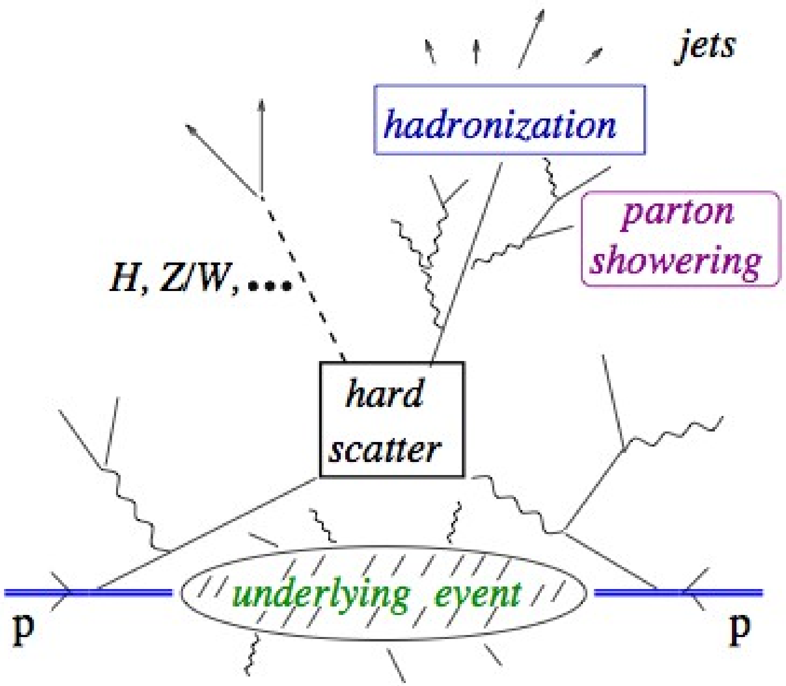


Lecture 1

MOTIVATION

BASIC QCD FACTORIZATION RESULTS

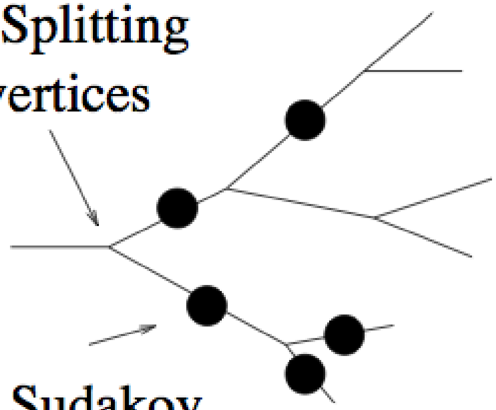
Lecture 2

PARTON SHOWERING

EXAMPLES

Lecture 2

PARTON SHOWERING INCLUDING TMDs



Based on reviews in
H, Acta Phys. Pol. B40 (2009) 2139;
ibid. B44 (2013) 761

COLLINEAR RADIATION:

$$d\mathcal{P} = \int \frac{dq^2}{q^2} \int dz \; \alpha_S \; P(z) \; \Delta(q^2, q_0^2)$$

• based on dominance of collinear evolution of jets developing (both "forwards" and "backwards") from hard event

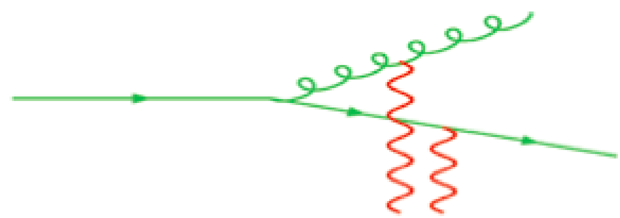
• Factorization of QCD cross sections in collinear limit
$\longrightarrow$ probabilistic picture

• summation of logarithmically enhanced radiative contributions
$(\alpha_S \;\; \ln p_T/\Lambda)^n$

NEXT: INCLUDE SOFT RADIATION

A) Soft gluon radiation by coherent branching

▷ soft gluons radiated over long times $\longrightarrow$ quantum interferences



$\swarrow$ factorization in soft limit

$$|M_{n+1}^{a_1 \ldots a_n a}(p_1, p_n, q)\rangle = \mathbf{J}^a |M_n^{a_1 \ldots a_n}(p_1, p_n)\rangle \ , \quad \mathbf{J}^{a\mu} = \sum_i \mathbf{Q}_i^a \, \frac{p_i^\mu}{p_i \cdot q} \ , \ \mathbf{Q} = \text{color charge}$$

interference terms $\downarrow$

$$d\sigma_{n+1} = d\sigma_n \ \frac{d^3 q}{(q^0)^3} \ \sum_{i,j} \mathbf{Q}_i \cdot \mathbf{Q}_j \ w_{ij} \quad , \qquad w_{ij} = \frac{(q^0)^2 \ p_i \cdot p_j}{(p_i \cdot q)(p_j \cdot q)}$$

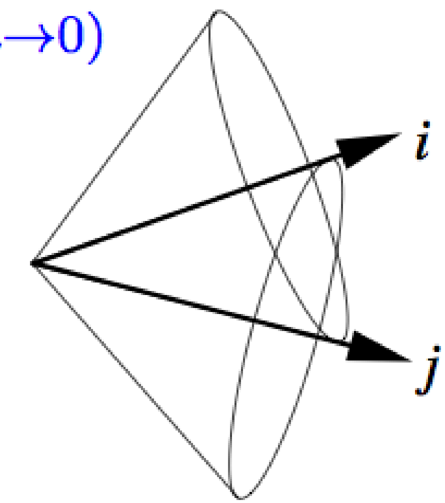
$\rightarrow$ spoils probabilistic picture? NO, owing to soft-gluon coherence $\hookrightarrow$

♣ single-emission: separate singularities along emitters' directions

$$\frac{(q^0)^2 p_i \cdot p_j}{(p_i \cdot q)(p_j \cdot q)} \equiv \frac{\zeta_{ij}}{\zeta_{iq}\zeta_{jq}}$$

$$= \frac{1}{2}\left(\frac{\zeta_{ij}}{\zeta_{iq}\zeta_{jq}} - \frac{1}{\zeta_{jq}} + \frac{1}{\zeta_{iq}}\right) + \frac{1}{2}\left(\frac{\zeta_{ij}}{\zeta_{iq}\zeta_{jq}} - \frac{1}{\zeta_{iq}} + \frac{1}{\zeta_{jq}}\right)$$

where $\zeta_{nk} \equiv \frac{p_n \cdot p_k}{p_n^0 p_k^0} \simeq 1 - \cos\theta_{nk} \quad (m \to 0)$



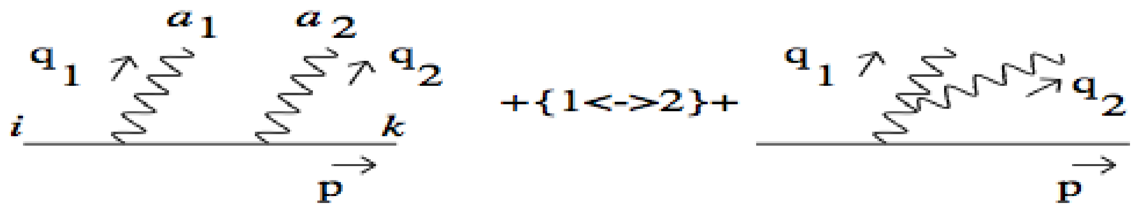
→ by azimuthal average

$$\langle \frac{\zeta_{ij}}{\zeta_{iq}\zeta_{jq}} \rangle = \frac{1}{\zeta_{iq}} \Theta(\zeta_{ij} - \zeta_{iq}) + \frac{1}{\zeta_{jq}} \Theta(\zeta_{ij} - \zeta_{jq})$$

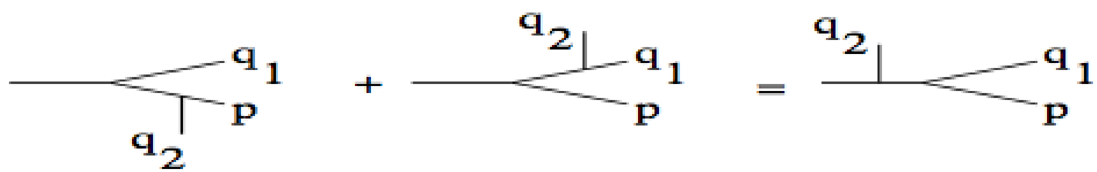
- large-angle emissions of soft gluons sum coherently outside angular-ordered cones

♣ multiple emission: (q_1, q_2 with $q_2^0 \ll q_1^0$)

$$\mathbf{J}_1^{\mu a_1} = \mathbf{Q}_p^{a_1} \frac{p^\mu}{p \cdot q_1} \quad , \quad \mathbf{J}_2^{\mu a_2} = \mathbf{Q}_p^{a_2} \frac{p^\mu}{p \cdot q_2} + \mathbf{Q}_{q_1}^{a_2} \frac{q_1^\mu}{q_1 \cdot q_2}$$



(a)



(b)

$$\mathcal{M}_{ki}^{a_1 a_2} = g_s^2 \, \langle a_1 \; k | \; \mathbf{J}_2 \cdot \varepsilon_2 \; | a' \; i' \rangle \; \langle \; i' \; | \mathbf{J}_1 \cdot \varepsilon_1 | \; i \; \rangle$$

$$= g_s^2 \, \frac{p \cdot \varepsilon_1}{p \cdot q_1} \left(\frac{p \cdot \varepsilon_2}{p \cdot q_2} \, t^{a_2} t^{a_1} + \frac{q_1 \cdot \varepsilon_2}{q_1 \cdot q_2} \, [t^{a_1}, t^{a_2}] \right)_{ki}$$

- small angle: bremsstrahlung cones
- large angle ($\theta_{pq_2} \gg \theta_{pq_1}$): sees total charge $\mathbf{Q}_p + \mathbf{Q}_{q_1}$

B) Coherence in the high energy limit

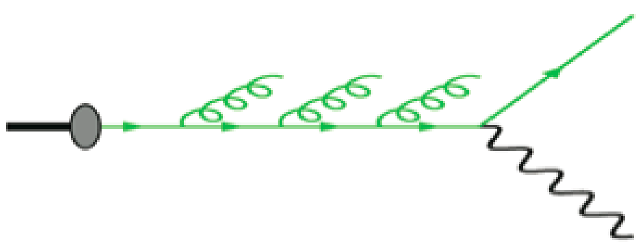
Arguments on soft vector emission current from external legs →

- leading IR singularities

[J.C. Taylor, 1980]

- fully appropriate in single-scale hard processes

Dokshitzer, Khoze, Mueller and Troian, RMP (1988); Webber, A. Rev. Nucl. Part. (1986)



multi-scale: $s = q_1^2 \gg \cdots \gg q_n^2 \gg \Lambda^2$
[e.g.: LHC final states with multi-jets]

$\Downarrow$

▷ internal emissions non-negligible

▷ current also factorizable at high-energy: *[Ciafaloni 1998; 1988]*

$$\begin{aligned} |M^{(n+1)}(k,p)|^2 &= \{[M^{(n)}(k+q,p)]^\dagger \, [\mathbf{J}^{(R)}]^2 \, M^{(n)}(k+q,p) \\ &- [M^{(n)}(k,p)]^\dagger \, [\mathbf{J}^{(V)}]^2 \, M^{(n)}(k,p)\} \quad . \end{aligned}$$

BUT... ▷

▷ … • J depends on total transverse momentum transmitted

⇒ matrix elements and pdf at fixed $k_\perp$ ("TMDs")

• virtual corrections not fully represented by Δ form factor

⇒ modified branching probability $P(z, k_\perp)$ as well

▷ enhanced terms $\mathcal{O}(\alpha_S^k \ln^m s/p_T^2)$

◇ Note: superleading logs $m > k$ cancel in fully inclusive quantities

e.g: high-energy corrections to anomalous dimensions γ^{ij}

at most single-logarithmic

$$\gamma^{ij}(\alpha_s, \omega) = \frac{\alpha_s}{\omega^p} \, c_0^{ij} \left[1 + \sum_{n=1}^{\infty} c_n^{ij} \left(\frac{\alpha_s}{\omega} \right)^n + \mathcal{O}\left(\alpha_s \left(\frac{\alpha_s}{\omega} \right)^{n-1} \right) \right]$$

ω - moment conjugate to $\ln s$ *BFKL; Jaroszewicz; Catani et al.*

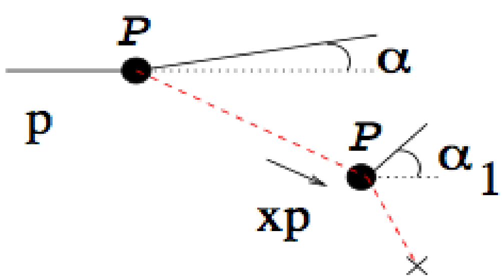
◇ but cancellations do not apply in exclusive final-state correlations

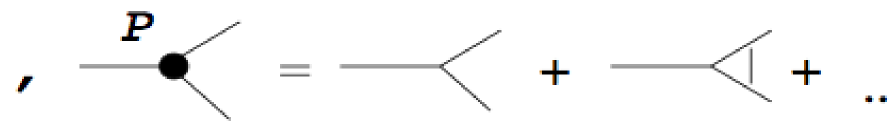
$K_\perp$-DEPENDENT PARTON BRANCHING

- MC for (almost-)NLO QCD evolution at unintegrated level
  proposed in Jadach & Skrzypek, arXiv:0905.1399 [hep-ph]

- $\{x\to 0\} \oplus \{x\to 1\}$ gluon branching eq. (leading-logarithms, all orders in α_s)
  CCFM evolution equation [Marchesini et al., 1990's]

$$\mathcal{G}(x,k_T,\mu) = \mathcal{G}_0(x,k_T,\mu) + \int \frac{dz}{z} \int \frac{dq^2}{q^2}\, \Theta(\mu - zq) \times \underbrace{\Delta(\mu, zq)}_{\text{Sudakov}} \, \underbrace{\mathcal{P}(z,q,k_T)}_{\text{unintegr. splitting}} \, \mathcal{G}\left(\frac{x}{z}, k_T + (1-z)q, q\right)$$





▷ Monte Carlo implementations CASCADE, LDCMC, ...

- unintegrated quark with k_T-dependent branching
  $\hookrightarrow$ ongoing work

CCFM exclusive evolution

→ Catani-Ciafaloni-Fiorani-Marchesini (1990's)

$$x\mathcal{A}(x,k_t,q) = x\mathcal{A}(x,k_t,q_0)\Delta_s(q) + \int dz \int \frac{dq'}{q'} \cdot \frac{\Delta_s(q)}{\Delta_s(q')} \tilde{P}(z,k_t,q') \frac{x}{z} \mathcal{A}\left(\frac{x}{z}, q'\right)$$

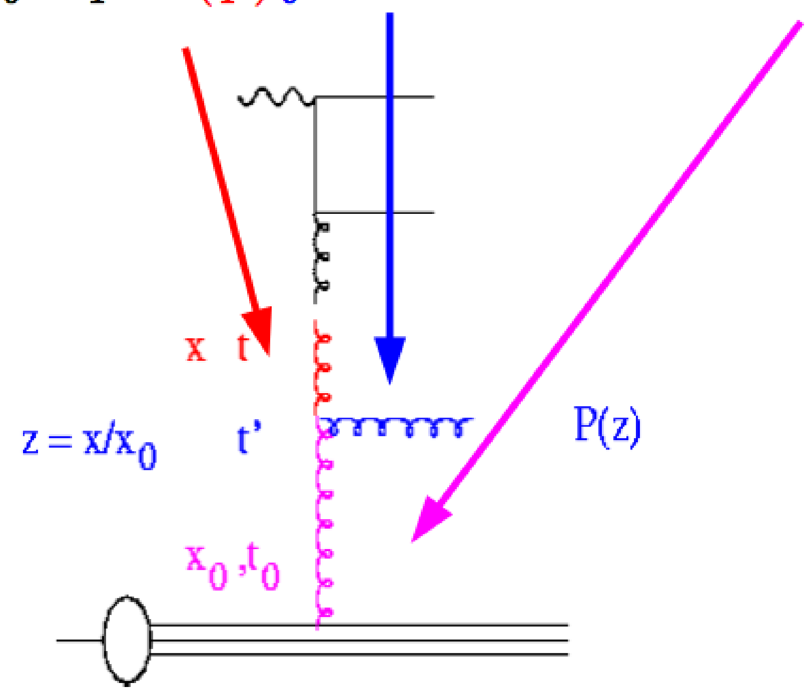
- solve integral equation via iteration:

from q' to q w/o branching | branching at q' | from q_0 to q' w/o branching

$$x\mathcal{A}_0(x,k_t,q) = x\mathcal{A}(x,k_t,q_0)\Delta(q)$$

$$x\mathcal{A}_1(x,k_t,q) = x\mathcal{A}(x,k_t,q_0)\Delta(q) + \int \frac{dq'}{q'} \frac{\Delta(q)}{\Delta(q')} \int dz \tilde{P}(z) \frac{x}{z} \mathcal{A}(x/z, k_t', q_0)\Delta(q')$$

- Note: evolution equation formulated with Sudakov form factor is equivalent to “plus” prescription, but better suited for numerical solution for treatment of kinematics

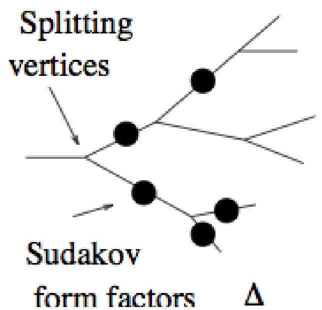


- evolution code uPDFevolv [Jung, Taheri Monfared & H, arXiv:1407.5935]

FROM QCD TO MONTE CARLO EVENT GENERATORS

- Factorizability of QCD x-sections $\longrightarrow$ probabilistic branching picture

  ◇ QCD evolution by "parton showering" methods:

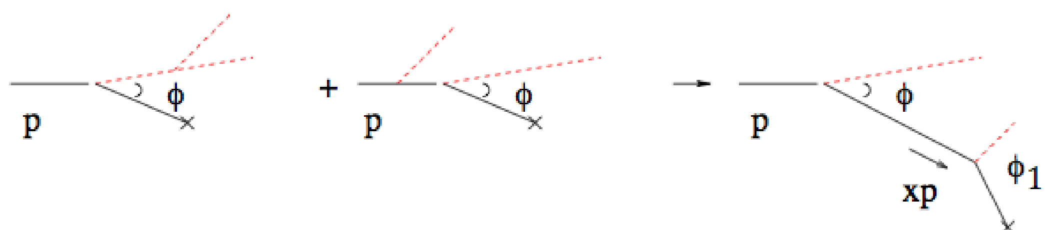


$$d\mathcal{P} = \int \frac{dq^2}{q^2} \int dz \, \alpha_S(q^2) \, P(z) \, \Delta(q^2, q_0^2)$$

$\hookrightarrow$ collinear, incoherent emission

◇ Soft emission $\longrightarrow$ interferences $\longrightarrow$ ordering in decay angles:

$\hookrightarrow$ gluon coherence for $x \sim 1$



◇ Gluon coherence for $x \ll 1$ $\Rightarrow$ corrections to angular ordering:

$\hookrightarrow$ $k_\perp$-dependent parton showers

CCFM equation is TMD branching equation which contains both Sudakov physics and BFKL physics

EXAMPLES:

TMD kinematic effects in parton shower evolution

Kinematic effects in parton shower evolution

S. Dooling, talk at DIS 2013, Marseille

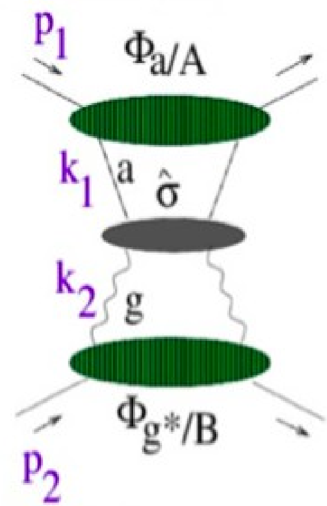
Longitudinal Momentum Shift

Dooling et al.
arXiv:1212.6264

In SMC:

hard subprocess is generated with full 4-momentum for the external lines

Factorized jet cross section at high rapidity



Momentum of the partons initiating the hard scatter: $k_j^{(0)} = x_j p_j$ on-shell and fully collinear with the incoming momenta

Applying shower algorithm

Complete final states: $k_j \neq x_j p_j$ no longer collinear

Energy momentum conservation ▷ Reshuffling in x_j (long. mom fraction)

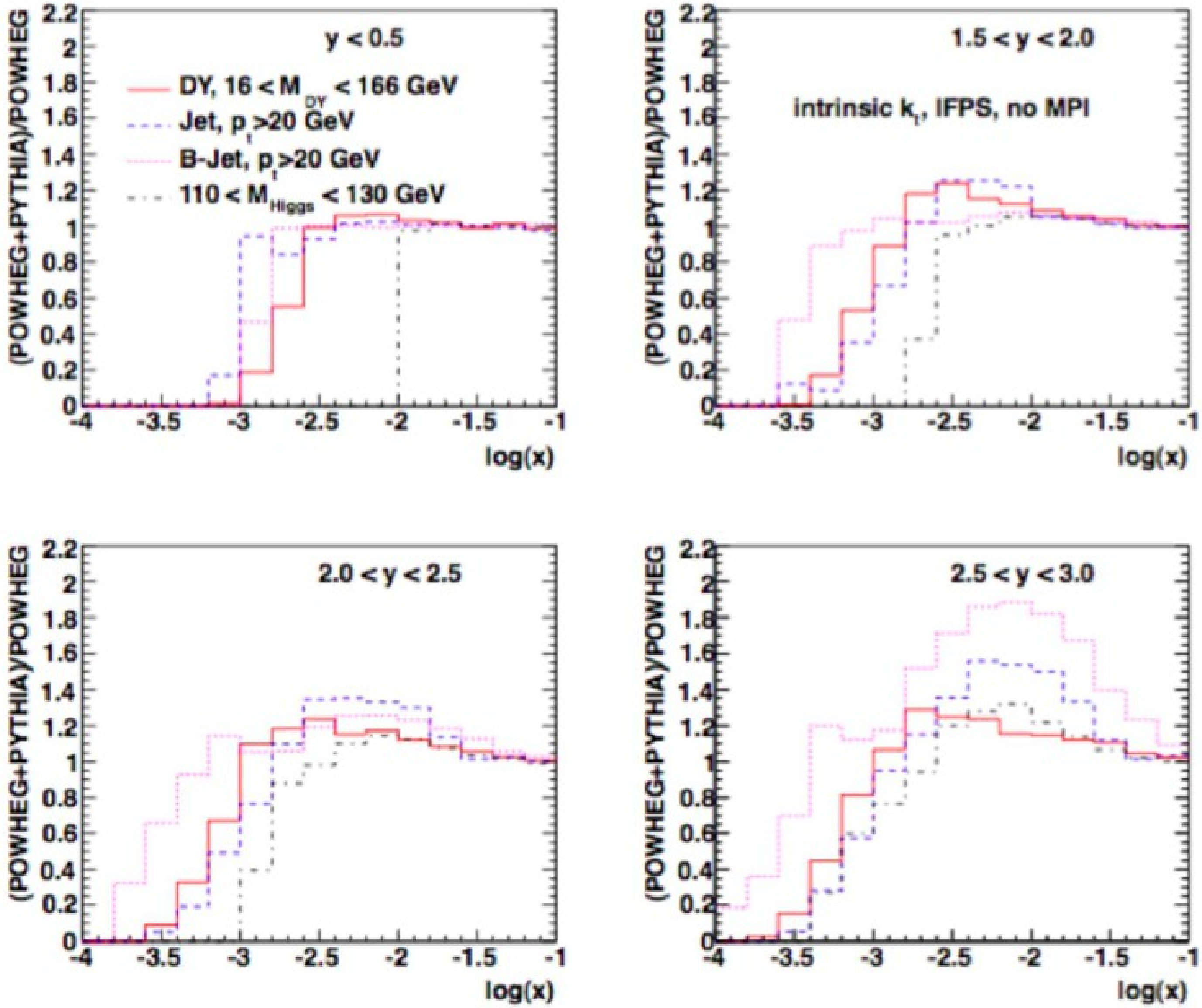
Collinear approximation ⊗ energy momentum conservation

=

kinematic shift in longitudinal momentum distribution due to showering

TMD effects in pp collisions

- Transverse momentum dependent (TMD) effects are relevant for many processes at the LHC
- parton shower matched with NLO generates additional k_t, leading to energy-momentum mismatch
- avoided by using formulation with TMD distributions from the outset



NONPERTURBATIVE (NP) AND SHOWERING (PS) CORRECTIONS

- Estimates using leading order (LO-MC):

$$K_0^{NP} = N_{LO-MC}^{(ps+mpi+had)} / N_{LO-MC}^{(ps)}$$

[CMS, PRL 107 (2011) 132001; ATLAS, PRD86 (2012) 014022]

— natural definition with LO-MC

— but affected by potential inconsistency if combined with NLO parton-level results

- Alternatively, assign NP correction factors by using NLO-MC:

[Dooling, Gunnellini, Jung & H, arXiv:1212.6164 [hep-ph]]

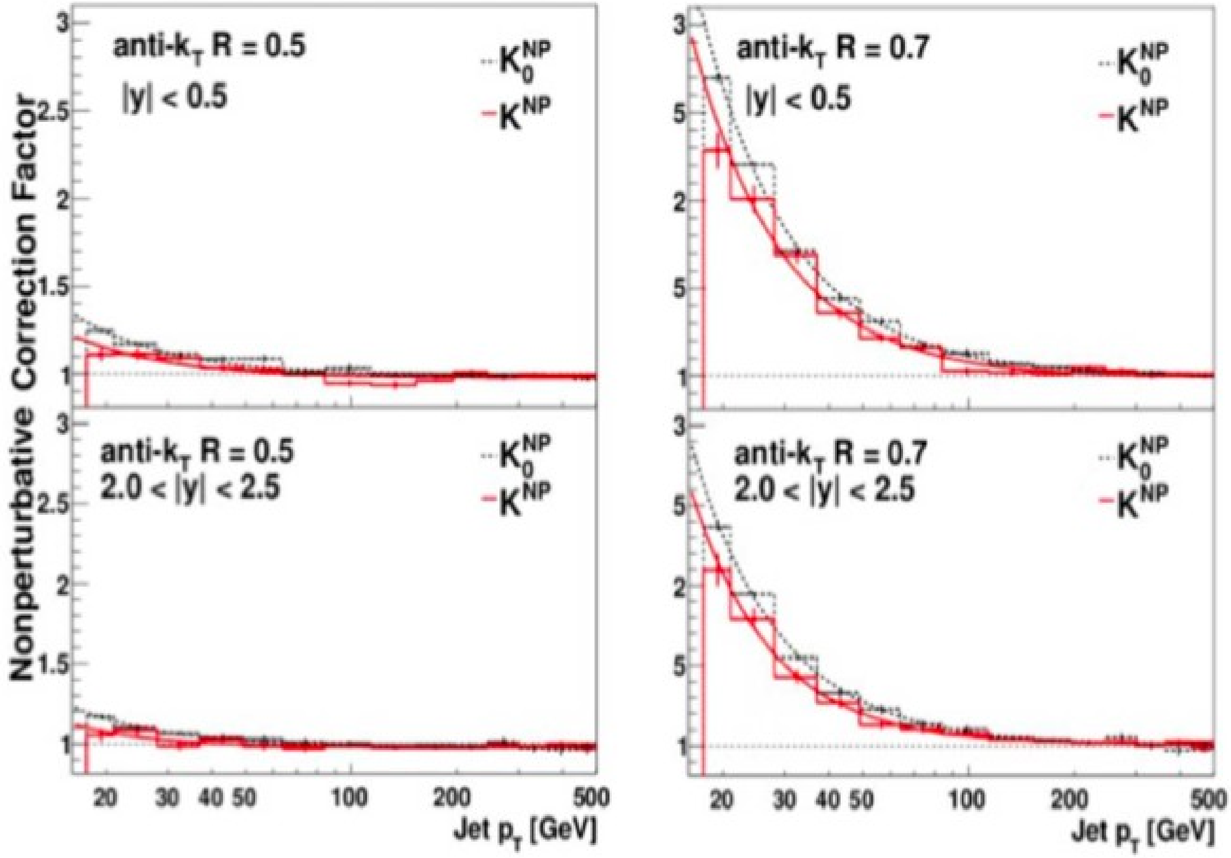
$$K^{NP} = N_{NLO-MC}^{(ps+mpi+had)} / N_{NLO-MC}^{(ps)}$$

$$K^{PS} = N_{NLO-MC}^{(ps)} / N_{NLO-MC}^{(0)}$$

♣ K^{NP} differs from K_0^{NP}

♣ K^{PS} is new

Nonperturbative Correction



Non-negligible effect from nonperturbative effects at small p_T

Difference between LO and NLO correction

▷ Matching of MPI to the NLO calculation because the MPI p_T scale is different in LO and NLO

$$K_0^{NP} = K_{LO-MC}^{(ps+mpi+had)} / K_{LO-MC}^{(ps)}$$

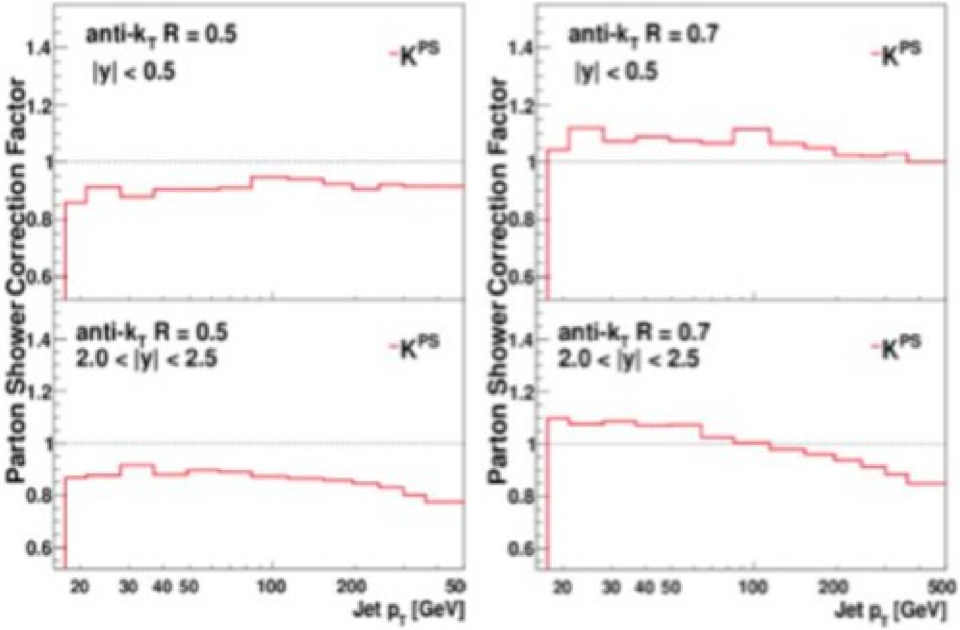
$$K^{NP} = K_{NLO-MC}^{(ps+mpi+had)} / K_{NLO-MC}^{(ps)}$$

Dooling et al.
arXiv:1212.6264

S. Dooling, talk at DIS 2013, Marseille

Parton Shower Correction

Dooling et al.
arXiv:1212.6264

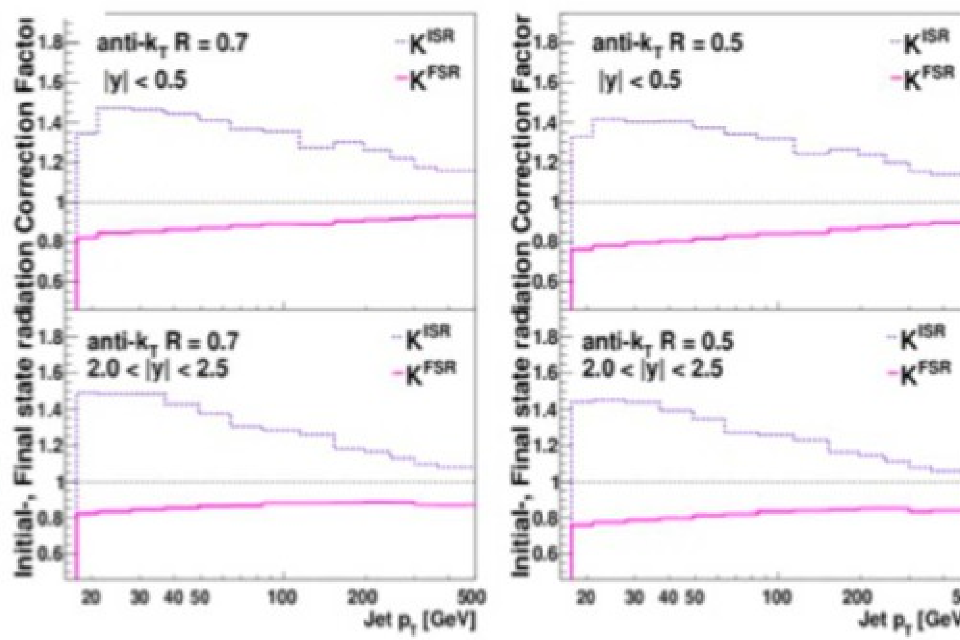


$$K^{PS} = K^{(ps)}_{NLO-MC} / K^{(0)}_{NLO-MC}$$

- Depends on rapidity and p_T especially in the forward region
- Finite effect also at large p_T

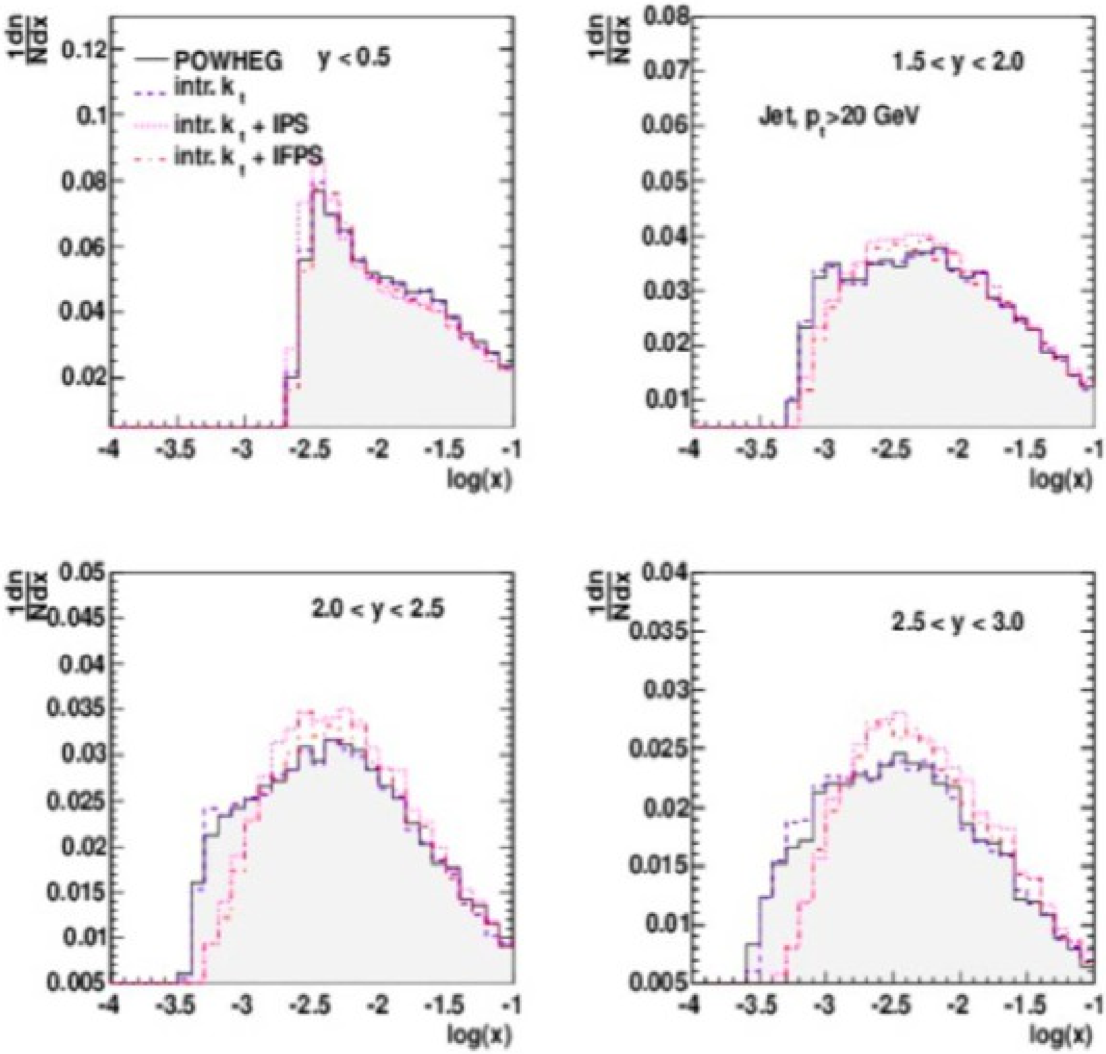
- Initial and Final State Parton Shower considered independently
- But they are interconnected: The combined effects cannot be obtained by adding the individual contributions
- ISR largest at low p_T, FSR significant for all p_T

[S. Dooling, talk at DIS 2013]



Longitudinal Momentum Shift – Inclusive Jets

Jet measurement in the rapidity range $y < 2.5$



Compute x_j from POWHEG before parton showering and after parton showering (using PYTHIA6)

Kinematic reshuffling in x is negligible for central rapidities but becomes significant for $y > 1.5$

▷ Kinematic shift can affect predictions through the PDFs

Dooling et al.
arXiv:1212.6264

[S. Dooling, talk at DIS 2013]

EXAMPLES:
VECTOR BOSON + JETS
FINAL STATES

Application to vector bosons + jets

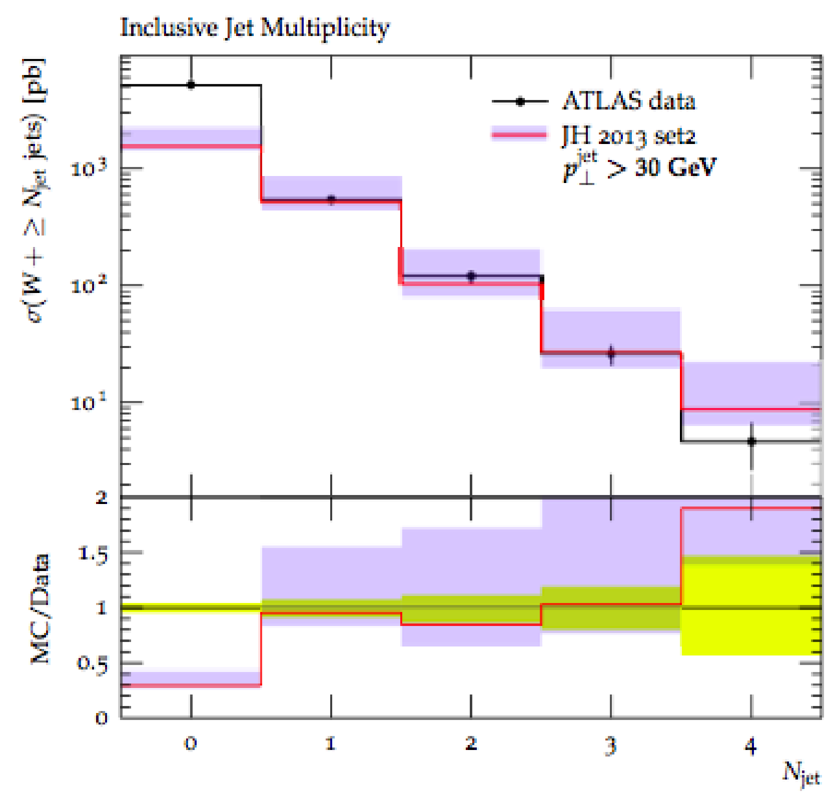
- Motivation: effects of not only collinear-ordered emissions but also non-ordered region which opens up at high s / pt^2 (and large pt).
- Finite angle multi-gluon radiation.
- Push limits of high-energy expansion beyond small-x region.

- Jet multiplicities associated with W boson production

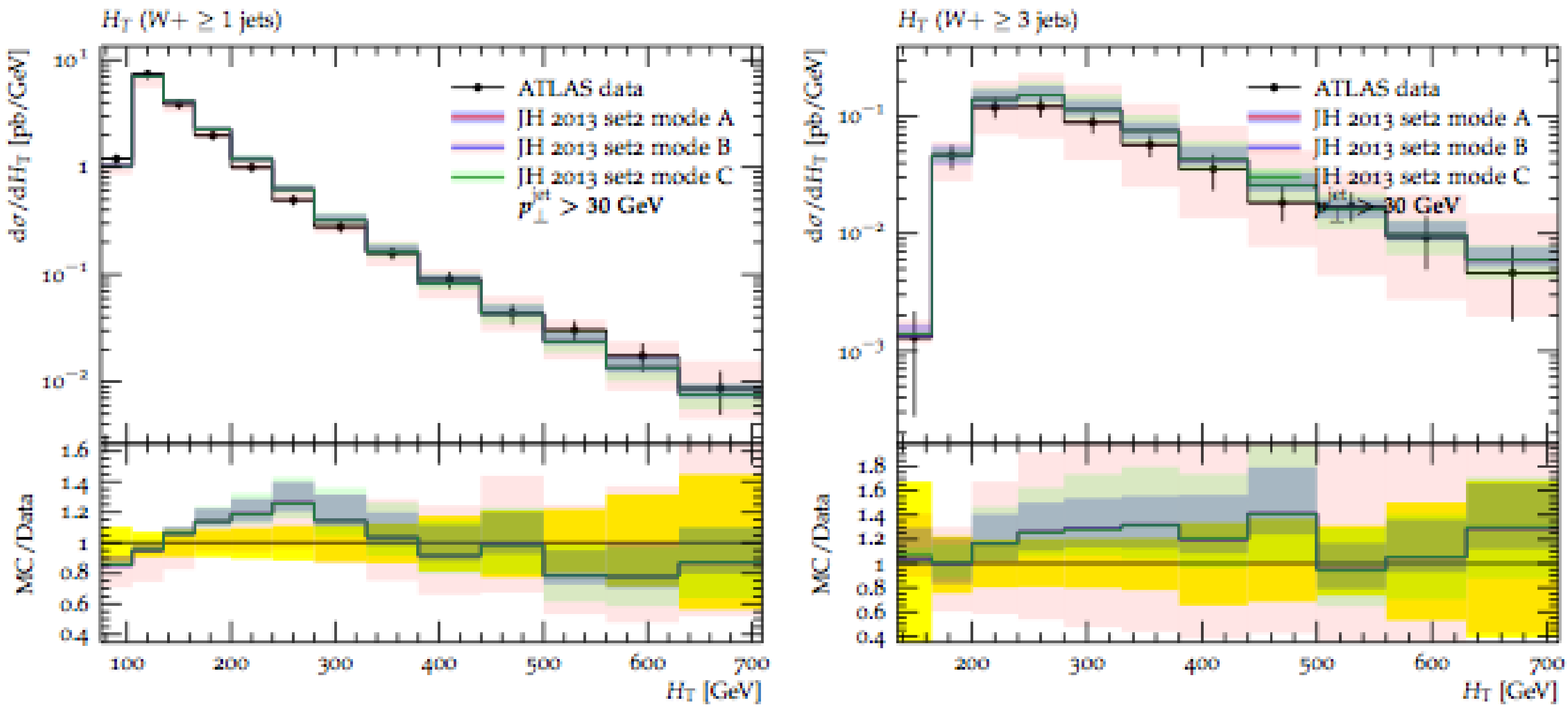
Atlas data PRD85 (2012) 092002: jet | y | < 4.4

Note: pt-ordered shower (eg, Pythia) cannot predict higher jet multiplicities

- Role of transverse-momentum kinematics on jets produced at moderately non-central rapidities



Theoretical uncertainties larger for larger H_T (increasing x) and, at fixed H_T, for higher jet multiplicities

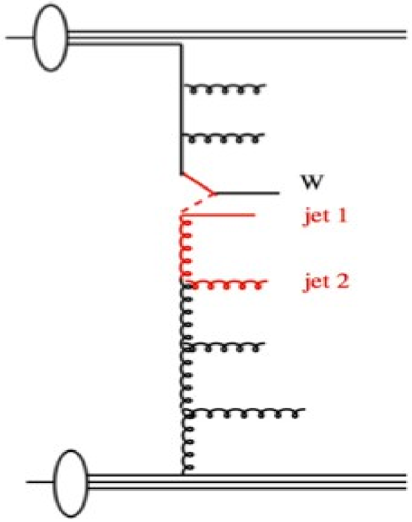


mu^2 = m^2 + qT^2

Dooling, Jung & H, Phys. Lett. B736 (2014) 293

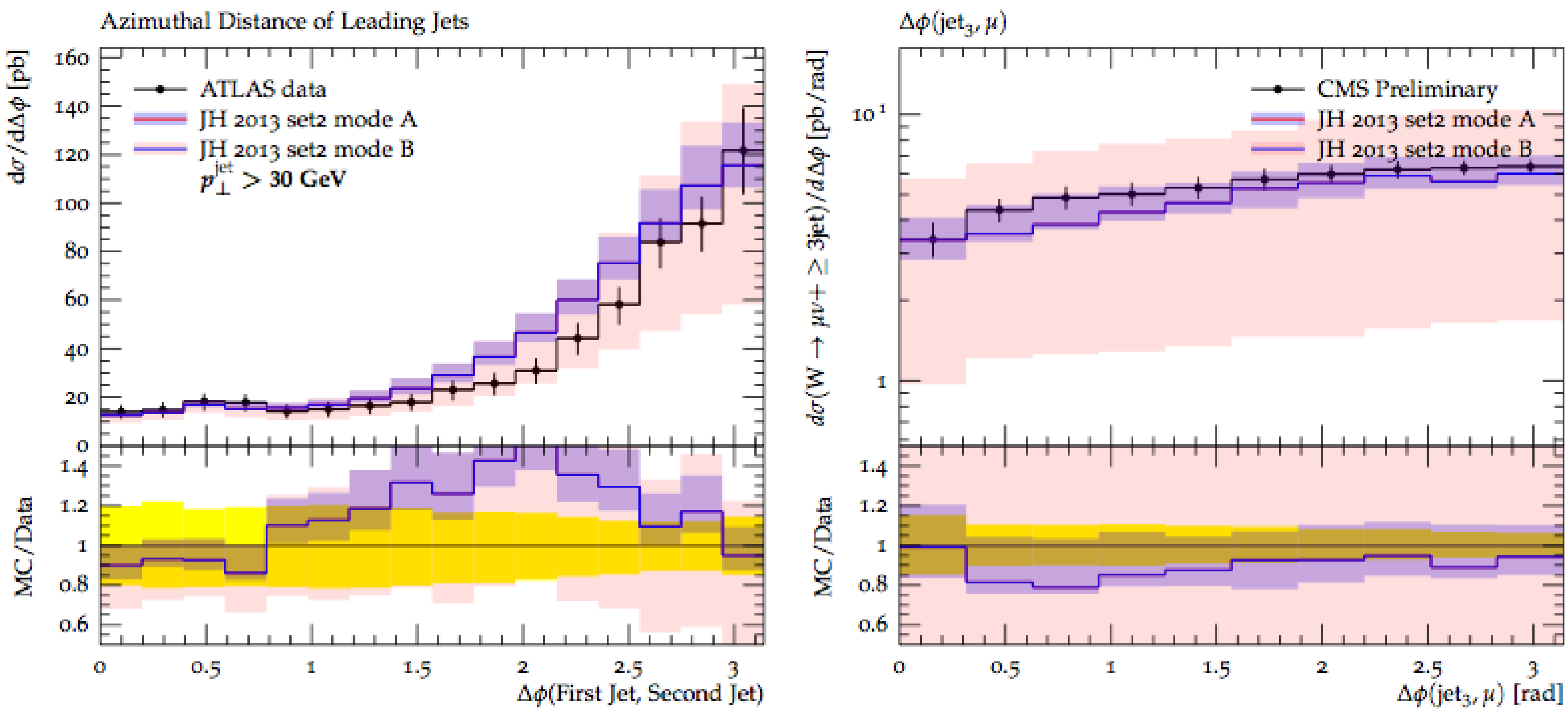
Mode C: vary transverse part of mu^2 by factor 2 above and below central value (more closely related to standard collinear calculations)

Mode B: include variation of longitudinal component (more conservative estimate – unlike standard collinear approximations)



Angular correlations in W + n jets final states

Dooling, Jung & H, Phys. Lett. B 736 (2014) 293



(left) Delta-phi between two hardest jets; (right) vector boson - third jet correlation

What do we gain?

- Uses of TMD pdfs + kt-dependent shower:

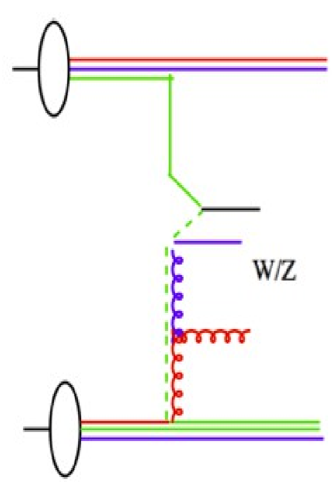
  matching with 2 $\longrightarrow$ n off-shell parton calculations

  (automated method, see van Hameren, Kotko & Kutak JHEP 1301 (2013) 078)
- Opens possibility for full LHC phenomenology of QCD, EWK and BSM processes

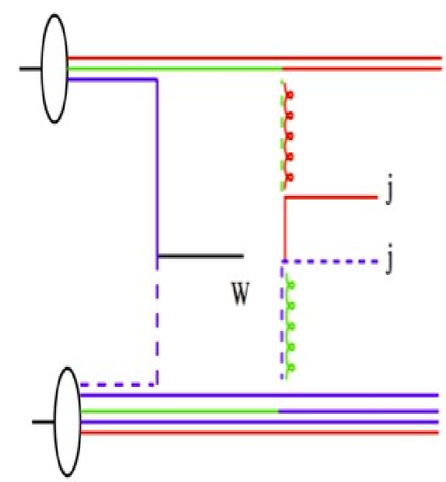
W + 2 jets as signal of double parton interactions

- Influence of TMD corrections to shower evolution on analysis of DPI?

- Formalism interpolates from low pT to high pT
- Incorporates experimental information from high-precision DIS measurements
- Takes into account transverse momentum kinematics without approximations in the branching

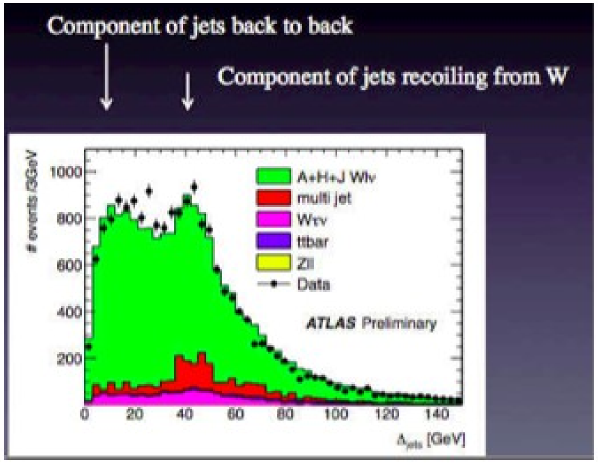


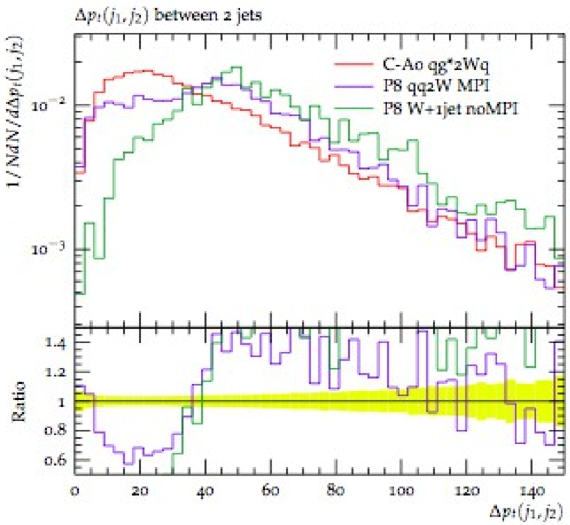
Single chain

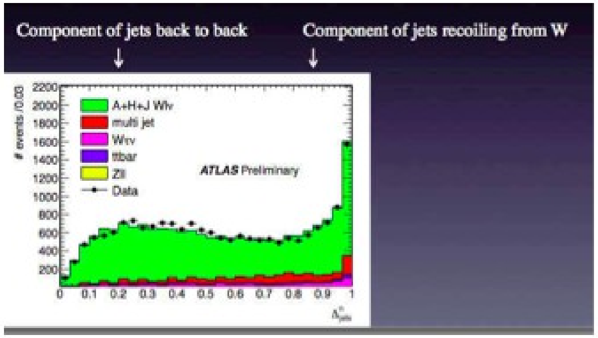


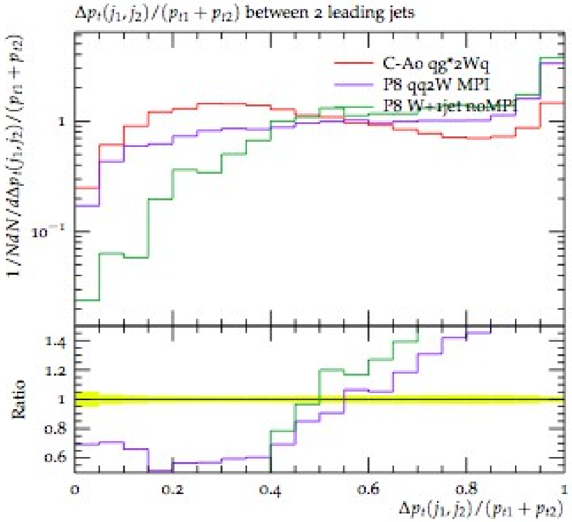
Double chain

W + 2 jets: signal for double parton interactions?









[E. Dobson, talk at MPI-TAU Workshop, October 2012]

ATLAS, New J Phys 15 (2013) 033038

For jet pT = O(20 GeV) effects from higher orders in kt-shower significant

Conclusion

- TMD parton distributions and showers relevant to both large pT and small pT processes, high x and low x:

  TMDlib platform http://tmdlib.hepforge.org/

- First determination of TMD gluon from combined high-precision DIS data, including uncertainties [→ herafitter]

- The approach has far reaching implications for LHC physics:

  treatment of kinematic corrections to parton showers;

  studies of theor uncertainties in multi-particle final states;

  ex.: W + jets pT spectra and angular correlations