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

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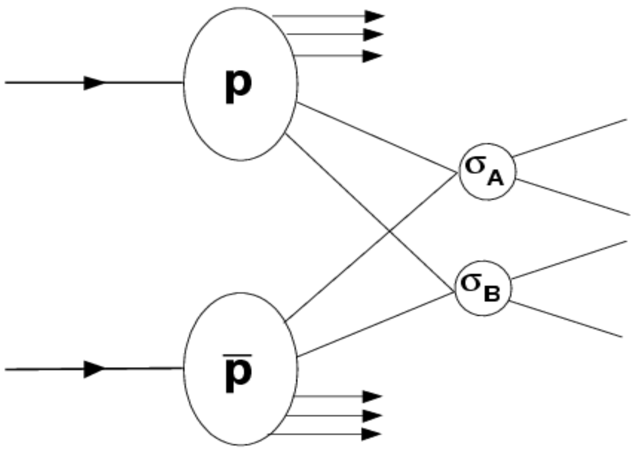
Outline

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



Motivations

- Most of the processes that cause MPI production are non-perturbative and implemented in some phenomenological models of a hadron structure and parton-to-hadron fragmentation.

=> Being phenomenological, the models strongly need experimental inputs.

- The provided experimental inputs have been based so far mainly on the minbias Tevatron (0.63, 1.8, 1.96 TeV), SPS (0.2, 0.54, 0.9 TeV) and Tevatron DY data.

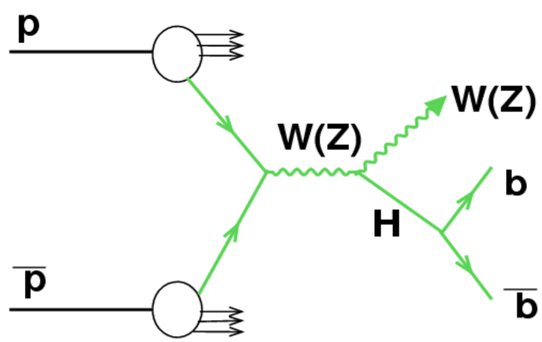
- However, there is a quite small amount of tests of MPI events in high pT regime, specifically with events having jet pT > 15 GeV,

=> i.e. right in the region used in many measurements (e.g. top-quark mass) and most important for searches of rare processes, especially with multi-jet final state.

=> MPI events can mimic a signature of a new physics processes and thus be a significant background to them.

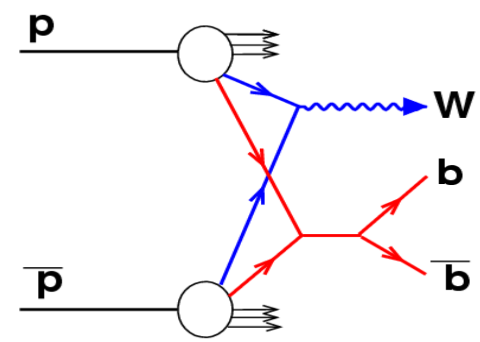
Double Parton events as a background to Higgs production

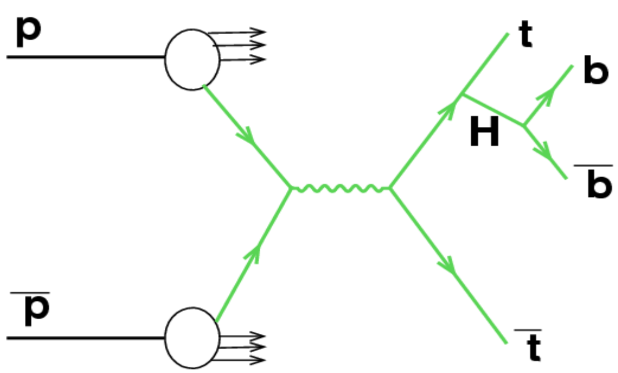
Signal

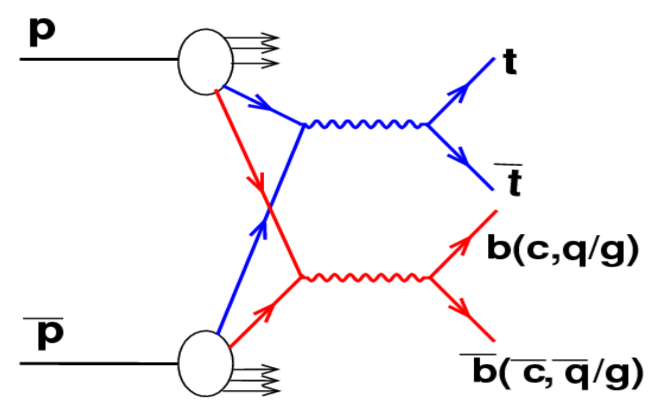


$$\sigma_{DP} = \frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

Double Parton background





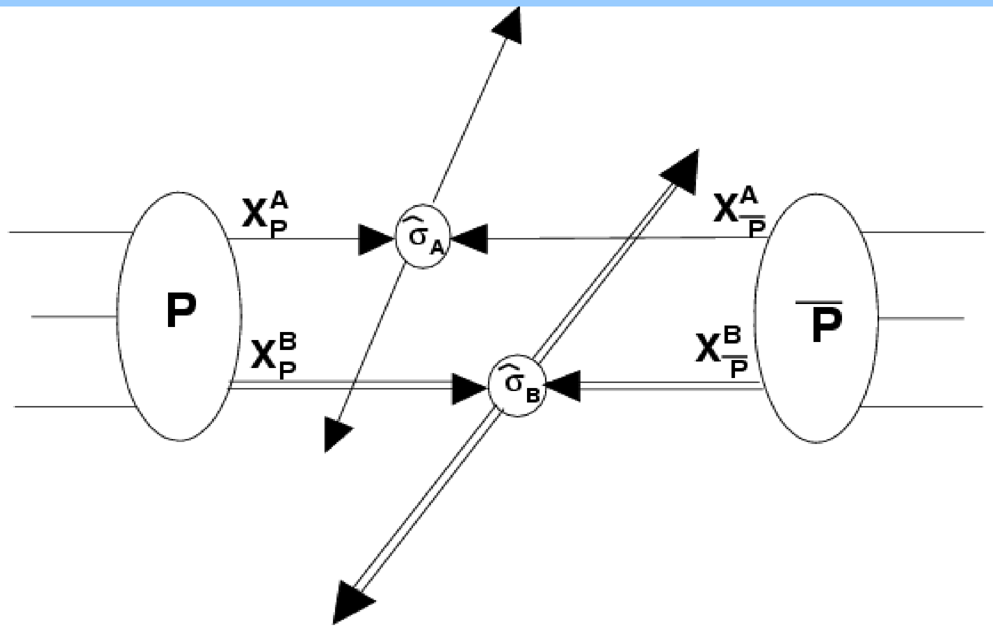


Estimates for Tevatron JHEP 1104:054(2011), LHC PRD61,077502(2000), PRD81,014014(2010)

- Many Higgs production channels can be mimicked by Double Parton events!
- Some of them can be significant even after signal selections.
- Dedicated cuts are required to increase sensitivity to the Higgs signal (same is true for many other rare processes)!

Double parton and effective cross sections

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



σ_{DP} - double parton cross section for processes A and B

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

→ can be directly related to the spatial distribution of partons f(b).

Uniform: σ_{eff} is large and σ_{DP} is small

Clumpy: σ_{eff} is small and σ_{DP} is large

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

→ Should be measured in experiment !!

Just 4 measurements existed up to recent time : AFS,UA2, 2 CDF [Run 1]

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

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

AFS'86, UA2'91 and CDF'93

4-jet samples, motivated by a large dijet cross section (but low DP fractions)

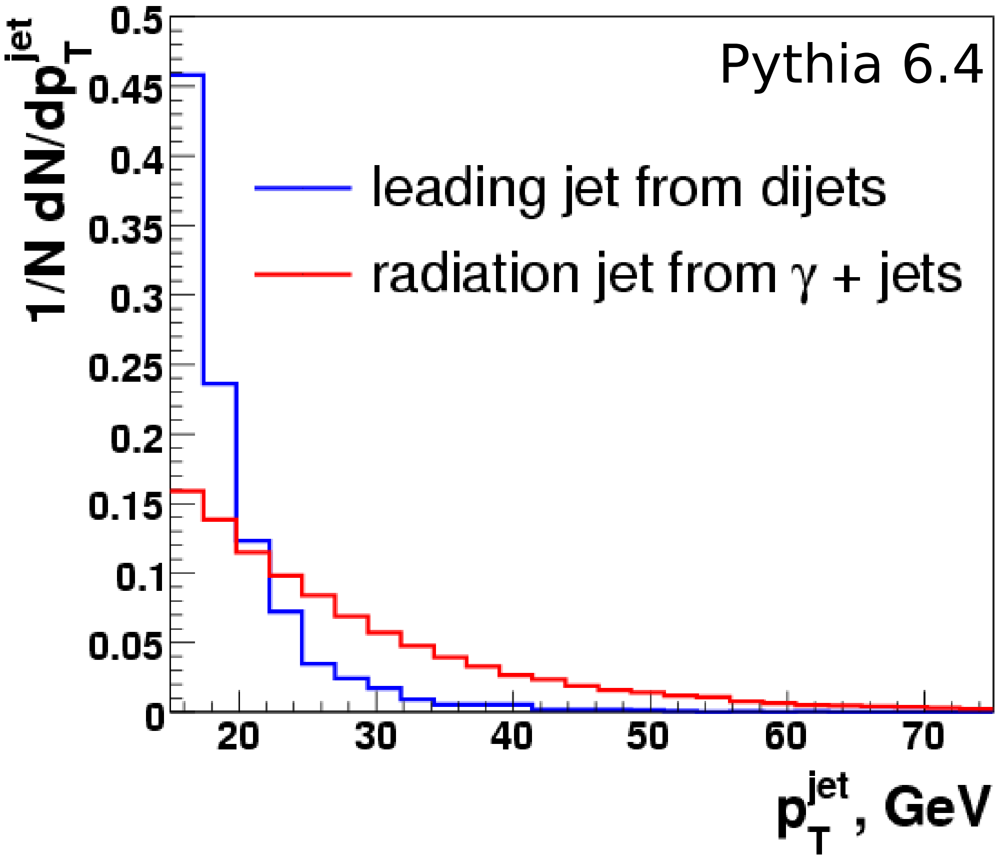
CDF’97, D0’10

γ+3jets events, data-driven method: use rates of Double Interaction (two separate ppbar collisions) and Double Parton (single ppbar collision) to extract $\sigma_{\rm eff}$ from their ratio.

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

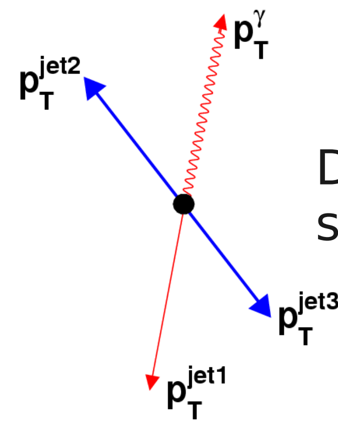
Motivation for jet pT binning

Jet PT: jet from dijets vs. radiation jet from γ+jet events

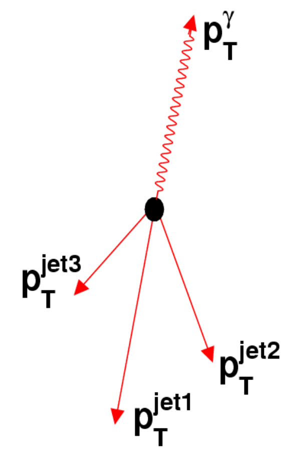


$\sim 1/p_T^4$

$\sim 1/p_T^2$



Double parton scattering



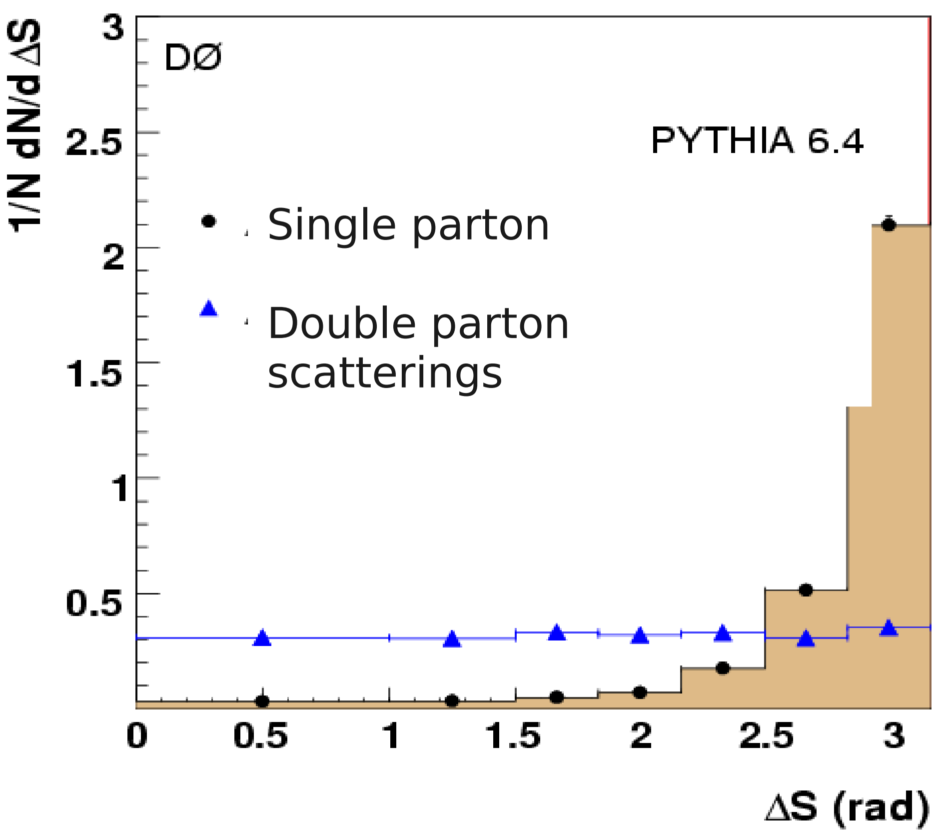
Single parton scattering

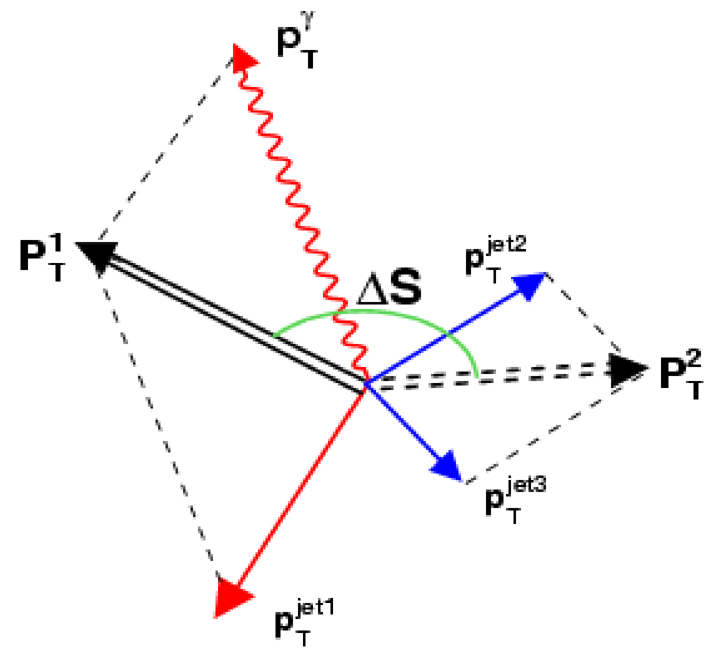
- Jet pT from dijets falls much faster than that for a radiation jet, i.e. Fraction of dijet (Double Parton) events should drop with increasing jet pT
  => Measurement is done in three bins of 2^{nd} jet pT: 15-20, 20-25, 25-30 GeV

Discriminating variables

- Main one is $\Delta\phi$ angle between two best pT-balancing pairs

$$\Delta S = \Delta\phi(p_T^{\gamma,\ \text{jet}}, p_T^{\text{jet}_i,\ \text{jet}_k})$$

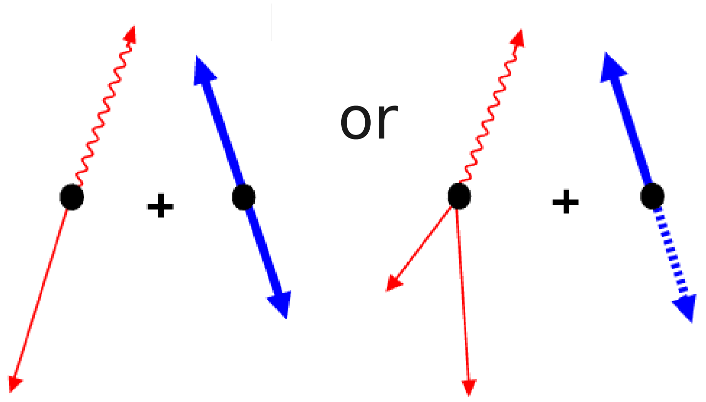




For "γ+3-jet" events from Single Parton scattering we expect ΔS to peak at π, while it should be flat for "ideal" Double Parton interaction (2nd and 3rd jets are both from dijet production) due to a pairwise pT balance.

Double Parton interaction model

Built from D0 data. Samples:



MixDP

A: photon + ≥1 jet from γ+jets data events:
- 1 VTX events
- photon pT: 60-80 GeV
- leading jet pT>25 GeV, |η|<3.0.

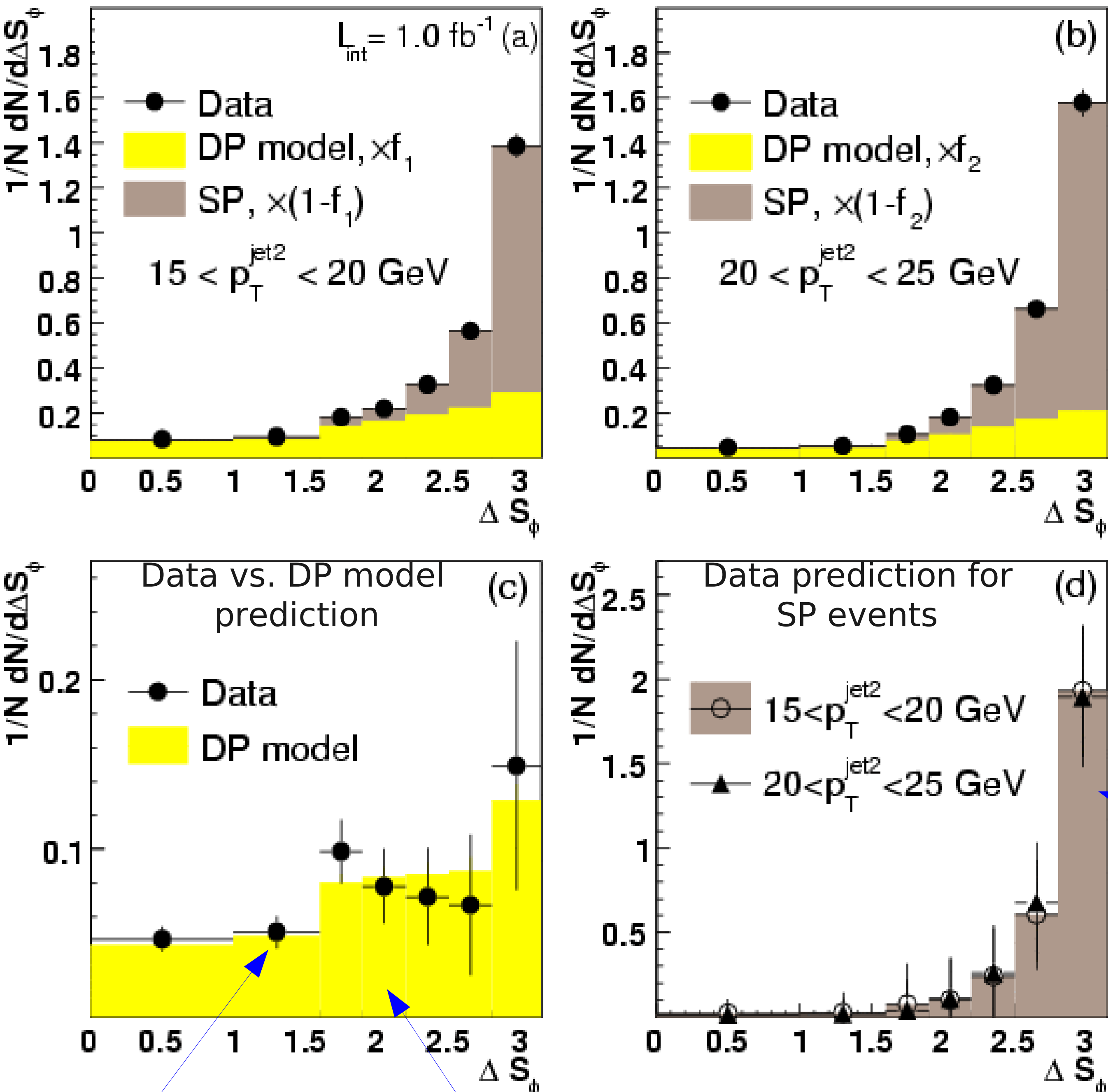
B: ≥1 jets from MinBias events:
- 1 VTX events
- jets with pT's recalculated to the primary vertex of sample A have pT>15 GeV and |η|<3.0.

- **A** & **B** samples have been (randomly) mixed with jets pT re-ordering
- Events should satisfy photon+≥3 jets requirement.
- △R(photon, jet1, jet2, jet3)>0.7

⇨ Two scatterings are independent by construction !

The two datasets method

Dataset 1: 2^{nd} jet pT: 15-20 GeV
Dataset 2: 2^{nd} jet pT: 20-25 GeV



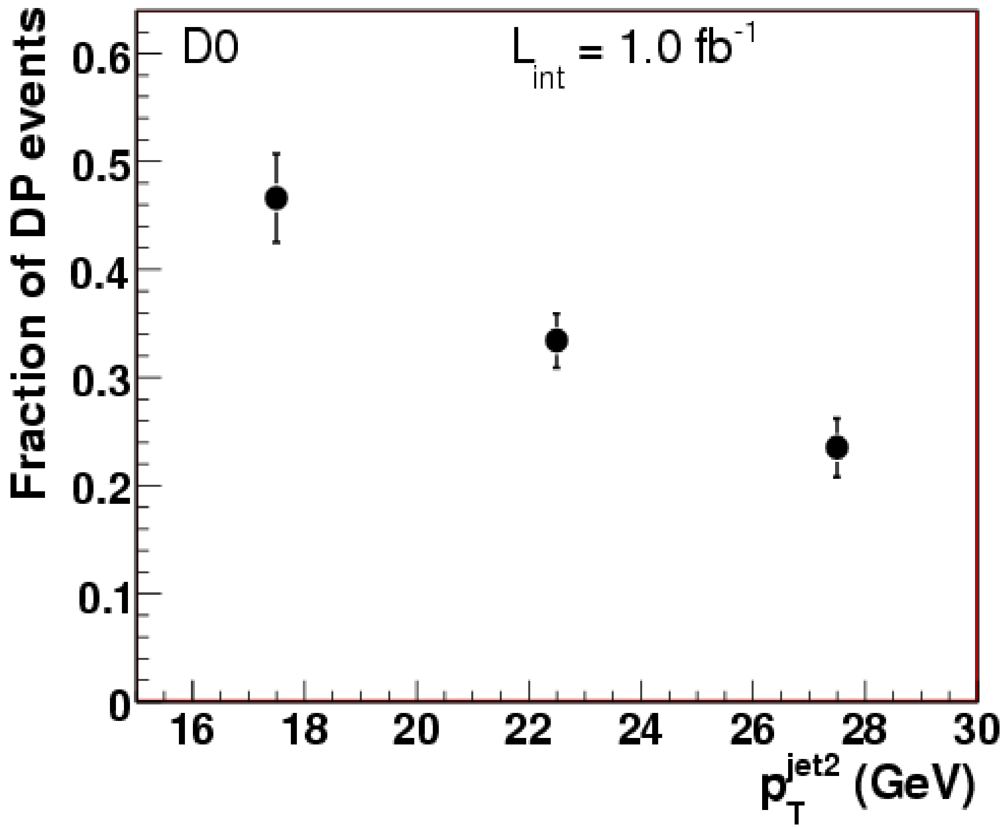
✓ Fraction of Double Parton in bin 15-20 GeV (f_1) is the only unknown
→ get from minimization.

Good agreement of the ΔS Single Parton distribution extracted in data and in MC (see previous slide)
→ another confirmation for the found DP fractions.

Data are corrected for the DP fractions

Good agreement of Data and DP model

Fractions of Double Parton γ+3-jet events

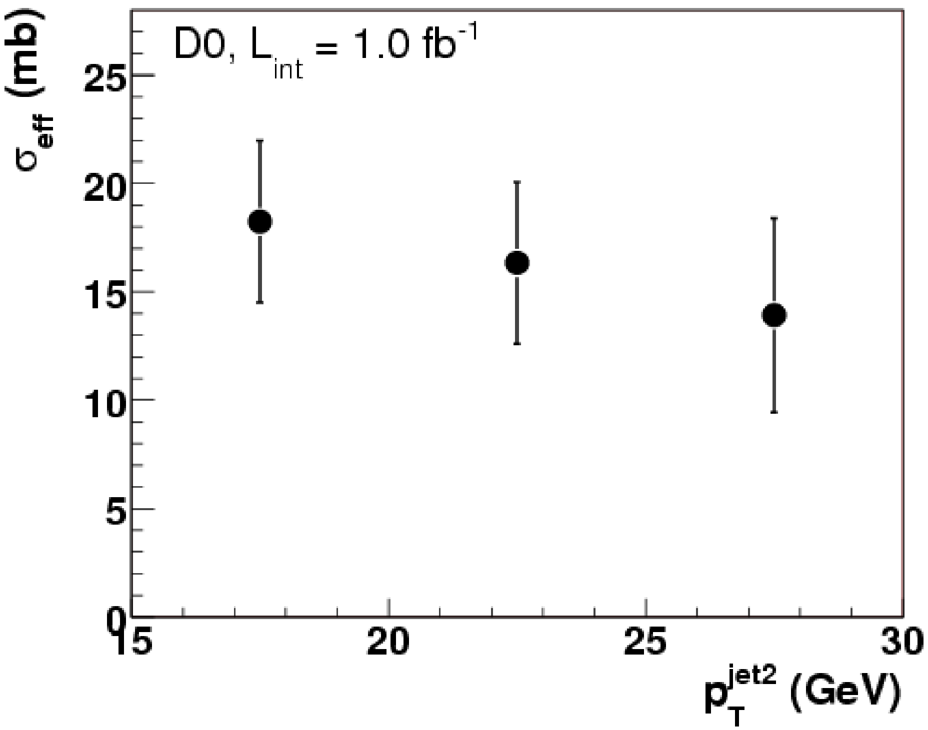


Found DP fractions are pretty sizable: they drop from ~46-48% at 2nd jet pT 15-20 GeV to ~22-23% at 2nd jet 25-30 GeV with relative uncertainties ~7-12%.

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

Calculation of σ_{eff}

Phys.Rev.D81,052012(2010), arXiv:0912.5104



- σ_{eff} values in different jet pT bins agree with each other within their uncertainties (also compatible with a slow decrease with pT).

- Uncertainties have very small correlations between 2nd jet pT bins.
- One can calculate the averaged (weighted by uncertainties) values over the pT bins:

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

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

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

p_T^{jet2} (GeV)	Systematic uncertainty sources f_{DP}	f_{DI}	$\varepsilon_{DP}/\varepsilon_{DI}$	JES	$R_c\sigma_{hard}$	δ_{syst} (%)	δ_{stat} (%)	δ_{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

Models of parton spatial density and σ_{eff}

- σ_{eff} is directly related with parameters of models of parton spatial density
- Three models have been considered: Solid sphere, Gaussian and Exponential.

TABLE VI: Parameters of parton spatial density models calculated from measured σ_{eff}.

Model for density	$\rho(r)$	σ_{eff}	R_{rms}	Parameter (fm)	R_{rms} (fm)
Solid Sphere	Constant, $r < r_p$	$4\pi r_p^2/2.2$	$\sqrt{3/5}r_p$	0.53 ± 0.06	0.41 ± 0.05
Gaussian	$e^{-r^2/2a^2}$	$8\pi a^2$	$\sqrt{3}a$	0.26 ± 0.03	0.44 ± 0.05
Exponential	$e^{-r/b}$	$28\pi b^2$	$\sqrt{12}b$	0.14 ± 0.02	0.47 ± 0.06

– The rms-radii above are calculated w/o account of possible parton spatial correlations. For example, for the Gaussian model one can write [Trelelani, Galucci, 0901.3089,hep-ph]:

$$\frac{1}{\sigma_{eff}} = \frac{3}{8\pi R_{rms}^2}(1 + Corr.)$$

- If we have rms-radii from some other source, one can estimate the size of the spatial correlations (larger corr. ↔ larger rms-radius with a fixed σ_{eff})

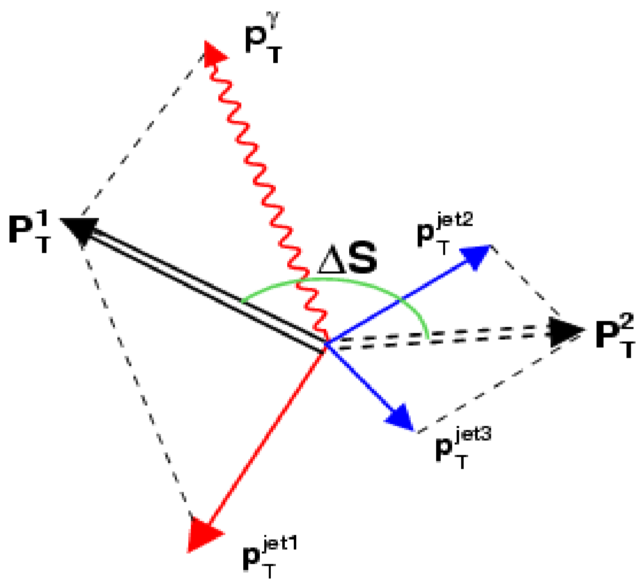
Angular decorrelations in γ+2 and γ+3 jet events

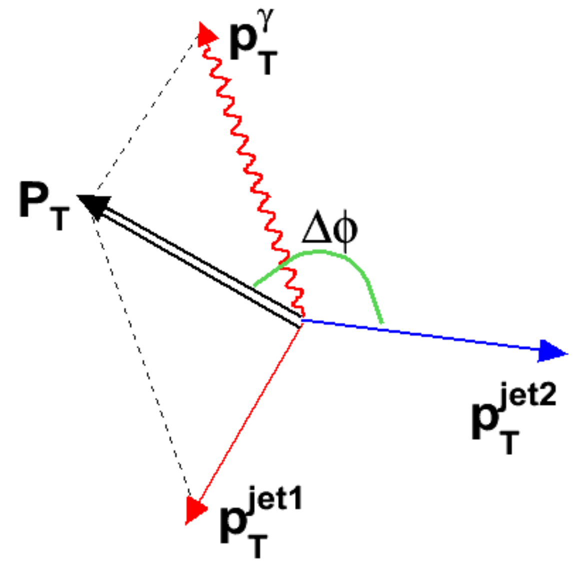
Motivations:

- 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.

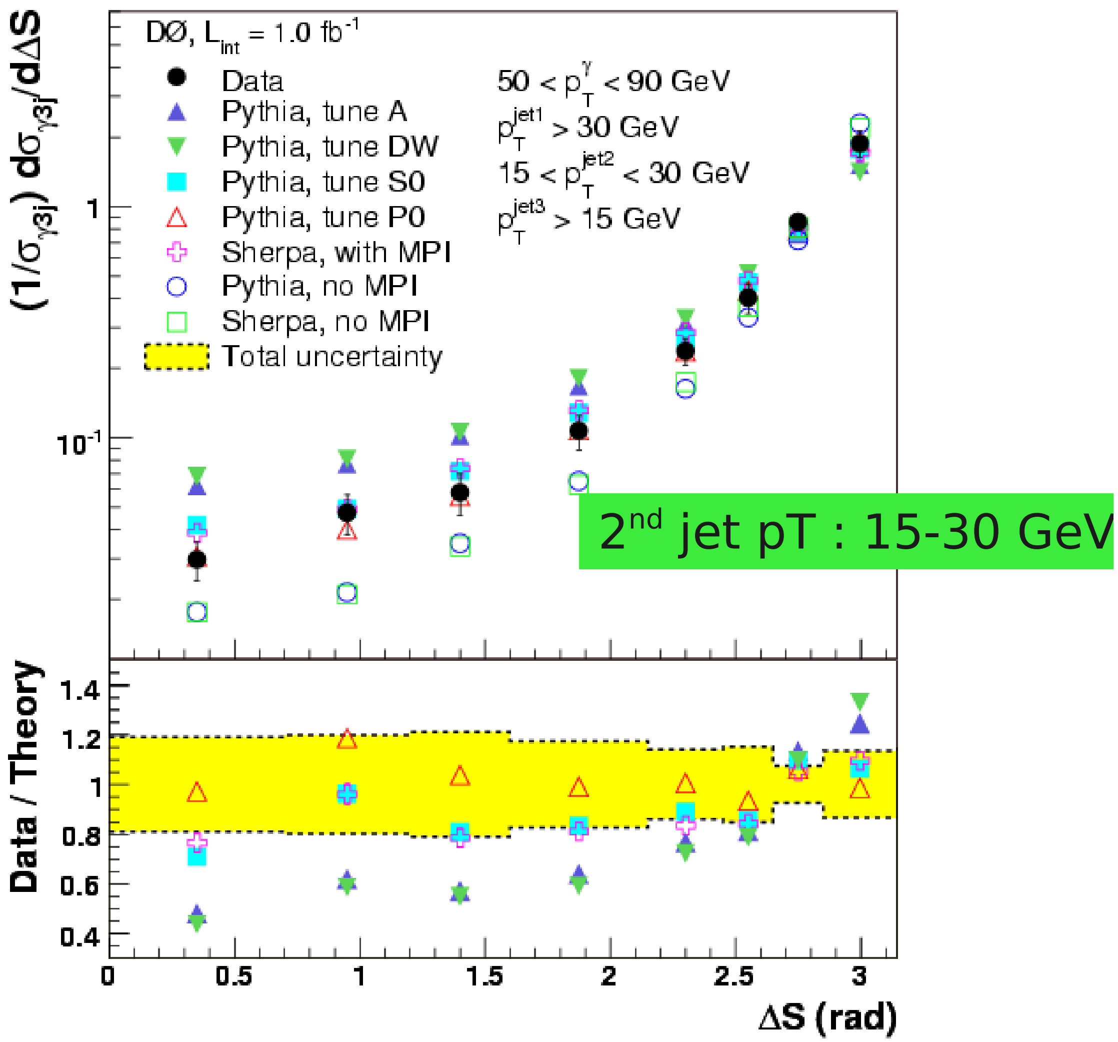
- Differentiation in jet pT increases sensitivity to the models even further.

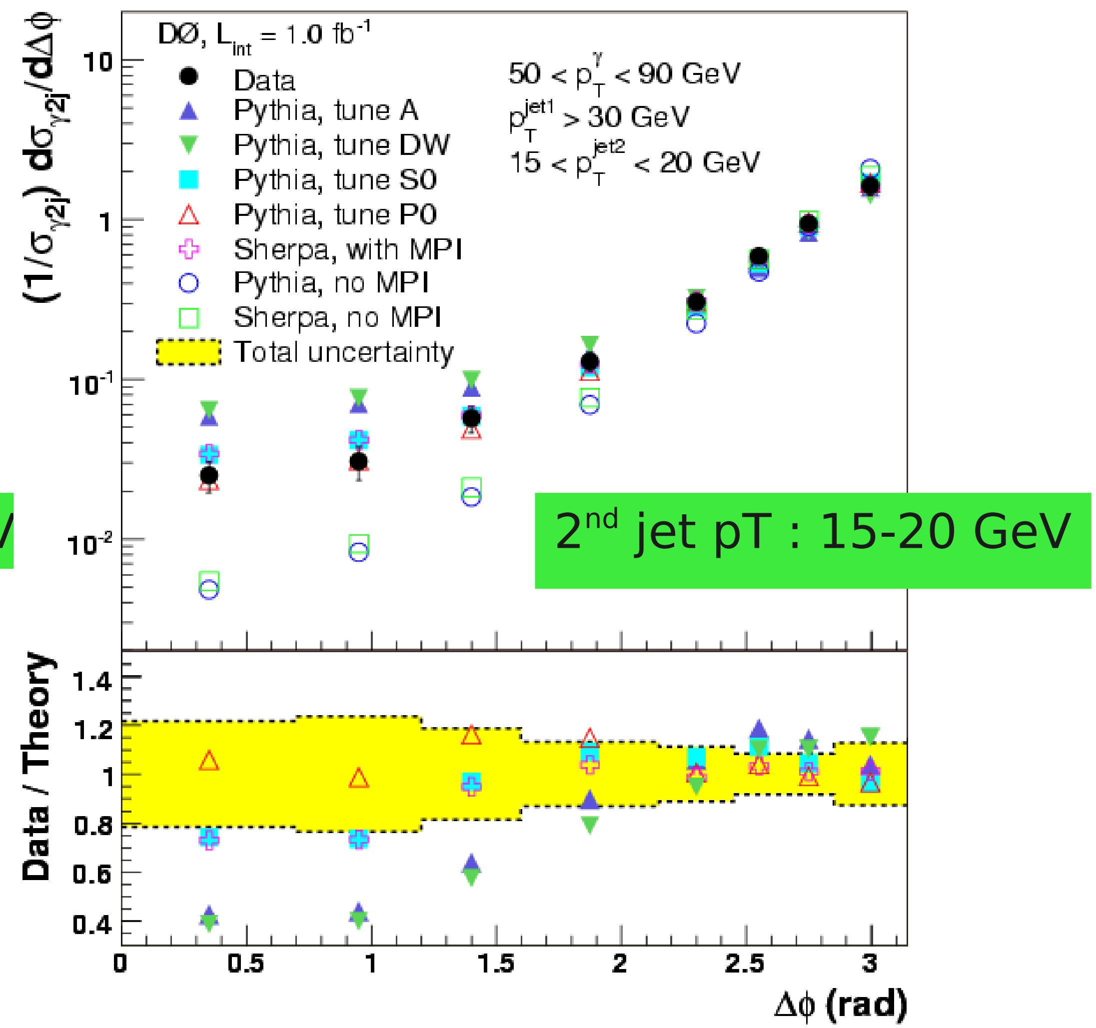
Four normalized differential cross sections are measured
- $\Delta\phi(\gamma$+jet1, jet2) in 3 bins of 2nd jet pT: 15-20, 20-25 and 25-30 GeV
- $\Delta S(\gamma$+jet1, jet2+jet3) for 2nd jet pT 15-30 GeV (larger for stat. reasons but still has good sensitivity to MPI models)





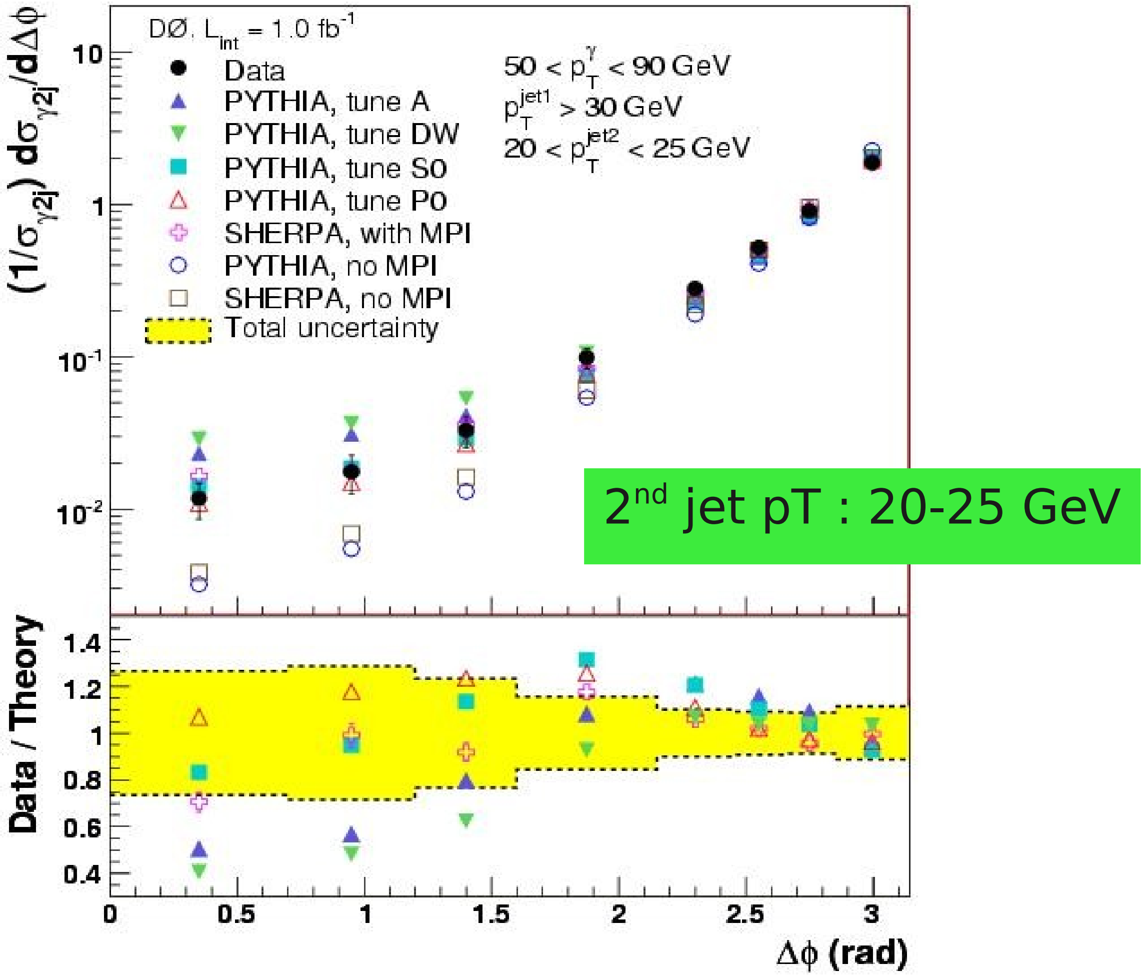
△S and $\Delta\phi$ cross sections





- MPI models substantially differ from any SP (=single parton scattering) prediction.
- Large difference between SP models and data confirms presence of DP events in data.
- MPI models differ noticeably, especially at small angles
  => we can tune the models or just choose the best one(s)
- Data are close to Perugia (P0), S0 and Sherpa MPI tunes.
  N.B.: the conclusion is valid for both the considered variables and 3 jet pT intervals!

$\Delta\phi$ cross sections



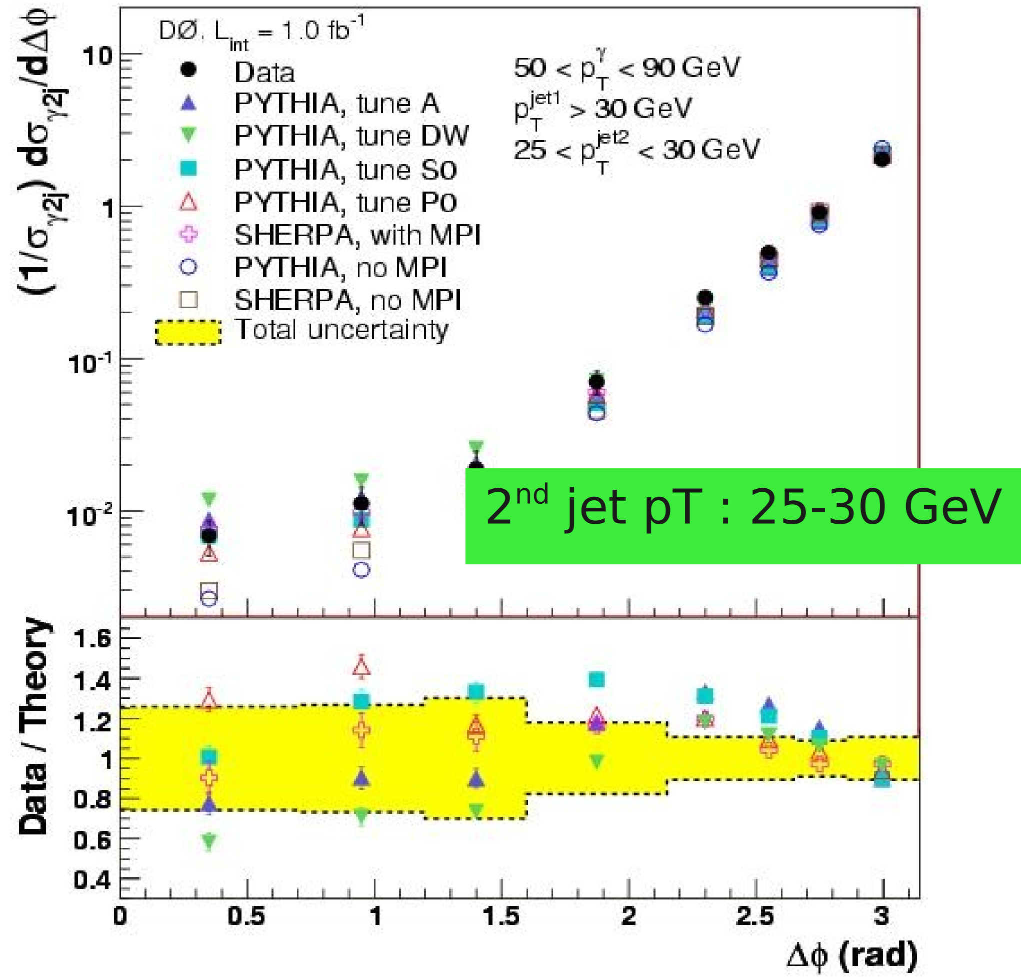


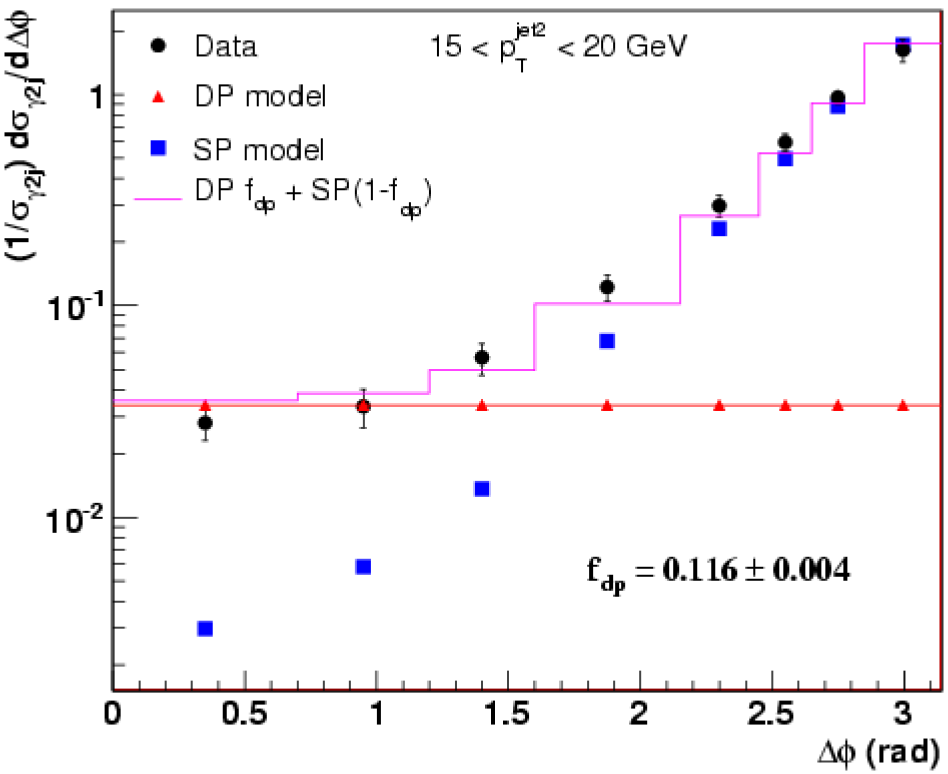
TABLE V: The results of a χ^2 test of the agreement between data points and theory predictions for the ΔS $(\gamma + 3$ jet) and $\Delta\phi$ $(\gamma + 2$ jet) distributions for $0.0 \leq \Delta S(\Delta\phi) \leq \pi$ rad. Values are χ^2/ndf.

Variable	p_T^{jet2} (GeV)	SP model		MPI model									
		PYTHIA	SHERPA	A	DW	S0	P0	P-nocr	P-soft	P-hard	P-6	P-X	SHERPA
ΔS	15 – 30	7.7	6.0	15.6	21.4	2.2	0.4	0.5	2.9	0.5	0.4	0.5	1.9
$\Delta\phi$	15 – 20	16.6	11.7	19.6	27.7	1.6	0.5	0.9	1.6	0.9	0.6	0.8	1.2
$\Delta\phi$	20 – 25	10.2	5.9	4.0	7.9	1.1	0.9	1.4	2.1	1.1	1.3	1.5	0.4
$\Delta\phi$	25 – 30	7.2	3.5	2.8	3.0	2.4	1.1	1.1	3.7	0.2	1.3	1.9	0.7

DP fractions in γ+2 jet events

- In γ+2 jet events in which 2nd jet is produced in the 2nd parton interaction, $\Delta\phi(\gamma$+jet1, jet2) distribution should be flat.
- Using this fact and also SP prediction for $\Delta\phi(\gamma$+jet1, jet2) one can get DP fraction from a maximal likelihood fit to data.

Example of the fit for 2nd jet pT bin 15 – 20 GeV



DP fractions fDP in γ+2 jet events

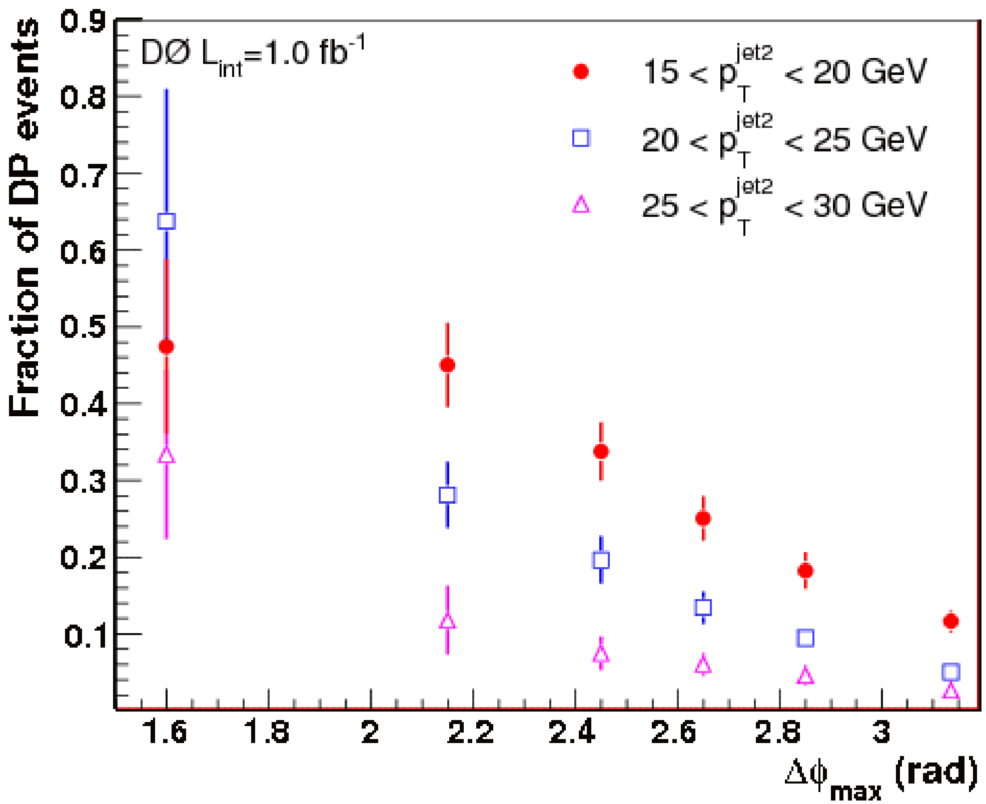
p_T^{jet2} (GeV)	$\langle p_T^{jet2} \rangle$ (GeV)	$f_{dp}^{\gamma 2j}$ (%)	Uncertainties (in %) Fit	δ_{tot}	SP model
15 – 20	17.6	11.6 ± 1.0	5.2	8.3	6.7
20 – 25	22.3	5.0 ± 1.2	4.0	20.3	11.0
25 – 30	27.3	2.2 ± 0.8	27.8	21.0	17.9

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

DP fractions in γ+2 jet events vs. $\Delta\phi$

- DP fractions should depend on $\Delta\phi(\gamma$+jet1, jet2): the smaller $\Delta\phi$ angle the larger DP fraction (see, for example, the plot on previous slide).
- We can find this dependence by repeating the same fits at smaller $\Delta\phi$ angles.

DP fractions vs $\Delta\phi$ bin for 3 bins of 2nd jet pT



=> DP fractions are larger at smaller angles and smaller 2nd jet pT

TP fractions

γ+3jet final state also can be produced by Tripple Parton interaction (TP).
In γ+3jet events all 3 jets should stem from 3 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:

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

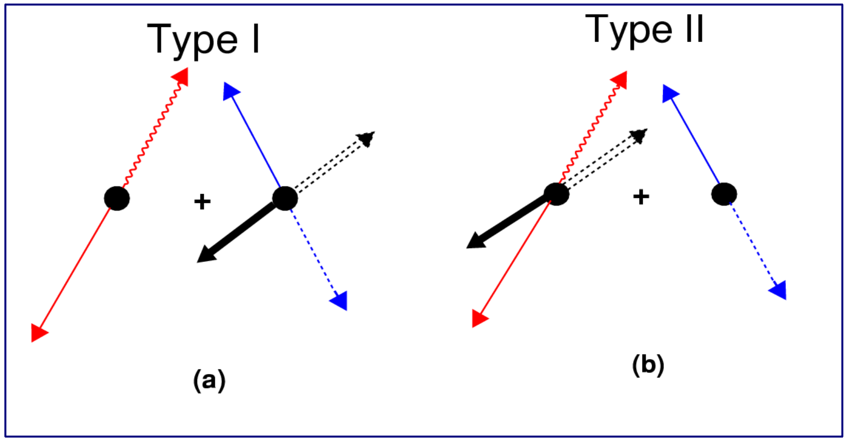
$f_{dp+tp}^{\gamma 3j}$ - measured in previous DP analysis;

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 $R = \sigma_{ij} / \sigma_{eff}$, the $f_{tp}^{\gamma 3j} / f_{dp}^{\gamma 3j}$ ratio should be proportional to *R*.



p_T^{jet2} (GeV) (GeV)	$f_{\text{tp}}^{\gamma 3j}$ (%)	$f_{\text{tp}}^{\gamma 3j} / f_{\text{dp}}^{\gamma 3j}$ (%)
$15 - 20$	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

Summary

- In D0 we have been studying DP production events and measured recently:
- Fraction of DP events in γ+3-jet events in three pT bins of 2nd jet : 15-20, 20-25, 25-30 GeV. It varies from ~47% at 15-20 GeV to ~23% at 25-30 GeV
- Effective cross section (process-independent, defines rate of DP events) σ_{eff} in the same jet pT bins with average value:

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

- The DP in γ+2jets: 11.6% at 15-20 GeV to 2.2% at 25-30 GeV.
- The TP fractions in γ+3-jet events are determined for the firs time. As a function of 2nd jet pT, they drop from ~5.5% at 15-20 GeV, to ~0.9% at 25-30 GeV.
- The ΔS and $\Delta\phi$ cross sections. They allow to better tune MPI models: Data prefer the Sherpa and Pythia MPI models (P0, P0-X, P0-hard) with pT-ordered showers.

- DP production can be a significant background to many rare processes, especially with multi-jet final state. A set of variables allowing to reduce the DP background is suggested.

BACK-UP SLIDES

Some still open questions and Prospects

- Is σ_{eff} really stable from small to very big scales μ of a hard interaction?

- How the spatial distribution should depend on the parton species (eg. valence vs. sea quarks / gluons) ?
  What observables could be used to improve understanding of transverse structure?

- Is the assumption G(x,b) = D(x) F(b) true ?
  How to make unambiguous test of this factorization?
  Interesting recent related analysis: 4-jet production in the light of two-parton GPD(x1,x2,b), where b is a transverse distance: arXiv:1009.2741 [hep-ph].

=> More measurements of DP fractions and σ_{eff} are needed in different processes having different initial state, but at similar energy scales as in the studied γ+3-jet events.
For example, di-b-jet+dijet, W/Z/photon + $\geq$2 heavy flavour jets, diphoton+dijet, mutlijet Drell-Yan events.

Summary (2)

- Studies of MPI events did not receive a proper attention up to recent time, but currently more people/groups are becoming involved in this business.

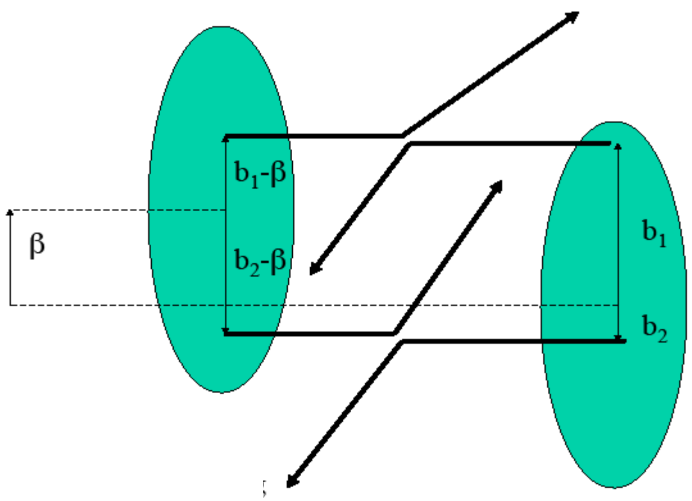
- Studies of MPI events are important since lead to a knowledge of the fundamental hadron structure.

- Rates of DP/MPI events are significant at the Tevatron, but should be much larger at the LHC (about a factor 2) mainly because PDF increase rapidly with $x \to 0$ and DP cross section grows as a product of 2x2 PDFs. Plus σ_{eff} seems should drop due to dPDF evolution.
  Thus, they can be important background to many 'new physics' processes at LHC.

Parton spatial density and σ_{eff}

Double parton cross section

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



Double parton scattering

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

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

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)

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 Double Interaction events:

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

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 Double Parton events:

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

Therefore one can extract:

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

Double parton interactions and dPDF evolution

From Phys.Rev.D81,065014(2010)(arXiv:1001.0104)
as an interpretation of the D0 measurement

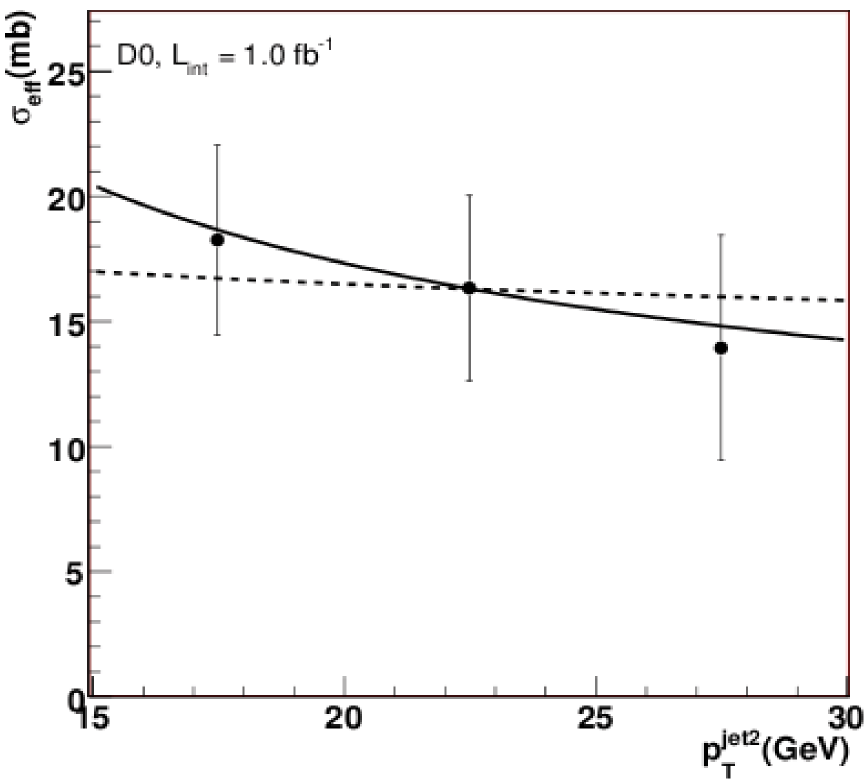


FIG. 1: Effective cross section $\sigma_{\rm eff}^{\rm exp}$ measured in the three $p_T^{\rm jet2}$ bins at the D0 experiment [5]. The solid ($k = 0.5$) and dashed ($k = 0.1$) lines are the results from Eq. (11) at $p_{T0}^{\rm jet2} = 22.5$ GeV and $\sigma_{\rm eff}^0 = 16.3$ mb.

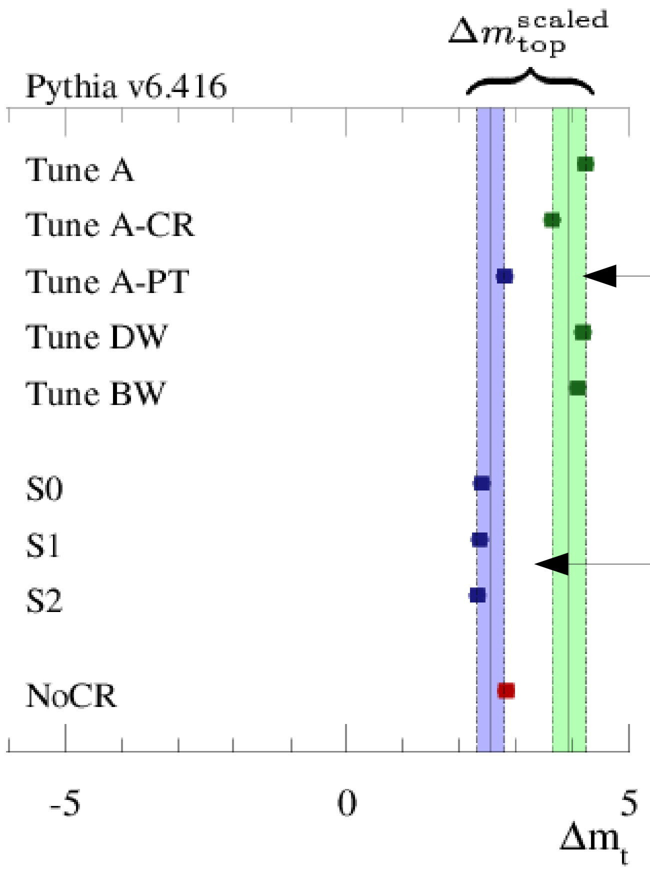
- If at any given scale $\mu 0$:
  D(x1,x2,$\mu 0$) = D(x1,$\mu 0$)*D(x2,$\mu 0$) θ(1-x1-x2)
  the dPDF evolution violates this factorization *inevitably* at any different scale $\mu \neq \mu 0$:
  D(x1,x2,μ) = D(x1,μ)*D(x2,μ) + R(x1,x2,μ),
  where R(x1,x2,μ) is a correlation term.

- Direct account of double PDFs: J.Gaunt and J.Stirling, JHEP 1003:005,2010.
  First software implemented evolution equations and solutions for dPDF
  To the large extent, being encouraged by the D0 measurement.

Motivations

Comparison of the top-quark mass offset corrections with a few MPI models

Plot from: D.Wicke, P.Z.Skands, Nuovo Cim. 123B, s1 (2008), arXiv:0807.3248v1 [hep-ph]



Models with virtuality-ordered parton shower

Models with pT-ordered parton shower

Difference between the two sets of the models leads to about 0.5-1.0 GeV uncertainty to the offset corrections for the top-quark mass.