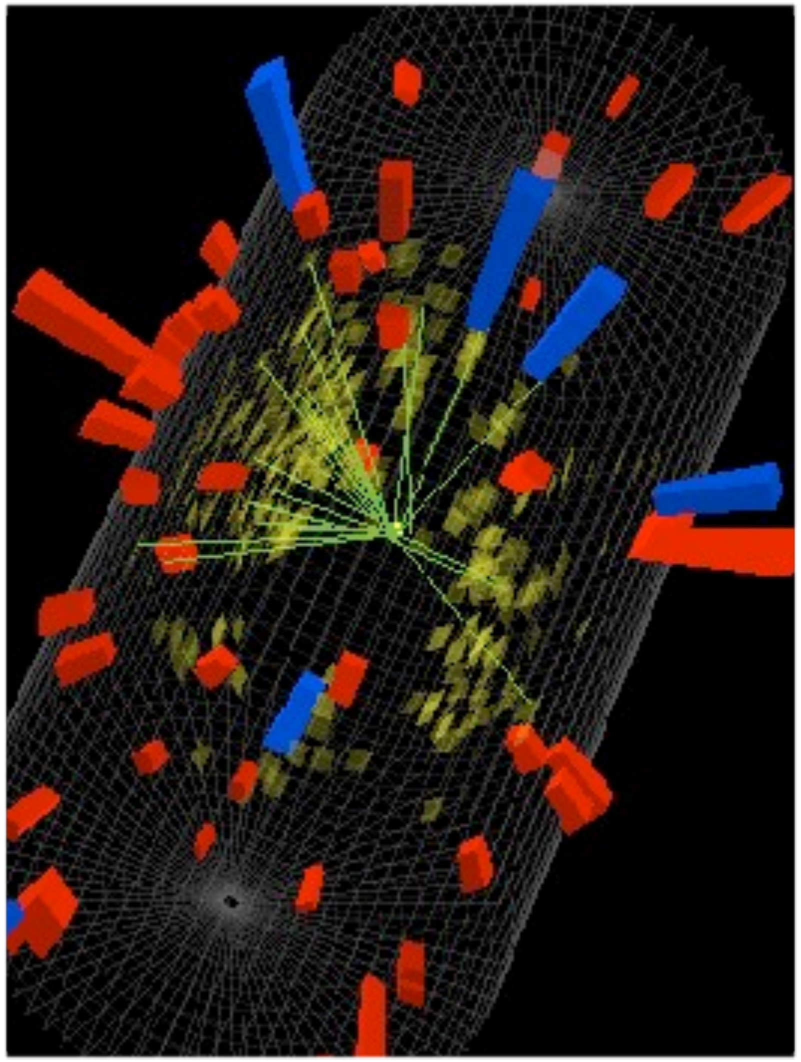
Double Parton Scattering at the LHC

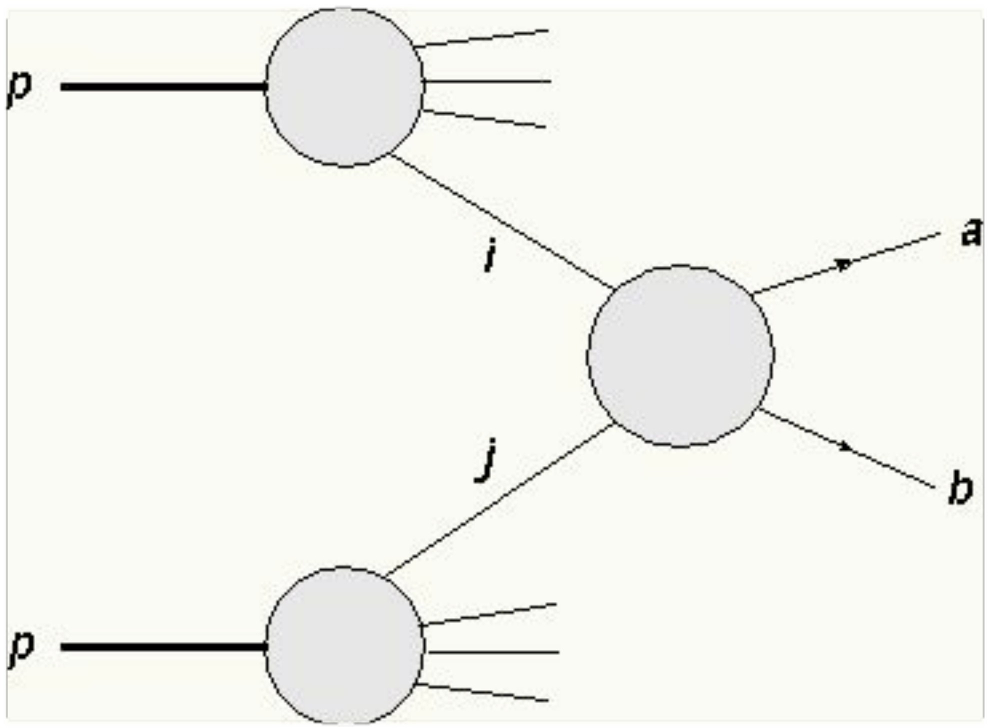
Chris Jackson
Argonne National Laboratory

- What is "Double Parton Scattering"...
  and why do we care?
- Past studies (both theoretical and experimental)
- DPS @ the LHC:
  - bb + jj
  - 4j



in collaboration with E. Berger & G. Shaughnessy (Phys. Rev D81, 014014)

theorist's view of pp collisions



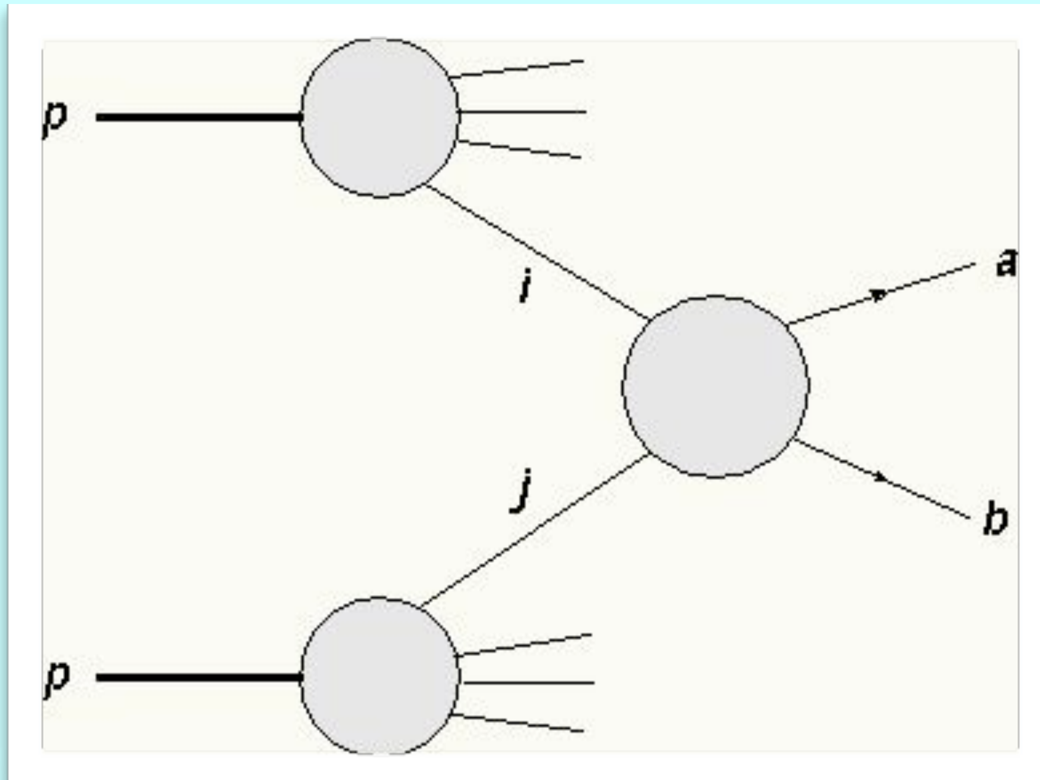
single parton scattering (SPS)

$$d\sigma^{SPS} = \sum_{i,j} \int f_p^i(x_1,\mu) f_p^j(x_1',\mu) d\hat{\sigma}_{(ij\to ab)}(x_1,x_1',\mu) dx_1 dx_1'.$$

$f(x_i,\mu)$ = (non-perturbative) PDF's

$d\sigma$ = perturbatively-calculable partonic cross section

theorist's view of pp collisions



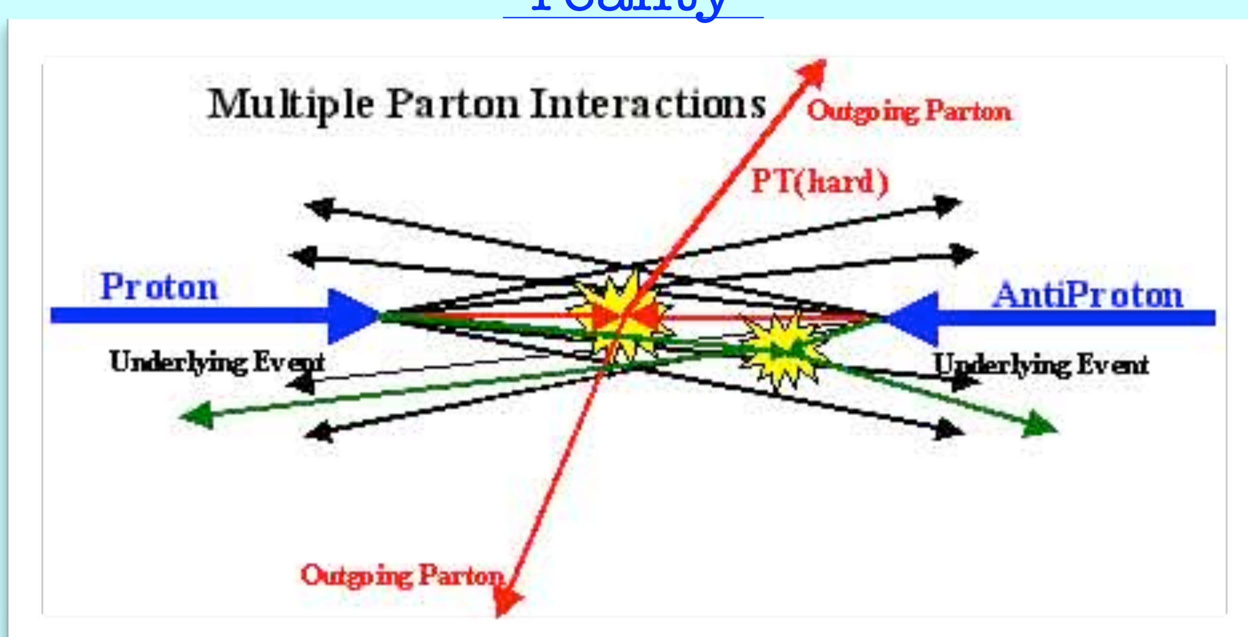
single parton scattering (SPS)

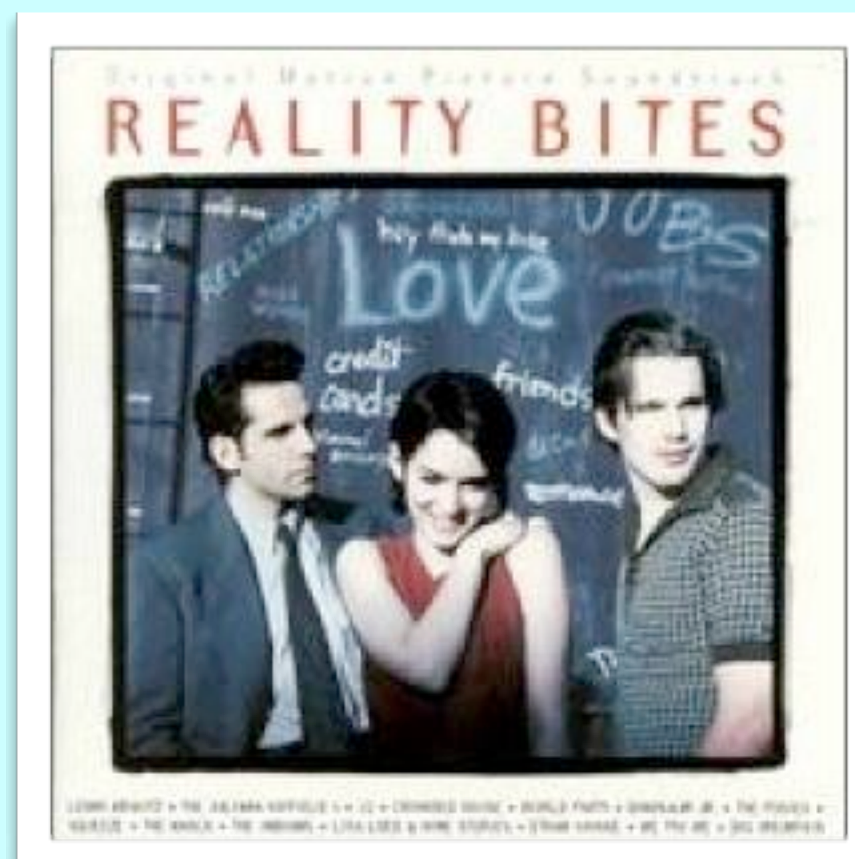
$$d\sigma^{SPS} = \sum_{i,j} \int f_p^i(x_1,\mu) f_p^j(x_1',\mu) d\hat{\sigma}_{(ij\to ab)}(x_1,x_1',\mu) dx_1 dx_1'.$$

$f(x_i,\mu)$ = (non-perturbative) PDF's

$d\sigma$ = perturbatively-calculable partonic cross section

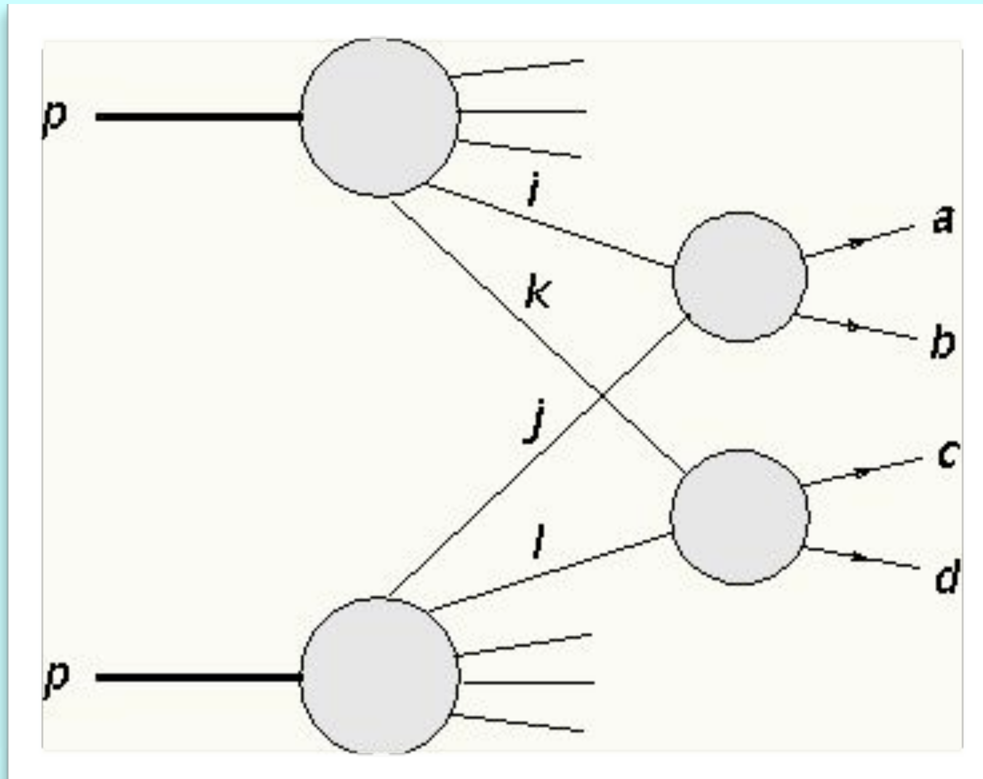
"reality"





double parton scattering (DPS)

- Two INDEPENDENT scatterings in ONE proton-proton collision:



- Cross section expressed as a product of two SPS cross sections:

$$\sigma_{DPS} = \frac{\sigma_a \sigma_b}{\sigma_{eff}},$$

- Motivation?
  - QCD: non-perturbative dynamics, parton distributions, etc.
  - Searches for complex signatures typically rely on fact that new, heavy particles decay "spherically" while QCD backgrounds are correlated.
  - Higgs searches? New Physics searches?

σ_{eff} and factorization

- What exactly is σ_{eff}? (besides a proportionality constant)
    - (σ_B/σ_{eff}) probability for scattering B to occur given scattering A already has
    - σ_{eff} measures the size of the partonic core in which the "B" partons are confined
    - σ_{eff} should be at most proportional to the transverse size of the proton
- Properties of σ_{eff}:
    - Process-independent?
      (If so, measure it for one process, use it to estimate others!)
    - Independent of HADRONIC c.o.m. energy???
- Typical approach: ignore correlations in longitudinal momentum of partons...

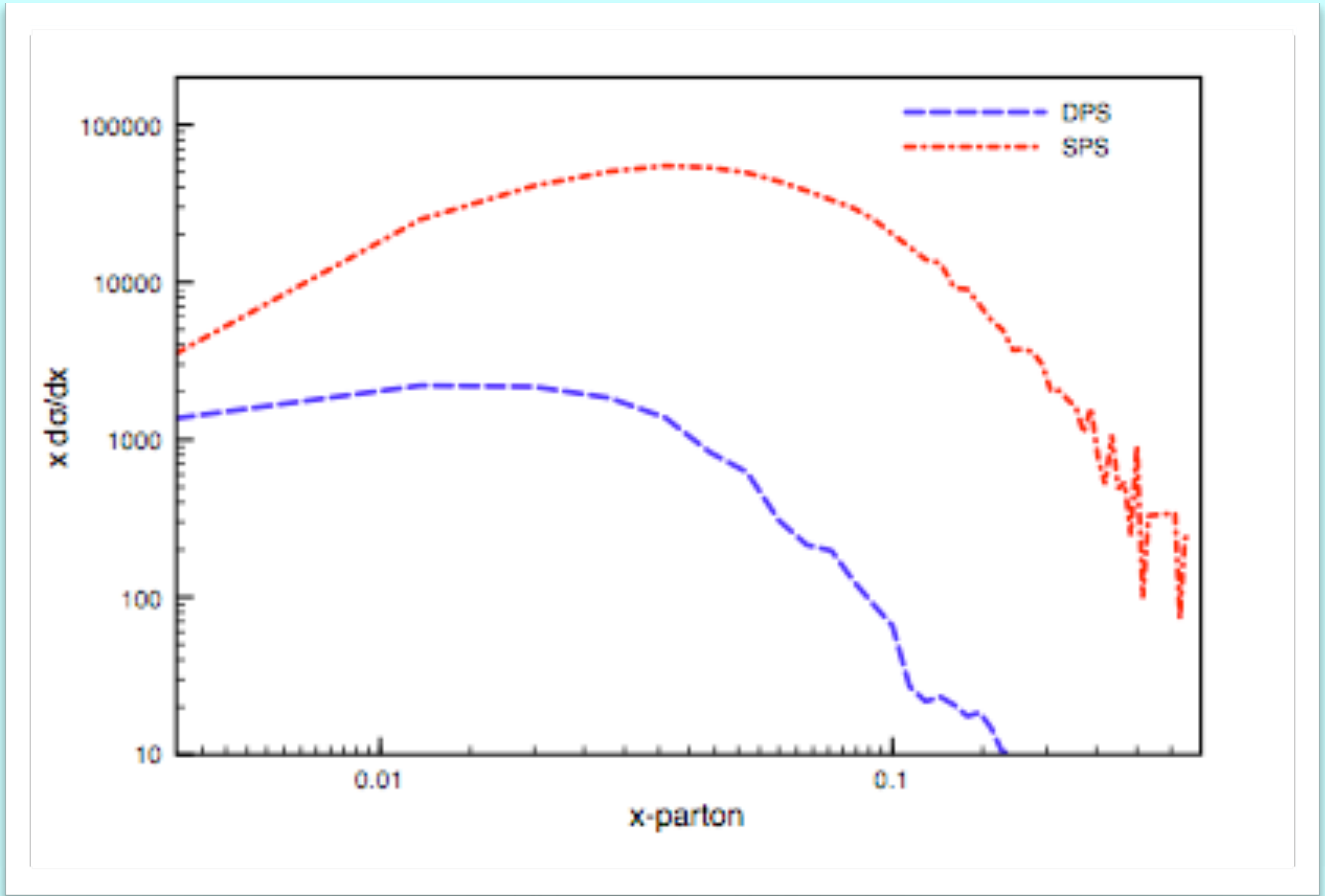
$$H_p^{i,k}(x_1, x_2, \mu_A, \mu_B) = f_p^i(x_1, \mu_A) f_p^k(x_2, \mu_B).$$

"Joint Probabilities"

- DPS cross section:

$$d\sigma^{DPS} = \frac{m}{2\sigma_{eff}} \sum_{i,j,k,l} \int H_p^{ik}(x_1, x_2, \mu_A, \mu_B) H_p^{jl}(x_1', x_2', \mu_A, \mu_B) \times d\hat{\sigma}_{ij}^A(x_1, x_1', \mu_A) d\hat{\sigma}_{kl}^B(x_2, x_2', \mu_B) dx_1 dx_2 dx_1' dx_2'.$$

DPS x values at the LHC



- Majority of DPS events are associated with LOW x values ($x \leq 0.2$)
- Momentum fraction carried by beam remnant = $(1-x_1-x_2)$ in DPS and $(1-x)$ in SPS
- Use of "joint probabilities" justified at LHC c.o.m. energies

(Dated) Example of the Importance of DPS

(Del Fabbro and Treleani, PRD61: 077502 (2000))

- Consider backgrounds to $HW^{\pm}$ production ($H \to bb$) at LHC

- DPS contribution:

$$pp \to bb \quad \otimes \quad pp \to W$$

- Naively, σ_{DPS} is small... but $\sigma_{SPS}(bb)$ and $\sigma_{SPS}(W)$ are HUGE!!!

(Dated) Example of the Importance of DPS

(Del Fabbro and Treleani, PRD61: 077502 (2000))

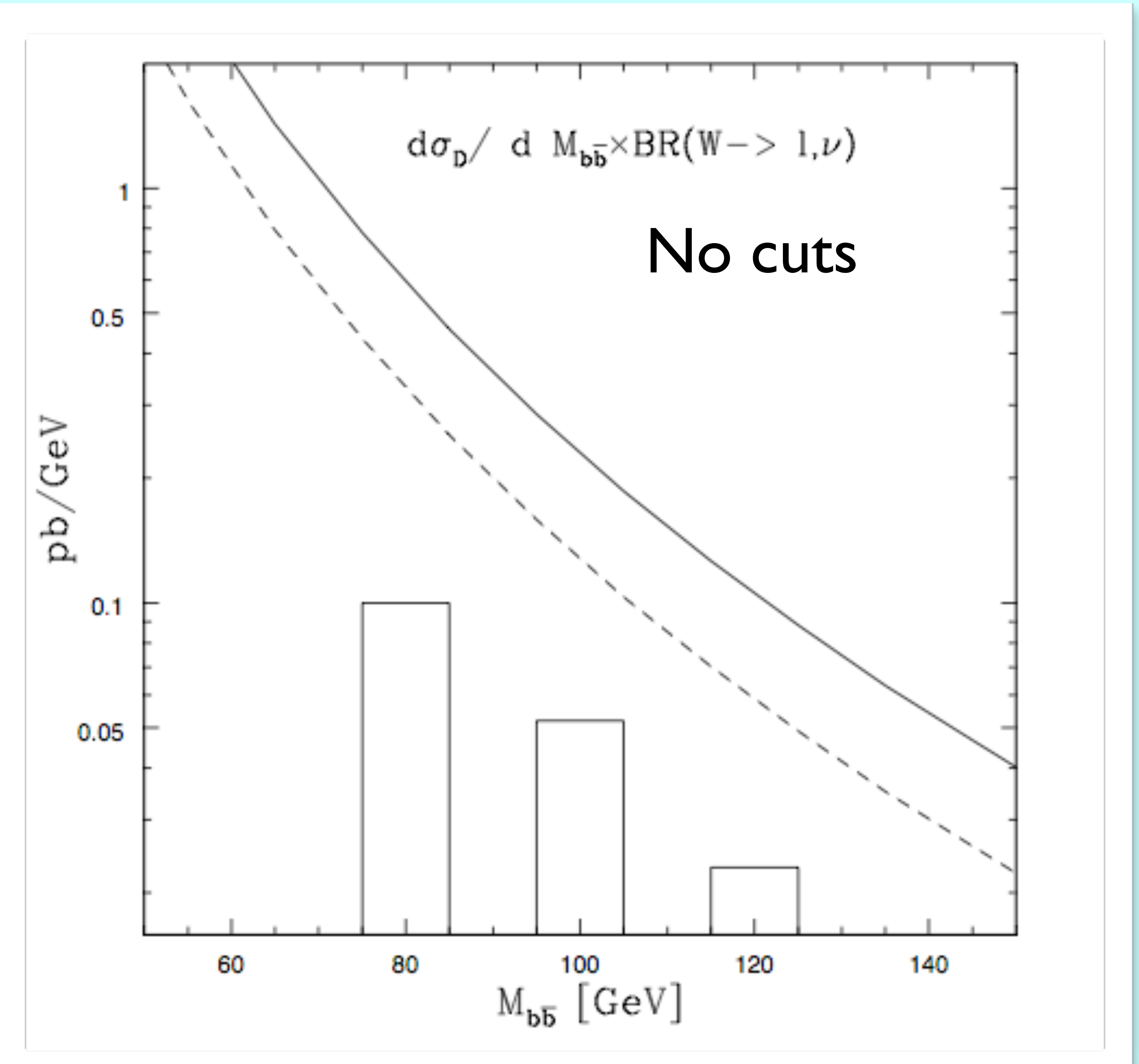
- Consider backgrounds to $HW^{\pm}$ production ($H \to bb$) at LHC

- DPS contribution:

$$pp \to bb \otimes pp \to W$$

- Naively, σ_{DPS} is small... but $\sigma_{SPS}(bb)$ and $\sigma_{SPS}(W)$ are HUGE!!!

- Consider bb invariant mass distribution for M_h = 80, 100, 120 GeV



(Dated) Example of the Importance of DPS

(Del Fabbro and Treleani, PRD61: 077502 (2000))

- Consider backgrounds to HW production (H→bb) at LHC
- DPS contribution:

$$pp \rightarrow bb \otimes pp \rightarrow W$$

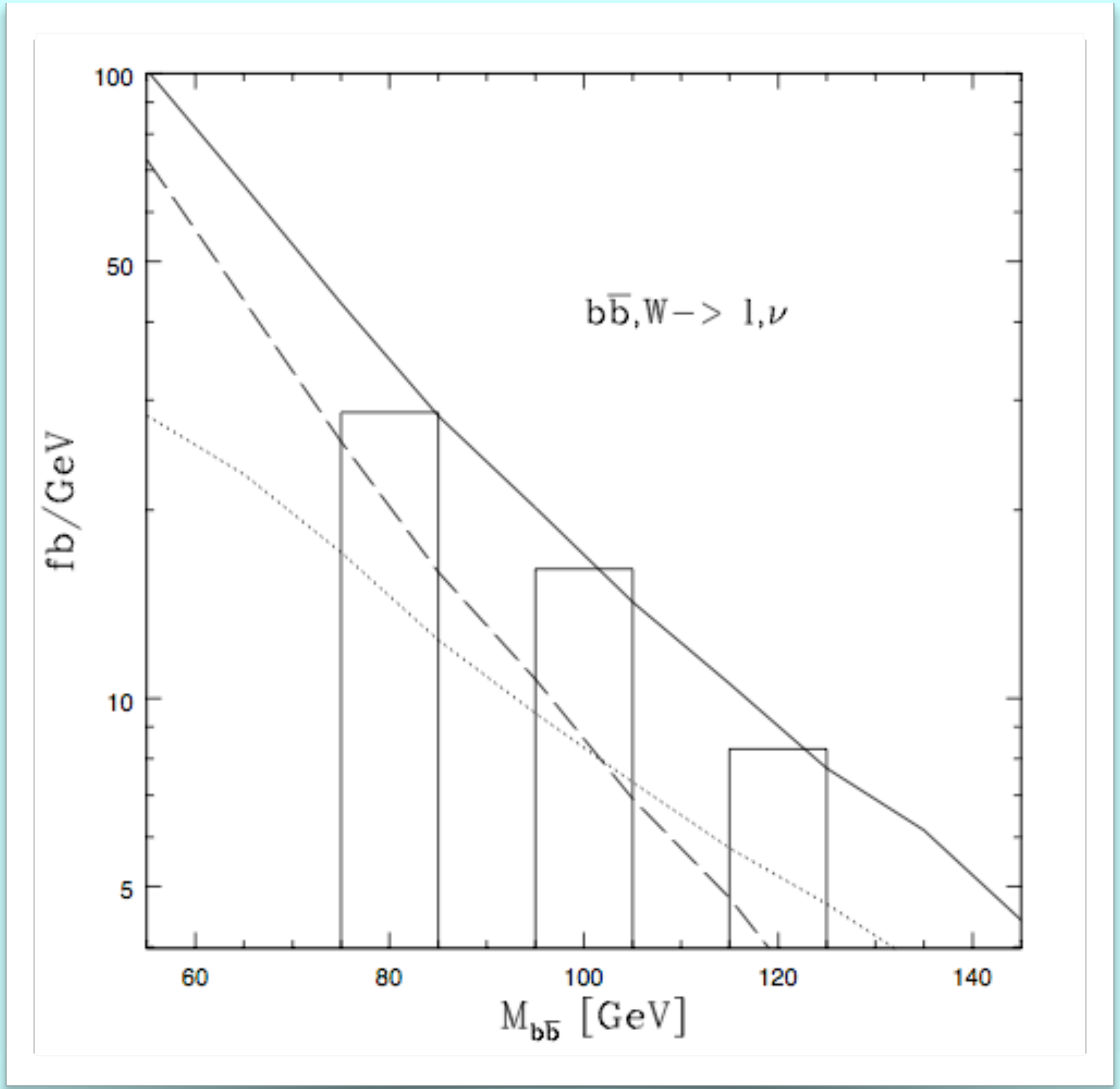
- Naively, σ_{DPS} is small... but $\sigma_{SPS}(bb)$ and $\sigma_{SPS}(W)$ are HUGE!!!
- Consider bb invariant mass distribution for M_h = 80, 100, 120 GeV
- Acceptance cuts:

lepton: $p_T > 20$ GeV, $|\eta| < 2$

b jets: $p_T > 15$ GeV, $|\eta| < 2$

$\Delta R > 0.7$

- Similar situation for NP searches?



Dotted: SPS; Dashed: DPS; Solid: Total Background

Past Searches for DPS

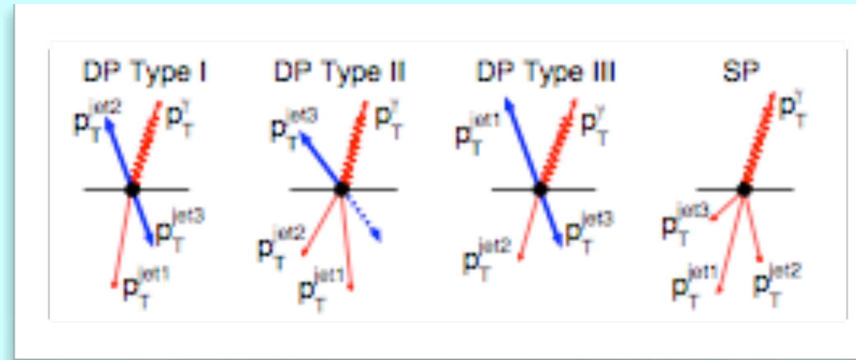
- Need a process with a large rate... and relatively clean signal
- Earlier searches focussed on the 4 jet final state... but, more recently, searches have focussed on multi-jet + prompt photons:

Experiment	$\sqrt{s}$ (GeV)	Final state	p_T^{min} (GeV)	η range	σ_{eff}
AFS (pp), 1986 [6]	63	4 jets	$p_T^{jet} > 4$	$\|\eta^{jet}\| < 1$	~ 5 mb
UA2 ($p\bar{p}$), 1991 [7]	630	4 jets	$p_T^{jet} > 15$	$\|\eta^{jet}\| < 2$	> 8.3 mb (95% C.L.)
CDF ($p\bar{p}$), 1993 [8]	1800	4 jets	$p_T^{jet} > 25$	$\|\eta^{jet}\| < 3.5$	$12.1^{+10.7}_{-5.4}$ mb
CDF ($p\bar{p}$), 1997 [9]	1800	$\gamma + 3$ jets	$p_T^{jet} > 6$	$\|\eta^{jet}\| < 3.5$	
			$p_T^{\gamma} > 16$	$\|\eta^{\gamma}\| < 0.9$	$14.5 \pm 1.7^{+1.7}_{-2.3}$ mb

- New measurement by D0 collaboration using γ + 3 jets:
  - DPS process: $pp \to \gamma j \otimes pp \to jj$
  - Better energy measurements of γ's allows for a better pairing of the two SPS events that make up the DPS event
  - Larger integrated luminosity allows selection of γ + 3 jet events with high photon p_T ($60 < p_T < 80$ GeV)... with a large photon purity
    - clean separation between jet produced with γ and other jets
    - better determination of energy scale of the γ + 3 jet process

Discriminating Variables

- Still need a way to discriminate DPS from SPS in “DP” events
(they differentiate between “DP” events and “double interaction” (DI) events)



- Try to exploit the back-to-back nature of the objects coming from DPS events (e.g., $\Delta\phi(\gamma, j_1)$)

- Do a lot better by taking into account information from the WHOLE SYSTEM:

$$S_{p'_T} = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{|\vec{p}_T(\gamma,i)|}{|\vec{p}_T^{\,\gamma}|+|\vec{p}_T^{\,i}|}\right)^2+\left(\frac{|\vec{p}_T(j,k)|}{|\vec{p}_T^{\,j}|+|\vec{p}_T^{\,k}|}\right)^2},$$

$$S_{\phi} = \frac{1}{\sqrt{2}}\sqrt{\left[\frac{\Delta\phi(\gamma,i)}{\delta\phi(\gamma,i)}\right]^2+\left[\frac{\Delta\phi(j,k)}{\delta\phi(j,k)}\right]^2}.$$

where: $\vec{p}_T(\gamma,i) = \vec{p}_T^{\,\gamma} + \vec{p}_T^{\,\mathrm{jet}_i}$

- For DPS alone, distribution for $S_{p_T'}$ (S_ϕ) should peak at 0 (π)… while SPS distributions alone should be relatively flat
(sum of DPS+SPS will take shape of DPS distribution)

- In the γ + 3 jet analysis, the i, j and k objects are chosen such as to minimize the S variables

- In this way, they are able to effectively split the γ + 3 jet into γ + jet and dijet pairs… based on the best pairwise balance

Results from D0

- Determine DPS fractions and σ_{eff} from three bins of $p_T(j_2)$: 15-20, 20-25, 25-30 GeV

- Fraction of DPS events in “DP” (= DPS + SPS) events:

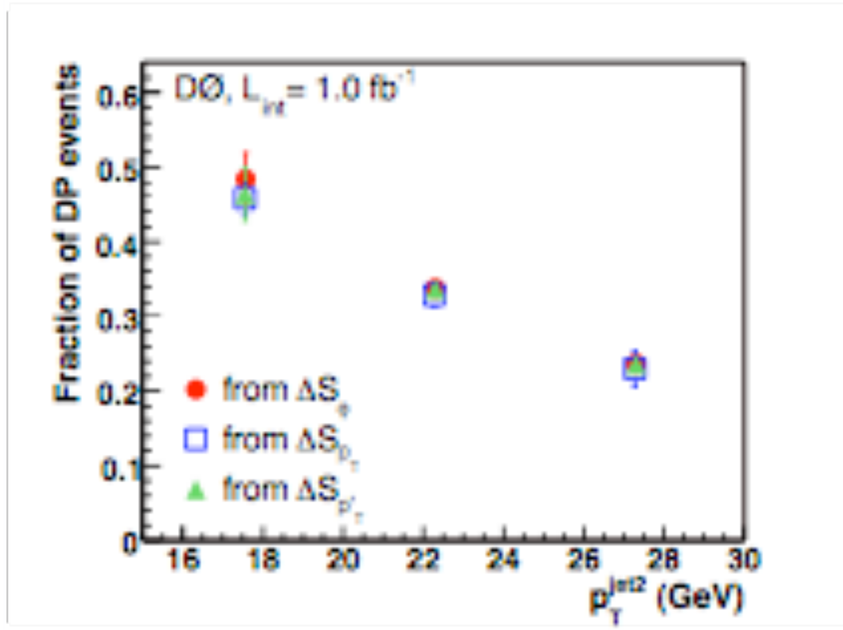
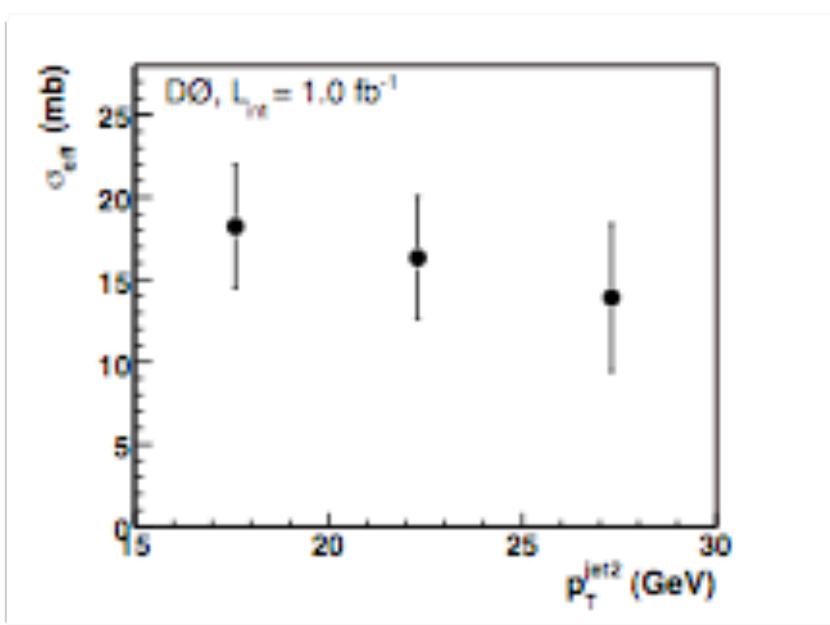


TABLE III: Fractions of DP events in the three p_T^{jet2} bins.

p_T^{jet2} GeV	$\langle p_T^{jet2} \rangle$ (GeV)	f_{DP}
15 – 20	17.6	0.466 ± 0.041
20 – 25	22.3	0.334 ± 0.023
25 – 30	27.3	0.235 ± 0.027

- Results for σ_{eff}:



D0 : σ_{eff} = 16.4 ± 0.3(stat)±2.3(syst)

CDF : σ_{eff} = 14.5 ± 1.7(stat)±2.0(syst)

DPS at the LHC

- Does σ_{eff} scale with c.o.m. energy? If so, need a precise measurement at the LHC!
- Would be nice to have a measurement relatively EARLY... then make predictions for backgrounds to NP and/or Higgs signals
- As we've seen from previous studies, in order to observe DPS, you need:
    - a (relatively) CLEAN SIGNAL
    - LARGE RATES for the SPS processes that make up the DPS process
- Early proposals focused on like-sign W pair production (A. Kulesza and Stirling '99)
- Bottom quark pair production with two jets (E. Berger, CJ, G. Shaughnessy):
    - LARGE RATES over a large kinematic range
    - b-tagging provides a relatively CLEAN SIGNAL
    - (Relatively) unambiguous which jets go with which other jets (one scattering produces the bb pair, the other produces the dijet final state)

$$pp \rightarrow bb \otimes pp \rightarrow jj$$

- $2 \rightarrow 2$ final states allow use of S variables

Study of bbjj at the LHC

- Basic strategy:
  - Produce DPS ($4 \to 4$) events using Madgraph/Madevent
  - Produce SPS ($2 \to 4$) events using Alpgen (much faster!)
  - Look for distributions where the two are discernible
- Basic acceptance cuts:

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

- Detector resolution effects/tagging efficiencies (w/ “PEAT”), e.g.:
  - $dE/E = a/\sqrt{E} \oplus b$ (where a = 50% and b = 3% for jets)
  - Bottom quark tagging efficiency of 60% (for $p_T > 20$ GeV and $|\eta| < 2.0$)
- All event rates quoted for $\sqrt{s} = 10$ TeV and 10 pb^{-1} of data
- We assume $\sigma_{eff} = 12$ mb

The bbjj Subprocesses

- DPS processes:

$$b\bar{b} \otimes jj$$

$\otimes$ denotes the combination of one event for each of the two final states it connects

$$bb(j) \otimes jj \ , \ bbj \otimes (j)j \ , \ bbj \otimes j(j)$$
$$bb \otimes (j)jj \ , \ bb \otimes j(j)j \ , \ bb \otimes jj(j) \, ,$$

We also account for additional jets which are undetected (either soft or outside of accepted rapidity range)

- SPS processes:

$$b\bar{b}jj \, ,$$

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

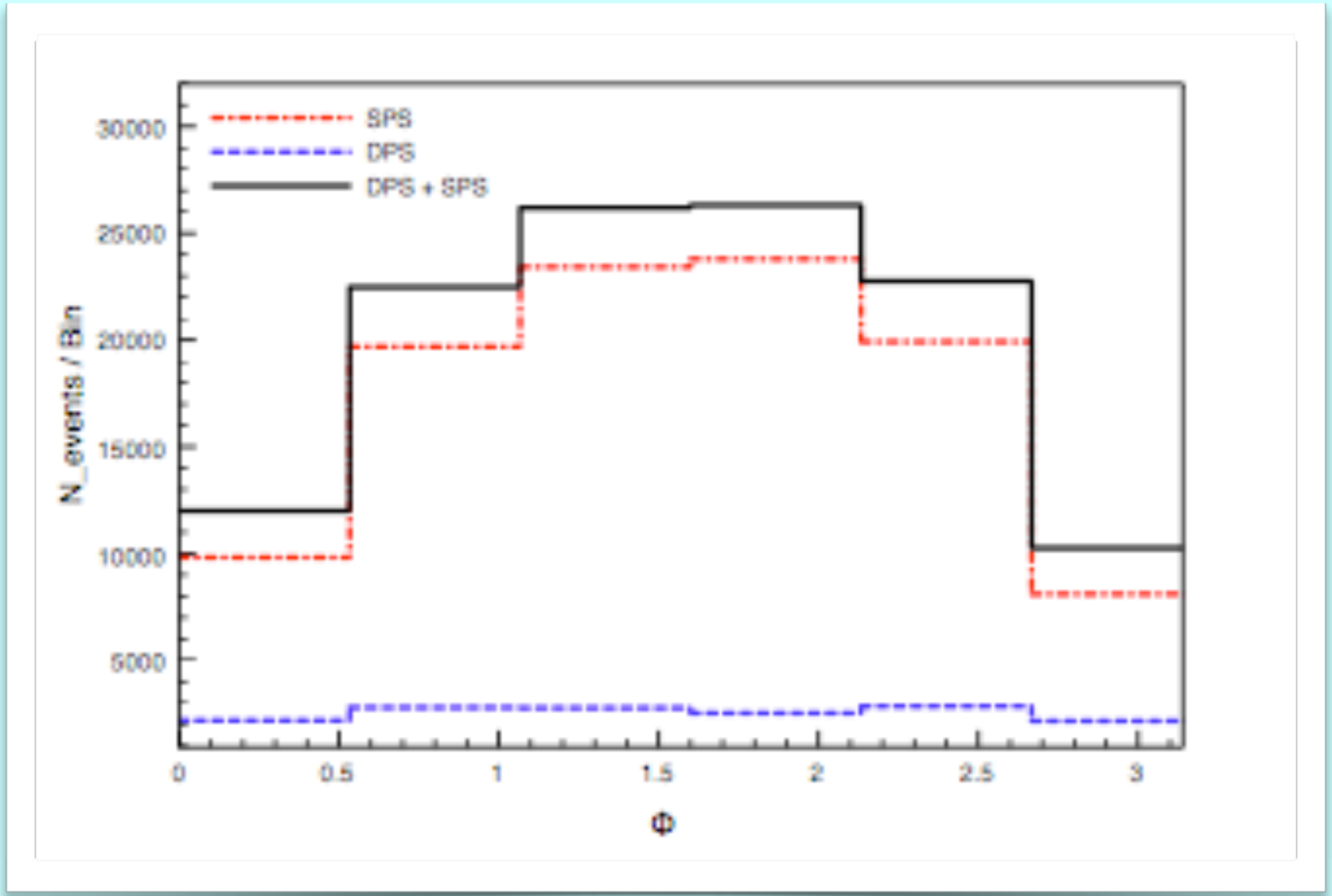
We also considered 4j and 5j final states where 2 j's fake b's

- Use CTEQ6L1 PDFs and a "dynamic" renormalization/factorization scale:

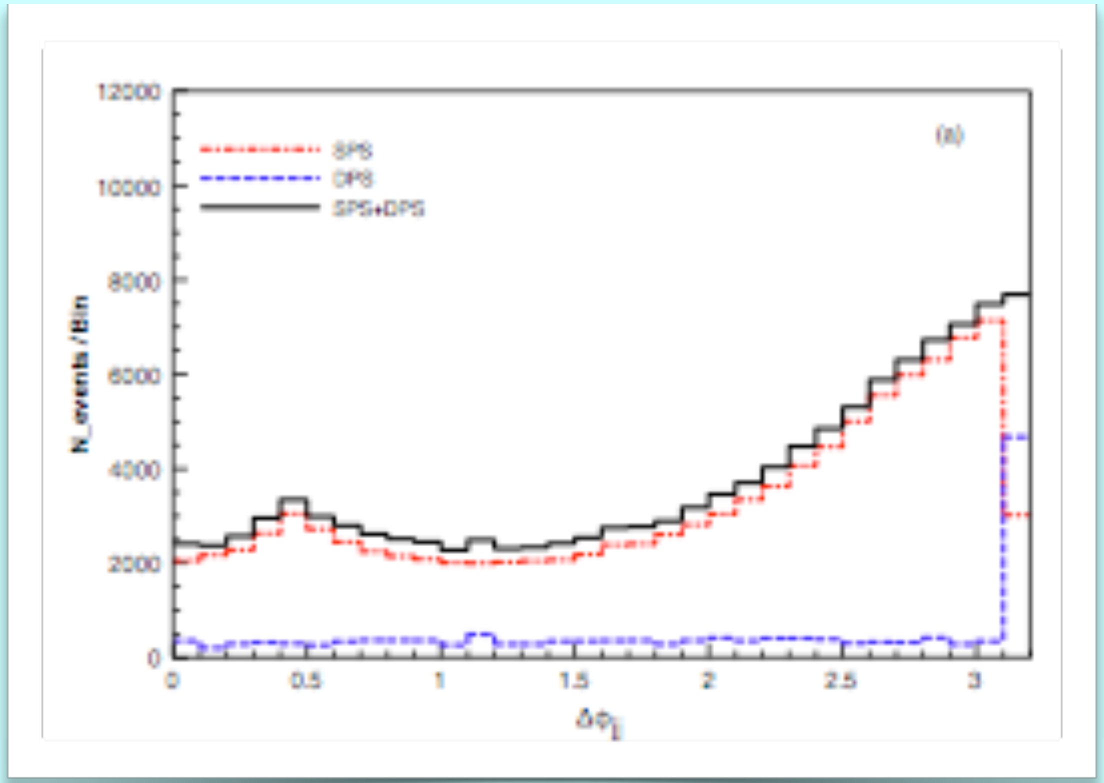
$$\mu^2 = \sum_i p_{T,i}^2 + m_i^2 \, ,$$

A Check on Our DPS Results

- Must check that we are generating DPS in an uncorrelated manner
- Study angle between plane defined by bb system and plane defined by jj system
- For truly uncorrelated scatterings, the DPS angle should be flat
- However, there are many diagrams which contribute to SPS s.t. some correlation between the two planes is expected

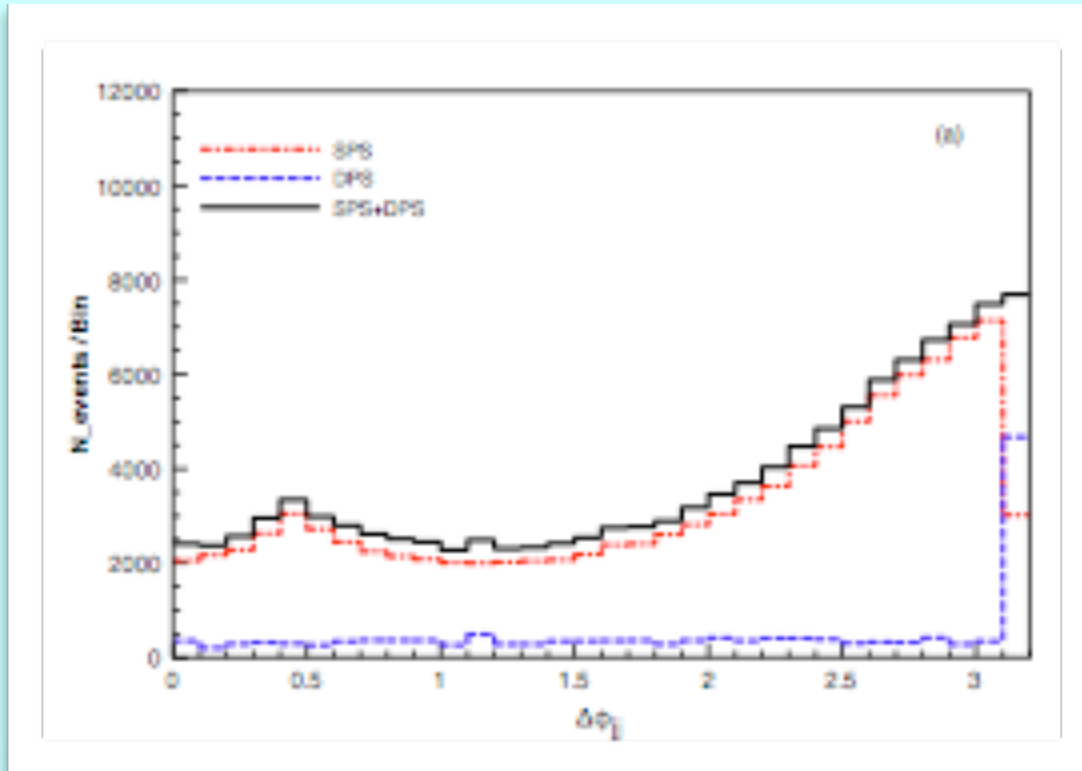


Angular Distributions



- Back-to-back nature of DPS events... azimuthal angle between pairs should peak near ≈ π
- Radiation of additional (undetected) jets should produce smearing of this peak
- Secondary peak from gluon splitting which produces nearly collinear jets
- Suppression at small Δϕ due to ΔR cut

Angular Distributions

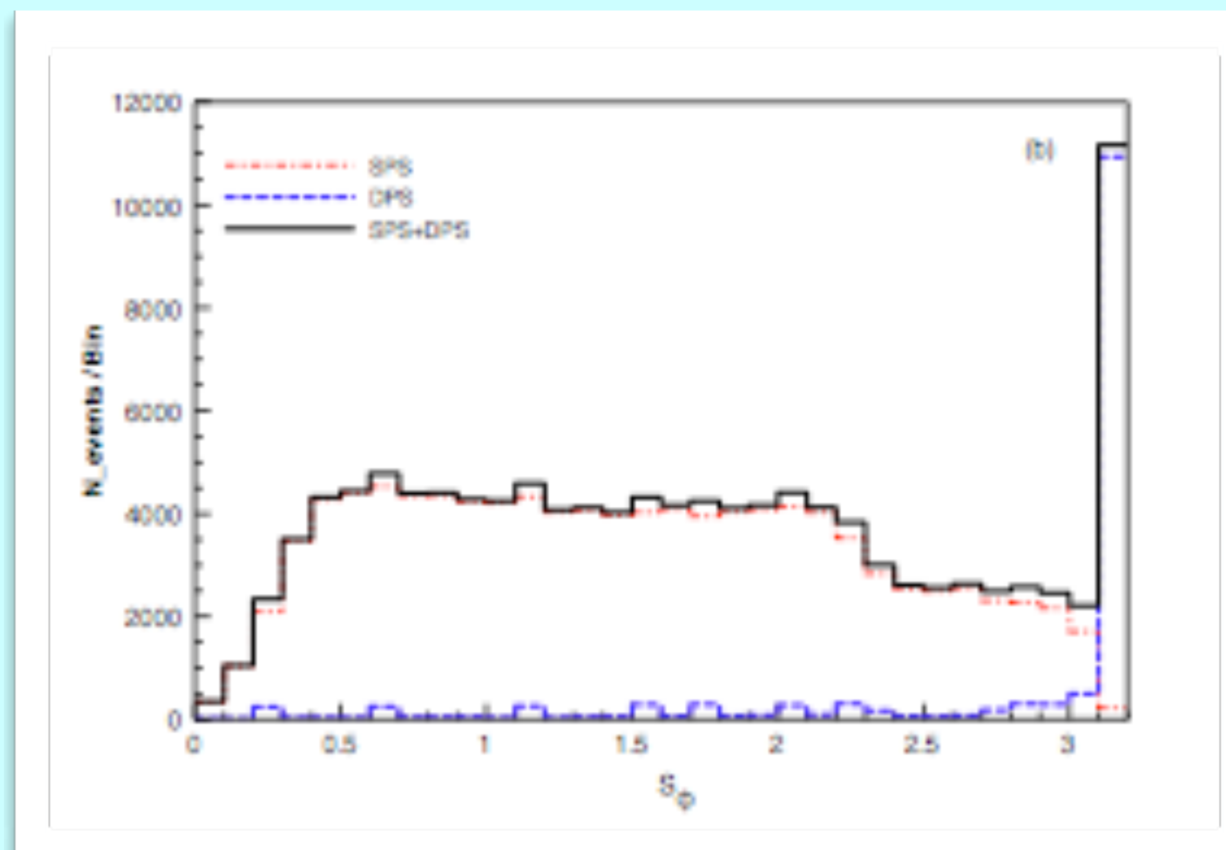


- Back-to-back nature of DPS events… azimuthal angle between pairs should peak near ≈ π
- Radiation of additional (undetected) jets should produce smearing of this peak
- Secondary peak from gluon splitting which produces nearly collinear jets
- Suppression at small Δϕ due to ΔR cut

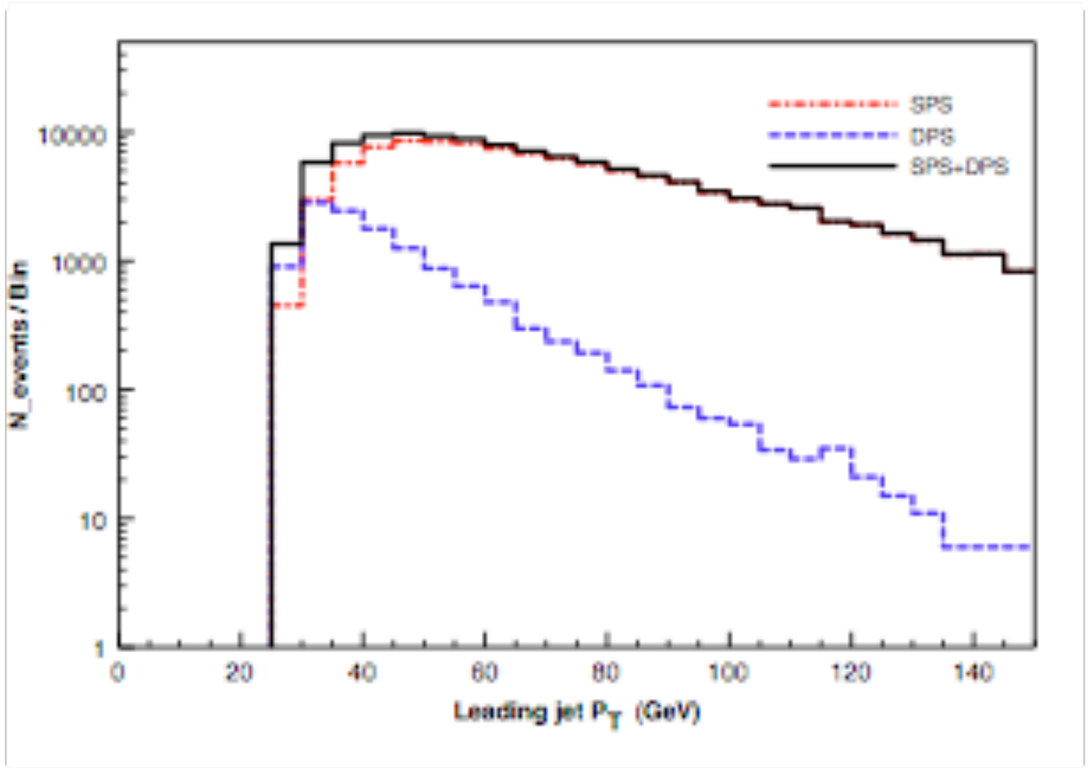
- Use information from bb AND jj systems:

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

- SPS events uniformly distributed
- Combining info. from both bb AND jj systems shows that DPS produces a sharp peak at $S_\phi \approx \pi$ which is well-separated from the total sample!

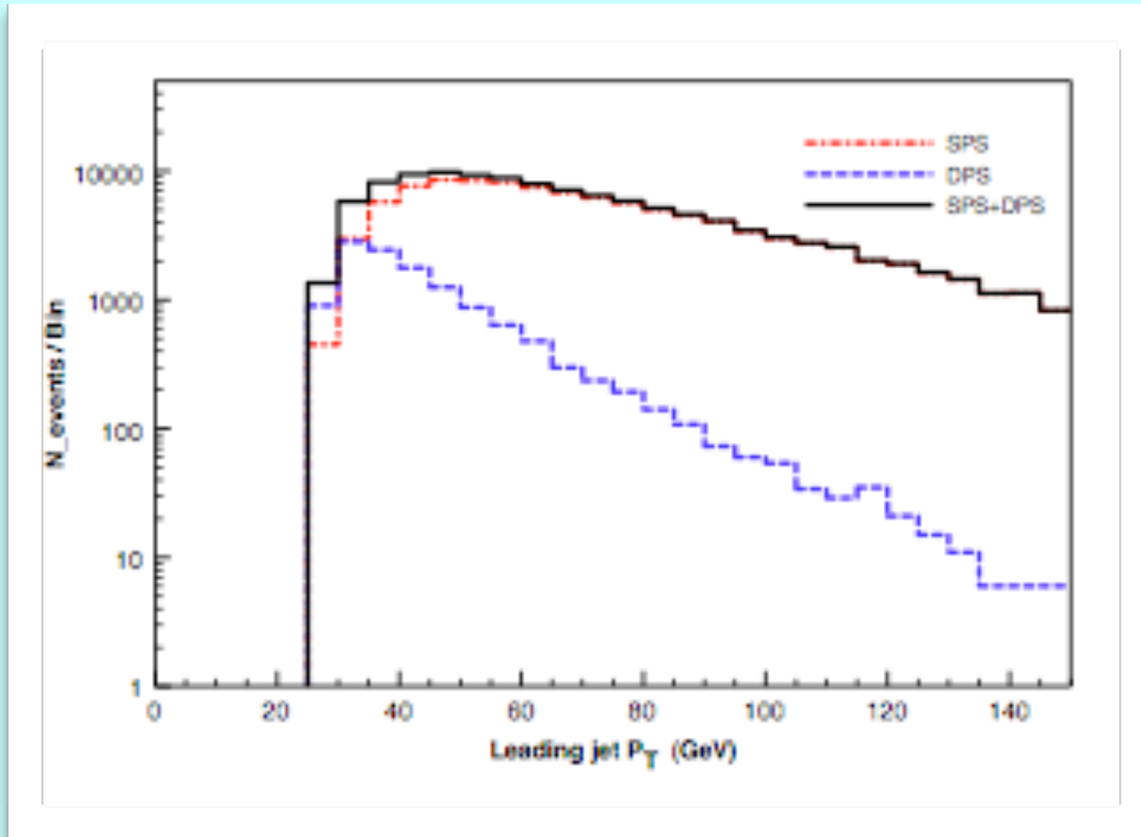


p_T Distributions



- p_T of leading jet (either b or j)
- SPS produces much harder spectrum
- DPS produces softer spectrum (due to back-to-back nature)
- DPS can dominate at lower p_T's... with a cross-over which depends on σ_{eff}

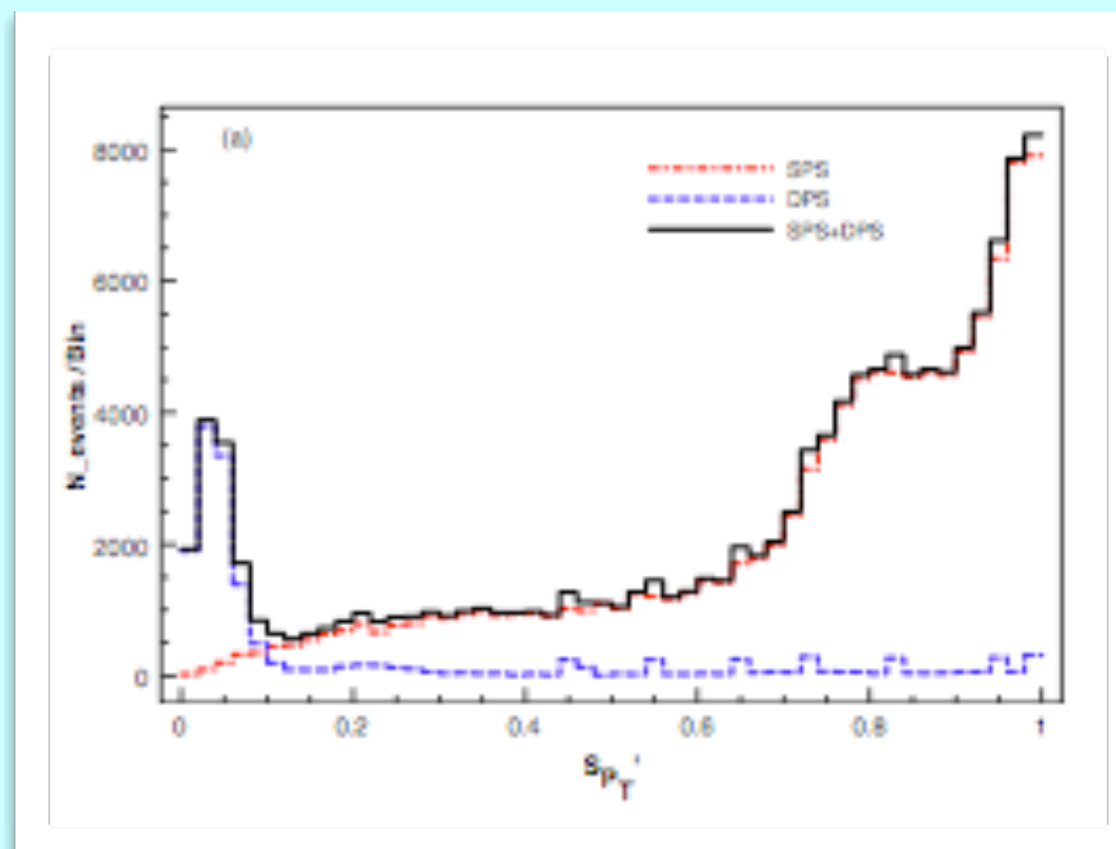
p_T Distributions



- p_T of leading jet (either b or j)
- SPS produces much harder spectrum
- DPS produces softer spectrum (due to back-to-back nature)
- DPS can dominate at lower p_T's... with a cross-over which depends on σ_{eff}

- Combining info. from both systems:

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

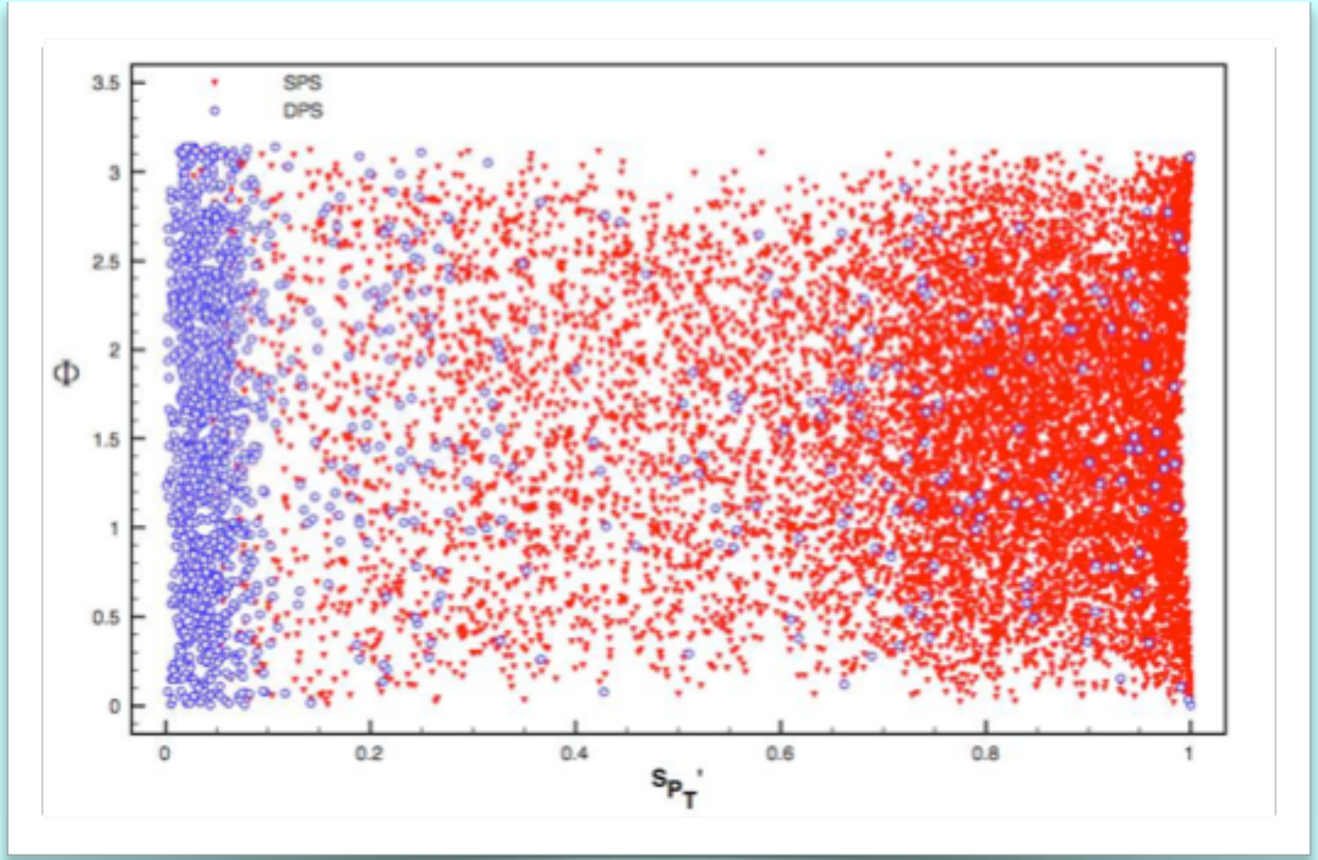


- SPS events tend to be far from back-to-back and lie at large values (gluon splitting?)
- DPS events produce a pronounced peak which is well-separated

Two-dimensional Distributions

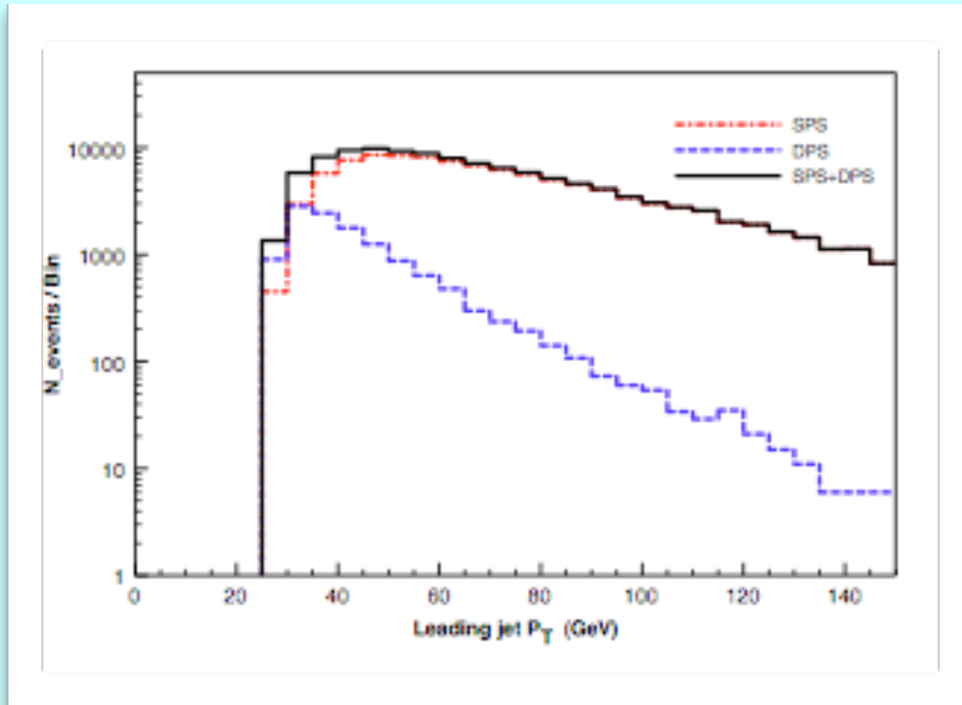
- Also looked at 2-d distributions to see if there is a clearer separation
- We examined plots involving two of Φ, S_ϕ, $\Delta\phi$ and $S_{pT'}$
- Strong correlations evident in many of the distributions

- DPS events are uniformly distributed in Φ and peak near $S_{pT'} = 0$
- SPS events show ~ sinΦ character
- Valley of low density between $S_{pT'} = 0.1 - 0.4$

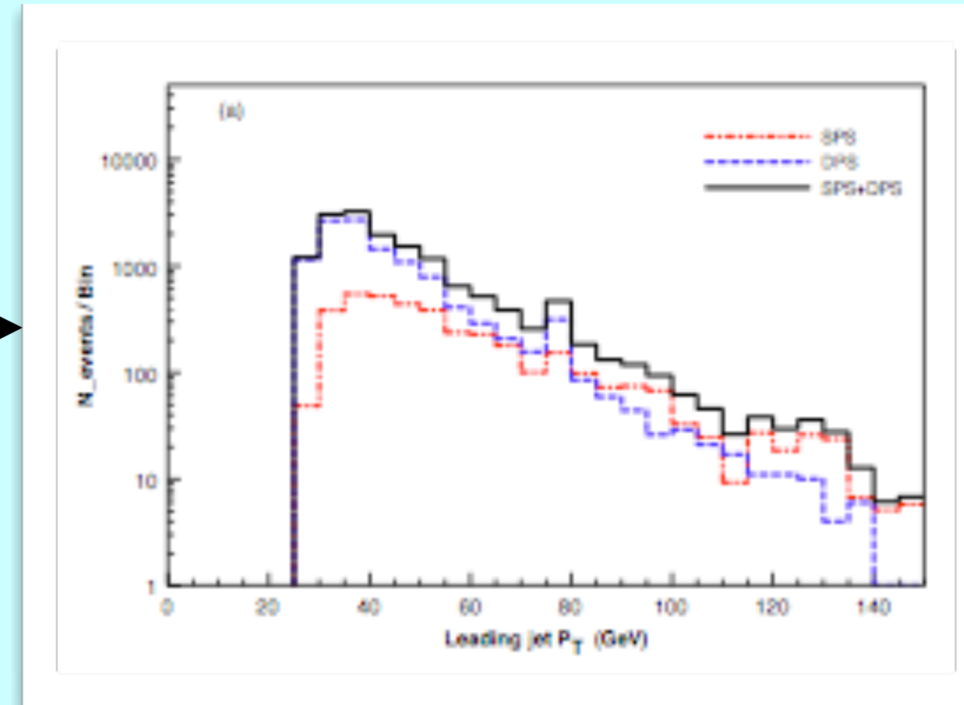


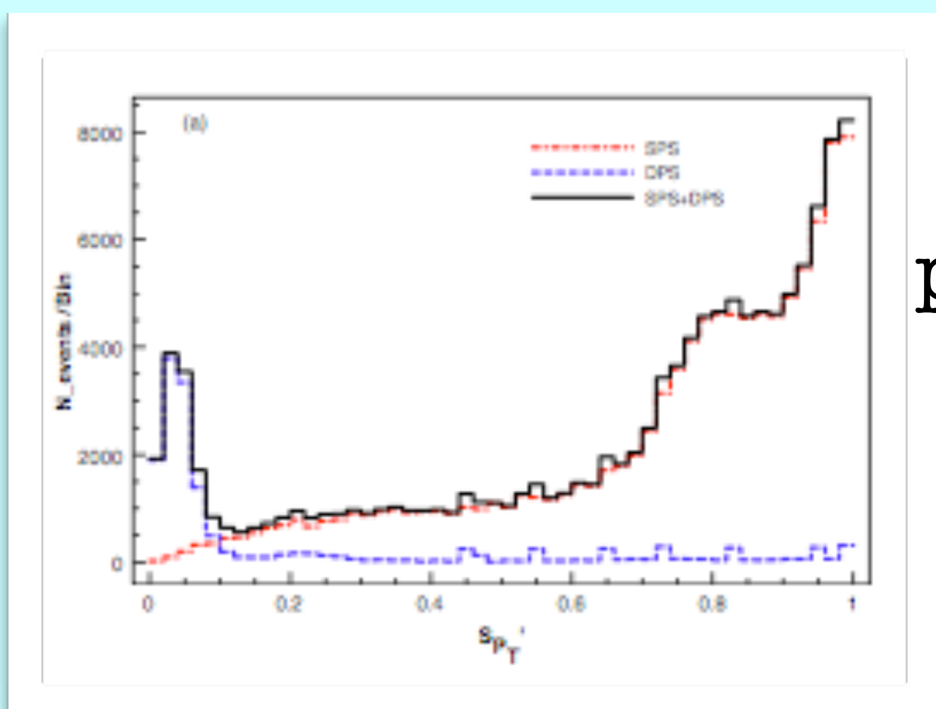
- In reality, shape of Φ distribution will take the form of the SPS
- However, by placing a cut on SpT' of 0.1 or 0.2, the Φ distribution should be flat... a clear signal of DPS!

Cutting on $p_T(j1)$ and $S_{pT'}$

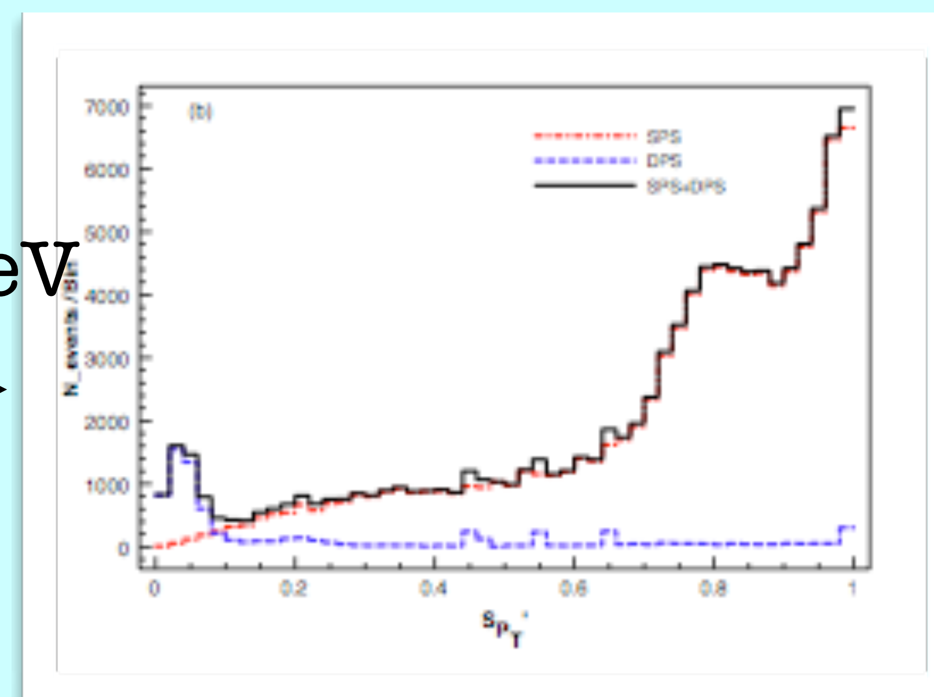


$S_{pT'} < 0.2$





pT(j1) > 40 GeV



DPS in 4 Light Jet Final State?

- Topologically the same as bbjj... but lose the "cleanness" from b tagging
- Fortunately, the dijet rate is MUCH LARGER than bb production... LARGE RATE for DPS!!!
- DPS processes:

$$jj \otimes jj \;,\; b\bar{b} \otimes jj,$$

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

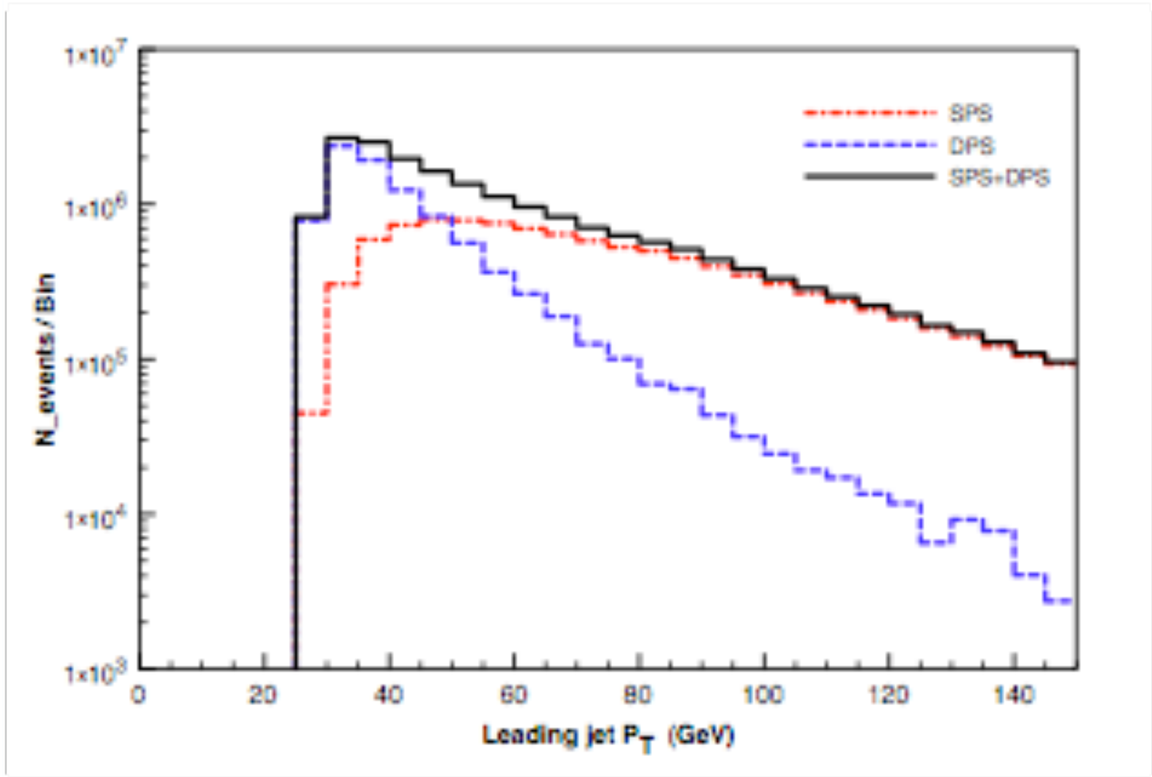
- SPS processes:

$$jjjj \;, b\bar{b}jj \,,$$

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

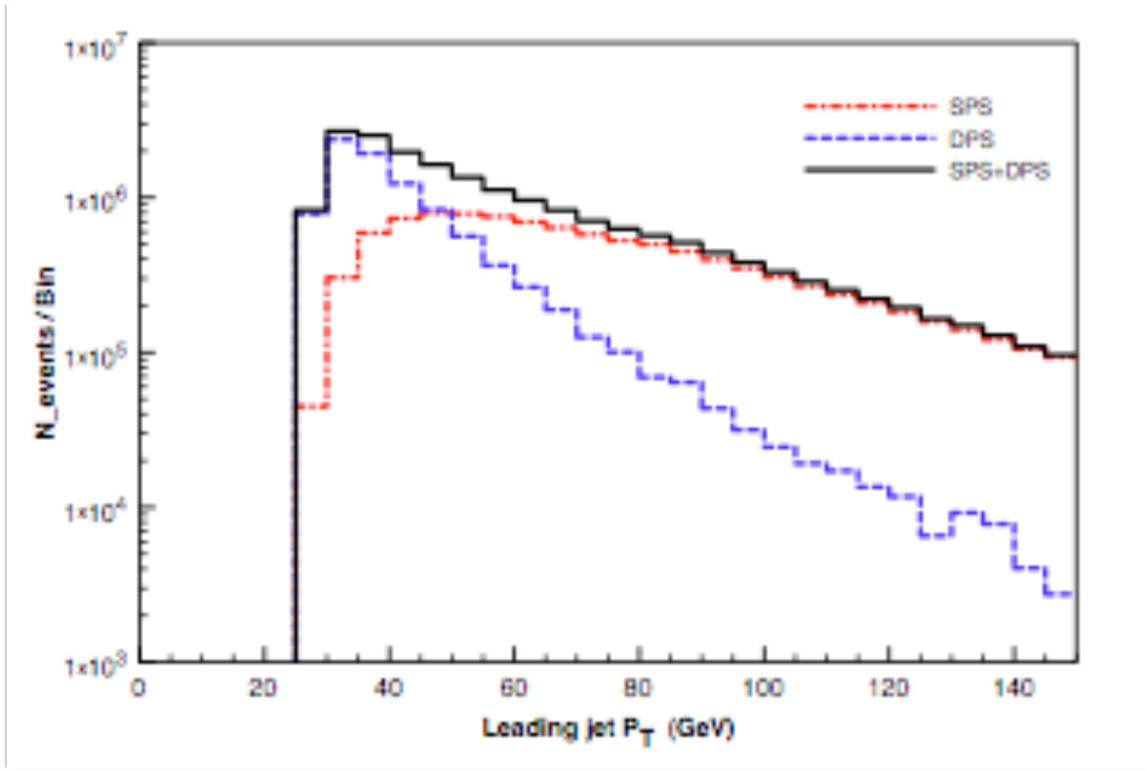
- Same acceptance cuts as before

p_T Distributions for 4j



- DPS exhibits much softer spectrum than SPS
- "Cross-over" between the two occurs around ~ 50 GeV or so... which is higher than the bbjj case (~ 30 GeV)

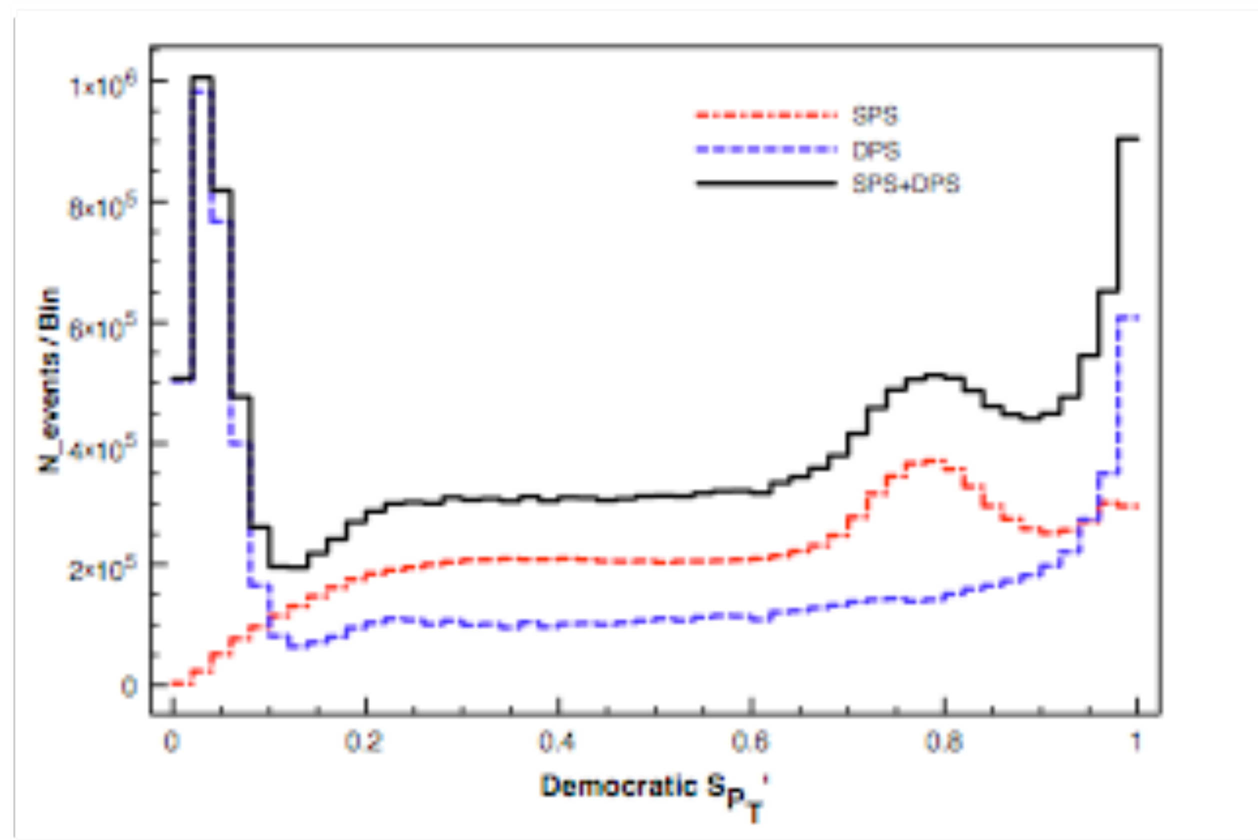
p_T Distributions for 4j



- DPS exhibits much softer spectrum than SPS
- "Cross-over" between the two occurs around ~ 50 GeV or so... which is higher than the bbjj case (~ 30 GeV)

$$S'_{p_T} = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{|p_T(j_a, j_b)|}{|p_T(j_a)| + |p_T(j_b)|}\right)^2 + \left(\frac{|p_T(j_c, j_d)|}{|p_T(j_c)| + |p_T(j_d)|}\right)^2}.$$

- How to choose pairs?
  In bbjj, b tags removed degeneracy.
- Democratic $S_{pT'}$
- Sum over all pairings and divide by 3 (one correct, two incorrect)



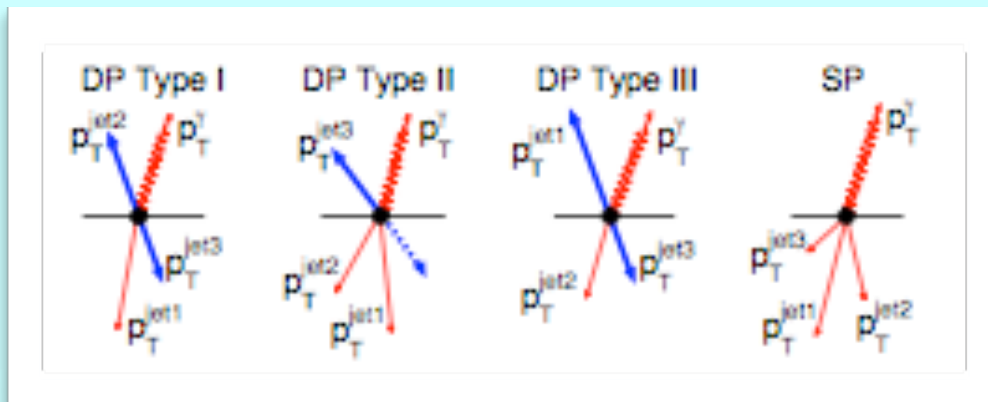
conclusions

- Double parton scattering can play an important role in QCD studies (underlying event, PDFs, etc.)... as well as the discovery of new physics and/or Higgs boson(s)
- It's real! DPS has been observed at the Tevatron and σ_{eff} has been measured (CDF and D0)
- Process independent? Scales with c.o.m energy? Need a measurement of σ_{eff}... and EARLY!!!
- Then, we can make confident predictions for backgrounds to NP and/or Higgs backgrounds
- We investigated the feasibility of using bottom quark pair production w/ dijets in order to measure σ_{eff} at the LHC
- The "usual" distributions (pT, invariant masses, etc.) don't show clear separation between DPS and SPS
- However, by using information from BOTH the bb AND jj systems, a clean separation between DPS and SPS can be made!
- Measurements in the 4 jet channel are also possible (thanks to large rates)
- Objective: provide a methodology for identifying and measuring the properties of DPS at the LHC
- "To do" list: inclusion of NLO corrections, more sophisticated "joint probabilities", etc.

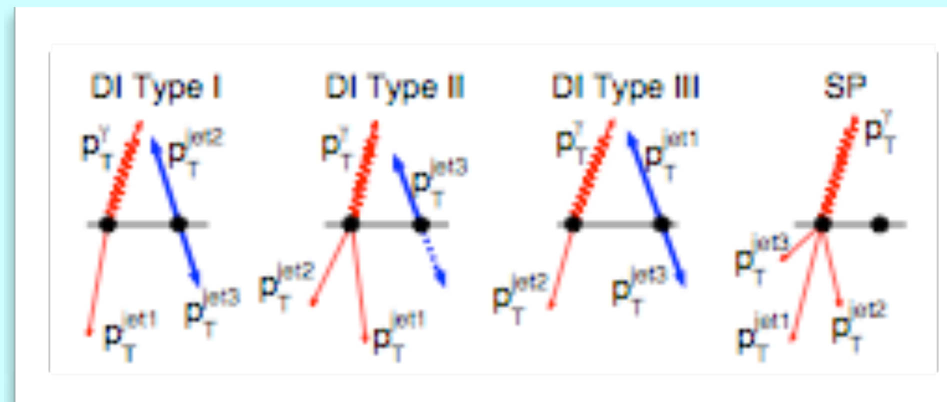
Backup Slides

Measurement of DPS @ D0

- Previous 4 jet measurements made use of theory/MC's (large uncertainties)
- γ + 3 jet measurements (CDF and D0) used a new technique... one which only uses quantities determined from data
- σ_{eff} extracted by comparing number of events produced in DPS interactions to those produced in "Double Interaction" (DI) events



$$N_{DP} = \frac{\sigma^{\gamma j}}{\sigma_{eff}} \frac{\sigma^{jj}}{\sigma_{hard}} N_{1coll}\, \epsilon_{DP}\, \epsilon_{1vtx}.$$



$$N_{DI} = 2\frac{\sigma^{\gamma j}}{\sigma_{hard}} \frac{\sigma^{jj}}{\sigma_{hard}} N_{2coll}\, \epsilon_{DI}\, \epsilon_{2vtx}.$$

- Taking the ratio of NDP and NDI, solve for σ_{eff}:

$$\sigma_{eff} = \frac{N_{DI}}{N_{DP}} \frac{\varepsilon_{DP}}{\varepsilon_{DI}} R_c \sigma_{hard},$$

$$R_c \equiv (1/2)(N_{1coll}/N_{2coll})(\varepsilon_{1vtx}/\varepsilon_{2vtx}).$$

- Note: σ_{eff} is independent of theory+MC's values for γj and jj cross sections