Double Parton Scattering at the LHC –
Dynamic and Kinematic Characteristics

Edmond L Berger
Argonne National Laboratory

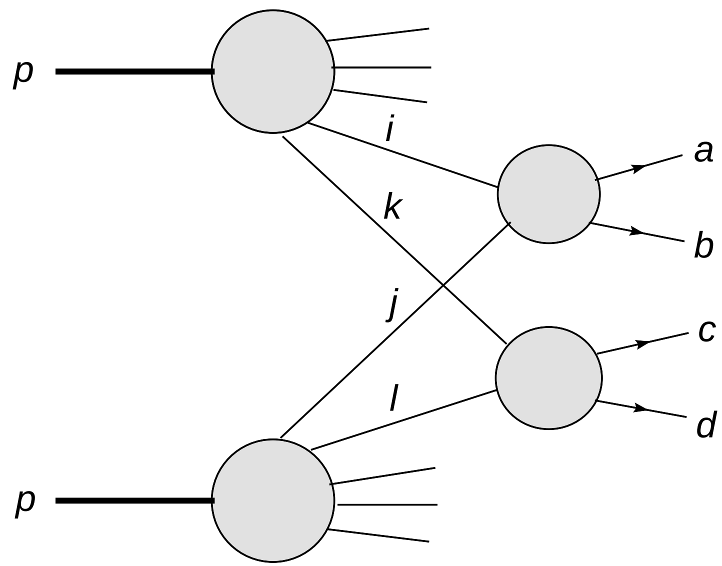
ELB, C Jackson, G Shaughnessy, Phys Rev D **81**, 014014 (2010) (arXiv:0911.5348 (hep-ph))

Outline

1. What is Double Parton Scattering (DPS)?
2. Aim: identify signature kinematic variables and characteristic concentrations in phase space that distinguish DPS events from the usual single parton scattering SPS events
3. Establish a methodology to measure the size of DPS
4. Once established in a well defined process, here, $pp \to b\bar{b}jjX$, then DPS contributions in other final states can be calculated; possibly important for background estimates in new physics searches
5. Further work – experiment, phenomenology, and theory
6. Conclusions

What is double parton scattering?

- Two hard collisions per pp interaction



- Does it exist as a discernable contribution?
- What are its characteristics, allowing its measurement?
- Heuristic cross section for $pp \to b\bar{b}j_1 j_2 X$,

$$d\sigma^{DPS}(pp \to b\bar{b}j_1 j_2 X) = \frac{d\sigma^{SPS}(pp \to b\bar{b}X)\, d\sigma^{SPS}(pp \to j_1 j_2 X)}{\sigma_{\text{eff}}}$$

Literature

- Long history theoretically, including:
  C. Goebel, F. Halzen, D. M. Scott, N. Paver, D. Treleani, B. Humpert, M. Mekhfi, R. Odorico, L. Ametller, P. Hoyer, W. J. Stirling, M. L. Mangano, R. M. Godbole, S. Gupta, J. Lindfors, M. Drees, T. Han, O. J. P. Eboli, J. K. Mizukoshi, F. Yuan, K. T. Chao, G. Calucci, A. Del Fabbro, A. Kulesza, V. L. Korotkikh, E. Cattaruzza, M. Y. Hussein, E. Maina, S. Domdey, H. J. Pirner, U. A. Wiedemann, D. d'Enterria, G. K. Eyyubova, V. L. Korotkikh, I . P. Lokhtin, S. V. Petrushanko, L. I. Sarycheva, A. M. Snigirev, J. R. Gaunt, C-H Kom, ...
  References in PRD **81**, 014014 (2010)
- Experimental activity:
  Axial Field Spectrometer Collaboration – CERN ISR, UA2 Collaboration, CDF Collaboration, D0 Collaboration
- At the LHC, double parton scattering could result in a larger than anticipated rate for multijet production

Several assumptions

$$d\sigma^{DPS}(pp \to b\bar{b}j_1j_2X) = \frac{d\sigma^{SPS}(pp \to b\bar{b}X)d\sigma^{SPS}(pp \to j_1j_2X)}{\sigma_{\text{eff}}}$$

- σ_{eff}
  - Given one hard-scatter, σ_{eff} measures the effective size of the core in which accompanying partons are confined
  - Bounded by the transverse size of a proton
  - Different for gg and qq subprocesses? Energy dependent?
- Factorization/independent hard scatters cannot be strictly true, certainly not if any parton $x > 0.5$
- Large dynamic range of LHC offers opportunity to explore this phenomenology; measure σ_{eff}

$pp \to b\bar{b}jjX$ at the LHC

Bottom quark pair production plus two jets

- Large rate over a wide kinematic range
- b tagging provides a clean signal
- Relatively unambiguous which final objects to pair: b with $\bar{b}$ and j with j

Calculation

- Generate DPS $4 \to 4$ events with Madgraph/Madevent
- Generate SPS $2 \to 4$ events with ALPGEN (faster)
- Look for kinematic distributions that show discrimination between DPS and SPS

Assume, for illustration, $\sigma_{\rm eff} = 12$ mb; event rates quoted for $\sqrt{s} = 10$ TeV and 10 pb^{-1} integrated luminosity

$pp \to b\bar{b}jjX$ at the LHC

Double parton contributions

- At LO, the only contribution is: $(ij \to b\bar{b}) \otimes (kl \to jj)$
- $\otimes$: overlay one event from $b\bar{b}$ and one from jj
- NLO real radiation effects modeled with

$$b\bar{b}(j) \otimes jj \;\; , \;\; b\bar{b}j \otimes (j)j \;\; , \;\; b\bar{b}j \otimes j(j)$$
$$b\bar{b} \otimes (j)jj \;\; , \;\; b\bar{b} \otimes j(j)j \;\; , \;\; b\bar{b} \otimes jj(j)$$

- (j) indicates j is undetected

Single parton contributions

- LO : $2 \to 4$ process $ij \to b\bar{b}jj$
- NLO modeled with contributions from the 5-jet final states:

$$b\bar{b}(j)jj \;\; , \;\; b\bar{b}j(j)j \;\; , \;\; b\bar{b}jj(j) \, .$$

Simulation details

- Acceptance cuts

$$p_{T,j} \geq 25 \text{ GeV}, \quad |\eta_j| \leq 2.5$$
$$p_{T,b} \geq 25 \text{ GeV}, \quad |\eta_b| \leq 2.5$$
$$\Delta R_{jj} \geq 0.4, \quad \Delta R_{bb} \geq 0.4$$

-

$$\Delta R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$$

- Include detector resolution effects

$$\frac{\delta E}{E} = \frac{a}{\sqrt{E/\mathrm{GeV}}} \oplus b,$$

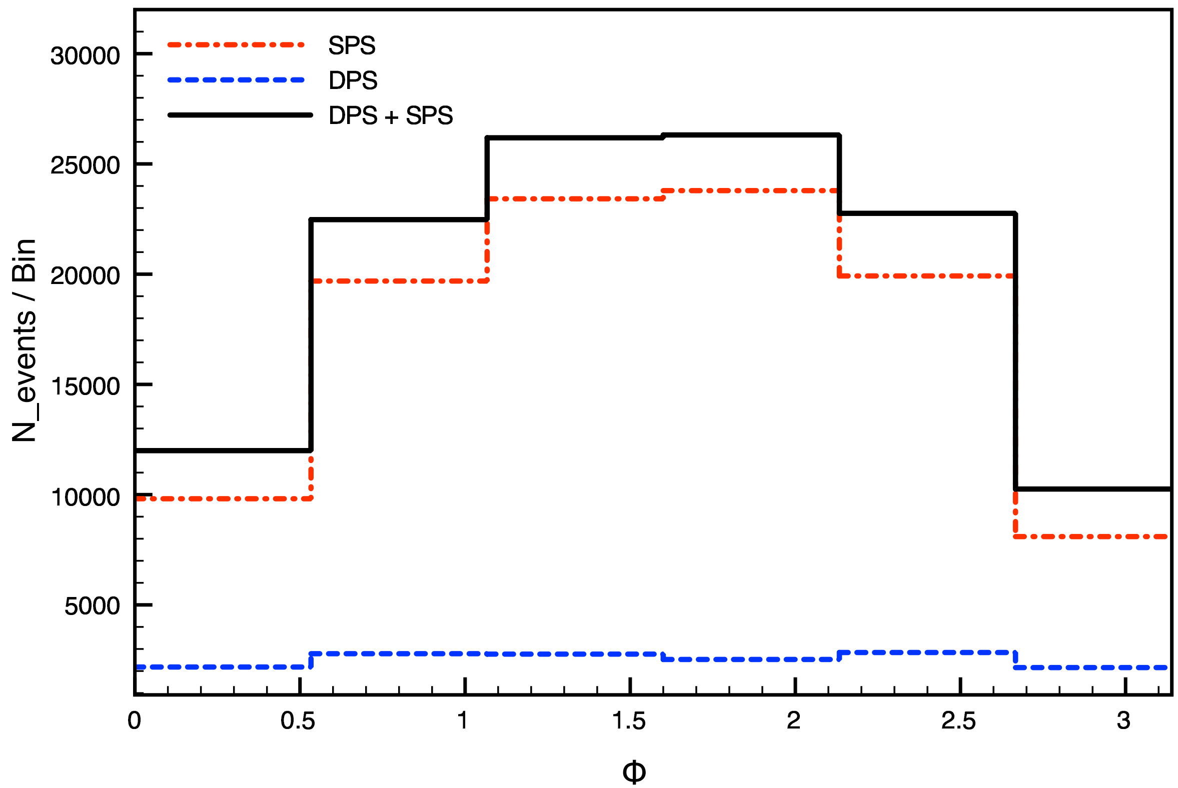
$a = 50\%$ and $b = 3\%$ for jets

- Assume a b-tagging rate of 60% for b-quarks with $p_T > 20$ GeV and $|\eta_b| < 2.0$
- Hard scale choice

$$\mu^2 = \sum_i p_{T,i}^2 + m_i^2$$

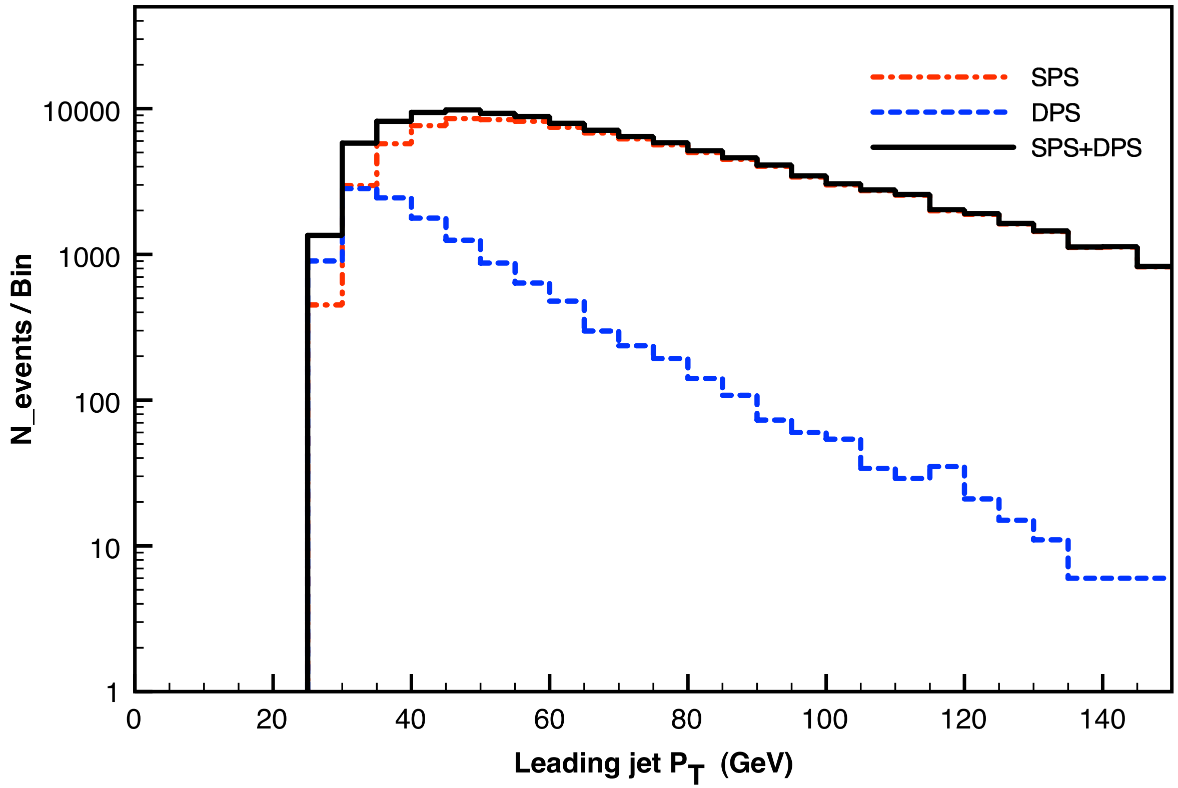
DPS $\to$ uncorrelated (sub)events

- Φ: angle between the planes defined by $b\bar{b}$ and jj systems
- Uncorrelated scatters: the DPS Φ distribution flat
- In SPS, $a + b \to b\bar{b}jjX$, many diagrams contribute; spin and kinematic correlations expected between the planes



Transverse momentum of leading jet

- p_T of the leading jet in $pp \to b\bar{b}jjX$, either a b or a light j



- DPS fills in the lower p_T region
- Sum does not allow us to establish a DPS signal; cross-over set by σ_{eff}

Distinguishing Variables - $\Delta\phi_{jj}$ and S_ϕ

- Topology of DPS events includes two $2 \to 2$ hard scatters
  - Expect 2 pairs of jets to be individually roughly back-to-back (up to effects of extra real radiation)
  - $\longrightarrow \Delta\phi_{jj} \sim \pi$ and $\Delta\phi_{b\bar{b}} \sim \pi$
- Even better is variable S_ϕ that combines this information from both $b\bar{b}$ and jj systems

$$S_\phi = \frac{1}{\sqrt{2}}\sqrt{\Delta\phi(b_1, b_2)^2 + \Delta\phi(j_1, j_2)^2}$$

D0 Collaboration, V. Abazov et al, Phys. Rev. D81, 052012 (2010)

$p\bar{p} \to \gamma + 3jX$ at $\sqrt{s} = 1.96$ TeV

Distinguishing Variables - S_ϕ

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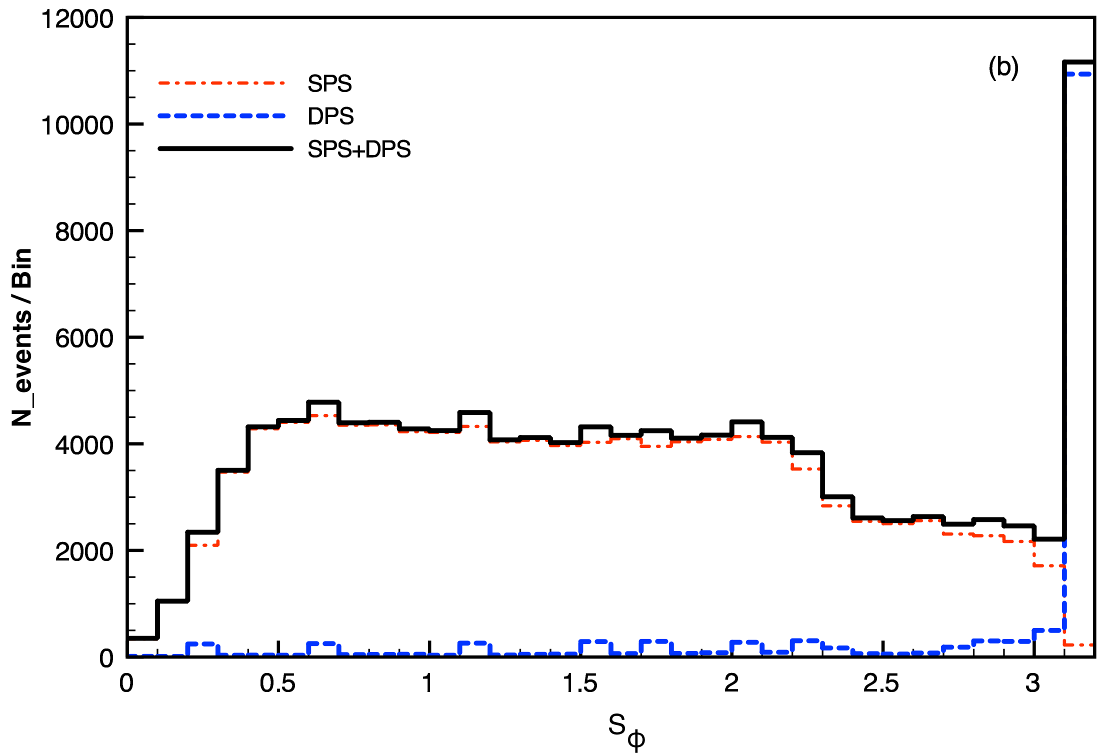

- DPS events are clustered near $S_\phi \sim \pi$, well separated from the total – expect some smearing from soft radiation
- SPS events are fairly uniformly distributed

Distinguishing Variables - $p_T(j_1, j_2)$ *and* S'_{p_T}

- Topology of DPS events includes two $2 \to 2$ hard scatters
  - Expect 2 pairs of jets to be individually roughly back-to-back (up to effects of extra real radiation)
  - At LO for a $2 \to 2$ process, the vector sum of the transverse momenta of the final state pair is zero: $p_T(b_1, b_2) \sim 0$ and $p_T(j_1, j_2) \sim 0$
  - NLO radiation and momentum mismeasurement smear the expected peak near zero
- Scaled variable $S_{p'_T}$ combines this information from both $b\bar{b}$ and jj systems

$$S'_{p_T} = \frac{1}{\sqrt{2}} \sqrt{\left(\frac{|p_T(b_1, b_2)|}{|p_T(b_1)| + |p_T(b_2)|}\right)^2 + \left(\frac{|p_T(j_1, j_2)|}{|p_T(j_1)| + |p_T(j_2)|}\right)^2}$$

D0 Collaboration, V. Abazov et al, Phys. Rev. D81, 052012 (2010)

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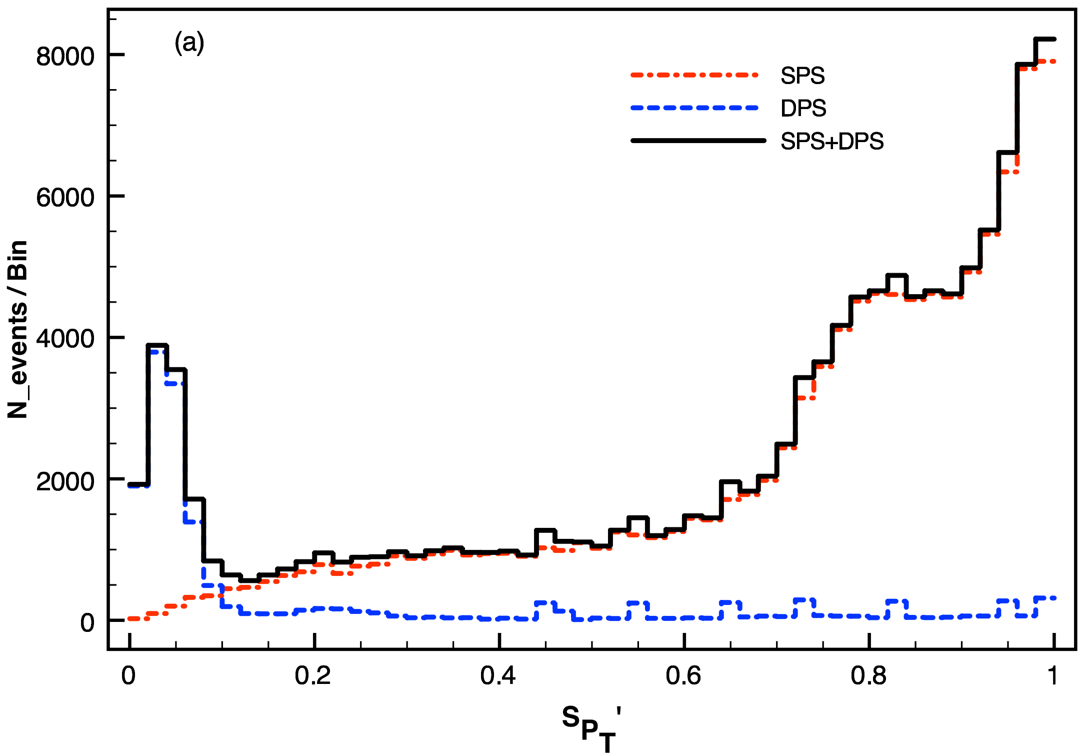
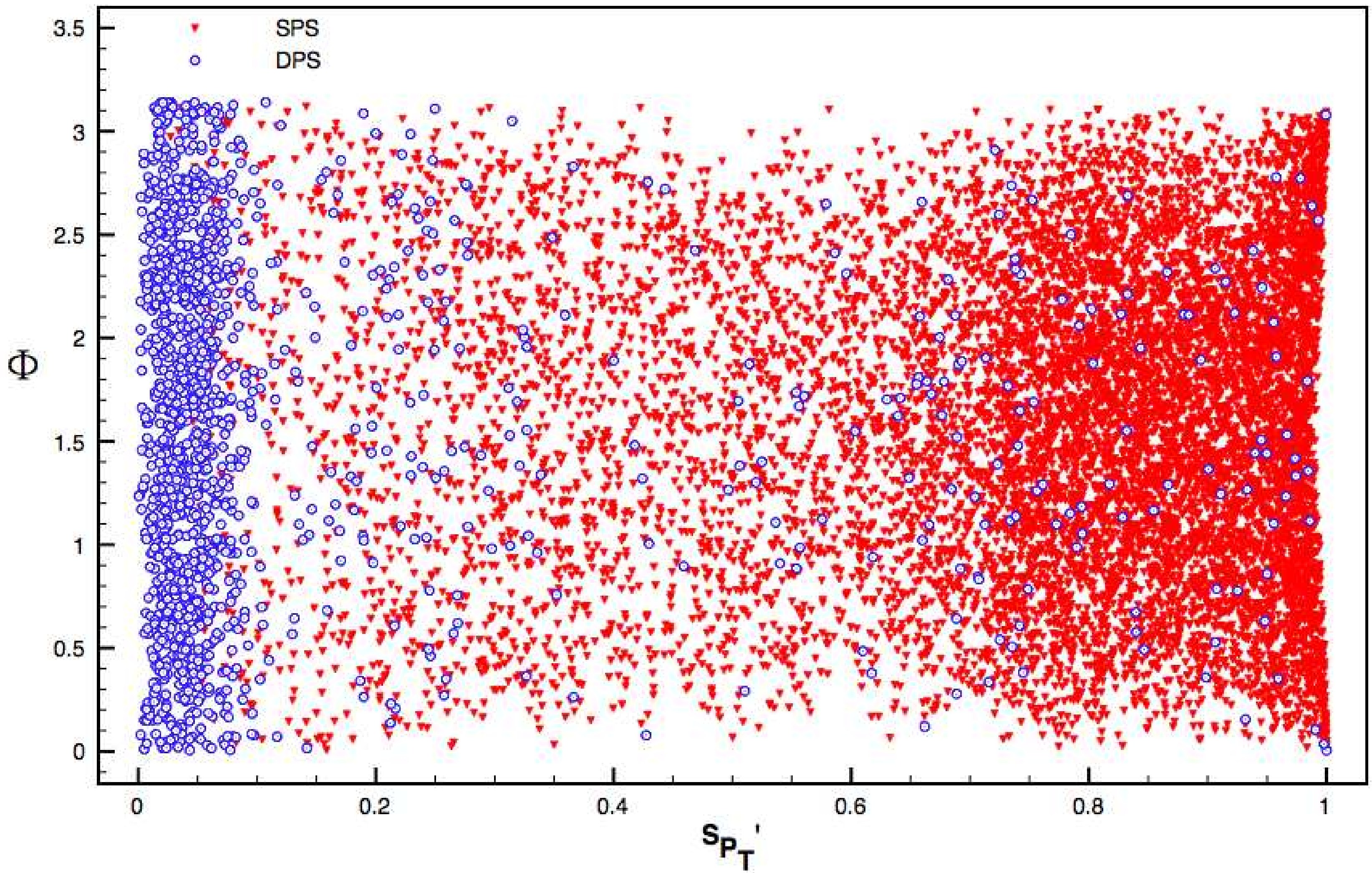


- DPS events produce a clear peak near $S'_{p_T} = 0$, well separated from the total (soft radiation smearing ....)
- SPS events are away from back-to-back (gluon splitting)

Two-dimensional distribution



Clear separation of DPS from SPS in the 2-D Φ and S'_{p_T} plane

Methodolgy/Strategy

Start with clean process $pp \to b\bar{b}jjX$

- Look at events in the 2-D Φ and S'_{p_T} plane
- Expect a concentration of events near $S'_{p_T} = 0$ that are distributed uniformly in the inter plane angle Φ. These are the DPS events
- Valley of low density between $S'_{p_T} \sim 0.1$ and 0.4 should allow a cut that enhances DPS
- This enhanced DPS sample should show a more rapid drop of the cross section vs p_T of the leading jet
- Measure $\sigma_{\rm eff}$
- Examine other processes, e.g., $pp \to 4{\rm jets}X$ see (arXiv:0911.5348); is the extracted $\sigma_{\rm eff}$ roughly the same?

Improvements/Further Work

Phenomenology

- Include NLO contributions. These change normalization and, more importantly here, the distributions in phase space, particularly for $b\bar{b}$ final states
- Incorporate correlated parton distribution functions, c.f., Gaunt and Stirling, JHEP 1003, 005 (2010) (arXiv:0910.4347)
- More processes

Theoretical issues (with J. W. Qiu)

- Basis for

$$d\sigma^{DPS}(pp \to b\bar{b}j_1j_2X) = \frac{d\sigma^{SPS}(pp \to b\bar{b}X)d\sigma^{SPS}(pp \to j_1j_2X)}{\sigma_{\rm eff}}$$

- Starting from

$$d\sigma(pp \to b\bar{b}j_1j_2X) = \frac{1}{2s}|M(pp \to b\bar{b}j_1j_2X)|^2 dPS_{b\bar{b}j_1j_2X}$$

Improvements/Further Work (continued)

General

$$d\sigma(pp \to b\bar{b}j_1j_2X) = \frac{1}{2s}|M(pp \to b\bar{b}j_1j_2X)|^2 dPS_{b\bar{b}j_1j_2X}$$

- Amplitude $M(pp \to b\bar{b}j_1j_2X)$ should include a sum of amplitudes for 2-parton collisions (one active from each incident hadron, i.e., $2 \to 4$; 3-parton collisions (two active from one hadron and one active from the other; and 4-parton collisions (two active from each hadron OR three from one and one from the other), and so forth that all yield the same 4 parton final state
- Contributions to the final state from the squares of individual amplitudes as well as interference terms
- So, why are we focused on $4 \to 4$ and $2 \to 2$, only?

Improvements/Further Work (continued)

Specialize to $4 \to 4$, i.e., DPS

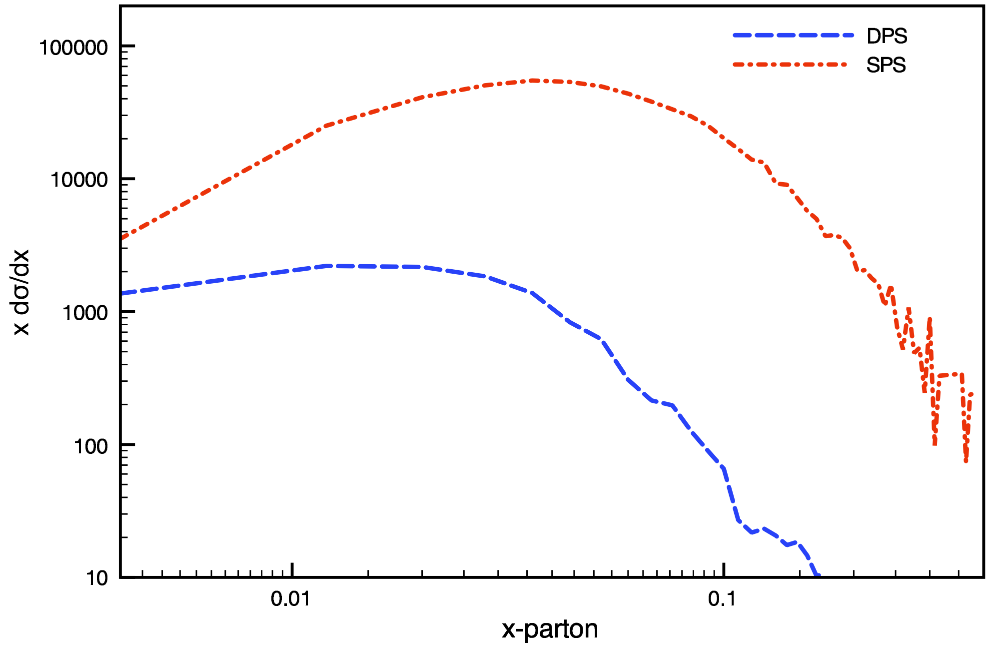
- Presumably one has in mind starting from a 4-parton $\to$ 4-parton hard part
- Not clear how (or whether) the four-parton matrix element can be reduced (even approximately) to a product of two matrix elements for the single parton scatterings
- How even does one flux factor $\frac{1}{2s}$ get replaced by a product of 2 flux factors $\frac{1}{2s}$?

Conclusions

- Developed the phenomenology of double scattering for $pp \to b\bar{b}jjX$ at LHC energies
- Identified distinct regions of phase space in which DPS should be relatively clean
- LHC operates in a different region of Bjorken x from the Tevatron: wider dynamic range provides opportunity to explore characteristics of DPS – factorization, process independence, ...
- Experiment Would be valuable to establish a DPS signal in early LHC runs and measure $\sigma_{\rm eff}$
- Once $\sigma_{\rm eff}$ is measured in a clean process, and DPS features are established in a clean process (or two), then estimates can be made for possibly important backgrounds to Higgs and new physics processes
- Attention to the basic theoretical underpinnings

BACKUPS

Parton x values for DPS and SPS



- Distributions in the parton x values for DPS and SPS contributions to $pp \to b\bar{b}jjX$ at LHC
- DPS events tend to have small values of x $(x < 0.2)$
- Momentum fraction carried by the beam remnant is $1. - x_1 - x_2$ for DPS and $1. - x$ in SPS: very similar

Past searches for DPS

- Good to have a process with a large rate and relatively clean signal
- Early searches focussed on 4 jet and γ plus jets

Table 1: DPS analyses by AFS, UA2, and CDF Collaborations.

Experiment	$\sqrt{s}$ (GeV)	Final state	p_T^{min} (GeV)	η range	$\sigma_{\rm eff}$
AFS (pp), 1986	63	4 jets	$p_{\rm T}^{\rm jet} > 4$	$\lvert\eta^{\rm jet}\rvert < 1$	$\sim$ 5 mb
UA2 ($p\bar{p}$), 1991	630	4 jets	$p_{\rm T}^{\rm jet} > 15$	$\lvert\eta^{\rm jet}\rvert < 2$	$>$ 8.3 mb (95% C.L.)
CDF ($p\bar{p}$), 1993	1800	4 jets	$p_{\rm T}^{\rm jet} > 25$	$\lvert\eta^{\rm jet}\rvert < 3.5$	$12.1^{+10.7}_{-5.4}$ mb
CDF ($p\bar{p}$), 1997	1800	γ + 3 jets	$p_{\rm T}^{\rm jet} > 6$	$\lvert\eta^{\rm jet}\rvert < 3.5$	
			$p_{\rm T}^{\gamma} > 16$	$\lvert\eta^{\gamma}\rvert < 0.9$	$14.5 \pm 1.7^{+1.7}_{-2.3}$ mb

- Wide range of values of $\sigma_{\rm eff}$
- Recent study by D0 of $p\bar{p} \to \gamma + {\rm jets} + X$ at $\sqrt{s} = 1.96$ TeV

$\sigma_{\rm eff}^{\rm ave} = 16.4 \pm 0.3({\rm stat}) \pm 2.3({\rm syst})$ mb

V. Abazov et al, Phys. Rev. D81, 052012 (2010)