Resummation and Phenomenology of Transverse Observables

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LHC, New Physics, and the pursuit of Precision

LHC as a **discovery machine**

- Higgs Boson ✓
- BSM particles ✗ (as of today)

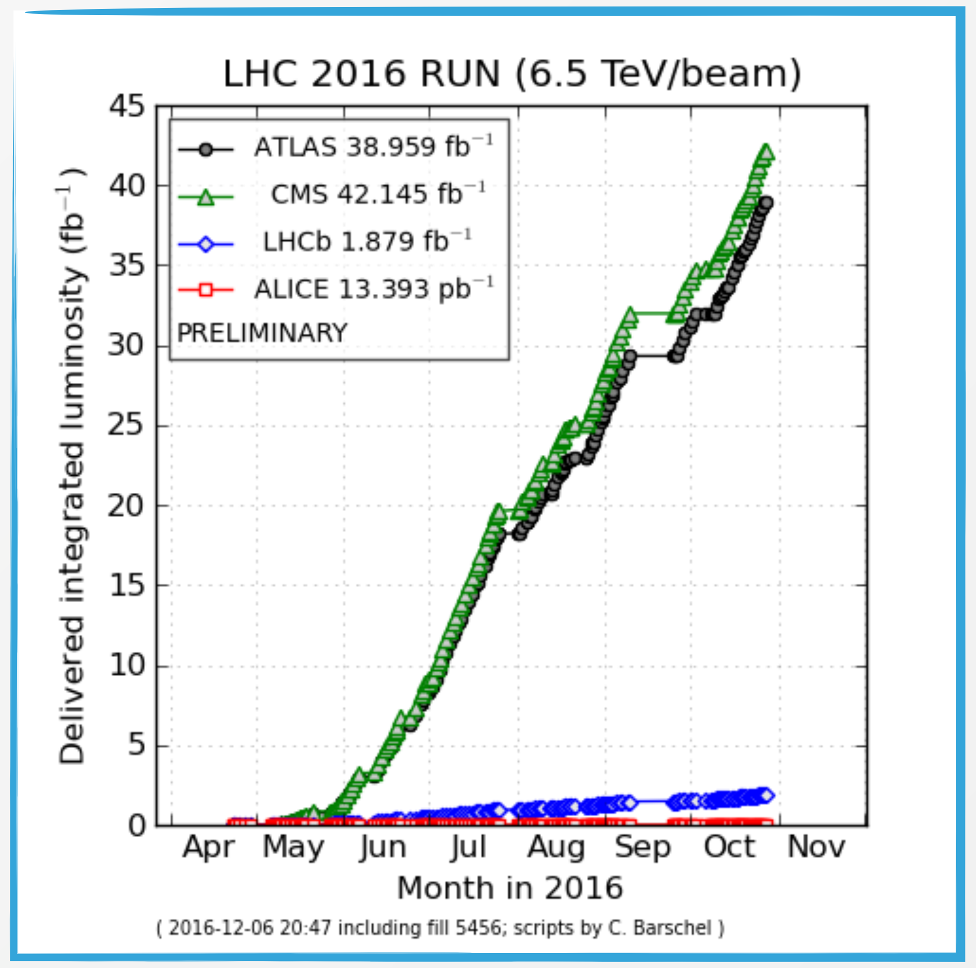
Focus in LHC run II

- Measurement of the Standard Model parameters with **very high precision**
- Signals of New Physics **beyond the Standard Model**

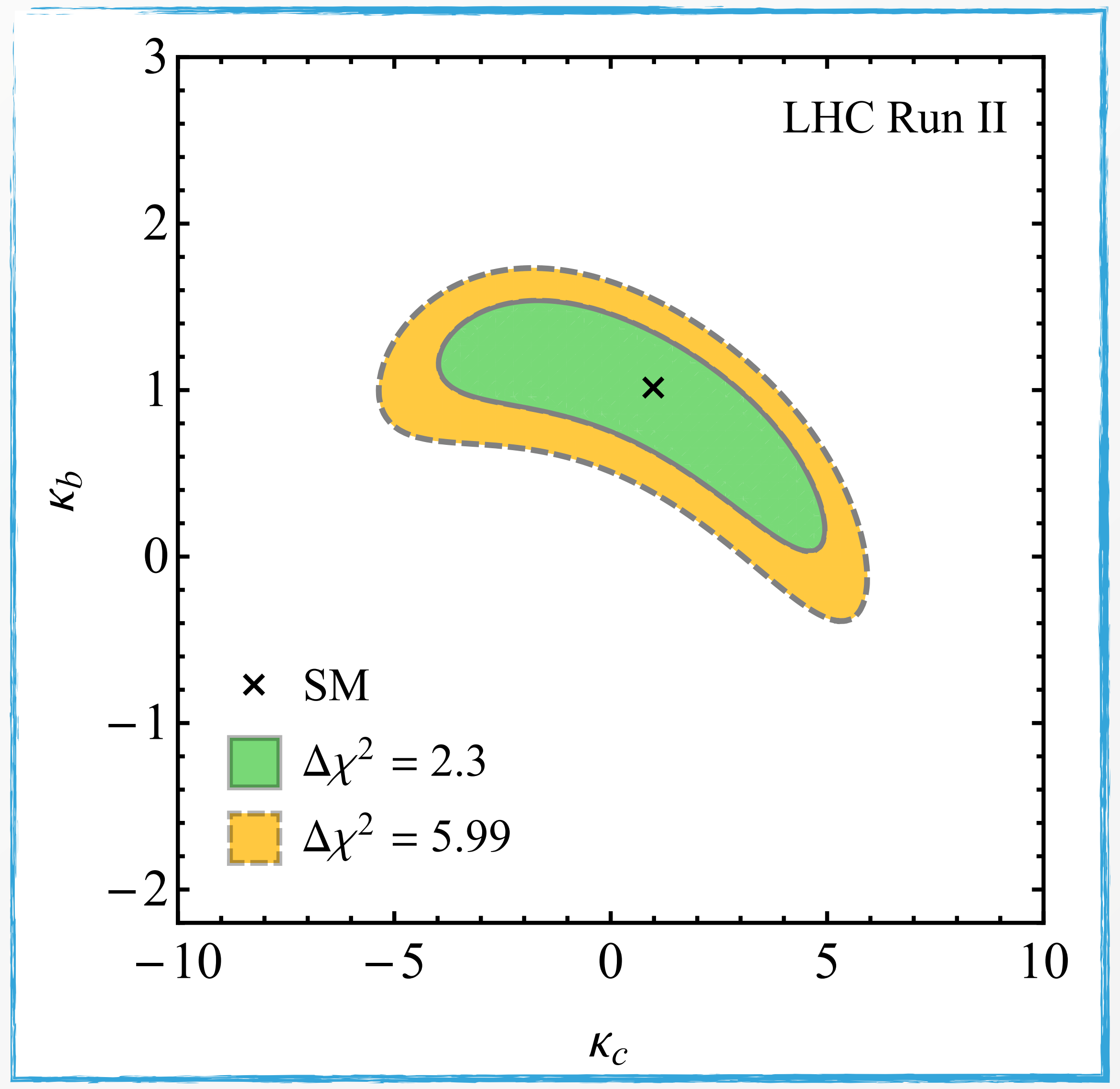
A theorist's Quest:

- New BSM scenarios to be tested
- New techniques to enhance signal/background ratio and isolate tiny deviations from SM predictions
- Development of **accurate** and **precise** theoretical predictions

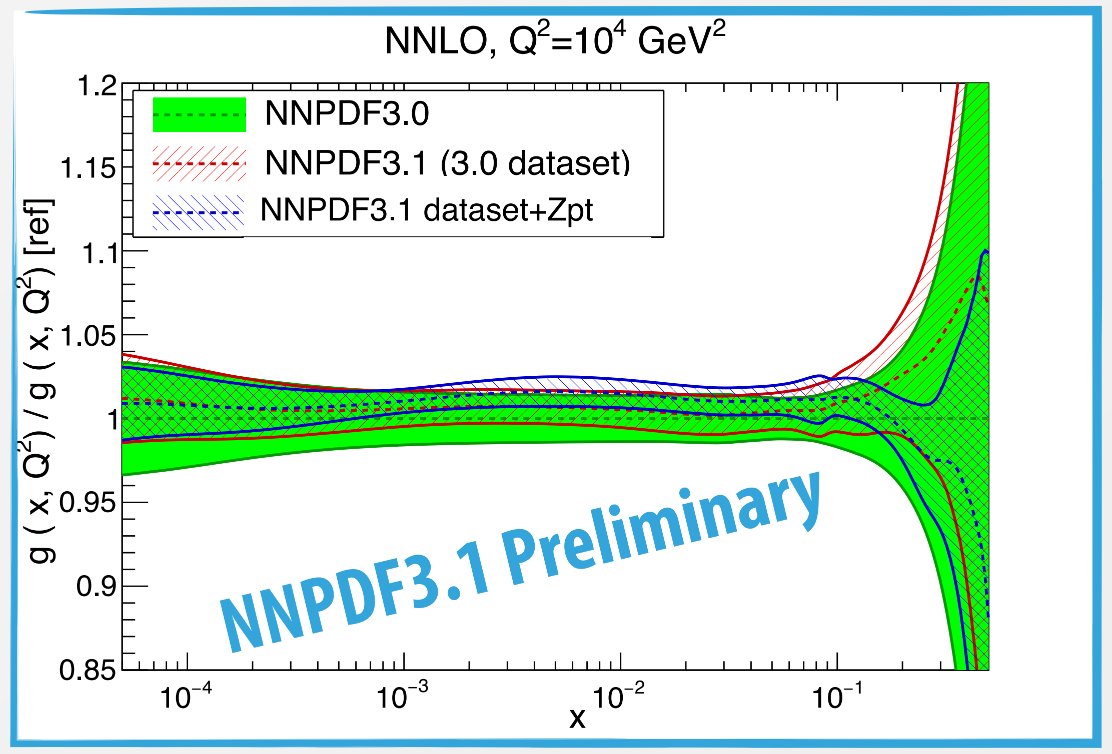
LHC, New Physics, and the pursuit of Precision



- ~40 inverse femtobarns collected in 2016
- Increase in statistics enables study of **differential distributions** in detail
- Physics results can be extracted only if **precise predictions** are available
  - Accurate determination of **Parton Distribution Functions**
  - Constraints on **New Physics** (e.g. light-quark Yukawa Couplings)
  - Probe on **non-perturbative effects** in distributions



arXiv:1606.09253



See talk by Marzani

Differential distributions in Colour Singlet Production

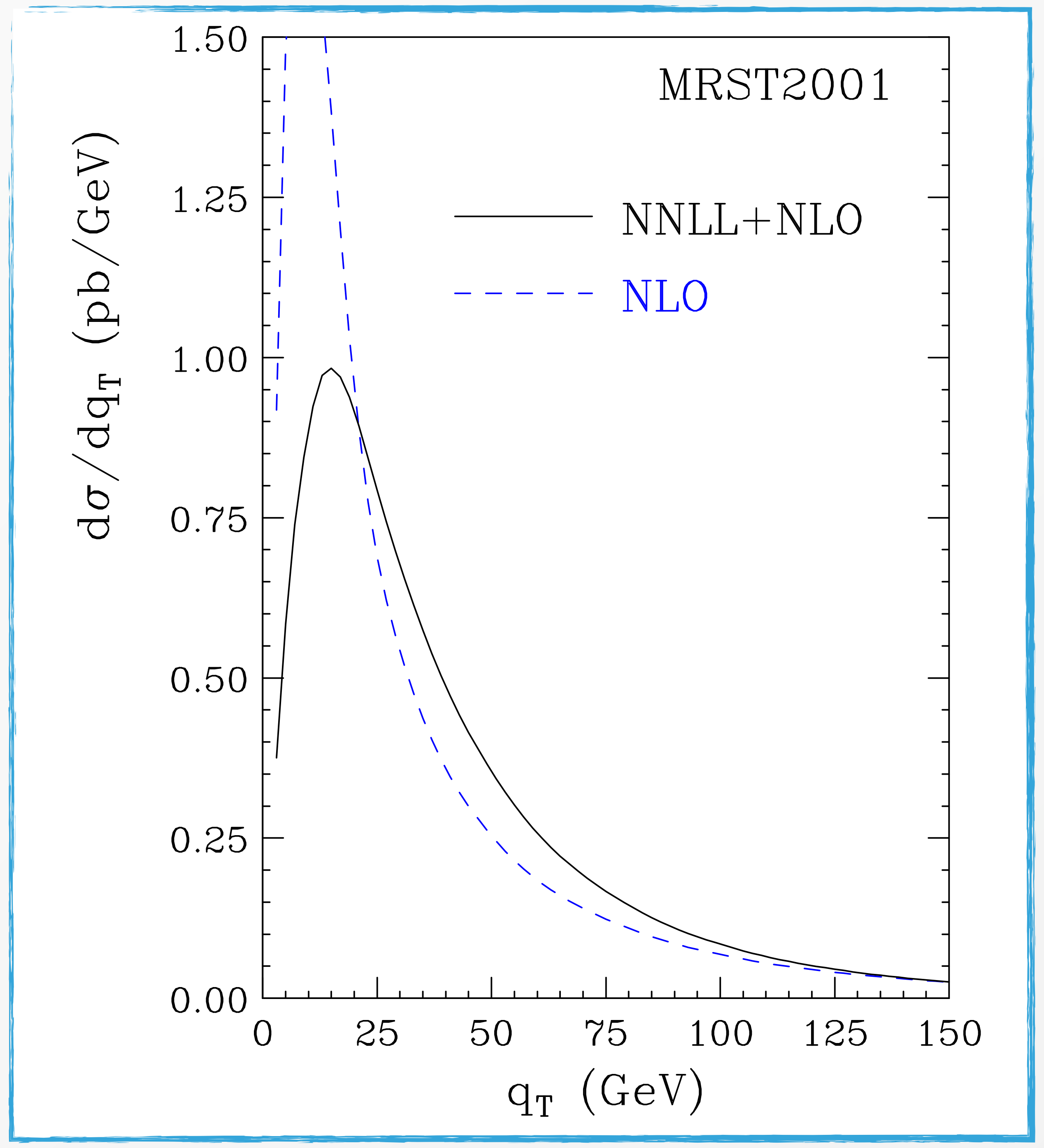
Fixed Order

Higgs Production

Inclusive cross-section available at N^{3}LO

NLO differential distributions known for several years

H+1 jet at NNLO available



[Bozzi *et al* '03]

Z Production

Inclusive Z-production available up to NNLO

Z-boson distribution at NNLO recently available

[Boughezal *et al* '15, Gehermann-De Ridder *et al* '16]

- Fixed-order perturbative description of differential distributions features **large logarithms** e.g.

$$\alpha_s^n \ln^m(m_H/p_t^H)/p_t^H \qquad m \leq 2n-1$$

- **All-order resummation** of these logarithms necessary to achieve accurate predictions

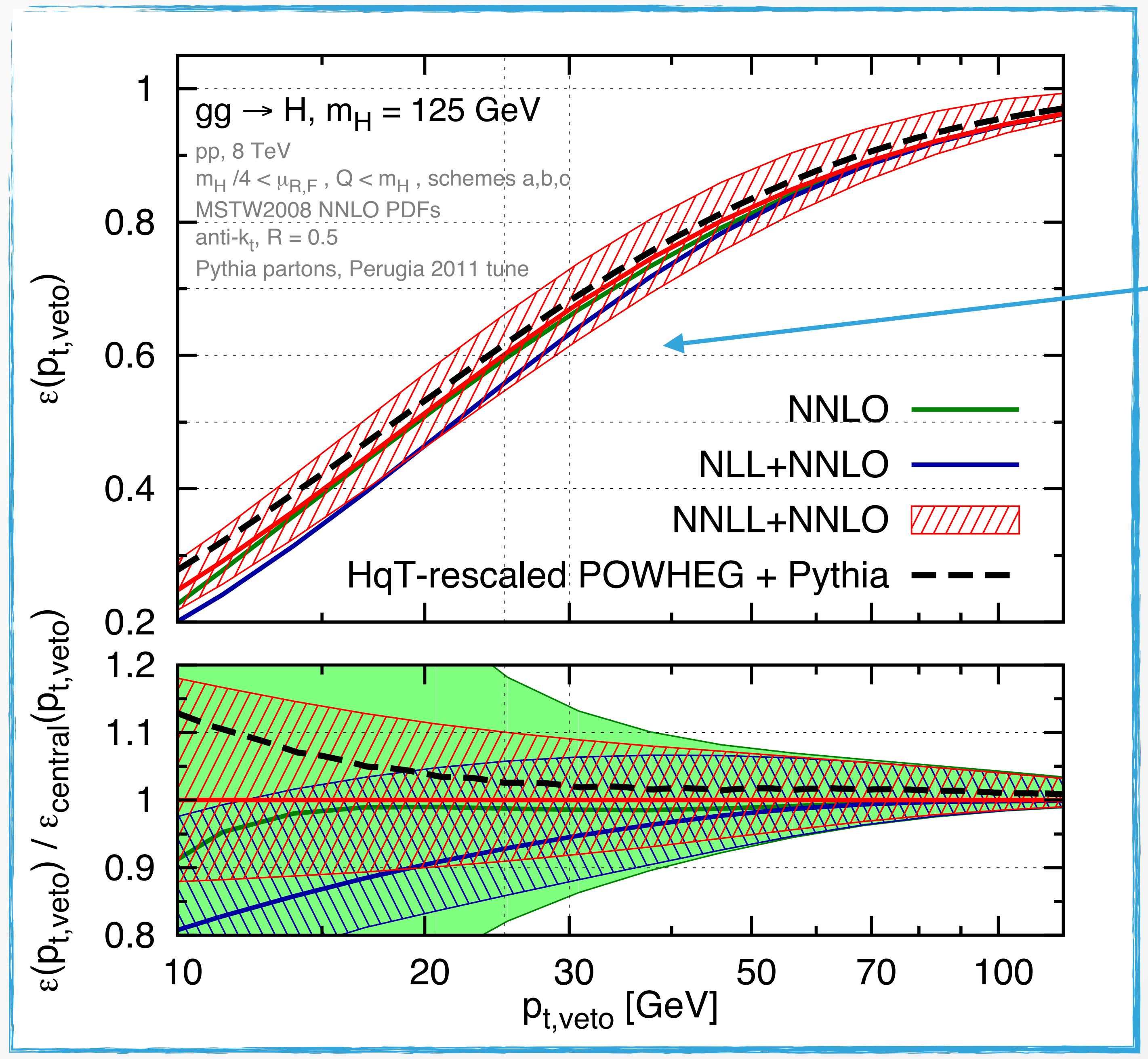
Transverse Observables in Colour Singlet Production

Consider observables which obey the following parameterization

$$v(k) = \left(\frac{k_t}{M}\right)^a f(\phi)$$

Transverse momentum of the emission wrt beam axis

Azimuthal angle



Banfi, Monni, Salam, Zanderighi '12

Many of this observables can be resummed in direct space in the (observable-independent) **ARES framework** (e.g. p_T^J, E_T)

However, other observables (e.g. colour singlet p_T, ϕ^*) have **azimuthal cancellations**

➡ Necessary to extend the formalism

Once extended, the method will be observable-independent for **all global rIRC observables**

No need for factorization theorems

scaling with respect to the transverse momentum of a soft and/or collinear emission is the same everywhere in phase-space

a) in the presence of multiple soft and/or collinear emissions, observable has the same scaling properties as with just one of them;

b) for sufficiently small values of the observable, emissions below εv do not significantly contribute to the observable

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Resummation in Parameter Space

- Standard resummation for p_T, ϕ^* rely on a formulation in **impact-parameter-space**

$$\frac{d\sigma}{dp_T^2} = \sigma_0 \int dx_1 dx_2 \int_0^\infty db \frac{b}{2} J_0(bp_T) S_c(b,Q) \int dz_1 dz_2 \delta\left(1 - z_1 z_2 \frac{x_1 x_2 s}{Q^2}\right) [HCC] f(x_1, 2\frac{e^{-\gamma_E}}{b}) f(x_2, 2\frac{e^{-\gamma_E}}{b})$$

- Observables **naturally factorize** in parameter space (**exponentiation**)
- Resummation performed in parameter space up to NNLL

[Bozzi, Catani, de Florian, Grazzini '03-'05; Becher, Neubert '10]
[Banfi, Dasgupta, Marzani, Tomlinson, '12]

- **Contour deformation** must be performed with care to avoid Landau pole
- **Stability** of the integral at large and small values of *b*
- **Speed** limited by the need to compute an inverse transformation
- Approach relies on factorization of the observables

Resummation in Direct Space

Unable to find closed analytic expressions which is both

- Free of logarithmically subleading corrections
- Free of singularities at finite p_T values

[Frixione, Nason, Ridolfi '98]

Consider ensemble of independent emissions $k_1, k_2 \ldots k_n$

$$q_{n+1} = \sum_{j=1}^{n+1} k_{t,j}$$

$$\Sigma(p_T) = \int_0^{p_T} dp'_T \frac{d\sigma(p'_T)}{dp'_T}$$

$$= \sigma_0 \int_0^{\infty} \langle dk_1 \rangle R'(k_{t,1}) e^{-R(\epsilon k_{t,1})} \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=2}^{n+1} \int_{\epsilon k_{t,1}}^{k_{t,1}} \langle dk_i \rangle R'(k_{t,i}) \Theta(p_t - |q_{n+1}|)$$

PDF scale dependence neglected here

Resummation obtained expanding $k_{t,i}$ around p_T and neglecting subleading effects. At NLL accuracy

$$\Sigma(p_T) = \sigma_0 e^{-R(p_T)} e^{-\gamma_E R'(p_T)} \frac{\Gamma(1 - R'(p_T)/2)}{\Gamma(1 + R(p_T)/2)} \sim \frac{1}{2 - R'(p_T)}$$

Geometric singularity at finite momentum values

However - expansion of the cross section in power of the coupling **contains the correct logarithms**: non-logarithmic effect missing

Resummation in Direct Space

Physical origin: two different mechanisms give a contribution in the small p_T region

- configurations where the transverse momenta of the radiated partons is small (Sudakov limit) Exponential suppression

- configurations where pT tends to zero because of cancellations of non-zero transverse momenta of the emissions Power-law suppression $\mathcal{O}(p_T^2)$

Non-logarithmic effects should be included when the second mechanism becomes dominant (R'~2)

Set the scale of real radiation to the **first emission** $k_{t,1}$ instead of p_T; **resummation of logarithms of** $m/k_{t,1}$

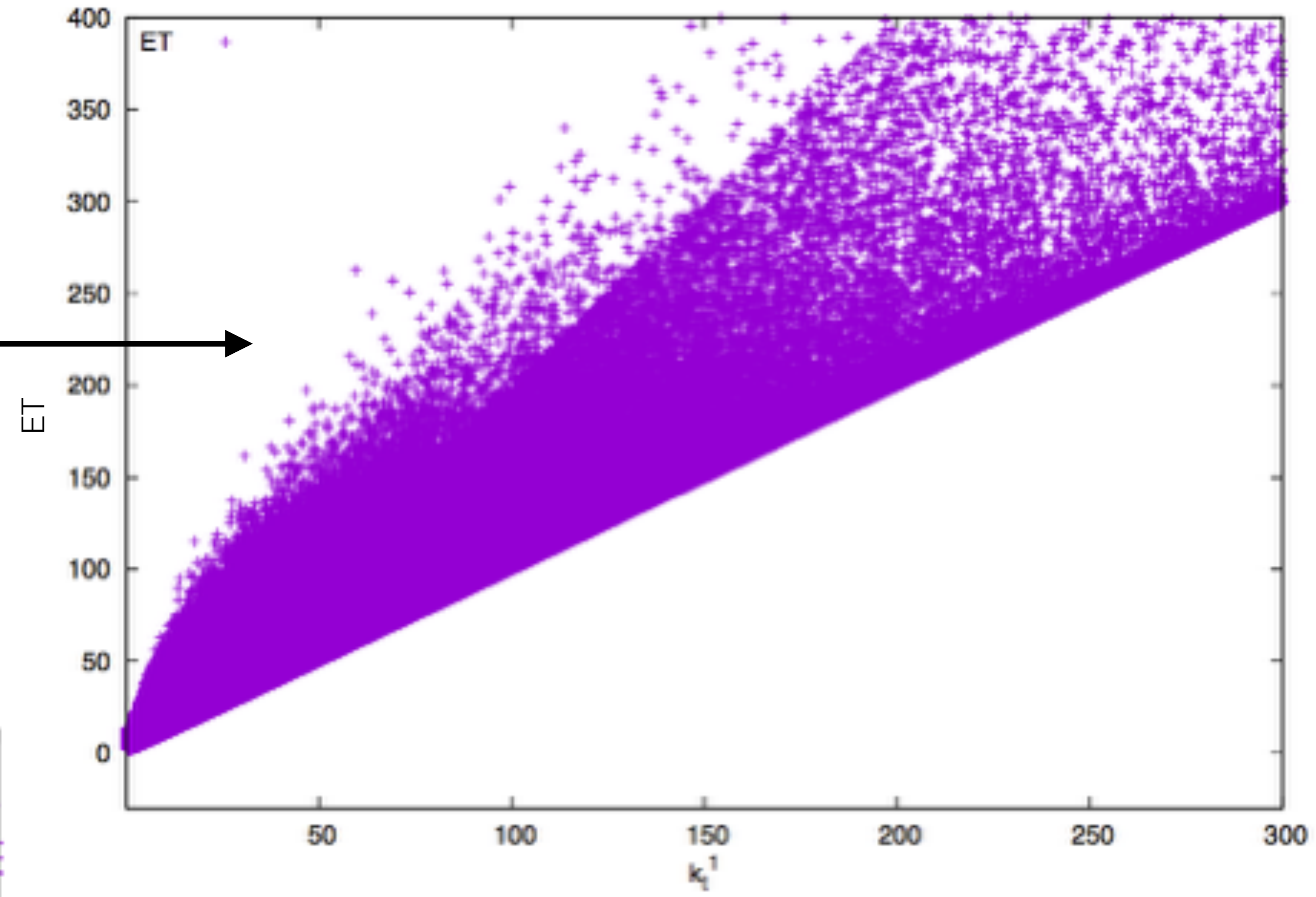
[Monni, Re, Torrielli '16]

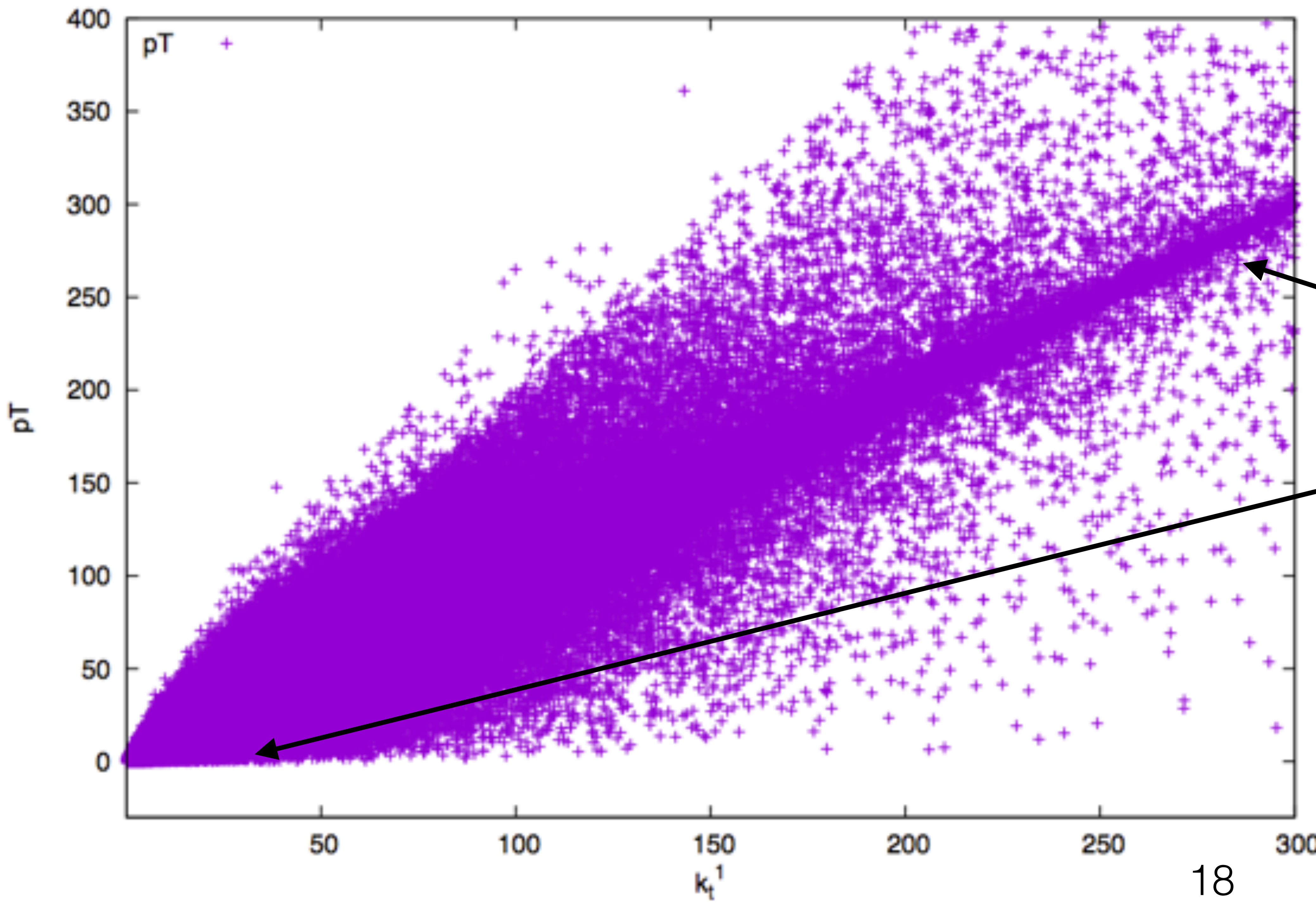
- In the Sudakov limit $k_{t,1} \leq p_T$ inclusion of subleading logarithmic terms
- When cancellations kick in $k_{t,1} \gg p_T$ real radiation described correctly

Thanks to P. Monni

pT vs. ET: dependence on the first emission

Transverse Energy: single (Sudakov) suppression mechanism for all values of kt1





Transverse Momentum:

$R'(k_{t1}) \ll 1$: few emissions $\rightarrow p_T \sim k_{t1}$

$R'(k_{t1}) \geq 2$: many emissions $\rightarrow$ azimuthal cancel.

At some value of $R'(k_{t1})$ a transition takes place and the more likely way to get pT->0 becomes the second mechanism

Resummation in Direct Space

Approach extends to a **wider class of observables** which features the same cancellations

$$\Sigma(v) = \int \frac{dv_1}{v_1}\frac{d\phi_1}{2\pi}[-e^{-R(v_1)}\partial_L \mathcal{L}(\mu_F e^{-L}) + e^{-R(v_1)}\mathcal{L}(\mu_F e^{-L})R'(v_1,\phi_1)]\left(\epsilon^{\hat{R}'(v_1)}\sum_{i=0}^{\infty}\frac{1}{n}\prod_{i=2}^{n+1}\int_{\epsilon}^{1}\frac{d\zeta_i}{\zeta_i}\frac{d\phi_i}{2\pi}\hat{R}'(v_1)\right)\Theta(v - v(\{k_i\}))$$

NLL accuracy

Shower ordered in the observable

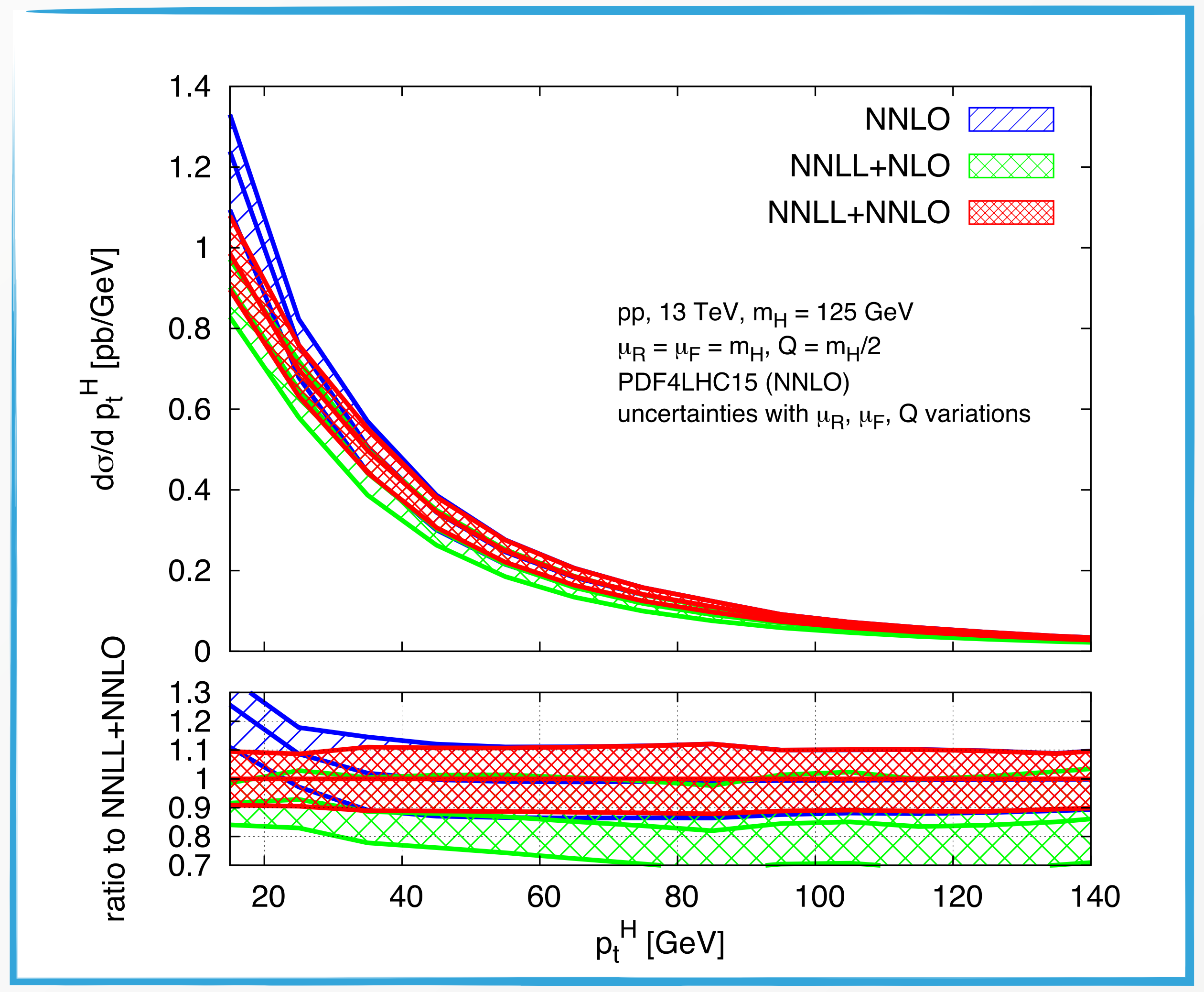
→ possible to implement **all rIRC observables for colour singlet** using same formalism

Advantages of a direct space approach:

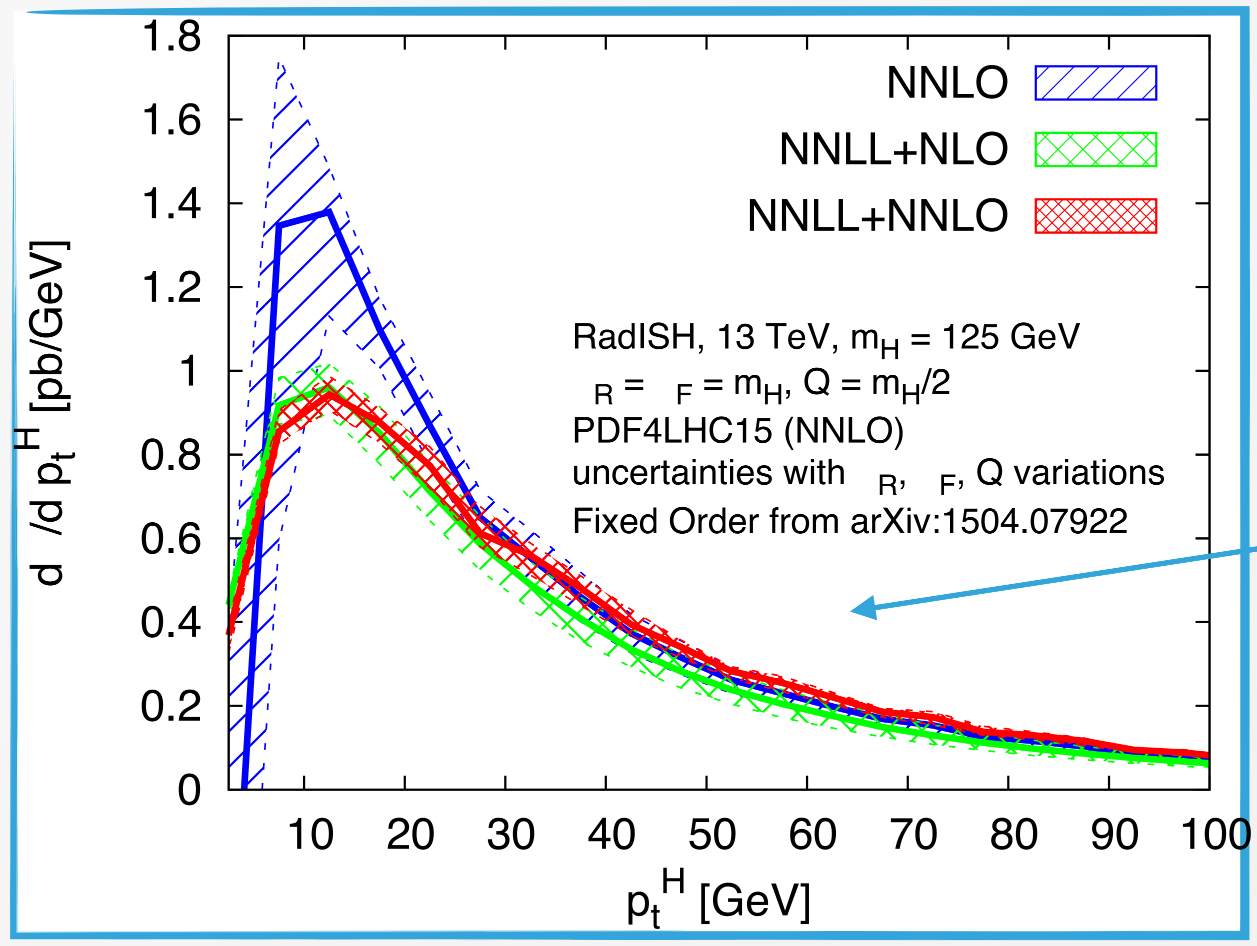
- **Computational speed**
- No need to have a factorization theorem established (**observable independent**)
- NNLL corrections computed with the ARES method
- **Fully exclusive** in Born kinematics (easy to implement cuts, dynamic scales, etc)
- **Joint resummation** of observables with the same Sudakov Radiator

Phenomenological applications

Formalism first applied to produce the first NNLO+NNLL predictions for Higgs pT by P. Monni, E. Re and P. Torrielli



[Monni, Re, Torrielli '06]



- Fast evaluation of master formula using **MC methods**
- Impact of resummation important for $p_T \lesssim 40$ GeV
- Resummation predictions reduce to NNLO at higher p_T

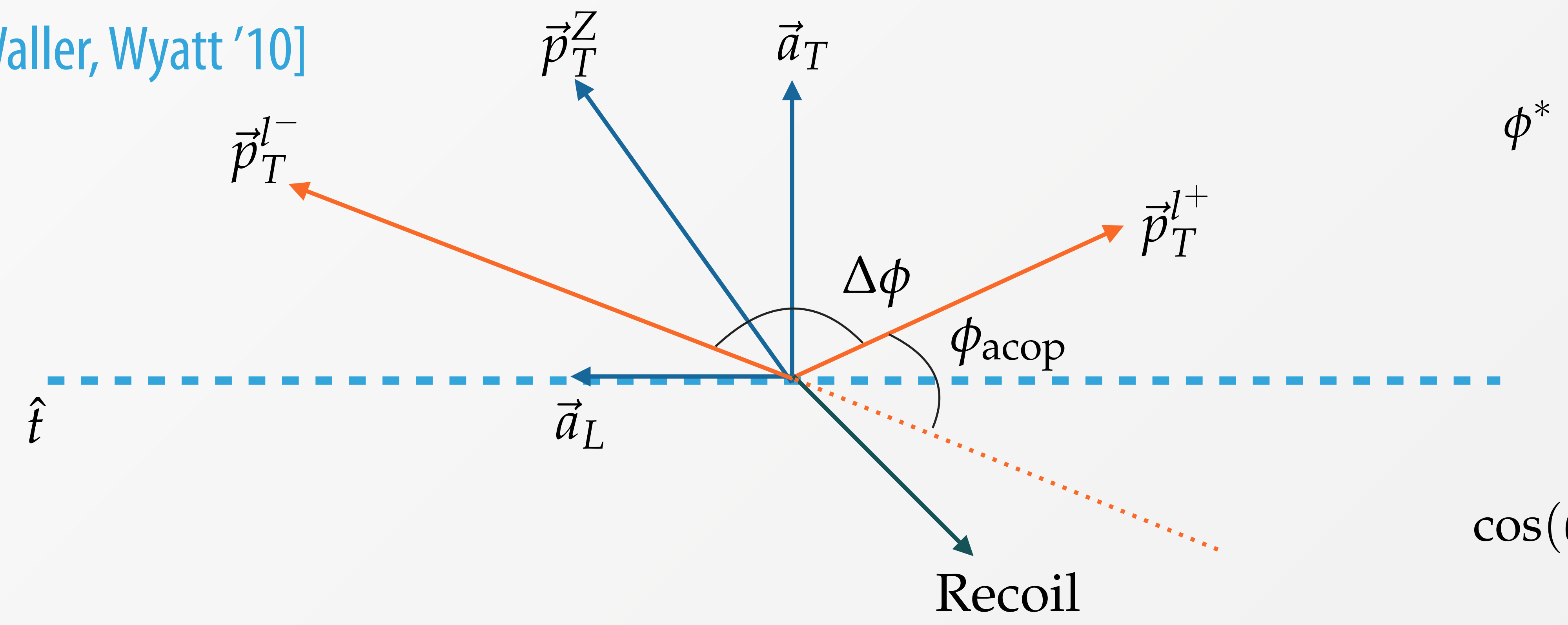
Results with **multiplicative matching**

Phenomenological applications

Thanks to a **new multiplicative matching** now easier to extend the formalism to new observables ➡ systematic matching at **NNLO**

Example: ϕ^* in Drell-Yan pair production

[Banfi, Redford, Vesterinen, Waller, Wyatt '10]



$$\phi^* \equiv \tan\left(\frac{\phi_{acop}}{2}\right) \cdot \sin(\theta^*)$$

$$\cos(\theta^*) \equiv \tanh\left(\frac{\eta^{l^-} - \eta^{l^+}}{2}\right)$$

- Precision measurement on the p_T^Z spectrum at small is limited by experimental resolution
- Experimental uncertainties are minimized when measuring ϕ^*
- ϕ^* measures deviations from co-planarity (vanishes at Born level)

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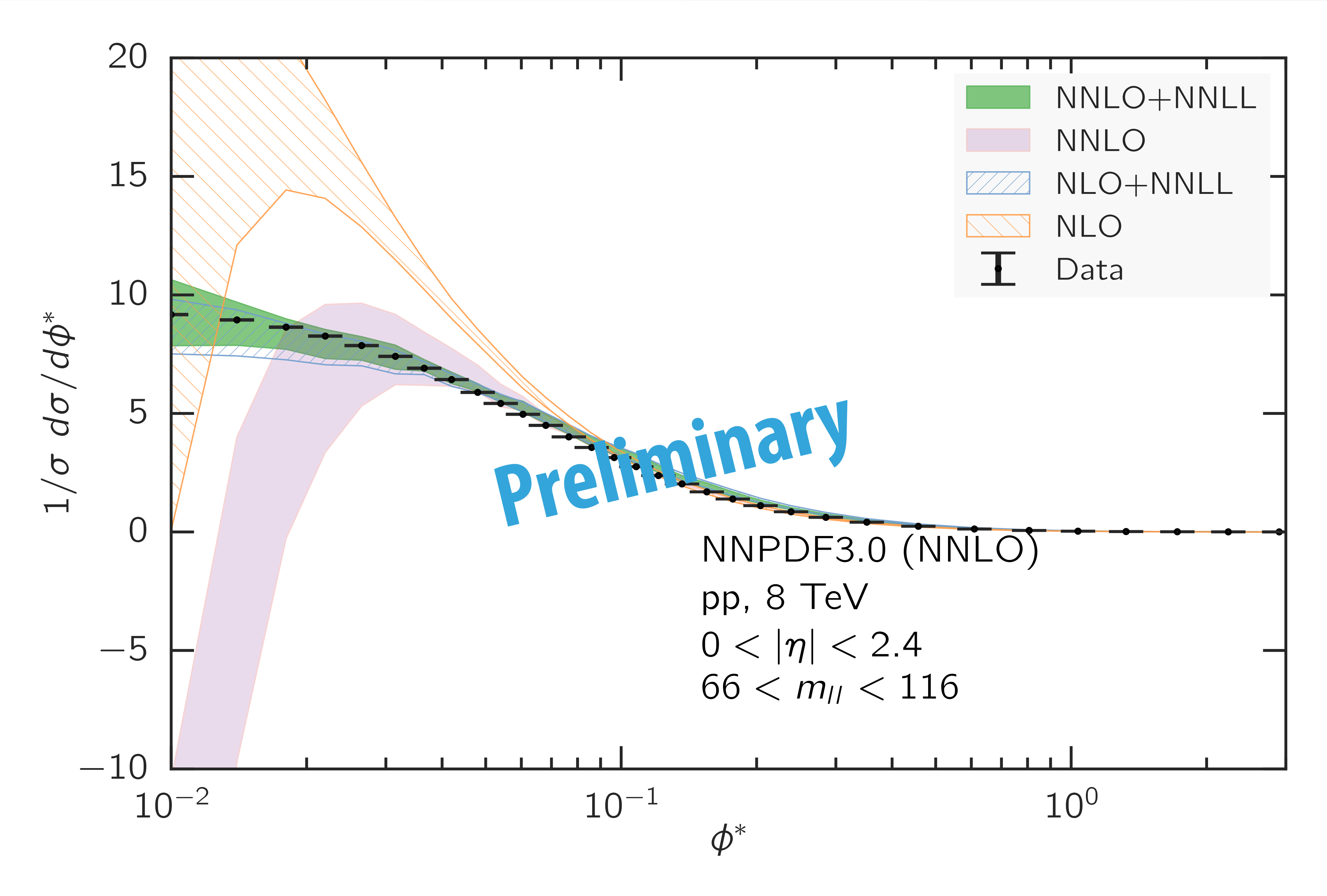
Phenomenological applications

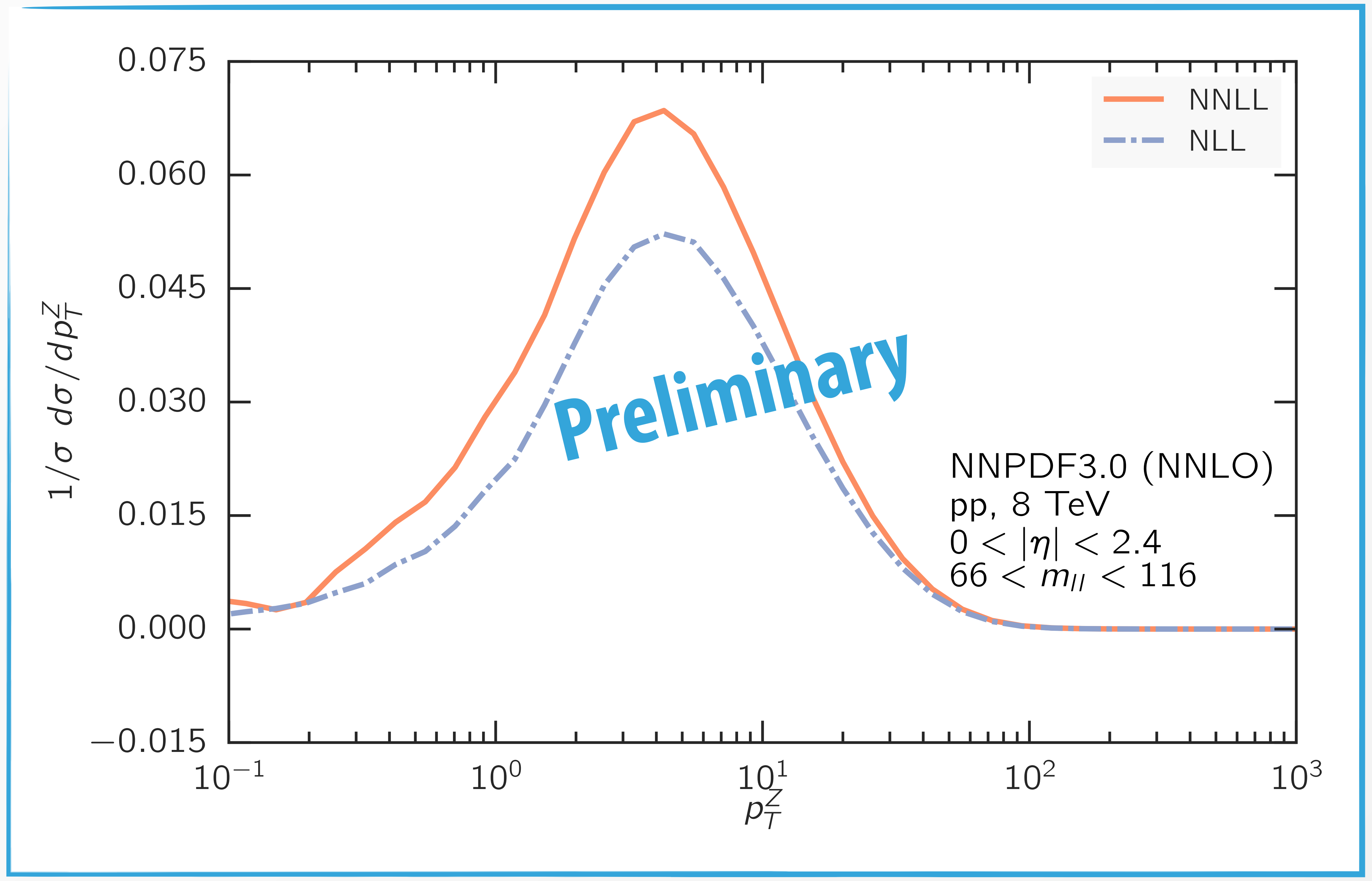


FO from Gehermann-De Ridder *et al* '16
ATLAS 8 TeV arXiv:1512.02192

Some details still to be finalized

- Choice of the resummation scale
- Form of the modified logarithms

Phenomenological applications



Some details still to be finalized

- Choice of the resummation scale
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Conclusions

- New method entirely formulated in direct space does not rely on any specific factorization theorem
- Formalism valid for **all colour singlet processes** and **all rIRC global observables**
- Systematic NNLO matching
- **Fully exclusive** in the Born phase-space

Outlook

- Full exclusivity in Born kinematics allows for **joint resummation** at NNLL (p_T^j, p_T^Z)
- Systematic inclusion of higher-order corrections