# *Double Parton Scattering at the LHC –*
## *Characteristics and Estimates*

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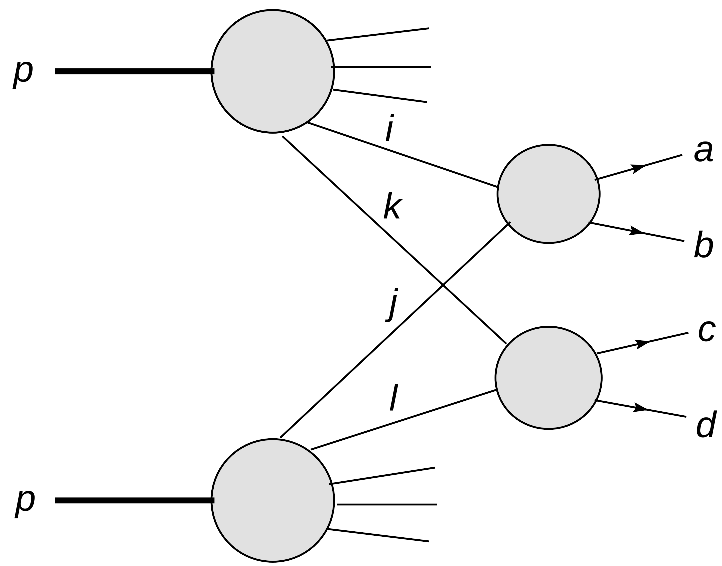
ELB, C Jackson, G Shaughnessy, Phys Rev D **81**, 014014 (2010) (arXiv:0911.5348 (hep-ph))

# *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 the cross section for DPS is established in a well defined process, here, $pp \to b\bar{b}jjX$, then one can calculate its contributions in other final states
5. Possibly important for background estimates in new physics searches
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 $pp \to b\bar{b}j_1j_2X$,

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

# Several assumptions

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

- $\sigma_{\text{eff}}$
  - Given one hard-scatter, $\sigma_{\text{eff}}$ 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 $\sigma_{\text{eff}}$

## $pp \to b\bar{b}jjX$ 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: $(ij \to b\bar{b}) \otimes (kl \to jj)$
- $\otimes$: combine one event from $b\bar{b}$ and one from $jj$
- NLO 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

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

-

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

- Include detector resolution effects

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

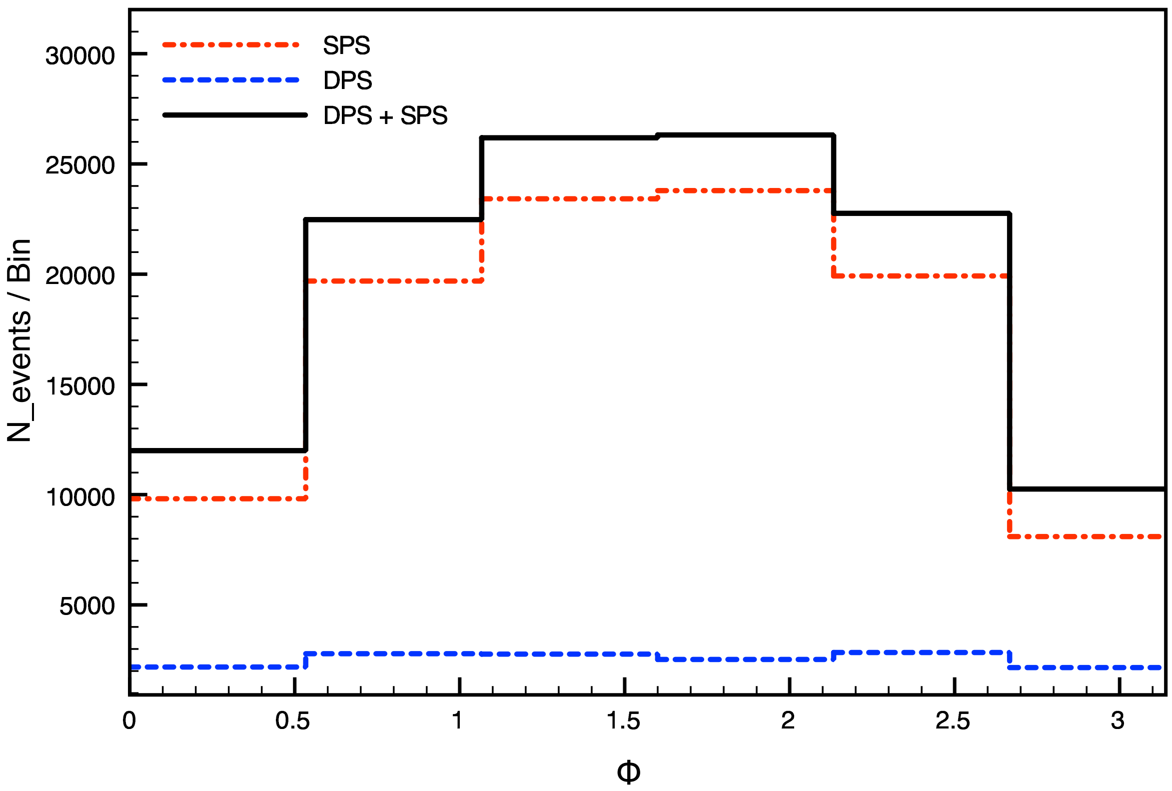
$a = 50\%$ and $b = 3\%$ for jets

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

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

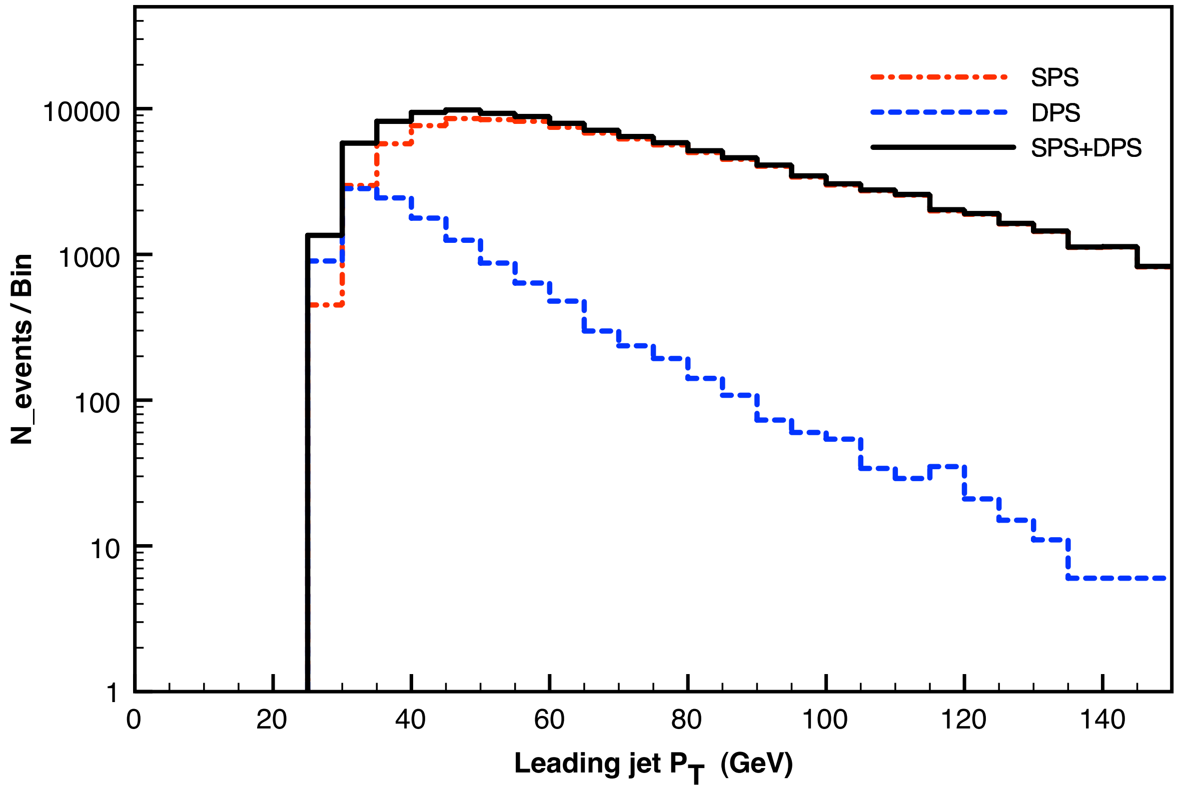
# *DPS → uncorrelated (sub)events*

- $\Phi$: angle between the planes defined by $b\bar{b}$ and $jj$ systems
- Uncorrelated scatters: the DPS $\Phi$ 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 $\sigma_{\rm eff}$

# Distinguishing Variables - $\Delta\phi_{jj}$ and $S_\phi$

- 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 $S_\phi$ 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

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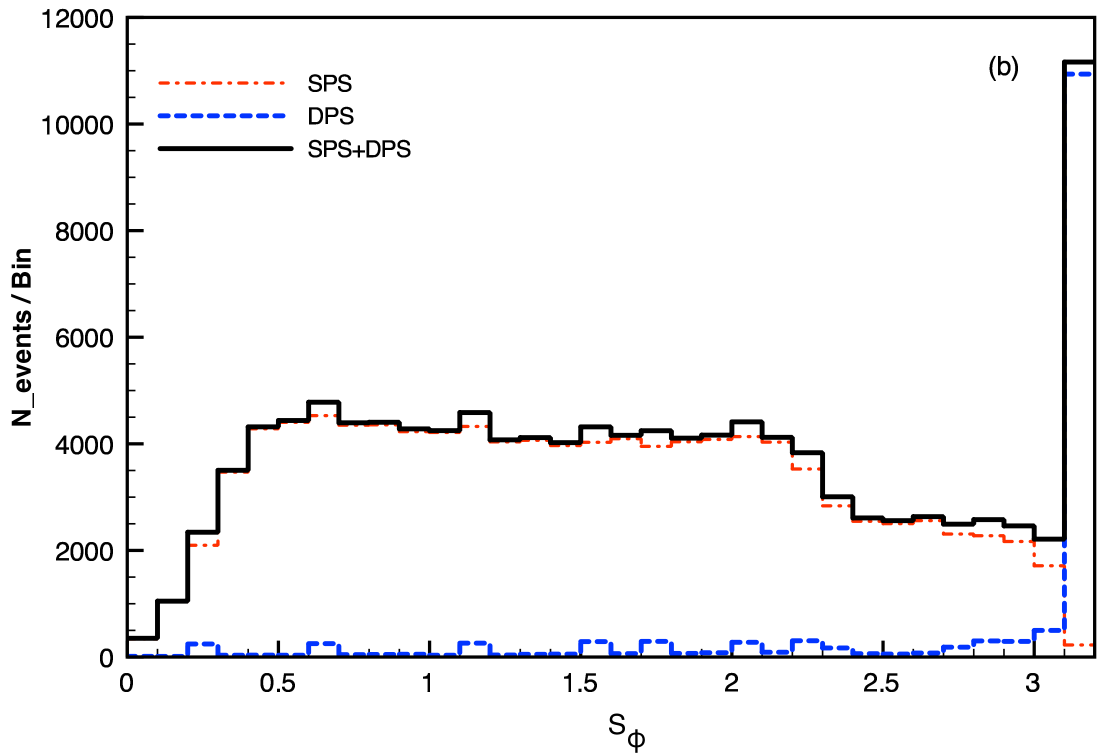


- DPS events are clustered near $S_\phi \sim \pi$, well separated from the total
- SPS events are fairly uniformly distributed

# 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

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

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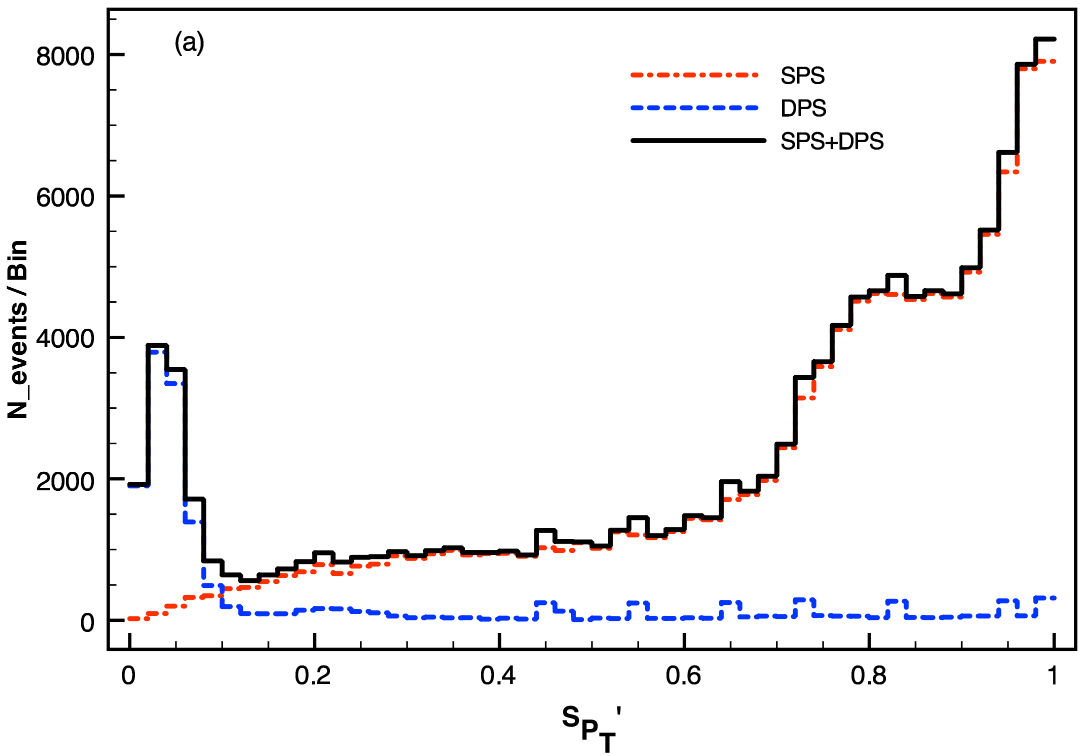
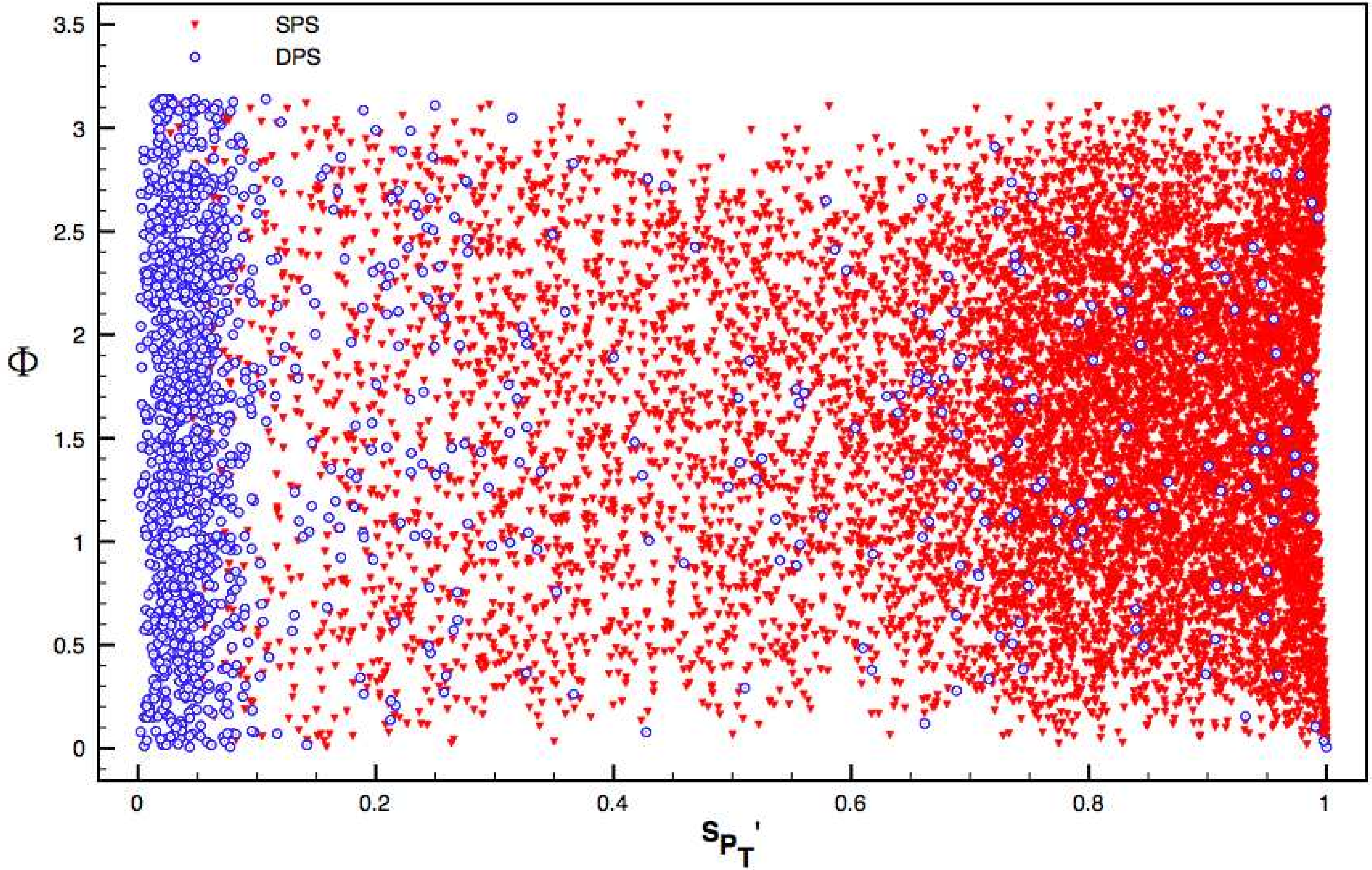



- DPS events produce a clear peak near $S'_{p_T} = 0$, well separated from the total
- SPS events are away from back-to-back (gluon splitting)

# *Two-dimensional distribution*




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

# Methodolgy/Strategy

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

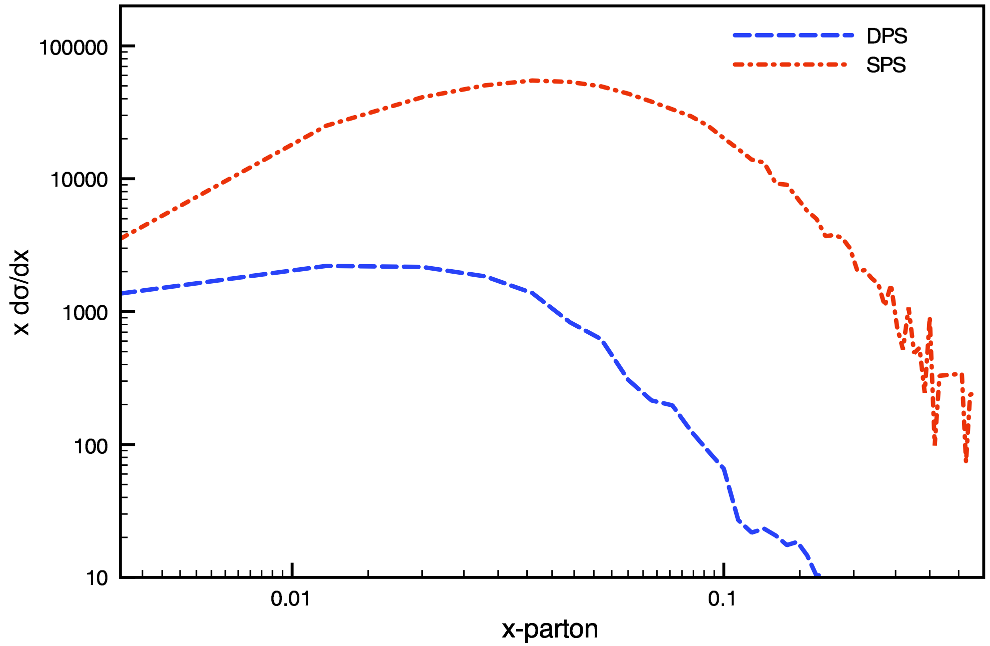
- Look at events in the 2-D $\Phi$ and $S'_{p_T}$ plane
- Expect a concentration of events near $S'_{p_T} = 0$ that are distributed uniformly in the inter plane angle $\Phi$. These are the DPS events
- Valley of low density between $S'_{p_T} \sim 0.1$ and $0.4$ should allow a cut that enhances DPS
- 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., $pp \to 4{\rm jets}X$; is the extracted $\sigma_{\rm eff}$ roughly the same?

# 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, ....
- Would be valuable to establish a DPS signal in early LHC runs and measure $\sigma_{\mathrm{eff}}$
- Once $\sigma_{\mathrm{eff}}$ is measured in a clean process, and dynamical features are established in a clean process (or two), then estimates can be made for possibly important backgrounds to Higgs and new physics processes

# 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 $\gamma$ plus jets

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

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