

Double Parton Scattering at the LHC – Dynamic and Kinematic Characteristics

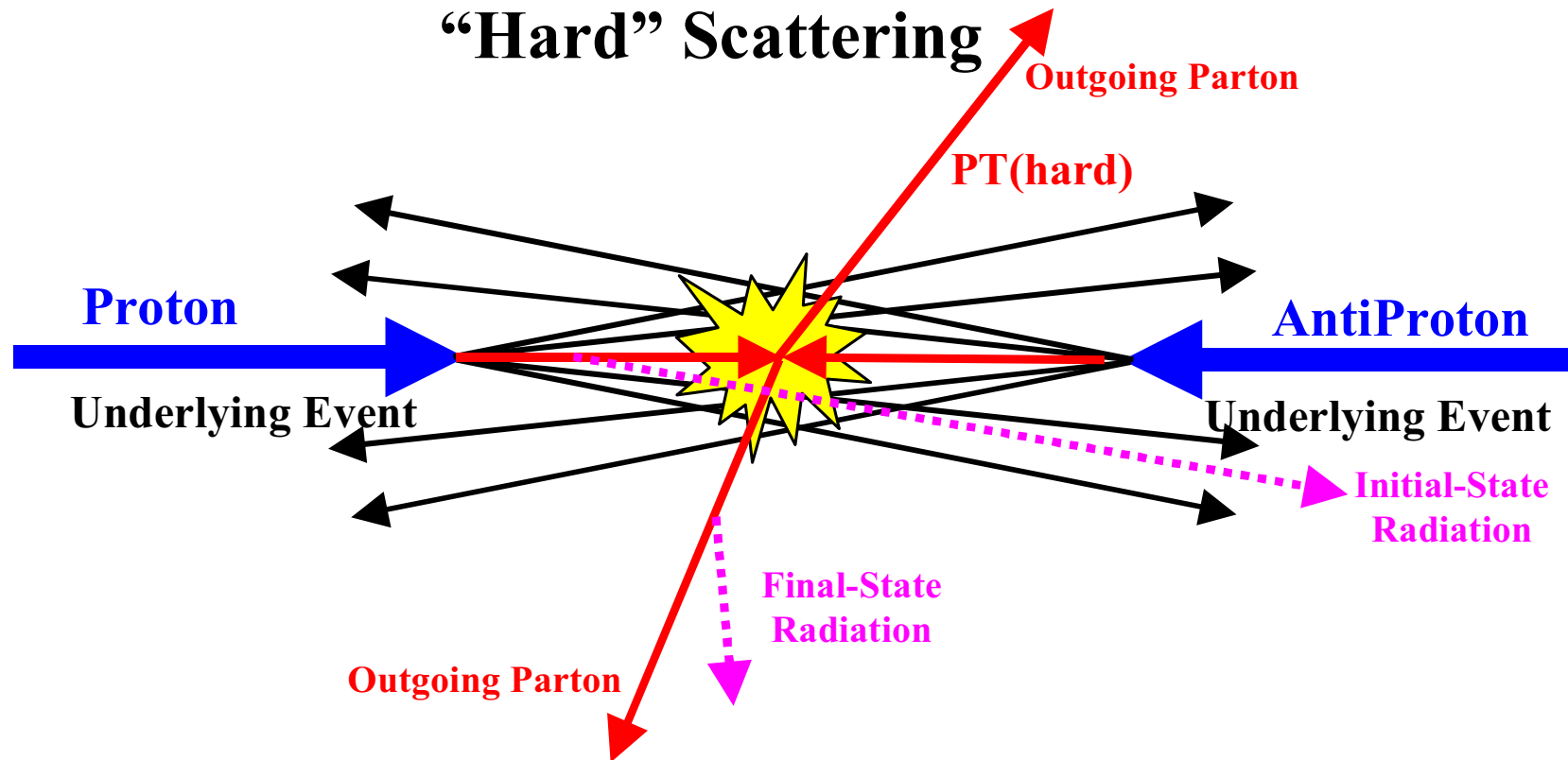
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ELB, C Jackson, G Shaughnessy, Phys Rev D **81**, 014014 (2010) (arXiv:0911.5348 (hep-ph))

High energy hard collision

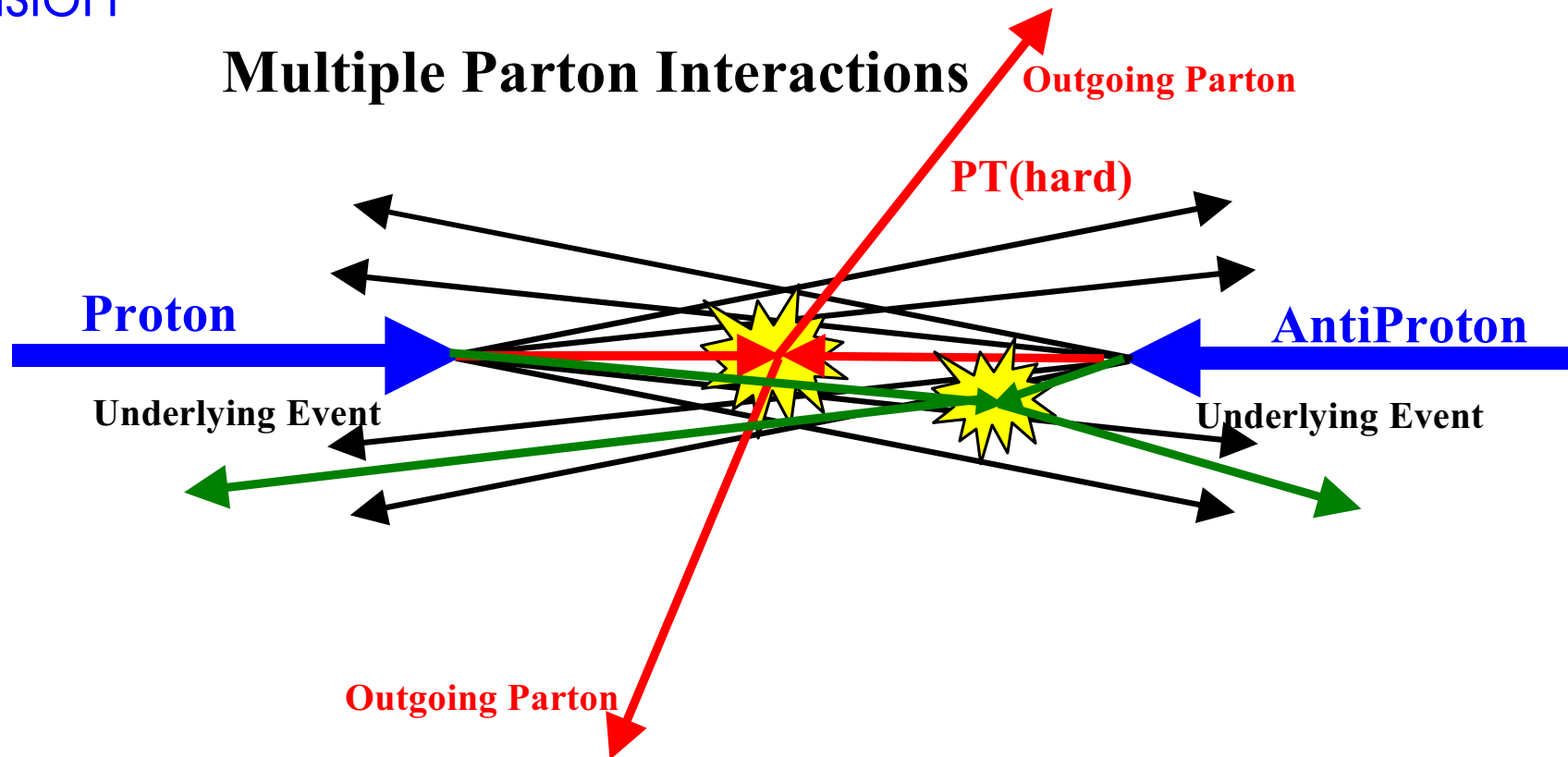
Generally a complex interaction, here a $p\bar{p}$ collision



- One "hard" 2 to 2-parton \rightarrow 2 "jets" with large $P_{T1}(\text{hard})$
- breakup of the p and \bar{p} ("beam remnants")
- "underlying event" = remnants + initial-state radiation
- can replace the 2 jets by $\gamma + \text{jet}$, W , Higgs, etc

Two hard interactions in one collision

Additional complexity: a second hard interaction in the collision



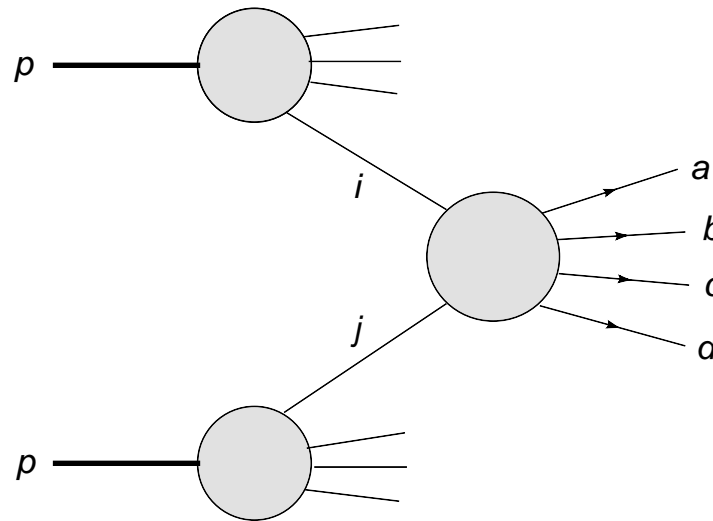
- “hard” 4 to 4-parton scattering \rightarrow 4 “jets” with large $P_{T1}(\text{hard}), P_{T2}(\text{hard})$, plus the underlying event
- also processes in which 2 initial partons produce 4 jets

Focus on 4 jet production

- Complete simulation of the event requires modeling the underlying event and calculating the hard subprocess
- Various Monte Carlo codes exist and are being refined for the underlying event (Herwig, Pythia,
- Focus here on calculation of hard collisions that produce 4 jets
- Two components of the hard collision
 - Single Parton Scattering (SPS) $2 \rightarrow 4\text{jets}$
 - Double Parton Scattering (DPS) $4 \rightarrow 4\text{jets}$

Single parton scattering

- One hard collision per pp interaction: $ij \rightarrow abcd$



- Well established methodology for calculations

$$d\sigma^{SPS} = \sum_{i,j} \int f_p^i(x_1, \mu) f_p^j(x'_1, \mu) d\hat{\sigma}_{(ij \rightarrow abcd)}(x_1, x'_1, \mu) dx_1 dx'_1$$

Single parton scattering

$$d\sigma^{SPS} = \sum_{i,j} \int f_p^i(x_1, \mu) f_p^j(x'_1, \mu) d\hat{\sigma}_{(ij \rightarrow abcd)}(x_1, x'_1, \mu) dx_1 dx'_1$$

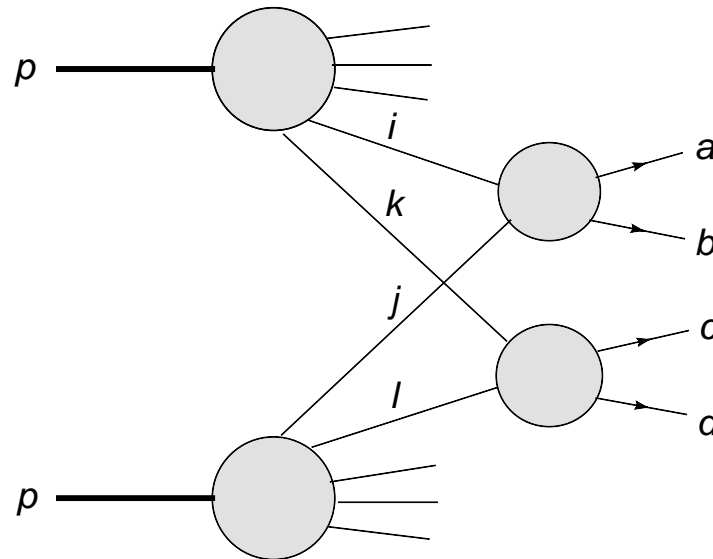
- usual factorization assumption
- indices i and j run over the different parton species in each of the incident protons
- well established QCD methods to compute hard subprocess cross section $d\hat{\sigma}_{(ij \rightarrow ab)}(x_1, x'_1, \mu)$ as a perturbative series in the strong coupling $\alpha_s(\mu)$
- parton distribution function $f_p^i(x_1, \mu)$ – probability that parton i is found with fractional longitudinal momentum x_1 at factorization scale μ in the proton

Outline

1. What is Double Parton Scattering (DPS)?
2. Work through $pp \rightarrow b\bar{b}jjX$ in detail
 - 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
 - Once established in a well defined process, here, $pp \rightarrow b\bar{b}jjX$, then DPS contributions in other final states can be calculated; possibly important for background estimates in new physics searches
4. Further work – experiment, phenomenology, and theory
5. Conclusions

1. 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 $pp \rightarrow b\bar{b}j_1j_2X$,

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

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	σ_{eff}
AFS (pp), 1986	63	4 jets	$p_T^{\text{jet}} > 4$	$ \eta^{\text{jet}} < 1$	~ 5 mb
UA2 ($p\bar{p}$), 1991	630	4 jets	$p_T^{\text{jet}} > 15$	$ \eta^{\text{jet}} < 2$	> 8.3 mb (95% C.L.)
CDF ($p\bar{p}$), 1993	1800	4 jets	$p_T^{\text{jet}} > 25$	$ \eta^{\text{jet}} < 3.5$	$12.1^{+10.7}_{-5.4}$ mb
CDF ($p\bar{p}$), 1997	1800	$\gamma + 3$ jets	$p_T^{\text{jet}} > 6$ $p_T^{\gamma} > 16$	$ \eta^{\text{jet}} < 3.5$ $ \eta^{\gamma} < 0.9$	$14.5 \pm 1.7^{+1.7}_{-2.3}$ mb

- Wide range of values of σ_{eff}
- Recent study by D0 of $p\bar{p} \rightarrow \gamma + \text{jets} + X$ at $\sqrt{s} = 1.96$ TeV
 $\sigma_{\text{eff}}^{\text{ave}} = 16.4 \pm 0.3(\text{stat}) \pm 2.3(\text{syst})$ mb

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

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

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

- 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}

2. Calculation of $pp \rightarrow b\bar{b}jjX$ 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 $4 \rightarrow 4$ events with Madgraph/Madevent
- Generate SPS $2 \rightarrow 4$ events with ALPGEN (faster)
- Look for kinematic distributions that show discrimination between DPS and SPS

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

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

Double parton contributions

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

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

- (j) indicates j is undetected

Single parton contributions

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

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

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

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

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

- Assume a b -tagging rate of 60% for b -quarks with

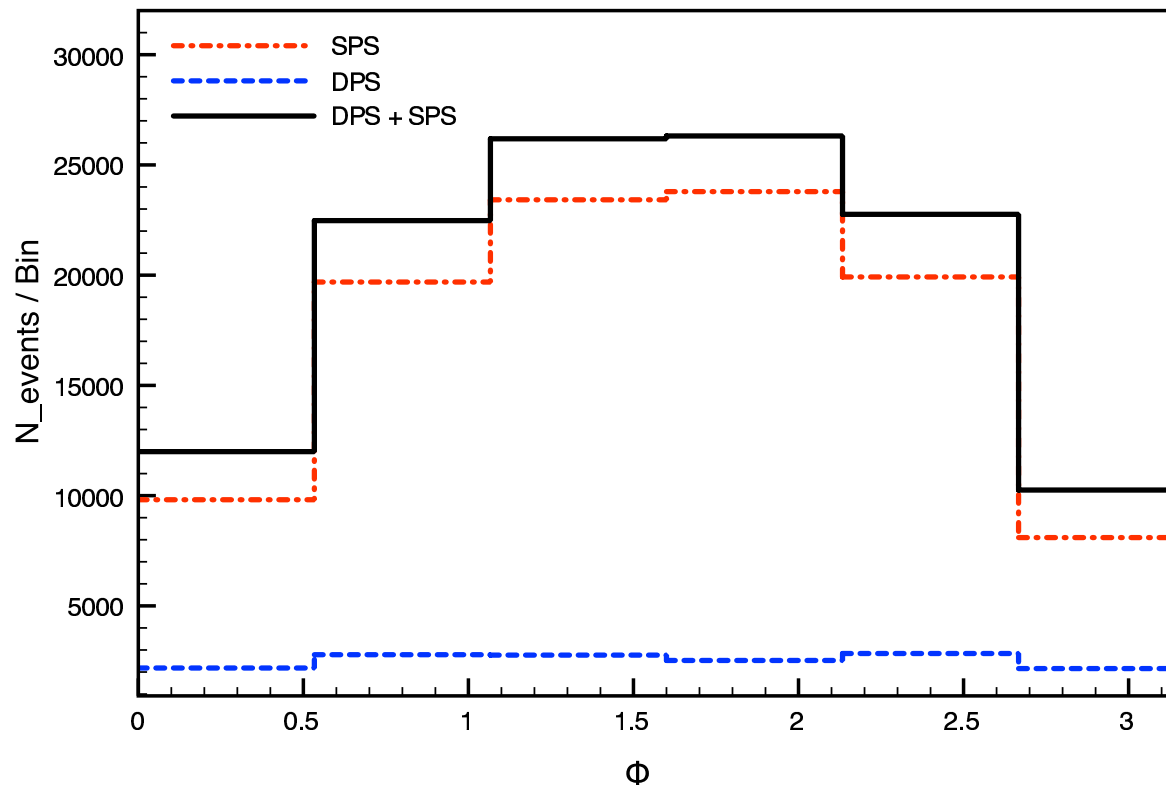
$$p_T > 20 \text{ GeV} \text{ and } |\eta_b| < 2.0$$

- Hard scale choice

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

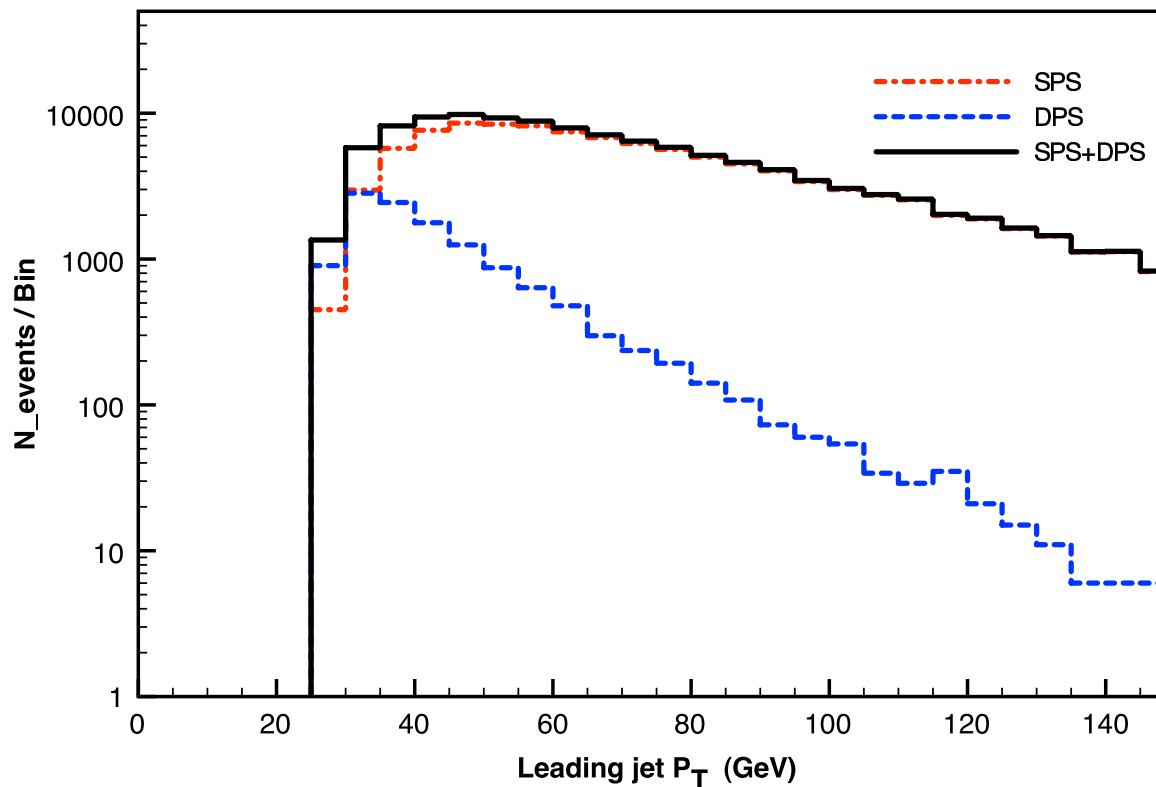
DPS \rightarrow uncorrelated (sub)events

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



Transverse momentum of leading jet

- p_T of the leading jet in $pp \rightarrow b\bar{b}jjX$, 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 $2 \rightarrow 2$ hard scatters
 - Expect 2 pairs of jets to be individually roughly back-to-back (up to effects of extra real radiation)
 - $\rightarrow \Delta\phi_{jj} \sim \pi$ 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

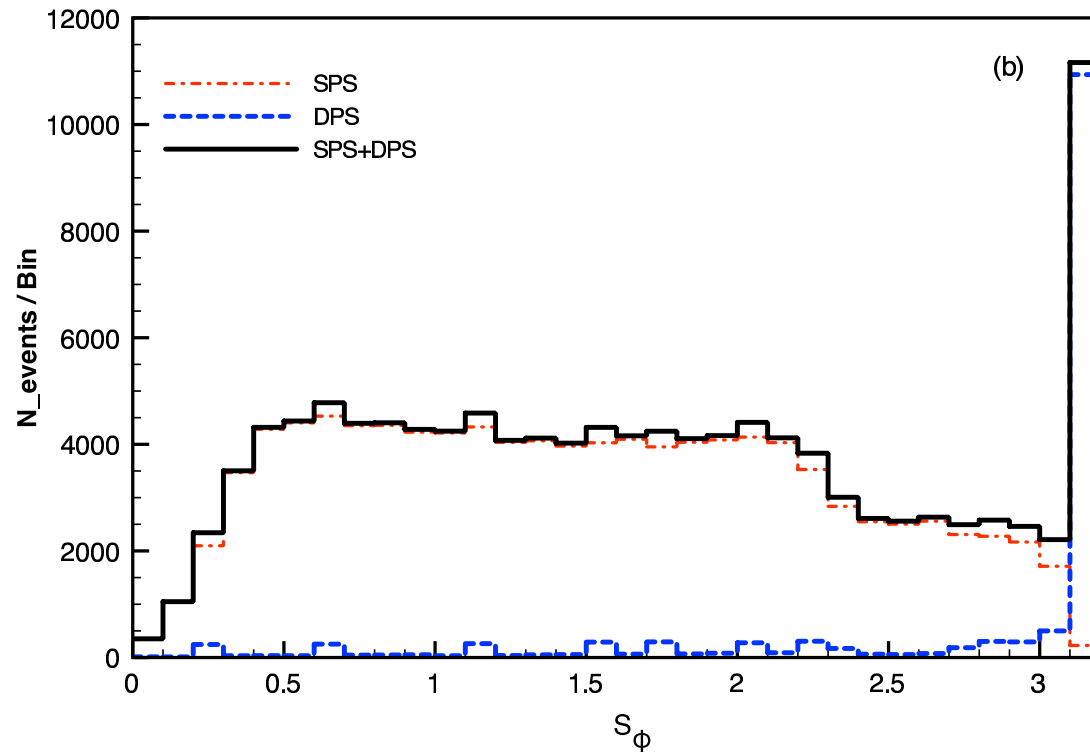
$$S_\phi = \frac{1}{\sqrt{2}} \sqrt{\Delta\phi(b_1, b_2)^2 + \Delta\phi(j_1, j_2)^2}$$

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

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

Distinguishing Variables - S_ϕ

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



- DPS events are clustered near $S_\phi \sim \pi$, well separated from the total – **expect some smearing from soft radiation**
- SPS 2 \rightarrow 4 events are fairly uniformly distributed

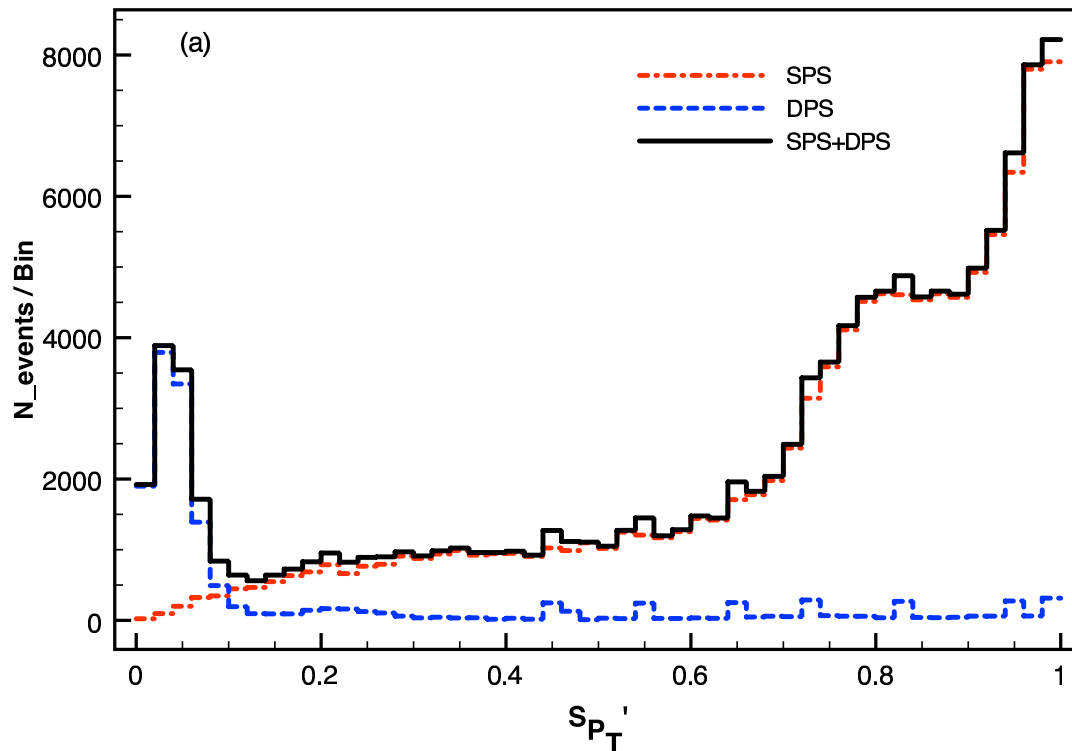
Distinguishing Variables - $p_T(j_1, j_2)$ and S'_{p_T}

- Topology of DPS events includes two $2 \rightarrow 2$ 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 $2 \rightarrow 2$ 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

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

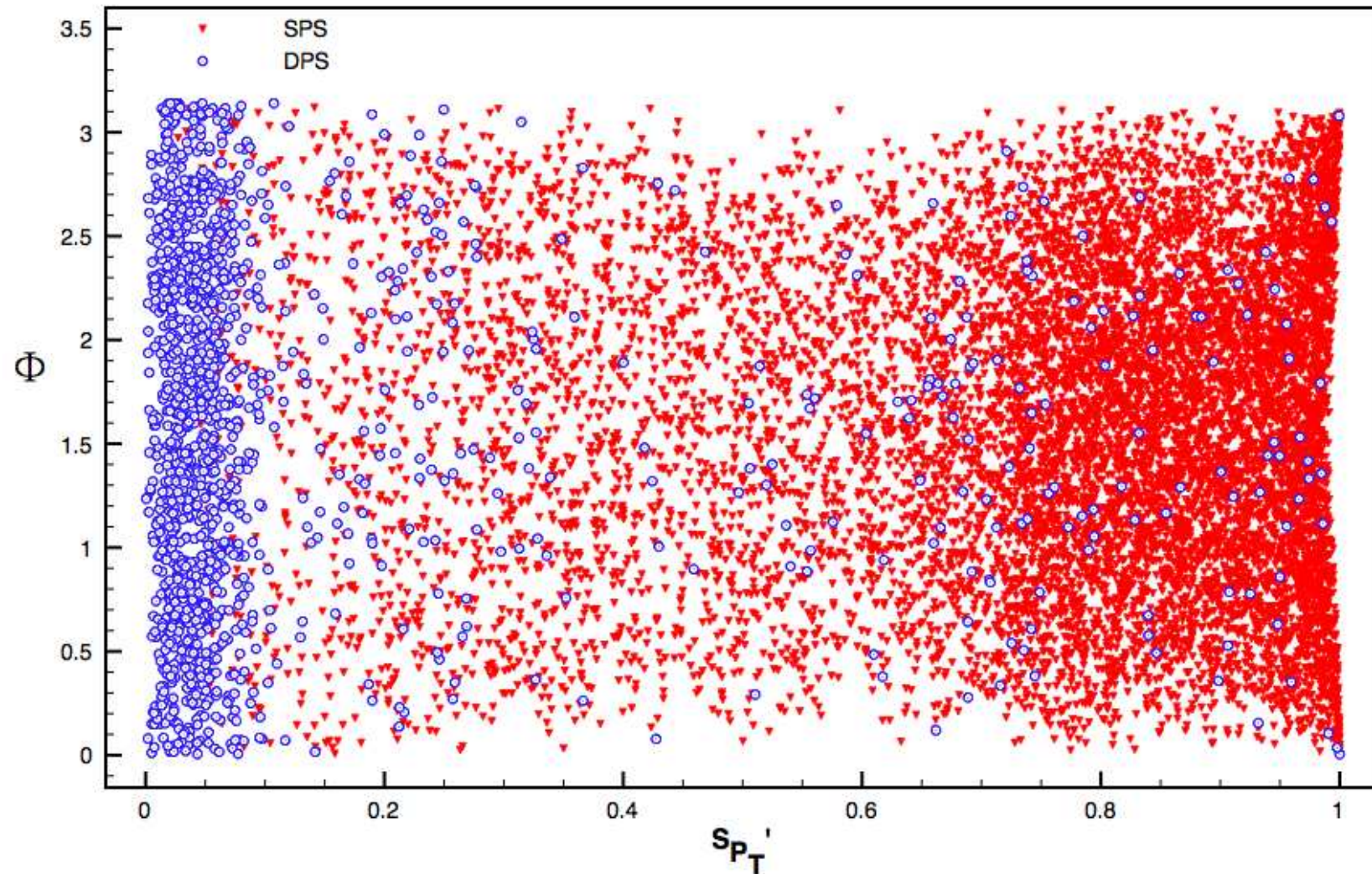
Distinguishing Variables - S'_{p_T}

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



- 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'_{pT} plane

3. Methodology/Strategy

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

- 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 σ_{eff}
- Examine other processes, e.g., $pp \rightarrow 4\text{jets}X$ see (arXiv:0911.5348); is the extracted σ_{eff} roughly the same?

4. 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 ($b\bar{b}t\bar{t}$, Wjj , $Wb\bar{b}$, Hjj , ...)

Theoretical issues (with J. W. Qiu)

- Basis for

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

- Starting from

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

Improvements/Further Work (continued)

General

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

- Amplitude $M(pp \rightarrow b\bar{b}j_1j_2X)$ should include a sum of amplitudes for 2-parton collisions (one active from each incident hadron, i.e., $2 \rightarrow 4$; 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 $4 \rightarrow 4$ and $2 \rightarrow 4$, only?

Improvements/Further Work (continued)

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

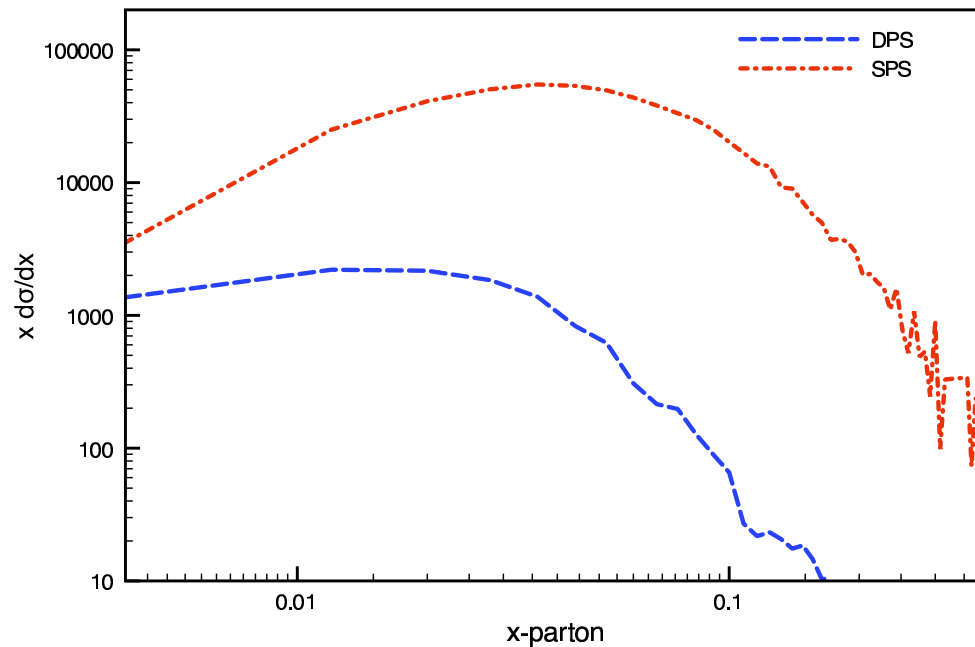
- Presumably one has in mind starting from a 4-parton \rightarrow 4-parton hard part
- Not clear how (or whether) the four-parton matrix element can be reduced (even approximately) to a product of two matrix elements for the single parton scatterings
- How even does one flux factor $\frac{1}{2s}$ get replaced by a product of 2 flux factors $\frac{1}{2s}$?
- In this way of looking at the physics, what is σ_{eff} and how does it emerge?

5. Conclusions

- Developed the phenomenology of double scattering for $pp \rightarrow b\bar{b}jjX$ 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 σ_{eff}
- Once σ_{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 $pp \rightarrow b\bar{b}jjX$ 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