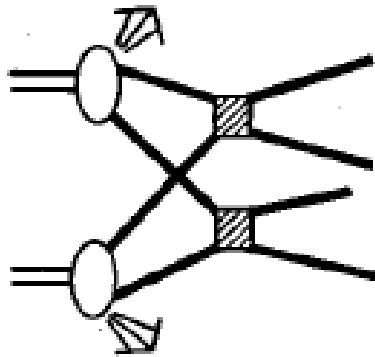




# Double Parton Interactions in $\gamma+3\text{jets}$ events in D0



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on behalf of D0 Collaboration

1st Joint Workshop on Energy Scaling of Hadron Collisions

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# Motivations

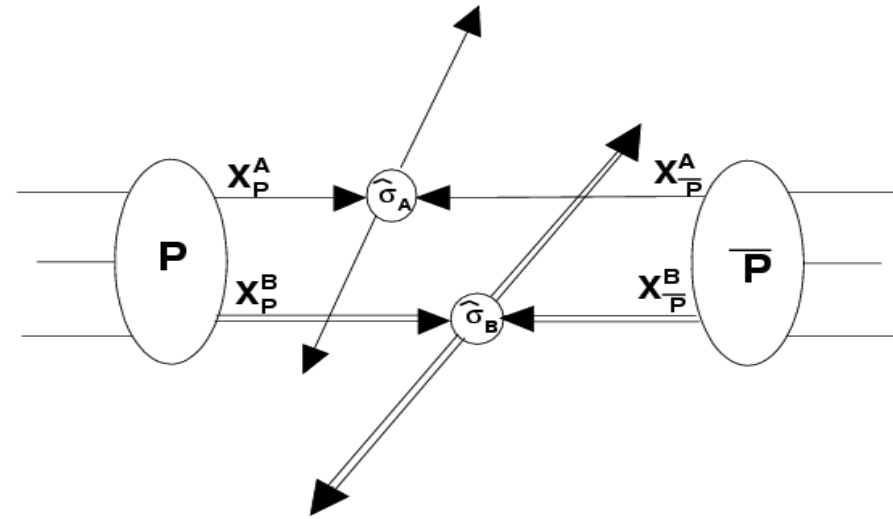
## *or Why we study DP events?*

- **New and complementary information about proton structure:**
  - spatial distribution of partons within proton;
  - possible parton-parton correlations.
  - impact on PDFs?
- **Needed for correct understanding of signal events and correct estimating background to many rare processes especially with multi-jet final state (many Higgs, SUSY productions).**
- **Especially important at high luminosities due to additional pp(bar) interactions.**

# Effective cross section

$$\sigma_{DP} = m \sigma_A \frac{\sigma_B}{2\sigma_{eff}}$$

Factor 2 is due to Poisson statistics  
 m is combinatorial factor  
 m=2 (1) when A and B are (not) distinguishable



$\sigma_A, \sigma_B$  - cross sections of the processes A, B.

$\sigma_{eff}$  - a factor characterizing a size of effective interaction region, i.e. contains information on the spatial distribution of partons.

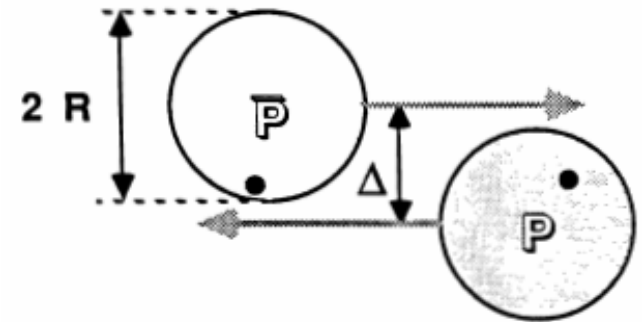
$\sigma_B / 2\sigma_{eff}$  - probability of 2<sup>nd</sup> interaction B with A already happened.

Uniform parton distribution

→  $\sigma_{eff}$  is large and  $\sigma_{DP}$  is small

Clumpy parton distribution

→  $\sigma_{eff}$  is small and  $\sigma_{DP}$  is large

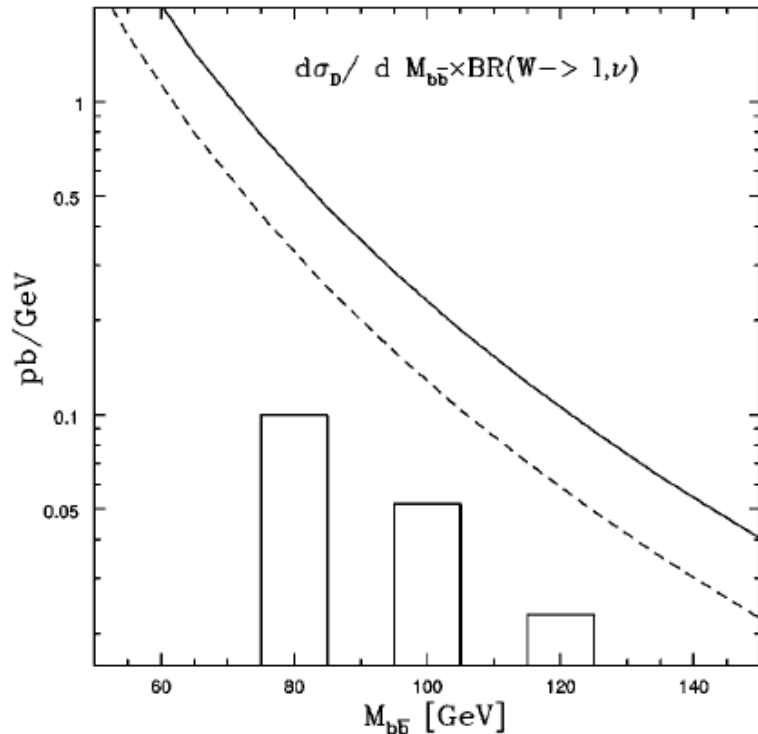
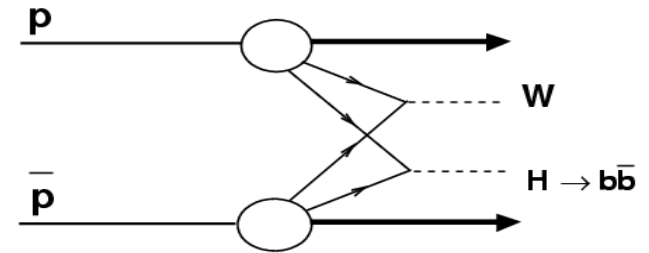


Parton-parton luminosity as a function of impact parameter  $\Delta$  and proton spatial density  $D(r)$

$$L_{eff}(\Delta) = \int D(r) D(r') dV_{overlap}$$

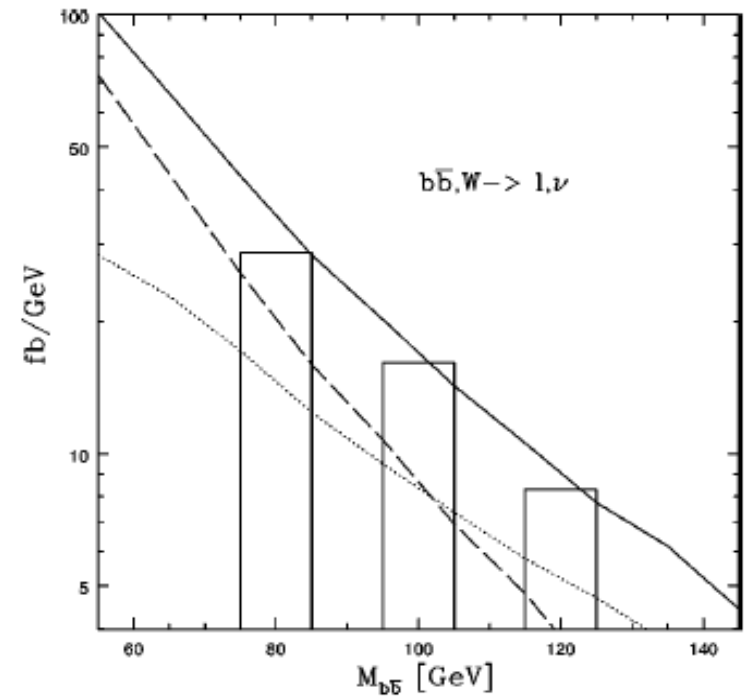
# Example: DPS as a background to $p + p \rightarrow WH$ (LHC)

From PRD61, Fabro, Treleani (2000)



DP background as a function of H mass:  
LO and NLO  $b\bar{b}$  production  
( $\sigma_{eff} = 14.5$  mb used here)

*DP background is 3 orders of magnitude higher than the HW cross section*



SM/SP (dotted) and DP (dashed) cross sections after selection cuts

*DP background is still very important even after selections*

# History of measurements

- ◆ Theoretical discussion on DPS continues for many years (~ beginning of 1980's)
- ◆ Experimental problem is extracting DP signal from more probable double bremstr. background.

Typical experiments choose 4-jet sample motivated by a large di-jet cross section. Measuring  $\sigma_{\text{eff}}$  in 4-jet sample:

$$\sigma_{\text{DP}} = \frac{\sigma_{\text{JJ}}^2}{2\sigma_{\text{eff}}}$$

- ☞ Measure  $\sigma_{\text{DP}}$  but need then QCD calculations of  $\sigma_{\text{jj}}$  to get  $\sigma_{\text{eff}}$   
And MC signal & background modeling.

CDF 1997: photon+3jet events. A new, data-driven, method developed:

- ☞ Use of Double interaction (two separate ppbar collisions) and DPS rates from a single ppbar collision rates to extract  $\sigma_{\text{eff}}$ , → reduce dependence on MC

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

# Measurement of $\sigma_{\text{eff}}$

At two hard scattering events:

$$P_{DI} = 2 \left( \frac{\sigma^{\gamma j}}{\sigma_{\text{hard}}} \right) \left( \frac{\sigma^{jj}}{\sigma_{\text{hard}}} \right)$$

The number of DI events:

$$N_{DI} = 2 \frac{\sigma^{\gamma j}}{\sigma_{\text{hard}}} \frac{\sigma^{jj}}{\sigma_{\text{hard}}} N_C(2) A_{DI} \epsilon_{DI} \epsilon_{2\text{vtx}}$$

At one hard interaction:

$$P_{DP} = \left( \frac{\sigma^{\gamma j}}{\sigma_{\text{hard}}} \right) \left( \frac{\sigma^{jj}}{\sigma_{\text{eff}}} \right)$$

Then the number of DP events:

$$N_{DP} = \frac{\sigma^{\gamma j}}{\sigma_{\text{hard}}} \frac{\sigma^{jj}}{\sigma_{\text{eff}}} N_C(1) A_{DP} \epsilon_{DP} \epsilon_{1\text{vtx}}$$

Therefore one can extract:

$$\sigma_{\text{eff}} = \frac{N_{DI}}{N_{DP}} \frac{N_C(1)}{2 N_C(2)} \frac{A_{DP}}{A_{DI}} \frac{\epsilon_{DP}}{\epsilon_{DI}} \frac{\epsilon_{1\text{vtx}}}{\epsilon_{2\text{vtx}}} \sigma_{\text{hard}}$$

# 1<sup>st</sup> and 2<sup>nd</sup> interactions: Estimates of possible correlations

... in the momentum space:

1st interaction: photon  $p_T \simeq 70$  GeV,  $\Rightarrow$  parton  $xT \simeq 0.035$

2nd interaction: jet  $p_T \simeq 20$  GeV,  $\Rightarrow$  parton  $xT \simeq 0.01$

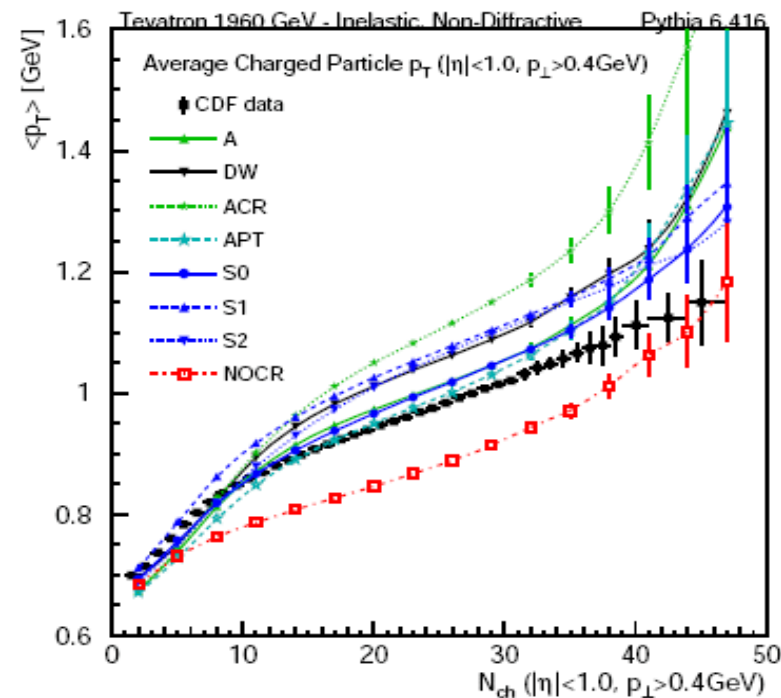
➡ large (almost unlimited) kinematic space for the 2<sup>nd</sup> interaction

... at the fragmentation stage :

=> Simulate  $\gamma+3$  jets and di-jets with switched off ISR/FSR; then additional 2 jets in  $\gamma+3$  jets should be from 2<sup>nd</sup> parton interaction

=> compare 2<sup>nd</sup> (3<sup>rd</sup>) jets  $p_T/\text{Eta}$  in  $\gamma+3$  jets with 1<sup>st</sup> (2<sup>nd</sup>) jet  $p_T/\text{Eta}$  in dijets

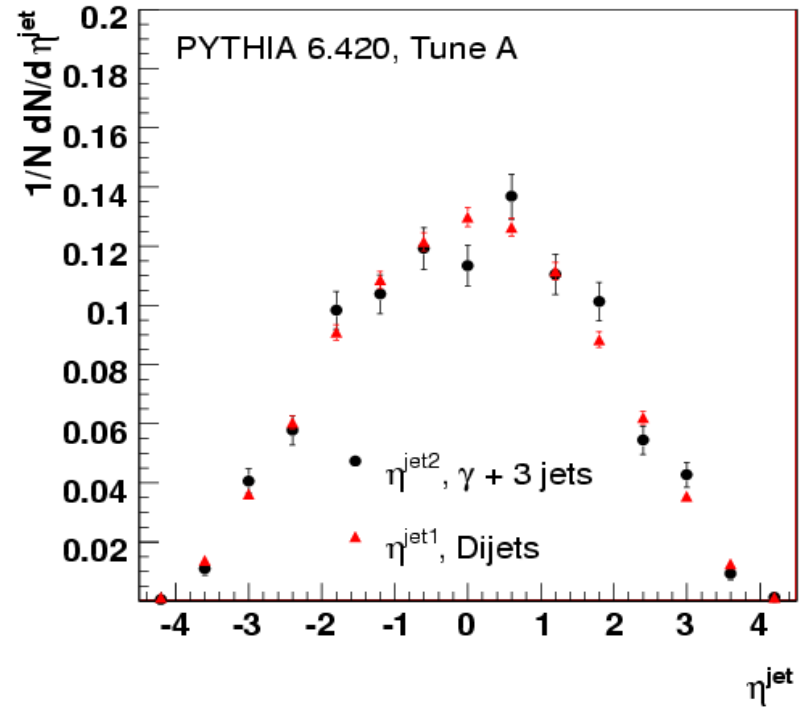
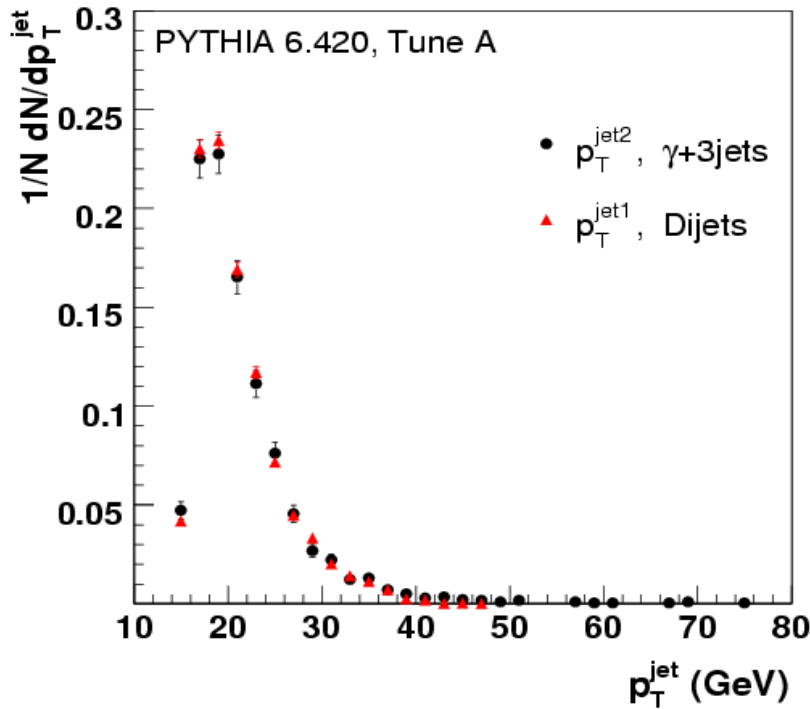
=> Tunes tested: A, A-CR, S0



From D.Wicke &  
P.Skands  
hep-ph:0807.3248

# $\gamma+3$ jets and di-jets, IFSR=OFF: jets $p_T$ comparison.

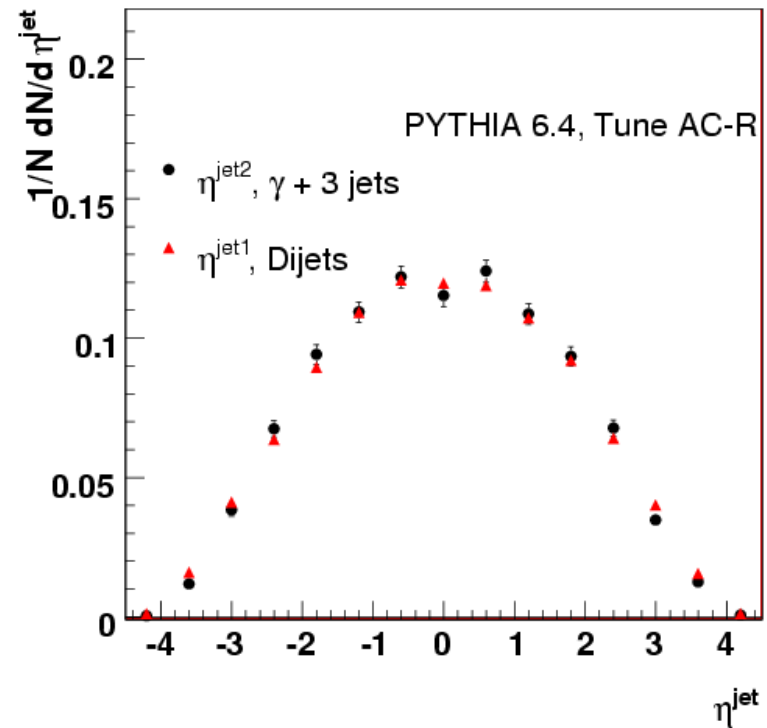
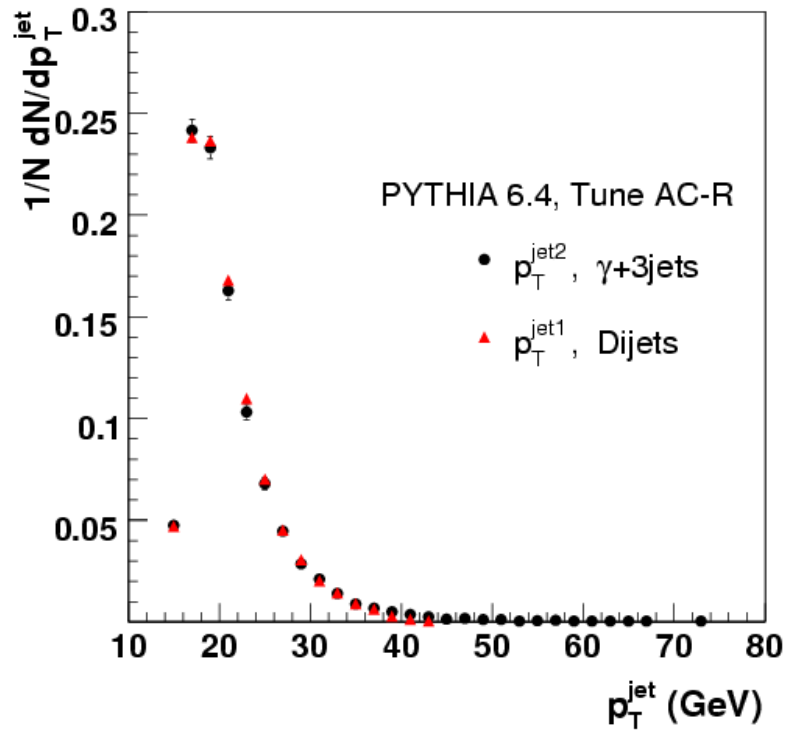
## Tune A



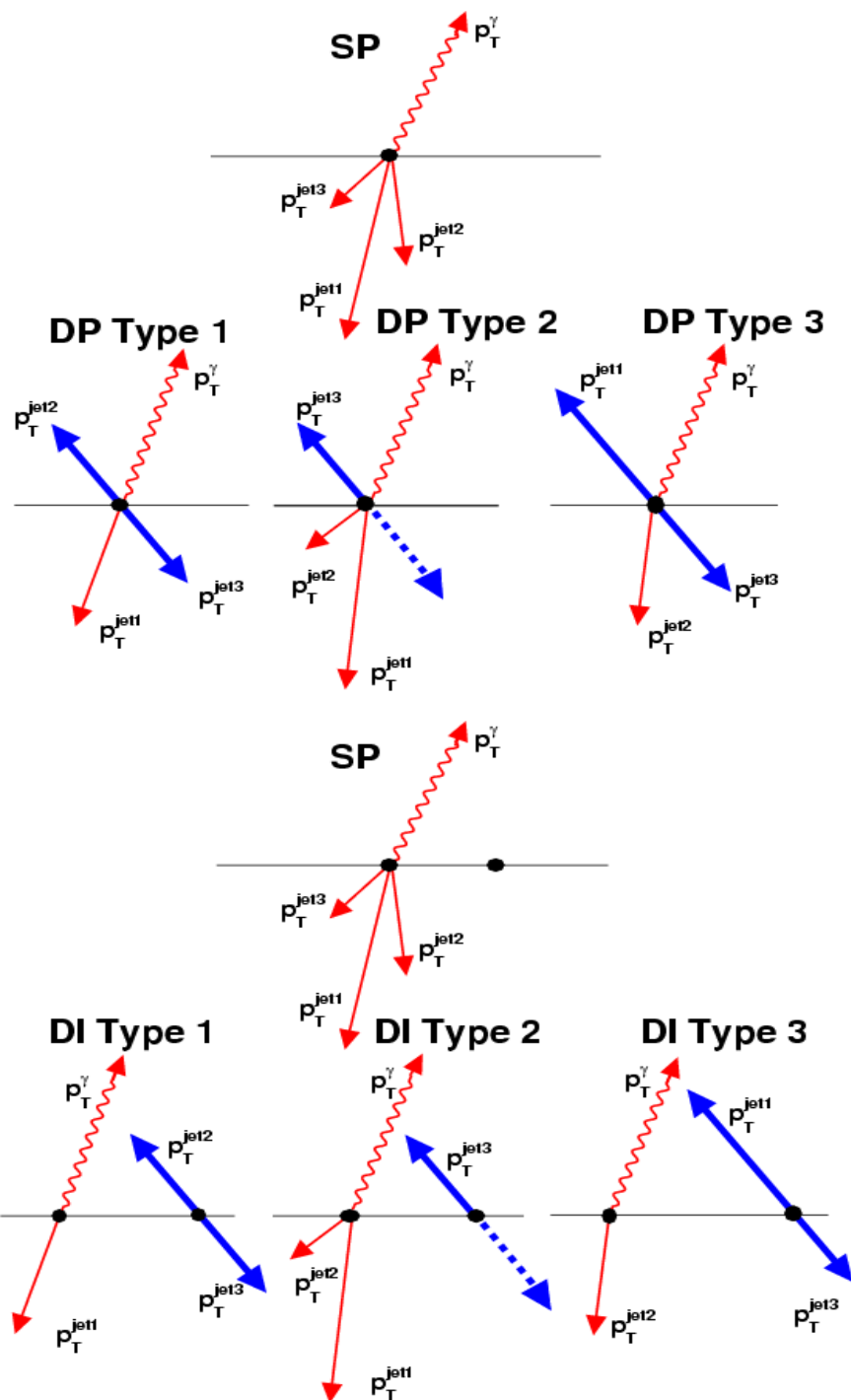
- $p_T$  and Eta distributions are analogous for jets from 2nd interaction in  $\gamma+3$  jets and di-jet events
- Analogous results (incl. 3<sup>rd</sup> jet from  $\gamma+3$  jets and 2<sup>nd</sup> from di-jets) are obtained for Tunes A-CR, S0.

# $\gamma+3$ jets and di-jets, IFSR=OFF: jets $p_T$ comparison.

## Tune A-CR



# $\gamma+3$ jets events topology: DP and DI events



**B: Single Parton (SP) 1PV production:** single hard scattering with bremsstrahlung radiation in 1vtx events.

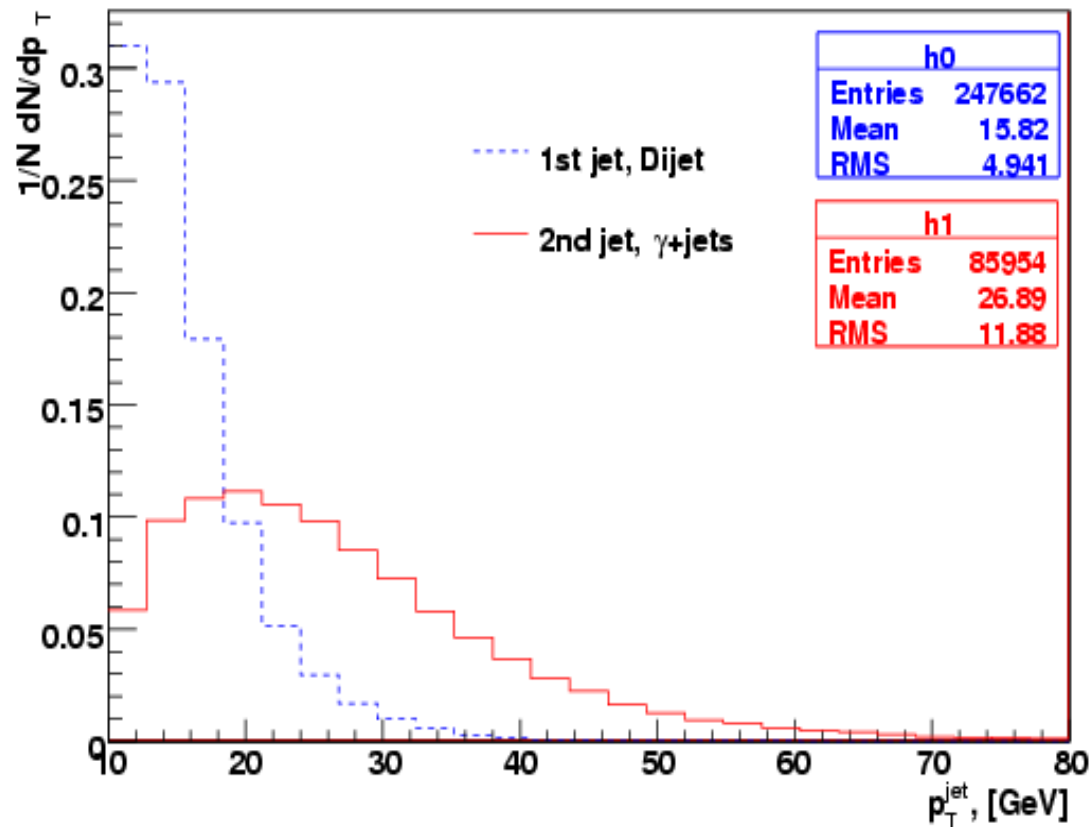
**S: Double Parton (DP) production:** 1<sup>st</sup> process produces photon-jet pair, while 2<sup>nd</sup> produces dijet pair or photon plus 2 jets from 1<sup>st</sup> interaction plus 1 observed jet from dijet pair.

**B: Single Parton (SP) 2PV production:** single hard scattering in 1vtx with bremsstrahlung radiation.

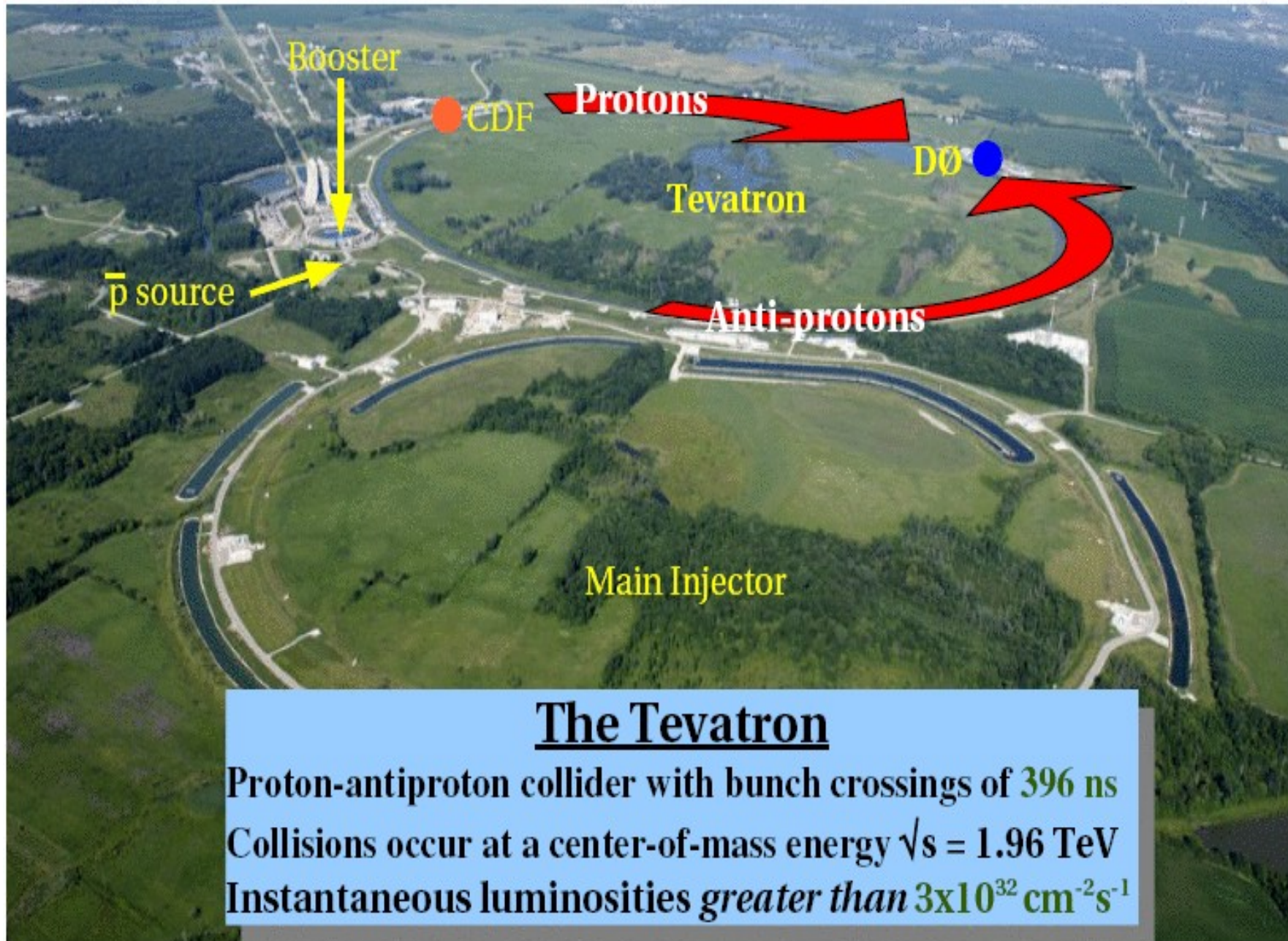
**S: Double Interaction (DI) production:** two separate collisions within the same beam crossing.

# Motivation of jet pT binning

Jet PT: jet from **dijets** vs. **bremstrahlung** jet from  $\gamma$ +jet events  
(Pythia 6.4)



- ▶ Fraction of dijet (DP) events drops with increasing jet PT
- ▶ Measurement is done in the three bins of 2<sup>nd</sup> jet pT: 15-20, 20-25, 25-30 GeV

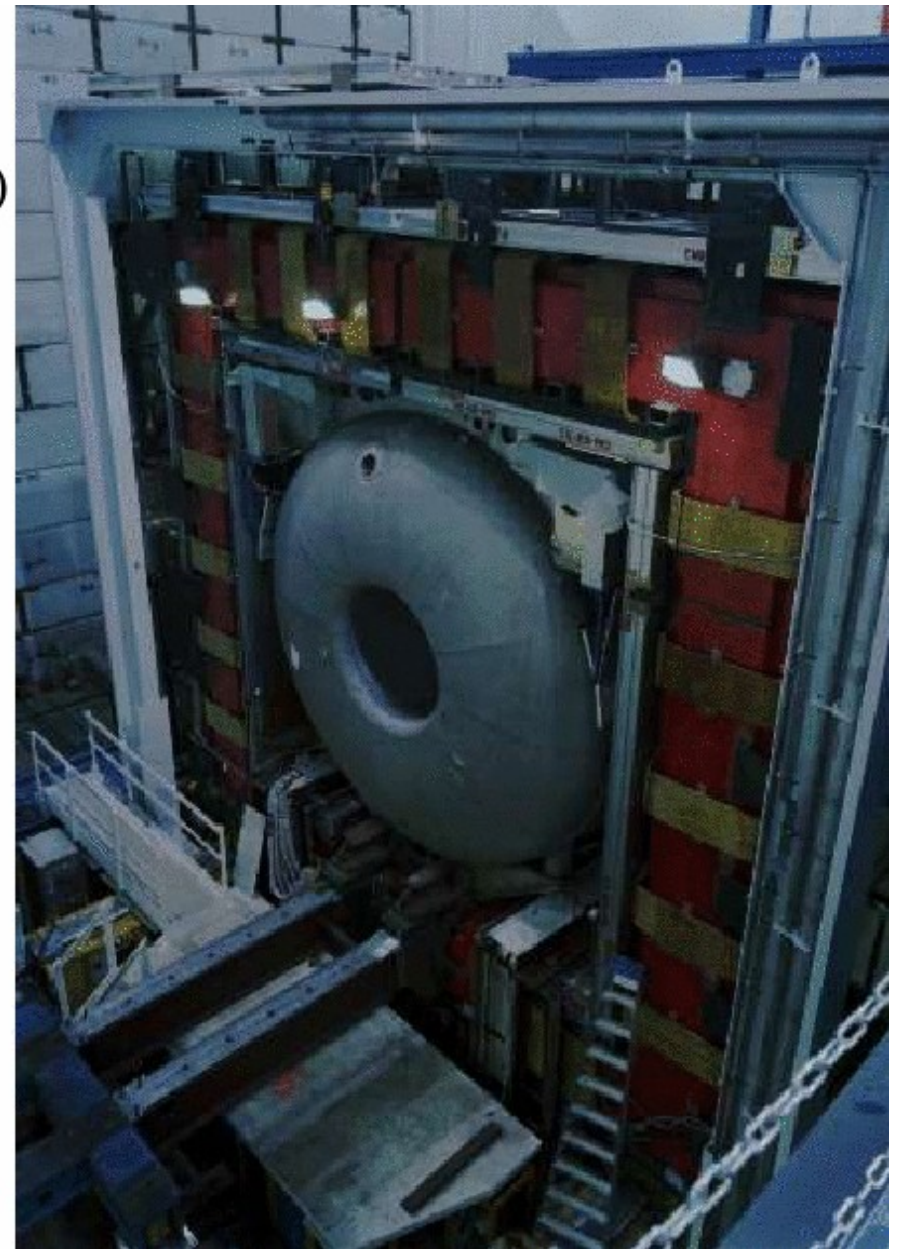
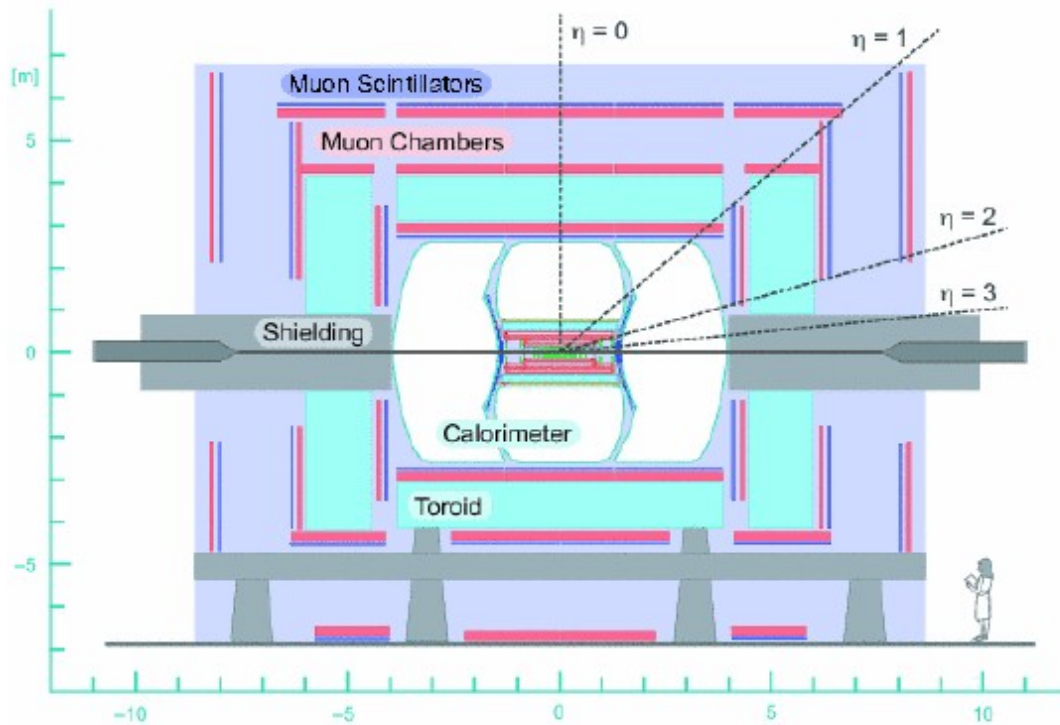


## The Tevatron

Proton-antiproton collider with bunch crossings of 396 ns  
Collisions occur at a center-of-mass energy  $\sqrt{s} = 1.96$  TeV  
Instantaneous luminosities *greater than*  $3 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

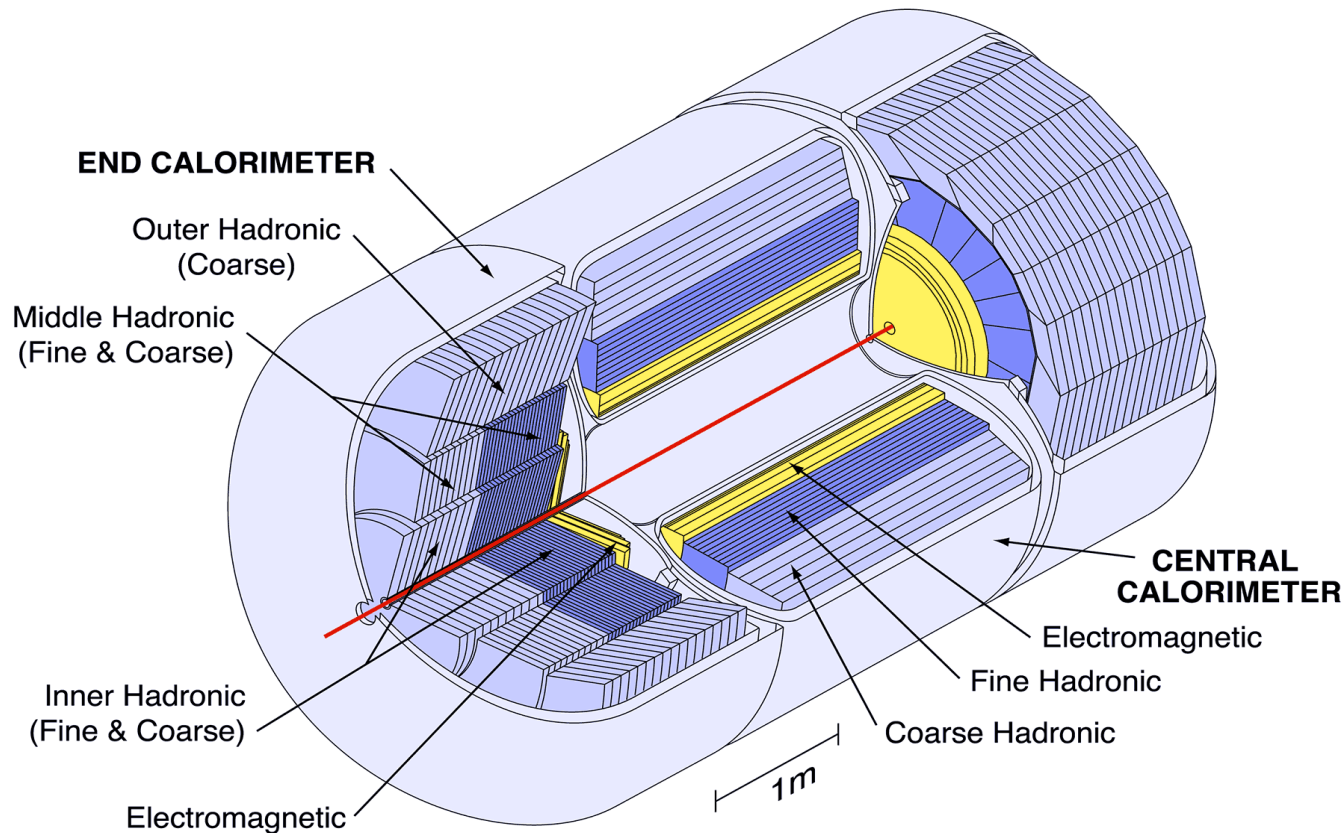
# D0 detector

- Three main systems:
  - Tracker (silicon and scintillating fibre)
  - Calorimeter (lAr/U, some scintillator)
  - Muon chambers and scintillators
- First two used in this measurement



# D0 calorimeter

- ✓ The most important detector for photon and jet measurements



- ✓ Calorimeter has three main subregions: Central ( $|\eta| < 1.1$ ), Intercryostat ( $1.1 < |\eta| < 1.5$ ) and End calorimeters ( $1.5 < |\eta| < 4.2$ )
- ✓ Liquid argon/Uranium Calorimeter:
  - Stable response, good resolution
  - Partially compensating ( $e/h \sim 1$ )

# Photon and jet identification

## JETS:

- Midpoint Cone algo with  $R=0.7$
- $|\eta| < 3.5$
- #jets  $\geq 3$
- $p_T$  of any jet  $> 15$  GeV
- $p_T$  of leading jet  $> 25$  GeV
- $p_T$  of 2<sup>nd</sup> jet (15,20), (20,25), (25,30) GeV.

## PHOTONS:

- photons with  $|\eta| < 1.0$  and  $1.5 < |\eta| < 2.5$
- $60 < p_T < 80$  GeV (good separation of lead. jet from 2 other jets)
- Shower shape cuts
- Calo isolation ( $0.2 < dR < 0.4$ )  $< 0.07$
- Track isolation ( $0.05 < dR < 0.4$ )  $< 1.5$  GeV
- Track matching probability  $< 0.001$
  
- $R(\text{any objects pair}) > 0.7$

# DOUBLE PARTON INTERACTION MODEL (MIXDP)

Built from D0 data. Samples:

**A:** photon +  $\geq 1$  jet from  $\gamma$ +jets data sample:

- 1 VTX events
- leading jet  $p_T > 25$  GeV,  $|\eta| < 3.5$ .

**B:**  $\geq 1$  jets from MinBias sample:

- 1 VTX events
- jets with  $p_T$ 's recalculated to the primary vertex of sample A have  $p_T > 15$  GeV and  $|\eta| < 3.5$ .

- ▶ **A & B** samples have been mixed with jets  $p_T$  re-ordering
- ▶ Events should satisfy photon+ $\geq 3$  jets requirement.
- ▶  $\Delta R(\text{photon}, \text{jet1}, \text{jet2}, \text{jet3}) > 0.7$

⇒ Two scatterings are assumed to be independent by construction

# DOUBLE $P\bar{P}$ INTERACTION MODEL (MIXDI)

Built from D0 data. Samples:

**A:** photon +  $\geq 1$  jet from  $\gamma$ +jets data sample:

- 2 VTX events
- jets with leading jet  $p_T > 25$  GeV,  $|\eta| < 3.5$ .

**B:**  $\geq 1$  jets from MinBias sample:

- 2 VTX events (to take in account underlying energy)
- jets with  $p_T$ 's recalculated to the vertex of sample A.

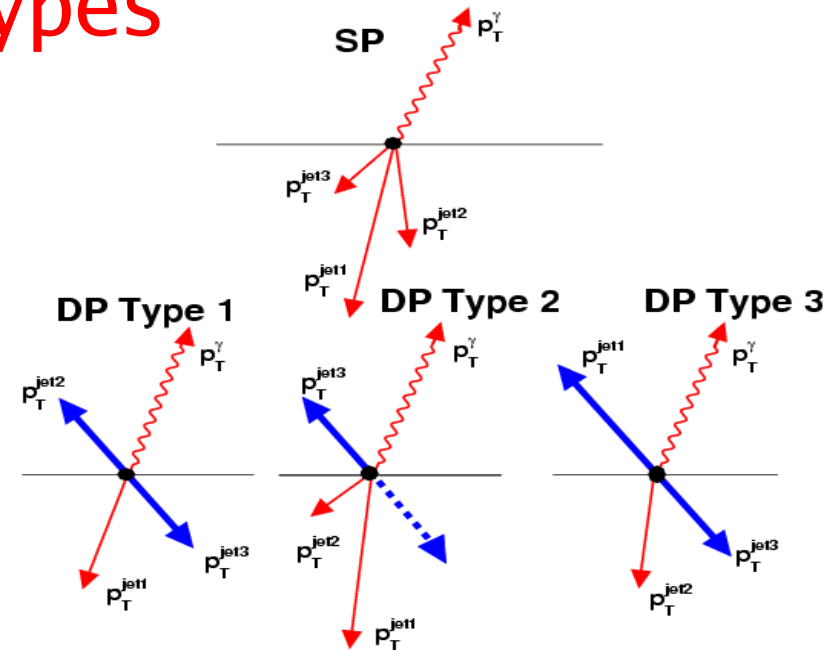
- ▶ in case of 2 jets, both jets are required to originate from the Primary Vertex (using jet track info).
- ▶ **A** & **B** samples have been mixed with jets  $p_T$  re-ordering
- ▶ Events should satisfy photon+ $\geq 3$  jets requirement.
- ▶  $\Delta R(\text{photon}, \text{jet1}, \text{jet2}, \text{jet3}) > 0.7$

## BGD2VTX (background sample)

Obtained by a direct requirement for all three jets to originate from one vertex using jet track information .

# Fractions of MixDP event types

Event Types	$p_T^{\text{jet}2}$ (GeV)		
	15 – 20	20 – 25	25 – 30
Type 1	$0.261 \pm 0.005$	$0.217 \pm 0.016$	$0.135 \pm 0.006$
Type 2	$0.729 \pm 0.007$	$0.778 \pm 0.008$	$0.861 \pm 0.009$
Type 3	$0.010 \pm 0.001$	$0.005 \pm 0.001$	$0.004 \pm 0.001$



- ◆ Type 2 events (1 jet from dijet and 1 brems. jet) dominate ( $\geq 73\%$ ): It is caused by jet reco eff-cy and threshold (6 GeV for  $p_{T\_raw}$ ) and difference in jet  $p_T$  (it is smaller for dijets)
- ◆ CDF ('97) found at least 75% Type 2 events: a good agreement.
- ◆ Small fraction of Type 3 events.
- ◆ Important: dominance of Type 2 naturally reduces a dependence of results (see variable  $\Delta S$  below) on possible issues with correlations between 1<sup>st</sup> & 2<sup>nd</sup> parton interactions.

# Distinguishing variables

“S-family” variables:

$$S_{p_T} = \frac{1}{\sqrt{2}} \sqrt{\left(\frac{|\vec{P}_T(\gamma, i)|}{\delta P_T(\gamma, i)}\right)^2 + \left(\frac{|\vec{P}_T(j, k)|}{\delta P_T(j, k)}\right)^2} \quad \vec{P}_T(\gamma, i) \quad \vec{P}_T(j, k) - \text{transverse momenta of the two-body system.}$$

$$S'_{p_T} = \frac{1}{\sqrt{2}} \sqrt{\left(\frac{|\vec{P}_T(\gamma, i)|}{|\vec{P}_T^\gamma| + |\vec{P}_T^i|}\right)^2 + \left(\frac{|\vec{P}_T(j, k)|}{|\vec{P}_T^j| + |\vec{P}_T^k|}\right)^2} \quad \Delta\phi(\gamma, i) \quad \Delta\phi(j, k) - \text{azimuthal angles between them}$$

$$S_\phi = \frac{1}{\sqrt{2}} \sqrt{\left(\frac{\Delta\phi(\gamma, i)}{\delta\phi(\gamma, i)}\right)^2 + \left(\frac{\Delta\phi(j, k)}{\delta\phi(j, k)}\right)^2} \quad \begin{array}{l} \delta P_T(\gamma, i) \quad \delta P_T(j, k) \\ \delta\phi(\gamma, i) \quad \delta\phi(j, k) \end{array} - \text{the corresponding uncertainties from MIXDP events}$$

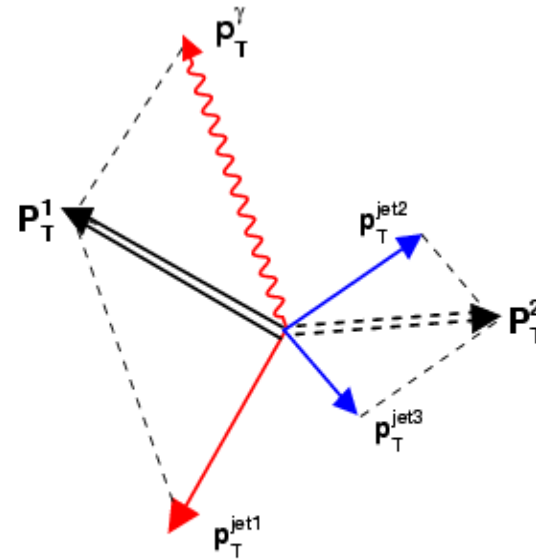
The pairs are constructed by grouping photon with 3 jets in three possible configurations:  $(\gamma + jet_i) \times (jet_j + jet_k)$  where  $i, j, k \in \{1, 2, 3\}$

In the signal sample most likely (>90%) S are minimized by pairing photon with the leading jet.

# “ $\Delta S$ -family” variables

$\Delta S_{p_T}$   $\Delta S'_{p_T}$   $\Delta S_\phi$  - azimuthal angles between  $p_T$ -vectors of the pairs that give minimum  $S$  value.

$$\Delta S = \Delta\phi \left( \mathbf{p}_T^{\gamma, jet_i}, \mathbf{p}_T^{jet_j, jet_k} \right)$$



- For “ $\gamma+3$ jets” events from the single parton interactions we expect  $\Delta S$  to peak at  $\pi$ , while it should be flat for “ideal” double parton interaction when both, 2<sup>nd</sup> and 3<sup>rd</sup> jets in the “ $\gamma+3$ jets” system are from 2<sup>nd</sup> (dijet) interaction.
- In reality, one of the dijet jets can be replaced by a radiation jet with a larger  $p_T$  what makes  $\Delta S$  distribution less flat with a bump closer to  $\pi$ .

# The number (fraction) of DP events

Since dijet pT cross section drops faster than that of radiation jets the different DP fractions in various (2<sup>nd</sup>) jet pT intervals are expected. The larger 2<sup>nd</sup> jet pT the smaller DP fraction.

Dataset 1 - “DP-rich”, smaller 2<sup>nd</sup> jet pT bin, e.g. 15-20 GeV

Dataset 2 - “DP-poor”, larger 2<sup>nd</sup> jet pT bin, e.g. 20-25 GeV

Each distribution can be expressed as a sum of DP and SP :

$$D_1 = f_1 M_1 + (1 - f_1) B_1$$

$$D_2 = f_2 M_2 + (1 - f_2) B_2$$

$$D_1 - f_1 M_1 = (1 - f_1) B_1$$

$$D_2 - f_2 M_2 = (1 - f_2) B_2$$

$$D_1 - \lambda K D_2 = f_1 M_1 - \lambda K f_2 M_2 \quad \text{where} \quad \lambda = \frac{B_1}{B_2} \quad K = \frac{(1 - f_1)}{(1 - f_2)}$$

- $D_i$  - data distribution
- $M_i$  - MIXDP distribution
- $B_i$  - background distribution
- $f_i$  - fraction of DP events
- $(1 - f_i)$  - fraction of SP events

$$D_1 - \lambda K D_2 = f_1 M_1 - \lambda K C f_1 M_2$$

Here  $C = \frac{f_2}{f_1}$  is a ratio of signal fractions.

Behaviour of the dijet events in the single interaction is found to be identical to the behaviour of dijets from the 2<sup>nd</sup> hard (DP) interaction. Therefore MIXDP sample should model correctly properties of DP events and one can write :

$$\frac{N_2^{DP}}{N_1^{DP}} = \frac{N_2^{MIXDP}}{N_1^{MIXDP}}$$

The C parameter is determined from the MIXDP and DATA samples, i.e. without knowledge of a real amount of DP fraction in data:

$$C = \frac{f_2}{f_1} = \left( \frac{N_2^{DP}}{N_2^{DATA}} \right) \left( \frac{N_1^{DATA}}{N_1^{DP}} \right) = \left( \frac{N_2^{MIXDP}}{N_2^{DATA}} \right) \left( \frac{N_1^{DATA}}{N_1^{MIXDP}} \right)$$

To get DP fraction in a given bin of 2<sup>nd</sup> jet pT, we fit MIXDP to data by minimizing  $\chi^2$ :

$$\chi^2 = \sum_{i=1}^{Nbins} (F_i)^2$$

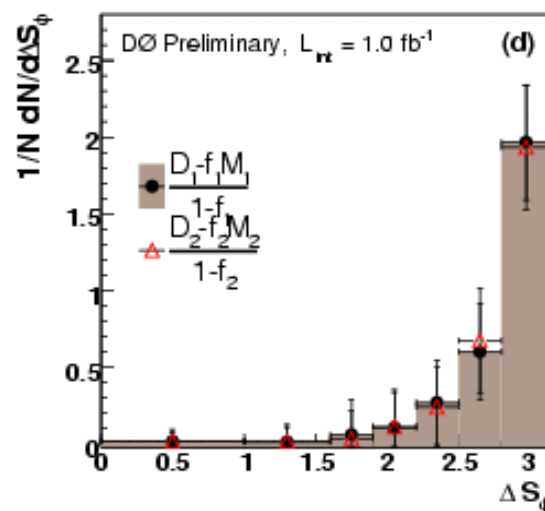
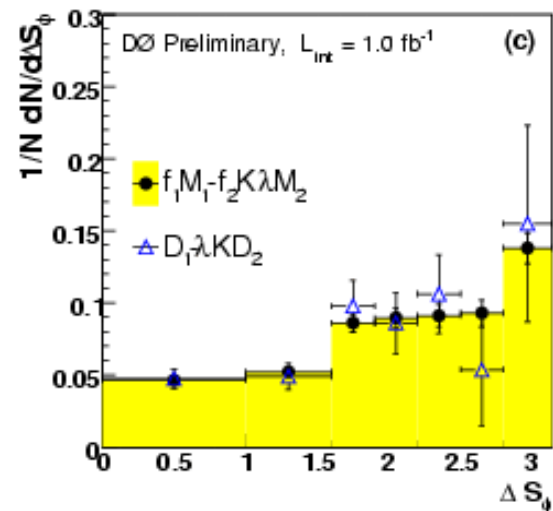
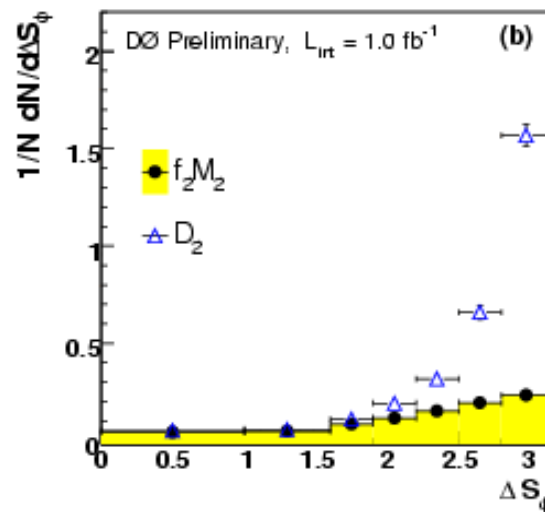
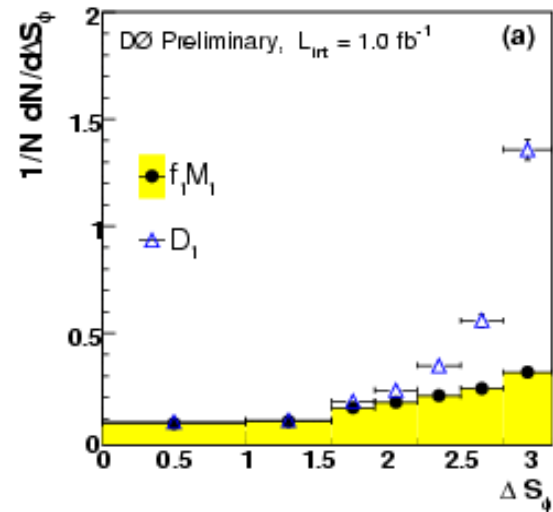
where  $F = |D_1 - f_1 M_1 - \lambda K D_2 + \lambda K C f_1 M_2| / \sigma$

and valid in each i-th bin of S.

Parameter contains uncertainties from  $C, D_1, D_2, M_1, M_2$  and .  
The only free parameter  $f_1$  is obtained from minimization.

Dataset 1: Photon pT: 60–80 GeV, 2<sup>nd</sup> jet pT: 15–20 GeV

Dataset 2: Photon pT: 60–80 GeV, 2<sup>nd</sup> jet pT: 20–25 GeV



a) Distributions for the 1<sup>st</sup> dataset: data points and MIXDP weighted with  $f_1$  found from the minimization.

b) Distributions for the 2<sup>nd</sup> dataset: data points and MIXDP weighted with  $f_2=C \cdot f_1$ .

c) Difference of the data distributions in 1 and 2 datasets i.e. the left side of the equation (1):

$$D_1 - KD_2$$

and MIXDP prediction i.e. right side of the equation (1):

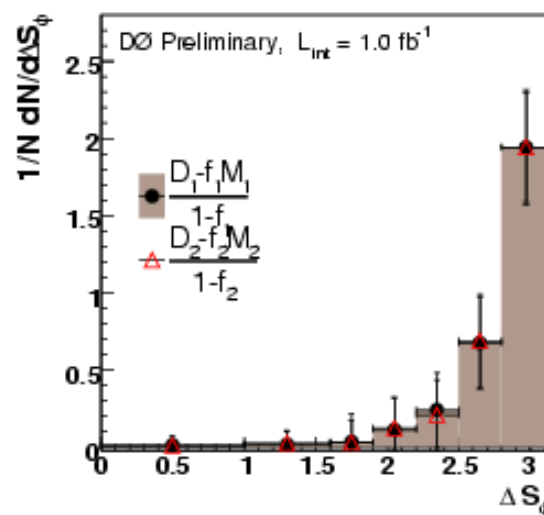
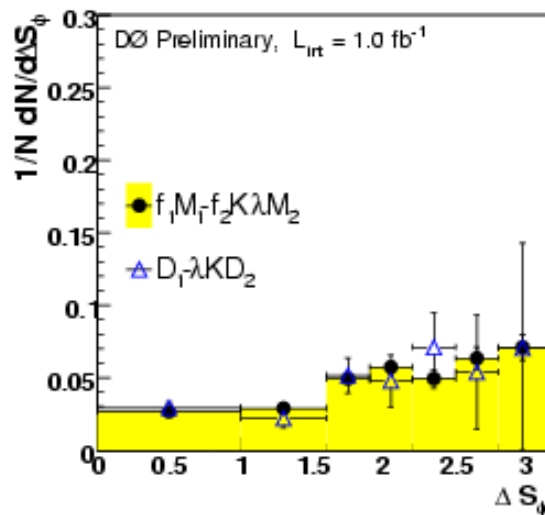
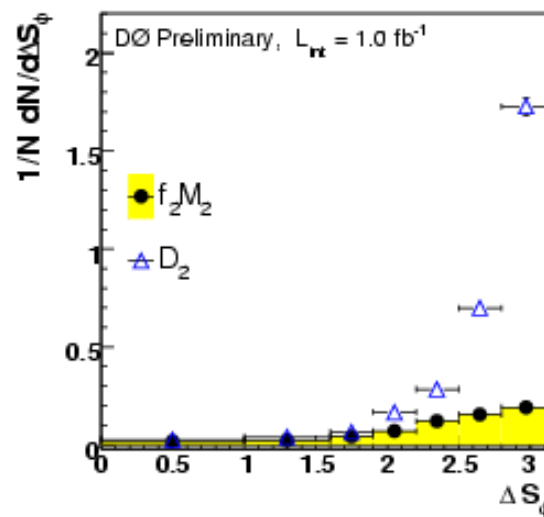
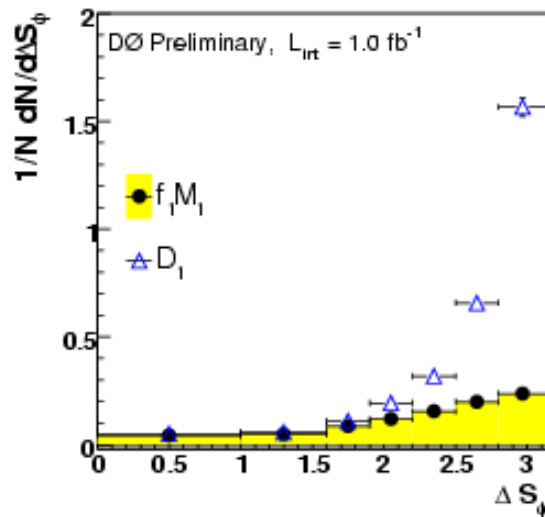
$$f_1 M_1 - C f_1 K M_2$$

d) Extracted SP distributions in the 1<sup>st</sup> and 2<sup>nd</sup> datasets, obtained by subtracting MIXDP from the Data.

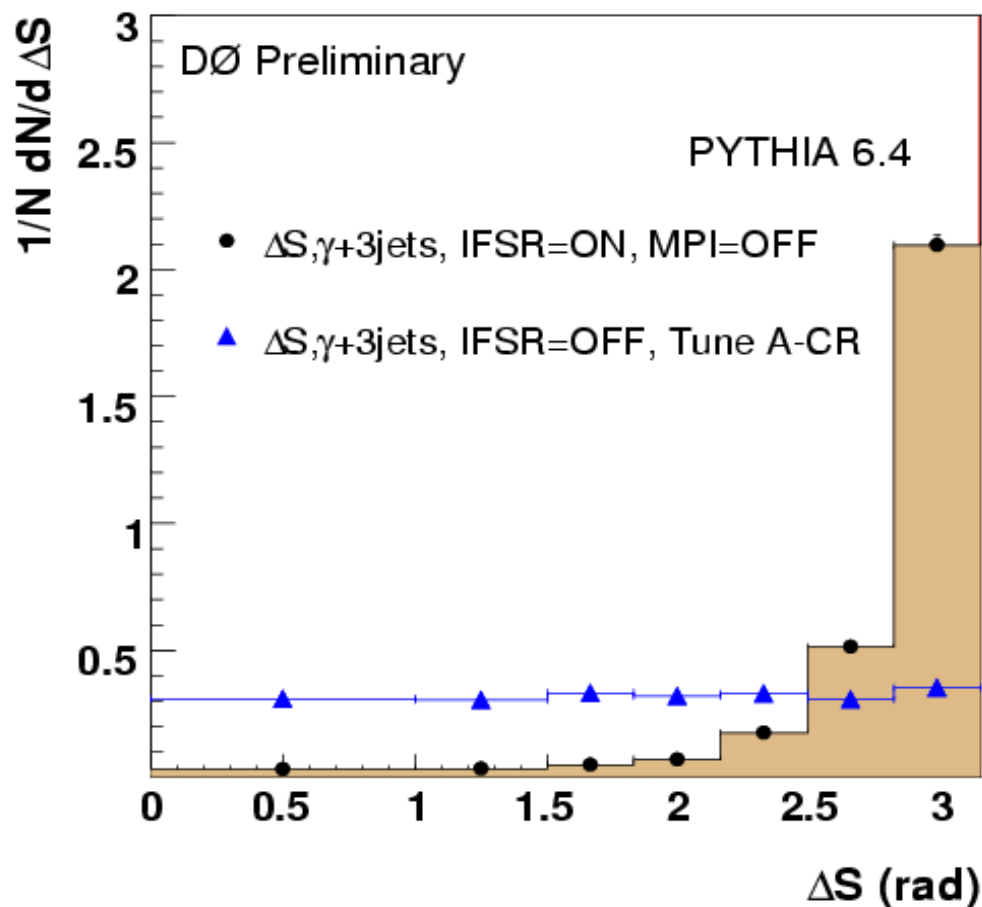
$$\frac{D_1 - f_1 M_1}{1 - f_1} \quad \frac{D_2 - f_2 M_2}{1 - C f_1}$$

$$D_1 - KD_2 = f_1 M_1 - K f_2 M_2$$

Dataset 1: Photon  $p_T$ : 60–80 GeV, 2<sup>nd</sup> jet  $p_T$ : 20–25 GeV  
 Dataset 2: Photon  $p_T$ : 60–80 GeV, 2<sup>nd</sup> jet  $p_T$ : 25–30 GeV

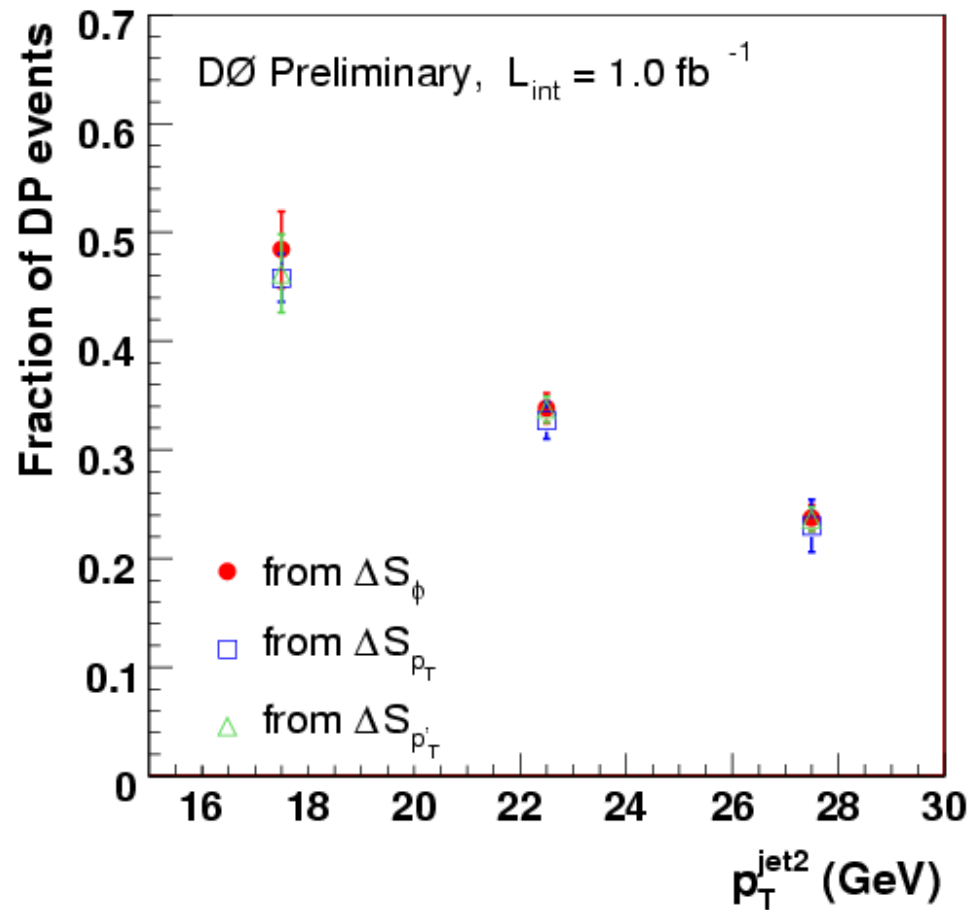


# $\Delta S$ distribution for $\gamma+3$ jets events for pure SP events (Pythia, particle distribution smeared with detector resolution)

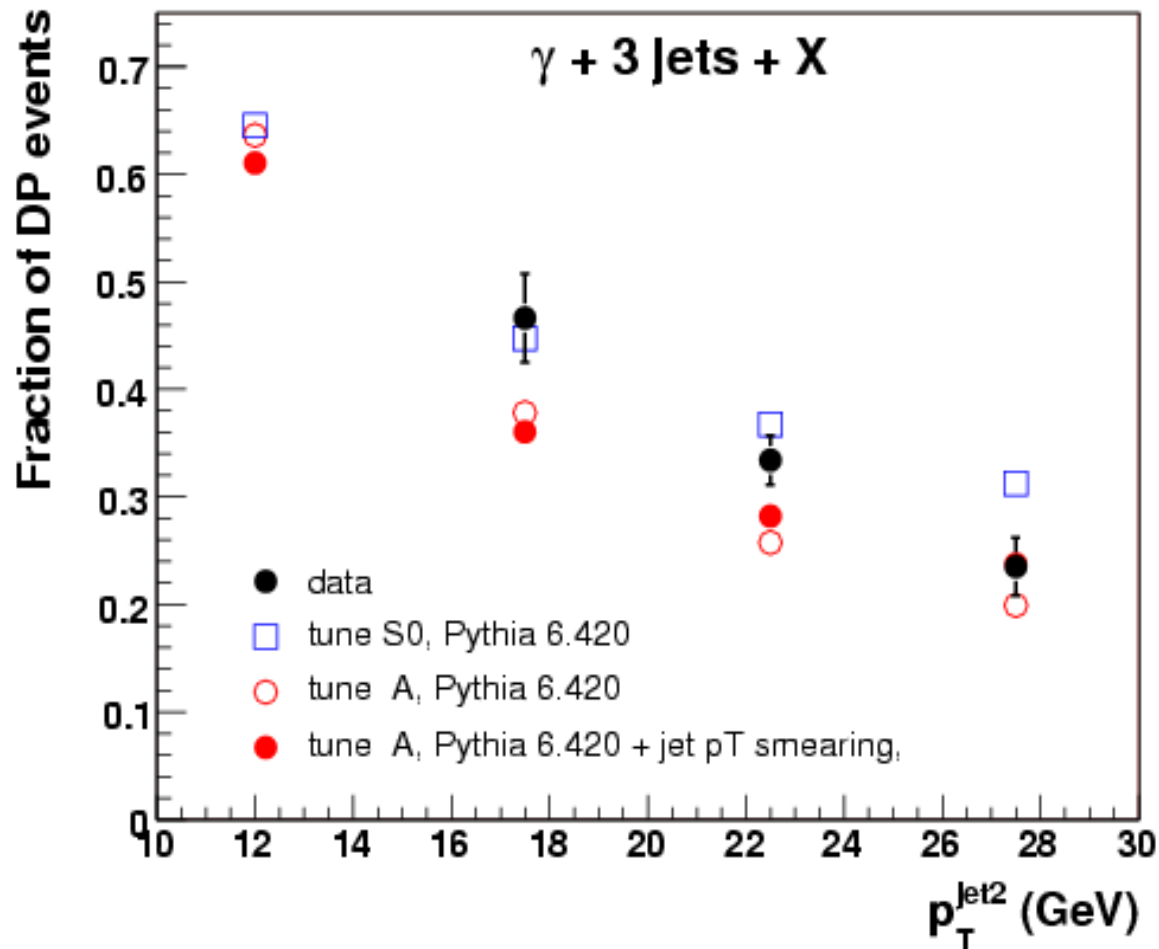


To be compared with bottom right plots from the previous 2 slides.

# Fractions of DP events



# Fractions of DP events extracted from the $\gamma+3$ jets events with different MPI models and in D0 data.



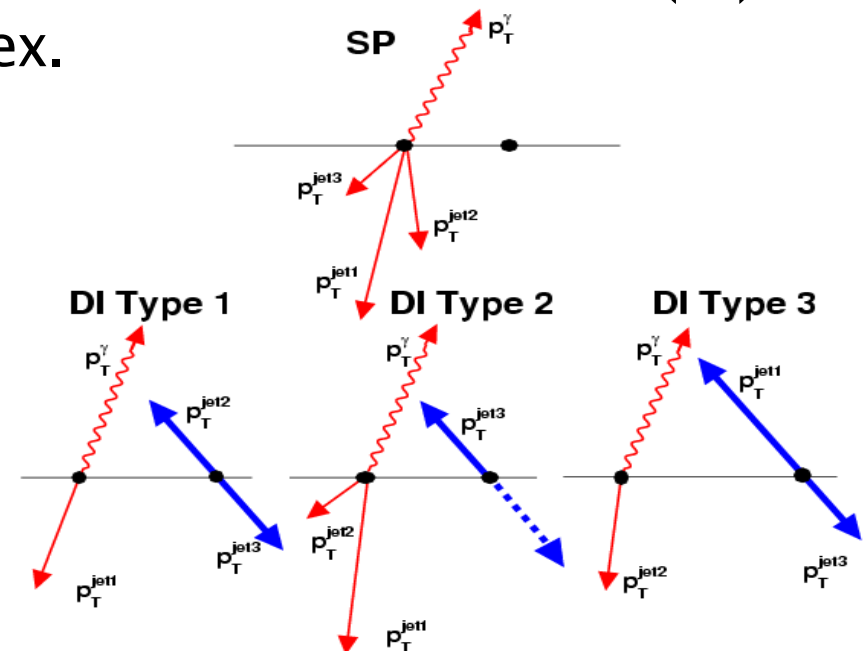
# The number (fraction) of DI events

Possible event classes can be defined according the jet origin vertex: 1<sup>st</sup> vertex (V1) or 2<sup>nd</sup> vertex (V2)

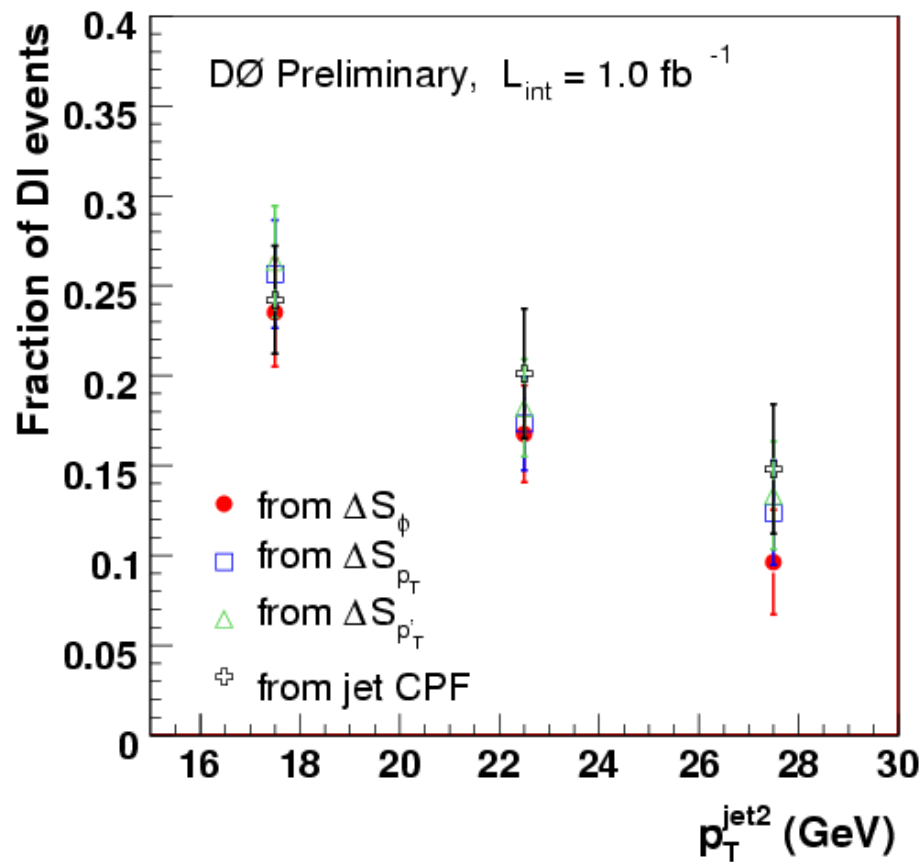
1. All three jets have originated from V1 or V2
2. Jet-1 and Jet-2 are from V1(V2) while Jet-3 is from V2(V1).
3. Jet-1 and Jet-3 are from V1(V2) while Jet-2 from V2(V1).
4. Jet-1 is from V1(V2) while Jet-2 and Jet-3 are from V2(V3).

Class (1) corresponds to “+3jets” coming from single ppbar collision, ie. same vertex. All other classes are events with double interactions (DI) in which 1 or 2 jets come from different vertex.

Fractions of DI events are found using the main distinguishing variables and cross checked using jet track information (looking at the vertex with largest track pT fractions).



# Fractions of DI events



# Photon and jet efficiencies

The difference in DI and DP efficiencies can be caused by different amount of underlying energy in the single and double ppbar collision events. As a result, one can expect different photon selection, jet reco and jet finding efficiencies as well as jet energy scale.

The jet efficiencies are calculated using MIXDP and MIXDI “ $\gamma+3$ jets” signal samples built in data. The ratios of DI/DP efficiencies are found to be varied as 0.58 – 0.55 for different 2<sup>nd</sup> jet pT. Systematics is relative 5.5%.

Photon efficiencies have been calculated in ' $\gamma+\geq 3$  jets' MC events with 1 and 2 vertices. Found ratio for 1VTX/2VTX events is  $0.96 \pm 0.03$ .

Agreement of photon purities has been checked separately using d-ijet QCD 1&2 VTX samples. The found ratio is  $0.99 \pm 0.06$ .

# Vertex efficiencies

- Distance to the detector center in Z :  $|Z| < 60\text{cm}$ ;
- The number of tracks associated with the vertex  $N_{\text{trk}}=3$ .

The vertex efficiency corrects for single (double) collision events that are lost in the DP (DI) candidate sample.

We found that both, 1- and 2-vertex, efficiencies do not depend on 2<sup>nd</sup> jet  $p_T$  and have similar luminosity dependencies.

We found the ratio  $2\text{vtx}/1\text{vtx} = 1.08 \pm 0.01$ .

## $N_c(n)$ and $\sigma_{hard}$

It is calculated from the expected average number of hard interactions at a given instantaneous luminosity  $L_{inst}$ :

$$\bar{n} = (L_{inst} / f_0) \sigma_{hard}$$

using Poisson statistics.

Here:

$f_0$  is frequency of beam crossings at the Tevatron in RunII.

$\sigma_{hard}$  is hard (non-elastic, ND) ppbar cross section.

$\sigma_{hard}$  can be obtained from the total inelastic cross section (FERMILAB-TM-2365)  $\sigma_{inel} = 60.7 \pm 2.4$  mb and single, double diffractive cross sections measured by CDF at  $\sqrt{s} = 1.8$  TeV ( $\sigma_{sd} = 9.46 \pm 0.44$  mb,  $\sigma_{dd} = 6.42 \pm 1.70$  mb) and extrapolated to  $\sqrt{s} = 1.96$  TeV.

Then  $\sigma_{hard}(1.96 \text{ TeV}) = 44.76 \pm 2.89$  mb.

$N_c(n)$  can be calculated using RunIIa luminosity profile using either averaged  $L_{inst}$  or integrating over the  $L_{inst}$  profile and summing  $N_c(1)$  and  $N_c(2)$  in all  $L_{inst}$  bins. The both methods give about the same result. The 2<sup>nd</sup> method is taken as default and it gives

$$R_C = \frac{N_C(1)}{2N_C(2)} \sigma_{hard} = 52.3 \text{ mb}$$

Variation of  $\sigma_{hard}$  within uncertainty (3.1 mb) gives the uncertainty for  $R_C \sim 1.0$  mb.

# Calculation of $\sigma_{\text{eff}}$

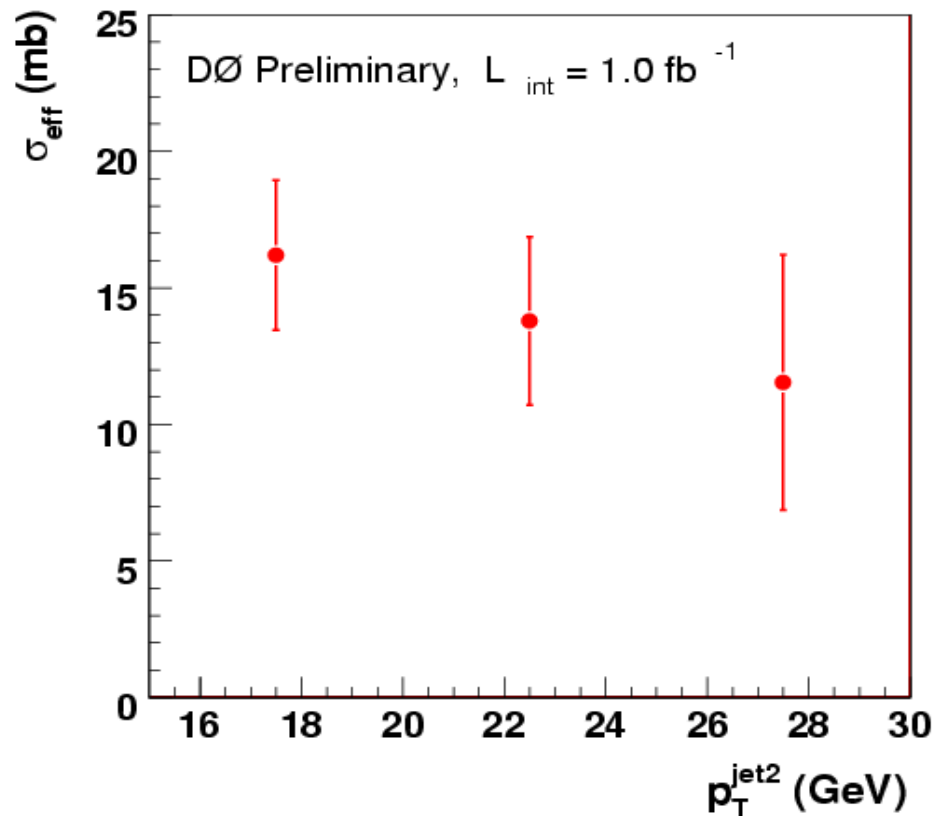
We sum up all together and calculate  $\sigma_{\text{eff}}$  in the three bins of 2<sup>nd</sup> jet pT:

TABLE IV: Effective cross section  $\sigma_{\text{eff}}$  (mb) found in the three  $p_T^{\text{jet}2}$  intervals (GeV).

$\sigma_{\text{eff}}$	15 – 20	20 – 25	25 – 30
$p_T^{\text{jet}2}$	$16.2 \pm 2.8$	$13.8 \pm 3.1$	$11.5 \pm 4.7$

TABLE V: Systematic and statistical uncertainties (in %) for  $\sigma_{\text{eff}}$ .

$p_T^{\text{jet}2}$ (GeV)	$f_{\text{DP}}$	$f_{\text{DI}}$	$\epsilon_{\text{DI}}/\epsilon_{\text{DP}}$	JES	$R_c \cdot \sigma_{\text{hard}}$	Syst. Total	Stat. Total	Exp. Total
15 – 20	8.8	11.5	6.5	5.5	2.0	16.9	2.8	17.1
20 – 25	6.9	20.0	6.5	2.0	2.0	22.3	2.3	22.5
25 – 30	11.4	38.2	6.5	3.0	2.0	40.6	2.5	40.6



We can state that  $\sigma_{\text{eff}}$  values in different jet  $p_T$  bins agree with each other within their uncertainties. Using this fact and also that syst. uncertainties between  $p_T$  bins have very small correlation one can calculate averaged value:

$$\sigma_{\text{eff}} = 15.1 \pm 1.9 \text{ mb}$$

# Summary

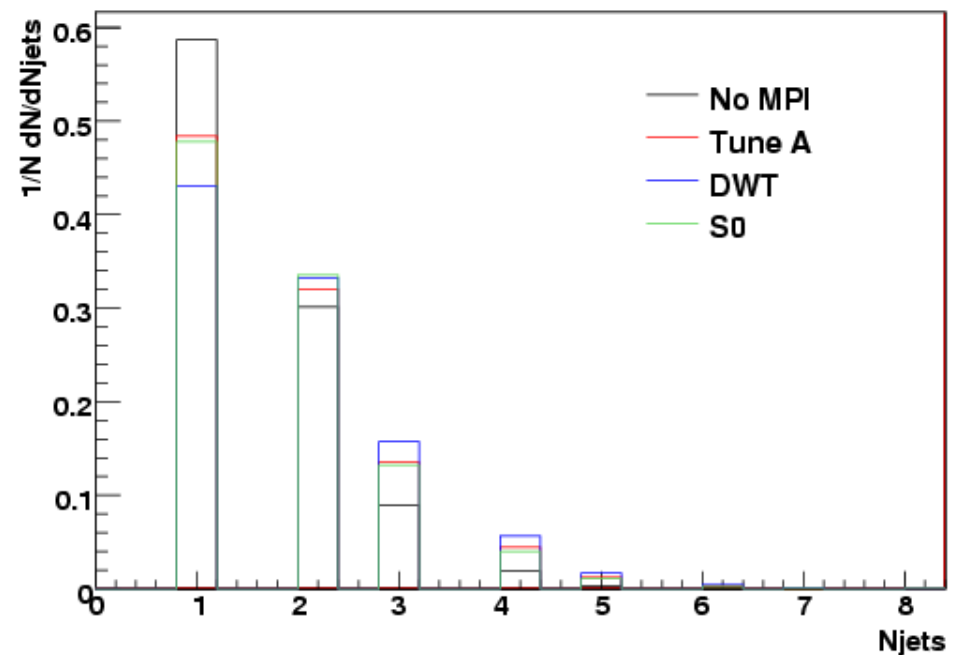
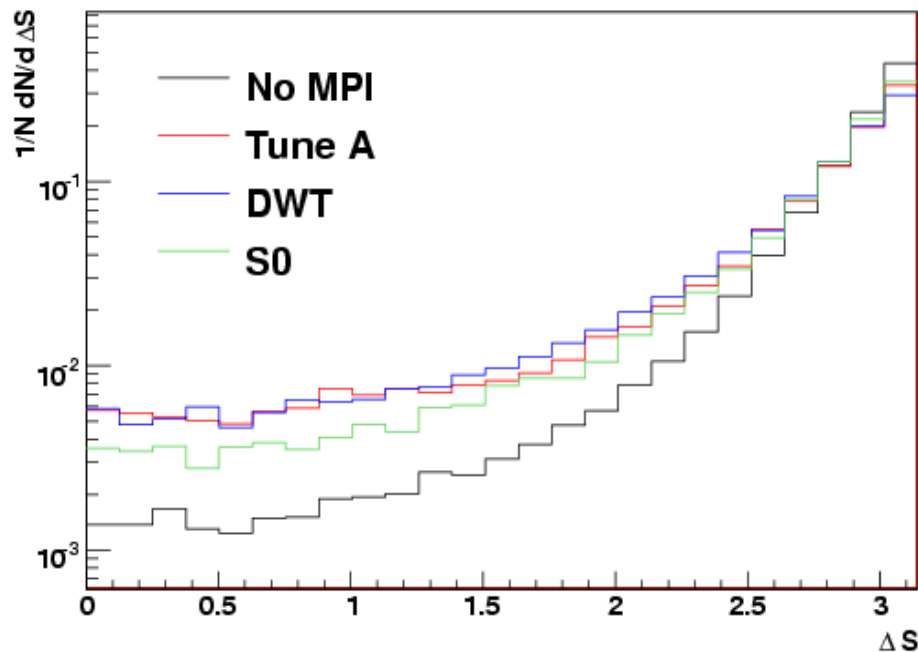
In the current analysis we have measured:

- DP fractions in three jet  $p_T$  intervals: 15-20, 20-25, 25-30 GeV). It drops from about 0.46 at  $15 < p_T < 20$  GeV to 0.22 at  $25 < p_T < 30$  GeV.
- Effective cross section  $\sigma_{\text{eff}}$  has been measured in the same jet  $p_T$  bins and found to be stable within uncertainties.
- Results are consistent with previous two CDF, UA2 (AFS?) measurements.

These facts indicate a stable behavior of  $\sigma_{\text{eff}}$  w.r.t. the transverse momentum of the jet produced in the second parton-parton interaction.

# BACK-UP SLIDES

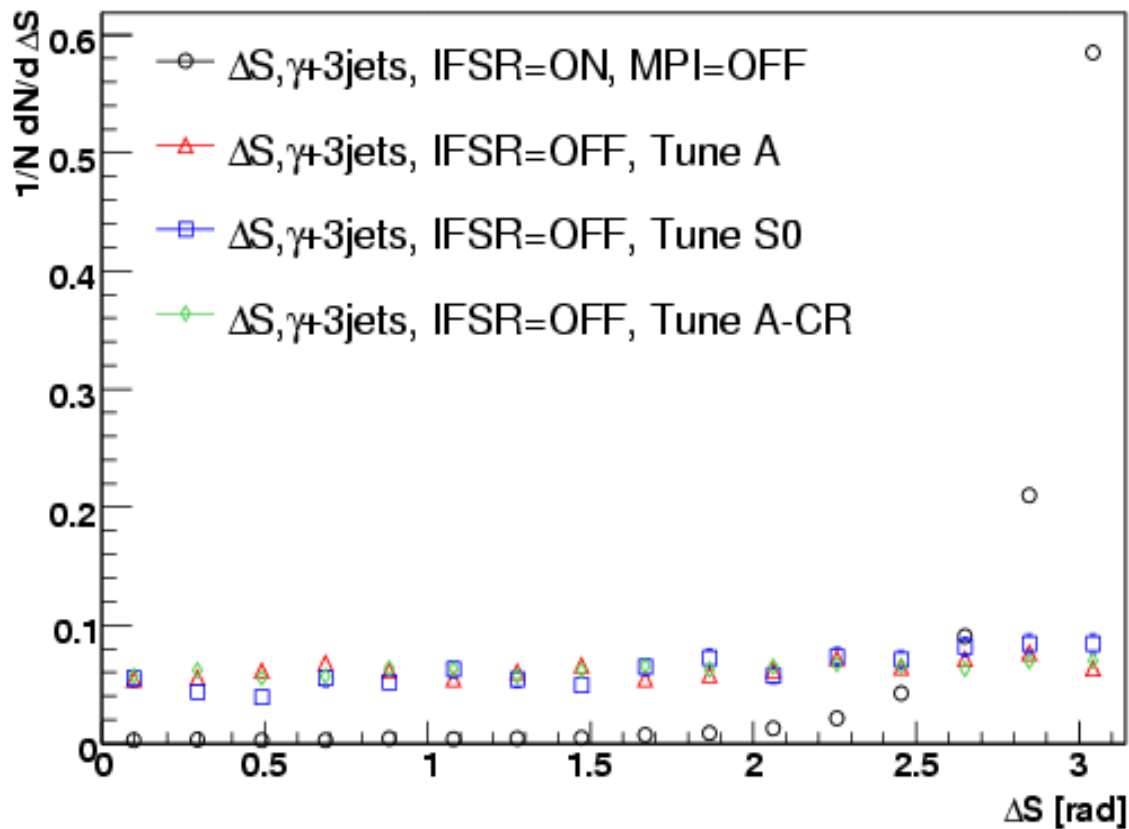
# Pythia MPI Tunes: $\Delta S$ and Njets



## Pythia predictions with MPI tunes:

- $\Delta S$  is much broader for events with MPI events and almost flat at  $\Delta S < 1.5$
- $\#events(N_{jets} \geq 1) / \#events(N_{jets} \geq 3)$  is larger by a factor 2(!) for MPI events

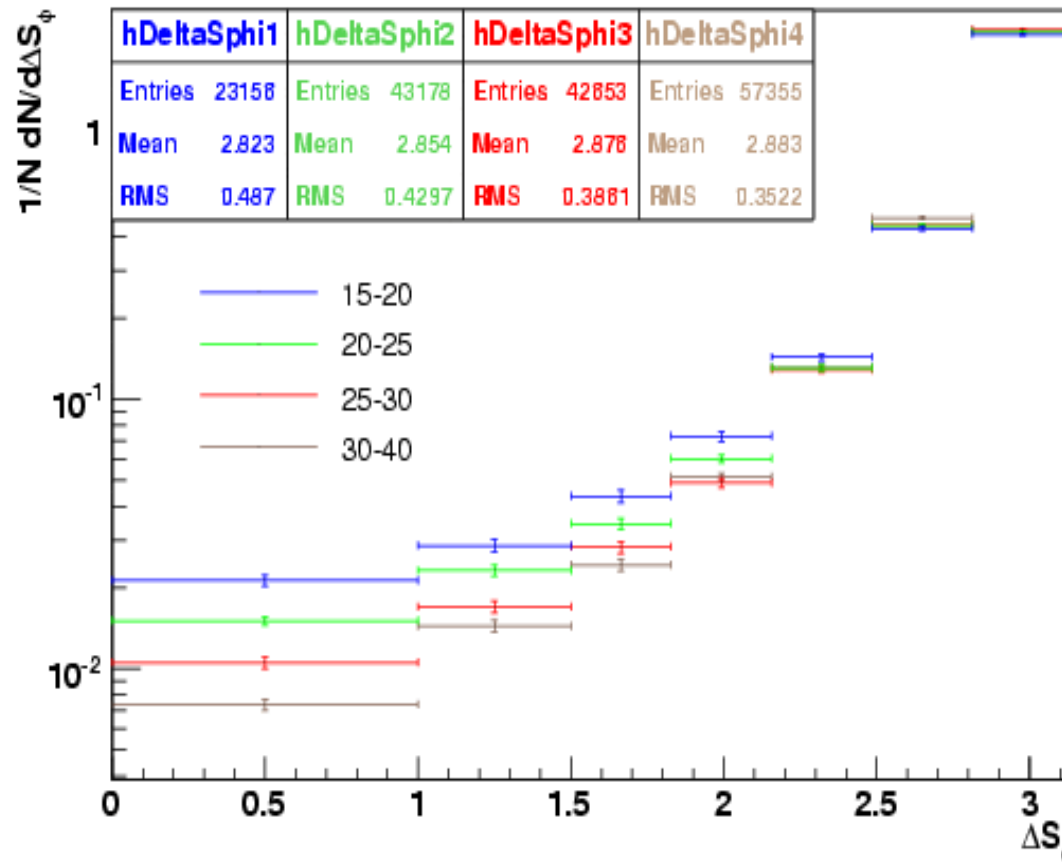
## $\gamma+3$ jets : Delta S for 3 MPI tunes vs. “no MPI”



- DeltaS for all the MPI tunes (A,S0, A-CR) is expected to be flat while for the single parton interactions (MPI is off) it peaks at .

# Extraction of $\lambda$ -factor

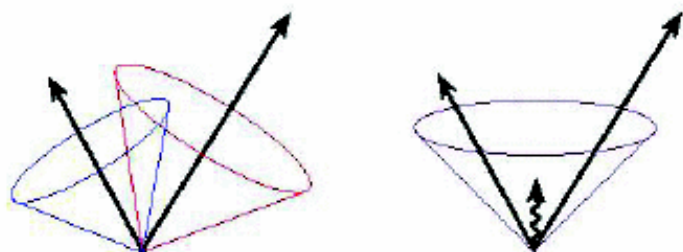
Factor is extracted as a ratio of the fits for  $\Delta S$ -family variables obtained from the SP (Pythia) background samples in each  $\Delta S$  bin of the adjacent 2<sup>nd</sup> jet pT intervals.



$\Delta S$  shifts more to with growing 2<sup>nd</sup> jet pT since they become less sensitive to the soft gluon radiation.

# Jet finding algorithm

- Detailed comparison to theory needs a precise definition of jet algorithm
- This measurement uses Run II Midpoint Cone with  $R_{\text{cone}} = 0.7$



## Run I Legacy Cone:

Draw a cone of fixed size in  $\eta$ - $\phi$  space around a seed

Compute jet axis from  $E_T$ -weighted mean and jet  $E_T$  from  $\sum E_T$ 's

Draw a new cone around the new jet axis and recalculate axis and new  $E_T$

Iterate until stable

Algorithm is **sensitive to soft radiation**

## Run II Midpoint Cone:

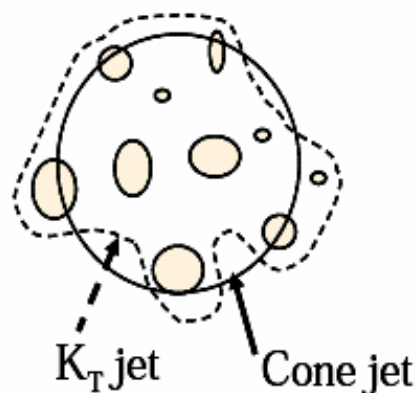
Use 4-vectors instead of  $E_T$

Add additional midpoint seeds between pairs of close jets

Split/merge after stable protojets found

**Improved infrared safety at NLO**

**(D0 Run II/CDF MIDPOINT)**



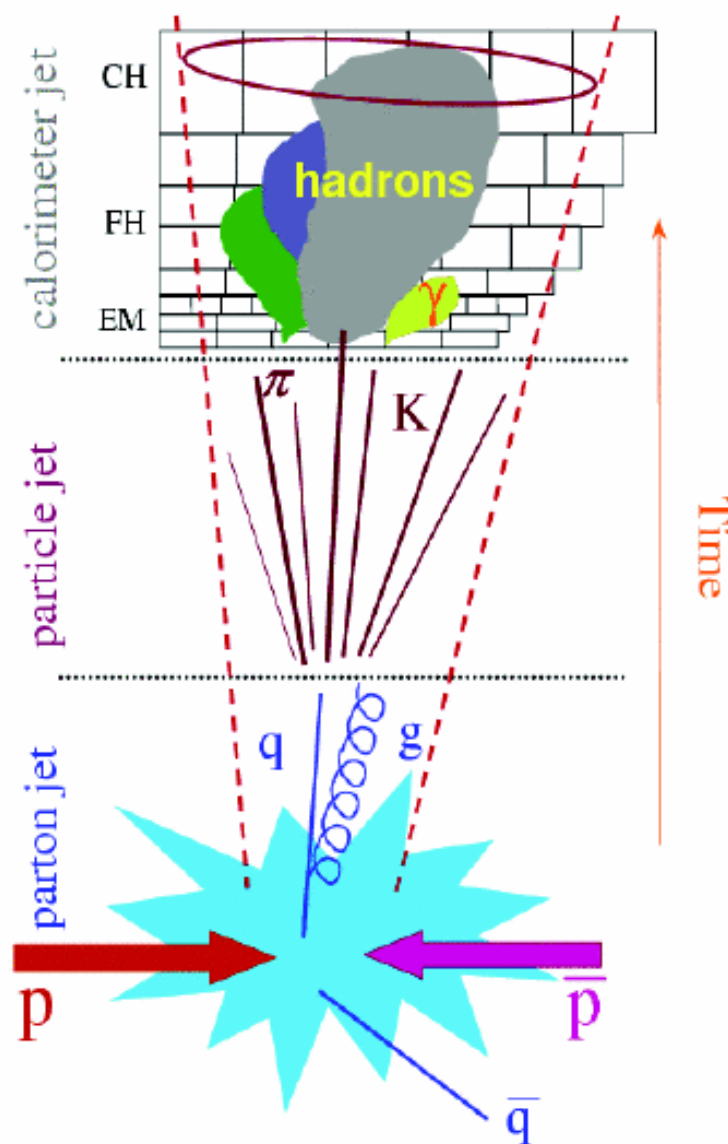
**We characterize jets in terms of  $p_T$  and  $y$**

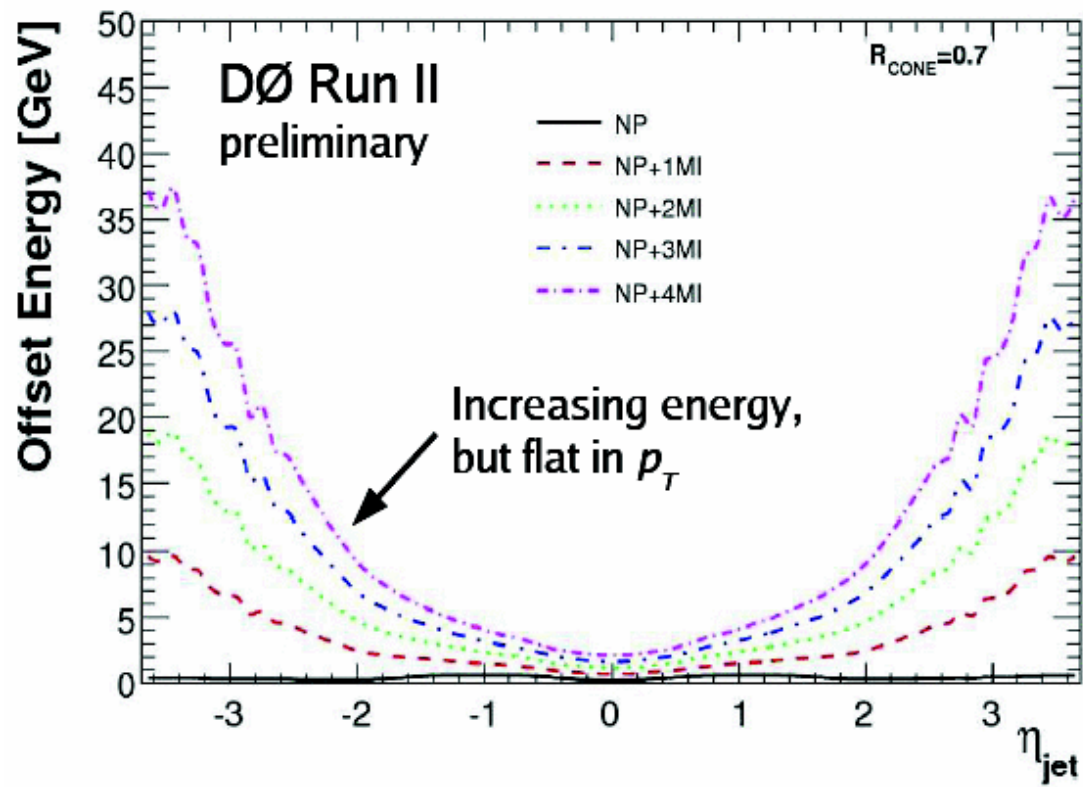
# Jet energy scale

- Jet Energy Scale returns the measured calorimeter jet **energy** to the **particle level**

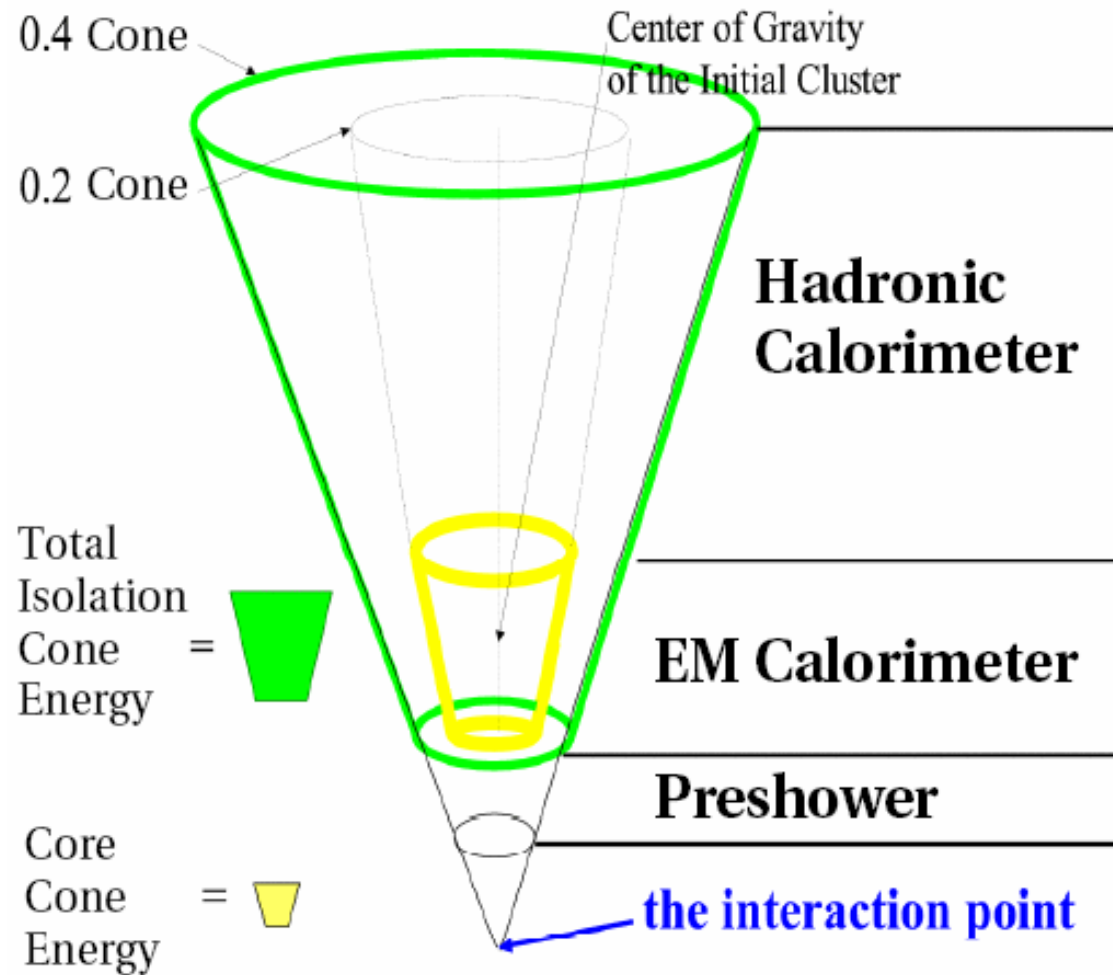
$$E_{ptcl} = \frac{E_{cal} - \text{Offset}}{(F_{\eta} \cdot R) \cdot S} \cdot k_{bias}$$

- Offset is energy not associated to the hard scatter: noise, pile-up, **multiple interactions**
- Response is the fraction of particle jet energy deposited in the calorimeter by the particles
- Detector showering accounts for **energy flow** in and out of the calorimeter jet due to detector effects (finite calorimeter tower and hadron shower size, magnetic field)
- Method biases corrected using tuned MC





# Photon Isolation



## Calorimeter Criteria

Fractional isolation



EM energy fraction



Energy shower  $\phi$  width

