# Application of effective theories to precision predictions

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EFT & Amplitude @ USTC, 2019

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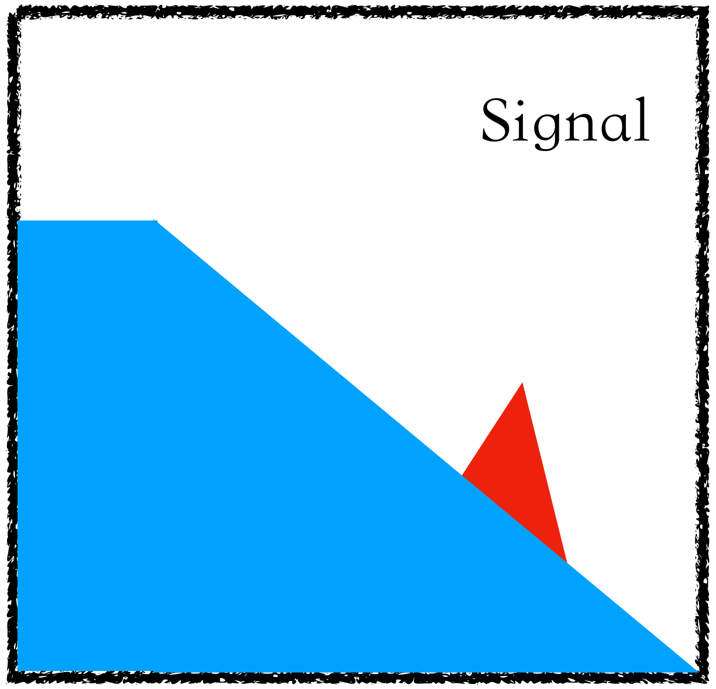
# Why Precision?

Example 1




An optimistic scenario: a clear resonance (e.g. Higgs discovery)

# Why Precision?

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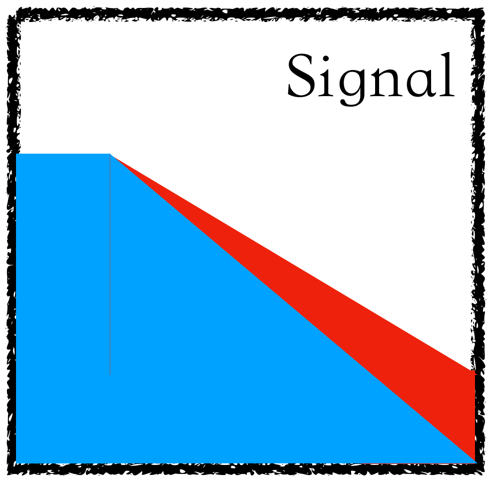
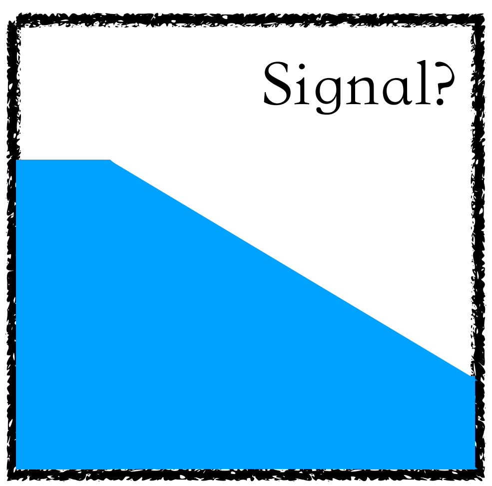
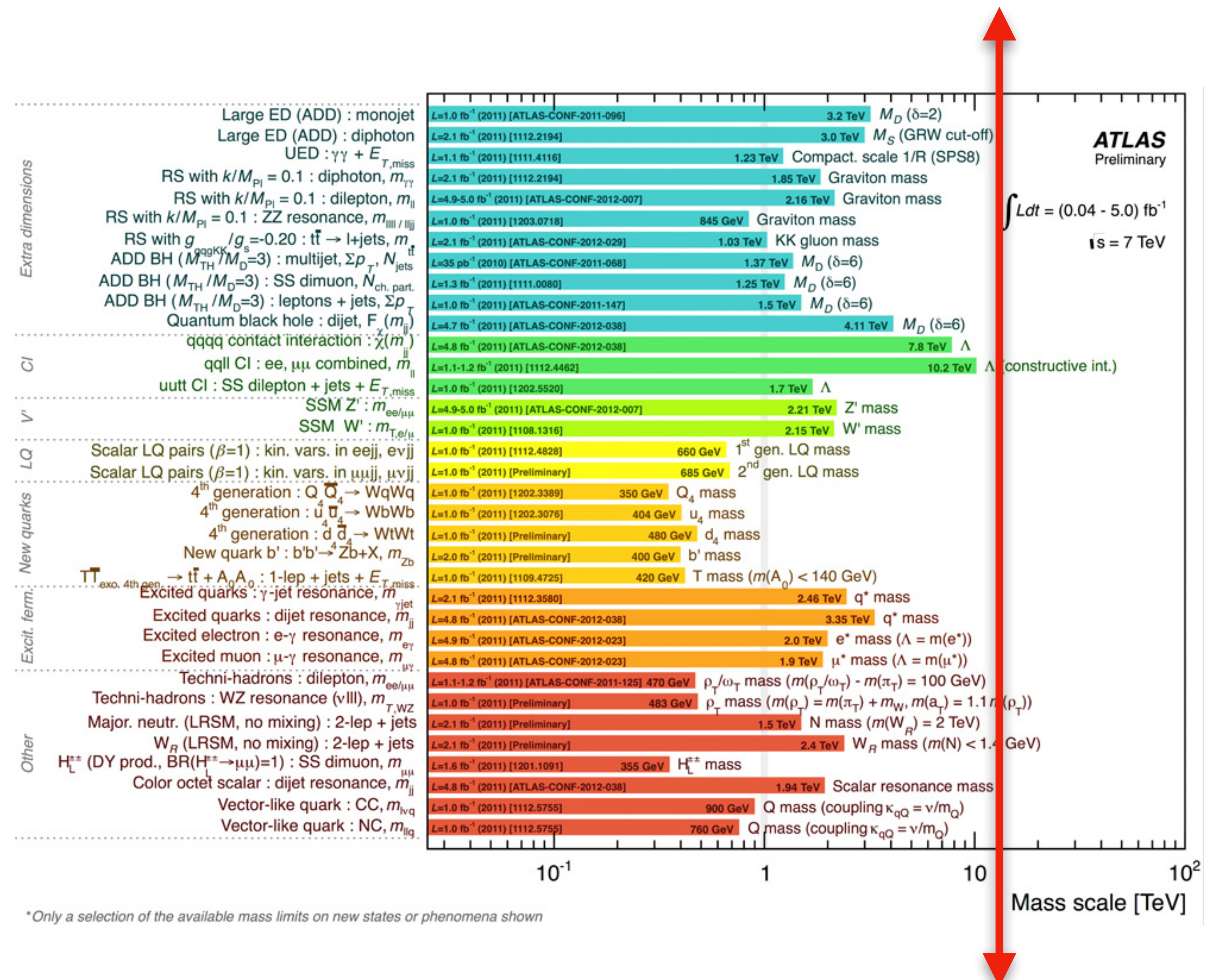


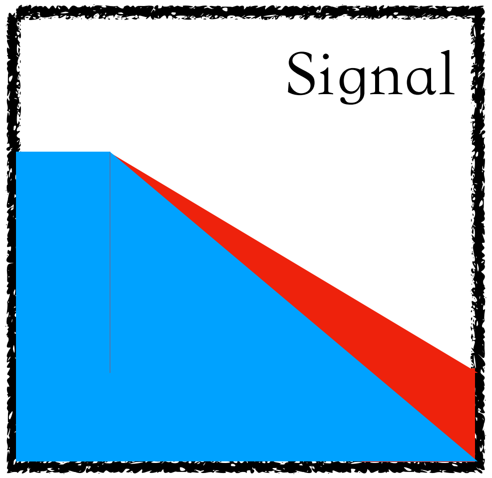



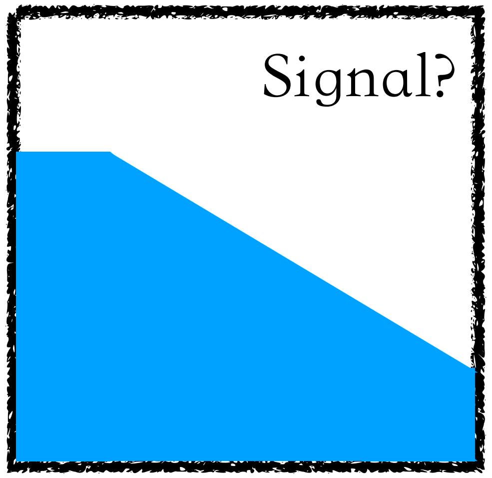

- Lower limits above 1—10 TeV now.
- New physics could be out of reach for current LHC
- Predicting the shape correctly will be crucial

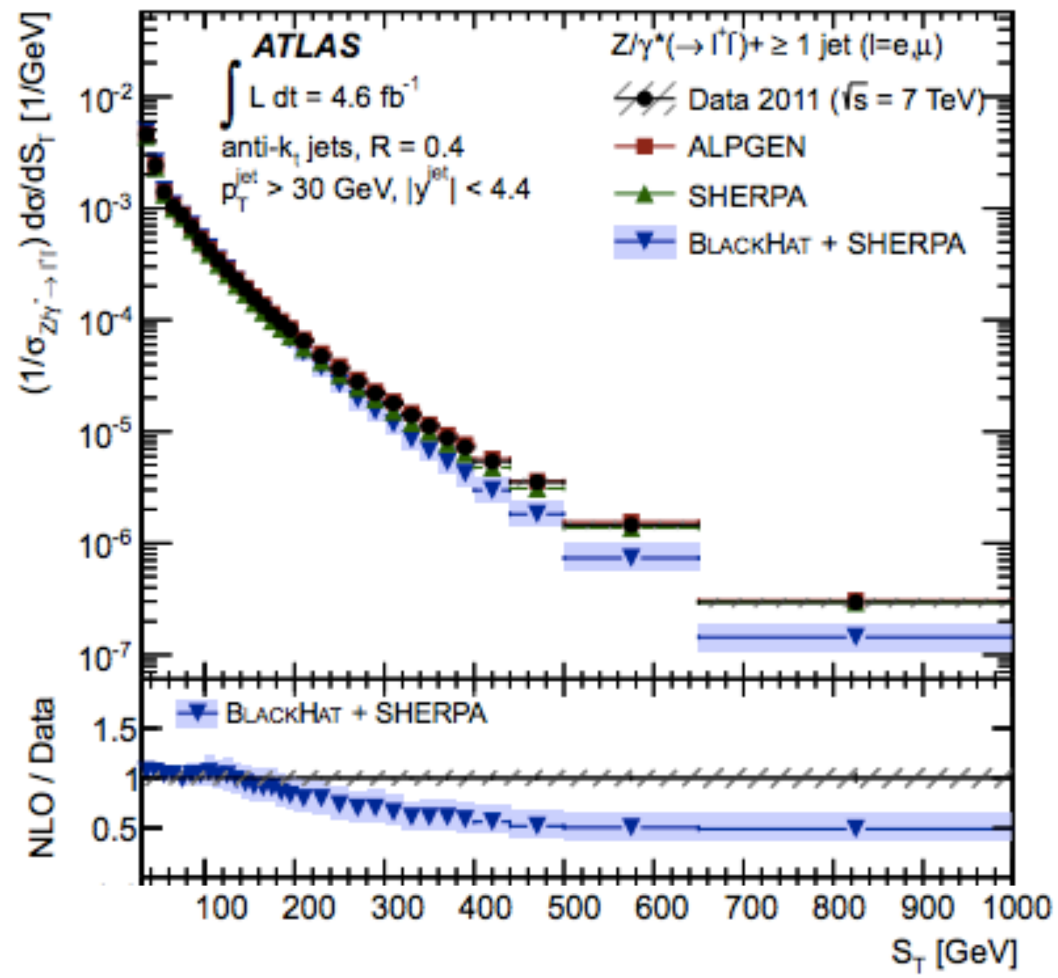
New Physics = precise Data - precise TH predictions!!

# Why Precision?

Example 1




$$S_T = \sum_i |p_{i,T}|$$

TH: NLO perturbation

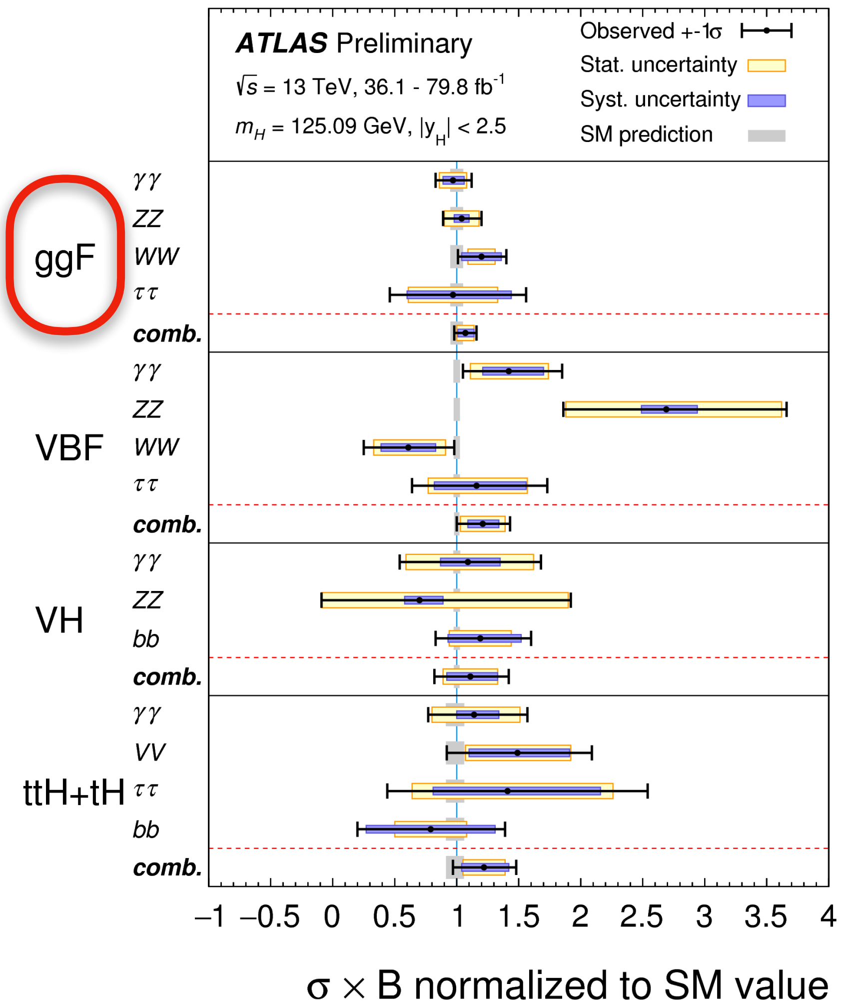
50% difference at high $S_T$ with NLO

New Physics? Missing Higher order?

# Why Precision?

## Example 2

Precision measurements of the SM param.




A Standard model Higgs?? Precision is the key!

$$\sigma_{ggH} = 48.58\,\text{pb}^{+4.56\%}_{-6.72\%}(\text{theory}) \pm 3.2\%(\text{PDF} + \alpha_s)$$

Anastasou, et.al., 2016

| | | | |
|---|---|---|---|
| 48.58 pb = | 16.00 pb | (+32.9%) | LO, rEFT |
| | + 20.84 pb | (+42.9%) | NLO, rEFT |
| | − 2.05 pb | (−4.2%) | Exact NLO |
| | + 9.56 pb | (+19.7%) | NNLO, rEFT |
| | + 0.34 pb | (+0.2%) | NNLO, 1/mt |
| | + 2.40 pb | (+4.9%) | EW, QCD-EW |
| | + 1.49 pb | (+3.1%) | N3LO, rEFT |

# Why Precision?

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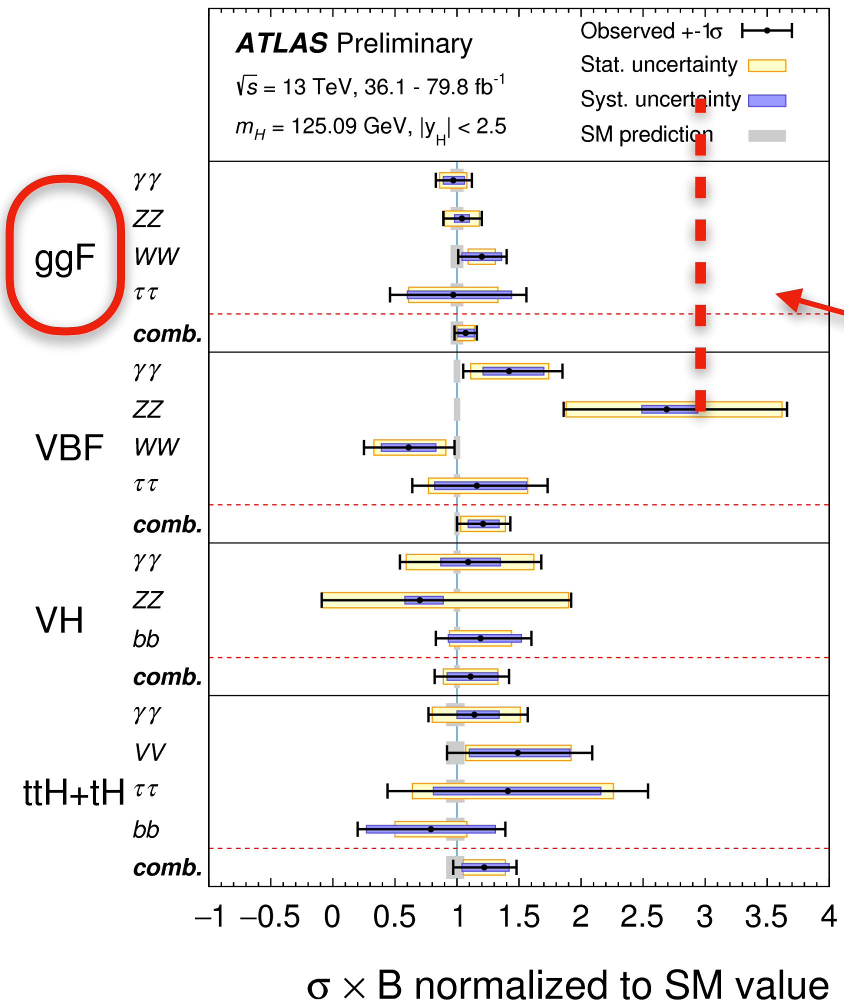


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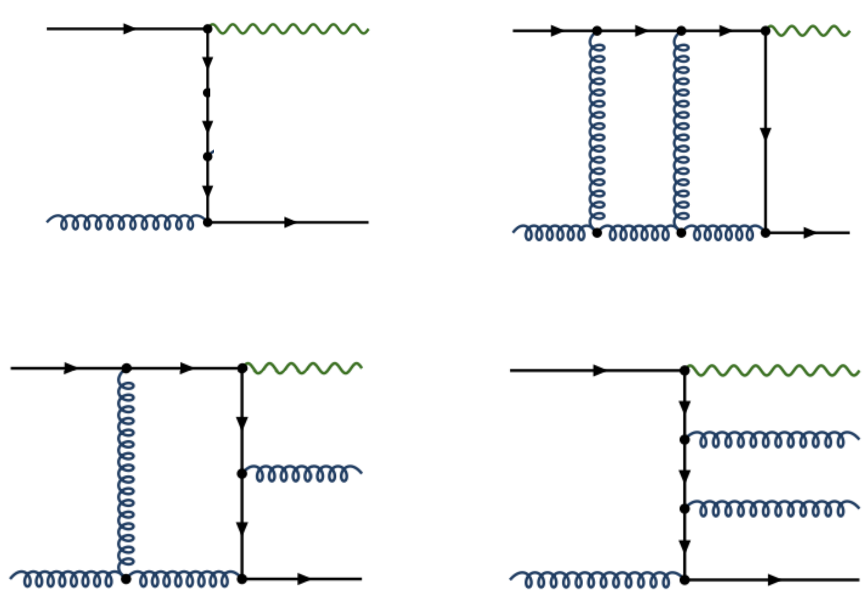
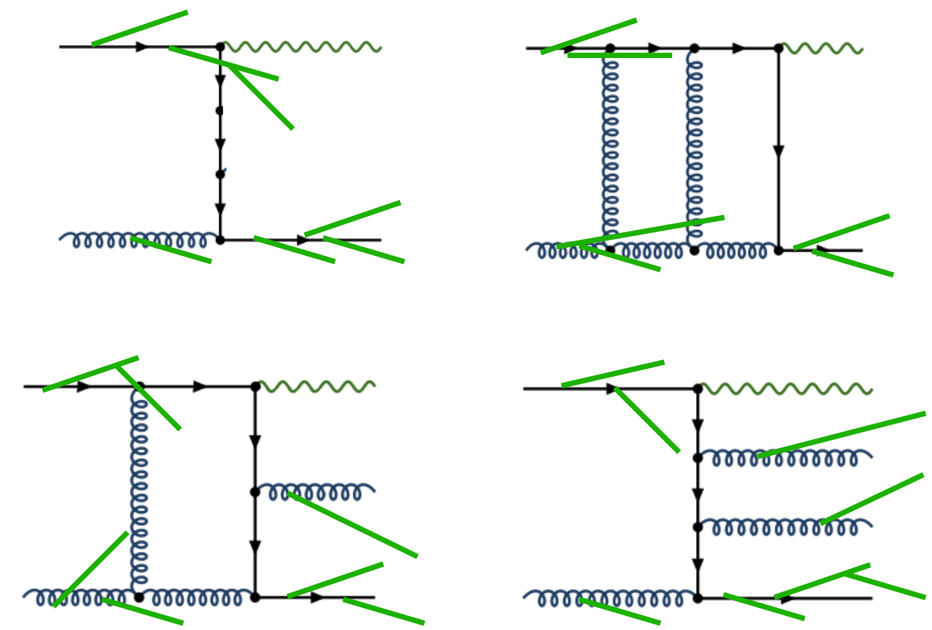
# How to achieve precision?



Fixed Order

+



Resummation

Fixed Order →

Resummation ↓

| | | | | | | |
|---|---|---|---|---|---|---|
| LO | 1 | | | | | |
| NLO | $\alpha_s L^2$ | $\alpha_s L$ | $\alpha_s$ | | | |
| NNLO | $\alpha_s^2 L^4$ | $\alpha_s^2 L^3$ | $\alpha_s^2 L^2$ | $\alpha_s^2 L$ | $\alpha_s^2$ | |
| ... | ... | ... | ... | ... | ... | |
| N$^k$LO | $\alpha_s^k L^{2k}$ | $\alpha_s^k L^{2k-1}$ | $\alpha_s^k L^{2k-2}$ | $\alpha_s^k L^{2k-3}$ | $\alpha_s^k L^{2k-4}$ | ... |

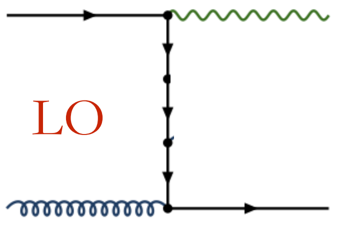
LL ↓ NLL ↓ NNLL ↓

# Outlines

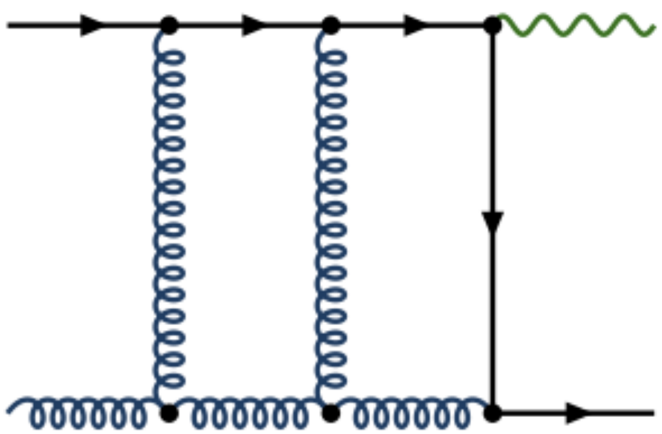
- EFT in FO @ colliders
- EFT in Resummation @ colliders
- Summary

# EFT in FO @ colliders

# Fixed order @ colliders



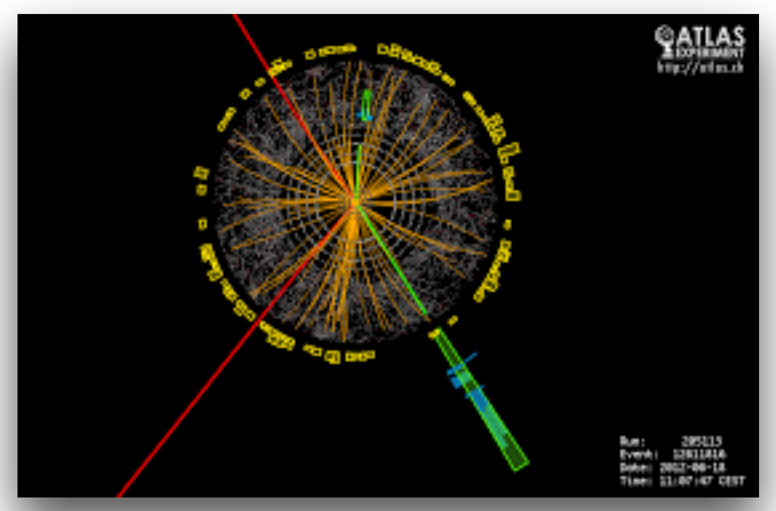

V + 1j at NNLO as an example

VV  $+ \cdots$

$$\int \mathrm{d}\Phi_2 \sum_{i=0}^{4} \frac{vv_i}{\epsilon^i}$$

D = 4 -> D = 4-2e

Divergence -> e-poles



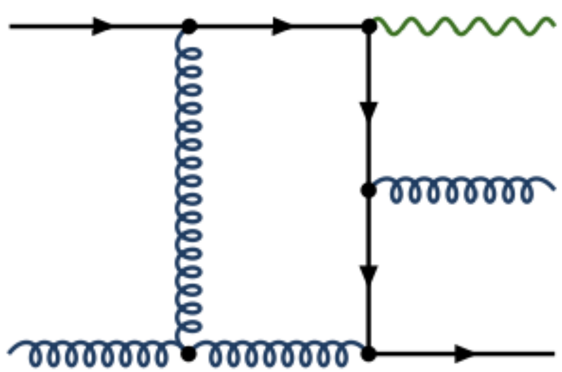

- Benefit from the amplitude community
- Explicit IR poles after loop integrations
- Pretty much limited to 2 → 1, 2 → 2. 2→ 3 starts to be available

# Fixed order @ colliders

Complicated experimental cuts, jet algorithms applied to the final states

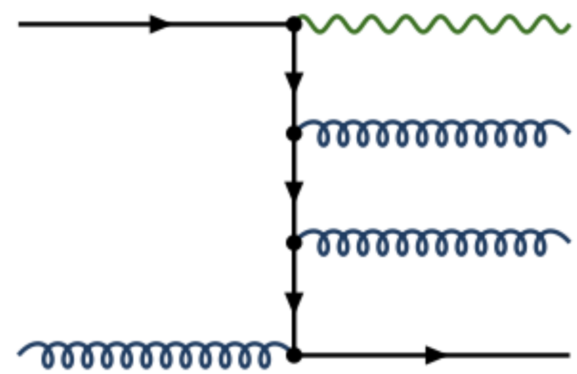
V + 1j at NNLO as an example

VR

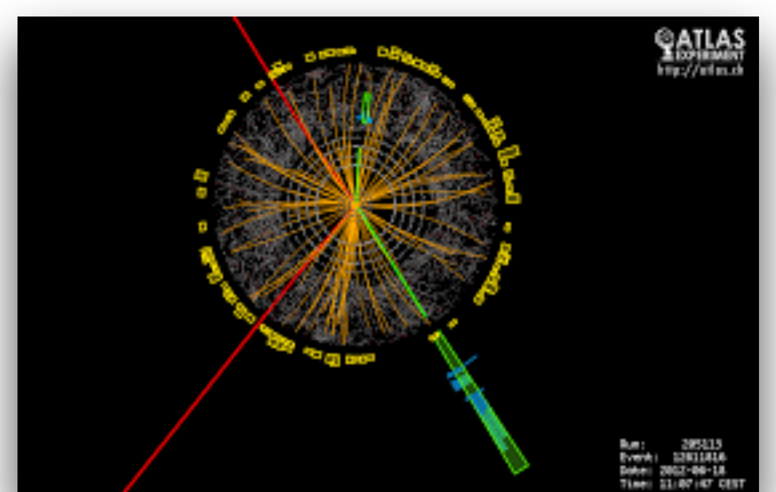


$$\int d\Phi_3 \sum_{i=0}^{2} \frac{vr_i}{\epsilon^i}$$

RR



$$\int d\Phi_4 \, rr$$

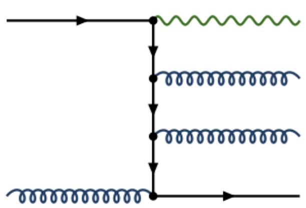



- We are mostly interested in fully differential cross section, which allows for experimental cuts, jet algorithms and parton showers $\cdots$
- IR poles fully show up for degenerate (soft/collinear) states ONLY after integrating over phase space, with all kinds of exp. cuts, jet algorithms $\cdots$
- How to isolate for numerical evaluation? A problem for ~15 years that prevents us from making NNLO predictions for the LHC.

# Fixed order @ colliders

## Subtraction

IRC limit of QCD



$$= \int \mathrm{d}z \, \frac{f(z)}{z^{1+a\epsilon}} \longrightarrow \int \mathrm{d}z \, \frac{f(z) - f(0)}{z} + \int \mathrm{d}z z^{-1-a\epsilon} f(0)$$

Jet algorithms, exp. cuts enter here. Finite and suitable for numerical evaluations

“inclusive”, loop techniques come into help

Construct counter terms point-wise in the phase space

- Antenna subtraction 2 Gehrmann, Glover
- STRIPPER + modifications Czakon + …

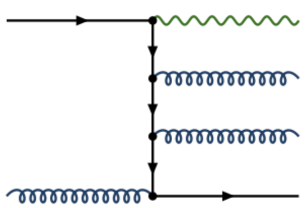
…

# Fixed order @ colliders

Slicing

One single **physical** observable to separate out all singularities

Power corrections of the EFT



$$= \int dz \frac{f(z)}{z^{1+a\epsilon}} \longrightarrow \int \frac{f(z)}{z}\theta(z > z_0) - f(0)\frac{z_0^{-a\epsilon}}{a\epsilon} + \ldots$$

Jet algorithms, exp. cuts enter here. Finite and suitable for numerical evaluations

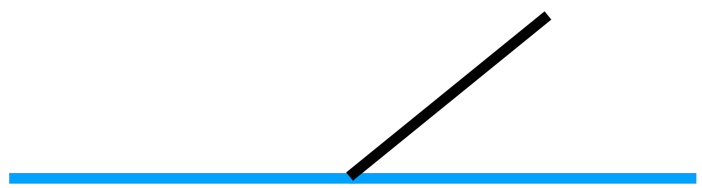
EFT of this observable enters to simplify the calculations; will also rely on various loop techniques

A physical observable ($z_0$) to regulate all related IR singularities

- qT-subtraction Catani, Grazzini
- N-jettiness subtraction Boughezal, Focke, **XL**, Petriello + …

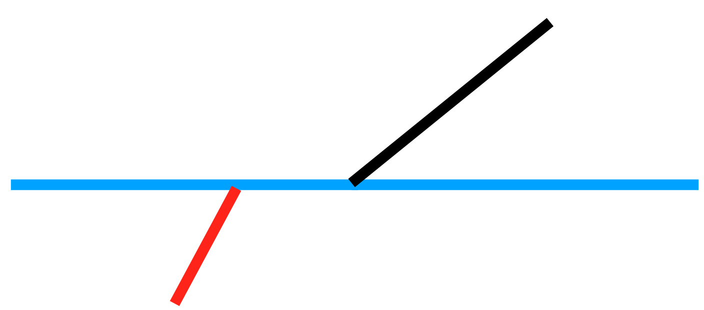
# Fixed order @ colliders

$q_T$ subtraction Catani, Grazzini



$q_T = 0$, if no radiation.

For color neutral final state @ LO



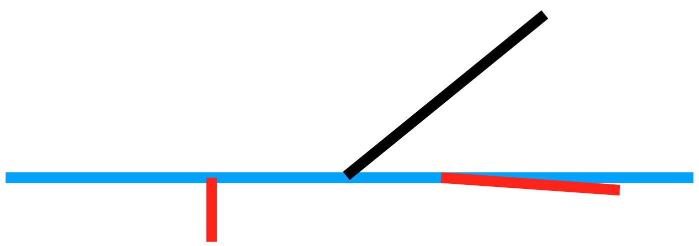
Finite $q_T$ means at least one additional radiation

Becomes color neutral final state + 1 jet @ LO

# Fixed order @ colliders

$q_T$ subtraction Catani, Grazzini

$$\int \frac{f(z)}{z}\theta(z > z_0) - f(0)\frac{z_0^{-a\epsilon}}{a\epsilon} + \ldots$$

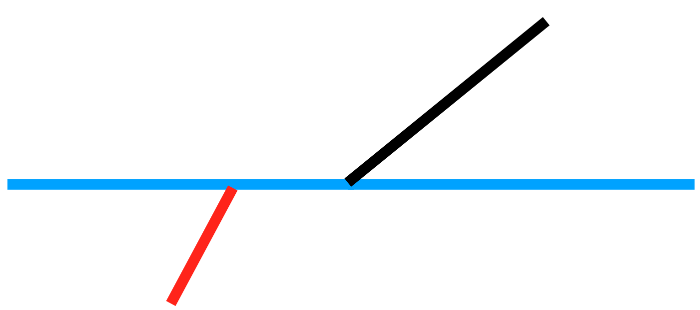


$q_T$ cut = small, only virtual + soft/collinear radiations.

EFT for small $q_T$ physics comes into play

$$\sigma = H\ [B \otimes B \otimes S]\,(q_T)$$

Some of them known to 3-loops



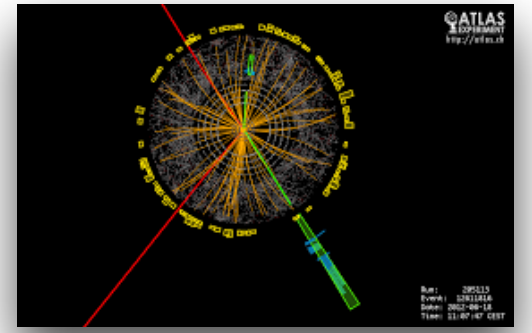
Above $q_T$ cut

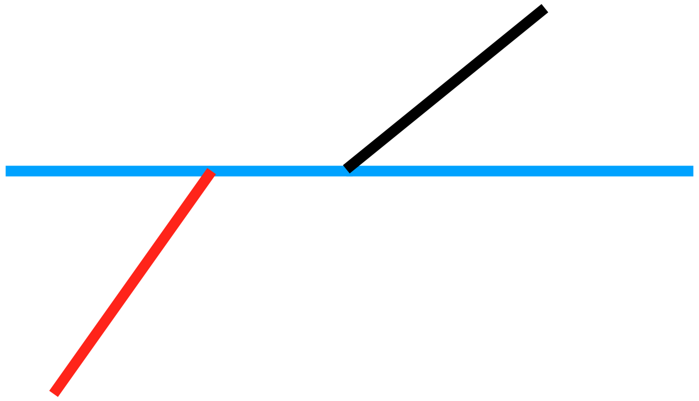
Recycle color neutral final state + 1 jet @ (N-1)LO results

# Fixed order @ colliders

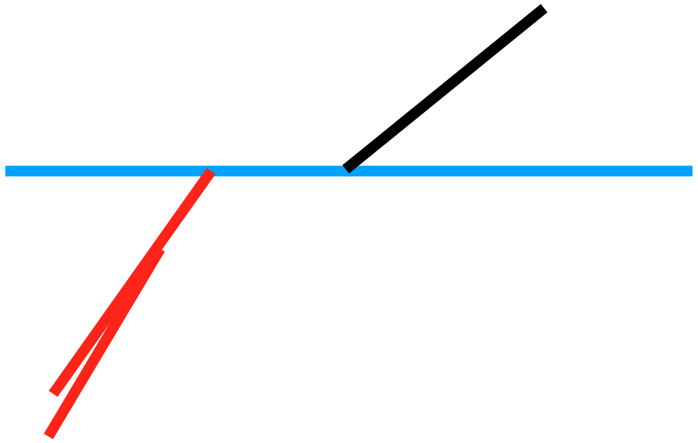
$q_T$ subtraction Catani, Grazzini

Difficulties in dealing with colored final state





LO



NLO

$q_T$ of the system can not single out the collinear divergence

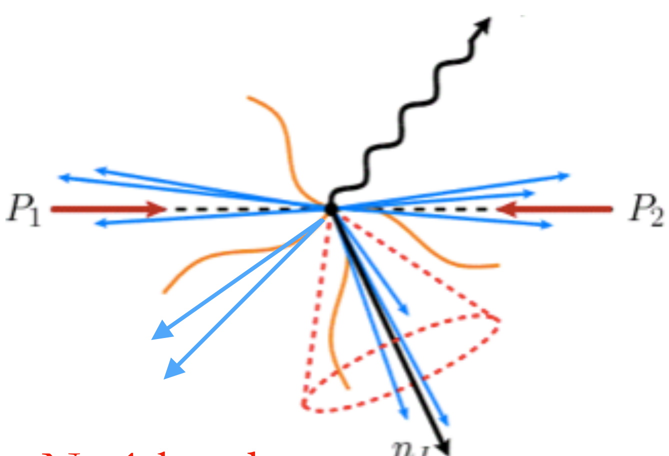
# Fixed order @ colliders

## N-jettiness subtraction

Bougehzal, **XL**, Petriello + ⋯

$$\tau_N = \sum_k \min\left[\frac{p_k \cdot n_a}{Q_a}, \frac{p_k \cdot n_b}{Q_b}, \frac{p_k \cdot n_1}{Q_1}, \ldots, \frac{p_k \cdot n_N}{Q_N}\right]$$

$\tau_N \to 0$, $p_k$ are soft or collinear

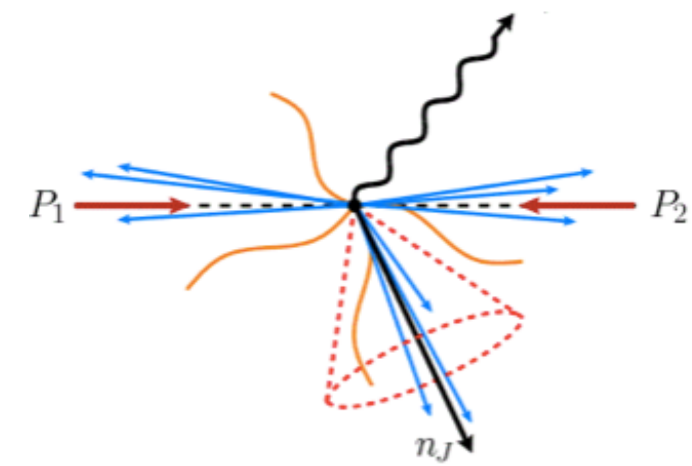



At least N+1 hard radiations, just NLO

$\tau_{cut}$

$$\int \frac{f(z)}{z}\theta(z > z_0) + f(0)\frac{z_0^{-a\epsilon}}{a\epsilon} + \ldots$$

$\tau_{cut} \to 0$




True NNLO is here

- N-jettiness to set the boundary between NLO and NNLO
- NNLO using EFT based on Factorization $\mathrm{Tr}[H \cdot S_N] \otimes B_a \otimes B_b \otimes J_i + \ldots$
- universal building blocks Stewart et. al.
- ignorant of the NLO details, conceptually appealing to implement

# Fixed order @ colliders

N-jettiness subtraction   Bougehzal, XL, Petriello + ⋯

$$\tau_N = \sum_k \min\left[\frac{p_k\cdot n_a}{Q_a}, \frac{p_k\cdot n_b}{Q_b}, \frac{p_k\cdot n_1}{Q_1}, \ldots, \frac{p_k\cdot n_N}{Q_N}\right]$$

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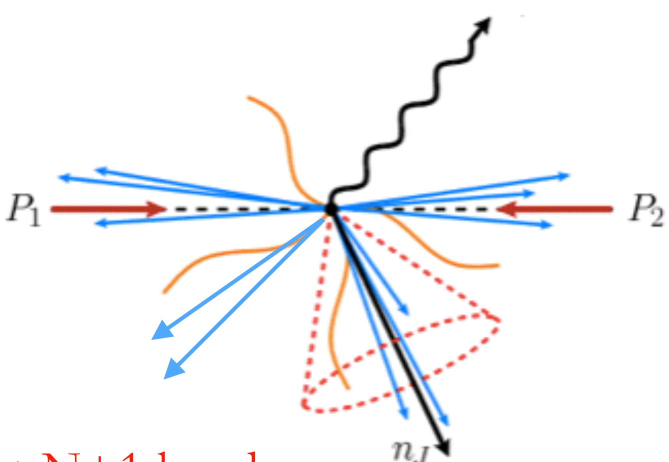


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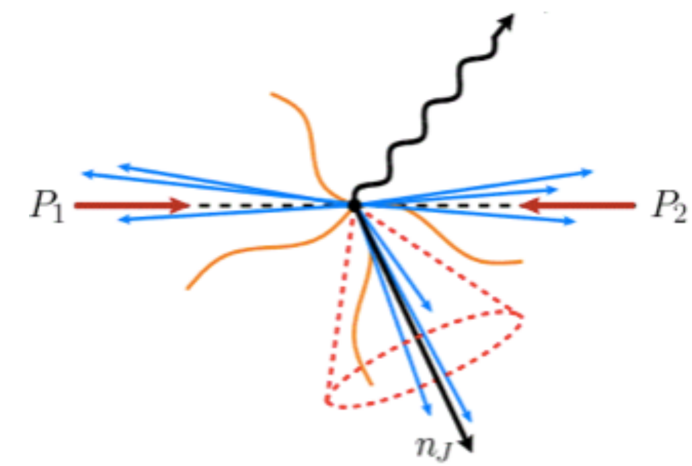



True NNLO is here

- B and J are all known to NNLO   Gaunt et al, 2014; Becher et al, 2004,2010
- Power corrections are known for Drell-Yan, ggH to NNLO leading logs   Zhu et al, 2017; XL et al, 2017
- NNLO S is known numerically, complicated due to the N-jettiness measure   XL et al, 2015, 2019 + ⋯ Liu and Wang, 2016

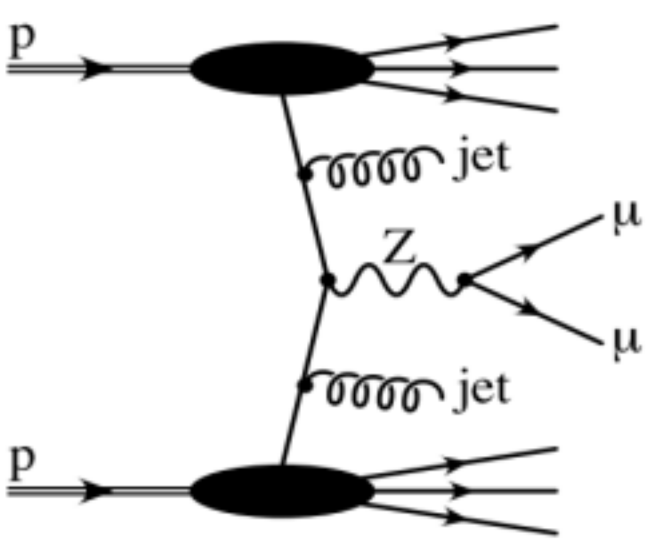
$$\mathrm{Tr}[H\cdot S_N]\otimes B_a\otimes B_b\otimes J_i + \ldots$$

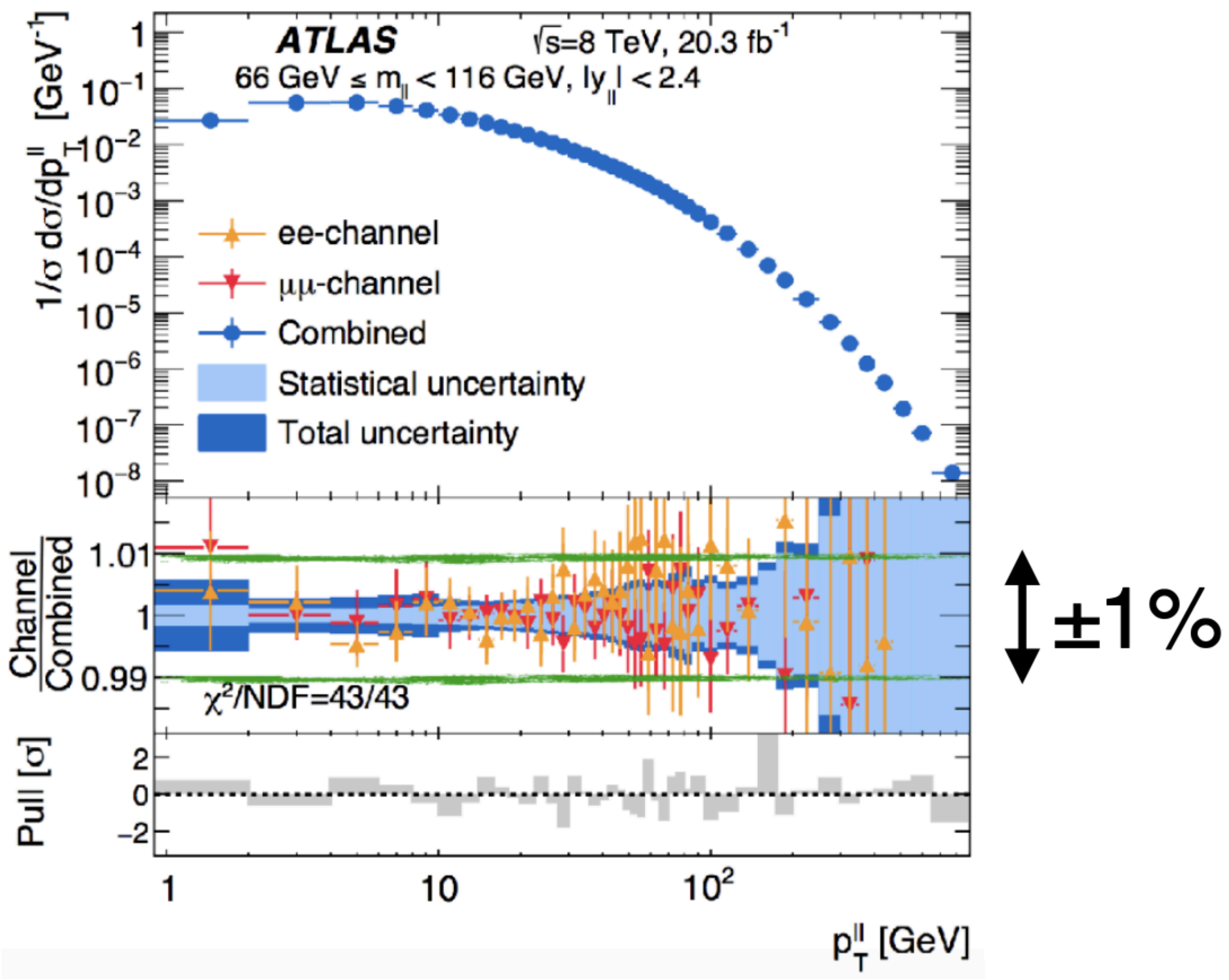
Stewart et. al.

# Fixed order @ colliders

## Impacts on the LHC physics: V+1j

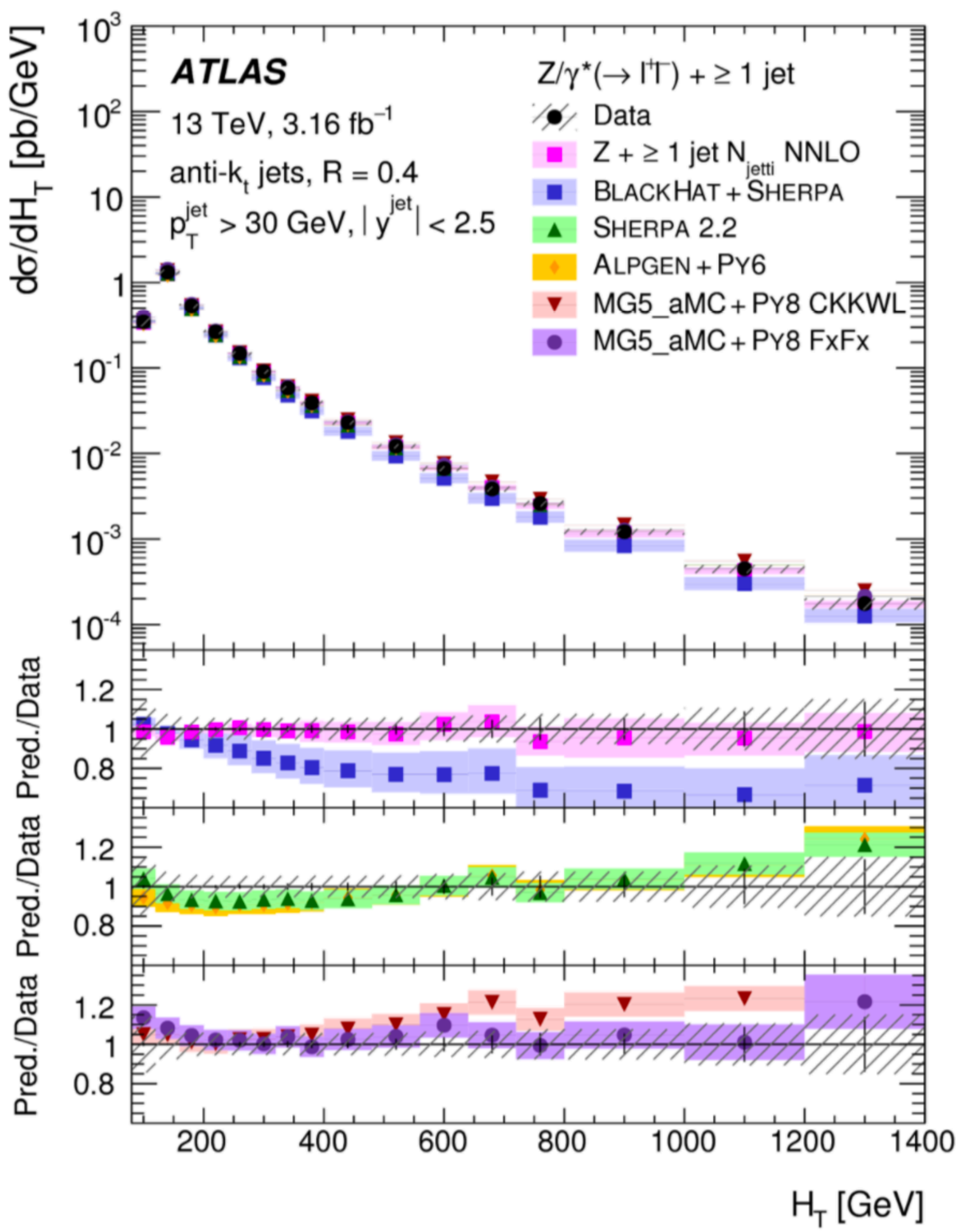
- Benchmark process at the LHC
- Clean signature, exp. uncertainty < 1%
- Irreducible background for NP searches
- Large pT Sensitive to PDFs, small pT imbalance can probe the medium effects



# Fixed order @ colliders

## Impacts on the LHC physics: V+1j



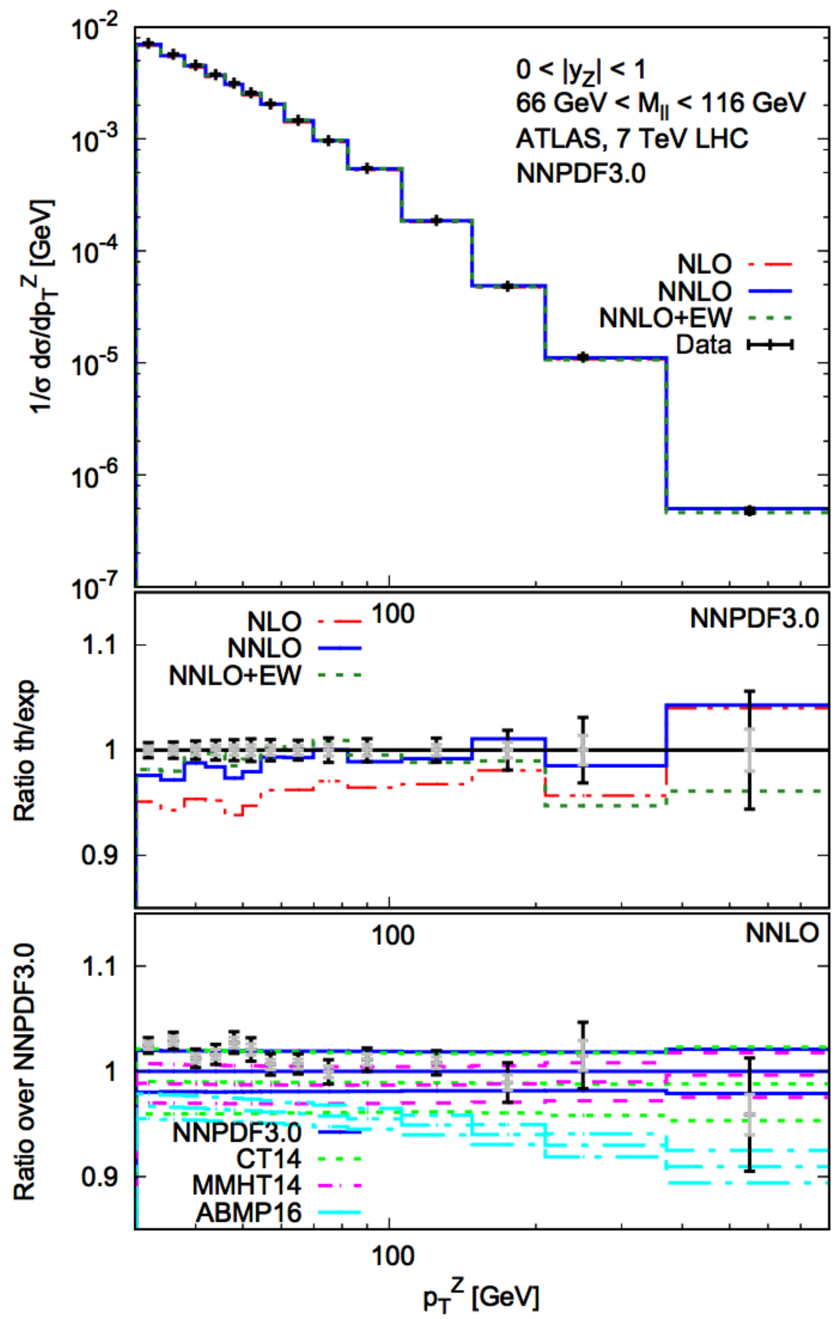

NLO underestimates the data by 50% !

NNLO recovers agreement with data by add on missing high orders.

Boughezal, Focke, **XL**, Petriello + MCFM, 2016

# Fixed order @ colliders

## Impacts on the LHC physics: V+1j



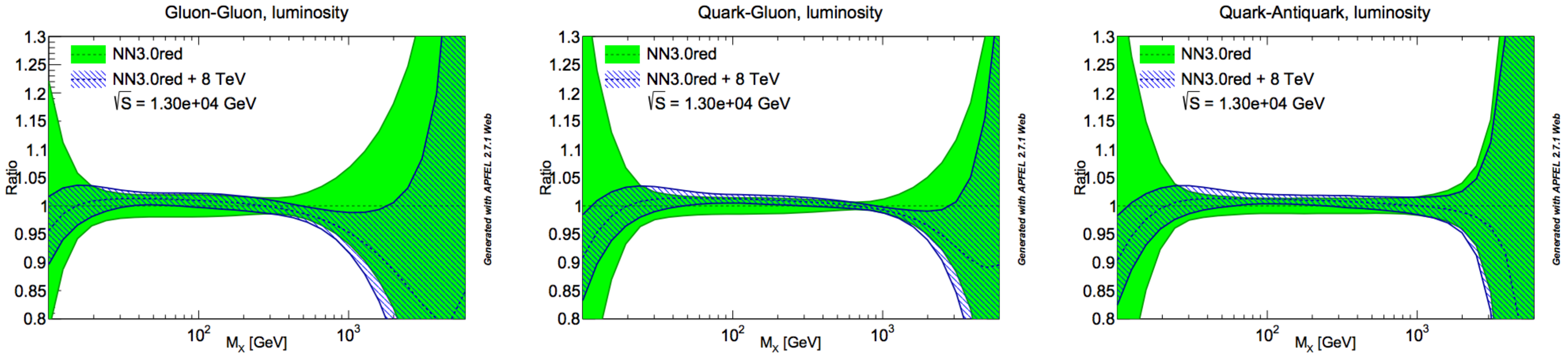

Z pT distribution

- Clean and very small exp. uncertainty $\sim 1\%$
- therefore standard candle at the LHC

NNLO agrees much better than NLO.

# Fixed order @ colliders

## Impacts on the LHC physics: V+1j

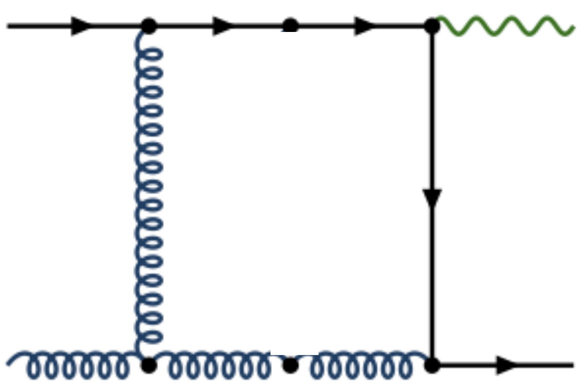



| | Before $p_T^Z$ data | After $p_T^Z$ data |
|---|---|---|
| $\sigma_{gg\to H}$ [pb] | $48.22 \pm 0.89$ (1.8%) | $48.61 \pm 0.61$ (1.3%) |
| $\sigma_{\rm VBF}$ [pb] | $3.92 \pm 0.06$ (1.5%) | $3.96 \pm 0.04$ (1.0%) |

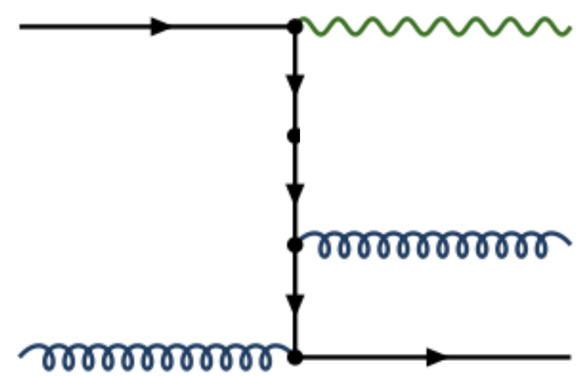
Error reduced by 30% when NNLO Z pT included

# EFT in resummation @ colliders

# Resummation @ colliders



$$\propto -\frac{1}{\epsilon^2} - \frac{1}{\epsilon}$$



$$\propto \frac{1}{\epsilon^2} + \frac{1}{\epsilon} + L^2 + L + \ldots$$

$$L = \log \frac{\text{exp. cuts}}{Q}$$

# Resummation @ colliders

Standard approaches to the predictions: FO + Res.

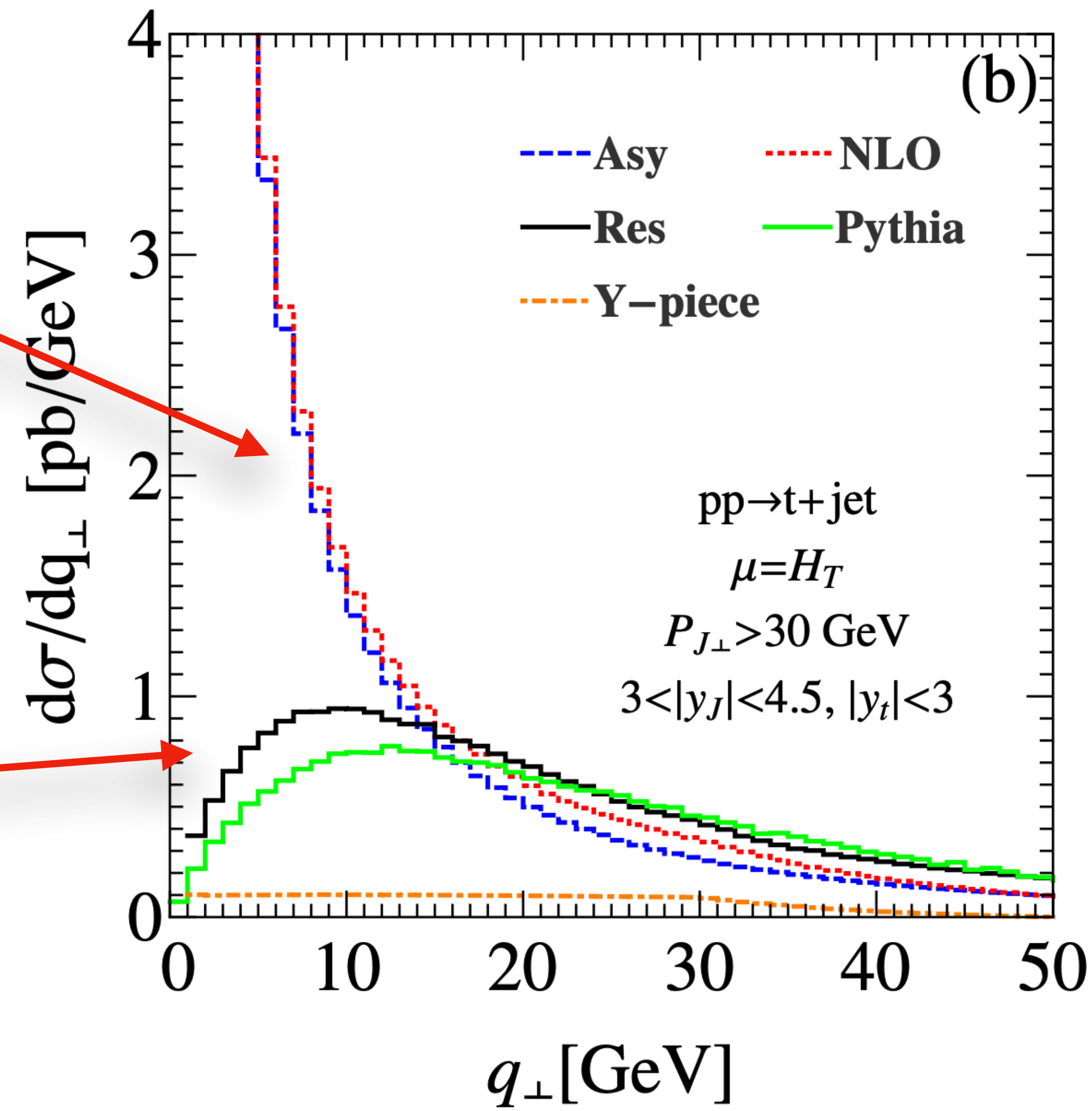
Fixed order

- Breaks down in the soft-collinear dominated regions

Resummation to rescue

- LL + NLL + NNLL + ⋯
- Parton shower (~ LL)
- Analytic ~ going beyond LL⋯

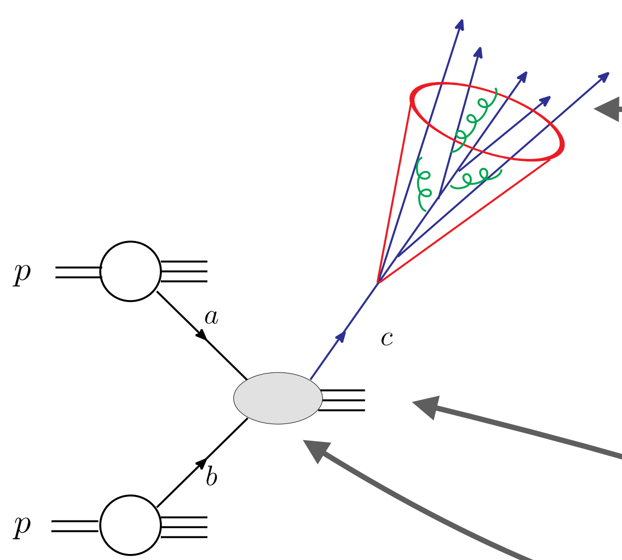
| | | | | | |
|---|---|---|---|---|---|
| LO | 1 | | | | |
| NLO | $\alpha_s L^2$ | $\alpha_s L$ | $\alpha_s$ | | |
| NNLO | $\alpha_s^2 L^4$ | $\alpha_s^2 L^3$ | $\alpha_s^2 L^2$ | $\alpha_s^2 L$ | $\alpha_s^2$ |
| | | | | | |
| N$^k$LO | $\alpha_s^k L^{2k}$ | $\alpha_s^k L^{2k-1}$ | $\alpha_s^k L^{2k-2}$ | $\alpha_s^k L^{2k-3}$ | $\alpha_s^k L^{2k-4}$ |
| | LL | NLL | | NNLL | |



# Resummation @ colliders

## Theoretical Options

- Parton Shower (Pythia, Herwig++, Sherpa, Geneva $\cdots$), mostly LL + tuning
- Conventional QCD approach, go beyond N$^2$LL? Complicated processes?
- EFT, based on (re)factorization theorem, supplemented with FO techniques




$$J = \mathcal{G} \otimes \mathcal{S}$$

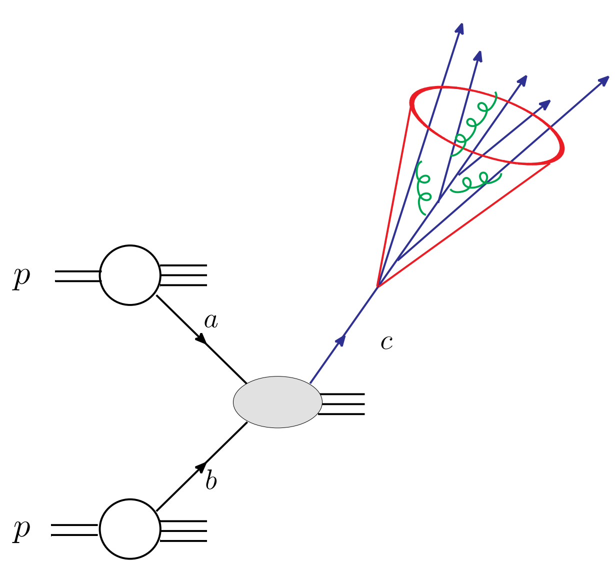
refactorization

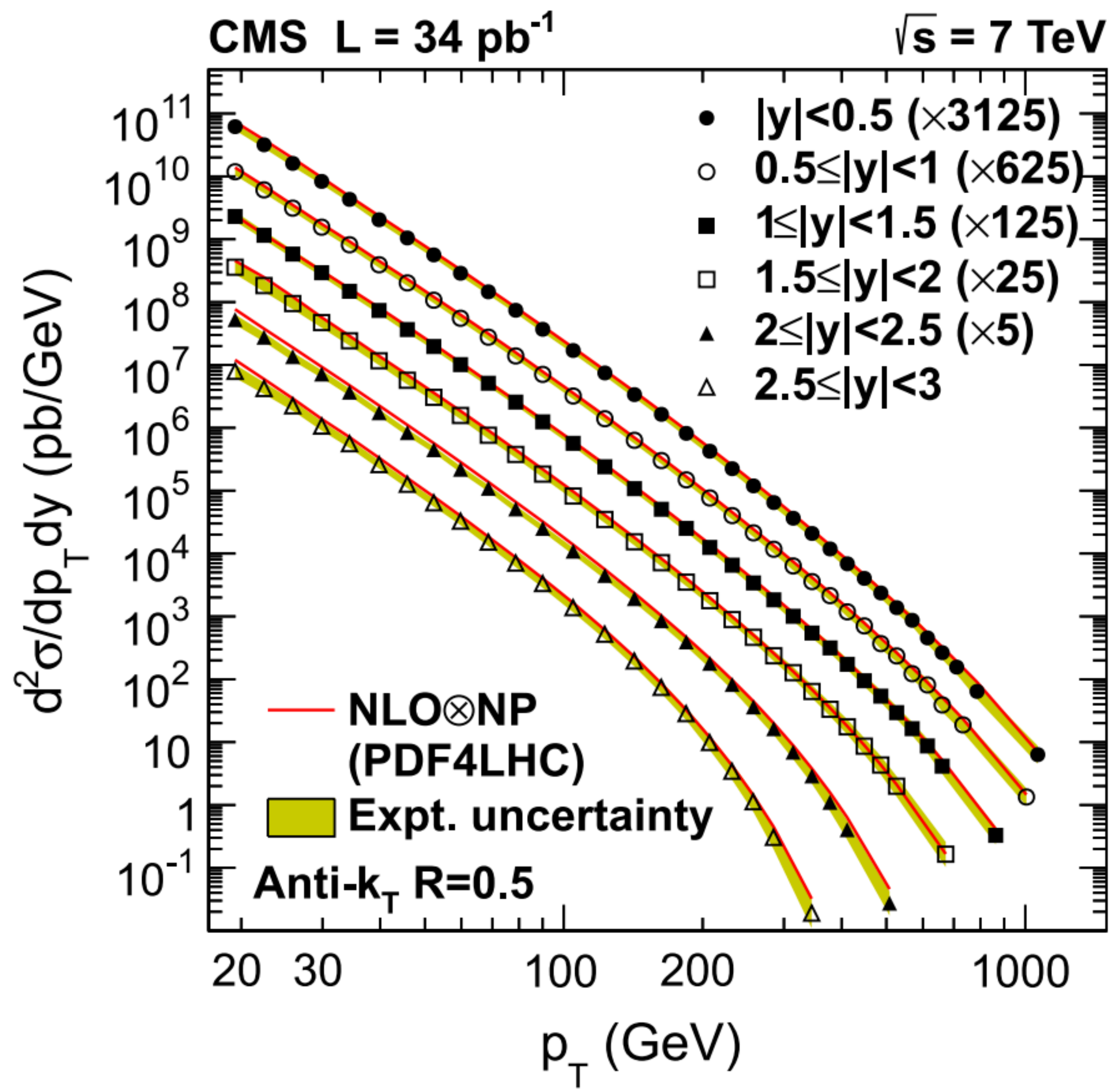
$$\mathrm{Tr}[H \cdot S_N] \otimes B_a \otimes B_b \otimes J_i + \ldots$$

All components can be calculated using modern loop techniques

# Inclusive jet production — where FO is not enough

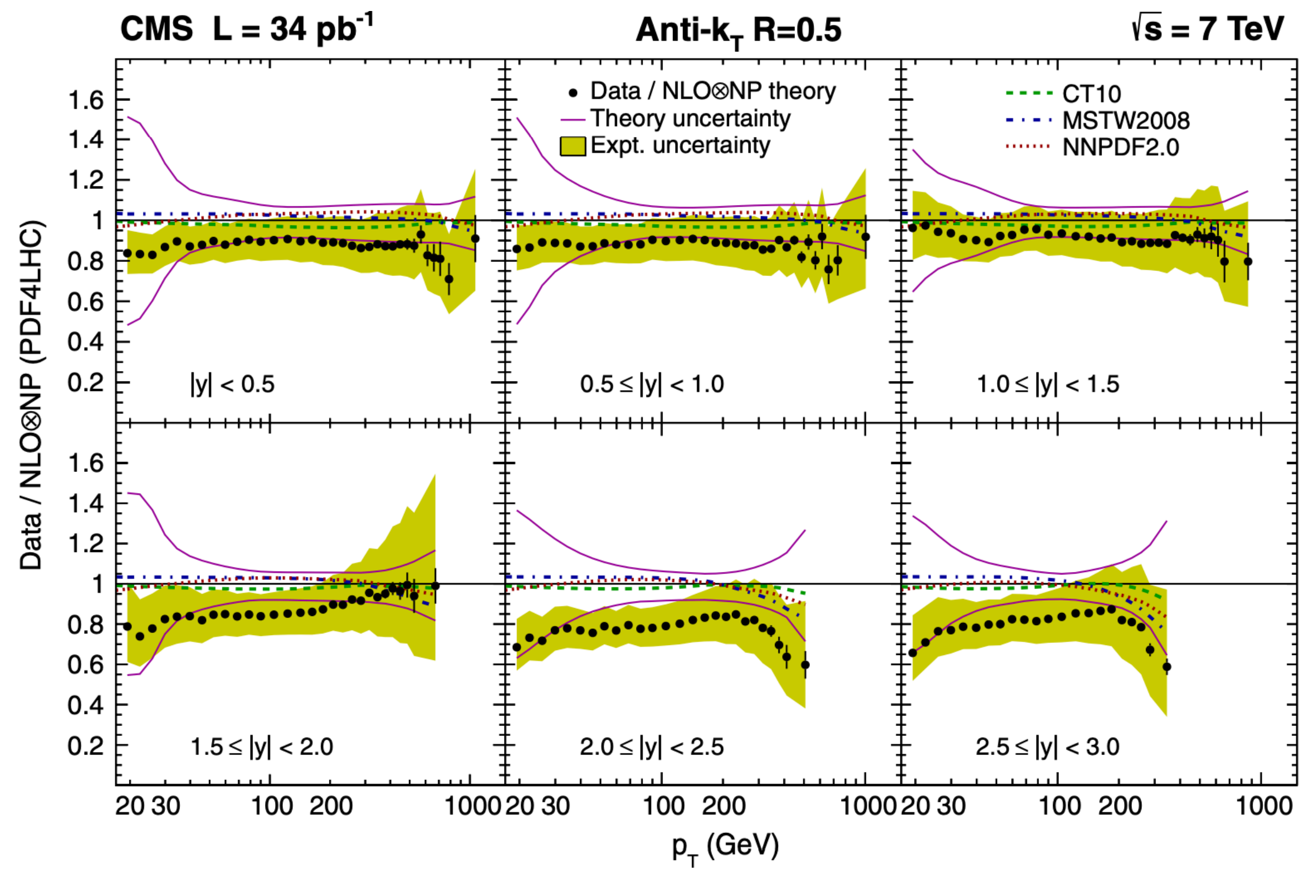
- Anther benchmark process at the LHC
- Related to new physics searches, PDF fitting ⋯



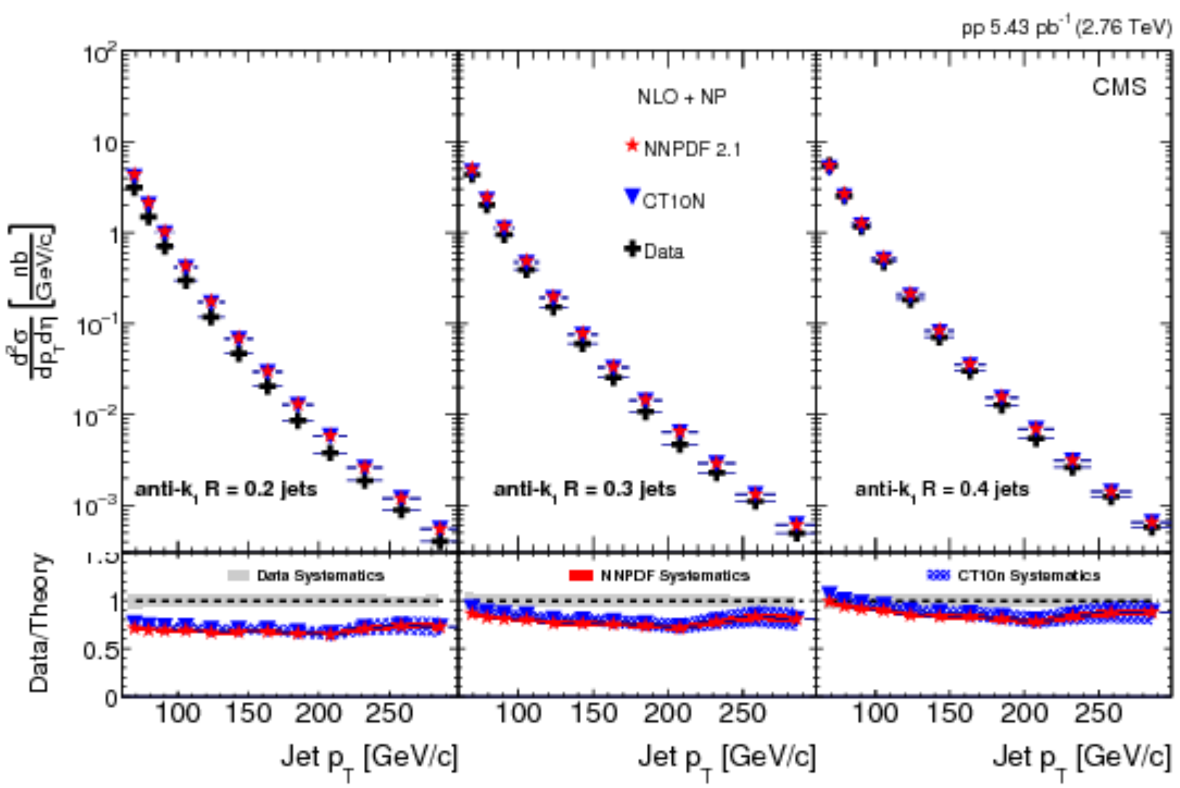




Overall good agreements with data, but ⋯

# Inclusive jet production — where FO is not enough




Long time systematic discrepancies between theory and the data

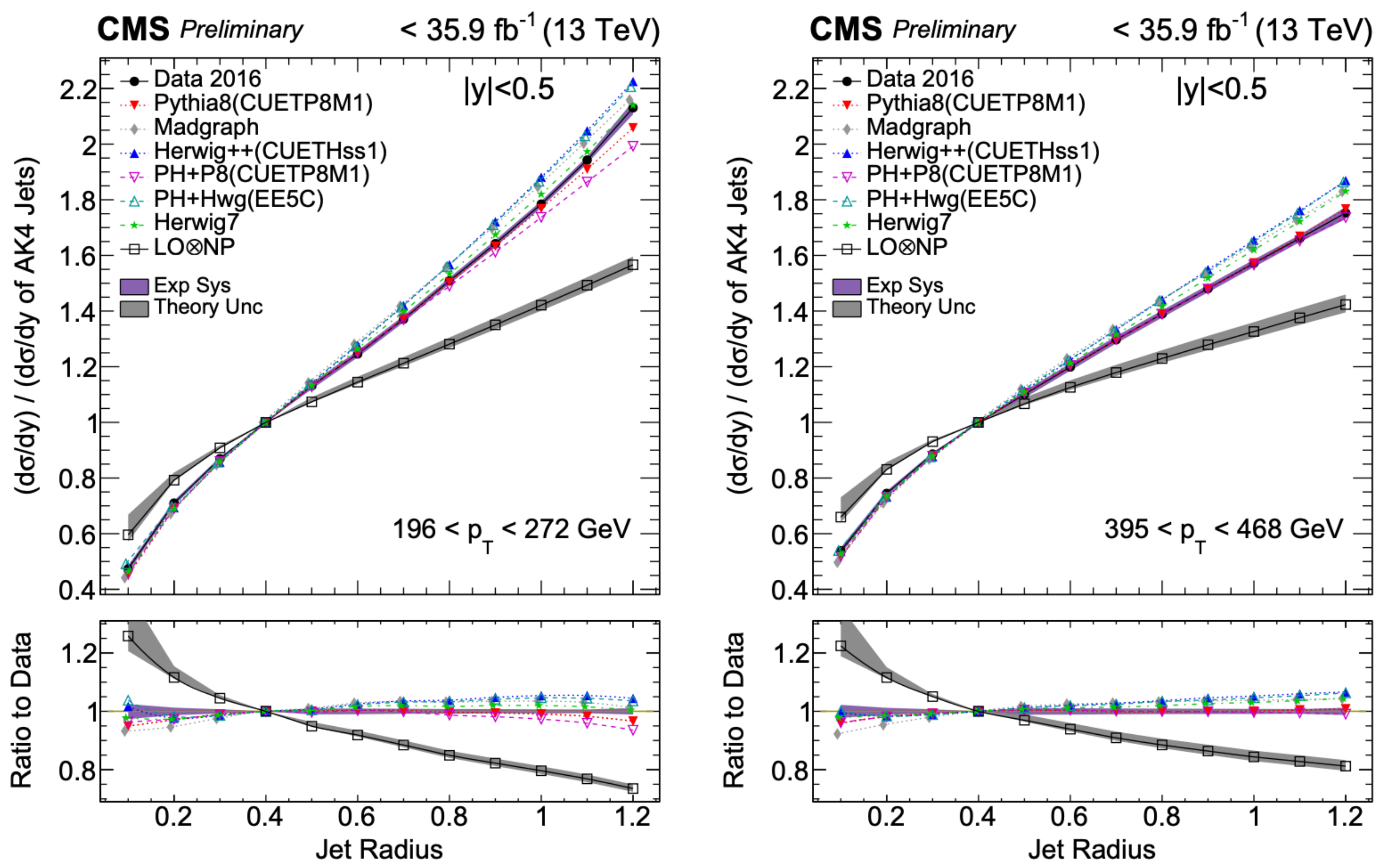



Happens for 7, 8, 13, ··· TeV

Strongly depends on the choice of R

# Inclusive jet production — where FO may not be enough

Long time systematic discrepancies between theory and the data



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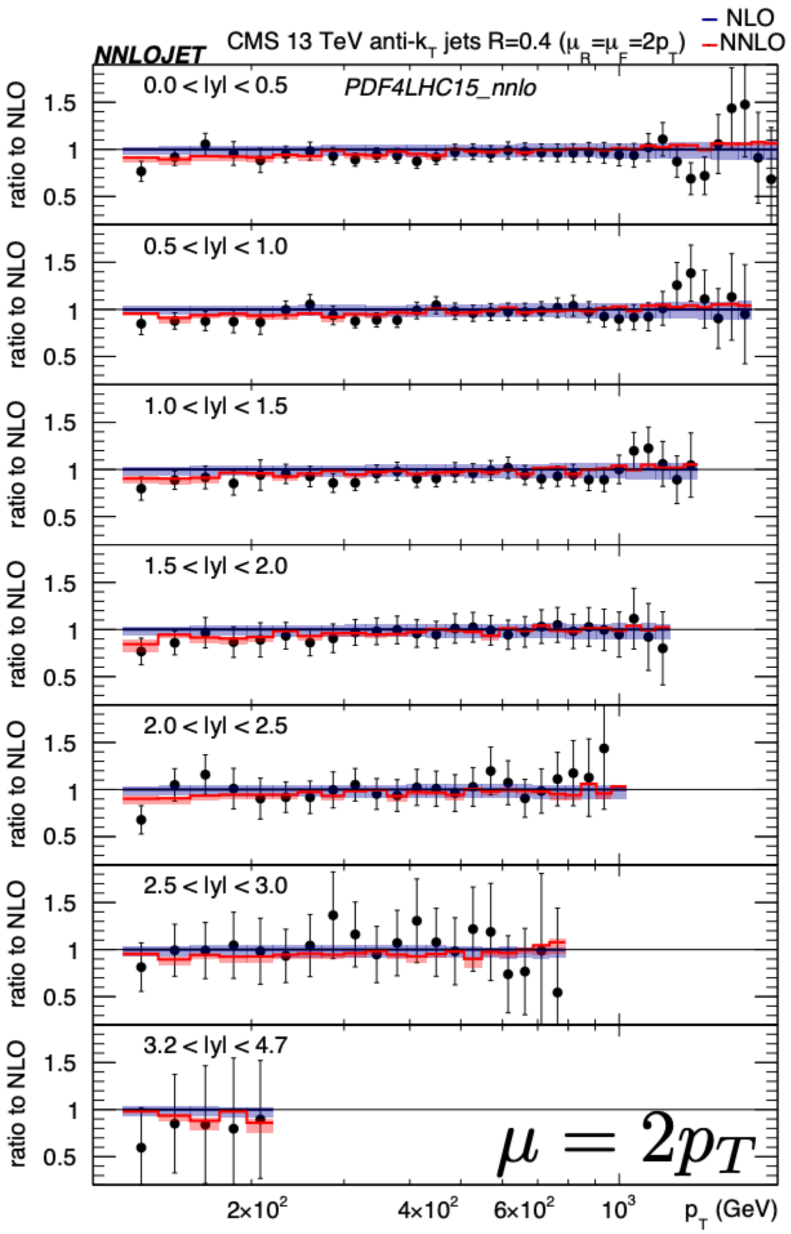
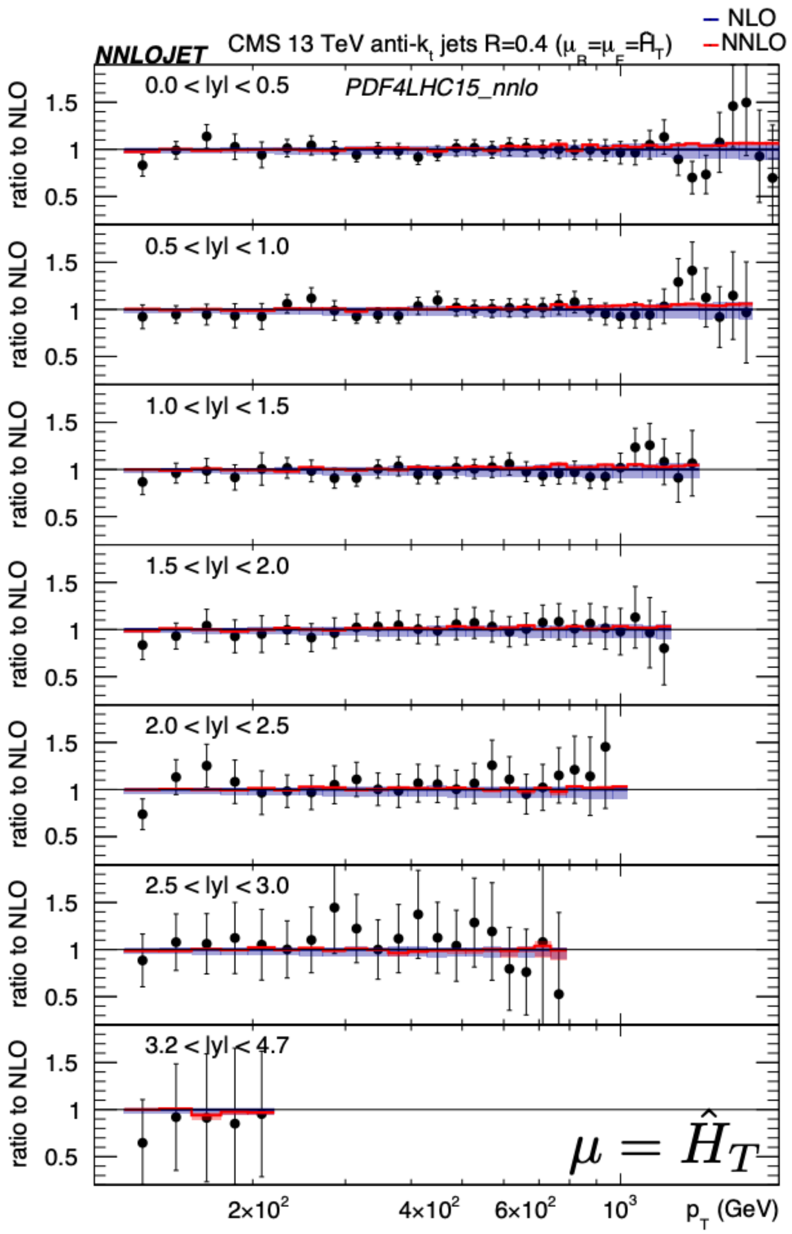
NNLO seems to help,
but Strongly depends on the scale choices!

"optimized" scale choice




João Pires, 2018

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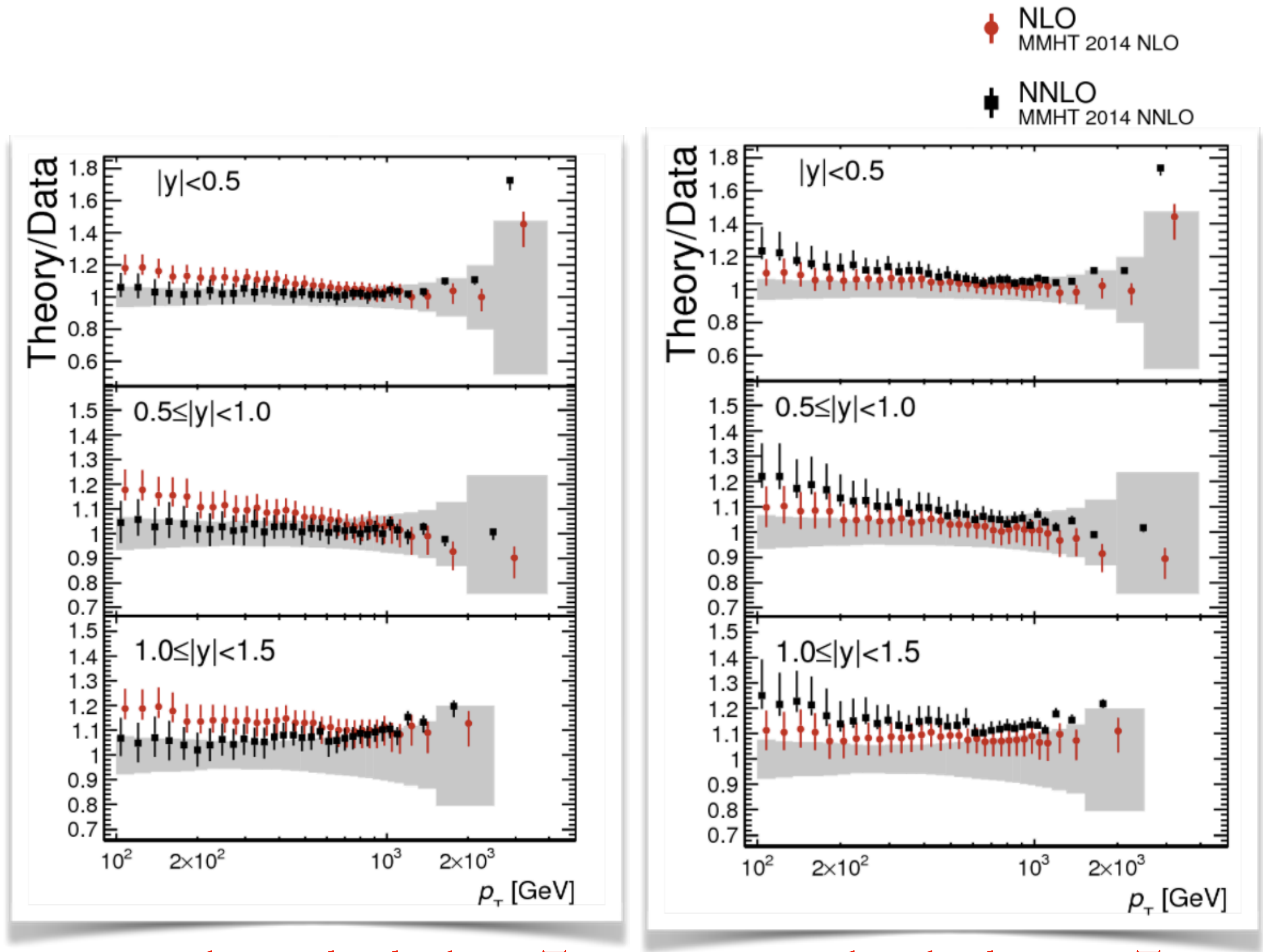


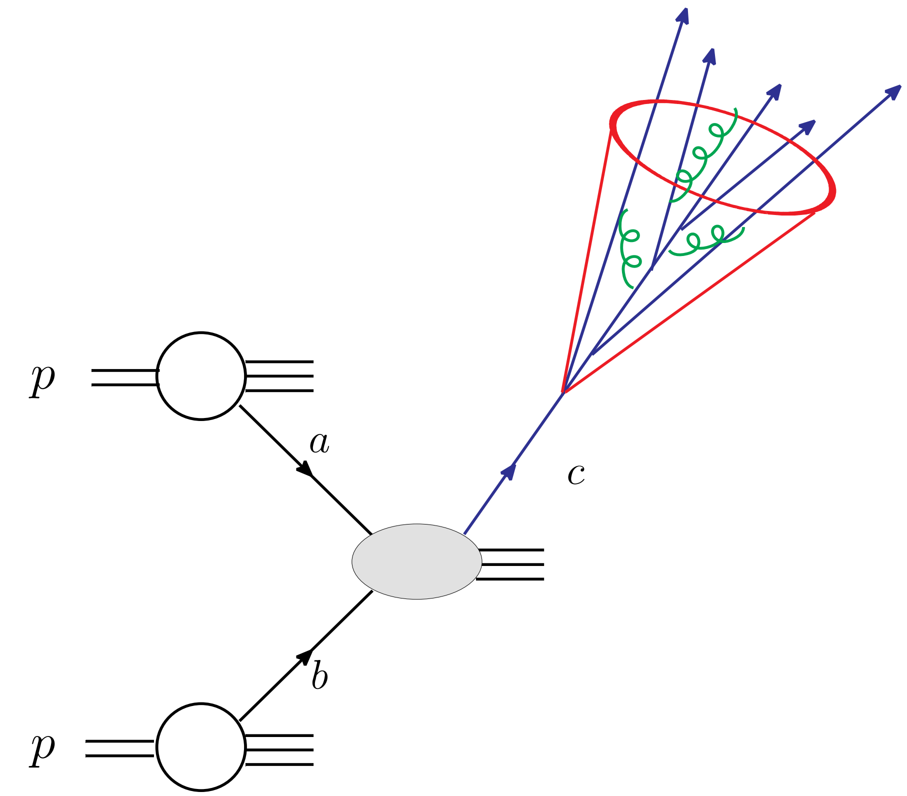

scale = individual jet pT

scale = leading jet pT

Currie, Glover, Pires, 2018

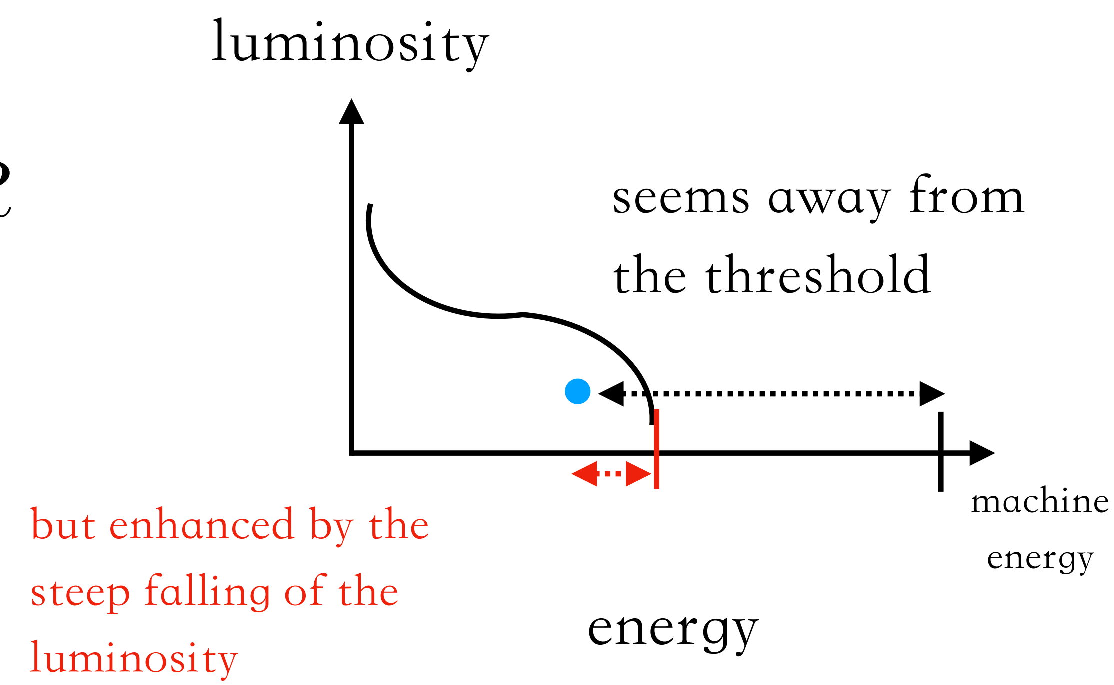
# Inclusive jet production — where FO is not enough

- Possible large corrections
  - small R
  - threshold




$$\sum_{m=0,k=1} \alpha_s^n \left[\frac{\ln^{2n-m-k} z}{z}\right]_+ \ln^m R$$

z measures the invariant mass outside the signal jet, characterize the distance to the threshold

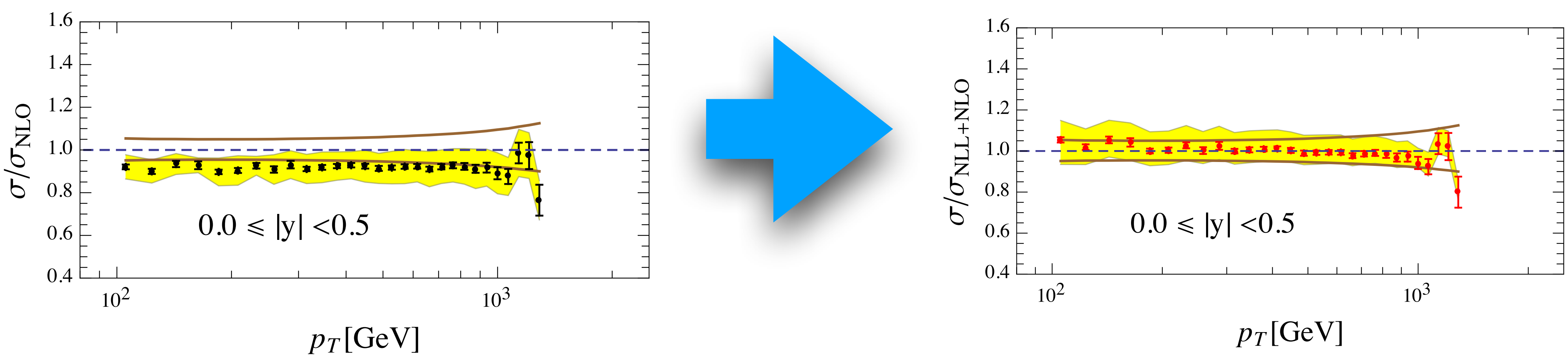


# Inclusive jet production — where FO is not enough

Resummation (small R + threshold) helps here

- Small R res. reduces the cross section
- Threshold enhances the cross section
- After resummation, the theory describes the data well

See also, Kang et.al., 2016, 2017




After resummation

**XL**, Moch, Ringer, 2018

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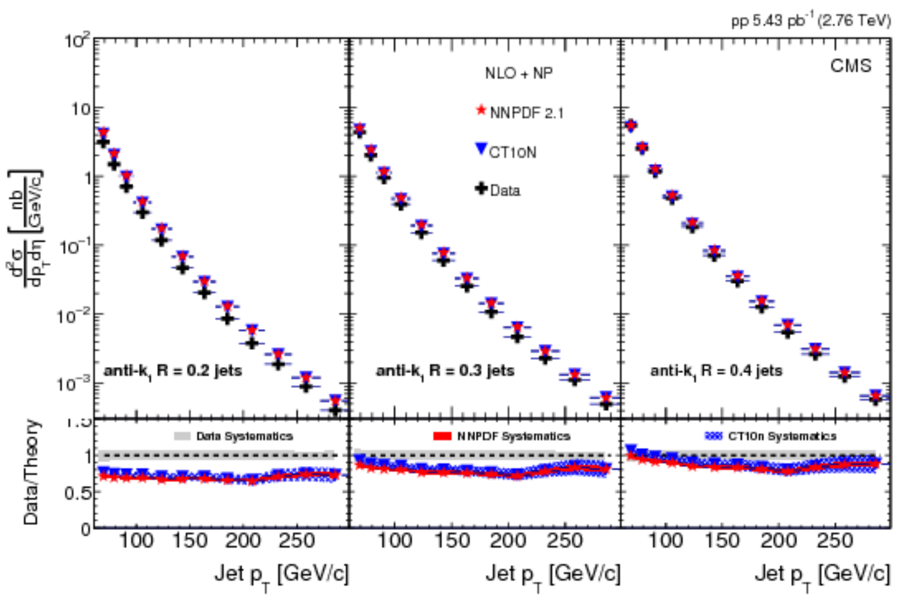


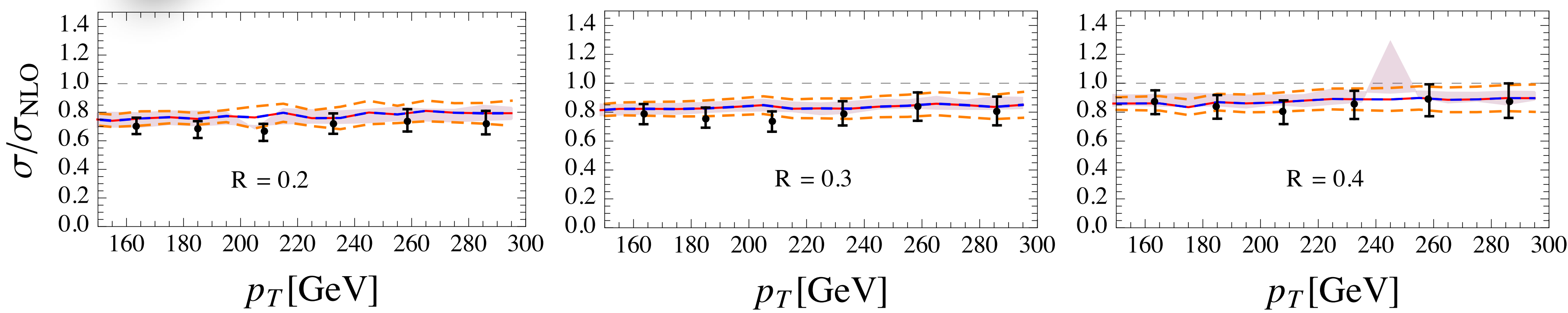


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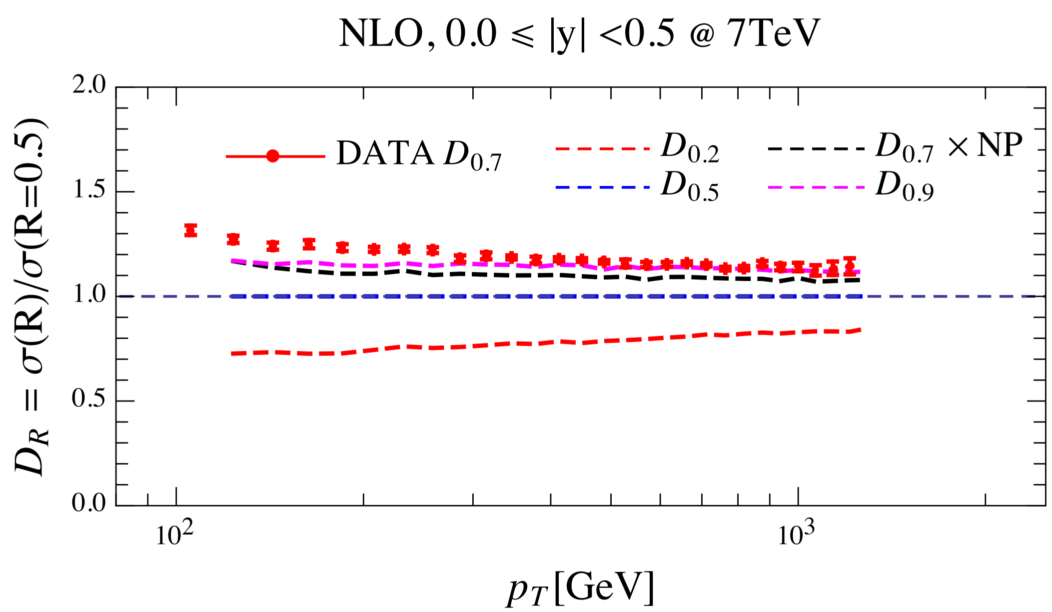


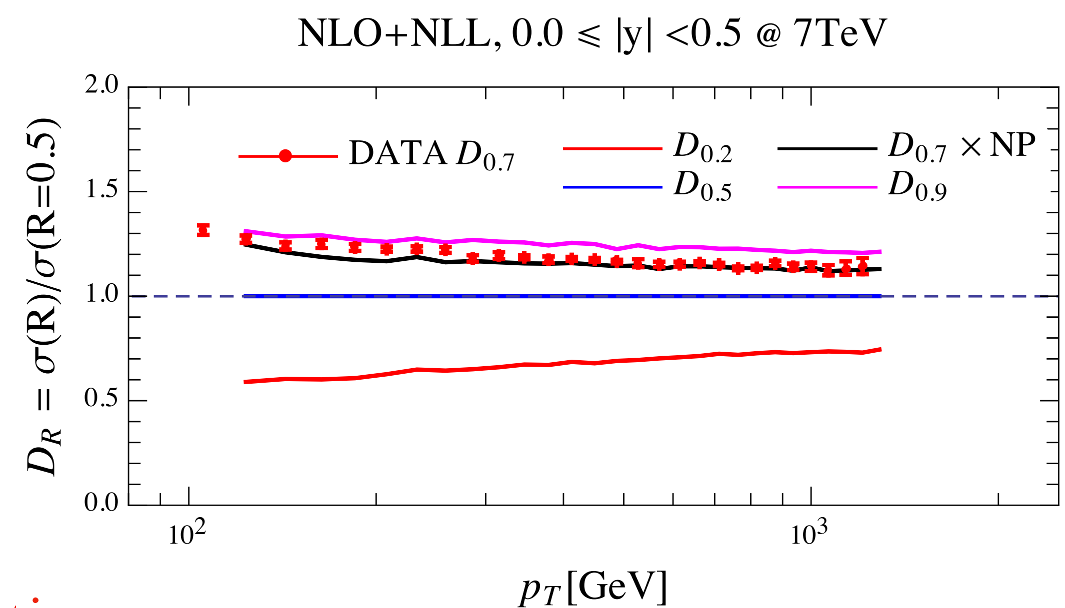


After resummation

Take ratios to reduce the impact of the PDFs

**XL**, Moch, Ringer, 2018

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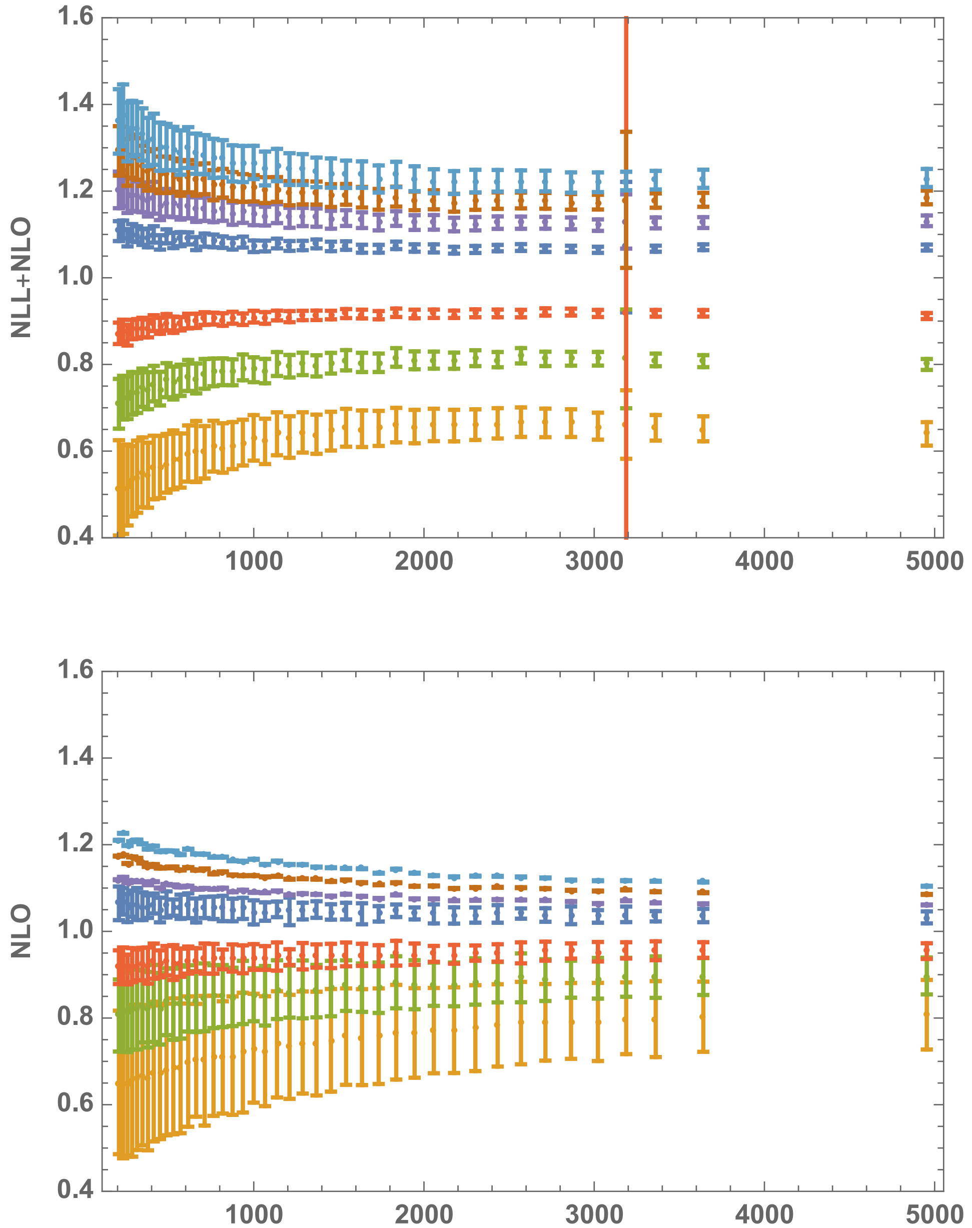


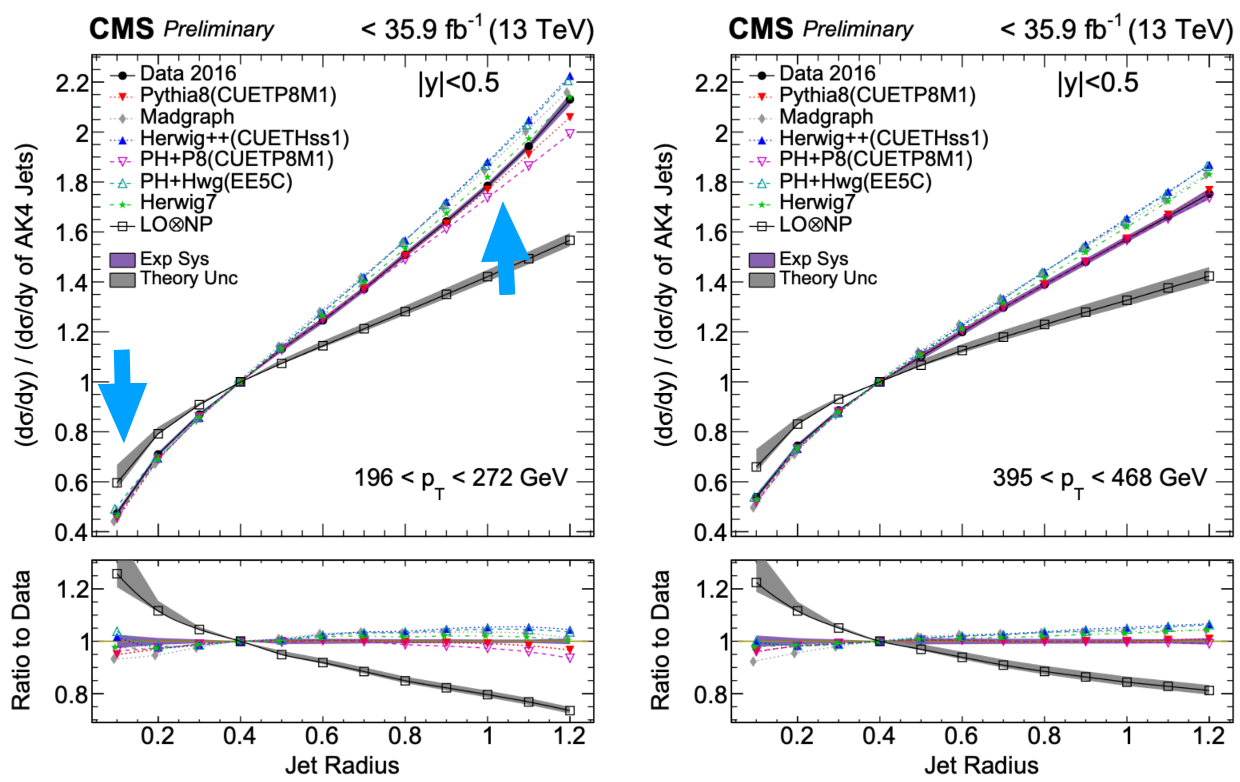

# Summaries

- A brief review the impacts of EFT on the collider precision calculations
- Quite useful in resummation and FO.
- Directions to explore:
  - Stability of the slicing schemes: power correction to NNLO and beyond, for general processes
  - …

Thanks!