DESY, June 2013

QCD and LHC Physics

F. Hautmann (Oxford & Sussex)

I. Motivation: Probing fundamental interactions at the shortest distances with TeV colliders

II. QCD calculational methods for high-energy scattering

III. Applications to heavy boson and jet final states at the LHC

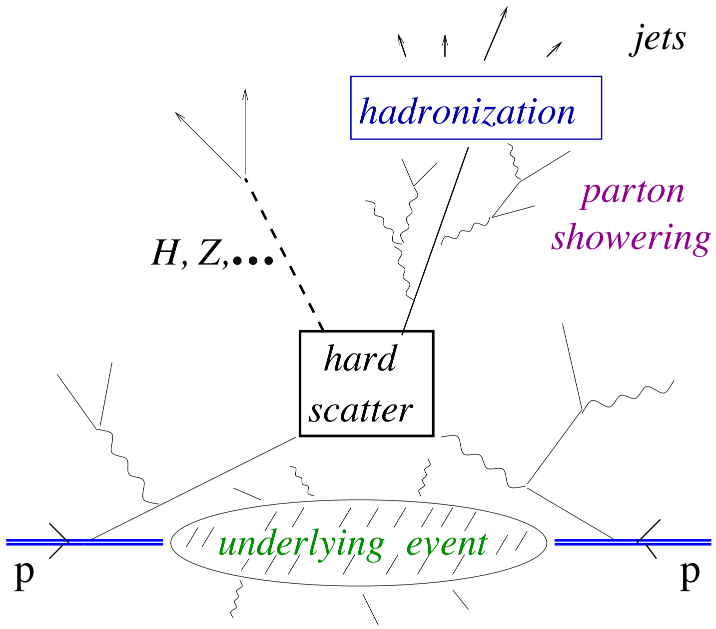
MOTIVATION

Physics at the TeV scale with the Large Hadron Collider:

- elucidate electroweak symmetry breaking
- uncover new aspects of the Standard Model
- search for physics beyond the SM

♠ Quantum Chromodynamics has key role in all of these areas

LHC pp collision event

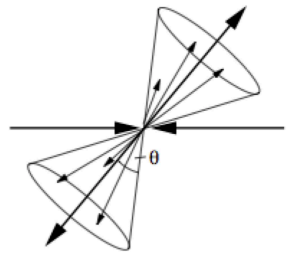


♣ Higgs and BSM searches based on study of
events containing energetic leptons, photons and jets

♣ strong interactions measured in new high-energy regions:
parton matter at high density; high energy limit of hadron scattering

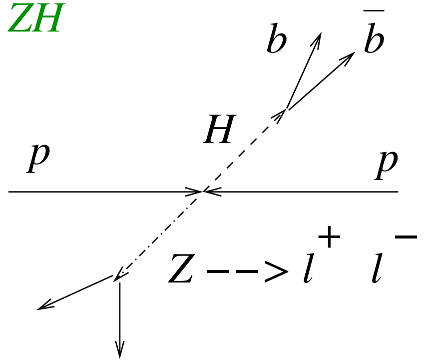
Example: hadronic-event and jet-shape variables

♠ event shape variables long been used to characterize QCD final states and event's energy flow



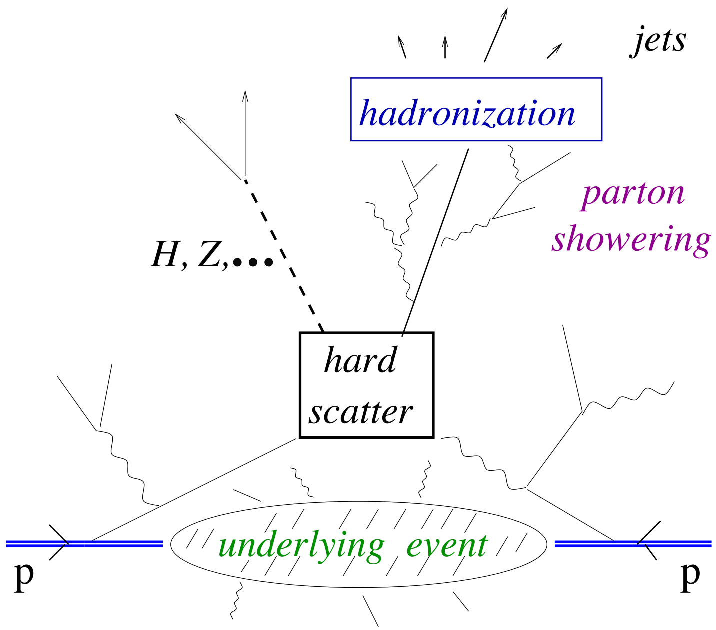
♠ shape variables describing jet's internal structure proposed for searches from highly boosted states at the LHC

e.g. Higgs–bottom coupling in
pp --> ZH



⇒ data interpretation requires understanding of overall QCD dynamics

- e.g., variables sensitive to jet substructure are also sensitive to initial state dynamical effects: pile-up, underlying events, multi-parton interactions, showering



QCD uses an array of techniques to treat high-energy multi-particle production:

- factorization of long-distance dynamics
- perturbative calculat.'s of short-distance processes at fixed order in α_s
- resummation of enhanced radiative corrections to all orders of PT

Outline

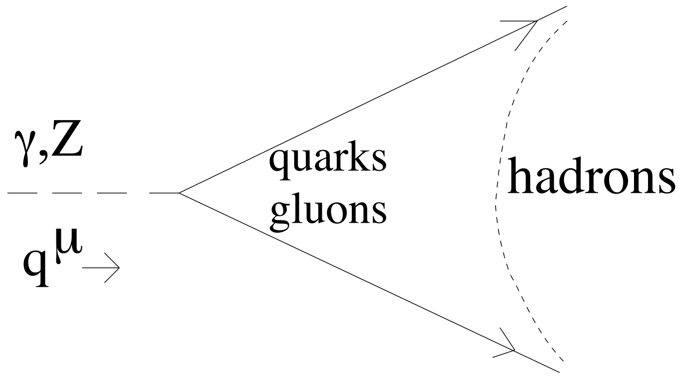
OVERVIEW OF FACTORIZATION PRINCIPLES

PARTON SHOWERING AND NONPERTURBATIVE EFFECTS

EXAMPLES IN DRELL-YAN PRODUCTION

II. PRINCIPLES OF FACTORIZATION

A) $V \to$ hadrons



• $(\Delta t)_{partonic} \approx Q^{-1} \ll (\Delta t)_{hadroniz.} \approx \Lambda_{\rm QCD}^{-1} \;\Rightarrow$

$$P(e^+e^- \to h) = P(e^+e^- \to q\bar{q})P(q\bar{q} \to h)$$

• Completeness $\sum_h P(i \to h) = 1 \;\Rightarrow$

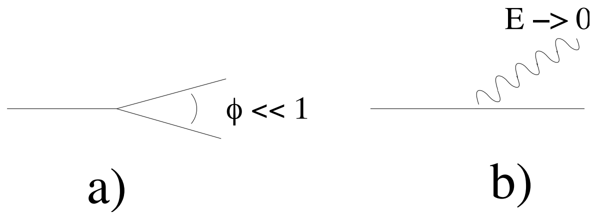
$$\begin{aligned}\sigma_{\rm tot}(e^+e^- \to h) &\equiv \sum_h P(e^+e^- \to h) \\ &= P(e^+e^- \to q\bar{q}) \sum_h P(q\bar{q} \to h) = P(e^+e^- \to q\bar{q})\end{aligned}$$

▷ almost right — but not quite: rhs is IR-divergent in PT... ↪

$\hookrightarrow$ particle number nonconservation $\Rightarrow$ add in multi-particle states

($q\bar{q}g$ to 1st order)

$\Rightarrow \sigma(e^+e^-\to q\bar{q}) + \sigma(e^+e^-\to q\bar{q}g)$ insensitive to long-time interactions,



i.e., insensitive to collinear and soft parton emission

• perturbative calculability (= "IR-safety")

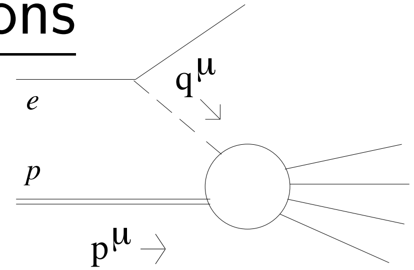
♠ valid to *any* order in α_s

♠ valid for large classes of *infrared-safe* observables

▷ jet physics from PETRA, PEP, LEP e^+e^- experiments

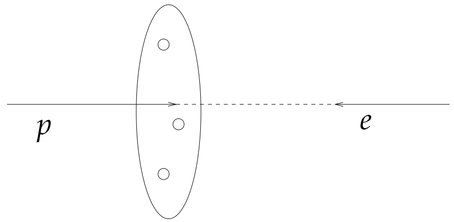
▷ accurate determinations of QCD running coupling $\alpha_s(Q^2)$

B) Single-scale hadron scattering. E.g., DIS structure functions



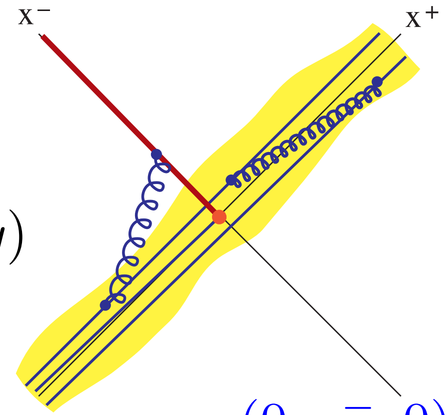
- necessarily sensitive to long timescales, BUT

$$\sigma(Q,m) = C(Q, \text{parton momenta } > \mu) \otimes f(\text{parton momenta } < \mu, m)$$



$\delta t_{\text{scatter}} \ll \tau_{\text{parton}}$ in "infinite-momentum" frame

$$\text{Pdf's}: \quad f(x,\mu) = \int \frac{dy^-}{2\pi}\, e^{-ixp^+y^-}\ \widetilde{f}(y)$$



$$\widetilde{f}(y) = \langle\ P \mid \overline{\psi}(y)\ V_y^\dagger(n)\ \gamma^+\ V_0(n)\ \psi(0) \mid P\ \rangle \quad , \qquad y = (0, y^-, 0)$$

$$V_y(n) = \mathcal{P}\exp\left(ig_s \int_0^\infty d\tau\ n\cdot A(y+\tau\ n)\right)$$

↖ correlation of parton fields at lightcone distances (analog of $a^\dagger a$ operator)

◇ Renormalization group invariance ⇒

$$\frac{d}{d\ln\mu}\,\sigma = 0 \quad \Rightarrow \quad \frac{d}{d\ln\mu}\,\ln f = \gamma = -\frac{d}{d\ln\mu}\,\ln C$$

↪ DGLAP evolution equations [Altarelli-Parisi
Dokshitzer
Gribov-Lipatov]

$$f = f_0 \times \exp \int \frac{d\mu}{\mu}\,\gamma(\alpha_s(\mu))$$

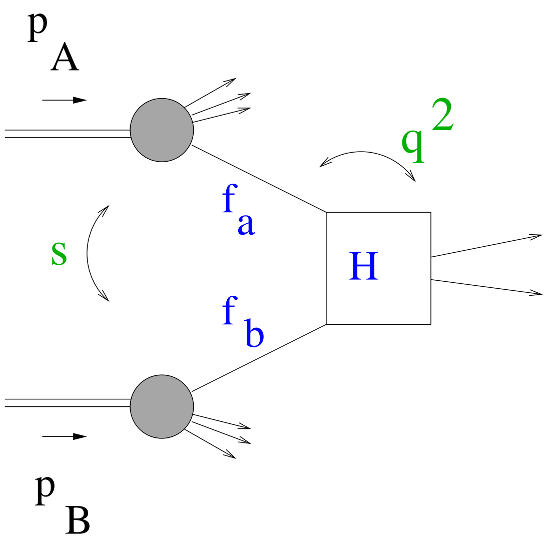
↗ resummation of $(\alpha_s \ln Q/\Lambda_{\rm QCD})^n$ to all orders in PT

Note: expansions $\gamma \simeq \gamma^{(LO)}\,(1 + b_1\alpha_s + b_2\alpha_s^2 + \ldots)$

$$C \simeq C^{(LO)}\left(1 + c_1\alpha_s + c_2\alpha_s^2 + \ldots\right)$$

give LO, NLO, NNLO, ... logarithmic corrections

C) Multi-scale processes. E.g., hard scattering at LHC energies



$$s \gg q_1^2 \gg \cdots q_n^2 \gg \Lambda$$

phase space opening up for large $\sqrt{s}$

$$\Downarrow$$

- large number of events with multiple hard scales: $q_1^2, \cdots, q_n^2$
  - potentially large corrections to all orders in α_s, $\sim \ln^k(q_i^2/q_j^2)$
- nonperturbative components probed near kinematic boundaries

$$(x \to 0,\ 1 - x \to 0)$$

♣ Part of the effects are "universal"

$$\mu \frac{d}{d\mu} f = \gamma \otimes f$$

$$\gamma \simeq \gamma^{(LO)} \left(1 + c_1 \alpha_s + \ldots + c_{n+m} \alpha_s^m (\alpha_s \ L)^n + \ldots\right) \ , \ L = \text{“large log”}$$

↗ resummation inside the kernels of RG evolution equations

♣ Part of them are not universal

↪ yet summable by QCD techniques that

▷ generalize RG factorization

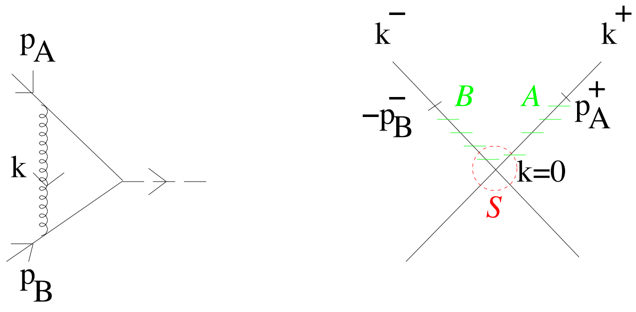
▷ extend parton correlation functions off the lightcone

⇒ unintegrated (or TMD) parton distributions

↗ generalized evolution equations ↪

Examples:

- Sudakov form factor S:



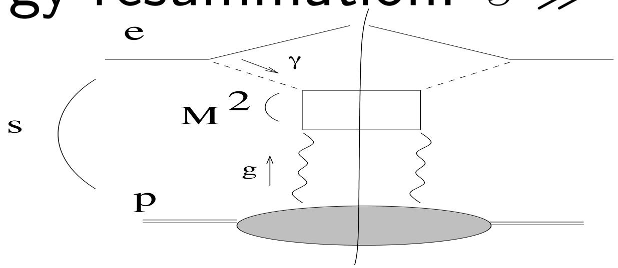
(a) (b)

▷ entering Drell-Yan production, W-boson $p_\perp$ distribution, ...

$\Rightarrow \partial S/\partial \eta = K \otimes S$ CSS evolution equations [Collins-Soper-Sterman]

$\nwarrow$ resums $\alpha_s^n \ln^m M/p_T$

- High-energy resummation: $s \gg M^2 \gg \Lambda^2_{\mathrm{QCD}}$

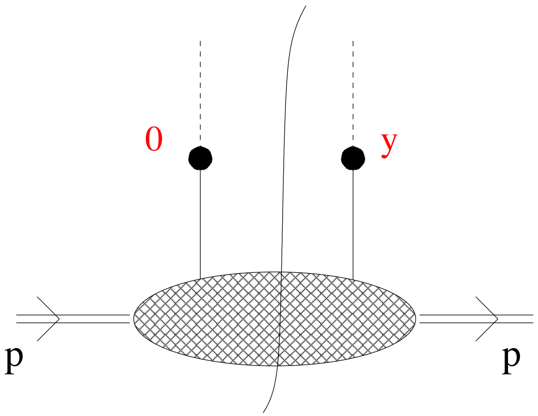


$\diamondsuit$ energy evolution: BFKL equation [Balitsky-Fadin-Kuraev-Lipatov]

$\hookrightarrow$ corrections down by $1/\ln s$ rather than $1/M$

UNINTEGRATED (OR TRANSVERSE MOMENTUM DEPENDENT) PARTON DISTRIBUTIONS

[J. Collins, Foundations of perturbative QCD, CUP 2011]



$p = (p^+, m^2/2p^+, 0_\perp)$

$$\widetilde{f}(y) = \langle \, P \mid \overline{\psi}(y) \; V_y^\dagger(n) \; \gamma^+ \; V_0(n) \; \psi(0) \mid P \, \rangle \quad , \qquad y = (0, y^-, y_\perp)$$

$$V_y(n) = \mathcal{P} \exp \left(i g_s \int_0^\infty d\tau \; n \cdot A(y + \tau \; n) \right)$$

correlation of parton fields ('dressed' with gauge links) at distances y, $y_\perp \neq 0$

Examples: • Sudakov region ⇒ resummation $\alpha_S^n \ln^k (M/q_T)$

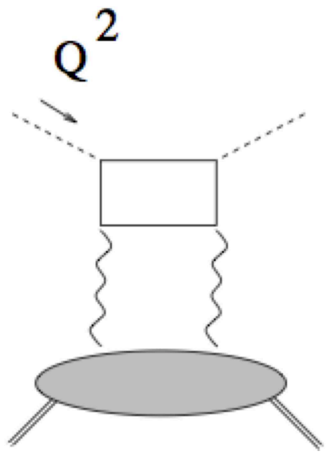
• high energy region ⇒ resummation $\alpha_S^n \ln^k (\sqrt{s}/E_T)$

▷ complete TMD factorization results are few and far between

▷ factorization-breaking effects are an active field of investigation

▷ TMD factorization at high energy (small x) is one of the solid results in this area

EXAMPLE: FLAVOR-SINGLET EVOLUTION AT SMALL X



$$\frac{d}{d\ln\mu^2}\begin{pmatrix}\Sigma\\ G\end{pmatrix} = \begin{pmatrix}P_{qq} & P_{qg}\\ P_{gq} & P_{gg}\end{pmatrix}\otimes\begin{pmatrix}\Sigma\\ G\end{pmatrix}$$

$$P_{gg} = \underbrace{\sum_{k=1}^{\infty} a_k \alpha_s^k x^{-1}\ln^{k-1} x}_{L(x)} + (b_0\alpha_s + \underbrace{\sum_{k=1}^{\infty} b_k \alpha_s \alpha_s^k x^{-1}\ln^{k-1} x}_{NL(x)}) + \dots$$

$$P_{qg} = c_0\alpha_s + \underbrace{\sum_{k=1}^{\infty} c_k \alpha_s \alpha_s^k x^{-1}\ln^{k-1} x}_{NL(x)} + \dots$$

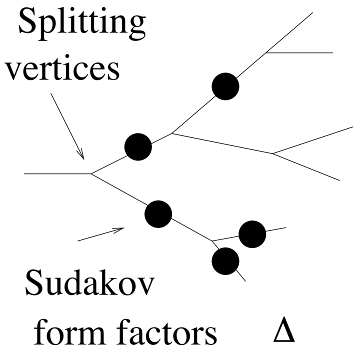
- TMD factorization $\Rightarrow$ well-defined resummation of $\alpha_s^n \ln^{n-m} x$ corrections to splitting functions

WHAT IS THE ROLE OF GENERALIZED TMD FACTORIZATION ON PARTON SHOWERS?

FROM QCD TO MONTE CARLO EVENT GENERATORS

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

$\diamondsuit$ QCD evolution by "parton showering" methods:

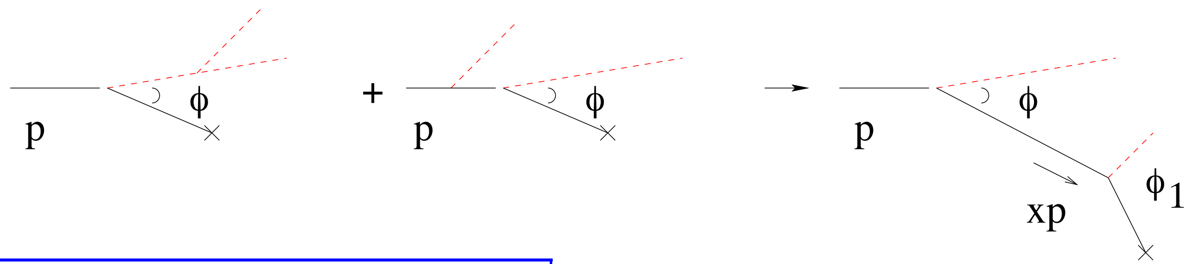


$$d\mathcal{P} = \int \frac{dq^2}{q^2} \int dz \; \alpha_S(q^2) \; P(z) \; \Delta(q^2, q_0^2)$$

$\hookrightarrow$ collinear, incoherent emission

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

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



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

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

Evolution equation and TMDs

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

- solve integral equation via iteration:

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

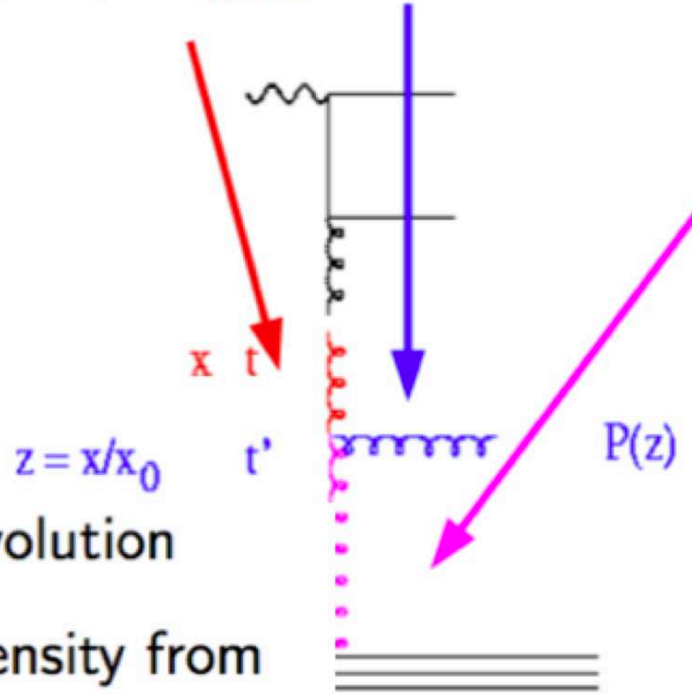
$$x\mathcal{A}_1(x,k_t,q) = x\mathcal{A}(x,k_t,q_0)\Delta(q) + \int \frac{dq'}{q'} \frac{\Delta(q)}{\Delta(q')} \int dz \tilde{P}(z) \frac{x}{z} \mathcal{A}(x/z, k_t', q_0)\Delta(q')$$

from q' to q w/o branching

branching at q'

from q_0 to q' w/o branching

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



- k_t-dependent shower by CCFM evolution

- new determination of TMD gluon density from DIS precision data [Jung & H, arXiv:1206.1796, and in preparation]

TMD kinematic effects
in parton shower evolution

S. Dooling, talk at DIS 2013, Marseille

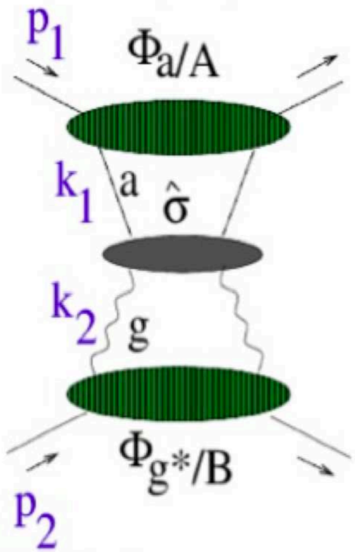
Longitudinal Momentum Shift

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)

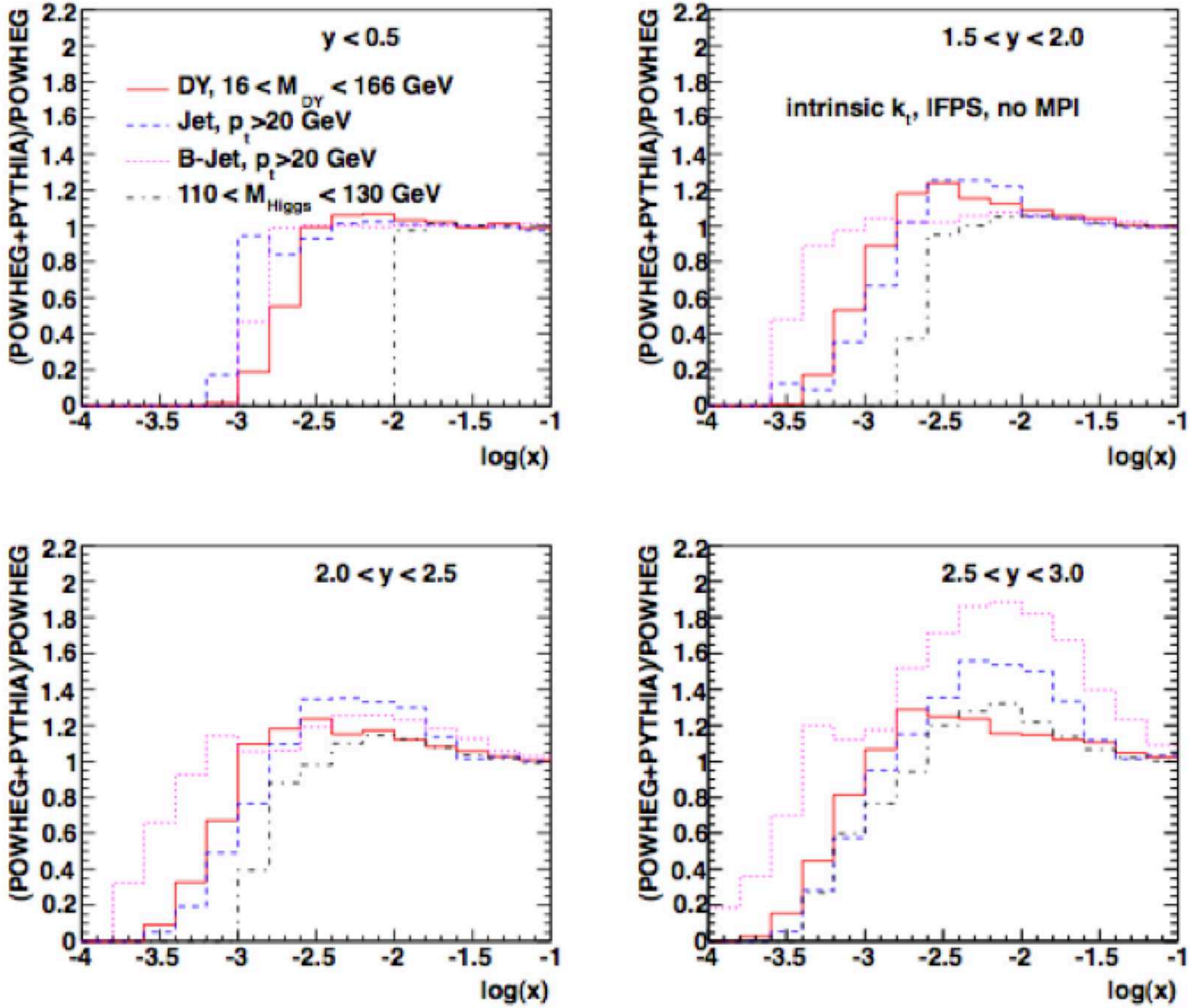
Collinear approximation ⊗ energy momentum conservation

=

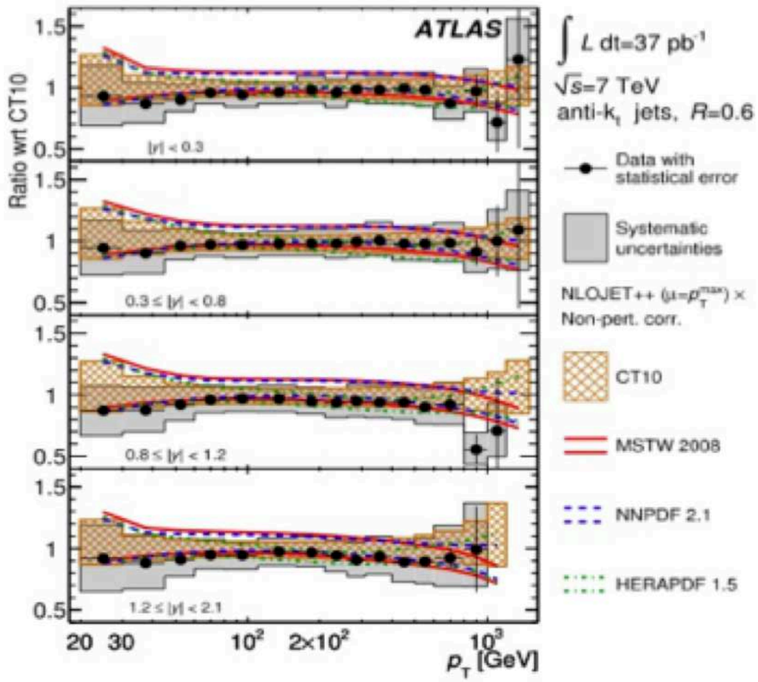
kinematic shift in longitudinal momentum distribution due to showering

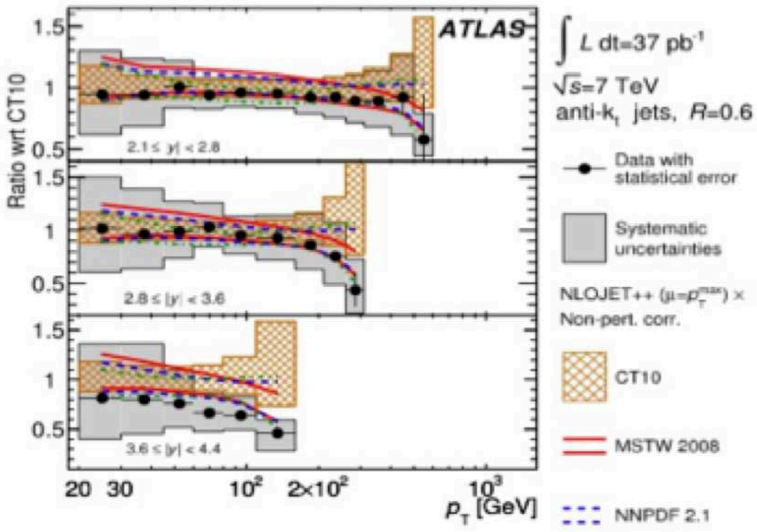
TMD effects in pp collisions

- 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



Inclusive jet production

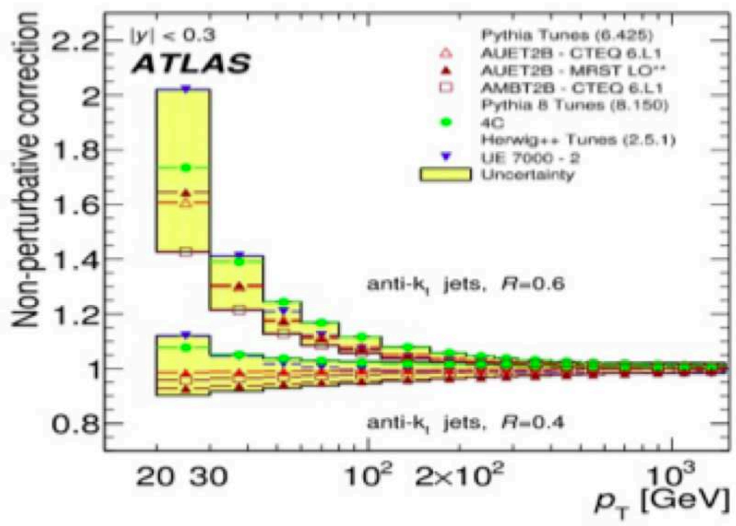




[ATLAS, PRD86 (2012) 014022]

NP correction

- hadronization ⊕ underlying events



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]]

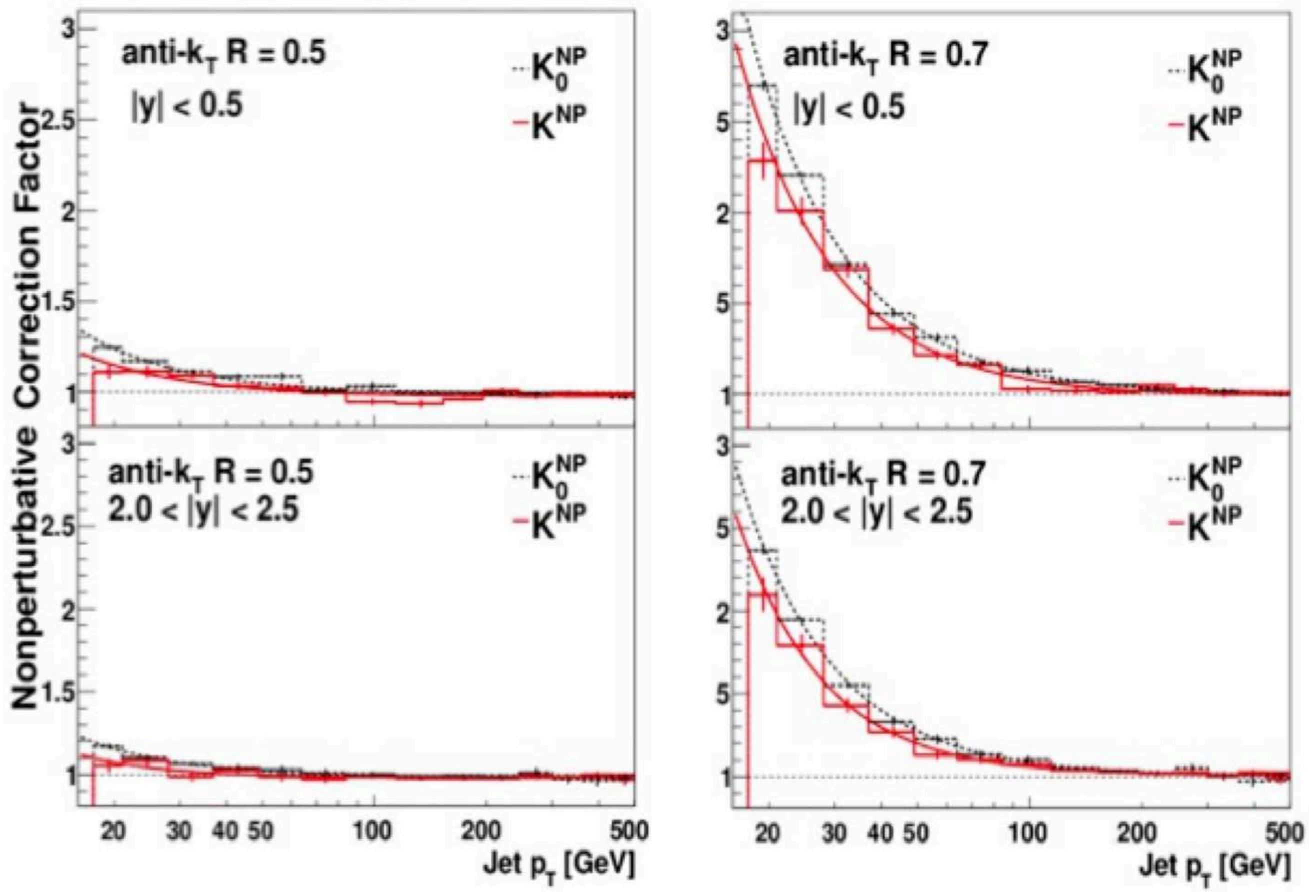
$$K^{NP} = N_{NLO-MC}^{(ps+mpi+had)} / N_{NLO-MC}^{(ps)}$$

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

♣ 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

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

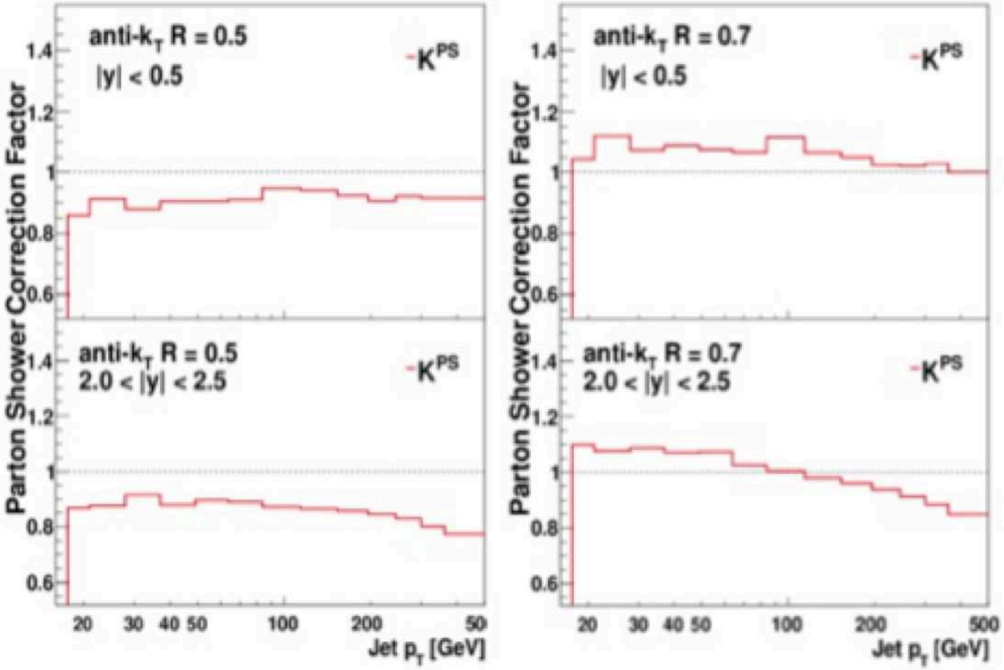
$$K^{NP} = K_{NLO-MC}^{(ps+mpi+had)} / K_{NLO-MC}^{(ps)}$$

Dooling et al.
arXiv:1212.6264

S. Dooling, talk at DIS 2013, Marseille

Parton Shower Correction

Dooling et al.
arXiv:1212.6264



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

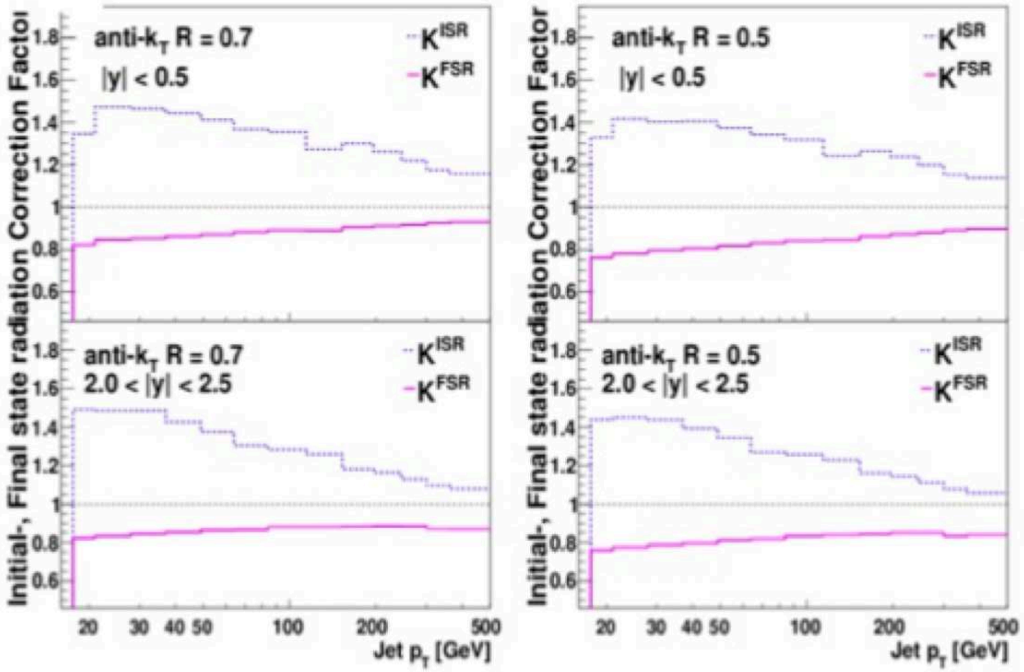
- Depends on rapidity and p_T especially in the forward region
- Finite effect also at large p_T

- Initial and Final State Parton Shower considered independently
- But they are interconnected:

The combined effects cannot be obtained by adding the individual contributions

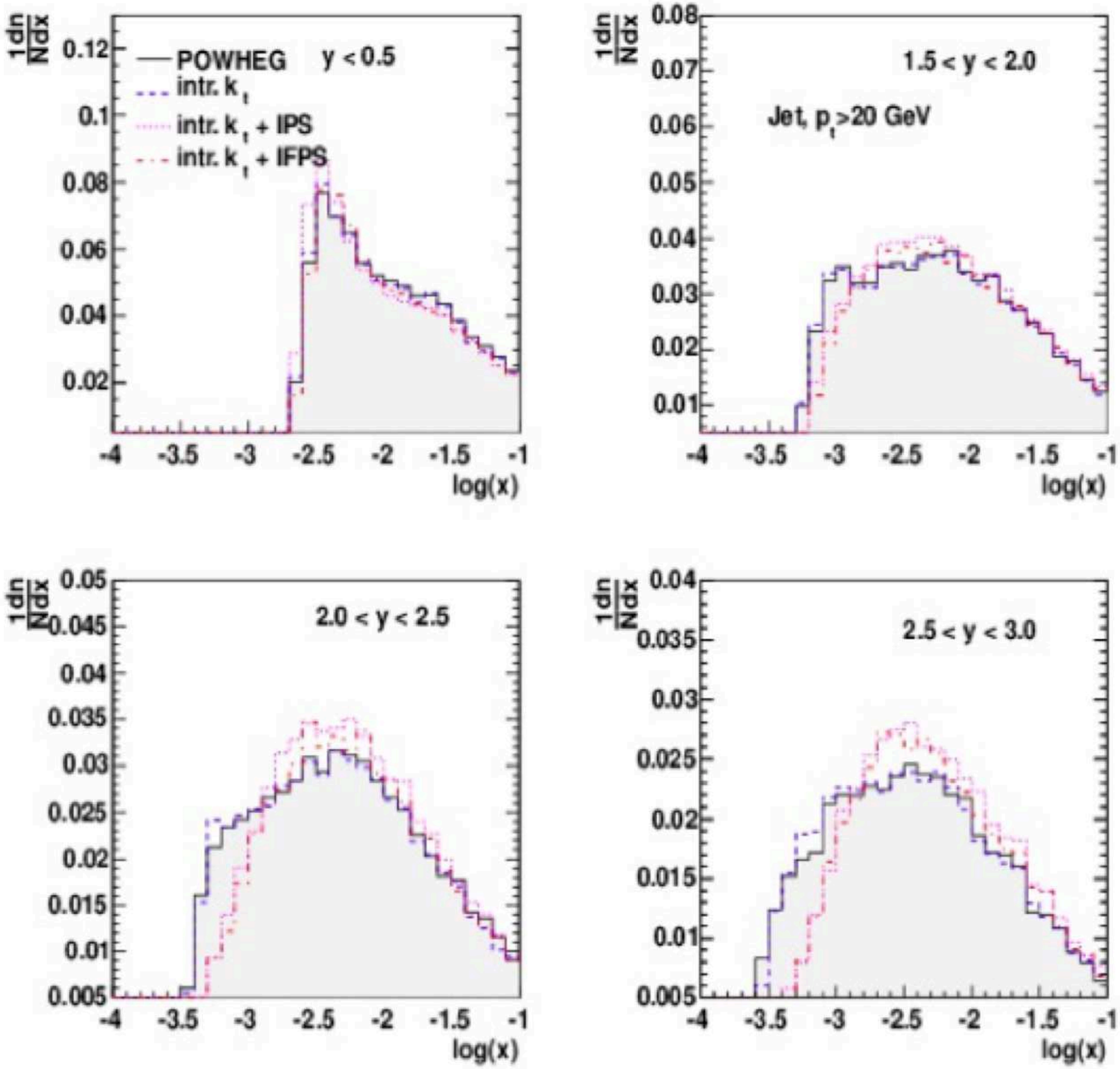
- ISR largest at low $p_{T,}$ FSR significant for all p_T

[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)

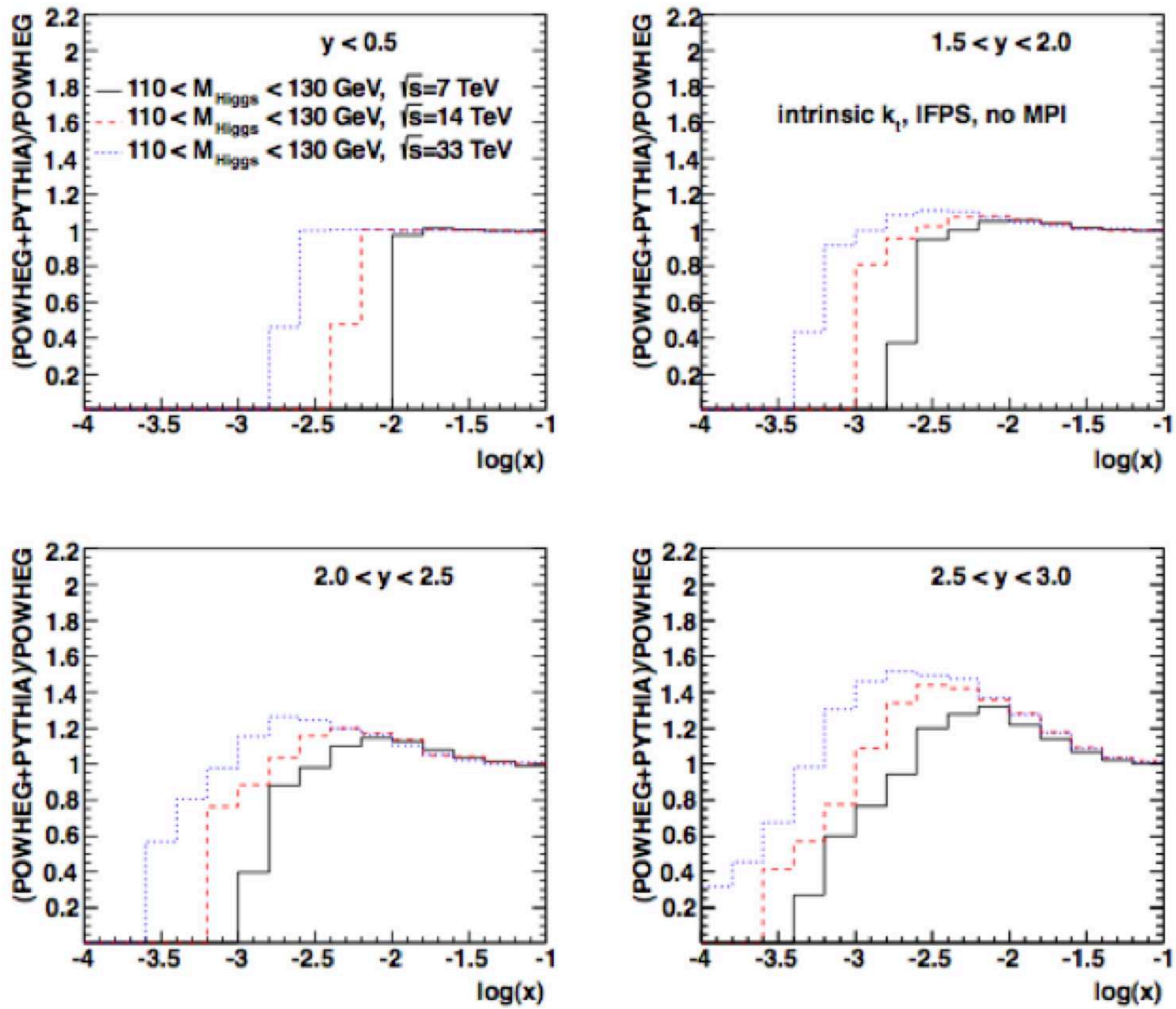
Kinematic reshuffling in x is negligible for central rapidities but becomes significant for $y > 1.5$

▷ Kinematic shift can affect predictions through the PDFs

Dooling et al.
arXiv:1212.6264

[S. Dooling, talk at DIS 2013]

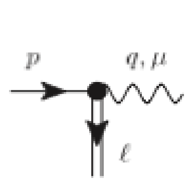
Longitudinal momentum shift: Higgs

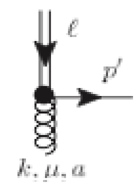


VECTOR BOSON AND JETS FINAL STATES

Vector bosons + jets at high energy

- High-energy effective theory → effective vertices

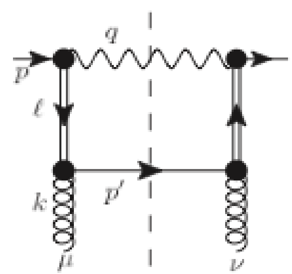




[Bogdan & Fadin, NPB740 (2006) 36]

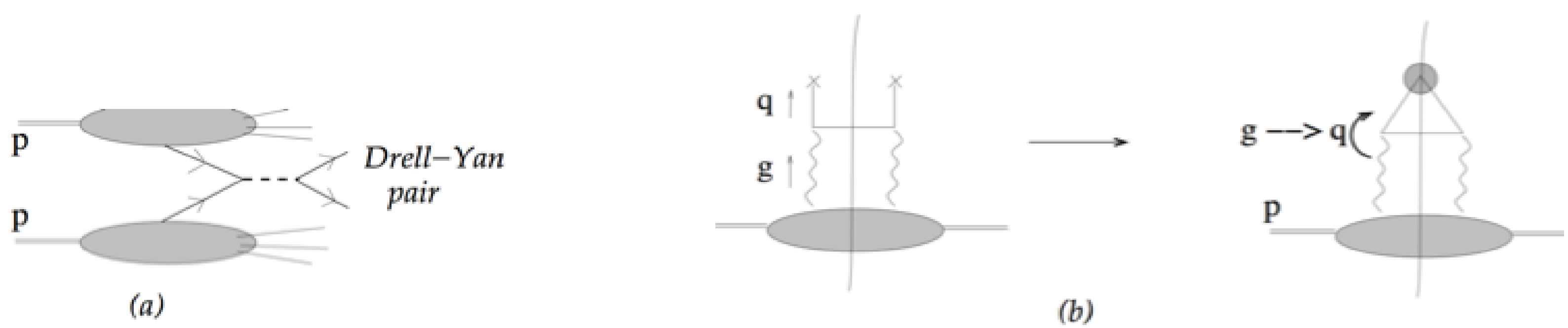
[Lipatov & Vyazovsky, NPB597 (2001) 399]

- Parton matrix elements (gauge-invariant, despite off-shell parton)



[Ball & Marzani, NPB814 (2009) 246]

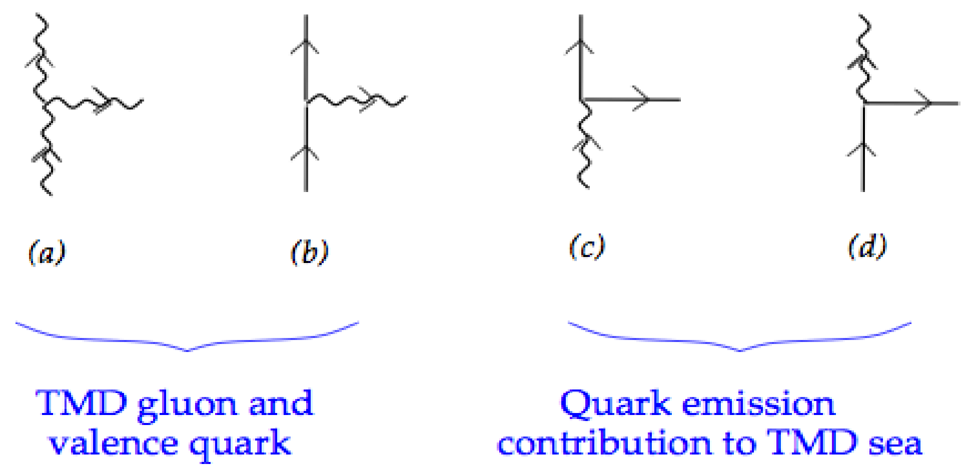
[Hentschinski, Jung & H, NPB865 (2012) 54]



a) $\bar{q}q$ Drell-Yan production; (b) $g \to q$ splitting contribution to sea quark distribution

Beyond quenched approximation: unintegrated quark evolution

[Hentschinski, Jung & H, arXiv:1205.1759; arXiv:1205.6358]



- sea: flavor-singlet evolution coupled to gluons at small x via

$$\mathcal{P}_{g\to q}(z;q,k) = P_{qg,\mathrm{DGLAP}}(z) \left(1 + \sum_{n=0}^{\infty} b_n(z)(k^2/q^2)^n\right)$$

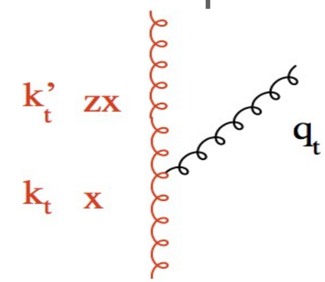
all b_n known; $\mathcal{P}_{g\to q}$ computed in closed form (positive-definite)

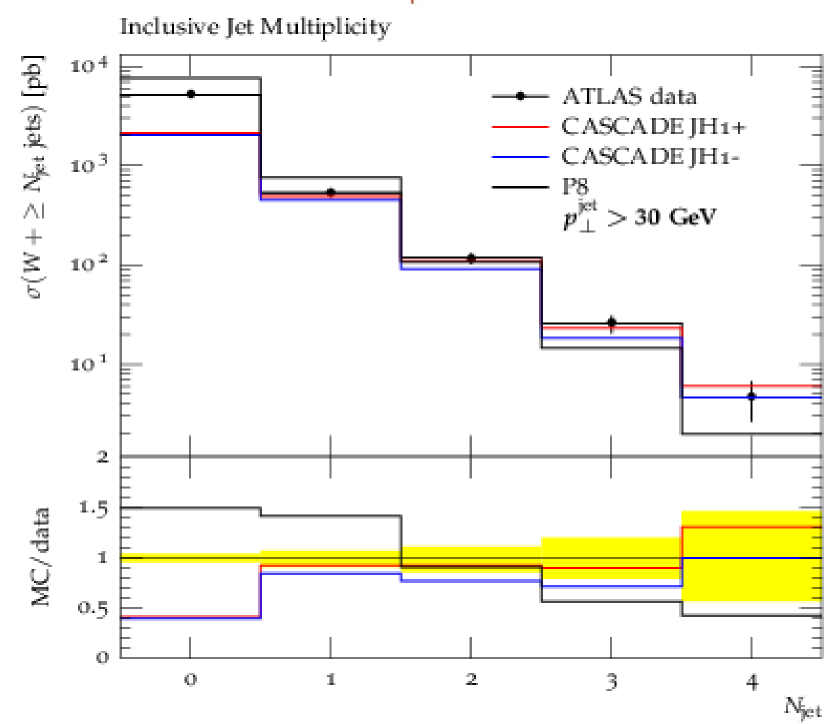
in *[Catani & H, 1994; Ciafaloni et al., 2005-2006]* by small-x factorization

- valence: independent evolution (dominated by soft gluons x $\to$ 1)

Application to W + jets at the LHC

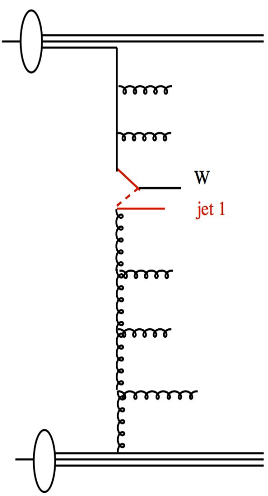
- use valence quarks and CCFM gluon (from DIS precision data), convoluted with off-shell high-energy matrix elements
- initial parton shower by CCFM evolution in angular ordered phase space:
  - $q_i > z_{i-1} q_{i-1}$ with $q_i = \dfrac{p_{ti}}{1-z}$
  - ➔ no p_t constraint at small x
  - ➔ jets can have large p_t

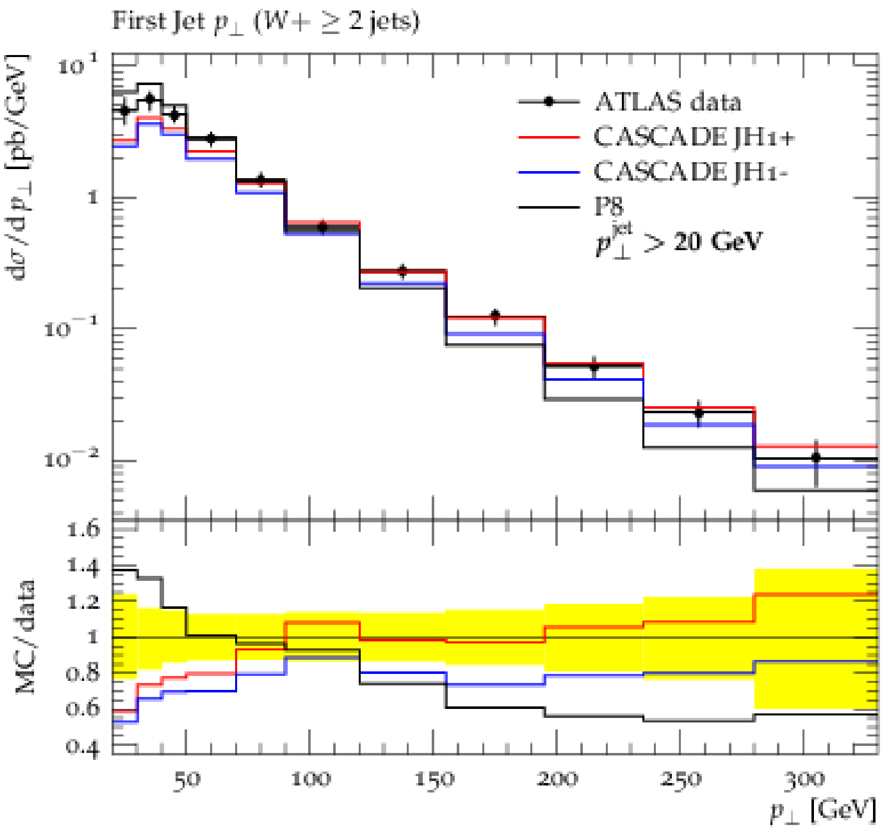




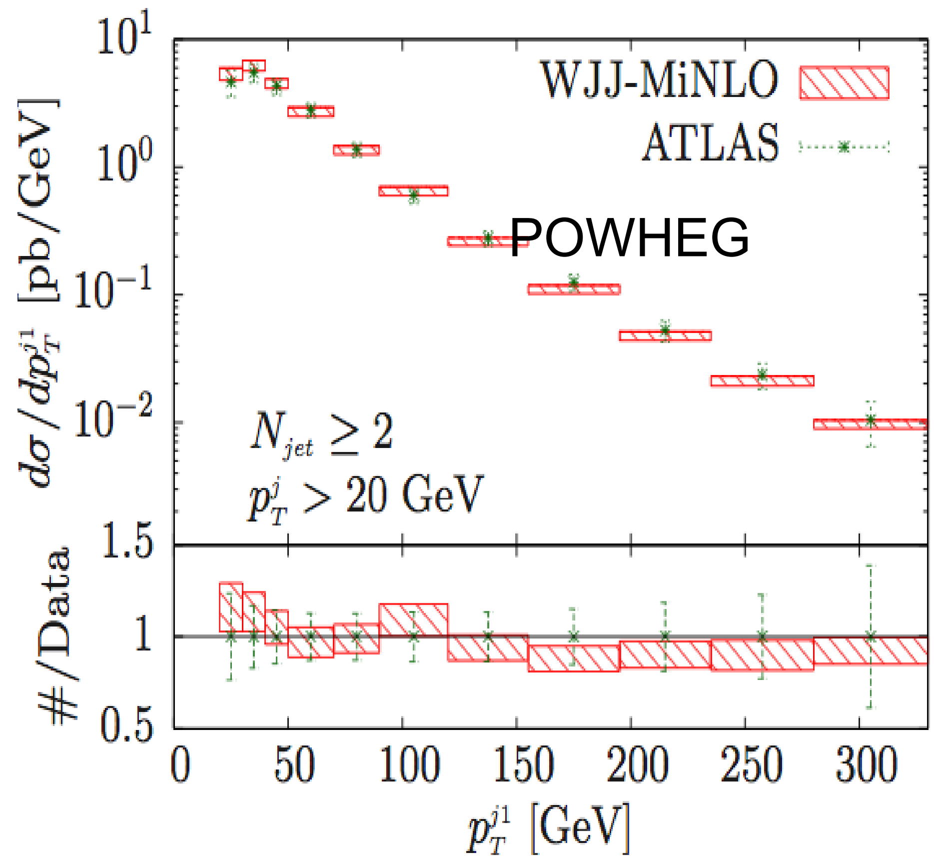
- Compare with W + jets measurements
- Jet multiplicities are reproduced:
  - 1 jet → from ME
  - 2-4 jets from shower
- Note: PYTHIA with p_t -ordered shower cannot predict higher jet multiplicities

W + 2 jets: k_t-shower vs. NLO-matched





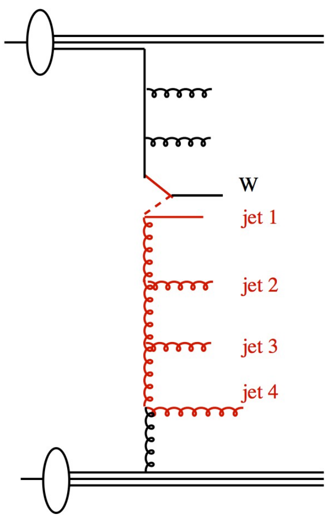
Campbell, Ellis, Nason, Zanderighi, arXiv 1303.5447

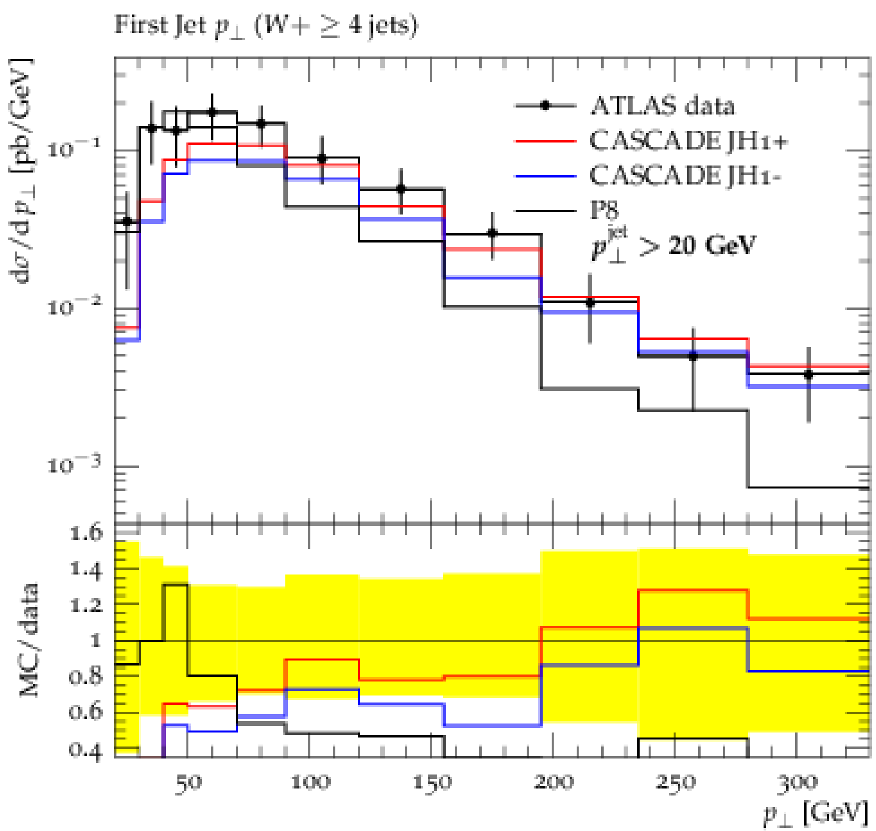


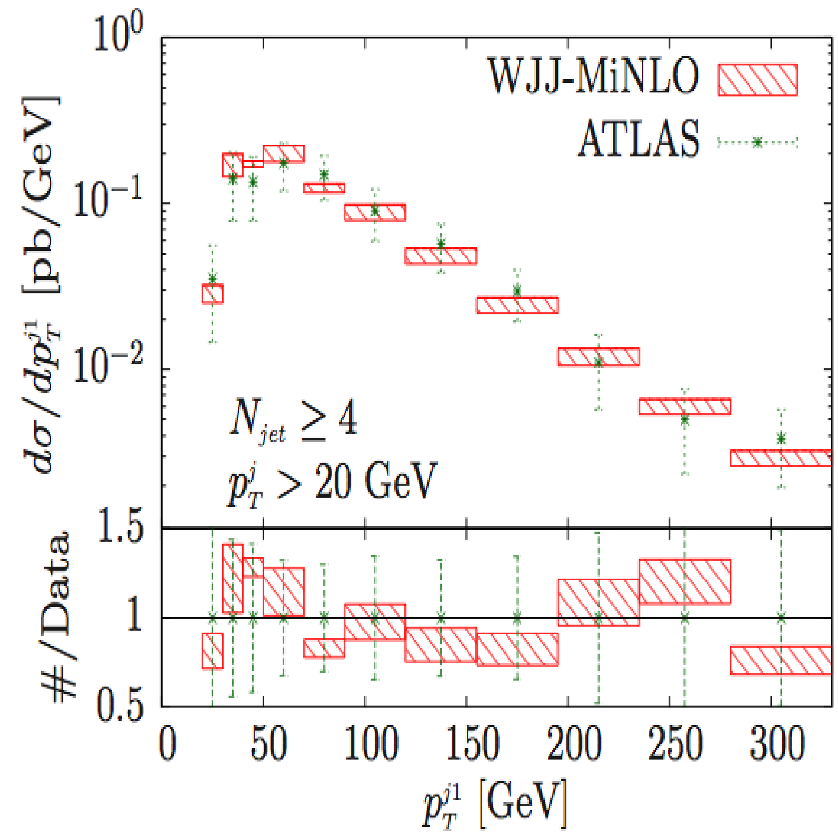
- 1st jet in W + (> 2) jet events:
  - off shell ME + CCFM k_t - shower (CASCADE) comparable with NLO W + 2 jet (POWHEG)
  - uncertainties studied in CASCADE: pdf and scale uncertainties
  - PYTHIA P8 shower starts to fail at large pt

W + n jets: k_t-shower vs. NLO-matched

Campbell, Ellis, Nason, Zanderighi, arXiv 1303.5447

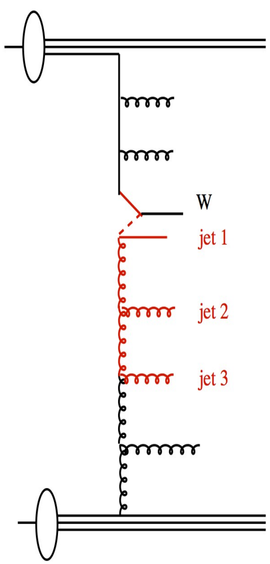


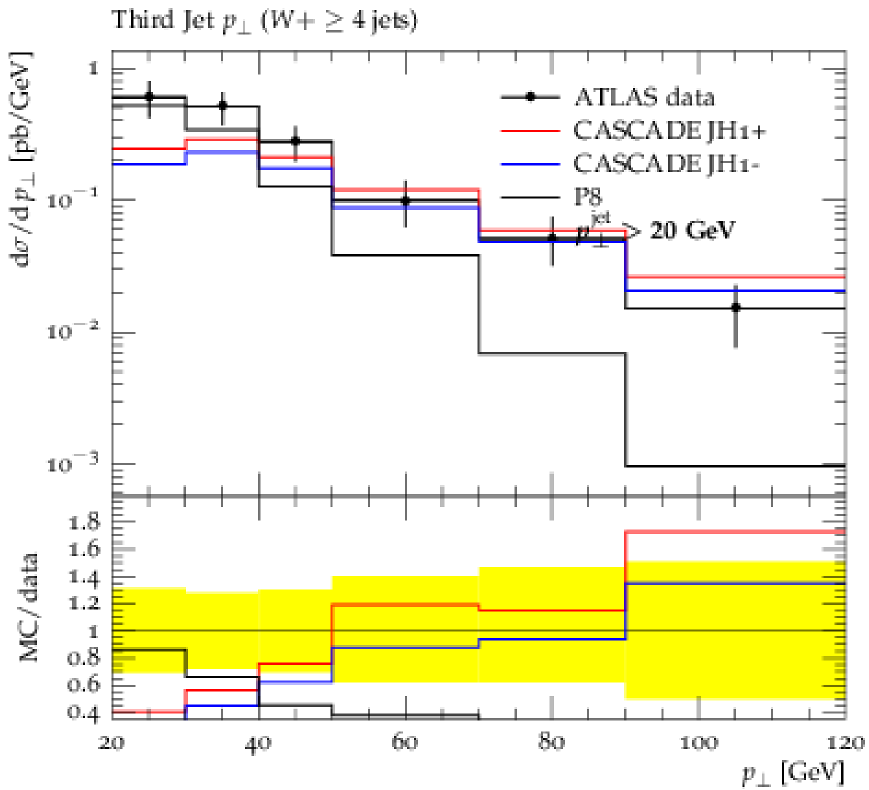




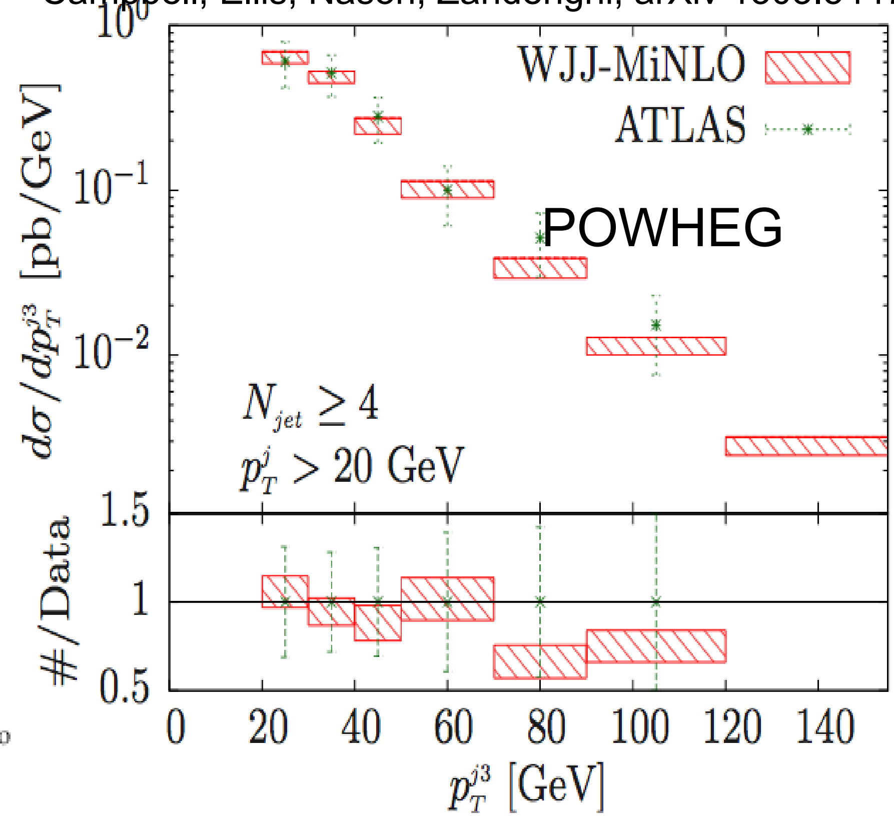
- off-shell ME + CCFM k_t - shower (CASCADE) comparable with NLO W+4jet
- first jet comes from hard process, other jets partially from shower
  - CCFM k_t - shower works fine even for high pt
  - P8 shower cannot describe shape

W + n jets: pt spectrum of third jet



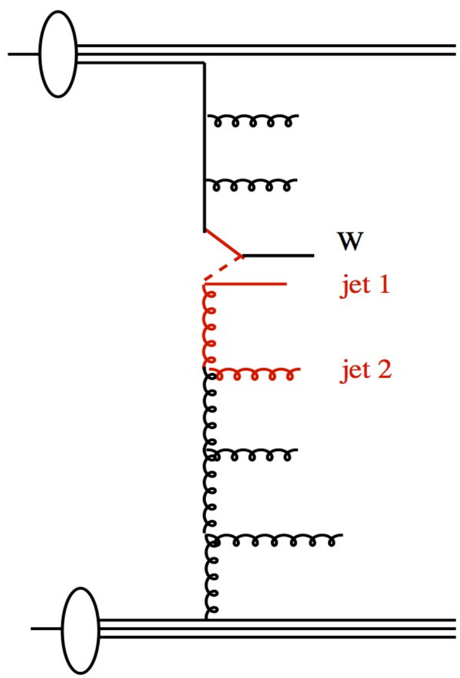


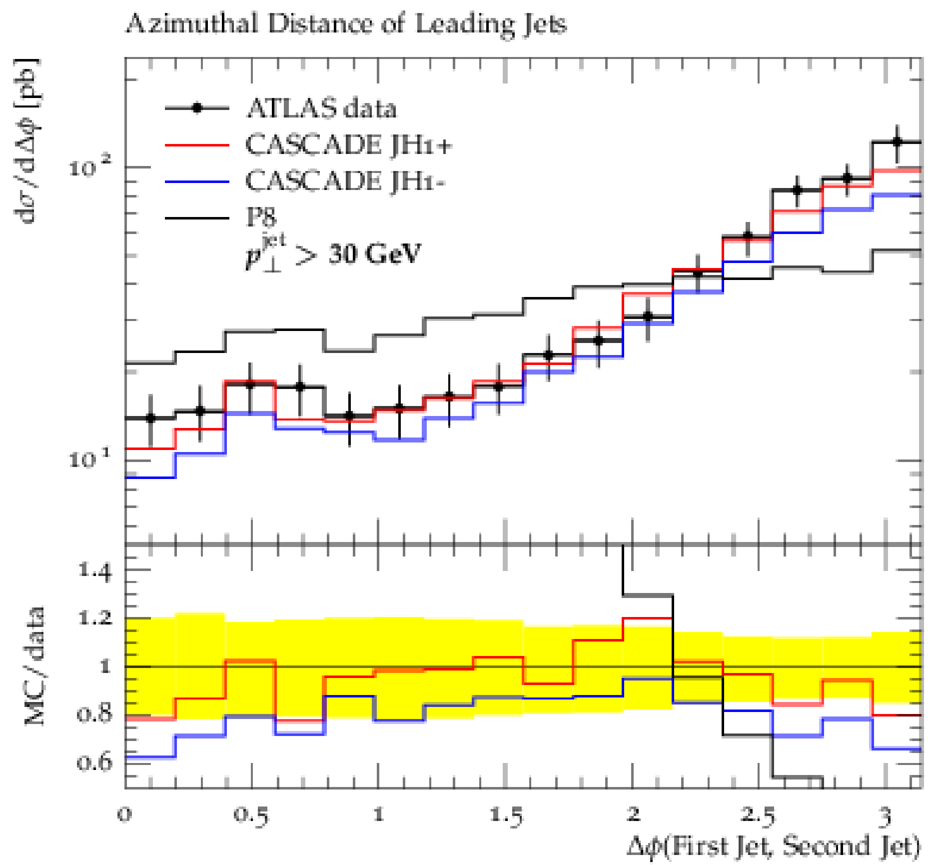
Campbell, Ellis, Nason, Zanderighi, arXiv 1303.5447



- off-shell ME + CCFM k_t - shower predicts correct x-section and shape for 3rd jet (similar to NLO-matched POWHEG) !
  - 3rd jet comes from CCFM k_t - shower
  - collinear (pt ordered) shower PYTHIA fails to describe shape

Application to angular correlations in W + n jets production





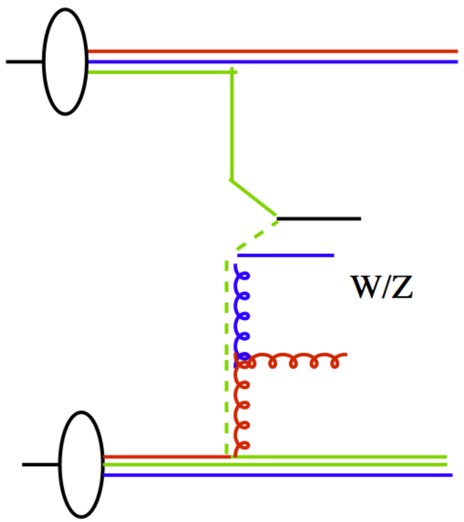
- off-shell ME + CCFM k_t - shower for x-section and shape for $\Delta\,\phi$ between first 2 jets agrees with measurements within uncertainties:
  - sensitive probe of shower:
    - back to back region and decorrelation region well reproduced !
    - not described by collinear pt ordered shower PYTHIA

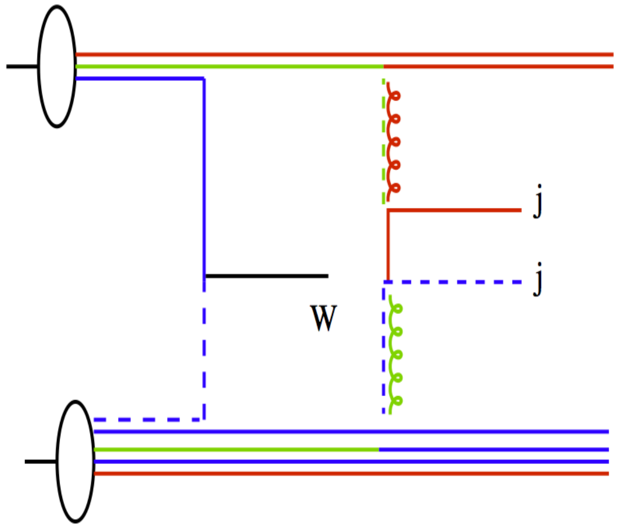
What is the gain ?

- CCFM gluon TMD and k_t dependent shower with off shell ME give similar results as NLO matched with collinear shower
- calculation arranged in a very efficiency way → fast calculation
- jet production from TMD and k_t dependent shower extendable to any number of jets without further adjustment and tuning
  - CCFM + k_t dependent shower describes well high pt jet production

- Advantage of CCFM+k_t dependent shower:
  - matching with 2 → n off-shell parton calculation (automated method, *see A. van Hameren, P. Kotko and K. Kutak, JHEP1301(2013)078.*)
  - opens possibility for full LHC phenomenology of QCD, EWK and BSM processes

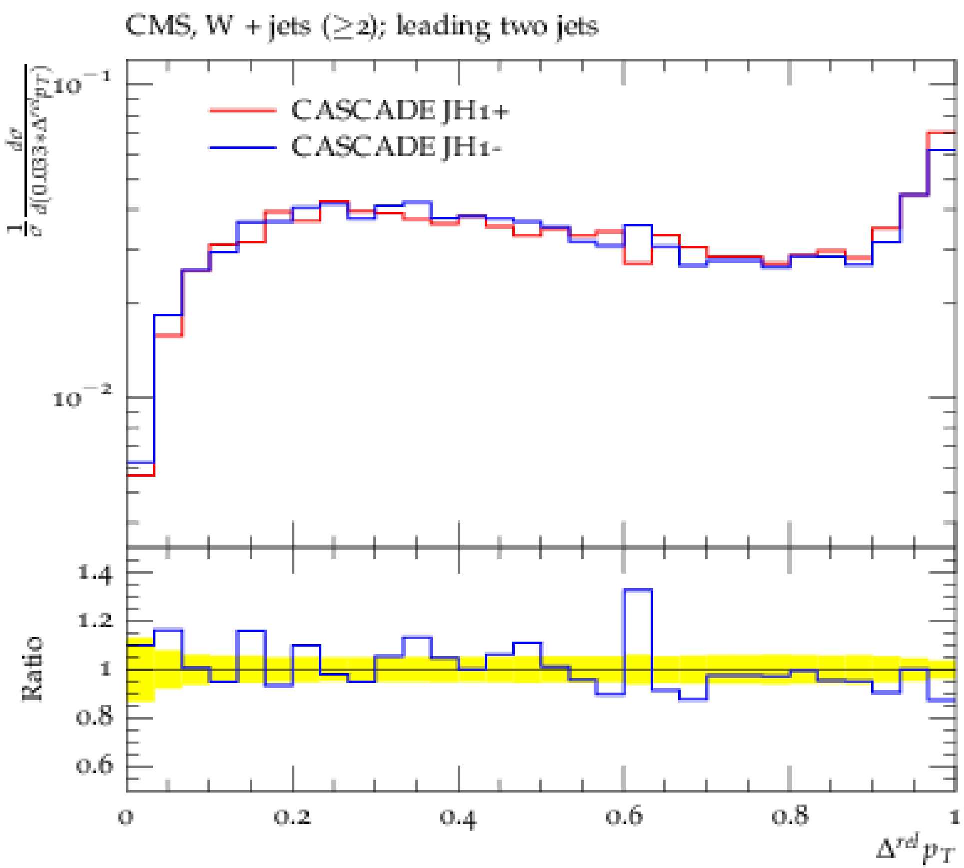
W + 2 jet: signal for double-parton scattering ?



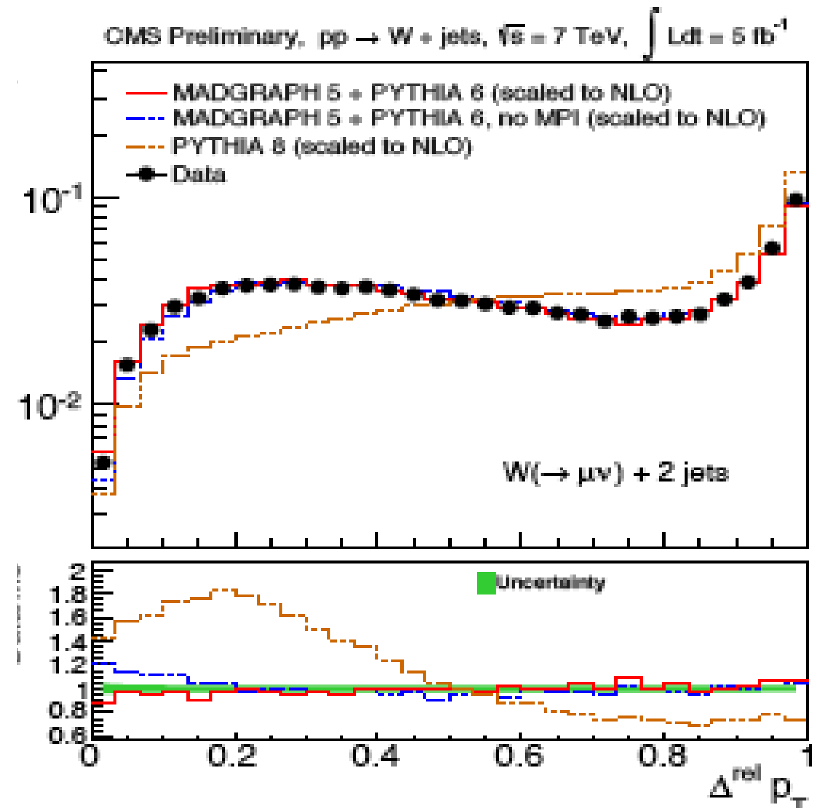


- DPS signal: de-correlated jets compared to W
  - what is the contribution from single chains ?
  - are jets coming from power-like terms in shower evolution or are they coming from independent scatterings ?

W+2 jet: signal for double-parton scattering ?

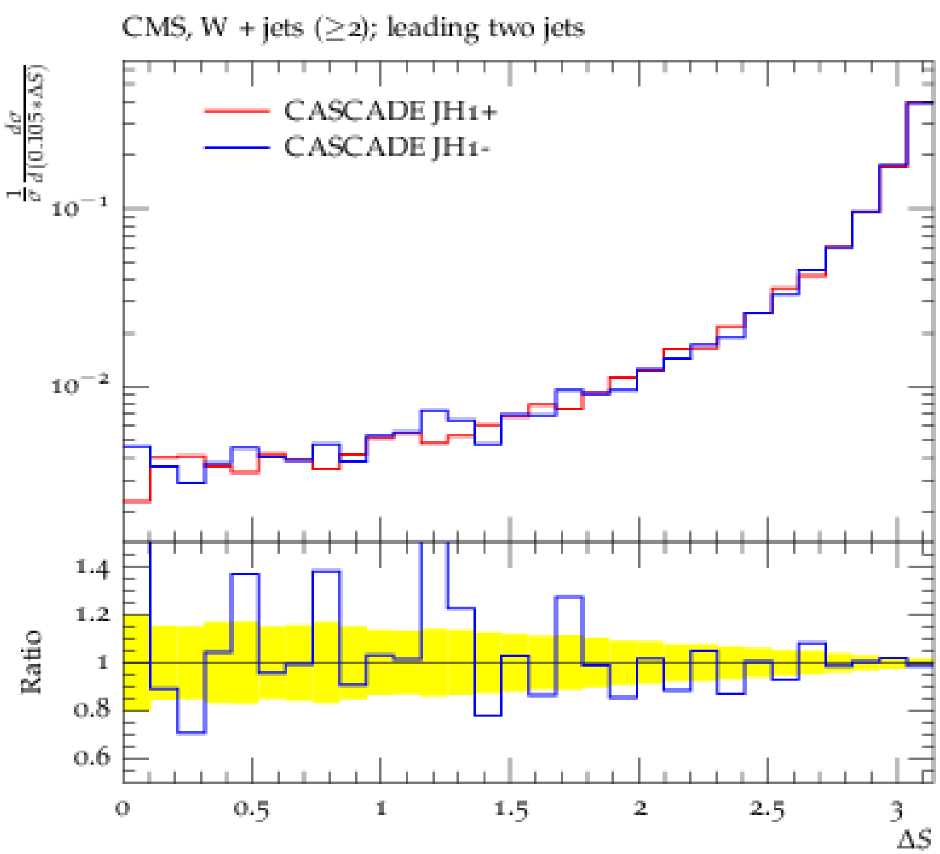


From P. Bartalini: MPI and DPS studies at CMS
WG2: Low x and Diffraction

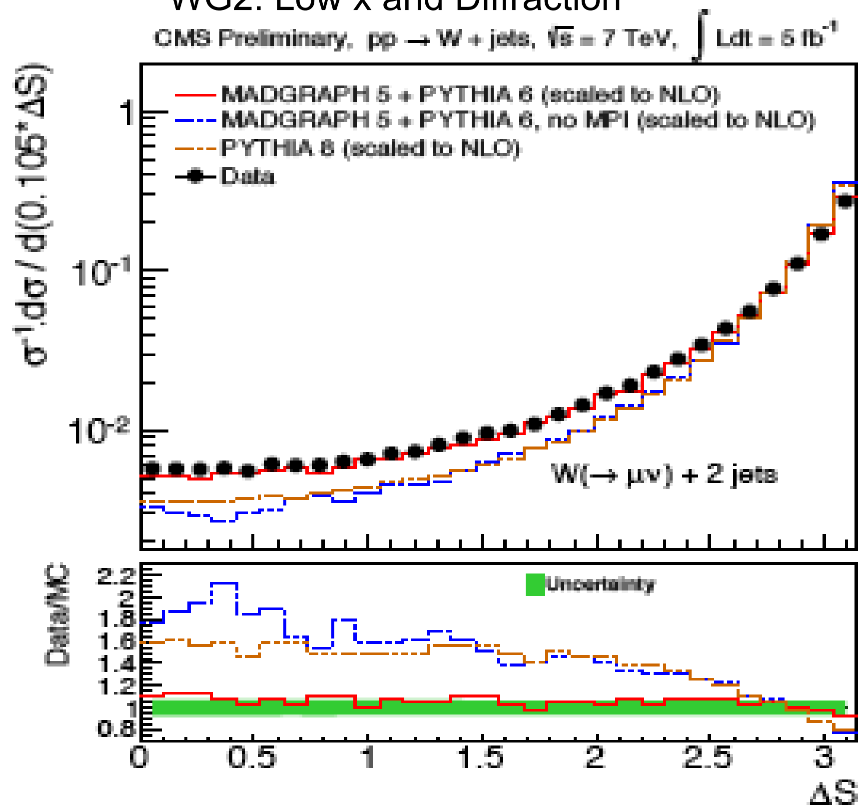


- off-shell ME & CCFM + k_t shower predict a similar shape as seen in latest CMS measurement

W+2 jet: signal for double-parton scattering ?



From P. Bartalini: MPI and DPS studies at CMS
WG2: Low x and Diffraction



- off-shell ME & CCFM + k_t shower predict a similar shape as seen in latest CMS measurement.
  - how much room for DPS is left in the framework of high-energy factorization?

WHAT HAPPENS AT LOW PT?

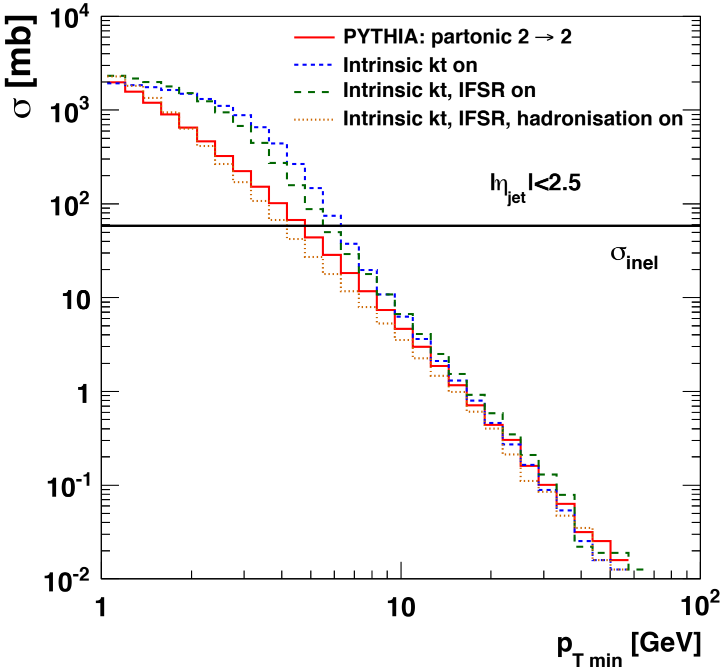
IV. Jets, MPI and the inelastic pp cross section

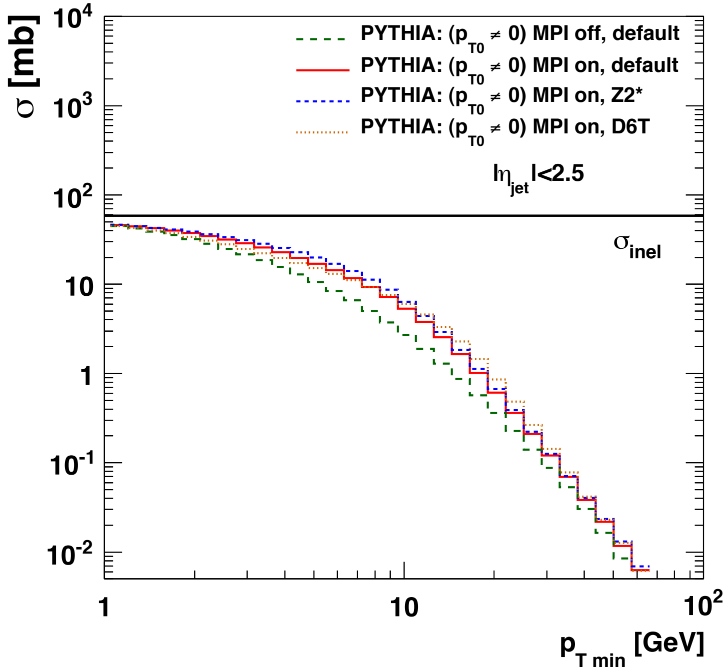
- Extend central jet measurements to lower $p_\perp$

$\Rightarrow$ visible jet cross section sensitive to bound from inelastic σ_{pp}

[ATLAS Coll., Nature Commun. 2 (2011) 46

CMS Coll., CMS PAS QCD-11-002]





(Left) cross section from purely partonic $2\to2$ process, including intrinsic k_t-effects, initial and final state parton showers (IFSR), hadronization;

(Right) result of applying $p_{T0} \neq 0$ and MPI with different UE tunes of PYTHIA.

[Grebenyuk et al., arXiv:1209.6265]

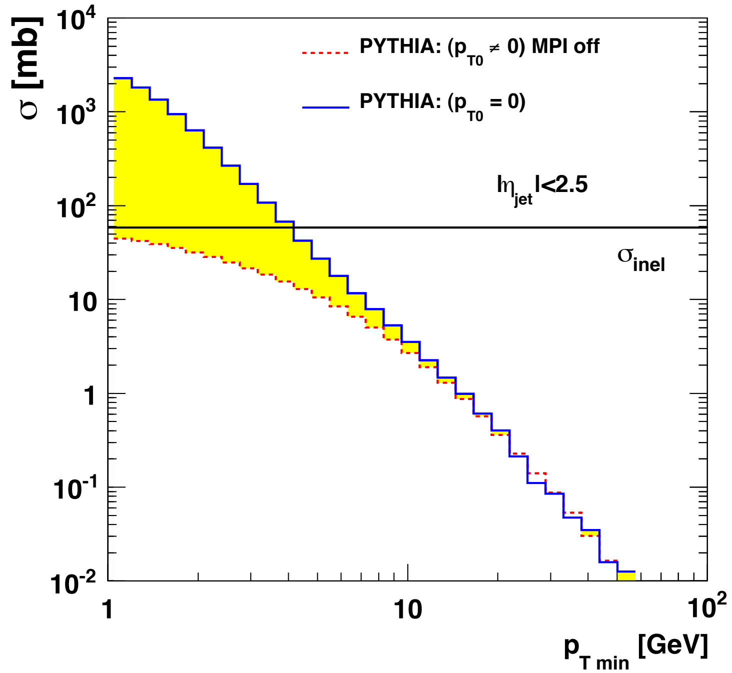
• low-p$_T$ model in collinear framework (Pythia):

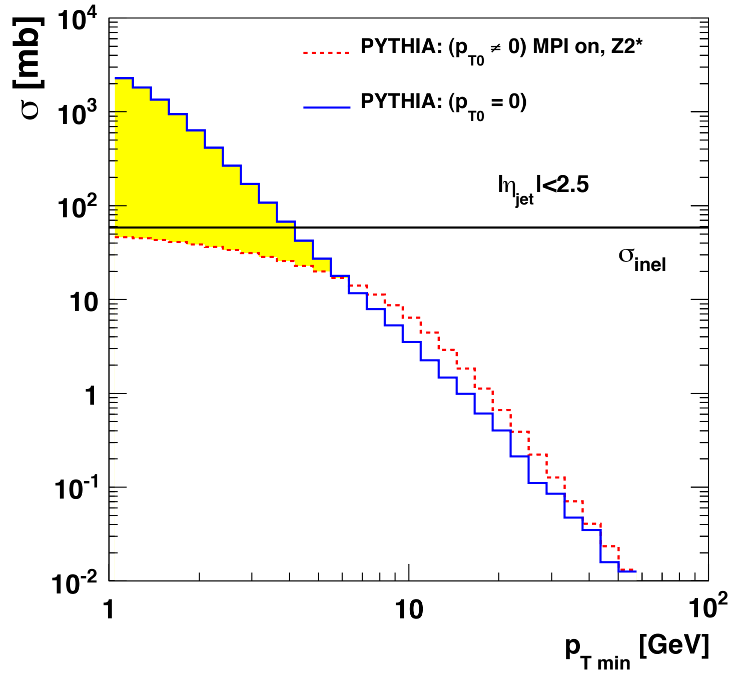
$$\sigma \to \sigma \times \frac{\alpha_s^2(p_{T0}^2 + p_T^2)}{\alpha_s^2(p_T^2)} \frac{p_T^4}{(p_{T0}^2 + p_T^2)^2}$$

• k$_T$ factorized: low-p$_T$ behavior results from

— ME dependence (standard low-p$_T$ rise for $k_T \ll p_T$, slower rise for $k_T \simeq p_T$)

— unintegrated pdf (suppression of the low-k$_T$ region)





Left: without MPI. Right: including MPI

[Grebenyuk et al., arXiv:1209.6265]

Comments

♠ even though at weak coupling, dynamical effects slowing down the rise of the cross section can involve strong fields and nonperturbative physics

• measure event cross sections (rather than jet cross sections including multiplicities)

• ATLAS Phys. Rev. D84 (2011) 054001 illustrates feasibility of measuring jets at low p_T but

▷ does not consider event cross sections ⇒ no study of unitarity effects

▷ normalizes MC to integrated rate ⇒ all models effectively norm.'d to lowest p_T bin

• CMS, PAS FSQ-12-026: leading track and leading jet studies

CONCLUSIONS

• Generalized QCD factorization ideas relevant at the LHC
both for low x and high x processes

• New definition of nonperturbative and showering correction factors
affects comparisons of theory with measurements of final states containing jets

• $W+$ jets production can be described using TMD parton shower approach

• Keep track of non-collinear momentum components from the outset?
$\Rightarrow$ new approaches to include nonperturbative effects (MPI, finite-k_T, hadronization) in
shower generators