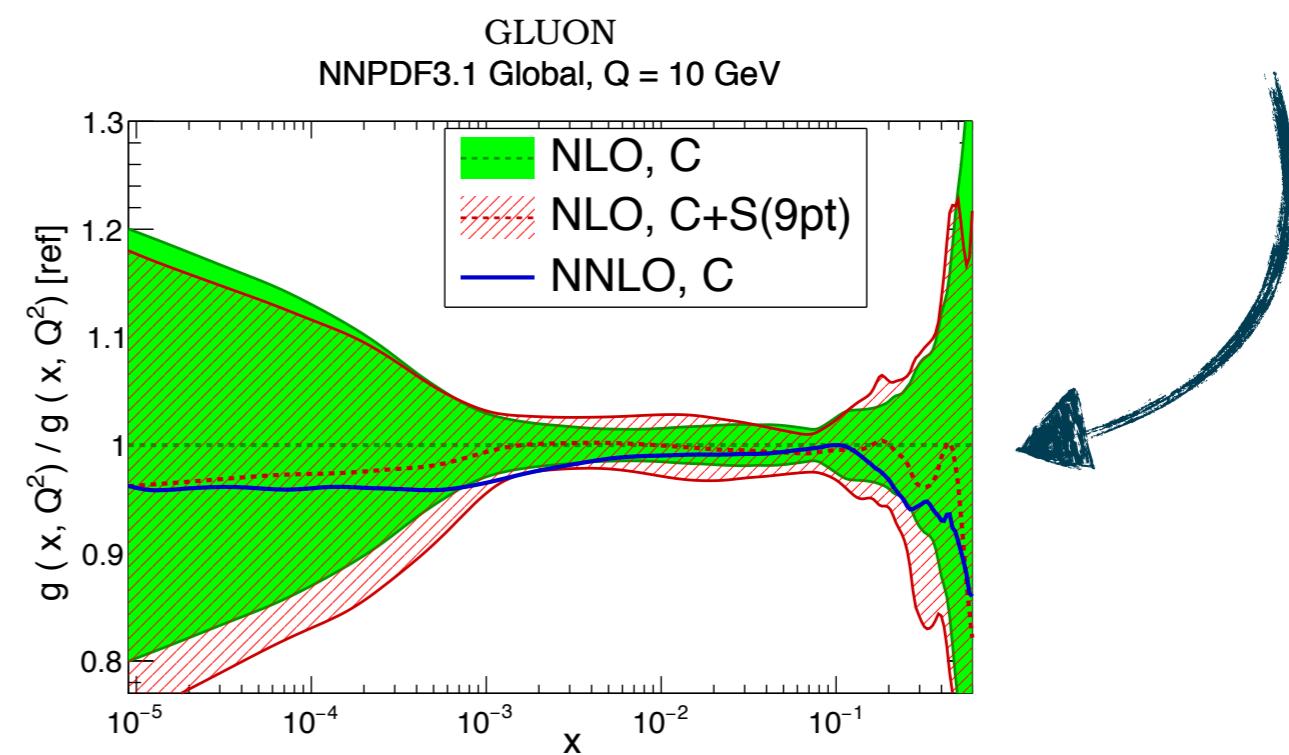
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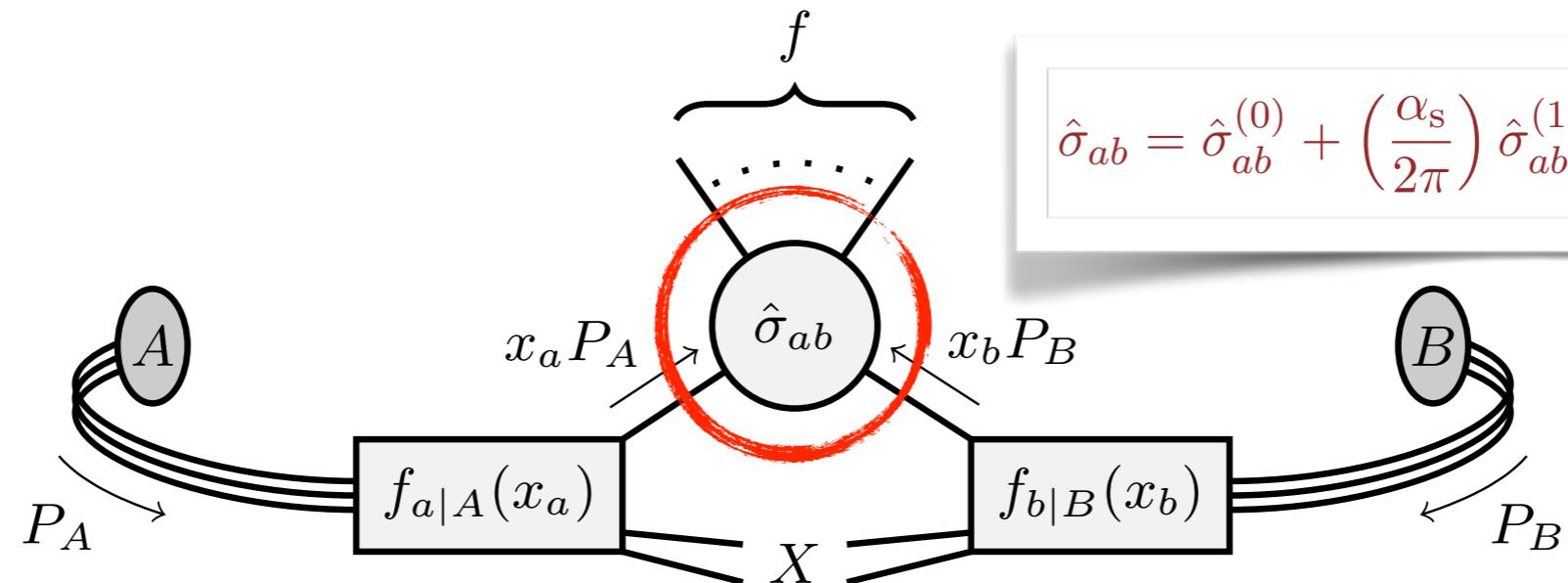
MHOU
 \leftrightarrow *nuisance parameters*
Theory Covariance Matrix



- missing higher order uncertainties (MHOU) not included in PDF fits
- becoming more and more **urgent**
[Harland-Lang, Thorne '19] [NNPDF '19]
- validation: central value → NNLO
- equally precise, but more accurate



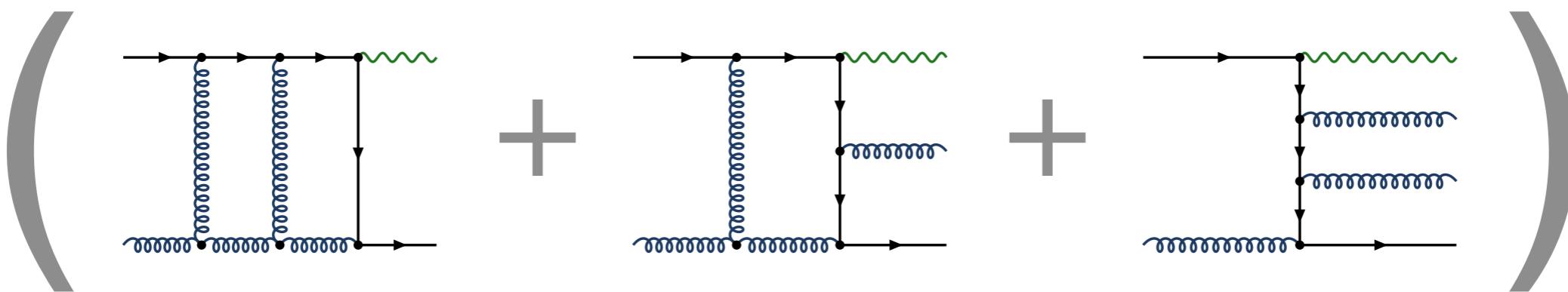
2. FACTORIZATION — HARD SCATTERING



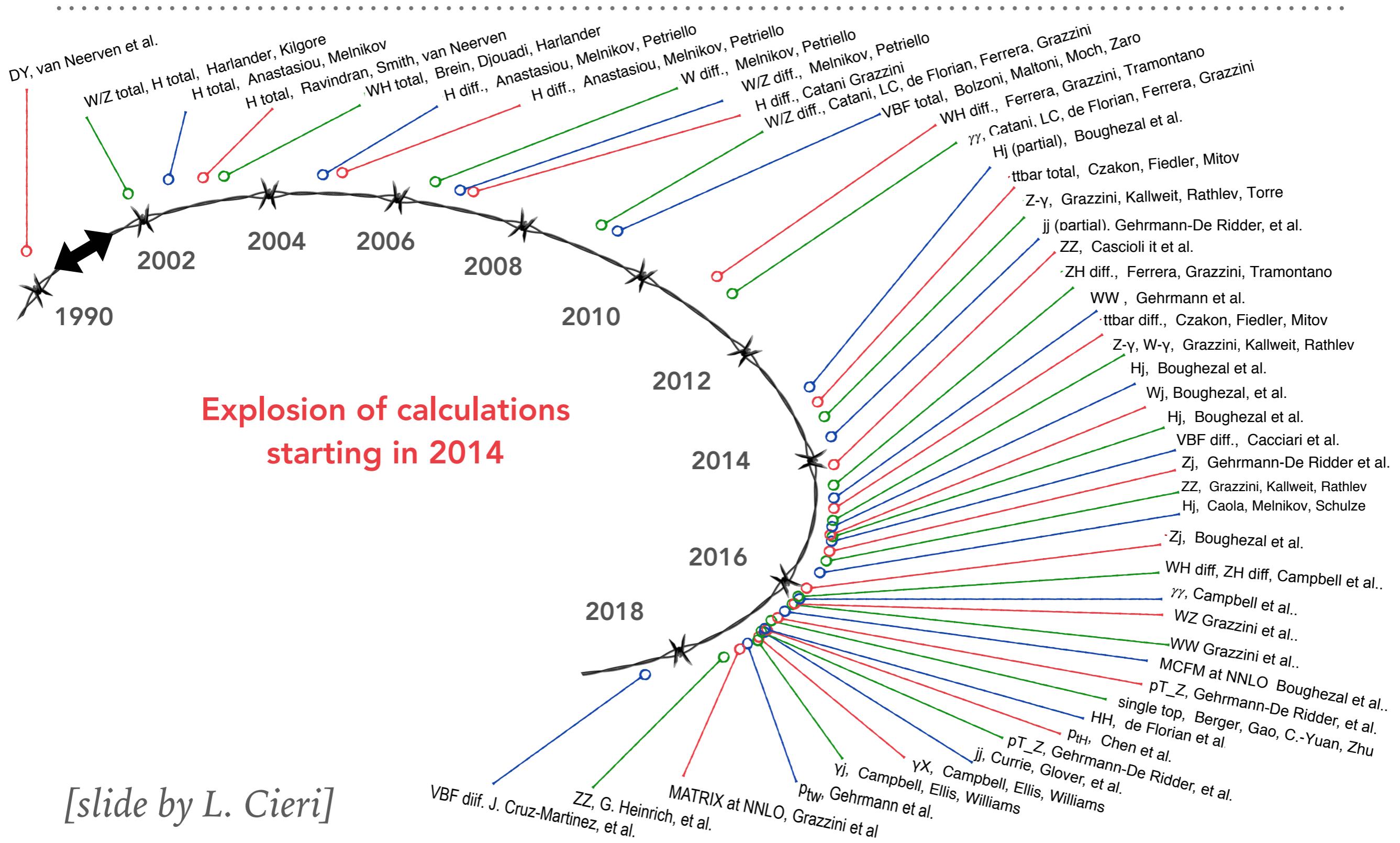
- **FOCUS** — clean processes with high momentum transfer
 - ▶ *perturbative QCD*
- with $\alpha_s \sim 0.1$
 - ▶ $NLO \sim \mathcal{O}(10\%)$, $NNLO \sim \mathcal{O}(1\%)$
 - ▶ *exceptions: Higgs, new channels, ...*
- (HL-)LHC — per-cent level!
 - ▶ predictions as close as possible to the experiment
 - ▶ *fiducial cross sections & differential distributions*

NNLO

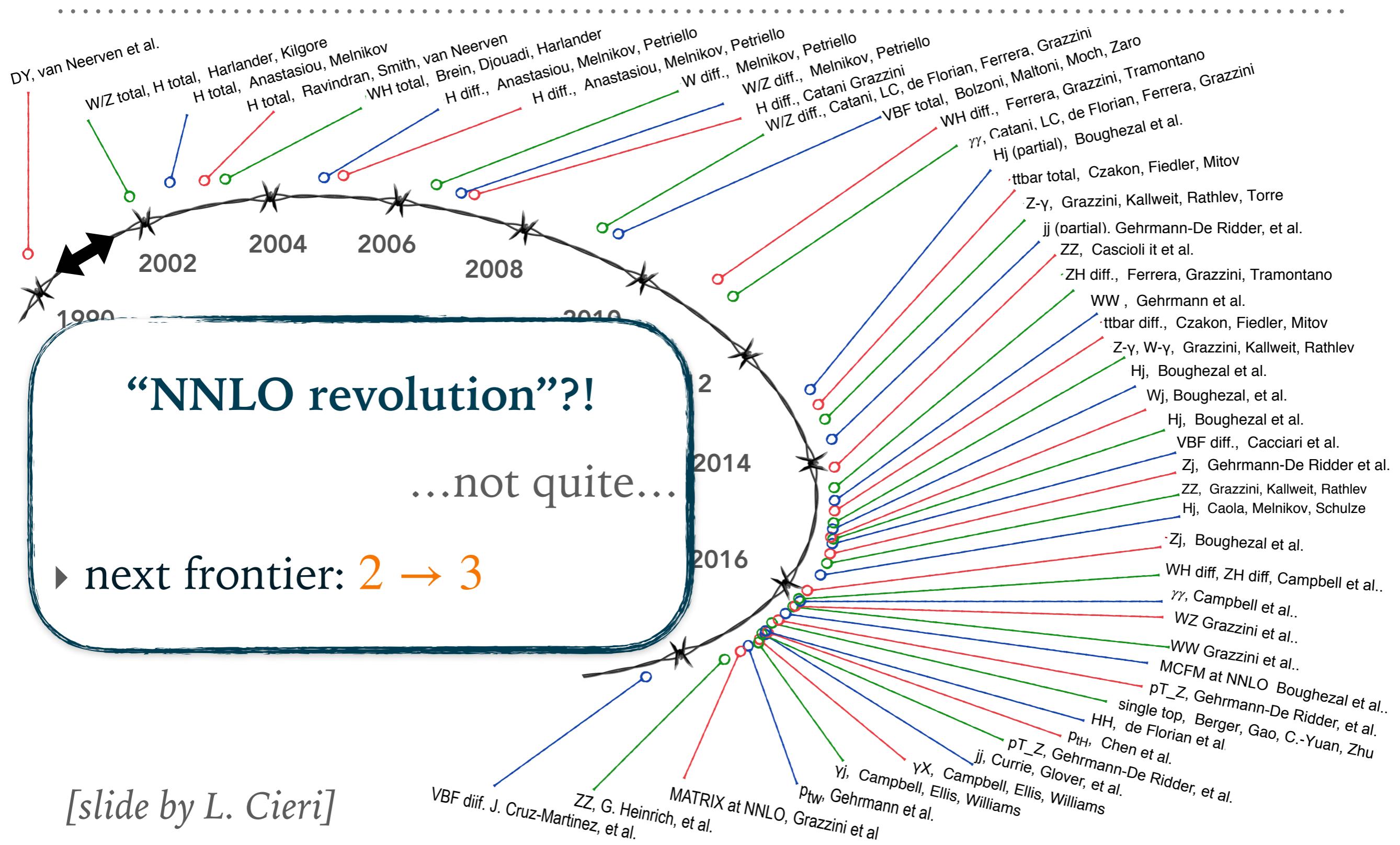
FULL ECHO



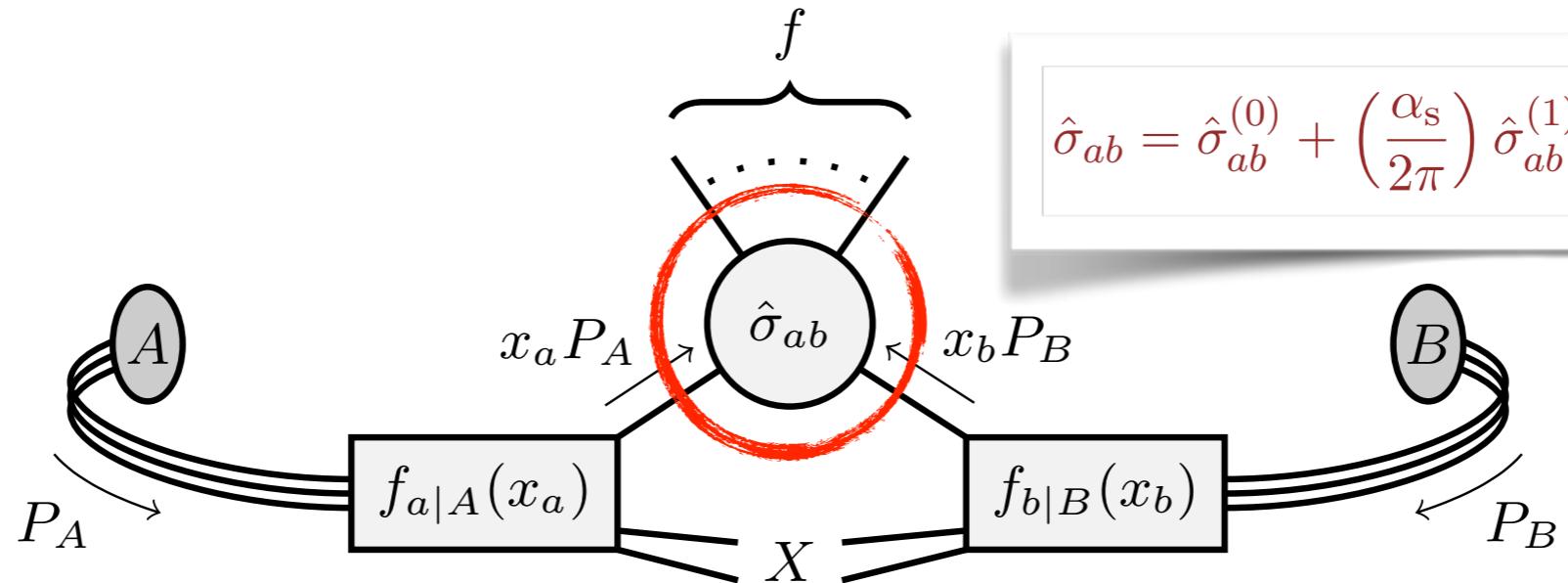
TIMELINE FOR NNLO @ HADRON COLLIDERS



TIMELINE FOR NNLO @ HADRON COLLIDERS

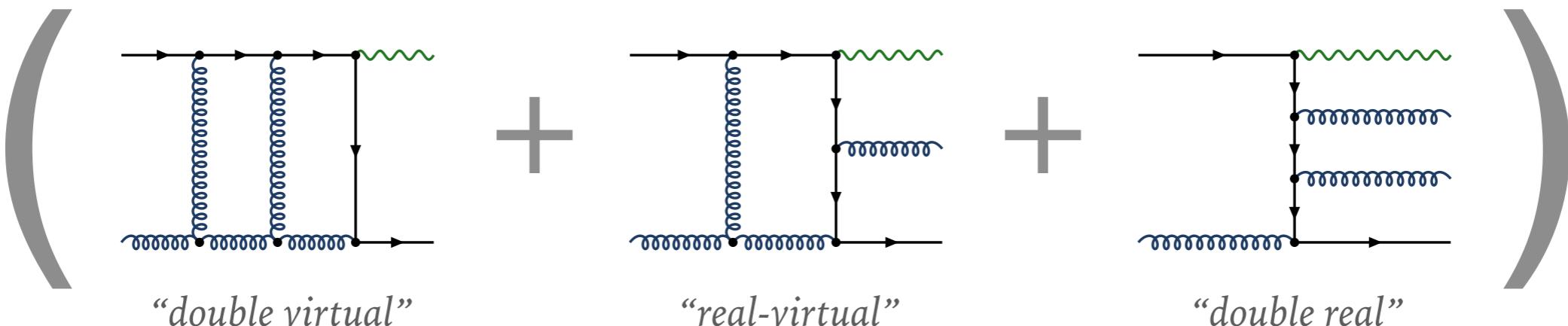


HARD SCATTERING @ NNLO



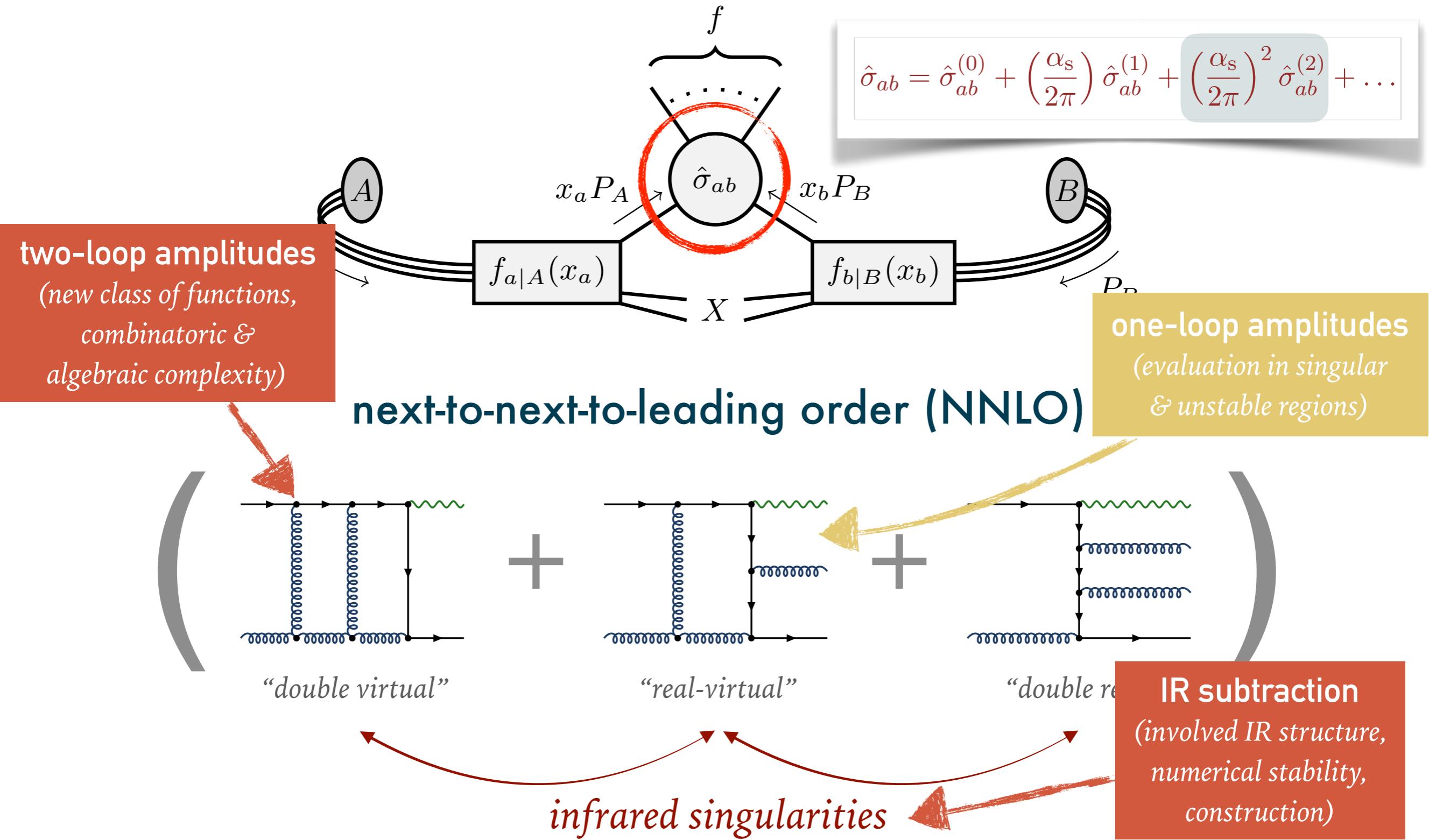
$$\hat{\sigma}_{ab} = \hat{\sigma}_{ab}^{(0)} + \left(\frac{\alpha_s}{2\pi}\right) \hat{\sigma}_{ab}^{(1)} + \left(\frac{\alpha_s}{2\pi}\right)^2 \hat{\sigma}_{ab}^{(2)} + \dots$$

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



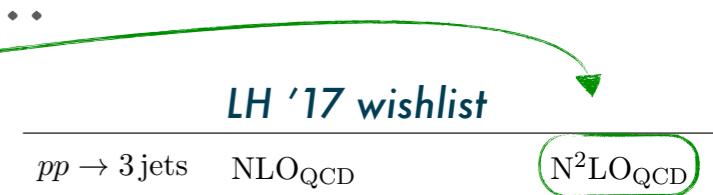
- $1/\varepsilon^4, 1/\varepsilon^3, 1/\varepsilon^2, 1/\varepsilon$
- $1/\varepsilon^2, 1/\varepsilon$
- *single unresolved*
- *double unresolved*
- *single unresolved*

NNLO — BOTTLE NECKS



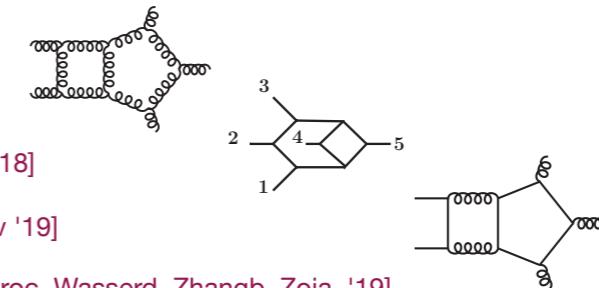
TWO-LOOP AMPLITUDES

- What we can do: $2 \rightarrow 1$ and $2 \rightarrow 2$ (mainly massless, 2 massive legs)
- What we want: $3j$, $V+2j$, $\gamma\gamma j$, ttH , EW corrections, ...



1. Progress in **5-parton amplitudes** [from LC 5-point gluon (all plus)]

- LC 5-point gluon (one minus) [Badger, Brønnum-Hansen, Hartanto, Peraro '18]
- LC 5-point gluon (all helicities) [Abreu, Dormans, Febres Cordero, Ita, Page '18]
- all masters (planar & non-planar) [Chicherin, Gehrmann, Henn, Wasser, Zhang, Zoia '18]
- LC 5-point parton (all helicities) [Abreu, Dormans, Febres Cordero, Ita, Page, Sotnikov '19]
- full 5-point gluon (all plus) [Badger, Chicherin, Gehrmann, Heinrich, M. Henn, Peraroc, Wasserd, Zhang, Zoia, '19]



2. Understanding of **elliptic integrals**

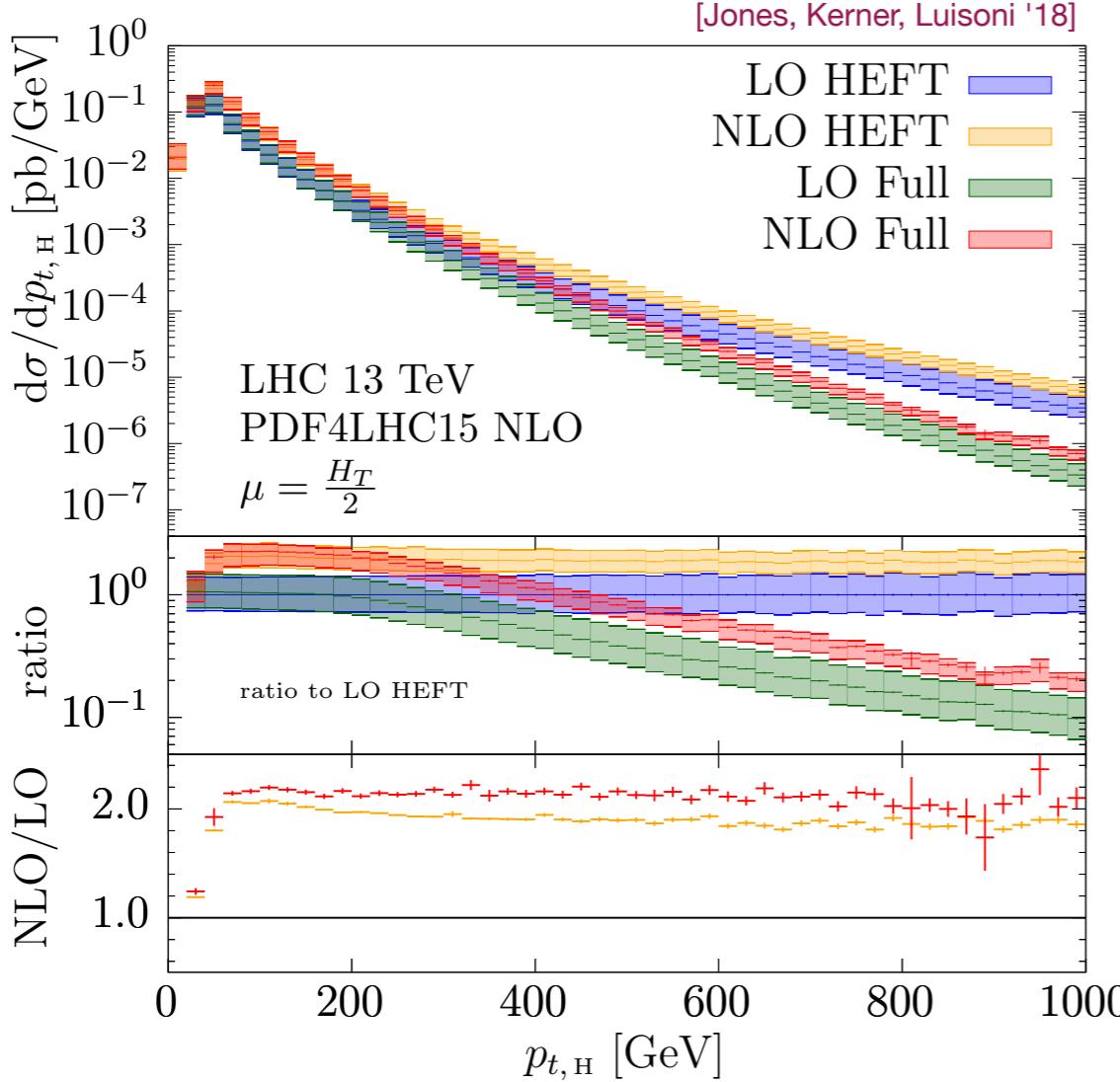
$$G(\{c_n, \vec{c}_{n-1}\}, x) = \int_0^1 \frac{dt}{t - c_n} G(\vec{c}_{n-1}, t) \longrightarrow K(x, a) = \int_0^x \frac{dt}{\sqrt{(1-t^2)(1-at^2)}}$$

[Remiddi, Tancredi]
[Adams, Chaubey, Weinzierl]
[Broedel, Duhr, Dulat, Penante, Tancredi]

3. numerical approaches: **tt** [Chen, Czakon, Poncelet '17], **pySecDec** (HH, H+j) [Borowka, Heinrich, Jahn, Jones, Kerner, Schlenk '19]

* more painful with masses & scales

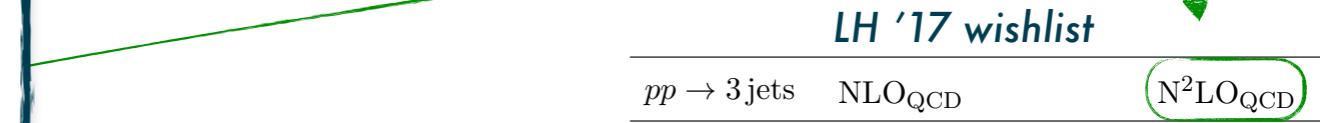
TWO-LOOP AMPLITUDES



- high- p_T : resolves top-loop
- K-factors very similar!
- combine with NNLO in HEFT

(mainly massless, 2 massive legs)

EW corrections, ...



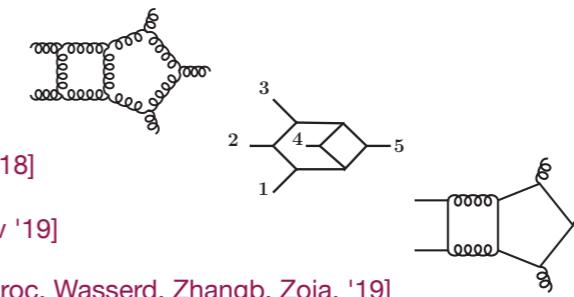
LC 5-point gluon (all plus)]

[o '18]
[ge '18]

Zhang, Zoia '18]

[age, Sotnikov '19]

Hennb, Peraroc, Wasserd, Zhangb, Zoia, '19]



$$\int_0^x \frac{dt}{\sqrt{(1-t^2)(1-at^2)}}$$

[Remiddi, Tancredi]
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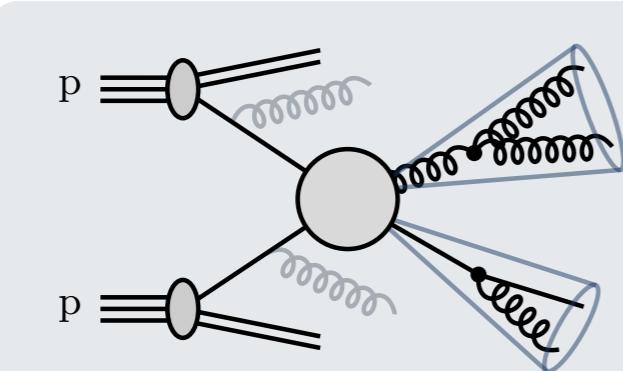
SUBTRACTION METHODS — CANCEL ∞ 'S

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

(not an exhaustive list)	local subtraction	analytic	pp collisions	final-state jet(s)
Antenna	✗ <small>(local after rotⁿ)</small>	✓	✓	✓
CoLorFul	✓	✓	✗	✓
q_T -Subtr.	✗	✓	✓	✗ <small>(only t)</small>
STRIPPER / nested soft-coll.	✓	✗ / ✓	✓	✓
N -jettiness	✗	✓	✓	✓ <small>(≤ 1 jet so far)</small>

- Projection-to-Born, Local Analytic Sectors, Geometric, ...

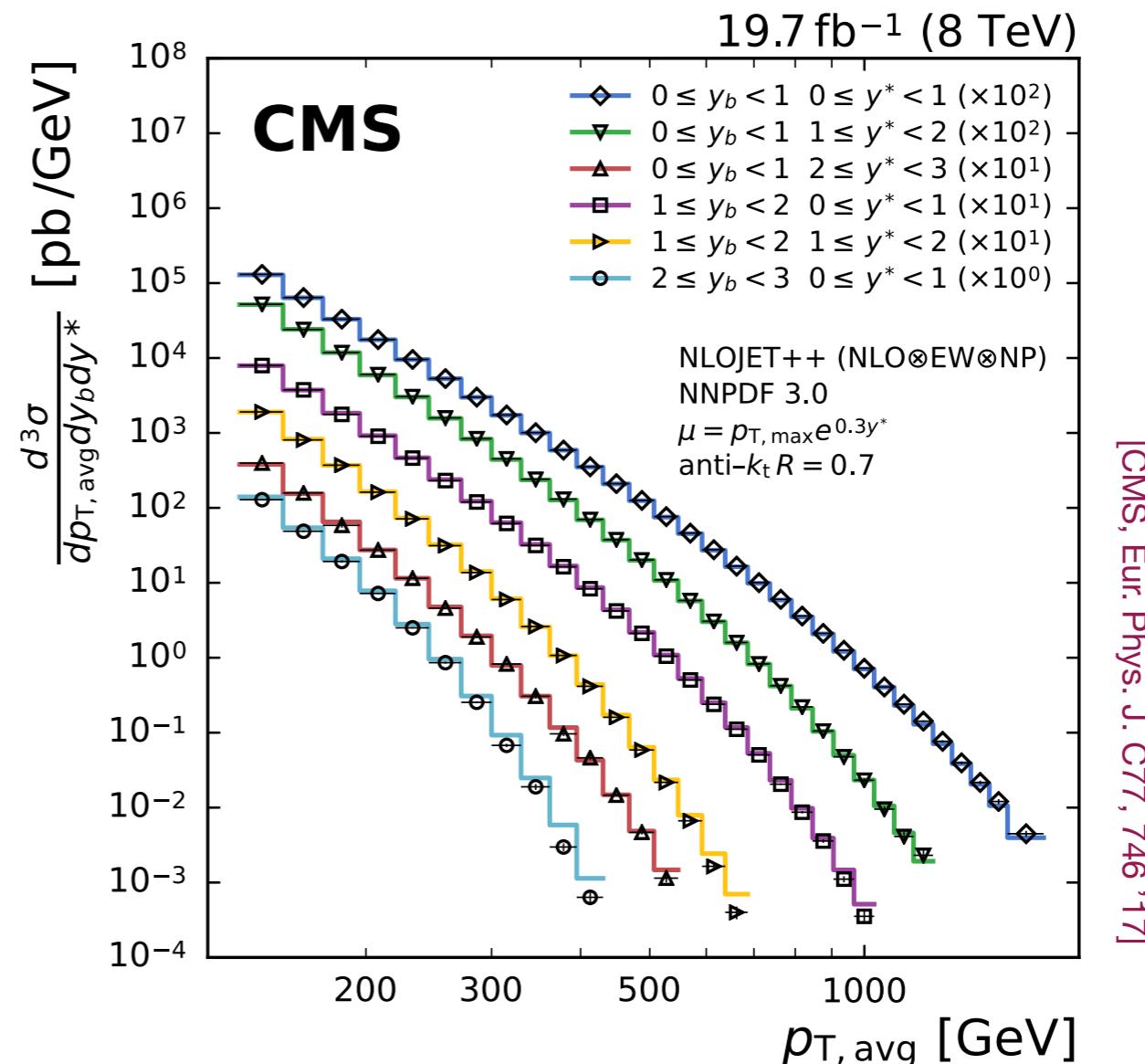
JET PRODUCTION AT THE LHC

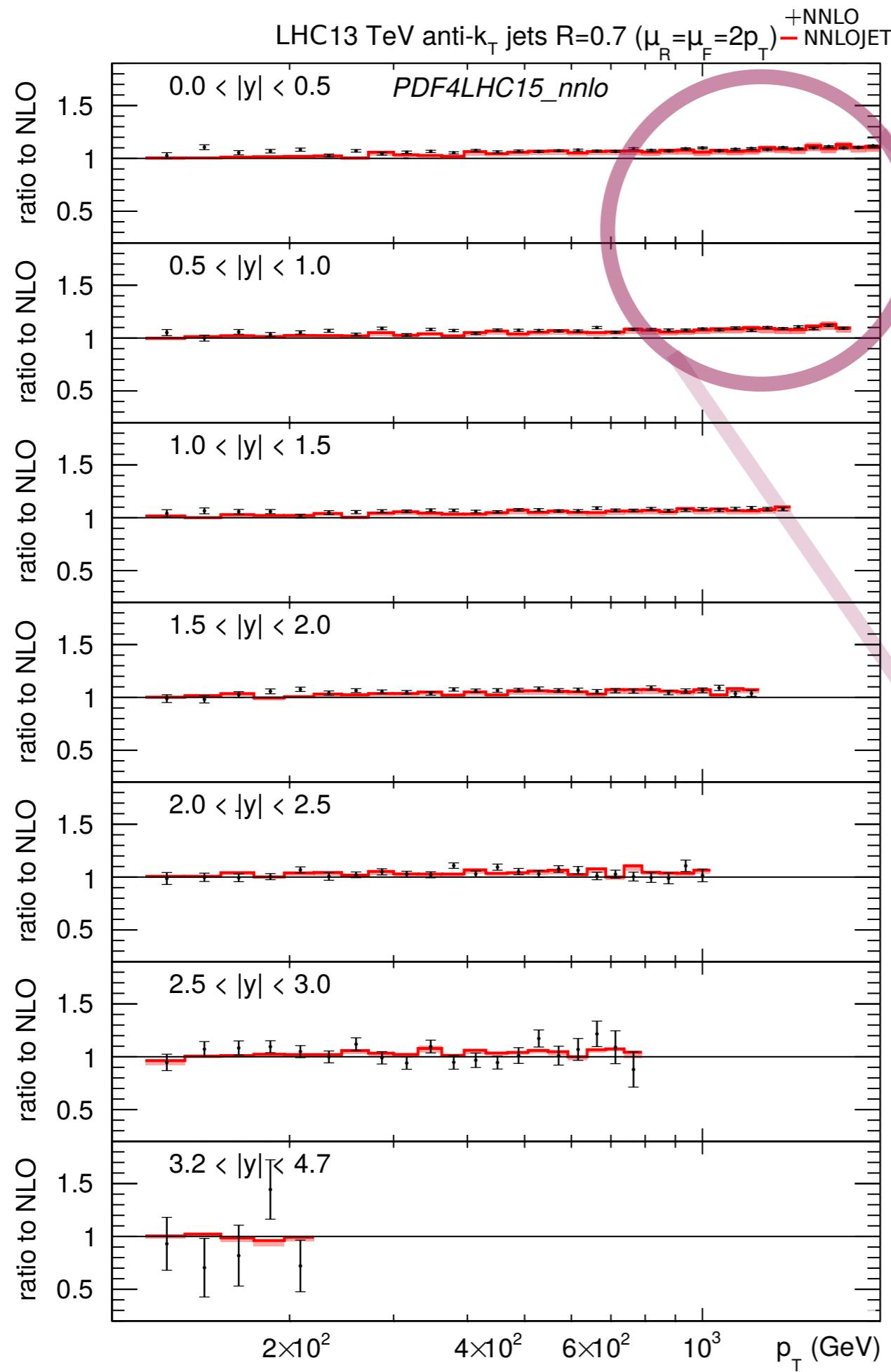


$p + p \rightarrow \text{jet(s)} + X$

- ▶ jets produced in abundance
- ▶ precise measurements ($p_{T,j} \gtrsim 20 \text{ GeV}$)
- ▶ wide kinematic range accessible

- ▶ test perturbative QCD
 - ↪ study scale choices
 - ▶ constrain PDFs
 - ↪ sensitive to gluon
 - ↪ probe wide x -range
 - ▶ $\alpha_s(M_Z)$ and running
 - ▶ search for BSM physics
- high-precision predictions
mandatory!





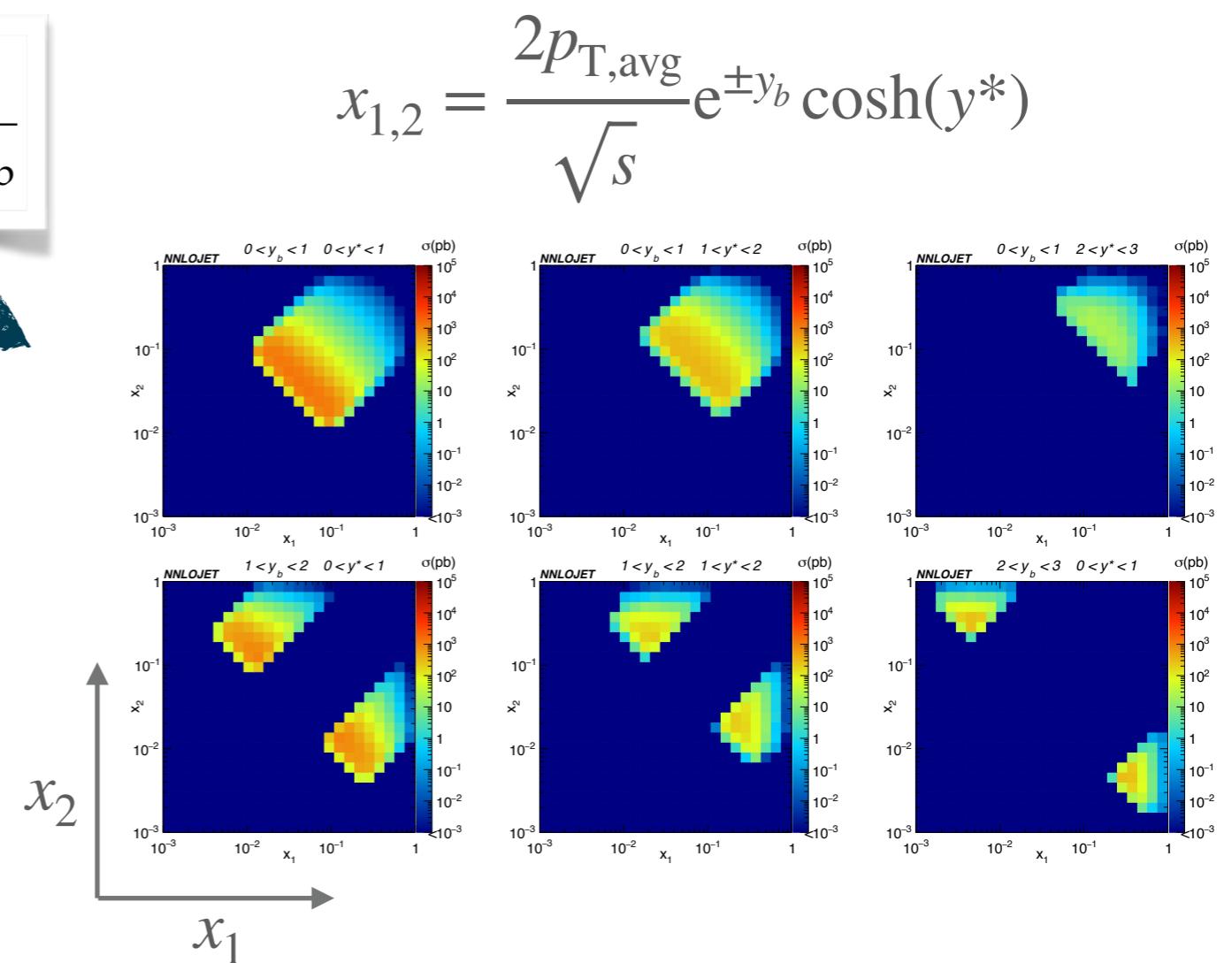
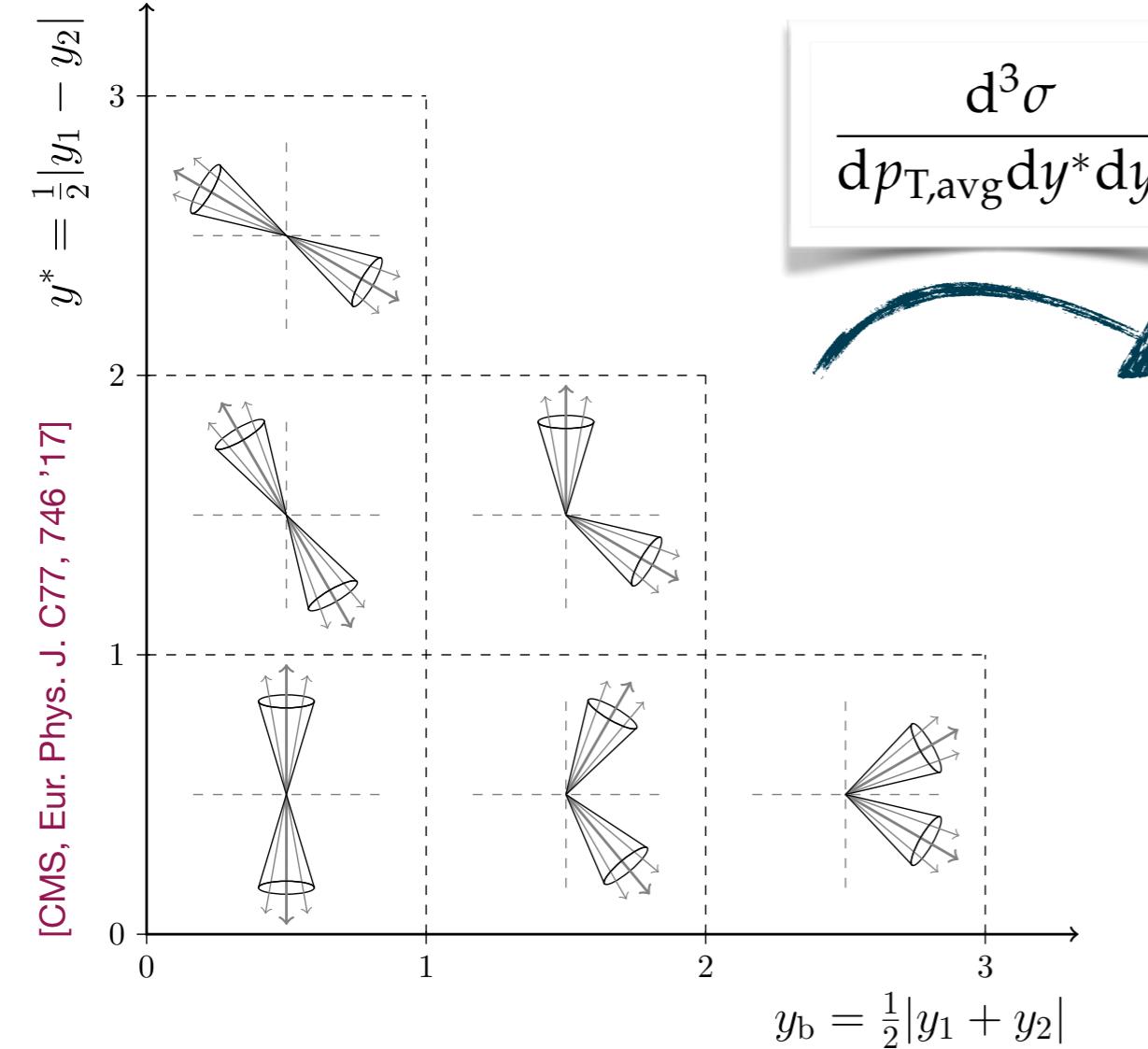
Two Calculations!

 NNLOJET [Currie, Glover, Pires '16]

STRIPPER [Czakon, van Hameren, Mitov, Poncelet '19]

- excellent agreement
 - sub-leading colour negligible
(missing in NNLOJET)

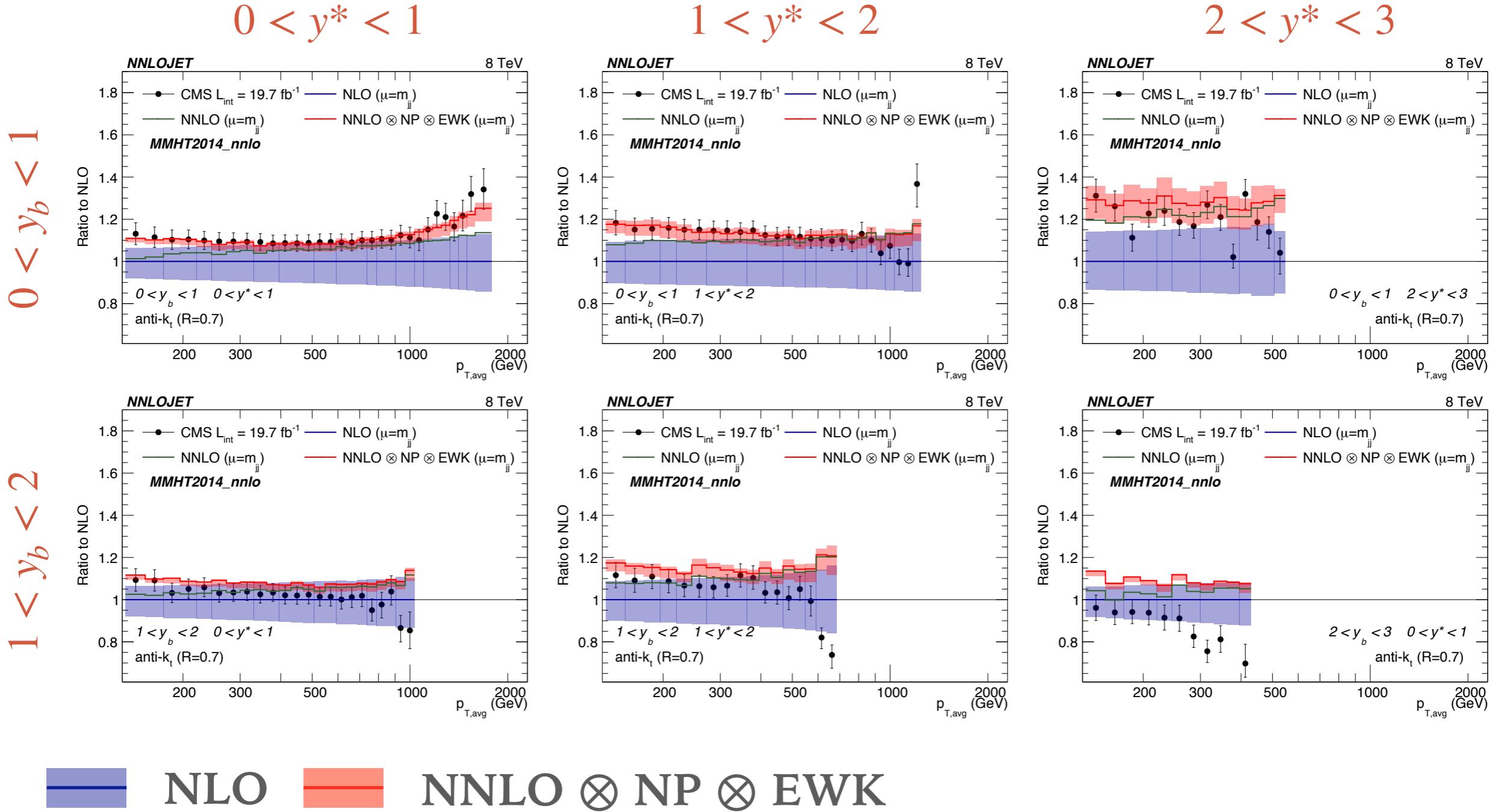
TRIPLE-DIFFERENTIAL CROSS SECTION



- study different kinematic regimes
- disentangle momentum fractions x_1 & x_2

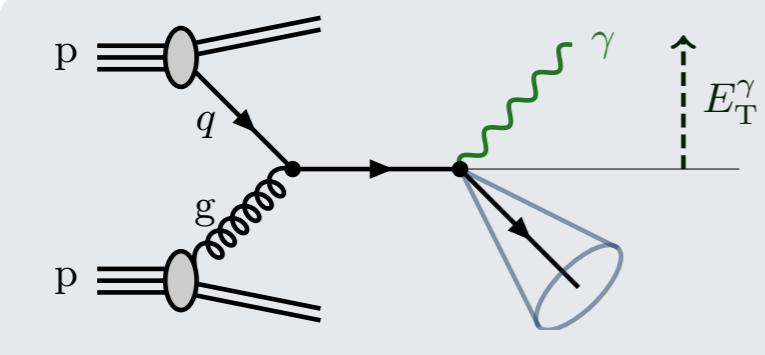
TRIPLE-DIFFERENTIAL CROSS SECTION @ NNLO

[Gehrman-De Ridder, Gehrman, Glover, AH, Pires '19]



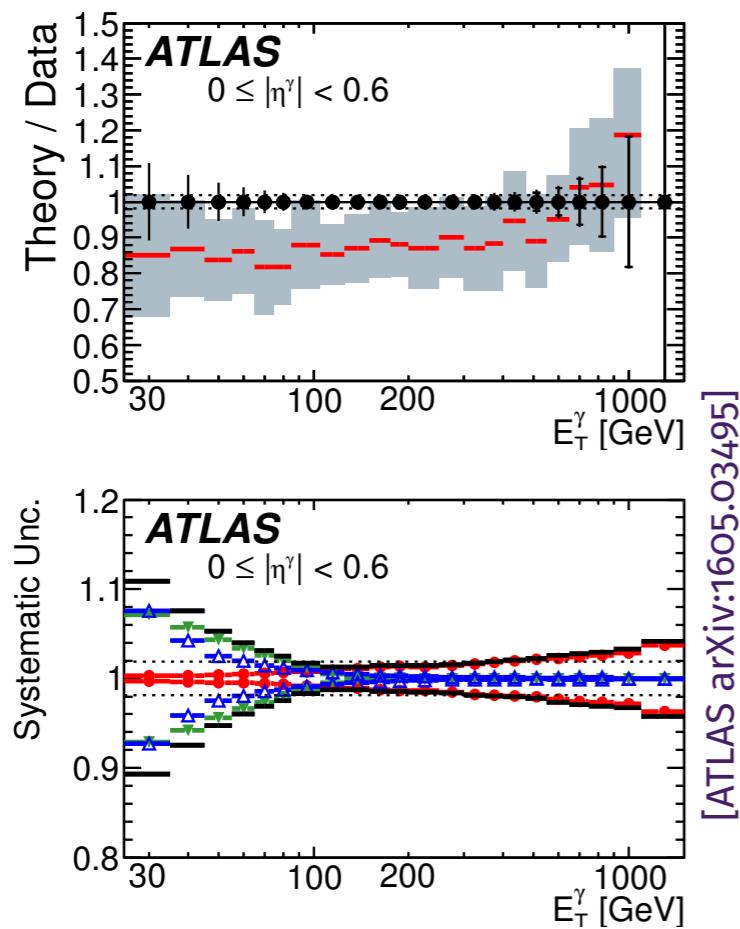
improved description of data & reduced uncertainties!

PHOTON & PHOTON+JET PRODUCTION



$$p p \rightarrow \gamma + X$$

- ▶ highest-rate electroweak process @ LHC
- ▶ photon as probe of hard scattering
- ~ sensitivity to α_s , gluon PDF

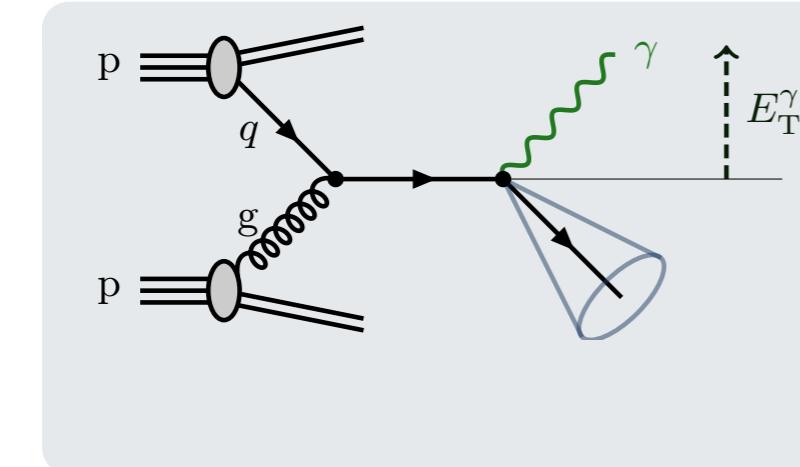


JetPhox (NLO QCD)

[Catani, Fontannaz, Guillet, Pilon '02]

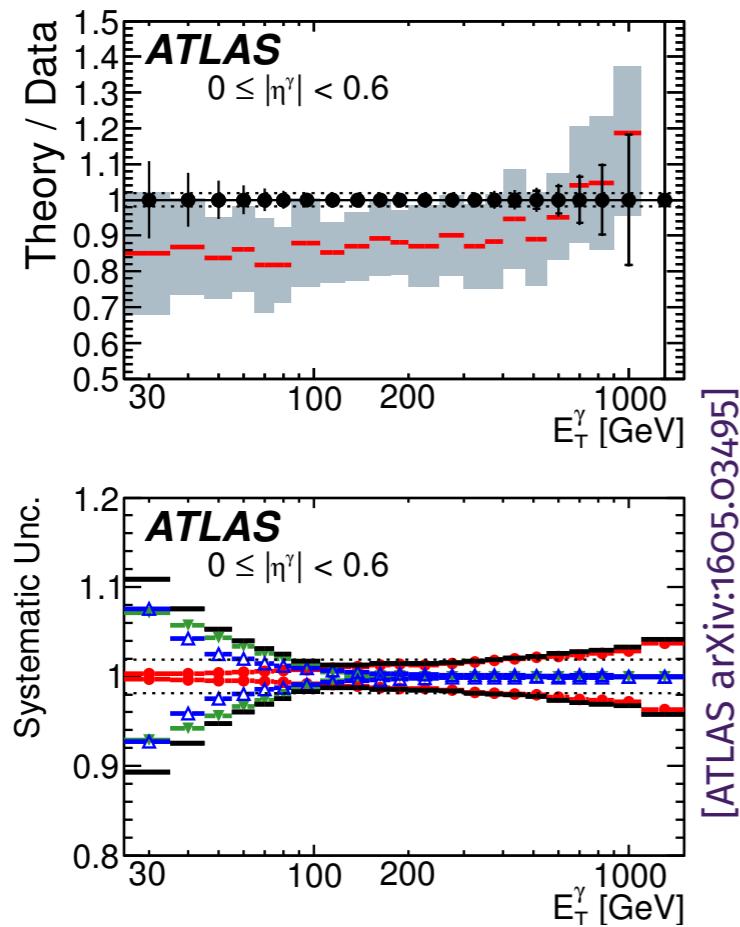
- tension between theory vs. data
- large scale uncertainties: $\sim \pm 10\%$
- ▶ experimental uncertainties $\lesssim \pm 3\text{--}5\%$
 - smaller than NLO theory
 - ⇒ NNLO QCD needed!

PHOTON & PHOTON+JET PRODUCTION



$p\ p \rightarrow \gamma + X$

- ▶ highest-rate
- ▶ photon a.
- ~ sensitivity



JetPhox (NLO)

[Catani, Fontannarive]

→ tension

→ large scale

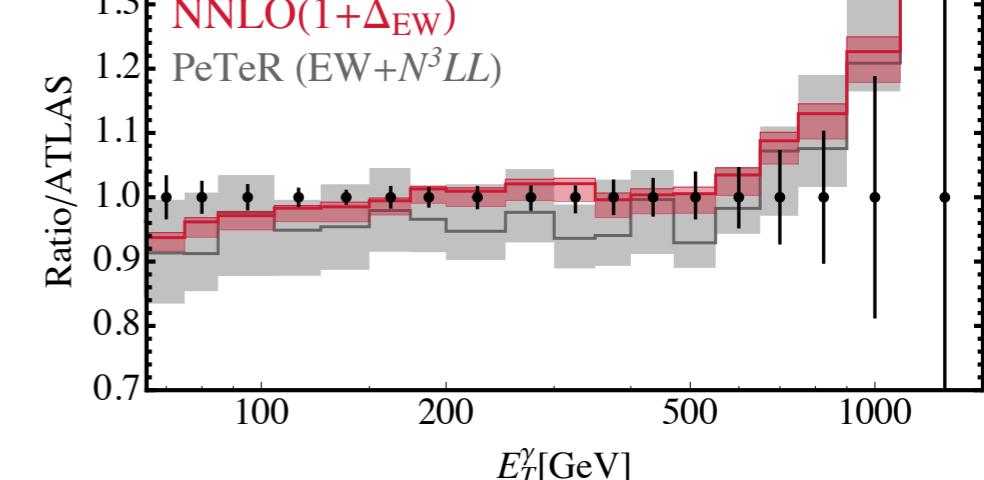
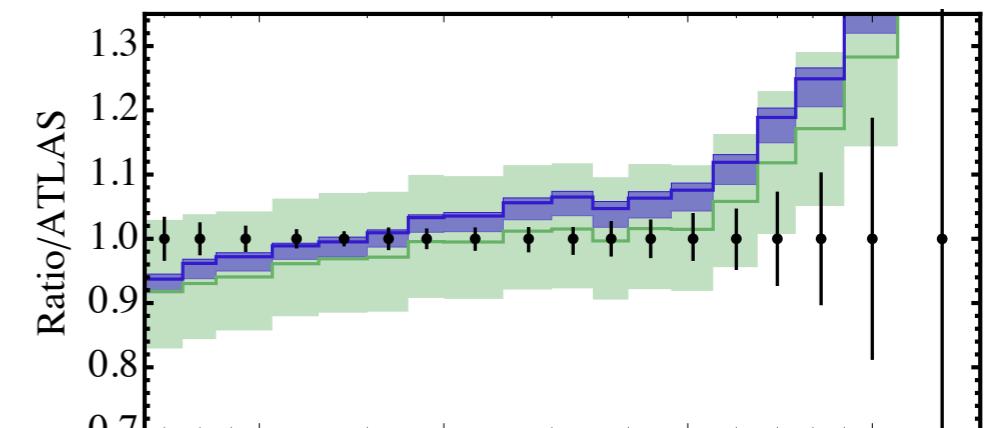
▶ experimental

→ smaller than NLO theory

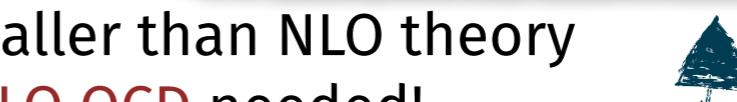
⇒ NNLO QCD needed!

$\gamma + X @ \text{NNLO}$

[Campbell, Ellis, Williams '17]



→ substantially reduced
scale uncertainties



PHOTON ISOLATION

Suppress contamination from secondary photons (e.g. $\pi^0 \rightarrow \gamma\gamma$)

~ *isolation cuts*: restrict hadronic activity in $R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$

Fixed cone isolation

can choose simple linear dependence:

$$E_T^{\text{had.}}(R) < E_T^{\max} = \epsilon E_T^\gamma + E_T^{\text{thresh.}}$$

- ✓ used in experiments
- ✗ sensitivity to fragmentation

Dynamic cone isolation [Frixione '98]

smoothly get rid of collinear radiation:

$$E_T^{\text{had.}}(r) < \epsilon E_T^\gamma \left(\frac{1 - \cos r}{1 - \cos R} \right)^n \quad \forall r < R$$

- ✓ eliminates fragmentation part
- ✗ no direct analogue in experiment

Mismatch: experiment vs. theory

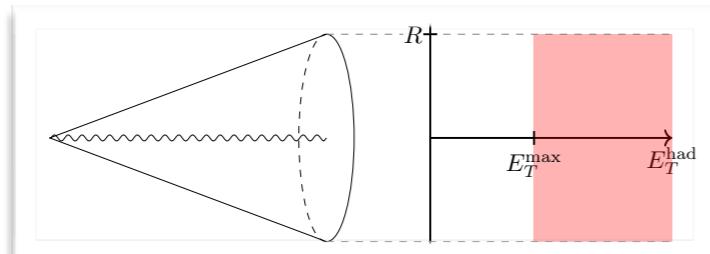
► “tight enough” isolation: ~ few % [Les Houches '13 '15]

But: experiment & NNLO theory: $\lesssim 5\%$

→ percent-level phenomenology a reality!

Can we do better?

PHOTON ISOLATION CONT.

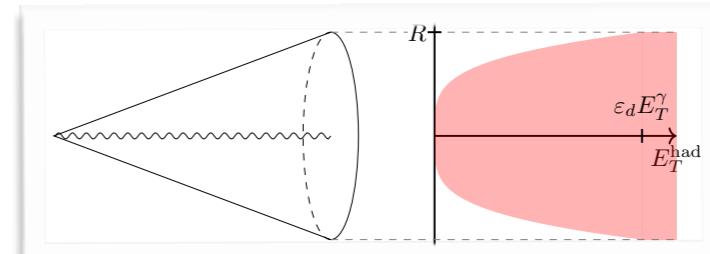


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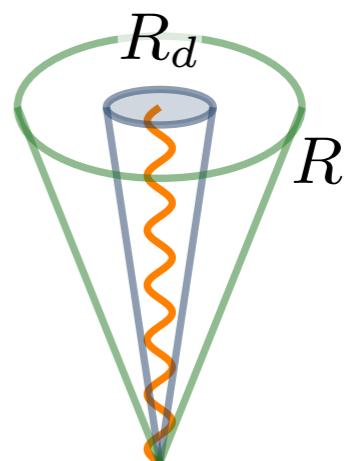
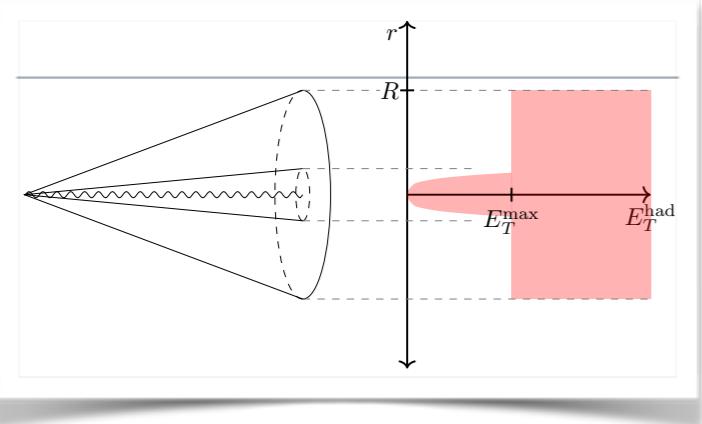
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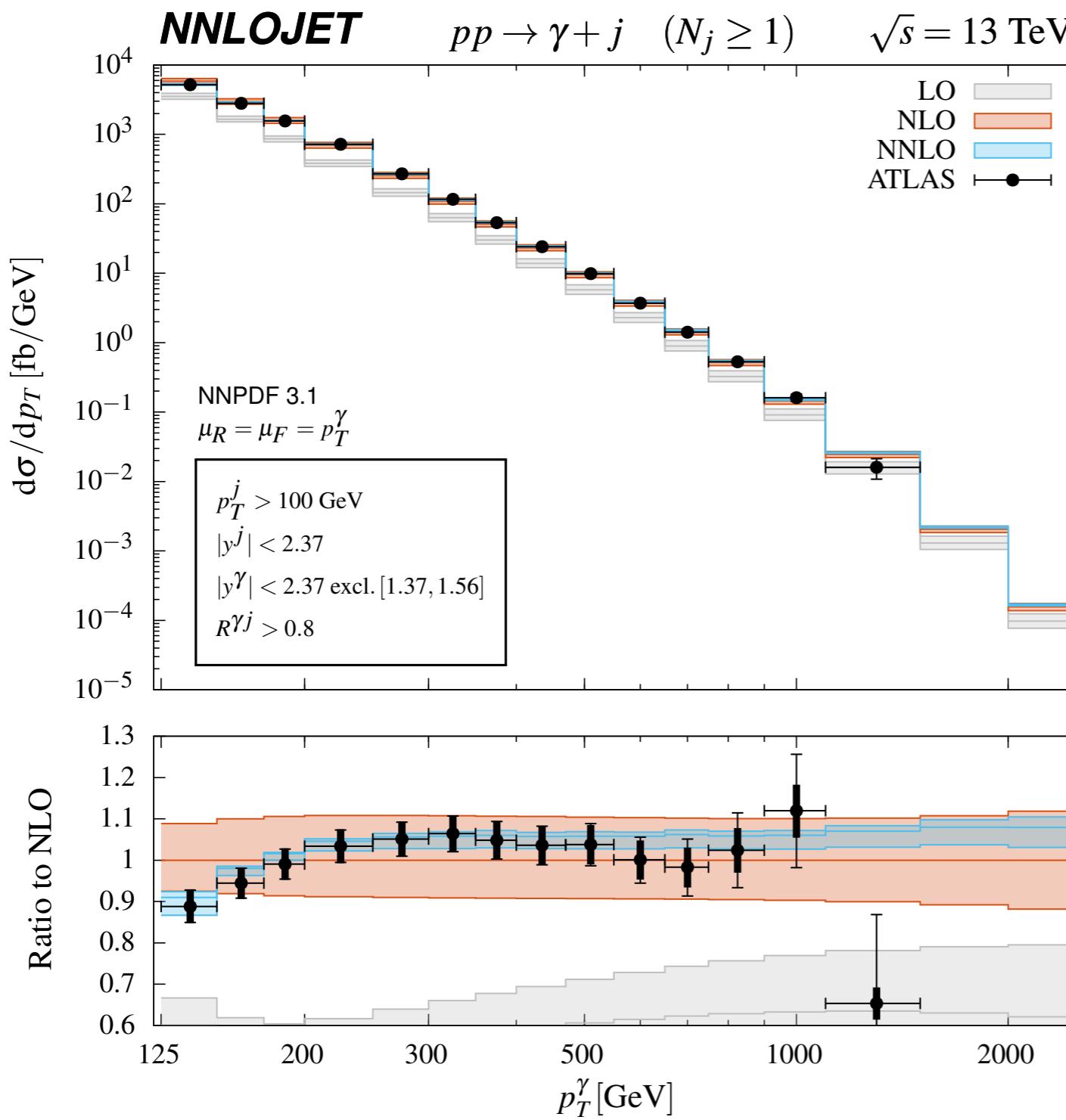
Hybrid cone isolation

[Siegert '17]

1. narrow dynamic cone $R_d < R$ (0.1)
 2. wider fixed cone R (0.4)
- ✓ eliminates fragmentation part
 - ✓ reduces mismatch to experiment
 - ✓ correct R dependence



PHOTON + JET @ 13 TeV



[Chen, Gehrmann, Glover, Höfer, AH '19]

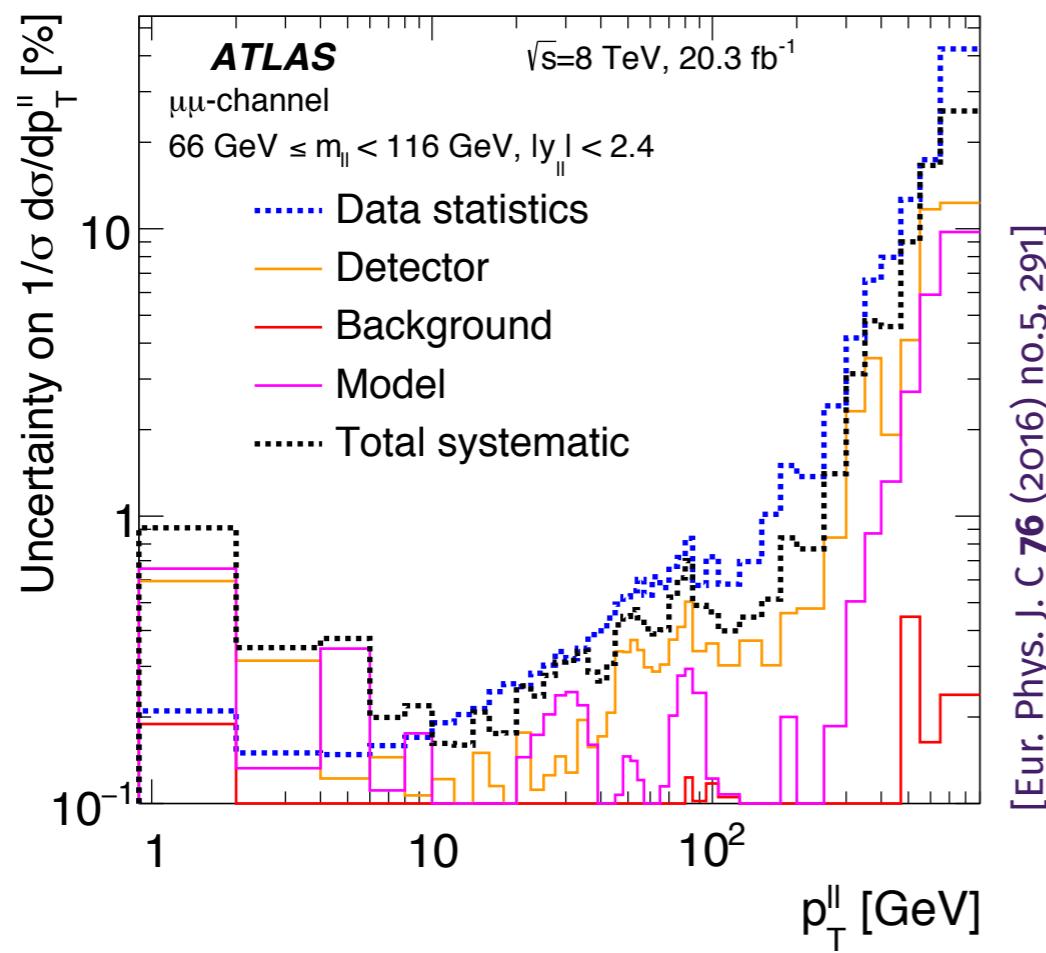
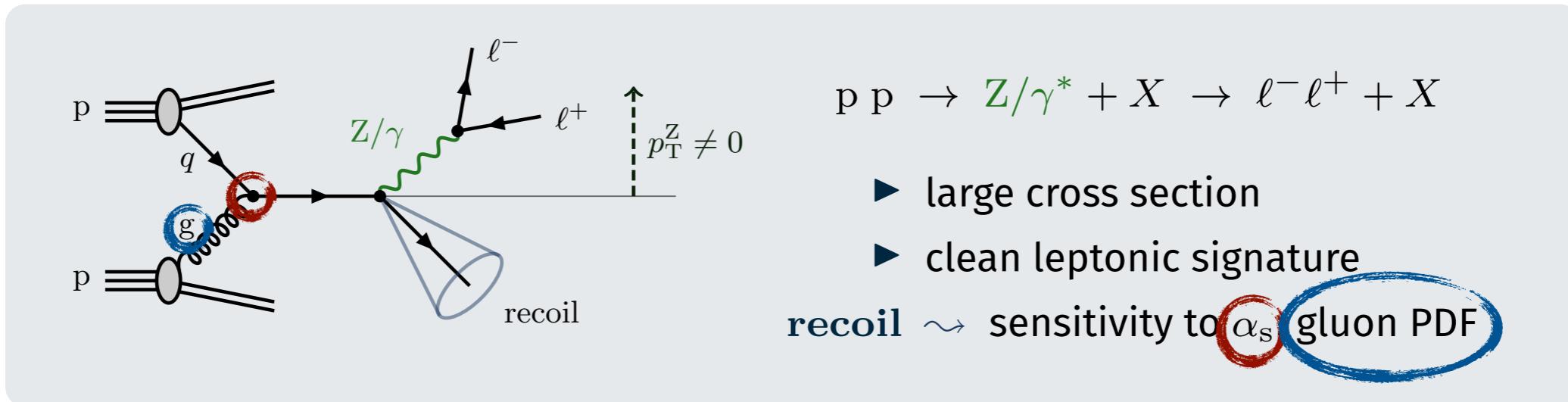
hybrid isolation

- **NLO** (~ 1)
 - +40% corrections
 - $\pm 10\%$ uncertainties

- **NNLO**
 - $\sim 5\%$ corrections
 - *shape distortions*
 - $\lesssim 5\%$ uncertainties

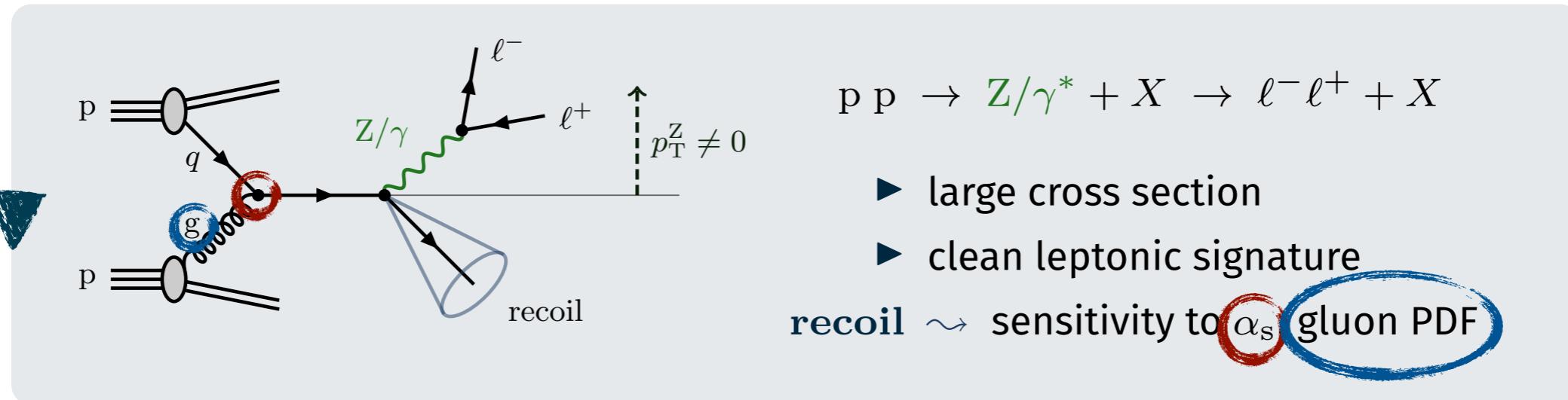
- previous NNLO calculation
 τ_N [Campbell, Ellis, Williams '17]
(dynamical cone isol.)

TOWARDS PER-CENT PHENOMENOLOGY



- ▶ only reconstruct ℓ^+, ℓ^-
 \leadsto sub-% accuracy!
- ▶ important constraints in PDF fits
[Boughezal et al. '17]
- ▶ probe various theory aspects:
very low p_T non-pert. effects
low p_T resummation
interm. p_T fixed order
high p_T EW Sudakov logs

TOWARDS PER-CENT PHENOMENOLOGY



[%]

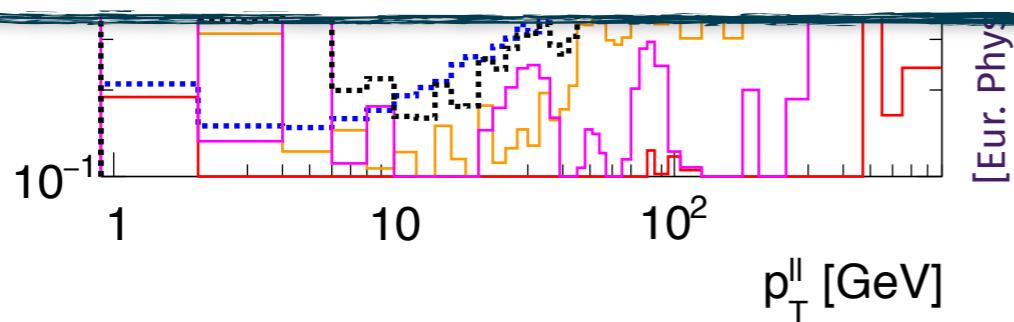
ATLAS

All V+jet processes known to NNLO

$Z + \text{jet}$ [Gehrman-De Ridder, Gehrman, Glover, AH, Morgan '15]
 [Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello.'15]

$W + \text{jet}$ [Boughezal, Liu, Petriello '16]
 [Gehrman-De Ridder, Gehrman, Glover, AH, Walker '17]

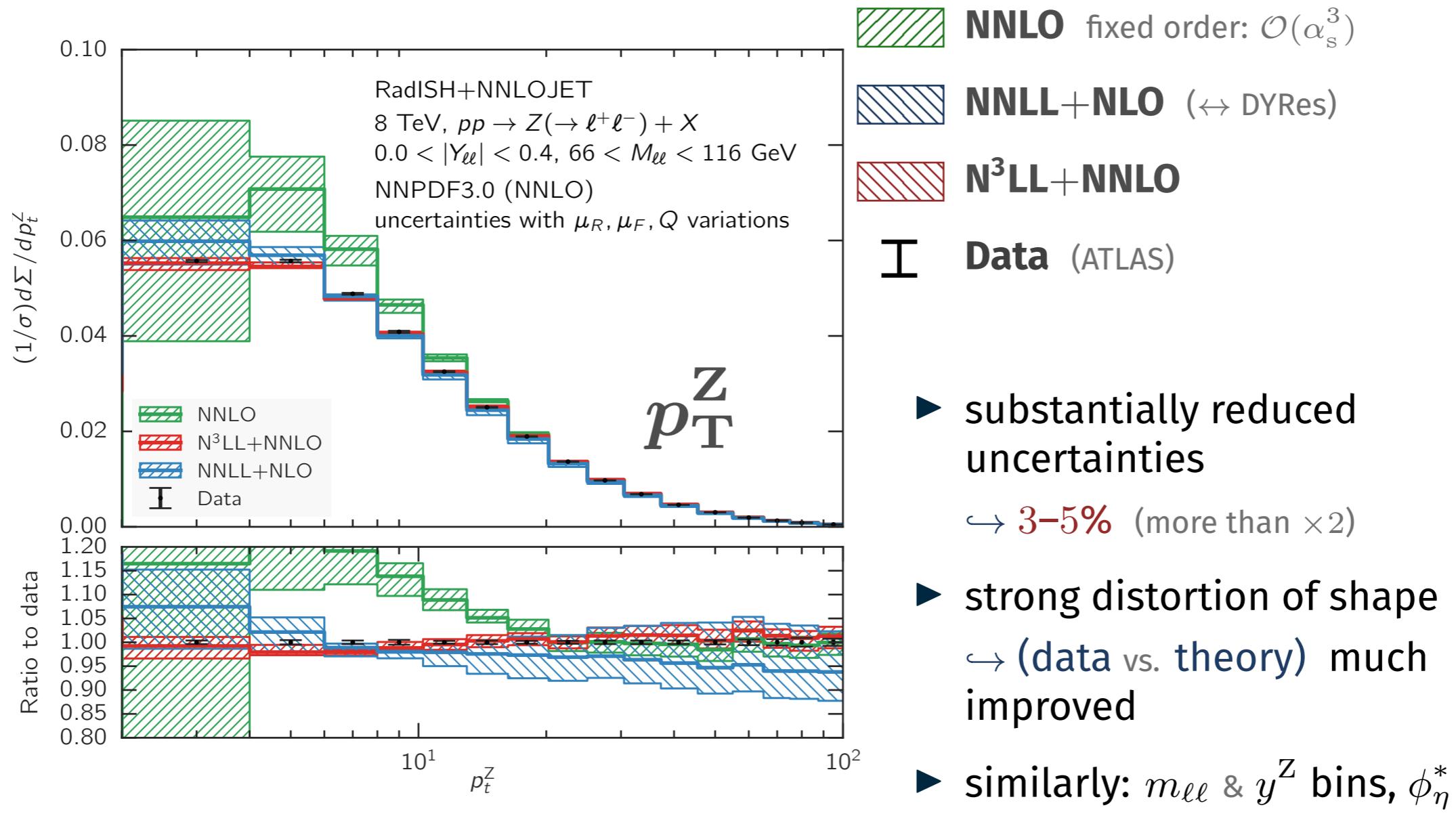
$\gamma + \text{jet}$ [Campbell, Ellis, Williams '16] [Chen, Gehrman, Glover, Höfer, AH '19]



low p_T resummation
 interm. p_T fixed order
 high p_T EW Sudakov logs

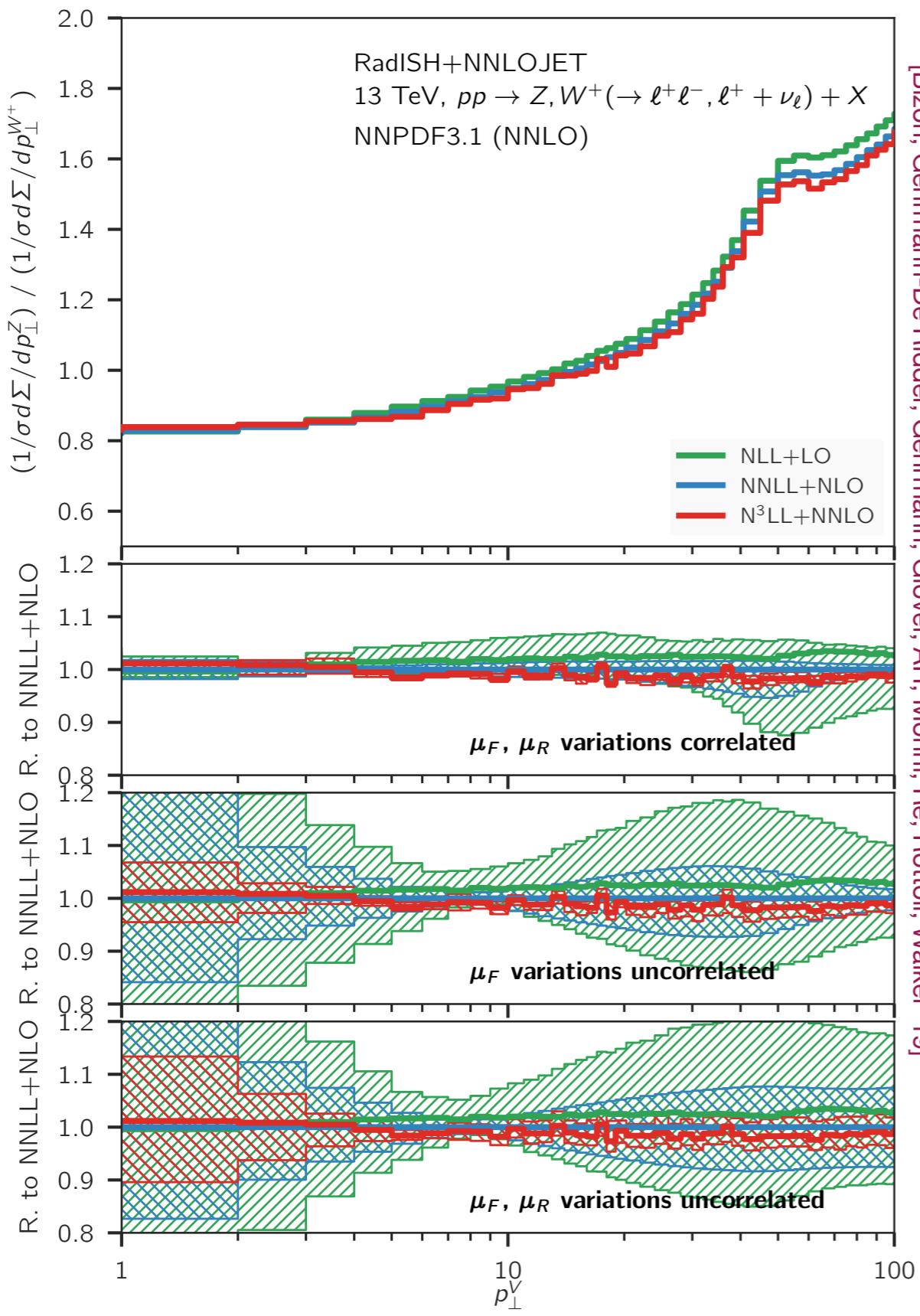
FIXED ORDER + RESUMMATION – NNLO + N³LL

[Bizoń, Chen, Gehrmann-De Ridder, Gehrmann, Glover, AH, Monni, Re, Rottoli, Torrielli '18]



also: p_T^W & p_T^W/p_T^Z (for M_W)

$$p_T^Z/p_T^W$$



CON – NNLO + N³LL

[Bizoń, Gehrmann, Glover, AH, Monni, Re, Rottoli, Torrielli '18]

■ **NNLO** fixed order: $\mathcal{O}(\alpha_s^3)$

■ **NNLL+NLO** (\leftrightarrow DYRes)

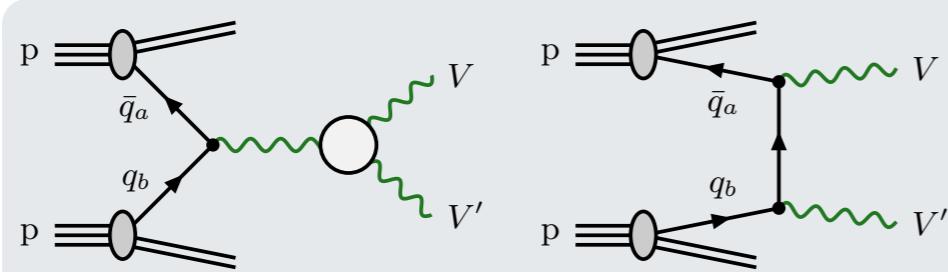
■ **N³LL+NNLO**

■ **Data** (ATLAS)

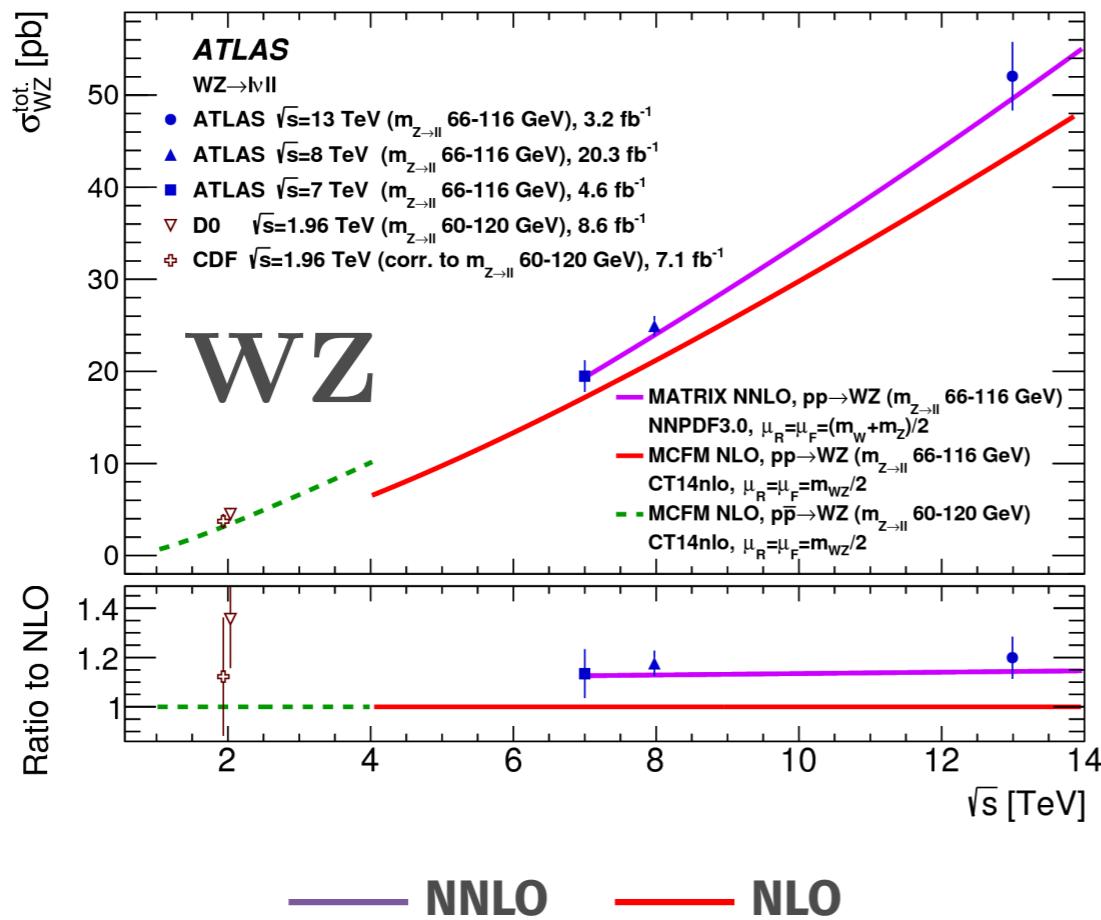
- ▶ substantially reduced uncertainties
 $\rightarrow 3\text{--}5\%$ (more than $\times 2$)
- ▶ strong distortion of shape
 \rightarrow (data vs. theory) much improved
- ▶ similarly: $m_{\ell\ell}$ & y^Z bins, ϕ_η^*

also: p_T^W & p_T^W/p_T^Z (for M_W)

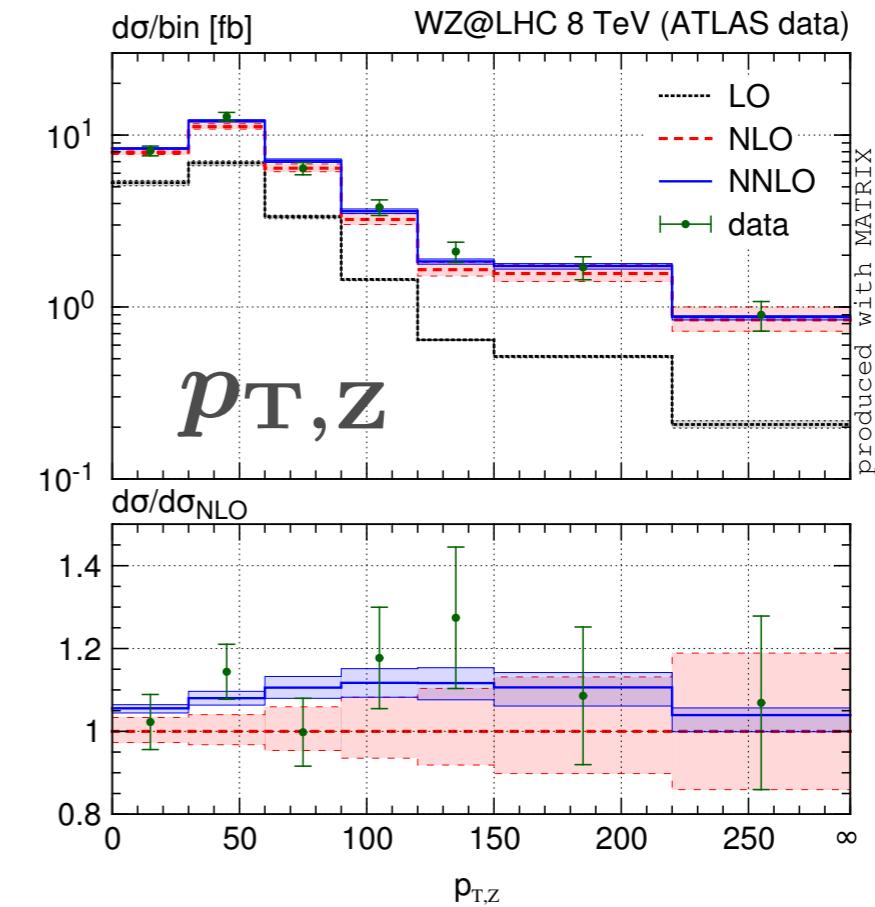
DI-BOSON PRODUCTION



- ▶ probe triple-gauge-couplings
→ test gauge structure of the SM
- ▶ important background
→ $H \rightarrow VV'$
→ BSM searches



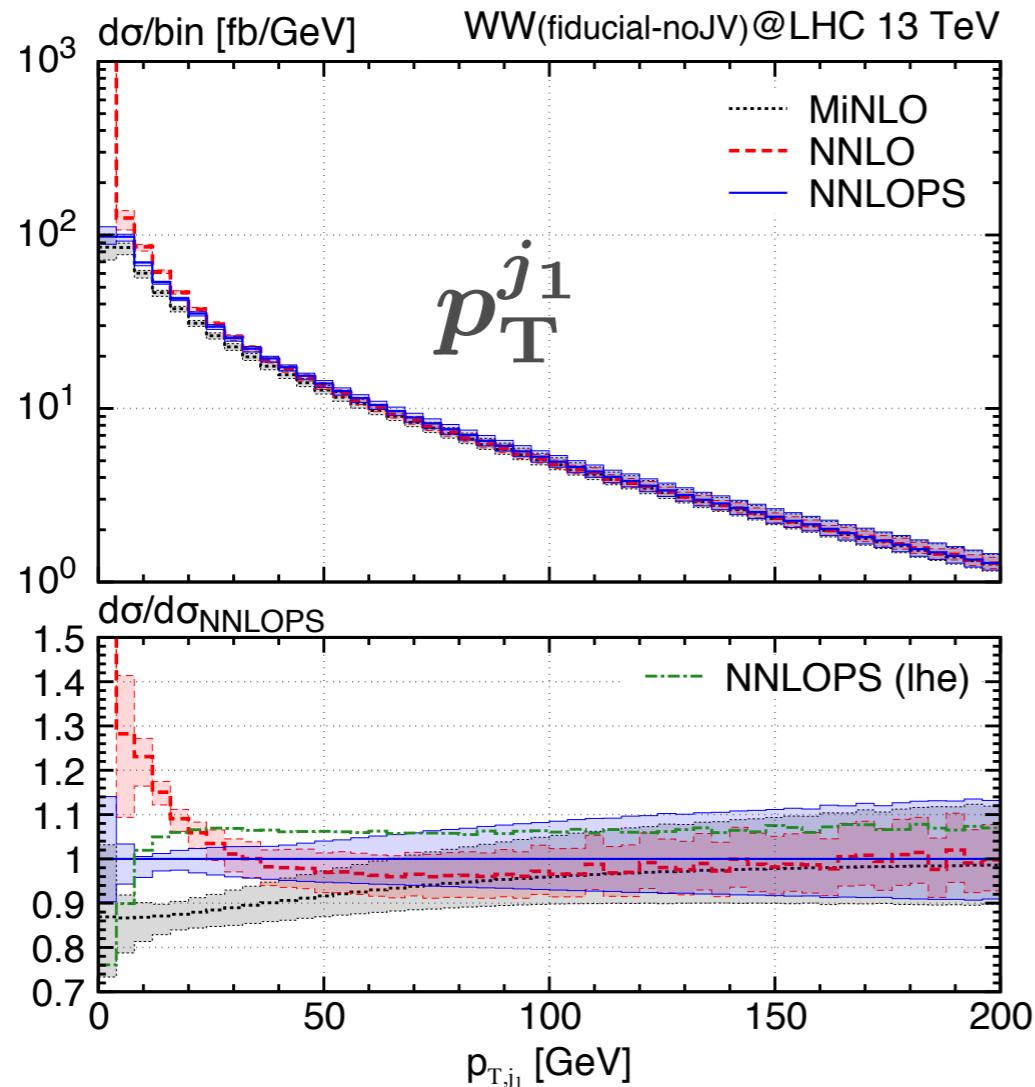
[ATLAS Phys. Lett. B 762 (2016) 1]



[Grazzini, Kallweit, Rathlev, Wiesemann '16 '17]

- ▶ NNLO essential in describing the data!

NNLO \otimes PS



[Re, Wiesemann, Zanderighi '18]



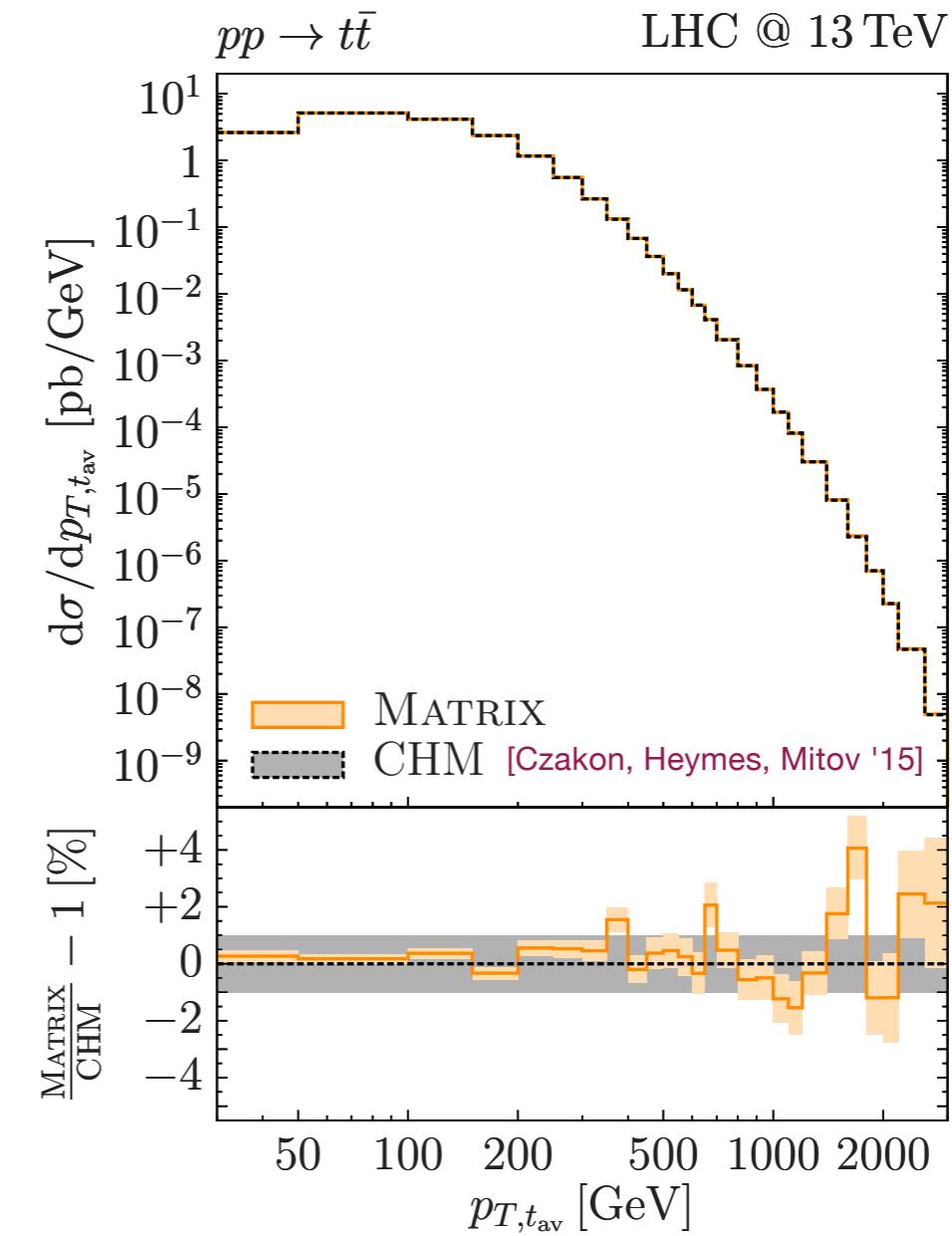
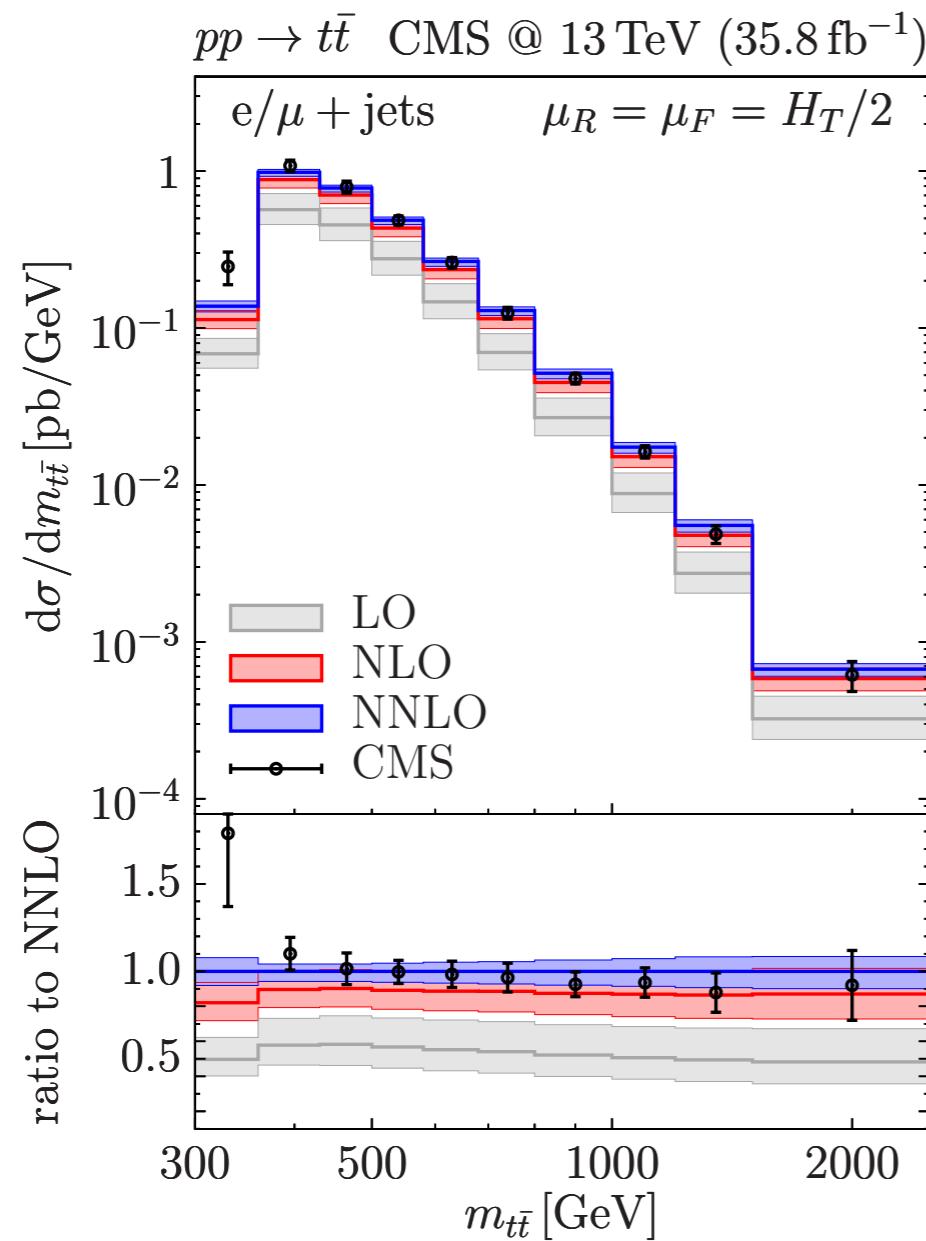
- ▶ high p_T : same nominal accuracy
→ NNLO \simeq MiNLO \simeq NNLOPS
- ▶ low p_T : sensitive to soft g effects
→ NNLO divergent
→ MiNLO \rightarrow NNLOPS: $\sim 15\%$

- ▶ **NLO** (loop-induced gg) [Caola, Melnikov, Röntsch, Tancredi '15]
↪ + Higgs interference [Caola, Dowling, Melnikov, Röntsch, Tancredi '16]
- ▶ **NLO EW** (different flavour) [Biedermann, Billoni, Denner, Dittmaier, Hofer, Jäger, Salfelder '16]
(+ same flavour) [Kallweit, Lindert, Pozzorini, Schönherr '17]

- ▶ colour-neutral: UN²LOPS [Hoeche, Li, Prestel '14], MiNLO [Karlberg, Re, Zanderighi '14], Geneva [Alioli et al. '15]

$t\bar{t}$ @ NNLO – Two Calculations!

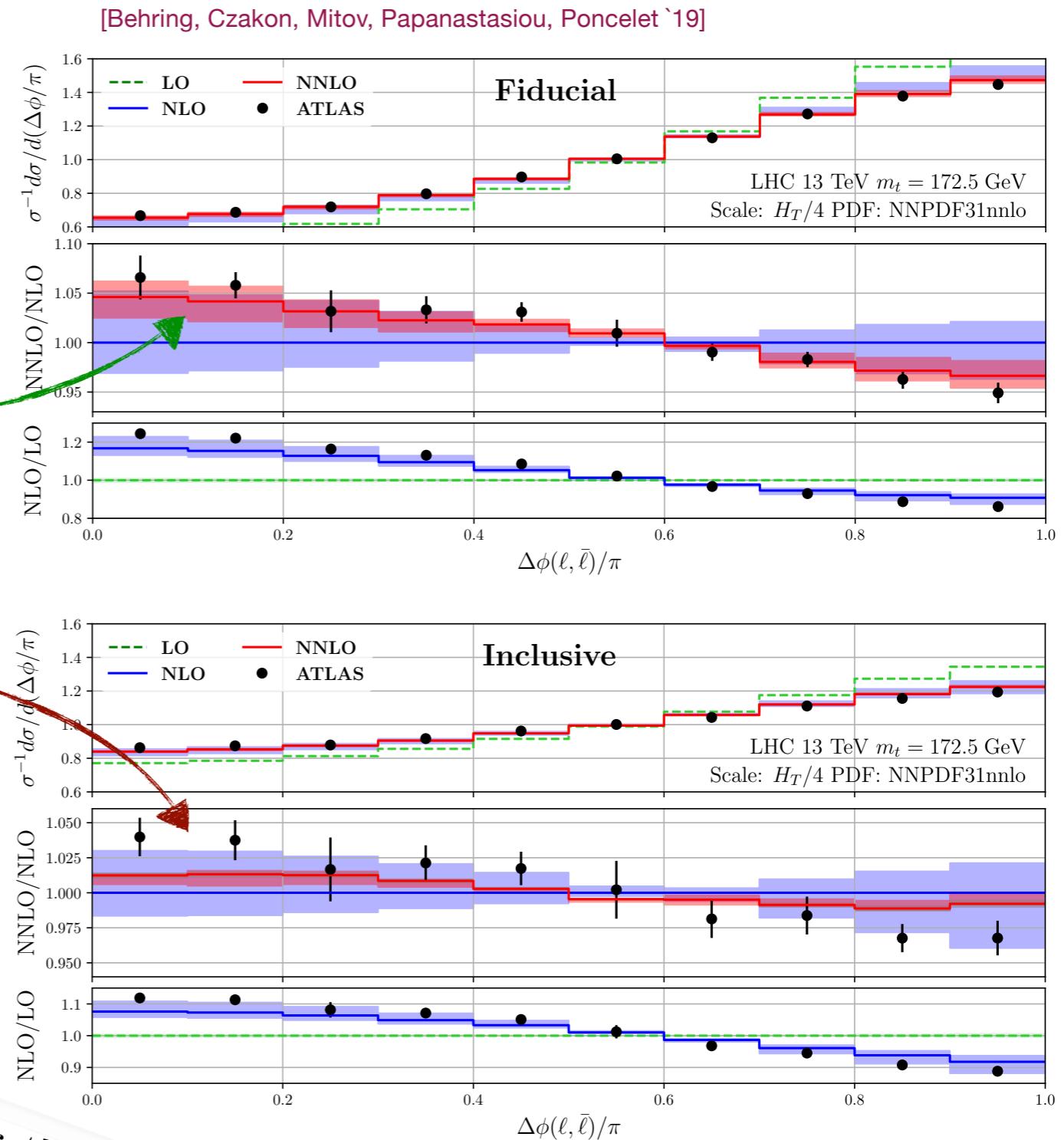
[Catani, Devoto, Grazzini, Kallweit, Mazzitelli '19]



- excellent agreement between the two calculations!

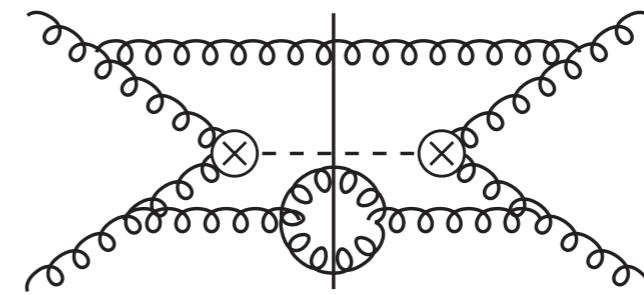
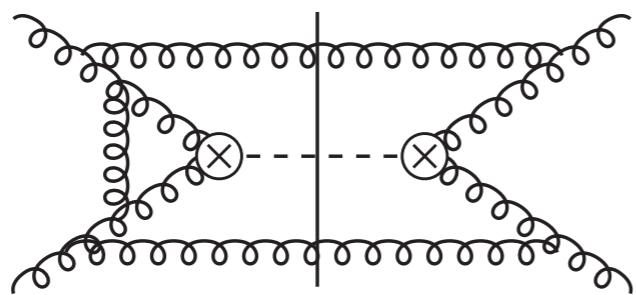
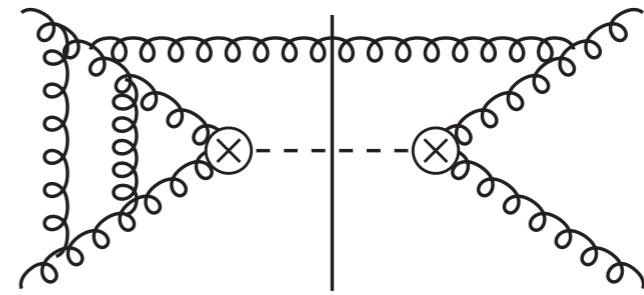
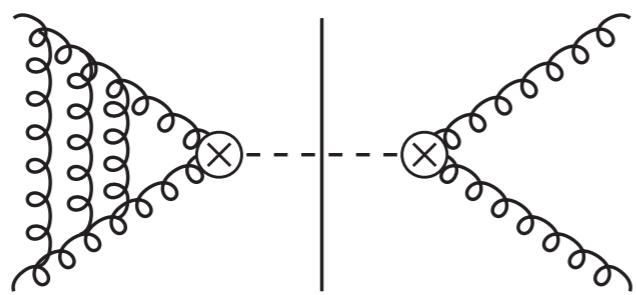
TOP QUARK SPIN CORRELATION AT NNLO

- leptons carry spin information of the tops
- fiducial: good agreement
- inclusive: some tension



In our view the most plausible explanation for this discrepancy lies in the extrapolation of the fiducial measurement to the full phase space.

N³LO



NEXT-TO-NEXT-TO-NEXT-TO-LEADING ORDER

Some benchmark processes require us to go even one order higher...

► inclusive results:

- ✓ $H(ggH)$ [Anastasiou et al. '15] [Mistlberger '18], $H(bbH)$ [Duhr, Dulat, Mistlberger '19]
- ✓ $H(VBF)$ [Dreyer, Karlberg '16], $HH(VBF)$ [Dreyer, Karlberg '18] \leftrightarrow (in DIS approx.)

► differential results:

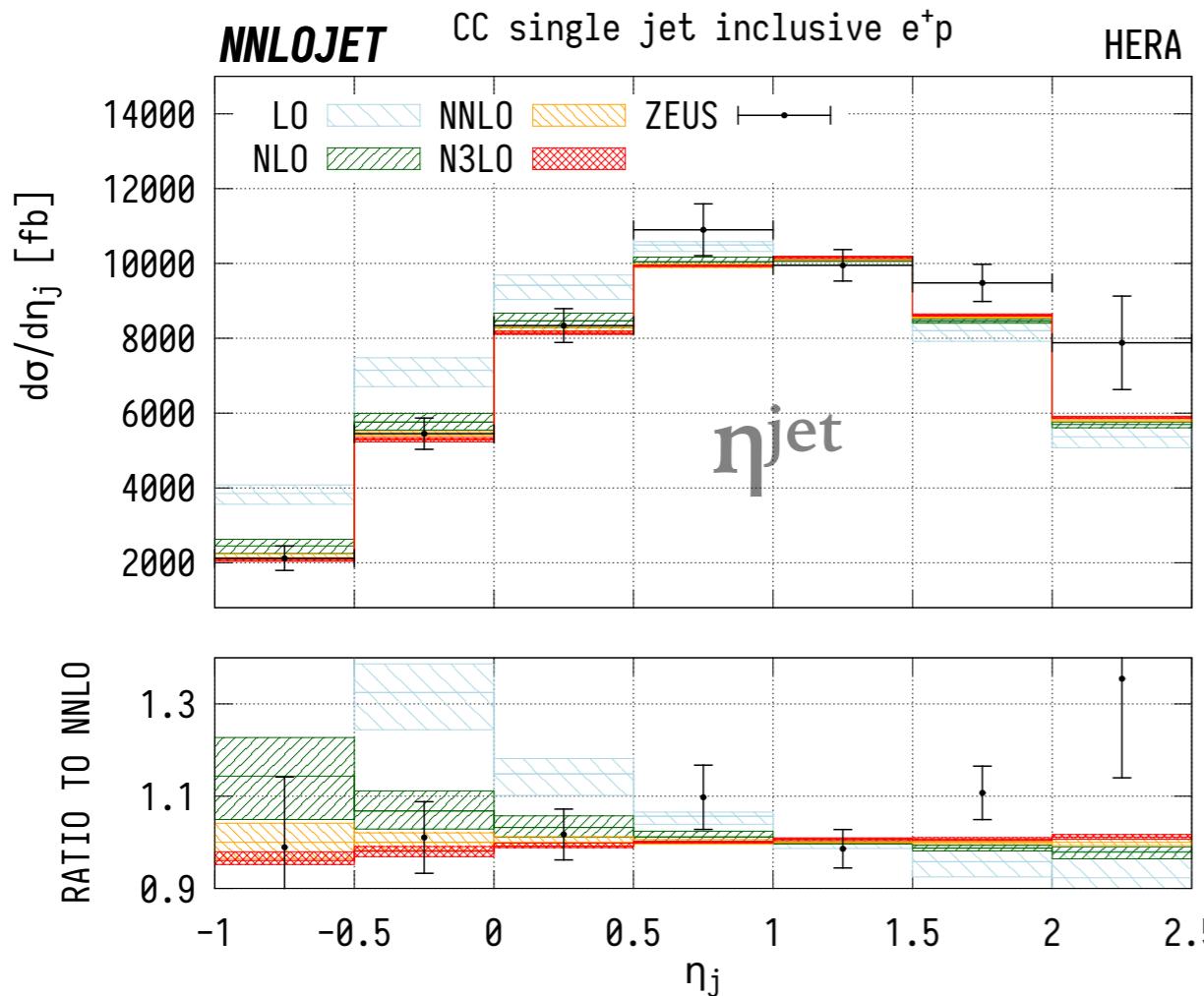
- ✓ $H(ggH)$: y_H analytic [Dulat, Mistlberger, Pelloni '18], q_T slicing [Cieri, Chen, Gehrmann, Glover, AH '18]
- ✓ $H \rightarrow bb$ [Mondini, Schiavi, Williams '19]
- ✓ DIS jet: NC [Currie, Gehrmann, Glover, AH, Niehues, Vogt '18], CC [Gehrmann, AH, Niehues, Vogt, Walker '18]

► expect more:

- fully differential $H(ggH, VBF)$, inclusive Drell-Yan, ...

NEXT-TO-NEXT-TO-NEXT-TO-LEADING ORDER

CC DIS jet production



- for the first time @ N^3LO :
 - overlapping bands!

- fully differential $H(ggH, VBF)$, inclusive Drell-Yan, ...

even one order higher...

H)

[Gehrmann, AH, Niehues, Vogt, Walker '18]

[Duhr, Dulat, Mistlberger '19]

[Meyer, Karlberg '18]

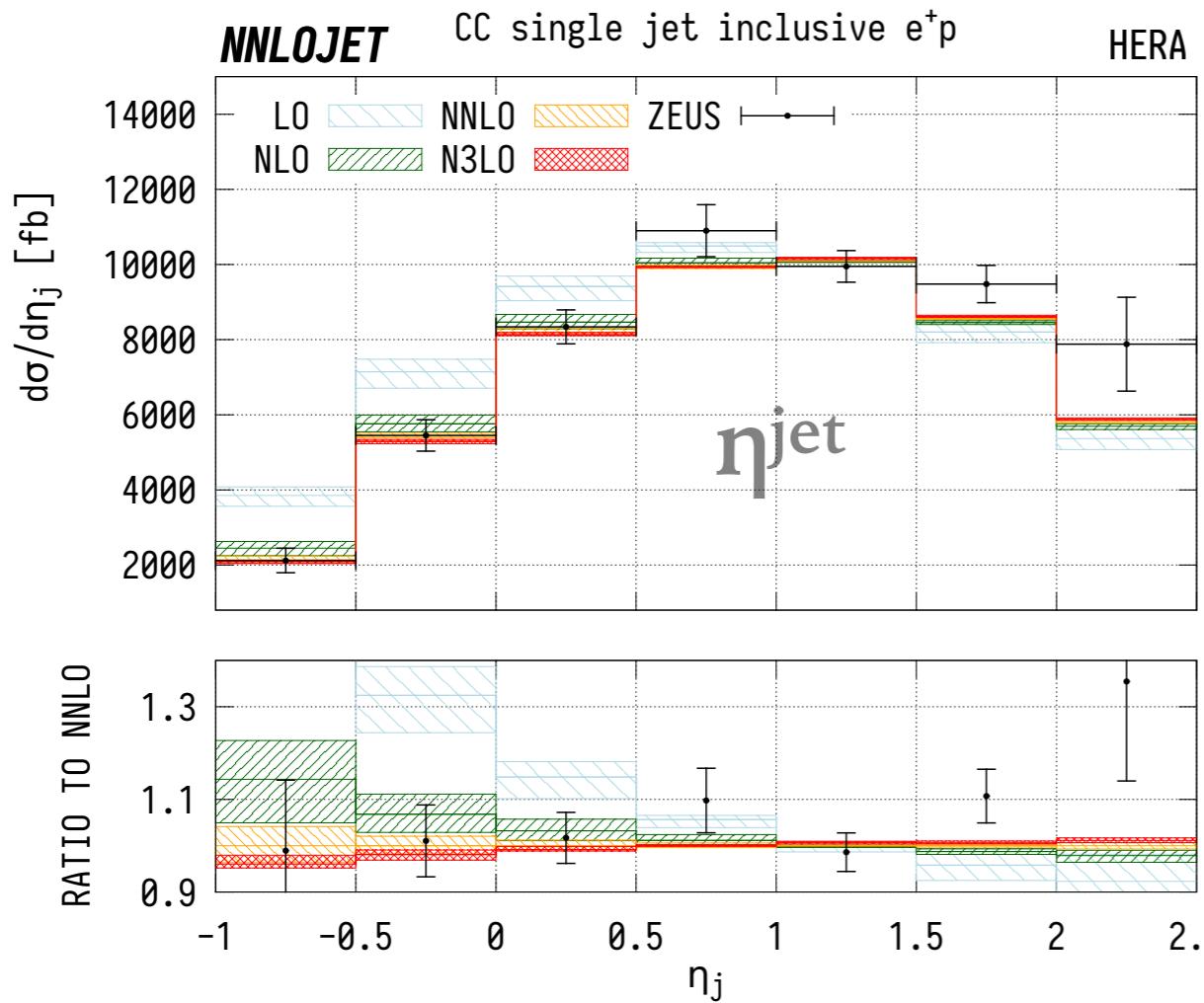
↔ (in DIS approx.)

[Cieri, Chen, Gehrmann, Glover, AH '18]

[Gehrmann, AH, Niehues, Vogt, Walker '18]

NEXT-TO-NEXT-TO-NEXT-TO-LEADING ORDER

CC DIS jet production

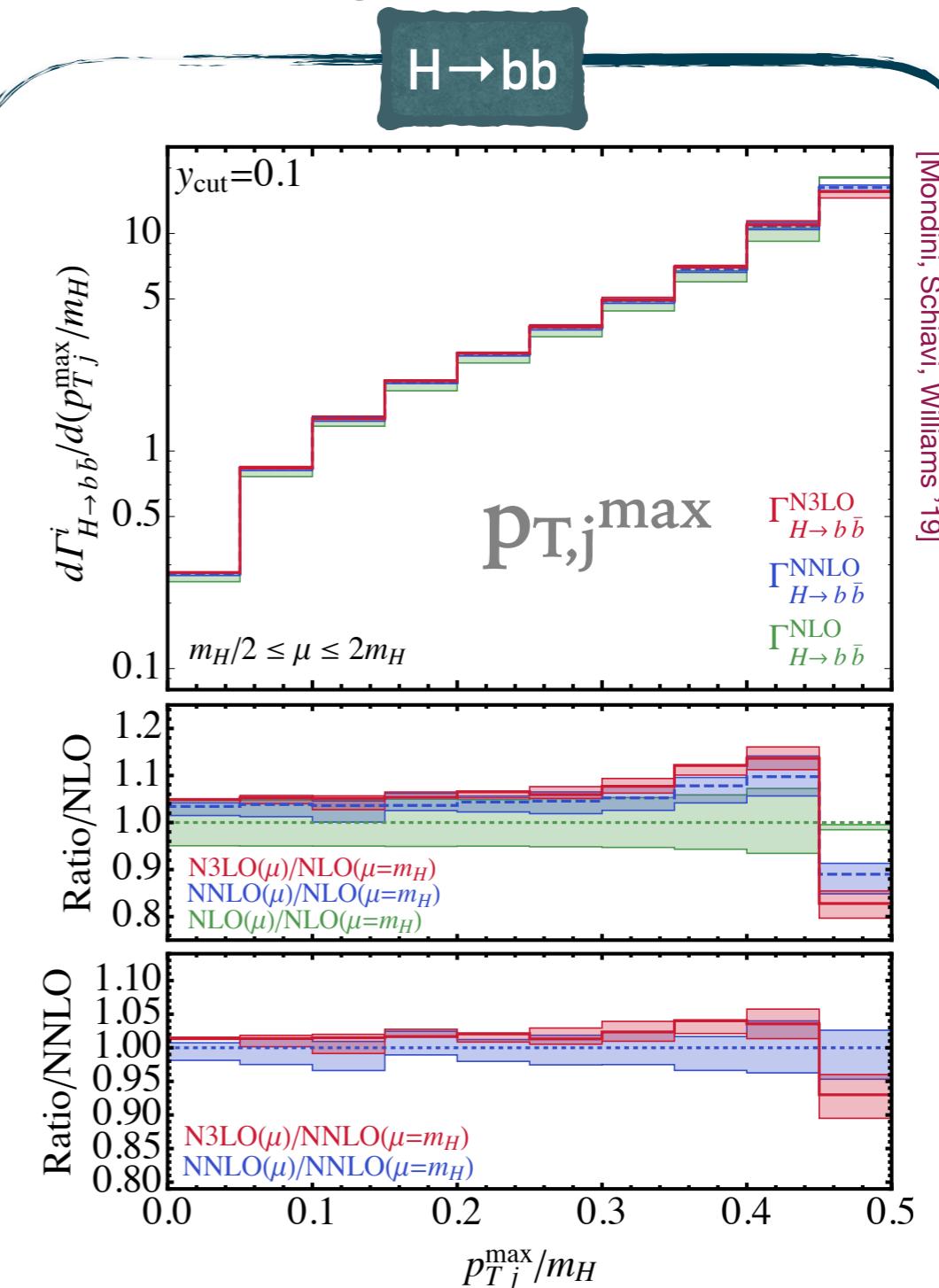


► for the first time @ N^3LO :

► overlapping bands!

- fully differential $H(ggH, VBF)$,

even one order higher...



LHC – GOING FULLY DIFFERENTIAL @ N³LO

inclusive

$$\sigma_{\text{tot}}^{\text{N}^3\text{LO}} = 48.68 \text{ pb}^{+2.07 \text{ pb}}_{-3.16 \text{ pb}}$$

- ✓ analytic integration over full phase space
- ✗ no information on final state

[Anastasiou et al. '15] [Mistlberger '18]

LHC

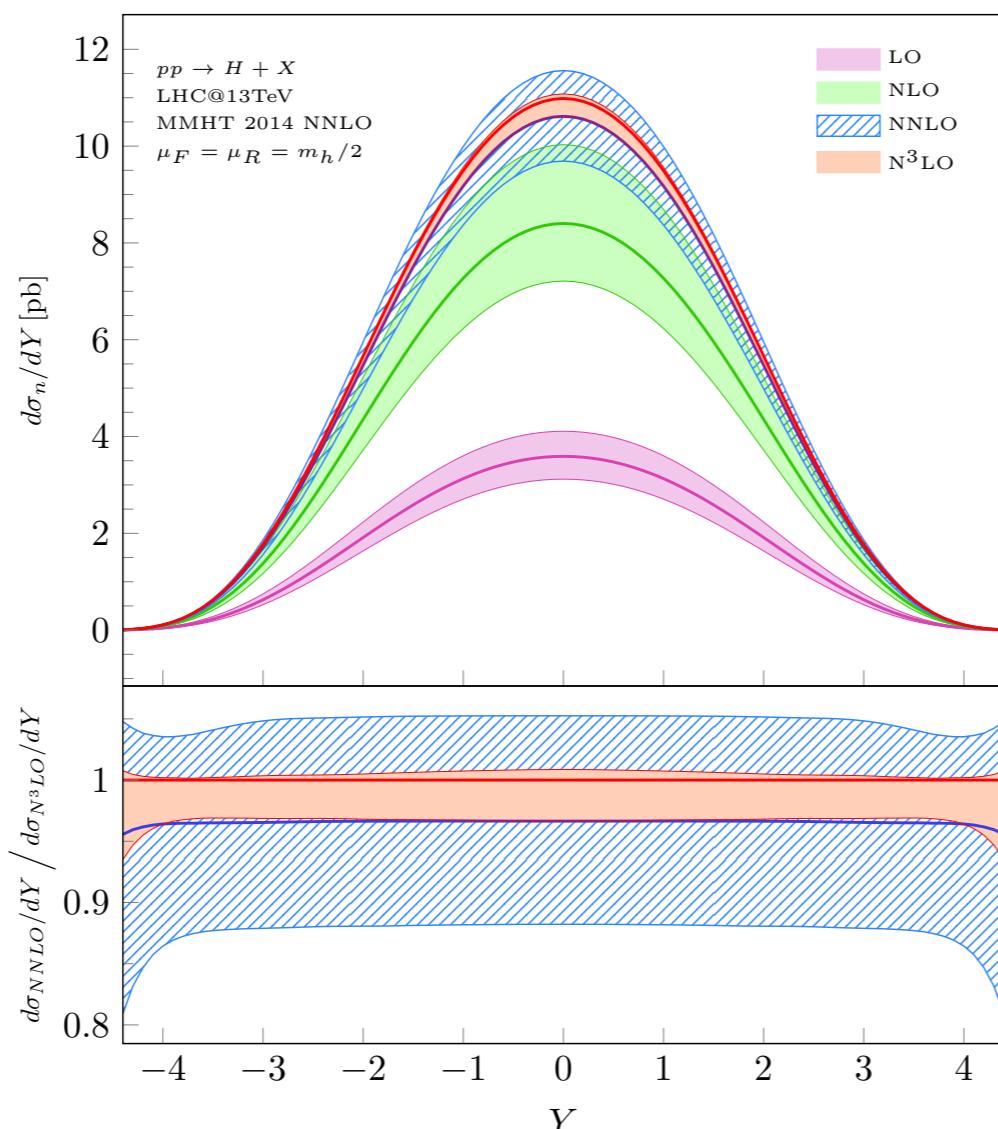
$\sigma_{\text{tot}}^{\text{N}^3\text{LO}}$

✓ analytic i

✗ no inform

y_H differential

N³LO



✓ analytic integration over QCD emissions

✗ partial information on final state

- only $y_H \rightsquigarrow$ no decay kinematics
- no information on final-state partons

LHC

$\sigma_{\text{tot}}^{\text{N}^3\text{LO}}$

✓ analytic info

✗ no information

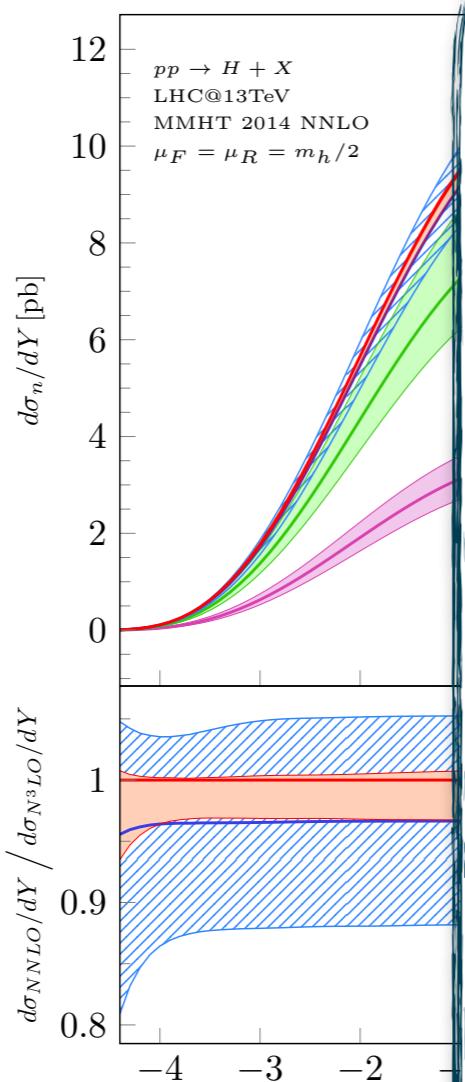
✓ analytic integration

✗ partial information

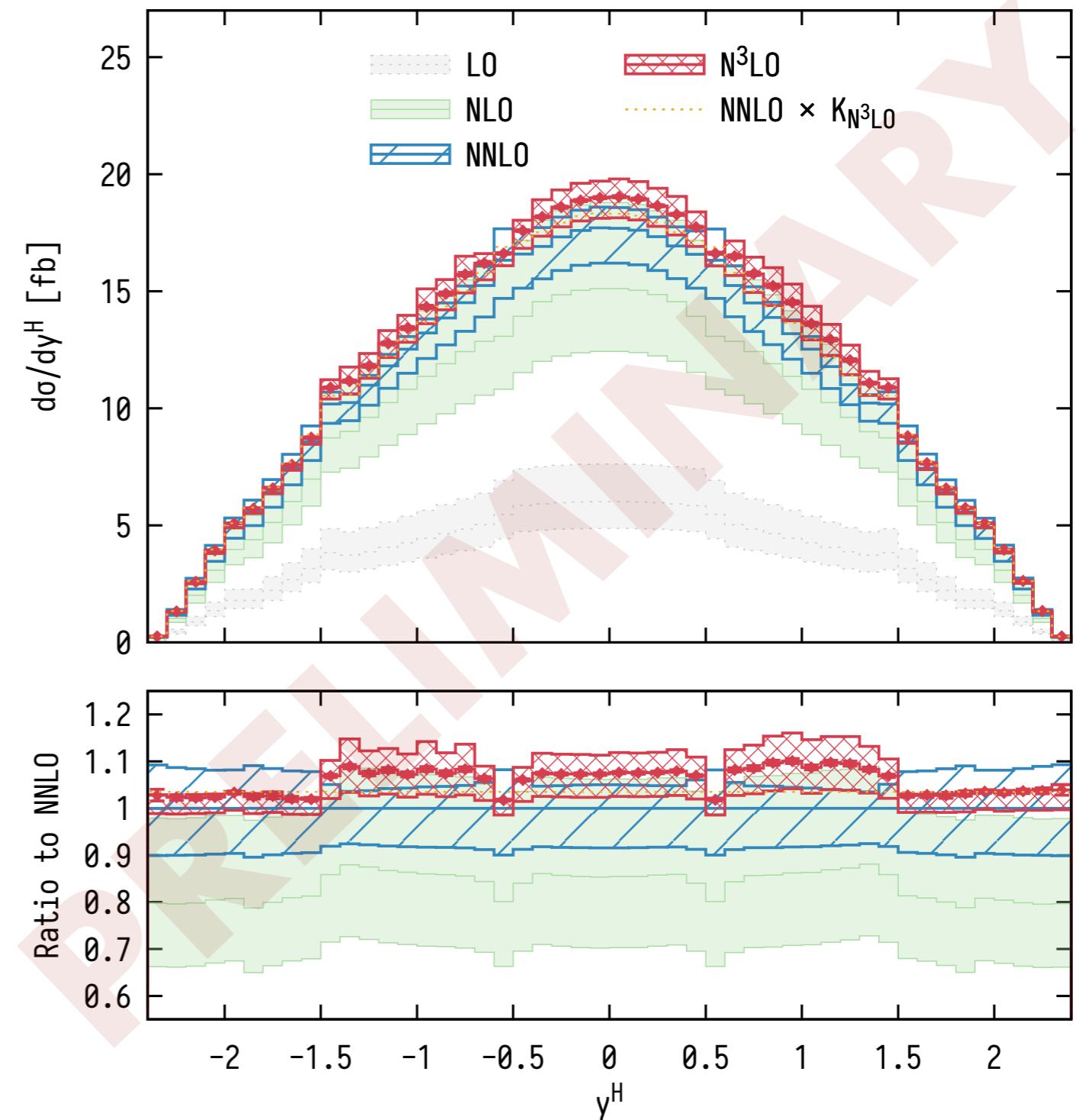
➢ only $y_H \rightsquigarrow r$

➢ no information

y_H differential



fully differential



✓ numerical integration of phase space

✓ complete final-state information (decay, isol., ...)

CONCLUSIONS & OUTLOOK

- LHC — remarkable opportunity to study high-energy physics
 - search for new physics & probe the Higgs sector
 - precision measurements using “standard candles”
- ⇒ high-precision predictions essential!
(reduced uncertainties & often resolves tension to data)
- Remarkable progress in precision calculations:
 - $2 \rightarrow 2$ @ NNLO, $2 \rightarrow 1$ @ N³LO, NLO EW $2 \rightarrow 6$
- precision phenomenology using these calculations has only started!

CONCLUSIONS & OUTLOOK

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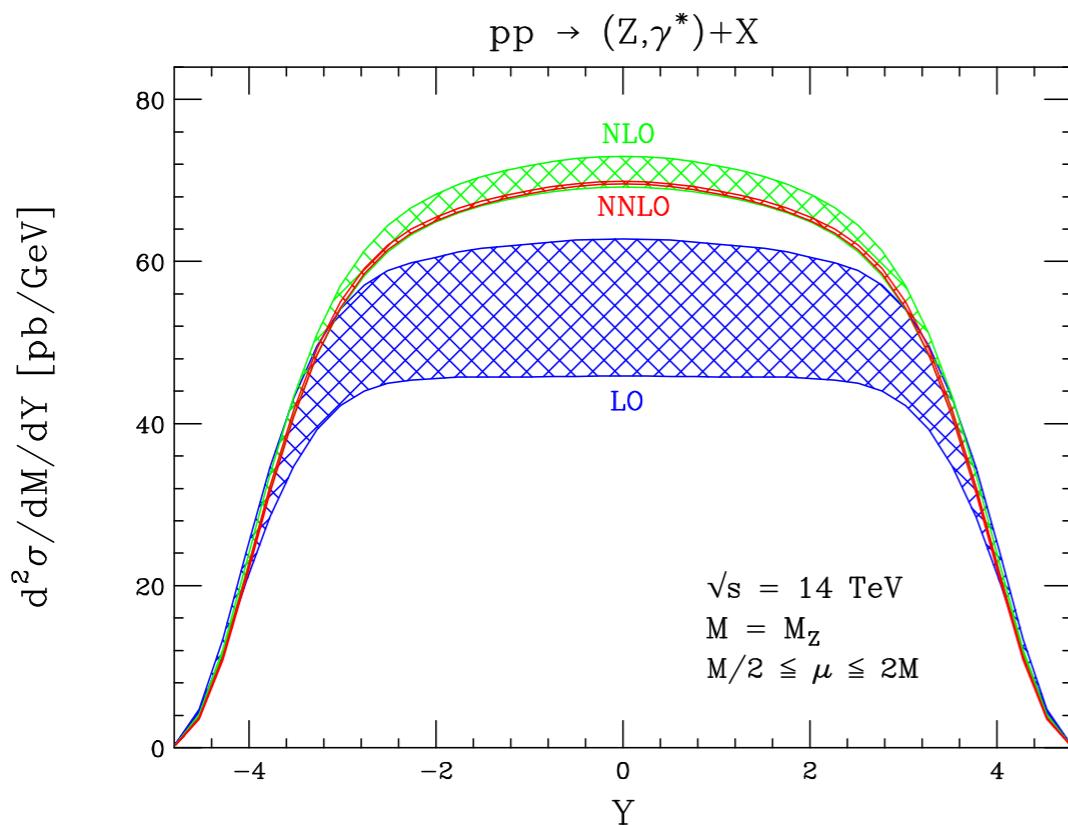
THANK YOU!

BACKUP.

BUCKOLY

WHY HIGHER ORDERS?

- ▶ high-precision mandatory
 - ↪ processes with large K -factors (H)
 - ↪ “standard candles” (jets, V , t , ...)
- ▶ reduction of scale uncertainties
 - ↪ variation of μ_R & μ_F



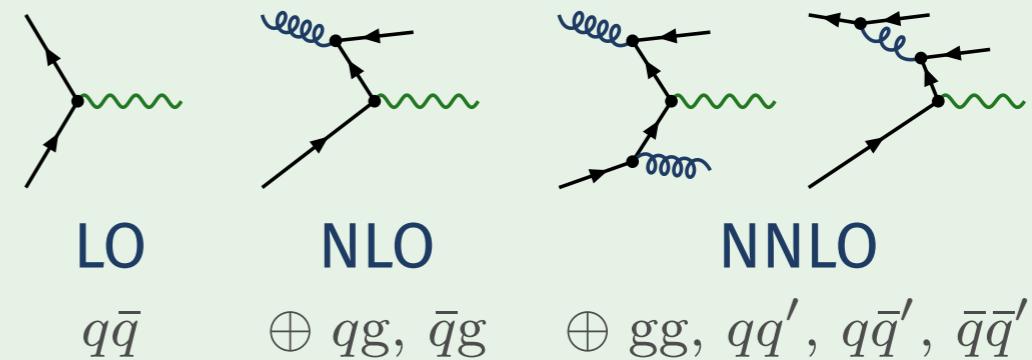
[Anastasiou, Dixon, Melnikov, Petriello '04]

Jet clustering



- ▶ better modelling of jet algorithm between theory & experiment

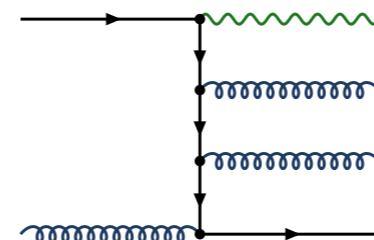
Initial-state radiation



- ▶ opening up of all channels
- ▶ more complicated p_T recoil

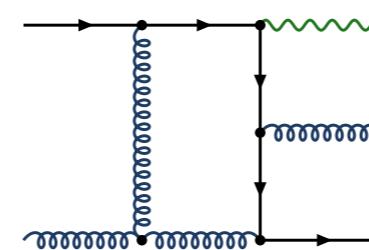
ANATOMY OF NNLO CALCULATIONS

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



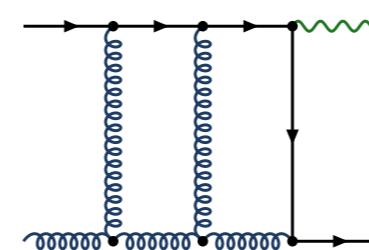
- ▶ single-unresolved
- ▶ double-unresolved

$$+ \int_{\Phi_{Z+2}} d\sigma_{\text{NNLO}}^{\text{RV}}$$



- ▶ single-unresolved
- ▶ $1/\epsilon^2, 1/\epsilon$

$$+ \int_{\Phi_{Z+1}} d\sigma_{\text{NNLO}}^{\text{VV}}$$

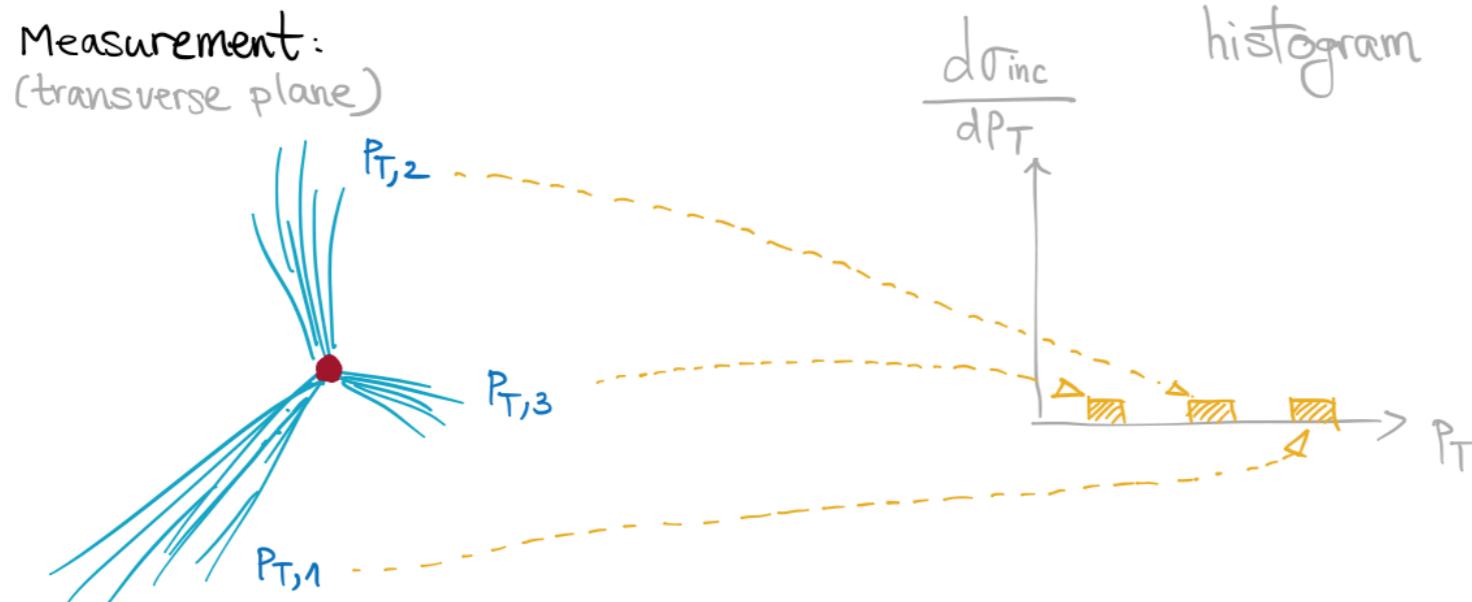


- ▶ $1/\epsilon^4, 1/\epsilon^3, 1/\epsilon^2, 1/\epsilon$

\sum finite (Kinoshita–Lee–Nauenberg & factorization)

Non-trivial cancellation of infrared singularities

INCLUSIVE JET PRODUCTION



$$\left\{ \begin{array}{l} n \text{ reconstructed jets} \\ \text{in the event} \end{array} \right\} \leftrightarrow \left\{ \begin{array}{l} n \text{ binnings to} \\ \text{the histogram} \end{array} \right\} \Rightarrow \sum_{\text{bins}} \frac{d\sigma_{\text{inc}}}{dp_T} \neq \sigma_{\text{tot}}$$

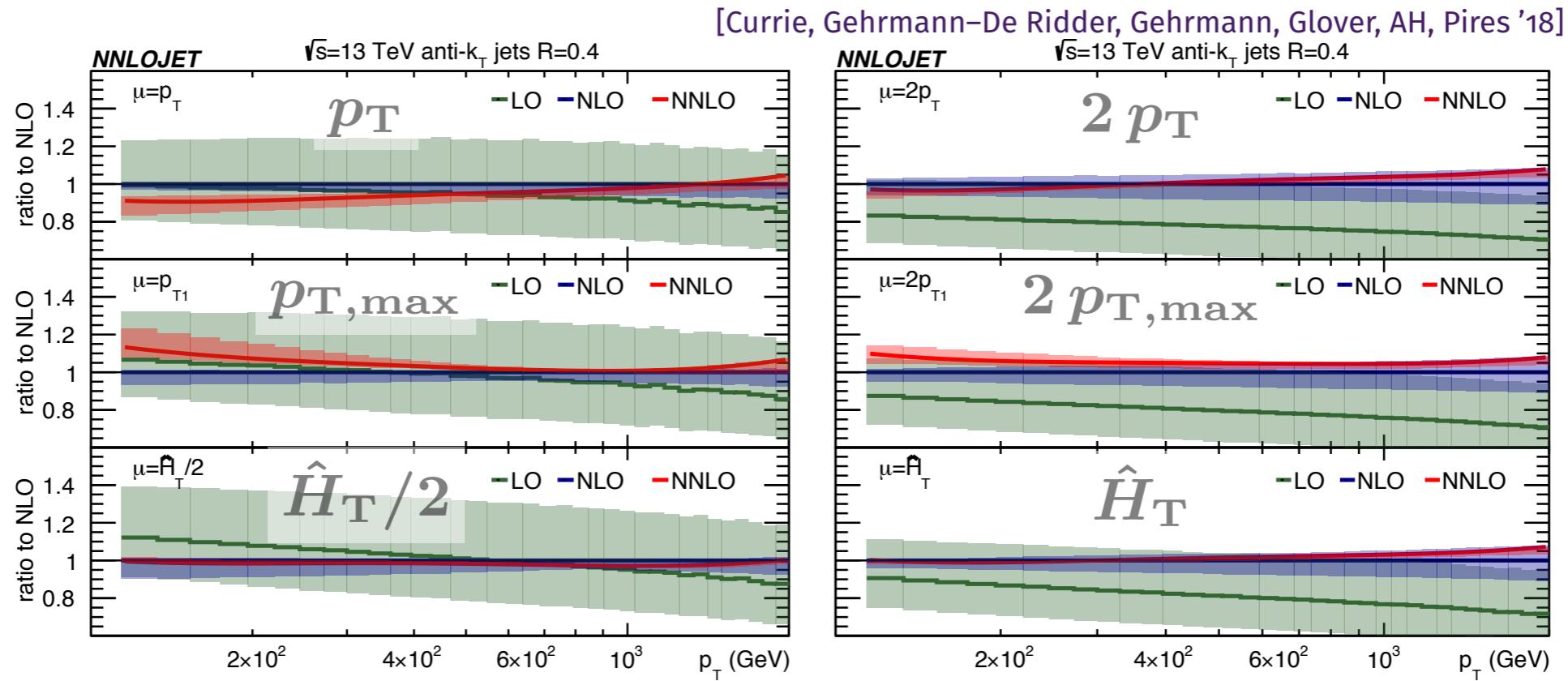
scale choices



binning of *individual jets vs. events*

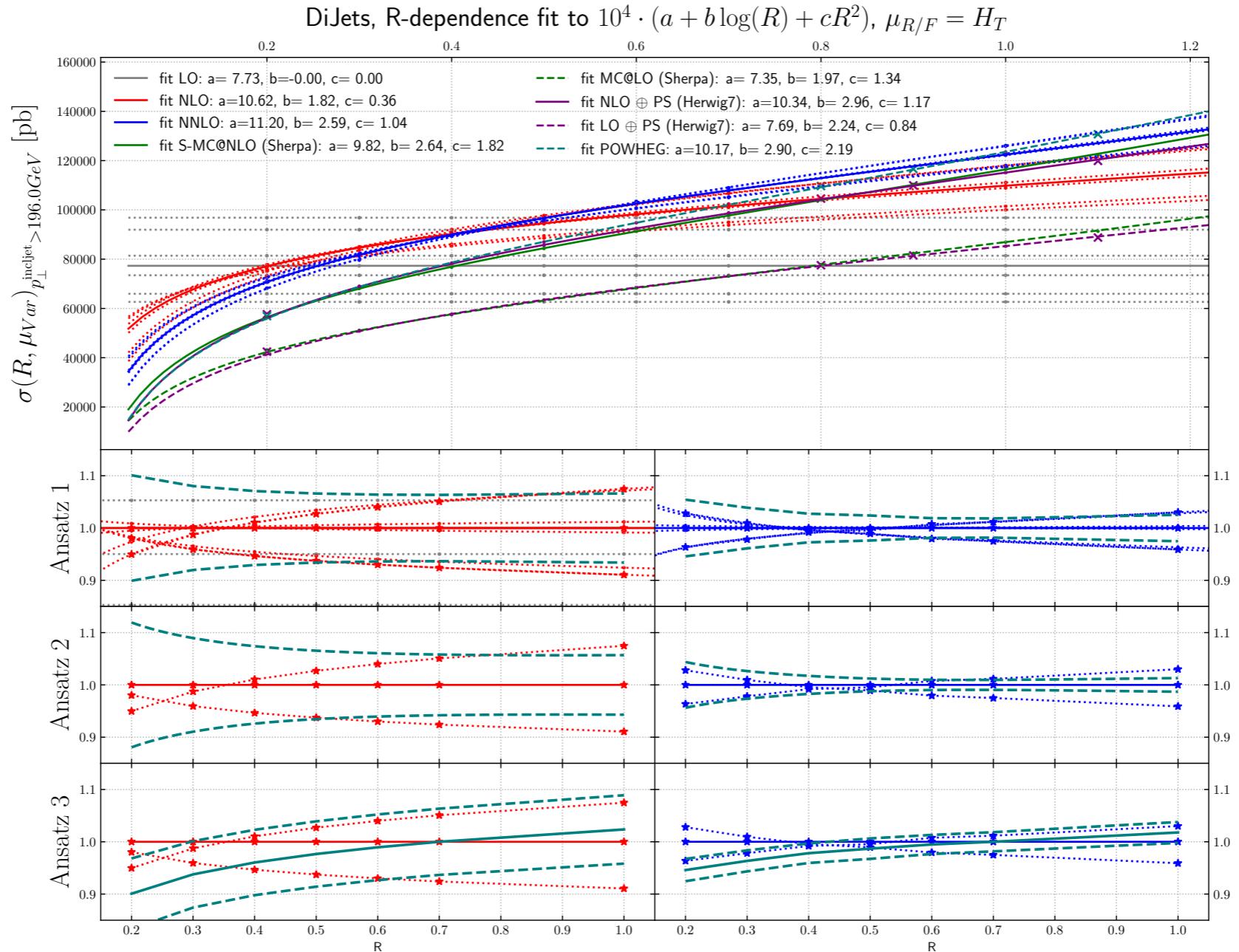
- ▶ “global” scales (event): $p_{T,\text{max}}, \langle p_T \rangle, \dots$
- ▶ “local” scales (jet): p_T, \dots

INCLUSIVE JET PRODUCTION — SCALE CHOICES ($R=0.4$)



- ▶ most common choice: $\mu = p_T$ & $\mu = p_{T,\max}$
 - ↪ worst perturbative behaviour
- ▶ harder scales preferred: $\mu = 2p_T$ & $\mu = \hat{H}_T$
 - ↪ show good properties
- ▶ origin: infrared sensitivity of the inclusive-jet observable
 - ↪ driven by 2nd leading jet distribution $p_T^{j_2}$ (very small @ NLO)
 - ↪ mismatch between real & virtual corrections (alleviated with larger R)

INCLUSIVE JET PRODUCTION — R DEPENDENCE



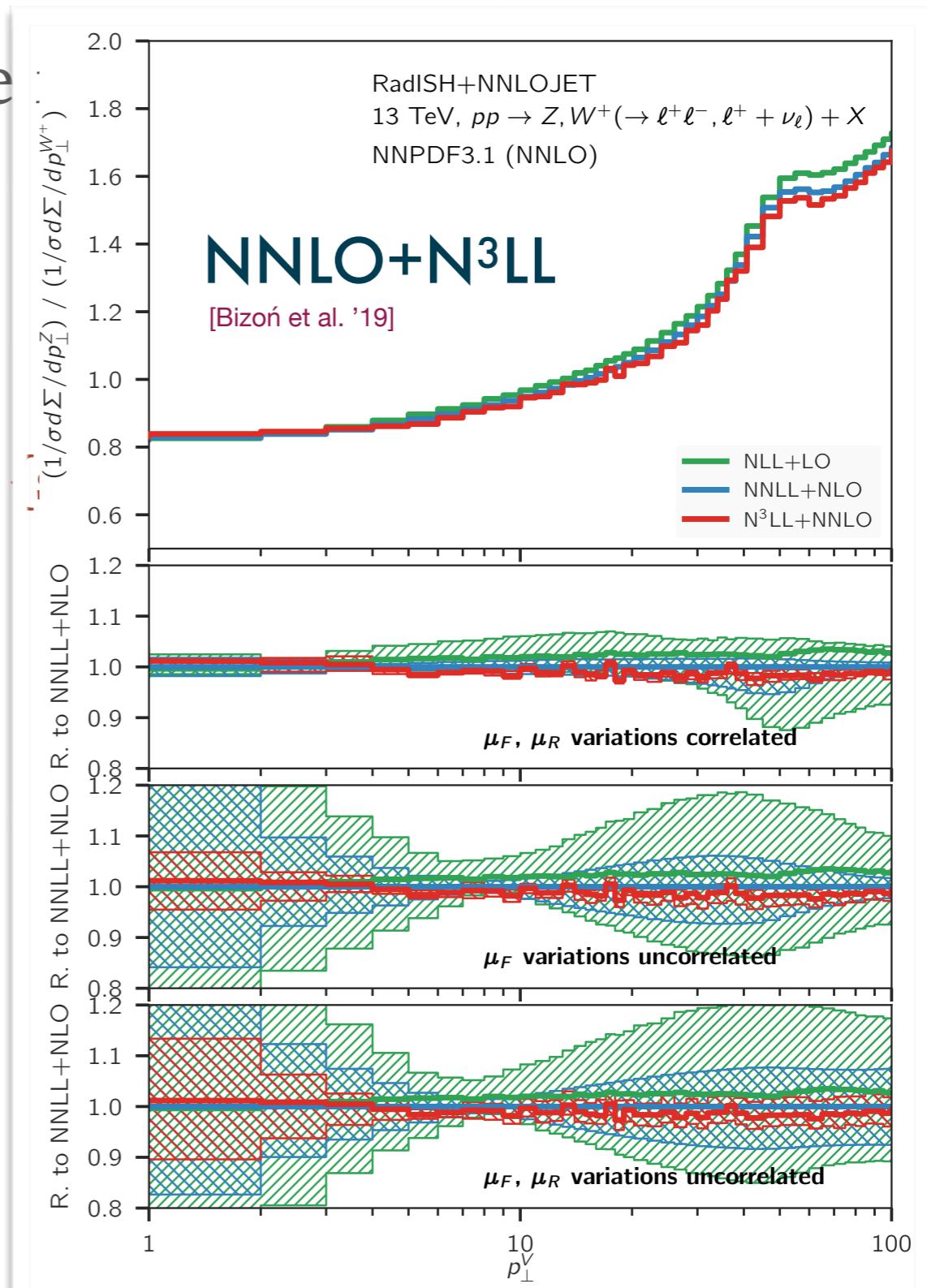
- accidental $\delta(\text{scale}) \sim 0$ at $R=0.4$
- small R: resummation [Dasgupta, Dreyer, Salam, Soyez '16] [Liu, Moch, Ringer '17 '18]

THEORY UNCERTAINTIES

- increasingly urgent to have more robust uncertainty estimates
- scale ambiguities in jets
- theory uncertainties in PDF fits
- scales in ratios:

THEORY UNCERTAINTIES

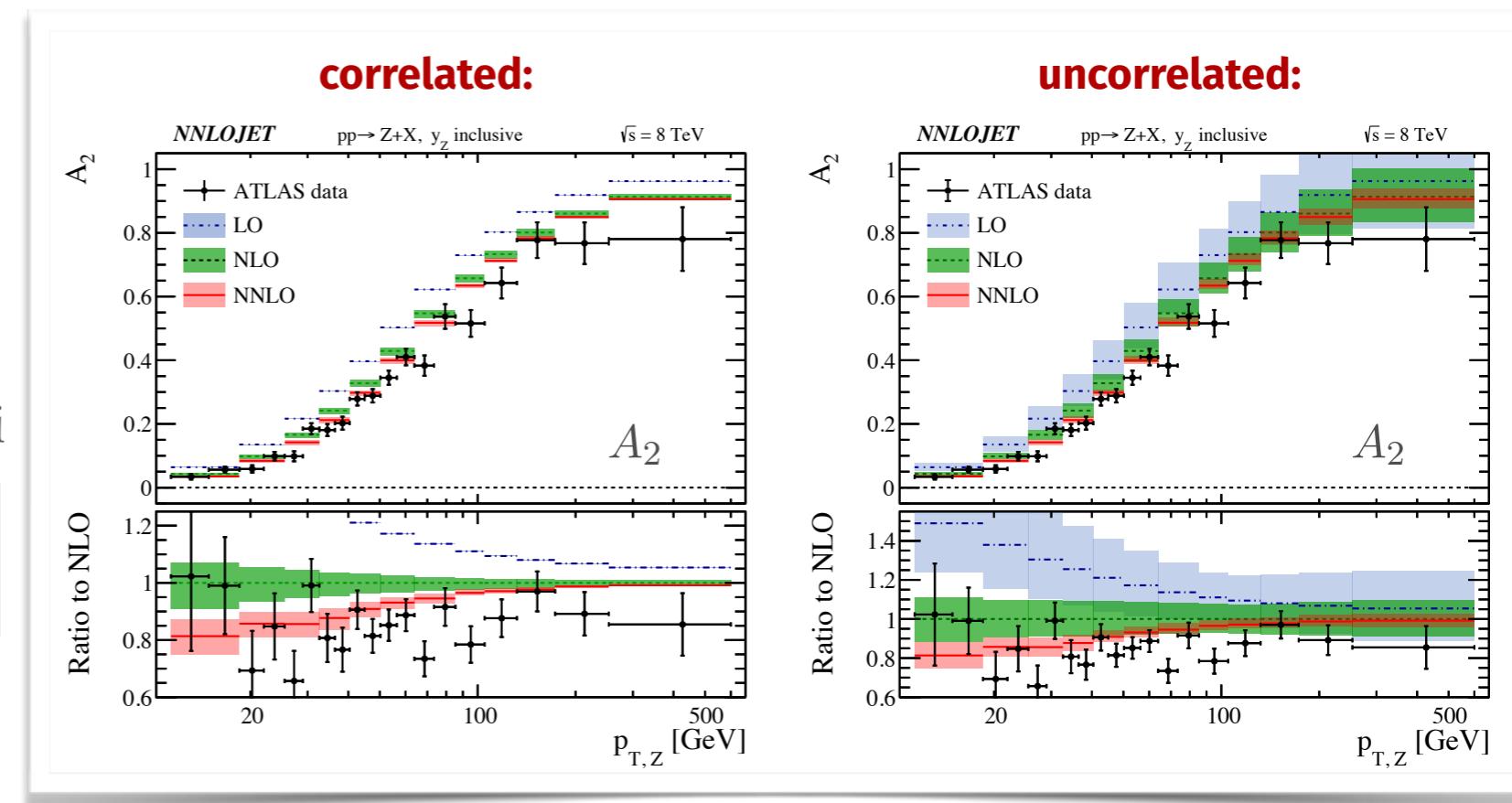
- increasingly urgent to have more
- scale ambiguities in jets
- theory uncertainties in PDF fits
- scales in ratios:
 - $p_T(Z) / p_T(W)$



THEORY UNCERTAINTIES

- increasingly urgent to have more robust uncertainty estimates
- scale ambiguities in jets
- theory uncertainties in PDF fits
- scales in ratios:
 - $p_T(Z) / p_T(W)$
 - ang. coefficients A_i

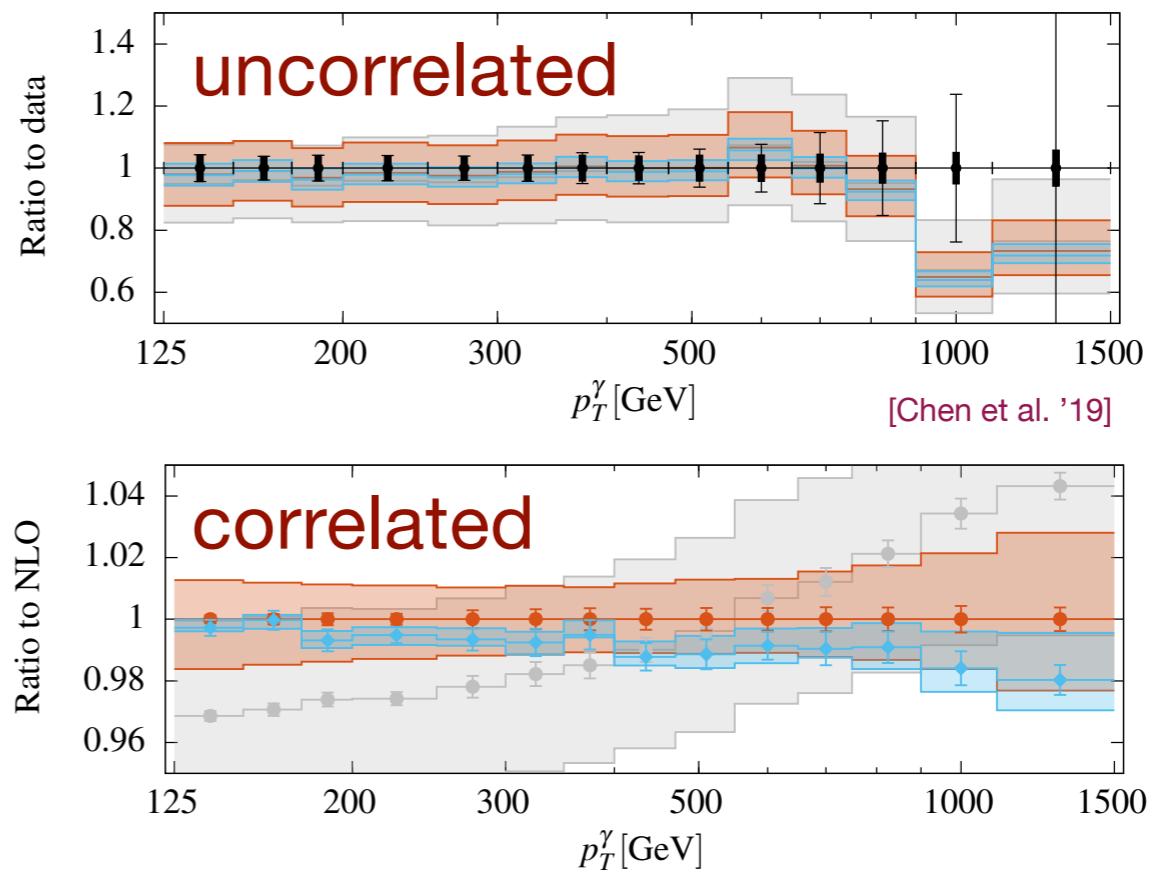
$$\langle f(\theta, \phi) \rangle = \frac{\int d\Omega d\sigma(\mu_F^{\text{num.}}, \mu_R^{\text{num.}}) f(\theta, \phi)}{\int d\Omega d\sigma(\mu_F^{\text{den.}}, \mu_R^{\text{den.}})}$$



[Gauld et al. '17]

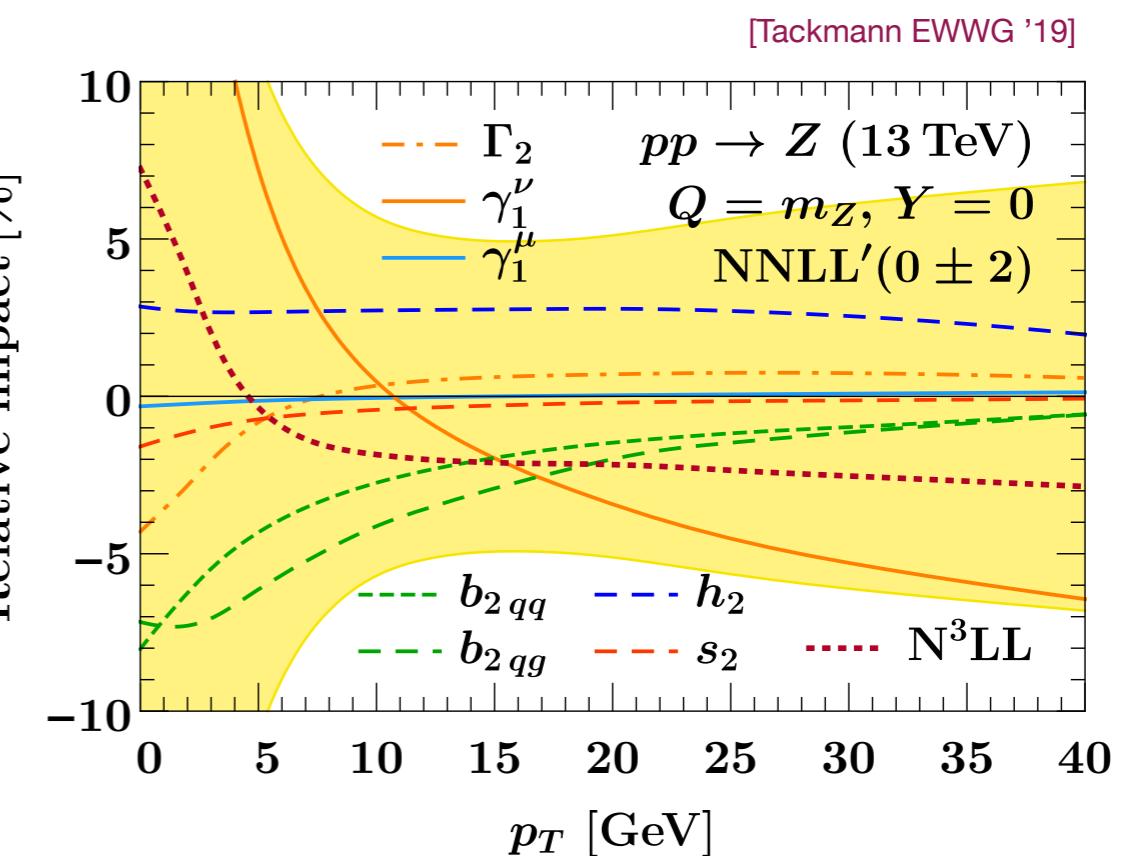
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 - ang. coefficients A_i
 - $p_T(\gamma)$: 13 TeV / 8 TeV

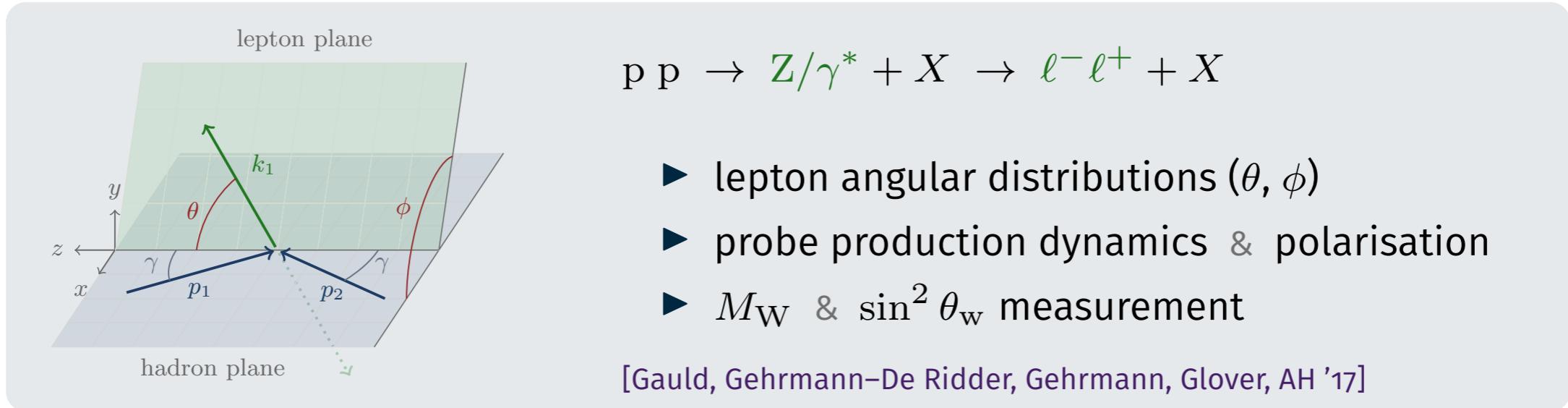


THEORY UNCERTAINTIES

- increasingly urgent to have more robust uncertainty estimates
- scale ambiguities in jets
- theory uncertainties in PDF fits
- scales in ratios:
 - $p_T(Z) / p_T(W)$
 - ang. coefficients A_i
 - $p_T(\gamma)$: 13 TeV / 8 TeV
- nuisance parameters in p_T res.



ANGULAR COEFFICIENTS



Angular coefficients: $A_i(p_T^Z, y^Z, m_{\ell\ell})$

$Y_{lm}(\theta, \phi), l = 0, 1, 2$

$$\frac{d\sigma}{d^4q \ d\cos\theta \ d\phi} = \frac{3}{16\pi} \frac{d\sigma^{\text{unpol.}}}{d^4q} \left\{ (1 + \cos^2\theta) + \frac{1}{2} \ A_0 \ (1 - 3\cos^2\theta) \right.$$

$$+ A_1 \ \sin(2\theta) \cos\phi + \frac{1}{2} \ A_2 \ \sin^2\theta \ \cos(2\phi)$$

$$+ A_3 \ \sin\theta \ \cos\phi + A_4 \ \cos\theta + A_5 \ \sin^2\theta \ \sin(2\phi)$$

$$\left. + A_6 \ \sin(2\theta) \ \sin\phi + A_7 \ \sin\theta \ \sin\phi \right\}$$

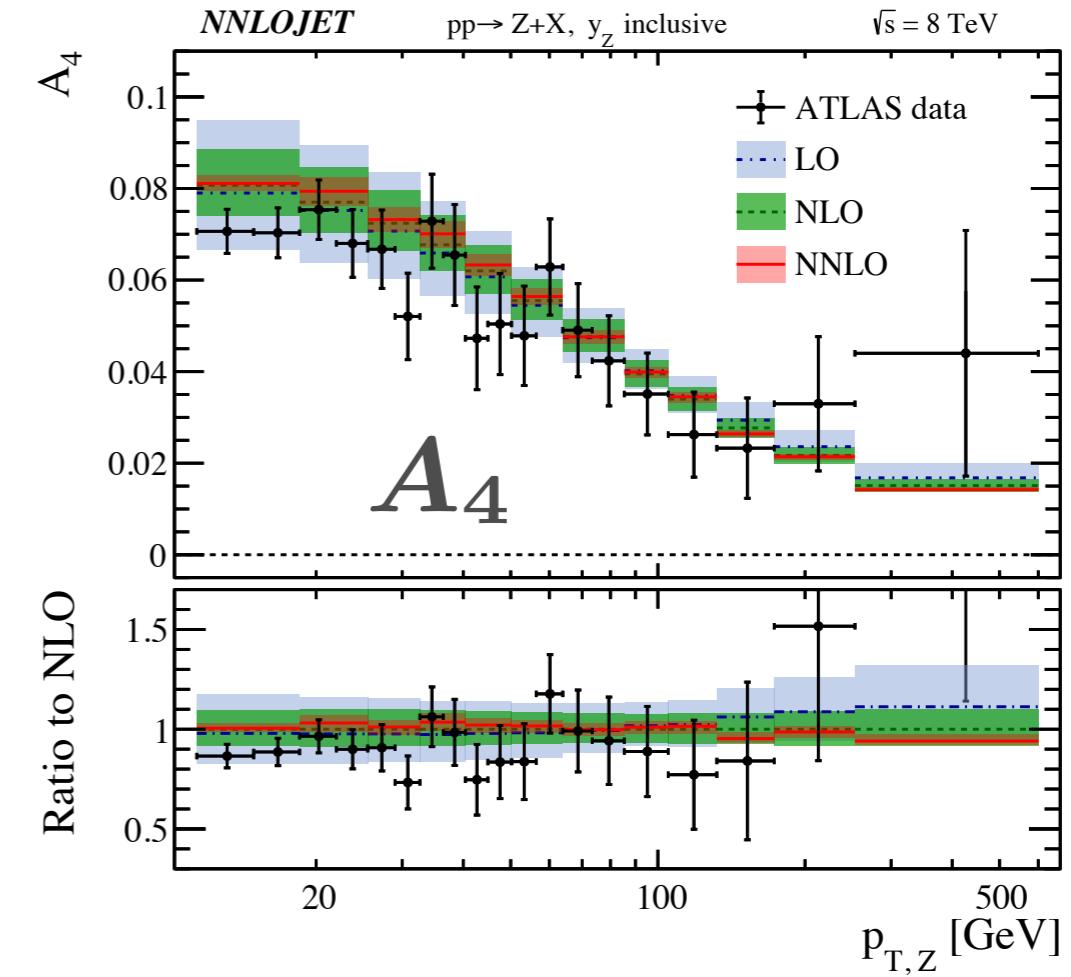
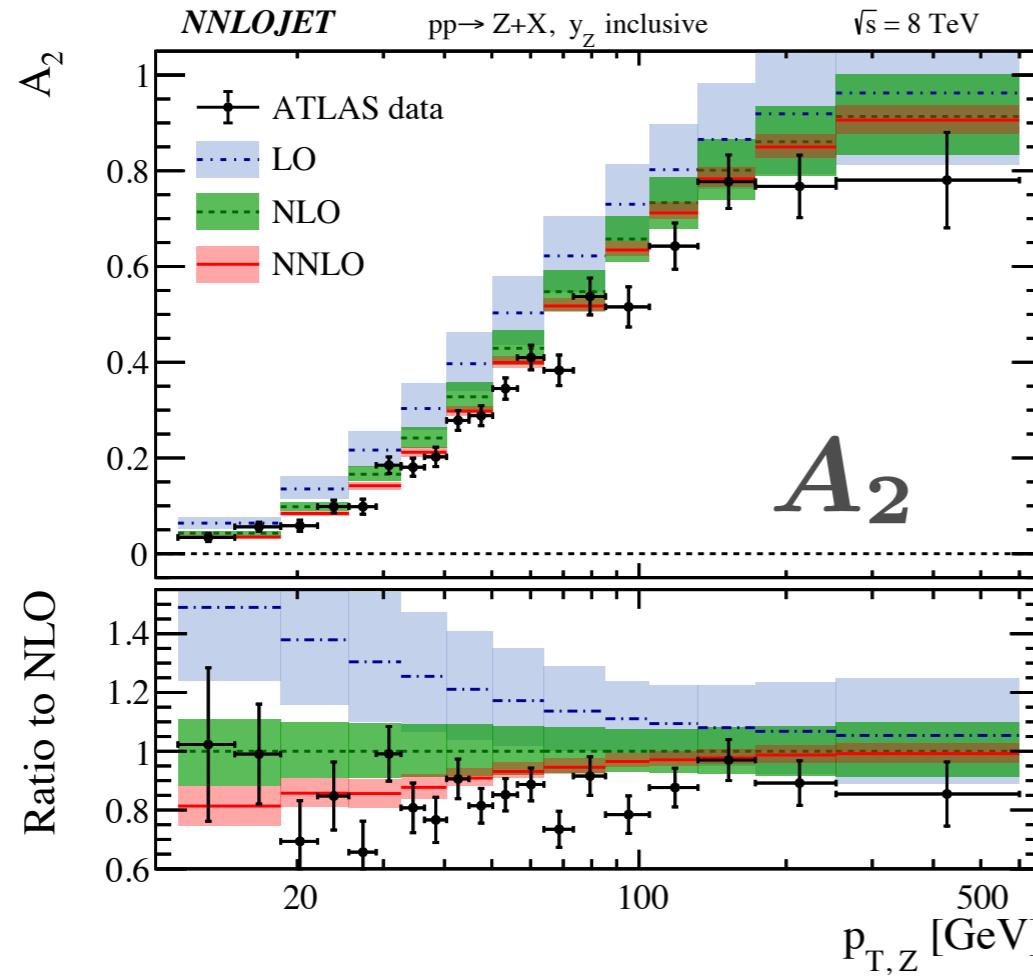
$A_i(q)$ + $\sigma^{\text{unpol.}}$
production dynamics

$Y_{lm}(\theta, \phi)$
lepton kinematics

$l = 0 :$	$m = 0$
$l = 1 :$	$m = \pm 1, 0$
$l = 2 :$	$m = \pm 2, \pm 1, 0$
total:	9

ANGULAR COEFFICIENTS — A_2 & A_4

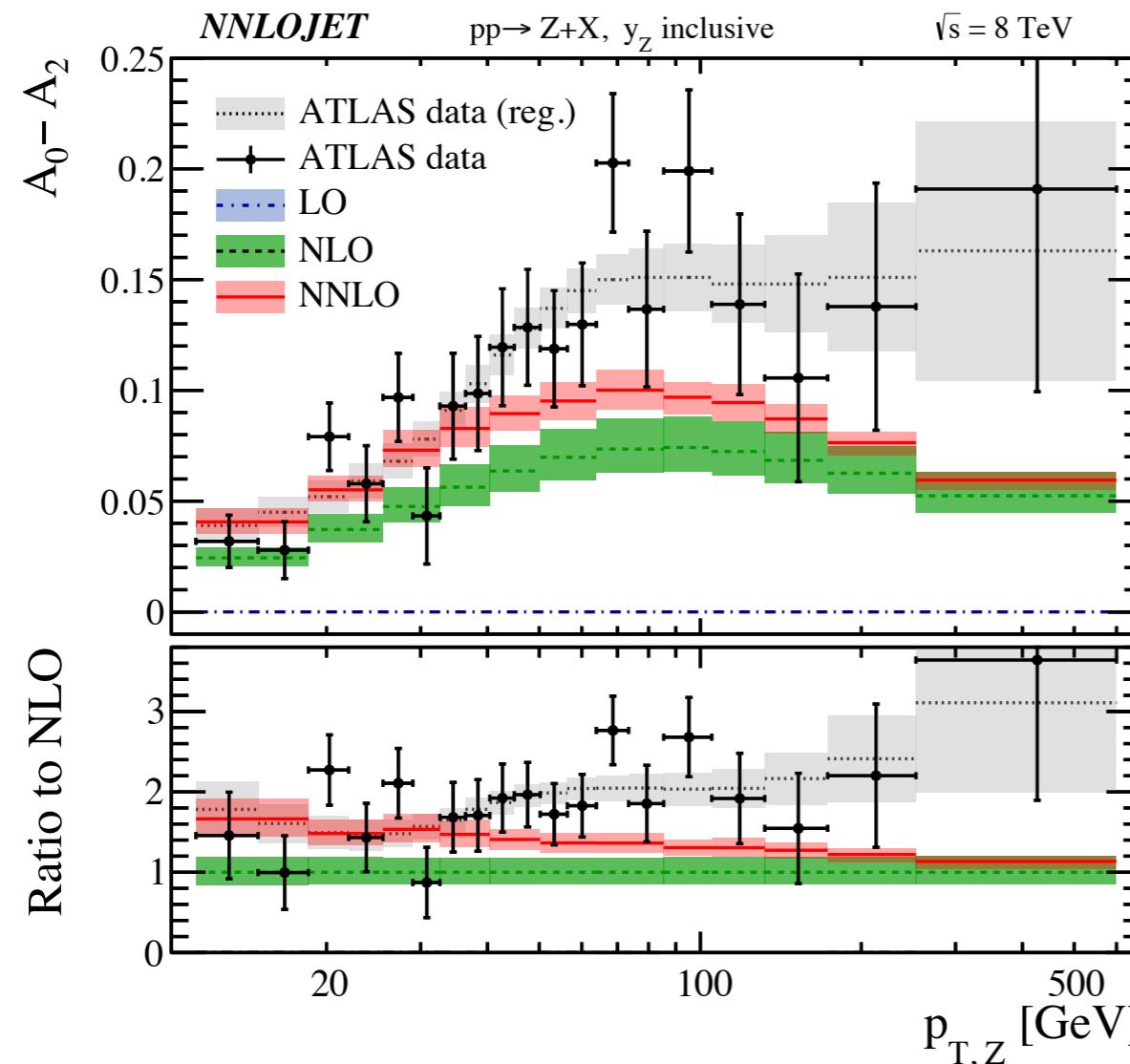
[Gauld, Gehrmann—De Ridder, Gehrmann, Glover, AH '17]



- ▶ A_2 drives Lam-Tung violation ($A_0 \neq A_2$)
- ▶ negative corrections (@ low $p_T T$)
 - ↪ **NNLO** $\sim -20\%$ (+ scale reduction)
- ▶ visible improvement (data vs. theory)

- ▶ A_4 sensitive to $\sin^2 \theta_W$
- ▶ very stable w.r.t. QCD corrections
 - ↪ **NLO** \rightarrow **NNLO** (mostly scale reduction)

ANGULAR COEFFICIENTS — LAM—TUNG



- $\mathcal{O}(\alpha_s)$ prediction:
↪ vanishes (Lam-Tung)
- $\mathcal{O}(\alpha_s^2)$ prediction:
↪ $\approx \text{DYNNLO (NNLO)}$
↪ tension with data
↪ $\chi^2/N_{\text{dat.}} \sim 4.89$
- $\mathcal{O}(\alpha_s^3)$ prediction:
↪ large positive corrections
↪ $\chi^2/N_{\text{dat.}} \sim 1.75$
- ▶ data: [ATLAS arXiv:1606.00689]
↪ applies “regularization”

No significant data* vs. theory disagreement between
(un-regularized) ATLAS & **theory @ $\mathcal{O}(\alpha_s^3)$**

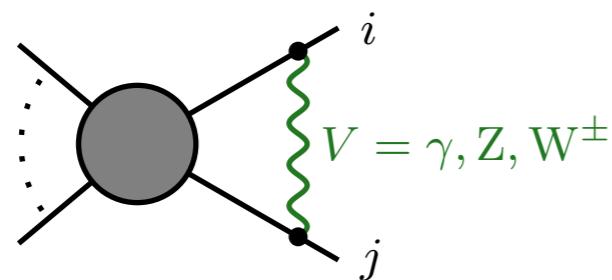
$$* \chi^2 = \sum_{i,j}^{N_{\text{dat.}}} (O_{\text{exp}}^i - O_{\text{th.}}^i) \sigma_{ij}^{-1} (O_{\text{exp}}^j - O_{\text{th.}}^j)$$

ELECTROWEAK INTERACTIONS

- generic size: $\mathcal{O}(a) \sim \mathcal{O}(a_s^2)$
- systematic **enhancements** possible:

SUDAKOV LOGARITHMS

(kinematic tails)

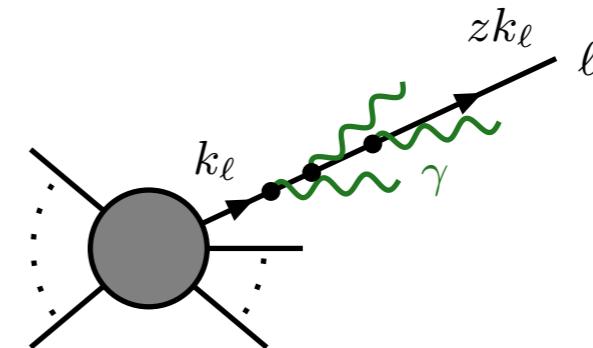


$$\sim \ln^2 \left(\frac{s_{ij}}{M_W^2} \right) + \text{sub-leading (collinear)}$$

O(10-20%)
corrections!

FINAL-STATE RADIATION

(resonances, shoulders, ...)

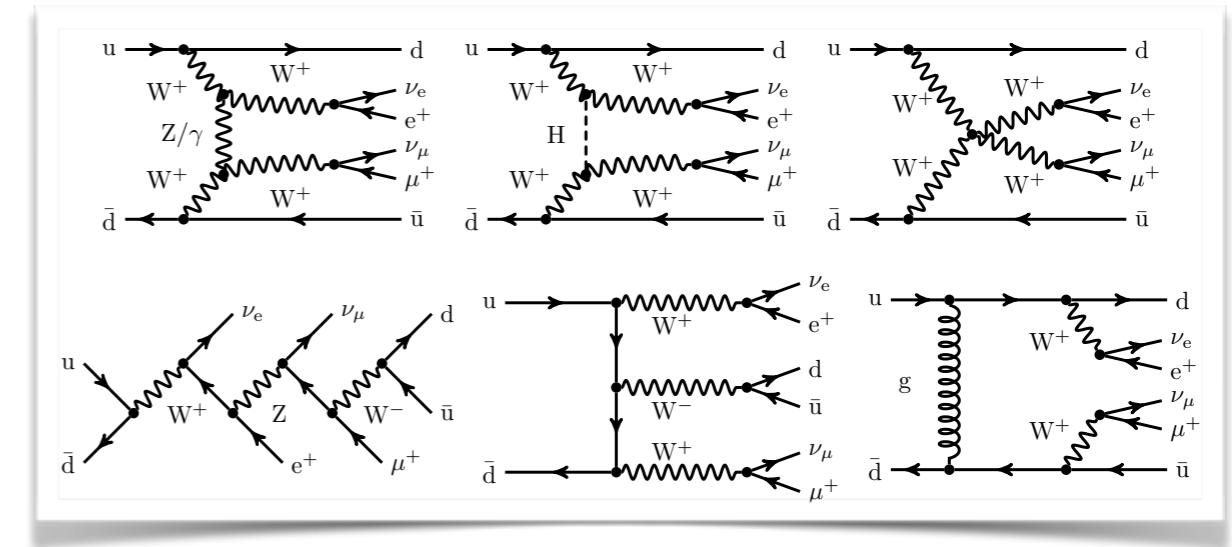
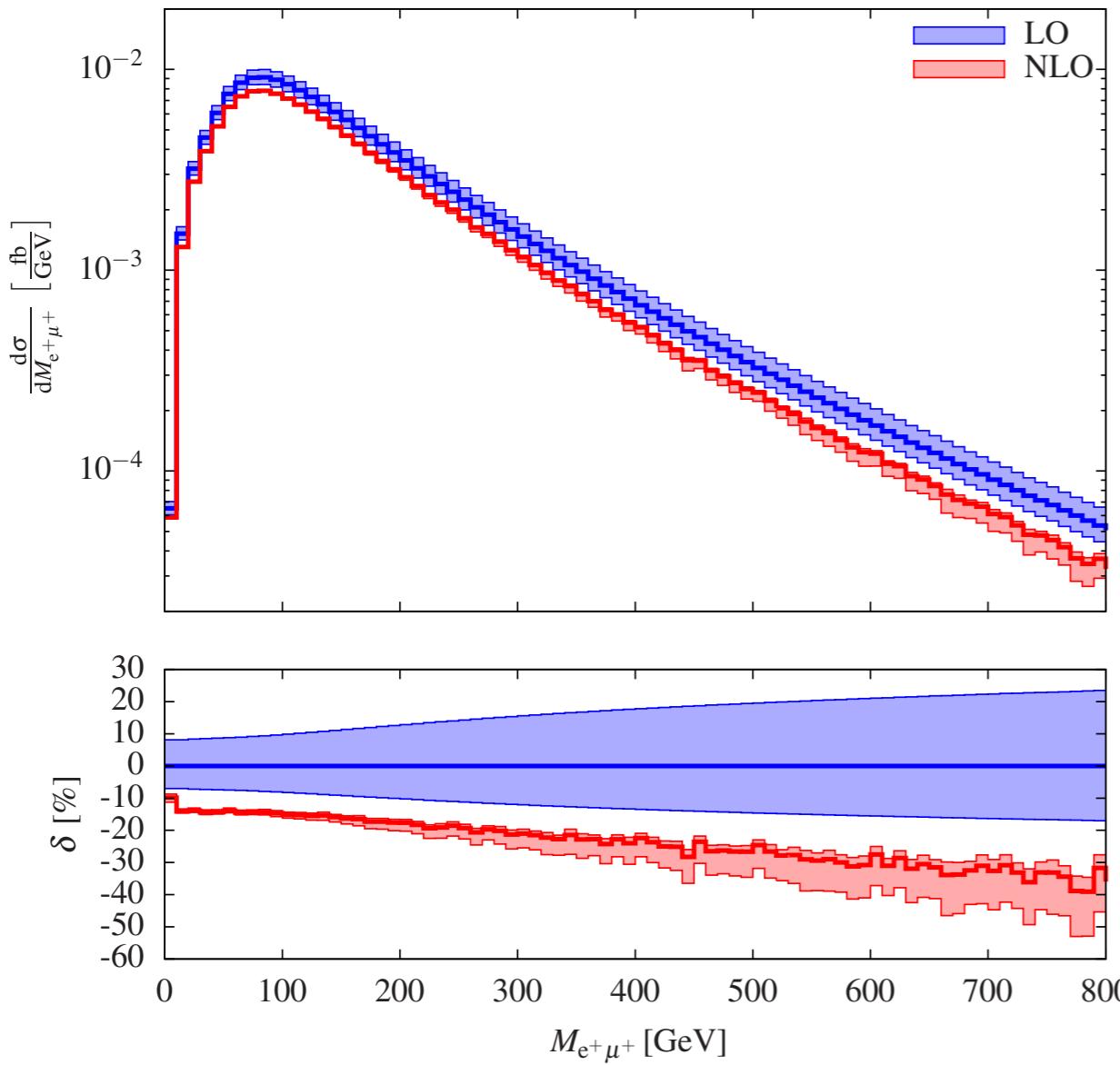


$$\sim \alpha^n \ln^n \left(\frac{Q^2}{m_\ell^2} \right)$$

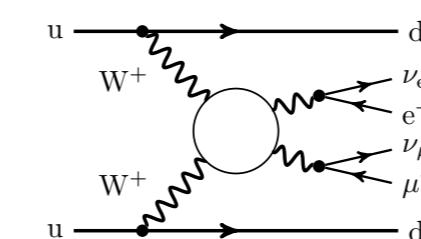
O(10-100%)
corrections!

EW — GOING OFF-SHELL

- now up to $2 \rightarrow 6$: WWW [Schönherr '18], W^+W^+ scattering [Biedermann, Denner, Pellen '17]
- full NLO VBS(W^+W^+):



► EW corrections dominant!



$$\sigma_{\text{LL}} = \sigma_{\text{LO}} \left[1 - \frac{\alpha}{4\pi} 4C_W^{\text{ew}} \log^2 \left(\frac{Q^2}{M_W^2} \right) + \frac{\alpha}{4\pi} 2b_W^{\text{ew}} \log \left(\frac{Q^2}{M_W^2} \right) \right],$$

+ PS [Chiesa, Denner, Lang, Pellen '19]