Mitigating Large Background in Jet Substructure

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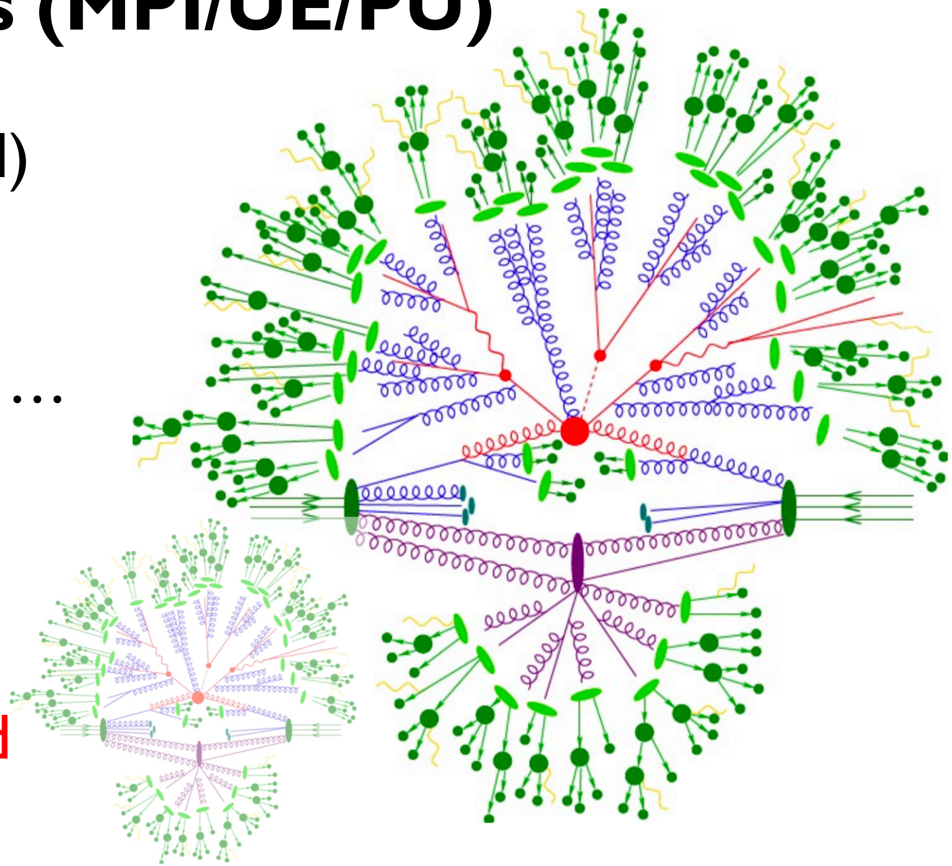
Soft background particles (MPI/UE/PU)

- Multi-particle interaction (MPI) in MC
- Underlying events (UE) including MPI, hadronic effect, $\cdots$
- Pileup (PU) events from independent collisions
- In many cases, MPI/UE/PU are soft particles uncorrelated with hard interactions.



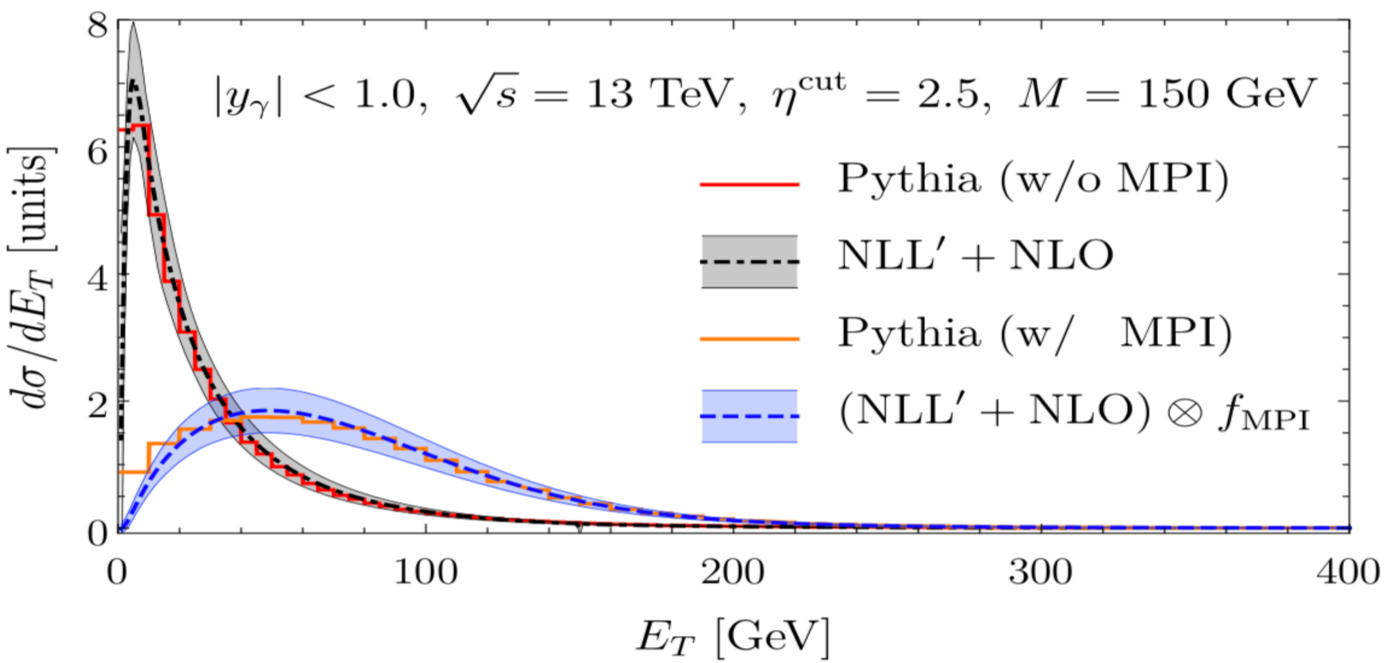
- Soft particles from hard interactions are correlated and NOT background.

Observables sensitive to background (MPI/UE/PU)

- Drell-Yan process: $pp \to \ell^+\ell^- + X$

  transverse energy (cf pT), beam thrust, $\cdots$

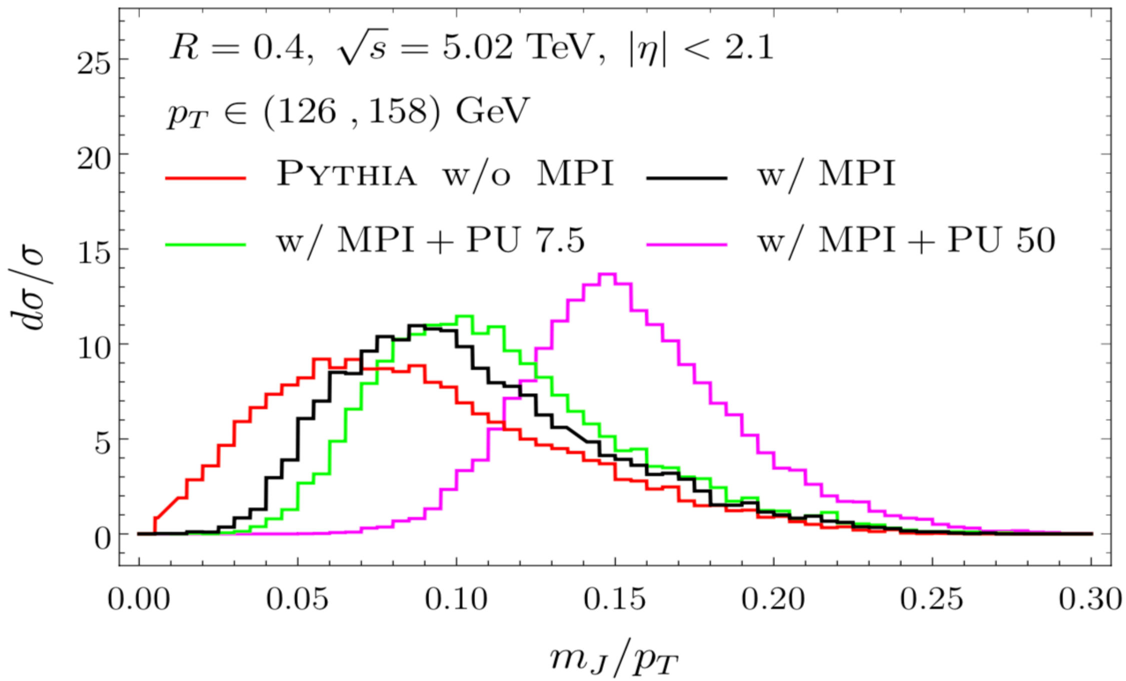
$$E_T(\eta_{\rm cut}) = \sum_i p_T^{(i)}\Theta(\eta_{\rm cut} - |\eta^{(i)}|)$$



Observables sensitive to background (MPI/UE/PU)

- jet substructures: jet mass, thrust, angularity, n-subjettiness, $\cdots$

Inclusive-jet mass distribution



Observables sensitive to background (MPI/UE/PU)

- No first principle solution available in practice.
  Important progress in double-parton scattering, Glauber gluon contribution, $\cdots$
- Large source of uncertainties in perturbative theory predictions.

- Several options to handle backgrounds:
    - tuned models MPI/soft QCD in Monte Carlo Simulation
    - robust observables: pT (over ET), small radius for jets
    - grooming algorithms (soft drop, collinear drop, $\cdots$)
      removing both uncorrelated and correlated soft particles
    - *new statistical approach: subtracted cumulants*

A lesson with a simple model in Drell-Yan

- a single parameter model $$f_{\rm MPI}(E_T, \eta_{\rm cut}) = \mathcal{N} \exp\left[-\left(\frac{E_T}{\alpha(\eta_{\rm cut})\sqrt{\pi}} \right)^2 \right]$$

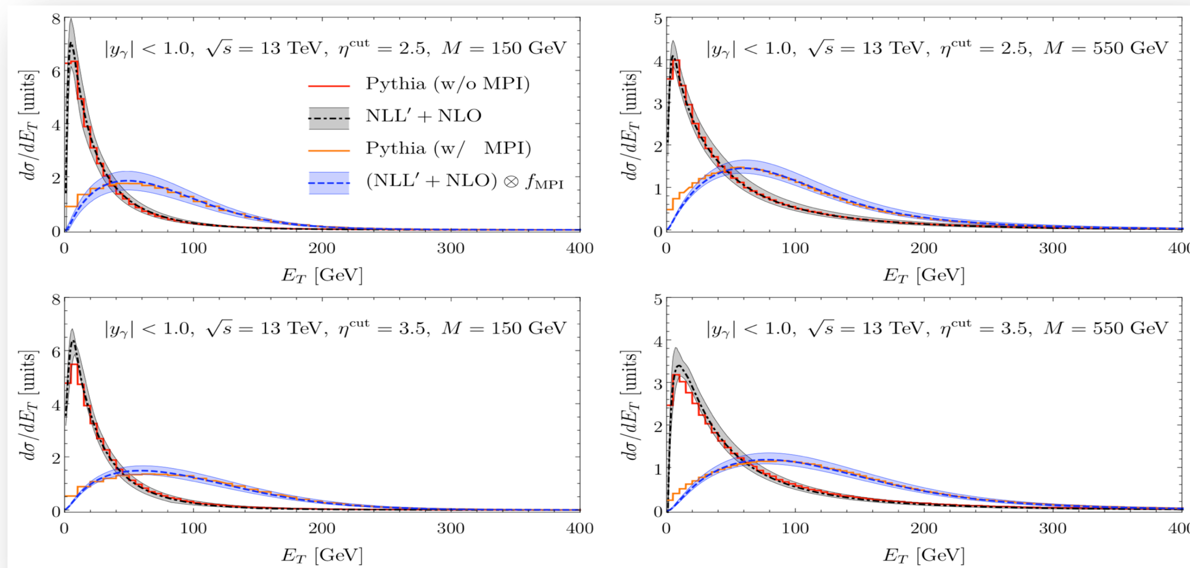
$$\frac{d\sigma^{\rm pert}}{dE_T} \otimes f_{\rm MPI}$$

$$[g \otimes f](E_T) \equiv \int dE'_T \, f(E_T - E'_T) g(E'_T)$$

- w/ $\alpha(\eta_{\rm cut}) = A\, \eta_{\rm cut}$

$$A = 22.7 \text{ GeV}$$

excellent agreement in wide range:
Q = [150, 550] GeV
η_{cut}=[2.5, 3.5]



- Similar observations in jet mass: inclusive jet, H/Z + jet process, top-quark jet

1405.6722 Stewart, Tackmann, Waalewjin, 1708.02586 Hoang, Mantry, Pathak, Stewart, 1803.03645 Z. Kang, Lee, Liu

Subtraction of moments

- The model is insensitive (un-correlated) to hard scale Q, while the perturbative contribution is correlated w/ Q.

$$\frac{d\sigma^{\rm pert}}{dE_T} \otimes f_{\rm MPI} \qquad f_{\rm MPI}(E_T, \eta_{\rm cut}) = \mathcal{N} \exp\left[-\left(\frac{E_T}{\alpha(\eta_{\rm cut})\sqrt{\pi}} \right)^2 \right]$$

- n-th moment

$$\langle E_T^n(Q) \rangle = \underline{\int_0^\infty dE_T\, E_T^n \frac{d\sigma(E_T, Q)}{dE_T}} \Big/ \int_0^\infty dE_T \frac{d\sigma(E_T, Q)}{dE_T}$$

$$\int dE_T E_T^n \int dE'_T\, f_{\rm MPI}(E_T - E'_T)\theta(E_T - E'_T)\, \sigma^{\rm pert}(E'_T, Q)$$

$$= \int dE'_T\, \sigma^{\rm pert}(E'_T, Q) \int d\omega\, (E'_T + \omega)^n f_{\rm MPI}(\omega)\theta(\omega)$$

For n=1, $\langle E_T(Q) \rangle_{\rm pert} + \langle E_T \rangle_{\rm MPI}$

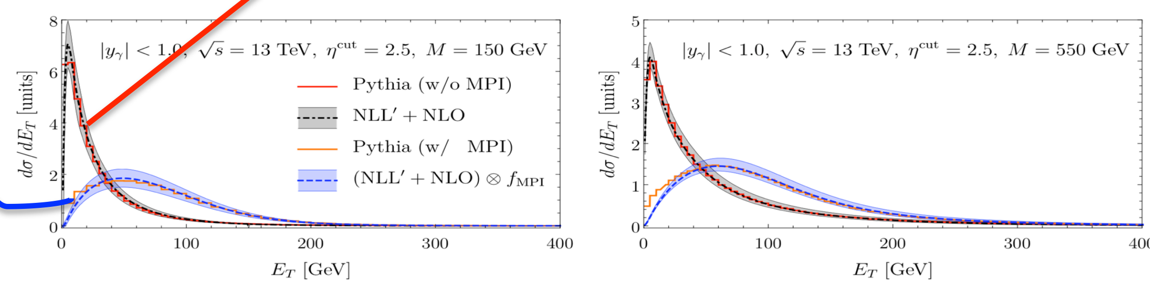
Subtraction of moments

- MPI contribution is additive and insensitive to Q

$$\langle E_T(Q)\rangle = \langle E_T(Q)\rangle_{\text{pert}} + \langle E_T\rangle_{\text{MPI}}$$

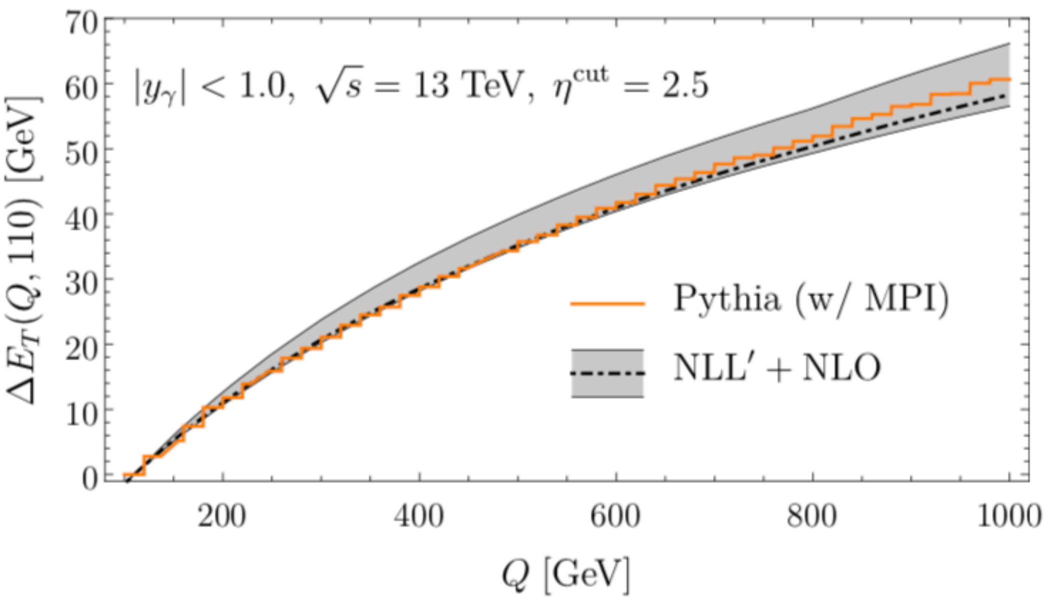
- MPI contributions cancel in subtraction between moments at Q and at Q_0

$$\begin{aligned}\Delta E_T(Q, Q_0) &\equiv \langle E_T(Q)\rangle - \langle E_T(Q_0)\rangle \\ &= \Delta E_{T,\text{pert}}(Q, Q_0)\end{aligned}$$



Subtraction of moments

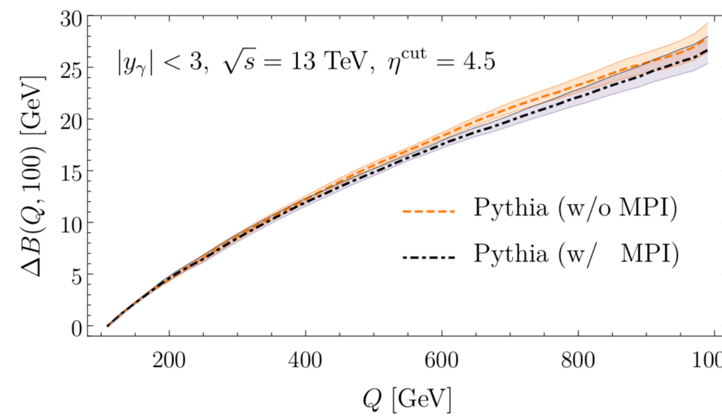
Transverse energy



Beam thrust (Pythia results)

$$B = \sum_{i\in X} p_T^{(i)} \exp(-\eta^{(i)})$$

$$\Delta B(Q, Q_0) \equiv \langle B(Q)\rangle - \langle B(Q_0)\rangle$$



Excellent agreement between subtracted moments w/ and w/ MPI!

Subtraction of higher-order moments

- Not simply additive beyond $n=1$

$$\langle E_T^n(Q)\rangle = \sum_{k=0}^{n} {}_nC_k \, \langle E_T^k(Q)\rangle_{\text{pert}} \times \langle E_T^{n-k}\rangle_{\text{MPI}}$$

- Subtracted moments for $n>1$ are sensitive to MPI.

$$\begin{aligned}
\Delta E_T^{(1)} &= \Delta E_{T,\text{pert}}^{(1)} \,, \\
\Delta E_T^{(2)} &= 2\Delta E_{T,\text{pert}}^{(2)} + \Delta E_{T,\text{pert}}^{(1)} \, \langle E_T\rangle_{\text{MPI}} \,, \\
\Delta E_T^{(3)} &= 3\Delta E_{T,\text{pert}}^{(3)} + 3\Delta E_{T,\text{pert}}^{(2)} \, \langle E_T\rangle_{\text{MPI}} + \Delta E_{T,\text{pert}}^{(1)} \, \langle E_T^2\rangle_{\text{MPI}}
\end{aligned}$$

One may need to find more sophisticated subtractions…

Subtracted *Cumulants*

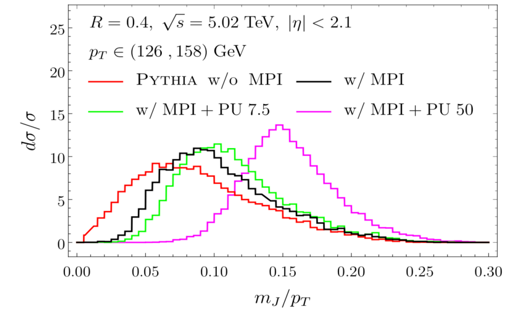
- The cumulant is an excellent quantity to generalize this idea
  - defined by a generating function
  - one-to-one correspondence with the moments
  - Additivity: if e_B and e_S are independent

$$\kappa_1(e) = \langle e \rangle$$
$$\kappa_2(e) = \langle e^2 \rangle - \langle e \rangle^2$$
$$\kappa_3(e) = \langle e^3 \rangle - 3\langle e^2 \rangle \langle e \rangle + 2\langle e \rangle^3$$

$$\kappa_n(e_S + e_B) = \kappa_n(e_S) + \kappa_n(e_B)$$

- At any n-th order the subtracted cumulants is insensitive to the uncorrelated contributions (e_B=UE, PU)
- Which observables applicable?
  Individual particle contributions are linearly added in total:
  transverse energy, beam thrust, jet thrust, jet mass (approx.), $\cdots$

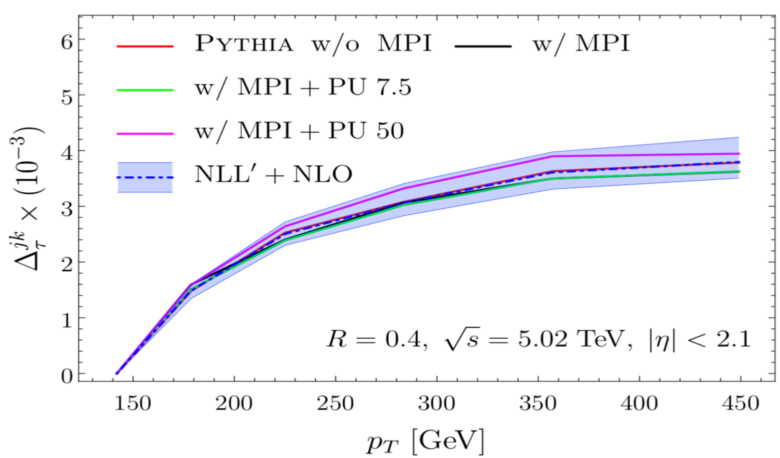
Example with jet substructure



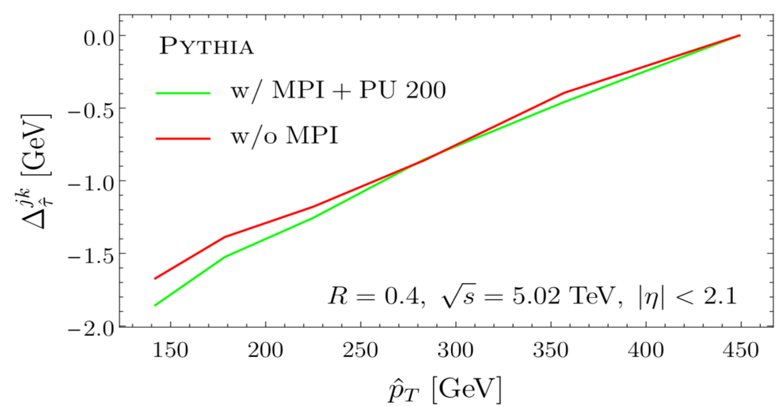
- jet mass $\hat{\tau} = 2\cosh(\eta)\sum_{i\in\text{jet}} p_i^+ = \frac{m_J^2}{p_T}\left[1 + \mathcal{O}\left(\frac{m_J^2}{p_T^2}\right)\right]$

- subtracted first cumulant $\Delta_\tau^{jk} = \langle\tau\rangle^{[j]} - \langle\tau\rangle^{[k]}\frac{\langle p_T^{-1}\rangle^{[j]}}{\langle p_T^{-1}\rangle^{[k]}}$

- robust under Pythia MPI and PU



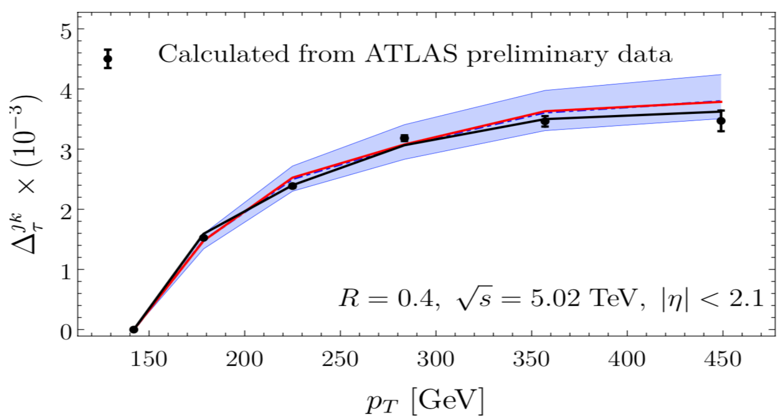
high luminosity (200 PU)



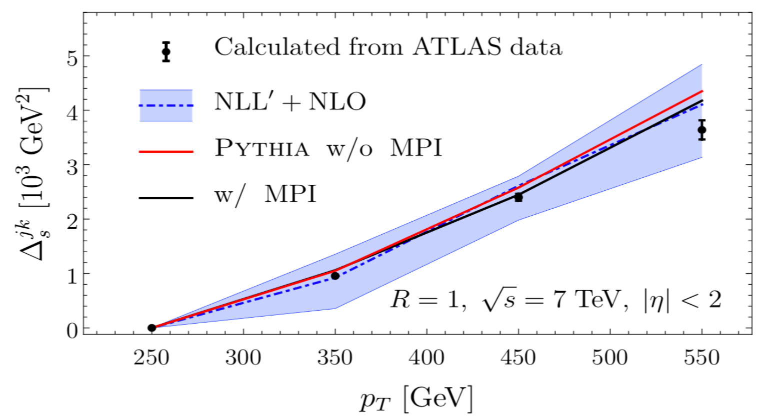
Comparison to ATLAS pp measurement

- We use ATLAS jet-mass distributions at 5 TeV and at 7 TeV and compute subtracted cumulants.

5 TeV ATLAS-CONF-2018-014



7 TeV JHEP 05,128 (2012)



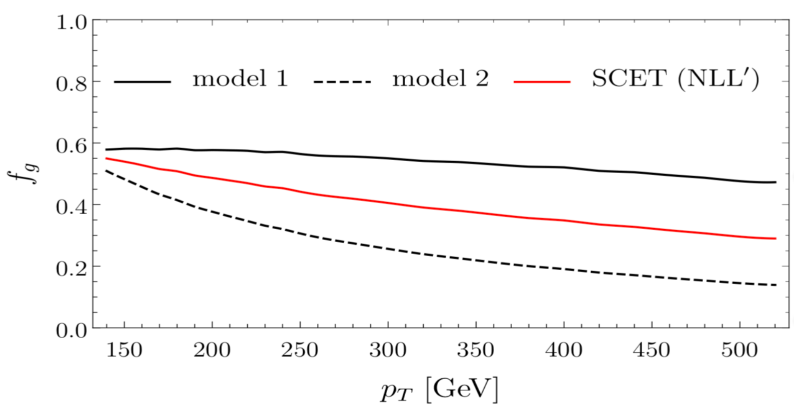
- two plots are different: $\tau = m_J^2/p_T^2$ (left) $s = m_J^2$ (right)
- *Error bars only include statistical uncertainties.*

Sensitivity to quark/gluon jet fraction

- Medium effect in heavy-ion collisions changes q/g jet fraction.

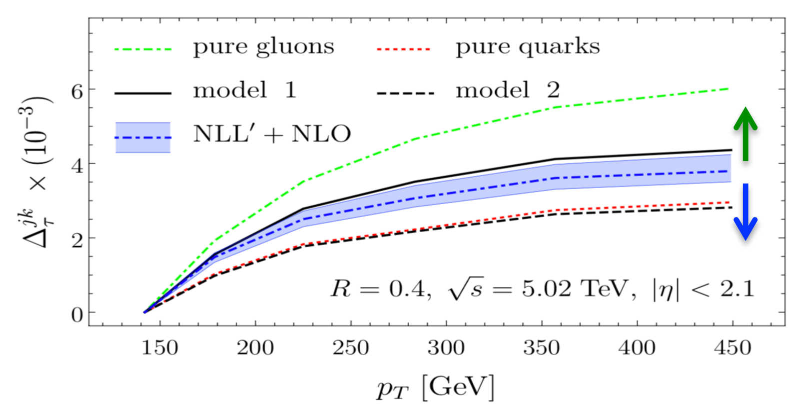
$$\langle \tau \rangle^{[j]} = f_g^{[j]} \, \langle \tau \rangle_g^{[j]} + (1 - f_g^{[j]}) \, \langle \tau \rangle_q^{[j]}$$

- Visible change in subtracted cumulant



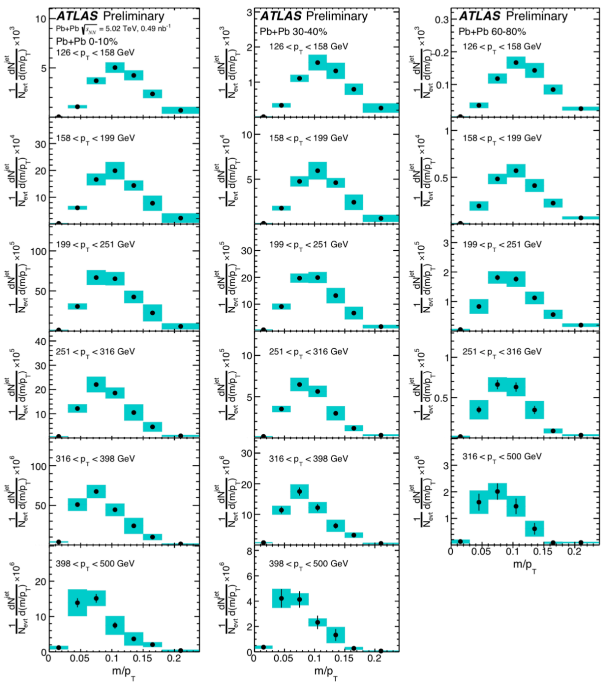
more gluons

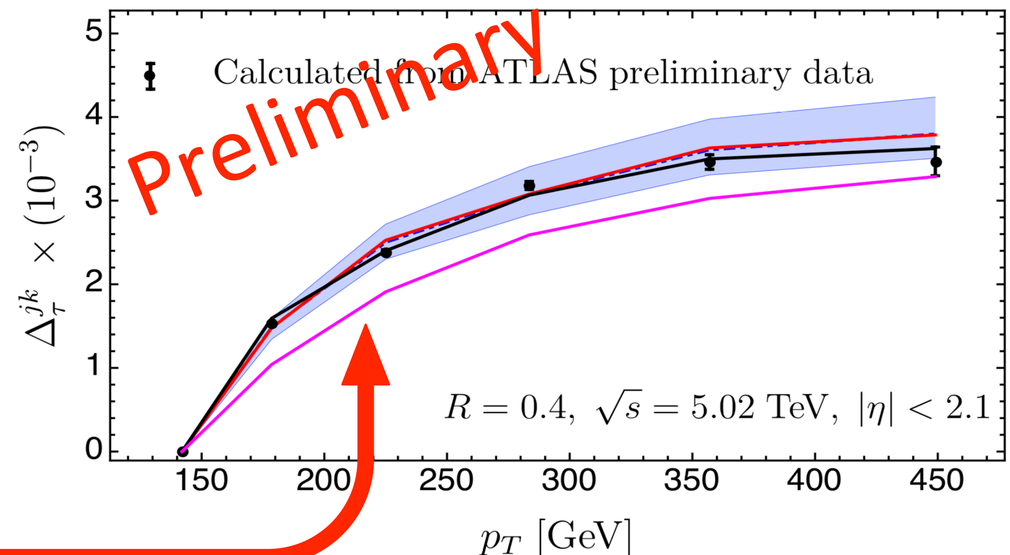
less gluons



Heavy-Ion collisions (ATLAS Pb+Pb)

ATLAS-CONF-2018-014





Summary

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- Excellent performance with a simple MPI model in DY.
  A subtracted moment mitigates large background (MPI/UE/PU).

- Subtracted cumulants:
  - valid for any n-th order cumulant
  - removing soft and uncorrelated particles
    while retaining soft and correlated particles (cf. soft drop)
  - new approach to jet physics using jet substructure observables
  - example: jet mass in a good agreement w/ ATLAS *pp* data

Outlook

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- higher-order cumulants and more jet substructure observables

- high-precision predictions beyond NLL'+NLO are available for several jet observables and can be tested.

- application to heavy-ion collisions with hard scattering

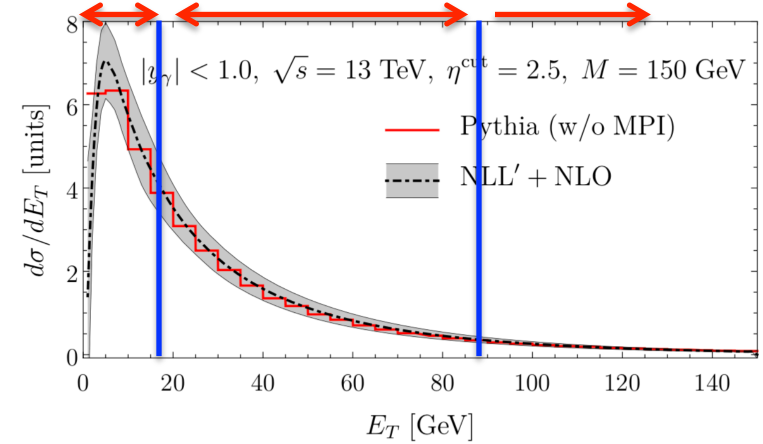
Thanks!

Perturbative prediction using SCET

$$\frac{d\sigma^{\text{pert}}}{dE_T} \otimes f_{\text{MPI}}$$

$$r = e^{-\eta_{\text{cut}} \mp y}$$

$E_T \lesssim Qr$ $\quad$ $E_T \gg Qr$ $\quad$ $E_T \sim Q$



- Region I: $\quad E_T \gg Qr$

$$E_T = \sum_{i \notin \{\ell^+, \ell^-\}} p_T^{(i)}$$

$$\text{soft}: \quad p_s^\mu = (p_s^+, p_s^-, p_s^\perp) \sim (E_T, E_T, E_T)$$

$$\text{collinear}: \quad p_c^\mu = (p_c^+, p_c^-, p_c^\perp) \sim (E_T^2/Q, Q, E_T)\ ,$$

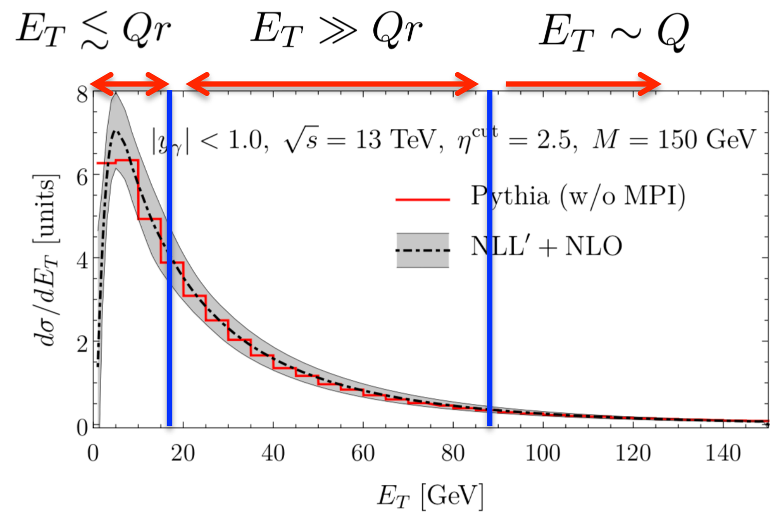
$$\frac{d\sigma^{(\mathrm{G})}}{dy\,dQ^2\,dE_T} = \sigma_0 H(Q;\mu) \times S_s(E_T;\mu,\nu) \otimes \mathcal{B}^{\mathrm{G}}_{q/P}(x_1, E_T;\mu,\nu) \otimes \mathcal{B}^{\mathrm{G}}_{\bar{q}/P}(x_2, E_T;\mu,\nu)$$

Perturbative prediction using SCET

- Region II: $E_T \lesssim Qr$

$$E_T(\eta_{\rm cut}) = \sum_{i \notin \{\ell^+,\ell^-\}} p_T^{(i)}\,\Theta(\eta_{\rm cut} - |\eta^{(i)}|)$$

$$\begin{aligned}
\text{(u}-\text{)soft}: &\quad p_s^\mu \sim (E_T, E_T, E_T) \\
\text{soft}-\text{collinear}: &\quad p_{sc}^\mu \sim (E_T r, E_T/r, E_T) \\
\text{collinear}: &\quad p_c^\mu \sim (Qr^2, Q, Qr)\,.
\end{aligned}$$



$$\frac{d\sigma^{(\rm II)}}{dy\,dQ^2\,dE_T} = \sigma_0 H(Q) \times S_s(E_T) \otimes [S_n \otimes \mathcal{B}^{\rm II}_{q/P}](x_1, E_T, r) \otimes [S_{\bar n} \otimes \mathcal{B}^{\rm II}_{\bar q/P}](x_2, E_T, r)$$

- resumming Log[E_T/Q], Log[r] upto NLL by evolving H, S, B
- Region E_T~Q: fixed-order perturbation theory at NLO