# Double Parton Interactions: Recent D0 Measurements and Prospects

**Dmitry Bandurin**

Florida State University

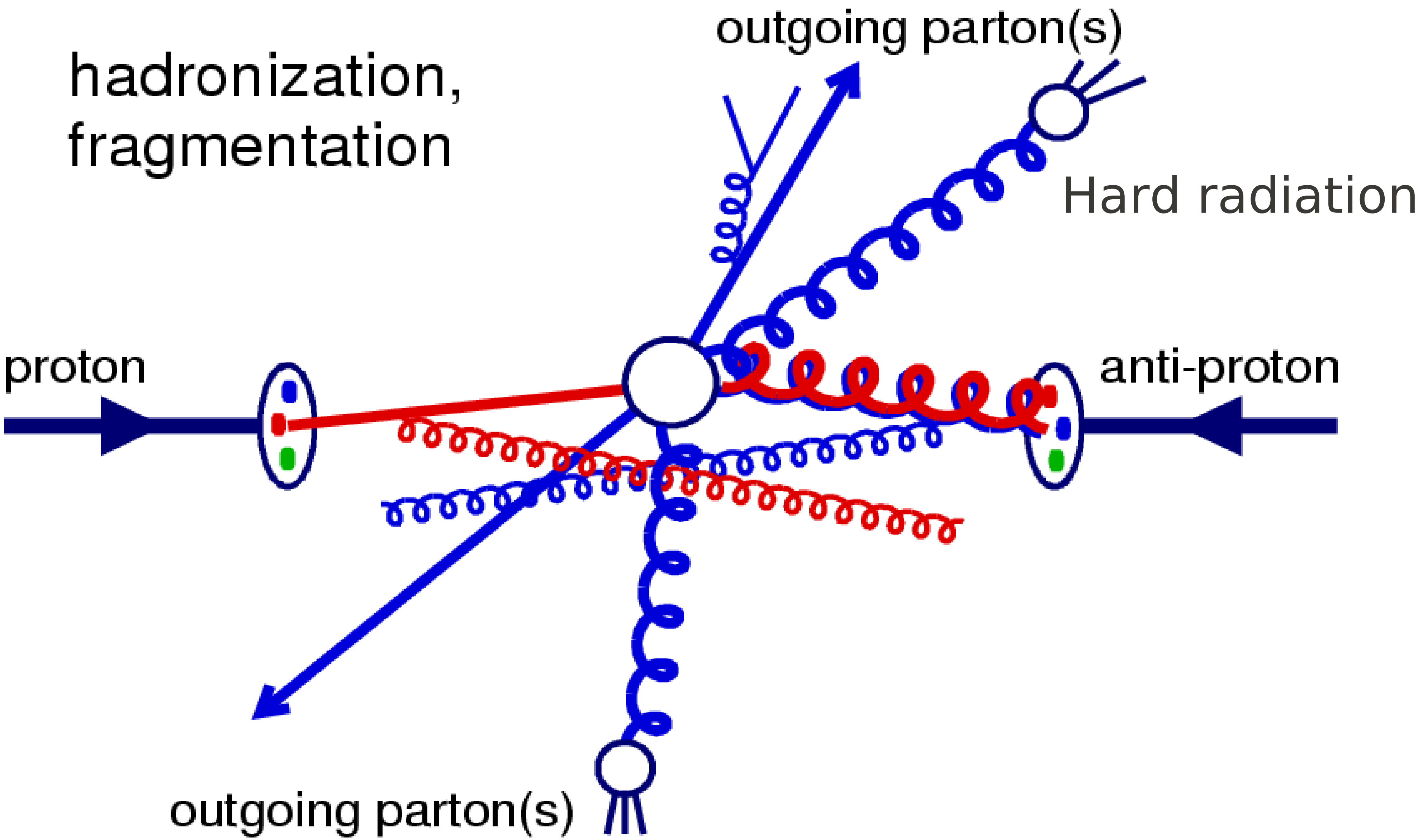
Workshop on LHC physics, Chicago

May 2, 2012

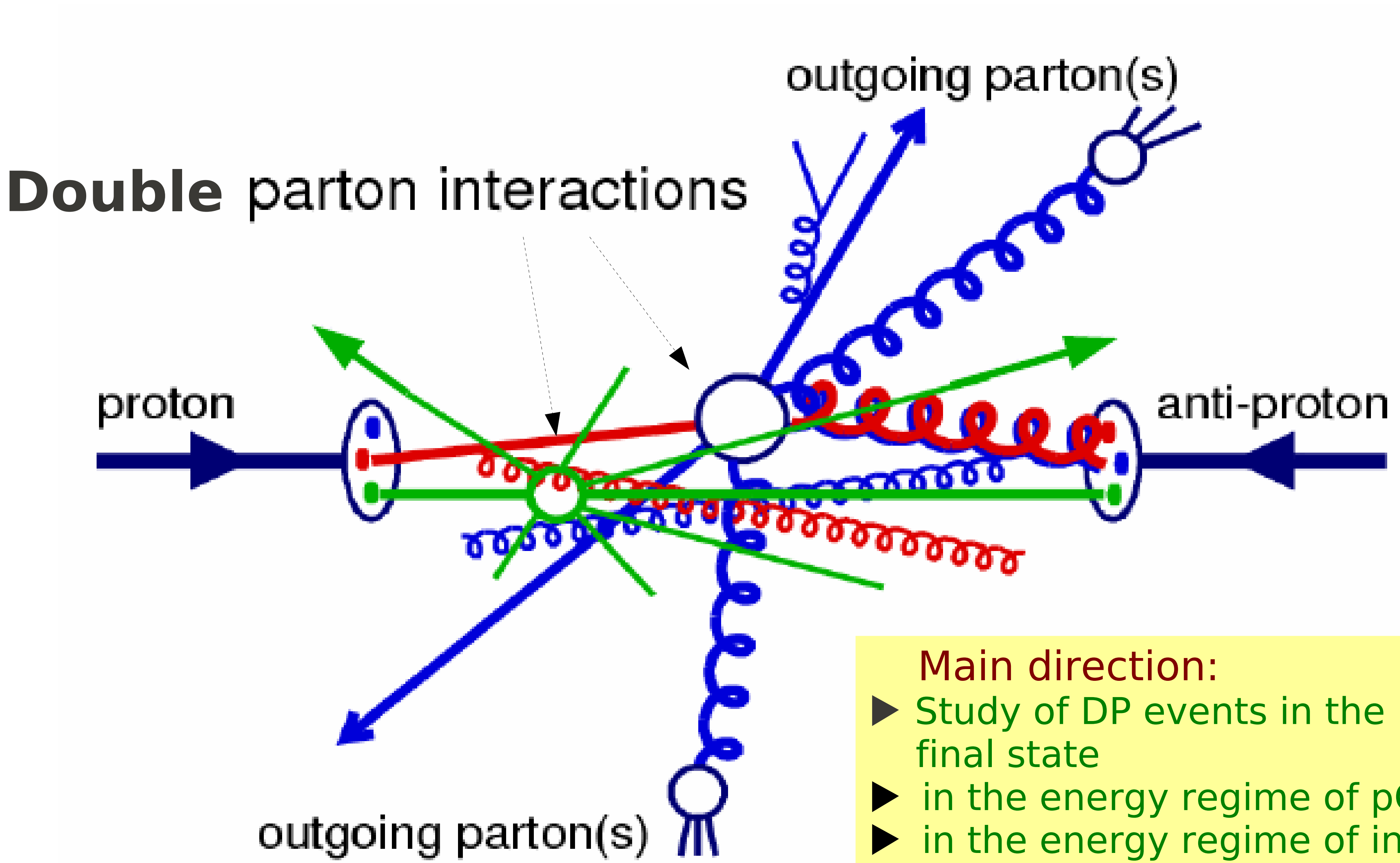
# Outline

- Double Parton interactions in $\gamma$+2 and $\gamma$+3-jet events
- Double Parton events as a background to rare processes
- Summary / prospects

# Hadron-Hadron Collision



# Hadron-Hadron Collision

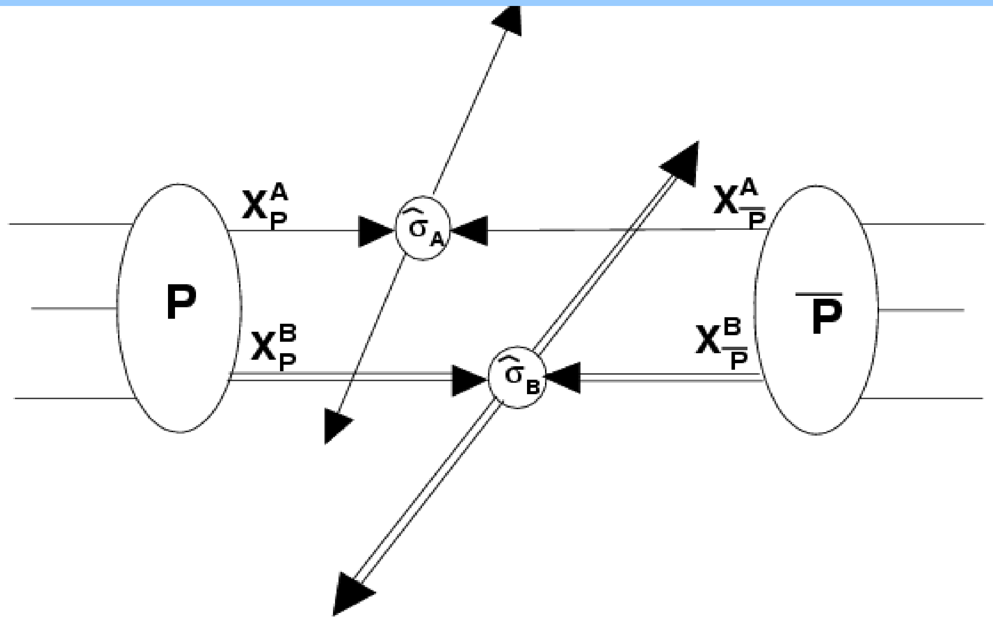



Main direction:

- Study of DP events in the multijet final state
- in the energy regime of pQCD
- in the energy regime of interest for many NP searches

# Double parton and effective cross sections

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




$\sigma_{DP}$ - double parton cross section for processes A and B

$\sigma_{eff}$ - factor characterizing size of effective interaction region

→ contains information on the spatial distribution of partons.

Uniform: $\sigma_{eff}$ is large and $\sigma_{DP}$ is small

Clumpy: $\sigma_{eff}$ is small and $\sigma_{DP}$ is large

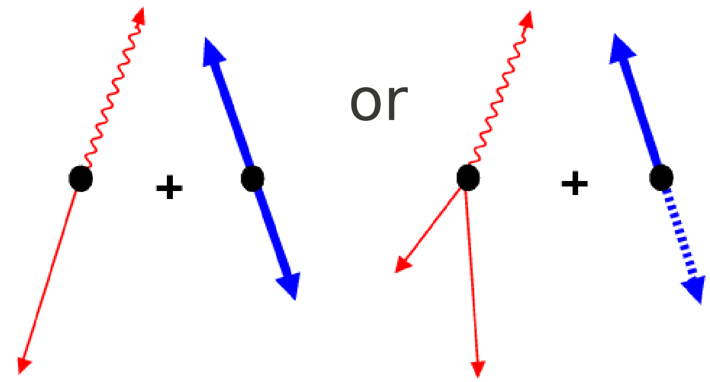
→ $\sigma_A$ and $\sigma_B$ grow with sqrt(s), => $\sigma_{DP}$ should grow even faster!

→ $\sigma_{eff}$ (on top of pure QCD motivations) is needed for precise estimates of background to many rare processes (especially with multi-jet final state)

→ Being phenomenological, it should be measured in experiment !!

# Double Parton interaction model (MixDP)

Built from D0 data. Samples:




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

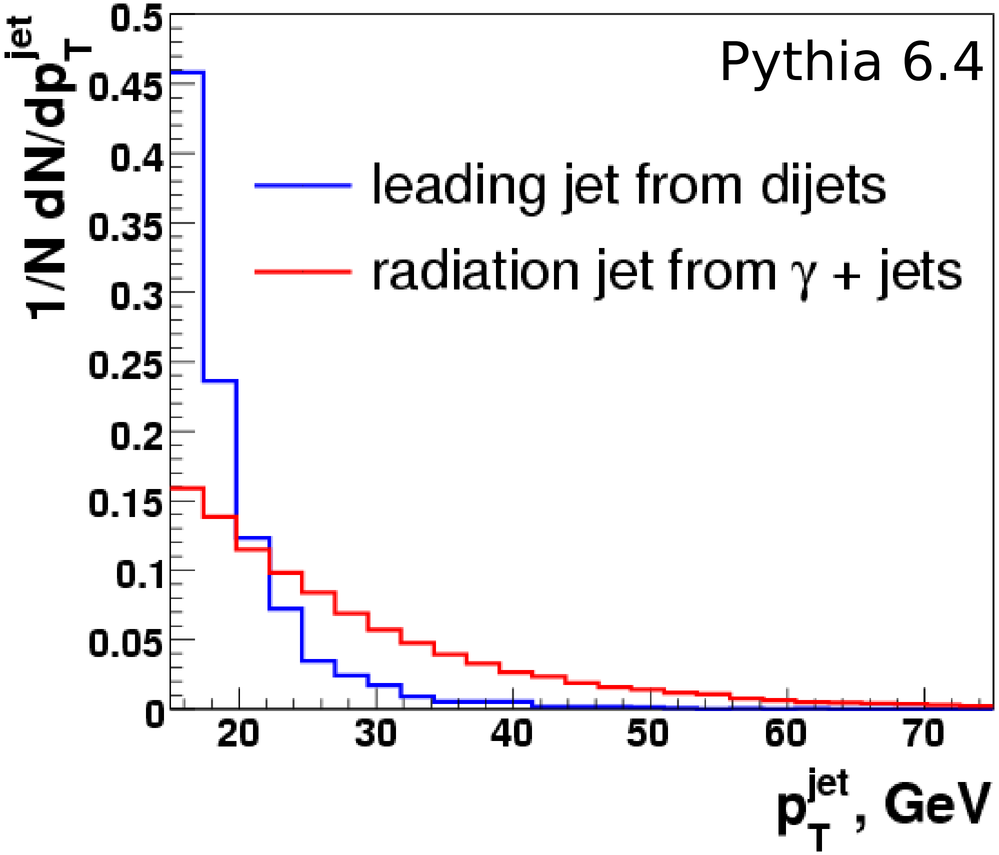
**B**: ≥1 jets from MinBias events:
- 1-vertex events
- jets with pT's recalculated to the primary vertex of sample A have pT>15 GeV and |η|<3.0.

- **A** & **B** samples have been (randomly) mixed with following jet pT re-ordering
- Events should satisfy photon+≥3 jets requirement.
- △R(photon, jet1, jet2, jet3)>0.9

⇨ Two parton scatterings are independent by construction!

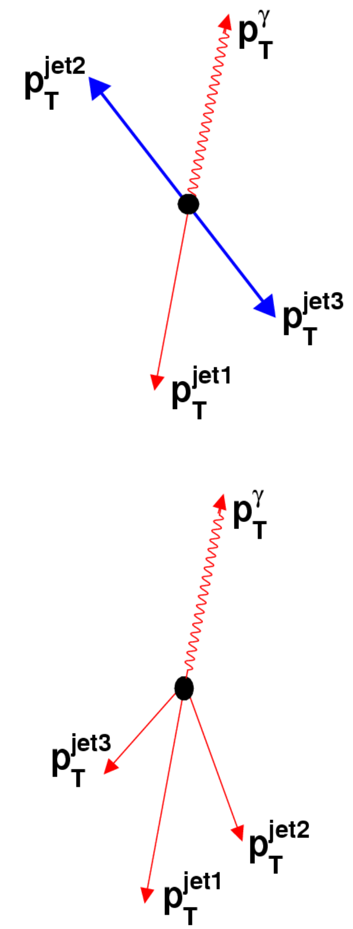
# Motivation for jet pT binning

Jet PT: jet from dijets vs. radiation jet
from $\gamma$+jet events



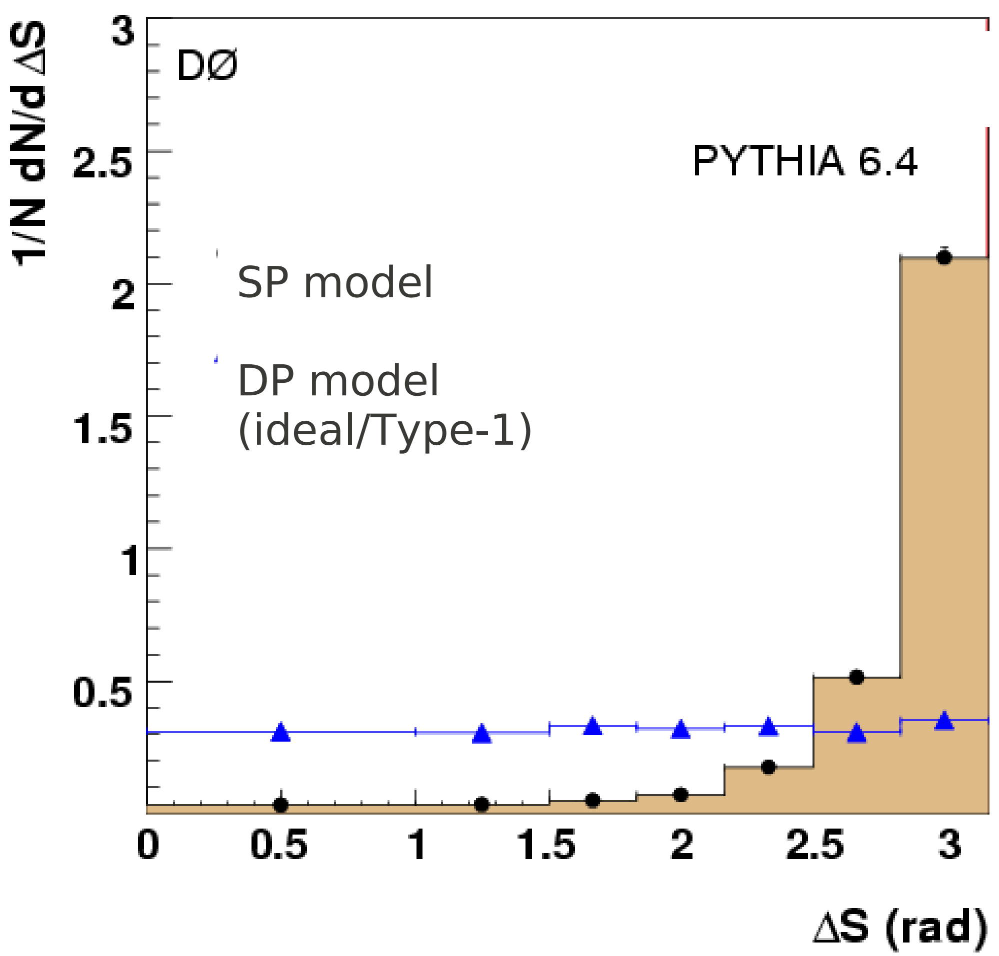

$\sim 1/p_T^4$

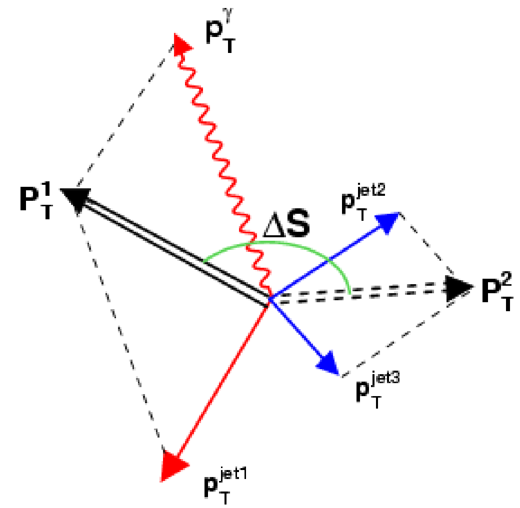
$\sim 1/p_T^2$




- 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 2nd jet pT: 15-20, 20-25, 25-30 GeV

# $\triangle$S distribution for $\gamma$+3-jet events from Single Parton scattering

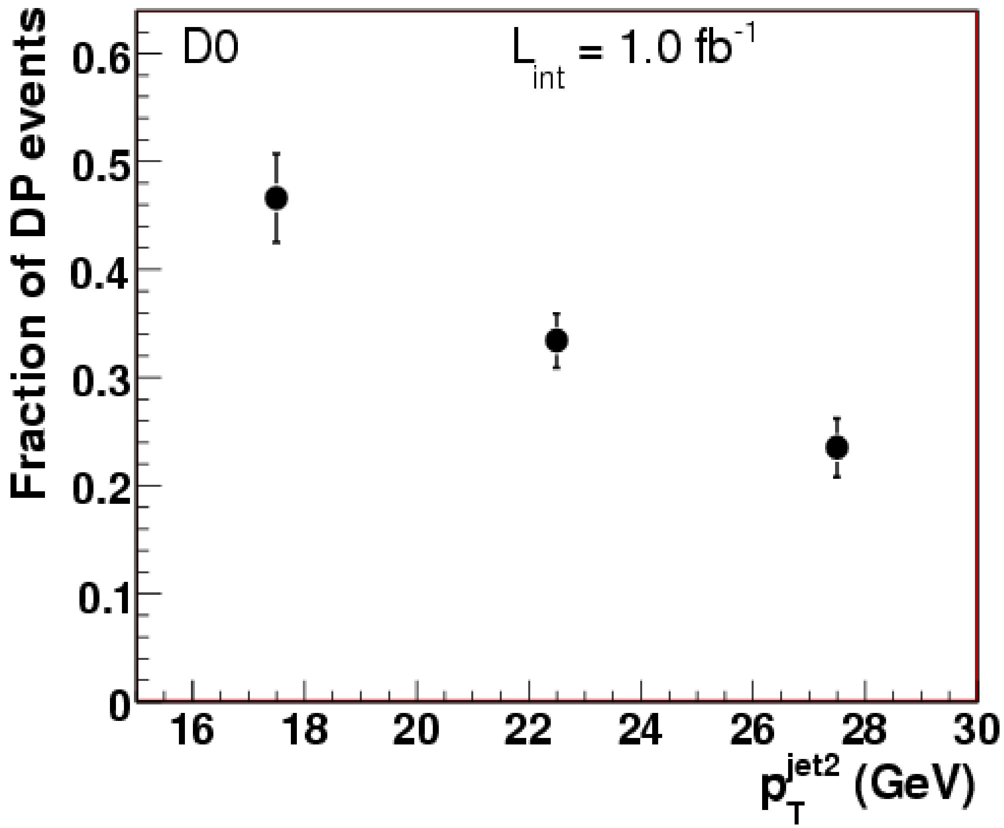



$$\Delta S = \Delta\phi(p_T^{\gamma,\,\text{jet}}, p_T^{\text{jet}_i,\,\text{jet}_k})$$

➔ For "$\gamma$+3-jet" events from Single Parton scattering we expect $\Delta$S to peak at $\pi$, while it should be flat for "ideal" Double Parton interaction (2nd and 3rd jets are both from dijet production).

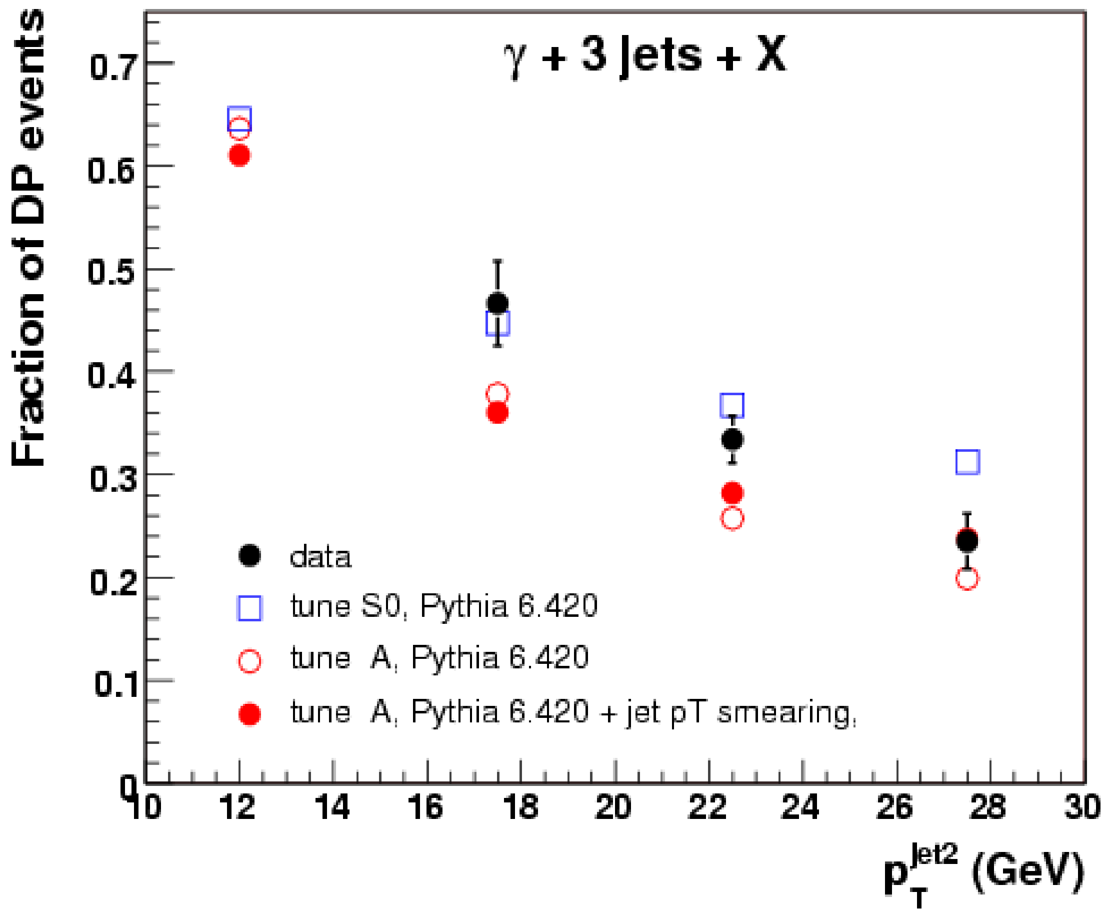
# Fractions of Double Parton $\gamma$+3-jet events




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.

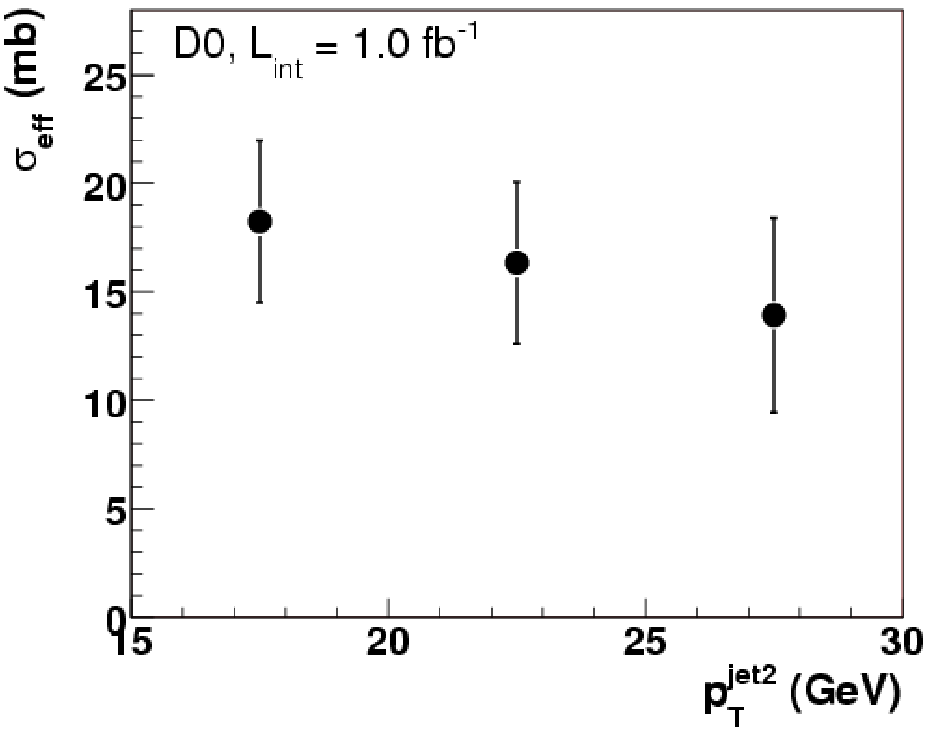
# Fractions of Double Parton events : MPI models and D0 data




- Pythia MPI tunes A and S0 are considered.
- Data are in between the model predictions.
- Results are preliminary: data should be corrected to the particle level.
- Will be done later to find the best MPI Tune

# Calculation of $\sigma_{eff}$

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




- $\sigma_{eff}$ 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:

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

Main systematic and statistical uncertainties (in %) for $\sigma_{eff}$.

| $p_T^{jet2}$ (GeV) | Systematic uncertainty sources $f_{DP}$ | $f_{DI}$ | $\varepsilon_{DP}/\varepsilon_{DI}$ | JES | $R_c\sigma_{hard}$ | $\delta_{syst}$ (%) | $\delta_{stat}$ (%) | $\delta_{total}$ (%) |
|---|---|---|---|---|---|---|---|---|
| 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 $\sigma_{\rm eff}$

- $\sigma_{\rm eff}$ 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 $\sigma_{\rm eff}$.

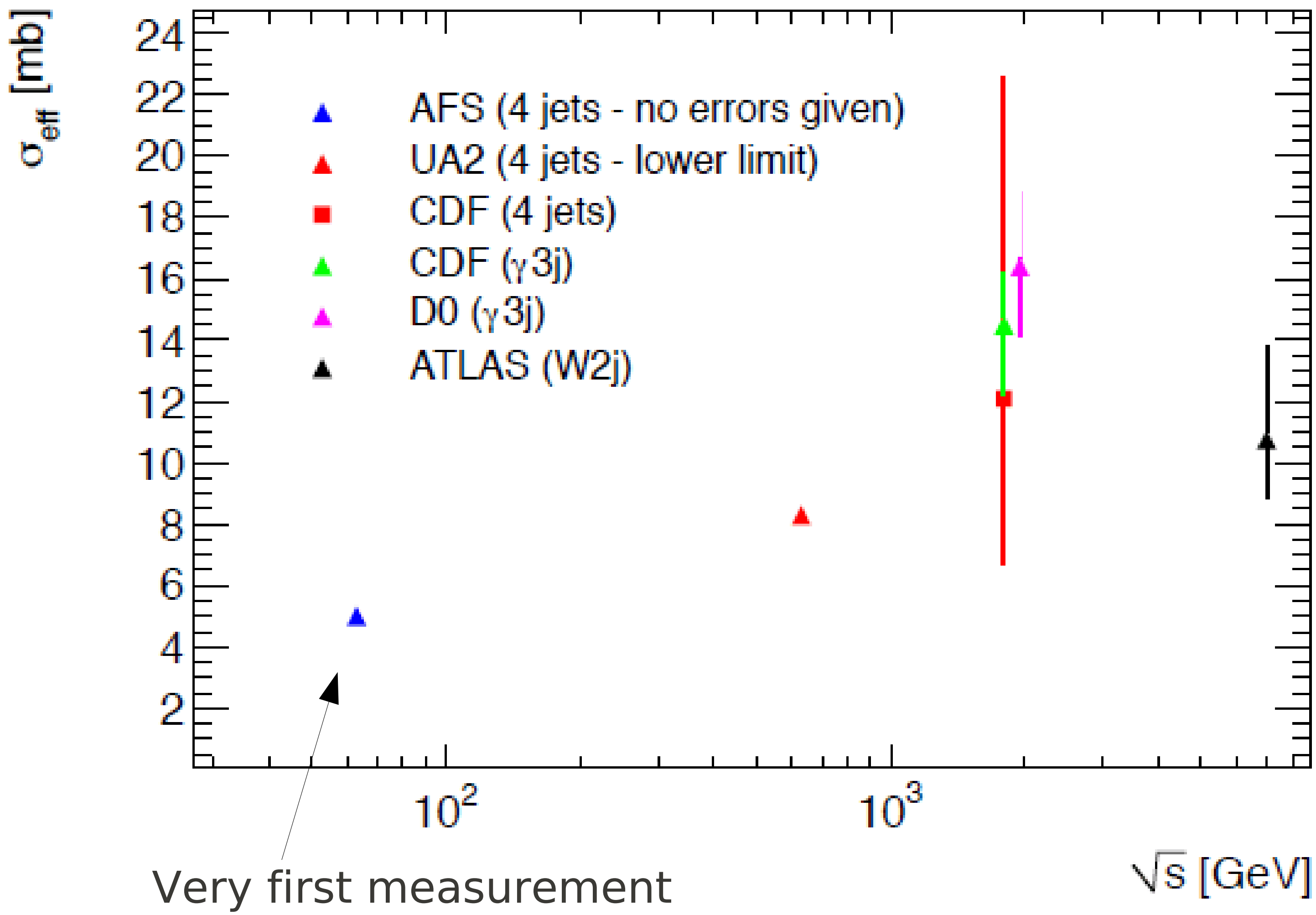
| Model for density | $\rho(r)$ | $\sigma_{\rm eff}$ | $R_{\rm rms}$ | Parameter (fm) | $R_{\rm rms}$ (fm) |
|---|---|---|---|---|---|
| Solid Sphere | Constant, $r < r_p$ | $4\pi r_p^2/2.2$ | $\sqrt{3/5}r_p$ | $0.53 \pm 0.06$ | $0.41 \pm 0.05$ |
| Gaussian | $e^{-r^2/2a^2}$ | $8\pi a^2$ | $\sqrt{3}a$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

– The rms-radia 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-radia from some other source, one can estimate the size of the spatial correlations (larger corr. ↔ larger rms-radius with a fixed $\sigma_{\rm eff}$)

# Experimental results on $\sigma_{eff}$




from Atlas talk
at MPI workshop,
DESY, 2011

Very first measurement
(pp, 4 jets, 1986)

=> No clear energy dependence so far...
=> More measurements are needed!

# Double parton interactions and dPDF evolution

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

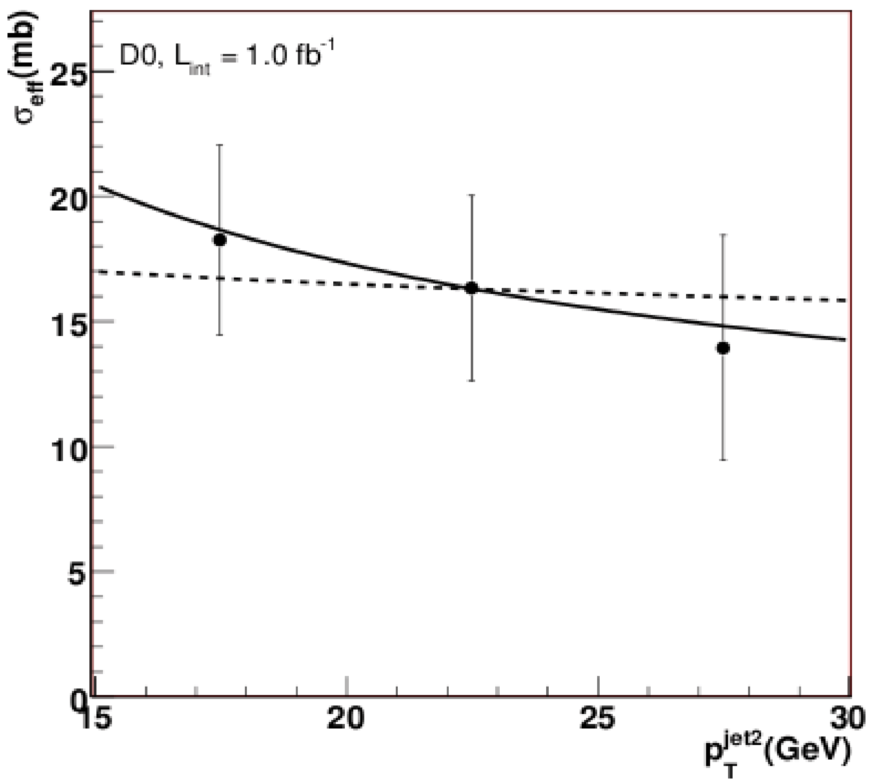



FIG. 1: Effective cross section $\sigma_{\rm eff}^{\rm exp}$ measured in the three $p_T^{\rm jet2}$ bins at the D0 experiment [5]. The solid ($k = 0.5$) and dashed ($k = 0.1$) lines are the results from Eq. (11) at $p_{T0}^{\rm jet2} = 22.5$ GeV and $\sigma_{\rm eff}^0 = 16.3$ mb.

If at any given scale $\mu_0$:
$D(x1,x2,\mu_0) = D(x1,\mu_0)*D(x2,\mu_0)\ \theta(1-x1-x2)$
the dPDF evolution violates this factorization *inevitably* at any different scale $\mu \neq \mu_0$:
$D(x1,x2,\mu) = D(x1,\mu)*D(x2,\mu) + R(x1,x2,\mu)$,
where $R(x1,x2,\mu)$ 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).

# Angular decorrelations in $\gamma$+2 and $\gamma$+3 jet events

Phys.Rev.D83, 052008 (2011), arXiv:1101.1509

**Motivations:**

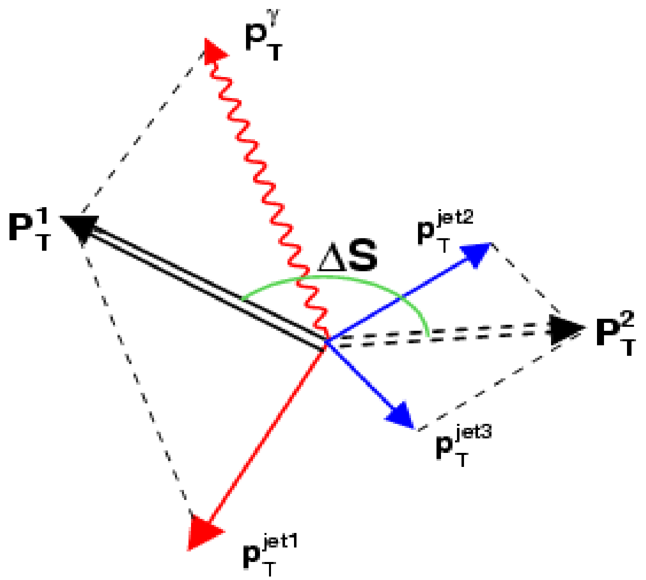
- The provided experimental inputs have been based so far mainly on the minbias and DY Tevatron data (0.63, 1.8, 1.96 TeV) and minbias SPS (0.2, 0.54, 0.9 TeV) data.

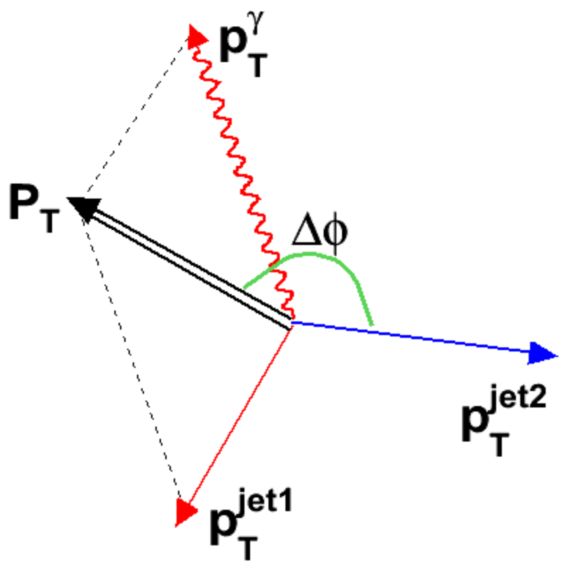
- By measuring **differential** cross sections vs. the azimuthal angles in $\gamma$+3(2) jet events we can better tune (or even exclude some) MPI models in events with high pT jets.

- 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



# ΔS and $\Delta\phi$ cross sections

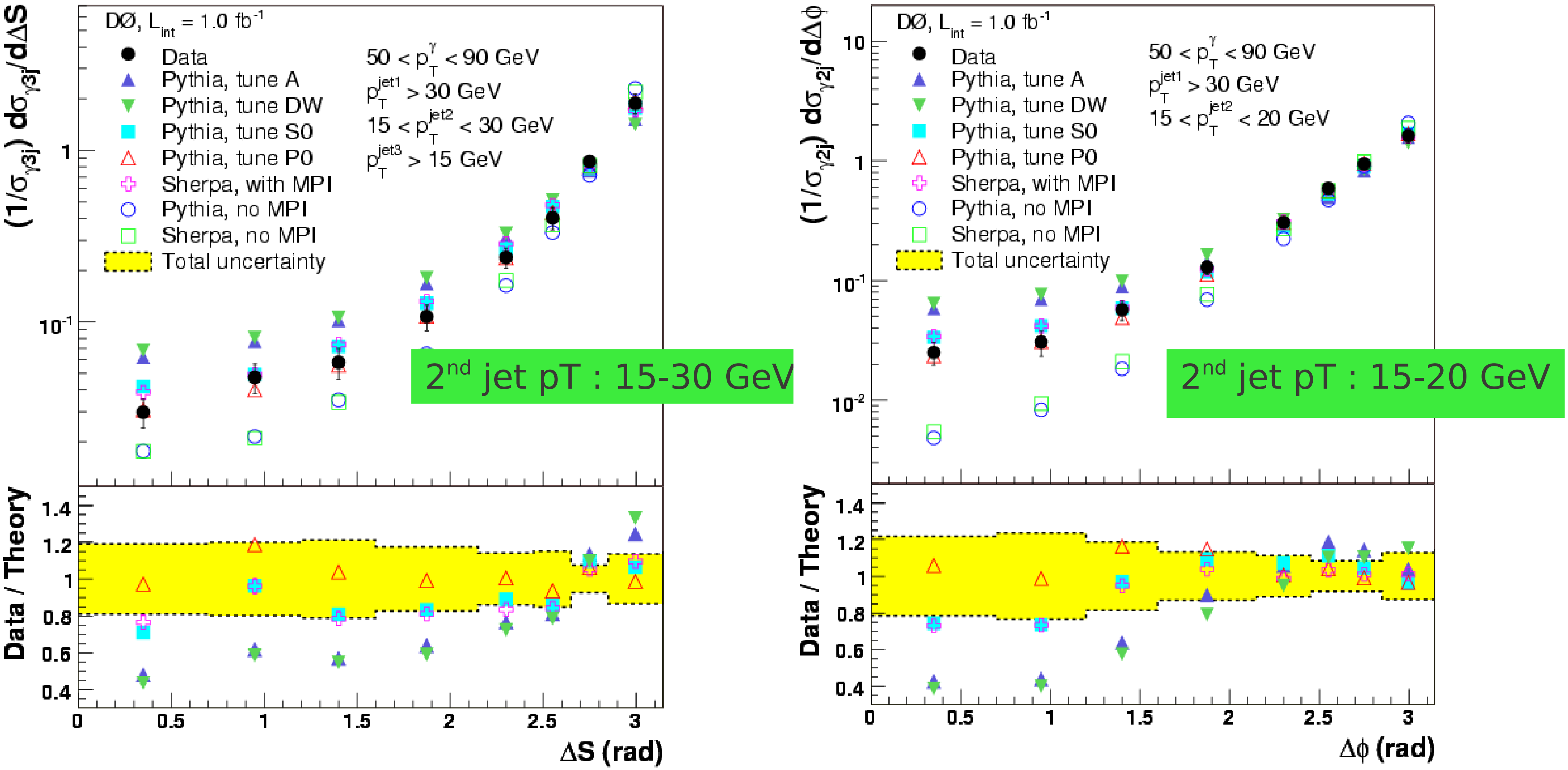


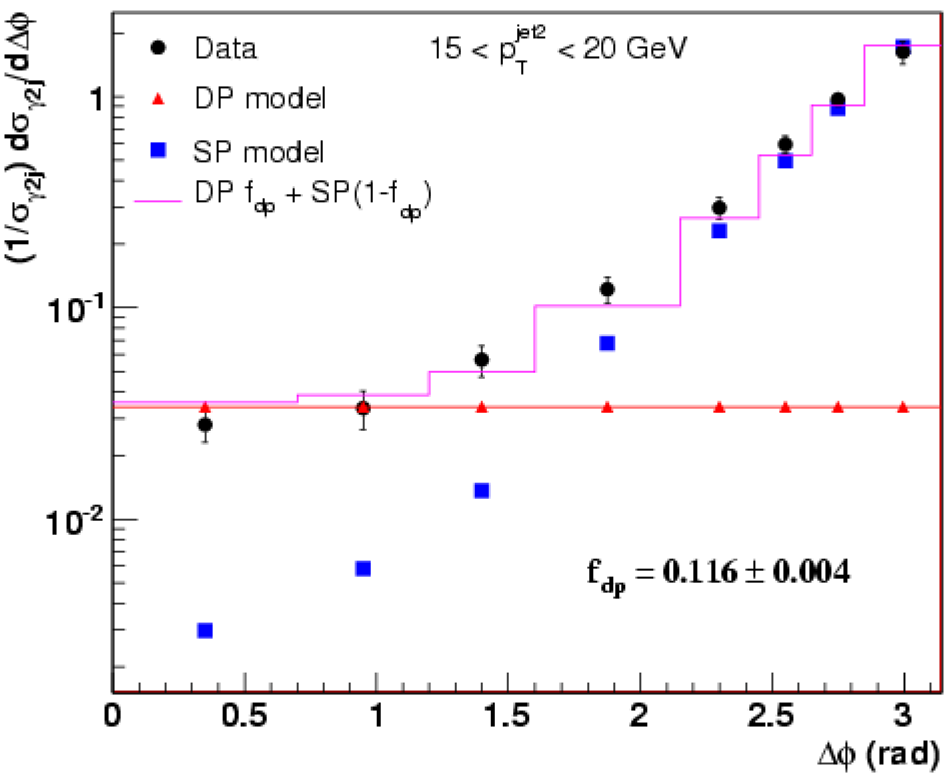

TABLE V: The results of a $\chi^2$ test of the agreement between data points and theory predictions for the $\Delta S$ ($\gamma + 3$ jet) and $\Delta\phi$ ($\gamma + 2$ jet) distributions for $0.0 \leq \Delta S(\Delta\phi) \leq \pi$ rad. Values are $\chi^2/ndf$.

| Variable | $p_T^{jet2}$ (GeV) | SP model PYTHIA | SP model SHERPA | MPI model A | DW | S0 | P0 | P-nocr | P-soft | P-hard | P-6 | P-X | SHERPA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\Delta S$ | 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 $\gamma$+2 jet events

- In $\gamma$+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 $\gamma$+2 jet events

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

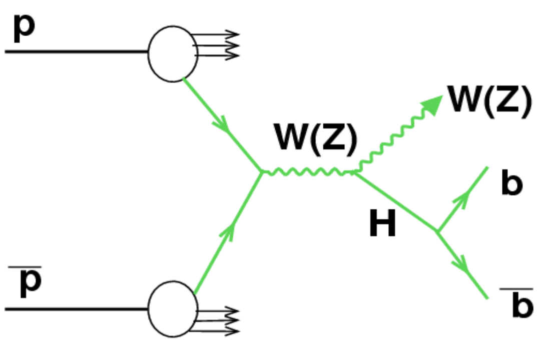
In agreement with CDF Run I:
$14^{+8}_{-7}$% at jet pT >8 GeV and photon pT >16 GeV

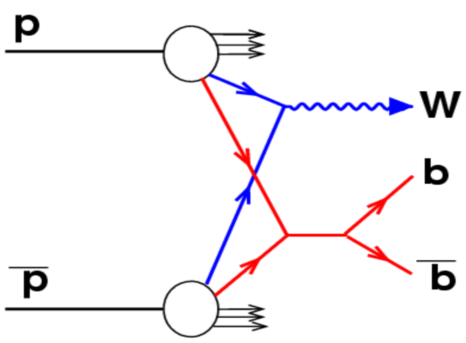
**The TP fractions in $\gamma$+3-jet events**
as a function of 2nd jet pT: ~5.5% at 15-20 GeV, ~2.1% at 20-25 GeV and ~0.9% at 25-30 GeV.

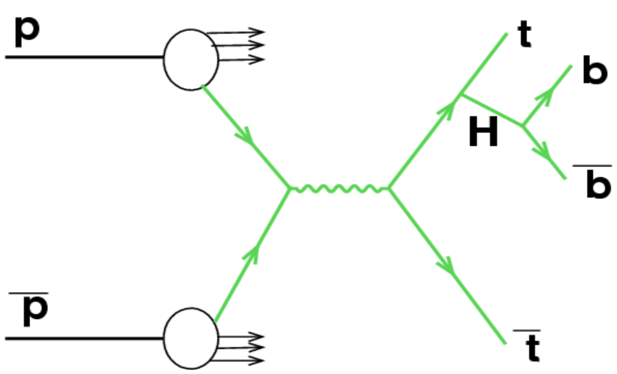
# Double Parton events as a background to Higgs production

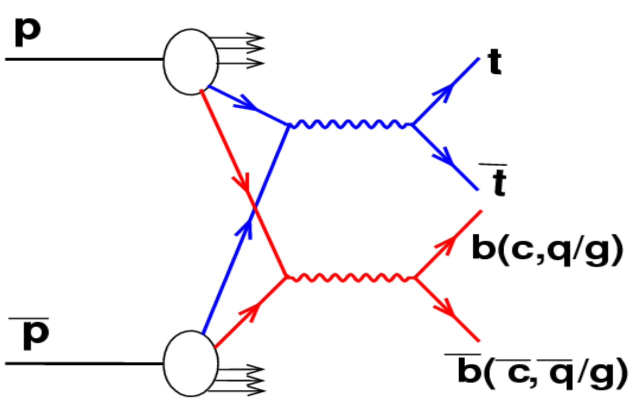
SP Signal

DP background




- Many Higgs production channel can be mimicked by Double Parton event!
- 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)!

=> see example of possible variables below (and also 0911.5348[hep-ph])

Several estimates for LHC: PRD 61 077502; PRD 66 074012; arXiv:0710.0203

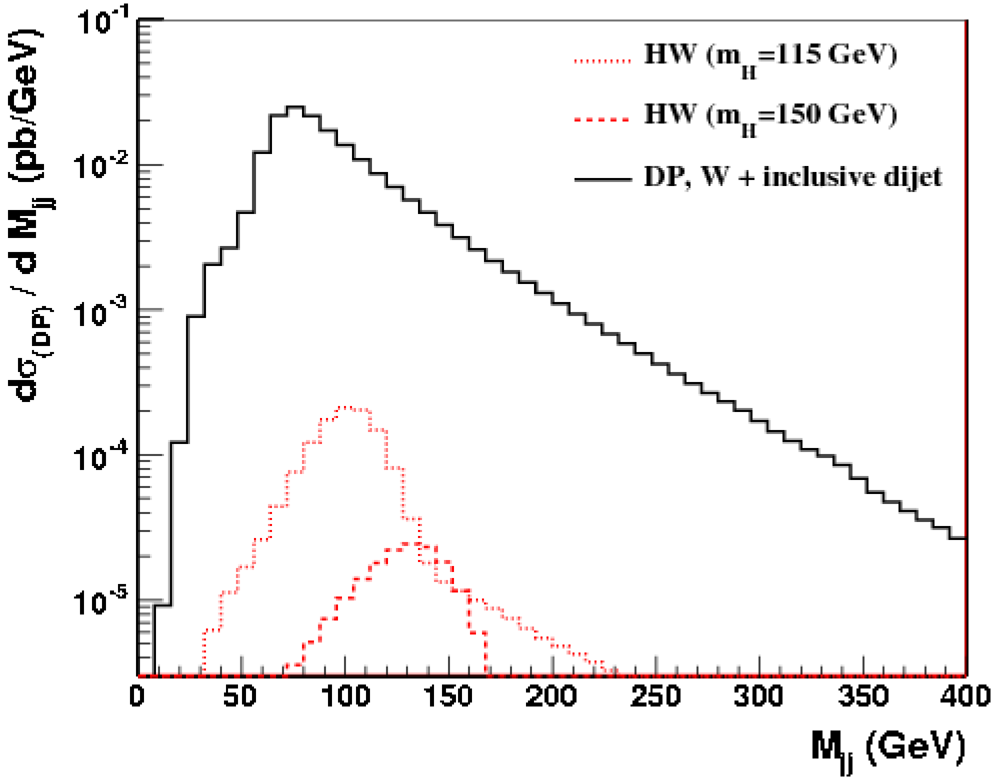
# DP as background to p+pbar→WH at Tevatron

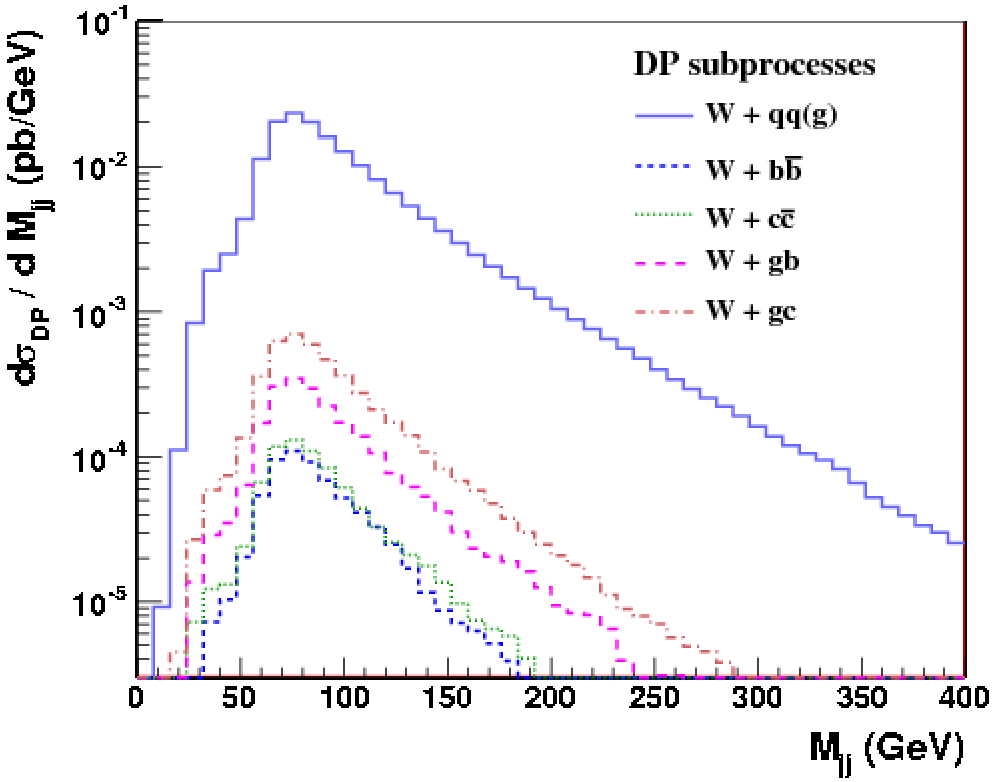
Fast MC based on Pythia-8
(+calorimeter smearing)

D.B.,G.Golovanov,N.Skachkov
JHEP 1104 (2011) 054

## HW, H→bb: DP and SP cross sections

No bID selections

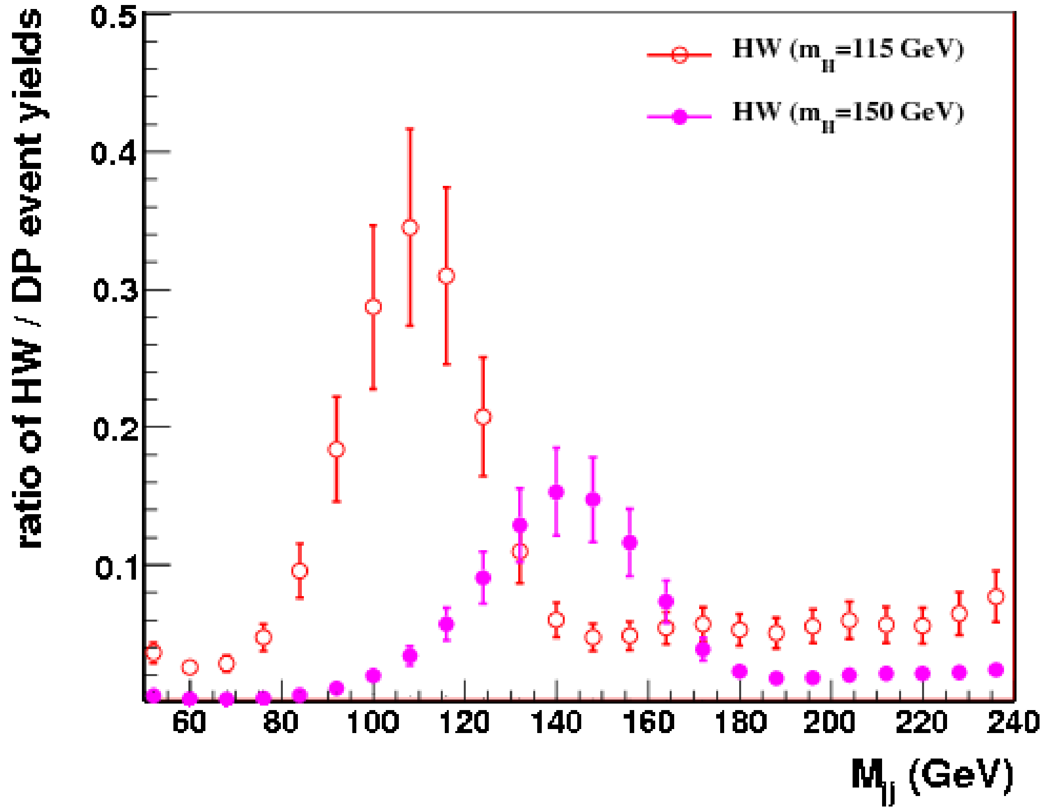



- Kinematic selections are same as in actual D0 analyses.
- Dijet d$\sigma$/dM and W(Z) cross sections are normalized to D0 measurements.
- DP background can be significant for both the associated Higgs production!
- Similar study and same conclusion for LHC: PRD61 (2000) 077502 (Fabbro,Treleani)

# DP as background to p+pbar→WH at Tevatron (2)

HW(Z) / DP cross sections with account of jet E smearing and b-tagging efficiencies for light/c/b jets.




The uncertainties are caused by K-factors (~10%) and $\sigma_{eff}$ (~15%)

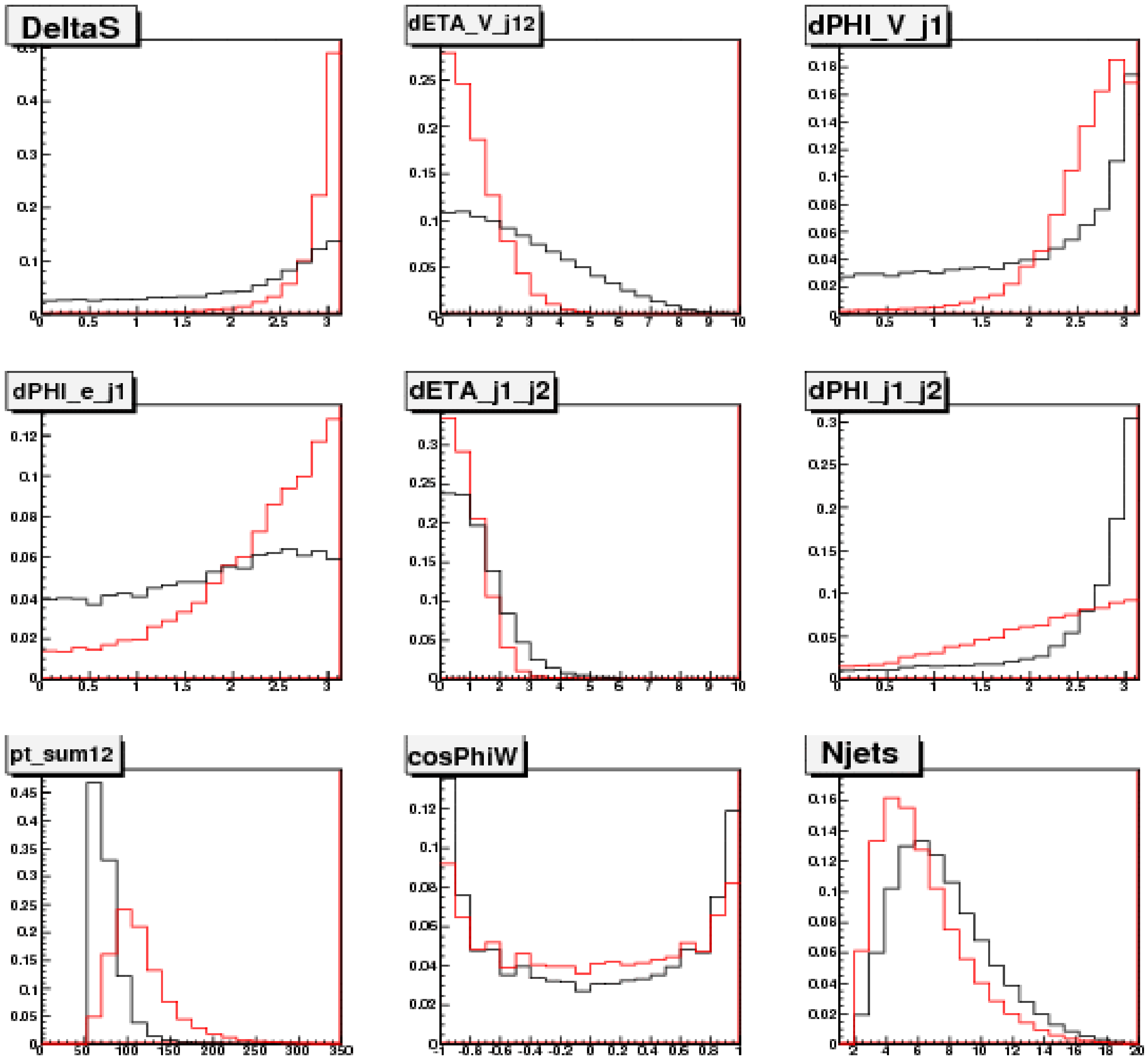
Fractions of events with single jet b-tagging and double b-tagging are chosen as in data/full reco for WH

– Higgs signal is suppressed even in the peak by a factor 2.5-5

Let's try to improve it:
=> Discriminator (ANN based) is built using all the variables sensitive to kinematics of HW /DP productions

# DP as background to p+pbar→W(Z)H at Tevatron (3)

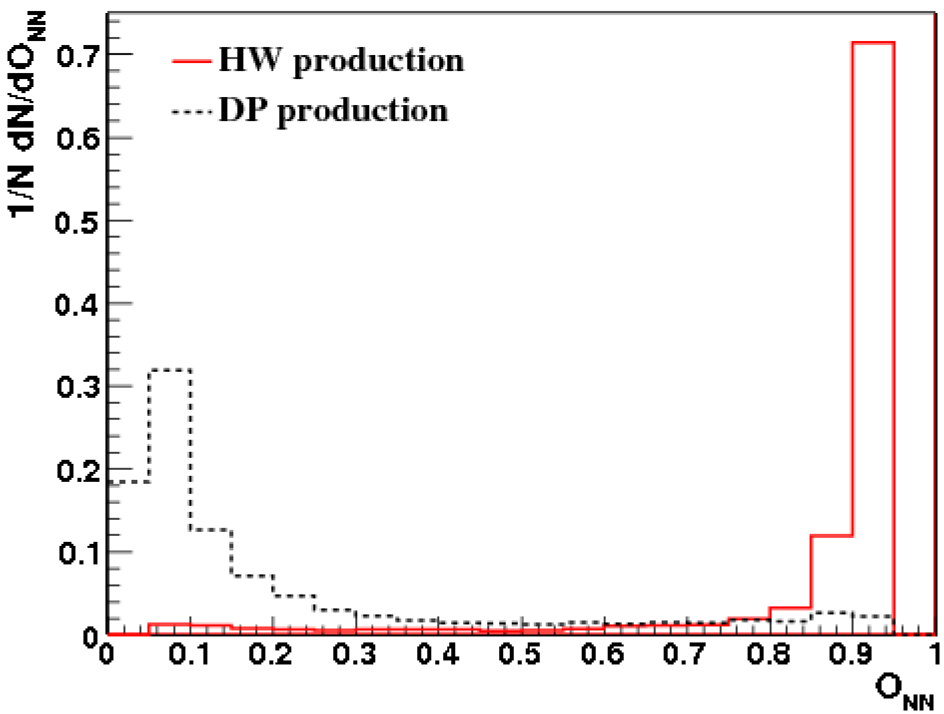
Input ANN variables

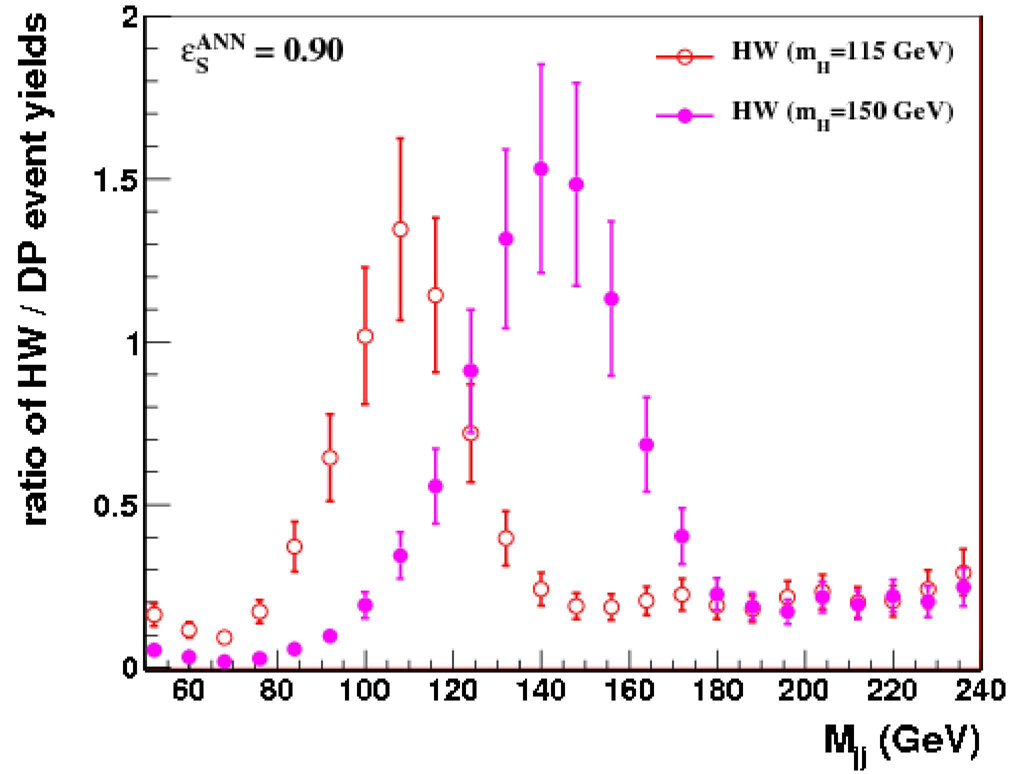



Red is WH
Black is DP

# DP as background to p+pbar→WH at Tevatron (4)

… and with account of a cut on the output value of the dedicated ANN
The cut is chosen to have 90% of signal HW events
The 85% cut gives another factor 1.5-1.8 of the S/B increase



# Di-photon+dijet and di-lepton+dijet events

– Two parton scatterings that can be separated kinematically and in ID space
– Initial state (mainly $q\,\overline{q}$ ) differs from the photon+3jet and 4-jet events
=> new and independent test of $\sigma_{\rm eff}$ and MPI models

– Expected DP fractions are higher than in photon+3jet events

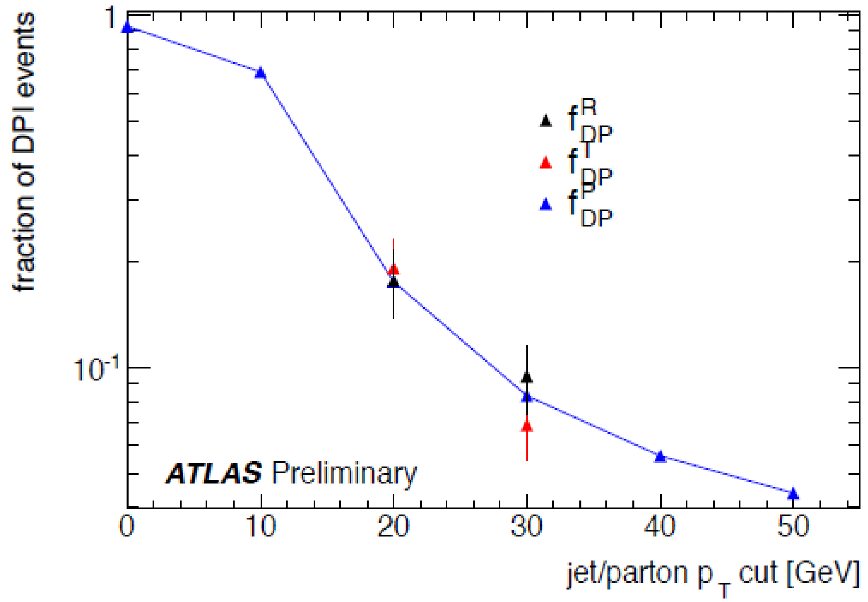
Cross sections (pb) of DP and SP events for various cuts on pT-imbalance

$$||\vec{p_T}(i)| - |\vec{p_T}(j)|| \le c_{ij}\sqrt{\delta^2[|\vec{p_T}(i)] + \delta^2[|\vec{p_T}(j)|]}.$$

hep-ph/9605430

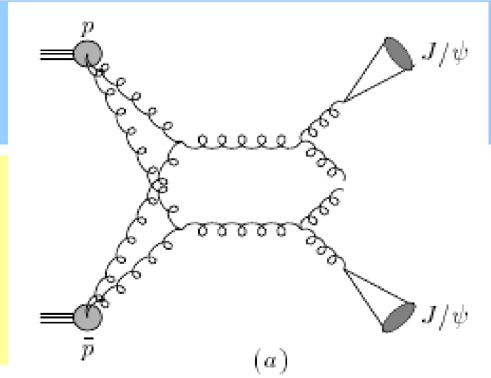
| | basic | $c_1 = c_2 = 5$ | $c_1 = c_2 = 2$ | $c_1 = 1,\ c_2 = 2$ | $c_1 = c_2 = 1$ |
|---|---|---|---|---|---|
| $\sigma(jj\gamma\gamma)$(S) | 1.86 | 0.96 | 0.71 | 0.59 | 0.37 |
| $\sigma(jj\gamma\gamma)$(B) | 20.8 | 2.34 | 1.16 | 0.94 | 0.52 |
| S/B | 0.089 | 0.41 | 0.61 | 0.63 | 0.71 |
| $\sigma(jjee)$(S) | 3.45 | 2.01 | 1.42 | 1.07 | 0.62 |
| $\sigma(jjee)$(B) | 19.0 | 1.94 | 1.00 | 0.70 | 0.37 |
| S/B | 0.18 | 1.04 | 1.42 | 1.53 | 1.68 |

from Atlas talk
at MPI workshop,
DESY, 2011




By analogy to photon+3j, the events can be split into jet pT bins. There should be enough events at both Tevatron and LHC to study DP events and extract $\sigma_{\rm eff}$

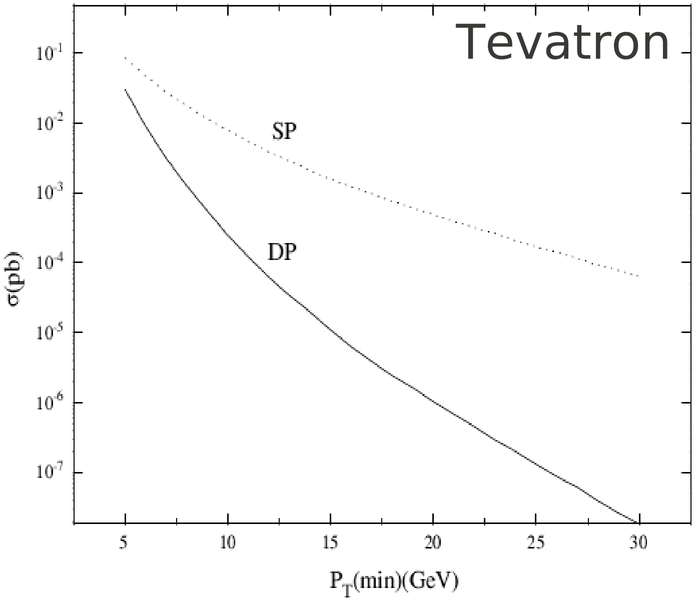
# Double J/psi production

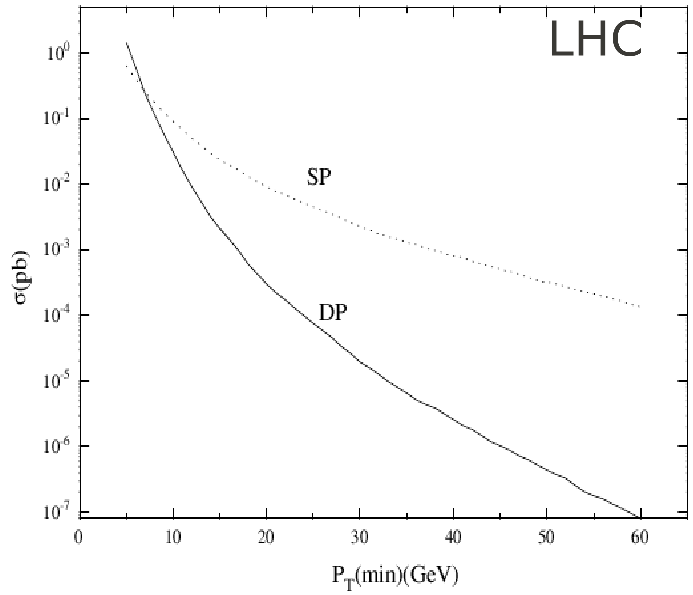


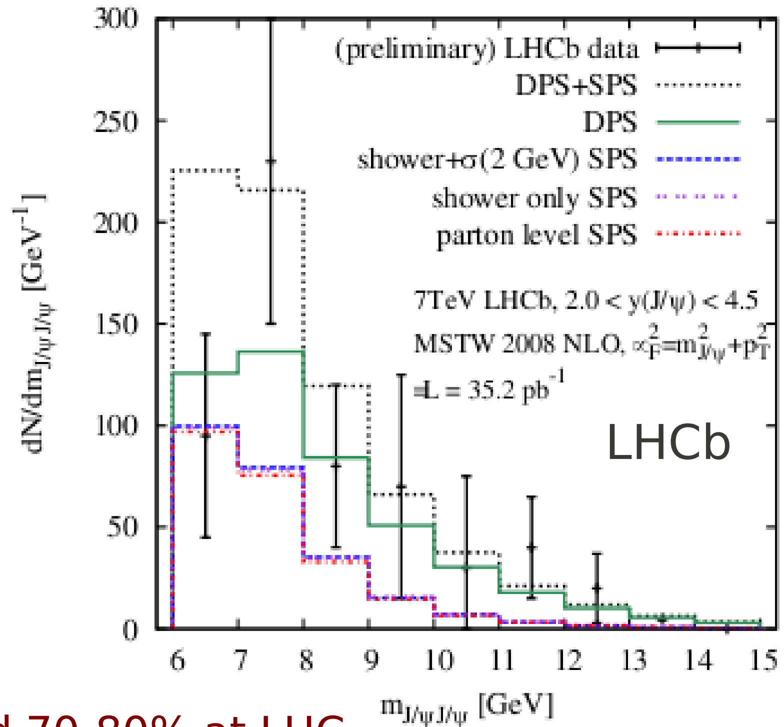

Goal: Meas. of double J/psi cross sections in SP and DP events
=> extraction of $\sigma_{\rm eff}$ at low pT (!)
=> test of $\sigma_{\rm eff}$ energy dependence

hep-ph/9706293

arXiV:1105.4186



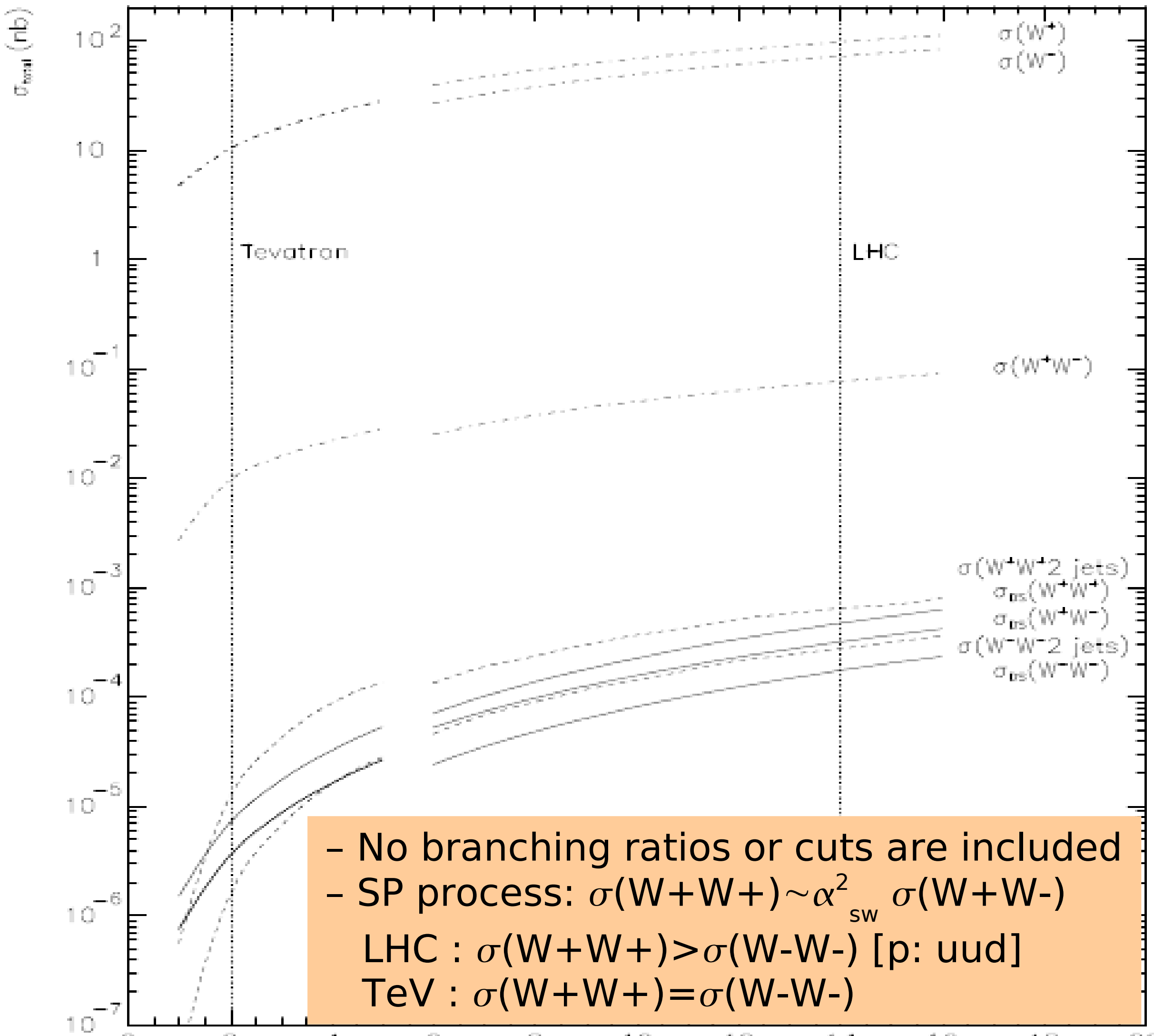

- Expected DP fractions at pT(Jpsi)>5 GeV: 10-20% at Tevatron and 70-80% at LHC (gluon-gluon luminosity is higher at LHC)
- About similar statistics of the selected events, $O$(100) is accumulated at Tevatron and LHC experiments for now
- Main background: b+bbar events with semileptonic B-meson decays into $J/\psi$+X

- LHCb sees about 3 times higher $J/\psi C$ ($C = D^0, D^+, D^+_s, \Lambda^+_c$) x-section than SP QCD (gg→cccc) prediction.

  Observed $\frac{\sigma_{C_1}\sigma_{C_2}}{\sigma_{C_1C_2}}$ is in agreement with $\sigma$eff measured at Tevatron!

# Like-sign WW boson production

From: Phys.Lett. B475 (2000), A.Kulesza,W.J.Stirling




- No branching ratios or cuts are included
- SP process: $\sigma(W+W+) \sim \alpha^2_{sw}\ \sigma(W+W-)$

  LHC : $\sigma$(W+W+)>$\sigma$(W-W-) [p: uud]

  TeV : $\sigma$(W+W+)=$\sigma$(W-W-)

| | $N(W^+W^-)$ | $N(W^+W^+)$ | $N(W^-W^-)$ |
|---|---|---|---|
| single scattering | 7,500,000 | 65,000 | 29,000 |
| double scattering | 46,000 | 31,000 | 17,000 |

Table 1: The expected number of $WW$ events expected for $\mathcal{L} = 10^5$ pb$^{-1}$ at the LHC from single and double scattering, assuming $\sigma_{\rm eff} = 14.5$ mb for the latter.

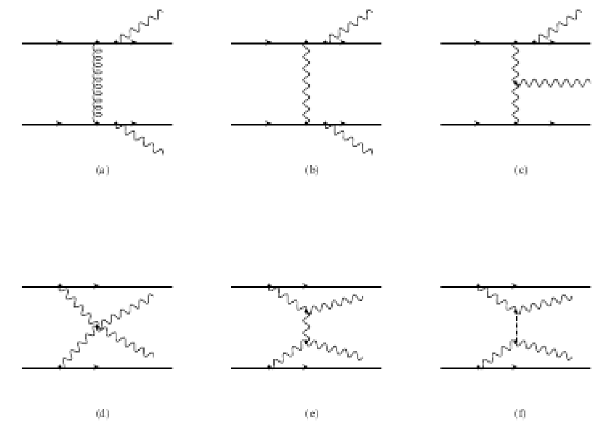



Figure 1: Examples of Feynman diagrams for the $uu \to W^+W^+dd$ scattering process, $\mathcal{O}(\alpha_S^2\alpha_W^2)$ (a) and $\mathcal{O}(\alpha_W^4)$ (b-f).

- Challenges: (a) SS/OS is ~0.02;
  (b) ratio SP/DP is ~2
- But: SP events always have ≥2 jets, and broader jet pT spetrum:

=> upper pT and #jets cuts should Increase DP fraction

- DP $\sigma$(WW) with W via e,mu channels: 2(3) fb at 7(8) TeV
- Possibility to measure $\sigma$eff at high E scale with a 15-20 fb$^{-1}$ data set!

# Summary

- In D0 we have been studying DP production events and measured:
- Fraction of DP events in $\gamma$+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) $\sigma_{\mathrm{eff}}$ 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 $\gamma$+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 △S 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.

# Some still open questions and prospects

- Is $\sigma_{\mathrm{eff}}$ really stable from small to very big scales $\mu$ of a hard interaction?

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

- When the assumption G(x,b) = D(x) F(b) is true ?
  In general, it is not :
  - $GPD_{ik}$(x1,x2,b) (see e.g. arXiv:1009.2714, 1106.5533);
    F(b) should depend on the parton species *i,k*;
    There is a log-dependence of gluon F(b) on parton *x* from excl. J/psi production in DESY
  – Correlation between different partons in the nucleon (in *x*, spin, flavor)

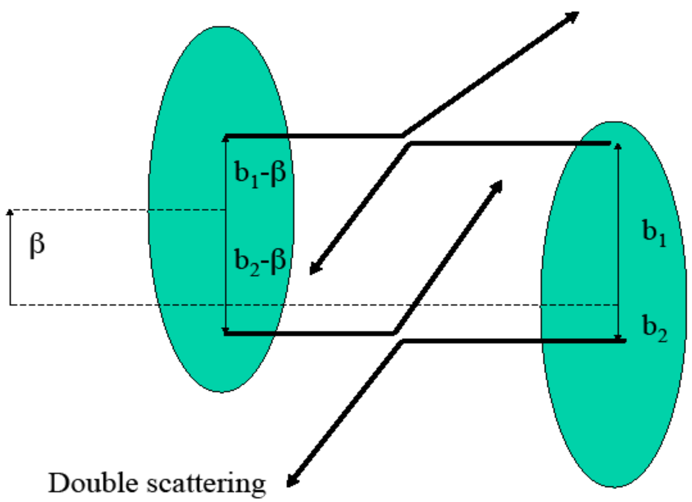
=> More measurements of DP fractions and $\sigma_{\mathrm{eff}}$ are needed
- in processes having different initial state, but at similar energy scales as in the studied $\gamma$+3-jet events.
  For example, di-b-jet+dijet, W/Z/photon + $\geq$2 heavy flavour jets, diphoton+dijet, mutlijet Drell-Yan events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

# BACK-UP SLIDES

# Parton spatial density and $\sigma_{\mathrm{eff}}$

Double parton cross section

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



Double scattering

Effective cross section

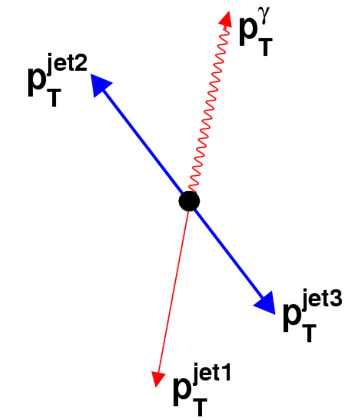
$$\sigma_{eff}^{-1} = \int d^2\beta [F(\beta)]^2,$$

$\beta$ 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.

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




For two hard scattering events
(two separate $p\overline{p}$ collisions):

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

The number of Double Interaction events:

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

For 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:

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

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

# The fraction of DP events: the two datasets method

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

Dataset 1 - “DP-rich”,  smaller 2nd jet pT bin, e.g. 15-20 GeV
Dataset 2 - “DP-poor”, larger 2nd jet pT bin, e.g. 20-25 GeV

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

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

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

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

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

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

From SP MC

From MixDP

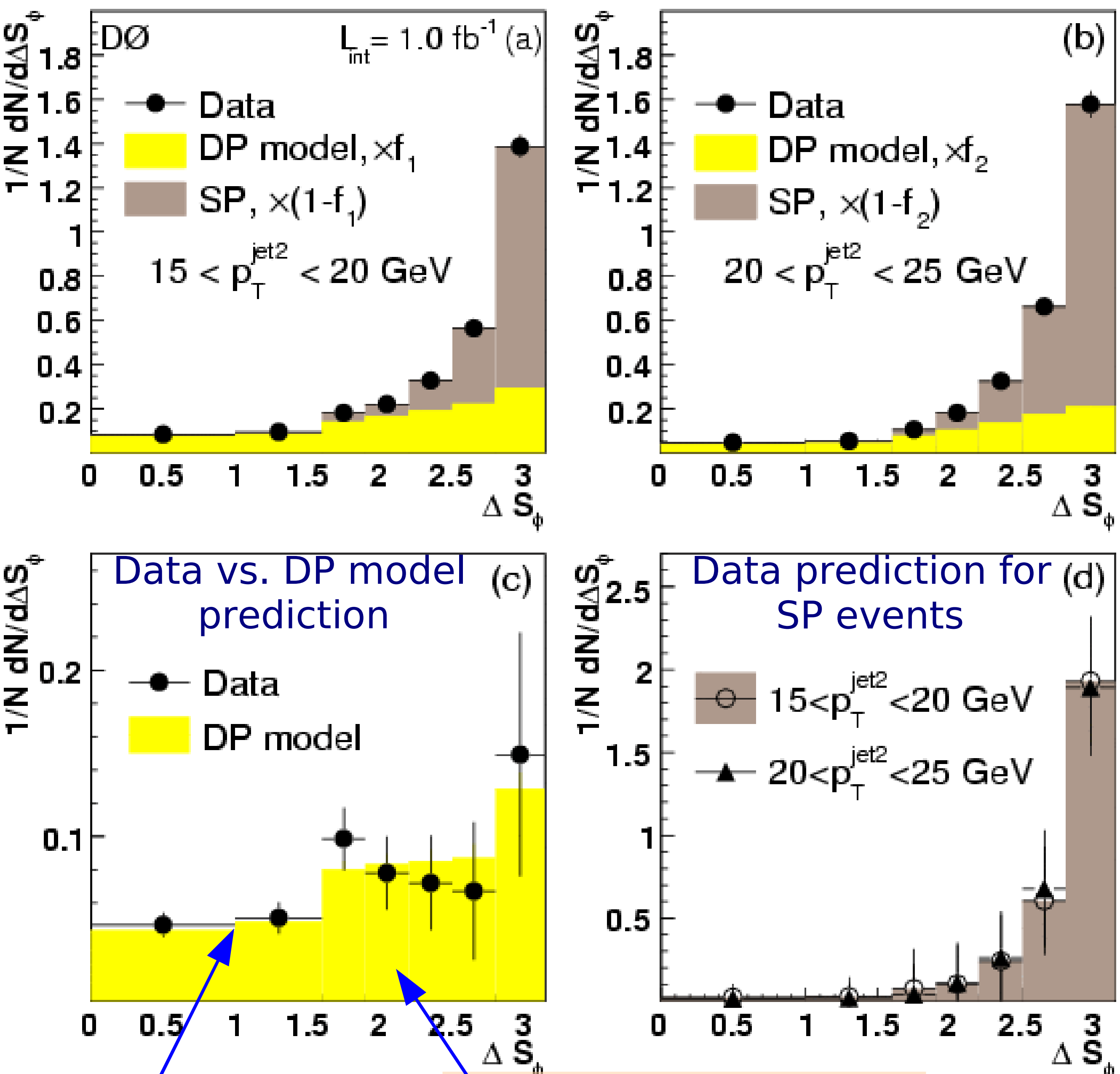
$$D_1 - \lambda K D_2 = f_1 M_1 - \lambda K C f_1 M_2$$

where

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

**$f_1$** is the only unknown, --> get from minimization

# The two datasets method




Dataset (a): 2[nd] jet pT: 15-20 GeV
Dataset (b): 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.

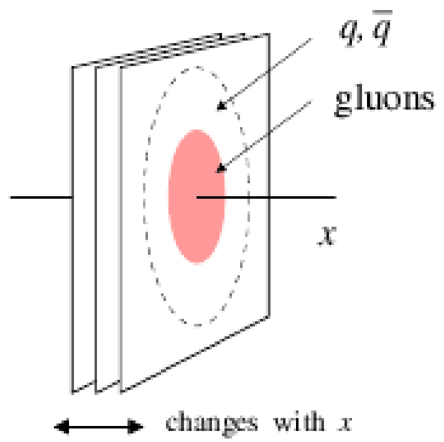
✓Good agreement of the ΔS Single Parton distribution extracted in data and in MC (see slide 24)
→another confirmation for the found DP fractions.

Data are corrected for the DP fractions

✓Good agreement of Data and DP model

# Transverse distributions: Gluons from $J/\psi$

From C.Weiss talk at DIS 2011

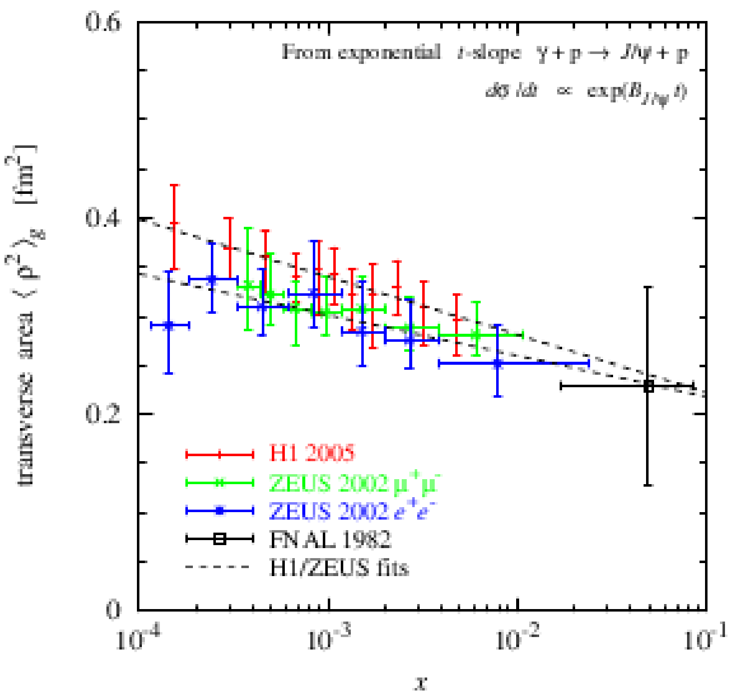



- Exclusive process $\gamma^* N \to J/\psi + N$
  also $\phi$, $\rho$

  Gluon GPD at $x \sim m_\psi^2 / W^2$, $Q^2 \sim 3\,\mathrm{GeV}^2$

  Reaction mechanism, universality tested at HERA H1, ZEUS

  Transverse profile from relative $t$–dependence




- Transverse gluonic size of nucleon

  Gluons concentrated at center
  $\langle \rho^2 \rangle_g (x \sim 10^{-2}) \; < \; \langle b^2 \rangle_{\mathrm{charge}}$

  Radius grows slowly with decreasing $x$
  $\alpha'_g \ll \alpha'_{\mathrm{P}} = 0.25\,\mathrm{GeV}^{-2}$
  Gribov diffusion suppressed by hard scale

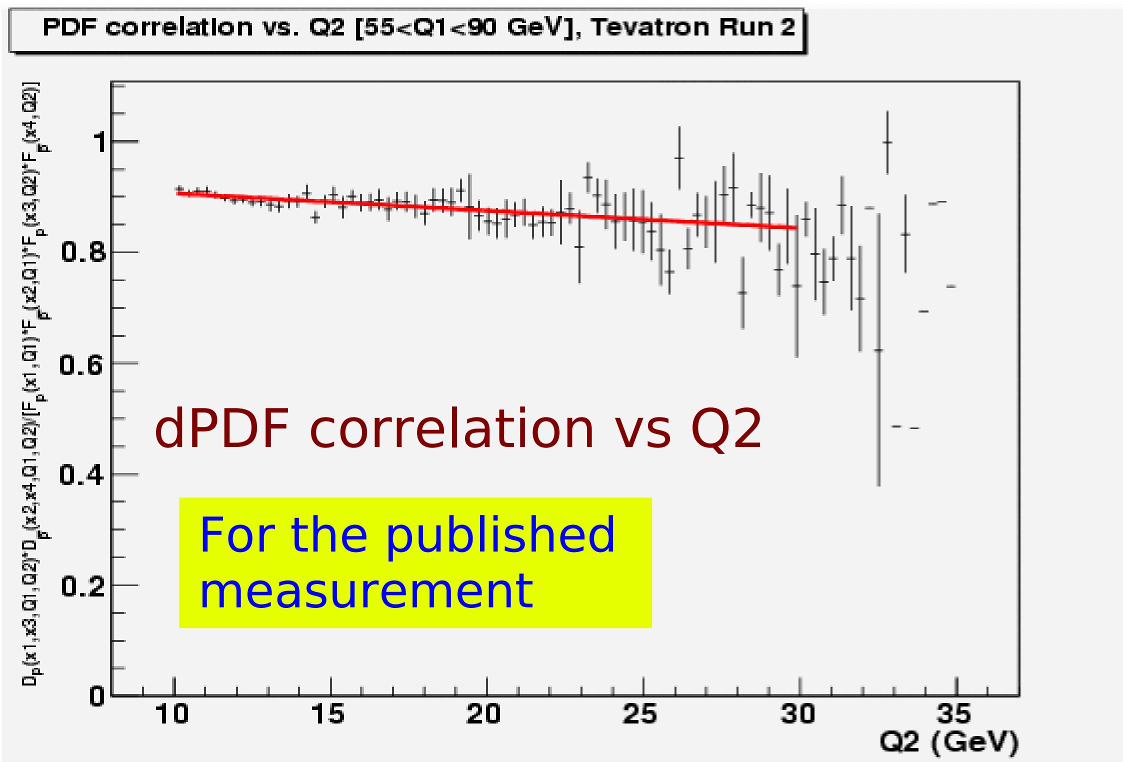
  $Q^2$ dependence from DGLAP evolution calculable, weak FSW, PRD69 (2004) 114010

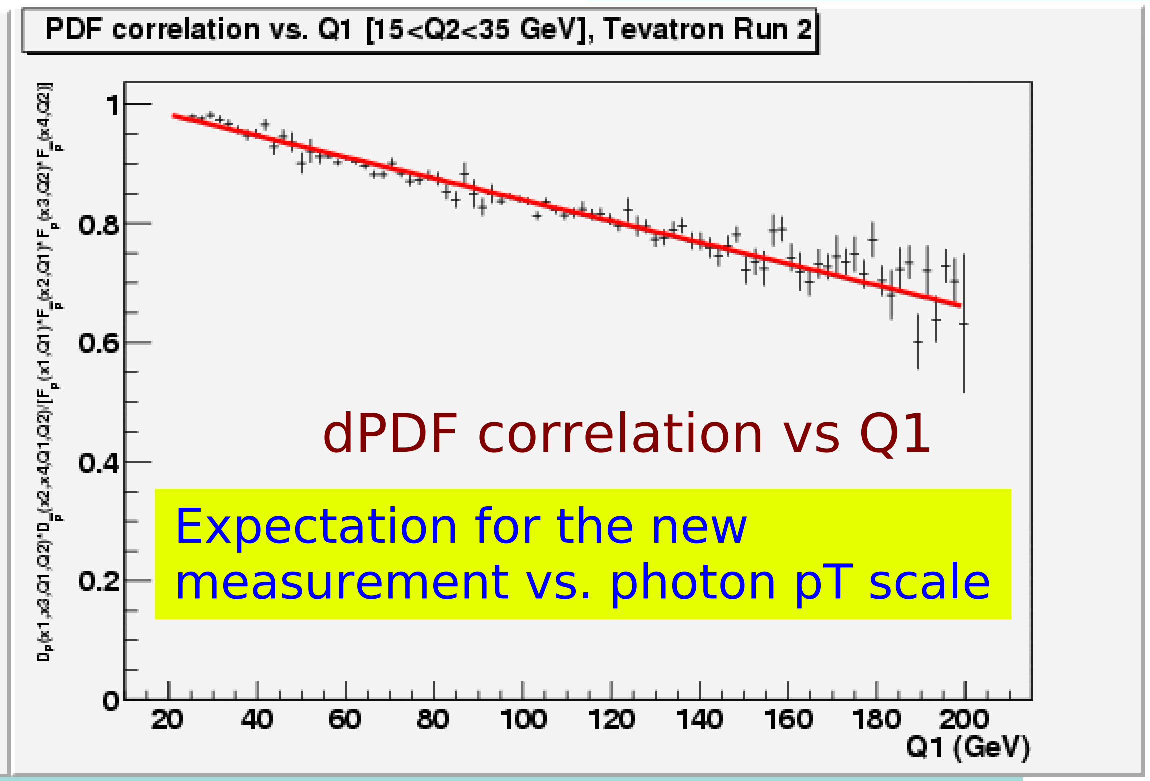
# dPDF evolution

Direct account of double PDFs:  J.Gaunt and J.Stirling, 0910.4347 [hep-ph].
--> **first software implemented evolution equations for dPDF !!**
--> LO dPDF grid files for  10^-6 < x1,x2 < 1.0 and two scales Q1, Q2

- The evolution strongly depends on the process (parton species, kinematics).
- The correlations are estimated using simulated kinematics of $\gamma$+jet events and the G&S evolution code.

D.B., Preliminary



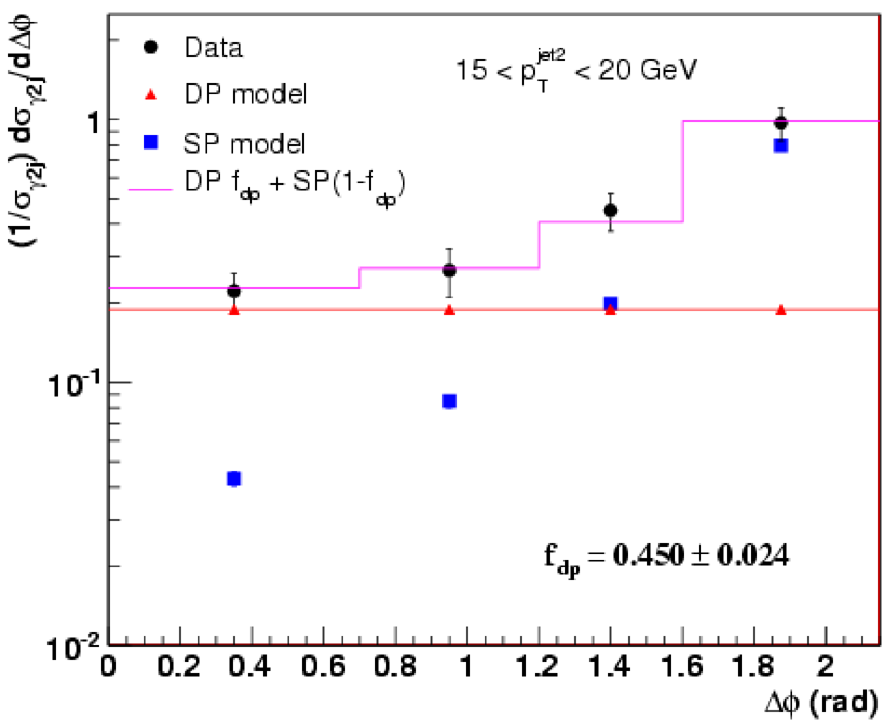




- Size of PDF correlation caused by the dPDF evolution (scaling violation) should be about 25% for photon pT varied as 25 → 120 GeV.

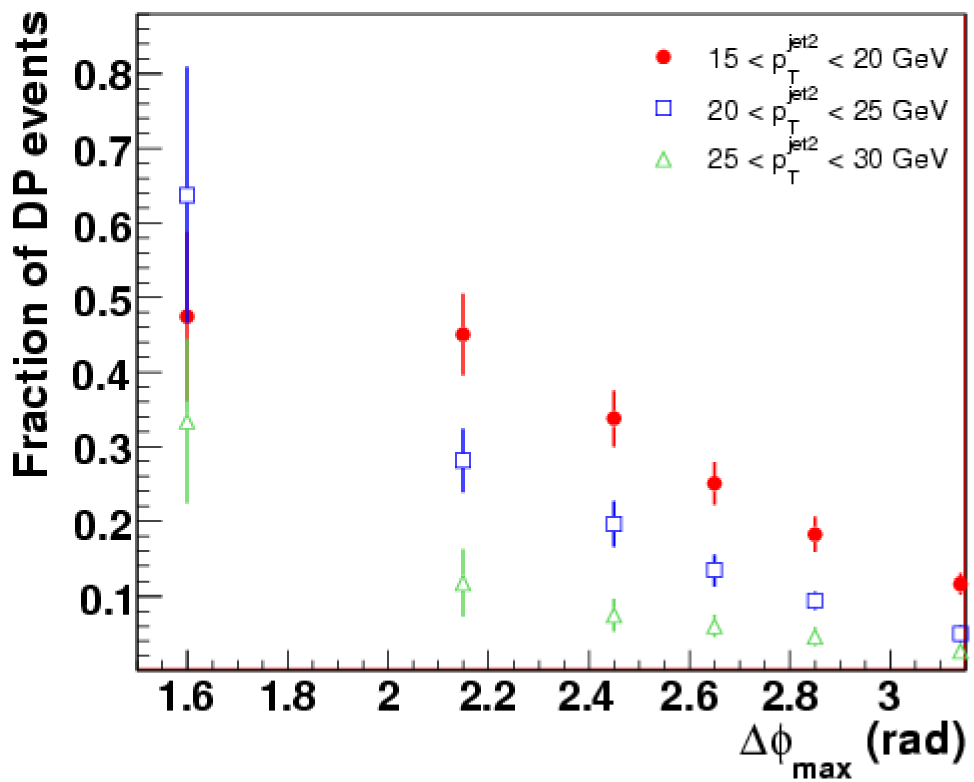
# DP fractions in $\gamma$+2 jet events vs. $\Delta\phi$

- 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 in smaller $\Delta\phi$ regions.

DP fit for 2nd jet pT bin 15 – 20 GeV
$0 < \Delta\phi < 2.15$




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 can also 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 Type I (II) events found in our previous measurement (p.27).
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:

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

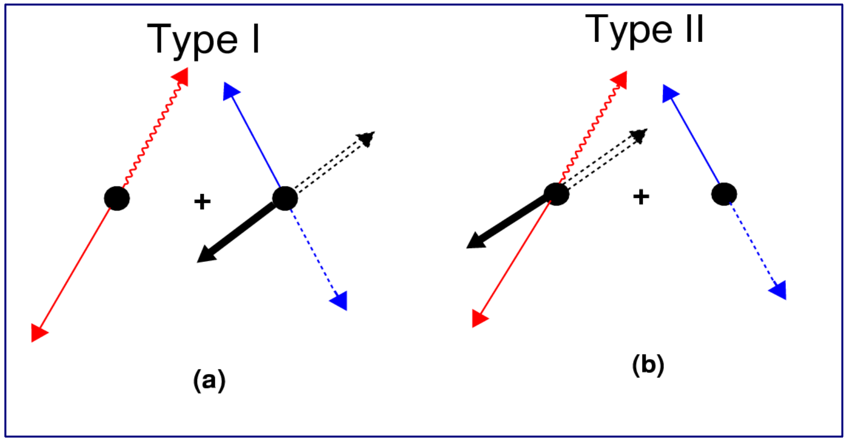
$f_{dp+tp}^{\gamma 3j}$ - measured in previous DP analysis;

$f_{dp}^{jj}$ - 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*.




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

# PDF correlation vs. factorisation

- Strictly speaking, the PDF factorization assumption (*used in our meas.*) is wrong!

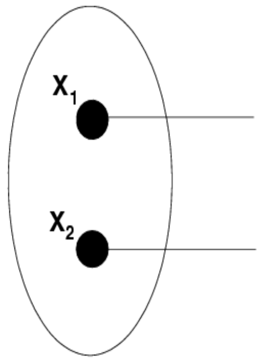
If at any given scale $\mu_0$ one assumes the factorized form

$D(x1,x2,\mu_0) = D(x1,\mu_0)*D(x2,\mu_0)\ \theta(1-x1-x2)$

then *dPDF evolution* violates this factorization *inevitably* at any different scale $\mu \neq \mu_0$:

$D(x1,x2,\mu) = D(x1,\mu)*D(x2,\mu) + R(x1,x2,\mu)$,

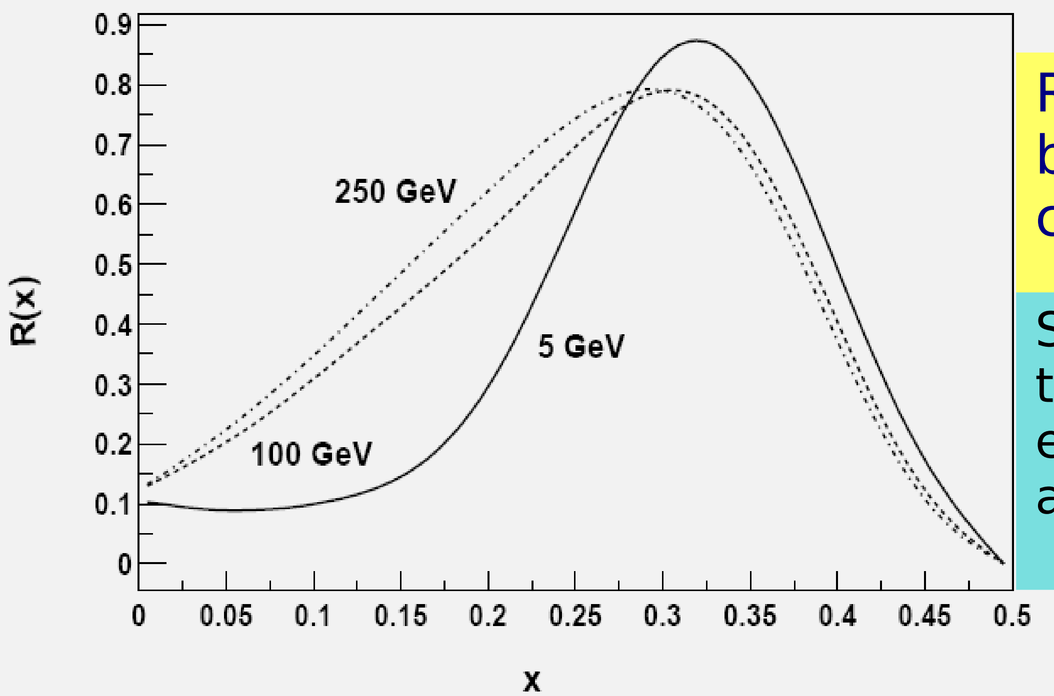
where $R(x1,x2,\mu)$ is a (positive) correlation term.




Correlations for 2 gluon PDFs as an example:

V.L.Korotkikh, A.M. Snigirev, hep-ph/0404155

$$R(x,t) = \left.\frac{D^{gg}_{p(\mathrm{QCD,corr.})}(x_1,x_2,t)}{D^g_p(x_1,t)D^g_p(x_2,t)(1-x_1-x_2)^2}\right|_{x_1=x_2=x}$$




Ratio of the PDFs correlation term, induced by the evolution to the factorization component (both PDFs are at one scale)

Size of the correlations should also depend on the types of PDFs used in the product: e.g. they will be different for ***qg*** and ***qq*** processes and depend on the quark species.

# Possible manifestation of PDF correlations

Following paper of A.M.Snigirev, http://arxiv.org/abs/1001.0104
appeared as an interpretation the D0 measurement.
... right in 4-5 days after submission!

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

Theoretical effective cross section (depends just on a parton spatial density)

$$\frac{\sigma_{DPS}^{\gamma+3j}}{\sigma^{\gamma j}\sigma^{jj}} = [\sigma_{\rm eff}^{\rm exp}]^{-1} \Rightarrow [\sigma_{eff}^{exp}]^{-1} = [\sigma_{eff}]^{-1}(1+\delta(\mu))$$

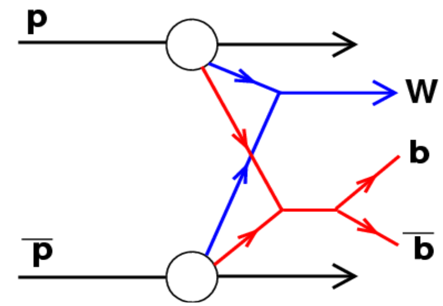
Theoretical and experimentally measured effective cross sections differ: the PDF factorization was assumed (made "by hands") in our data-driven method, and used in the measurement of $\sigma_{eff}^{exp}$ .

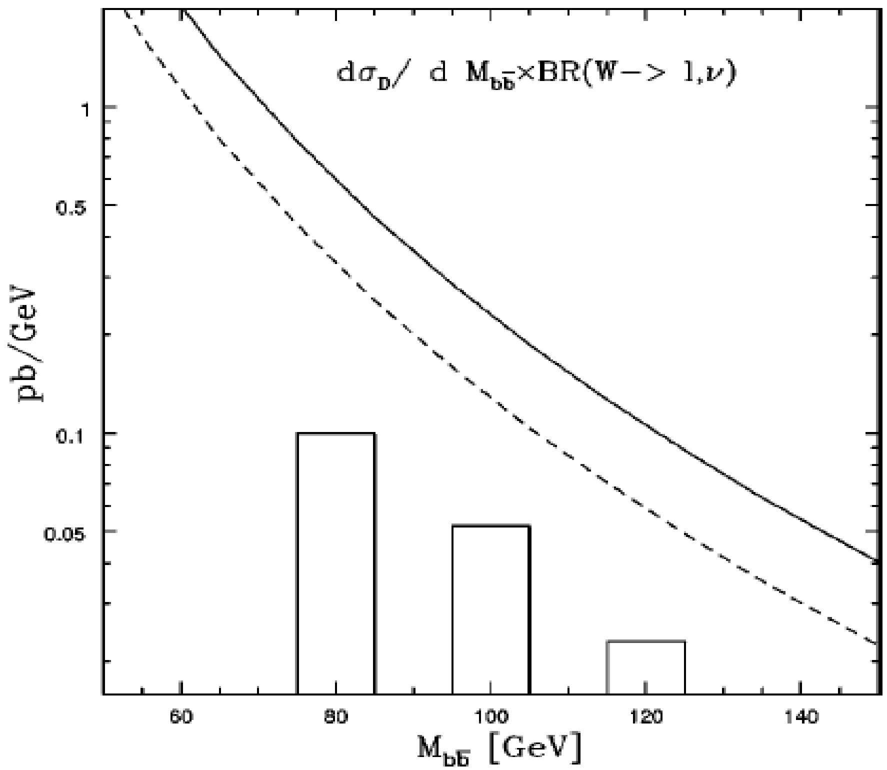
Assumption: $$\sigma_{\rm eff}^{\rm exp} = \sigma_{\rm eff}^{0}[1 + k \ln(p_T^{\rm jet2}/p_{T0}^{\rm jet2}]^{-1}.$$

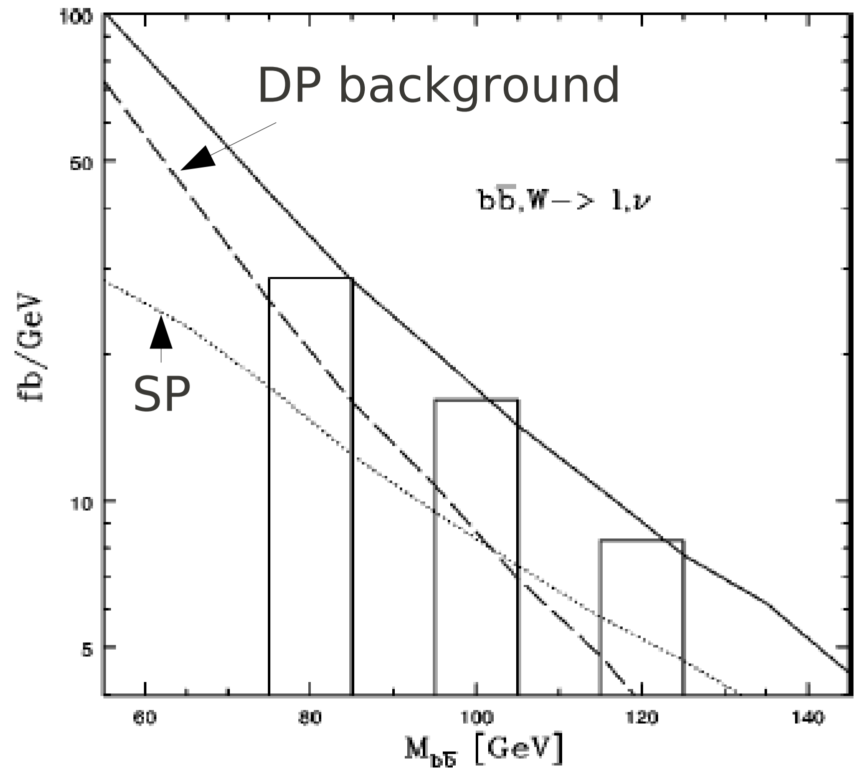
Same general conclusions should be true for the two different photon pT scales!

# Example: DP as background to p+p → WH at LHC

From PRD61 (2000) 077502 by Fabbro, Treleani




DP background as a function of H mass:
LO and NLO bb production
($\sigma_{eff}$ = 14.5 mb used here)
DP background is 3 orders of magnitude higher than the HW cross section

SP (dotted) and DP (dashed) cross sections after selection cuts
DP background is still very important even after selections

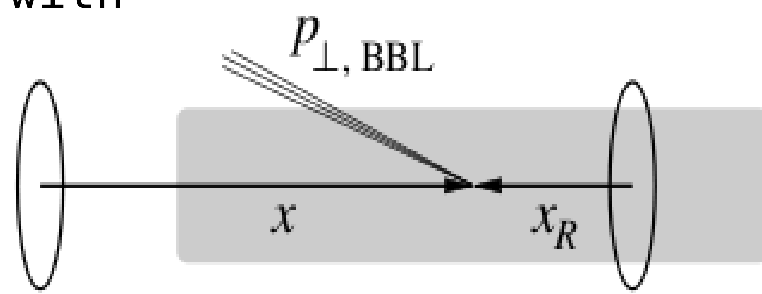
# Some other possible DP studies

•Measurement of DP and TP x-sections in the same type of events.

• Study of the gluon matter density in SP and DP events

A small–x spectator parton (not involved in main hard parton scattering)from the left proton propagates through the strong gluon field and acquires large pT (BBL pT≫ Λ_QCD). (The small–x parton is then resolved in a collision with a large–xR parton from the right proton):

$$x = \frac{4\,p_\perp^2}{x_R\,s}$$

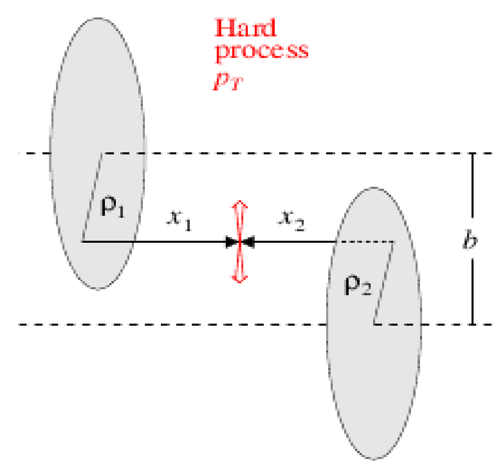



=> results in extensive hadron production with pT>1-2 GeV in the backward(forward) rapidity region
In D0, the calorimeter can be used for this aim
(with SPR correctrions)

=> Potentially may explain CMS "ridge" structure
(arXiv:1009.4122)

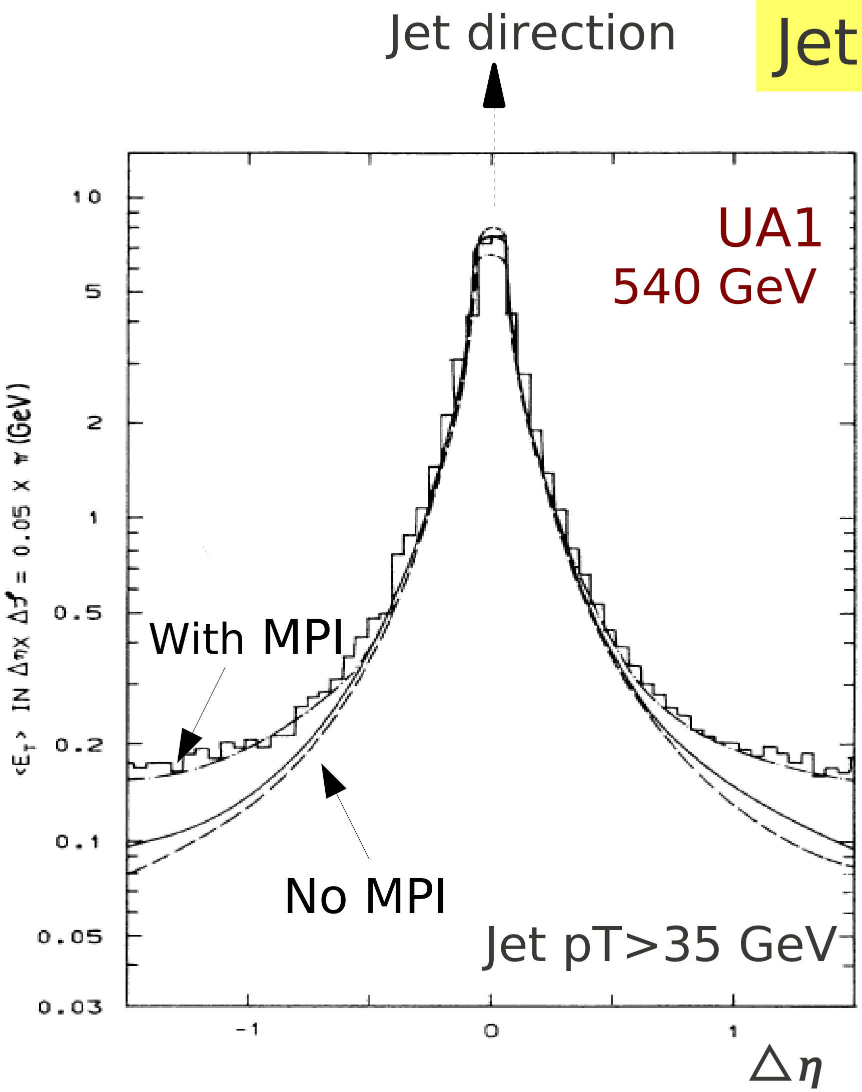
Average impact parameter ***b*** in hard SP, DP and incl. inelastic events

| Facility | $\sqrt{s}$/GeV | $\langle b^2\rangle_2/\mathrm{fm}^2$ | $\langle b^2\rangle_4/\mathrm{fm}^2$ | $\langle b^2\rangle_{\mathrm{in}}/\mathrm{fm}^2$ |
|---|---|---|---|---|
| LHC | 14000 | 0.67 | 0.26 | 2.7 |
| Tevatron | 1800 | 0.63 | 0.24 | 1.8 |
| RHIC | 500 | 0.59 | 0.23 | 1.43 |

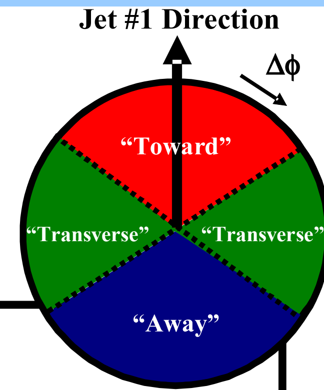


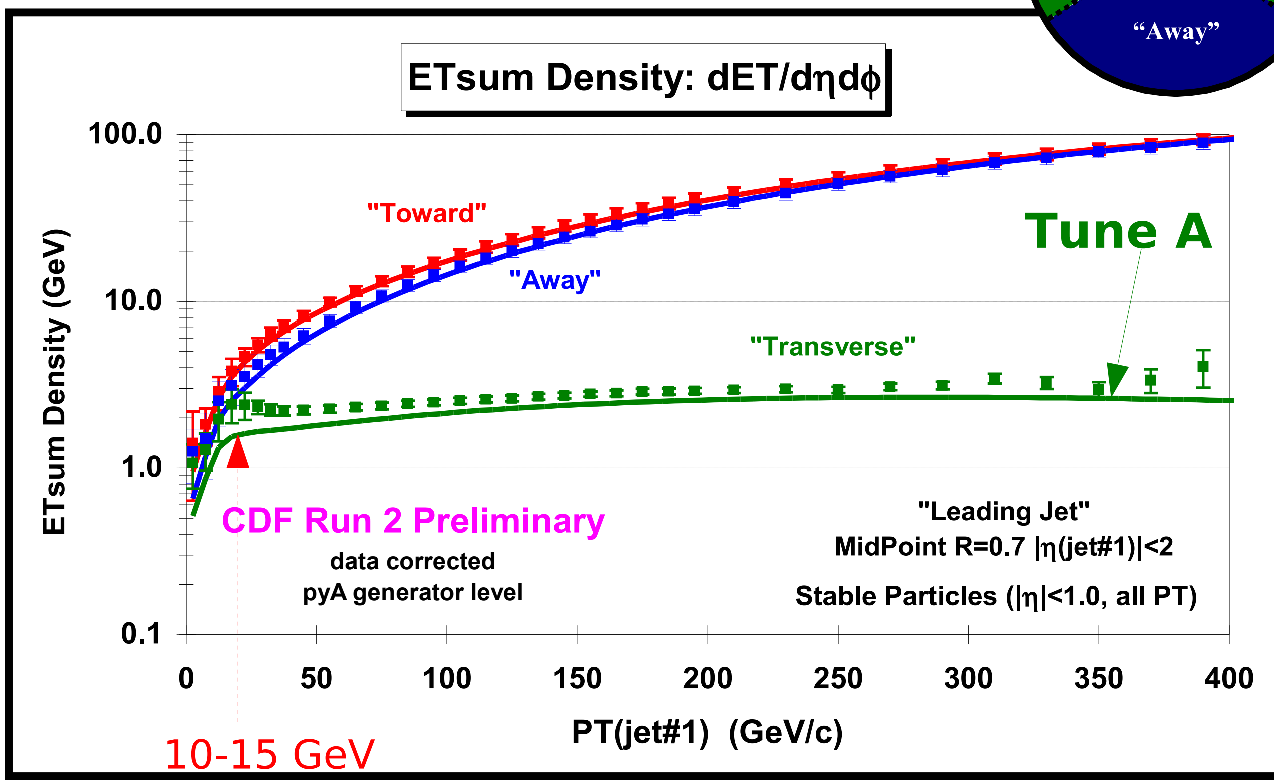
# Experimental tests (2)

## Jet pedestal effect

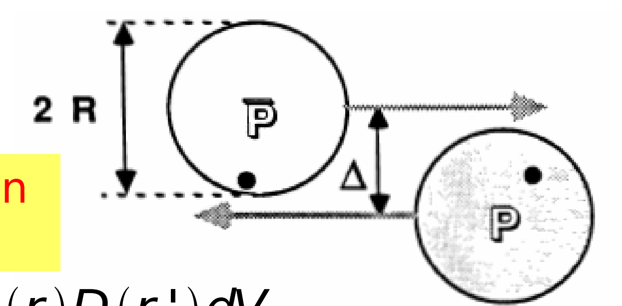



CDF (Run 2)




- Presence of high pT 1st interaction biases events towards smaller p-pbar impact parameters and hence leads to a higher additional activity but saturates at $\sigma(pT\_jet) \ll \sigma\_nd$ ("nd" = non-diffractive).
- The height of the pedestal depends on the overlap, i.e. on the parton matter distribution function.



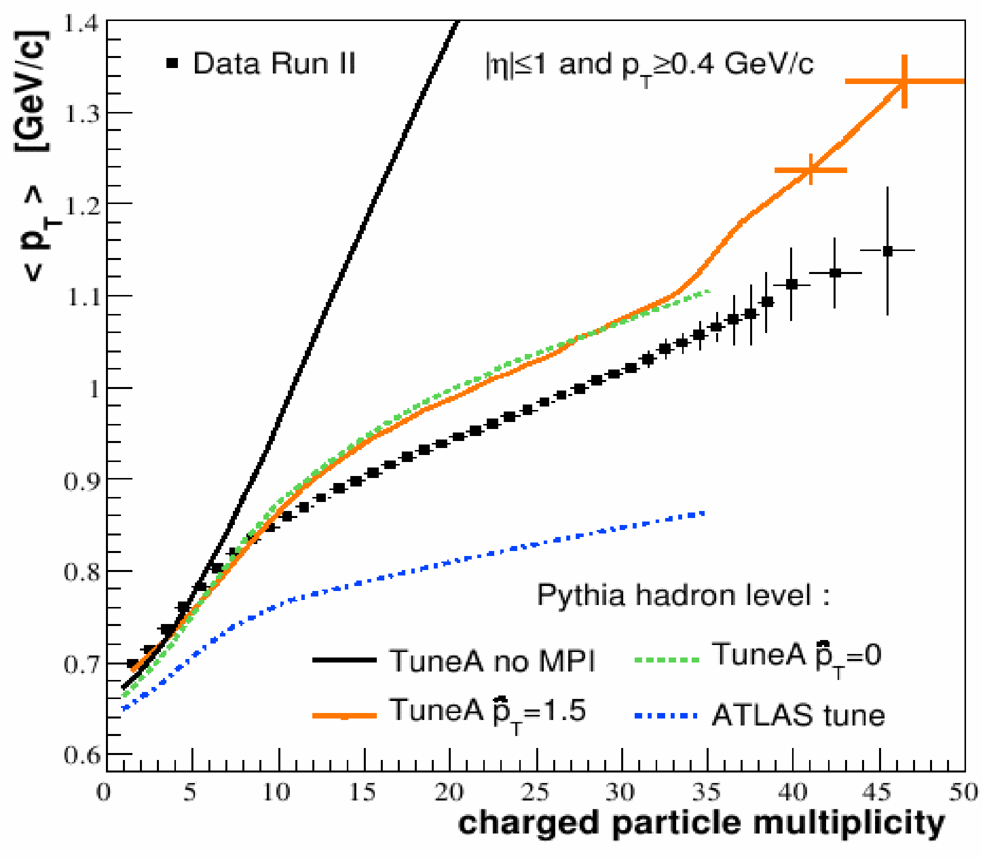

Effective parton Luminosity:

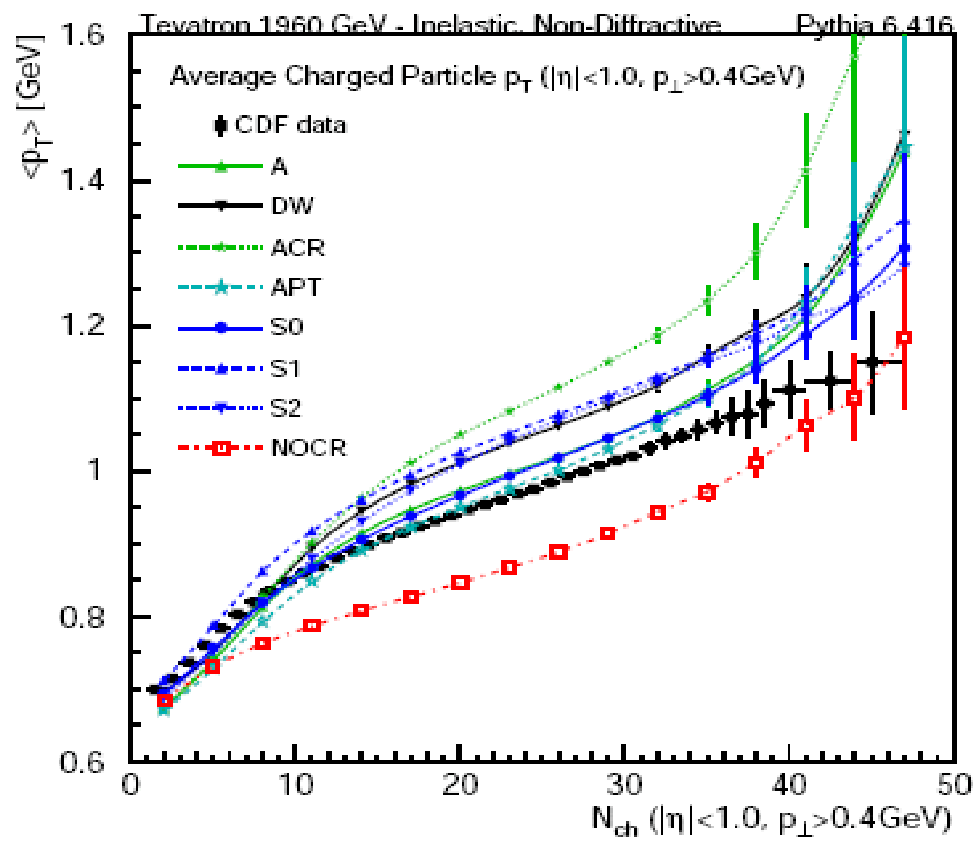
$$L_{eff}(\Delta)=\int D(r)D(r')dV_{overlap}$$

# Experimental tests (3)

## <pT> vs. Nch

### CDF (Run2) minimum bias data vs. MPI models




- In case of no MPI events, <pT> grows too rapidly.
- MPI lead to larger Nch that are harder than the beam remnants but not as hard in pT as for the primary hard 2->2 scattering.
- The larger #MPIs the more trend to higher Nch and smaller <pT>.
- The details (fit to data) are regulated by the string "drawing" e.g. "minimal" to the nearest neighbor vs. "maximal" across the whole event (A-CR vs No-CR is an example of two extreme cases ).