STUDIES OF MULTI-PARTON INTERACTIONS IN PHOTON + JETS EVENTS AT DØ

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for DØ Collaboration

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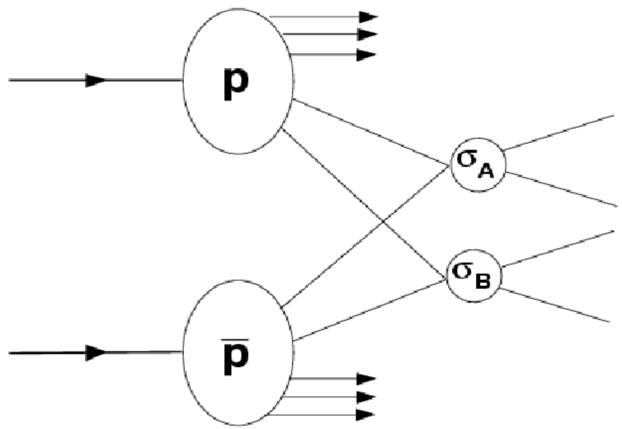
OUTLINE



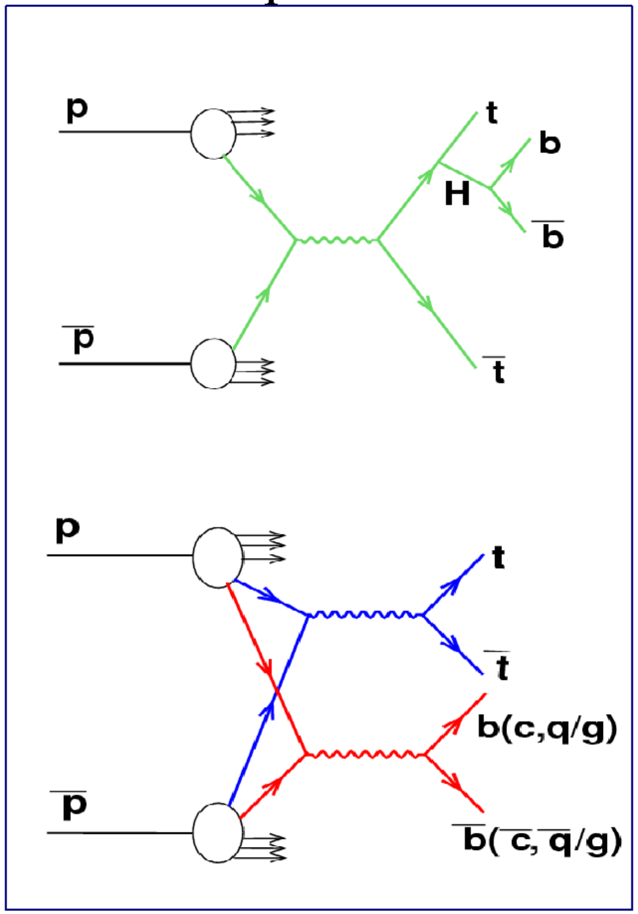
- Motivations
- Event topology
- Discriminating variables
- Fraction of the events with Double Parton interactions
- Effective cross-section measurement
- Comparison/tuning to MPI models
- Summary

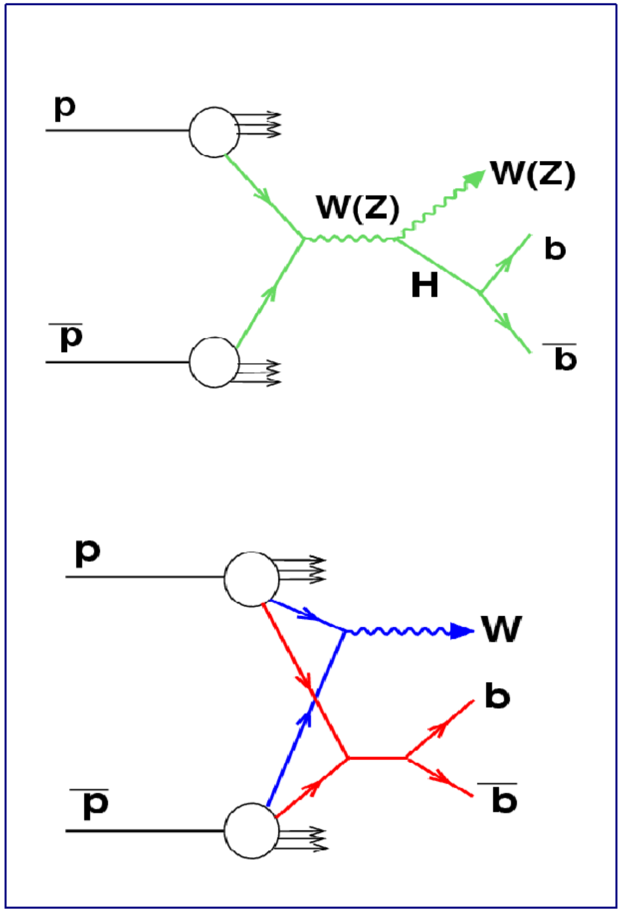
MOTIVATION TO STUDY DP EVENTS

- New and complementary information about proton structure:
  - spatial distribution of the partons within proton;
  - possible parton-parton correlations.
- Needed for an understanding of nature of signal events and correct estimating of background to many rare processes especially with multi-jet final state, for example SM Higgs and SUSY productions.

Higgs signal

DP bkgd.



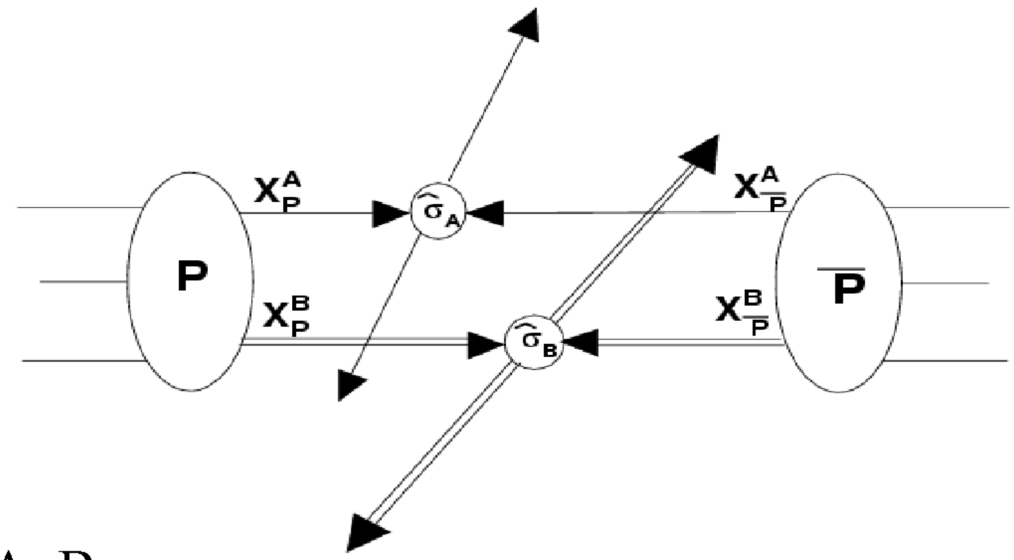


Each Higgs production channel can be accompanied by Double Parton background event!
Some of them can be significant even after current signal selections.

Same is true for many other rare processes!

DOUBLE PARTON AND EFFECTIVE CROSS SECTION

$$\boxed{\sigma_{DP} = \frac{\sigma_A \sigma_B}{\sigma_{eff}}}$$



σ_{DP} - Double Parton cross section for processes A and B.

σ_A, σ_B - cross section of any processes A, B.

σ_B / σ_{eff} - probability of 2nd interaction B with process A has already happened.

σ_{eff} - factor characterizing size of the effective interaction region.

σ_{eff} contains information about the parton spatial density distribution:

Uniform parton distribution: σ_{eff} is large and σ_{DP} is small;

Clumpy parton distribution: σ_{eff} is small and σ_{DP} is large.

HISTORY OF THE MEASUREMENTS

Experiment	$\sqrt{s}$ (GeV)	Final state	p_T^{min} (GeV)	η range	$\sigma_{\rm eff}$
AFS (pp), 1986	63	4 jets	$p_{\rm T}^{\rm jet} > 4$	$\lvert\eta^{\rm jet}\rvert < 1$	~ 5 mb
UA2 ($p\bar{p}$), 1991	630	4 jets	$p_{\rm T}^{\rm jet} > 15$	$\lvert\eta^{\rm jet}\rvert < 2$	> 8.3 mb (95% C.L.)
CDF ($p\bar{p}$), 1993	1800	4 jets	$p_{\rm T}^{\rm jet} > 25$	$\lvert\eta^{\rm jet}\rvert < 3.5$	$12.1^{+10.7}_{-5.4}$ mb
CDF ($p\bar{p}$), 1997	1800	$\gamma + 3$ jets	$p_{\rm T}^{\rm jet} > 6$ $p_{\rm T}^{\gamma} > 16$	$\lvert\eta^{\rm jet}\rvert < 3.5$ $\lvert\eta^{\gamma}\rvert < 0.9$	$14.5 \pm 1.7^{+1.7}_{-2.3}$ mb
DØ ($p\bar{p}$), 2010	1960	$\gamma + 3$ jets	$60 < p_T^{\gamma} < 80$ $15 < p_T^{\rm jet2} < 30$	$\lvert\eta^{\gamma}\rvert < 1.0$ || $1.5 < \lvert\eta^{\gamma}\rvert < 2.5$ $\lvert\eta^{jet}\rvert < 3.0$	$\sigma_{eff} = 16.4 \pm 0.3(\text{stat}) \pm 2.3(\text{syst})$ mb

D0, Phys. Rev. D81, 052012(2010)

AFS'86, UA2'91 and CDF'93

choose 4-jets sample motivated by a large dijet cross section.

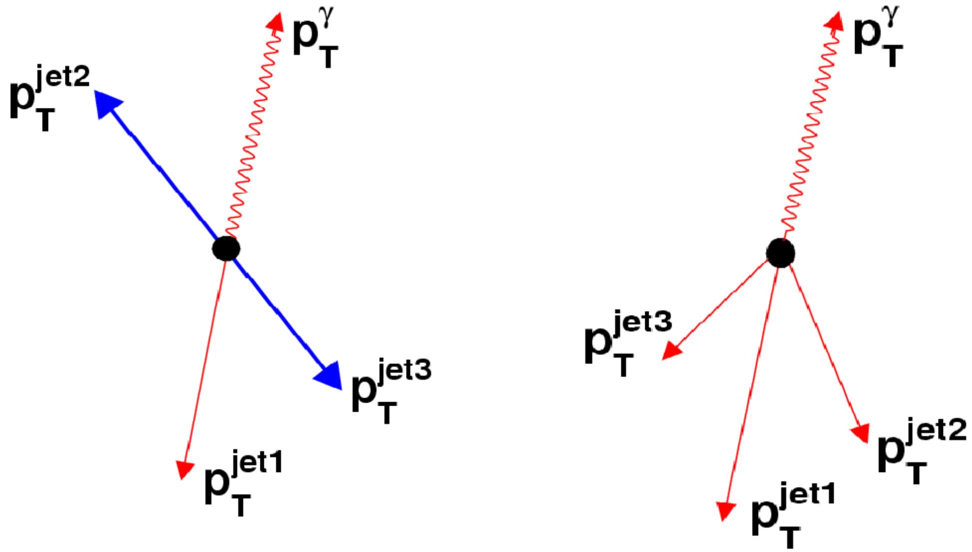
CDF’97, D0’10

γ+3jets events, data-driven method:

use rates of Double Interaction (two separate ppbar collisions) and Double Parton (single ppbar collision) to extract σ_{eff} from their ratio.

It reduces dependence on Monte-Carlo and NLO QCD theory predictions.

DOUBLE PARTON EVENTS TOPOLOGY



Signal

Double Parton (DP) 1-vtx production: 1st parton process produces γ-jet pair; 2nd process produces dijet pair.

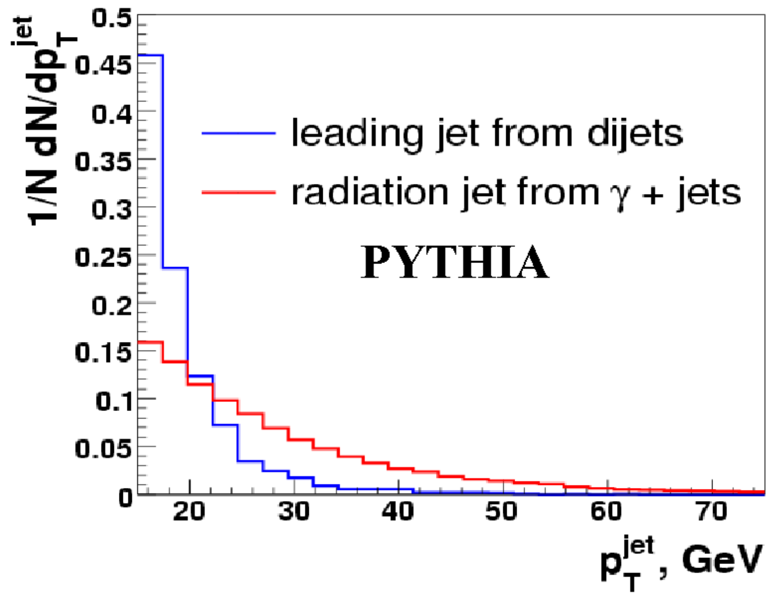
Background

Single Parton (SP) 1-vtx production: single hard γ-jet scattering with 2 radiation jets.

MOTIVATION OF CHOOSING 2nd JET pT BINNING

Jet pT from dijets falls much faster than that for radiation jets, i.e.
→ Fraction of dijet (Double Parton) events should drop with increasing jet pT.

Measurement is done in three bins of p_T^{jet2} :
15-20, 20-25, 25-30 GeV (serves as a pT scale of the 2nd parton interaction).



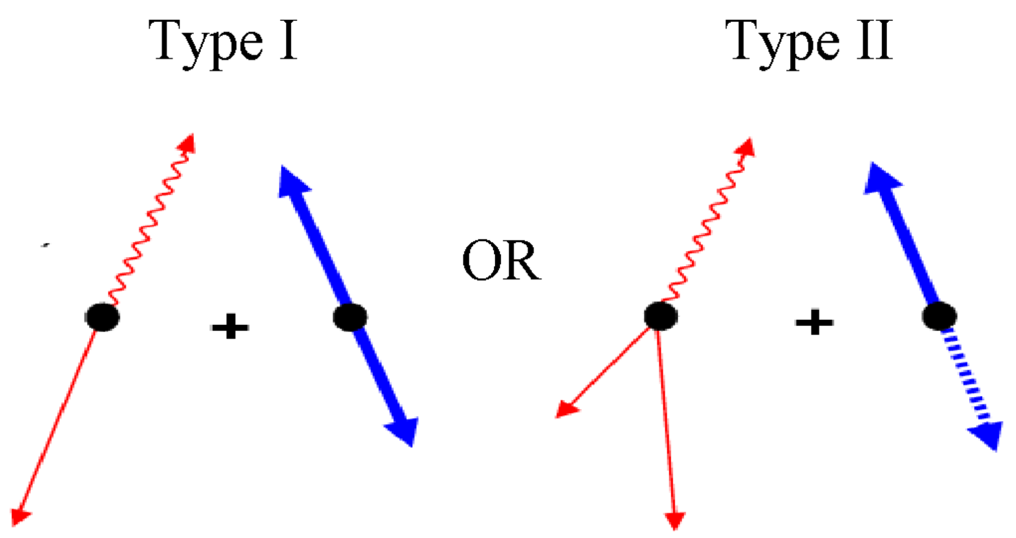
DOUBLE PARTON MODEL

DOUBLE PARTON MODEL built from D0 data.

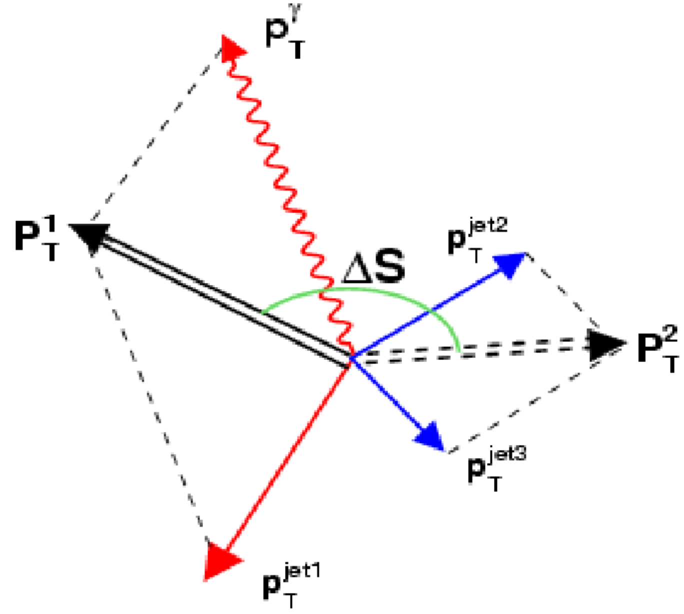
A: γ + $\geq$1 jets from 1-vertex γ + jets data events;
B: $\geq$1 jets from 1-vertex dijet events.

- A & B samples have been (randomly) mixed;
- jets have been re-arranged (in pT decreasing order).
- Events should satisfy γ + $\geq$3 jets requirement.
- ΔR(any objects pair)>0.7

Two scatterings are independent by construction.



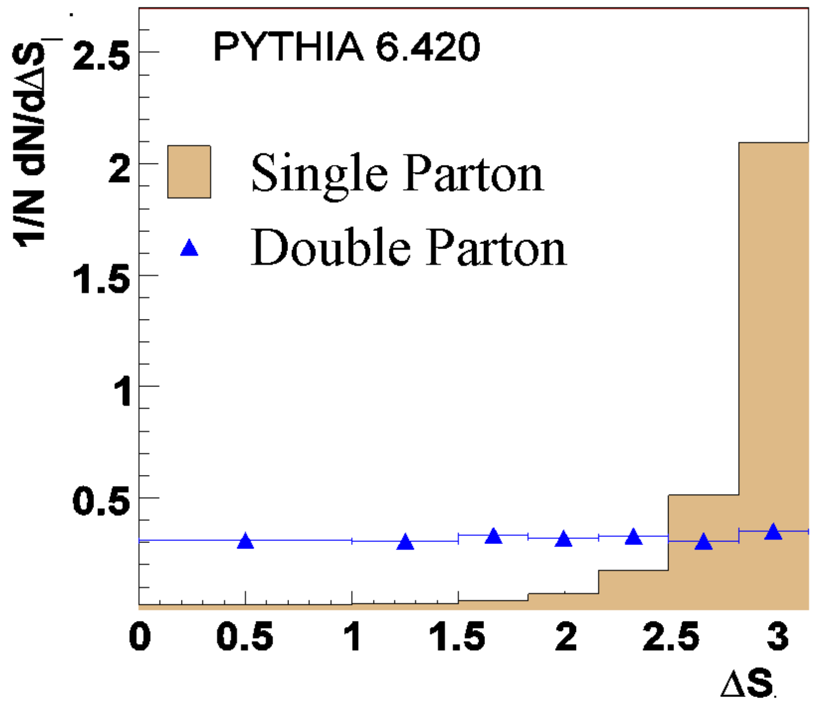
One jet from dijets can be not reconstructed or beyond the kinematics region.
Type II is dominated in our measurement.



ΔS variable:

$$\Delta S \equiv \Delta\phi\left(\vec{p}_T(\gamma, i),\ \vec{p}_T(j,k)\right)$$

$\Delta\phi$ - an azimuthal angle between two pT-balanced pairs.

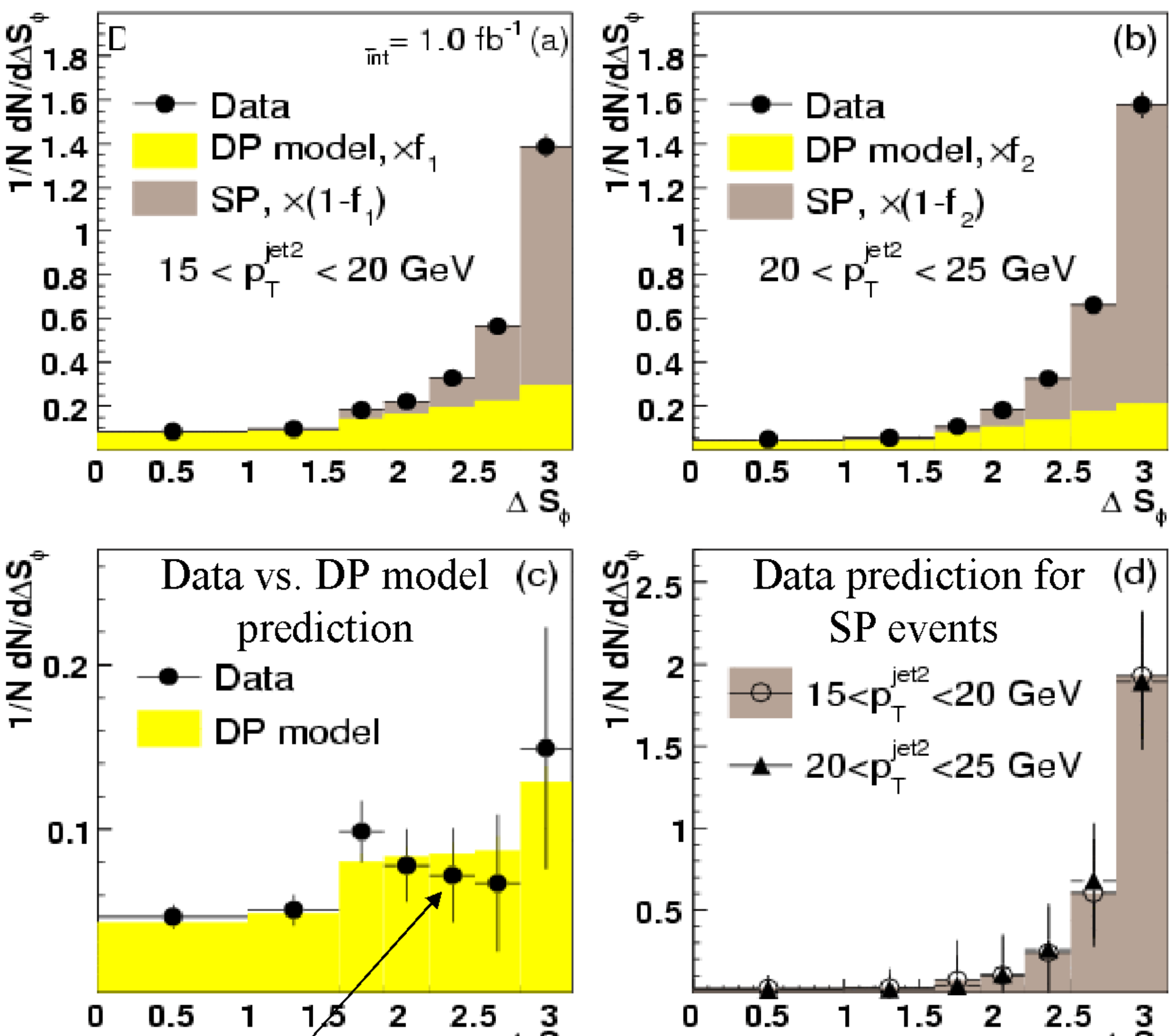


In Single Parton events ΔS is expected to peak at π due to the pT conservation in an event, while in Double Parton events it should be flat due to the independence of two parton interactions.

In practice, one of the dijet jets can be replaced by a radiation jet with a larger pT what makes ΔS distribution less flat with a bump closer to π.

THE TWO DATASETS METHOD

Dataset 1 - "DP-rich", bin 15-20 GeV
Dataset 2 - "DP-poor", bin 20-25 GeV



Data are corrected to remove the SP contribution

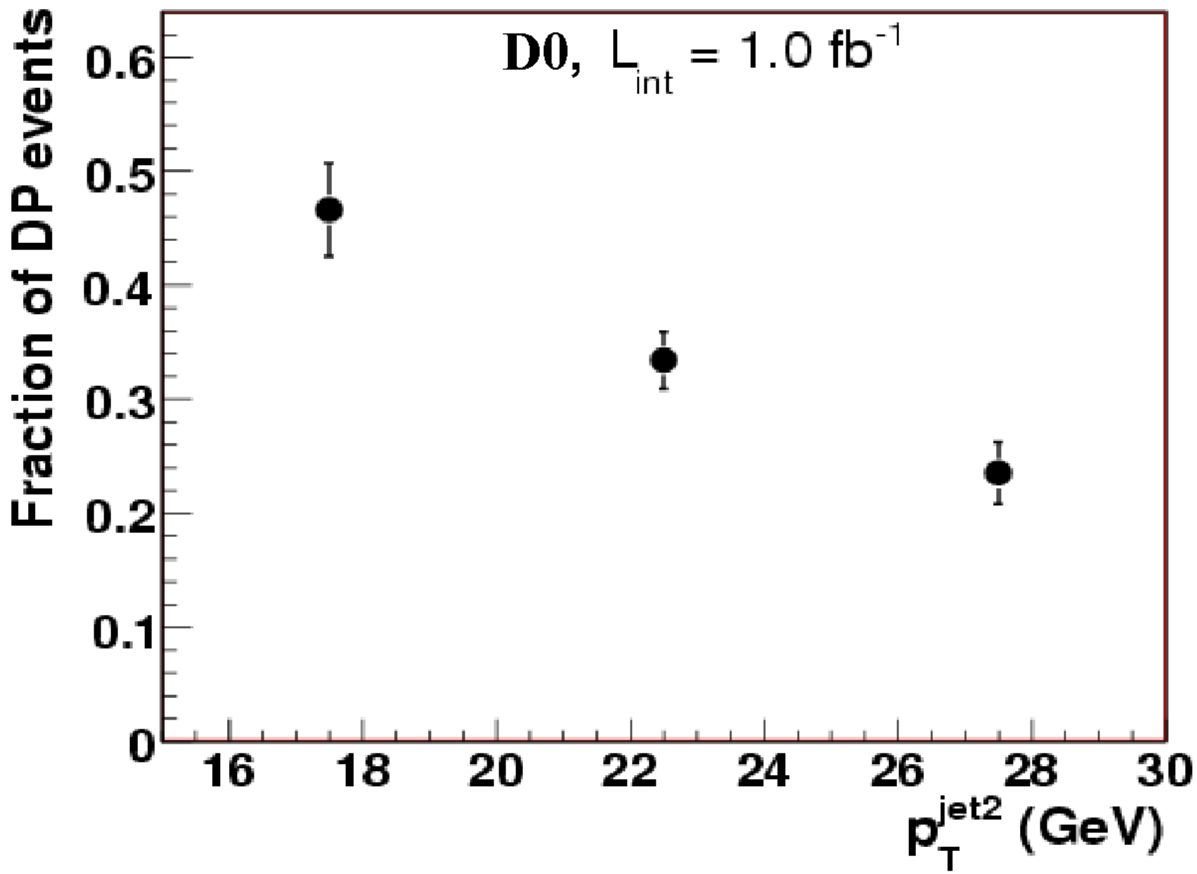
Each distribution can be expressed as a sum of DP and SP.

$$D_1 = f_1 \times DP_1 + (1 - f_1) \times SP_1$$
$$D_2 = f_2 \times DP_2 + (1 - f_2) \times SP_2$$

Fraction of Double Parton in bin 15-20 GeV (f_1) is the only unknown
→ get from minimization.

a) Distributions for the 1st dataset: data, DP model weighted by found fraction f_1 and SP contribution.
b) Distributions for the 2nd dataset: data, DP model weighted by fraction and SP contribution.
c) Residuals of the two dataset distributions of Data and DP model prediction in two datasets.
d) Extracted SP distributions in the two datasets, obtained by subtracting the DP contribution from the Data.

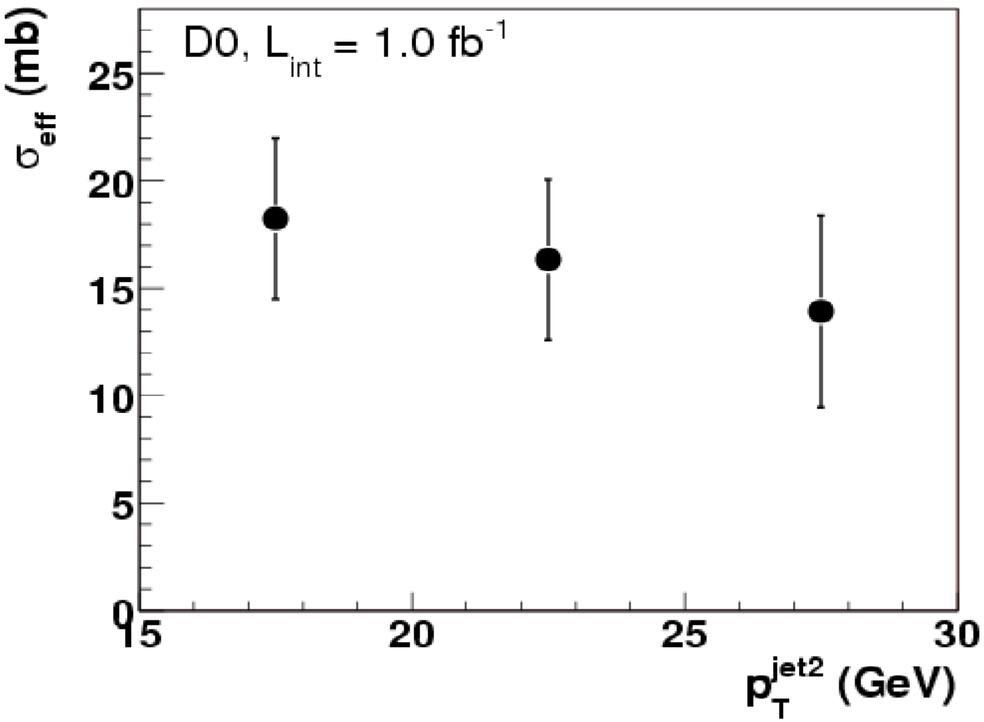
FRACTIONS OF DOUBLE PARTON EVENTS



Fractions drop from ~46-48% at $15 < p_T^{jet\,2} < 20$ GeV to ~22-23% at $25 < p_T^{jet\,2} < 30$ GeV with relative uncertainties ~7-12%.

CDF Run I: 53±3% at 5-7 GeV of (uncorr.) jet pT

CALCULTAION OF σ_{eff}



σ_{eff} values in different $p_T^{jet\,2}$ bins agree with each other within their uncertainties (also compatible with a slow decrease with pT). Uncertainties have very small correlations between $p_T^{jet\,2}$ bins.

One can calculate the average (weighted by uncertainties) values over $p_T^{jet\,2}$ bins:

$$\sigma_{eff}^{ave} = 16.4 \pm 0.3(stat) \pm 2.3(syst)\ \ mb$$

CDF Run I: σ_{eff} is $14.5 \pm 1.7^{+1.7}_{-2.3}$ mb

Main systematic and statistical uncertainties (in %) for σ_{eff}.

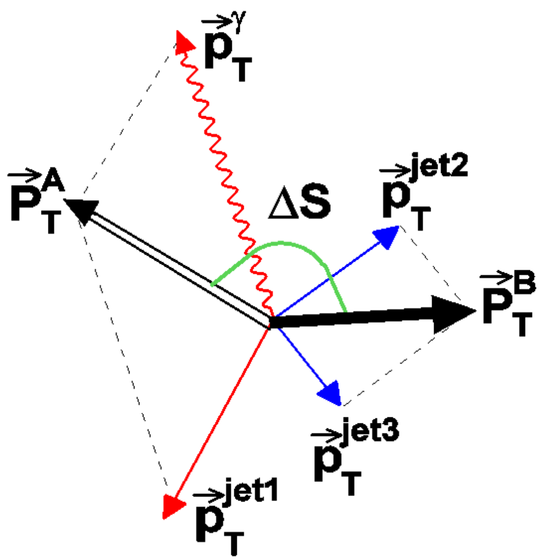
$p_T^{\rm jet2}$ (GeV)	Systematic uncertainty sources $f_{\rm DP}$	$f_{\rm DI}$	$\varepsilon_{\rm DP}/\varepsilon_{\rm DI}$	JES	$R_c\sigma_{\rm hard}$	$\delta_{\rm syst}$ (%)	$\delta_{\rm stat}$ (%)	$\delta_{\rm total}$ (%)
15 – 20	7.9	17.1	5.6	5.5	2.0	20.5	3.1	20.7
20 – 25	6.0	20.9	6.2	2.0	2.0	22.8	2.5	22.9
25 – 30	10.9	29.4	6.5	3.0	2.0	32.2	2.7	32.3

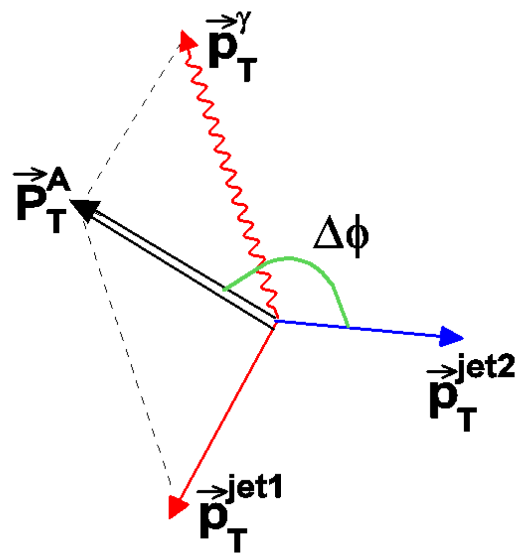
TUNING MPI MODELS

Motivations:

By measuring **differential** cross sections vs. the azimuthal angles in γ+3(2) jet events we can better tune (or even exclude some) MPI models in events with high pT jets.

Differentiation in jet pT increases sensitivity to the models even further.



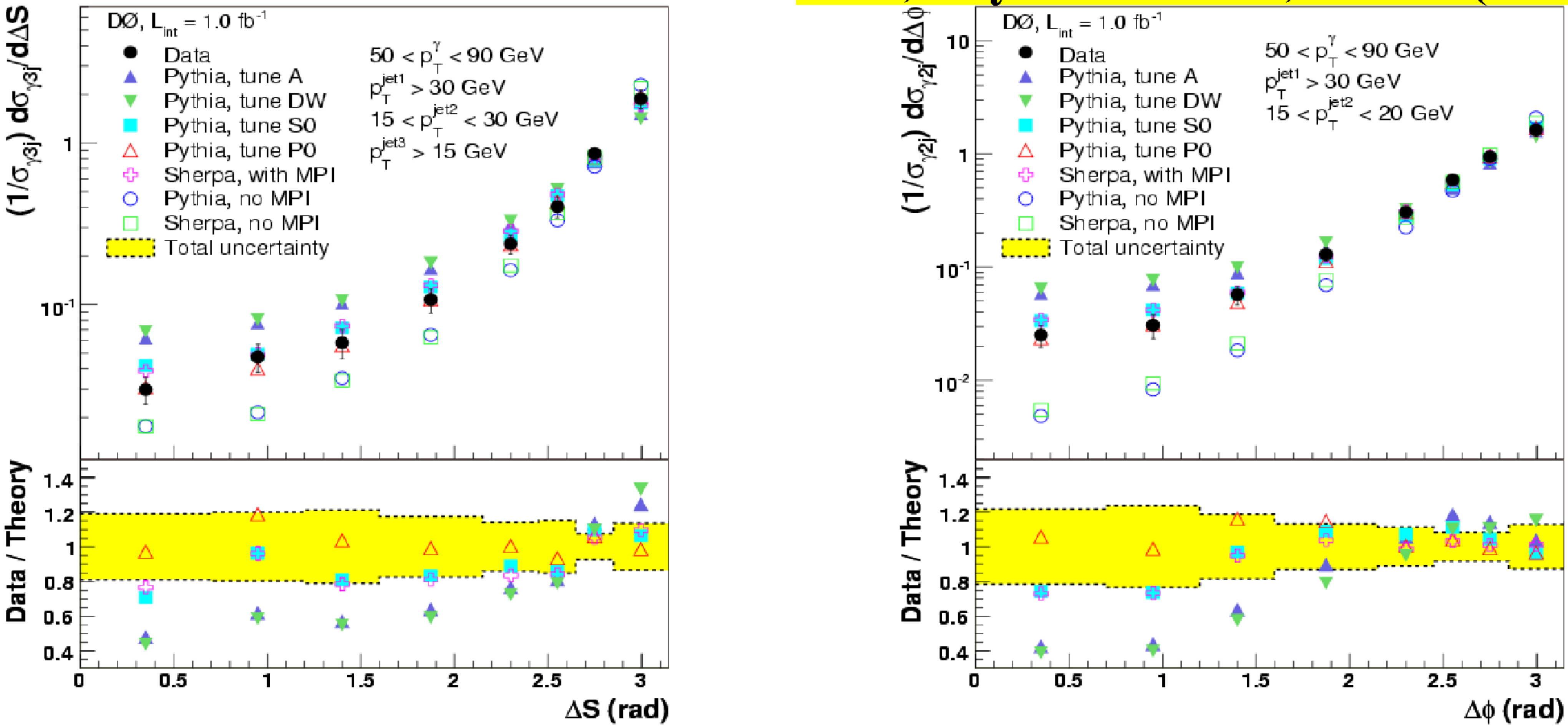


Four normalized differential cross sections are measured

- ΔS(γ+jet1, jet2+jet3) for $p_T^{jet\,2}$ 15-30 GeV (larger for stat. reasons but still has good sensitivity to MPI models)
- $\Delta\phi$ (γ+jet1, jet2) in 3 bins of $p_T^{jet\,2}$: 15-20, 20-25 and 25-30 GeV

CROSS SECTION

D0, Phys. Rev. D 83,052008 (2011)



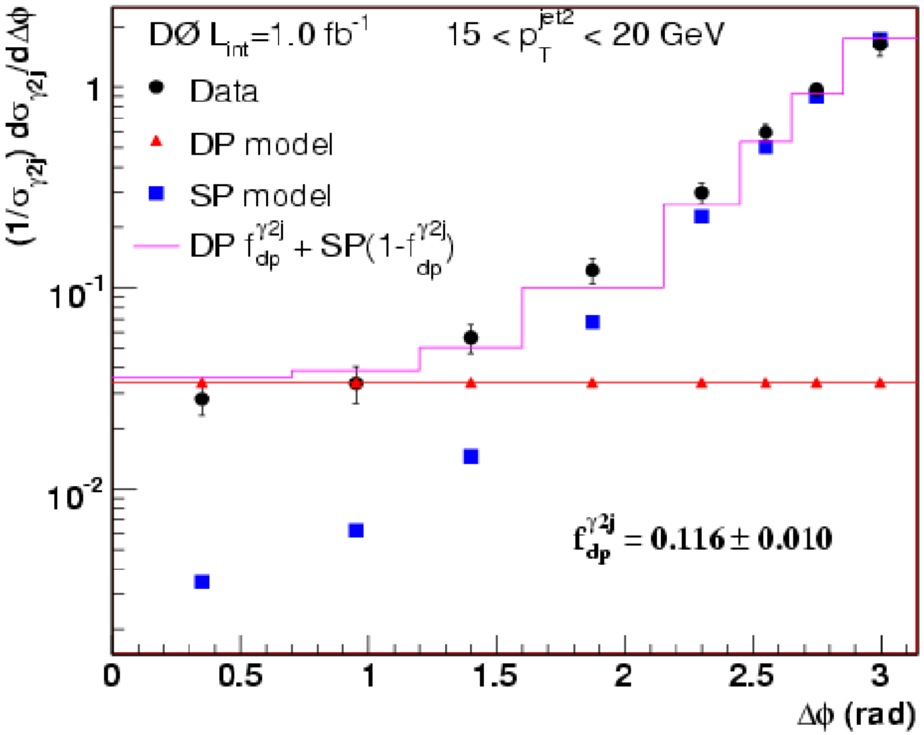
- MPI models substantially differ from any SP prediction.
- Large difference between SP models and data are confirm presence of DP events in the sample.
- Data are close to Perugia0 (P0), S0 and Sherpa MPI tunes.

The conclusion is valid for both the considered variables and all pT intervals!

DOUBLE PARTON FRACTIONS

- In γ+2 jet events in which 2nd jet is produced in additional independent parton interaction, $\Delta\phi$ (γ+jet1, jet2) distribution should be flat.
- Using this fact and also Single Parton prediction for $\Delta\phi$ (γ +jet1, jet2) we can get Double Parton fraction from fit to data.
- Sources of uncertainties: (a) syst+stat (~10-20%) for data cross sections and (b) SP models (~10-15%, Sherpa and Pythia).

DP fit for $15 < p_T^{jet\,2} < 20$ GeV



DP fractions and uncertainties in γ +2 jets

$p_T^{\rm jet2}$ (GeV)	$\langle p_T^{\rm jet2}\rangle$ (GeV)	$f_{\rm dp}^{\gamma 2j}$ (%)	Uncertainties (in %) Fit	$\delta_{\rm tot}$	SP model
$15-20$	17.6	11.6 ± 1.4	5.2	8.3	6.7
$20-25$	22.3	5.0 ± 1.2	4.0	20.3	11.0
$25-30$	27.3	2.2 ± 0.8	27.8	21.0	17.9

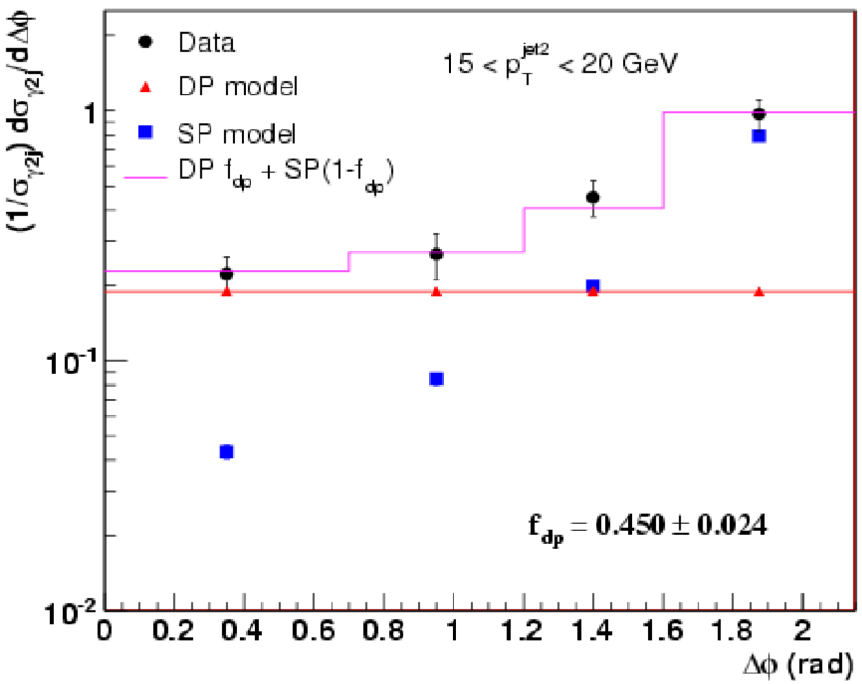
CDF Run I: 14^{+8}_{-7} % at jet pT > 8 GeV and photon pT > 16 GeV

DOUBLE PARTON FRACTIONS

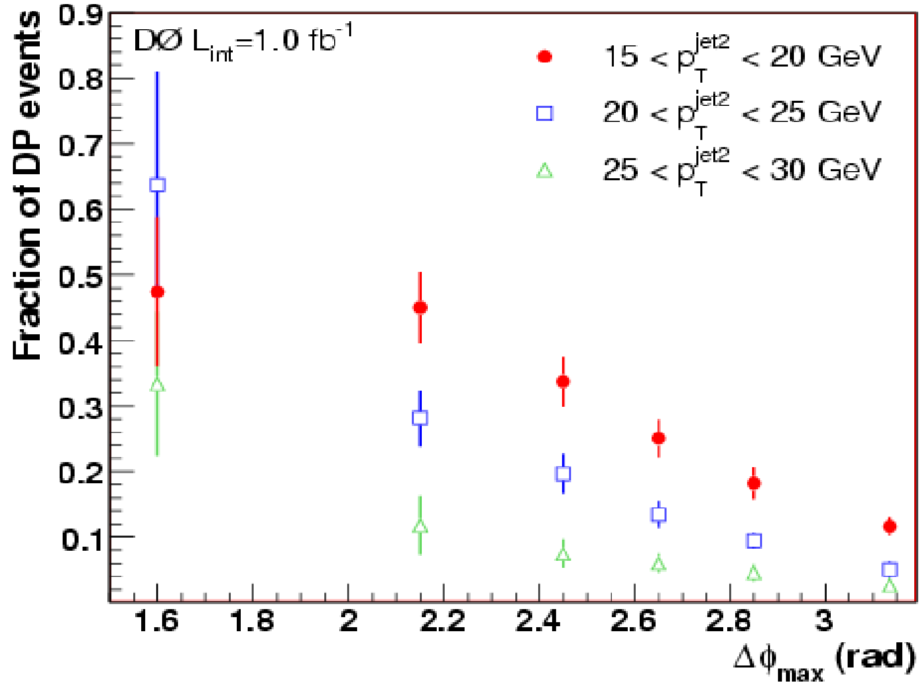
- Double Parton fractions should depend on $\Delta\phi$ (γ+jet1, jet2) intervals:
  the smaller $\Delta\phi$ angle the larger DP fraction.

- We can find this dependence by repeating the same fits in smaller $\Delta\phi$ regions.

DP fit for $15 < p_T^{jet\,2} < 20$ GeV, $0 < \Delta\phi < 2.15$



DP fractions as a function of the upper limit on $\Delta\phi$ for 3 bins of $p_T^{jet\,2}$



Fractions of Double Parton events increase toward to smaller angles and smaller jet PT.

SUMMARY

In the γ+3jets analysis we have measured:

- Fraction of Double Parton events in three $p_T^{jet\,2}$ intervals: 15-20, 20-25, 25-30 GeV. It varies from about 47% at 15-20 GeV to 23% at 25-30 GeV.

- Effective cross section (scale parameter, defines rate of Double Parton events) σ_{eff} in the same $p_T^{jet\,2}$ bins with average value:

$$\sigma_{eff}^{ave} = 16.4 \pm 0.3\,(stat) \pm 2.3\,(syst)\ mb$$

  The found σ_{eff} is in the range of those found in CDF measurements it might indicate a stable behaviour w.r.t. the energy scales in the parton scatterings.

- Normalized differential cross sections for ΔS(γ+jet1, jet2+jet3) and $\Delta\phi$ (γ+jet1, jet2). Data prefer the Sherpa and Pythia MPI models (P0, P0-X, P0-hard) with pT-ordered showers.

- Fraction of Double Parton events in γ+2jets: 11.6% at 15-20 GeV to 2.2% at 25-30 GeV.

- Fraction of Triple Parton events in γ+3jets: 5.5% at 15-20 GeV to 0.9% at 25-30 GeV.

THANKS FOR YOUR ATTENTION!

BACK-UP SLIDES

MEASUREMENT OF σ_{eff}

At two hard scattering events:

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

The number of DI events:

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

At one hard interaction:

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

Then the number of DP events:

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

Therefore one can extract:

$$\boxed{\sigma_{eff} = \frac{N_{DI}}{N_{DP}}\frac{N_C(1)}{2N_C(2)}\frac{A_{DP}}{A_{DI}}\frac{\varepsilon_{DP}}{\varepsilon_{DI}}\frac{\varepsilon_{1\mathrm{vtx}}}{\varepsilon_{2\mathrm{vtx}}}\sigma_{hard}}$$

SELECTION CRITERIA

VERTEX:

- $|Z|<60$cm,
- Ntrk>=3

JETS (pT corrected):

- Midpoint Cone algo with R=0.7
- $|\eta|<3.0$
- #jets ≥ 3
- pT of any jet > 15 GeV
- pT of leading jet > 25 GeV
- pT of 2nd jet: (15,20), (20,25), (25,30) GeV.

PHOTONS:

- photons with $|\eta|<1.0$ and $1.5<|\eta|<2.5$
- 60< pT< 80 GeV (good separation of 1st and 2nd parton interactions)
- 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
- ΔR(any objects pair)>0.7

SOME FORMULAS

1. "S-family" variables:

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

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

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

2. Data-driven method:

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

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

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

From SP MC

$$\lambda = \frac{B_1}{B_2} \qquad K = \frac{(1 - f_1)}{(1 - f_2)}$$

From MixDP

$$C = \frac{f_2}{f_1}$$

We assume that MIXDP sample models correctly properties of DP events

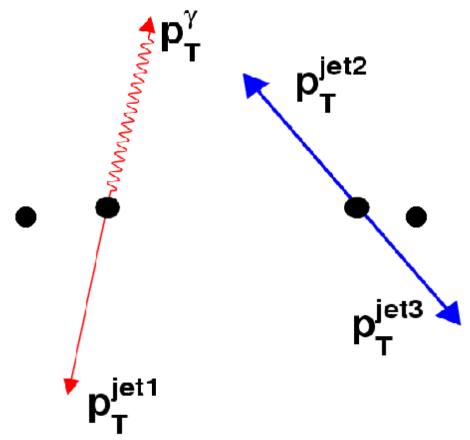
$$C = \frac{f_2}{f_1} = \left(\frac{N_2^{DP}}{N_2^{DATA}}\right)\left(\frac{N_1^{DATA}}{N_1^{DP}}\right) = \left(\frac{N_2^{MIXDP}}{N_2^{DATA}}\right)\left(\frac{N_1^{DATA}}{N_1^{MIXDP}}\right)$$

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

DOUBLE PPBAR INTERACTION MODEL

Built from D0 data by analogy to Double Parton model with the only difference: ingredient events (γ+jets and dijets) are 2-vertex events.

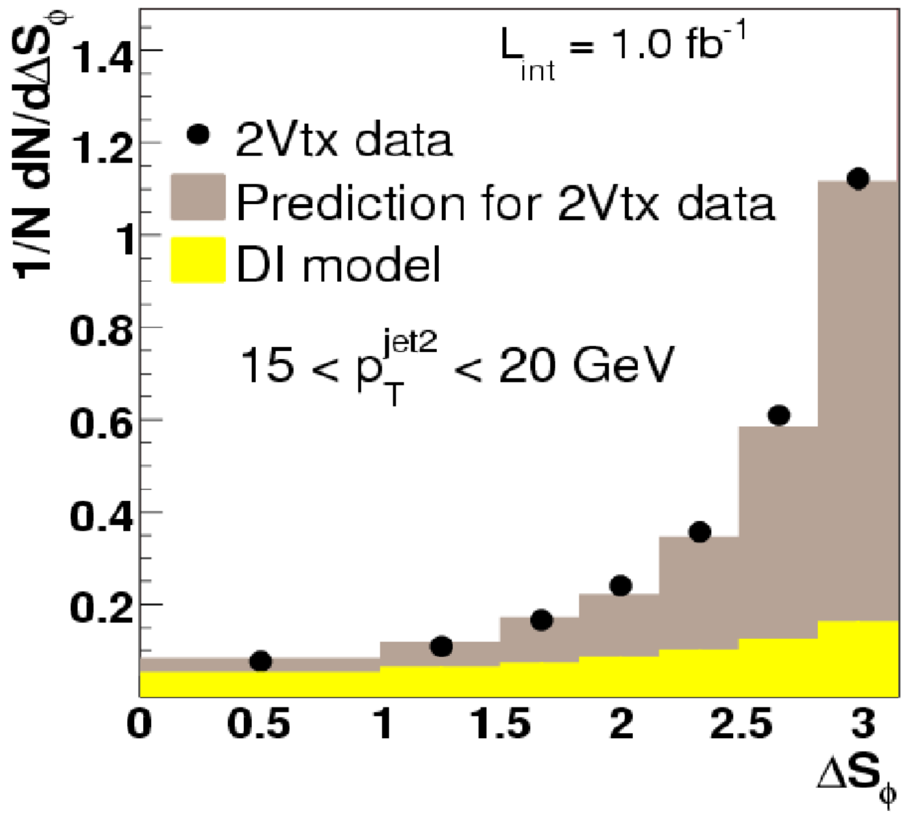
In case of 2 jets, both jets are required to originate from the same vertex using jet track information.

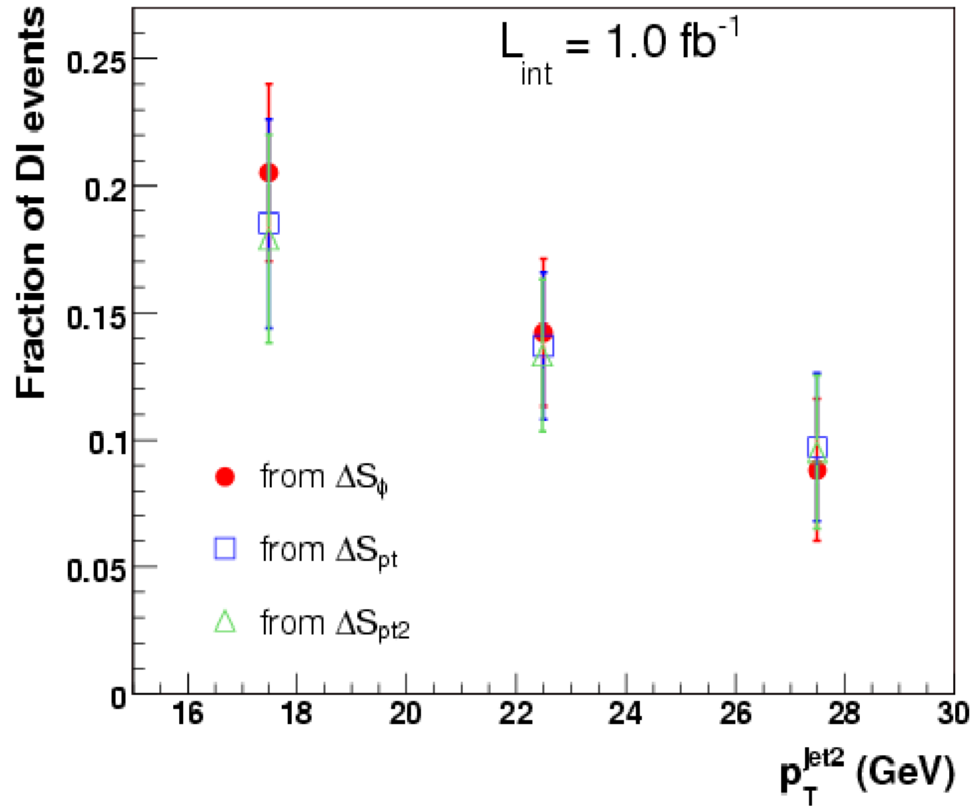


Main difference of Double Parton and Double Interaction signal events and corresponding SP backgrounds: different amount of soft unclustered energy in 1-vertex vs. 2-vertex events
→ different photon and jet ID efficiencies.

FRACTIONS OF DOUBLE PPBAR INTERACTIONS

To calculate σ_{eff} we also need $N_{DI} = f_{DI} * N_{2vtx}$
use ΔS shapes and get f_{DI} by fitting DI signal and background distributions to 2-vertex data.





Total sum of DI signal+bkgd, weighted with DI fractions, is in agreement with data

Main uncertainties in DI fractions are from building DI signal and background models

CALCULATION OF $Nc(n)$ AND σ_{hard}

Total number of ppbar events with 1 and 2 hard collisions, $Nc(1)$ and $Nc(2)$ are calculated from the expected average number of hard interactions at a given instantaneous luminosity L_{inst} :

$$\overline{n} = \left(L_{inst} / f_0\right)\sigma_{hard}$$

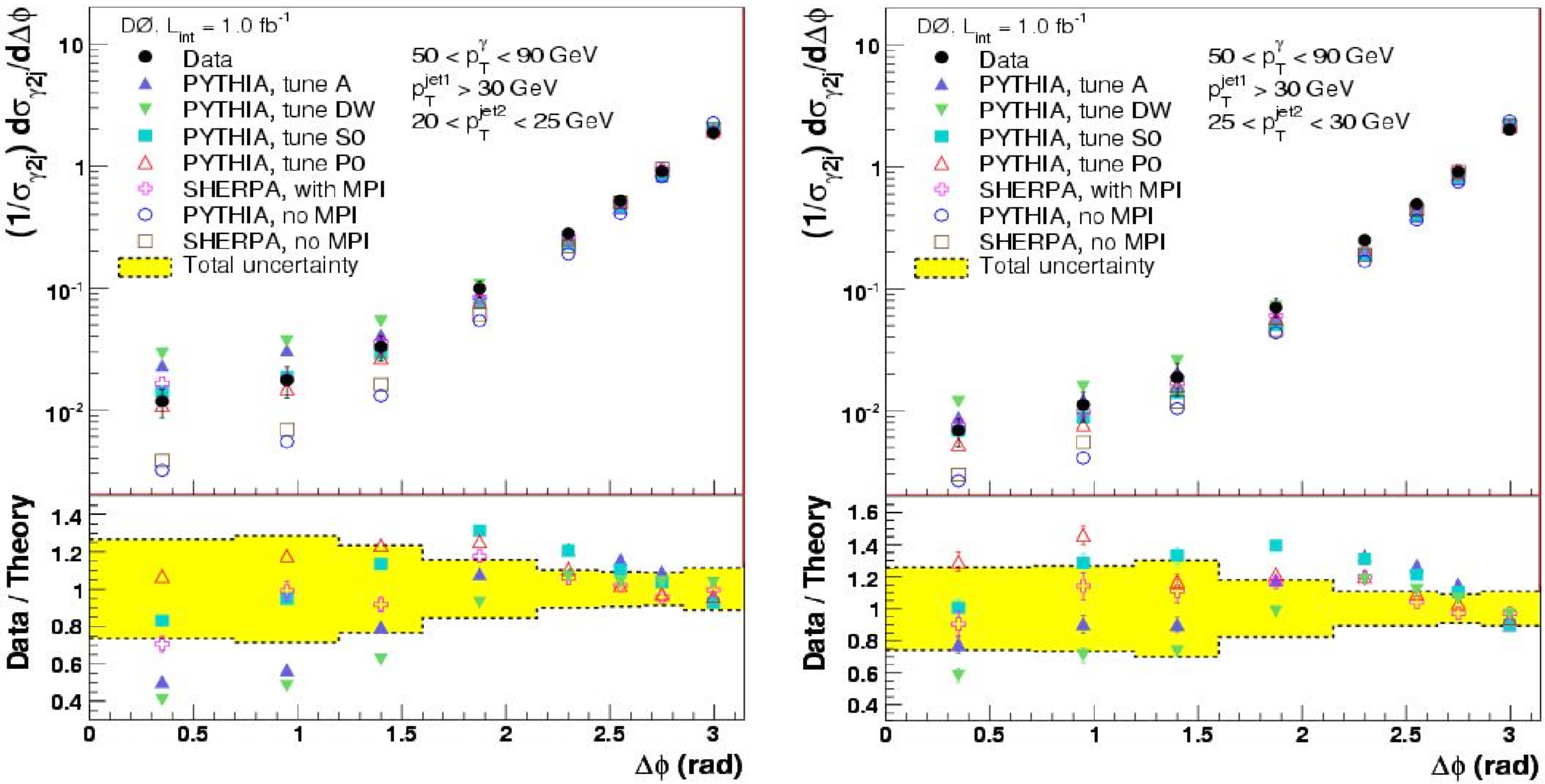
using Poisson statistics.

f_0 is a frequency of the beam crossings at the Tevatron in RunII.
σ_{hard} is hard (non-elastic, non-diffractive) ppbar cross section.
It is 44.7±2.9 mb : from Run I → Run II extrapolation.

$$Rc = \frac{Nc(1)}{2\,Nc(2)}\sigma_{hard} = 52.3 \;\; mb$$

Variation of σ_{hard} within uncertainty (2.9 mb) gives the uncertainty for Rc of just about 1.0 mb: increase of σ_{hard} leads to decrease of $Nc(1)/Nc(2)$ and vice versa.

CROSS SECTION



TRIPLE PARTON FRACTIONS

γ+3jet final state also can be produced by Tripple Parton interaction (TP).
In γ+3jet events all 3 jets should stem from three different parton scatterings.
To estimate the TP fraction the we used results on DP+TP fractions and fractions of TypeI(II) events found in our previous measurement.
TP in γ+3jet data is calculated as:

$$f_{tp}^{\gamma 3j} = f_{dp+tp}^{tp} \cdot f_{dp+tp}^{\gamma 3j}$$

The fraction of TP in MixDP can be found as:

$$f_{tp}^{dp+tp} = F_{typeII} \cdot f_{dp}^{\gamma 2j} + F_{typeI} \cdot f_{dp}^{jj}$$

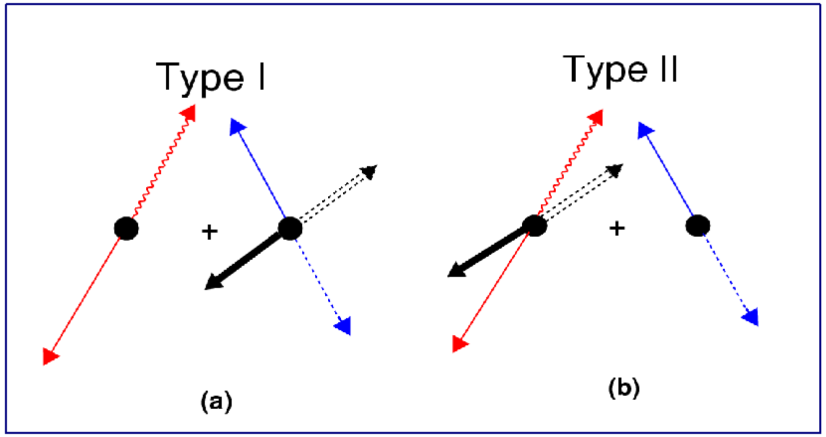
$f_{dp+tp}^{\gamma 3j}$ - measured in previous DP analysis;

f_{dp}^{jj} - estimated using dijet cross section;

$f_{dp}^{\gamma 2j}$ - measured;

$F_{typeI\ (II)}$ - found from the model (MixDP).

Probability to produce another parton scattering is proportional to $R = \sigma_{jj} / \sigma_{eff}$, the $f_{tp}^{\gamma 3j} / f_{dp}^{\gamma 3j}$ ratio should be proportional to R.

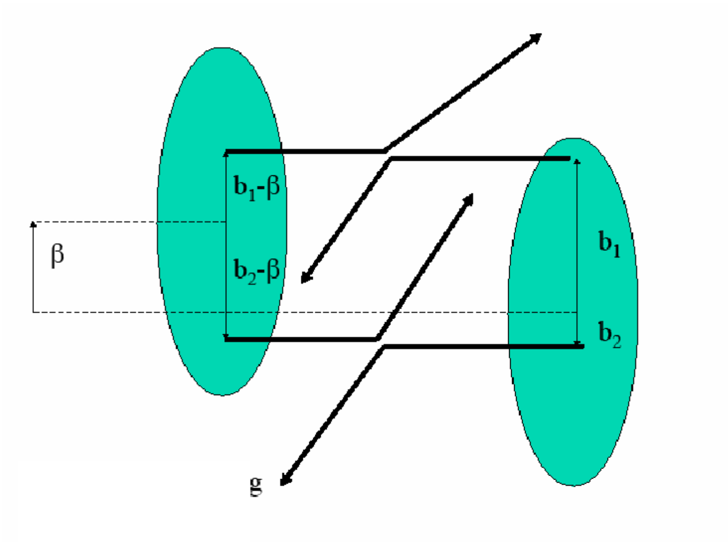


$p_T^{\rm jet2}$ (GeV) (GeV)	$f_{\rm tp}^{\gamma 3j}$ (%)	$f_{\rm tp}^{\gamma 3j} / f_{\rm dp}^{\gamma 3j}$ (%)
$15-20$	5.5 ± 1.1	13.5 ± 3.0
$20-25$	2.1 ± 0.6	6.6 ± 2.0
$25-30$	0.9 ± 0.3	3.8 ± 1.4

PARTON SPATIAL DENSITY AND σ_{eff}

Double Parton cross section

$$\sigma_{\rm dp} = \sum_{q/g} \int \frac{\sigma_{12}\sigma_{34}}{2\sigma_{\rm eff}} D_p(x_1, x_3) D_{\bar{p}}(x_2, x_4) dx_1 dx_2 dx_3 dx_4$$



Double Parton scattering

Effective cross section σ_{eff} is directly related with parton spatial density:

$$\sigma_{eff}^{-1} = \int d^2\beta \left[F(\beta)\right]^2,$$

β is impact parameter

$$F(\beta) = \int f(b) f(b - \beta) d^2 b,$$

where f(b) is the density of partons in transverse space.

=> Having σ_{eff} measured we can estimate f(b)