Transverse momentum effects in high energy hadronic collisions

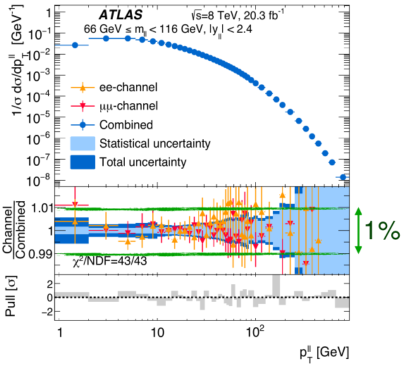
Emanuele Re

LAPTh Annecy

Atelier sur la physique théorique des deux infinis

7 June 2021

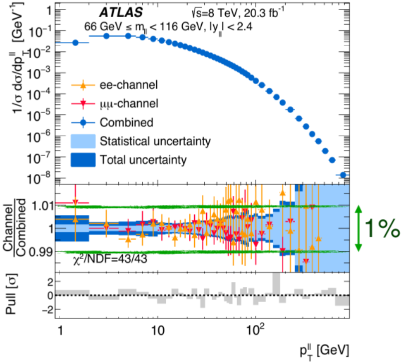
Transverse momentum in hadronic collisions



- **Focus**: transverse momentum of a massive system
- $p_{\mathrm{T,V}}$: Drell-Yan data are extremely precise:
  - SM measurement: test QCD at higher orders, extract PDFs, ...
  - W-mass extraction

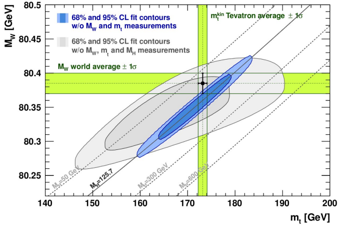
    [ATLAS '17: $m_W = 80370 \pm 19$ MeV]
- $p_{\mathrm{T,H}}$: central observable for current Higgs studies at the LHC:
  - probe BSM effects: tail, but also at medium-small $p_{\mathrm{T,H}}$ [charm Yukawa]

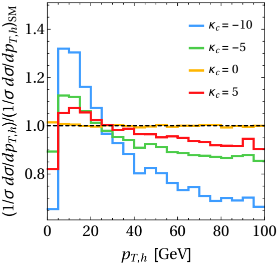
Transverse momentum in hadronic collisions



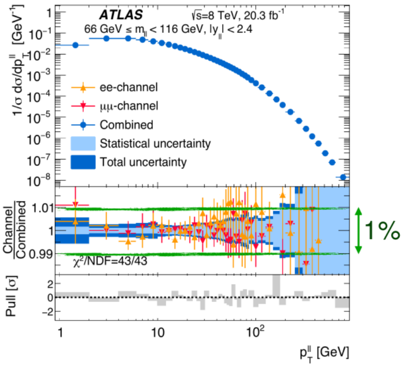
- Focus: transverse momentum of a massive system
- $p_{\mathrm{T,V}}$: Drell-Yan data are extremely precise:
  - SM measurement: test QCD at higher orders, extract PDFs, ...
  - W-mass extraction

    [ATLAS '17: $m_W = 80370 \pm 19$ MeV]
- $p_{\mathrm{T,H}}$: central observable for current Higgs studies at the LHC:
  - probe BSM effects: tail, but also at medium-small $p_{\mathrm{T,H}}$ [charm Yukawa]





Transverse momentum in hadronic collisions

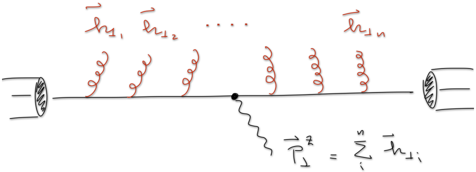


- Focus: transverse momentum of a massive system
- $p_{\mathrm{T,V}}$: Drell-Yan data are extremely precise:
  - SM measurement: test QCD at higher orders, extract PDFs, ...
  - W-mass extraction
    [ATLAS '17: $m_W = 80370 \pm 19$ MeV]
- $p_{\mathrm{T,H}}$: central observable for current Higgs studies at the LHC:
  - probe BSM effects: tail, but also at medium-small $p_{\mathrm{T,H}}$ [charm Yukawa]

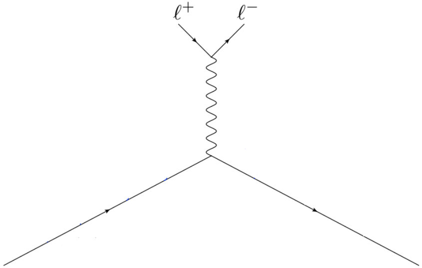
- clean experimental and theoretical environment for precision physics
- very minor sensitivity to non-perturbative effects
- the cross-section is peaked for $\mathbf{p_T \ll Q}$
- Large logarithms arise at all order: resummation becomes necessary

All-order p_{T}-resummation

images credit: P. Monni

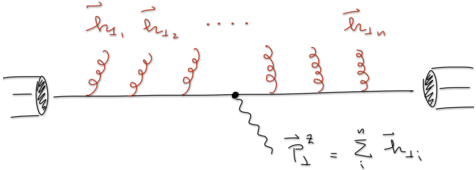


$$|\vec{k}_{t1} + ... + \vec{k}_{tn}| := p_{\mathrm{T}}$$

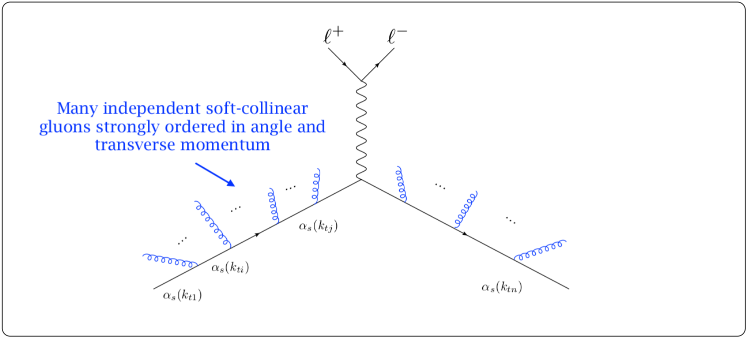


All-order p_{T}-resummation

images credit: P. Monni

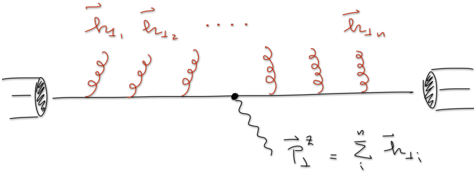


$$|\vec{k}_{t1} + \ldots + \vec{k}_{tn}| := p_{\mathrm{T}}$$

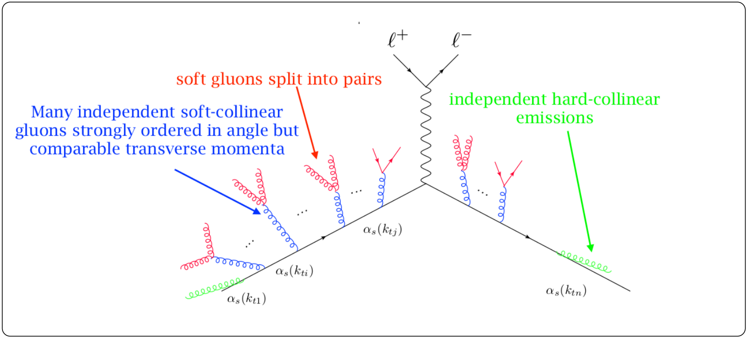


All-order p_{T}-resummation

images credit: P. Monni

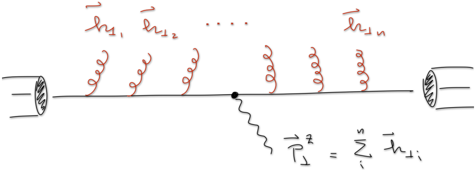


$$|\vec{k}_{t1} + \ldots + \vec{k}_{tn}| := p_{\mathrm{T}}$$

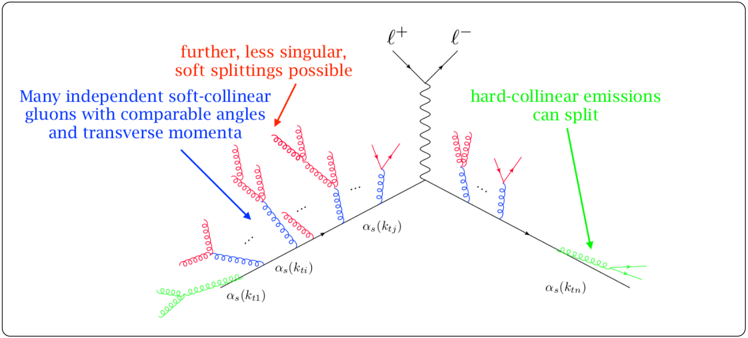


All-order p_{T}-resummation

images credit: P. Monni

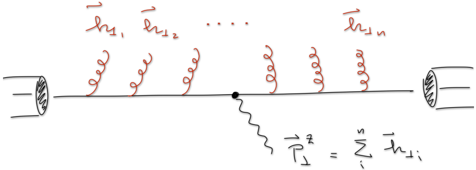


$$|\vec{k}_{t1} + ... + \vec{k}_{tn}| := p_{\mathrm{T}}$$

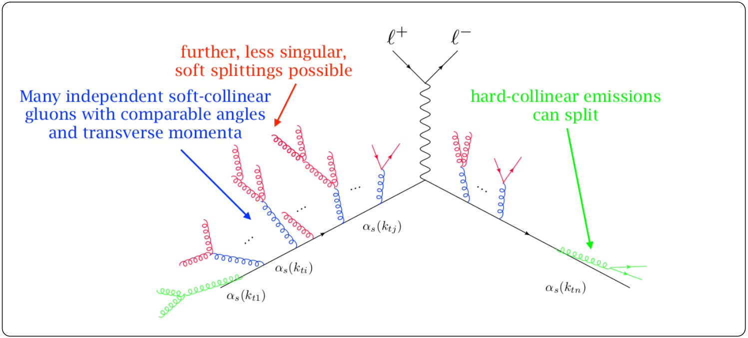


All-order p_T-resummation

images credit: P. Monni



$$|\vec{k}_{t1} + \ldots + \vec{k}_{tn}| := p_\mathrm{T}$$



- Logarithmic accuracy, $L = \log(Q/p_\mathrm{T})$:

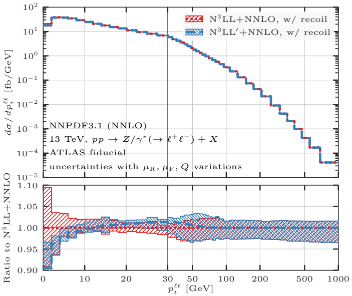
$$\Sigma(p_\mathrm{T}) = \int_0^{p_\mathrm{T}} dp'_\mathrm{T} \frac{d\sigma}{dp'_\mathrm{T}} \sim \exp\Big\{ \big[\underbrace{\mathcal{O}(\alpha_\mathrm{S}^n L^{n+1})}_{\text{LL}} + \underbrace{\mathcal{O}(\alpha_\mathrm{S}^n L^{n})}_{\text{NLL}} + \underbrace{\mathcal{O}(\alpha_\mathrm{S}^n L^{n-1})}_{\text{NNLL}} + \ldots \big] \Big\}$$

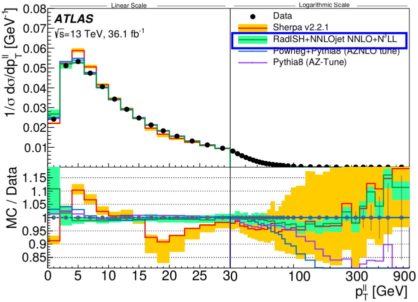
Resummation in momentum space

New method to resum “transverse and inclusive” observables (in momentum space)

[Monni,ER,Torrielli ’16, Bizon,Monni,ER,Rottoli,Torrielli ’17]

- N3LL’+NNLO: state of the art accuracy for Higgs and Drell-Yan transverse momentum
- momentum space: closer connection to parton showers
- public code: **RadISH**: “Radiation off Initial State Hadrons”





- 5-10 % corrections wrt N3LL+NNLO below 10 GeV ; order few % residual uncertainty
- matching to fixed-order at large p_{T} [NNLOJET]

plot from [ER,Rottoli,Torrielli ’21]   anom. dimensions: [Catani et al. ’11, Gehrmann et al. ’14, Li, Zhu ’16, Vladimirov ’16]

Formalism in a nutshell

- Our approach: all-order cross-section [$v = p_{\mathrm{T}}$]

$$\Sigma(v) = \int d\Phi_B \mathcal{V}(\Phi_B) \sum_{n=0}^{\infty} \int \prod_{i=1}^{n} [dk_i] |M(\tilde{p}_1, \tilde{p}_2, k_1, \ldots, k_n)|^2 \, \Theta\left(v - V(\{\tilde{p}\}, k_1 \ldots k_n)\right)$$

$\mathcal{V}(\Phi_B)$: all-order form factor $|M(\tilde{p}_1, \tilde{p}_2, k_1, \ldots, k_n)|^2$: real emissions

Formalism in a nutshell

- Our approach: all-order cross-section [$v = p_{\rm T}$]

$$\Sigma(v) = \int d\Phi_B \mathcal{V}(\Phi_B) \sum_{n=0}^{\infty} \int \prod_{i=1}^{n} [dk_i] |M(\tilde{p}_1, \tilde{p}_2, k_1, \ldots, k_n)|^2 \, \Theta\left(v - V(\{\tilde{p}\}, k_1 \ldots k_n)\right)$$

$\mathcal{V}(\Phi_B)$: all-order form factor $|M(\tilde{p}_1, \tilde{p}_2, k_1, \ldots, k_n)|^2$: real emissions

- re-organize multiple-emission squared amplitudes into (iterations of) "n-particle-correlated blocks": rIRC-safety [Banfi,Salam,Zanderighi] guarantees "log" hierarchy among different blocks
- cancel the IRC poles between $\mathcal{V}$ and real emissions [resolution: ϵk_{t1} (not $\epsilon\, p_{\rm T}$)] $\Rightarrow$ Sudakov factor
- the resolved blocks left contribute to the observable: treated exclusively in 4 dimensions, generated as MC events

Formalism in a nutshell

- Our approach: all-order cross-section [$v = p_T$]

$$\Sigma(v) = \int d\Phi_B \mathcal{V}(\Phi_B) \sum_{n=0}^{\infty} \int \prod_{i=1}^{n} [dk_i] |M(\tilde{p}_1, \tilde{p}_2, k_1, \ldots, k_n)|^2 \, \Theta\left(v - V(\{\tilde{p}\}, k_1 \ldots k_n)\right)$$

$\mathcal{V}(\Phi_B)$: all-order form factor $|M(\tilde{p}_1, \tilde{p}_2, k_1, \ldots, k_n)|^2$: real emissions

- re-organize multiple-emission squared amplitudes into (iterations of) "n-particle-correlated blocks": rIRC-safety [Banfi,Salam,Zanderighi] guarantees "log" hierarchy among different blocks
- cancel the IRC poles between $\mathcal{V}$ and real emissions [resolution: ϵk_{t1} (not $\epsilon\, p_T$)] $\Rightarrow$ Sudakov factor
- the resolved blocks left contribute to the observable: treated exclusively in 4 dimensions, generated as MC events

- Final result (very schematic):

$$\Sigma(v) = \int \frac{dk_{t1}}{k_{t1}} \frac{d\phi_1}{2\pi} \int d\mathcal{Z}[\{R', k_i\}] \Theta\left(v - V(\{\tilde{p}\}, k_1, \ldots, k_{n+1})\right) \left[\partial_L \left(-e^{-R(k_{t1})} \mathcal{L}_{\mathrm{N^3LL}}(k_{t1})\right)\right]$$

$$+ \int \frac{dk_{t1}}{k_{t1}} \frac{d\phi_1}{2\pi} \int \frac{dk_{t,s}}{k_{t,s}} \frac{d\phi_s}{2\pi} d\mathcal{Z}[\{R', k_i\}] (\Theta_{n+1} - \Theta_{n+1,s}) \left[\text{1 special emission correction}\right]$$

$$+ \int \frac{dk_{t1}}{k_{t1}} \frac{d\phi_1}{2\pi} \int \frac{dk_{t,s1}}{k_{t,s1}} \frac{d\phi_{s1}}{2\pi} \int \frac{dk_{t,s2}}{k_{t,s2}} \frac{d\phi_{s2}}{2\pi} d\mathcal{Z}[\{R', k_i\}] (\ldots) \left[\text{2 special emissions correction}\right]$$

$$+ \ldots.$$

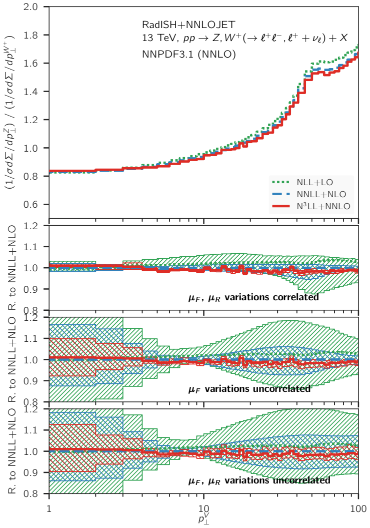
Recent applications

[Bizon,Chen,Gehrmann-De Ridder,Gehrmann,Glover,Huss,Monni,ER,Rottoli,Walker '19]

- m_W measured through template fits to lepton observables: $p_{T,Z}$ & $p_{T,W}$ modeling crucial
- data driven methods: measure Z, fit predictions, transfer to W

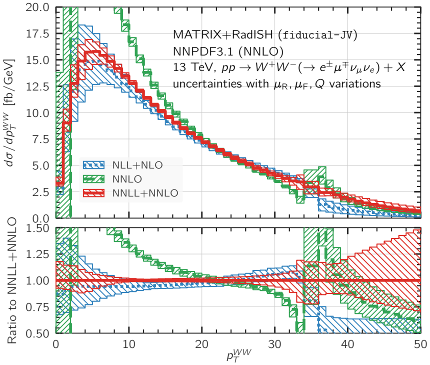
$$\frac{1}{\sigma^{\mathrm{W}}}\frac{d\sigma^{\mathrm{W}}}{dp_{\perp}} \simeq \frac{1}{\sigma^{\mathrm{Z}}_{\mathrm{data}}}\frac{d\sigma^{\mathrm{Z}}_{\mathrm{data}}}{dp_{\perp}} \frac{\frac{1}{\sigma^{\mathrm{W}}_{\mathrm{theory}}}\frac{d\sigma^{\mathrm{W}}_{\mathrm{theory}}}{dp_{\perp}}}{\frac{1}{\sigma^{\mathrm{Z}}_{\mathrm{theory}}}\frac{d\sigma^{\mathrm{Z}}_{\mathrm{theory}}}{dp_{\perp}}}$$

- so far, typically done by tuning a (LO!) MC
- studied this issue at N3LL+NNLO: very stable predictions
- relevant for LHC analysis + ongoing studies of a broad community within the LHC EWWG (several groups involved)



Recent applications

[Kallweit,ER,Rottoli,Wiesemann '20]



- `RadISH+Matrix` : automated N3LL+NNLO results for all color-singlet processes
- fully public software: works out of the box
- many possible applications, e.g. in VV processes
- formalism allows for a double-differential resummation: [Monni,Rottoli,Torrielli '19]

$$p_{\rm T} \quad \& \quad p_{\rm T,jet}$$

- interesting for TH and relevant for several Higgs analysis: measure of $p_{\rm T}$ with a veto on jets

Future plans & Outlook

- Resummation can be used to build subtraction terms for fixed-order results
  - Differential cross section at N3LO for Higgs and DY production
- Applications to state-of-the-art Monte Carlo event generators
  - Formalism used to build a new method to match NNLO QCD computations with Parton Showers

[Monni,Nason,ER,Wiesemann,Zanderighi '19, Monni,ER,Wiesemann '20, ...]

- Phenomenology: applications in EXP analysis (e.g. to VH production)
- Extend formalism to colored final state (resummation for $t\bar{t}$)

- Until now, main collaborations with CERN, Zurich, Turin, MPI Munich
- Several EXP applications, including in analysis performed by French groups
- Overlap with TMD community

Future plans & Outlook

- Resummation can be used to build subtraction terms for fixed-order results
  - Differential cross section at N3LO for Higgs and DY production
- Applications to state-of-the-art Monte Carlo event generators
  - Formalism used to build a new method to match NNLO QCD computations with Parton Showers

[Monni,Nason,ER,Wiesemann,Zanderighi '19, Monni,ER,Wiesemann '20, ...]

- Phenomenology: applications in EXP analysis (e.g. to VH production)
- Extend formalism to colored final state (resummation for $t\bar{t}$)

- Until now, main collaborations with CERN, Zurich, Turin, MPI Munich
- Several EXP applications, including in analysis performed by French groups
- Overlap with TMD community

Thank you for your attention!