Double Parton Interactions: Recent DZero measurements and Prospects

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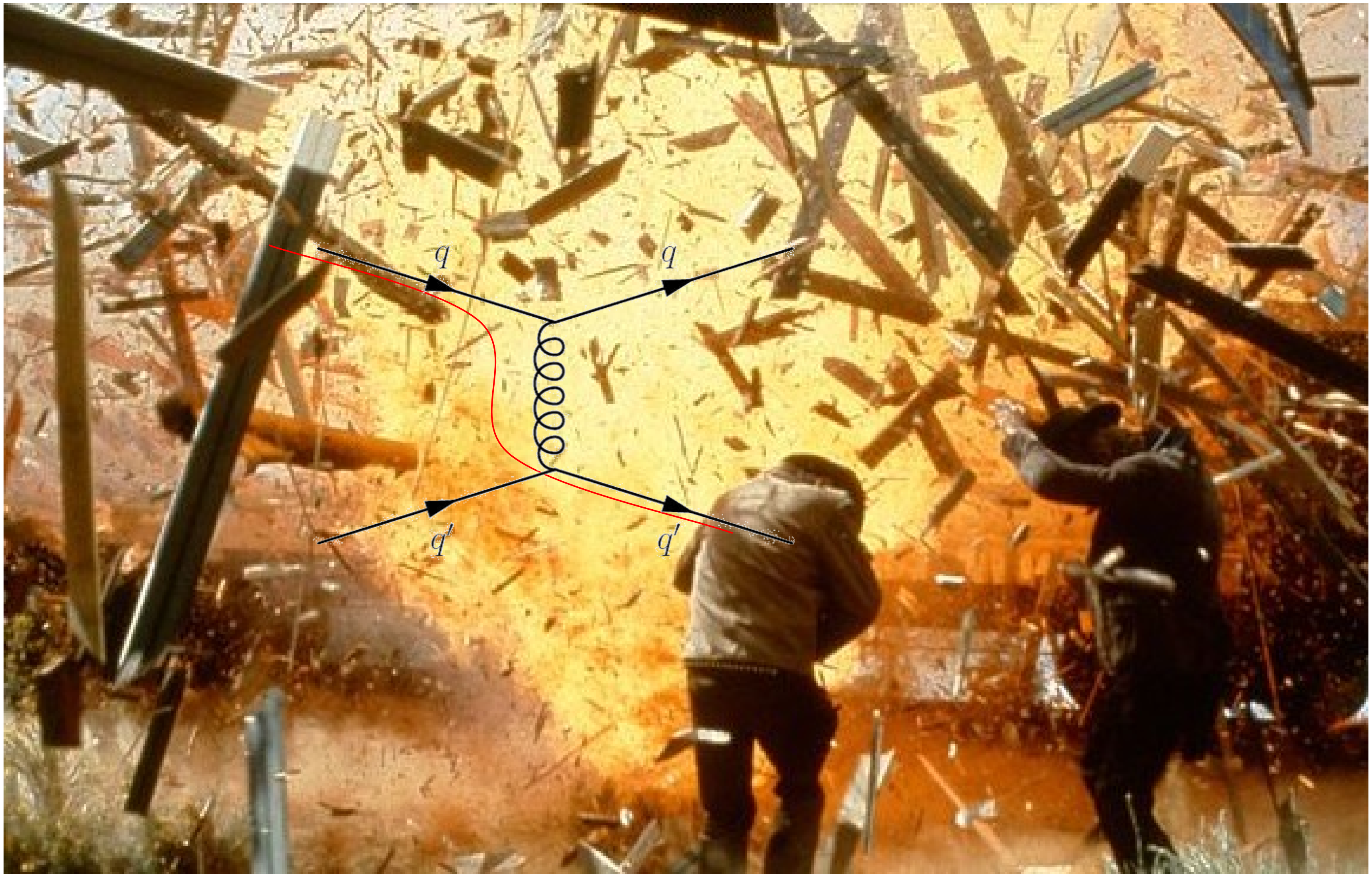
Outline

- History and experimental tests
- Double Parton interactions in γ+2 and γ+3-jet events
- Double Parton interaction as a background to rare processes
- Prospects and Summary

QCD in Hadron-Hadron Collisions

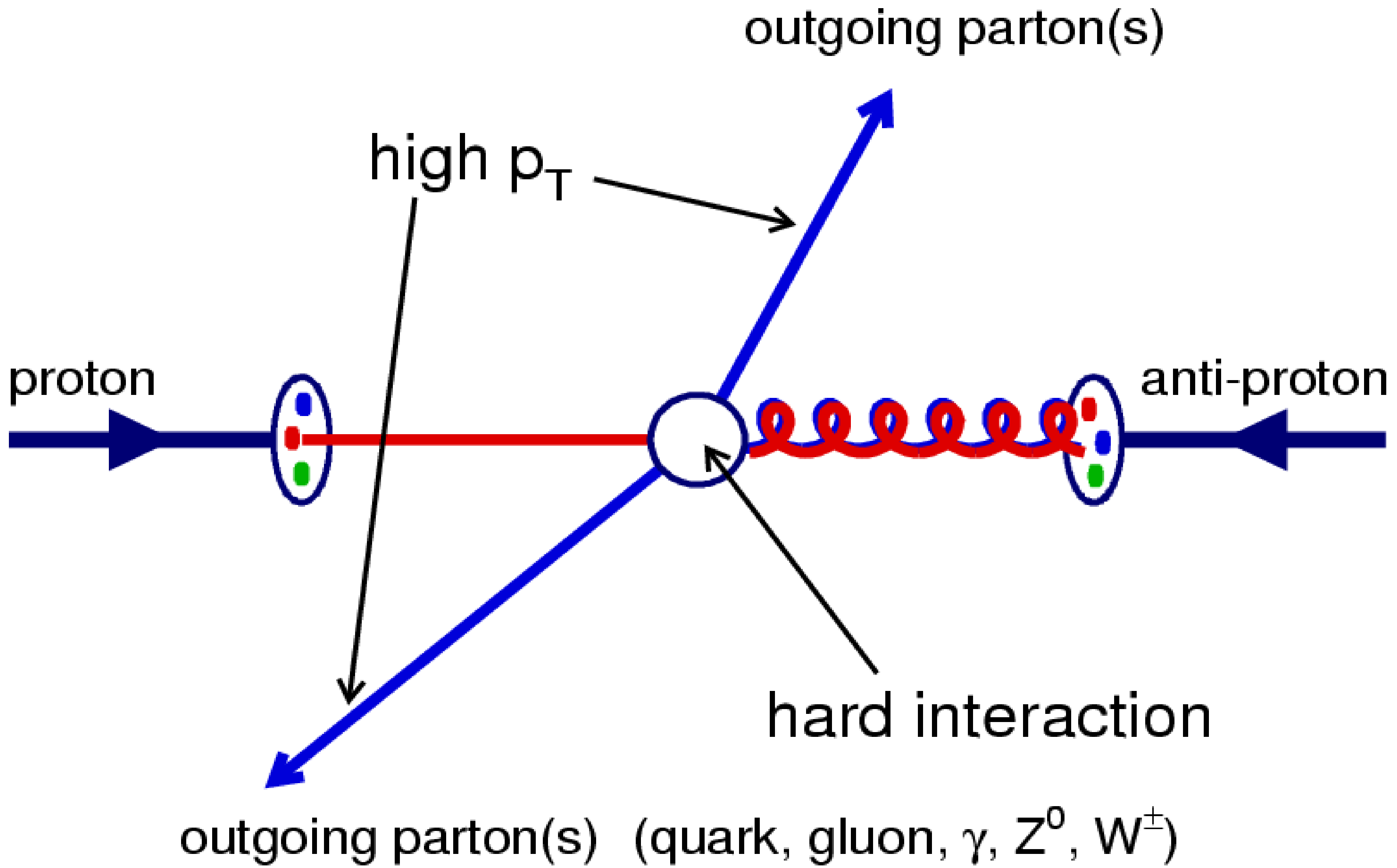
Object reconstruction in the hadron-hadron collisions
Goal is to reconstruct the initial “building”



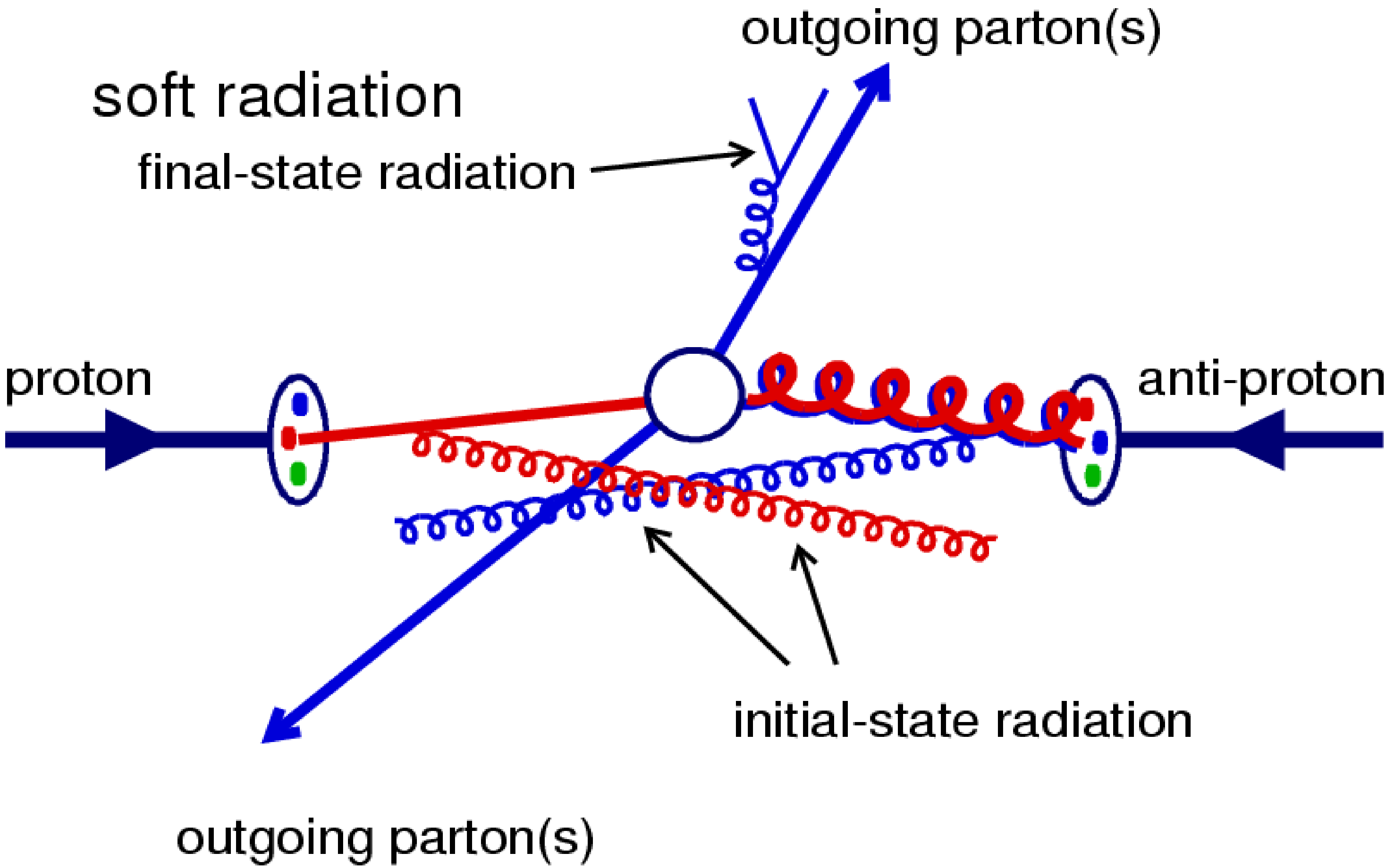
from P.Skands talk, 2009

Sometimes the reality is even more complicated

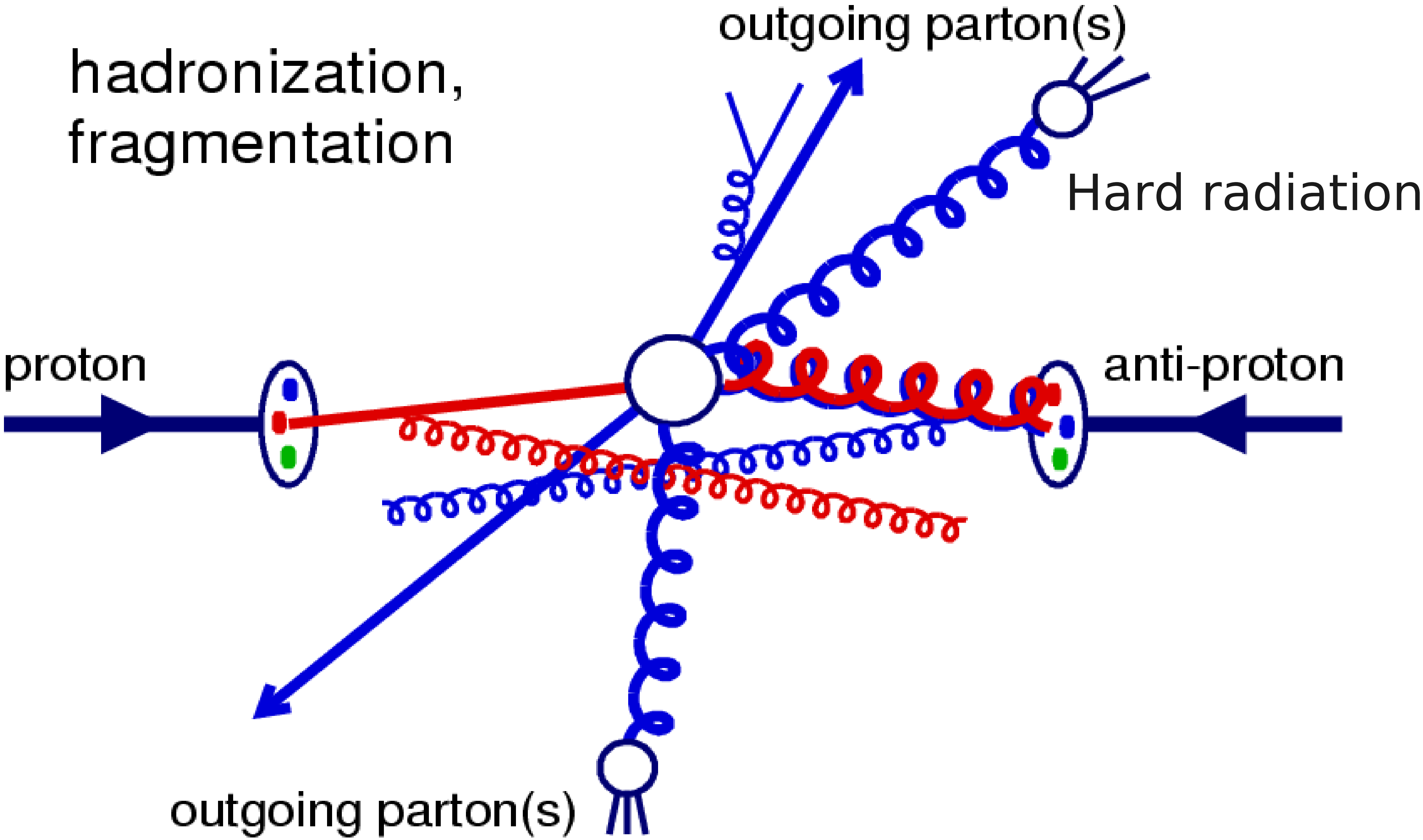
Hadron-Hadron Collision



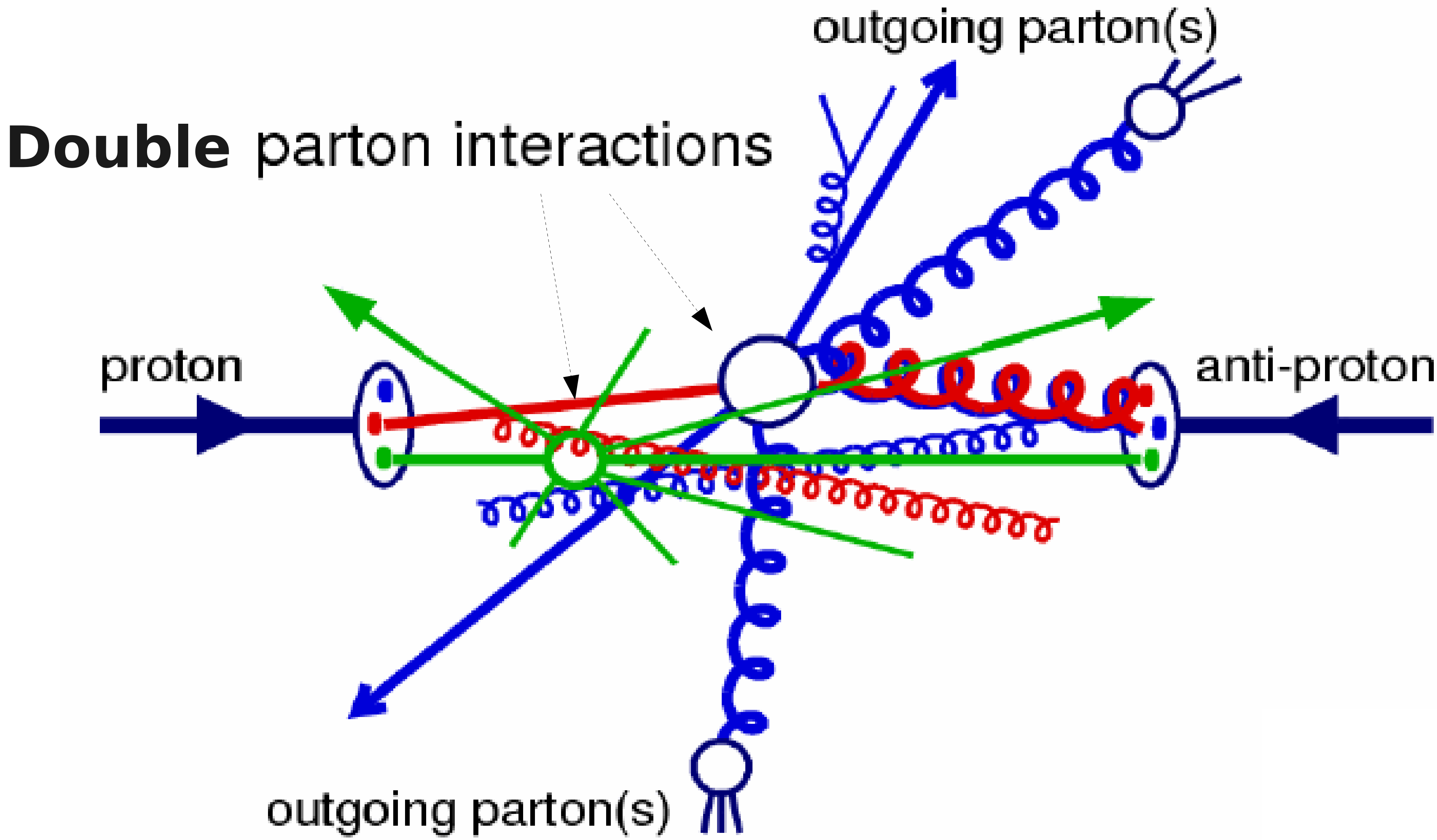
Hadron-Hadron Collision



Hadron-Hadron Collision



Hadron-Hadron Collision: from Single to Double parton interactions



Some history

– Simple models of double di-jet, double Drell-Yan productions

P.V.Landshoff and J.C. Polkinghorne - 1978
C.Goebel et al - 1980
E. Takagi (MPI in pN interactions) - 1979 (MPI ≡ Multiple Parton Interactions)

– ... with extension to perturbative QCD

B.Humpert et al - 1983-85
L.Ametller, N.Paver, D.Treleani - 1982-1986
....

– First real, software-implemented MPI model (aka “Tune A”, updated by R.Field).

T. Sjostrand and M.van Zijl : PRD36 (1987)2019
Description of many “puzzling features” in jet productions in UA1-UA5.

– 2002-today : 20-30 new MPI tunes appeared:

http://theory.fnal.gov/trtles/ : MPI/UE workshop (Fermilab, Apr, 2009)
http://mpi11.desy.de : 3rd MPI workshop (DESY, November, 2011)

– Most features of MPI events are studied experimentally.

Current emphasis is detailed aspects: parton transverse structure, long. and trans. momentum distributions, correlations, etc.

– Amount of theor.&exp. publications is rapidly growing last years:

-2011: >20 papers (>50% on the LHCb double J/psi result)
-Nov 3rd 2011: “Elements of a theory for MPI in QCD”,hep-ph/1111.0910

Experimental tests (1)

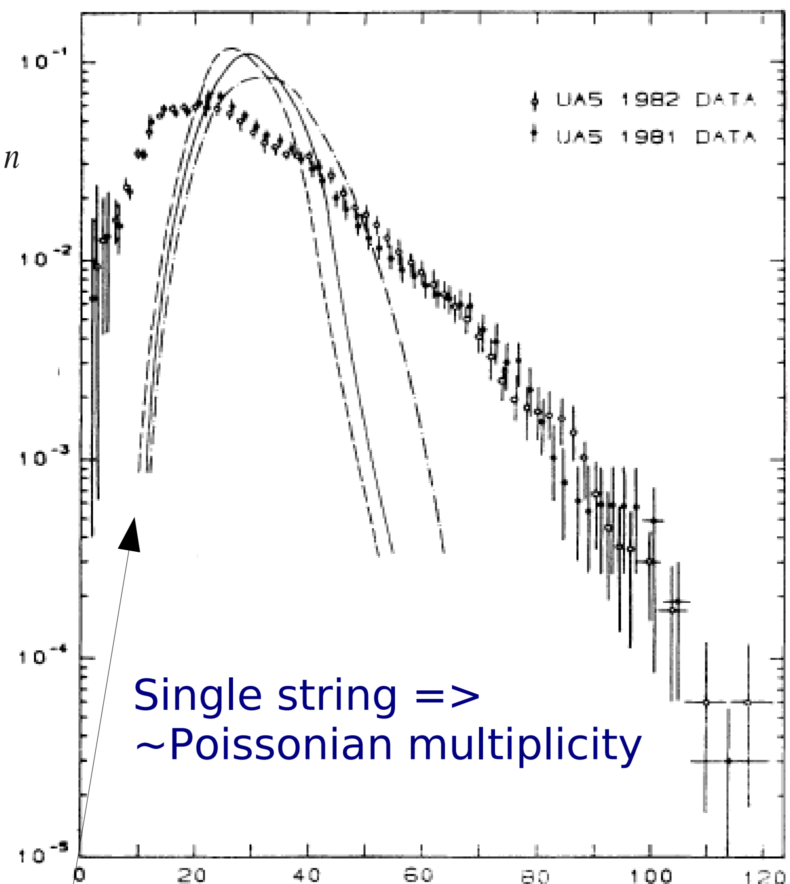
Charged multiplicity

UA5, 540 GeV, ppbar

Hard scattering only; +ISR/FSR

MPI models (fixed and varying impact parameter)

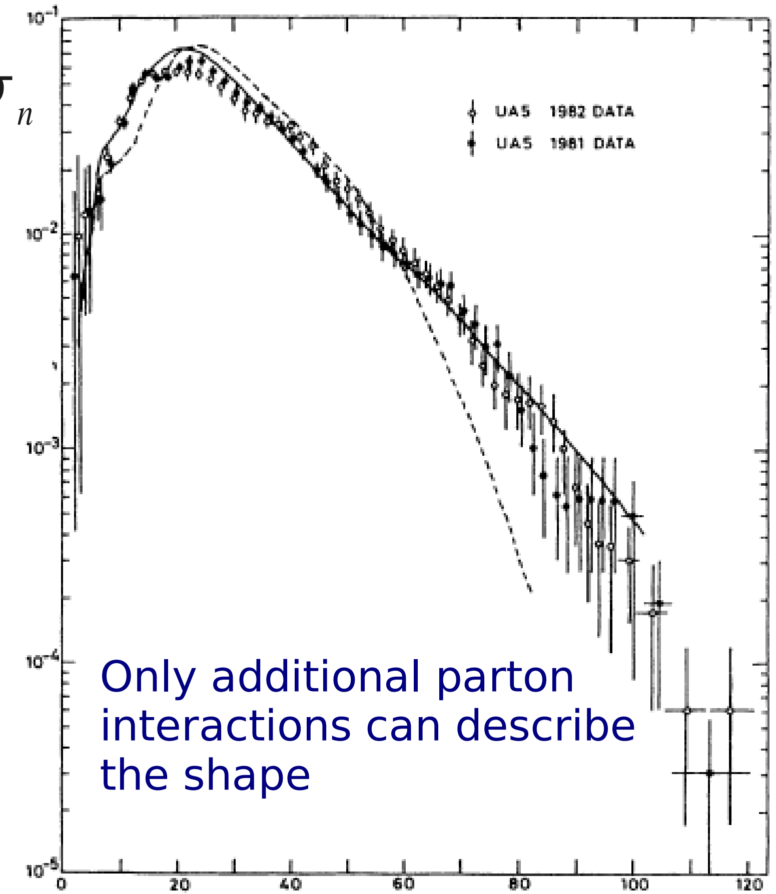
$\sigma_n / \sum \sigma_n$



Single string =>
~Poissonian multiplicity

Nch

$\sigma_n / \sum \sigma_n$



Only additional parton interactions can describe the shape

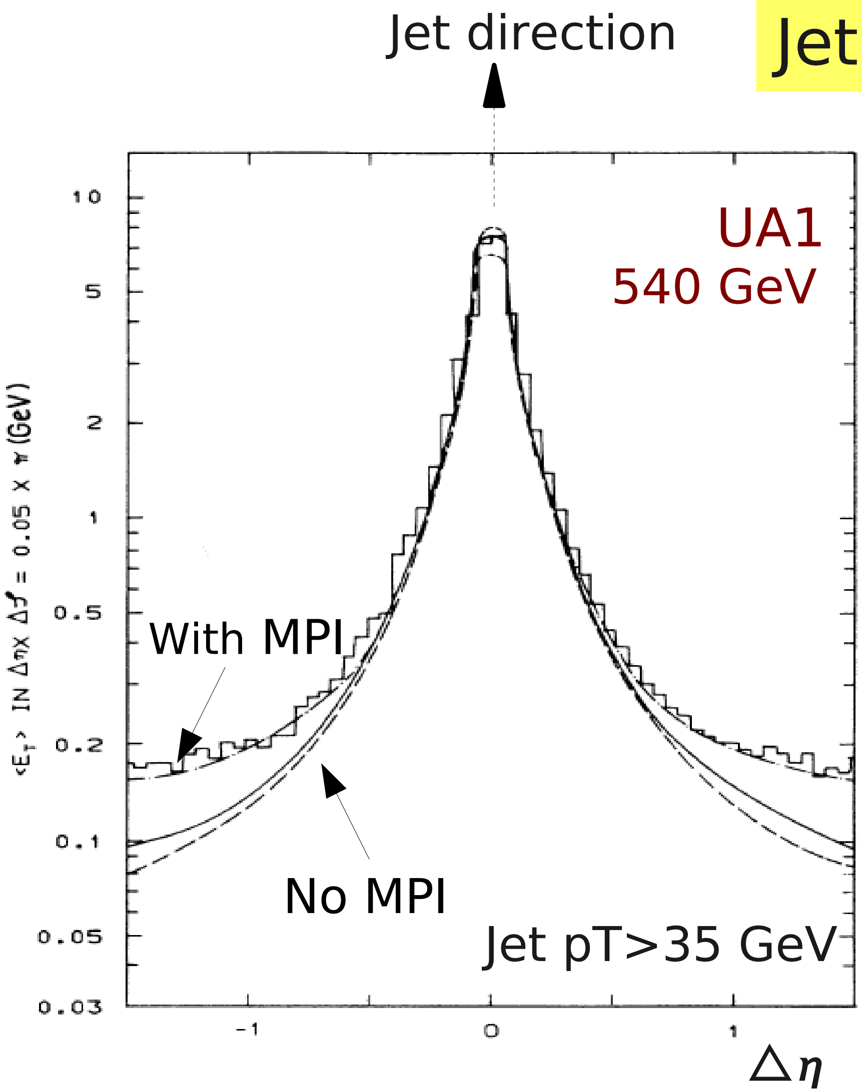
Nch

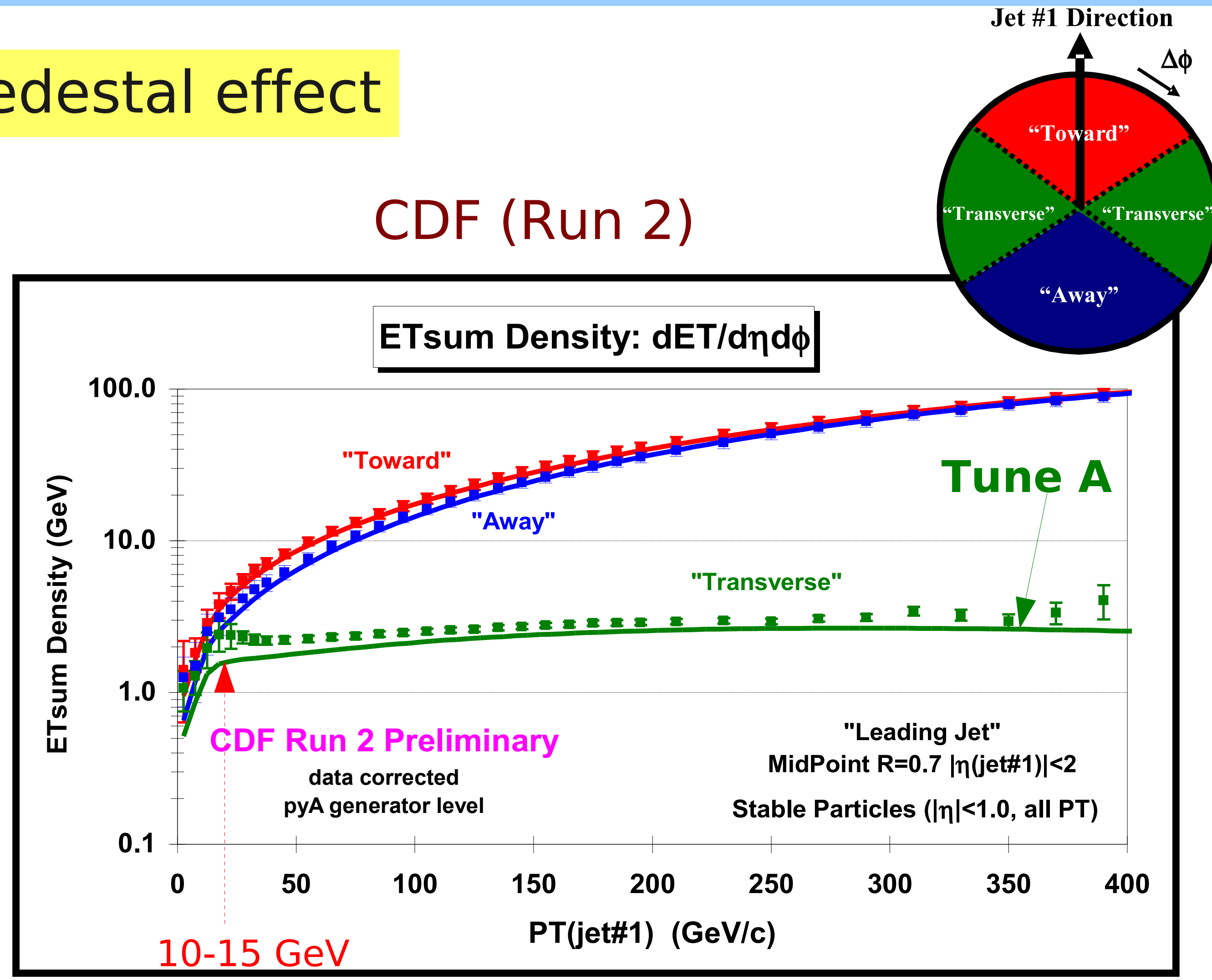
σ_n is a cross section to produce a final state with *n* tracks (Nch).

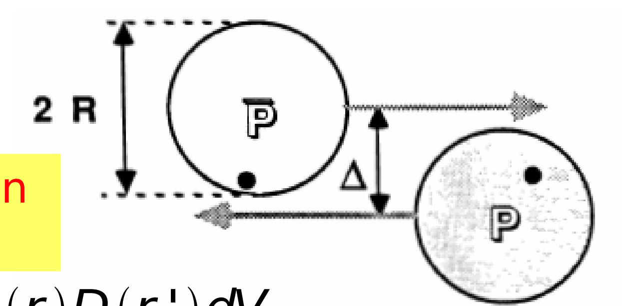
"Poissonian hadronization" of the string model does not work!

Experimental tests (2)

Jet pedestal effect







Effective parton Luminosity:

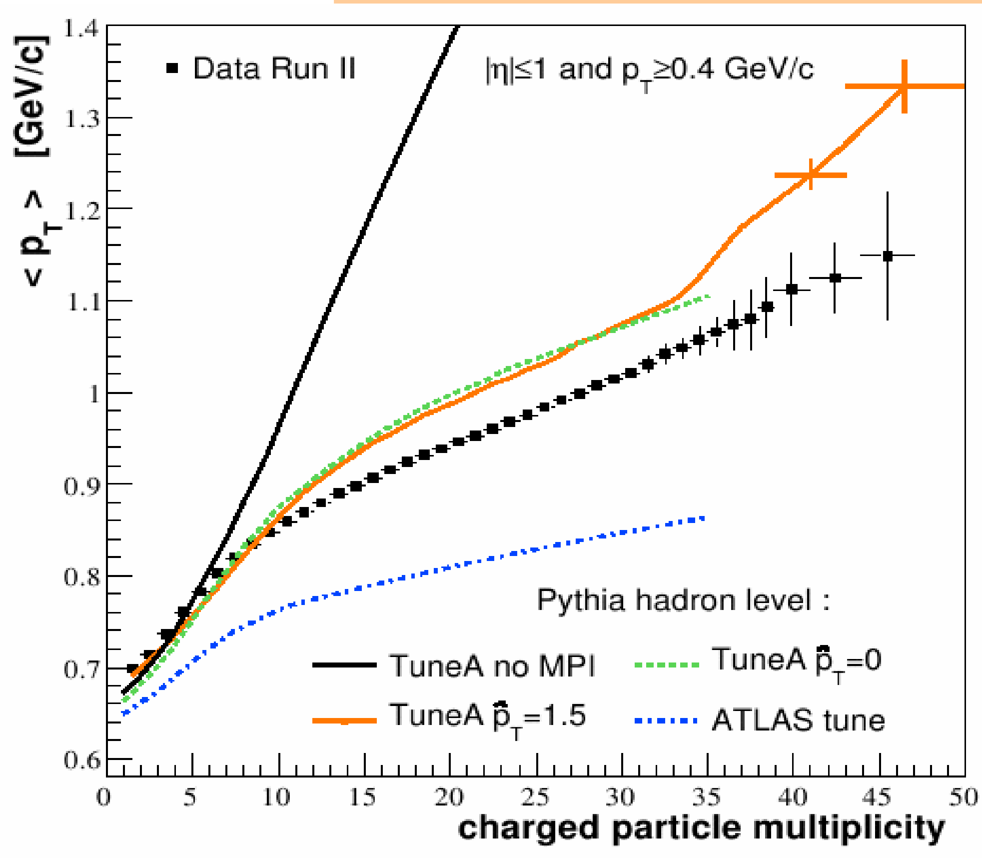
$$L_{eff}(\Delta)=\int D(r)D(r')dV_{overlap}$$

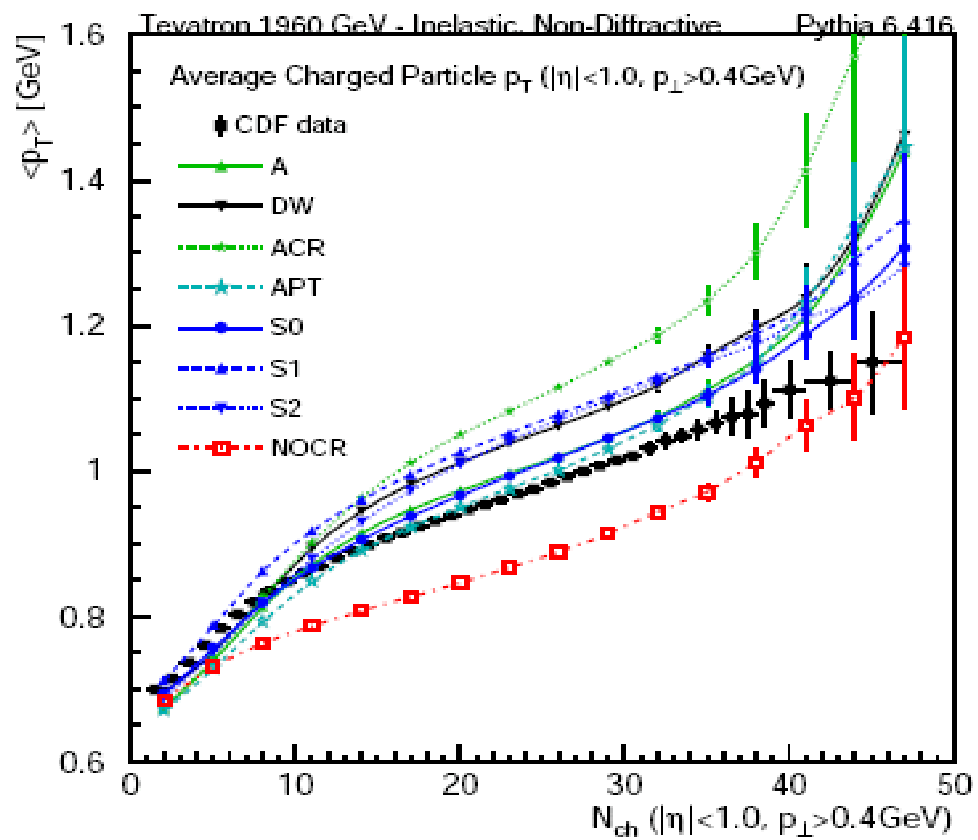
- Presence of high pT 1[st] interaction biases events towards smaller p-pbar impact parameters and hence leads to a higher additional activity but saturates at σ(pT_jet) ≪ σ_nd (“nd” = non-diffractive).
- The height of the pedestal depends on the overlap, i.e. on the parton matter distribution function.

Experimental tests (3)

<pT> vs. Nch

CDF (Run2) minimum bias data vs. MPI models



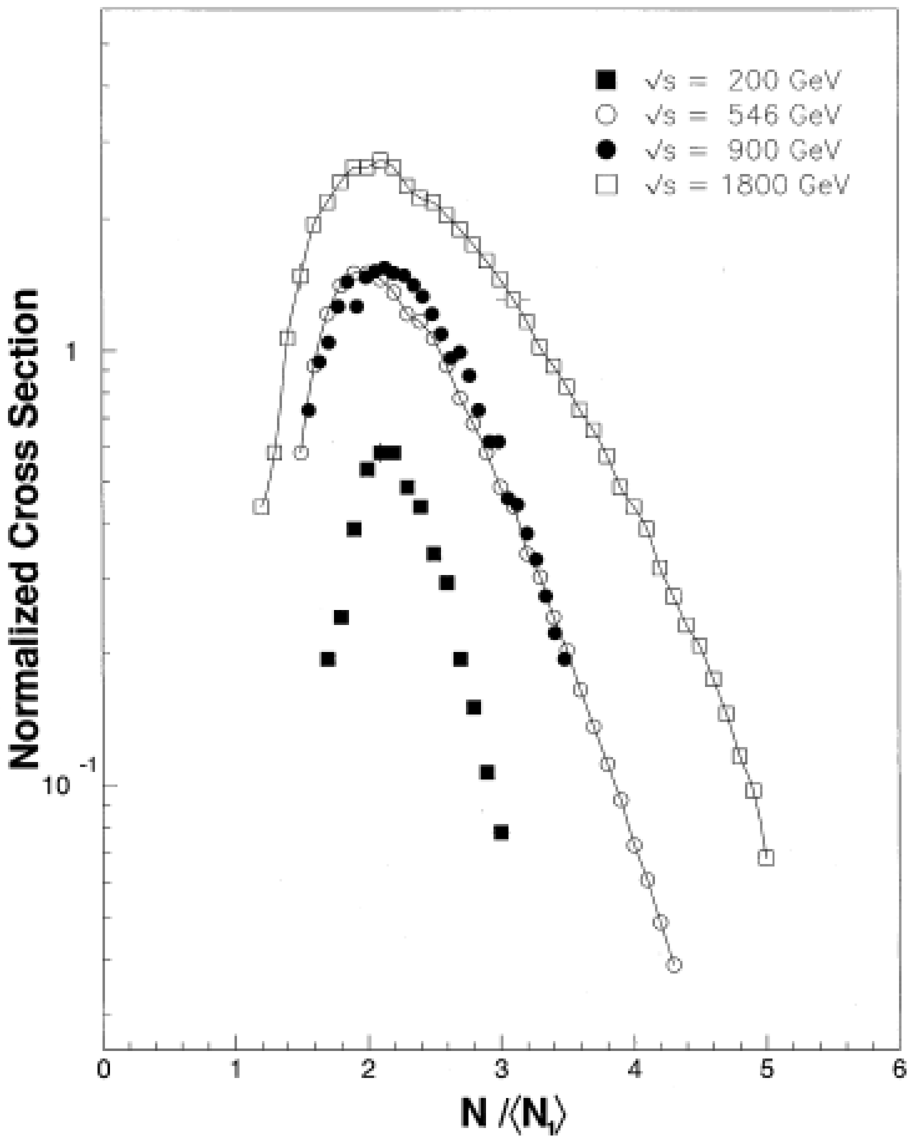


- In case of no MPI events, <pT> grows too rapidly.
- MPI lead to larger Nch that are harder than the beam remnants but not as hard in pT as for the primary hard 2->2 scattering.
- The larger #MPIs the more trend to higher Nch and smaller <pT>.
- The details (fit to data) are regulated by the string “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).

Experimental tests (4)

Charged multiplicity

E735, 200-1800 GeV, ppbar minimum bias events



<N1> is the average (KNO) multiplicity for a simple single-parton scattering process

- Most probable ratio N/<N1> is close to 2 (a bit larger)
- Width is close to sqrt(2) x SP width

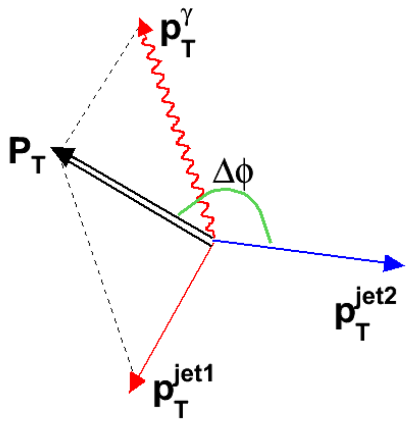
=> strong indication to 2 distinct parton scattering processes occuring at the same ppbar collision

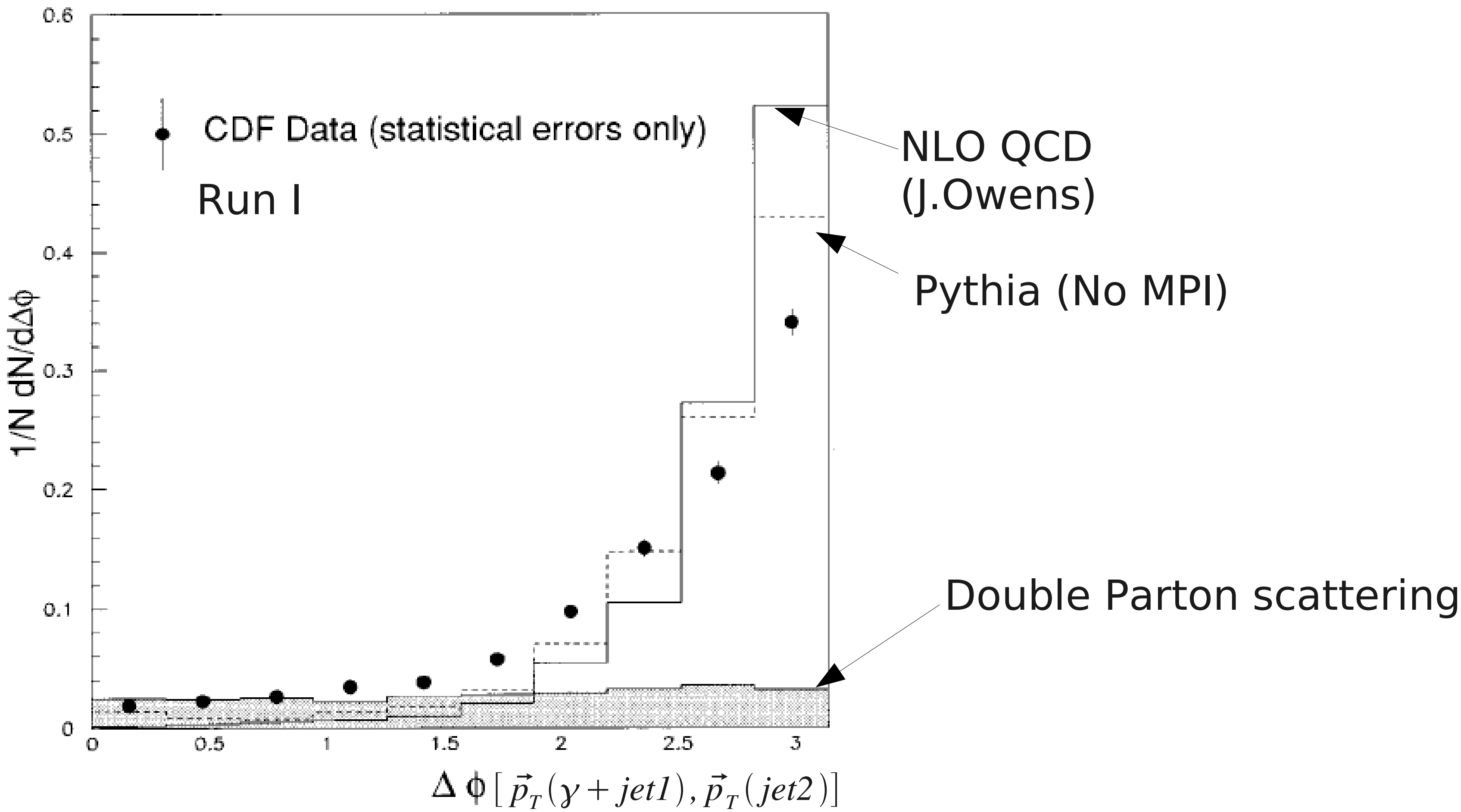
From: PLB 435 (1998) 453, E735 Collaboration

Experimental tests (5)

Photon+2 jets study

The difference in azimuthal angle between the transverse momentum vector sum of (photon + lead. jet) and 2nd jet





- Conservation of momentum biases the distribution towards π.
- Tail at small angles determines the amount of double parton interaction in data.

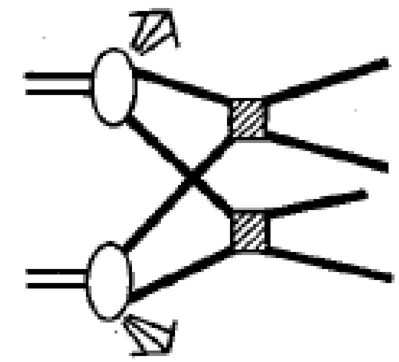
Double Parton Interactions in γ+3 (and 2) jet events:

from low pT to high pT in MPI studies

- New motivations and prospects
- New effects

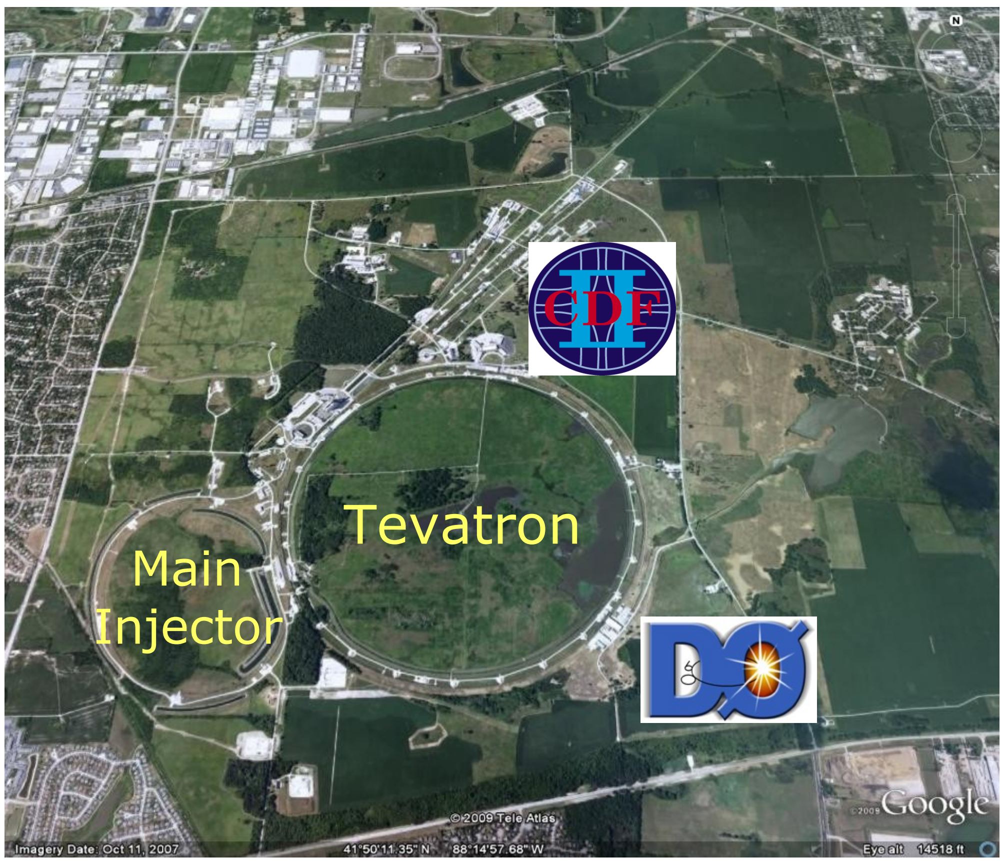
Overview

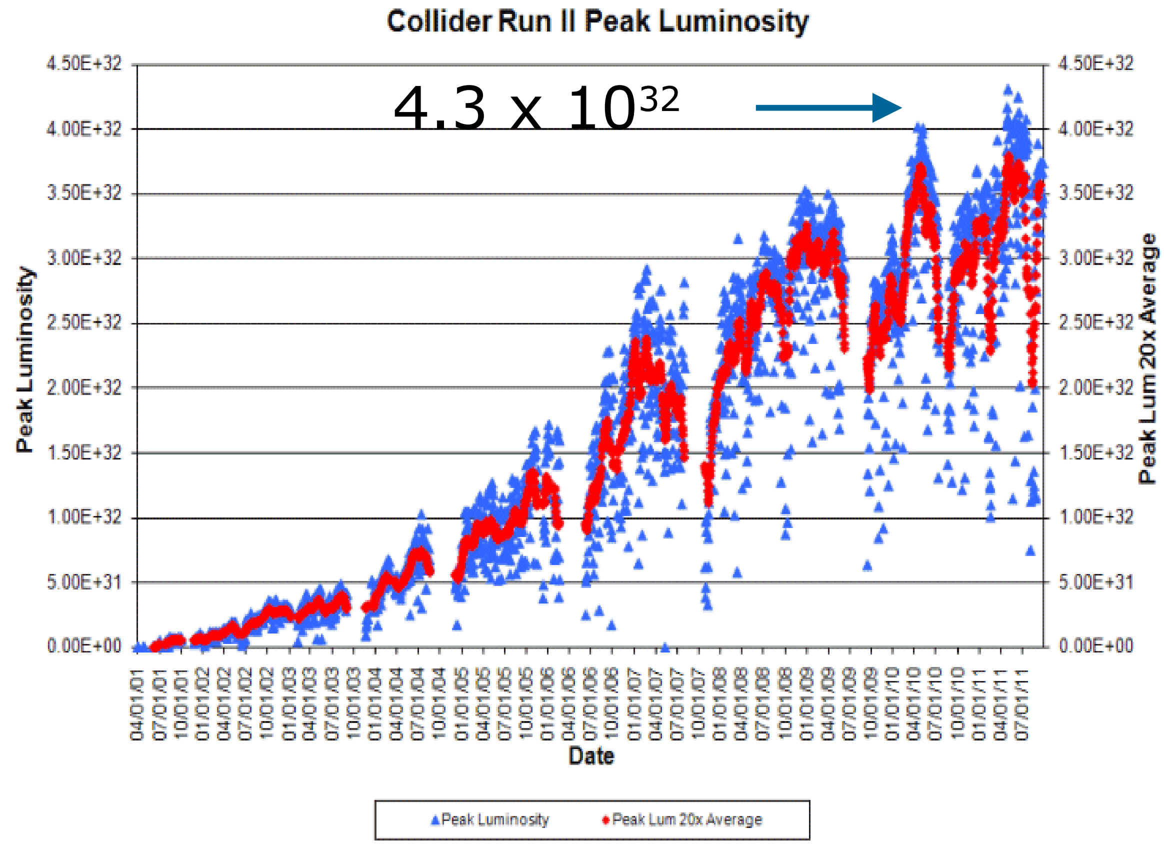
- Tevatron
- Motivations
- Event topology
- Discriminating variables
- Fraction of double parton events
- Effective cross-section
- Interpretations
- Prospects

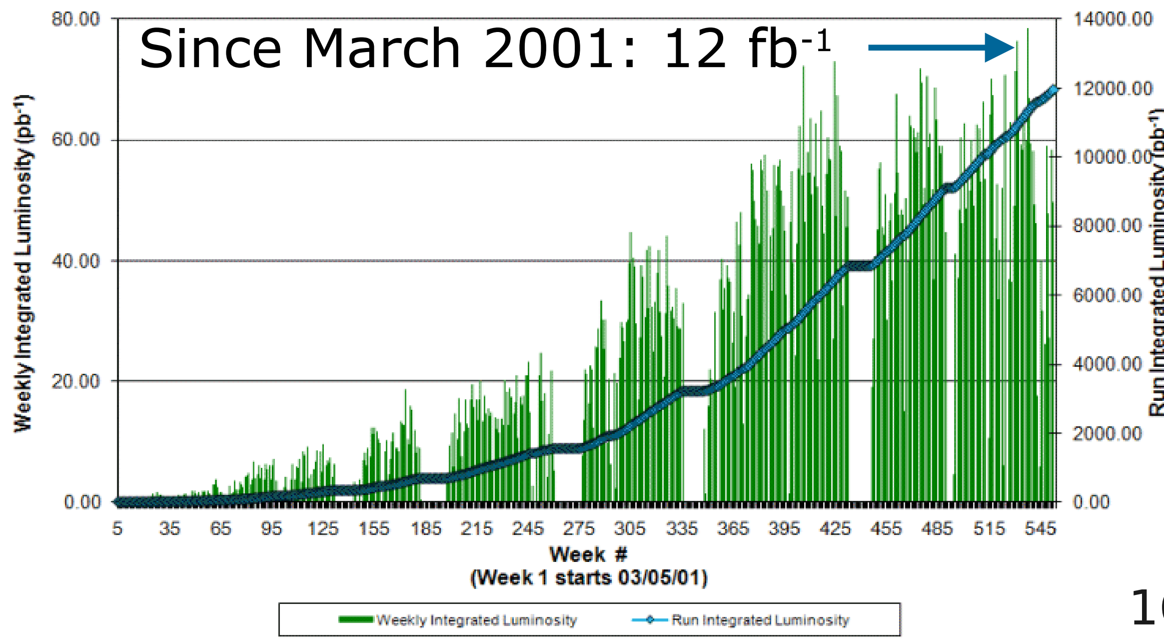


Fermilab Tevatron Run II

Run II ended on Sep 30, 2011
Typical data collection eff-cy is 90-92%
Peak Luminosity: 4.3×10^{32} $cm^{-2}s^{-1}$
Delivered about 12 fb^{-1}
To compare: Run I delivered 120 pb^{-1}

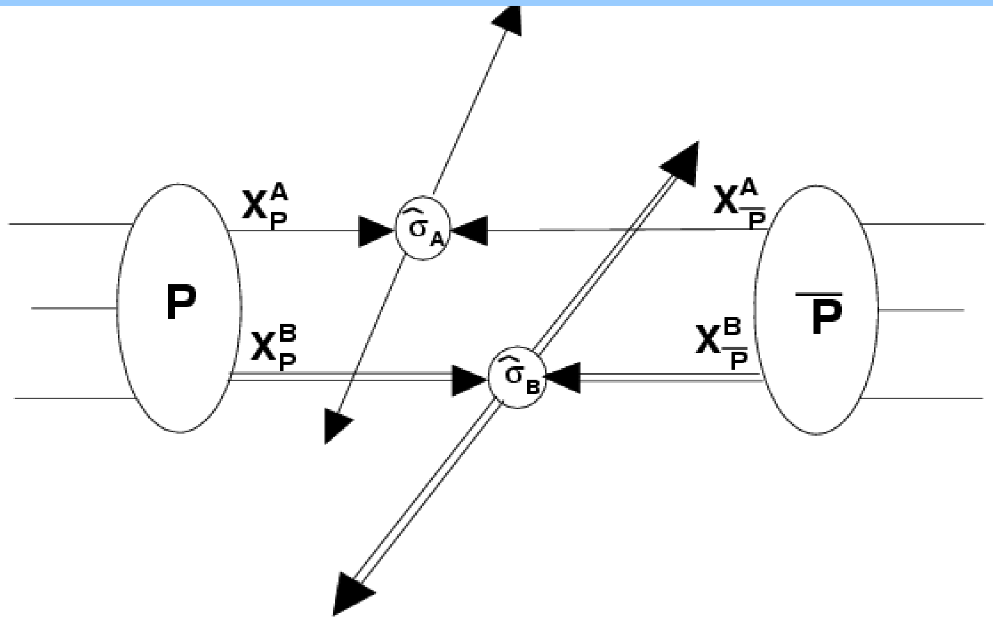






Double parton and effective cross sections

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



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

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

→ contains information on the spatial distribution of partons.

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

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

→ σ_A and σ_B grow with sqrt(s), => σ_{DP} should grow even faster!

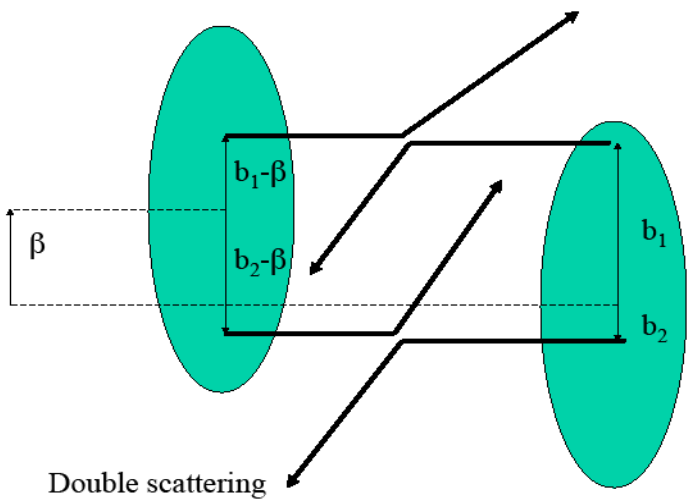
→ σ_{eff} (on top of pure QCD motivations) is needed for precise estimates of background to many rare processes (especially with multi-jet final state)

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

Parton spatial density and σ_{eff}

Double parton cross section

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



Effective cross section

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

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.

(Slide 76 shows an extended version)

History of the measurements

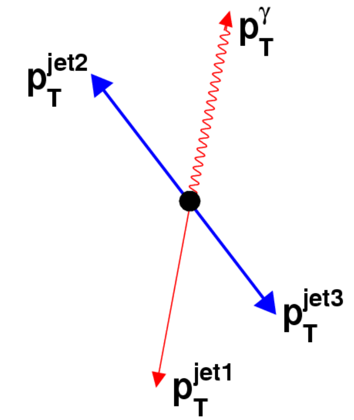
Experiment	$\sqrt{s}$ (GeV)	Final state	p_T^{min} (GeV)	η range	$\sigma_{\rm eff}$
AFS (pp), 1986	63	4 jets	$p_T^{\rm jet} > 4$	$\|\eta^{\rm jet}\| < 1$	~ 5 mb
UA2 ($p\bar{p}$), 1991	630	4 jets	$p_T^{\rm jet} > 15$	$\|\eta^{\rm jet}\| < 2$	> 8.3 mb (95% C.L.)
CDF ($p\bar{p}$), 1993	1800	4 jets	$p_T^{\rm jet} > 25$	$\|\eta^{\rm jet}\| < 3.5$	$12.1^{+10.7}_{-5.4}$ 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 events (two separate ppbar collisions) and Double Parton (single ppbar collision) events to extract $\sigma_{\rm eff}$ from their ratio.
=> reduces dependence on Monte-Carlo and NLO QCD theory predictions.

Measurement of σ_{eff}



For two hard scattering events (two separate $p\bar{p}$ 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:

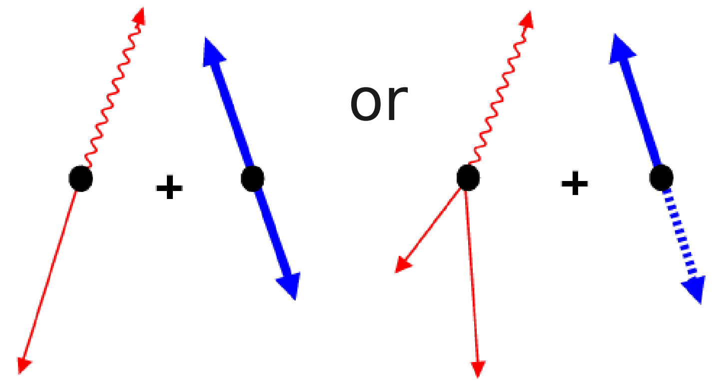
$$N_{DP} = \frac{\sigma^{\gamma j}}{\sigma_{hard}}\frac{\sigma^{jj}}{\sigma_{eff}} N_C(1) A_{DP}\,\epsilon_{DP}\,\epsilon_{1vtx}$$

Therefore one can extract:

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

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.

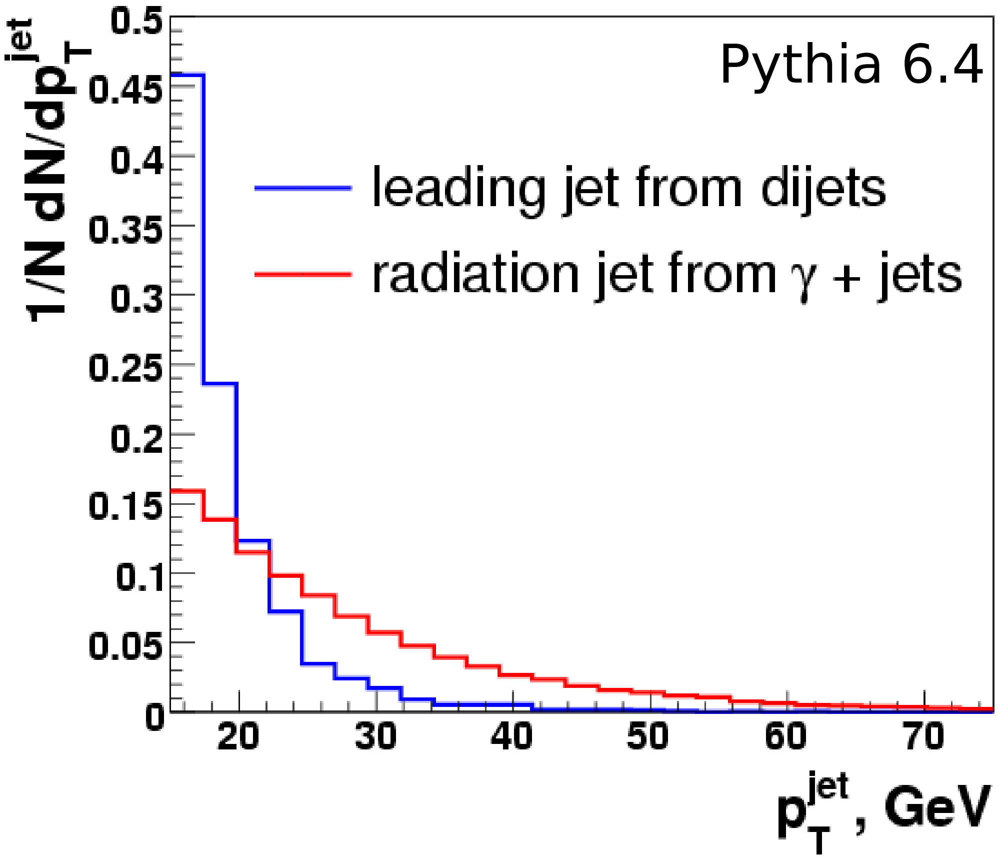
B: ≥1 jets from MinBias events:
- 1-vertex events
- jets with pT's recalculated to the primary vertex of sample A have pT>15 GeV and |η|<3.0.

- **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!

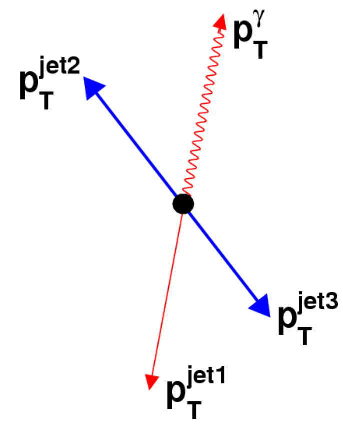
Motivation for jet pT binning

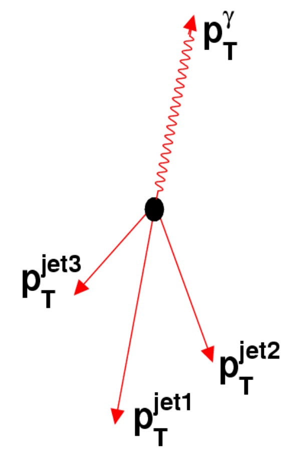
Jet PT: jet from dijets vs. radiation jet
from γ+jet events



$\sim 1/p_T^4$

$\sim 1/p_T^2$





- 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

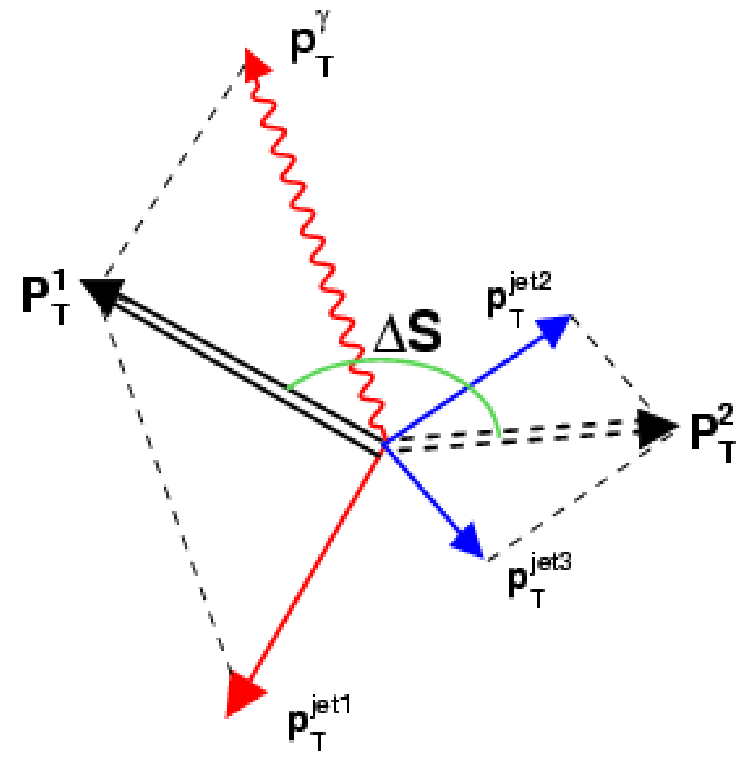
Discriminating variables

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

- $\Delta\phi$ angle between two best pT-balancing pairs →
- The pairs should correspond to a minimum S value:

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

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

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In the signal DP sample most likely (>94%) S-variables
are minimized by pairing photon with the leading jet.
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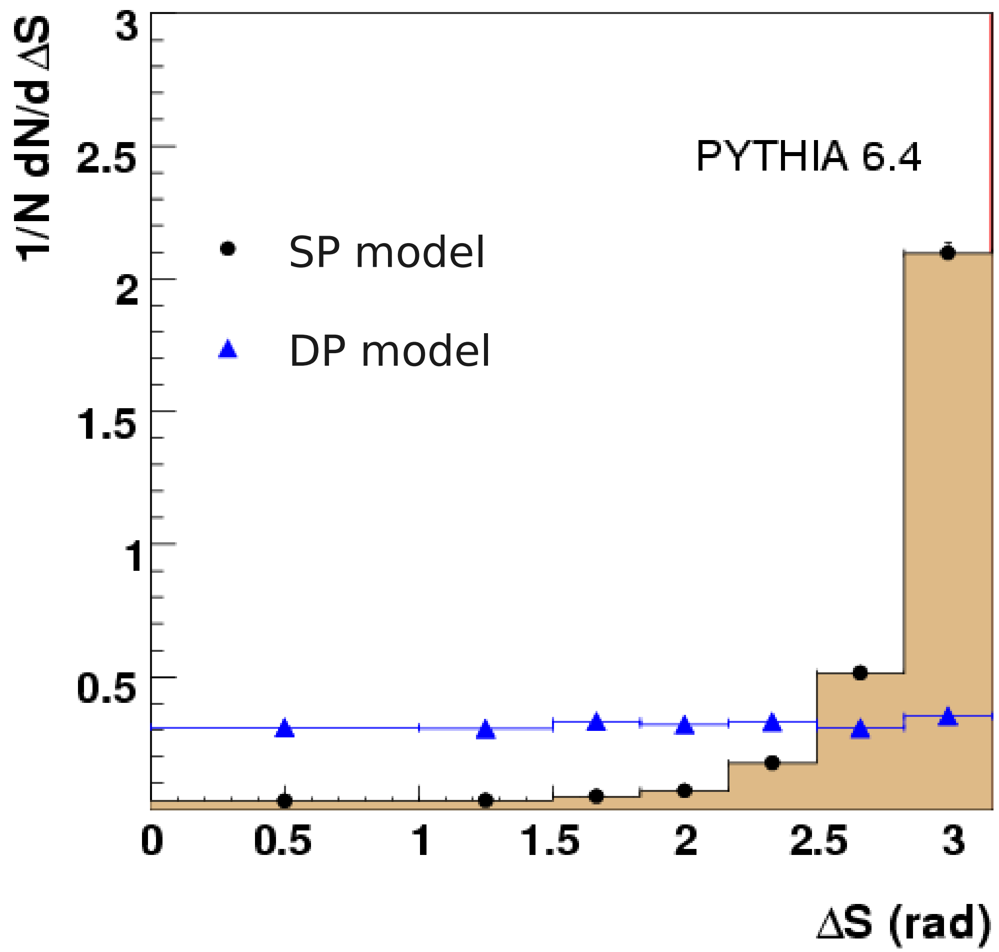
△S distribution for γ+3-jet events from Single Parton scattering



➔ 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 (2^{nd} and 3^{rd} jets are both from dijet production).

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

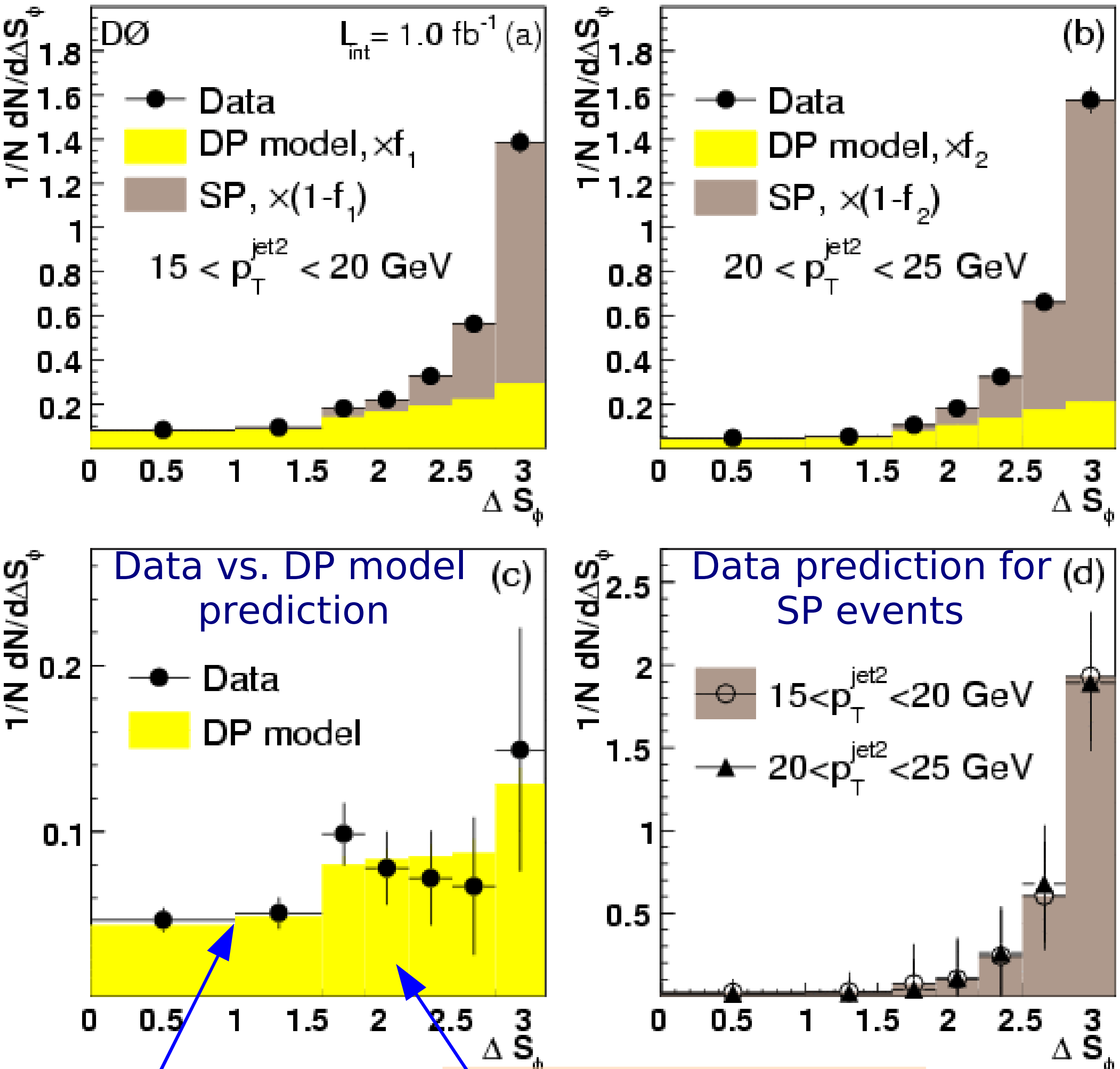
$$D_1 - \lambda K D_2 = f_1 M_1 - \lambda K C f_1 M_2$$

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

f₁ is the only unknown, --> get from minimization

The two datasets method

Dataset (a): 2nd jet pT: 15-20 GeV
Dataset (b): 2nd jet pT: 20-25 GeV



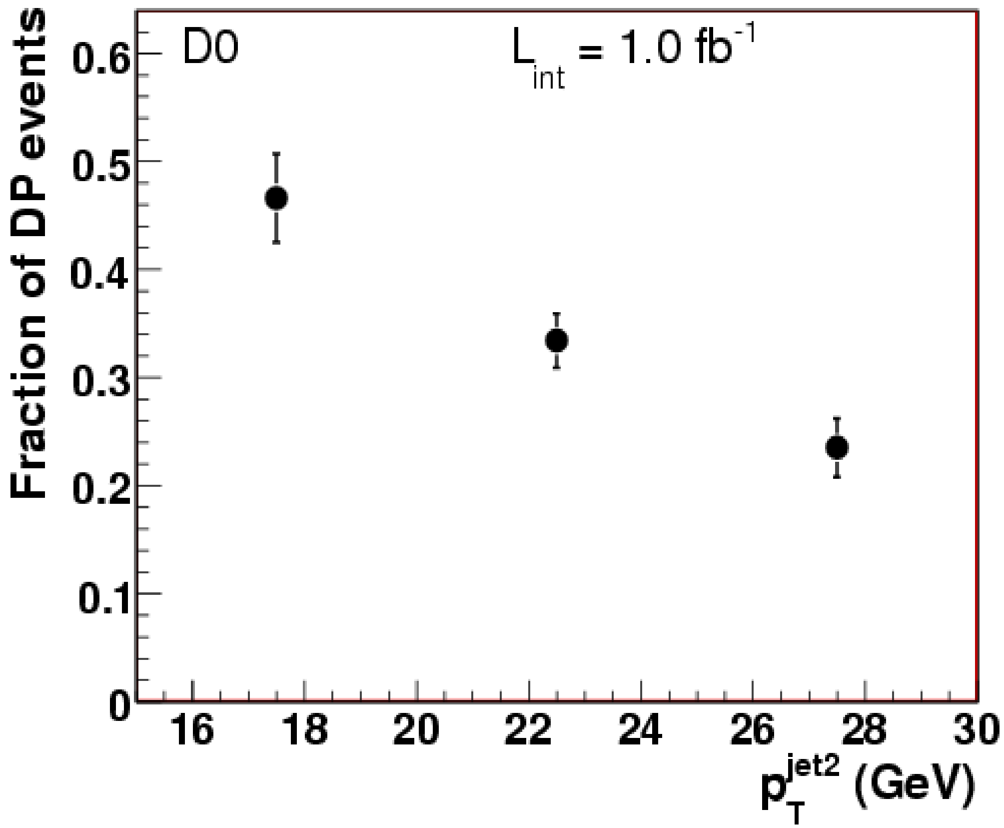
✓ Fraction of Double Parton in bin 15-20 GeV (f_1) is the only unknown
→ get from minimization.

✓ 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

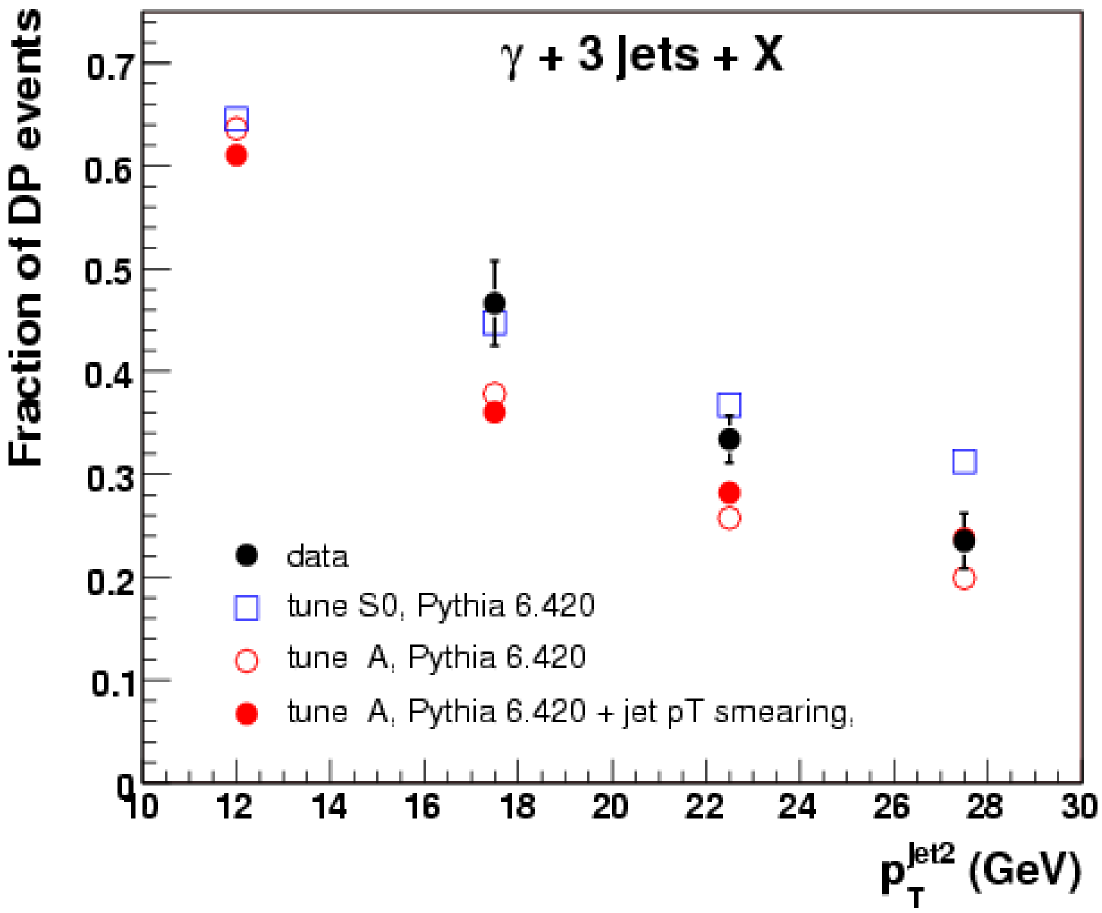
Fractions of Double Parton γ+3-jet events



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.

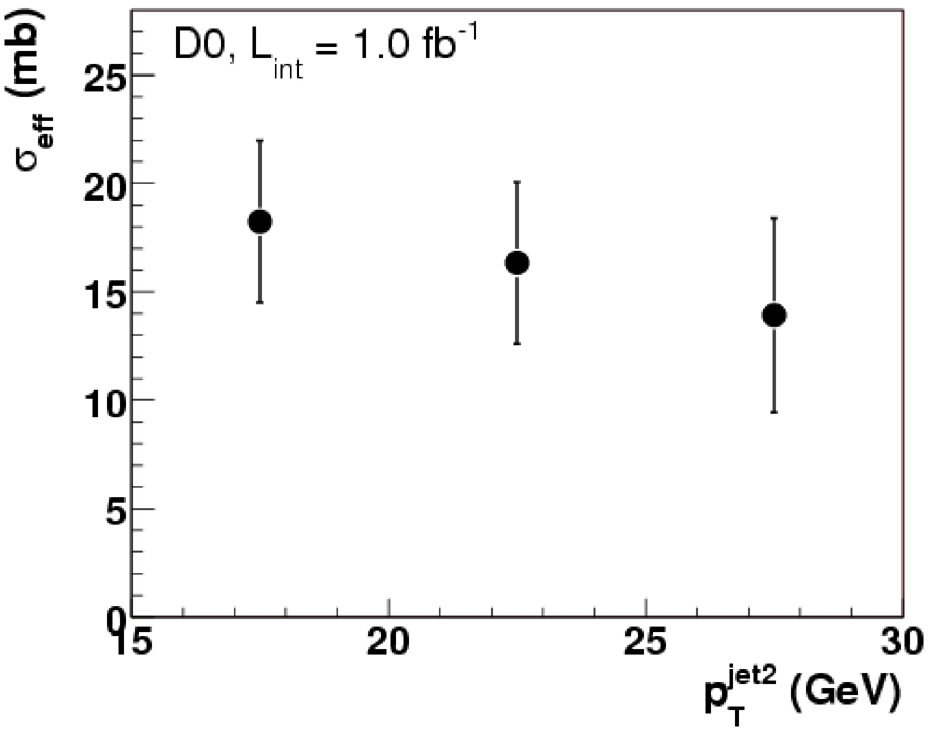
Fractions of Double Parton events : MPI models and D0 data



- 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 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:

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

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-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 σ_{eff})

PDF correlation vs. factorisation

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

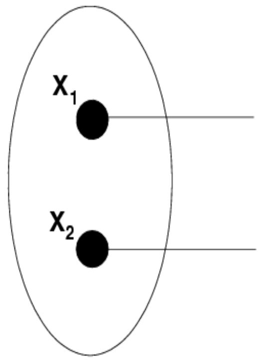
If at any given scale μ_0 one assumes the factorized form

D(x1,x2,μ_0) = D(x1,μ_0)*D(x2,μ_0) θ(1-x1-x2)

then *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),

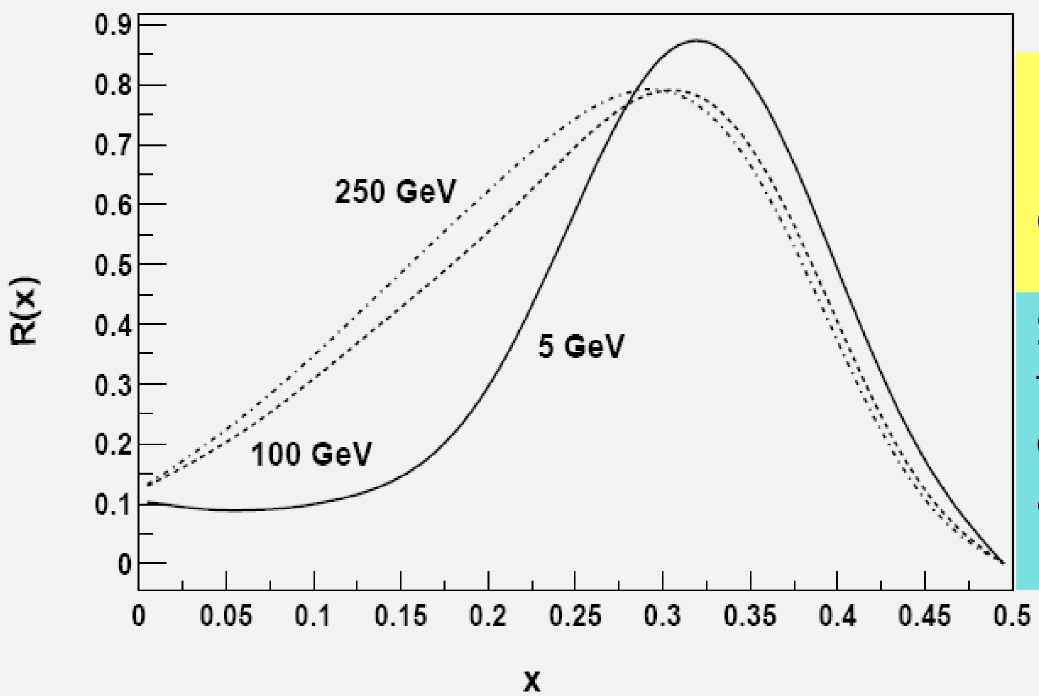
where R(x1,x2,μ) is a (positive) correlation term.



Correlations for 2 gluon PDFs as an example:

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

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



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)

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

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 σ^{exp}_{eff} .

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

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

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

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

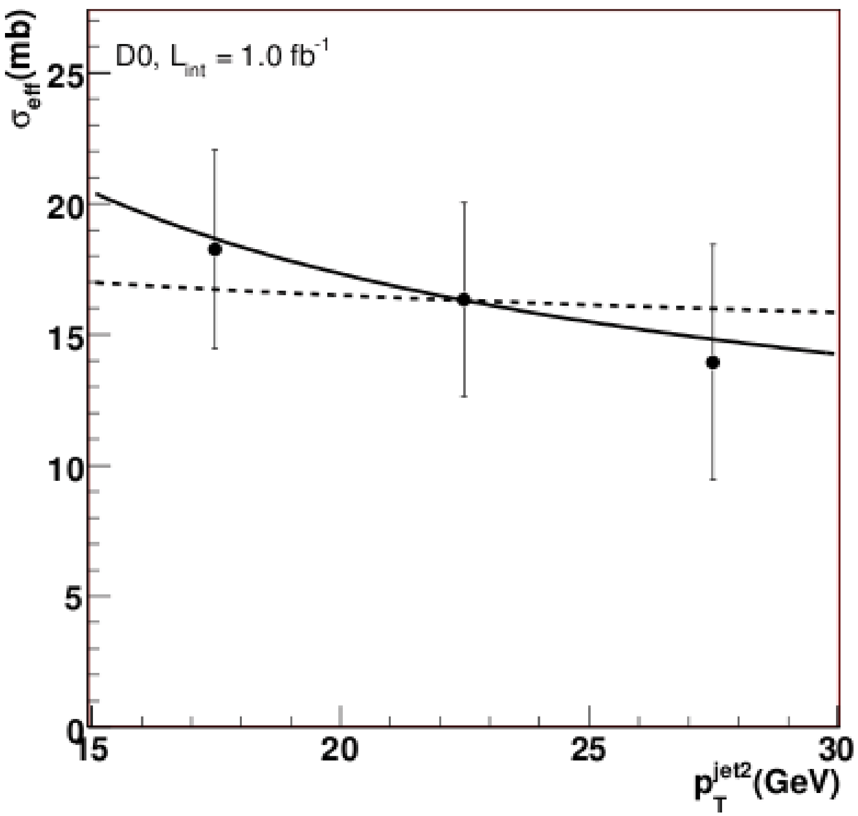


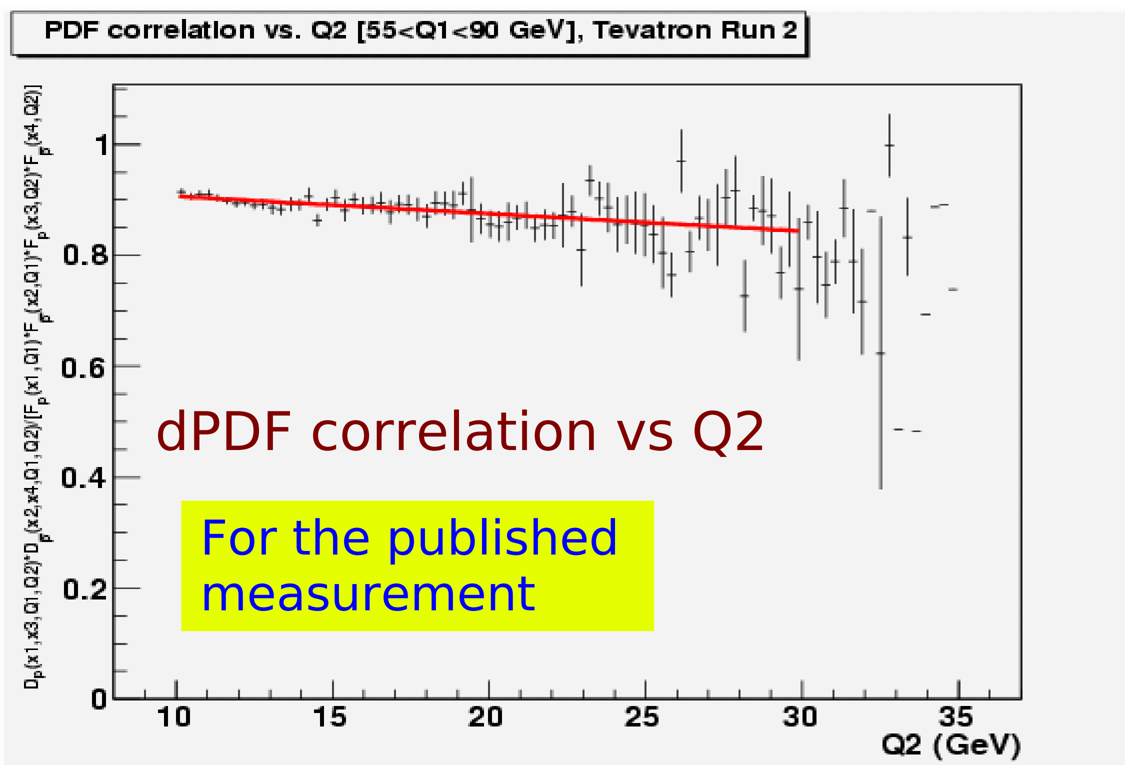
FIG. 1: Effective cross section $\sigma_{\rm eff}^{\rm exp}$ measured in the three $p_T^{\rm jet2}$ bins at the D0 experiment [5]. The solid ($k = 0.5$) and dashed ($k = 0.1$) lines are the results from Eq. (11) at $p_{T0}^{\rm jet2} = 22.5$ GeV and $\sigma_{\rm eff}^0 = 16.3$ mb.

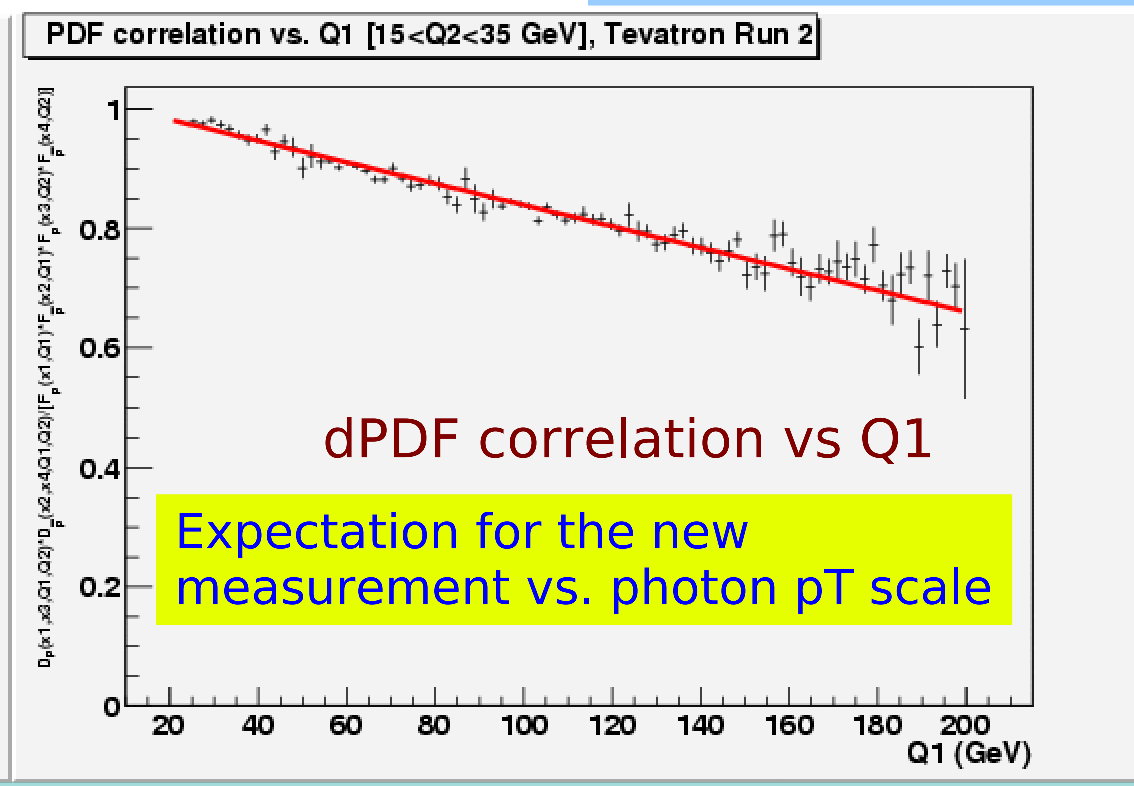
dPDF evolution

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 γ+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.
- **Planned** as a next D0 measurement at the full data set!

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

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

Motivations:

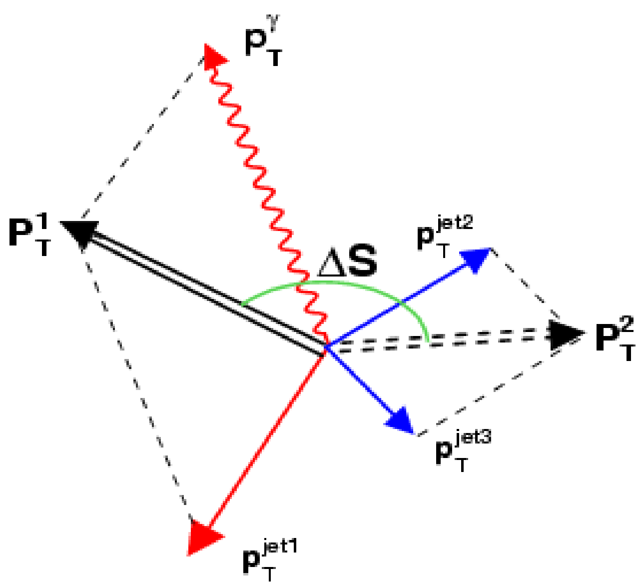
- The provided experimental inputs have been based so far mainly on the minbias and DY Tevatron data (0.63, 1.8, 1.96 TeV) and minbias SPS (0.2, 0.54, 0.9 TeV) data.

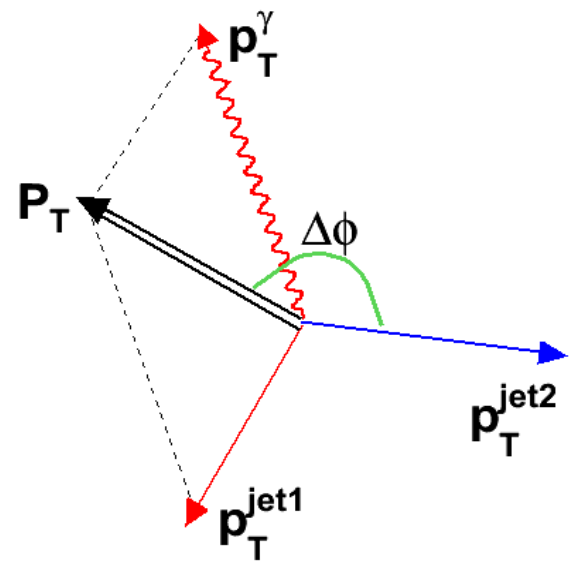
- By measuring **differential** cross sections vs. the azimuthal angles in γ+3(2) jet events we can better tune (or even exclude some) MPI models in events with high pT jets.

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

Four normalized differential cross sections are measured

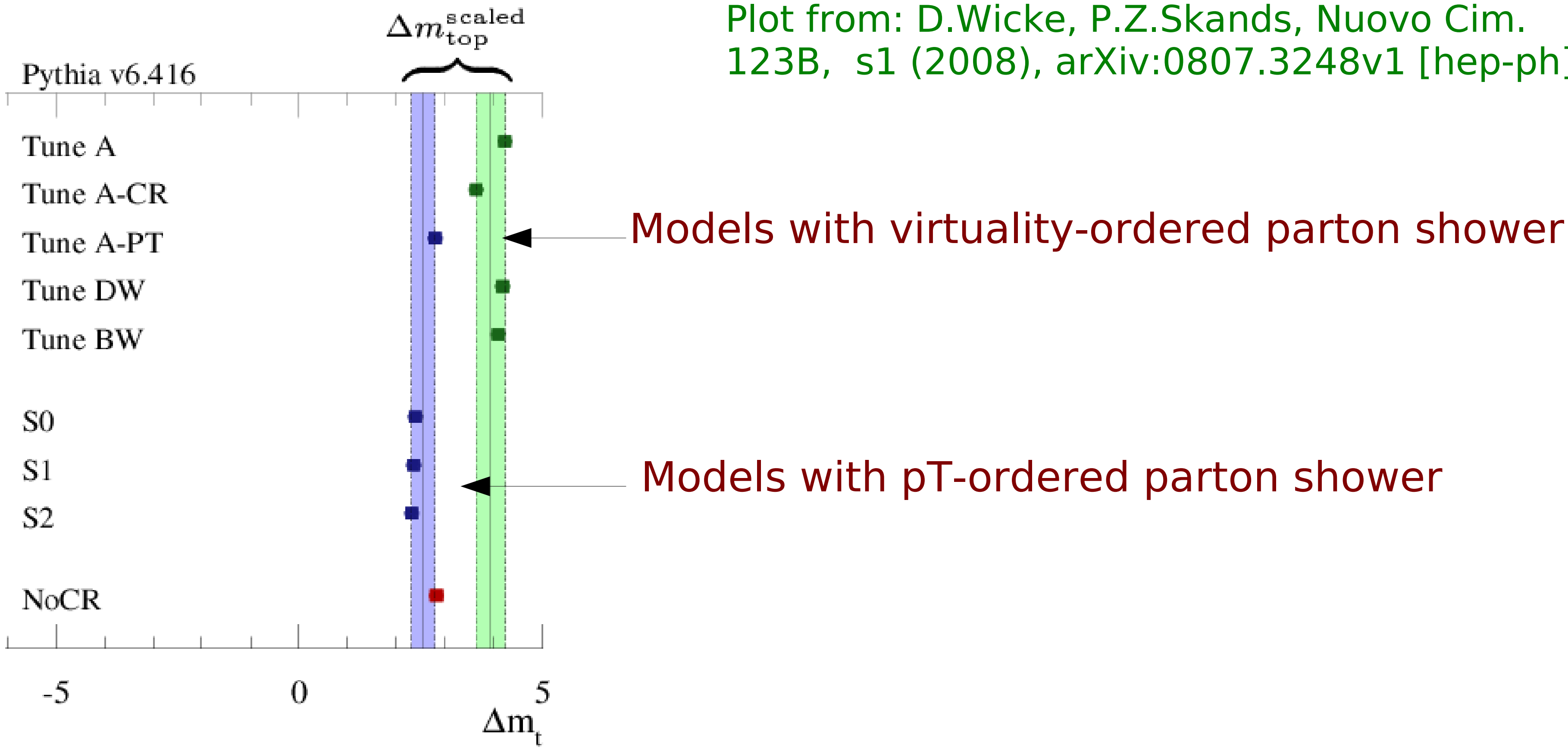
- $\Delta\phi(\gamma$+jet1, jet2) in 3 bins of 2nd jet pT: 15-20, 20-25 and 25-30 GeV
- $\Delta S(\gamma$+jet1, jet2+jet3) for 2nd jet pT 15-30 GeV





Another motivation

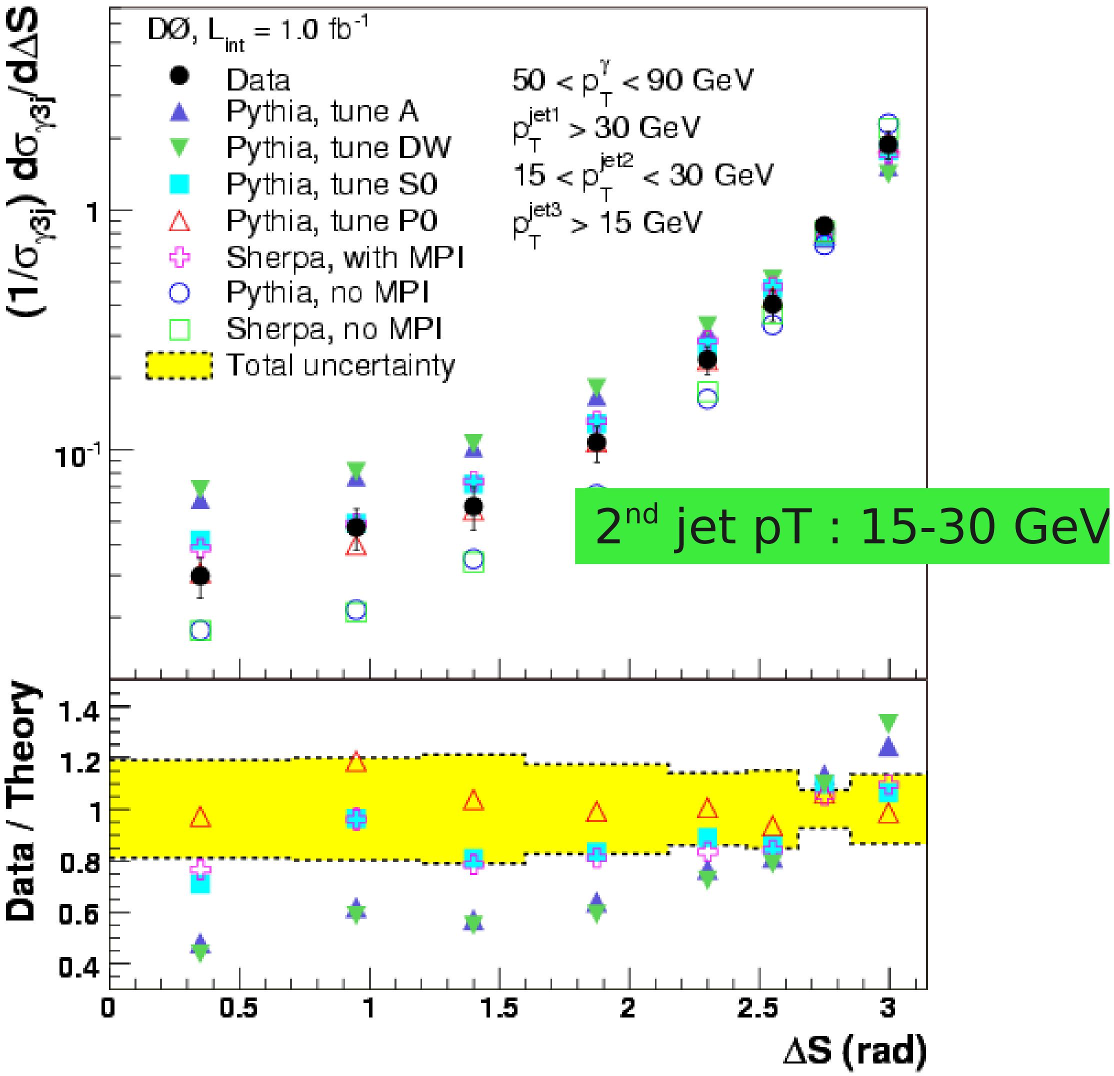
Comparison of the top-quark mass offset corrections with a few MPI models

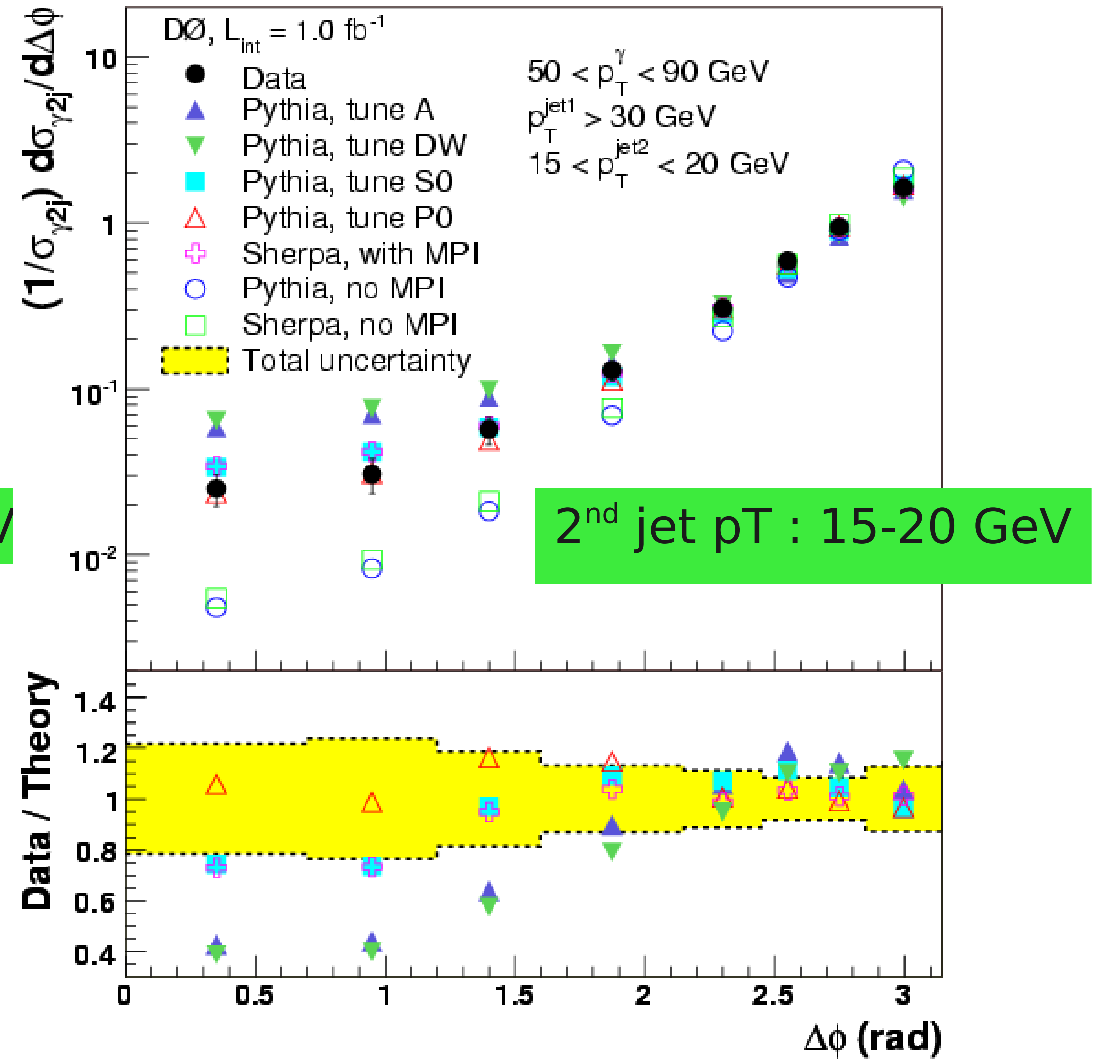


Plot from: D.Wicke, P.Z.Skands, Nuovo Cim. 123B, s1 (2008), arXiv:0807.3248v1 [hep-ph]

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.

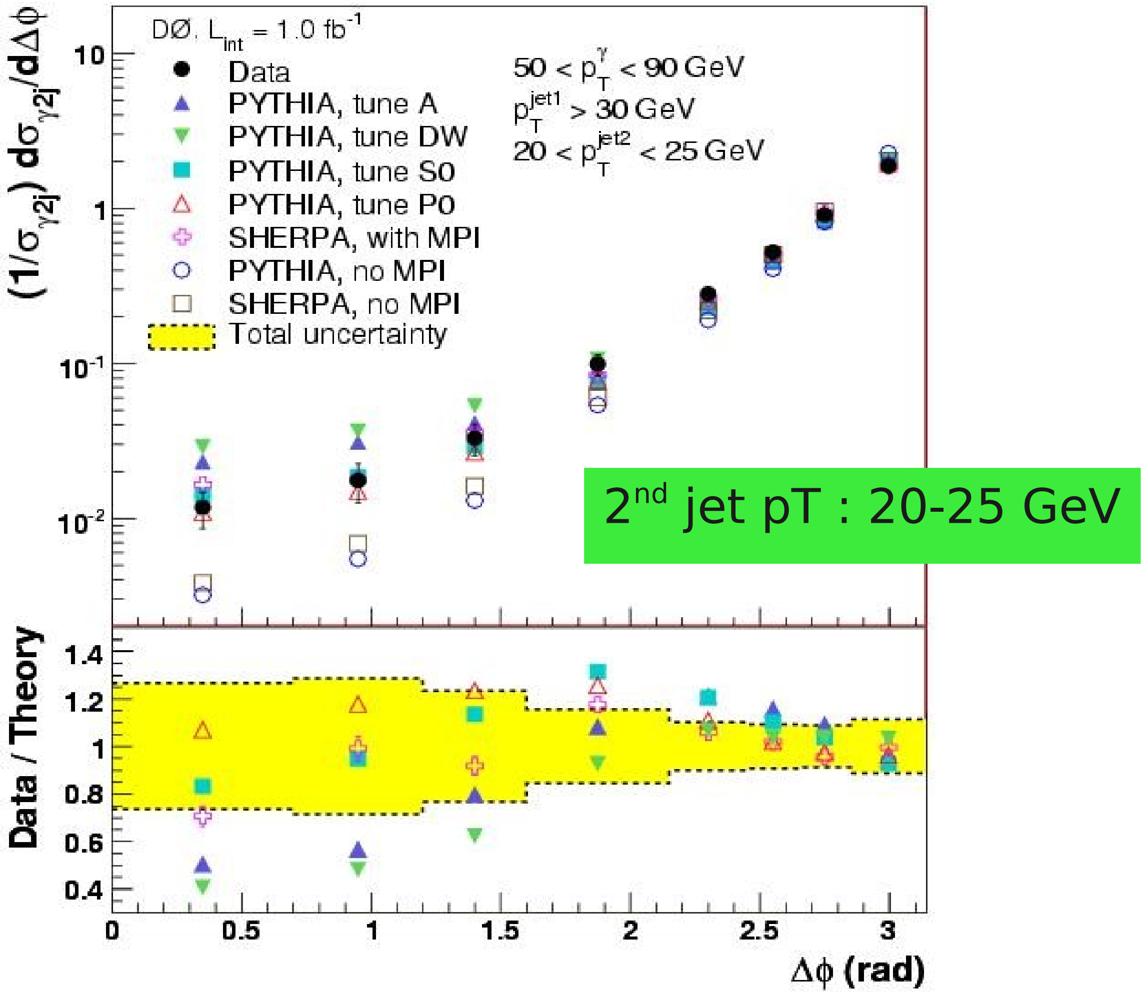
ΔS and $\Delta\phi$ cross sections





- 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



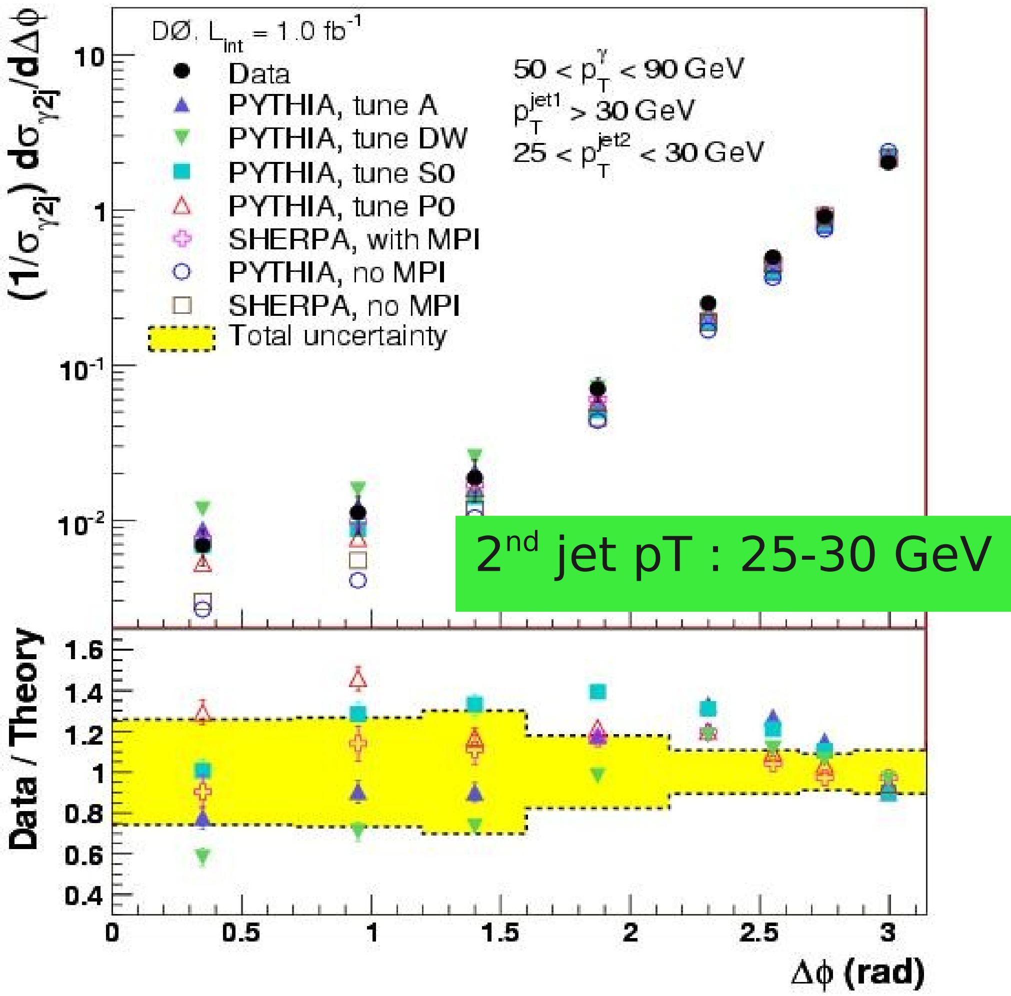


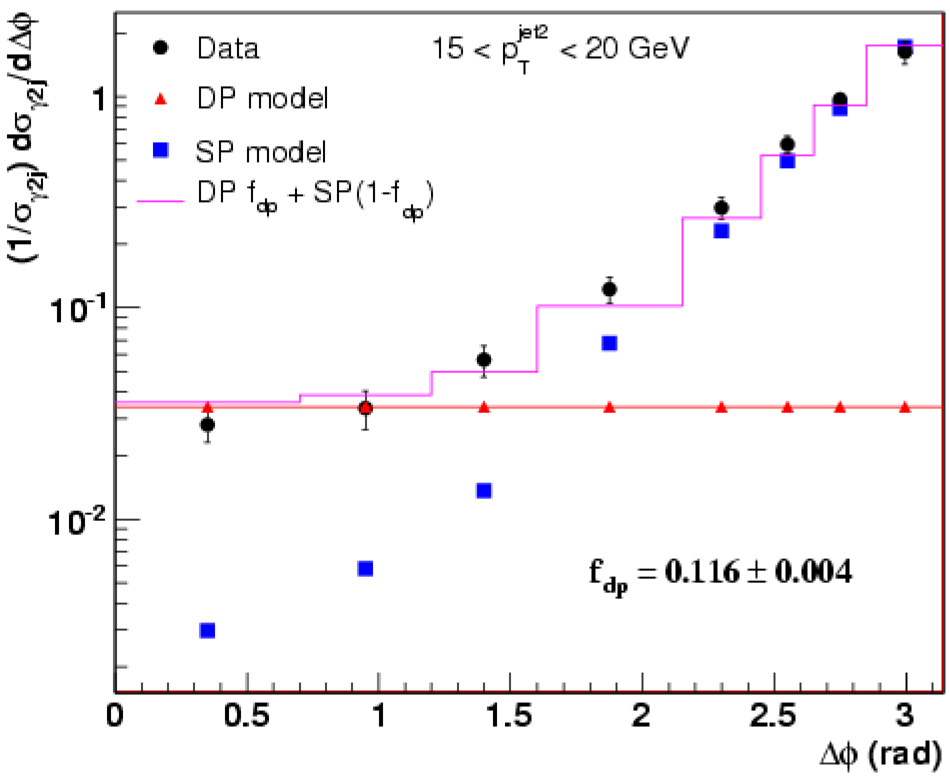
TABLE V: The results of a χ^2 test of the agreement between data points and theory predictions for the ΔS ($\gamma + 3$ jet) and $\Delta\phi$ ($\gamma + 2$ jet) distributions for $0.0 \leq \Delta S(\Delta\phi) \leq \pi$ rad. Values are χ^2/ndf.

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, $\Delta\phi(\gamma\text{+jet1, jet2})$ distribution should be flat.
- Using this fact and also SP prediction for $\Delta\phi(\gamma\text{+jet1, jet2})$ 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 f_{DP} in γ+2 jet events

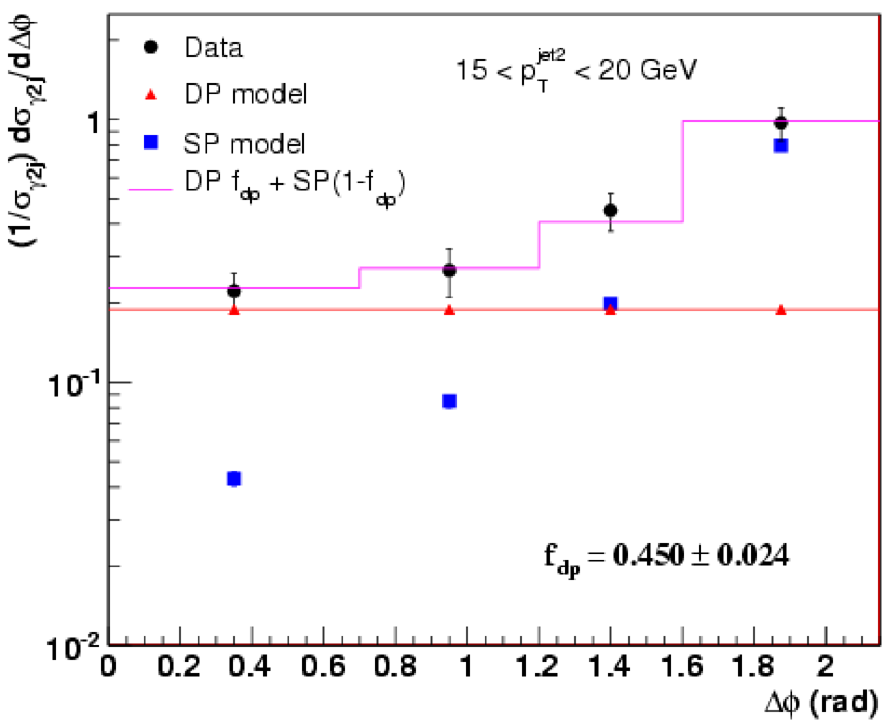
p_T^{jet2} (GeV)	$\langle p_T^{jet2} \rangle$ (GeV)	$f_{dp}^{\gamma 2j}$ (%)	Uncertainties (in %) Fit	δ_{tot}	SP model
15 – 20	17.6	11.6 ± 1.0	5.2	8.3	6.7
20 – 25	22.3	5.0 ± 1.2	4.0	20.3	11.0
25 – 30	27.3	2.2 ± 0.8	27.8	21.0	17.9

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

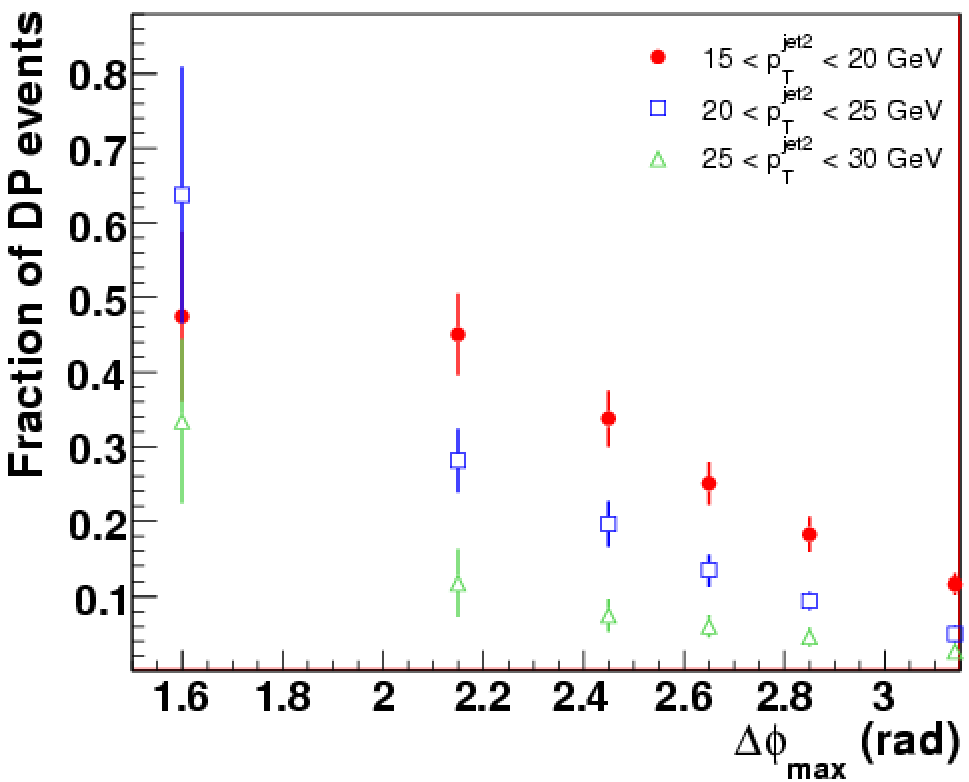
DP fractions in γ+2 jet events vs. $\Delta\phi$

- 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 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:

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

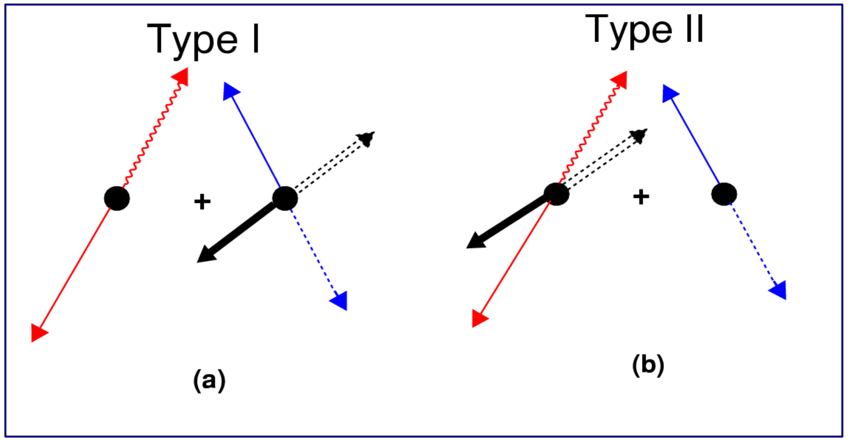
$f_{dp+tp}^{\gamma 3j}$ - measured in previous DP analysis;

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*.



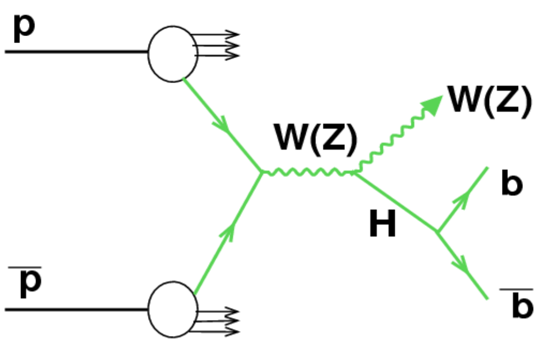
p_T^{jet2} (GeV) (GeV)	$f_{\mathrm{tp}}^{\gamma 3j}$ (%)	$f_{\mathrm{tp}}^{\gamma 3j} / f_{\mathrm{dp}}^{\gamma 3j}$ (%)
$15 - 20$	5.5 ± 1.1	13.5 ± 3.0
$20 - 25$	2.1 ± 0.6	6.6 ± 2.0
$25 - 30$	0.9 ± 0.3	3.8 ± 1.4

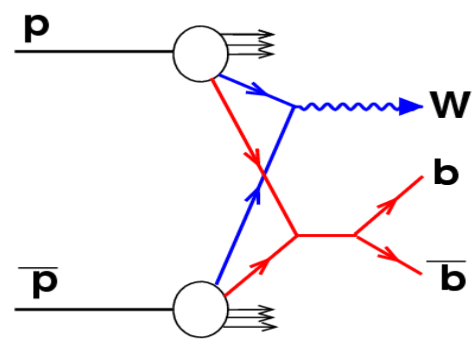
Double Parton Interactions

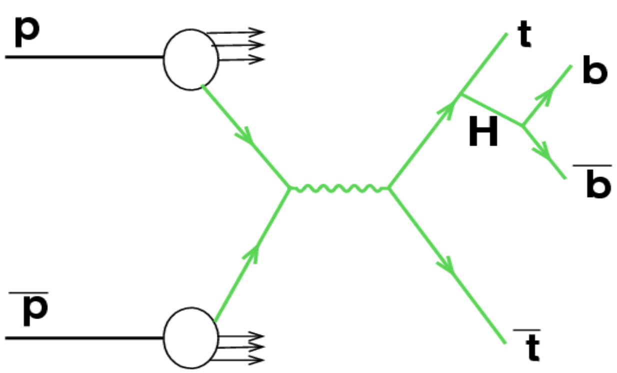
As Background to Rare Processes

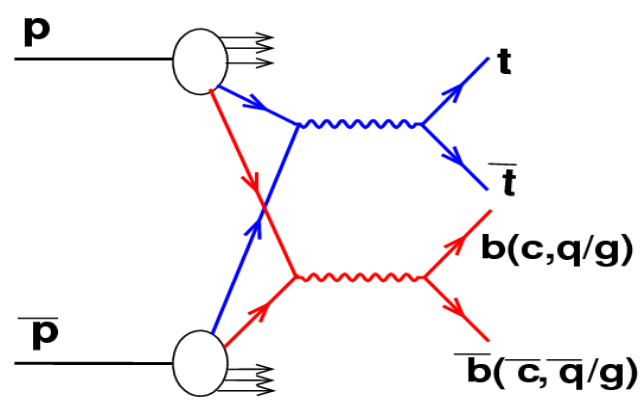
Double Parton events as a background to Higgs production

Signal	Double Parton 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

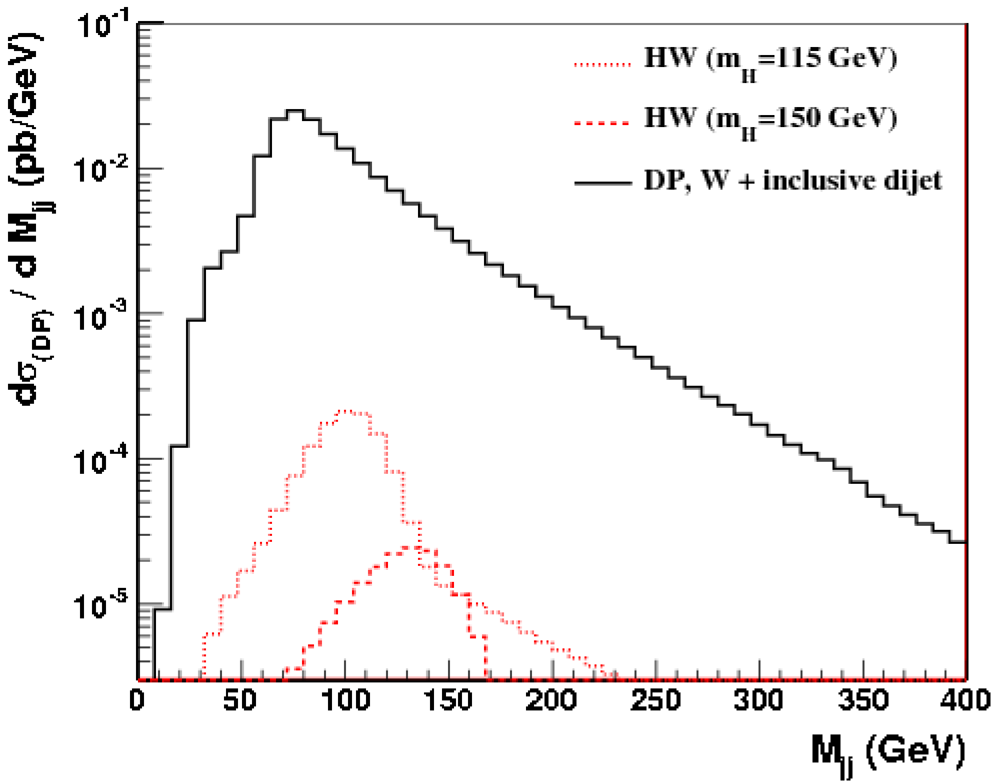
DP as background to p+pbar→WH at Tevatron

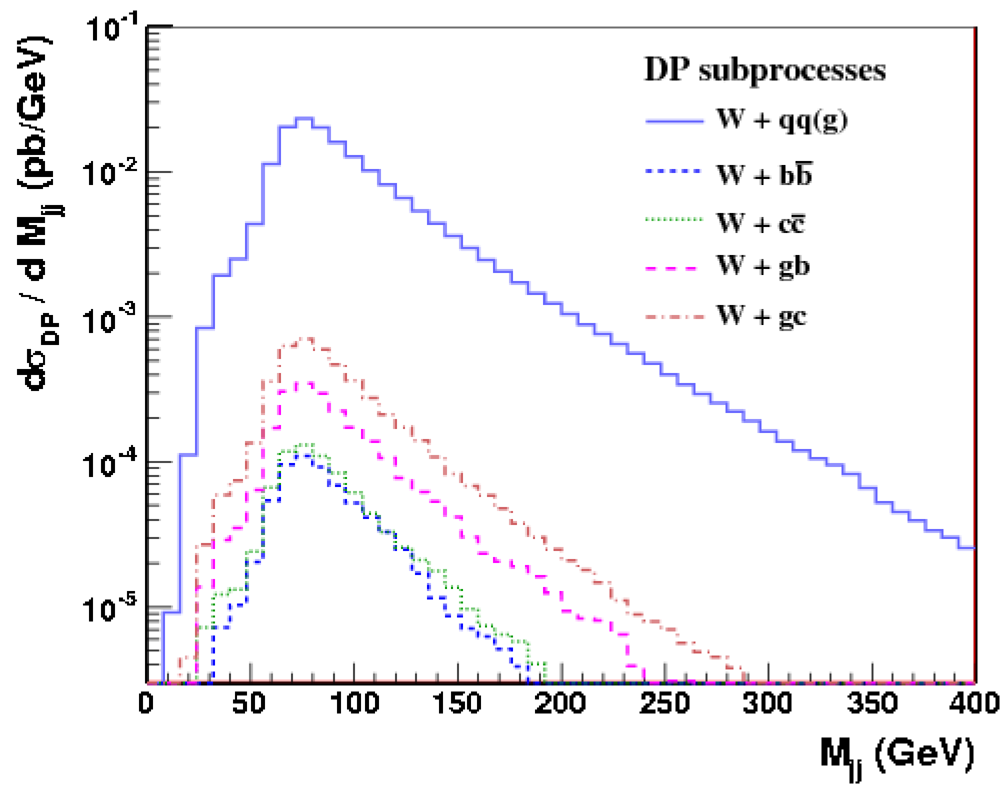
Fast MC based on Pythia-8
(detector smearing)

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 dσ/dM and W(Z) cross sections are normalized to D0 measurements.
– DP background can be significant for both the Higgs productions channels!

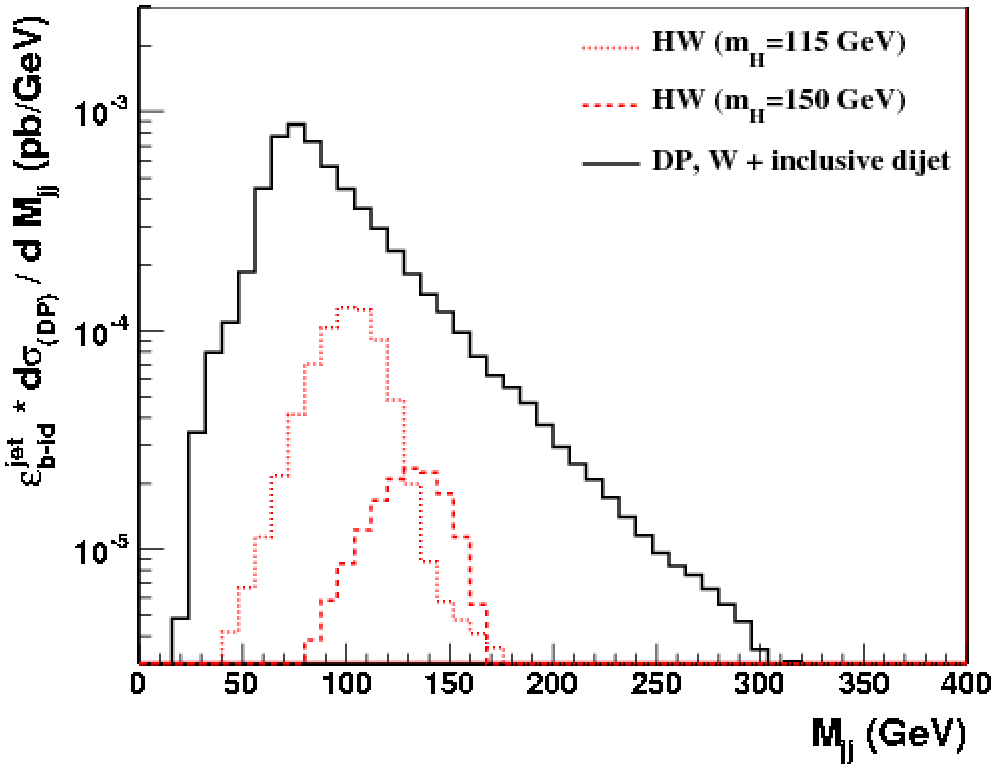
DP as background to p+pbar→WH at Tevatron (2)

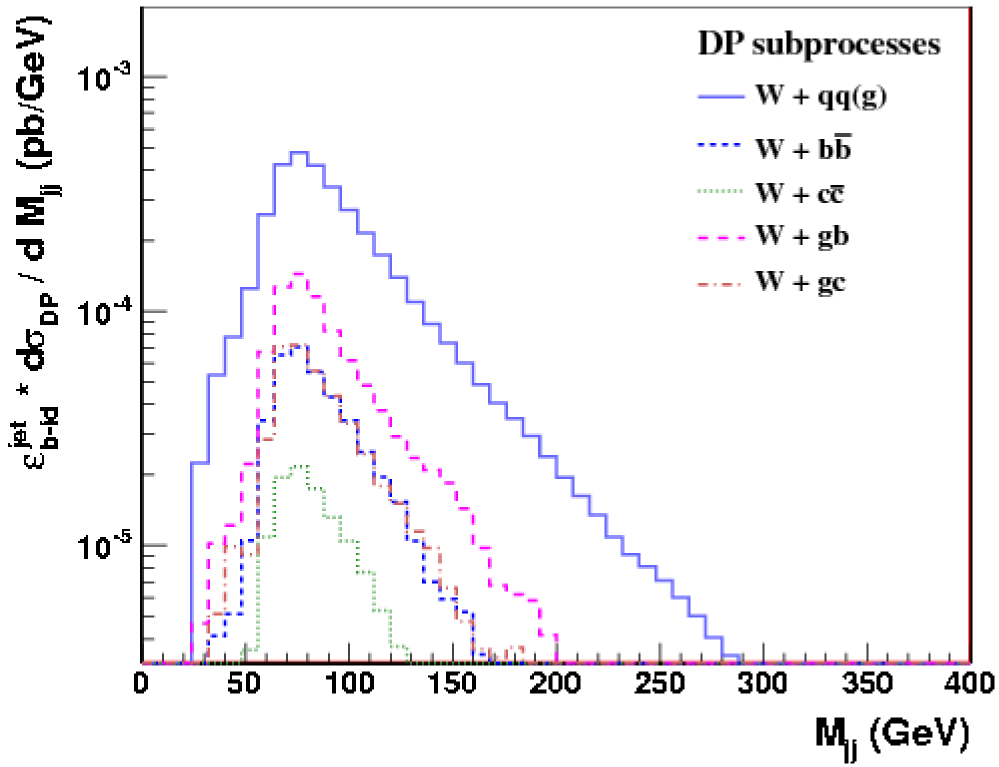
Fast MC based on Pythia-8
(detector smearing+TRF)

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

HW, H→bb: DP and SP cross sections

With bID selections (TRFs)

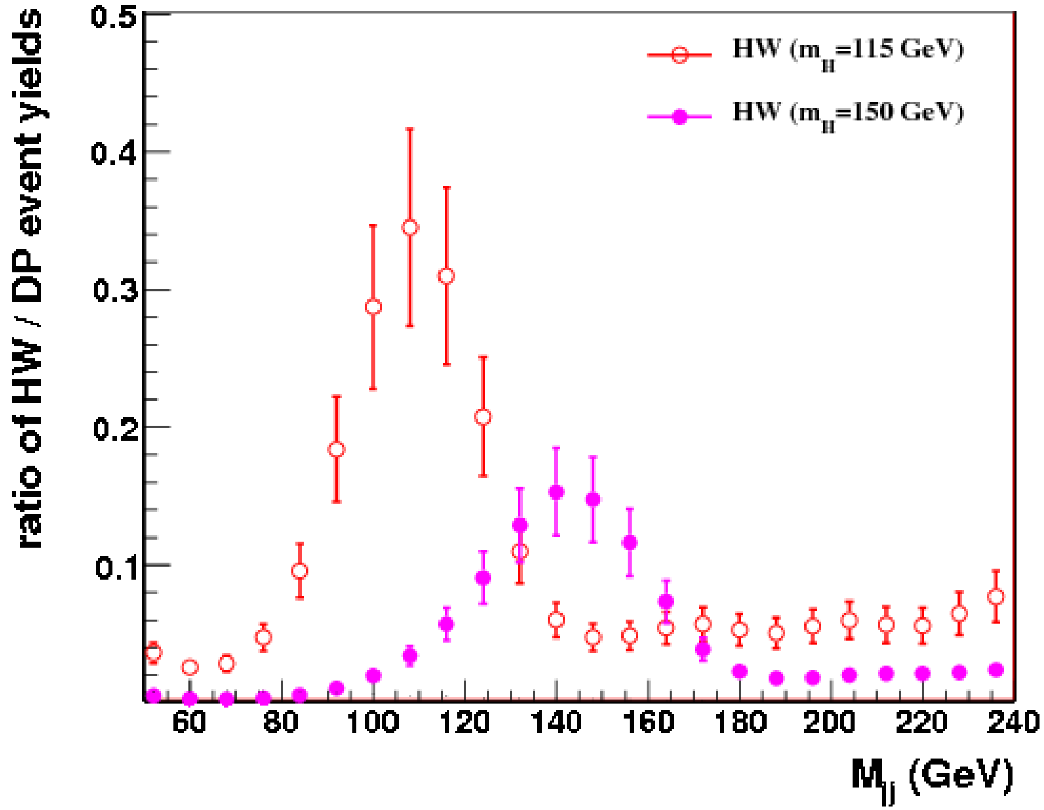




– Kinematic + bID selections are same as in actual D0 analyses.
– Dijet dσ/dM and W(Z) cross sections are normalized to D0 measurements.
– DP background can be significant for both the Higgs productions channels!

DP as background to p+pbar→WH at Tevatron (3)

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 σ_{eff} (~15%)

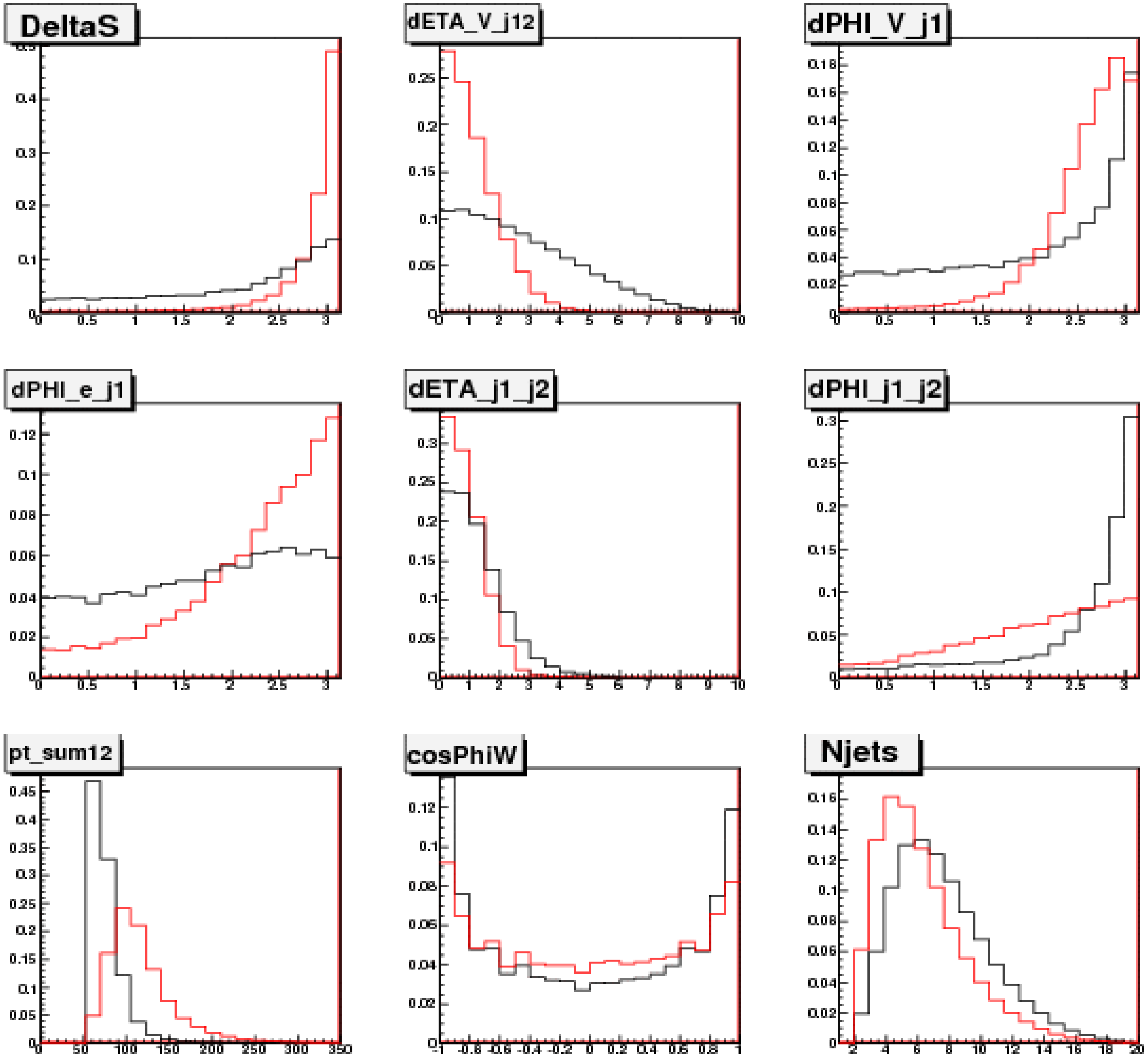
Fractions of events with single jet b-tagging and double b-tagging are chosen as in data/full reco for WH

– 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)

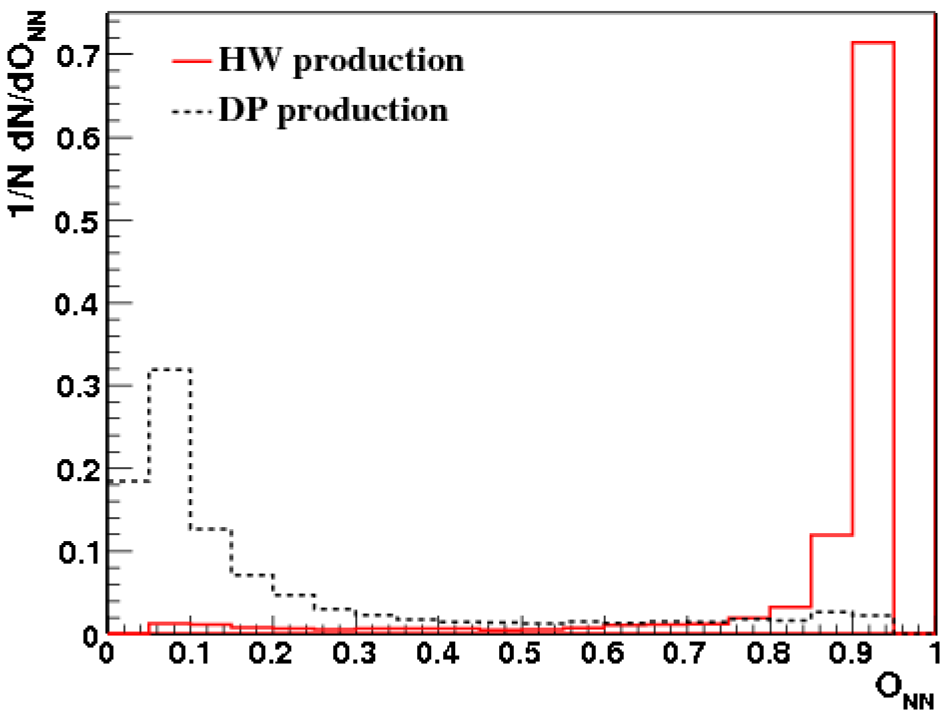
Input ANN variables

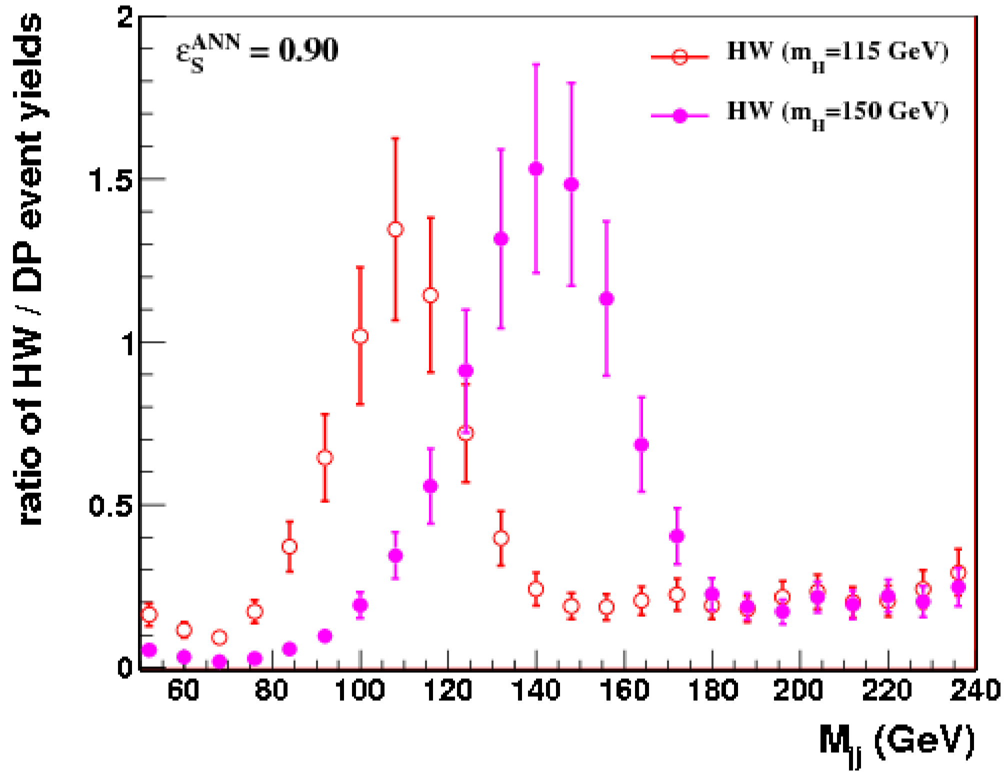


Red is WH
Black is DP

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



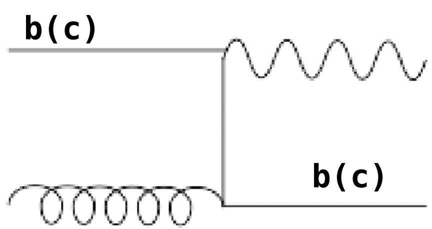


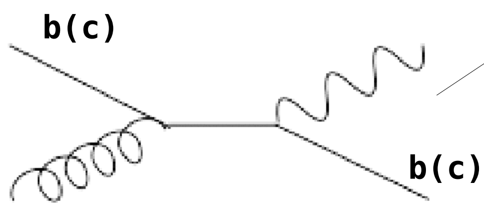
Some more ongoing studies

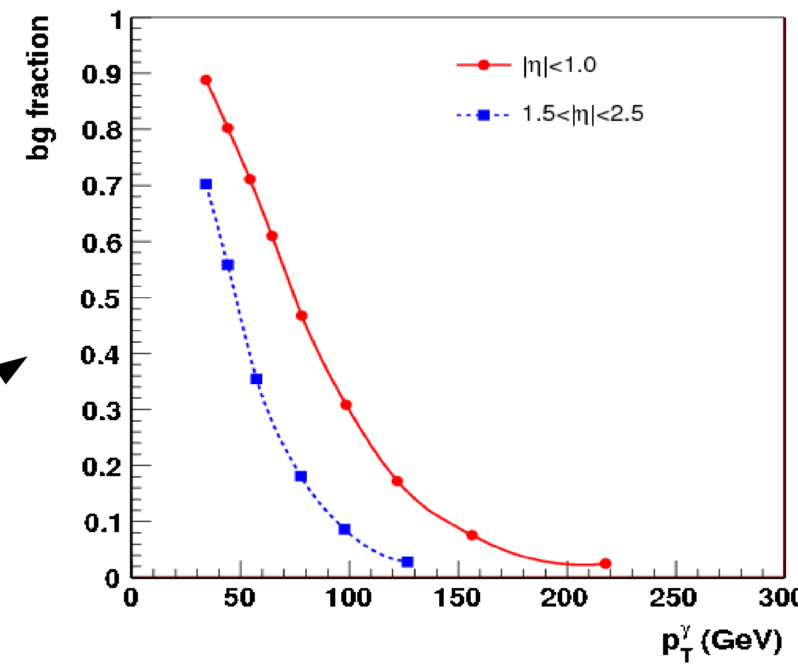
Photon+HF+2jet DP events

Goal: Measurement of σ_{eff} in the events with initial b or c quark
=> sensitivity to HF (sea) quark spatial distribution

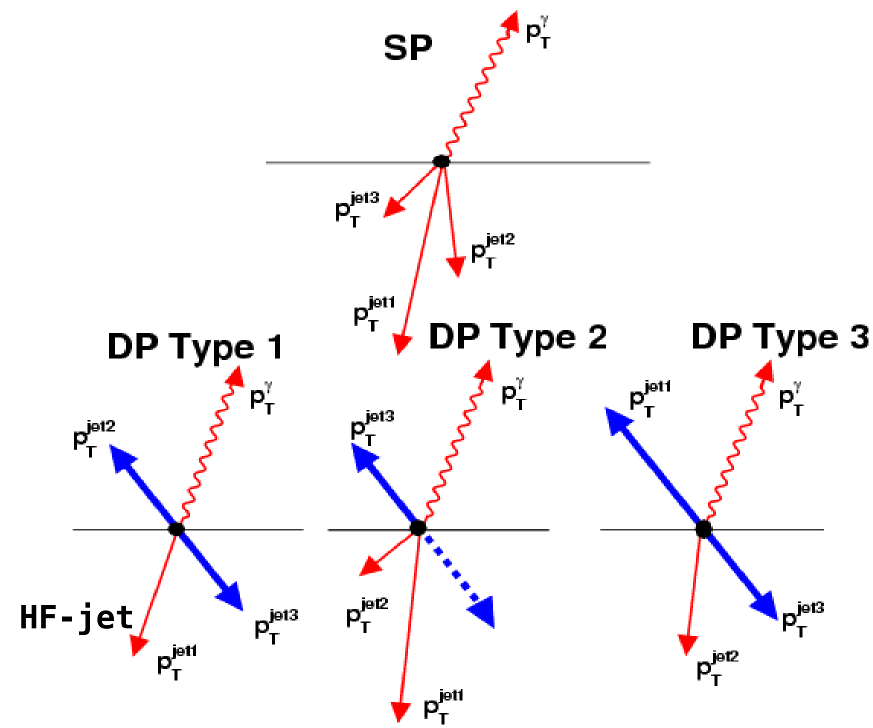
- Main scattering is caused by photon+HF production with dominating contribution from $Qg \rightarrow Q\gamma$ (Q=c,b) scattering



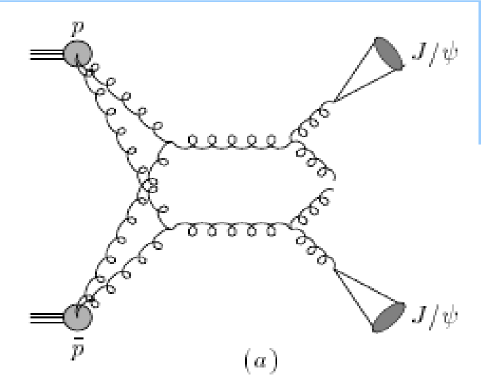




- At least one HF-jet is required (a jet passed Tight b-ID) => estimated HF fraction is 75-80%
- Photon pT>30 GeV
  Two 2nd jet pT bins: 15-23 and 23-35 GeV
- Use of data-driven method to calculate σ_{eff}

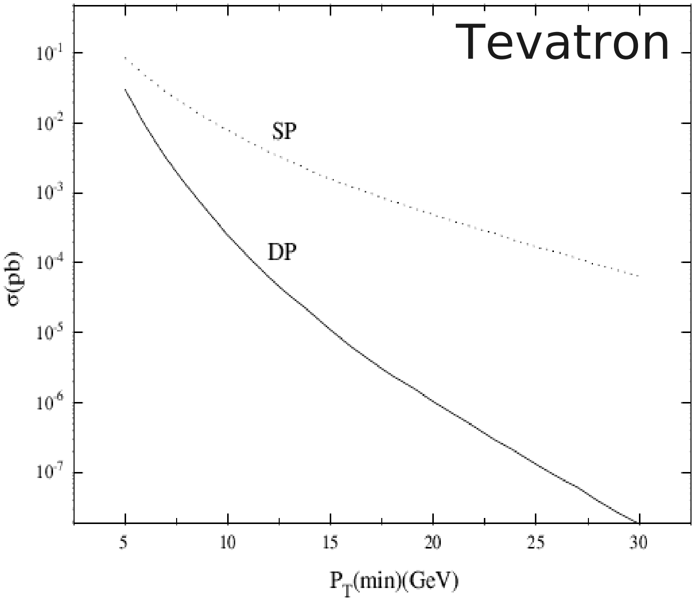


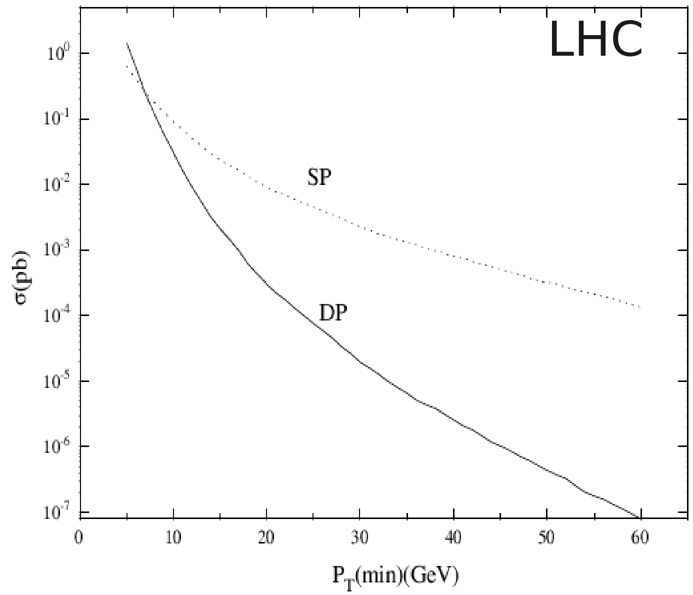
Double J/psi production



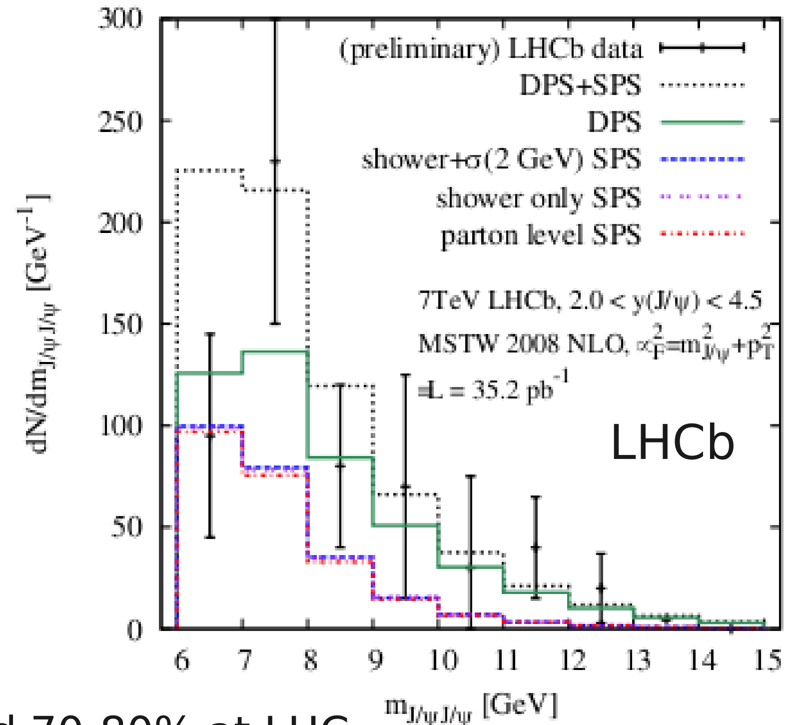
Goal: Meas. of double J/psi cross sections in SP and DP events
=> extraction of σ_{eff} at low pT (!)
=> test of σ_{eff} energy dependence : see slide 34

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 are higher at LHC)

– The measurements of the cross sections are at the full speed in D0, CMS and Atlas experiments (about similar statistics of the selected events, $O(100)$, in the three experiments for now)

– Main background: b+bbar events with semileptonic B-meson decays into J/psi+X

– DP and SP events should be separated by using $\Delta\eta$ & $\Delta\Phi$ distributions.

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

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

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

	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

hep-ph/9605430

– The measurement with $\gamma\gamma$+jj events is started recently.

– By analogy to photon+3j, the events are split into jet pT bins.
About 3,000 of 1-vertex events with photon pT>18 and jet pT>15 GeV
are selected at ~7.5 fb-1.

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 $\triangle$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.

Summary (2)

- Studies of MPI events (esp at high pTs) 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 2 dPDFs. Plus σ_{eff} should drop due to the dPDF evolution.
  Thus, MPI can be important background to many 'new physics' processes at LHC.

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 (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(x1,x2,b) (e.g. arXiv:1009.2741);
    F(b) should depend on the parton species;
    There is a log-dependence of gluon F(b) on parton *x* from excl. J/psi production in DESY (see Backup)

  – Correlation between different partons in the nucleon (in *x*, spin, flavor)

=> More measurements of DP fractions and σ_{eff} are needed
  - in 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.

BACK-UP SLIDES

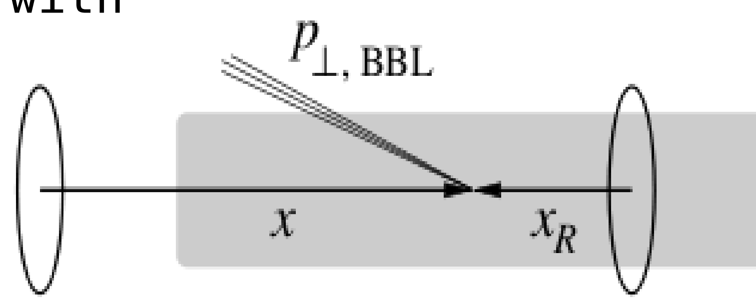
Some other possible DP studies

- 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):

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

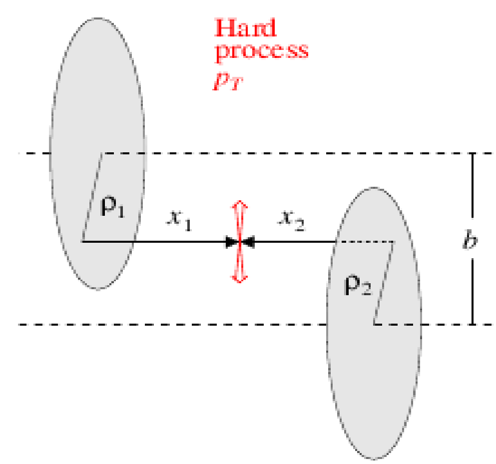


=> results in extensive hadron production with pT>1-2 GeV in the backward(forward) rapidity region
In D0, the calorimeter can be used for this aim (with SPR correctrions)

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

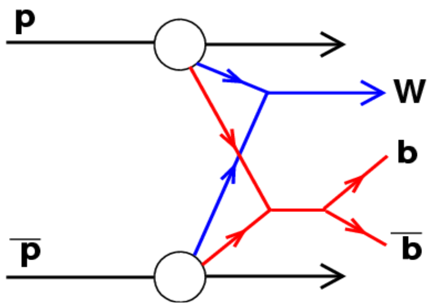
Average impact parameter ***b*** in hard SP, DP and incl. inelastic events

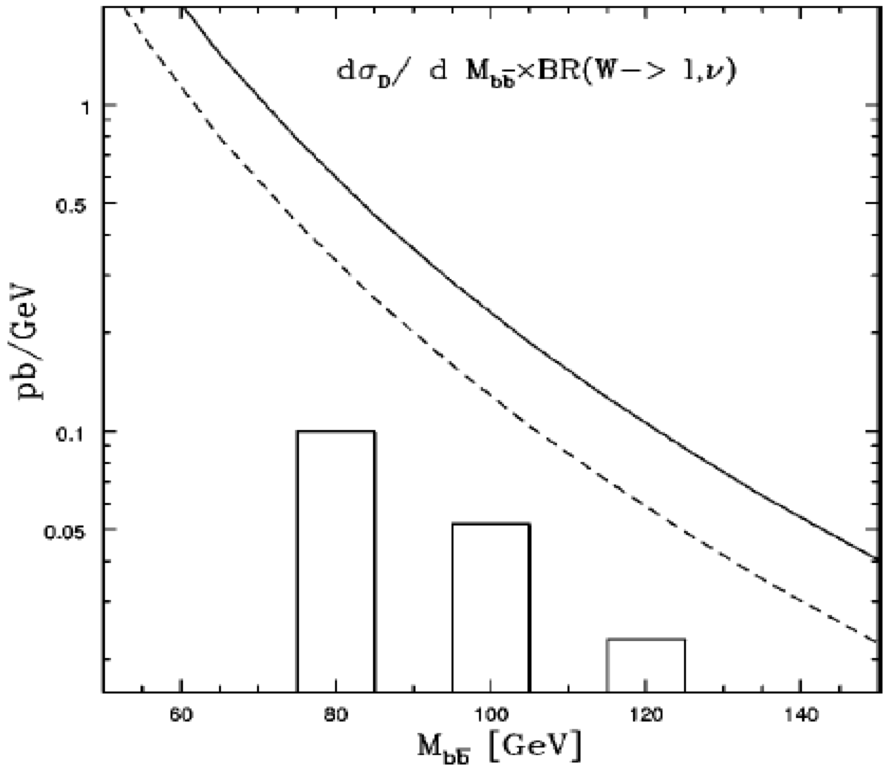
Facility	$\sqrt{s}$/GeV	$\langle b^2\rangle_2/\mathrm{fm}^2$	$\langle b^2\rangle_4/\mathrm{fm}^2$	$\langle b^2\rangle_{\mathrm{in}}/\mathrm{fm}^2$
LHC	14000	0.67	0.26	2.7
Tevatron	1800	0.63	0.24	1.8
RHIC	500	0.59	0.23	1.43

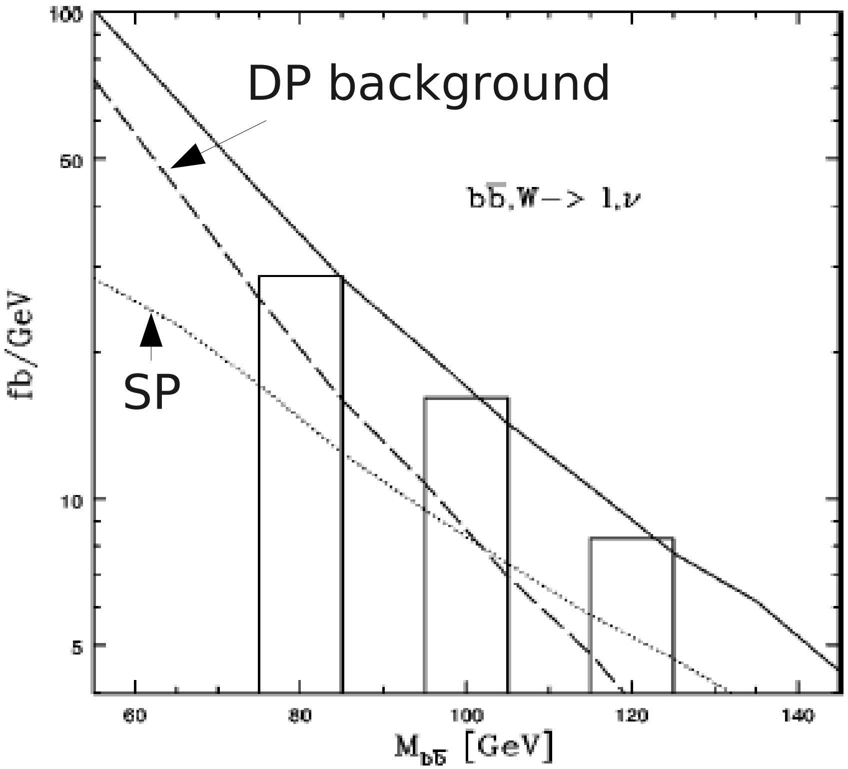


Example: DP as background to p+p → WH at LHC

From PRD61 (2000) 077502 by Fabbro, Treleani







DP background as a function of H mass:
LO and NLO bb production
(σ_{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

Prospects

Measurements coming soon in D0:

(1) γ+heavy flavor jet + 2jets events :

Measurements of σ_{eff} in the events with initial b or c quark in the initial state

=> sensitivity to the b&c quark spatial distribution

(2) Study of DP events in $\gamma\gamma$+2jet final state

=> New and independent test of σ_{eff} and MPI models

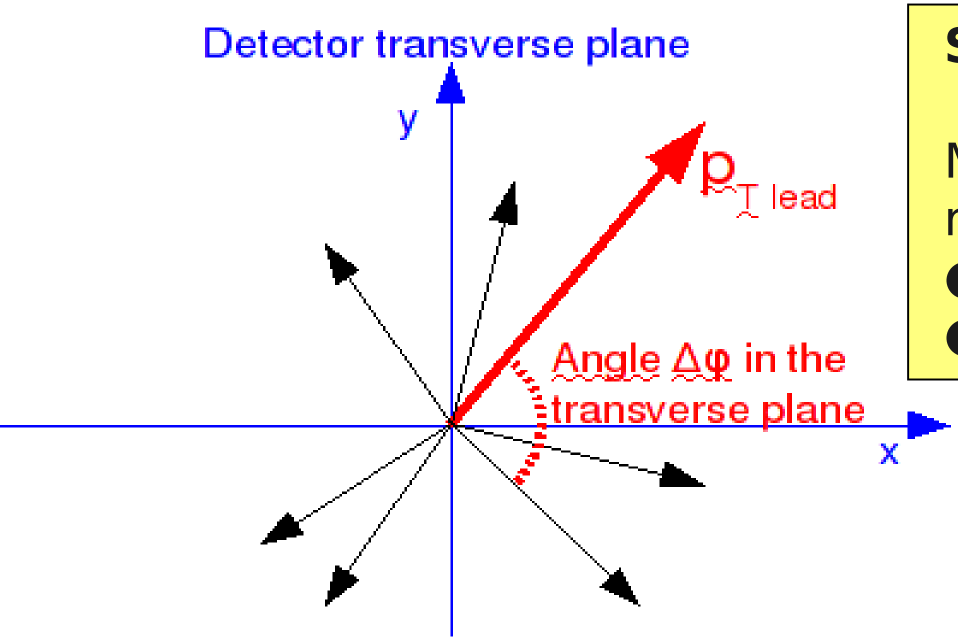
(3) DP events in the double J/psi production

=> Extraction of σ_{eff} at low pT

Test of σ_{eff} energy dependence

Track angular correlations in minbias events

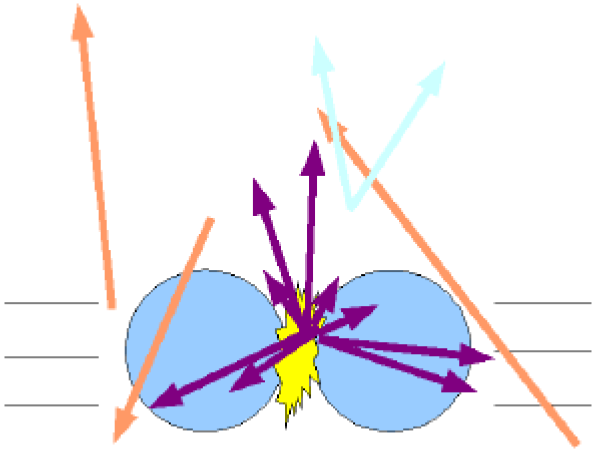
- Use correlations in Δ φ to characterize Minimum Bias Events
- Compare data to various Monte Carlo tunes and models



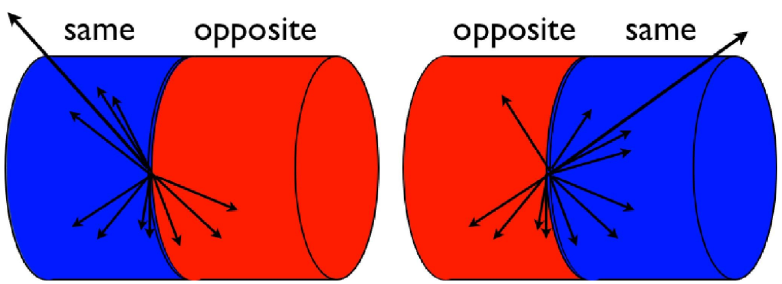
Strategy: Associate all tracks to PVs and then select good quality tracks associated to minbias PVs. Minimize fakes, cosmics, conversions, long-lived resonances, vertex mis-associations

- pT>0.5GeV
- |η|<2

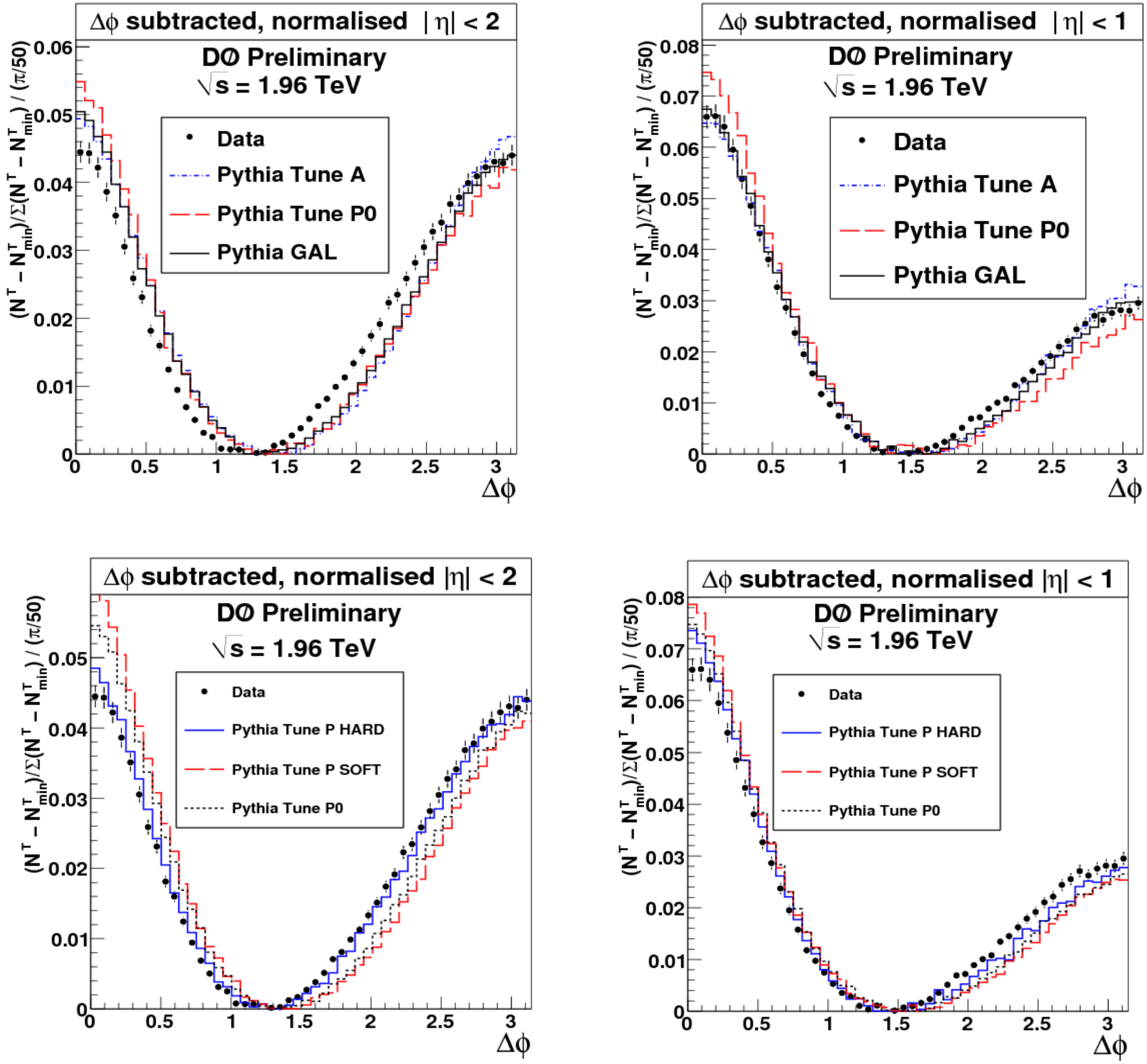
- Trigger on dimuon events
- Require exactly 2 muons w/ p_T > 2 GeV associated with the same vertex
- Then require one or more Minimum Bias PVs
  - At least 5 tracks
  - At least 0.5cm from triggered PV
  - Within 20cm of center of detector



Tests with same-sign and opposite-sign events in η

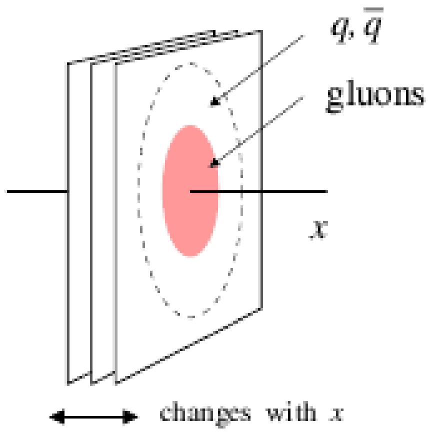


Δφ comparison to MC



From C.Weiss talk
at DIS 2011

Transverse distributions: Gluons from J/ψ

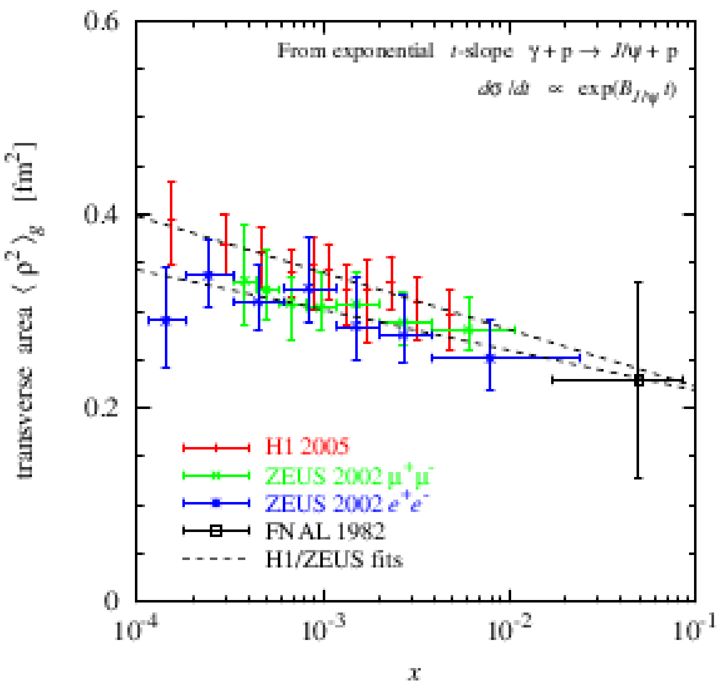


- Exclusive process $\gamma^* N \to J/\psi + N$
  also ϕ, ρ

  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



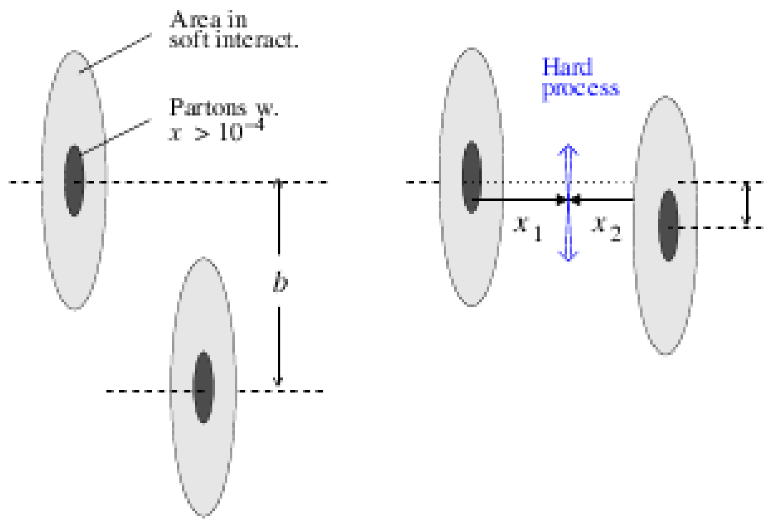
- Transverse gluonic size of nucleon

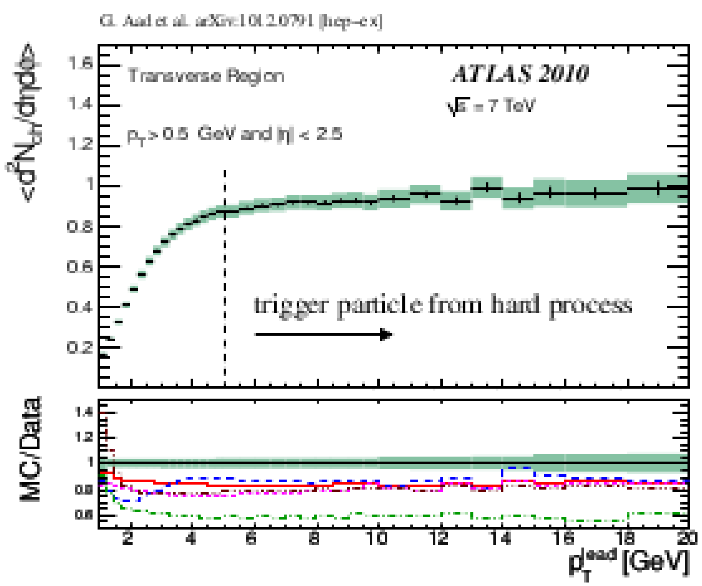
  Gluons concentrated at center
  $\langle \rho^2 \rangle_g (x \sim 10^{-2}) \; < \; \langle b^2 \rangle_{\mathrm{charge}}$

  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

Final states: Underlying event





- Two different sizes

  $$R^2(\text{soft}) \gg R^2(\text{partons } x > 10^{-4})$$

  Hard parton–parton processes require central pp collisions

  Trigger on high–p_T jet selects central pp collisions!

- Geometric correlations

  High–p_T trigger $\rightarrow$ central collisions $\rightarrow$ event characteristics

  Example: Transverse multiplicity
  Also: Rapidity dependence, energy flow, . . .

  Reveals minimum p_T for hard production: Test of production mechanism
  FSW, PRD83 (2011) 054012

  Model–independent! Benchmarks for detailed MC simulations

Nch in MPI models

From: PRD 36, No.7 (1987)2019, T.Sjostrand, M.van Zijl

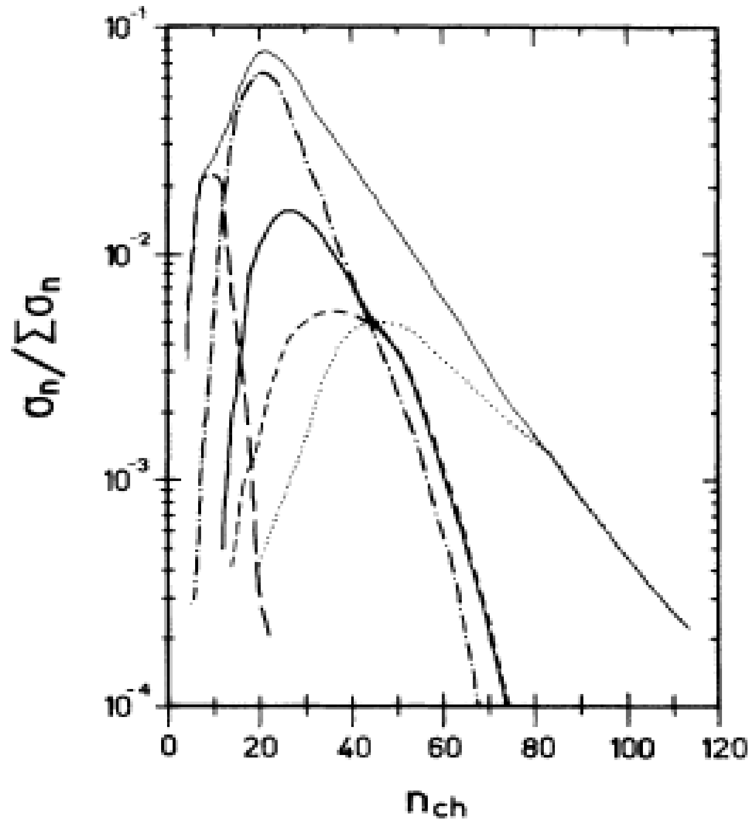


FIG. 13. Separation of multiplicity distribution at 540 GeV by number of interactions in event for double-Gaussian matter distribution. Long dashes, double diffractive; dashed-dotted one interaction; thick solid line, two interactions; dashed line, three interactions; dotted line, four or more interactions; thin solid line, sum of everything.

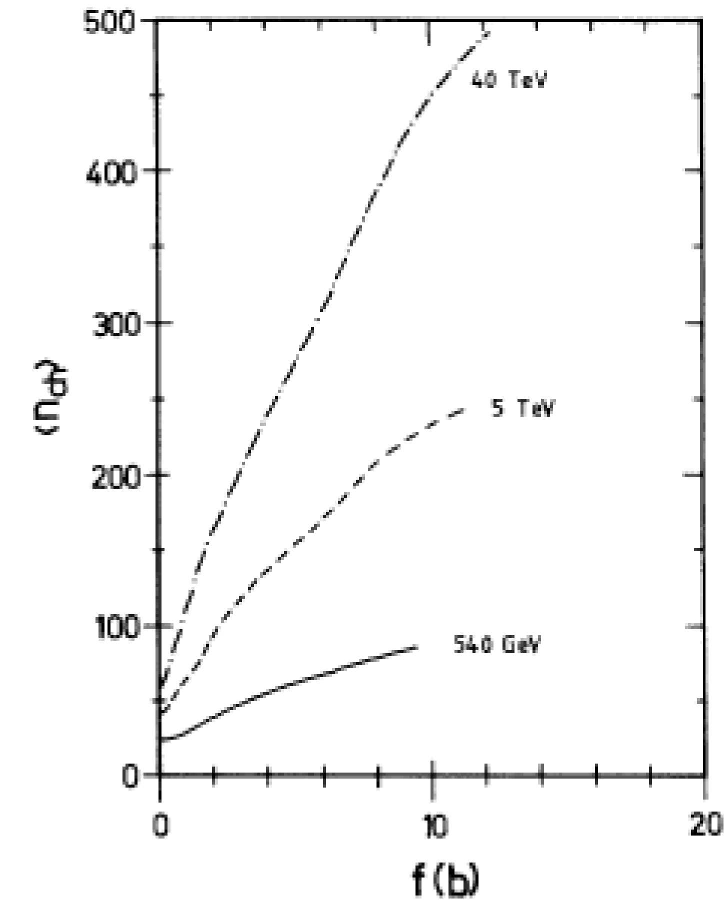
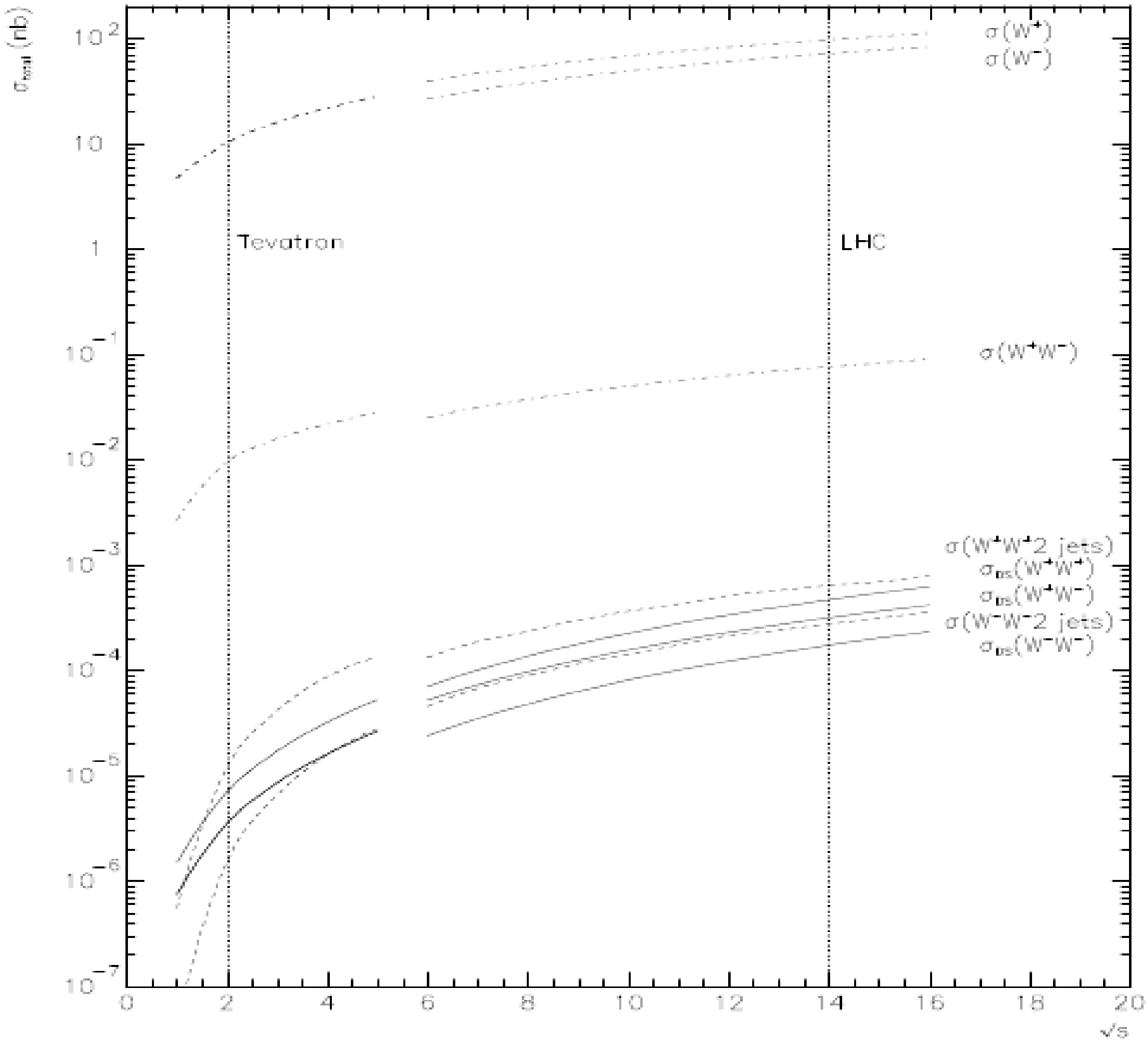


FIG. 15. Average charged multiplicity as a function of the "enhancement factor" $f(b)$. Notation as in Fig. 14.

Like-sign WW boson production

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



	$N(W^+W^-)$	$N(W^+W^+)$	$N(W^-W^-)$
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.

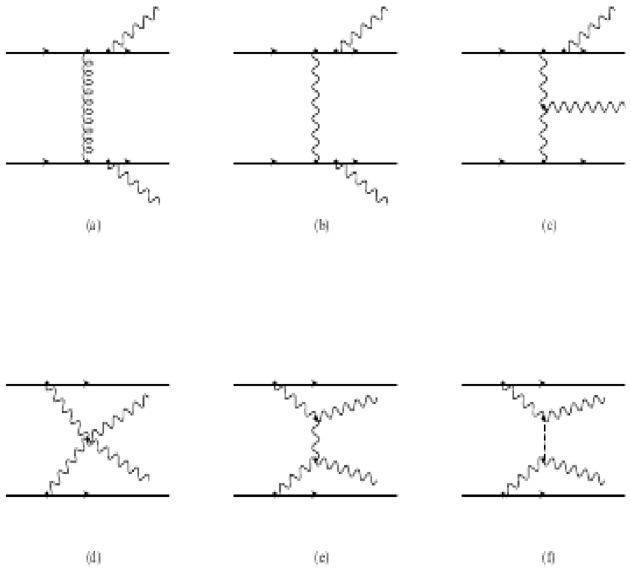


Figure 1: Examples of Feynman diagrams for the $uu \to W^+W^+dd$ scattering process, $\mathcal{O}(\alpha_S^2\alpha_W^2)$ (a) and $\mathcal{O}(\alpha_W^4)$ (b-f).

– No branching ratios or cuts are included

– SP process: σ(W+W+)~α^2_{sw} σ(W+W-)
LHC : σ(W+W+)>σ(W-W-)
TeV : σ(W+W+)=σ(W-W-)

1st and 2nd interactions: Estimates of possible correlations

... in the momentum space:

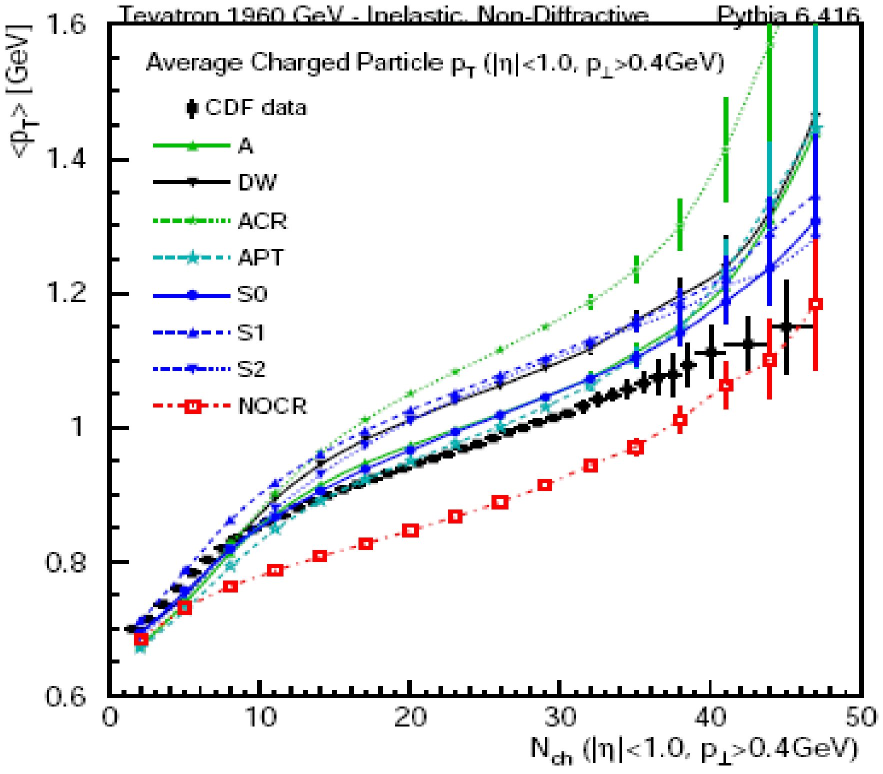
1st interaction: photon pT $\simeq$ 70 GeV, $\Rightarrow$ parton *xT* $\simeq$ *0.07*
2nd interaction: jet pT $\simeq$ 20 GeV, $\Rightarrow$ parton *xT* $\simeq$ *0.02*

➲ large (almost unlimitted) kinematic space for the 2nd interaction

... at the fragmentation stage :

=> Simulate γ+3 jets and di-jets with switched off ISR/FSR; then additional 2 jets in γ+3 jets should be from 2nd parton interaction
=> compare 2nd (3rd) jets pT/Eta in γ+3 jets with 1st (2nd)jet pT/Eta in dijets

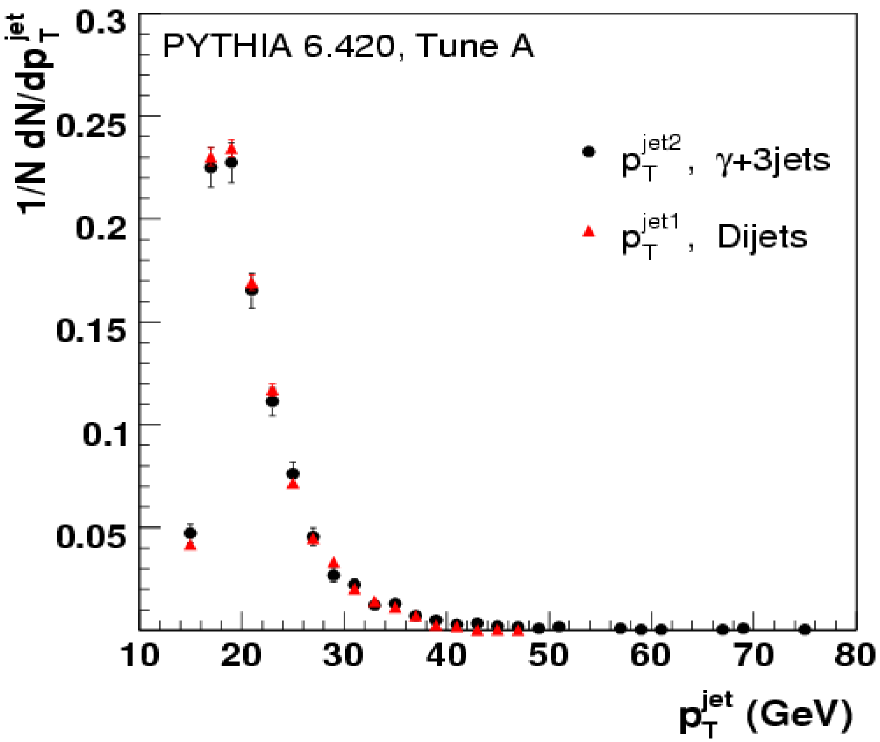
=>Tunes tested: A, A-CR, S0

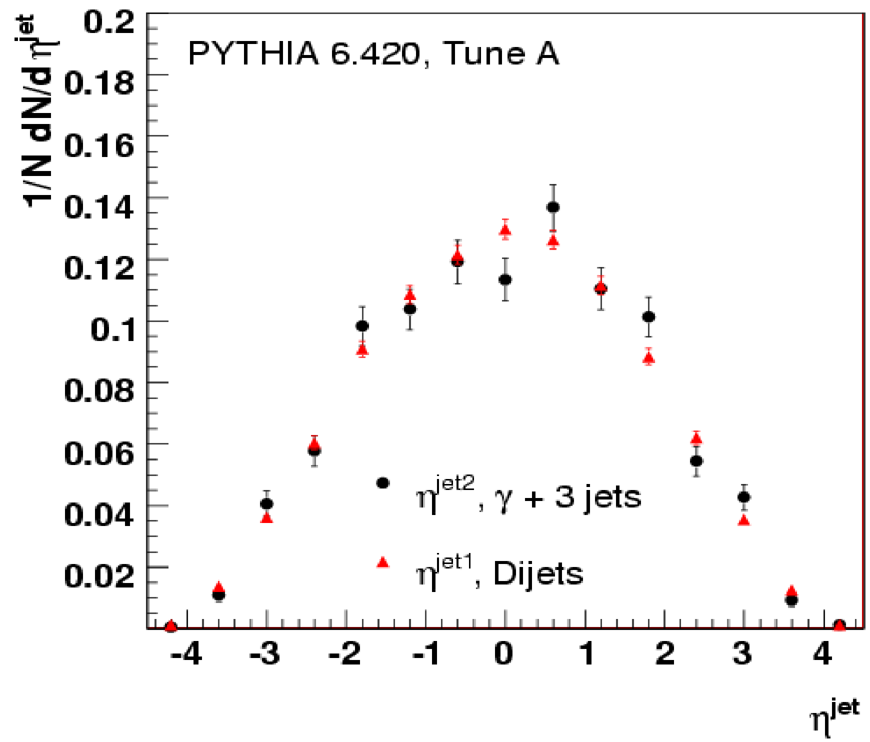


From D.Wicke & P.Skands hep-ph:0807.3248

γ+3 jets and di-jets, IFSR=OFF: jets pT comparison.

Tune A

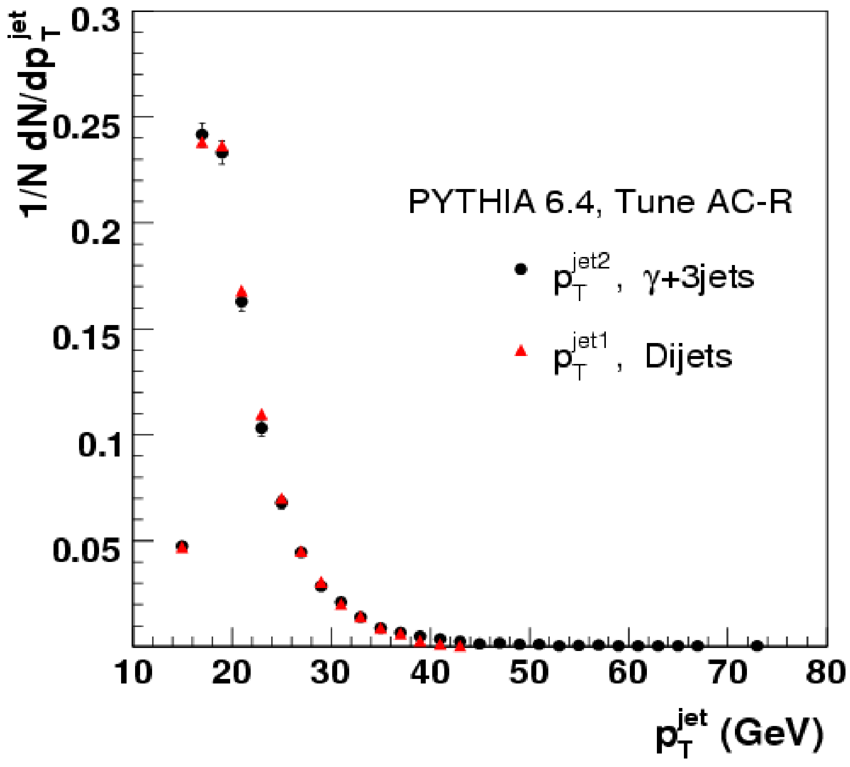


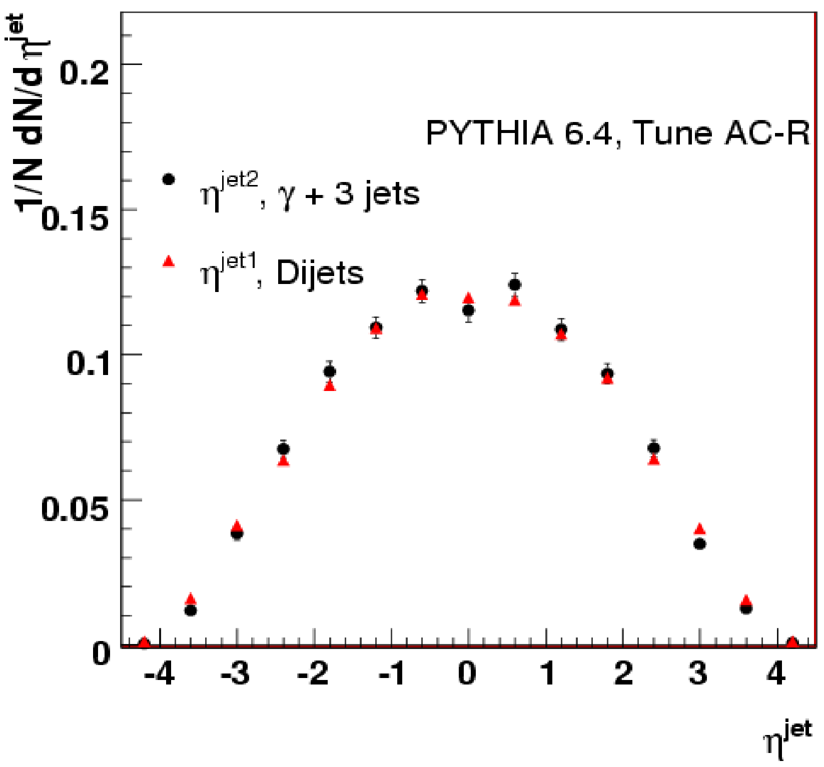


- pT and Eta distributions are analogous for jets from 2nd interaction in γ+3jets and di-jet events
- Analogous results (incl. 3rd jet from γ+3jets and 2nd from di-jets) are obtained for Tunes A-CR, S0.

γ+3 jets and di-jets, IFSR=OFF: jets pT comparison.

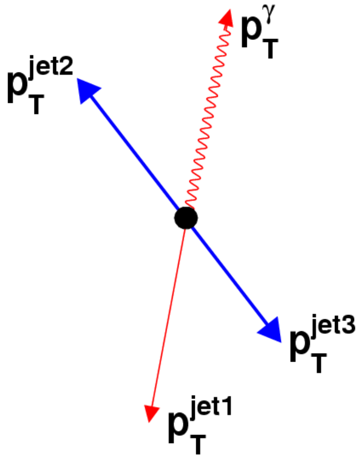
Tune A-CR



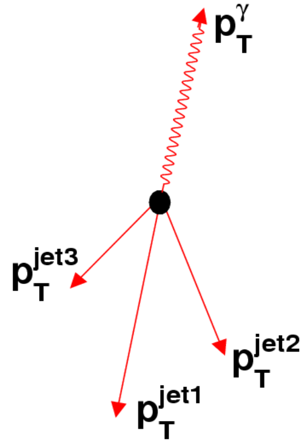


γ+3 jets events topology: Double Parton and Double Interaction events

DP



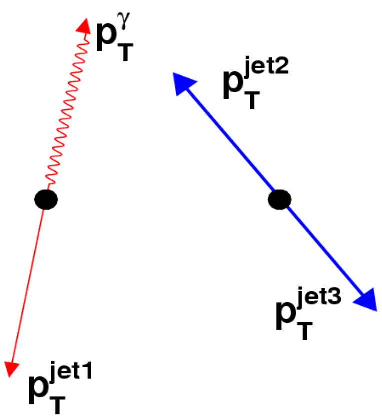
SP



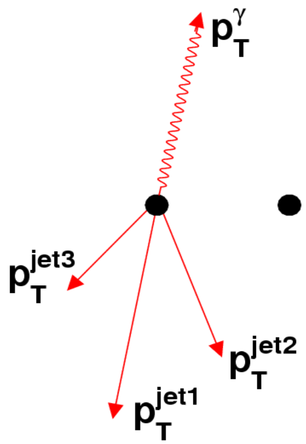
Signal: Double Parton (DP) production:
1st parton process produces γ-jet pair, while 2nd process produces dijet pair.

Background: Single Parton (SP) production:
single hard γ-jet scattering with 2 radiation jets in 1vertex events.

DI



SP



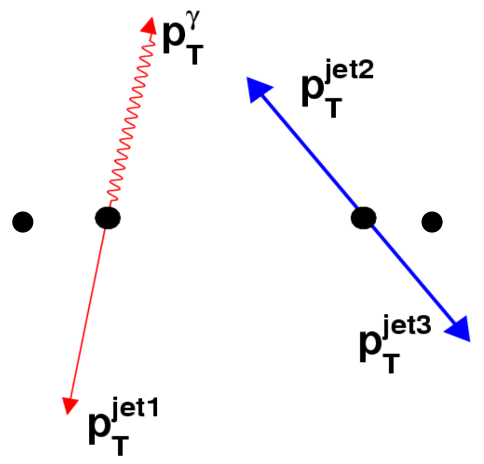
Background: Single Parton (SP) production:
single hard γ-jet scattering in one vertex with 2 radiation jets and soft unclustered energy in the 2nd vertex.

Signal: Double Interaction (DI) production:
two separate collisions within the same beam crossing, producing γ-jet and dijet pairs.

Double $p\bar{p}$ 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.

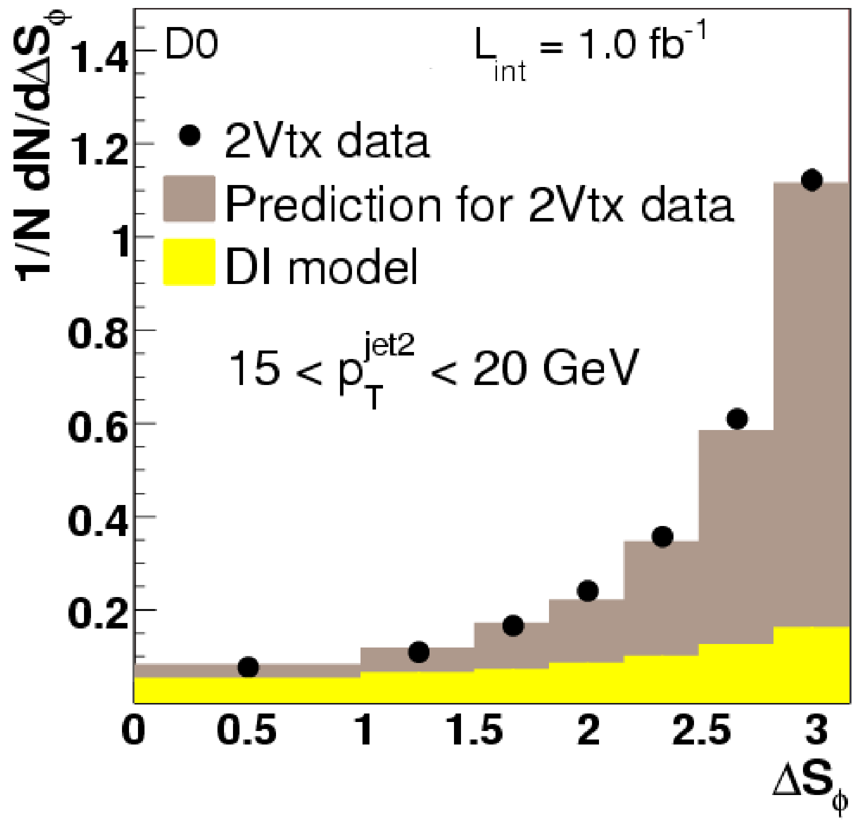
In case of 2 jets, both jets are required to originate from the same vertex using jet track information.

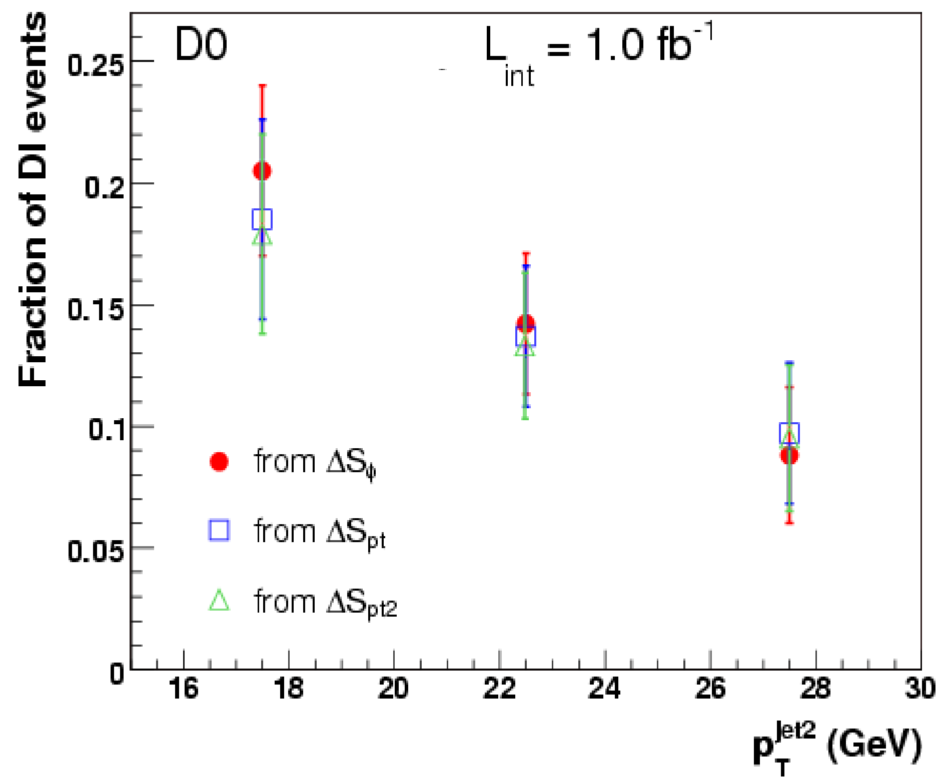


⇨ Main difference of Double Parton and Double $p\bar{p}$ Interaction signal events and corresponding SP backgrounds: different amount of soft unclustered energy in 1-vertex vs. 2-vertex events
→ different photon and jet ID efficiencies.

Fractions of Double $p\bar{p}$ Interactions (DI) events

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

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

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) $p\bar{p}$ cross section.

It is 44.7 ± 2.9 mb : from Run I → Run II extrapolation.

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

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.

Comparison of γ+3 jets measurements: CDF'97 vs. D0'09

- ✓ Center of mass energy : 1.8 → 1.96 TeV

- ✓ About a factor 60 increase in the integrated luminosity allows to change selections:
  photon pT > 16 GeV (CDF) → 60 < pT < 80 GeV (D0)
  ⇨ A better separation of 2 partonic scatterings in the momentum space
  ⇨ A higher photon purity (due to also tighter photon ID)
  ⇨ A better determination of energy scales of 1^{st} parton process

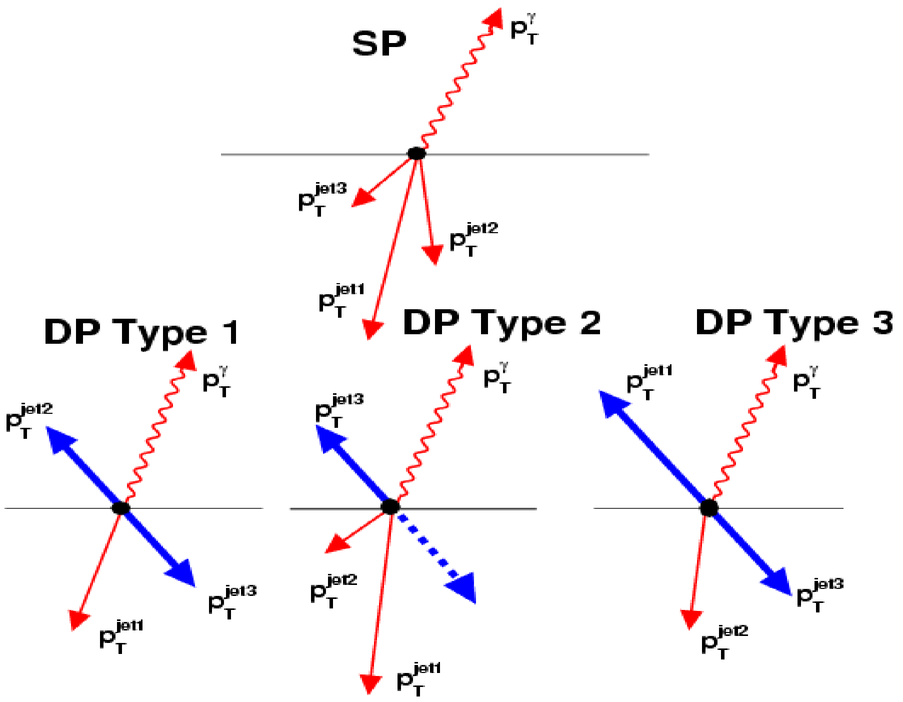
- ✓ Higher jet pTs and JES correction to the particle level
  Jet pT (uncorr.) > 6 GeV → pT (corr.) > 15 GeV

- ✓ Binning in the 2^{nd} jet pT : 15 - 20; 20 - 25, 25 – 30 GeV
  ⇨ A better determination of energy scales of 2^{nd} process
  ⇨ Study of Double Parton fractions and σ_{eff} vs. 2^{nd} jet pT

- ✓ Double Parton fractions and σ_{eff} are inclusive: we do not subtract fractions of events with triple parton (TP) interactions
  (TP fractions are presented as a separate result)

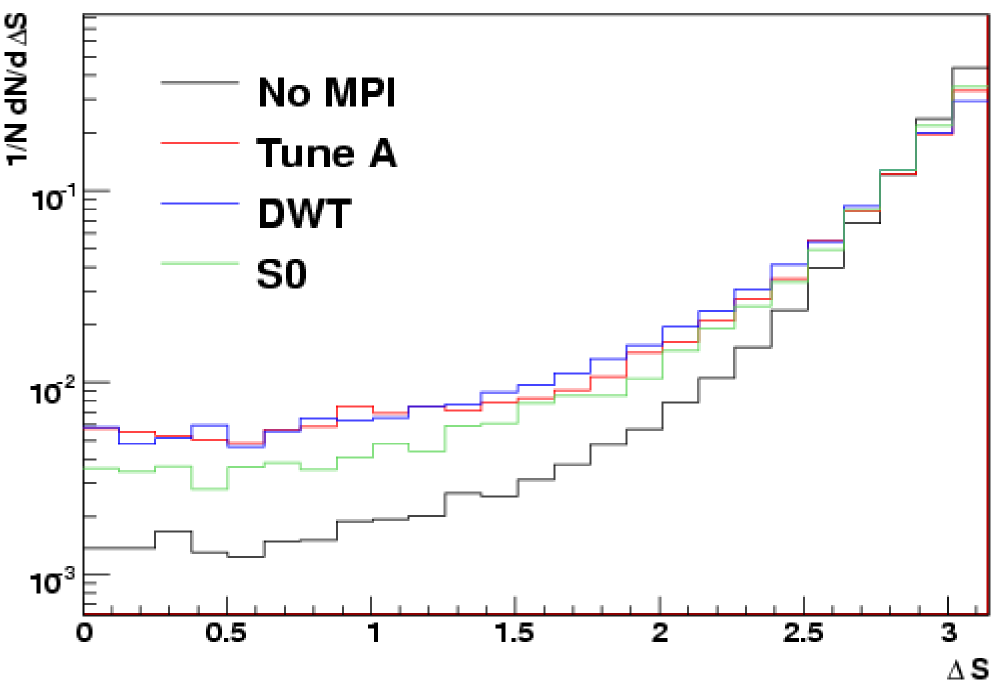
Types of DP events

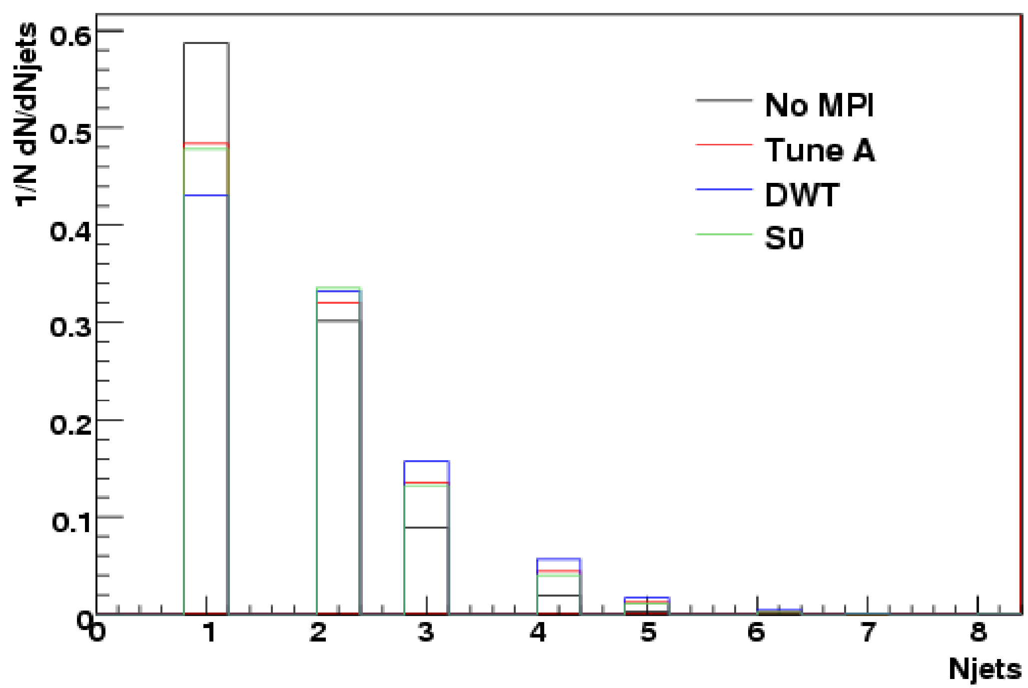
Event Types	p_T^{jet2} (GeV)		
	$15-20$	$20-25$	$25-30$
Type I	0.261	0.217	0.135
Type II	0.729	0.778	0.861
Type III	0.010	0.005	0.004



- Type II events (1 jet from dijet and 1 brems. jet) dominate (≥73%): It is caused by jet reco eff-cy and threshold (6 GeV for pT_raw) and difference in jet pT (it is smaller for dijets)
- CDF ('97) found at least 75% Type II events: a good agreement.
- Small fraction of Type III events.
- Dominance of Type II naturally reduces a dependence of results (see variable ΔS below) on possible issues with correlations between 1st & 2nd parton interactions.

Pythia MPI Tunes: ΔS and Njets

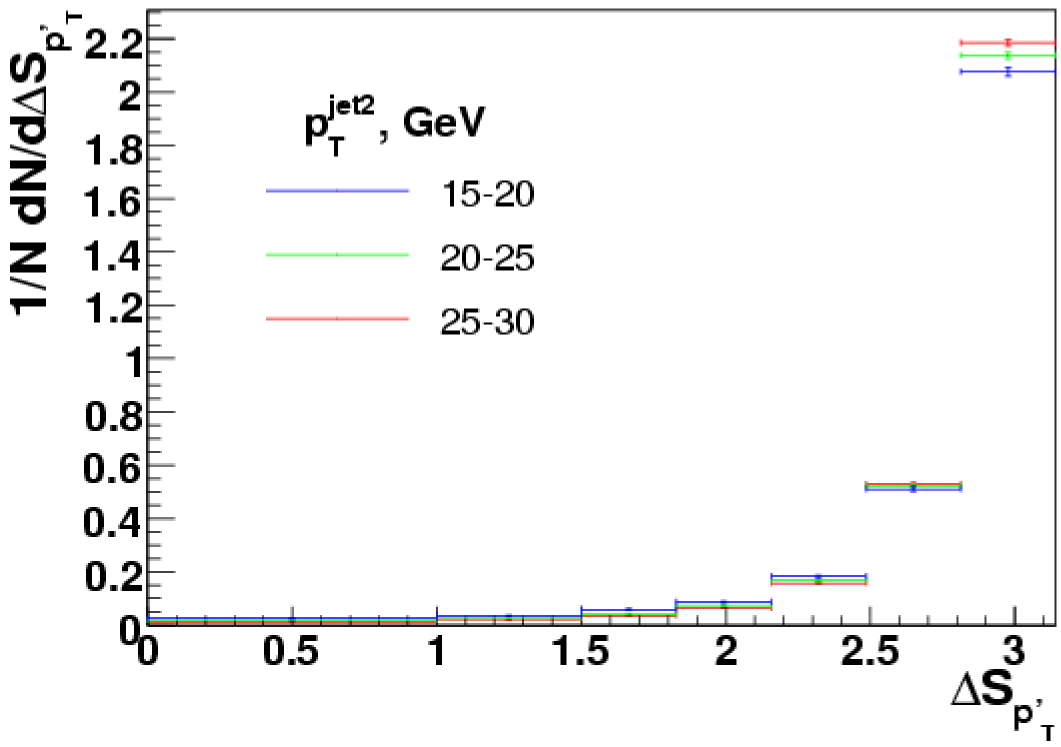


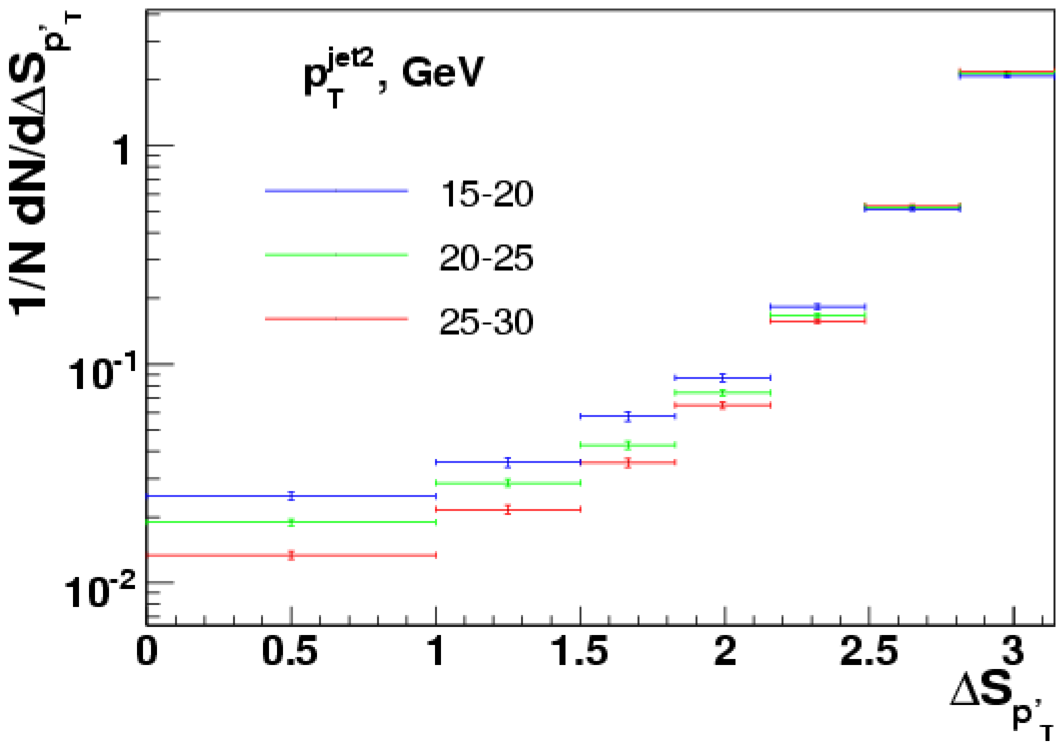


Pythia predictions with MPI tunes:

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

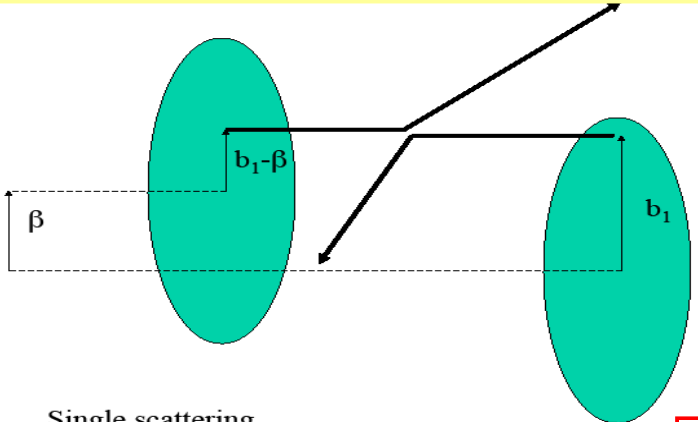
SP events (Pythia): ΔS distributions





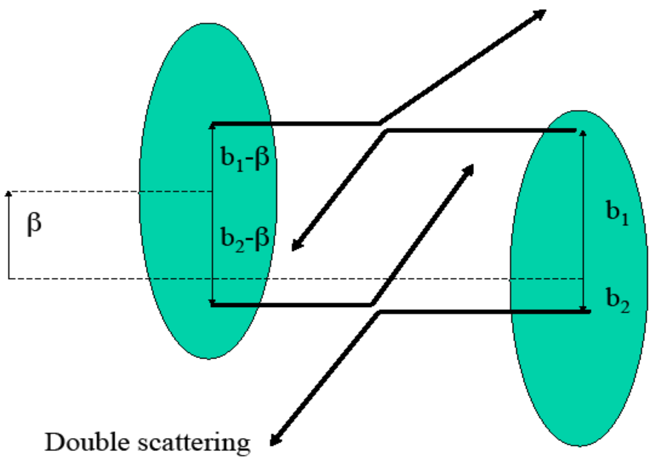
Parton spatial density and σ_{eff}

Introducing the 3D parton density $\Gamma(x,b)$ and making the assumption $\Gamma(x,b)=G(x)f(b)$ one may express the single scattering inclusive cross section as



Single scattering

$$\sigma_S = \int_{p_t^c} G(x)\hat{\sigma}(x,x')G(x')dxdx'$$
$$= \int_{p_t^c} G(x)f(b)\hat{\sigma}(x,x')G(x')f(b-\beta)d^2bdxdx'd^2\beta$$



Double scattering

$$\sigma_D = \frac{1}{2!}\int_{p_t^c} G(x_1)f(b_1)\hat{\sigma}(x_1,x_1')G(x_1')f(b_1-\beta)d^2b_1dx_1dx_1' \times$$
$$\times G(x_2)f(b_2)\hat{\sigma}(x_2,x_2')G(x_2')f(b_2-\beta)d^2b_2dx_2dx_2'd^2\beta$$
$$= \frac{1}{2!}\int\Big(\int_{p_t^c} G(x)f(b)\hat{\sigma}(x,x')G(x')f(b-\beta)d^2bdxdx'\Big)^2 d^2\beta$$
$$= \frac{1}{2}\frac{\sigma_S^2}{\sigma_{eff}}$$

where $\sigma_{eff}^{-1} = \int d^2\beta\big[F(\beta)\big]^2$ is effective cross section

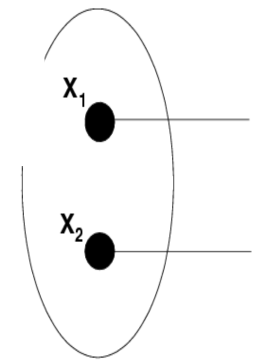
$$F(\beta) = \int f(b)f(b-\beta)d^2b,$$

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

PDF correlation vs. factorisation (1)

DP cross section: $\sigma^D_{(A,B)} = \frac{m}{2} \sum_{i,j,k,l} \int \Gamma_{ij}(x_1, x_2, b; Q_1^2, Q_2^2) \hat{\sigma}^A_{ik}(x_1, x_1') \hat{\sigma}^B_{jl}(x_2, x_2')$

$$\times \Gamma_{kl}(x_1', x_2', b; Q_1^2, Q_2^2) dx_1 dx_2 dx_1' dx_2' d^2b.$$



Generalized 2-parton distributions: $\Gamma_{ij}(x_1, x_2, b; Q_1^2, Q_2^2) = D_h^{ij}(x_1, x_2; Q_1^2, Q_2^2) F_{ij}(b).$

b – distance between two partons in the transverse plane
$F_{ij}(b)$ – parton spatial density functions

2-parton momentum density function $D_h^{ij}(x_1, x_2; Q_1^2, Q_2^2) = D_h^i(x_1, Q_1^2) D_h^j(x_2, Q_2^2).$

← Factorization assumption (used in the meas.)

⇩

$$\sigma^D_{(A,B)} = \frac{m}{2} \frac{\sigma^S_{(A)} \sigma^S_{(B)}}{\sigma_{\text{eff}}},$$

$F_{ij}(b)$ is also assumed to be same for partons of types i and j

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

Selection criteria for γ+3jet events

PHOTON:

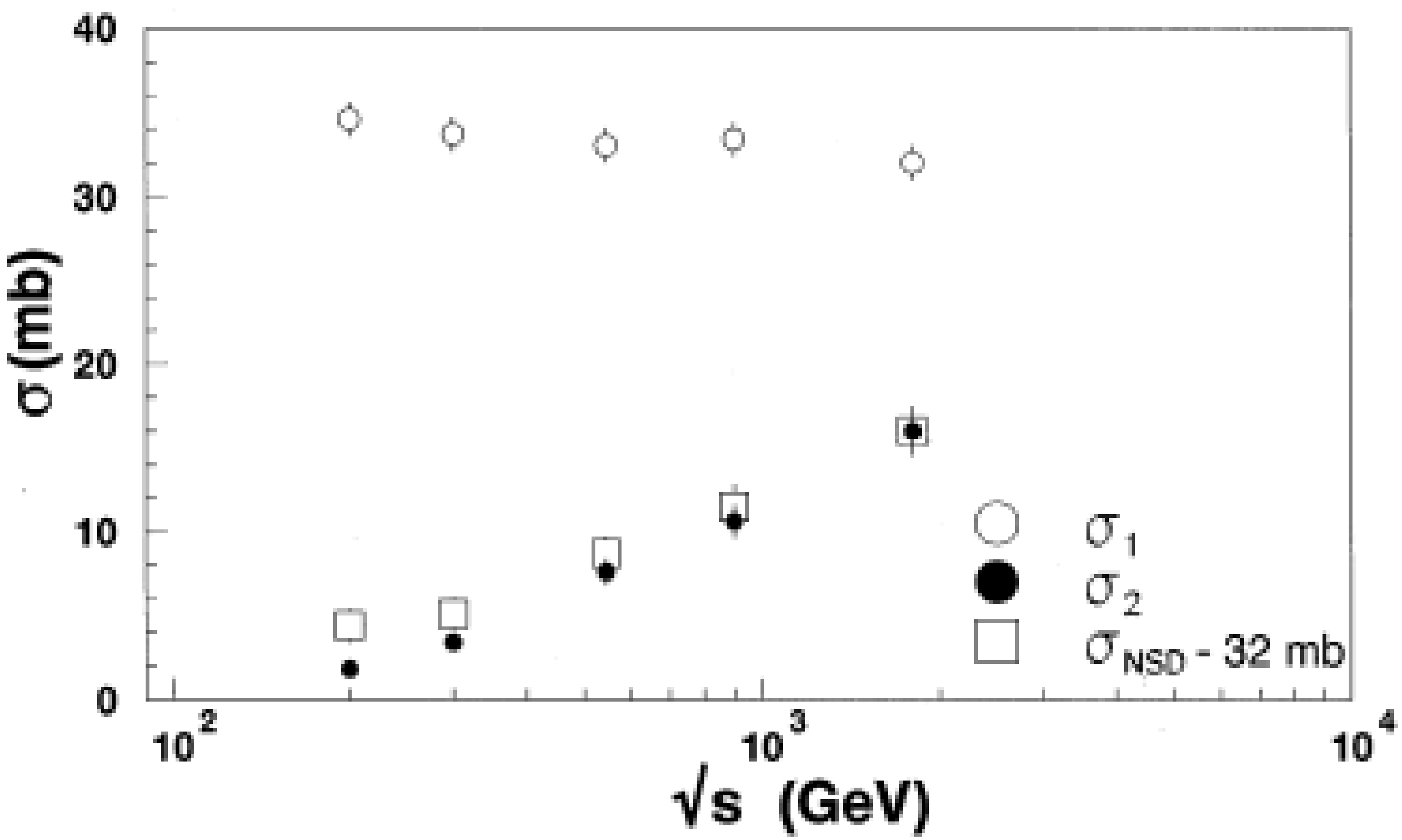
- photons with $|\eta|<1.0$ and $1.5<|\eta|< 2.5$
- $60< pT< 80$ GeV (good separation of 1st and 2nd parton interactions)
- Shower shape cuts
- Calo isolation ($0.2< dR <0.4$) < 0.07
- Track isolation ($0.05< dR <0.4$) < 1.5 GeV
- Track matching probability < 0.001

JETS (pT corrected):

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

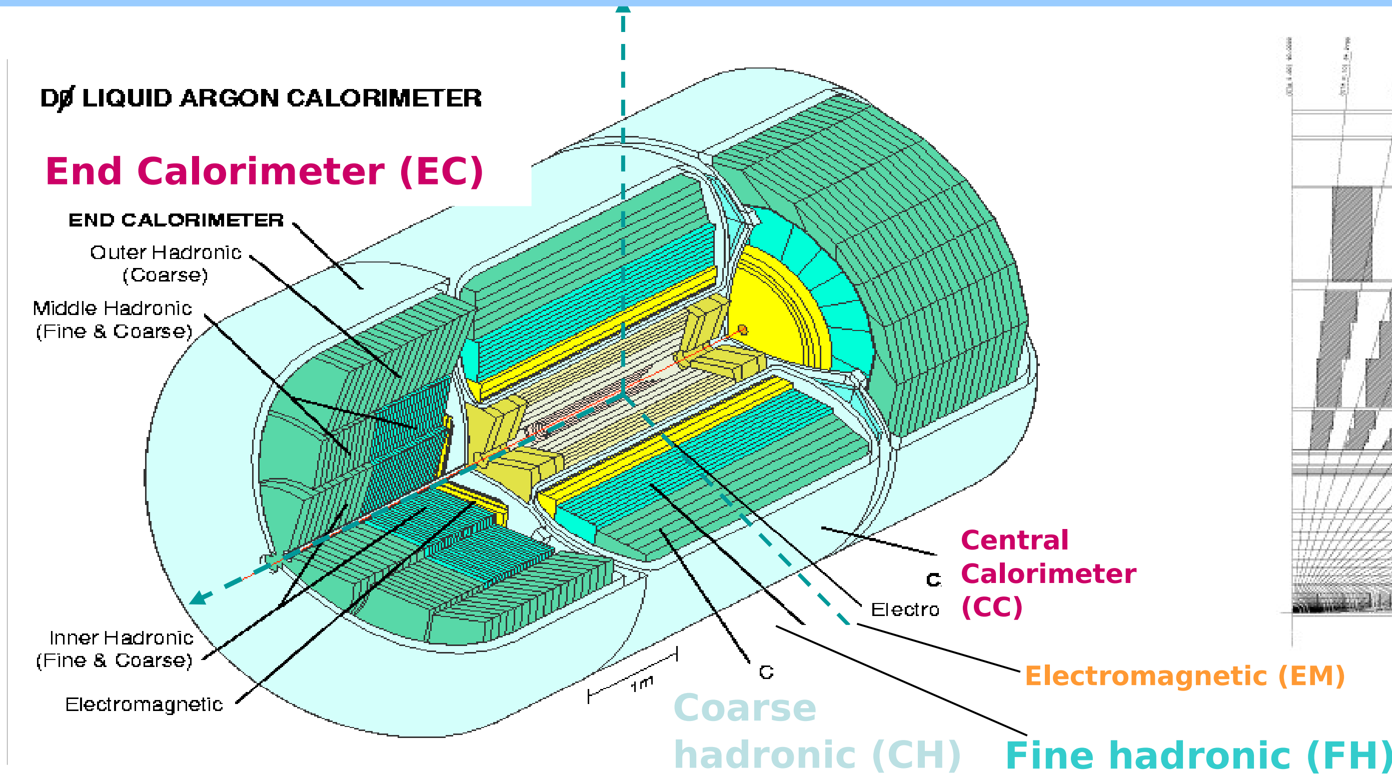
- ΔR(any objects pair)>0.9

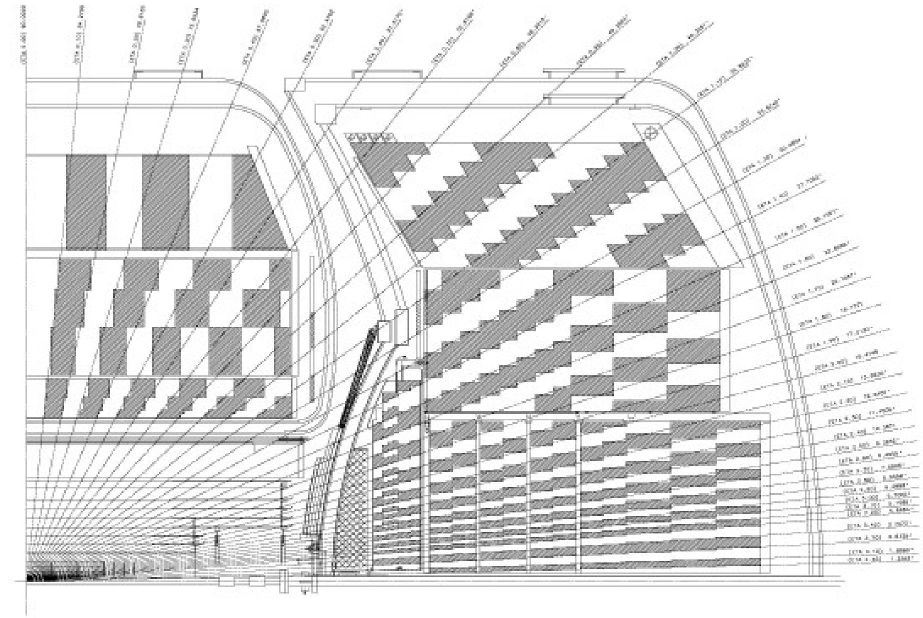
From: PLB 435 (1998) 453, E735 Collaboration



A comparison of the cross sections for single and double encounter process with increase in sigma_NSD above its minimum of about 32 mb, as a function of Sqrt(s).

Overview of the calorimeter





46000 channels

50 non-working channels

- ✓ Liquid argon active medium and (mostly) uranium absorber
- ✓ Hermetic with full coverage : $|\eta| < 4.2$
- ✓ Segmentation (towers): $\Delta\eta \times \Delta\Phi = 0.1 \times 0.1$ (0.05x0.05 in 3rd EM layer)
- ✓ Three main subregions: Central ($|\eta|<1.1$), Intercryostat ($1.1<|\eta|<1.5$) and End calorimeters ($1.5 < |\eta| < 4.2$)
- ✓ Stable response, good resolution