QCD and collider physics IV: Multiparton Interactions; Heavy Quarks

H. Jung (DESY)

- Multiparton Interactions
  - idea
  - relation to parton model
  - relevance for LHC
- Heavy Quark Production

http://www-h1.desy.de/~jung/qcd_collider_physics_sose_2007

Factorisation is violated ...

arXiv:0705.2141v1 [hep-ph]

ANL-HEP-PR-07-25

Factorization is violated in production of high-transverse-momentum particles in hadron-hadron collisions

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(Dated: 15 May 2007)

We show that hard-scattering factorization is violated in the production of high-p_T hadrons in hadron-hadron collisions, in the case that the hadrons are back-to-back, so that k_T factorization is to be used. The explicit counterexample that we construct is for the single-spin asymmetry with one beam transversely polarized. The Sivers function needed here has particular sensitivity to the Wilson lines in the parton densities. We use a greatly simplified model theory to make the breakdown of factorization easy to check explicitly. But the counterexample implies that standard arguments for factorization fail not just for the single-spin asymmetry but for the unpolarized cross section for back-to-back hadron production in QCD in hadron-hadron collisions. This is unlike corresponding cases in e^+e^- annihilation, Drell-Yan, and deeply inelastic scattering. Moreover, the result endangers factorization for more general hadroproduction processes.

factorisation is violated ...

arXiv:0705.2141v1 [hep-ph]

- in kt-factorisation

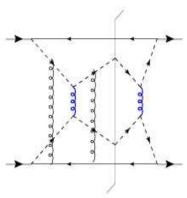


FIG. 8: The exchange of two extra gluons, as in this graph, will tend to give non-factorization in unpolarized cross sections.

- collinear factorisation:
  this would happen only at NNNLO

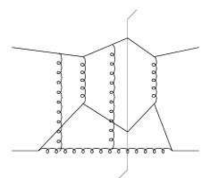
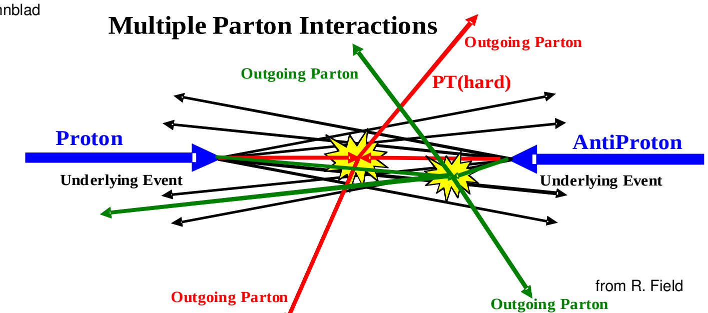


FIG. 9: In a conventional perturbative QCD calculation for an unpolarized partonic cross section, non-factorization by the mechanisms discussed in this paper would first appear in graphs of this order.

Multiparton Interactions

from L. Loennblad



from R. Field

What is the underlying event (UE)?

➔ Everything, except the LO process we're currently interested in
- parton showers
- additional remnant – remnant interactions (multi-parton interactions,soft/hard)

✗ NOT pile-up events (luminosity dependent)

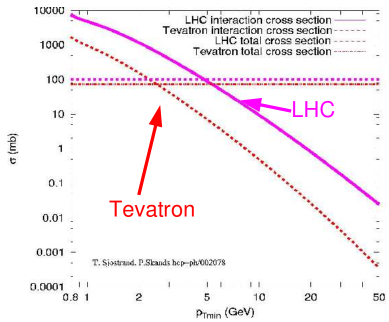
Underlying event - Multiple Interaction

- Basic partonic perturbative cross section

$$\sigma_{\rm hard}(p^2_{\perp \rm min}) = \int_{p^2_{\perp \rm min}} \frac{d\sigma_{\rm hard}(p^2_\perp)}{dp^2_\perp} dp^2_\perp$$

➔ diverges faster than $1/p^2_{\perp \rm min}$ as $p_{\perp \rm min} \to 0$ and exceeds eventually total inelastic (non-diffractive) cross section

- Interaction x-section exceeds total xsection
- happens well above λ_{QCD}
- still in perturbative region



Underlying event-Multiparton Interaction

- Basic partonic perturbative cross section

$$\sigma_{\rm hard}(p^2_{\perp \rm min}) = \int_{p^2_{\perp \rm min}} \frac{d\sigma_{\rm hard}(p^2_\perp)}{dp^2_\perp} dp^2_\perp$$

➔ diverges faster than $1/p^2_{\perp \rm min}$ as $p_{\perp \rm min} \to 0$ and exceeds eventually total inelastic (non-diffractive) cross section, resulting in more than 1 interaction per event (multiparton interactions, MI).

➔ Average number of interactions per event is given by:

$$\langle n \rangle = \frac{\sigma_{\rm hard}(p_{\perp \rm min})}{\sigma_{nd}}$$

- It depends on how soft interactions are treated, **BUT** also on the parton densities and factorization scheme, parton evolution (DGLAP/BFKL) !!!!!!!!

Formalism for MI (Sjostrand, Zijl) I

T. Sjostrand, M. Zijl
PRD 36 (1987) 2019

- define: $p(x_t) = \frac{1}{\sigma_{nd}} \frac{d\sigma}{dx_t}$
- probability for hardest scattering at x_{t1}:
  $$P_1 = p(x_{t1}) \exp\left(-\int_{x_{t1}}^{1} p(x')dx'\right)$$
- probability for second hardest scattering at x_{t2}:
  $$P_2 = \int_{x_{t2}}^{1} dx_{t1} p(x_{t1}) \exp\left(-\int_{x_{t1}}^{1} p(x')dx'\right) p(x_{t2}) \exp\left(-\int_{x_{t2}}^{x_{t1}} p(x')dx'\right)$$
- probability for 3rd hardest scattering at x_{t3}:
  $$\begin{aligned} P_3 &= \int_{x_{t2}}^{1} dx_{t1} \int_{x_{t3}}^{x_{t1}} dx_{t2} p(x_{t1}) \exp\left(-\int_{x_{t1}}^{1} p(x')dx'\right) \\ &\times\ p(x_{t2}) \exp\left(-\int_{x_{t2}}^{x_{t1}} p(x')dx'\right) p(x_{t3}) \exp\left(-\int_{x_{t3}}^{x_{t2}} p(x')dx'\right) \end{aligned}$$
- for nth scattering:
  $$P_N = p(x_{tN}) \frac{1}{(N-1)!} \left(\int_{x_{tn}}^{1} p(x')dx'\right)^{N-1} \exp\left(-\int_{x_{tn}}^{1} p(x')dx'\right)$$

Formalism for MI (Sjostrand, Zijl) II

T. Sjostrand, M. Zijl
PRD 36 (1987) 2019

- compare to Poisson distribution:
  $$p_r = \frac{\mu^r}{r!} \exp(-\mu)$$
- total probability to have any scattering at x_{t1}:
  $$\begin{aligned} \sum_N P_N &= \sum_N p(x_t) \frac{1}{(N-1)!} \left(\int_{x_t}^{1} p(x')dx'\right)^{N-1} \exp\left(-\int_{x_t}^{1} p(x')dx'\right) \\ &= p(x_t) \end{aligned}$$
- preserving total probability
- recovering parton model result
  - Poisson distribution with mean $\mu = \int_{x_t}^{1} p(x')dx' = \frac{1}{\sigma_{nd}} \int_{x_t}^{1} \frac{d\sigma}{dx'_t} dx'_t$
- recover AGK rules...

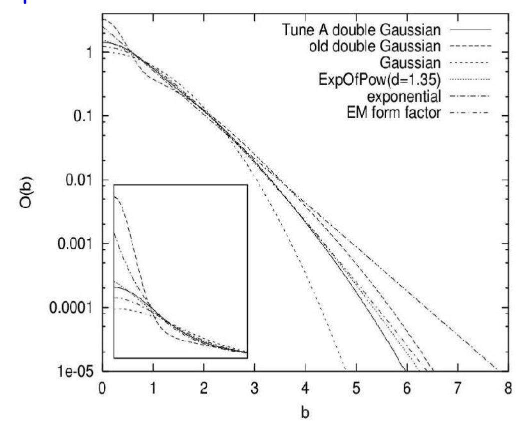
Hadronic final state with MI

- Nr of hard scatterings
  - according to poisson distribution
    - also impact parameter dependent
- initial and final state parton showers
  - initial and final state PS only for 1st hard scattering
- color flow
  - make simple assumptions
- beam remnants
  - color connections only to first hard scattering
- hadronisation
  - assume universality: use parameters obtained from e+e-

Impact parameter dependence

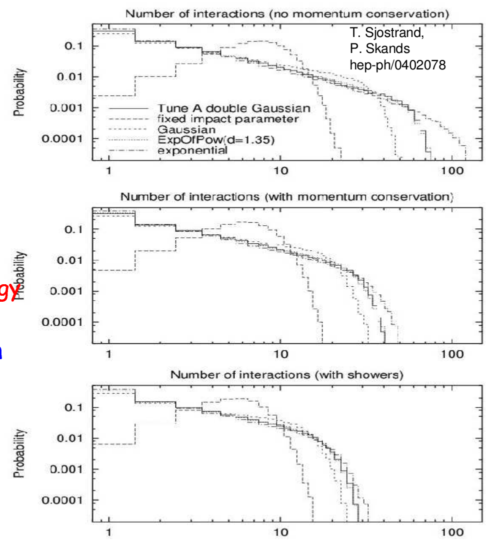
T. Sjostrand, P. Skands
hep-ph/0402078

- different choices for overlap function:
  - ➔ single Gauss
  - ➔ exponential
  - ➔ double Gauss
  - ➔ $\exp(-b^d)$



Nr of Interactions

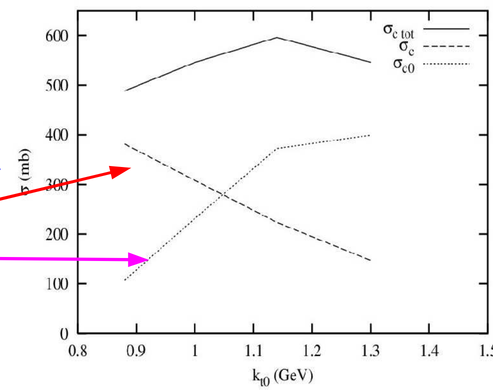
- Nr of interactions in $p\bar{p}$ at $\sqrt{s} = 1.8$ TeV
- different choices for overlap function:
  - ➔ single Gauss
  - ➔ exponential
  - ➔ double Gauss
  - ➔ $\exp(-b^d)$
- significant effects from energy momentum conservation
- Nr of interactions depends on ptmin cutoff...



Improvements: k_t-factorisation

G. Gustafson, L.Lonnblad,G.Miu PRD67 034020 (2003)

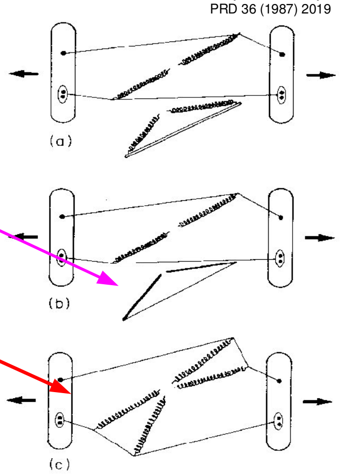
- using uPDFs no artificial ptmin cutoff is needed... since uPDFs are defined (and fitted) over whole range in $k_\perp$, also for $k_\perp \to 0$
- example: LDC (Linked Dipole Chain MC) (CCFM)
  - hard emissions
  - soft emissions
  - sum is nearly independent of k_{t0} cut



Color flow in MI (Sjostrand, Zijl)

- possible scenarios for color string connection in multiparton events
- 33% quarks
  66% gluons
  out of which 33 %
  are

T. Sjostrand, M. Zijl
PRD 36 (1987) 2019



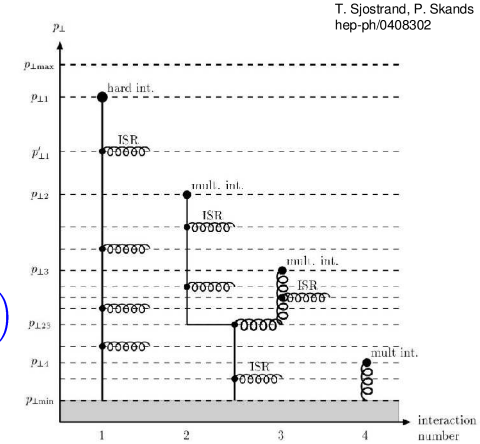
Improvements: interleaved PS & MI

- until now, PS only for hardest interaction...

➔ new approach which treats initial state PS and MI at the same time

$$\frac{dP}{dp_t} = \left(\frac{dP_{MI}}{dp_t} + \sum \frac{dP_{IPS}}{dp_t}\right) \otimes \exp\left(\frac{dP_{MI}}{dp_t} + \sum \frac{dP_{IPS}}{dp_t}\right)$$

T. Sjostrand, P. Skands
hep-ph/0408302



Full hadron level events with MI...

- Nr of hard scatterings
  - according to poisson distribution
    - also impact parameter dependent
- initial and final state parton showers
  - initial and final state PS only for 1st hard scattering
- color flow
  - make simple assumptions
- beam remnants
  - color connections only to first hard scattering
- hadronisation
  - assume universality: use parameters obtained from e+e-

Determine free parameters by experiment !!!

Other approaches

- HERWIG: soft underlying events
- → no simulation of multi-parton interactions. Uses parameterisation in pt and rapidity of minimum bias events
- JIMMY package:
- → multi-parton interaction (add-on package). Similar approach as in Torbjorn/Zijl with impact parameter dependence
- MI in SHERPA:
- → similar to Torbjorn/Zijl

- **Terminology:**
- → Soft Underlying Events (SUE): soft processes, small transverse momenta involved
- → Multiparton interactions: hard processes involved, including extension to smallest transverse momenta

Open points in MI

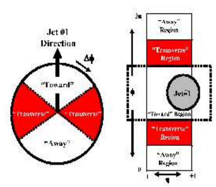
- general consensus on approach reached (MI workshop 18-19 May 2007, DESY)
- open issues:
  - ➔ is collinear factorisation (DGLAP) appropriate ?
  - ➔ is linear evolution appropriate, or need to include saturation etc ?
  - ➔ how to treat color flow in different chains ?
  - ➔ what about overlapping chains ?
  - ➔ how to include diffractive interactions ?
  - ➔ etc ???

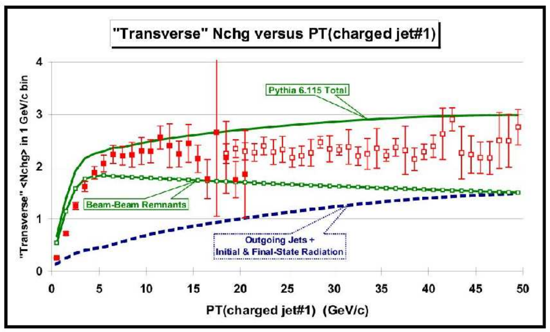
Multiparton Interactions

Comparison with Measurements

Soft Underlying Events at CDF

CDF coll. PRD 65, 092002 (2002)





- Multiplicity distribution in region transverse to jet can only be described by adding multi-parton interactions (Remnant- Remnant Interactions)

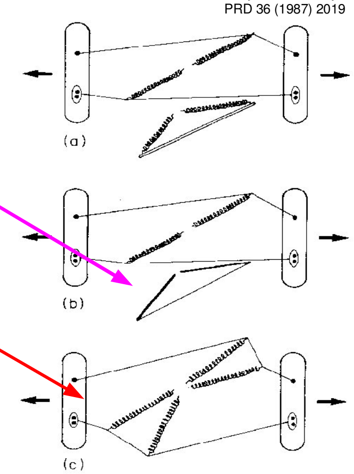
Tuning to CDF data... Color flow in MI

T. Sjostrand, M. Zijl
PRD 36 (1987) 2019

- possible scenarios for color string connection in multiparton events
- to describe underlying events.... need (CDF Tune A)
  5 % quarks (default 33 %)
  95 % gluons (default: 66%)
  out of which 90 %
  (default 33 %) are

➔ smaller multiplicity with large transverse energy

- Are there good phyiscs reasons for this mix ???
- **Highly nontrivial to describe multiplicity AND transverse energy distributions ...**



Underlying events and NLO ...

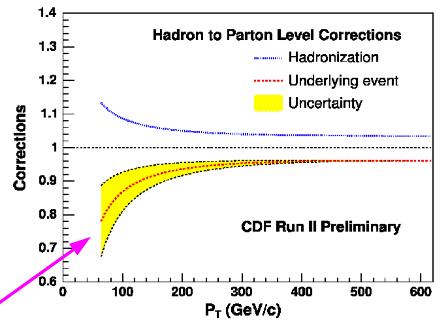
Campbell, Huston Stirling
Rep.Prog.Phys 70 (2007) 89

- Usual Folklore:

$$\sigma_{qcd} = \sigma_{nlo} \cdot (1 + \delta^{u.e.} + \delta^{hadr.})$$

- calculate correction factor for underlying event:

$$\delta^{u.e.} = \frac{\sigma^{\text{with u.e.}}}{\sigma^{\text{without u.e.}}} - 1$$



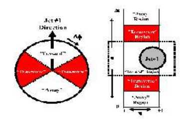
➔ **factor of ~ 0.75 at E_t ~ 50 GeV**

➔ at larger E_t.... running out of phase space for multi-parton interactions at TeVatron **BUT NOT at LHC**

- similar effects also at HERA
- similar folklore used...

Soft Underlying Events at LHC

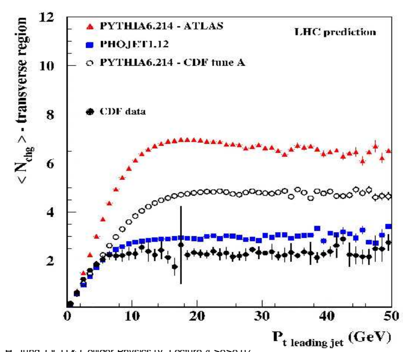
C. Buttar et al in HERA – LHC workshop proceedings hep-ph/0601012

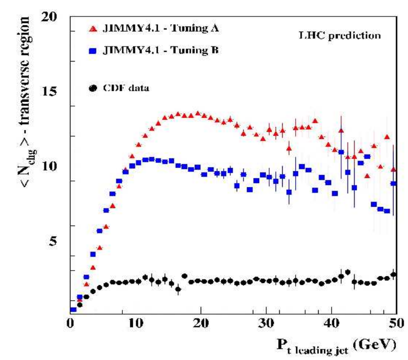


Charged multiplicities in transverse region

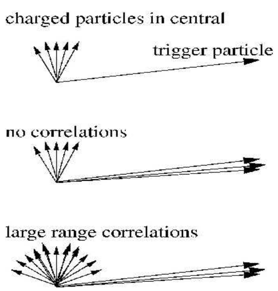
- Models tuned to TeVatron data

➔ give **HUGE** differences at LHC ...

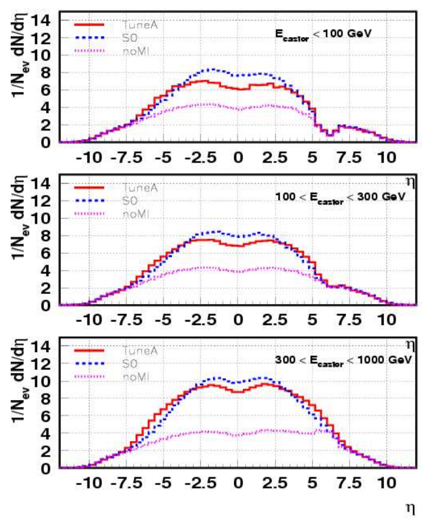




Particle correlation: fwd - central



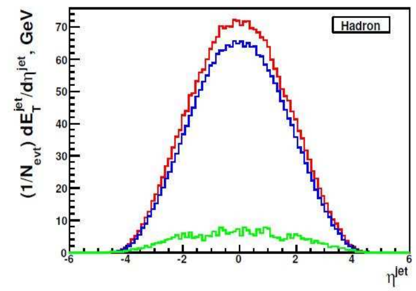
- charged particles multiplicity as function of trigger multiplicity in fwd region: $5.2 < \eta < 6.6$
- Multiple Interactions show large long range correlations...
- measurement of trigger particle in fwd region is important !!!

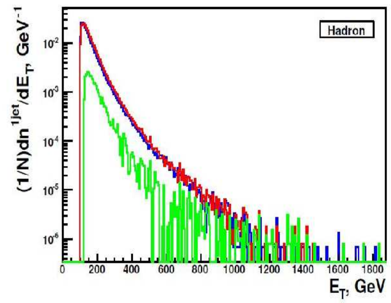


Underlying event and jets

- SHERPA: $E_T > 100\,\mathrm{GeV}, |\eta| < 5$

P. Starovoitov, T. Carli
HERA-LHC WS, June 2006

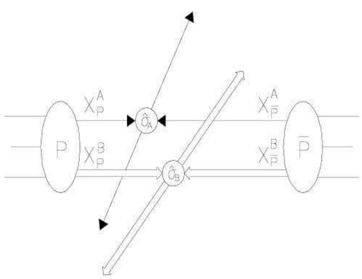




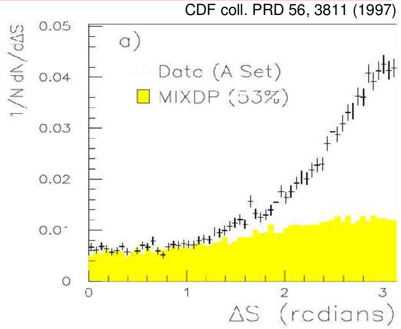
Hard Scale, HS+UE, Difference

- UE contributes ~ 10 - 30 % to Jets, even at large E_t !!!!
- **need reliable model for UE**
- **Factorization ??!!??**

Evidence for Multi-Parton Interactions



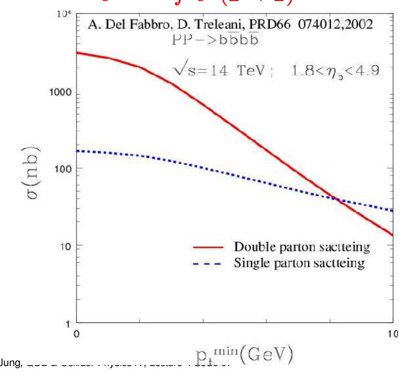
CDF coll. PRD 56, 3811 (1997)



- look at $\gamma + 3$ Jets with
  $E_T^{\gamma} > 16 GeV$
  $E_T^{Jets} > 5 GeV$
- angular correlation of jet/photon pairs ΔS
- compare to $\gamma + 3$ Jets calculation
- **Need > 50 % double parton interaction to describe data**

Double-Parton Interactions at LHC

- xsection for $p + p \to b\bar{b}b\bar{b}$
  single parton exchange (SP)
  $\sigma^{SP} \sim f^2 \hat{\sigma}(2 \to 4)$
  double parton exchange (DP)
  $\sigma^{DP} \sim f^4 \hat{\sigma}^2(2 \to 2)$



- PYTHIA predictions:
  $\sigma^{DP} = 0.8 \cdots 11.1 \ \mu b$

➔ Depending on model for underlying event/muli-parton interactions...

Multi-Parton Interactions at LHC

- Higgs: $p+p \to W+H+X$

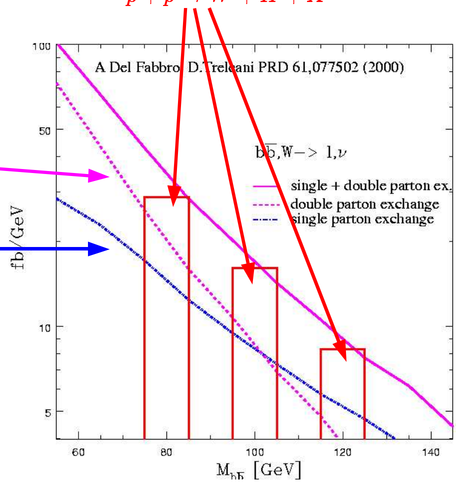
  with $W \to l\nu, \;\; H \to b\bar{b}$
- Double parton scattering:

➔ $p+p \to b\bar{b}X$

  $p+p \to W+X$

- $p+p \to W+b\bar{b}+X$

$p+p \to W+H+X$



Multiparton Interactions at LHC

- Multiparton Interactions play a role in soft **BUT** also in high pt processes
- Theoretical description is tricky ...
- Models can be tuned to describe TeVatron measurements
  - at the price of "just reasonable" parameters
- **Extrapolation to LHC:**
  - questionable, because of high parton densities at small x
  - possible non-linear effects: saturation, small x increase
  - Color flow is far from clear...
  - Stay tuned to surprises ...

References for Multiple Interactions

- T. Sjostrand, M. Zijl PRD 36 (1987) 2019
- T. Sjostrand, P Skands hep-ph/0401078
- G. Gustafson, talk at HERA – LHC workshop DESY 2007
- A. Del Fabbro, D. Treleani hep-ph/9911358
- A. Del Fabbro, D. Treleani hep-ph/0207311
- A. Del Fabbro, D. Treleani hep-ph/0301178