Double Parton Scattering at the LHC

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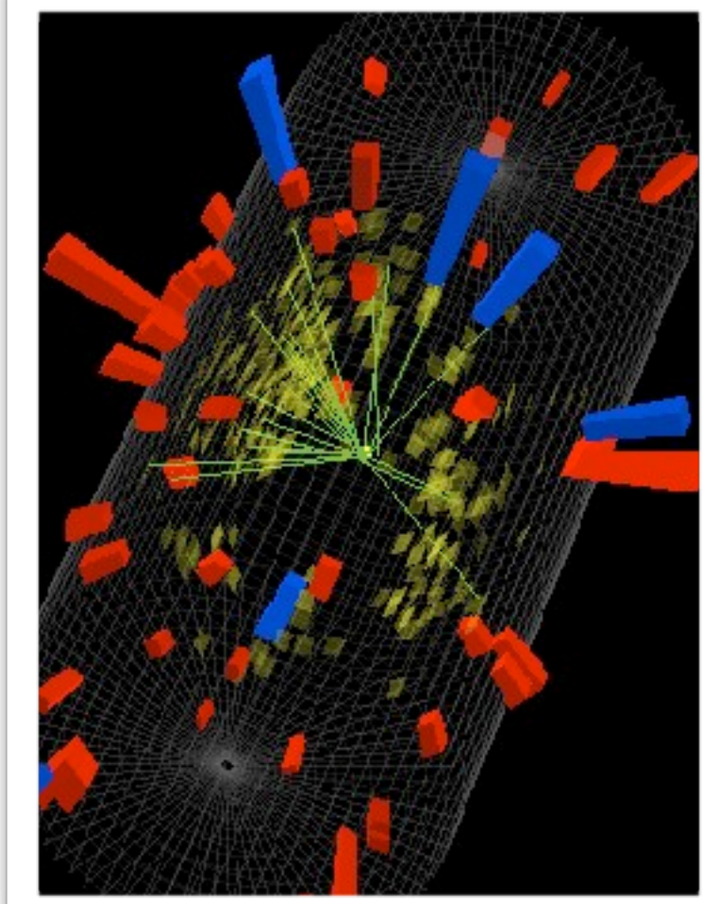
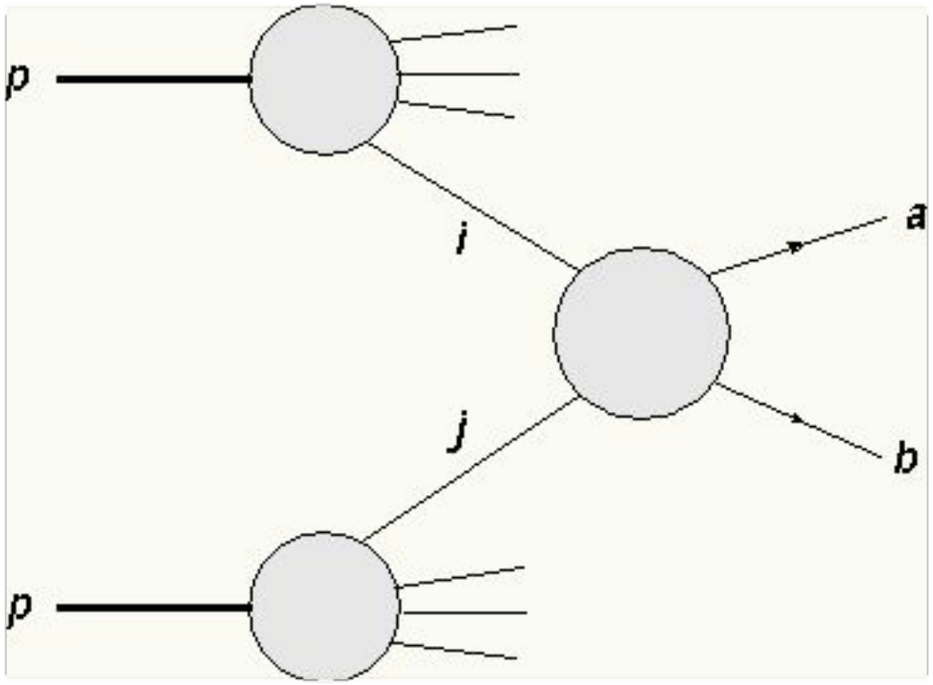
- What is Double Parton Scattering? (and why do we care?)
- Past studies (both theoretical and experimental)
- Double Parton Scattering at the LHC
- Case study: bottom quark pair production with two jets
- Conclude/outlook



(in collaboration with E. Berger and G. Shaughnessy, Phys. Rev. D81, 014014 (2010))

Theorist's view of pp Collisions



Single Parton Scattering (SPS)

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

(Non-perturbative) PDFs

(Perturbative) Partonic Cross Section

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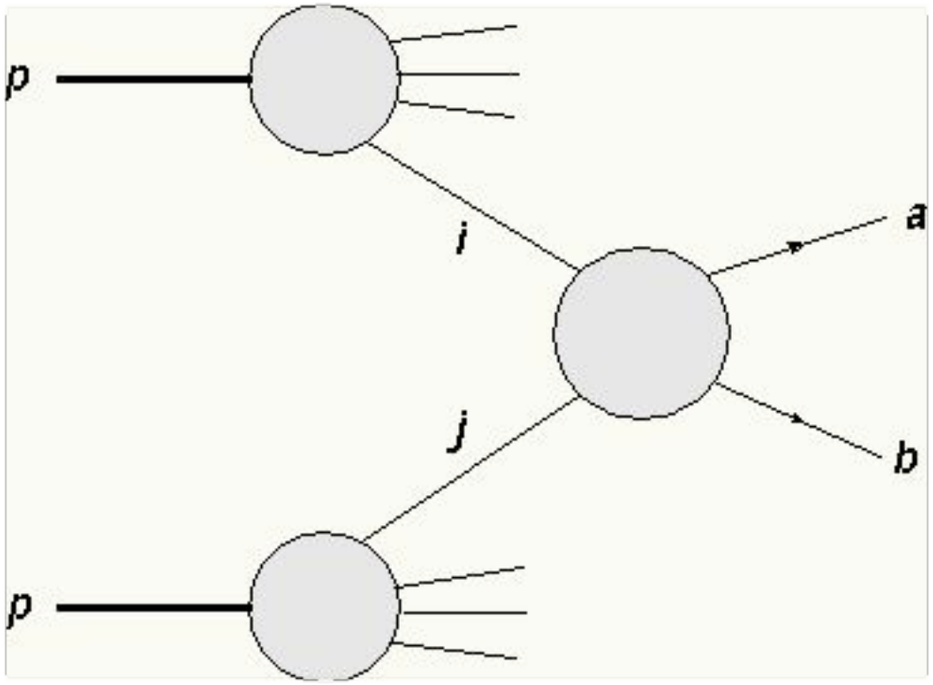

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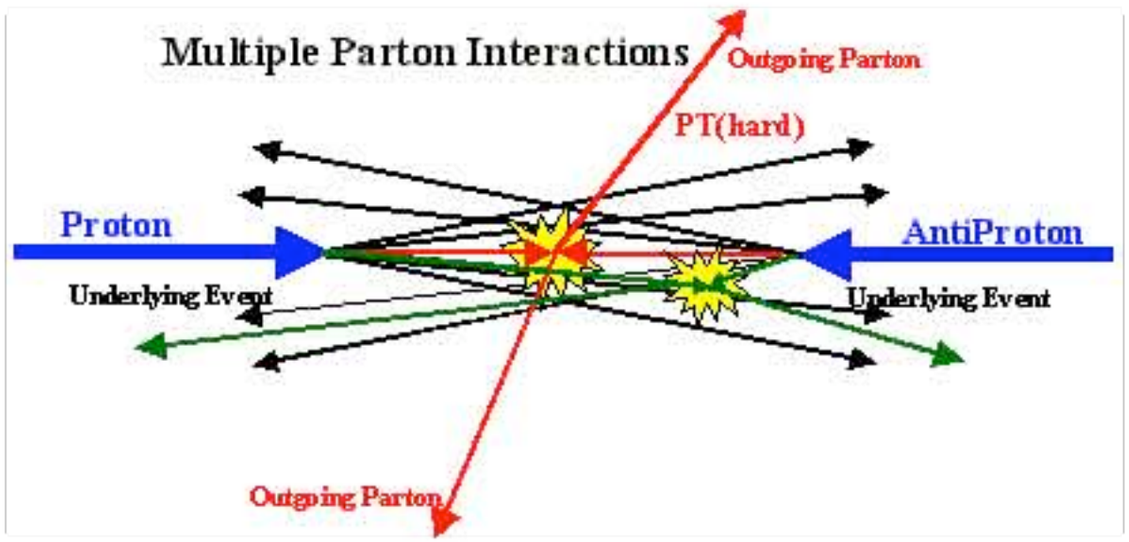
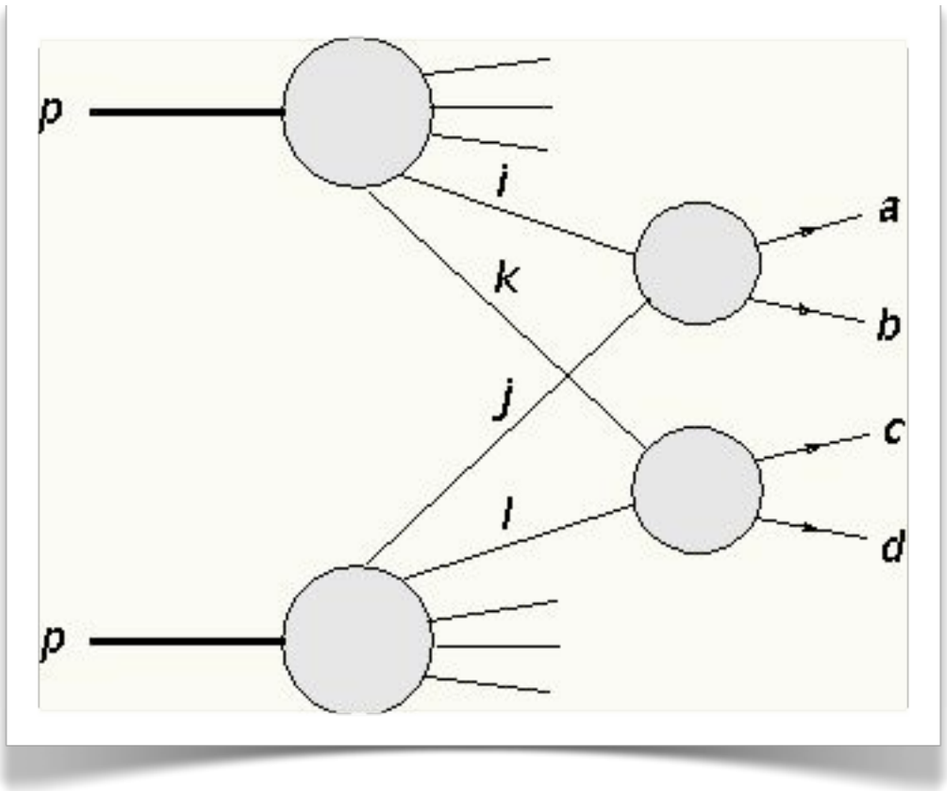
(Perturbative) Partonic Cross Section

"Reality"



Double Parton Scattering

- Two INDEPENDENT scatterings in ONE proton-proton scattering:



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 center-of-mass energy???
- Typical approach: ignore correlations in longitudinal momentum of partons...

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

- DPS cross section:

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

Past Studies of DPS

- Need a process with a large rate... and relatively "clean" signature (e.g., multi-jet plus a prompt photon)

- Most (if not all) experimental studies to day have focused on γ + 3 jets:

$$pp \to \gamma j \otimes pp \to jj$$

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Measurement of Double Parton Scattering in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

Double parton interactions in $\gamma + 3$ jet events in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV in DØ

The DØ Collaboration
URL: *http://www-d0.fnal.gov*
(Dated: April 24, 2009)

- Measurements of σ_{eff}:

$$\sigma_{eff} = \begin{array}{l} 14.5 \pm 1.7 \text{ mb [CDF]} \\ 15.1 \pm 1.9 \text{ mb [D0]} \end{array}$$

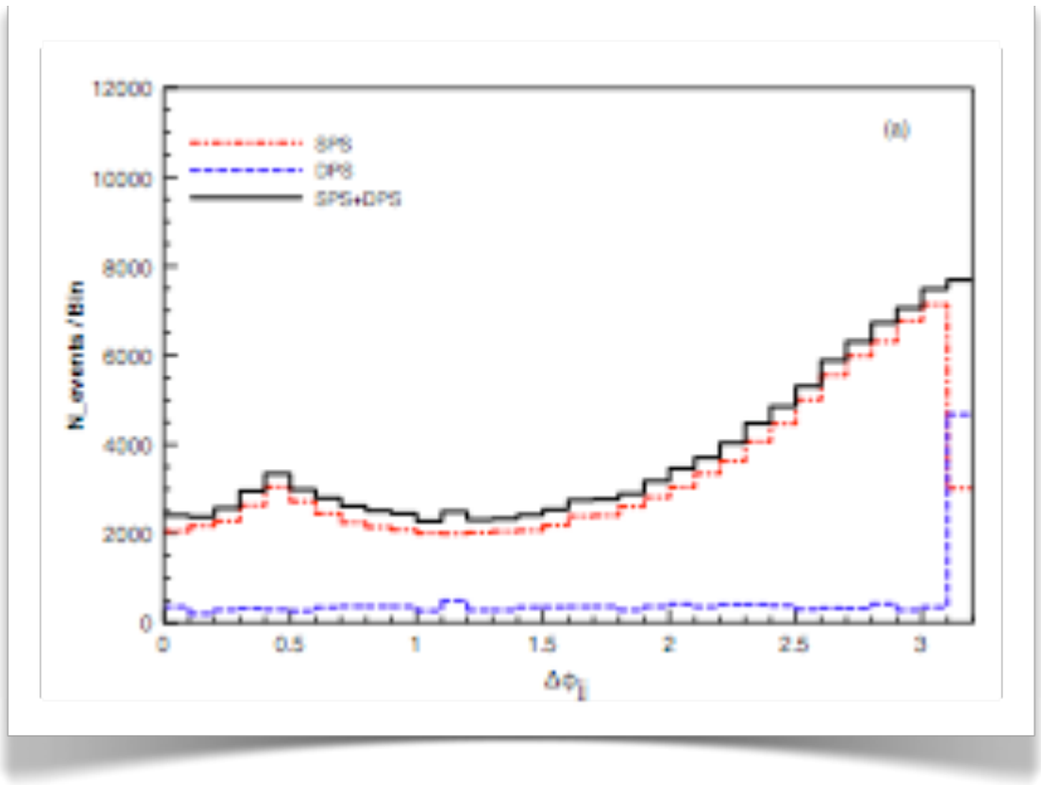
DPS at the LHC

- 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 predictions 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 (Kulesza and Sterling)
- Bottom quark pair production with two jets (E. Berger, CJ and G. Shaughnessy)
  - LARGE (QCD) RATES over a large kinematic range
  - b-tagging provides a relatively CLEAN SIGNAL
  - (Relatively) unambiguous which jets go with which other jets

$$pp \to bb \otimes pp \to jj$$

  - Focused on $\sqrt{s}$ = 10 TeV and σ_{eff} = 12 mb

Angular Distributions for bbjj



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

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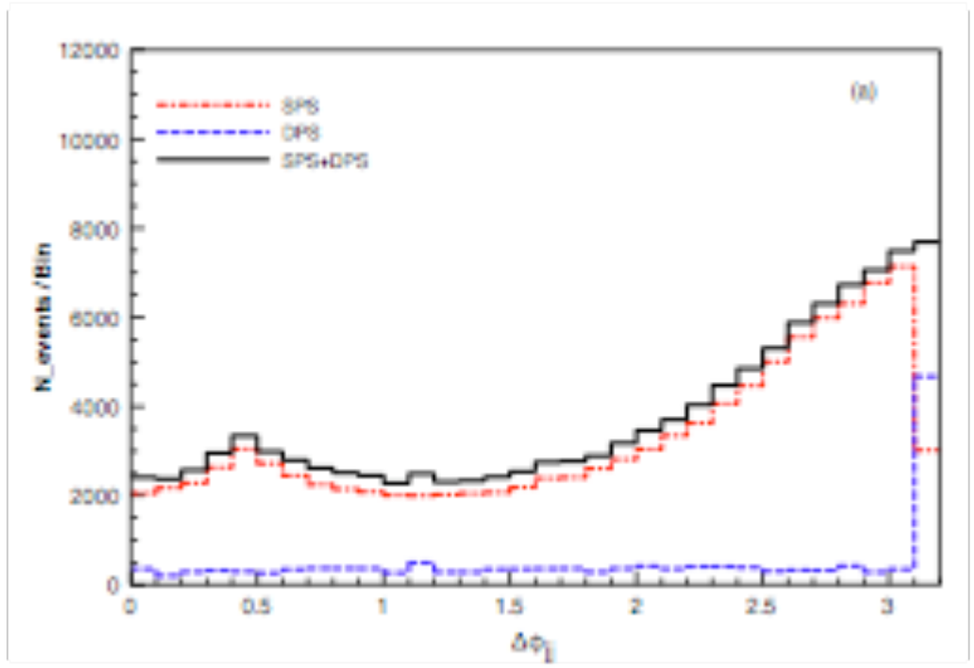

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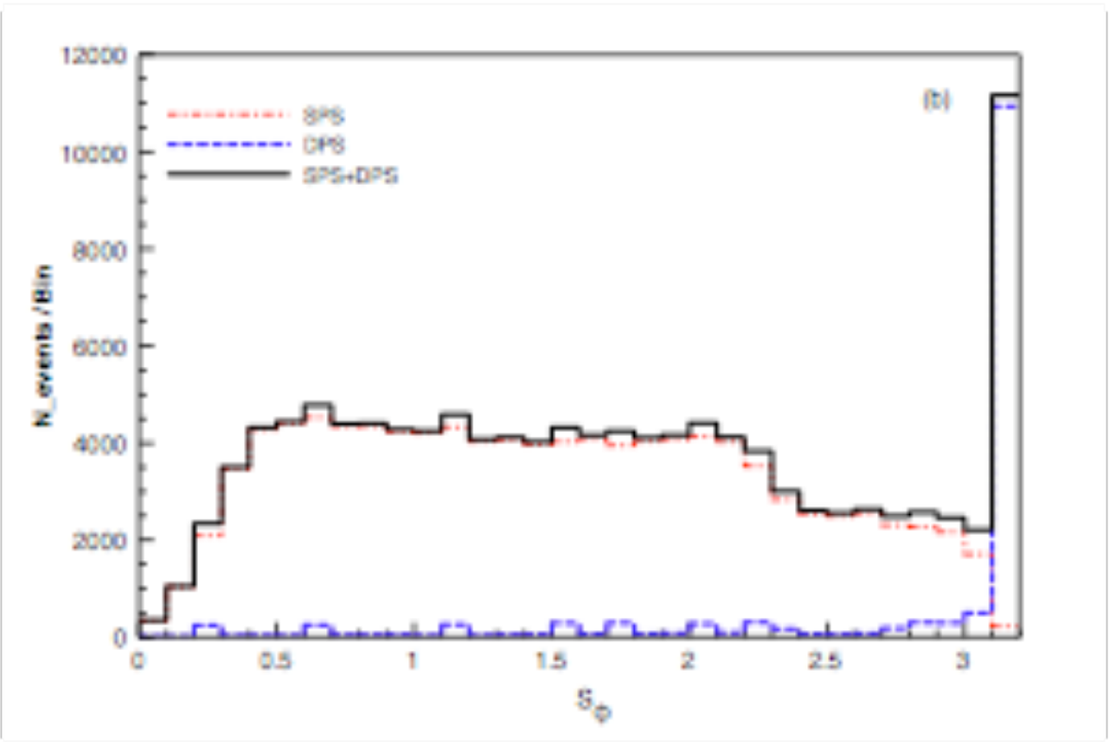
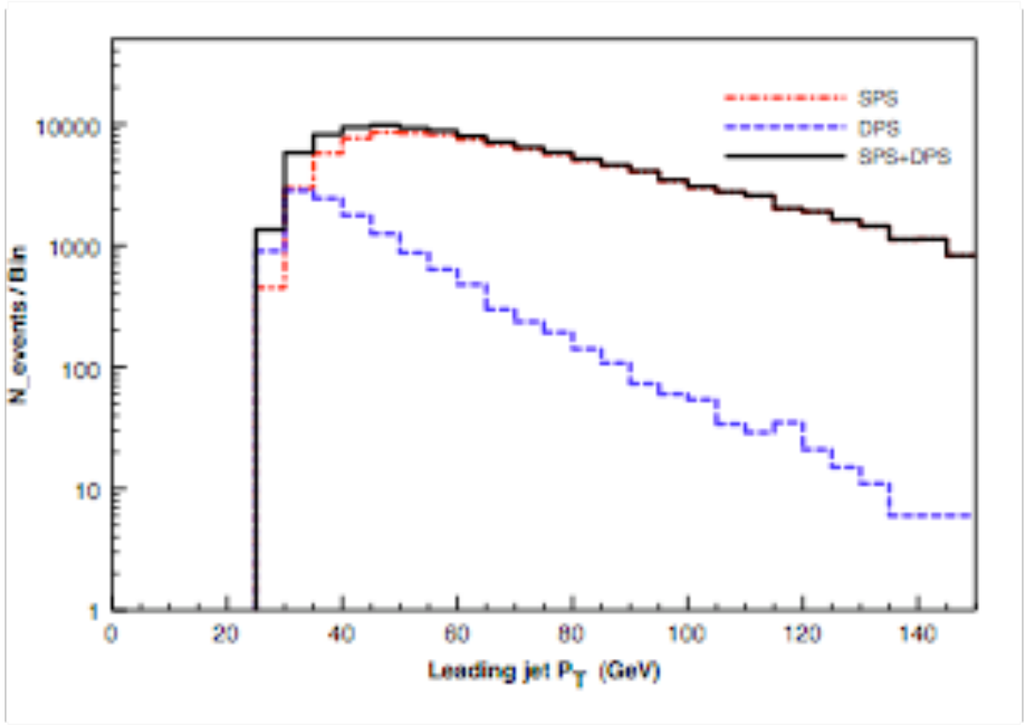
- Use information from bb AND jj systems:

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

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



p_T Distributions for bbjj



- 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}

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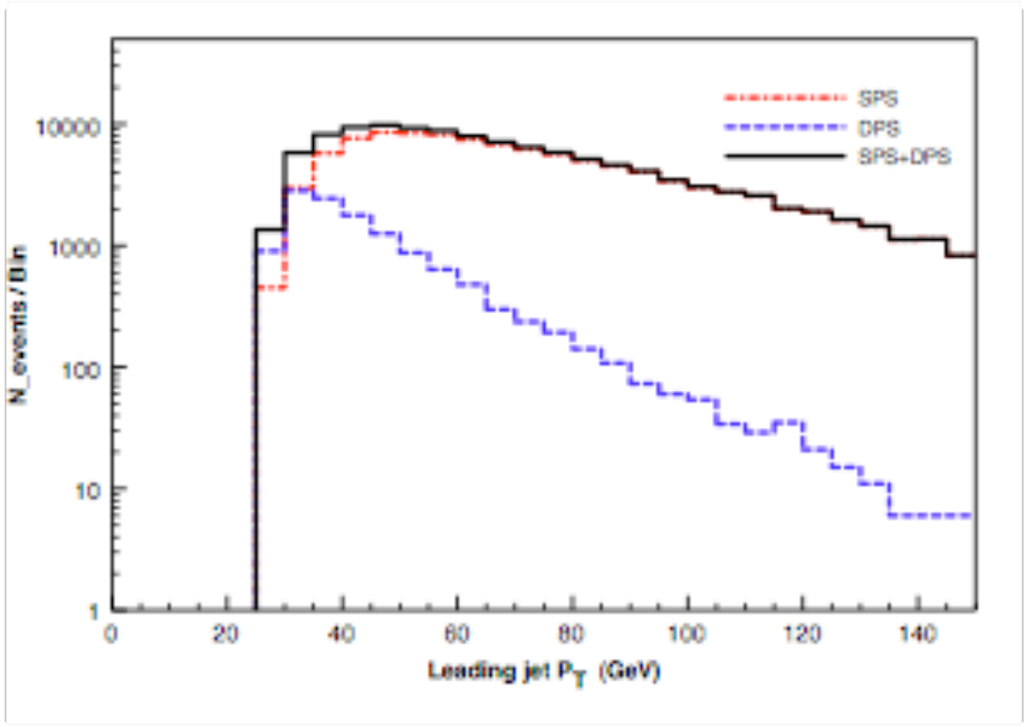

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- SPS produces much harder spectrum
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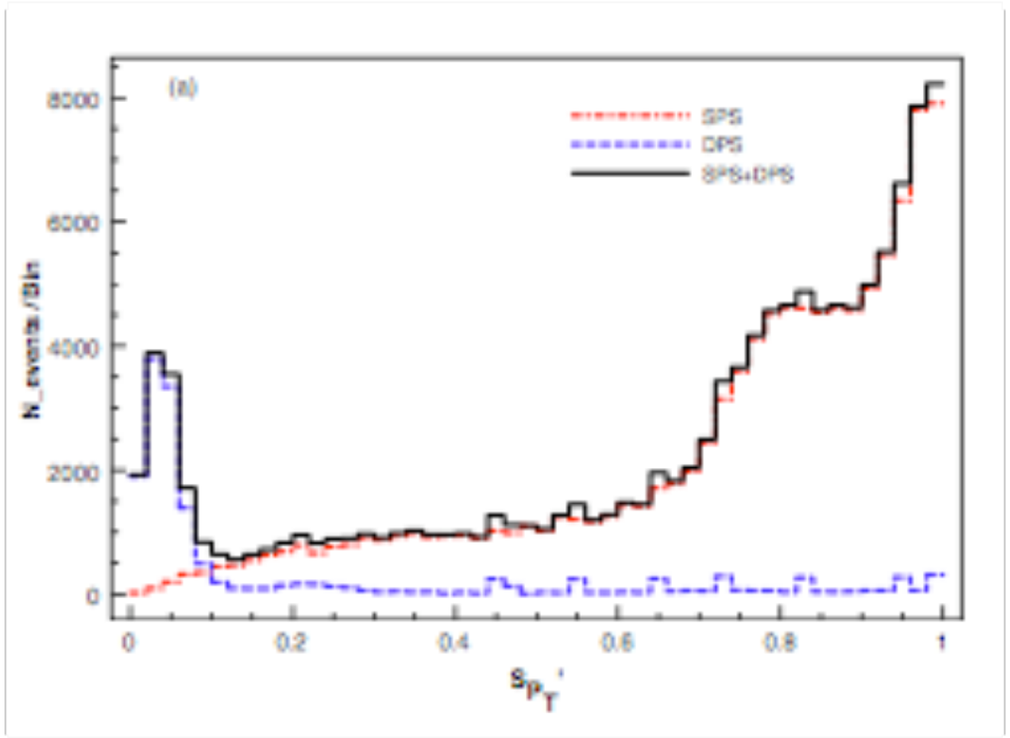
- DPS can dominate at lower p_T's... with a cross-over which depends on σ_{eff}

- 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



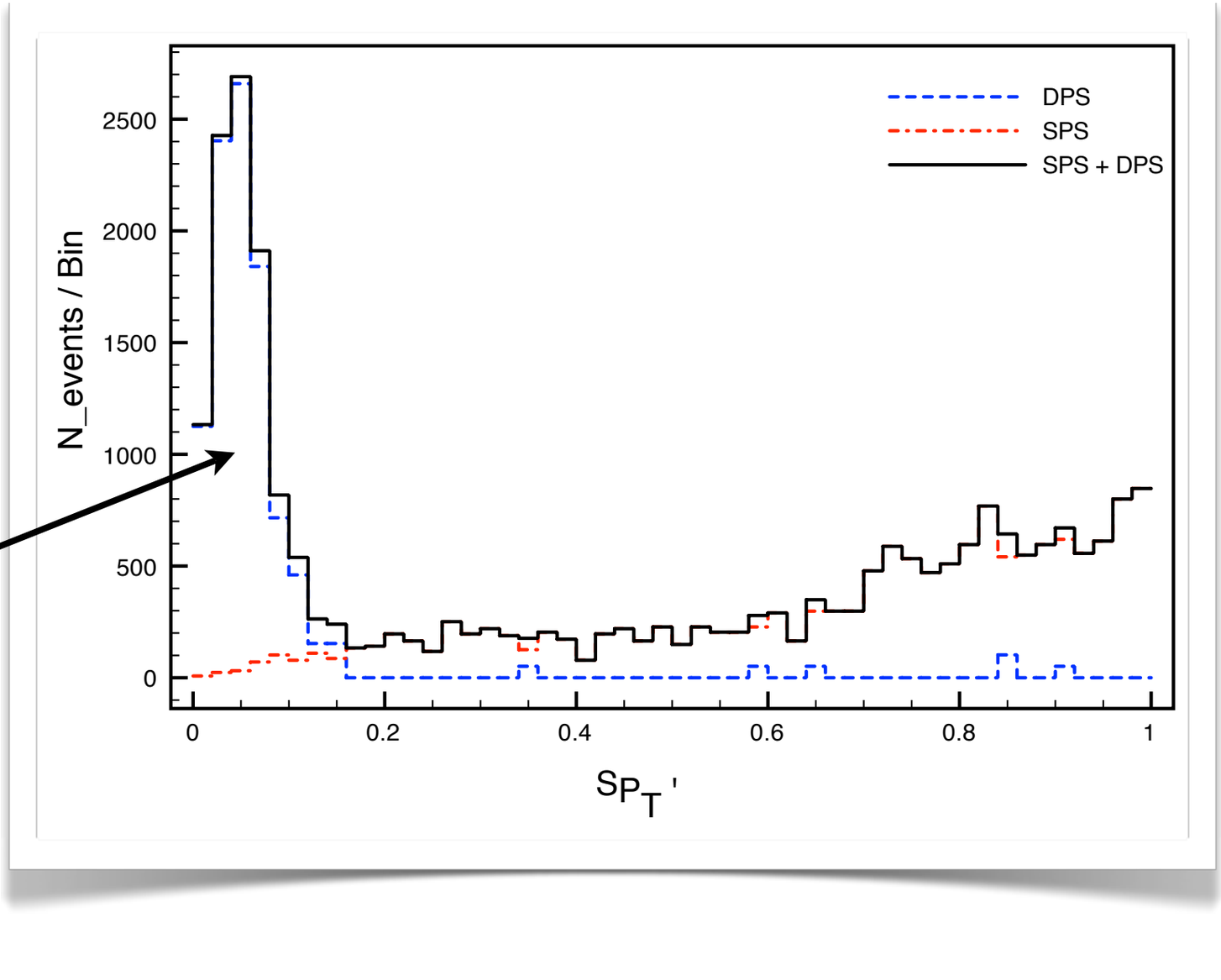
DPS at the EARLY LHC!

- Preliminary results for the "early days" at the LHC:

$$\sqrt{s} = 7\ \text{TeV}$$

$$L = 400\ \text{nb}^{-1}$$

- DPS peak!



Conclusions/Outlook

- Double parton scattering can play an important role in QCD studies (underlying event, PDFs, etc.)... as well as NP and/or Higgs searches!
- It's real! DPS has been observed at the Tevatron and σ_{eff} has been measured
- Process dependent? Scales with c.o.m. energy? Need a measurement of σ_{eff} at the LHC... and early!
- We propose using bb + dijets:
  - LARGE RATES
  - CLEAN SIGNAL (due to b-tagging)
- Separation of SPS and DPS possible with variables which take into account information from the ENTIRE final state
- To do list:
  - Inclusion of NLO corrections
  - More sophisticated "joint probabilities"

Back-up Slides

(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!!!

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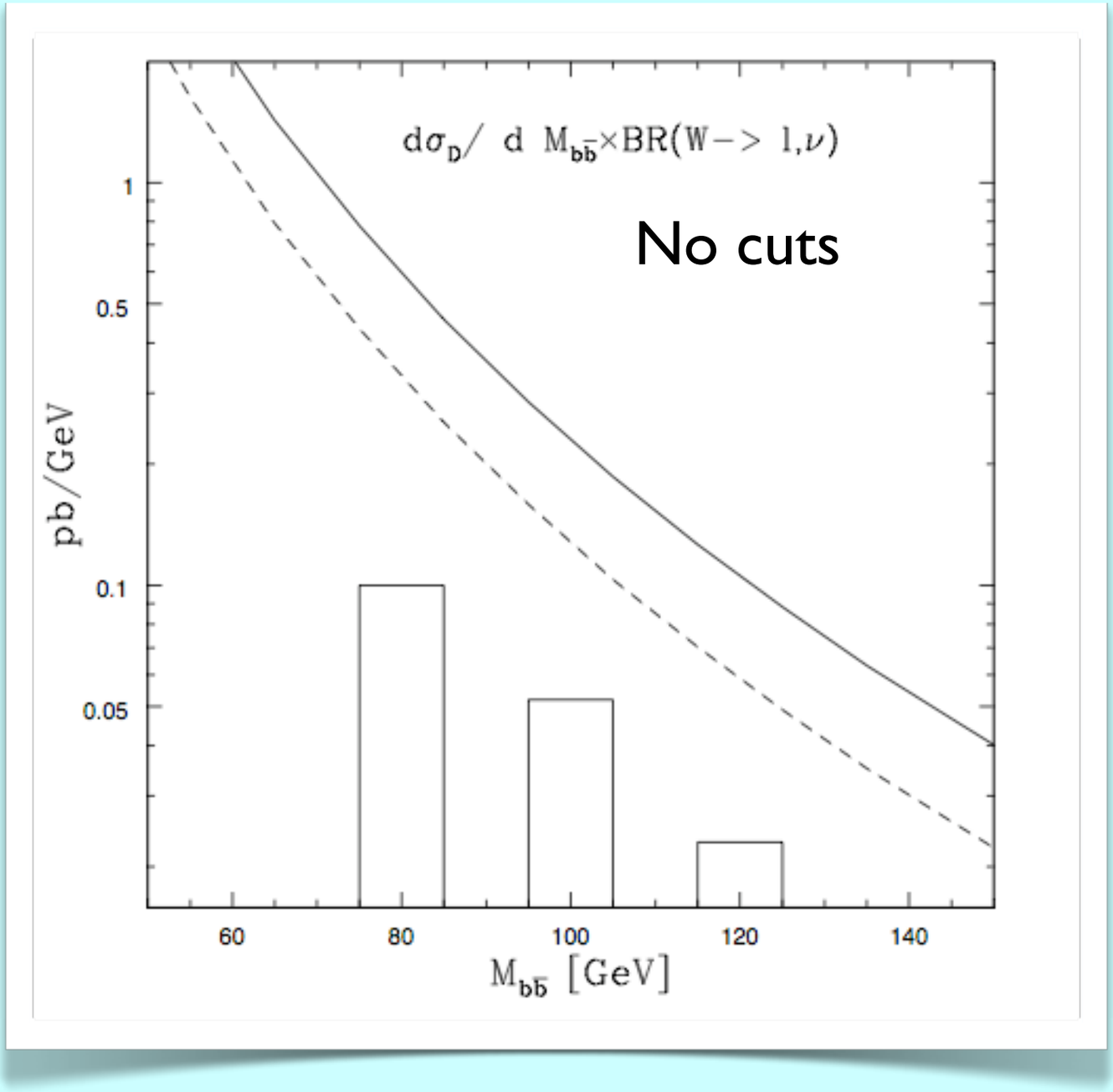
- Consider bb invariant mass distribution for M_h = 80, 100, 120 GeV



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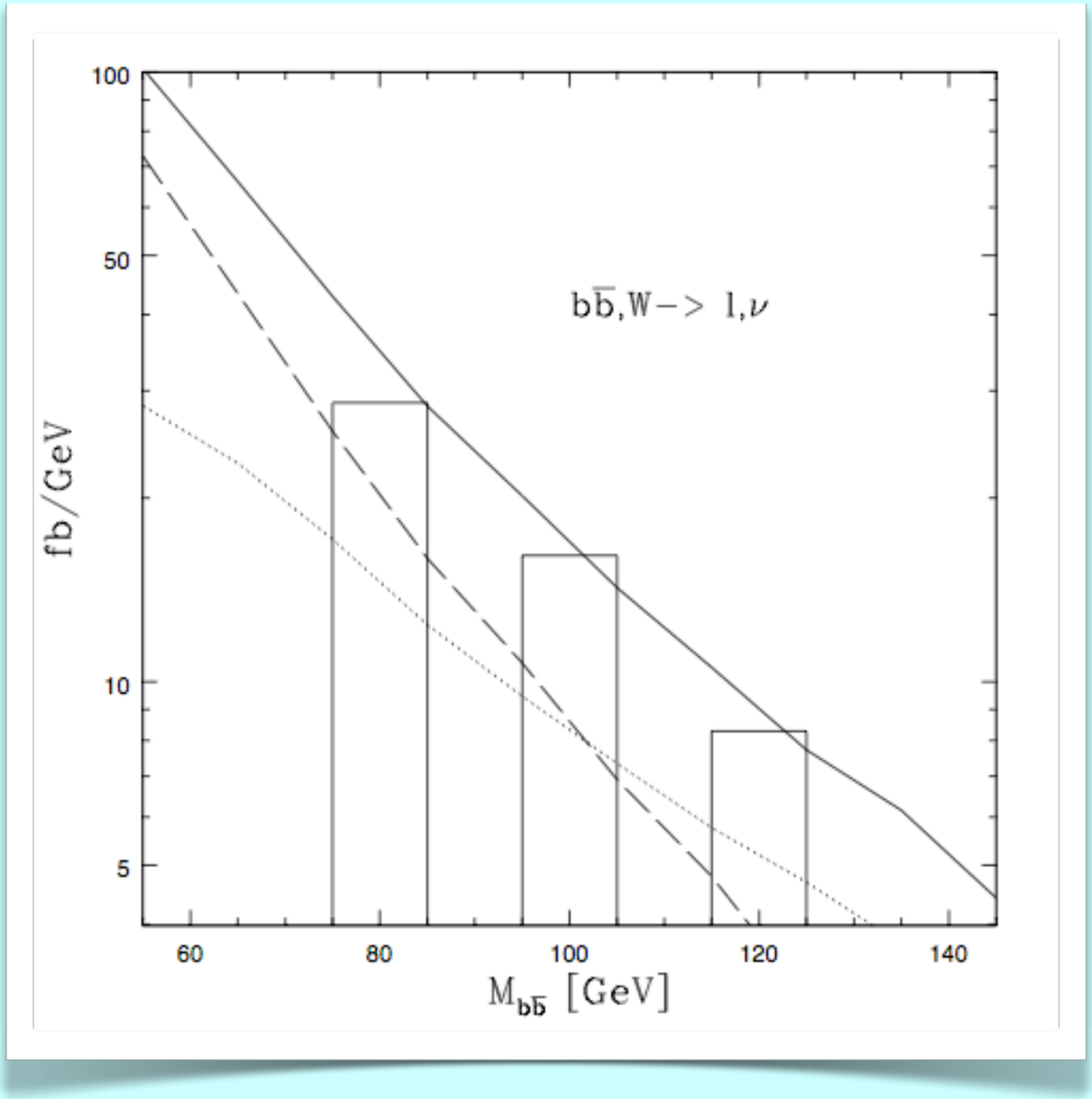
- Naively, σ_{DPS} is small... but $\sigma_{SPS}(bb)$ and $\sigma_{SPS}(W)$ are HUGE!!!
- Consider bb invariant mass distribution for M_h = 80, 100, 120 GeV
- Acceptance cuts:

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

Study of bbjj at the LHC

- Basic strategy:
  - Produce DPS ($4 \rightarrow 4$) events using Madgraph/Madevent
  - Produce SPS ($2 \rightarrow 4$) 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:

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

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

$$bb \otimes (j)jj \;,\quad bb \otimes j(j)j \;,\quad bb \otimes jj(j)\,,$$

⊗ denotes the combination of one event for each of the two final states it connects

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

- SPS processes:

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

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

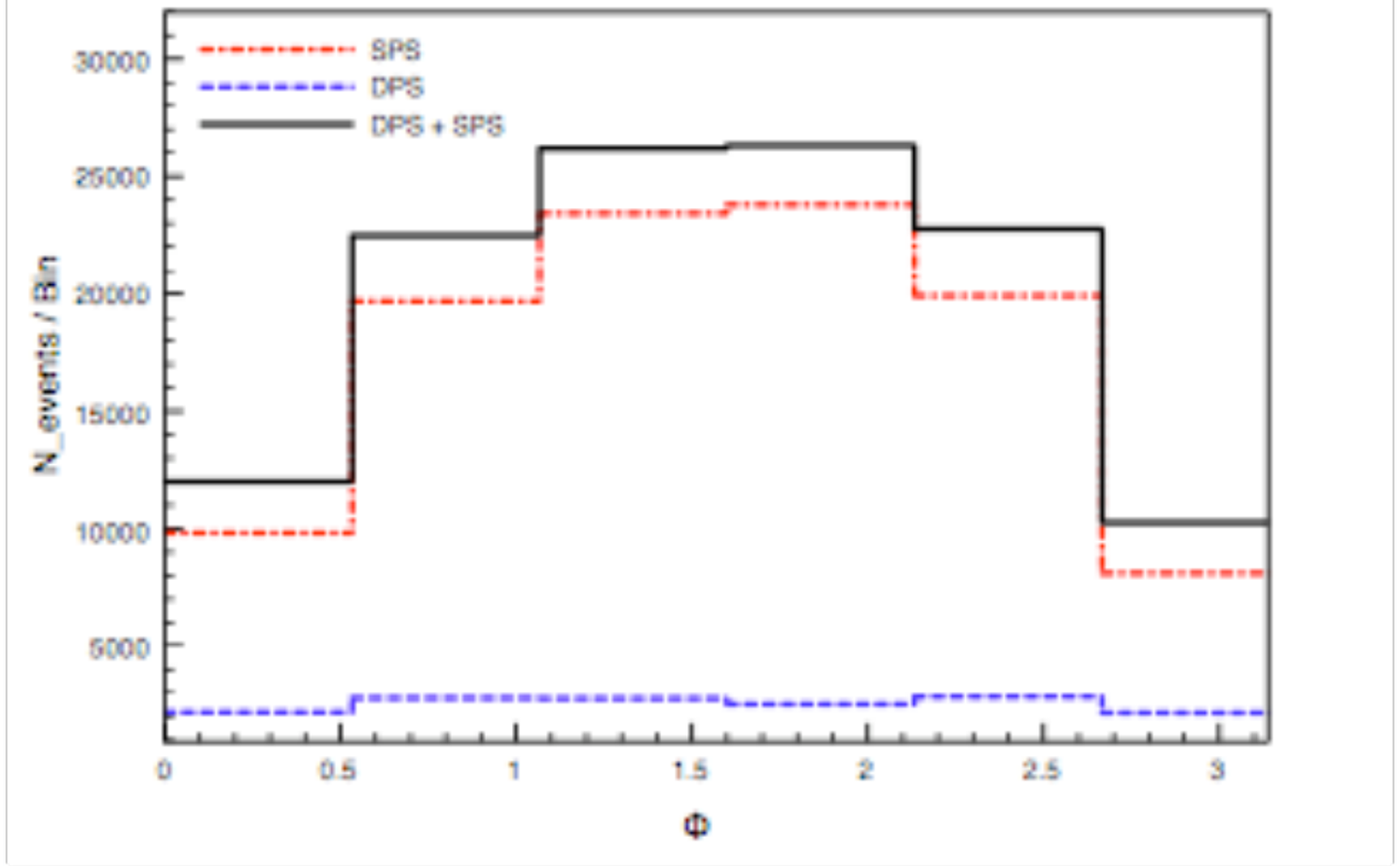
We also considered 4j and 5j final states where 2 j's fake b's

- 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

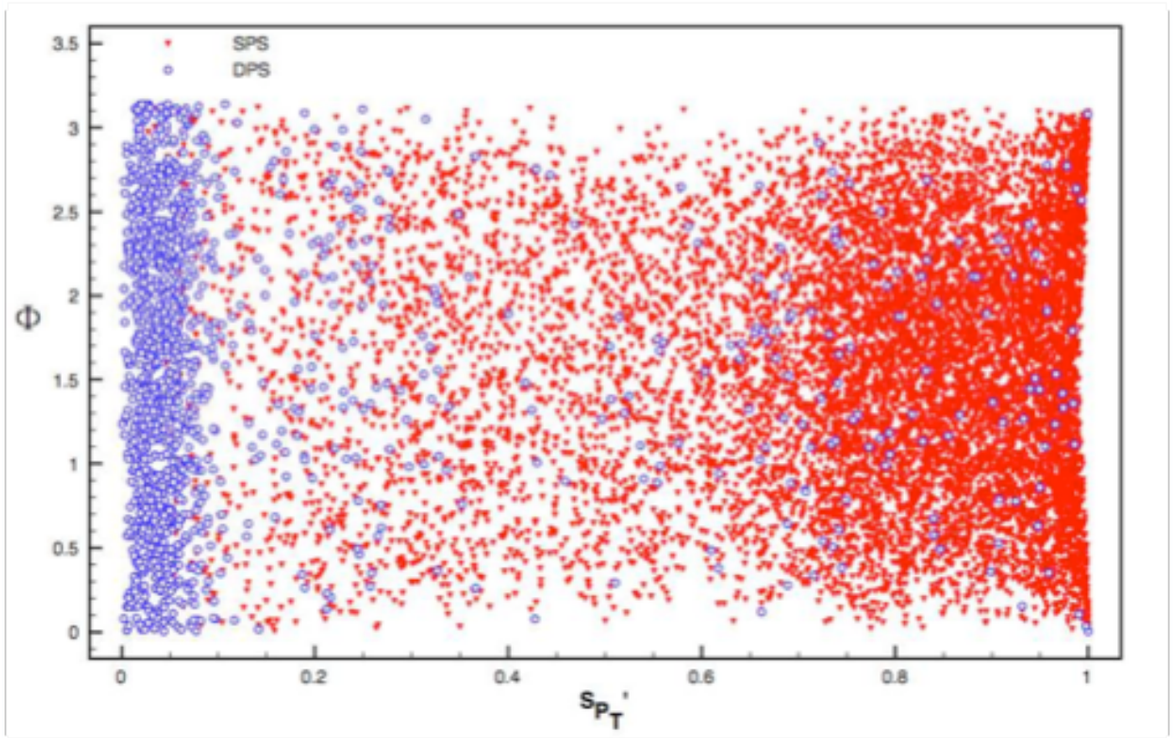
- Must check that we are generating DPS in an uncorrelated manner
- Study angle between plane defined by bb system and plane defined by jj system
- For truly uncorrelated scatterings, the DPS angle should be flat
- However, there are many diagrams which contribute to SPS s.t. some correlation between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



Two-dimensional Distributions

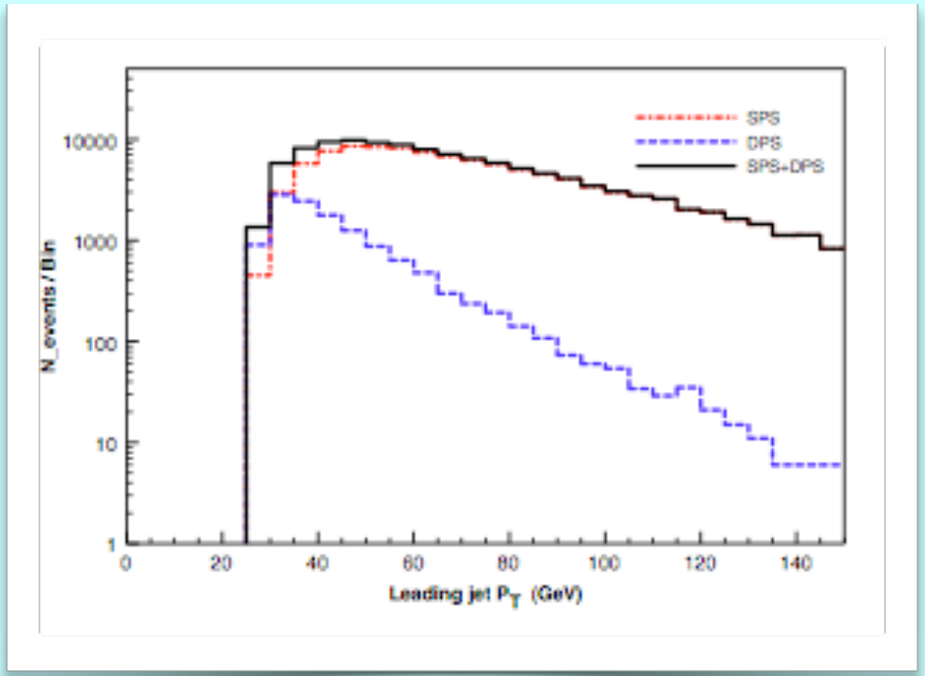
- Also looked at 2-d distributions to see if there is a clearer separation
- We examined plots involving two of Φ, S_ϕ, $\Delta\phi$ and $S_{pT'}$
- Strong correlations evident in many of the distributions

- 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

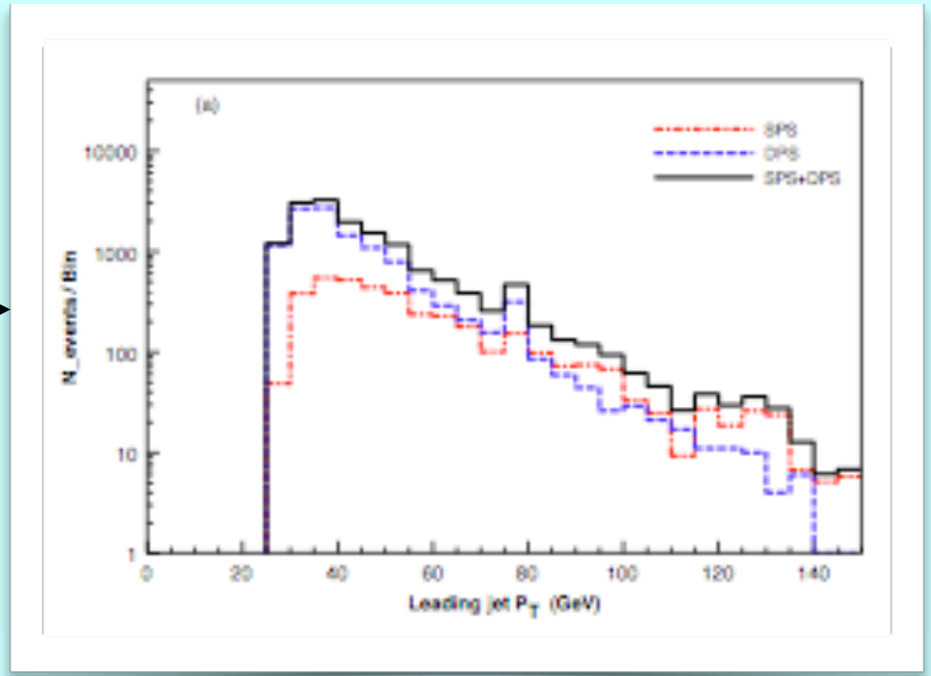


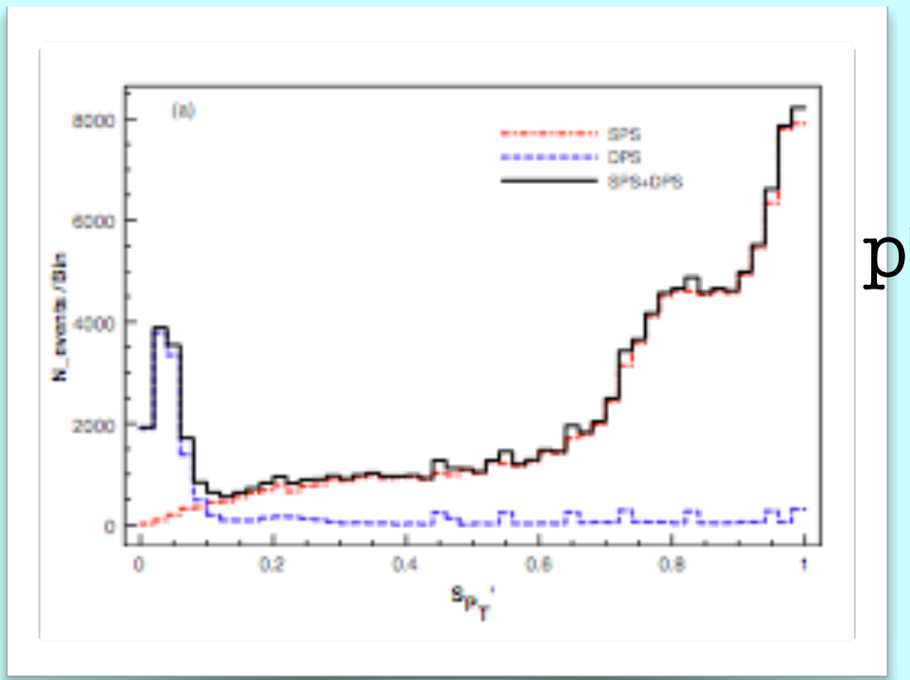
- In reality, shape of Φ distribution will take the form of the SPS
- However, by placing a cut on SpT' of 0.1 or 0.2, the Φ distribution should be flat... a clear signal of DPS!

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

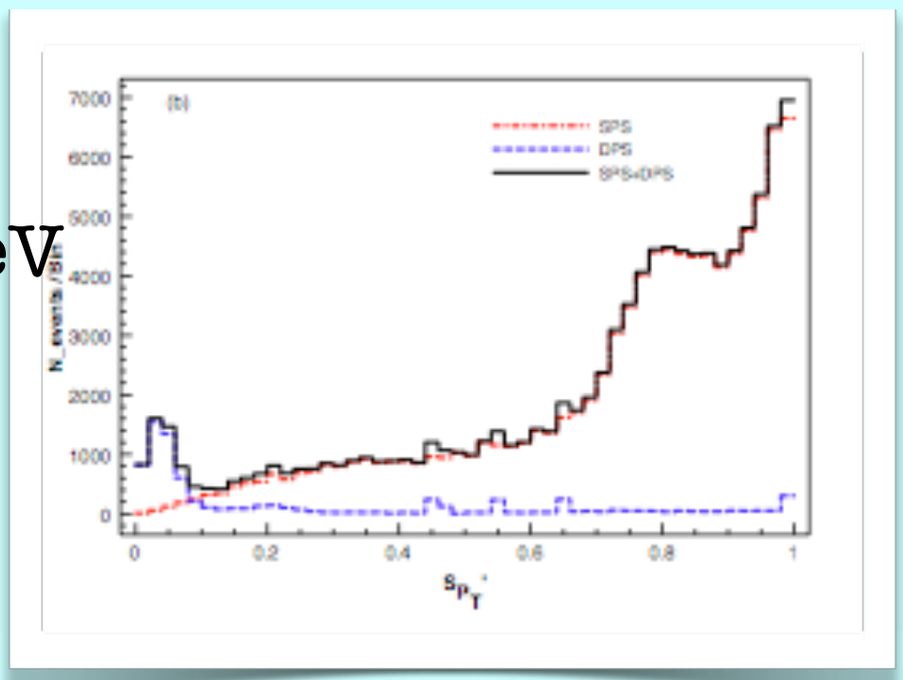


$S_{pT'} < 0.2$





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:

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

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

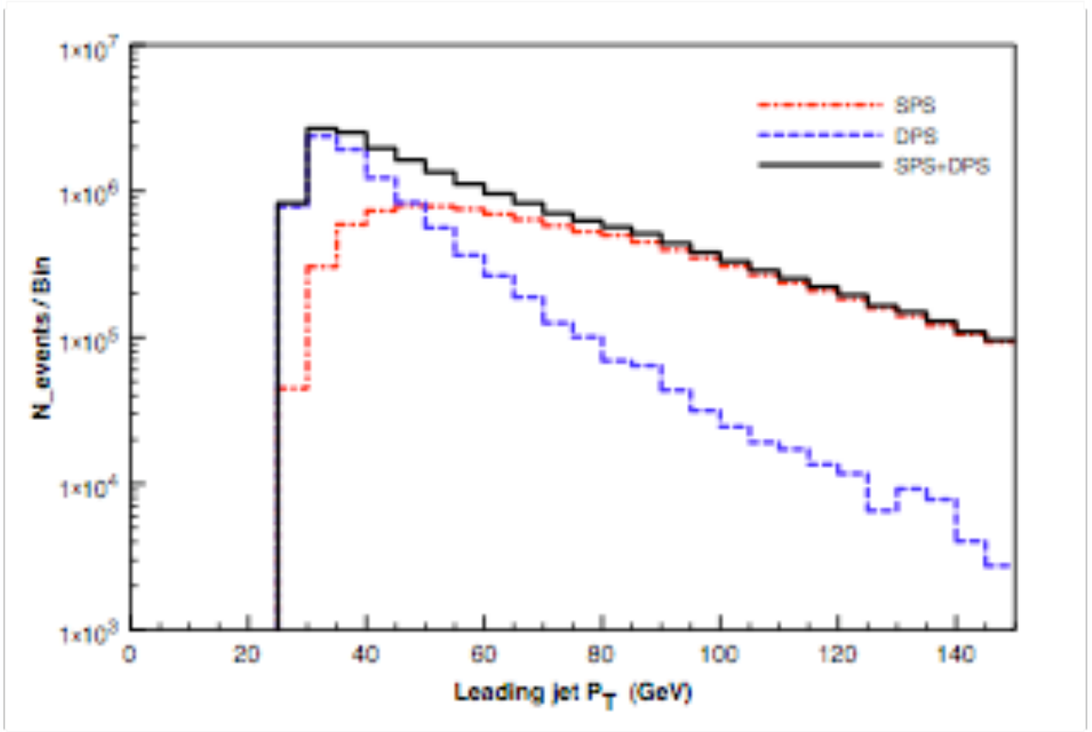
- SPS processes:

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

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

- Same acceptance cuts as before

p_T Distributions for 4j



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

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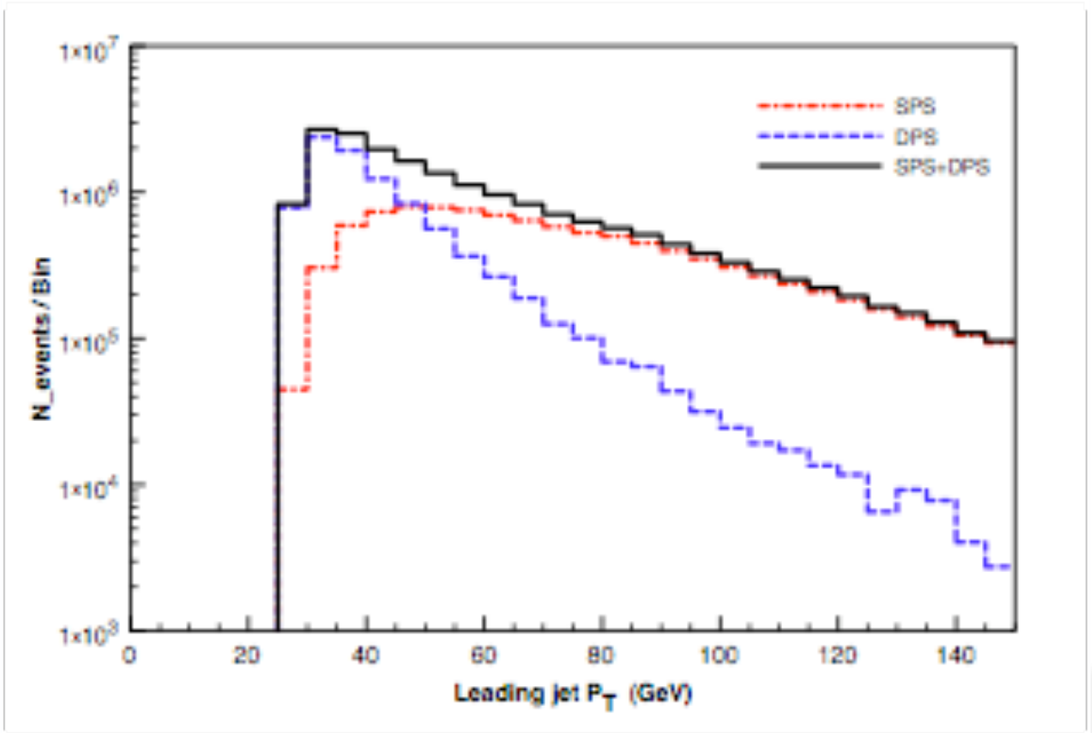

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- How to choose pairs?
  In bbjj, b tags removed degeneracy.
- Democratic $S_{pT'}$
- Sum over all pairings and divide by 3
  (one correct, two incorrect)