MPI@LHC Workshop, CERN, December 2012

MPI and High-energy QCD Showers

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Thanks for discussion and collaboration to
H. Jung, A. Grebenyuk, M. Hentschinski,
K. Kutak, A. Knutsson, P. Katsas

Multiple parton interactions

◊ required by most UE / MC analyses

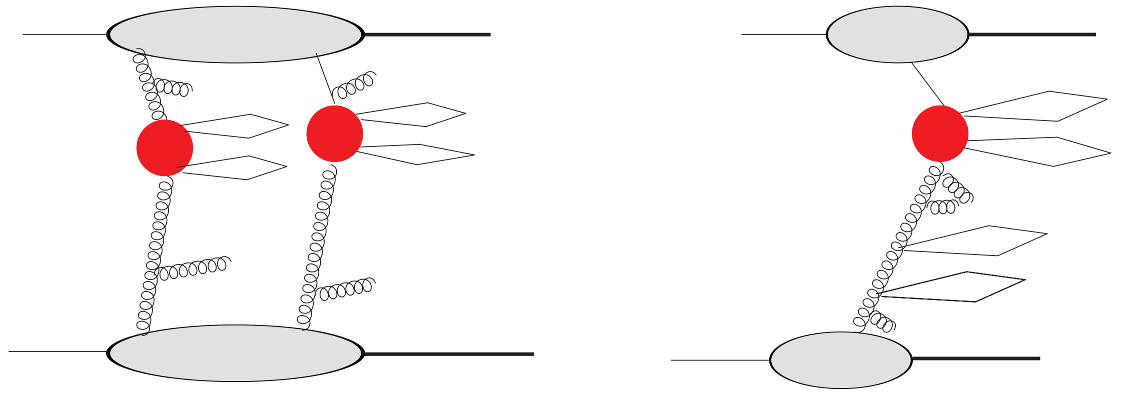
◊ direct evidence still lacking

◊ no systematic theory as yet

◊ significant contributions to MC simulations also for high mass states

[see e.g. F. Krauss, talk at MPI-TAU Workshop, October 2012]

Multiple parton interactions



Multi-jet production by

(left) multiple parton chains; (right) single parton chain

• modeled in shower Monte Carlo event generators

[Sjöstrand & van Zijl, 1987]

[Sjöstrand & Skands, 2004]

• multiple collisions are increasingly important as parton density grows

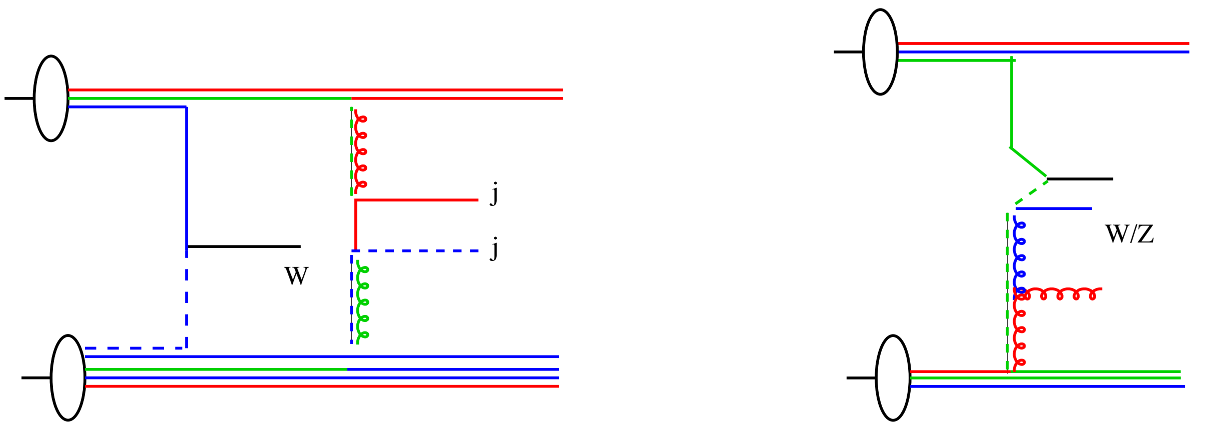
• contribute primarily to highly differential cross sections

♣ dependence on detailed distribution of states produced by parton evolution?

Example: $W + 2j$

- test for double parton scattering ($\hookrightarrow$ back-to-back jet region)

- multi-gluon emission effects (hard scale $\ll \sqrt{s}$)

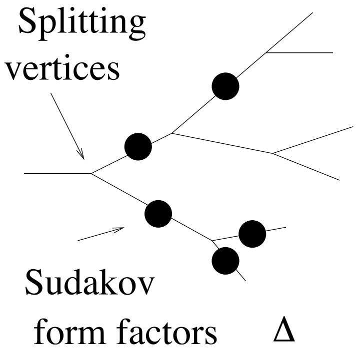


(*left*) double chain production; (*right*) single chain production

QCD MULTI-PARTON CASCADES

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

◇ QCD evolution by "parton showering" methods:

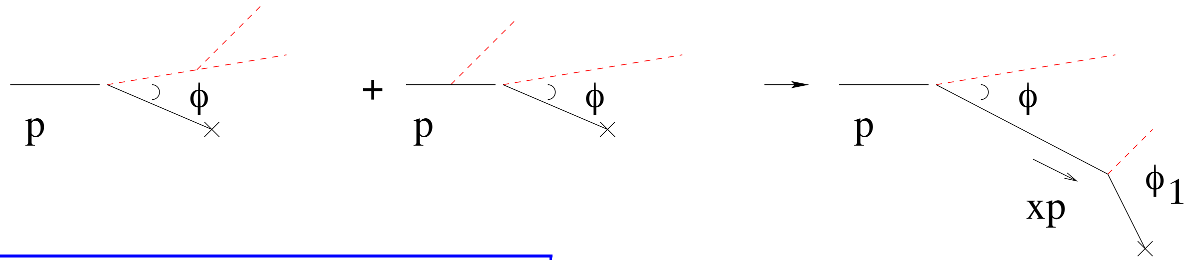


$$d\mathcal{P} = \int \frac{dq^2}{q^2} \int dz \; \alpha_S(q^2) \; P(z) \; \Delta(q^2, q_0^2)$$

$\hookrightarrow$ collinear, incoherent emission

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

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

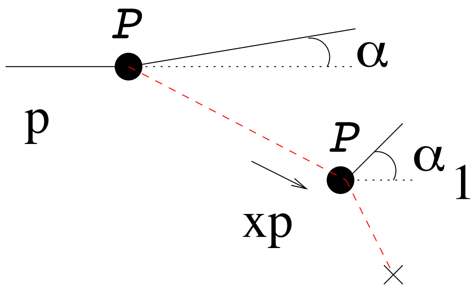


◇ Gluon coherence for $x \ll 1$ $\Rightarrow$ corrections to angular ordering:

$\hookrightarrow$ MC based on $k_\perp$-dependent unintegrated pdfs and MEs

EXAMPLE: SMALL-X COHERENCE and CCFM PARTON BRANCHING

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



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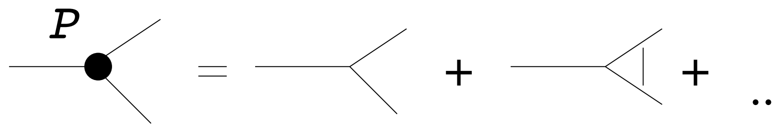


(left) Coherent radiation in the space-like parton shower for $x \ll 1$;
(right) the unintegrated splitting function $\mathcal{P}$, including small-x virtual corrections.

$$\alpha / x > \alpha_1 > \alpha \quad (\mathrm{small} - \mathrm{x} \;\; \mathrm{coherence} \;\; \mathrm{region})$$

- how do coherence effects influence analysis of MPI?

OUTLINE

- Vector bosons plus jets

- Energy flow observables

- Mini-jets and the inelastic pp cross section

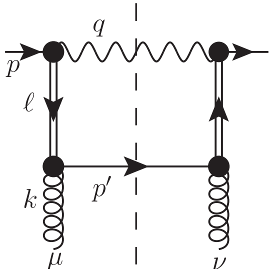
II. Vector bosons + jets at high energy

- High-energy effective theory → effective vertices

[Bogdan & Fadin, NPB740 (2006) 36]

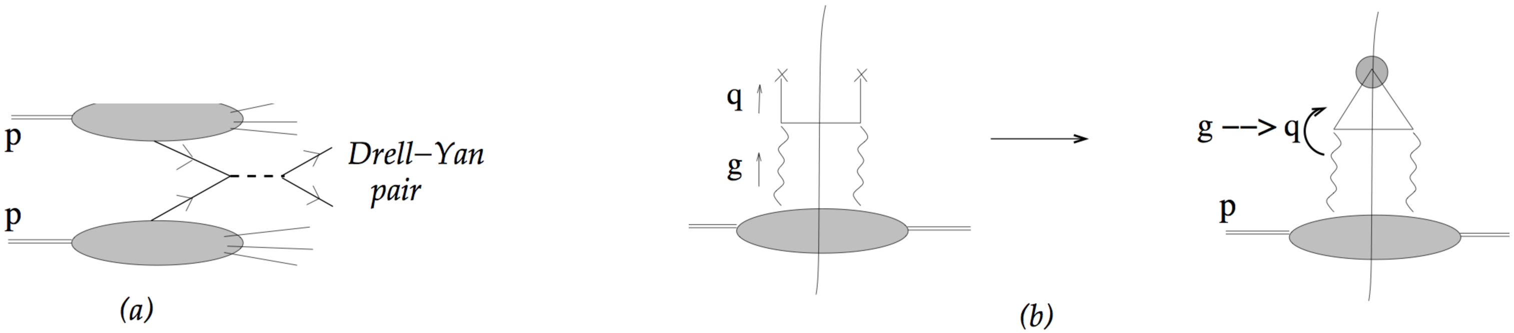
[Lipatov & Vyazovsky, NPB597 (2001) 399]

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



[Ball & Marzani, NPB814 (2009) 246]

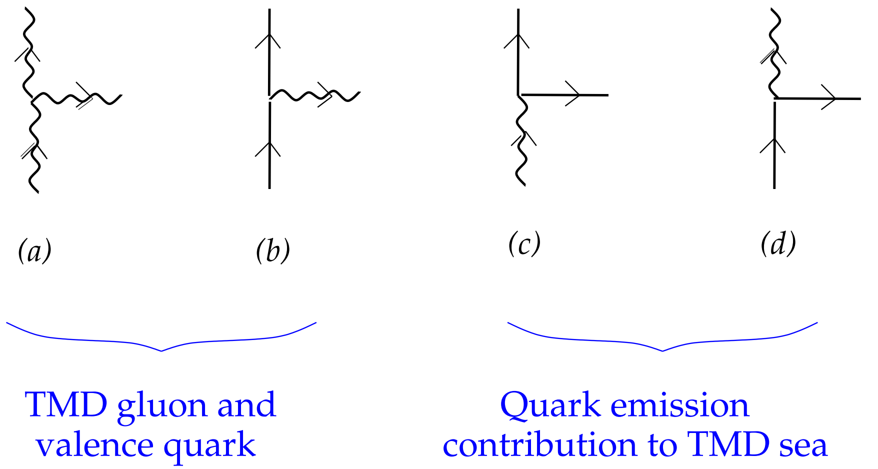
[Hentschinski, Jung & H, NPB865 (2012) 54]



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

$k_\perp$-dependent branching 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

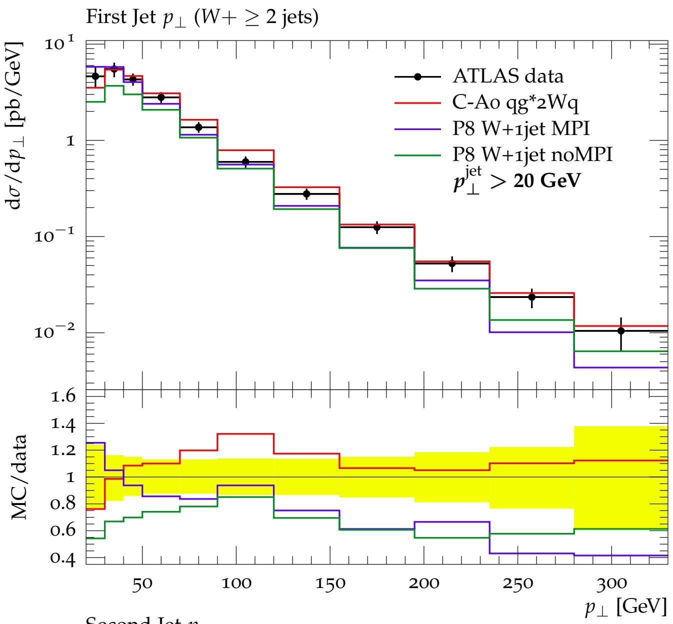
$$\mathcal{P}_{g\to q}(z;q,k) = P_{qg,\mathrm{DGLAP}}(z) \left(1 + \sum_{n=0}^{\infty} b_n(z)(k^2/q^2)^n\right)$$

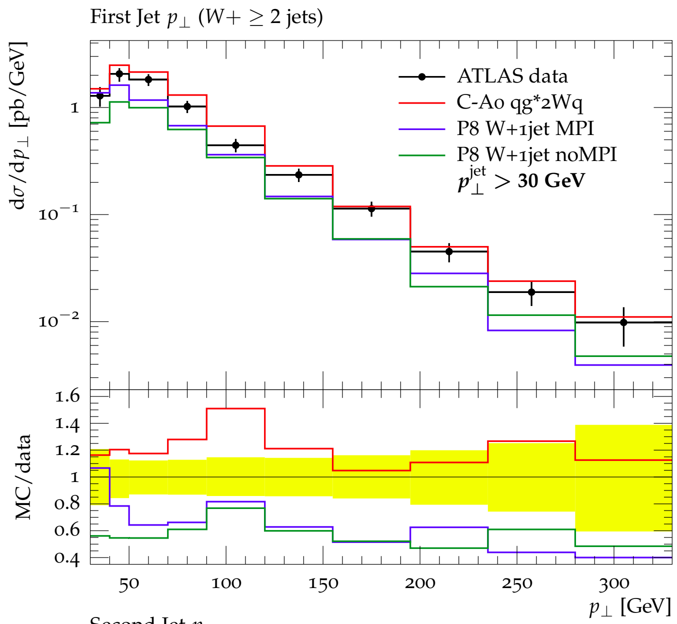
all b_n known; $\mathcal{P}_{g\to q}$ computed in closed form (positive-definite)

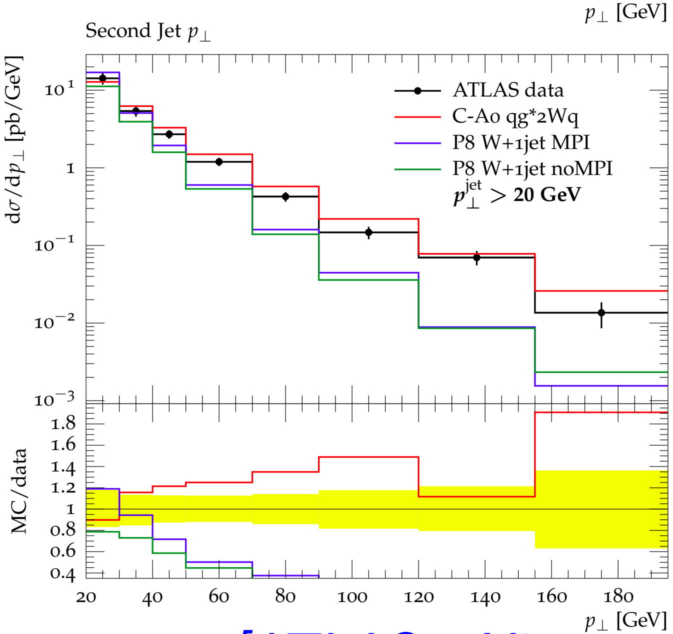
in *[Catani & H, 1994; Ciafaloni et al., 2005-2006]* by small-x factorization

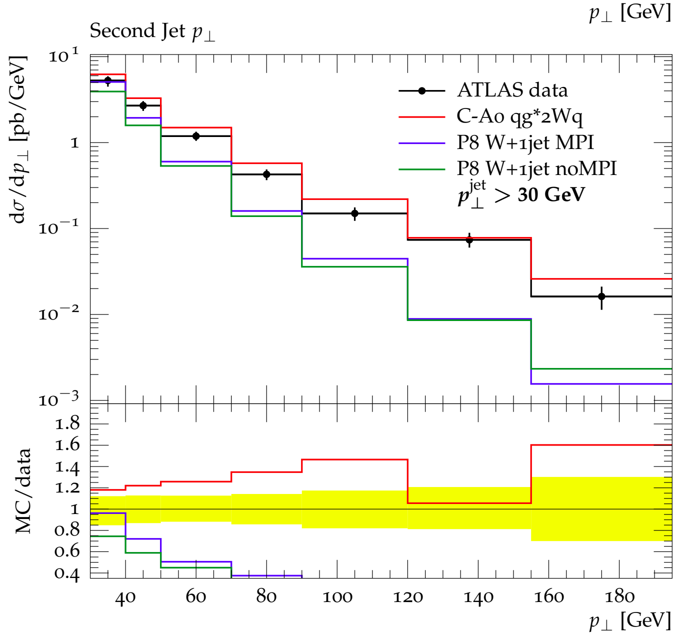
- valence: independent evolution (dominated by soft gluons x $\to$ 1)

W + 2 jets





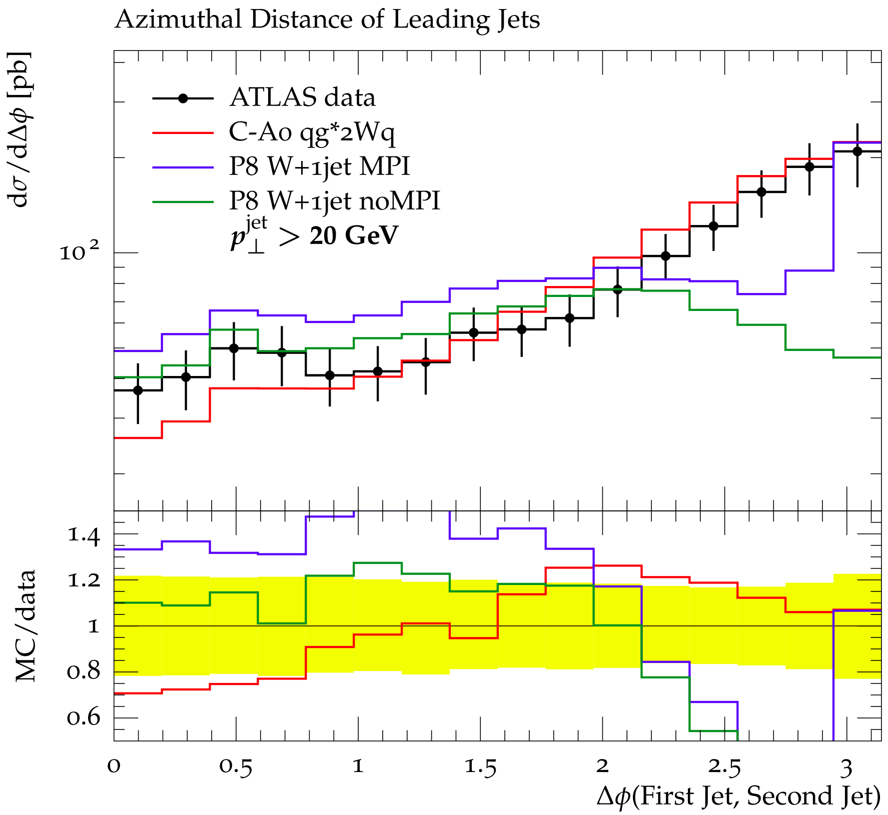


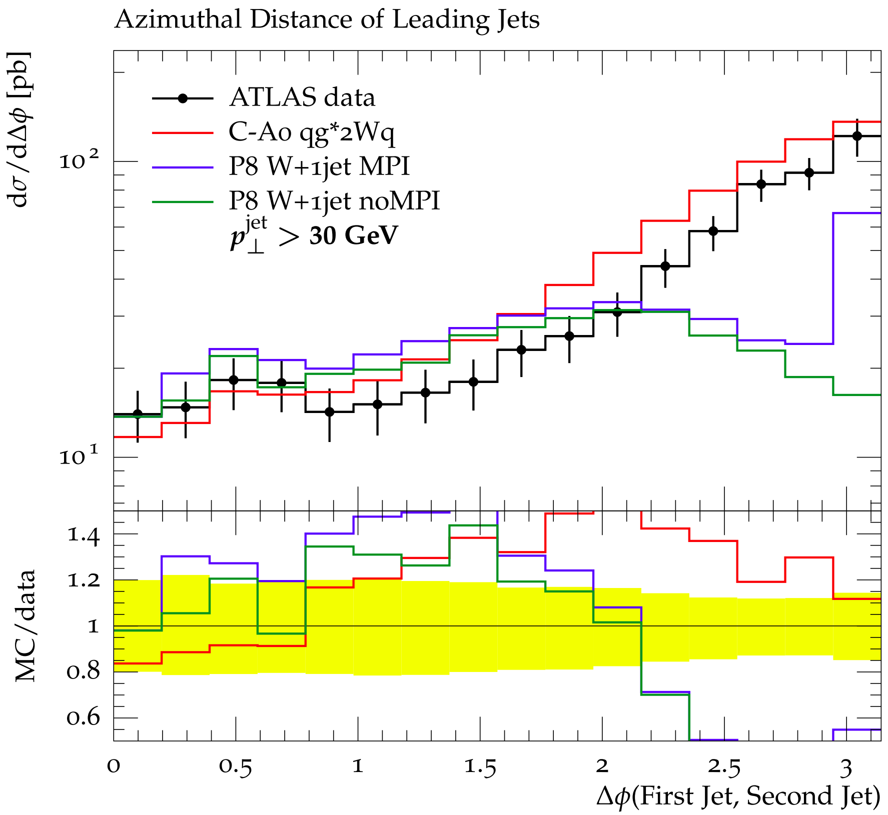


[ATLAS arXiv:1201.1276]

- plots produced by RIVET package

W + 2 jets





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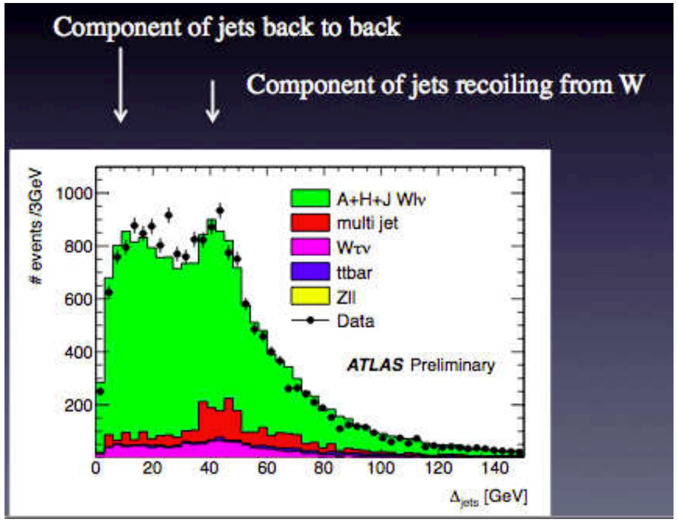
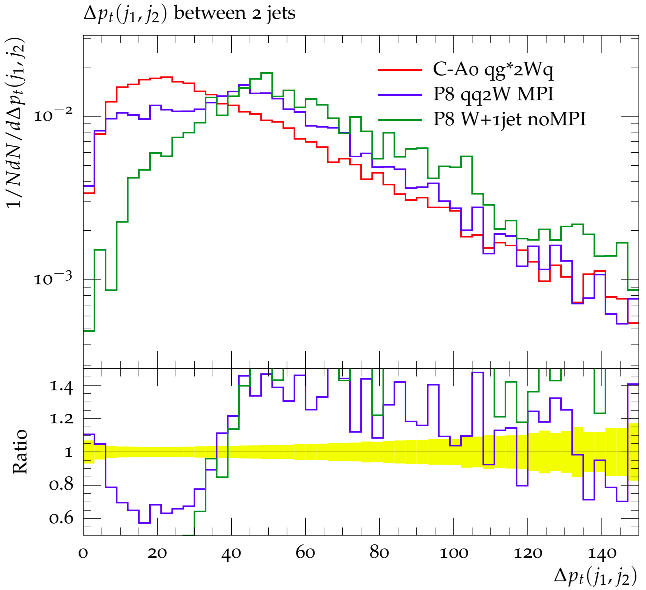
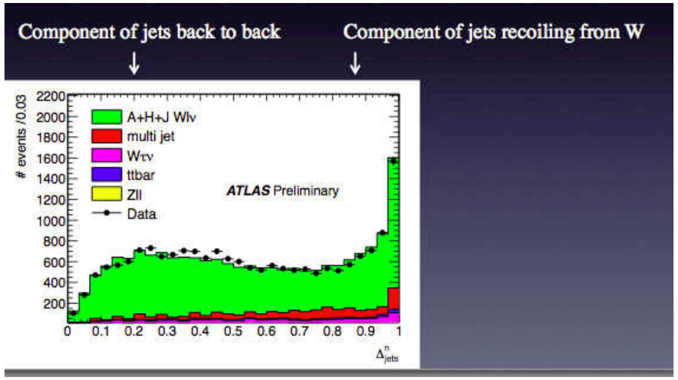
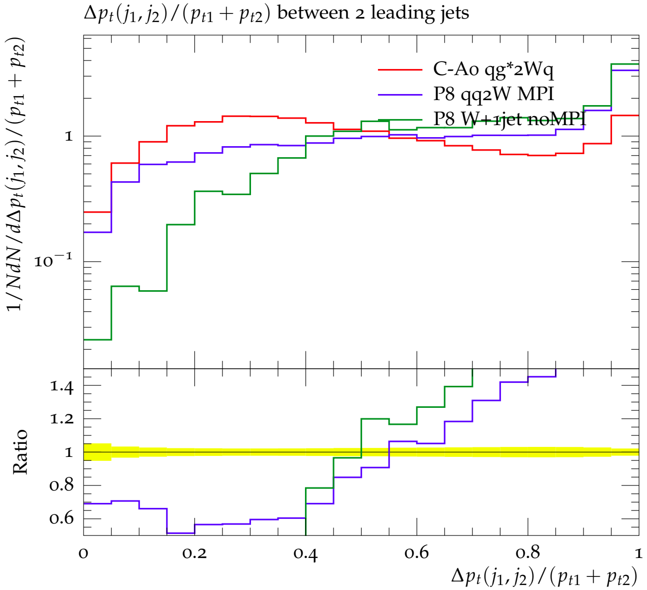
W + 2 jets









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

Remarks

- For jet $p_T \sim \mathcal{O}(20\ \mathrm{GeV})$ effects from higher orders (k_T-shower) to the near back-to-back region are significant.

- MPI may be mimicking these effects.

- Construct consistent picture from multiple processes?

♢ Example: $b\bar{b} + 2j$

▷ MPI analysis using gluonic probe

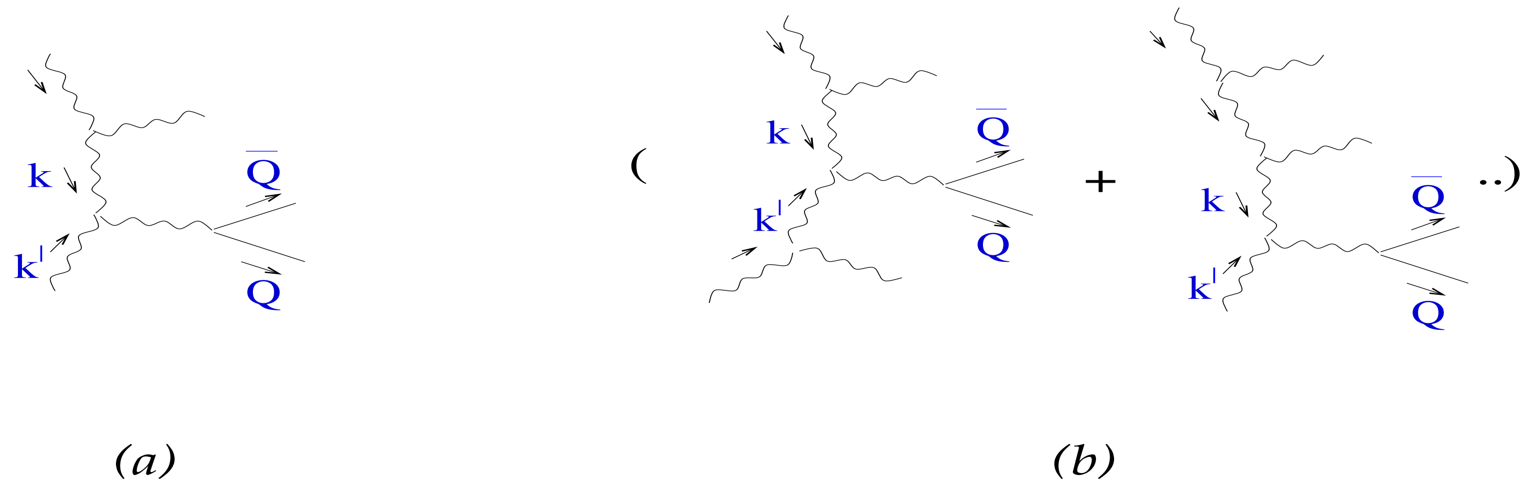
- complementary to W/Z-boson + jets
- perturbative calculation down to $p_\perp$ of order heavy flavor mass

♢ Can this be extended to charm?

Example: $b\bar{b} + 2j$

- test for double parton scattering ($\hookrightarrow$ back-to-back region)

- multi-gluon emission effects ($m_b \ll \sqrt{s}$)



(a) heavy quark hadroproduction from gluon showering;

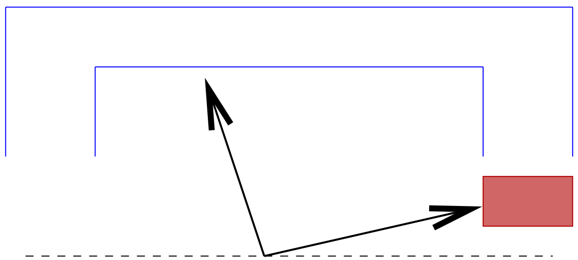
(b) next correction from extra jet emission

strongest $\sqrt{s}\to\infty$ singularity from $\quad m_b \ll p_t^{(b\bar{b})} \ll p_t^{(j)}$

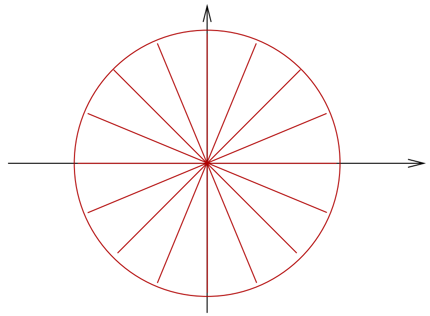
III. MULTIPLE JETS AT THE LHC: ASSOCIATED FORWARD AND CENTRAL JETS

- polar angles small but far enough from beam axis
  - measure correlations in azimuth, rapidity, p_T

$$p_\perp \gtrsim 20 \text{ GeV} \; , \; \Delta\eta \gtrsim 4 \div 6$$



central + forward detectors



azimuthal plane

[see CMS and ATLAS presentations at this workshop]

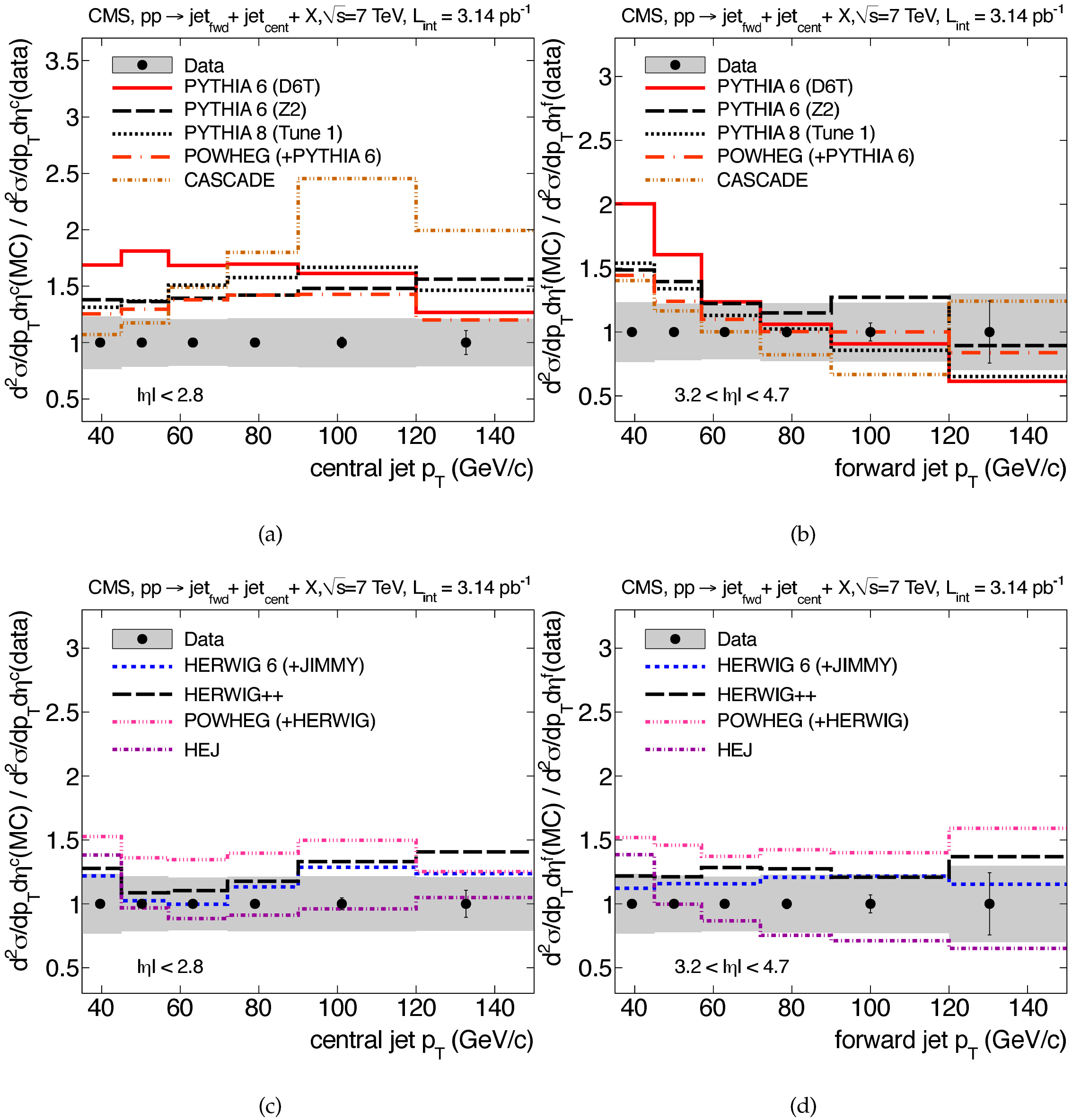
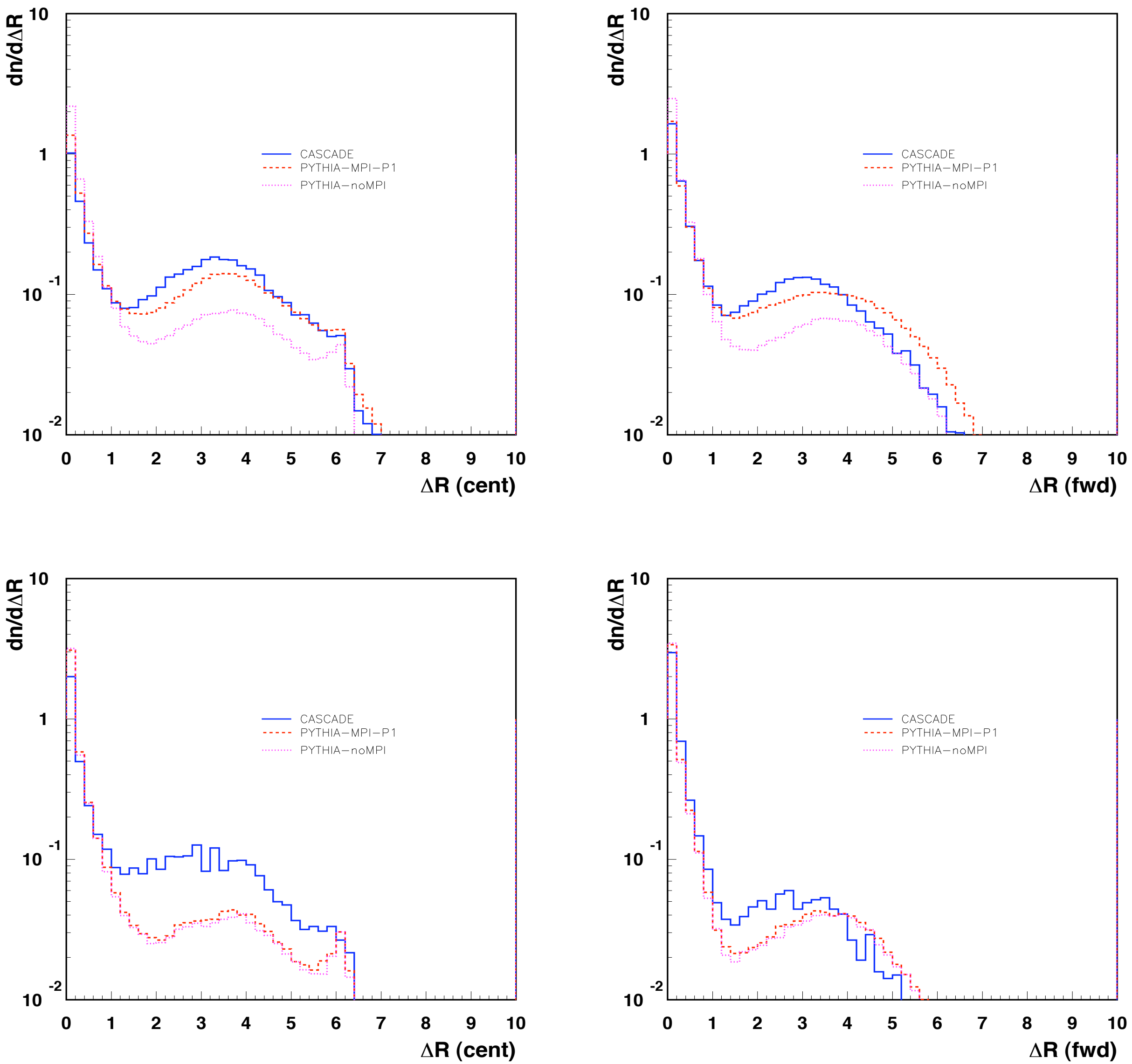


Figure 8: Ratio of theory to data for differential cross sections as a function of p_T, for central ((a) and (c)) and forward ((b) and (d)) jets produced in dijet events. The error bars on all data points reflect just statistical uncertainties, with systematic uncertainties plotted as grey bands.

[CMS Coll., JHEP 1206 (2012) 036 [arXiv:1202.0704]]

- large differences between Powheg/ Pythia and Powheg/ Herwig



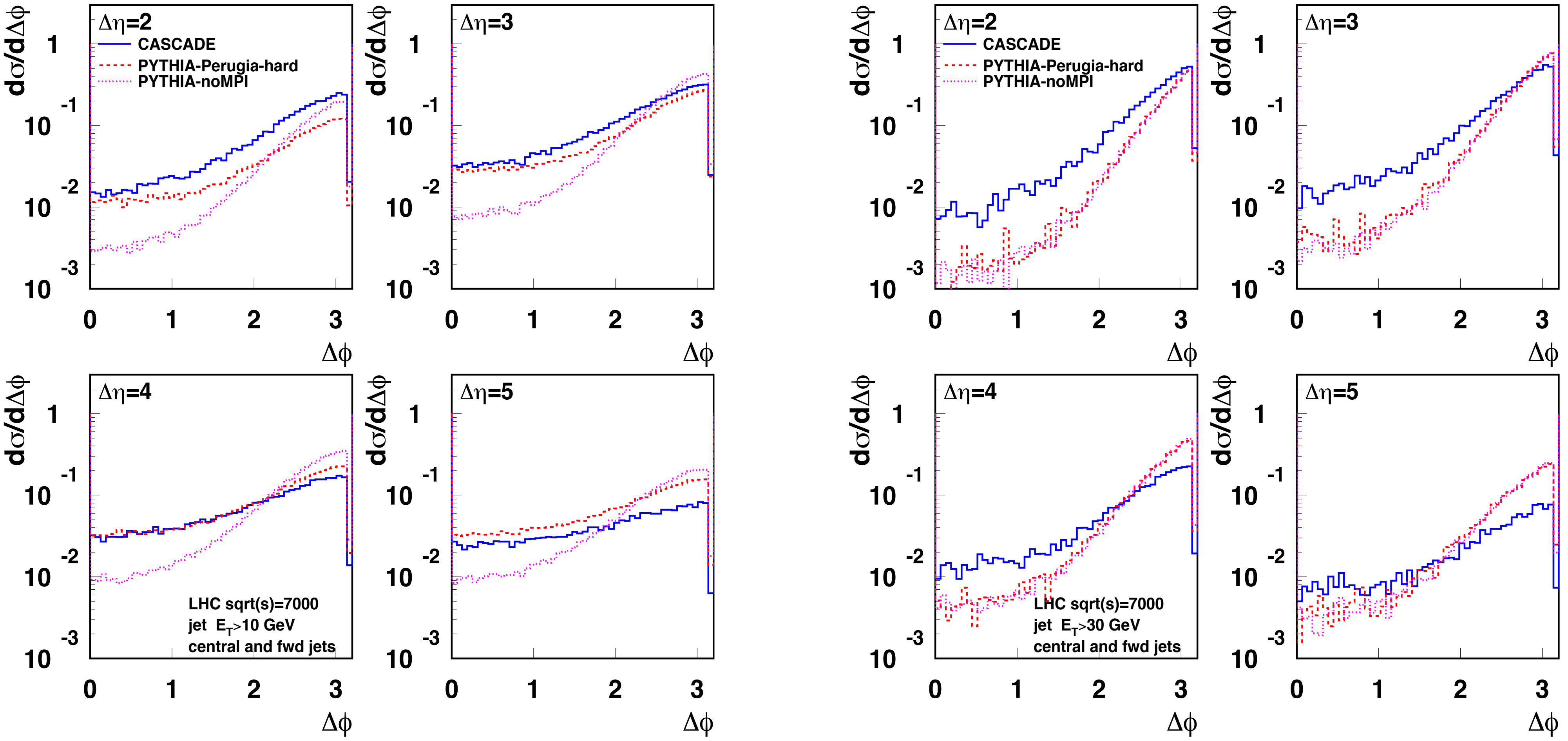
[Deak et al., arXiv:1012.6037]

- sizeable contributions to jets from showers (large-ΔR)

Figure 5: ΔR distribution of the central ($|\eta_c| < 2$, left) and forward jets ($3 < |\eta_f| < 5$, right) for $E_T > 10$ GeV (upper row) and $E_T > 30$ GeV (lower row). The prediction from the k$_\perp$ shower (CASCADE) is shown with the solid blue line; the prediction from the collinear shower (PYTHIA) including multiple interactions and without multiple interactions is shown with the red and purple lines. $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$, where $\Delta\phi = \phi_{jet} - \phi_{part}$, $\Delta\eta = \eta_{jet} - \eta_{part}$

Cross section as a function of the azimuthal difference $\Delta\phi$ between central and forward jet for different rapidity separations

[Deak et al., arXiv:1012.6037]

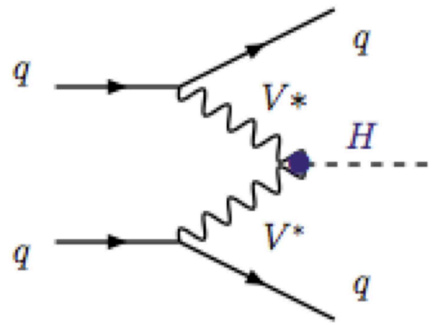


(left) low E_T: decorrelation increasing with $\Delta\eta$ from non-collinear corrections (Cascade) and from MPI (Pythia); (right) high E_T: MPI effect dies out

Extension to forward-backward kinematics

♢ search for Mueller-Navelet effects

♢ background to searches in vector boson fusion channels



♢ large-Δy dijet data not well understood

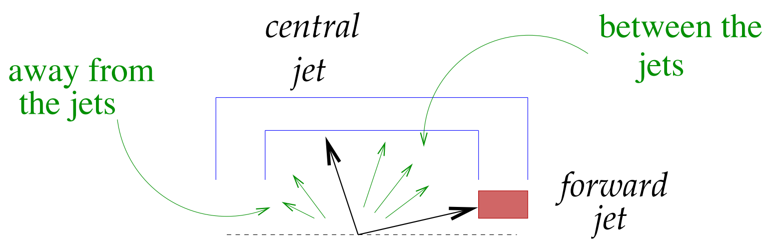
[CMS, arXiv:1204.0696]

[ATLAS, arXiv:1107.1641]

ENERGY FLOW OBSERVABLES

Transverse energy flow as a function of rapidity and azimuthal angle

$$1 < \eta_c < 2 \ , \qquad -5 < \eta_f < -4$$



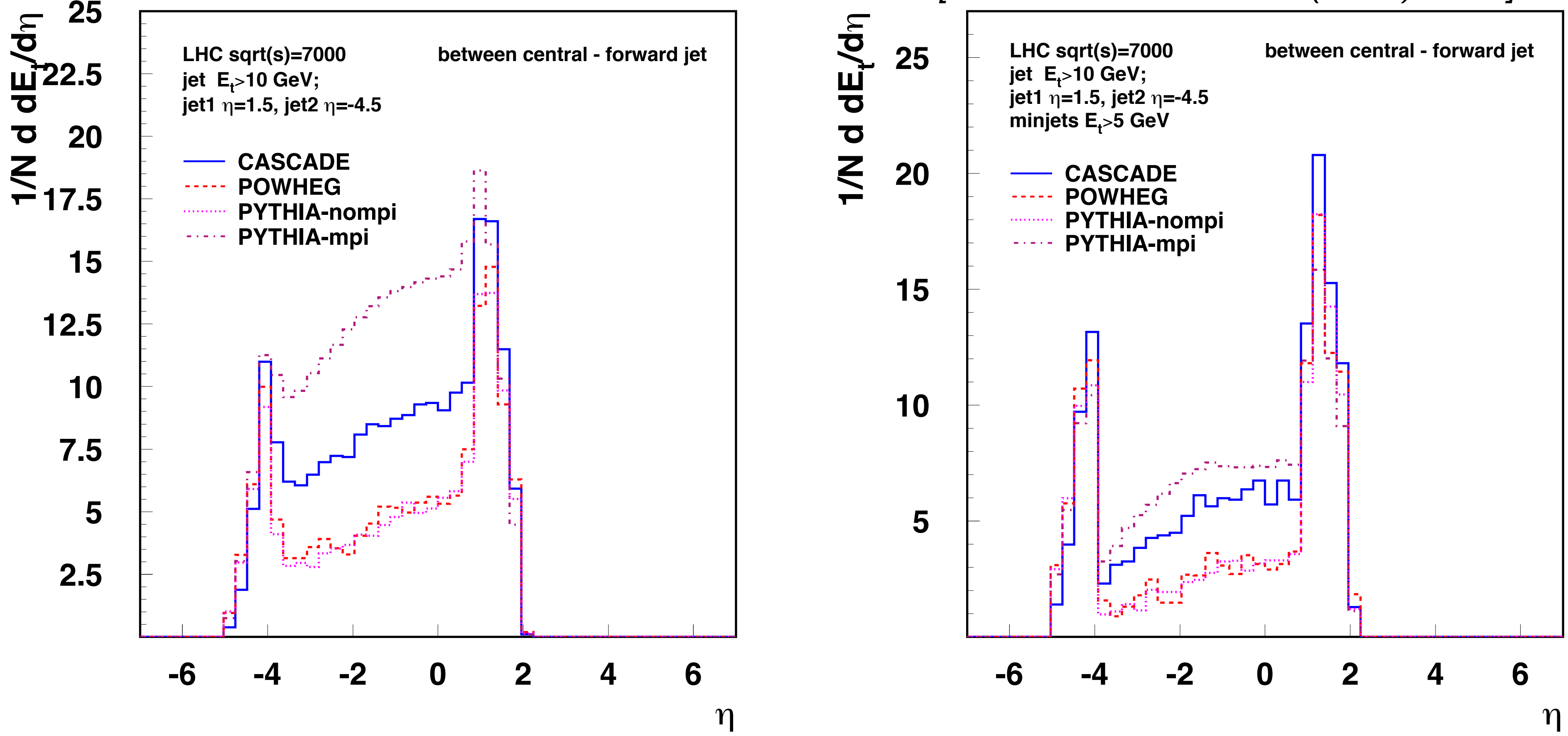
$$\frac{dE_\perp}{d\eta} = \frac{1}{\sigma} \int dq_\perp \ q_\perp \ \frac{d\sigma}{dq_\perp \ d\eta}$$

“Minijet” energy flow

- merge particles into jets via jet algorithm
- construct energy flow from jets with $q_\perp > q_0$
- $q_0 = \mathcal{O}(\text{a few GeV})$ feasible at the LHC

Transverse energy flow in the inter-jet region

[Deak et al., EPJC 72 (2012) 1982]

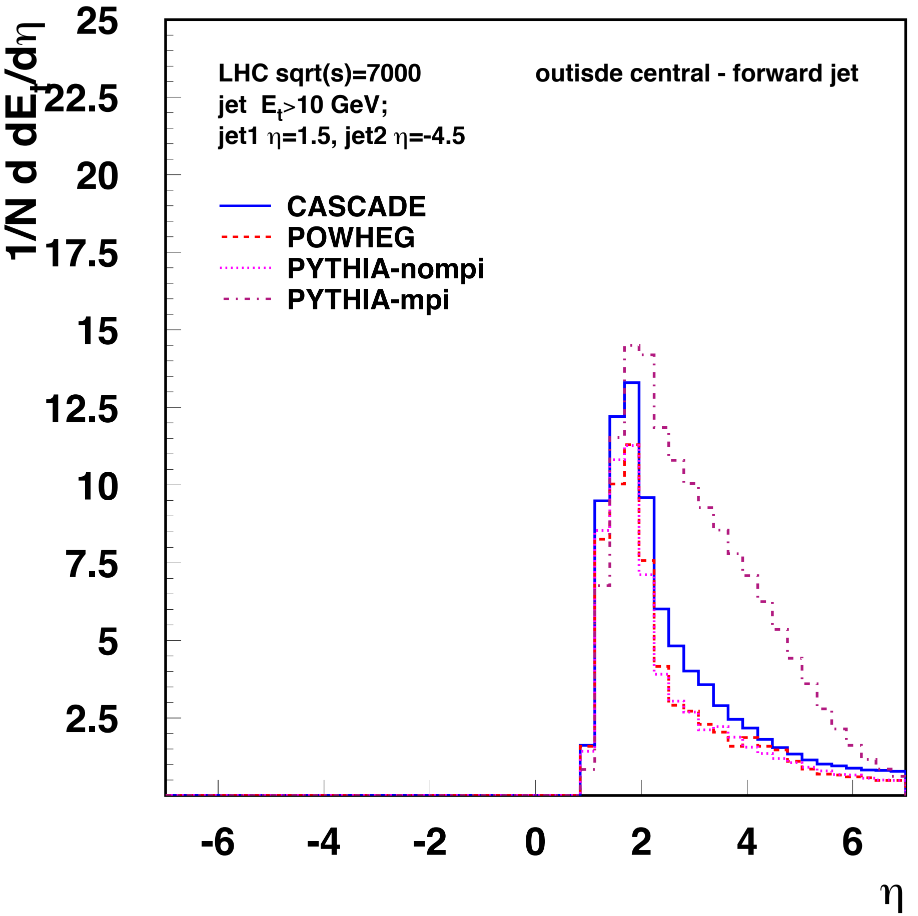


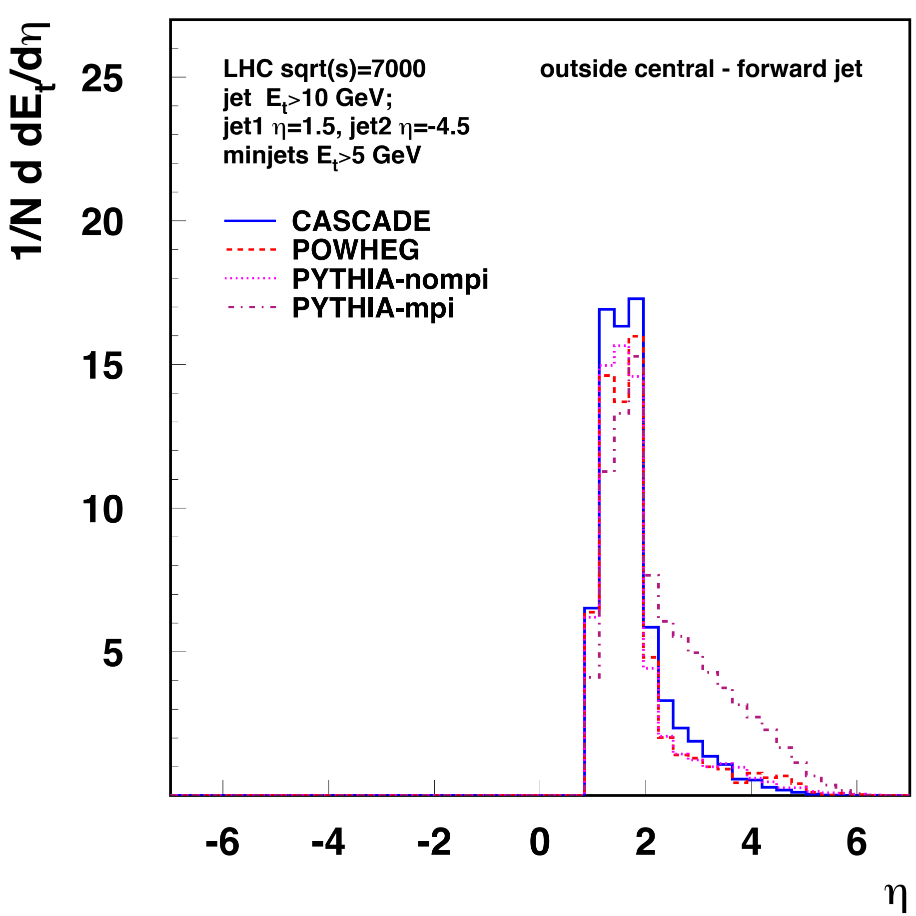
(left) particle flow; (right) minijet flow

▷ higher mini-jet activity in the inter-jet region
from corrections to collinear ordering and from MPI (tune Z1)

▷ little effect from NLO hard correction in POWHEG

Transverse energy flow in the outside region



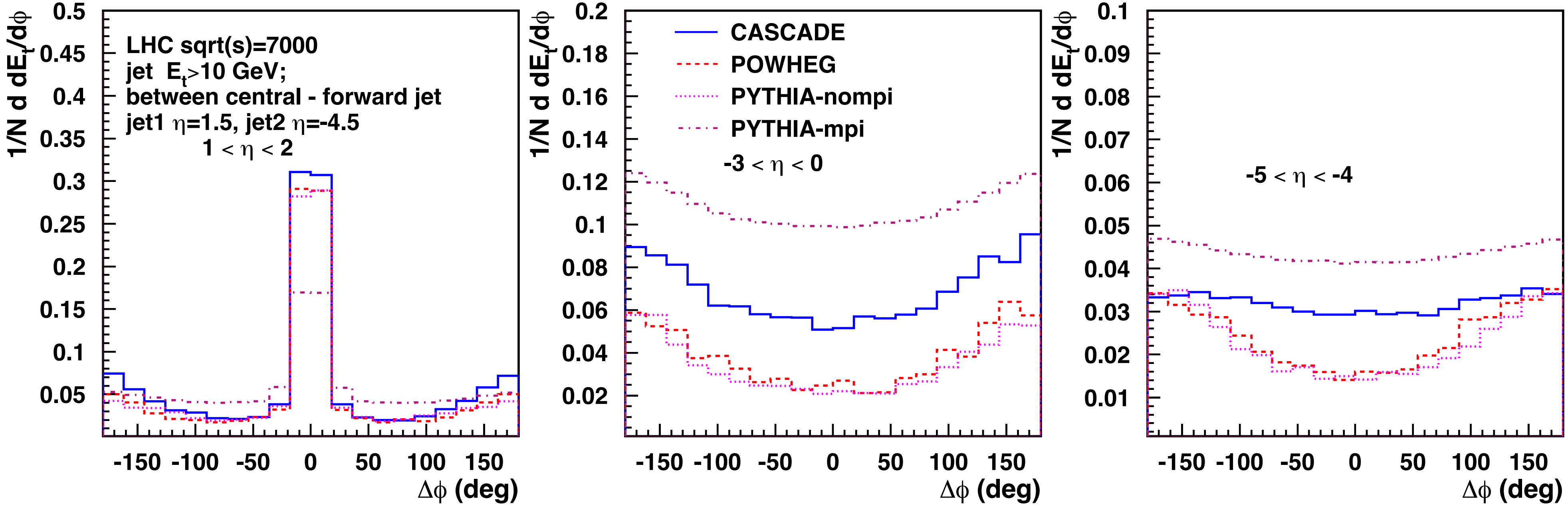


▷ at large (opposite) rapidities, full branching well approximated by collinear ordering

▷ higher energy flow only from multiple interactions

Azimuthal dependence of transverse energy flow

(left) central-jet; (middle) intermediate; (right) forward-jet rapidities



- more pronounced flattening of the $\Delta\phi$ distribution from CASCADE and PYTHIA-mpi (tune Z1) compared to POWHEG and PYTHIA-nompi

$\diamondsuit$ Particle spectra are used more commonly

$\diamondsuit$ Energy flow due to minijets

($q_T > q_0,\ e.g.\ q_0 = 5$ GeV)

has different advantages:

- IR sensitivity controllable by jet clustering
- observables applicable uniformly at low and high transverse momenta (*e.g.* multiplicity distributions)

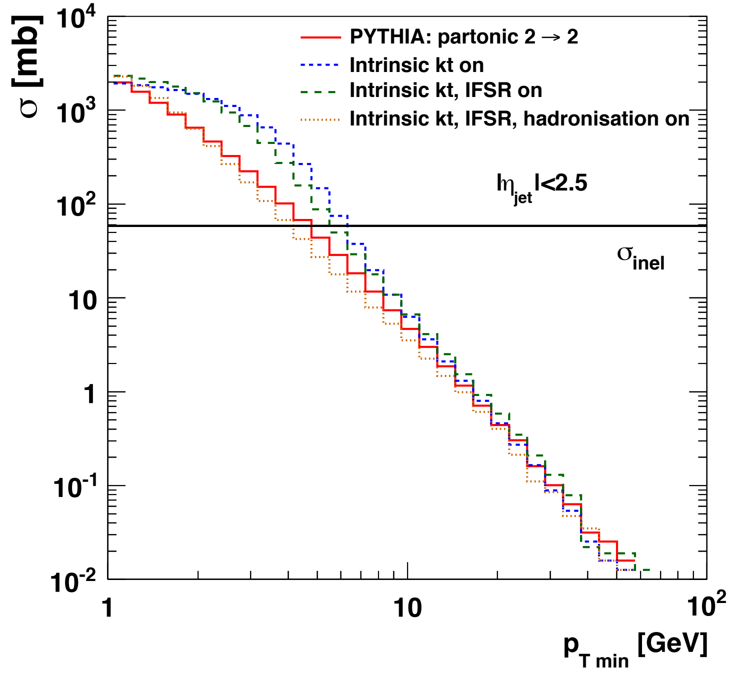
IV. Jets, MPI and the inelastic pp cross section

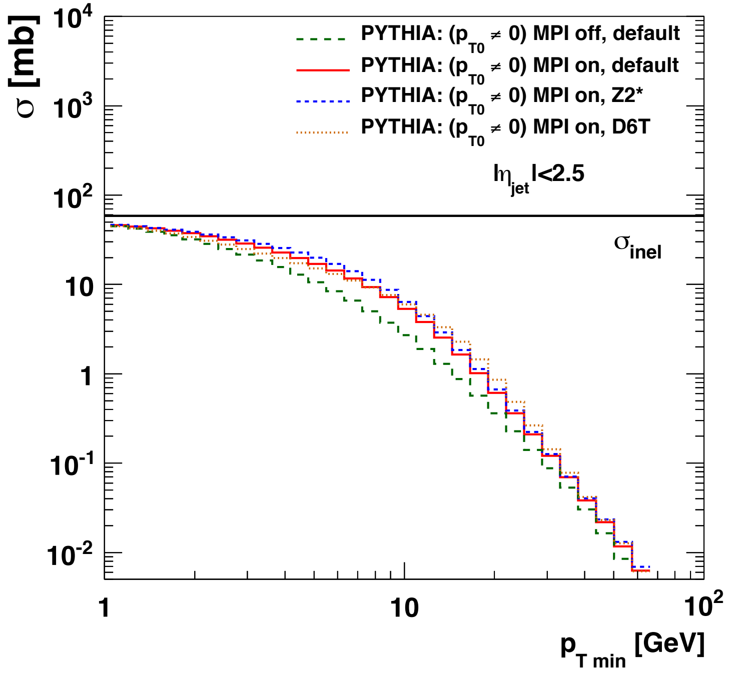
• Extend central jet measurements to lower $p_\perp$

$\Rightarrow$ 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 $2 \to 2$ 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]

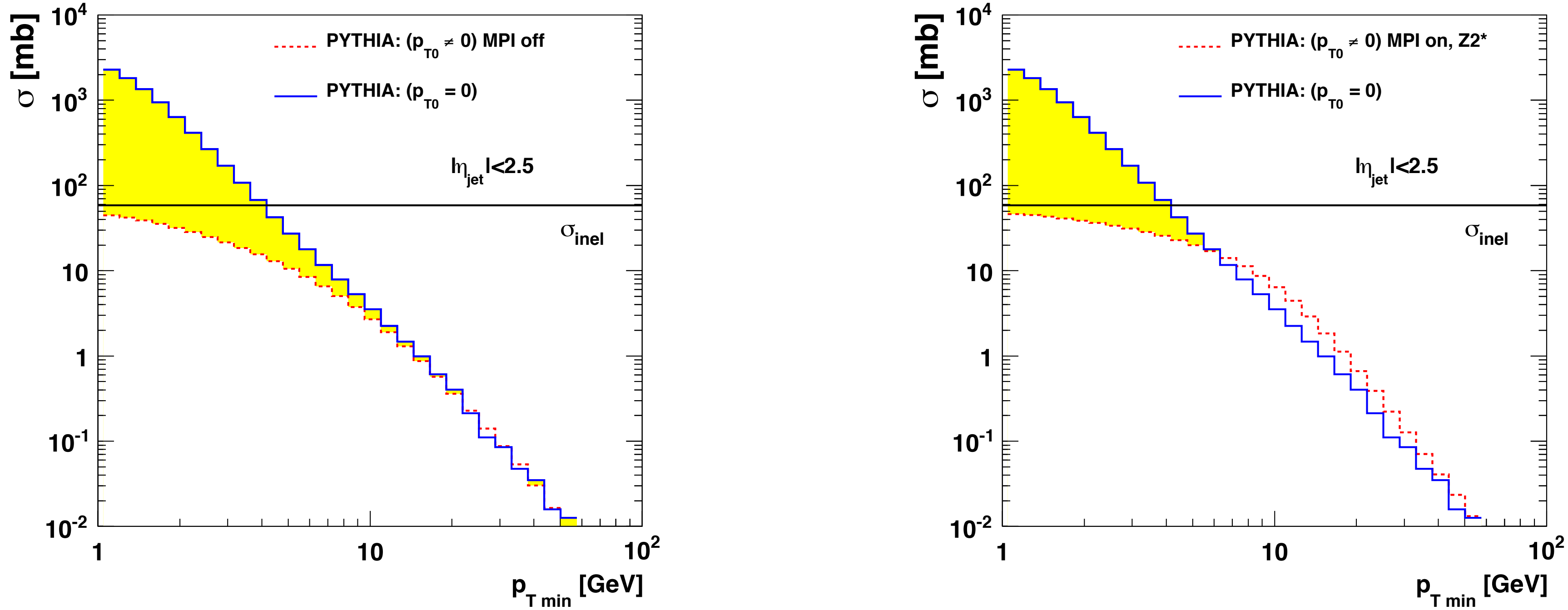
- low-p$_T$ model in collinear framework (PYTHIA):

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

- 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

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

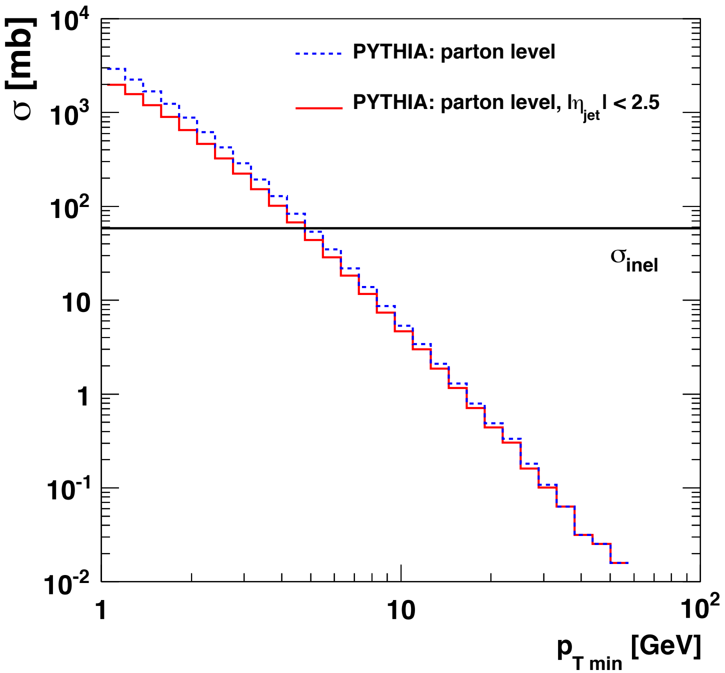
- measure ratio of fixed p_T rate to total minimum bias rate

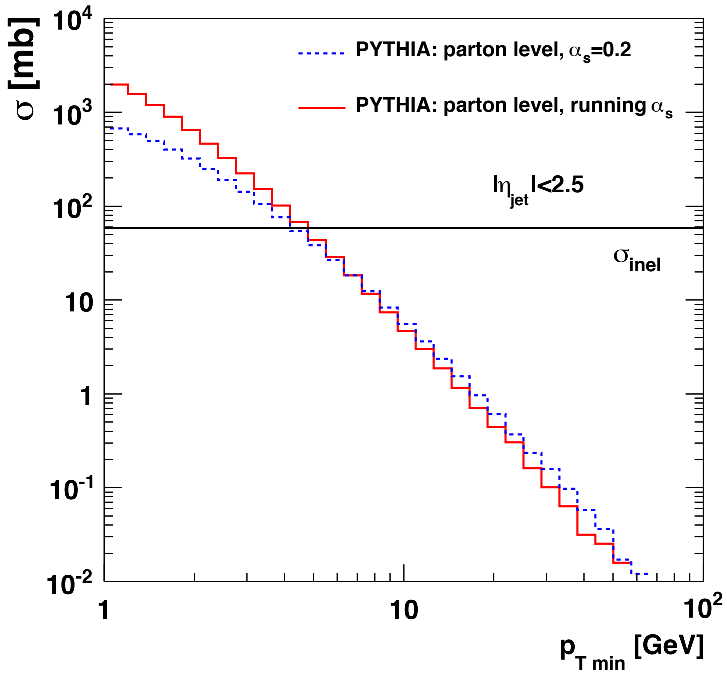
- ATLAS Phys. Rev. D84 (2011) 054001 illustrates feasibility of measuring jets at low p_T but
  - ▷ does not consider event cross sections $\Rightarrow$ no study of unitarity effects
  - ▷ normalizes MC to integrated rate $\Rightarrow$ all models effectively norm.'d to lowest p_T bin

- it is interesting to extend this to pA

• low p_T $\Rightarrow$ jets constructed from charged tracks $\Rightarrow$ *visible* cross section

• comparison with inelastic $\sigma(pp)$ within acceptance — no extrapolation needed

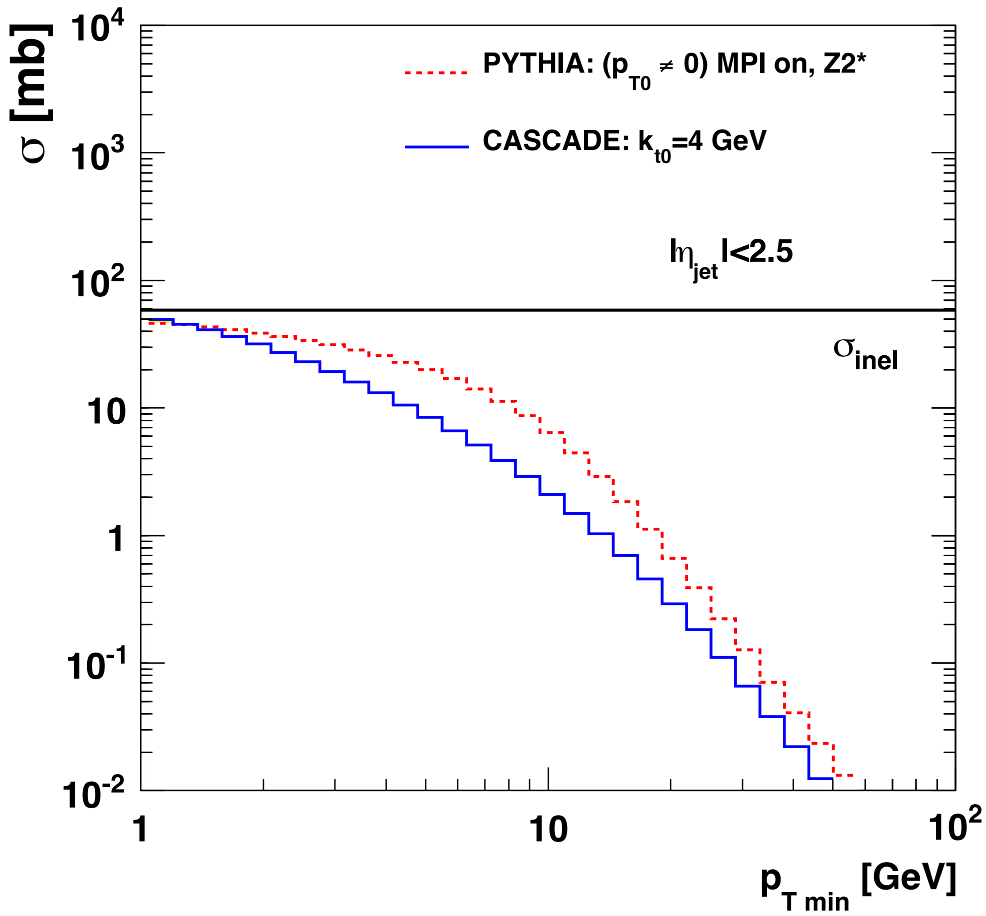




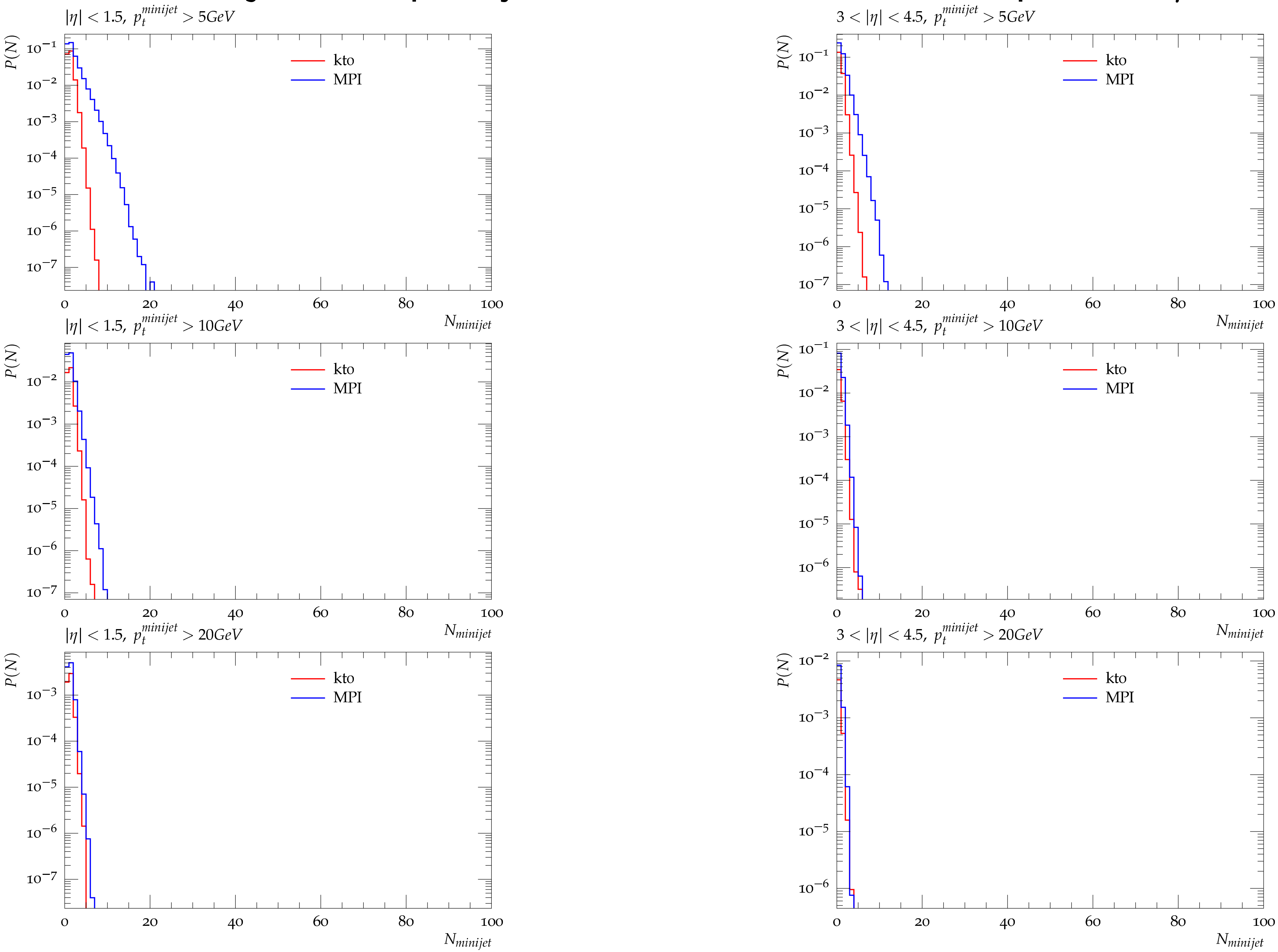
• no large effect from infrared behavior of the QCD coupling in the p_T region where jet cross section approaches the inelastic bound

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

- Low transverse momentum cross section from k_T-shower and PYTHIA MPI model



• Mini-jet multiplicity distributions for different p_T and η



REMARKS

• besides cross sections, measure (mini)jet multiplicity distributions
for different transverse momenta $q_T > q_0$:
e.g. $q_0 = 2$ GeV, 5 GeV, 10 GeV, 20 GeV

• MC / UE analyses ⇒ MPI contribution to high multiplicities for low q_0;
how does this vary with increasing q_0?

⇒ probe separately contribution from different
regions in impact parameter
using (mini)jet multiplicities uniformly from low to high p-transverse

• spacetime picture of QCD showers?

CONCLUSIONS

• MPI increasingly important as parton densities grow with energy

▷ sensitive to detailed structure of final states produced by shower evolution

⇒ what level accuracy required in parton branching algorithms?

⇒ amount of MPI reduced by inclusion of non-collinear-ordered effects to showers?

• $W + 2j$

• energy flow associated to forward+central jets

• Measure visible jet cross section down to $p_T \sim$ a few GeV using tracker and (mini-)jet multiplicity distributions per rapidity bin from low to high p_T

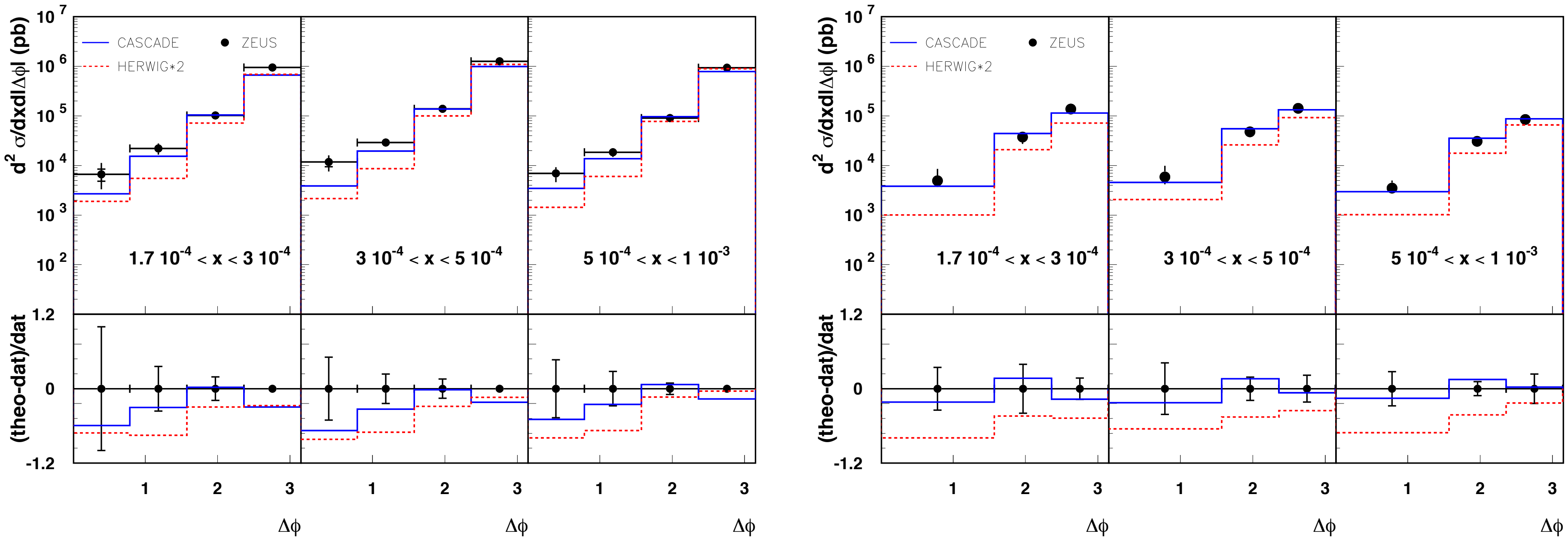
⇒ how does MPI contribution to high multiplicities change with p_T?

⇒ p_{Tmin} dependence and inelastic pp cross section

weak-coupling but nonperturbative QCD physics

EXTRA SLIDES

NO-MPI CASE: ANGULAR JET CORRELATIONS IN EP FROM K$_\perp$-SHOWER (CASCADE) AND COLLINEAR-SHOWER (HERWIG)

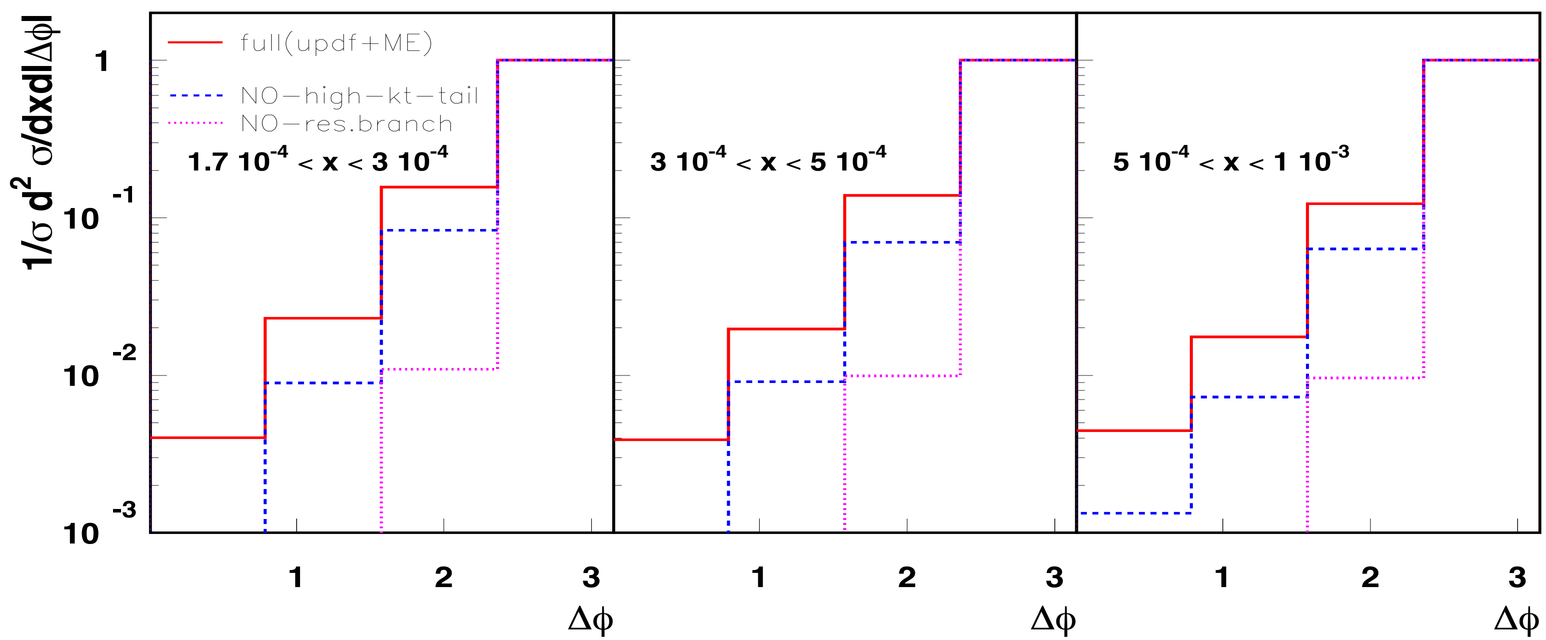


(left) di-jet cross section; (right) three-jet cross section

Jung & H, JHEP 0810 (2008) 113

- quantitative effects of small-x coherence sizeable
- largest differences at small $\Delta\phi$
- good description of shapes by k$_\perp$-shower
- HERWIG normalized to 2-jet region by K-factor

Normalize to the back-to-back cross section:



updf $\oplus$ ME

- - - updf $\oplus$ ME$_{collin.}$: $\mathcal{M} \to \mathcal{M}_{collin.}(k_T) = \mathcal{M}(0_\perp)\ \Theta(\mu - k_T)$

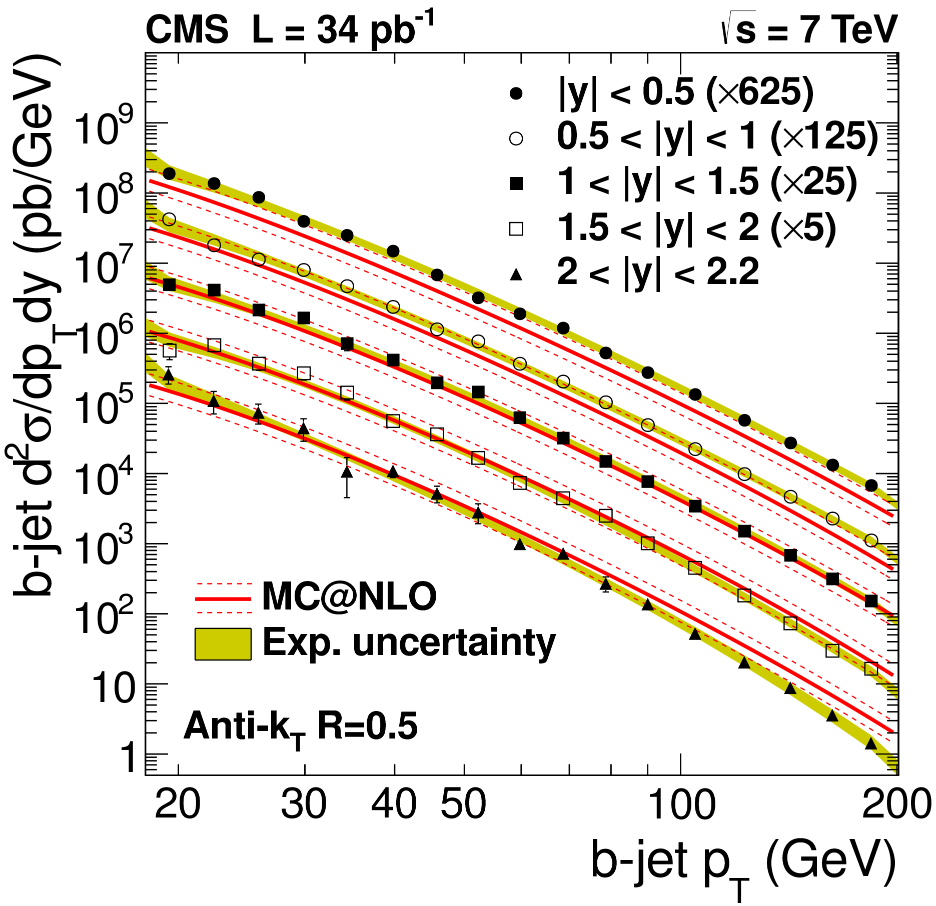
· · · · · · no resolved branching : $\mathcal{A} \to \mathcal{A}_{no-res.}(x, k_T, \mu) = \mathcal{A}_0(x, k_T, Q_0)\ \Delta(\mu, Q_0)$

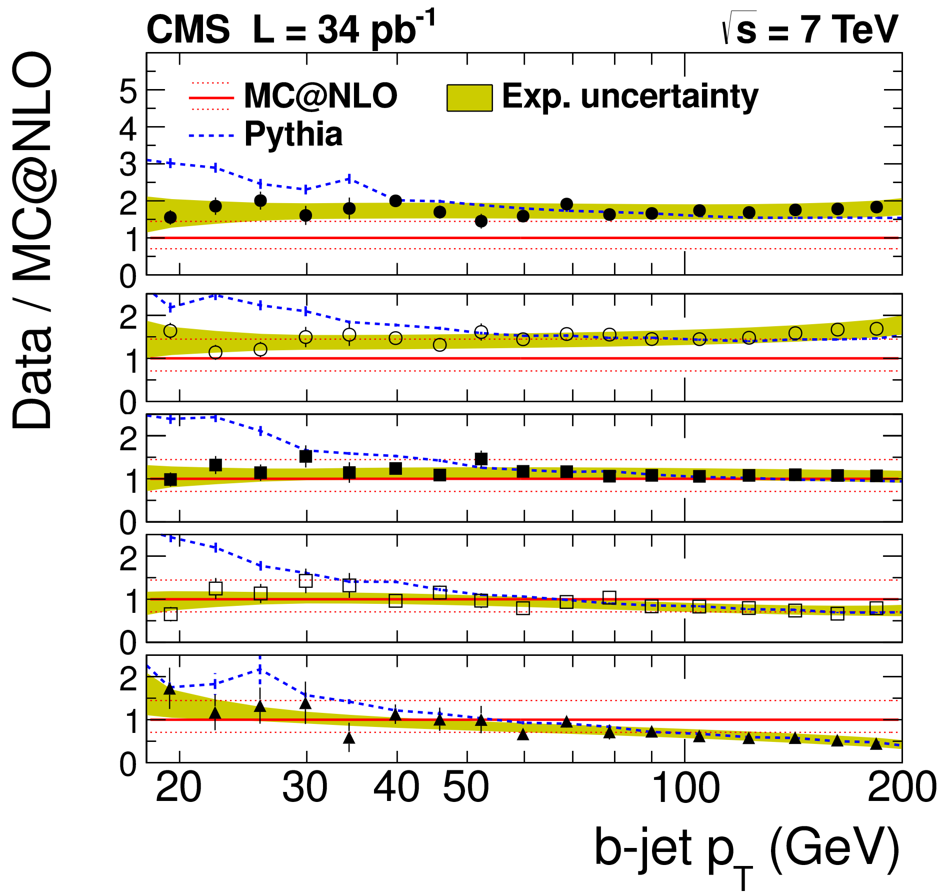
▷ high-k$_\perp$, coherent effect essential for correlation at small $\Delta\phi$

(cfr., e.g., MC by *Höche, Krauss & Teubner, EPJC 58 (2008) 17* (KMR approach):
u-pdf but no ME correction

Inclusive b-jets

[CMS, JHEP1204 (2012) 084 [arXiv:1202.4617]]

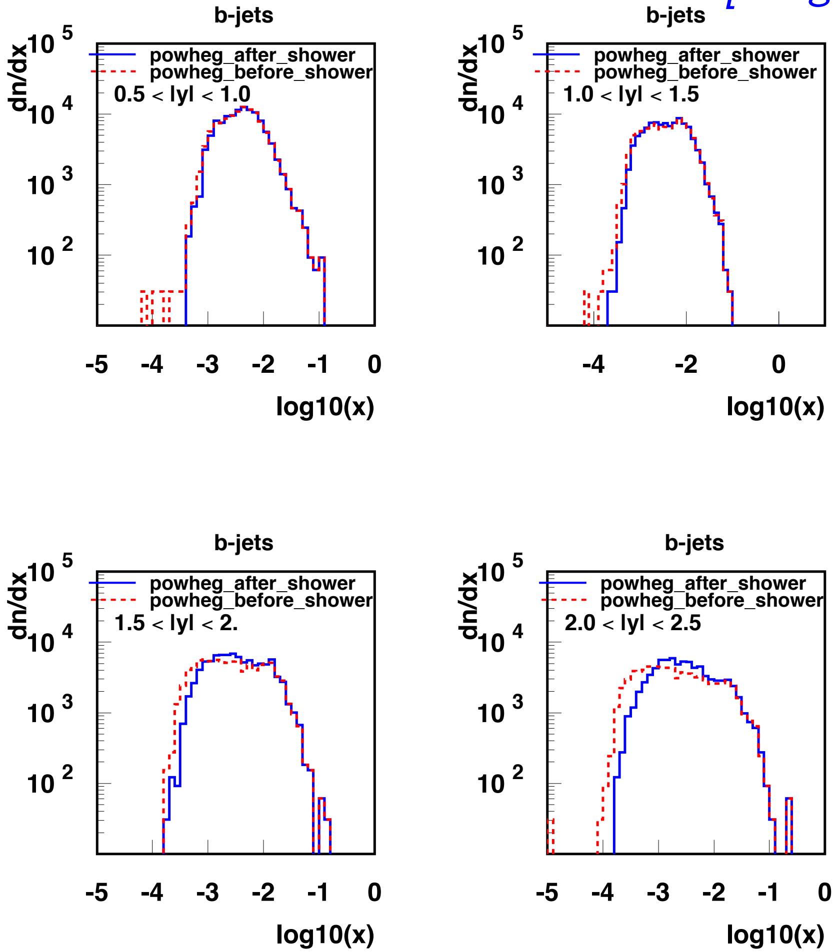




- reasonable description by NLO-matched shower MC@NLO at central rapidities
  - data below the prediction at large y and large p_T

Collinear shower kinematics effects in b production

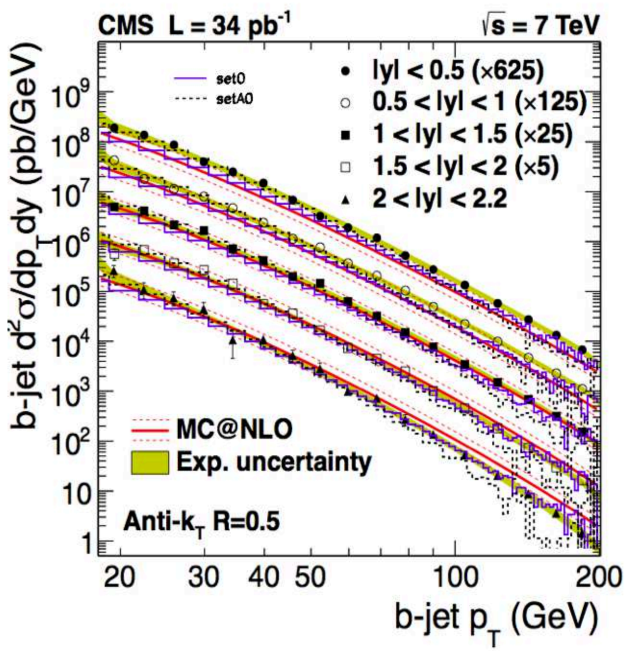
[Jung and H, arXiv:1209.6549]



Production of b-jets: distribution in x, before and after parton showering, for different rapidity regions.

b-jets using k$_\perp$-dependent showers

[H. Jung et al., arXiv:1206.1796]

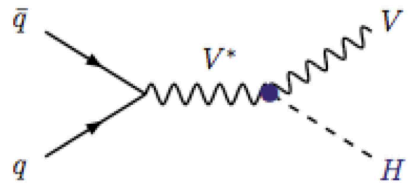


♠ similar description to MC@NLO at central rapidities

♠ shape in p_T closer to data at large y

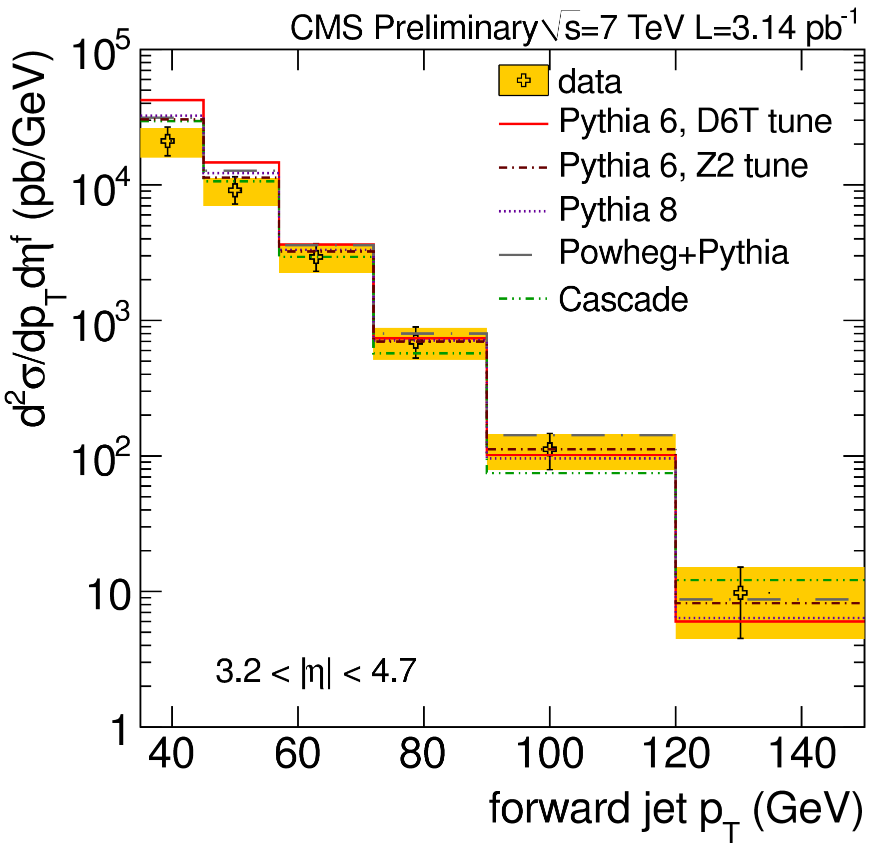
♢ Is this effect of QCD high-energy resummation or mainly kinematics?

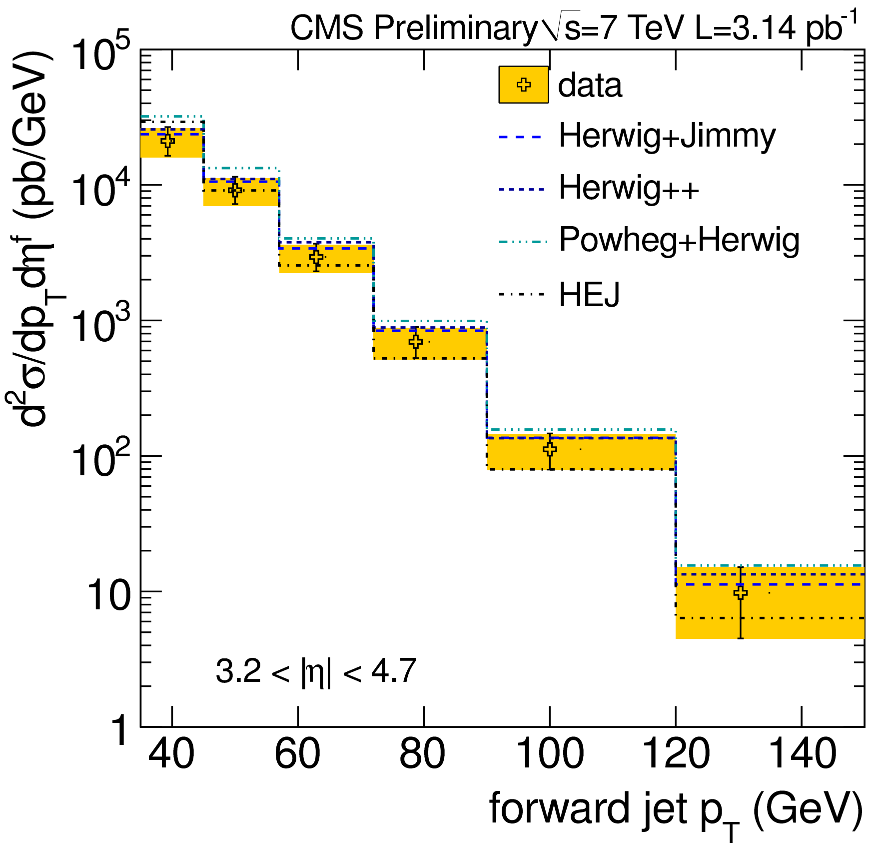
• relevant for $H \to b\bar{b}$ in VH associated production



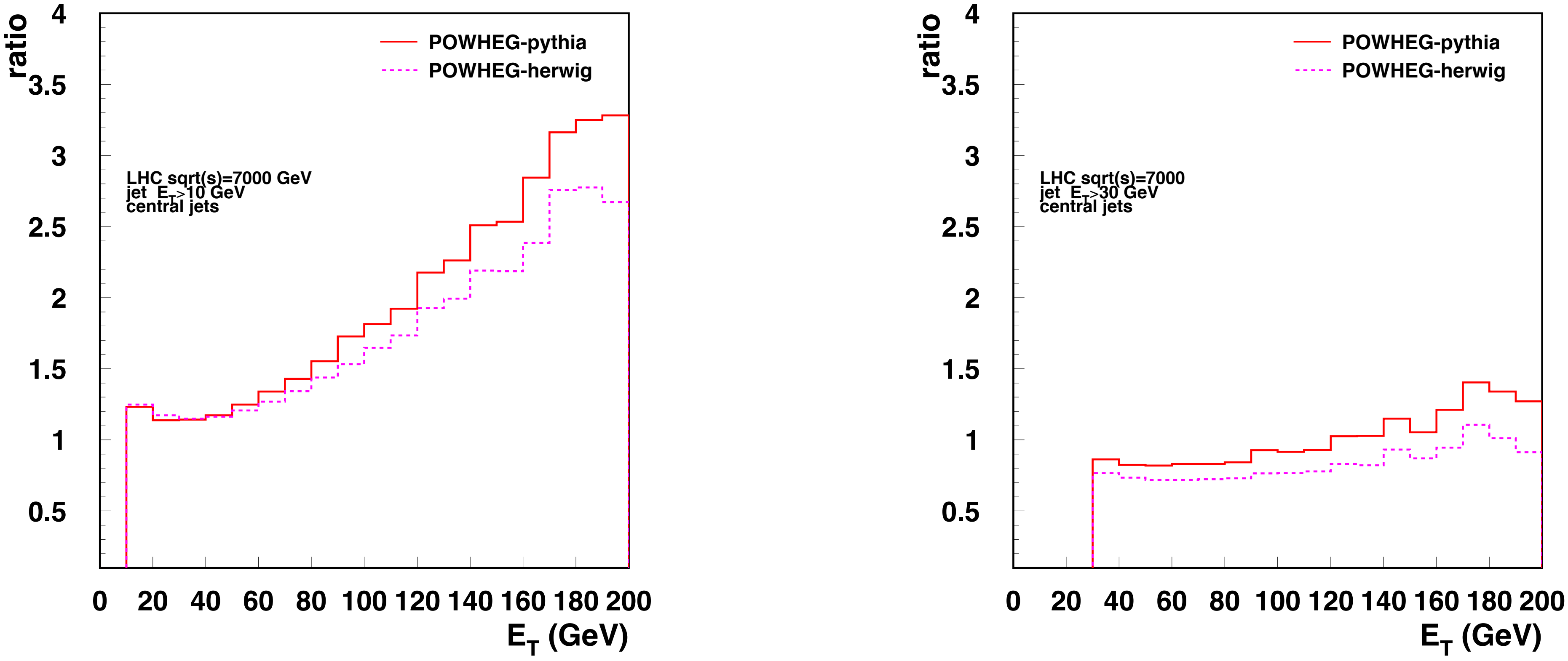
Forward jet spectrum

[CMS Coll., JHEP 1206 (2012) 036 [arXiv:1202.0704]]





- spectrum in rough agreement with Monte Carlo results
  - but detailed forward-central correlations are not ↪



Dijet events with a central and a forward jet:

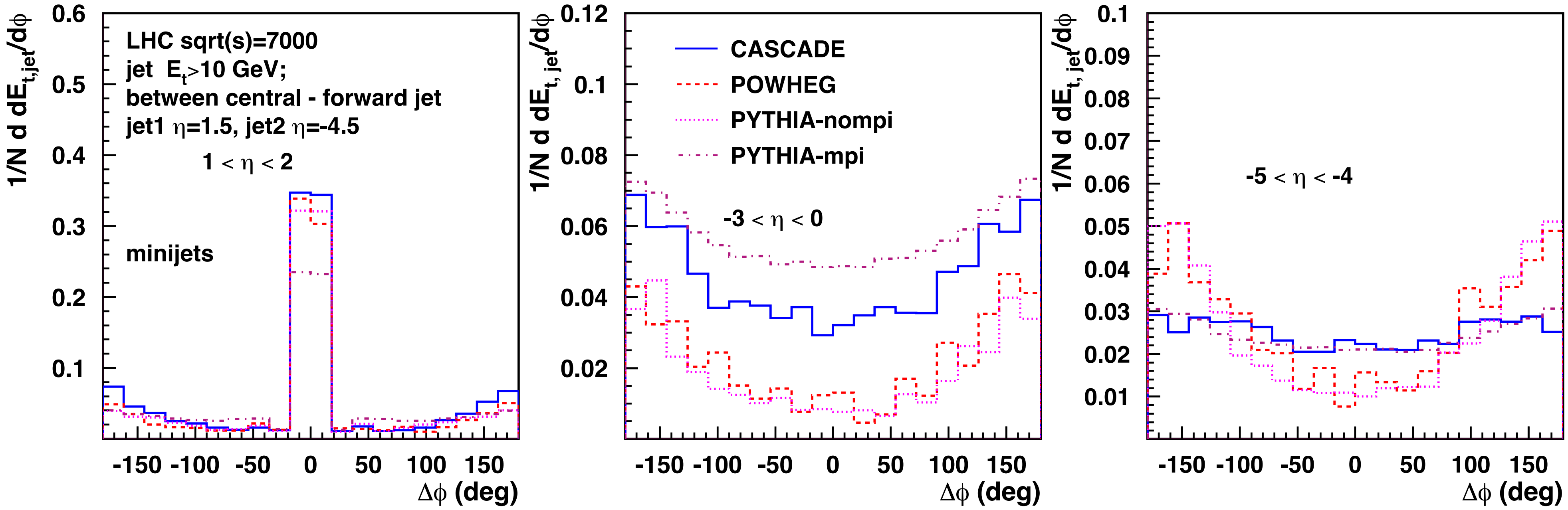
ratio of central jet transverse energy spectra from the NLO-matched Monte Carlo generator POWHEG, interfaced with PYTHIA and HERWIG parton showers, to the no-showering result.

(left) $E_T > 10$ GeV; (right) $E_T > 30$ GeV.

[Deak et al., arXiv:1206.7090]

Azimuthal dependence of transverse energy flow

(left) central-jet; (middle) intermediate; (right) forward-jet rapidities

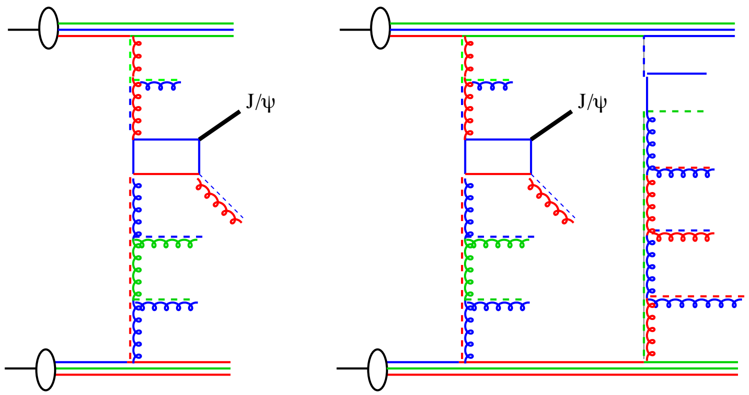


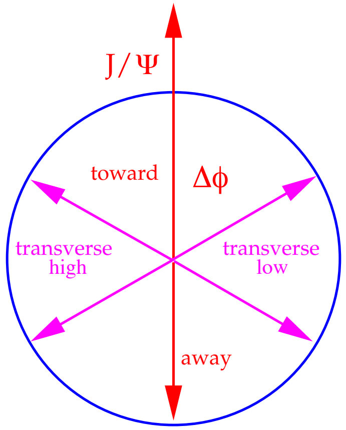
- mini-jet energy flow

J/ψ and associated jet multiplicities

▷ MPI / UE analysis using gluonic probe

- complementary to W/Z-boson + jets
- perturbative calculation down to p$_\perp$ of order m_ψ





▷ See also: J/ψ vs. charged particle multiplicity *[Portebeuf & Granier, arXiv:1012.0719]*

[ALICE Coll., arXiv:1202.2816]

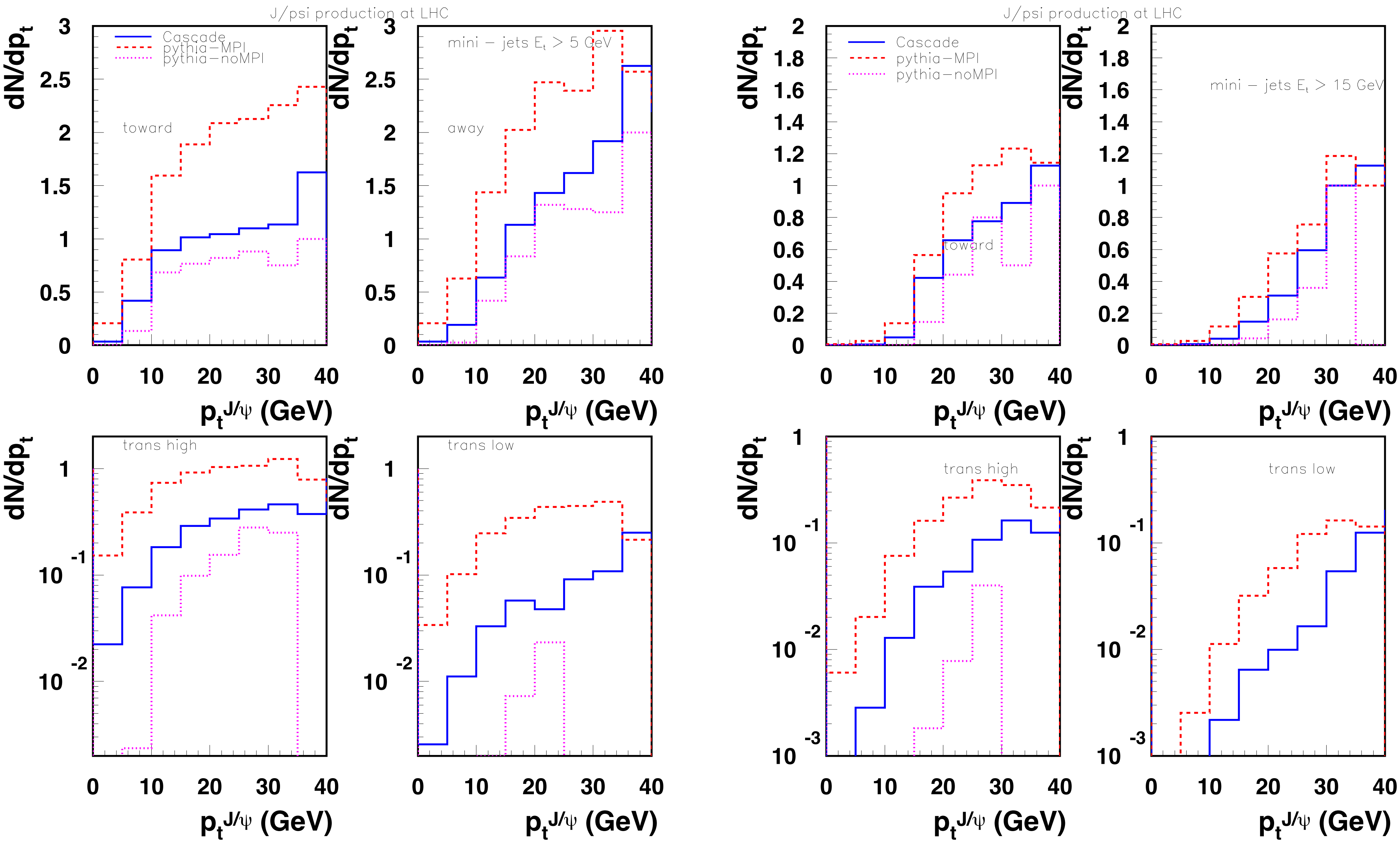
▷ J/ψ pairs as a probe of DPI *[Kom, Kulesza & Stirling, arXiv:1105.4186]*

[Baranov et al., arXiv:1105.6276]

[LHCb Coll., arXiv:1109.0963]

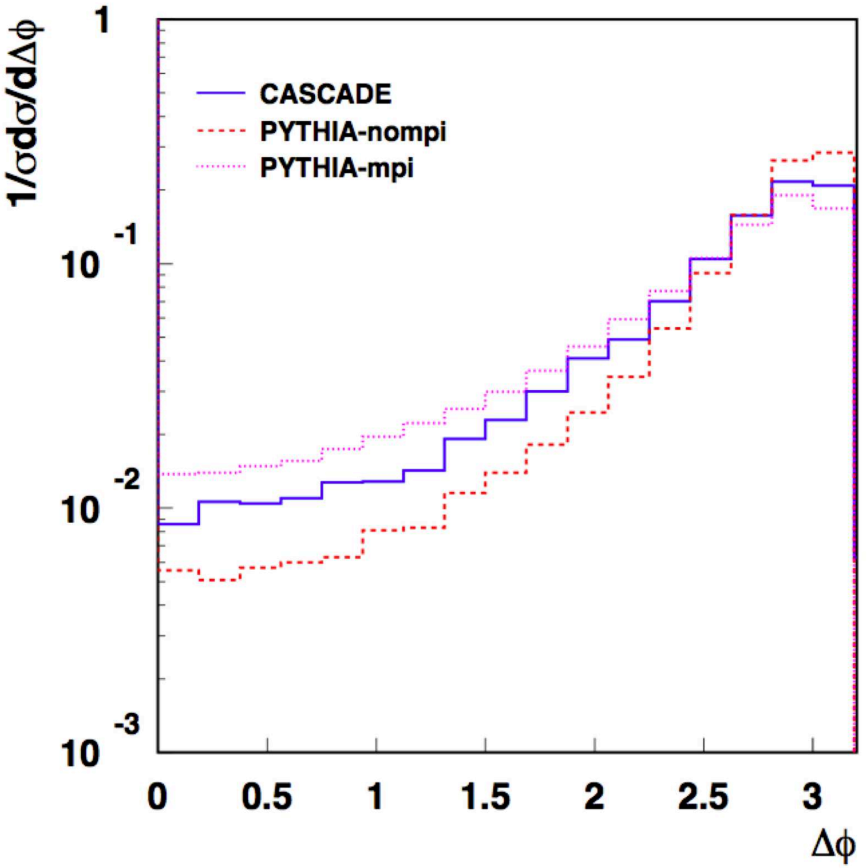
Mini-jets associated with J/ψ

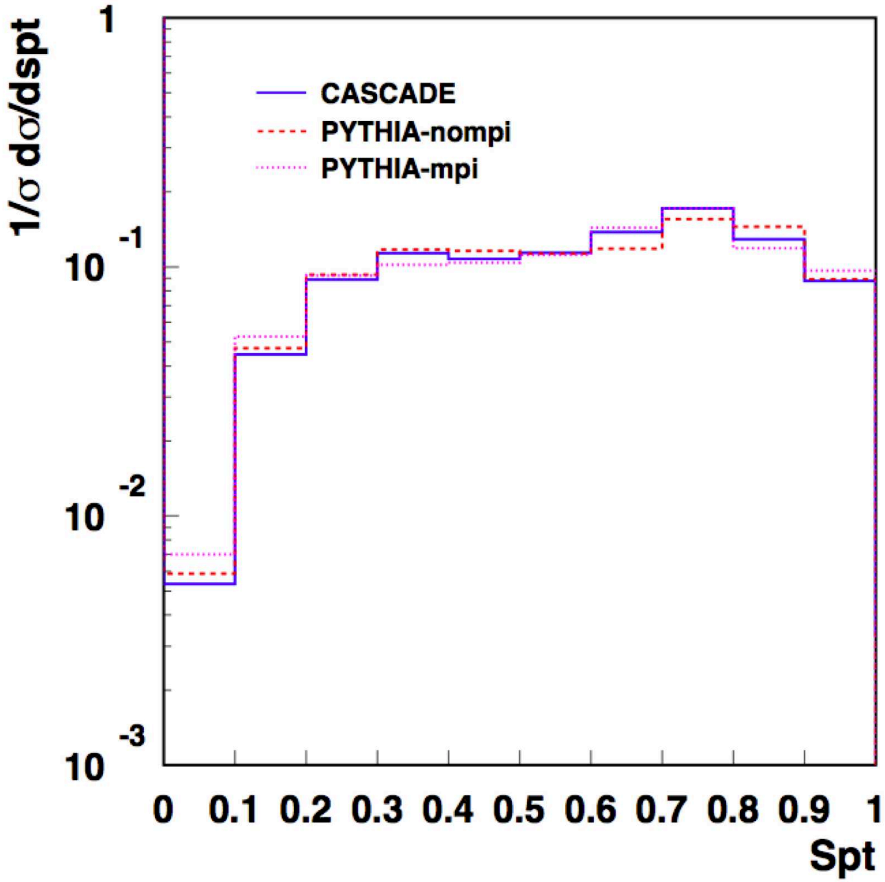
[Jung et al., in progress]



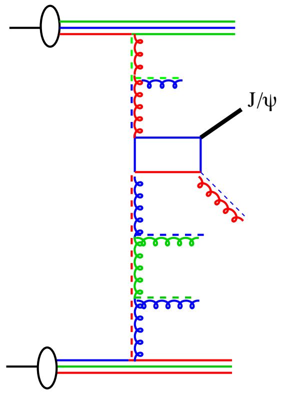
(left) $E_t > 5$ GeV; (right) $E_t > 15$ GeV

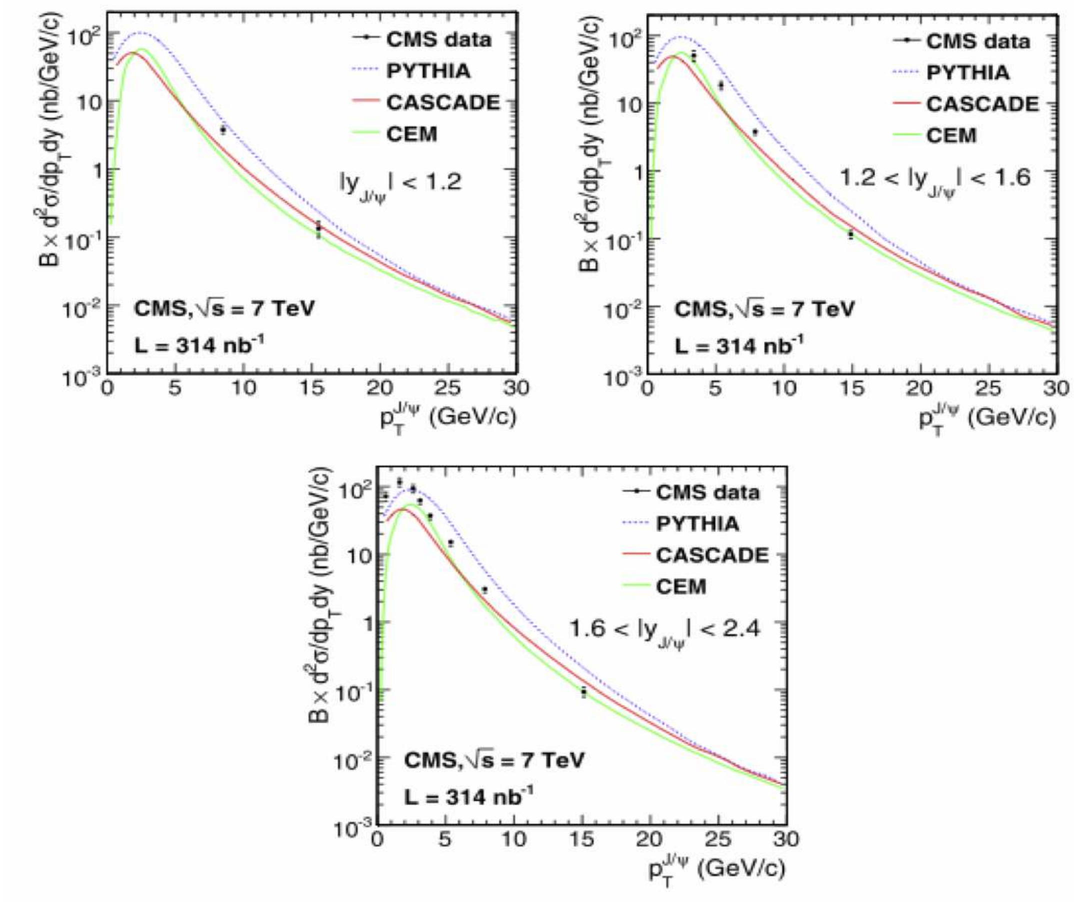
$J/\psi + 3$ jets


1/σdσ/dΔφ
CASCADE
PYTHIA-nompi
PYTHIA-mpi
1
10^-1
10^-2
10^-3
0
0.5
1
1.5
2
2.5
3
Δφ


1/σ dσ/dspt
CASCADE
PYTHIA-nompi
PYTHIA-mpi
1
10^-1
10^-2
10^-3
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Spt

Inclusive J/ψ spectra: comparison with CMS measurement

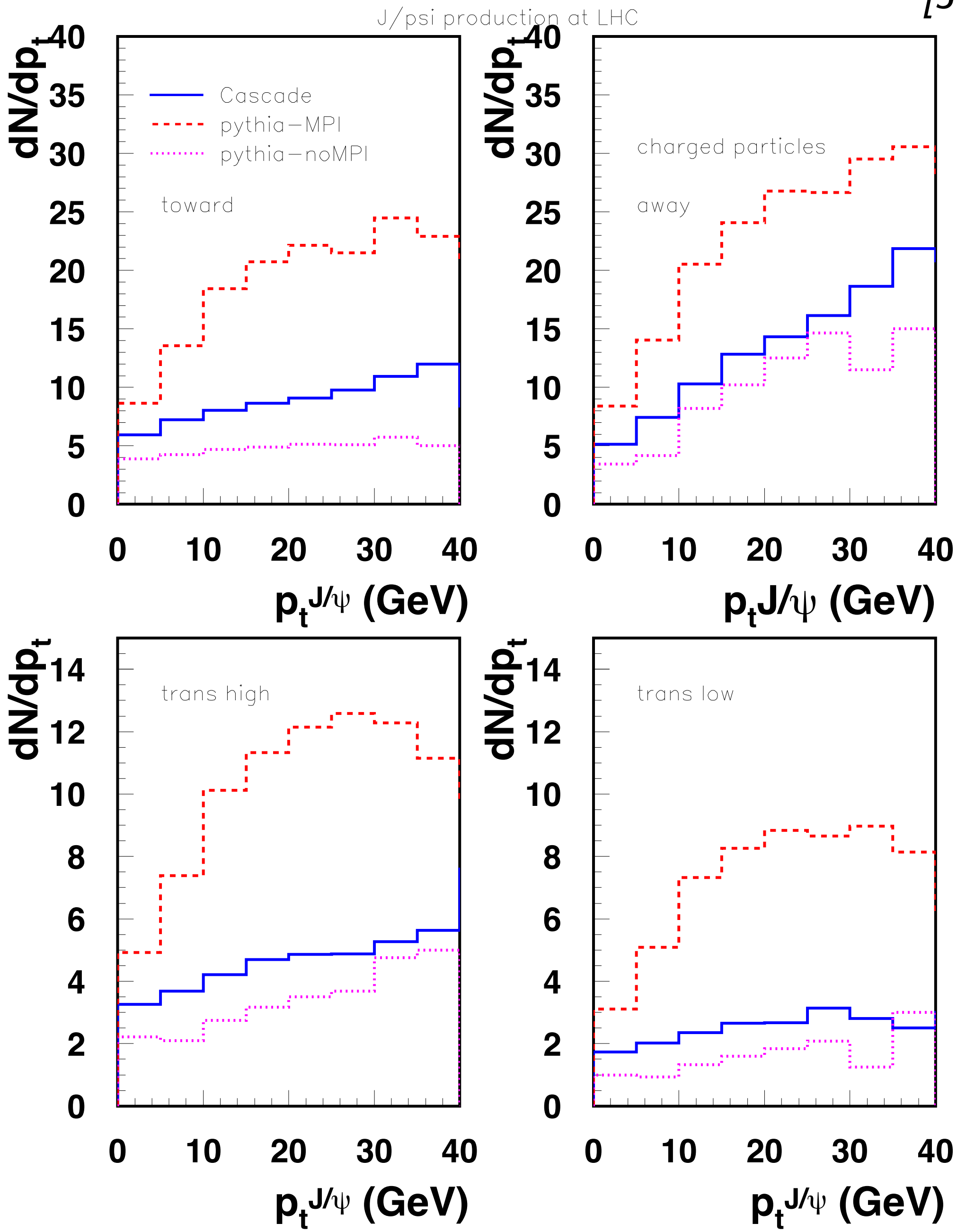




CMS Coll, Eur.Phys.J. C71 (2011) 1575

Charged particle multiplicity associated with J/ψ

[Jung & H, in progress]

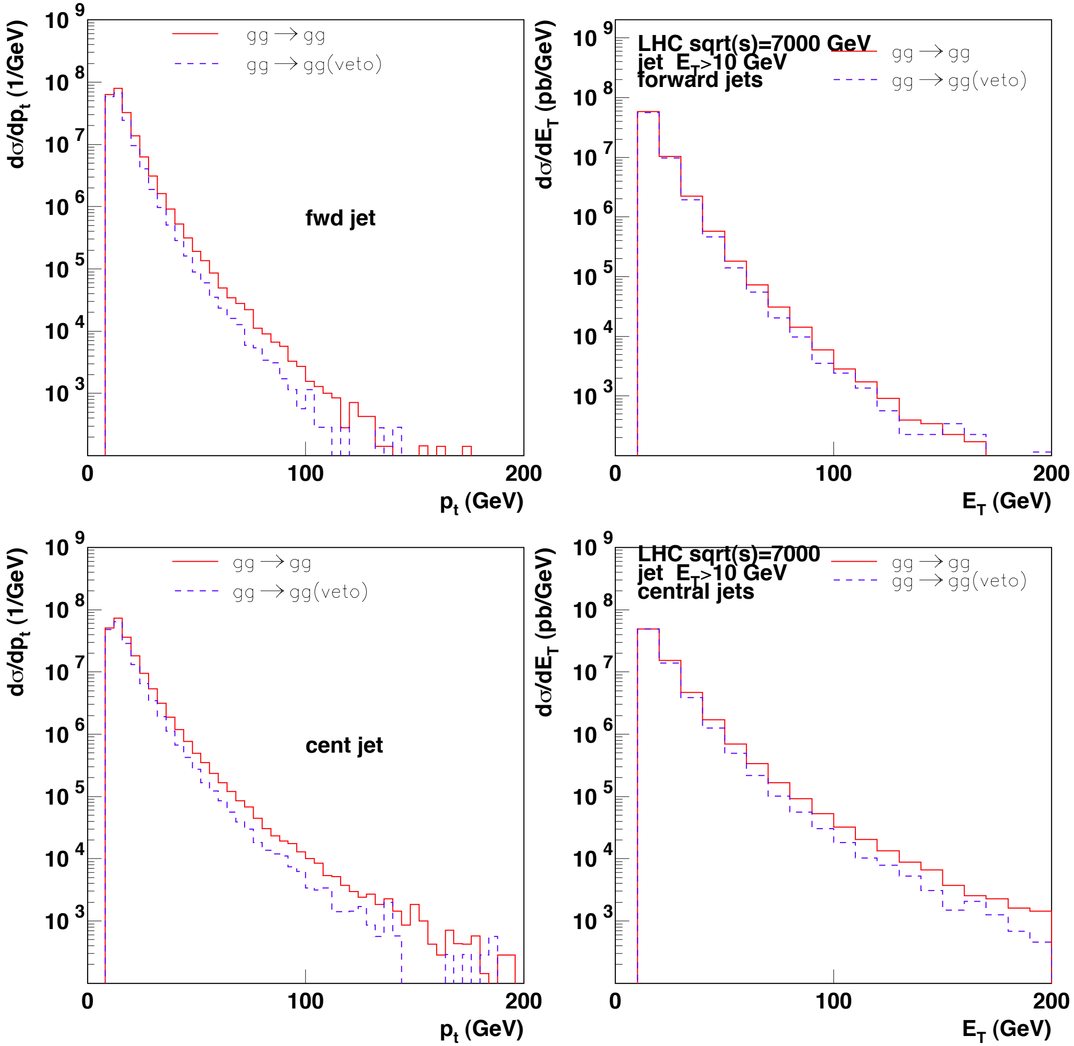


Toward higher $p_\perp$

♠ $k_\perp$-shower contains radiative corrections beyond leading order

⇒ *vetoed branching* to merge ME and shower *[Deak et al., arXiv:1206.1745]*

Ex.: $gg \to qq$ from direct production and from $gg \to gg \otimes g \to qq$



(left) parton-level; (right) jet-level