Scalable NNLO Phenomenology

Radja Boughezal

Argonne National Laboratory

ACAT 2016, Valparaiso, January 18-22

- Recent breakthrough in High Energy Particle Physics: a Higgs was discovered in 2012!

2013

Is this the predicted Standard Model Higgs? Could there be hidden new physics? Can only tell if SM signal and backgrounds are predicted very precisely.

- *From the U.S. DOE:* *" ...The full discovery potential of the Higgs will be unleashed by <u>percent-level precision studies</u> of the Higgs properties. The measurement of these properties is a top priority in the physics program of high-energy colliders. "* Particle Physics Project Prioritization Panel (P5) report

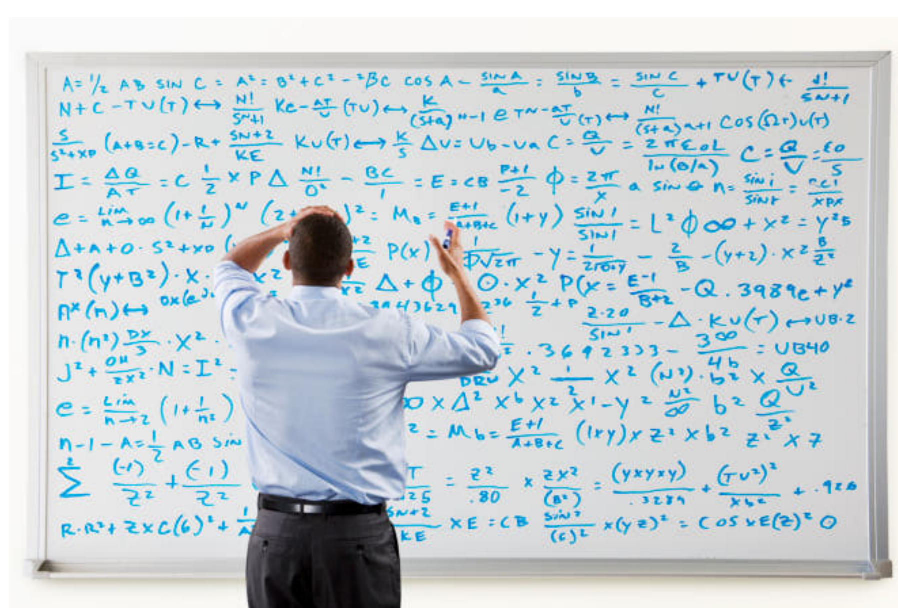
- Recent breakthrough in High Energy Particle Physics: a Higgs was discovered in 2012!

2013

Is this the predicted Standard Model Higgs? Could there be hidden new physics? Can only tell if SM signal and backgrounds are predicted very precisely. Goal can be achieved if we have:

Sophisticated box of tools

Automatic packages for cross section calculations



New techniques for calculating high precision predictions

LHC Run 1 & Theory

$H \to ZZ^*$

ATLAS

Source of uncertainty	4μ	$2e2\mu$	$2\mu 2e$	$4e$	combined
Electron reconstruction and identification efficiencies	–	1.7%	3.3%	4.4%	1.6%
Electron isolation and impact parameter selection	–	0.07%	1.1%	1.2%	0.5%
Electron trigger efficiency	–	0.21%	0.05%	0.21%	<0.2%
$\ell\ell + ee$ backgrounds	–	–	3.4%	3.4%	1.3%
Muon reconstruction and identification efficiencies	1.9%	1.1%	0.8%	–	1.5%
Muon trigger efficiency	0.6%	0.03%	0.6%	–	0.2%
$\ell\ell + \mu\mu$ backgrounds	1.6%	1.6%	–	–	1.2%
QCD scale uncertainty					6.5%
PDF, α_s uncertainty					6.0%
$H \to ZZ^*$ branching ratio uncertainty					4.0%

LHC Run 1 & Theory

ATLAS

$H \to ZZ^*$

Source of uncertainty	e	4e	combined
Electron reconstruction and	%	4.4%	1.6%
Electron isolation and impac	%	1.2%	0.5%
Electron trigger efficiency	%	0.21%	<0.2%
$\ell\ell + ee$ backgrounds	%	3.4%	1.3%
Muon reconstruction and ide	%	–	1.5%
Muon trigger efficiency	%	–	0.2%
$\ell\ell + \mu\mu$ backgrounds		–	1.2%
QCD scale uncertainty			6.5%
PDF, α_s uncertainty			6.0%
$H \to ZZ^*$ branching ratio u			4.0%

$H \to WW^*$

Source	Observed $\mu = 1.09$ Error +	−	Plot of error (scaled by 100)
Data statistics	0.16	0.15	
Signal regions	0.12	0.12	
Profiled control regions	0.10	0.10	
Profiled signal regions	-	-	-
MC statistics	0.04	0.04	
Theoretical systematics	0.15	0.12	
Signal $H \to WW^*$ $\mathcal{B}$	0.05	0.04	
Signal ggF cross section	0.09	0.07	
Signal ggF acceptance	0.05	0.04	
Signal VBF cross section	0.01	0.01	
Signal VBF acceptance	0.02	0.01	
Background WW	0.06	0.06	
Background top quark	0.03	0.03	
Background misid. factor	0.05	0.05	
Others	0.02	0.02	
Experimental systematics	0.07	0.06	
Background misid. factor	0.03	0.03	
Bkg. $Z/\gamma^* \to ee, \mu\mu$	0.02	0.02	
Muons and electrons	0.04	0.04	
Missing transv. momentum	0.02	0.02	
Jets	0.03	0.02	
Others	0.03	0.02	
Integrated luminosity	0.03	0.03	
Total	0.23	0.21	
			-30 -15 0 15 30

LHC Run 1 & Theory

ATLAS

$H \rightarrow ZZ^*$

Source of uncertainty	4e	combined
Electron reconstruction and	4.4%	1.6%
Electron isolation and impac		0.5%
Electron tri		.2%
$\ell\ell + ee$ back		3%
Muon recon		5%
Muon trigge		2%
$\ell\ell + \mu\mu$ bac		2%
QCD scale		5%
PDF, α_s un		0%
$H \rightarrow ZZ^*$ b		0%

$H \rightarrow WW^*$

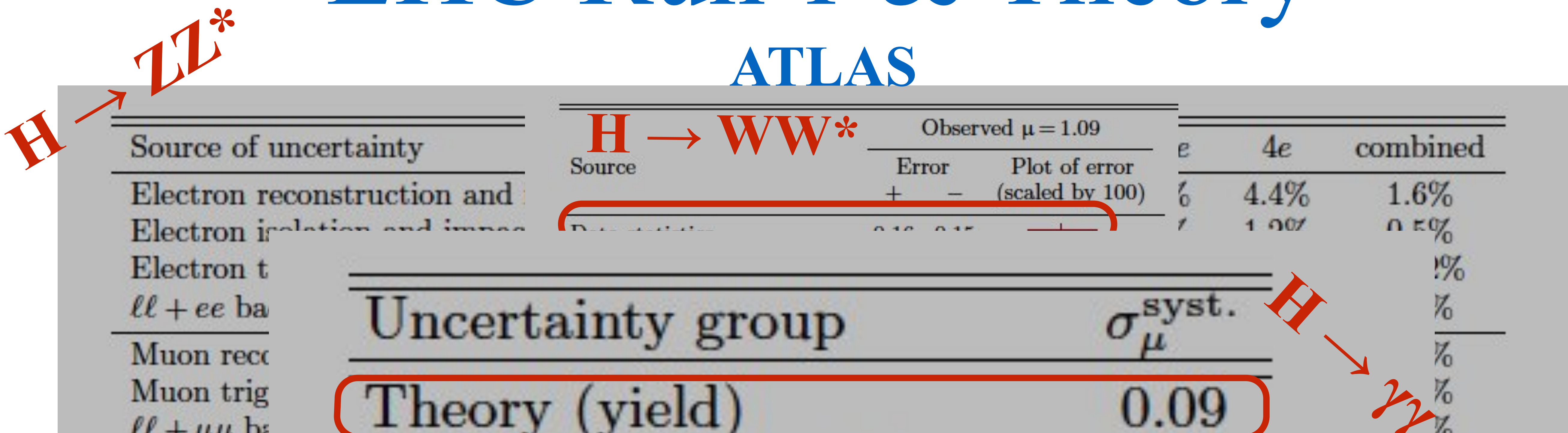
Source	Observed $\mu = 1.09$ Error +	−	Plot of error (scaled by 100)

$H \rightarrow \gamma\gamma$

Uncertainty group	$\sigma_{\mu}^{\text{syst.}}$
Theory (yield)	0.09
Experimental (yield)	0.02
Luminosity	0.03
MC statistics	< 0.01
Theory (migrations)	0.03
Experimental (migrations)	0.02
Resolution	0.07
Mass scale	0.02
Background shape	0.02

LHC Run 1 & Theory

ATLAS



For all three Higgs ‘precision’ channels, theory uncertainty is the dominant source of systematic uncertainty !

LHC Run 2

theguardian
Winner of the Pulitzer prize

Easter morning excitement as the CERN accelerator team send beams around the LHC for the first time in many months - a major milestone on the way to even higher energy collisions!

(05–Apr–2015 10:40:17)
All collimators open
Circulating beam 2

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Large Hadron Collider: World's biggest physics experiment restarts

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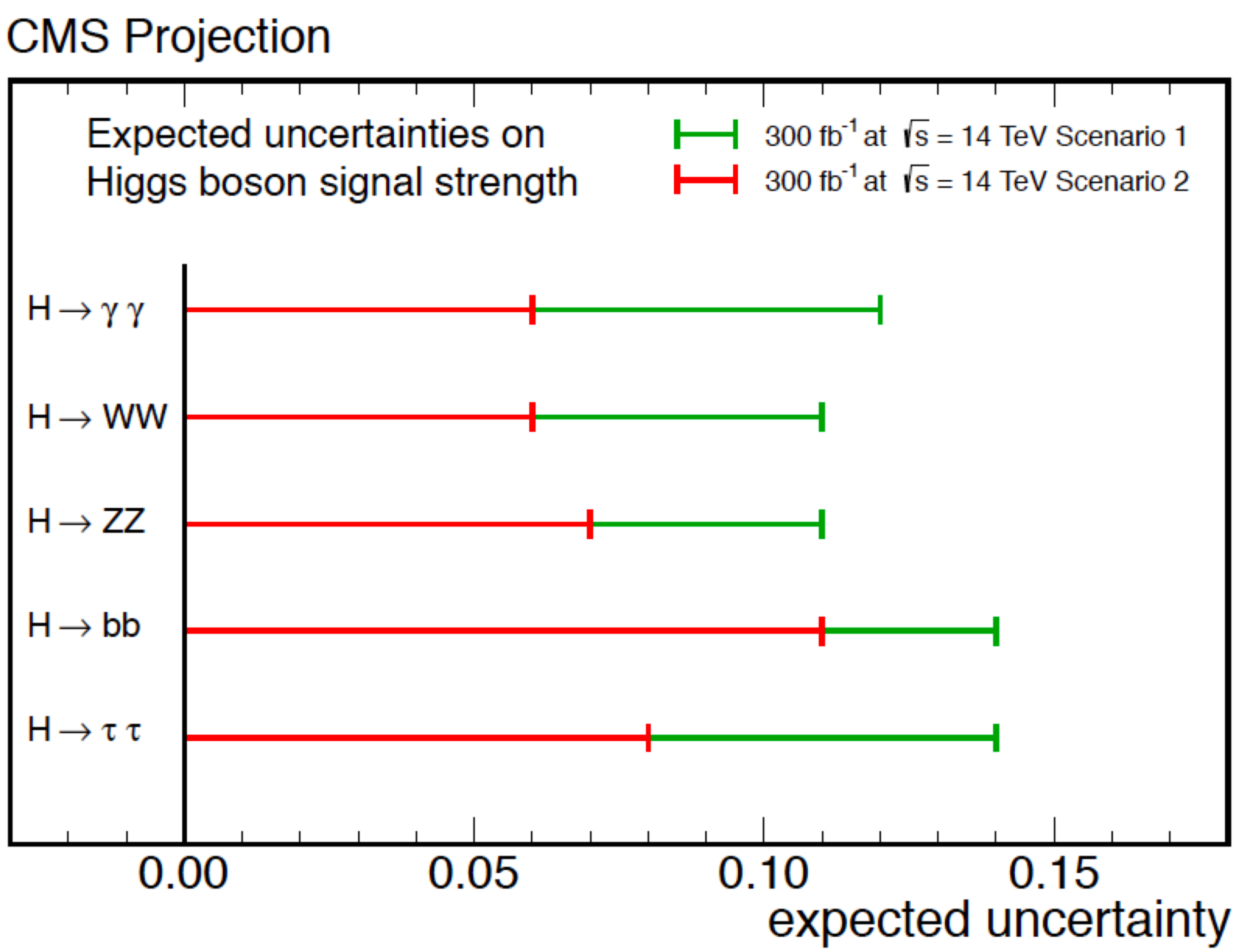
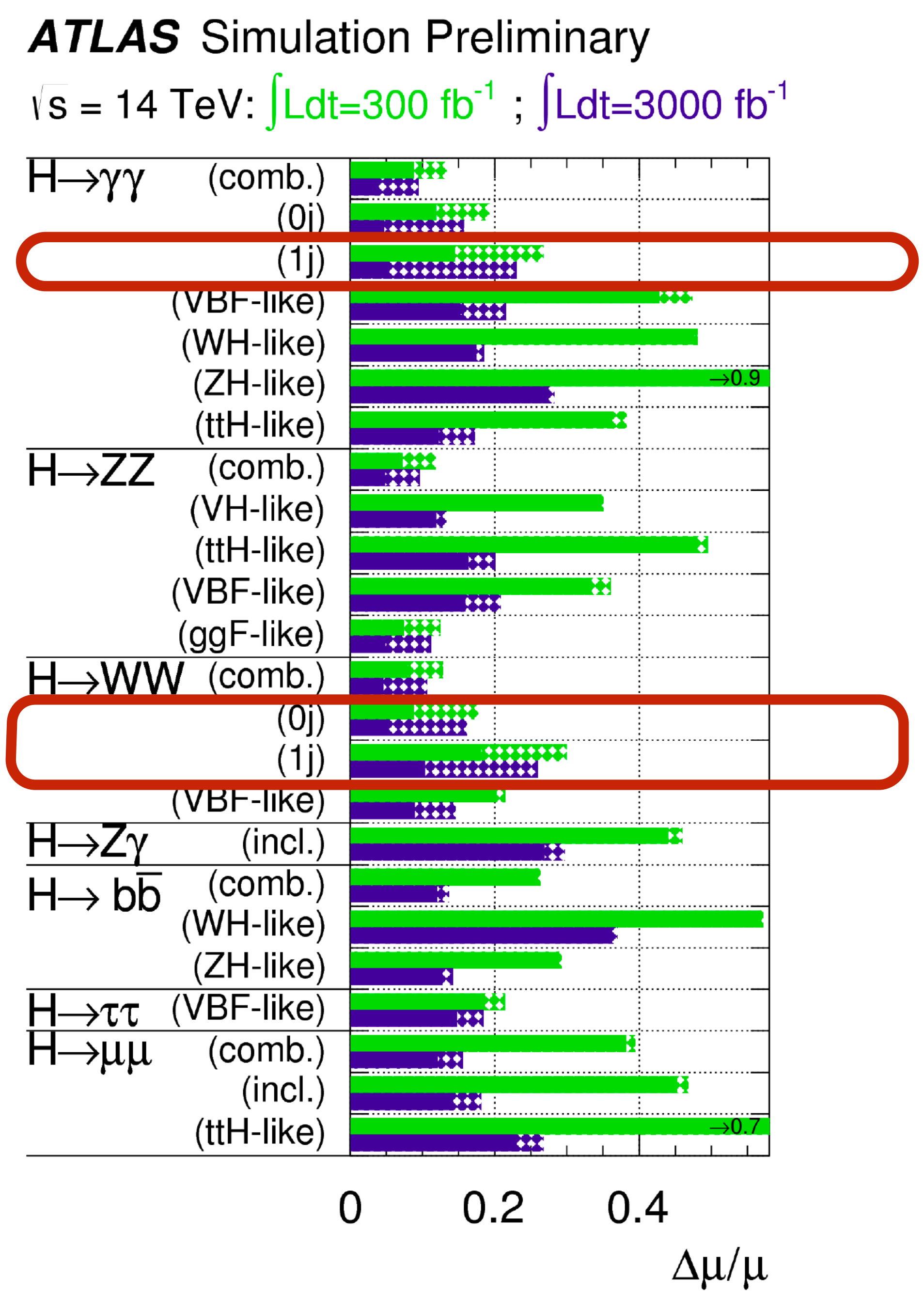
LHC restart: 'We want to break physics'

LHC Run 2: Prospects

- High expectations from the higher energy (13-14 TeV) and luminosity ($\sim 300 fb^{-1}$)





Scenario 1: all systematic uncertainties same as now

Scenario 2: scale theory unc. by 1/2, experimental sys. by 1/sqrt(L)

Large impact from theory uncertainties (dashed) coming from QCD scale, jet binning, PDF+α_s

How we make predictions for the LHC

- For low multiplicity processes include higher order terms in the fixed order calculations (LO $\rightarrow$ NLO $\rightarrow$ NNLO,…)

$$\Rightarrow \quad \sigma = \sigma_0 + \alpha_s\, \sigma_1 + \alpha_s^2\, \sigma_2 + \ldots$$

- For higher multiplicity use the tree-level results when NLO is not available

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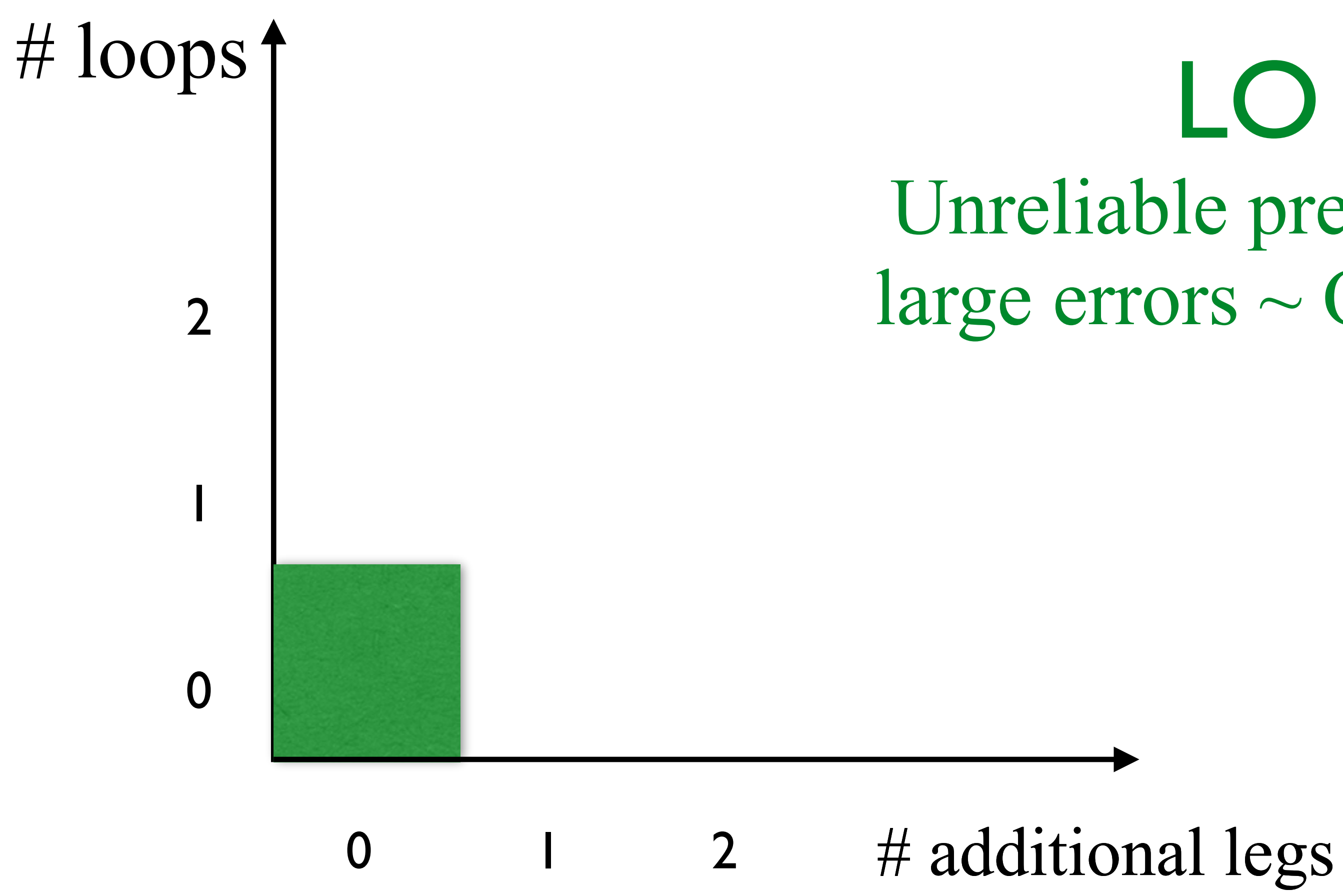

LO
Unreliable predictions
large errors ~ O(100%)

How we make predictions for the LHC

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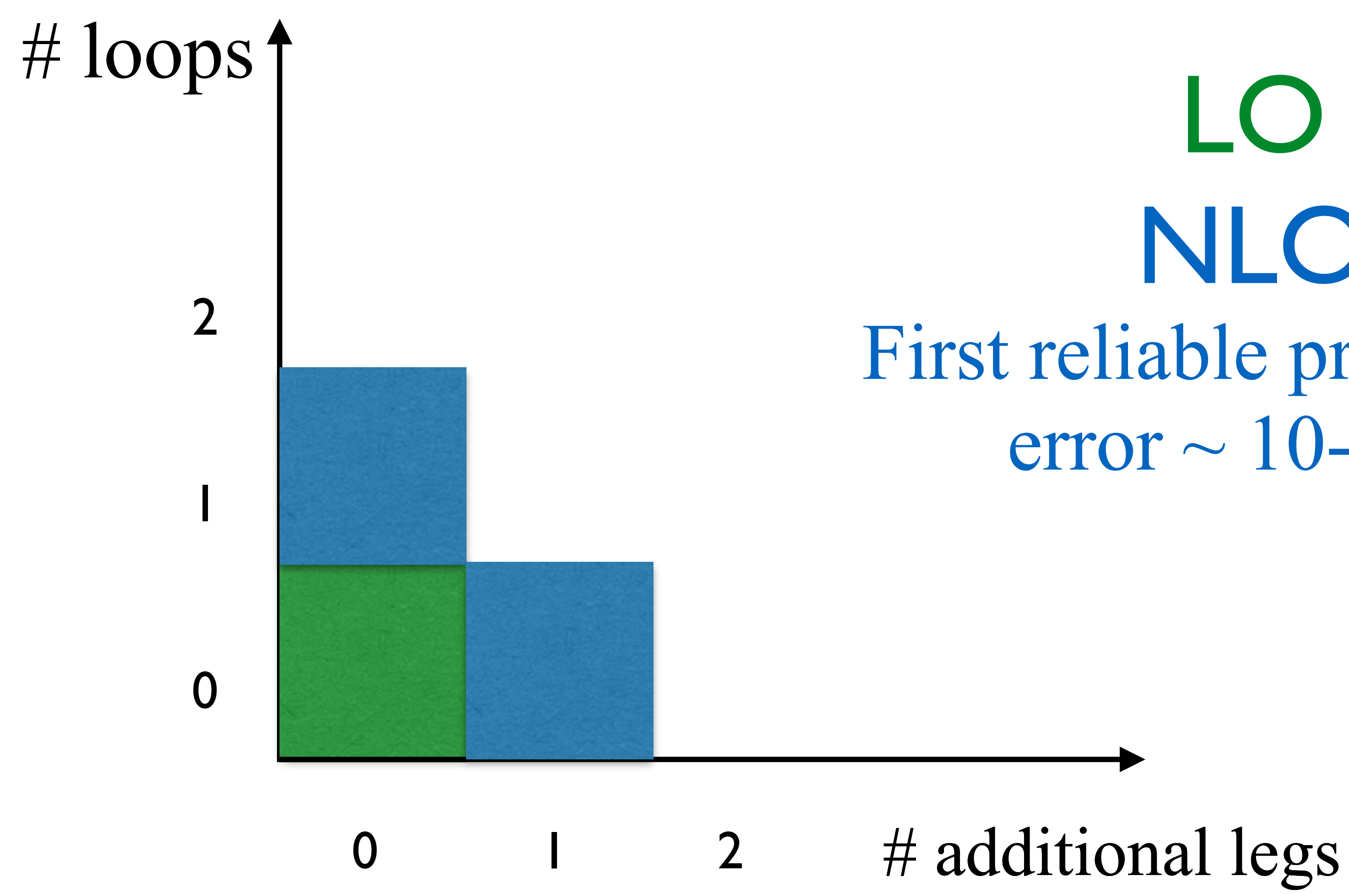

LO

NLO

First reliable predictions
error ~ 10-30%

How we make predictions for the LHC

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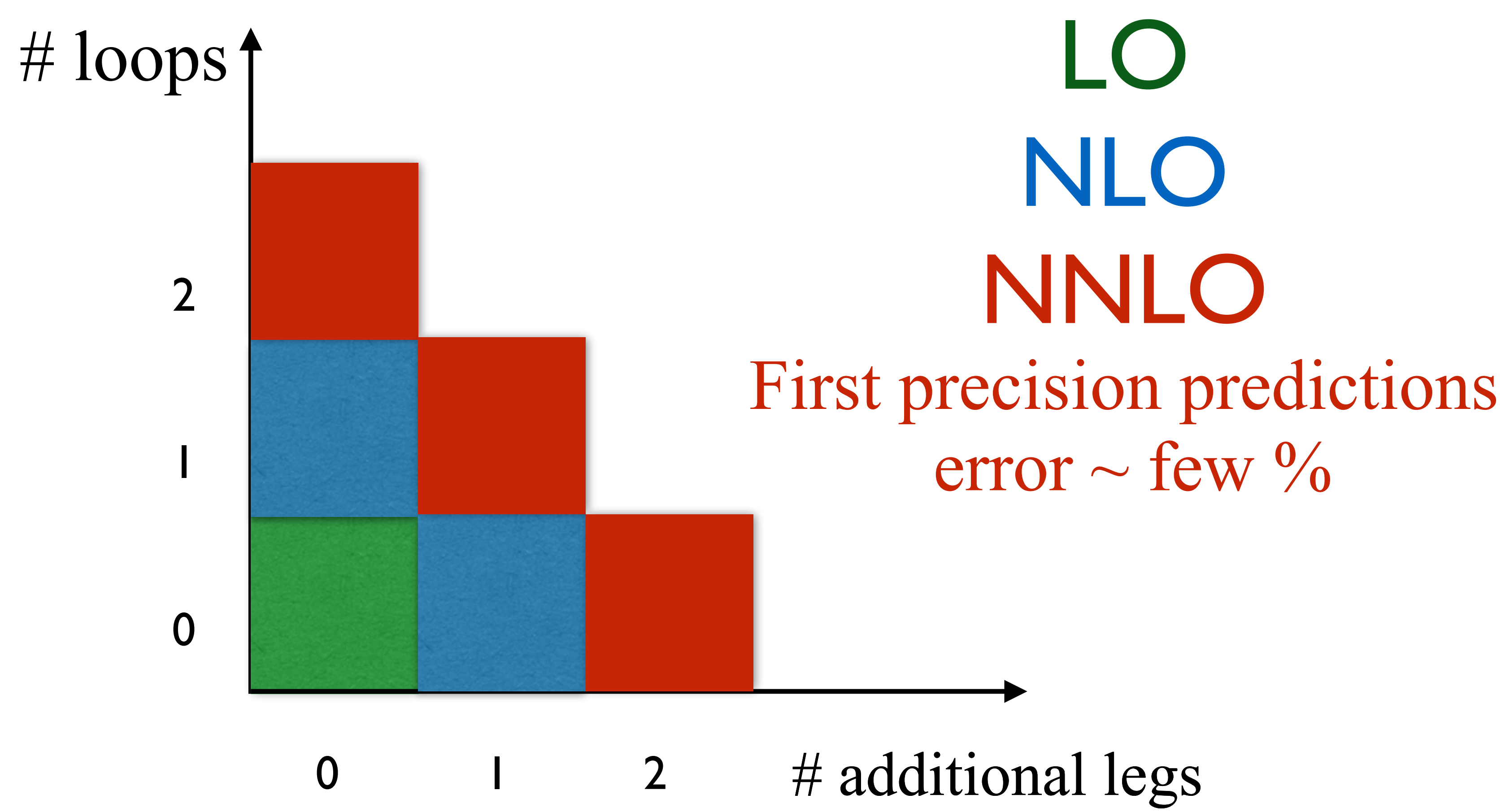
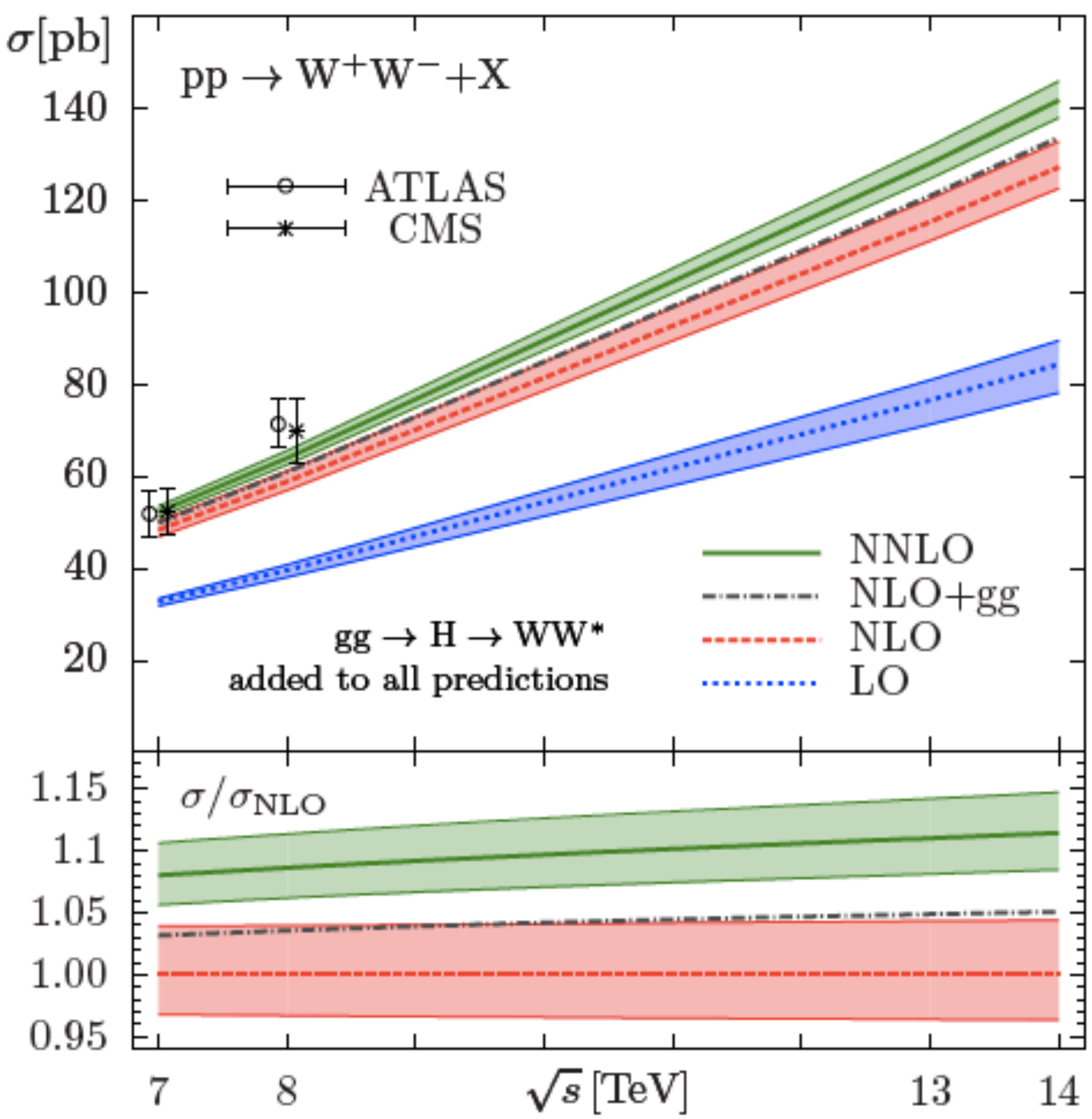


NNLO Cross Sections

The Importance of Higher Orders

- Example: until recently, WW cross section showed a >2σ excess at both ATLAS and CMS, and for both 7 and 8 TeV. Could it be light charginos? (Curtin, Jaiswal, Meade 1206.6888)



- Sizable NNLO QCD corrections!

Gehrmann, Grazzini, Kallweit, Maierhofer, von Manteuffel, Pozzorini, Rathlev, Tancredi 1408.5243

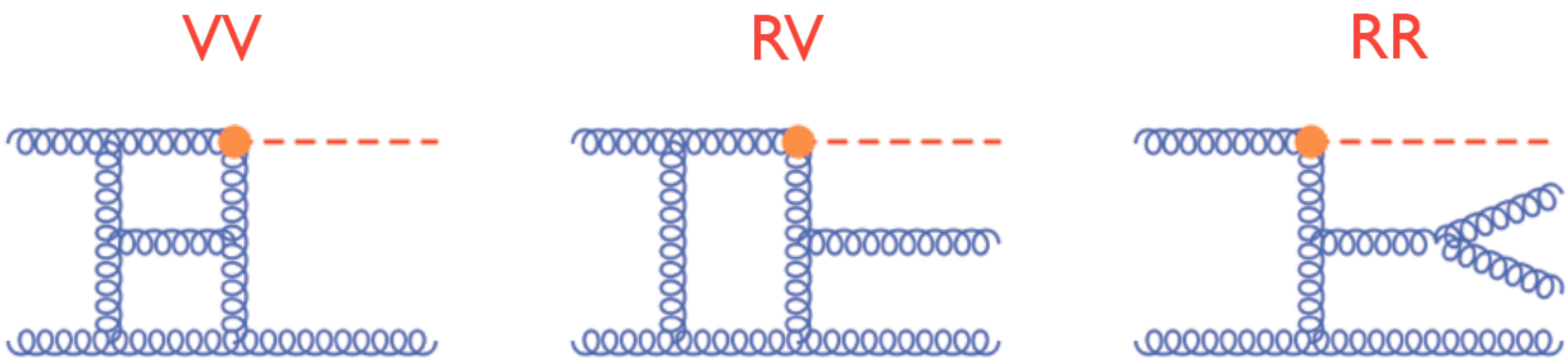
- Additional enhancement when extrapolating from 0-jet bin to full cross section

Curtin, Meade, Tien 1406.0848; Jaiswal, Okui, 1407.4537; Monni, Zanderighi 1410.4745

- Theory within 1σ agreement of ATLAS and CMS for both CM energies; proper interpretation not possible without NNLO QCD

Ingredients for NNLO Calculations

- Need the following ingredients for NNLO cross sections



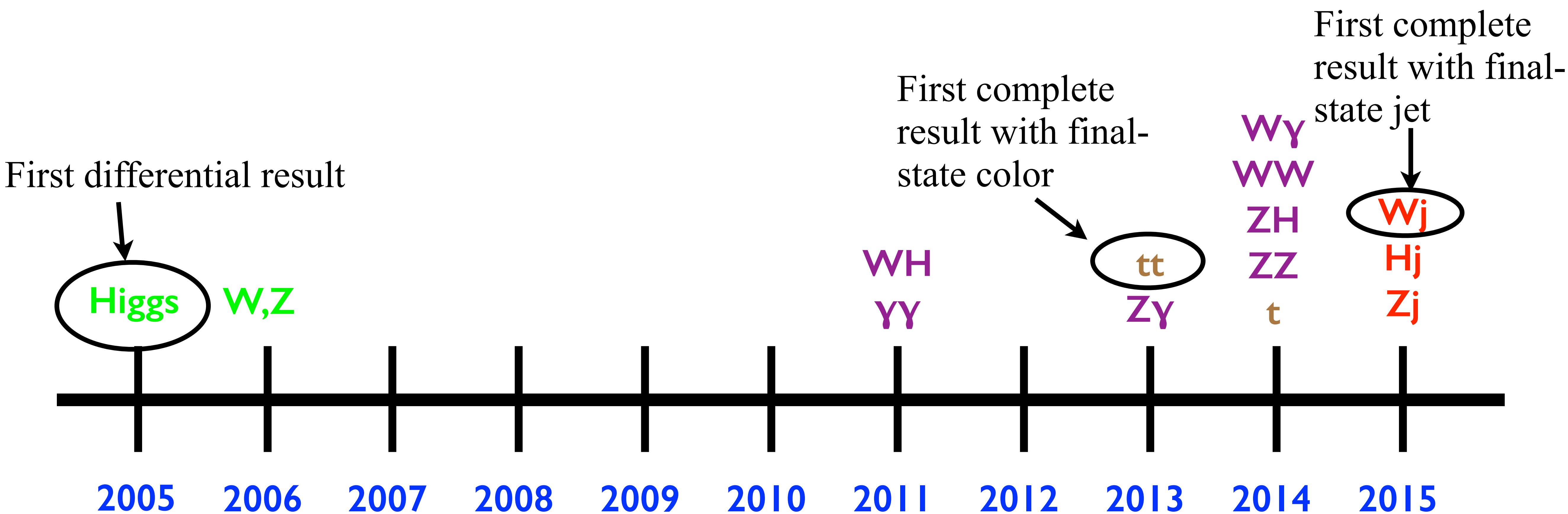
- IR singularities cancel in the sum of real and virtual corrections and mass factorization counterterms but only after phase space integration for real radiations.

- Virtual corrections have explicit IR poles, whereas real corrections have implicit IR poles that need to be extracted.

- A generic procedure to extract IR singularities from RR and RV was unknown when jets in the final state are involved, until very recently.

A Time Line for NNLO Hadron Collider Cross Sections

- Complete NNLO hadron-collider cross sections with control over kinematics:



NNLO has become the standard for 2→2 scattering over the past 2-3 years

Techniques for NNLO

- Numerous proposed techniques for handling singularities at NNLO, which can be divided into two distinct categories:

(quasi-)Local: add and subtract counterterms that approximate real-emission matrix elements in all singular limits

Resummation-assisted: leverage knowledge of analytic resummation to remove double-real emission singularities.

Local:

- Sector decomposition: Binoth, Heinrich; Anastasiou, Melnikov, Petriello
- Antennae subtraction: Gehrmann, Gehrmann-de Ridder, Glover
- Sector-improved residue subraction: Czakon; RB, Melnikov, Petriello
- Colorful subtraction: Del Duca, Somogyi, Trocsanyi
- Projection-to-Born: Cacciari, Dreyer, Karlberg, Salam, Zanderighi

RG-assisted:

- q_T-subtraction: Catani, Grazzini
- N-jettiness subtraction: RB, Focke, Liu, Petriello; Gaunt, Stahlhofen, Tackmann, Walsh

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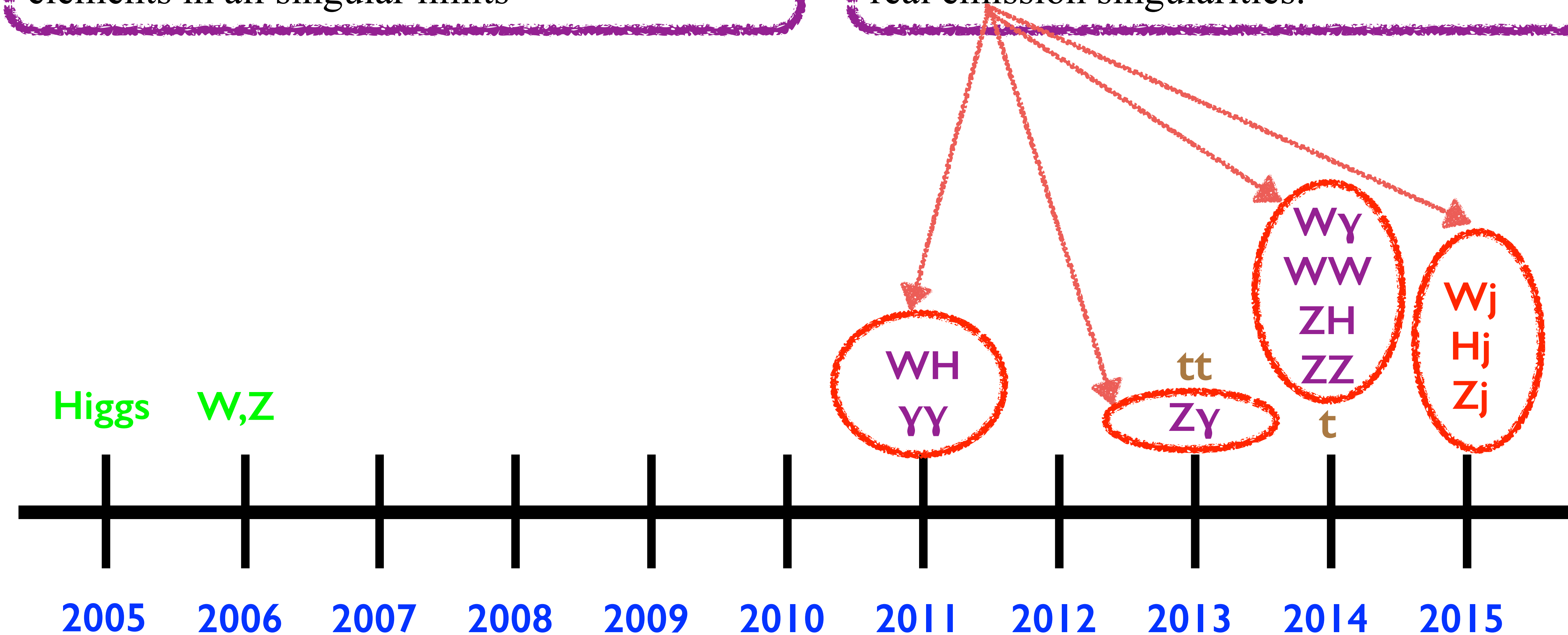


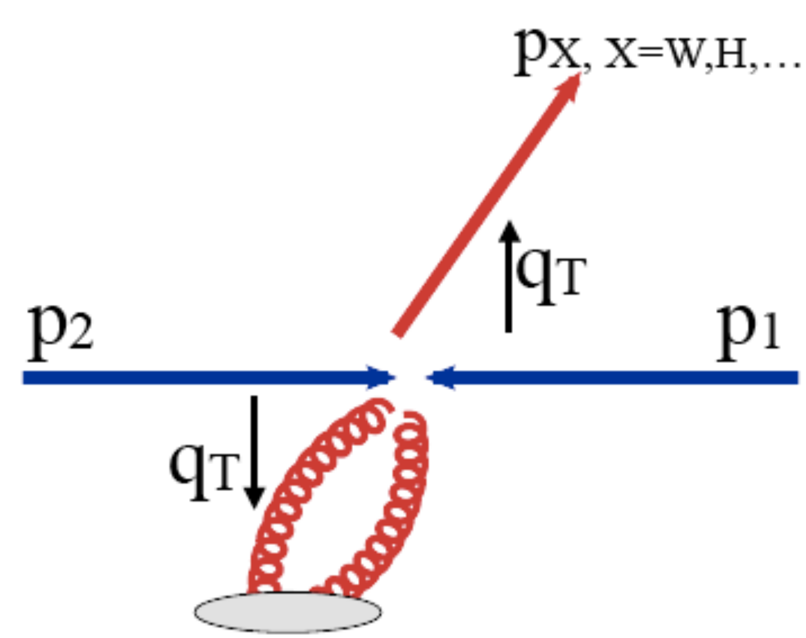
q_T-subtraction

- For color-neutral final states, the transverse momentum completely determines the double-unresolved singular limit of the final state Catani, Grazzini (2007)

$$\sigma_{NNLO} = \int dq_T \frac{d\sigma}{dq_T} \theta(q_T^{\rm cut} - q_T) + \int dq_T \frac{d\sigma}{dq_T}\theta(q_T - q_T^{\rm cut})$$

Obtained from the Collins-Soper-Sterman factorization theorem for small-q_T

This is an NLO cross section for the color-neutral final state plus an additional jet

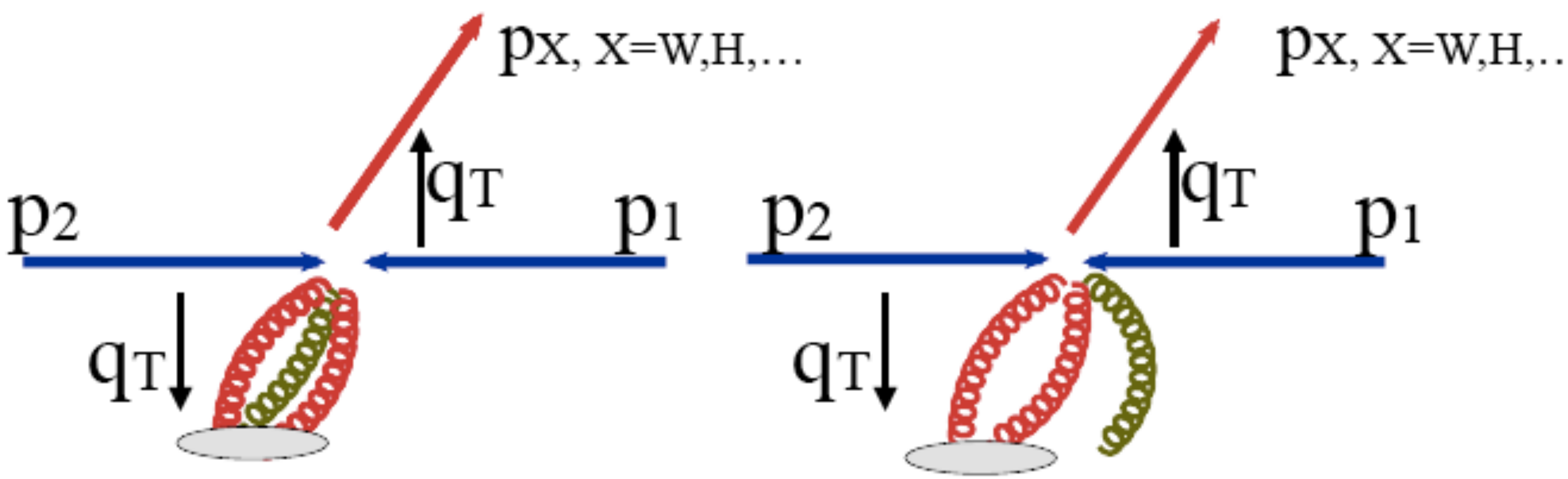


- Maximally reuses information from existing NLO calculations

☛ Computationally efficient

q_T-subtraction

- Difficult to extend beyond color-neutral final states; q_T no longer separates double-unresolved limit from NLO singular limits



double-unresolved

single-unresolved

Need a different resolution parameter when final-state jets are present!

- Two requirements: must separate double-unresolved limits from single-unresolved and hard regions, and must be resummable

N-jettiness

- N-jettiness, τ_N: a resummable event-shape variable designed to veto final-state jets Stewart, Tackmann, Waalewijn 0910.0467

$$\mathcal{T}_N = \sum_k \min_i \left\{ \frac{2p_i \cdot q_k}{Q_i} \right\}.$$

N=number of final-state jets

Momenta of the two beams and the final-state jets

Measure of the jet hardness (we take $Q_i=2E_i$)

All final-state partons

$\tau_N=0$: all radiation is either soft, or collinear to a beam/jet; at NNLO, gives the double-unresolved limit

$\tau_N>0$: at least one additional radiation is resolved; have N+1 final-state jets

This is the resolution parameter we are looking for!

N-jettiness

- N-jettiness can be applied to obtain exact NNLO cross sections

RB, Focke, Liu, Petriello   Phys.Rev.Lett. 115 (2015) 6, 062002

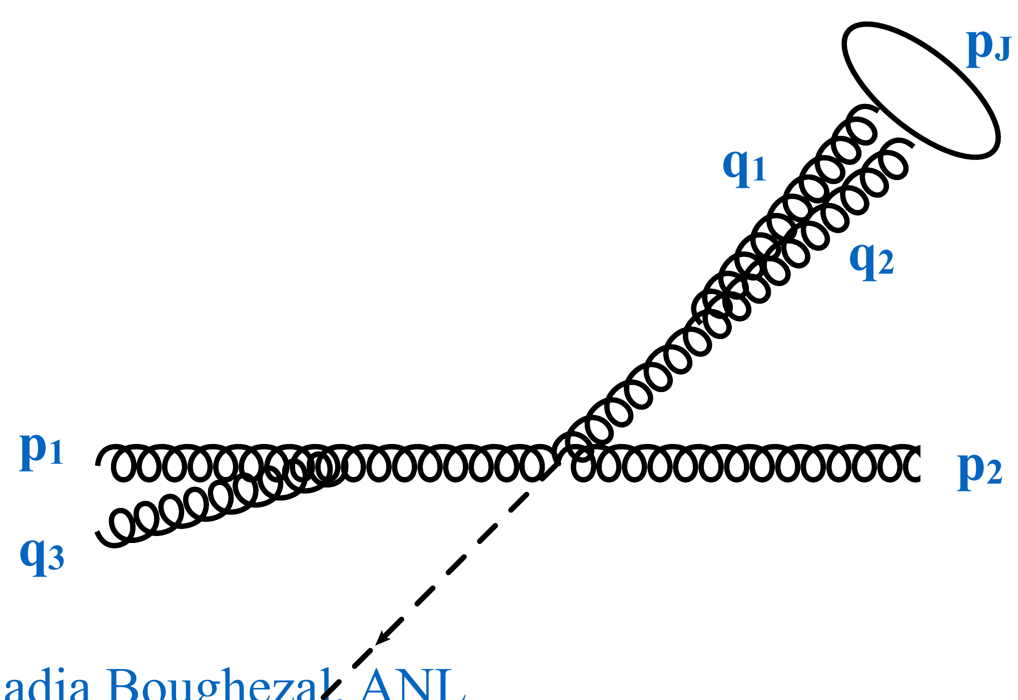
$\tau_N \approx 0$: all radiation is either soft, or collinear to a beam/jet; at NNLO, gives the double-unresolved limit

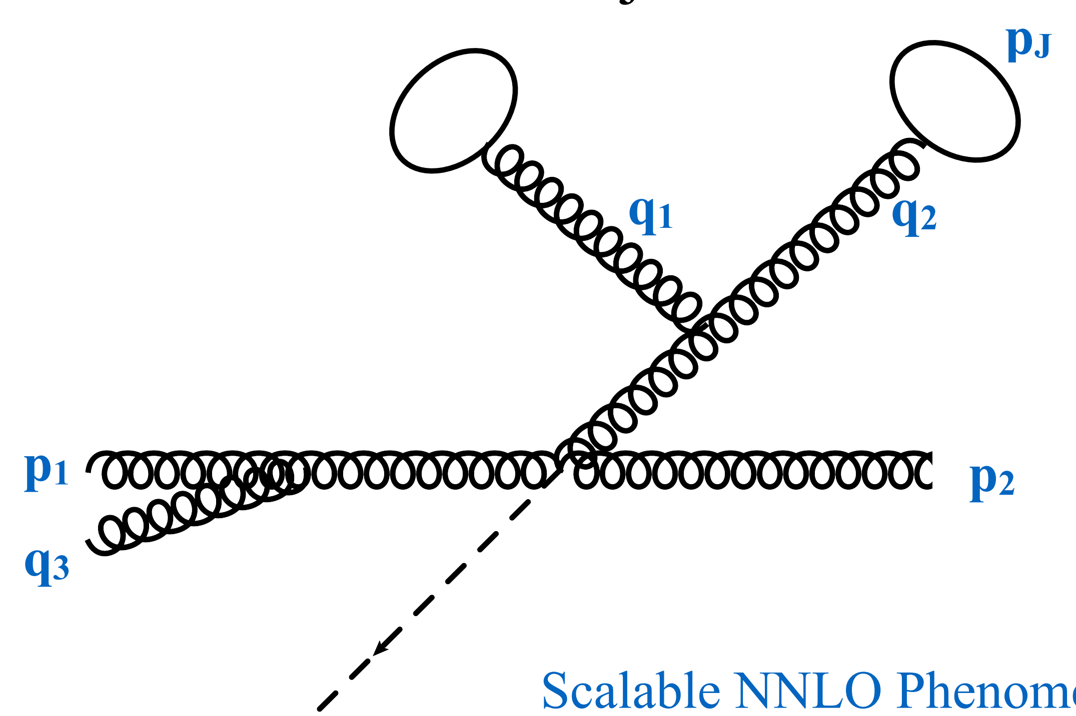
$\tau_N > 0$: at least one additional radiation is resolved; have N+1 final-state jets

$$\tau_N = \sum_k \min_i \left\{ \frac{2p_i \cdot q_k}{Q_i} \right\}$$

Must all nearly vanish for **$\tau_N \approx 0$**

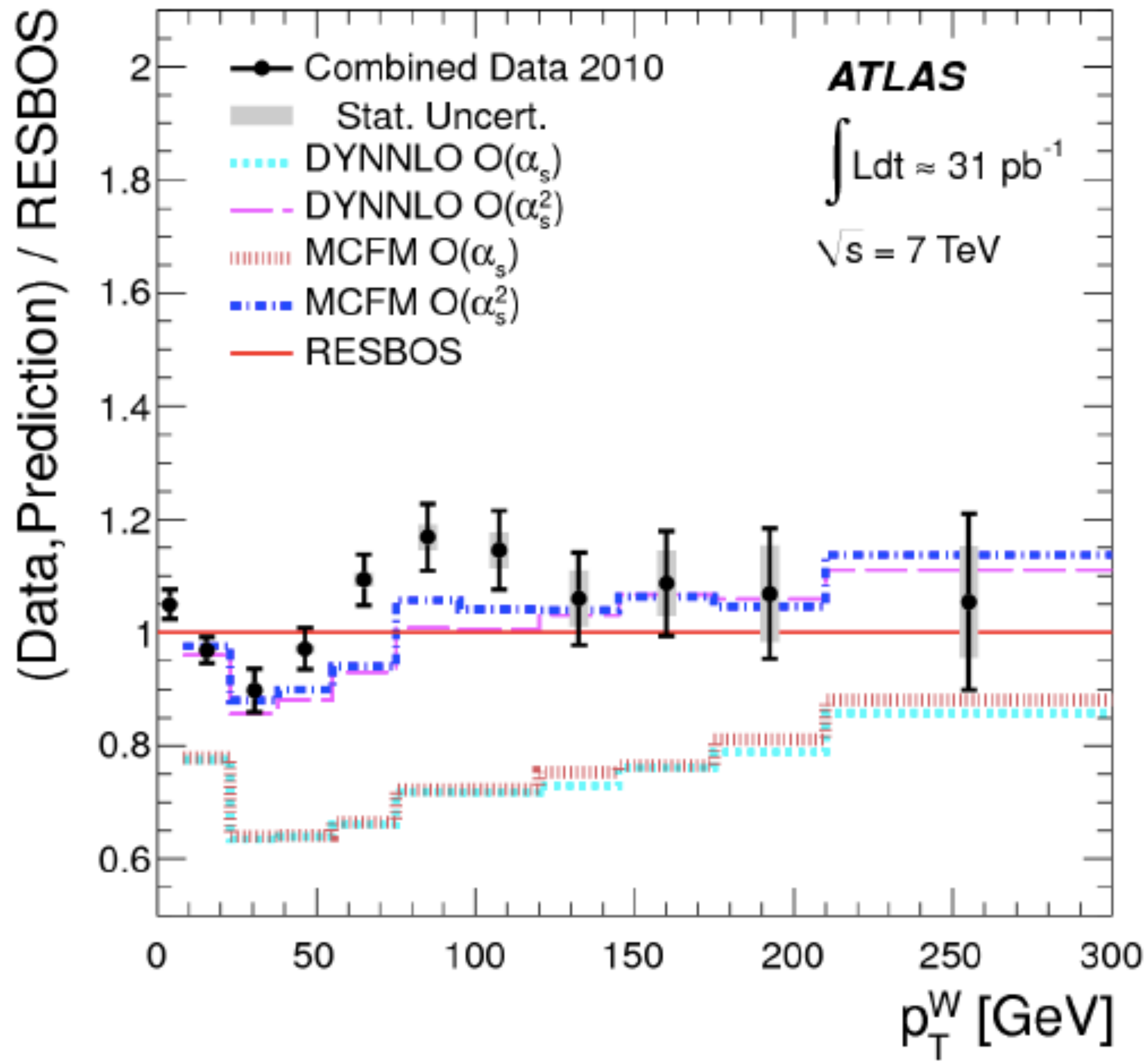
Must have at least one dot product non-vanishing; clearly can obtain from an NLO calculation with N+1 jets





W+jet@NNLO

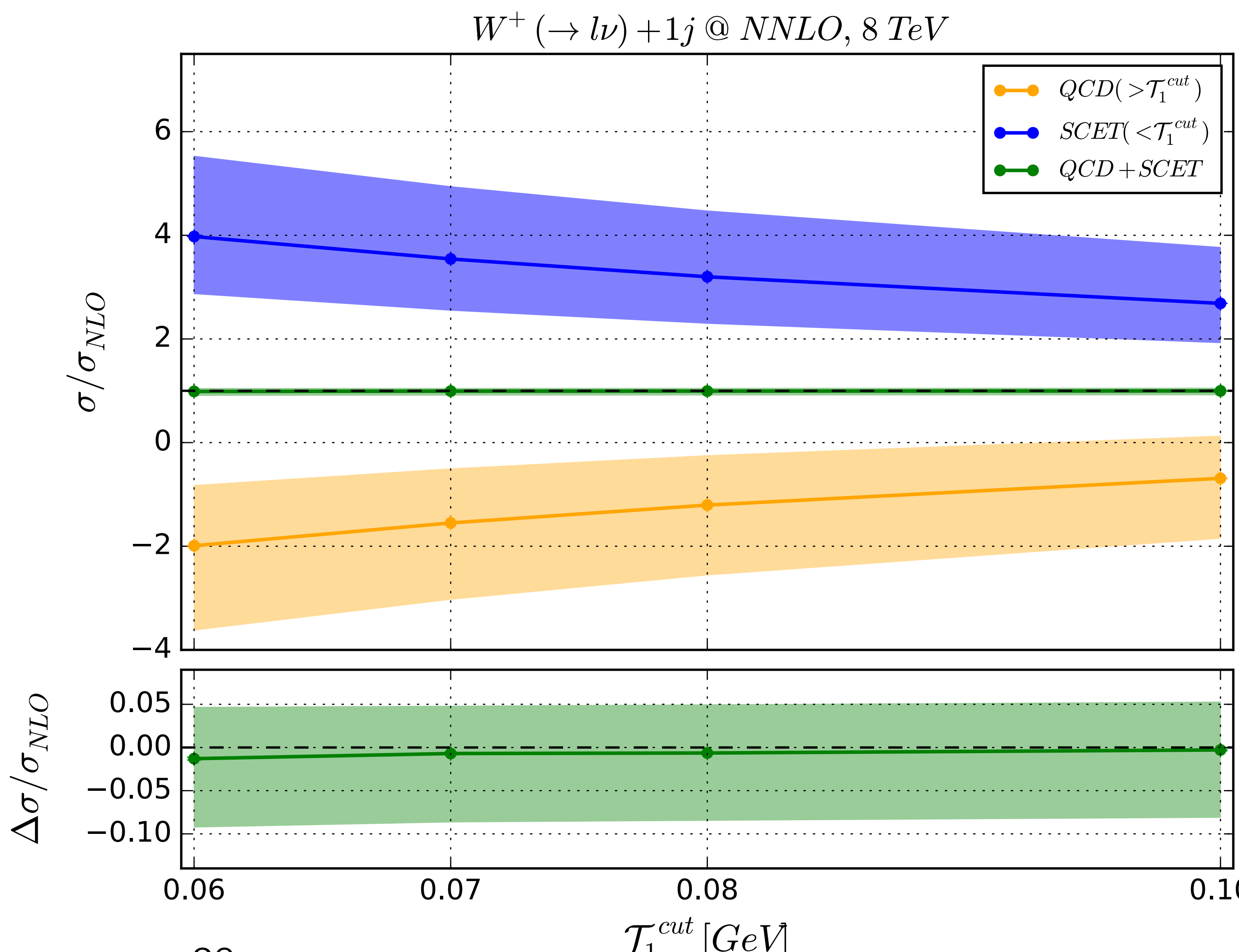
- W+jet and the associated W-p_T spectrum are important benchmark processes in the SM
- Can be used to determine the high-x gluon PDF, at ATLAS/CMS or LHCb. In the latter case, the NLO theoretical error is a limiting factor Farry, Gauld 1505.01399



W+jet@NNLO: validation

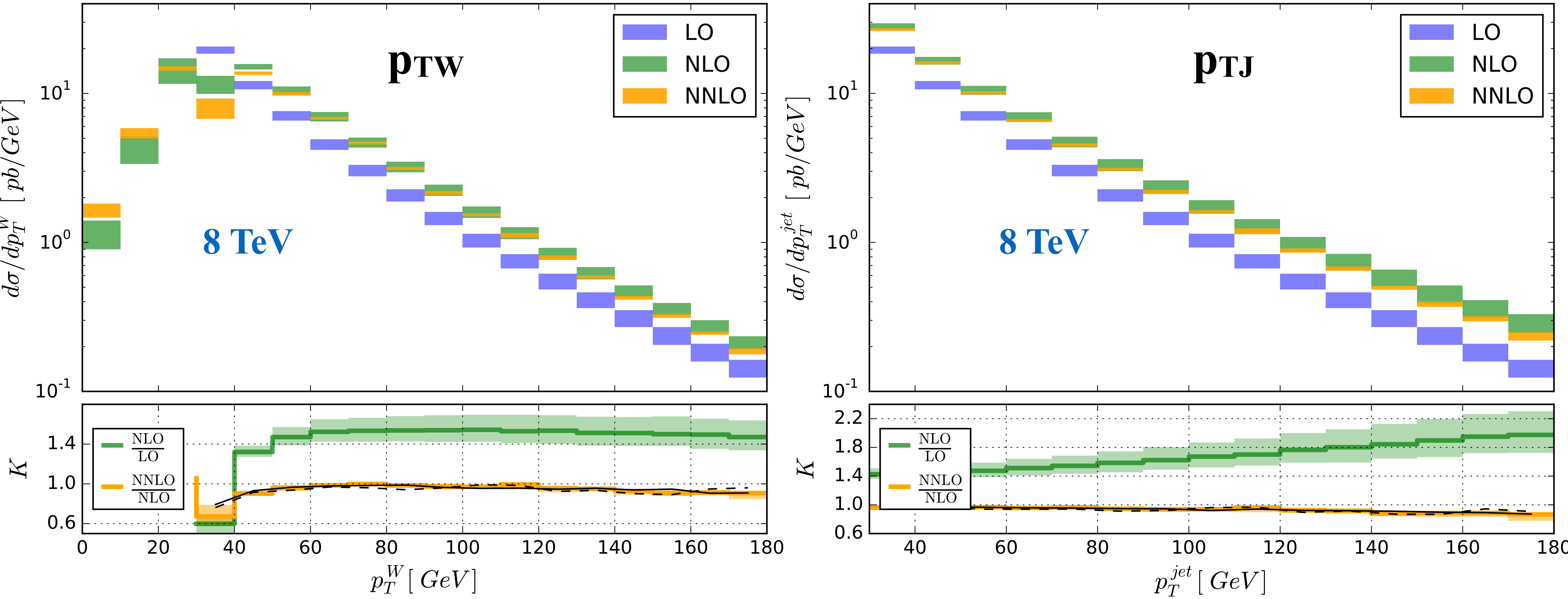
- A powerful check of the N-jettiness subtraction formalism is the independence of the final result from τ_N^{cut}.
- The above-cut and below cut contributions separately depend on $\ln^n(\tau_N^{cut})$, where n ranges from 1 to 4 at NNLO. This dependence must cancel when the two regions are summed.

  - CMS cuts: p_{TJ}>30 GeV, $|\eta_J|$<2.4
  - CT10 PDFs, μ_0=M_W, vary by factor of 2 to estimate error
  - NLO prediction using N-jettiness agrees with known results.
  - Sum of above-cut and below-cut contributions stable to better than 0.1% of σ_{total}



W+jet@NNLO

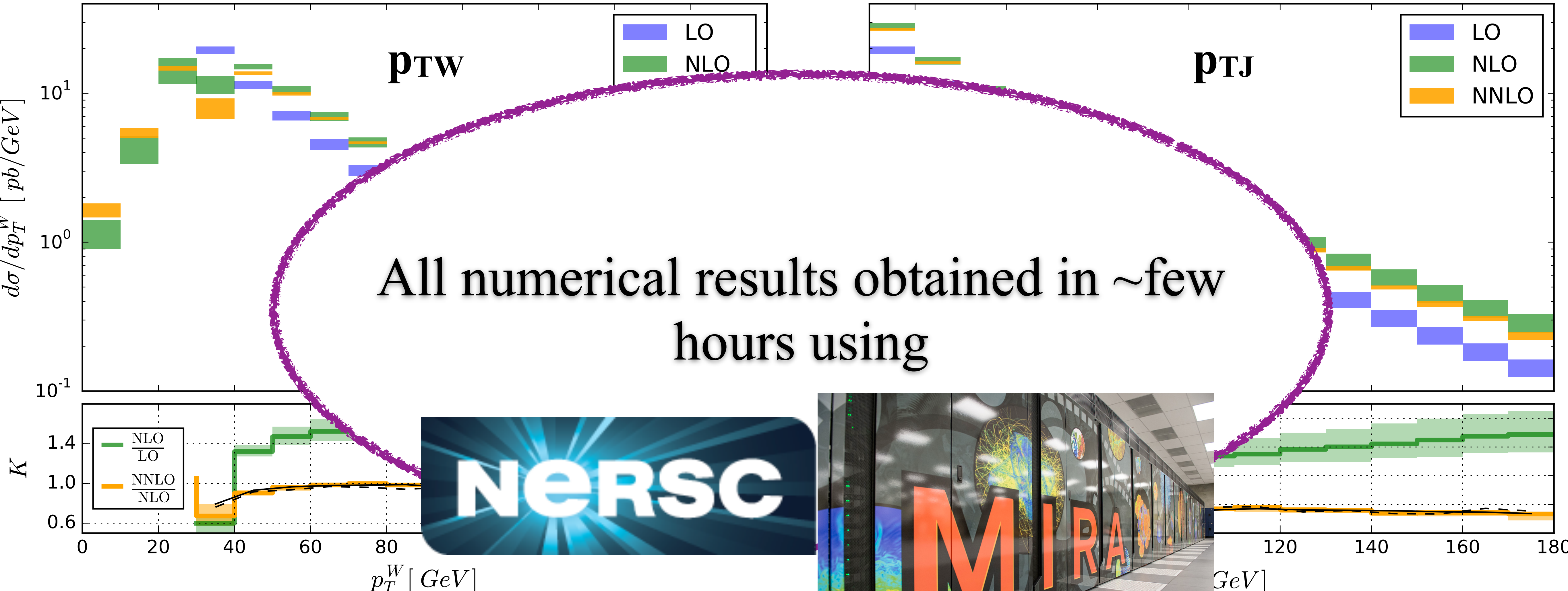
R.B., Focke, Liu, Petriello 1504.02131



- Tiny NNLO corrections; at the -1% level for the central scale choice ($\mu = m_W$)
- For transverse momenta less than 200 GeV, ratio of NNLO over NLO cross section is flat (with the exception of the Sudakov shoulder in the p_{TW} distribution caused by the p_{TJ}>30 GeV cut)

W+jet@NNLO

R.B., Focke, Liu, Petriello 1504.02131

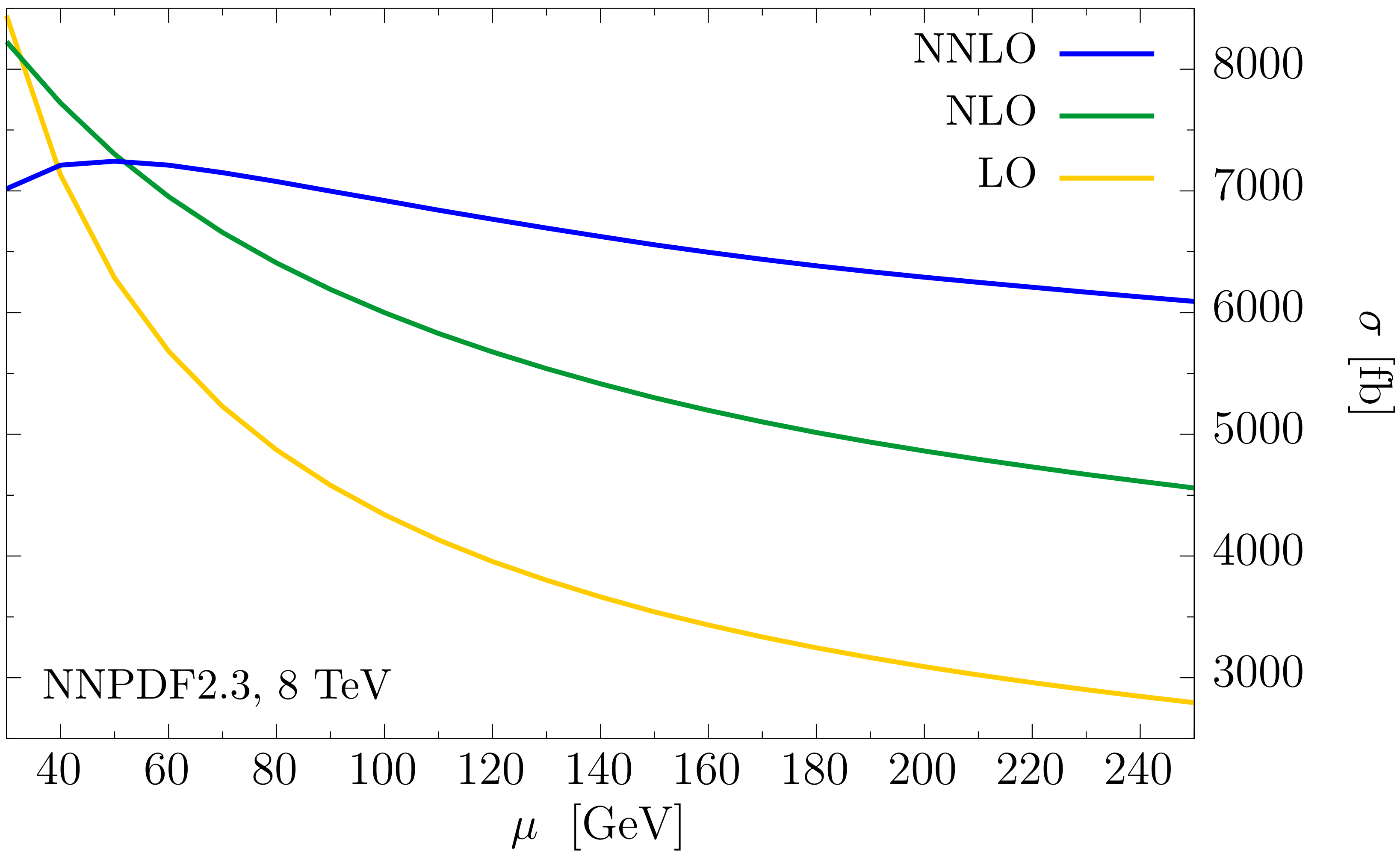


All numerical results obtained in ~few hours using

- Tiny NNLO corrections; at the -1% level for the central scale choice
- For transverse momenta less than 200 GeV, ratio of NNLO over NLO cross section is flat (with the exception of the Sudakov shoulder in the p_{TW} distribution caused by the p_{TJ}>30 GeV cut)

H+jet@NNLO: validation

- An additional check is possible in this case. The dominant qg and gg scattering channels were also computed using the sector-improved residue subtraction technique R.B., Caola, Melnikov, Petriello, Schulze 1504.07922



- Agreement between the two calculations at the per-mille level
- Effect of missing qq channels in the sector-improved calculation at the 1-2% level
- Reduced scale dependence at NNLO; preference for smaller scales

Important, unique validation of NNLO calculational technology!

H+jet@NNLO: validation

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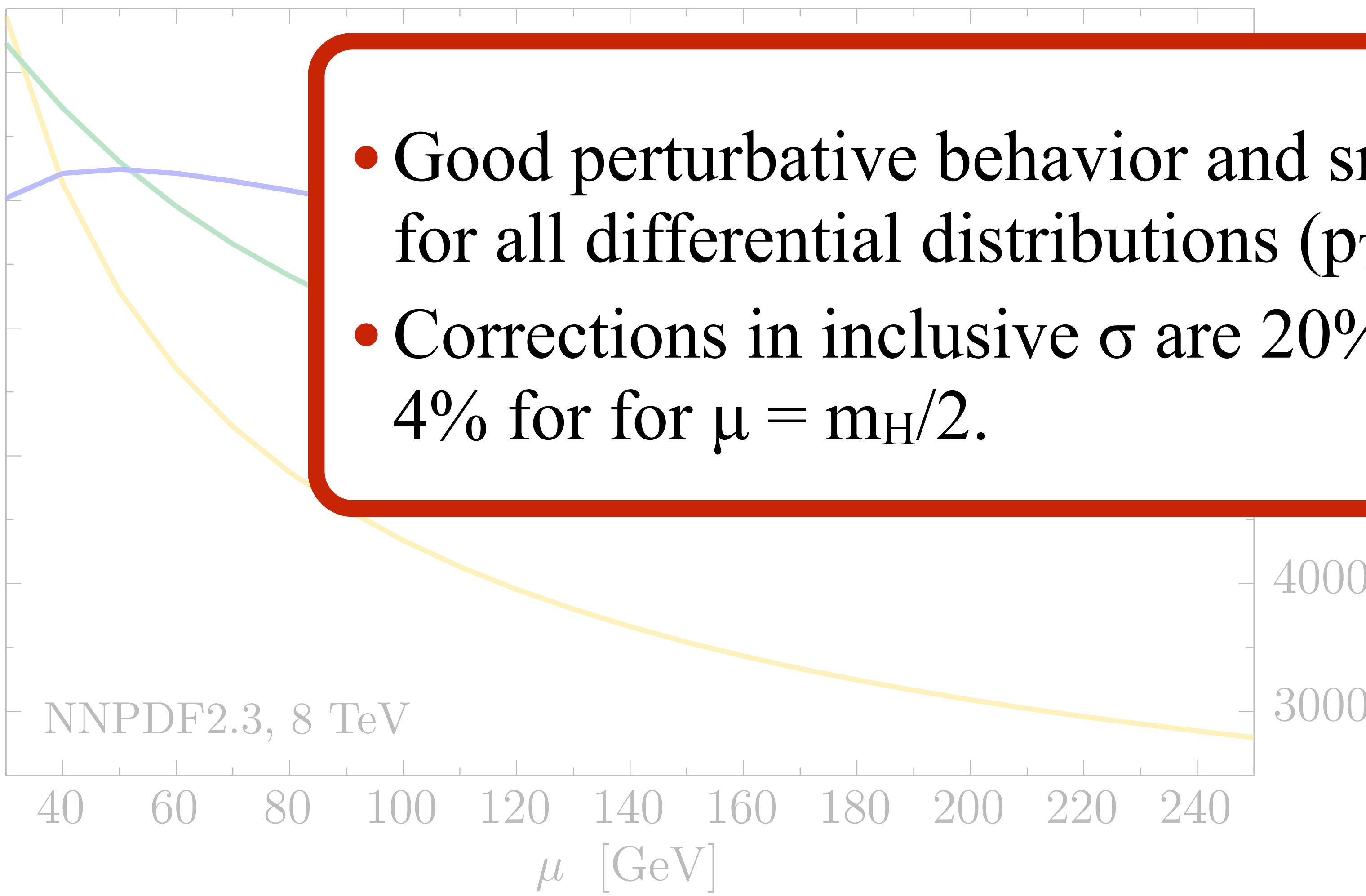

- Good perturbative behavior and smaller uncertainties for all differential distributions (p_{TH}, p_{Tj}, Y_j)
- Corrections in inclusive σ are 20% for for $\mu = m_H$ and 4% for for $\mu = m_H/2$.

tween the
at the per-

ing qq
ector-
ation at the
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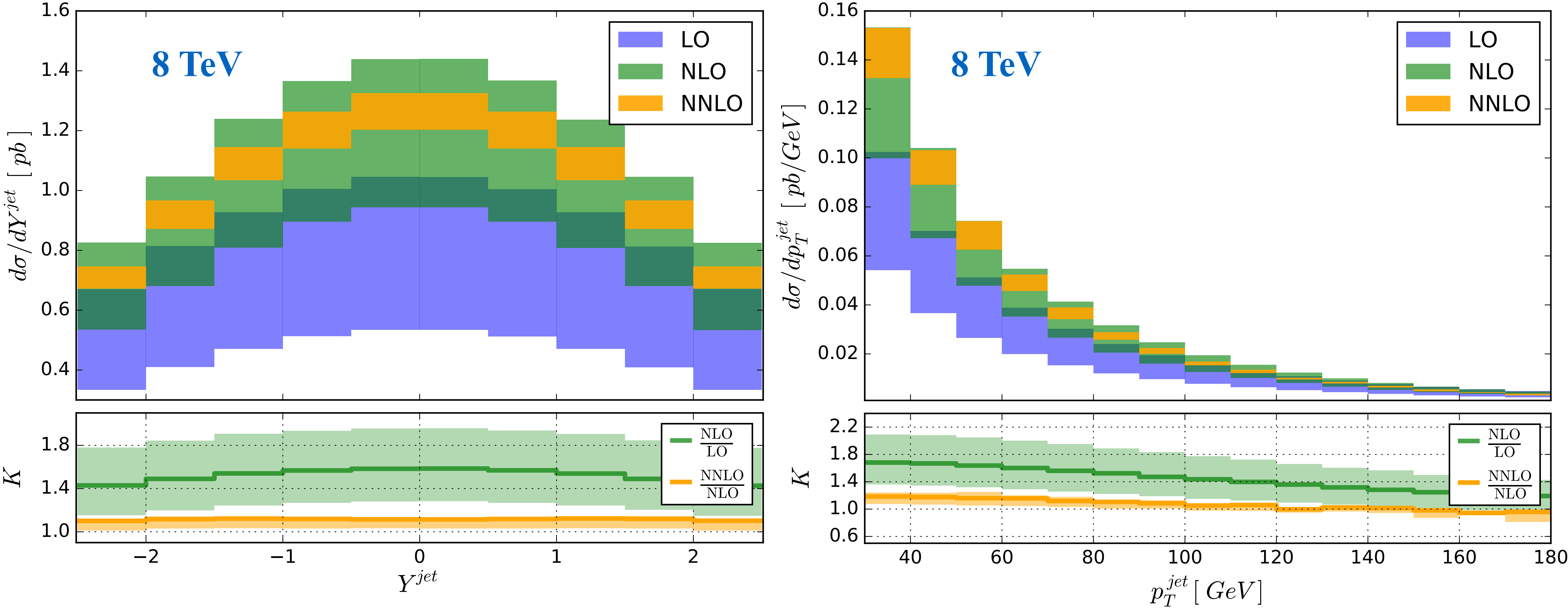
H+jet@NNLO

$\mathbf{Y_J}$ R.B., Focke, Giele, Liu, Petriello 1505.03893 $\mathbf{p_{TJ}}$

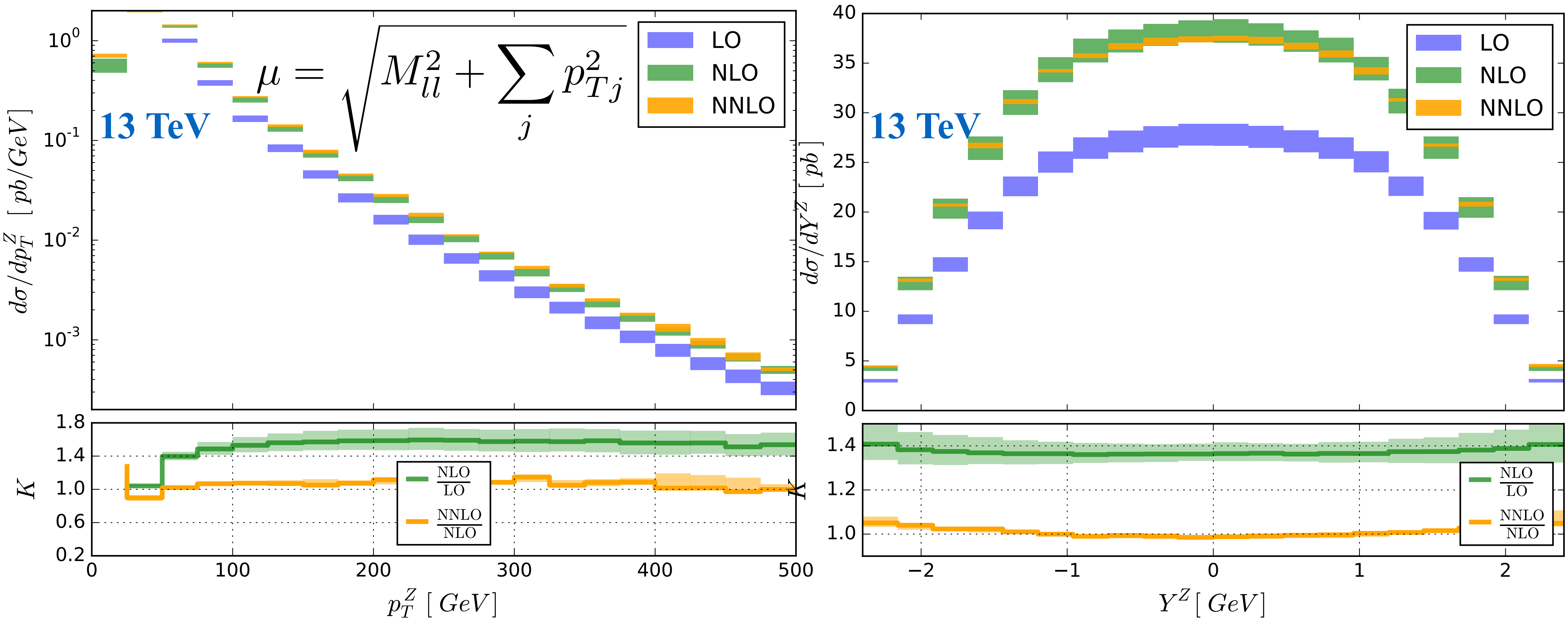


- NNLO corrections are flat as a function of jet rapidity
- However, the NNLO/NLO ratio for the p_{TJ} distribution varies by ~20% as p_{TJ} is varied from 30 GeV to 180 GeV (similar observation for p_{TH})

Z+jet@NNLO

- Z+jet is another important SM benchmark; needed for gluon PDF determination; detector calibration; background to dark matter searches in the mono-jet channel

R.B., Campbell, Ellis, Focke, Giele, Liu, Petriello 1512.01291



- Z-boson p_T and Y receive small NNLO corrections, with a flat K-factor

Z+jet@NNLO

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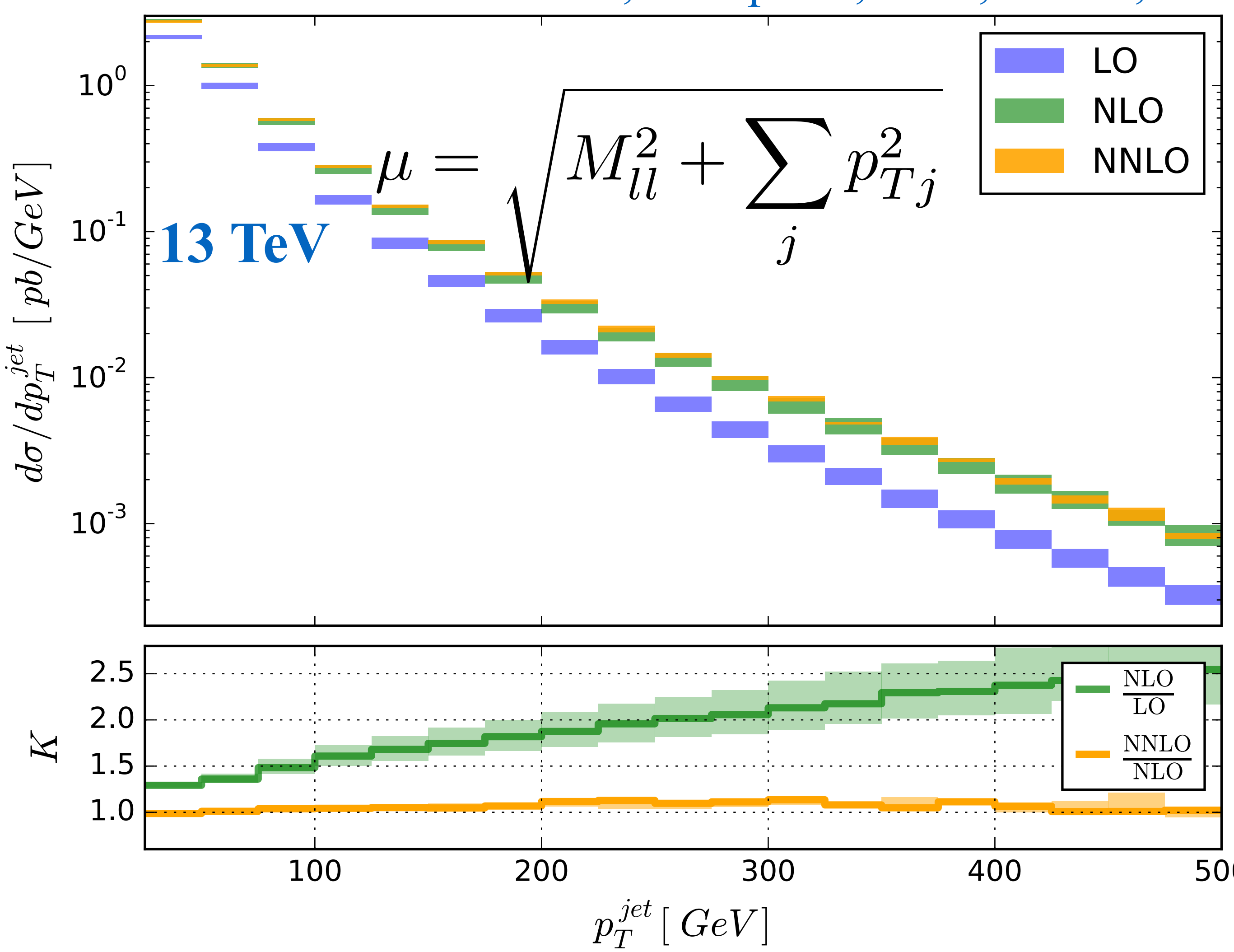

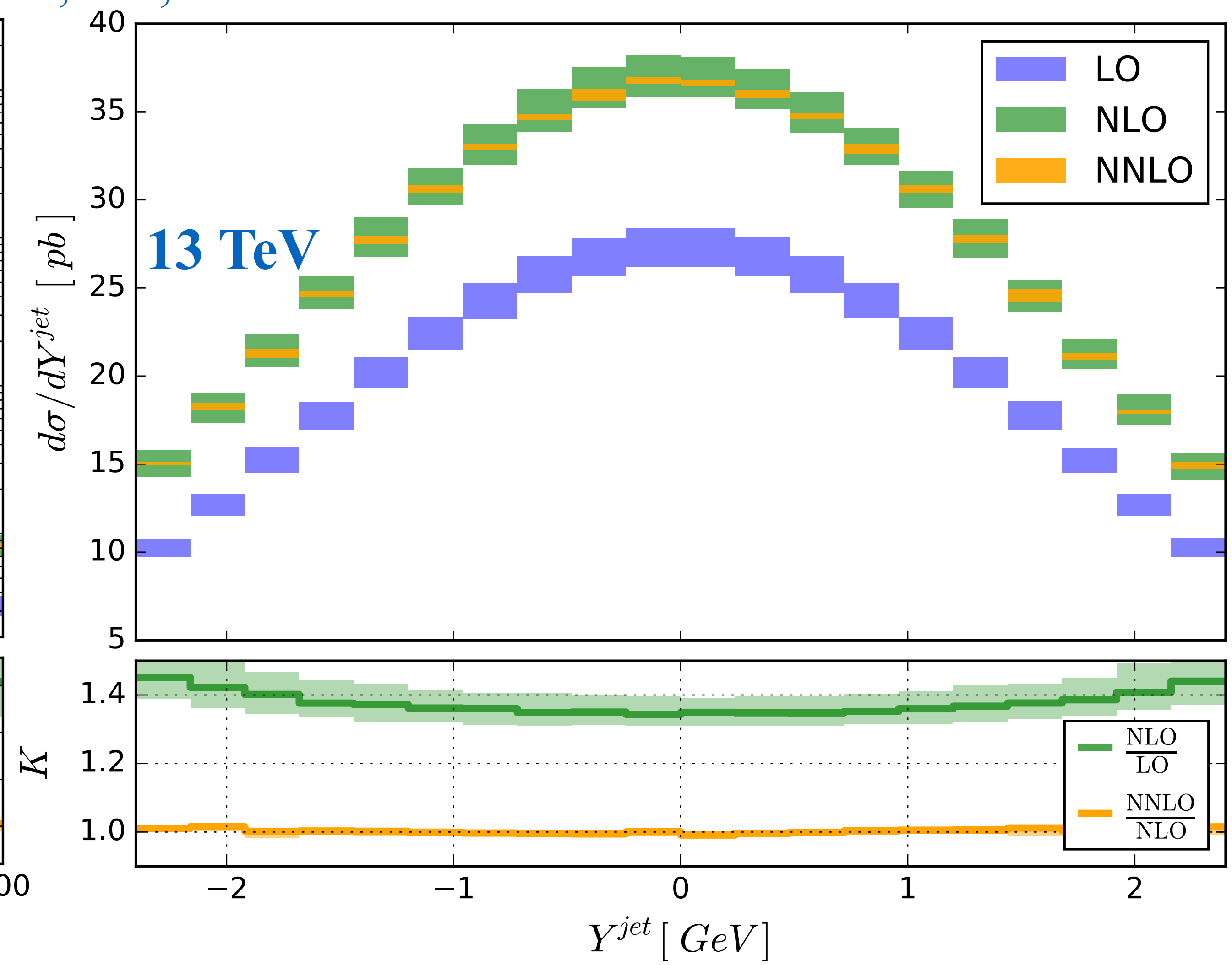

- NNLO jet distribution corrections also small, even though NLO corrections are large and very dependent on kinematics

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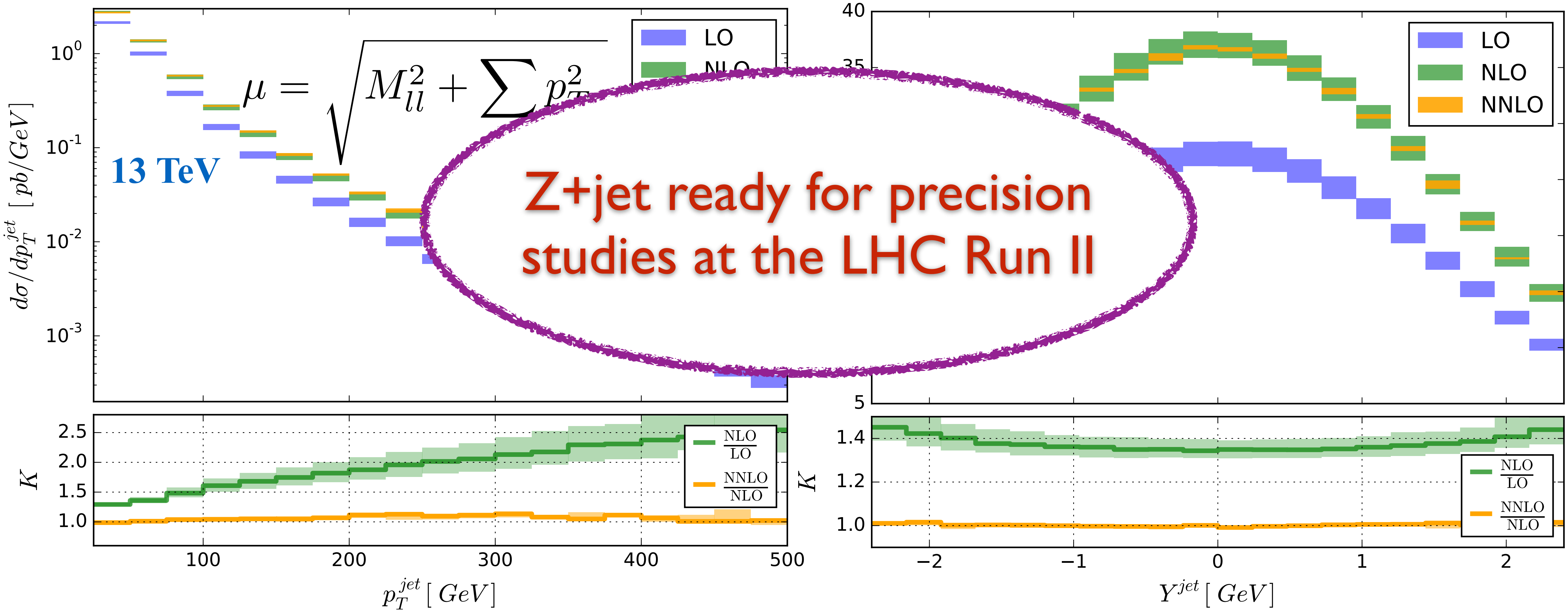


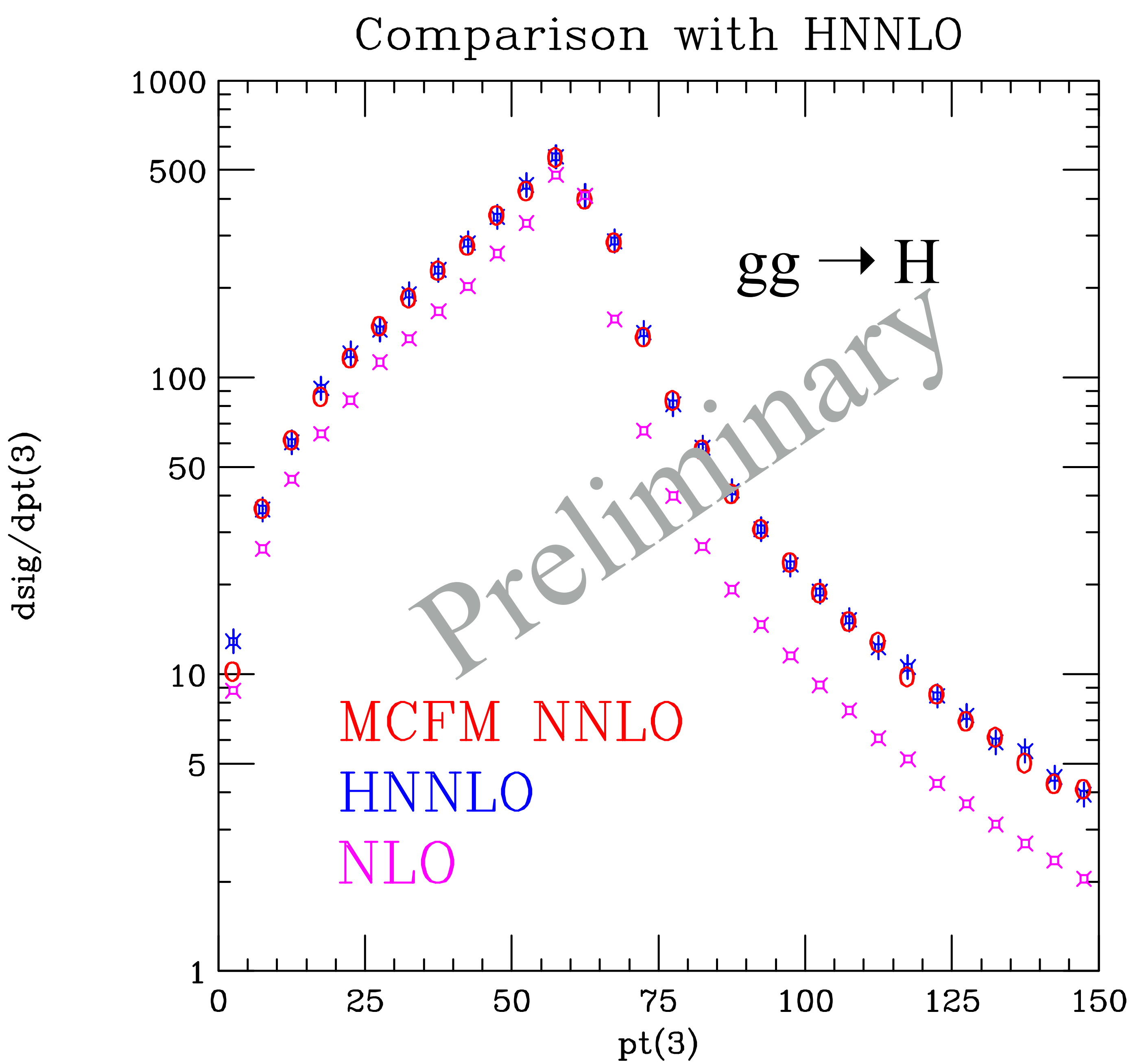
- NNLO jet distribution corrections also small, even though NLO corrections are large and very dependent on kinematics

Public Release of the NNLO Code

- A nice feature of N-jettiness subtraction is that it maximally reuses information available in existing NLO calculations/codes.

- This simplifies the public release of NNLO results: we can build upon existing NLO codes.

- We have calculated W+j, Z+j, H+j, as well as inclusive W/Z/H cross sections @ NNLO and incorporated them within the MCFM framework. We can do the same with any other NLO results/codes.



THE ERA OF SUPERCOMPUTERS

Argonne Leadership Computing Facility

Mira System Configuration

- **Architecture: IBM BG/Q**
- Nodes: 49,152
- Cores/node: 16
- **Total cores: 786,432 cores**
- Memory/node: 16 GB RAM per node
- Memory/core: 1 GB

National Energy Research Scientific Computing Center, Berkeley

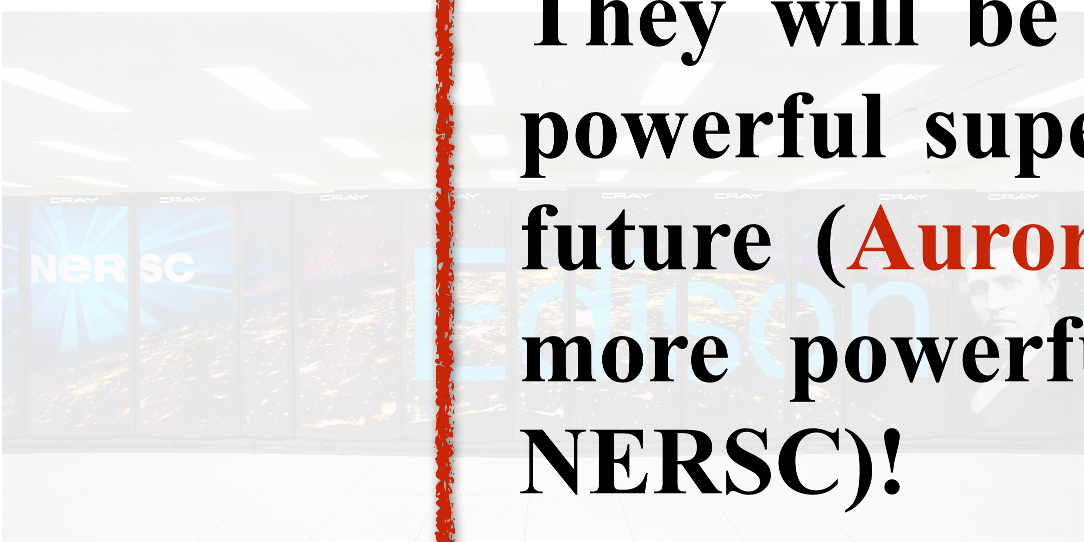
Edison System Configuration

- **Architecture: Cray XC3**
- Nodes: 5,576
- Cores/node: 24
- **Total cores: 133,824 cores**
- Memory/node: 64 GB RAM per node
- Memory/core: 2.66 GB

THE ERA OF SUPERCOMPUTERS

A Blue Gene/P supercomputer at Argonne National Laboratory

National Energy Research Scientific Computing Center, Berkley



Argonne Leadership Computing Facility (ALCF)

They will be replaced by even more powerful supercomputers in the near future (Aurora at Argonne, 18 times more powerful than Mira; Cori at NERSC)!

Edison System Configuration

- Architecture: Cray XC30
- Nodes: 5,576
- Cores/node: 24
- Total cores: 133,824 cores
- Memory/node: 64 GB RAM per node
- Memory/core: 2.66 GB

Mira System Configuration

- Architecture: IBM BG/Q
- Nodes: 49,152
- Cores/node: 16
- Total cores: 786,432 cores
- Memory/node: 16 GB RAM per node
- Memory/core: 1 GB

NNLO QCD in the Era of Supercomputers

- An impressive amount of computing resources is available to the users. But there is a price for that: your code must be structured to run on the supercomputers local architectures.
- Crucial for efficient run: your code must have a hybrid implementation of MPI+OpenMP protocols.

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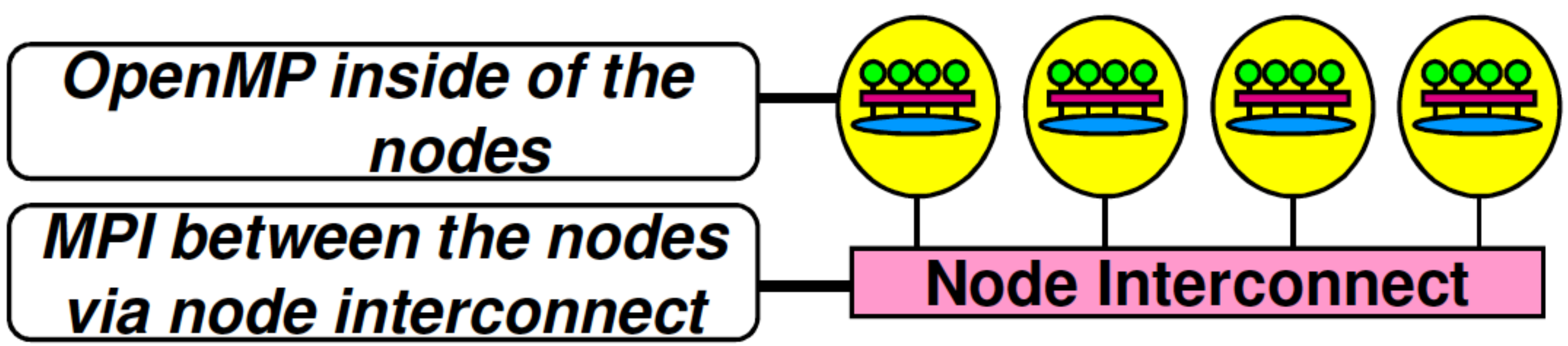
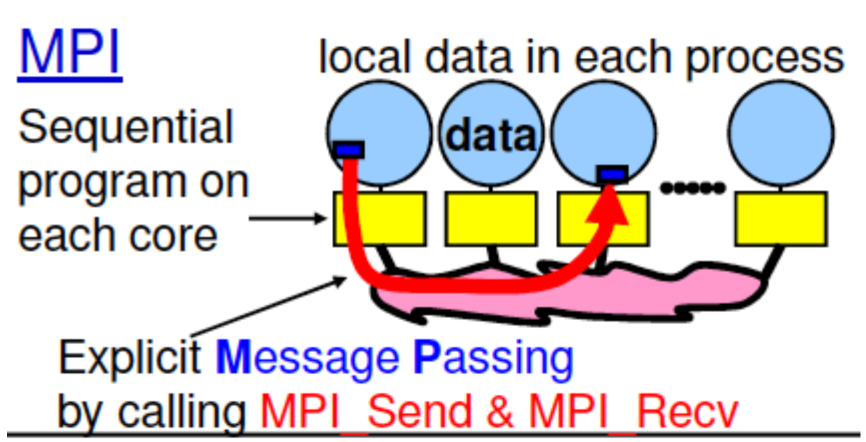
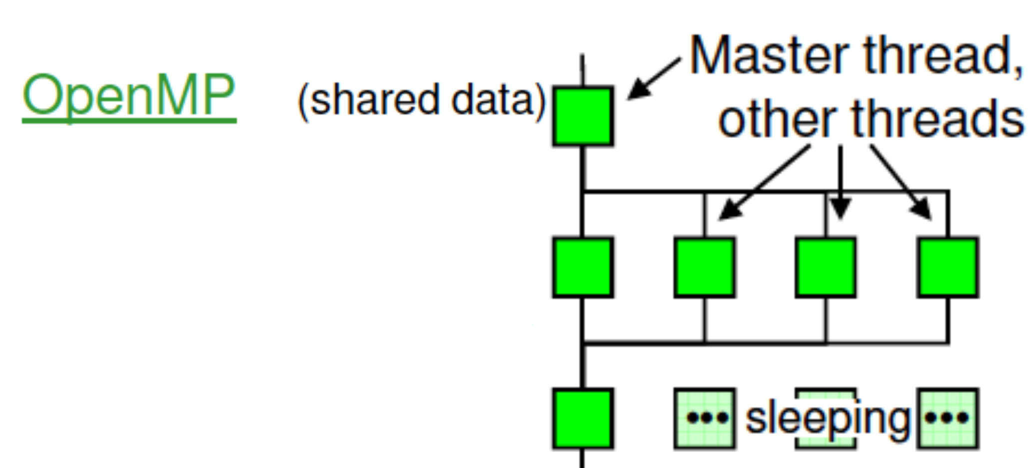
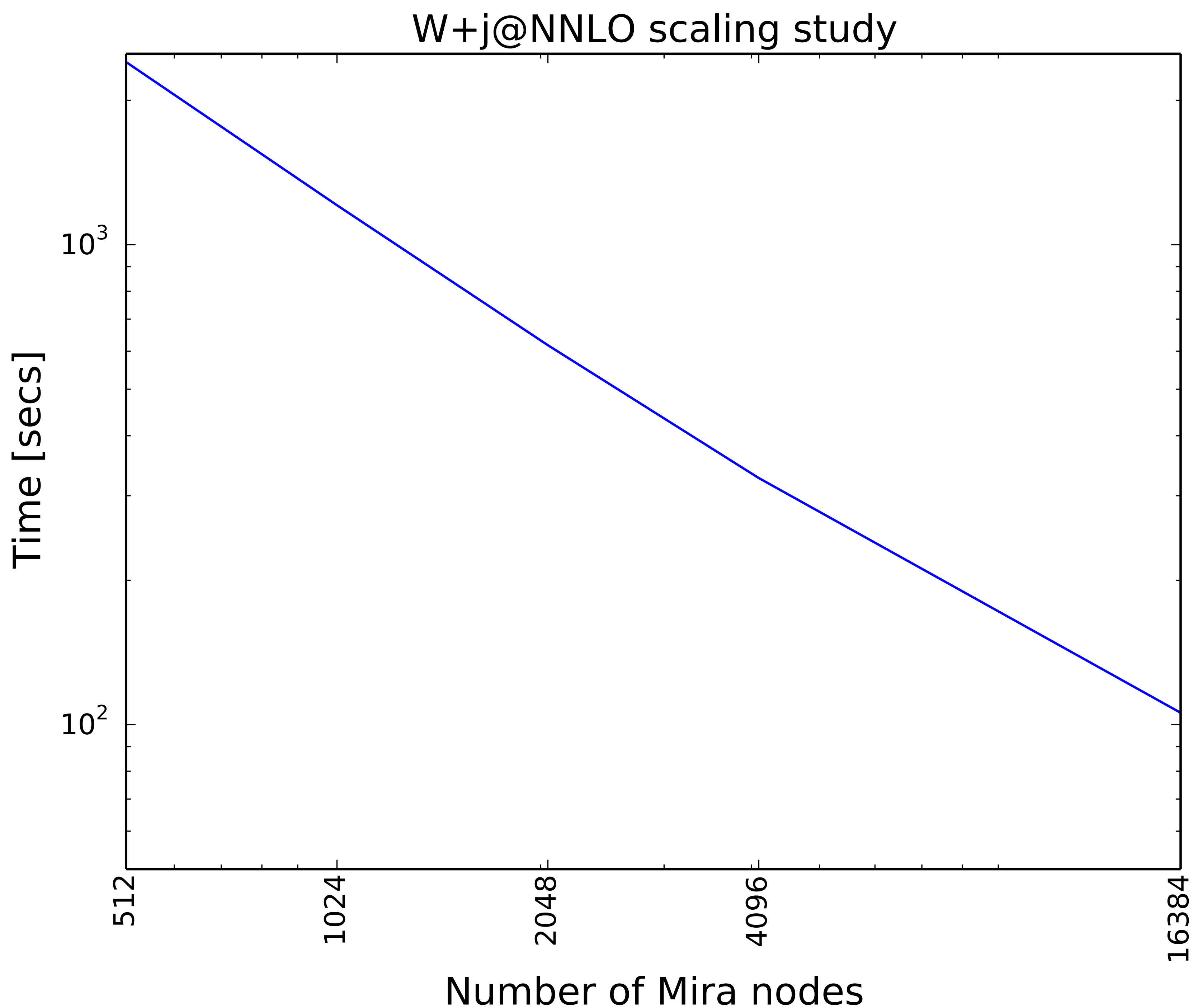






NNLO QCD in the Era of Supercomputers

- Our NNLO code supports such a hybrid implementation of MPI+OpenMP. Strong scaling to the several-thousand nodes level!



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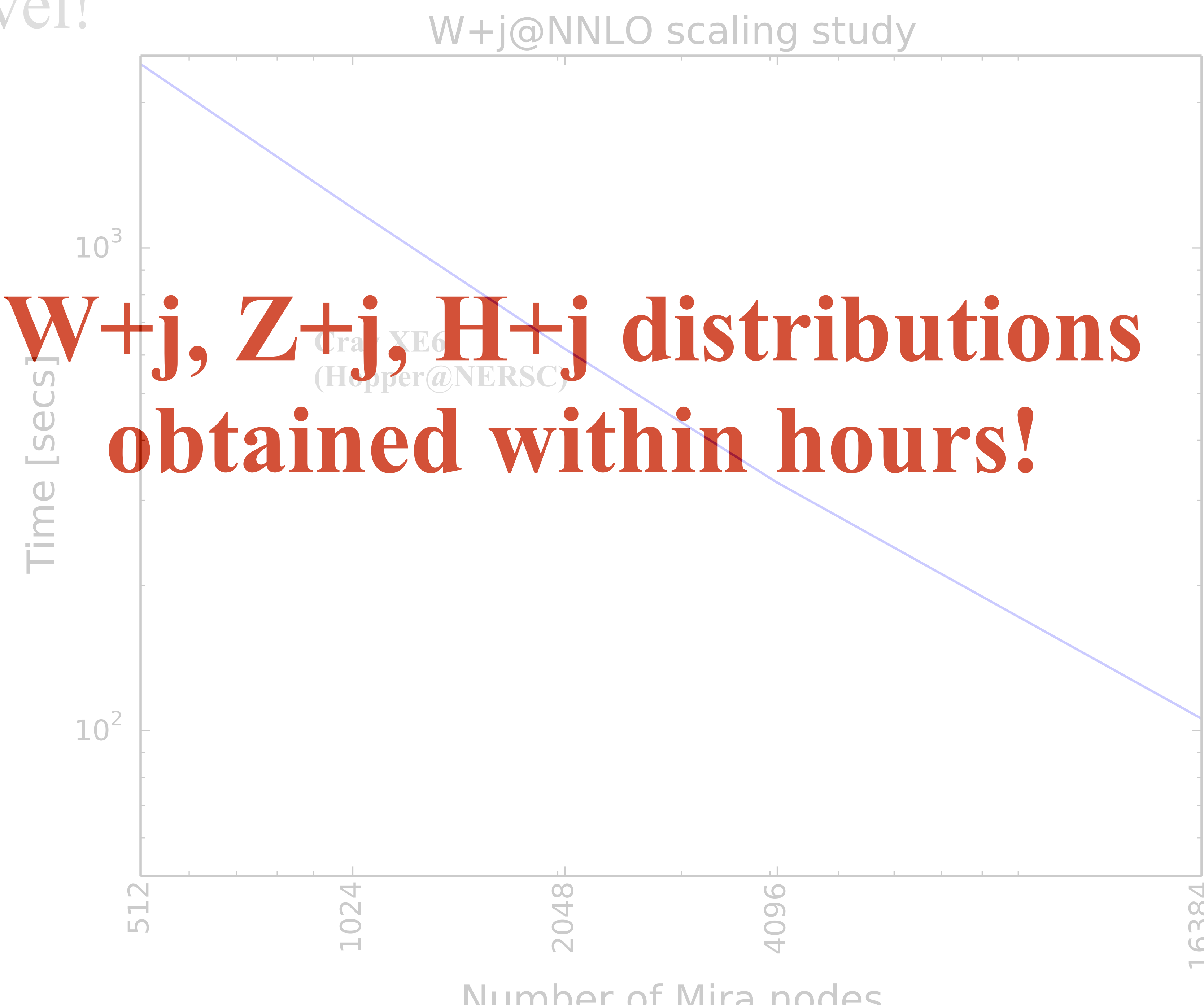

W+j, Z+j, H+j distributions obtained within hours!

Conclusions

- We have entered the era of percent-level jet phenomenology
- The N-jettiness subtraction scheme is a powerful method in predicting NNLO cross sections for jet production processes
- NNLO corrections to V+jet are at the percent level; ready for precision measurements at the LHC Run II
- NNLO results for Higgs+j makes us ready for continued exploration of the Higgs sector.
- We are at the point where standard computing with small clusters is not enough for precision physics. The use of supercomputers for NNLO calculations is a new paradigm!