

# 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

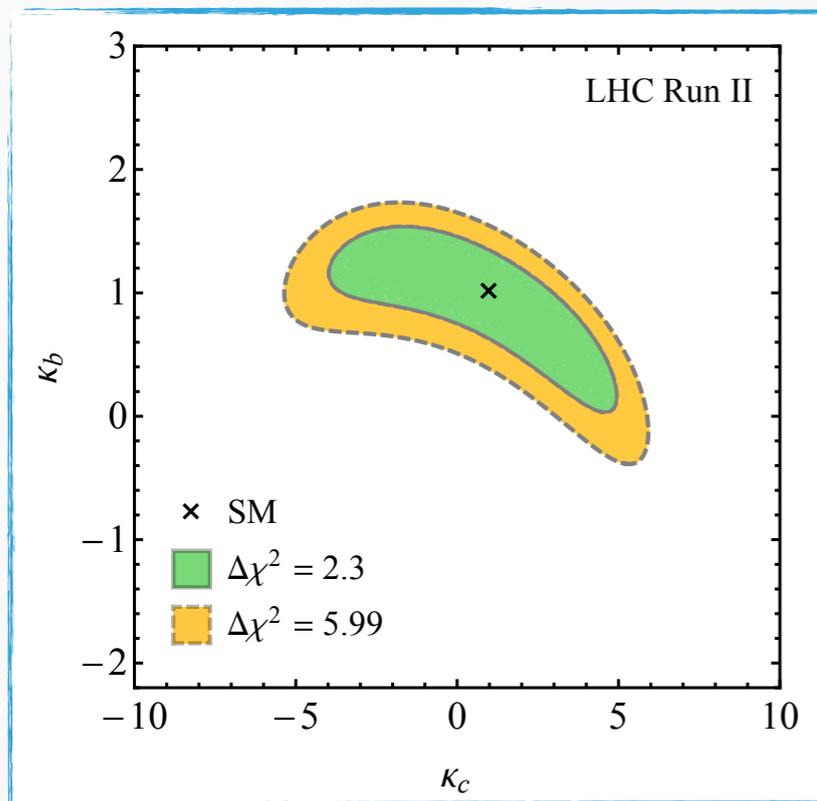
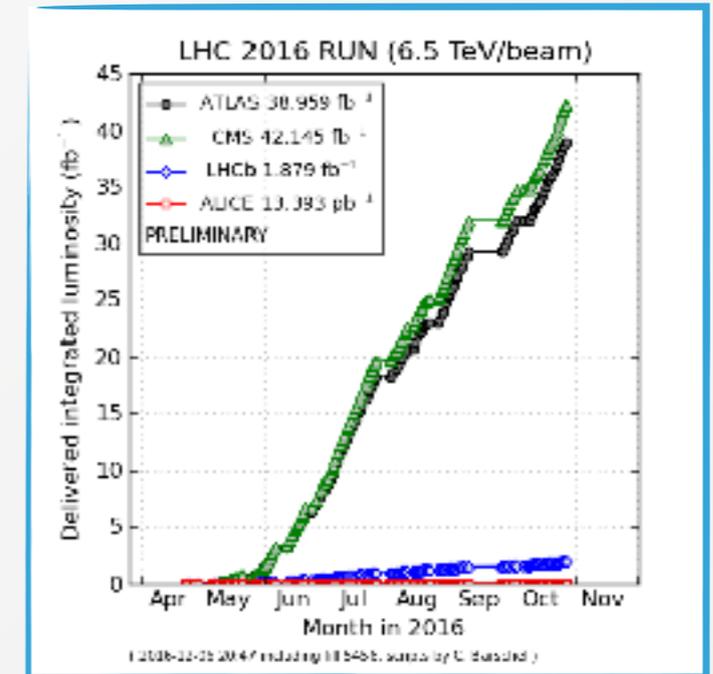
- ▶ Measurement of the Standard Model parameters with **very high precision**
- ▶ Signals of New Physics **beyond the Standard Model**

## 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

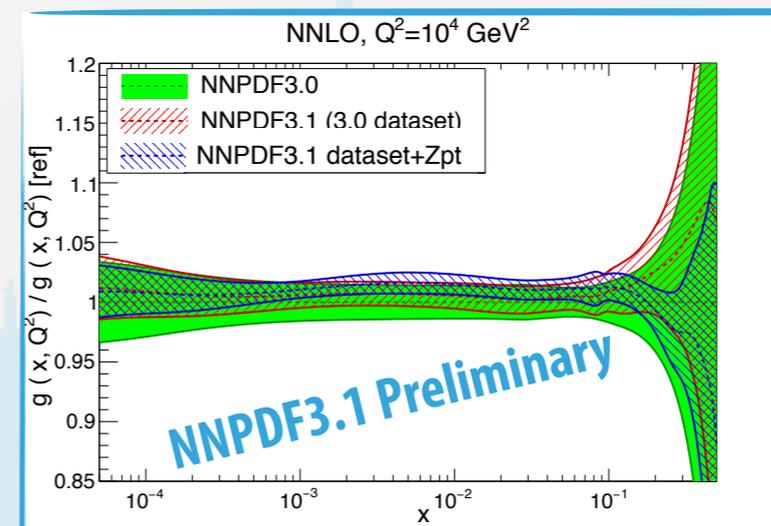
# LHC, New Physics, and the pursuit of Precision

- ▶ ~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



arXiv:1606.09253

- ▶ Accurate determination of **Parton Distribution Functions**
- ▶ Constraints on **New Physics** (e.g. light-quark Yukawa Couplings)
- ▶ Probe on **non-perturbative effects** in distributions



See talk by Marzani

# Differential distributions in Colour Singlet Production

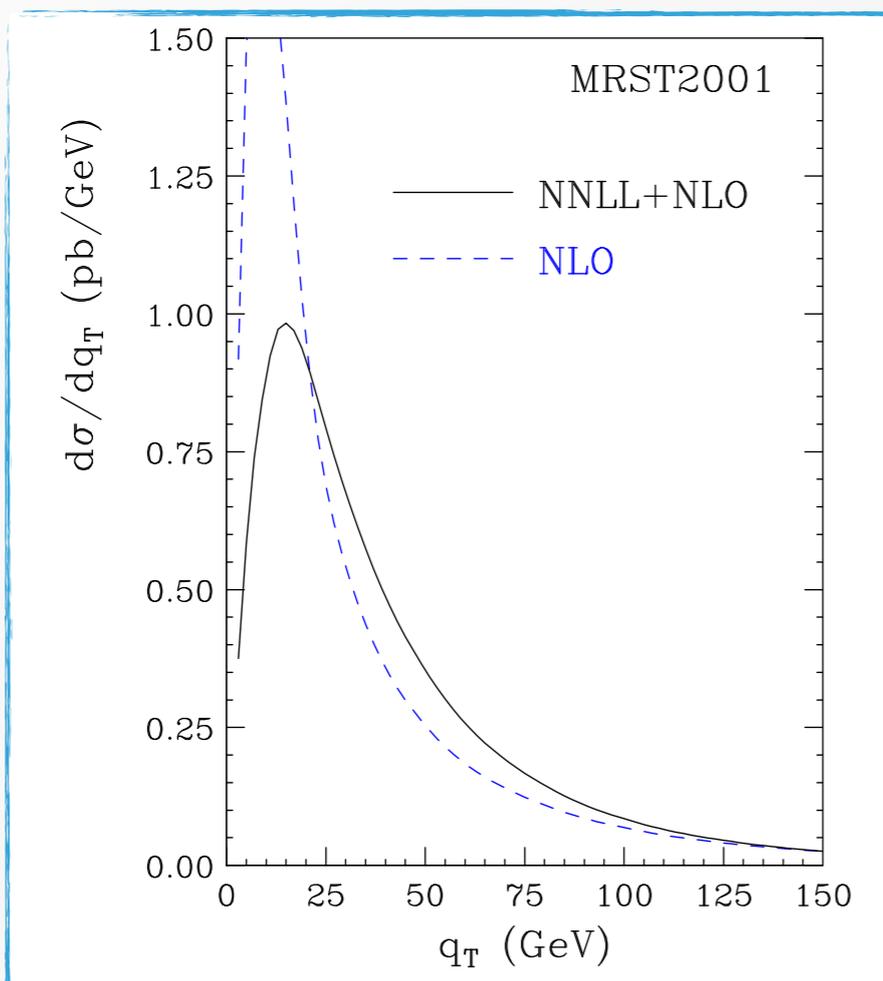
Fixed Order

## Higgs Production

Inclusive cross-section available at N<sup>3</sup>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, Gehrmann-De Ridder *et al*'16]

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

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

- ▶ **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

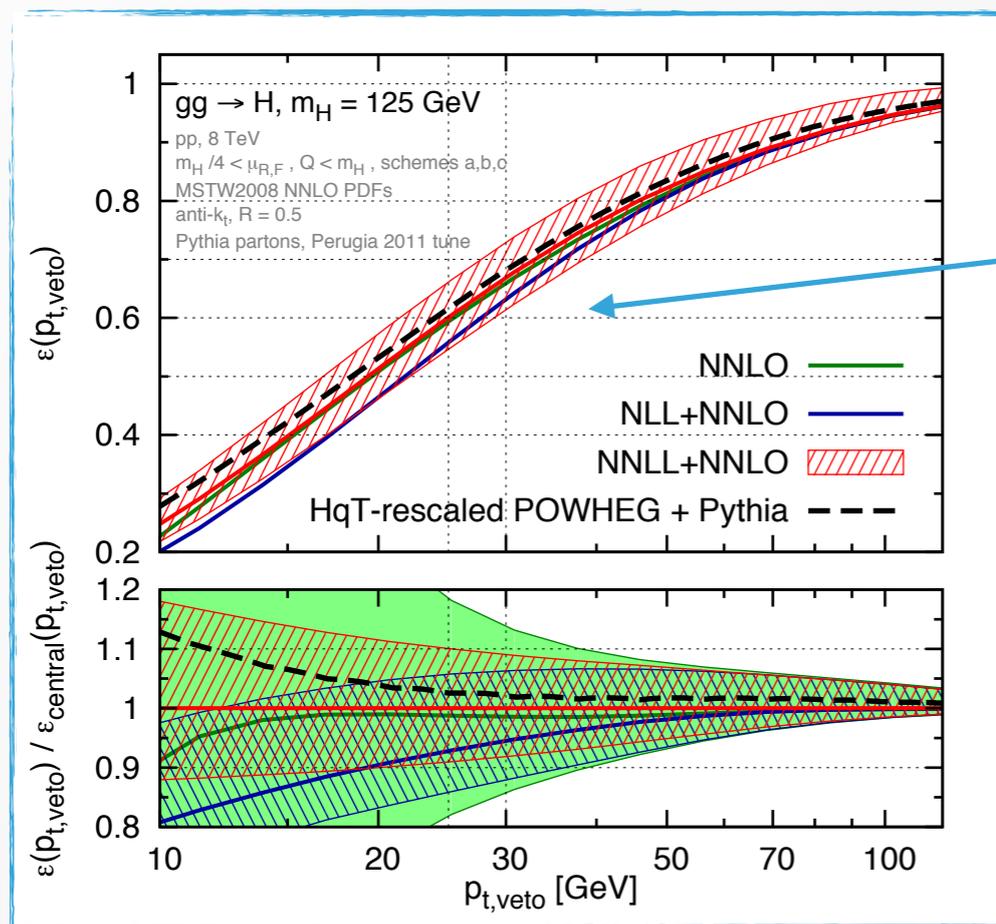
Many of these observables can be resummed in direct space in the (observable-independent) **ARES framework** (e.g.  $p_T^J, E_T$ )

However, other observables (e.g. colour singlet  $p_T, \phi^*$ ) 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



Banfi, Monni, Salam, Zanderighi '12

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  $\epsilon v$  do not significantly contribute to the observable

# Resummation in Parameter Space

- ▶ Standard resummation for  $p_T, \phi^*$  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

**Need for a general method for resummation of observables with azimuthal cancellations**

# 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  $k_1, k_2 \dots k_n$

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

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

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

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  $p_T$  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 ( $R' \sim 2$ )

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

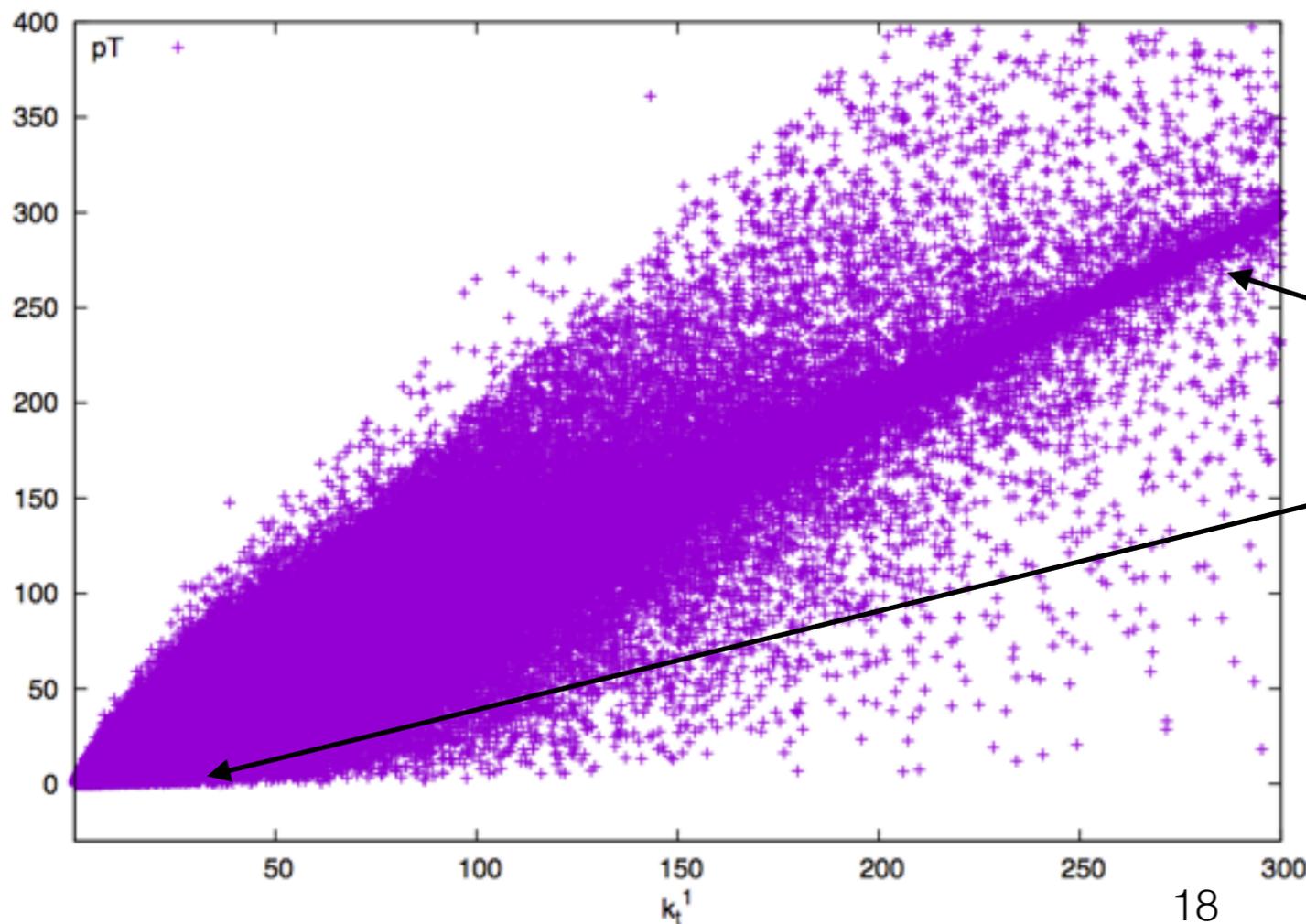
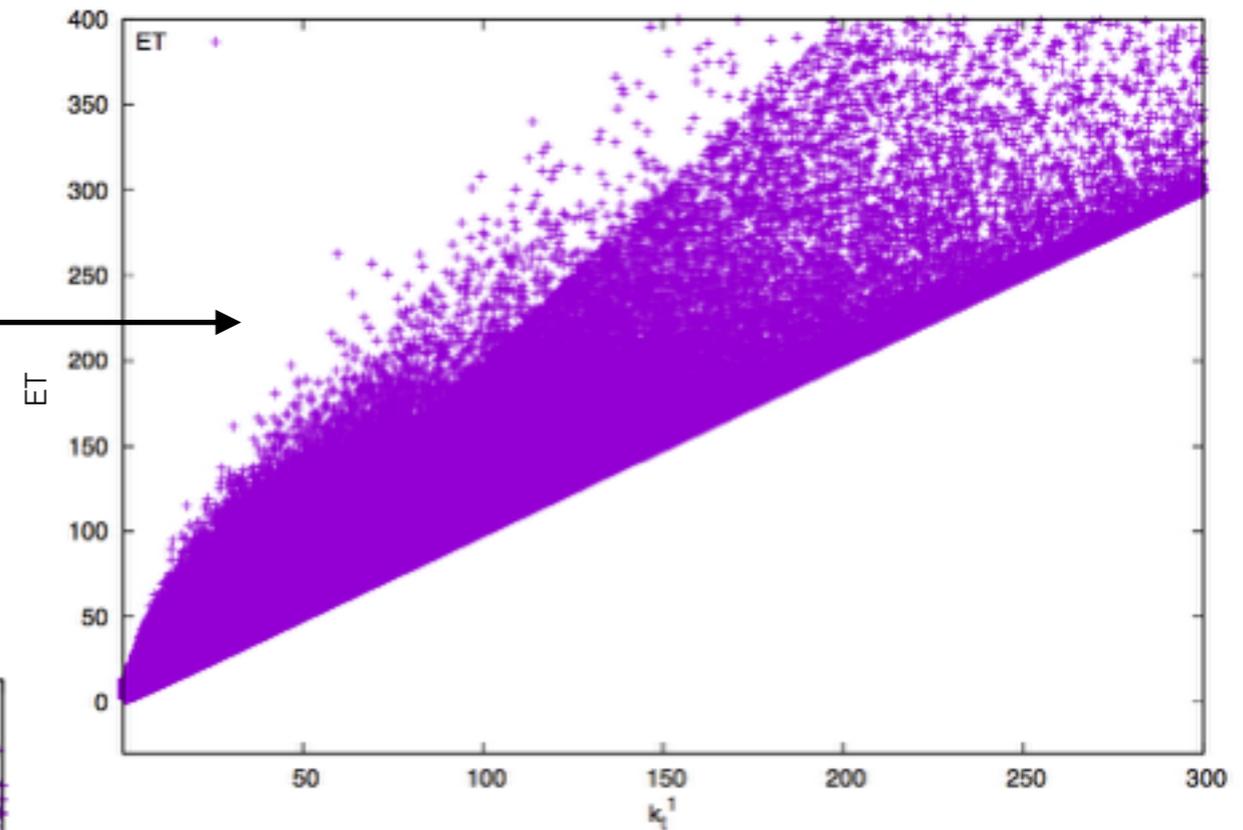
[Monni, Re, Torrielli '06]

- ▶ 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

# pT vs. ET: dependence on the first emission

Transverse Energy: single (Sudakov) suppression mechanism for all values of  $k_{t1}$



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  $p_T \rightarrow 0$  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

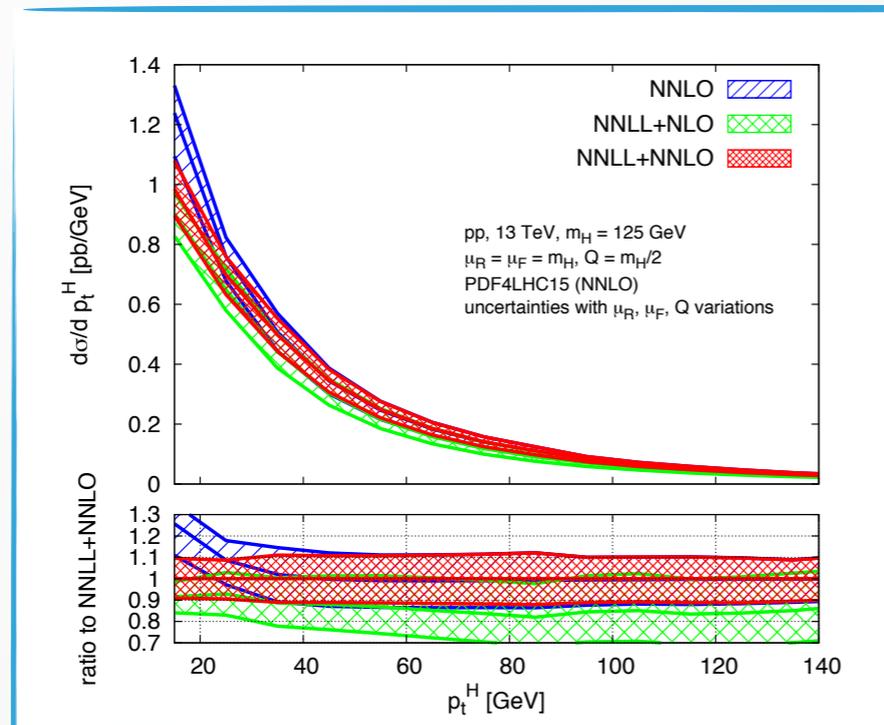
→ possible to implement **all rIRC observables for colour singlet** using same formalism

**Advantages** of a direct space approach:

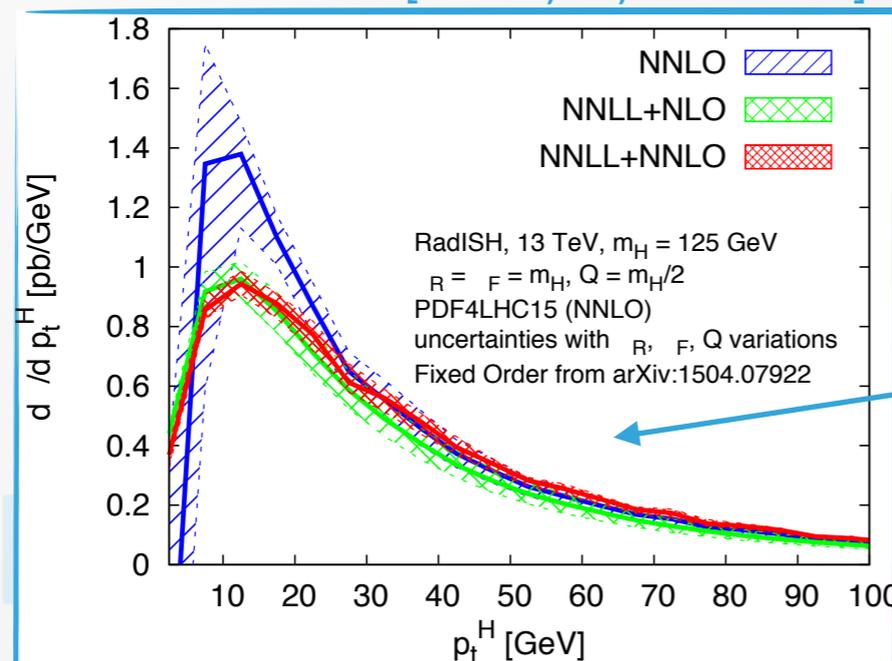
- ▶ **Computational speed**
- ▶ No need to have a factorization theorem established (**observable independent**)
- ▶ NNLL corrections computed with the ARES method
- ▶ **Fully exclusive** in Born kinematics (easy to implement cuts, dynamic scales, etc)
- ▶ **Joint resummation** of observables with the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

# Phenomenological applications

Formalism first applied to produce the first NNLO+NNLL predictions for Higgs  $p_T$  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  $p_T$

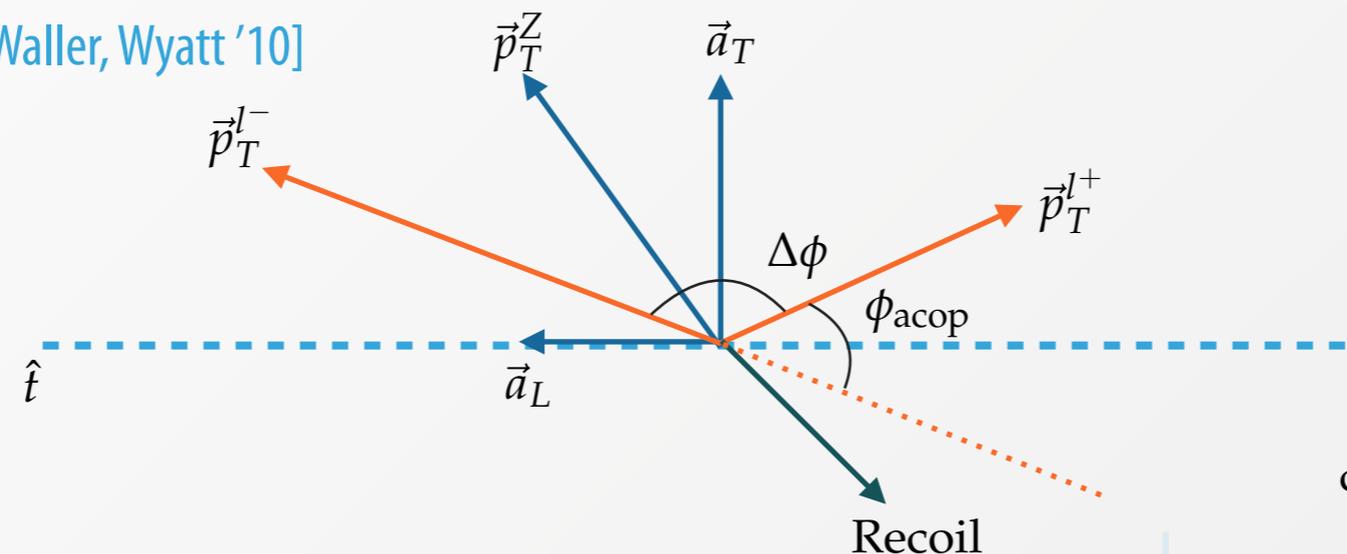
Results with **multiplicative matching**

# Phenomenological applications

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

Example:  $\phi^*$  in Drell-Yan pair production

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

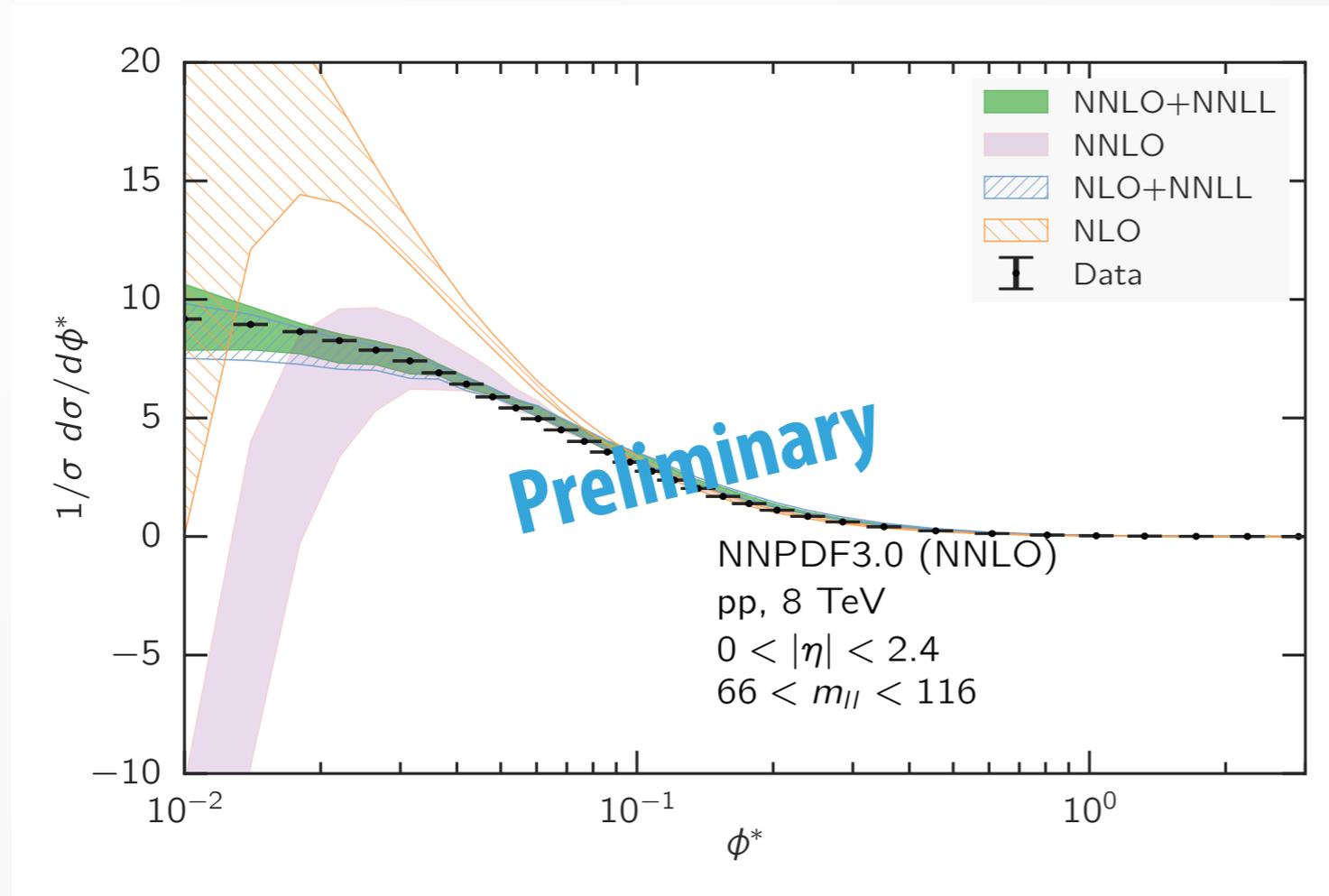


$$\phi^* \equiv \tan\left(\frac{\phi_{acop}}{2}\right) \cdot \sin(\theta^*)$$

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

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

# Phenomenological applications

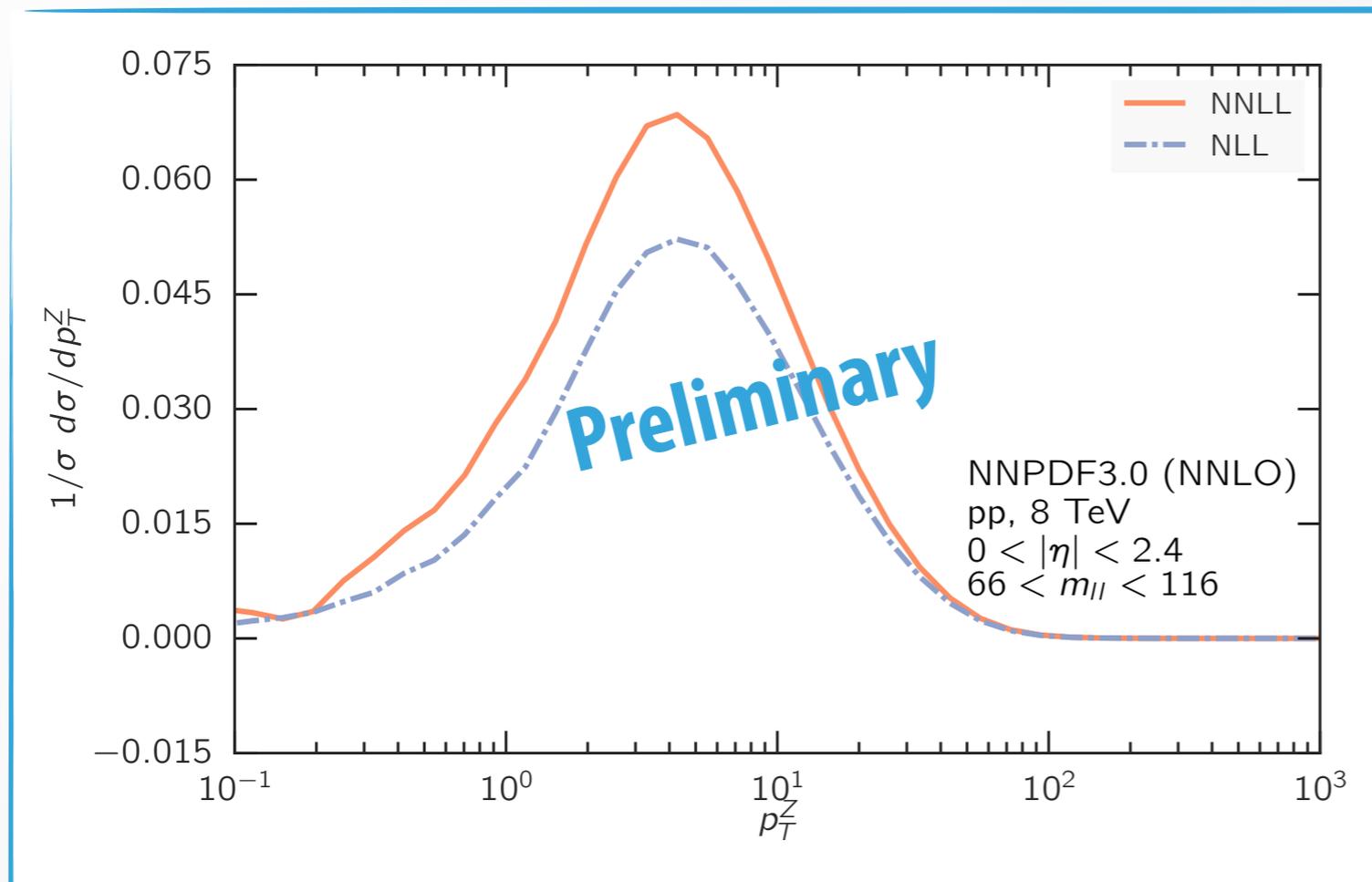


Some details still to be finalized

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

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

# Phenomenological applications



Some details still to be finalized

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

# 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