Probing the Nucleon Structure with Multiple Parton Interactions at D0

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on behalf of the DØ Collaboration

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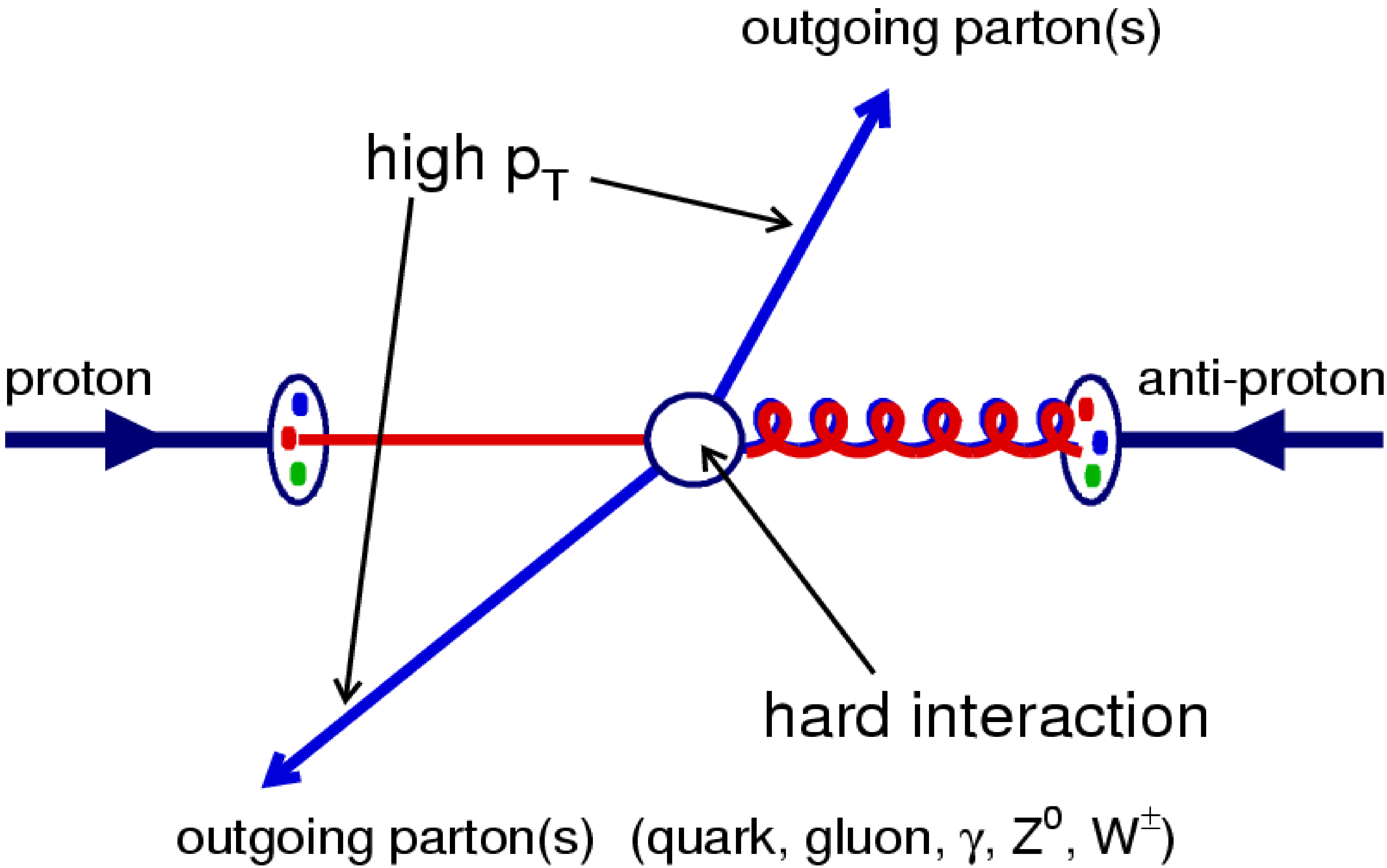
Outline

- Some history and experimental tests
- Double Parton interactions in γ+b/c+dijet and γ+3-jet events
- Double Parton interaction in double J/ψ events
- Summary

Hadron-Hadron Collision



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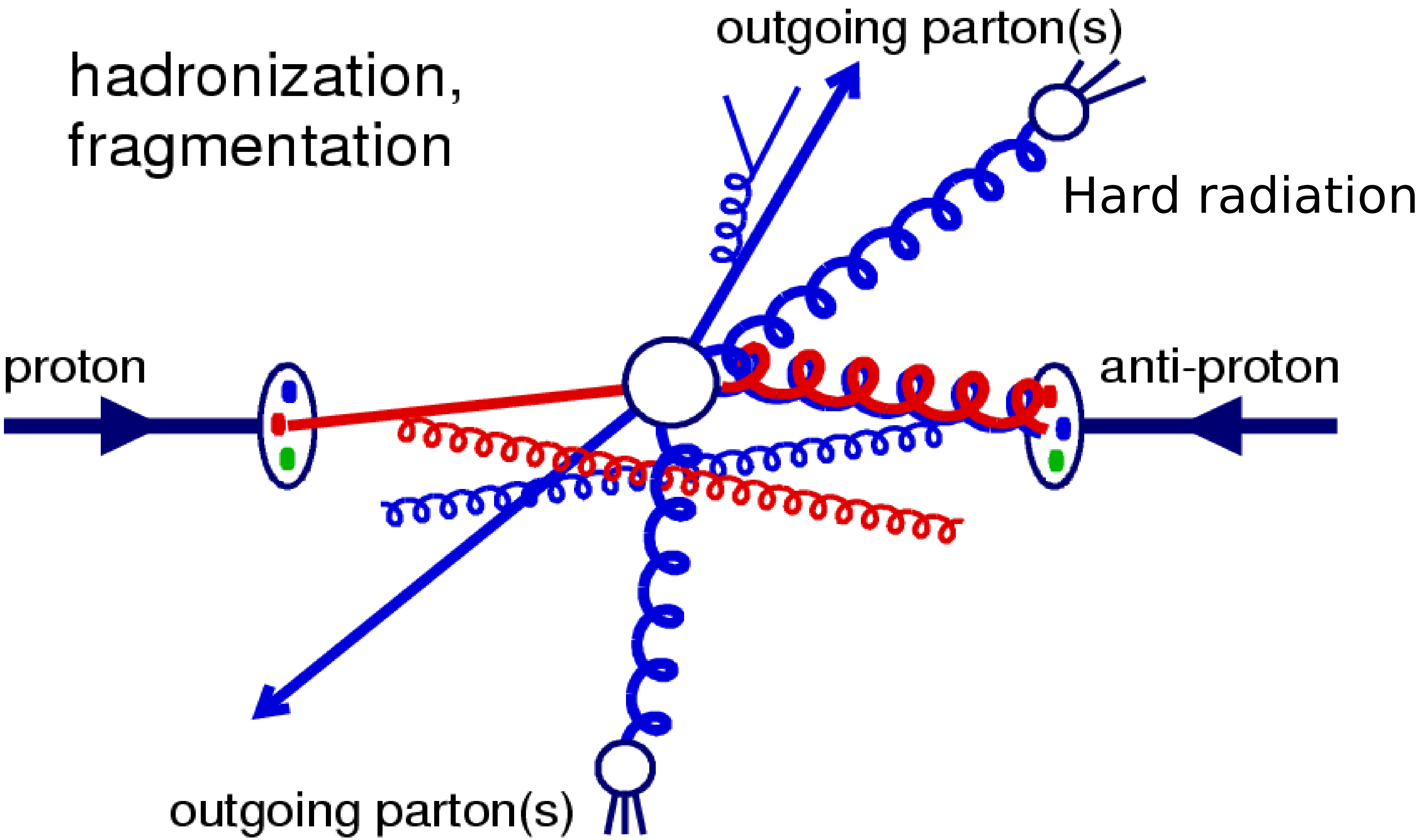
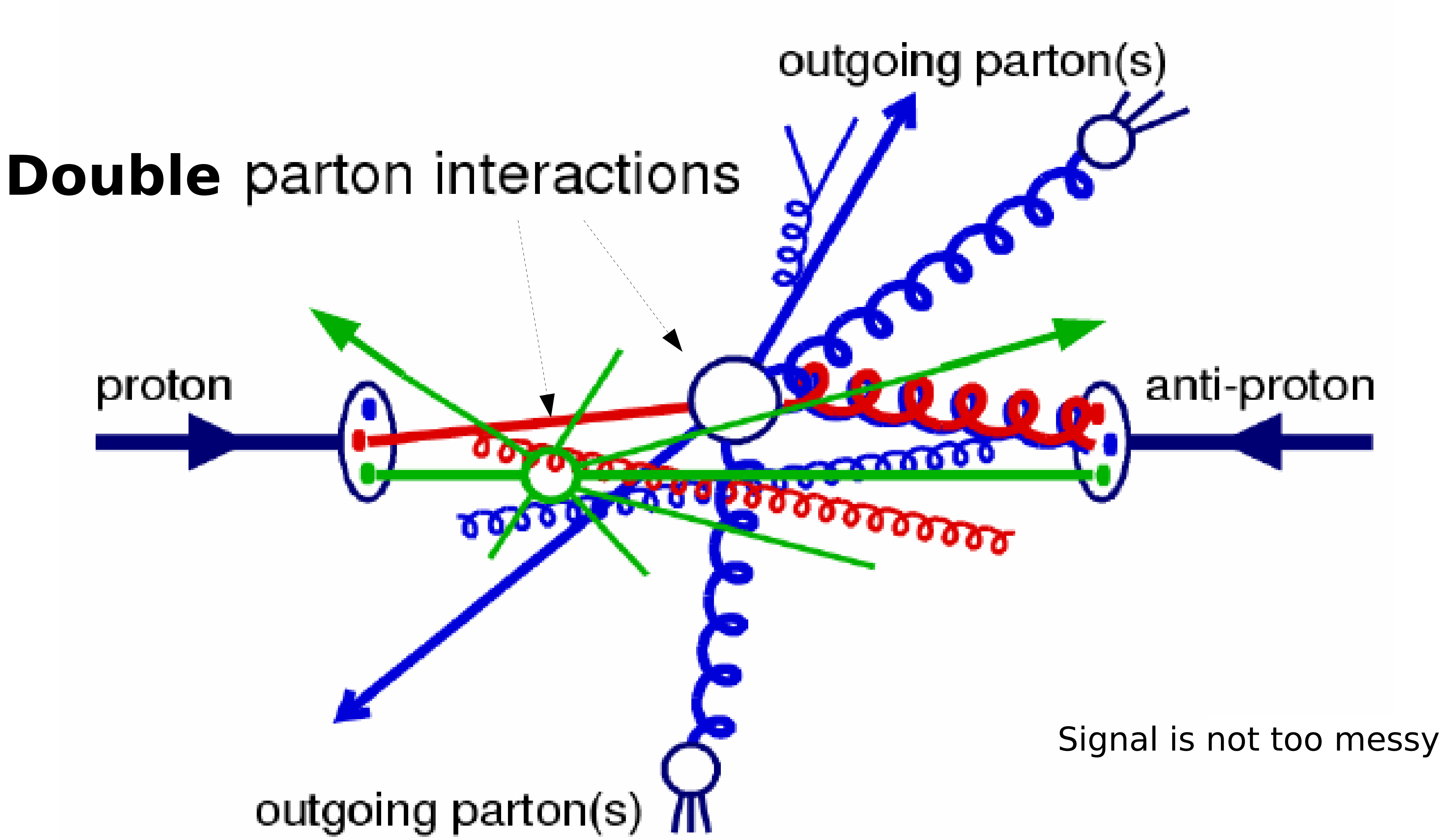


Hadron-Hadron Collision: from Single to Double parton interactions



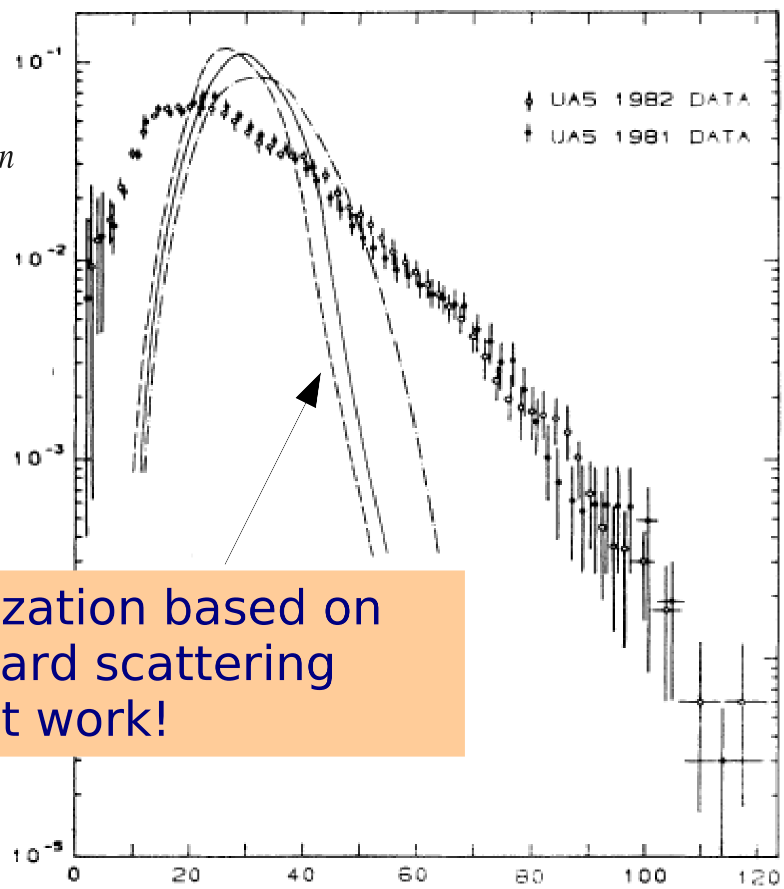
Signal is not too messy

Experimental tests (1)

Charged particle multiplicity

UA5, 540 GeV, ppbar

Hard scattering only; +ISR/FSR

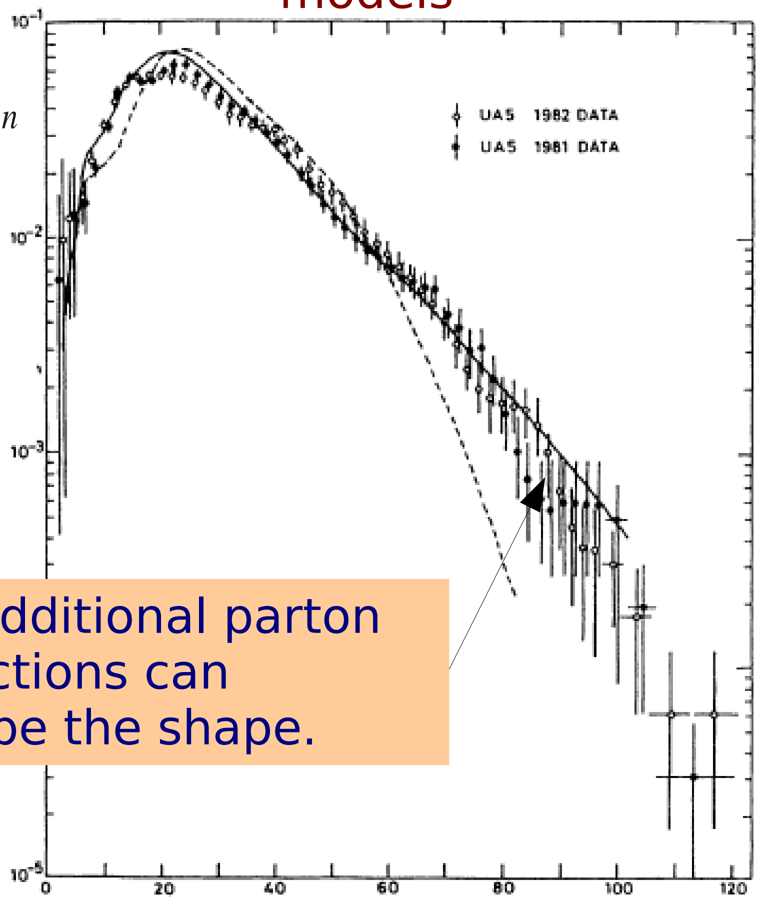


$\sigma_n / \sum \sigma_n$

Nch

Hadronization based on single hard scattering does not work!

Multiple Parton Interaction models



$\sigma_n / \sum \sigma_n$

Nch

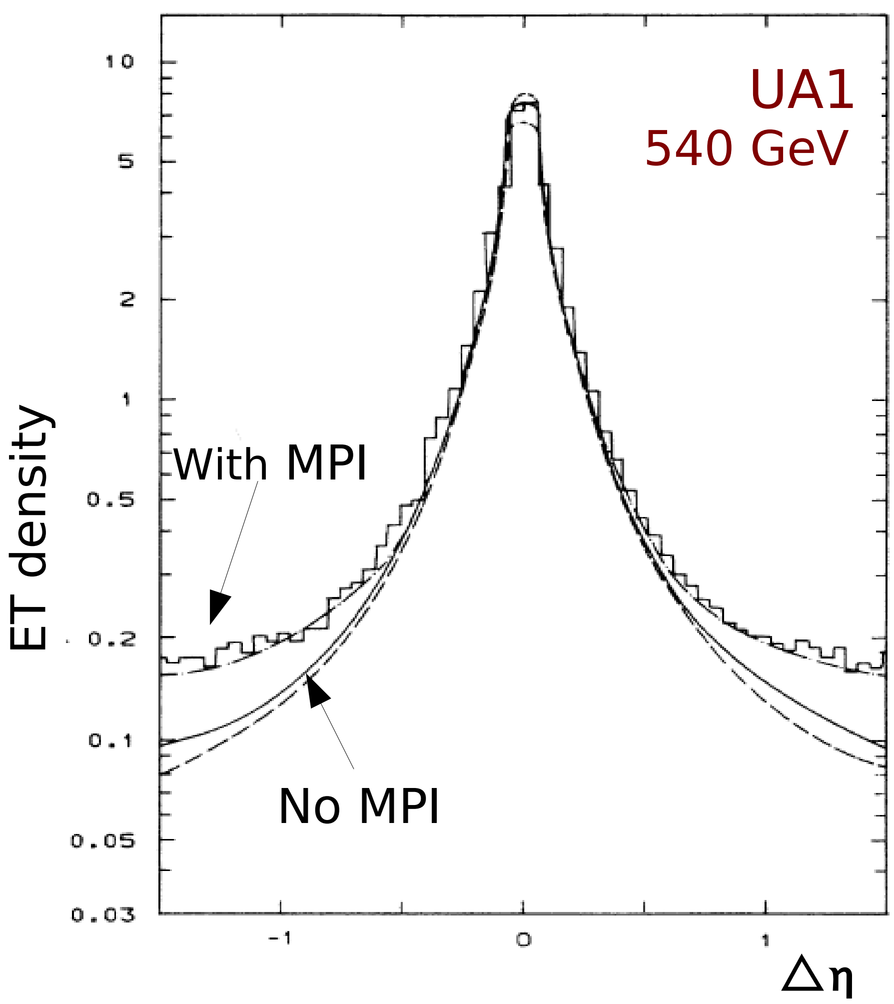
Only additional parton interactions can describe the shape.

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

Experimental tests (2)

Jet pedestal effect

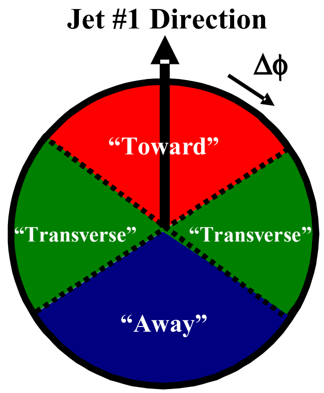
Jet pT>35 GeV



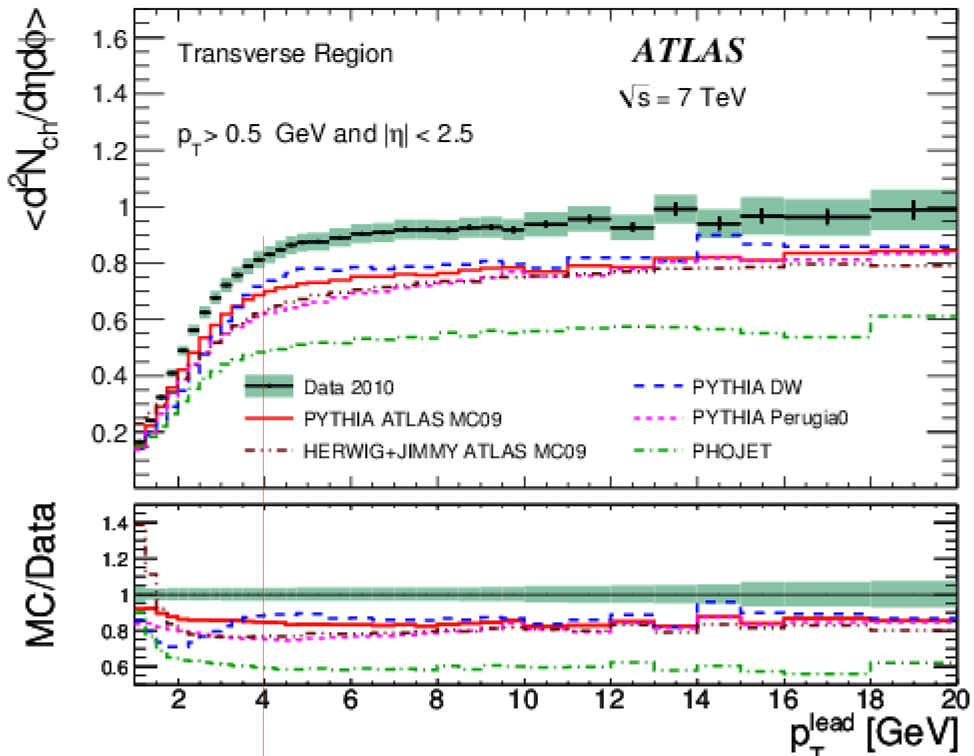
ET density distribution inside and around jet can only be described if MPI contribution is taken into account.

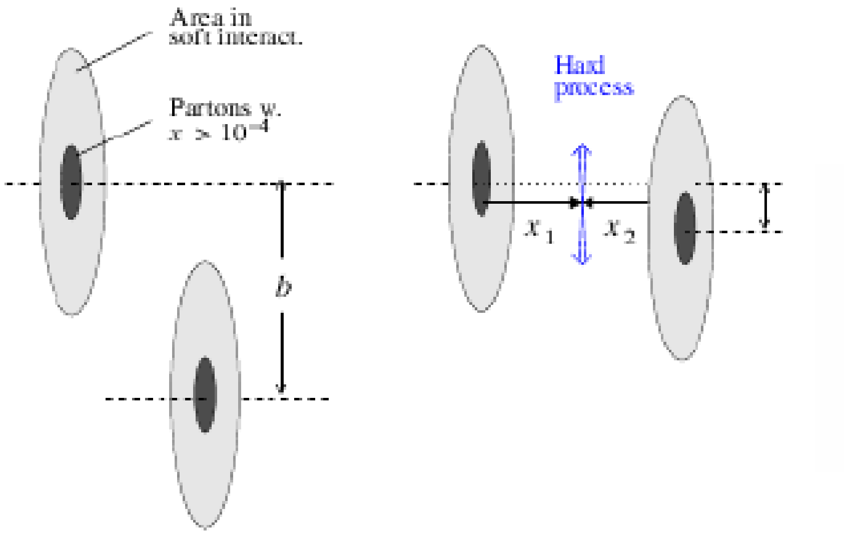
ET density and charge particle multiplicities allowed T.Sjostrand and M.van Zijl to build first real, software-implemented MPI model (aka “Tune A”) and describe many “puzzling features” in jet productions in UA1-UA5: PRD36 (1987)2019

Experimental tests (3)



Charged particle density in the "transverse region"



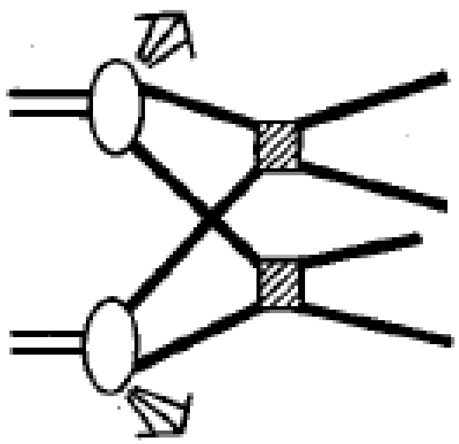


Events from hard collision

- Presence of high pT 1st interaction biases events towards smaller p-pbar impact parameters and hence leads to a higher additional activity in the transverse region.
- The height of the pedestal depends on the overlap, i.e. on the parton matter distribution function (see eg. R.Field's studies at Tevatron and LHC)

Double Parton Interactions
in γ+3 and γ+b/c+dijet events:
from low pT to high pT in MPI studies

- New motivations and prospects
- New effects



Motivations

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

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

- The provided experimental inputs have been based so far mainly on the minbias Tevatron (0.63, 1.8, 1.96 TeV; + recent 0.3, 0.9 runs), SPS (0.2, 0.54, 0.9 TeV), Tevatron DY and similar LHC data.

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

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

=> i.e. right in the region of interest of many measurements (e.g. top-quark mass)

=> in the energy regime of perturbative QCD!

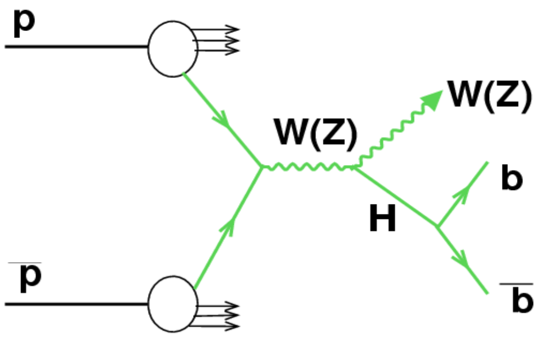
Having measured MPI observable and reliably calculable partonic cross section, one can limit MPI phenomenological models.

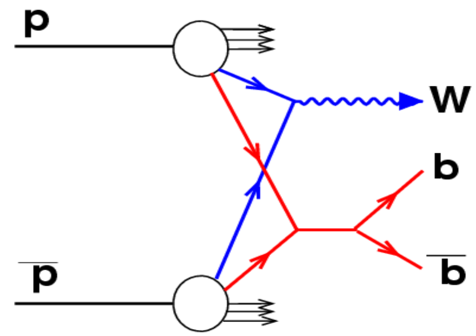
=> MPI events can mimic a signature of a new physics processes and thus be a significant background to them.

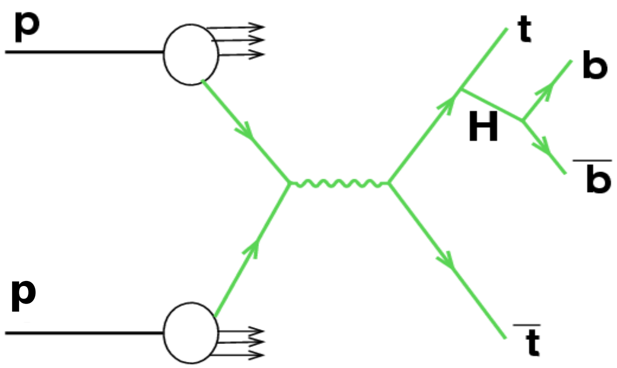
Double Parton events as a background to Higgs production

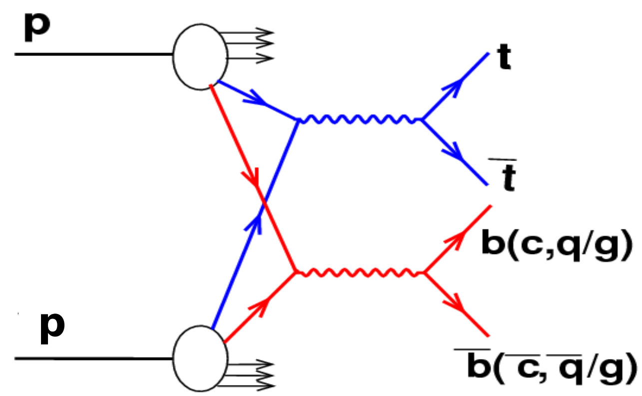
SP Signal

DP background





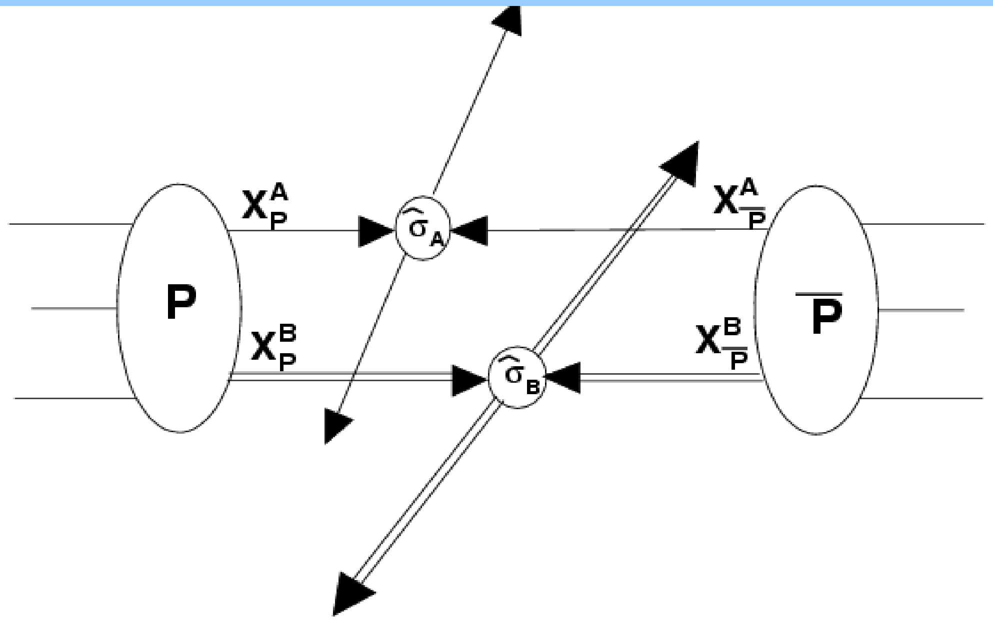




- Many Higgs production channels can be mimicked by Double Parton event!
- Same is true for many other rare (especially multijet) processes

Double parton and effective cross sections

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



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

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

→ contains information on the spatial distribution of partons.

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

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

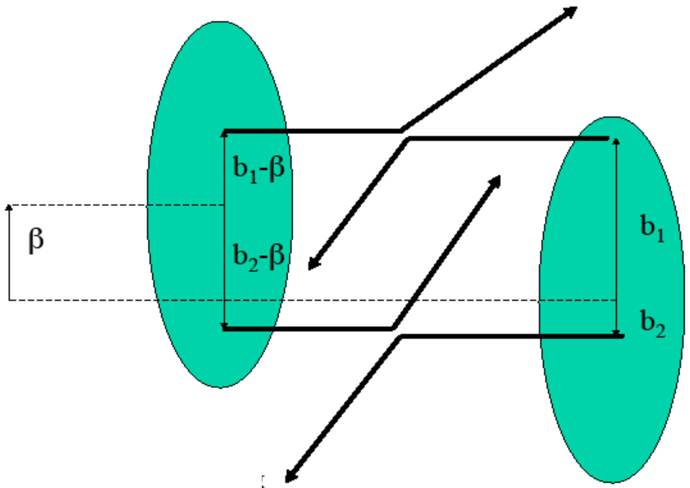
→ σ_{eff} is phenomenological parameter

=> should be measured in experiment !

Parton spatial density and σeff

Double parton cross section

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



Double parton scattering

Effective cross section σeff is directly related with parton spatial density:

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

β is impact parameter

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

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

=> Having σeff measured we can estimate f(b)

Models of parton spatial density and σ_{eff}

From Phys.Rev.D81, 052012 (2010): "DP in γ+3 jet events in ppbar collisions"
(WC seminar, Dec 13, 2009)

D0
1 fb^{-1}

- σ_{eff} is directly related with parameters of models of parton spatial density

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

Example: Gaussian spatial density:

$$F(\beta) = (4\pi a^2)^{-1} \exp(-\beta^2/2a^2) \quad => \quad \sigma_{eff} = 8\pi a^2$$

– 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

History of the measurements

	$\sqrt{s}$ (GeV)	final state	p_T^{cut} (GeV)	η range	σ_{eff}
AFS [11]	63	4 jets	$p_T^{jet} > 4$	$\lvert\eta^{jet}\rvert < 1$	≈ 5 mb
UA2 [12]	630	4 jets	$p_T^{jet} > 15$	$\lvert\eta^{jet}\rvert < 2$	> 8.3 mb (95% C.L.)
CDF [13]	1800	4 jets	$p_T^{jet} > 25$	$\lvert\eta^{jet}\rvert < 3.5$	$12.1^{+10.7}_{-5.4}$ mb
CDF [14]	1800	$\gamma + 3$ jets	$p_T^{jet} > 6$ $p_T^{\gamma} > 16$	$\lvert\eta^{jet}\rvert < 3.5$ $\lvert\eta^{\gamma}\rvert < 0.9$	$14.5 \pm 1.7\,(\text{stat})\ ^{+1.7}_{-2.3}\,(\text{syst})$ mb
D0 [15]	1960	$\gamma + 3$ jets	$60 < p_T^{\gamma} < 80$ $p_T^{jet} > 15$	$\lvert\eta^{\gamma}\rvert < 1.0$ $1.5 < \lvert\eta^{\gamma}\rvert < 2.5$	$16.4 \pm 0.3\,(\text{stat}) \pm 2.3\,(\text{syst})$ mb
ATLAS [17]	7000	$W + 2$ jets	$p_T^{jet} > 20$	$\lvert\eta^{jet}\rvert < 2.8$	$15 \pm 3\,(\text{stat})\ ^{+5}_{-3}\,(\text{syst})$ mb
CMS [18]	7000	$W + 2$ jets	$p_T^{jet} > 20$	$\lvert\eta^{jet}\rvert < 2.0$	$20.7 \pm 0.8\,(\text{stat}) \pm 6.6\,(\text{syst})$ mb

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DP frac

5-8%

53%

22-47%

6-10%

¿

AFS'86, UA2'91 and CDF'93

4-jet samples, motivated by a large dijet cross section (but low DP fractions)
Use theory predictions for the dijet cross sections.

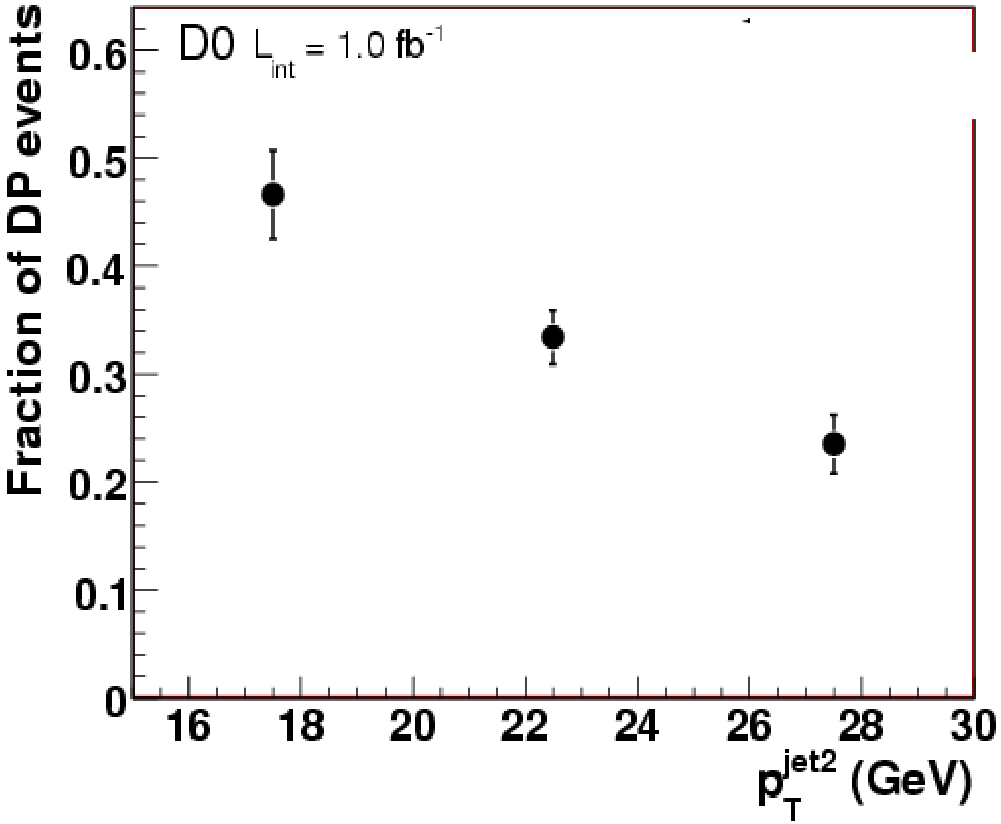
CDF’97, D0’10

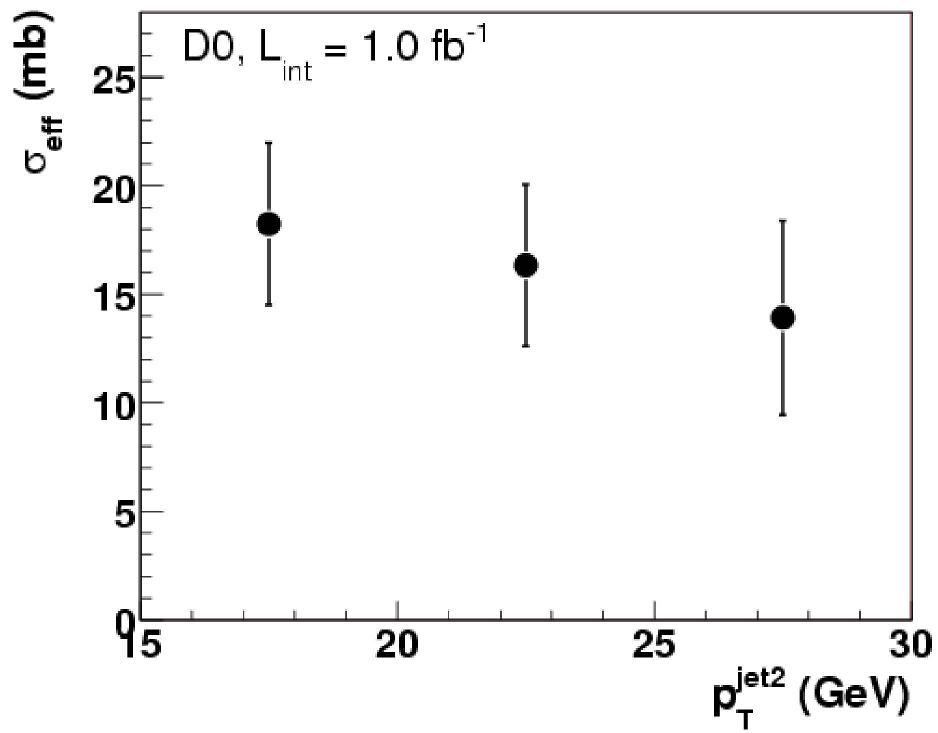
γ+3jets events, data-driven method: use rates of Double Interaction events (two separate ppbar collisions) and Double Parton (single ppbar collision) events to extract σ_{eff} from their ratio.

Double Parton fractions and σ_{eff}

D0
1 fb^{-1}

From Phys.Rev.D81, 052012 (2010): "DP in γ+3 jet events in ppbar collisions"
(WC seminar, Dec 13, 2009)



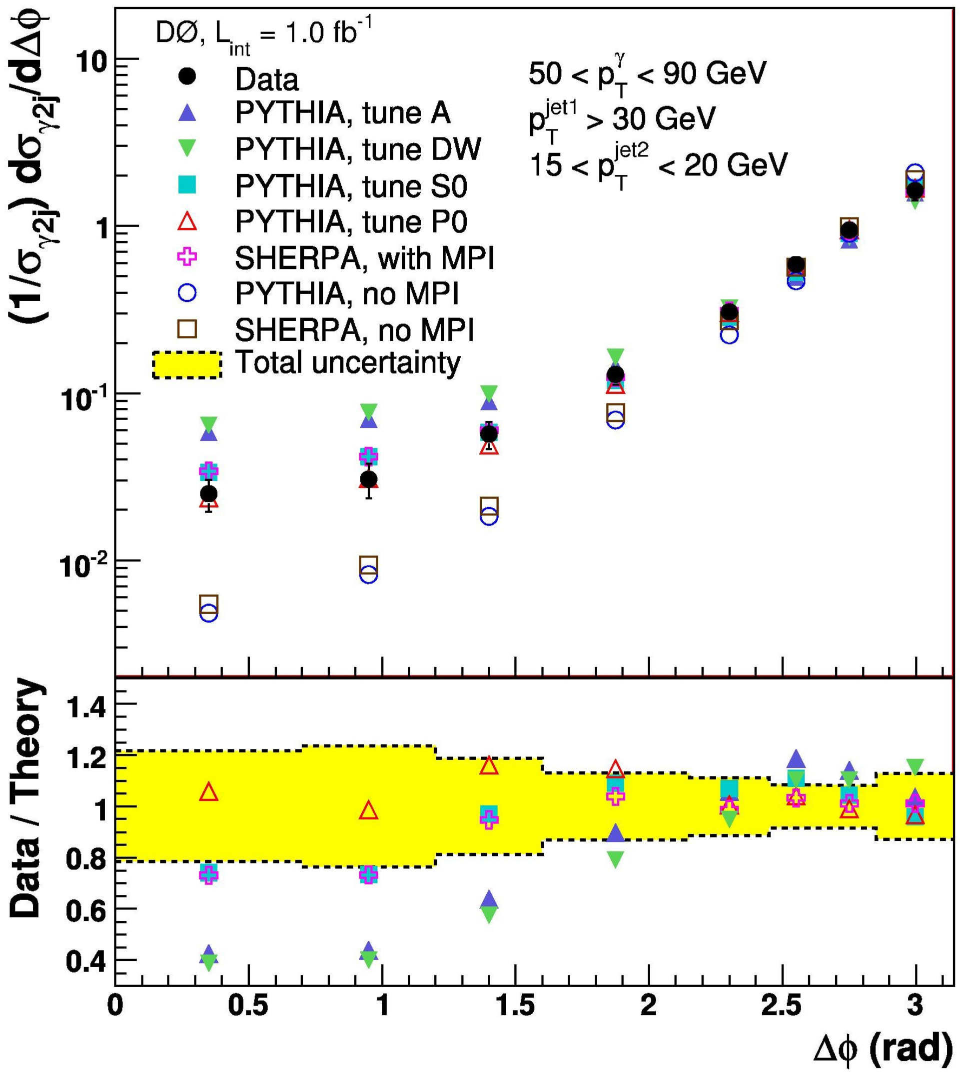


Found DP fractions are pretty sizable: they drop from ~46-48% at 2nd jet pT 15-20 GeV to ~22-23% at 2nd jet 25-30 GeV with relative uncertainties ~7-12%.

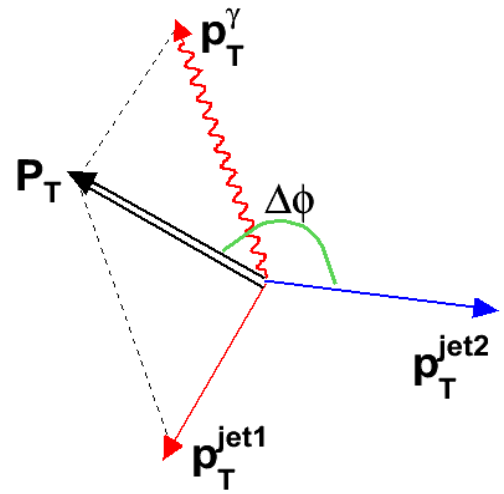
$$\sigma_{eff}^{ave} = 16.4 \pm 0.3(stat) \pm 2.3(syst)\, mb$$

Tuning MPI models

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



Using azimuthal angle between pT imbalance vector in the 1st parton scattering and 2nd jet, and different 2nd jet pT bins, we can tune MPI models.

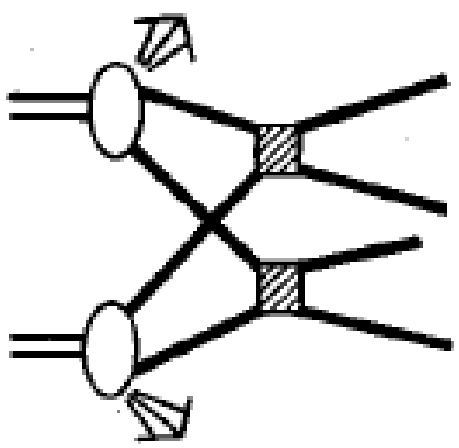


χ^2 test for MPI models

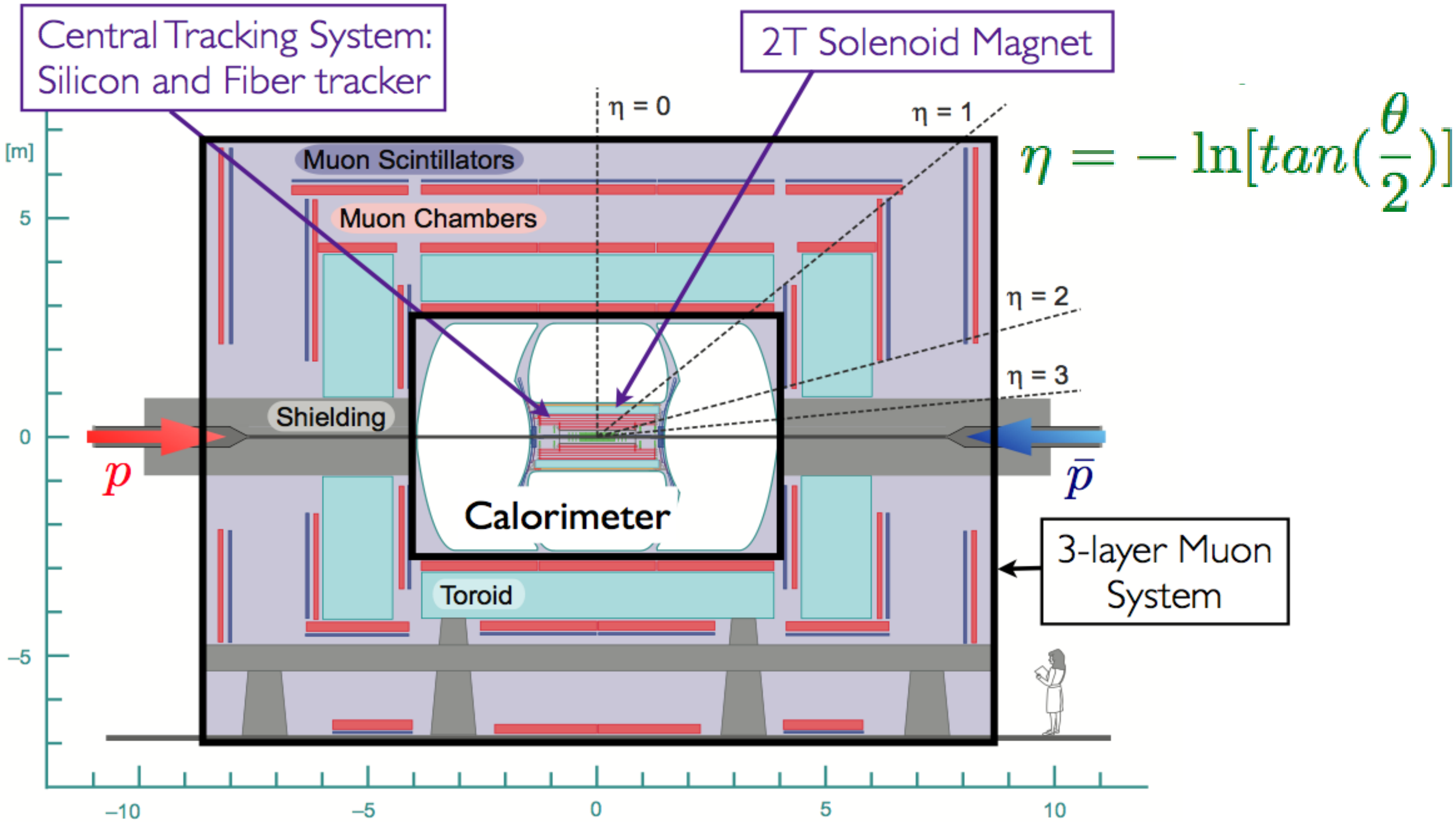
Variable	p_T^{jet2} (GeV)	SP model PYTHIA	SP model SHERPA	MPI model A	DW	S0	P0	P-nocr	P-soft	P-hard	P-6	P-X	SHERPA
ΔS	15 – 30	10.9	11.3	31.0	42.9	3.4	0.4	0.5	4.9	0.9	0.5	0.4	2.6
$\Delta\phi$	15 – 20	30.2	26.0	40.7	61.1	2.2	0.9	1.6	1.5	1.2	1.2	1.0	2.4
$\Delta\phi$	20 – 25	15.4	12.1	6.8	18.0	1.0	1.8	2.7	1.7	1.5	2.5	2.4	0.6
$\Delta\phi$	25 – 30	7.1	5.3	1.3	5.6	1.6	1.1	1.0	2.1	0.3	1.4	1.6	0.5

Double Parton Interactions
in γ+3 and γ+b/c+dijet events:

- Extraction of DP events
- Measurement of effective cross section



D0 detector

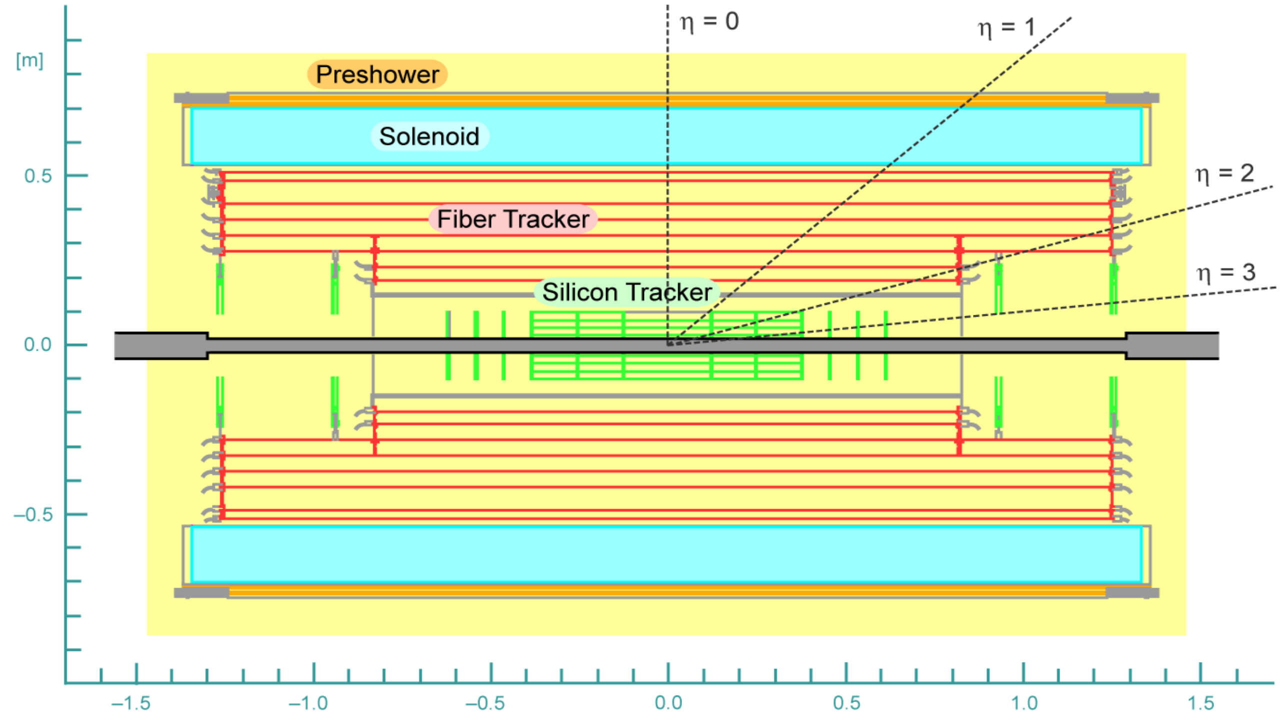


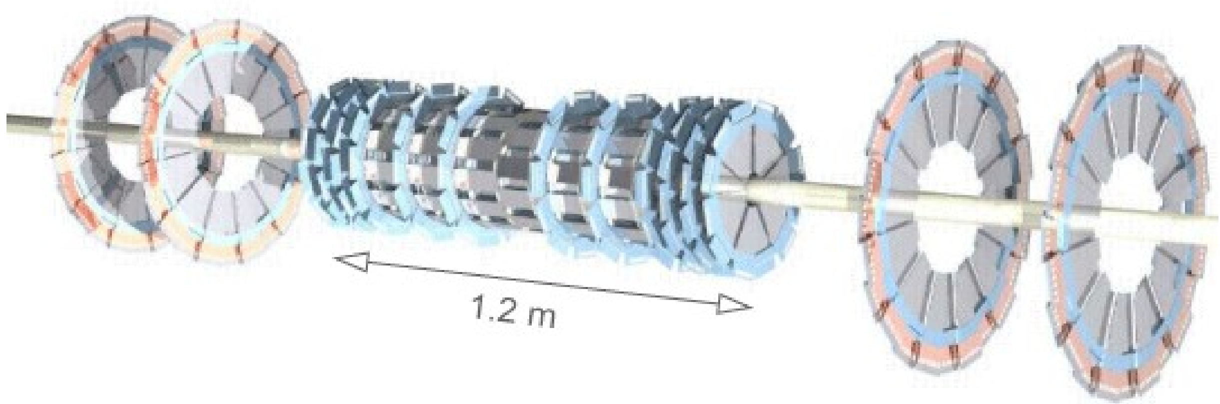
- Tracking in magnetic field of 2T:
  - Silicon microstrip and central fiber tracker
- Calorimeter: Liquid argon sampling calorimeter
  - Central and Endcap, coverage : |η|<4.2
- Muon system: Drift chambers and scintillation counters,1.8 T toroid

  Wide muon system coverage (|η|<2); thick shielding suppresses background.

D0 detector: Tracker

- Important for heavy flavor jet identification
- Precise reconstruction of primary interaction vertex and secondary vertices
- Accurate determination of impact parameter of tracks



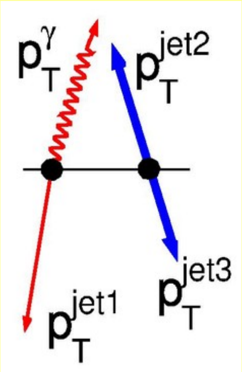


Measurement of σ_{eff}

Same approach as in $1fb^{-1}$ measurement, PRD81, 052012 (2010)

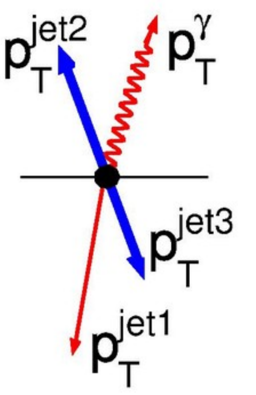
For two hard scattering events at two separate $p\bar{p}$ collisions (Double Interaction):

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



For two hard interactions at one $p\bar{p}$ collision (Double Parton scattering)

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



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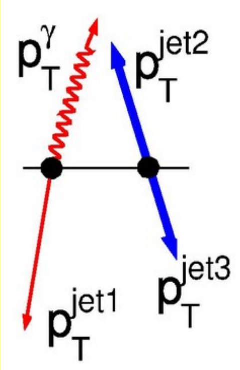

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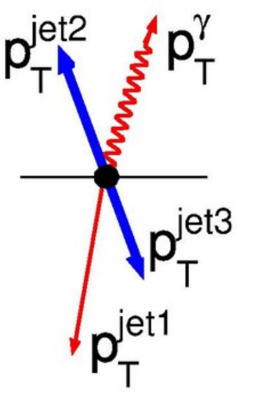


NB: with same kinematic cuts, γ+jet and dijet cross sections are same for Double Interaction and Double Parton events.

Therefore σ_{eff} can be extracted from P_{DP}/P_{DI} ratio:

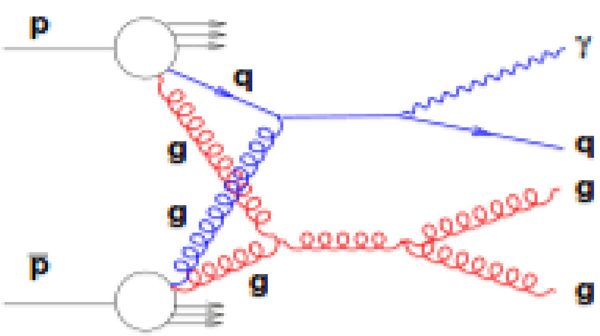
=> Data-driven method
=> reduces dependence on Monte-Carlo and NLO QCD theory predictions.

Selection criteria

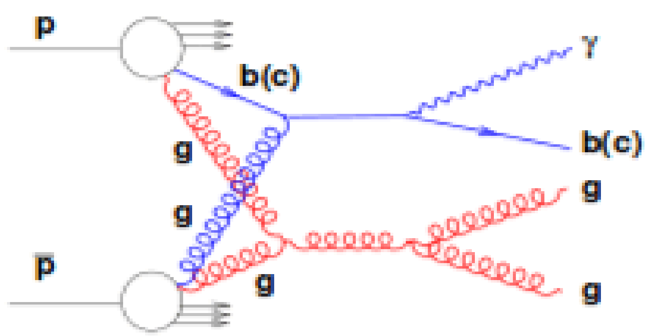
D0
8.7 fb^{-1}

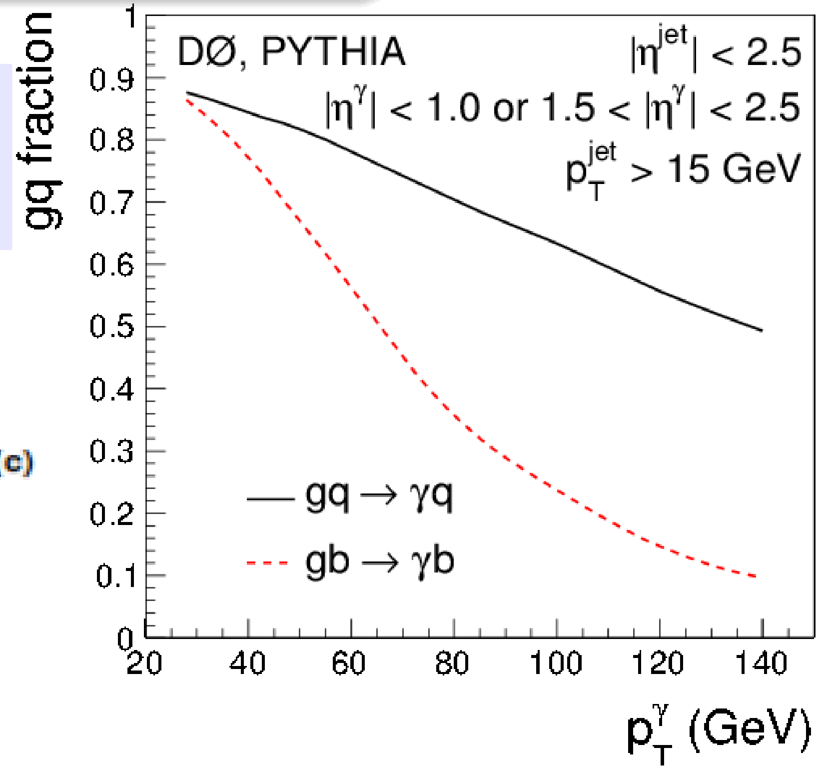
- Photon: $p_T^{\gamma} > 26$ GeV, $|\eta| < 1.0$ or $1.5 < |\eta| < 2.5$
- At least 3 jets with $p_T^{jet} > 15$ GeV and $|\eta| < 2.5$
  $15 < p_T^{jet2} < 35$ GeV
- Topology: $\Delta R(\gamma, jet) > 0.7$, $\Delta R(jet, jet) > 1.0$

Case 1: No leading jet flavor requirement (Inclusive sampe)



Case 2: Leading jet Heavy flavor requirement (HF sample)



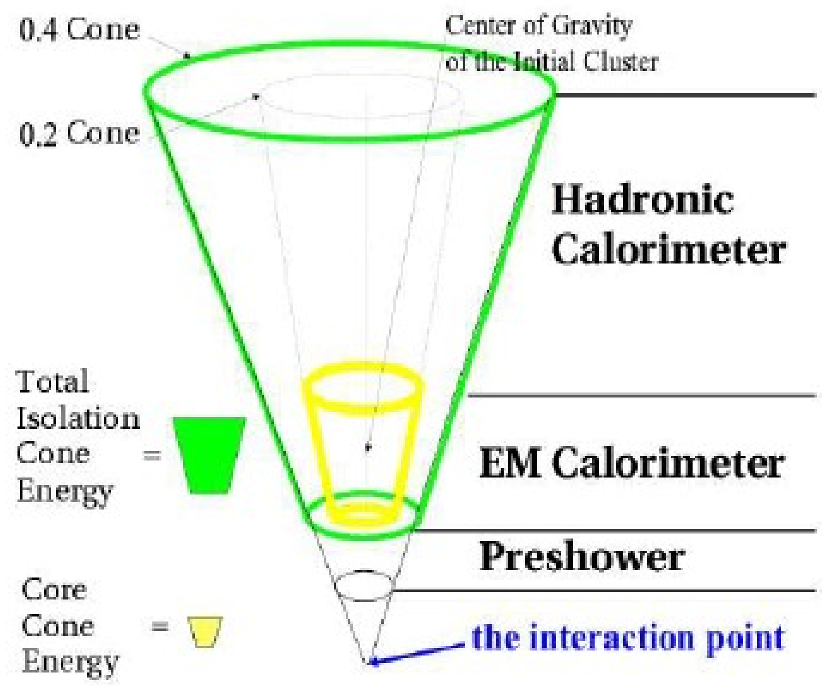


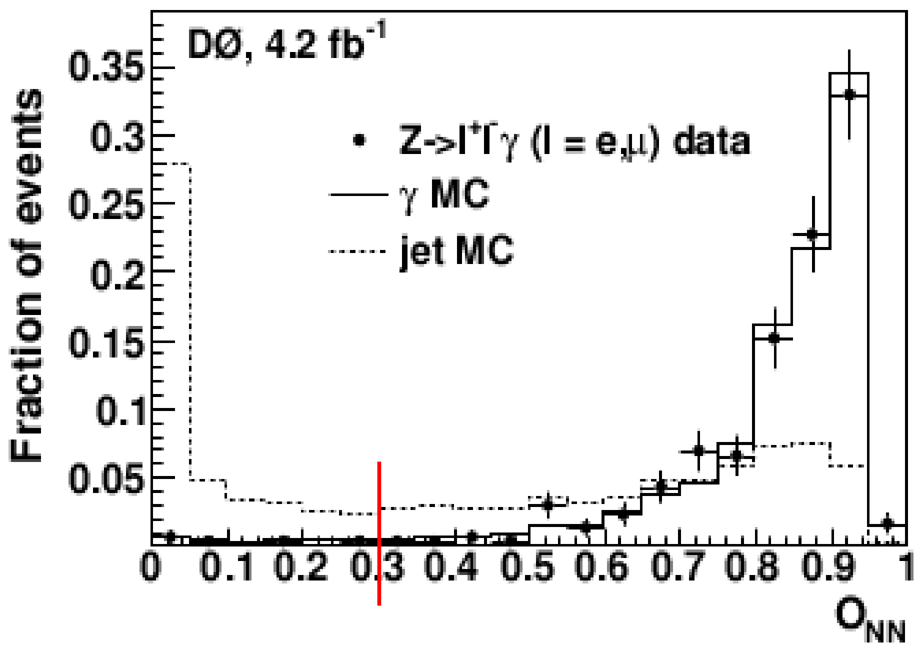
Check dependence on initial parton flavor!

Data Sample	1Vtx	2Vtx
inclusive	218686	269445
HF	5004	5811

Photon Identification

- Photons with pT>26 GeV in
- EM fraction > 97%
- EM cluster isolation in the calorimeter.
- EM cluster isolation in the tracker.
- Shower width in EM calorimeter section consistent with EM object
- Cut on photon neural network, NN>0.3 (uses calorimeter, preshower and tracking information)
- Central photons are required to originate from the primary vertex using hits in preshower
- Typical photon efficiency is ~80%
  Main backgrounds: dijet events

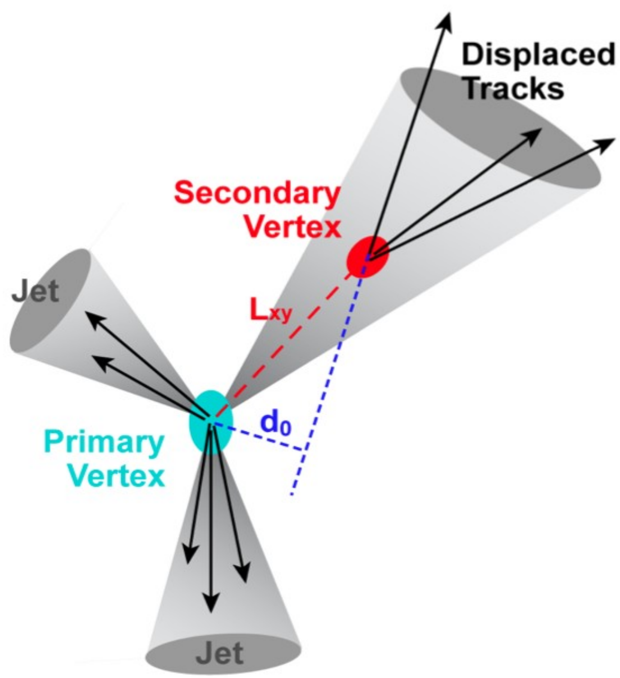


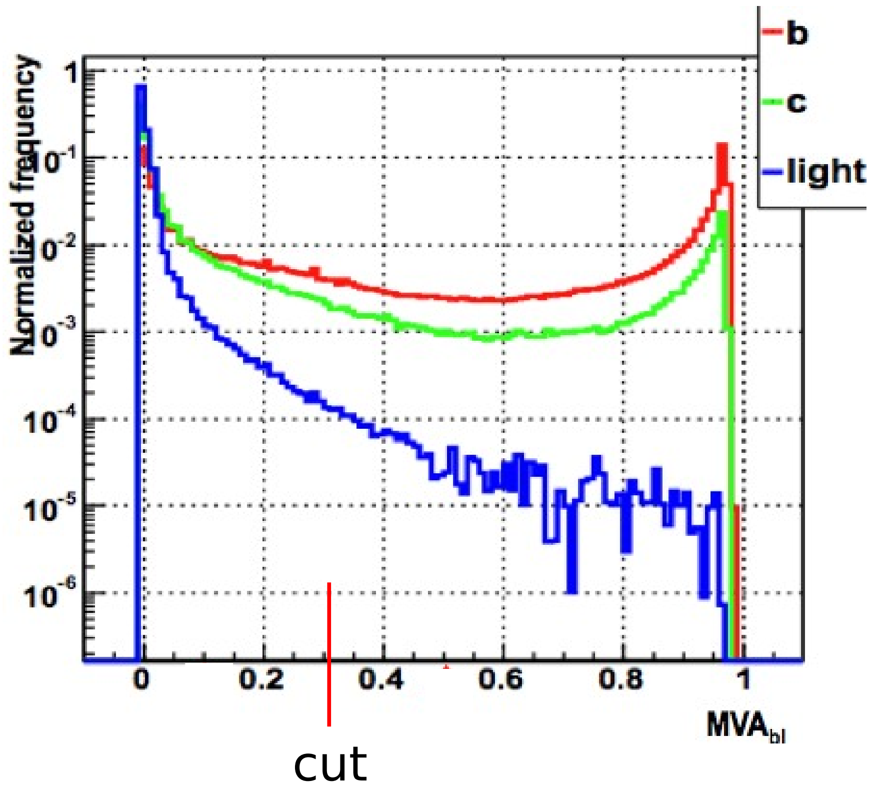


Heavy flavor Jet Identification

NIM A, 620, 490 (2010)

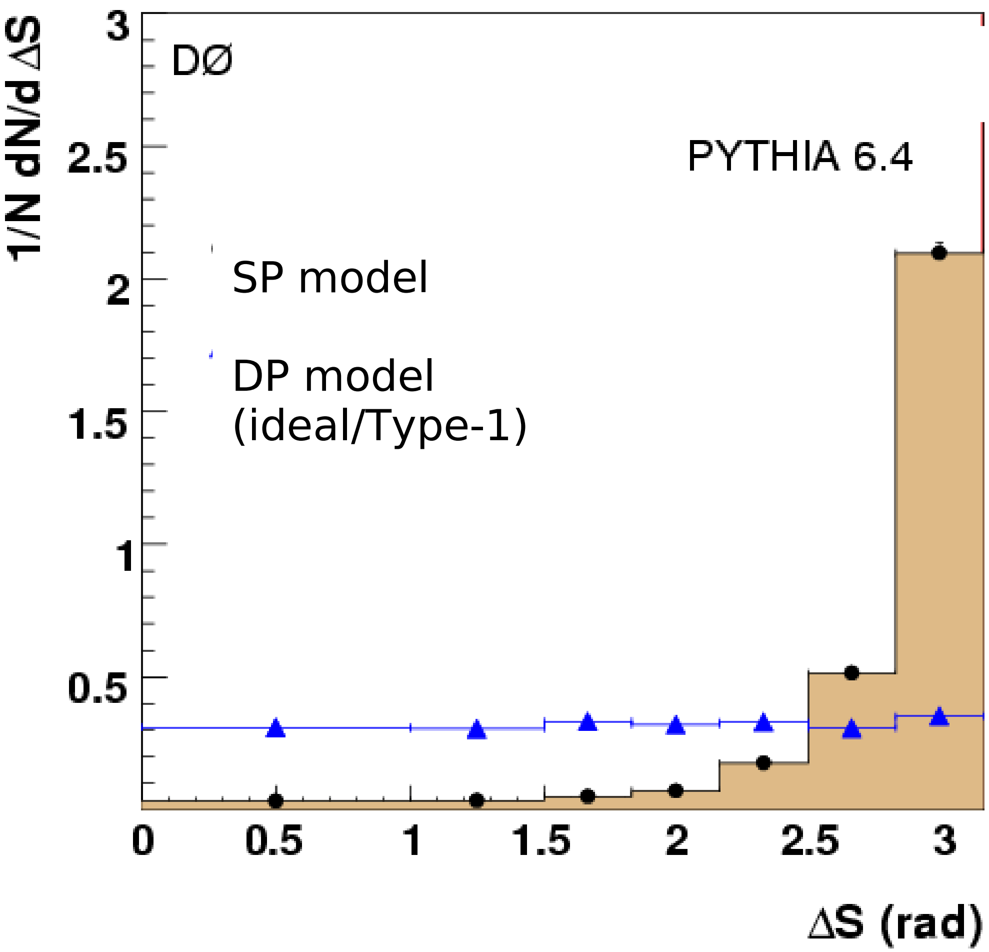
- B and C hadrons have a relatively long lifetime (~1 ps) and travel ~100-500 μm before decay.
  - Tracks displaced from primary vertex with large impact parameters

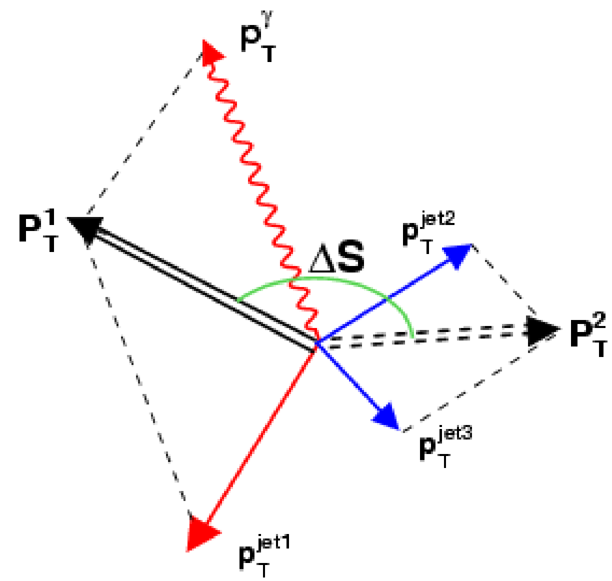




- Heavy flavor tagging exploits these characteristics of the tracks to create a discriminant used to enrich sample with HF-jets

△S distribution : Single Parton vs Double Parton





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

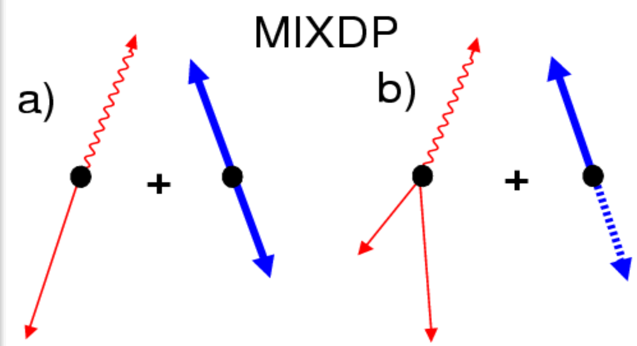
Double Parton events: pairwise pT balance needs to be preserved, but no correlation between two parton scatterings.

➔ 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).

Signal and background event models

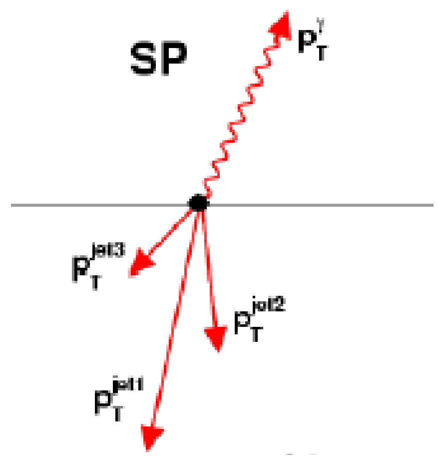
Signal event model (MIXDP)

1. Photon + ≥ 1 jets with $R_{cone} = 0.5$ (from EM inclusive skim) selected with:
   - 1 Primary vertex; $p_T^{\gamma} > 26$ GeV, $p_T^{jet1} > 15$ GeV, $|\eta^{jet}| < 2.5$.
2. At least 1 jet with $R_{cone} = 0.5$ (from MinBias skim) selected with:
   - 1 Primary vertex, $p_T^{jet} > 15$ GeV; $|\eta^{jet}| < 2.5$.
3. Samples 1 & 2 are mixed;
4. $\gamma + \geq 3$ jets.



Background event model (SP1VTX)

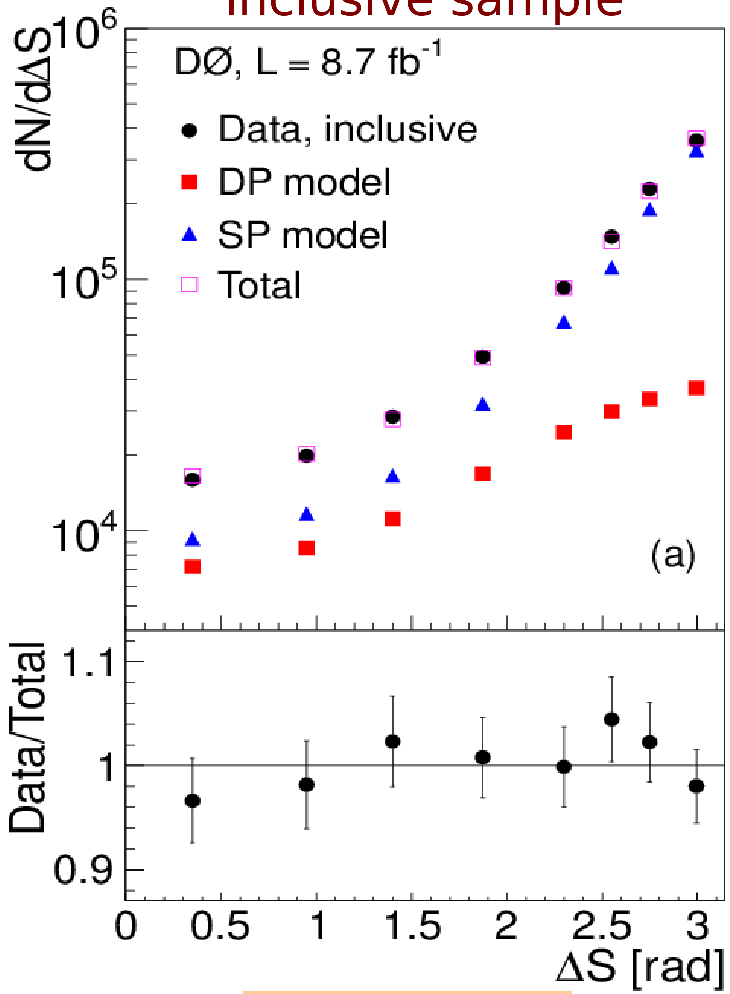
1. PYTHIA and SHERPA full MC
2. Single Parton sample (MPI modeling = off)
3. 1-vtx $\gamma + \geq 3$ jets events
4. Same kinematical requirements in Data and MIXDP.



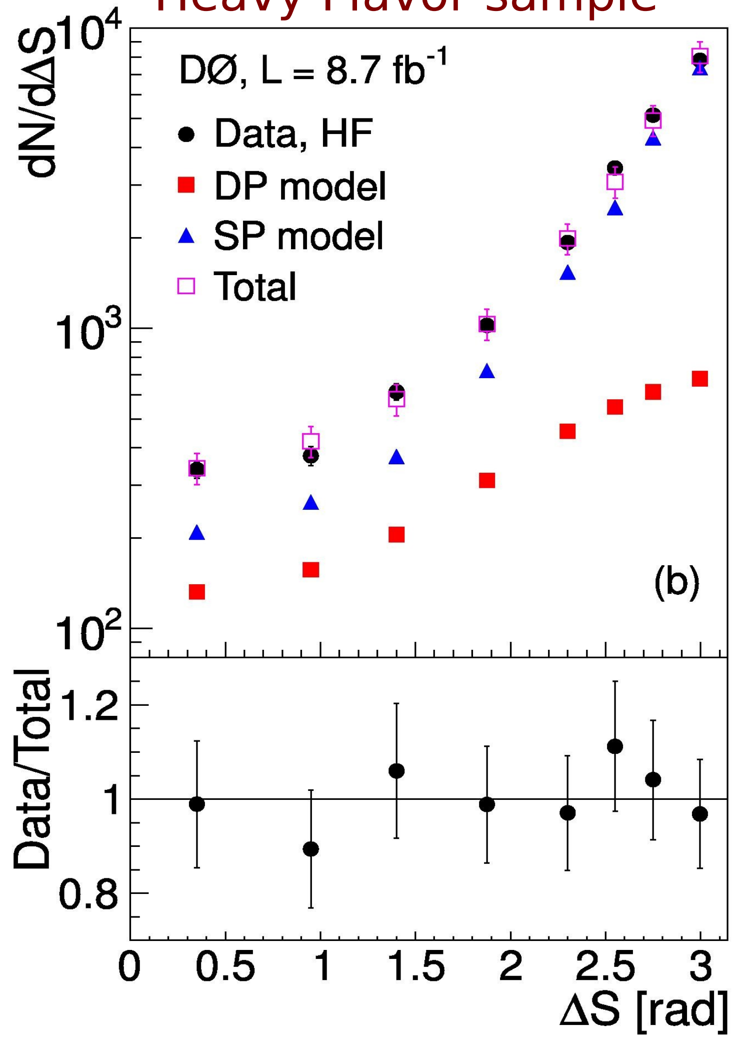
Fractions of Double Parton events

DP event fraction is found by maximul likelihood fitting Single Parton event model (Sherpa) and Double Parton signal event model (MixDP) to data.

Inclusive sample



Heavy Flavor sample



DP fractions

γ+HF+dijet	γ+3 jet
0.171 ± 0.020	0.202 ± 0.007

Numbers include syst. uncertainty due to choice of SP model.

Fractions of Double Interaction events

Data

- 2vtx data sample w/ and w/o leading jet b-id criterion (Tight: $MVA\_BL > 0.225$)
- Photon originates from PV0
- Photon Ncps > 0
- Jets are required to have at least 2 tracks , CPF>0.5
- Leading jet is required to originate from PV0

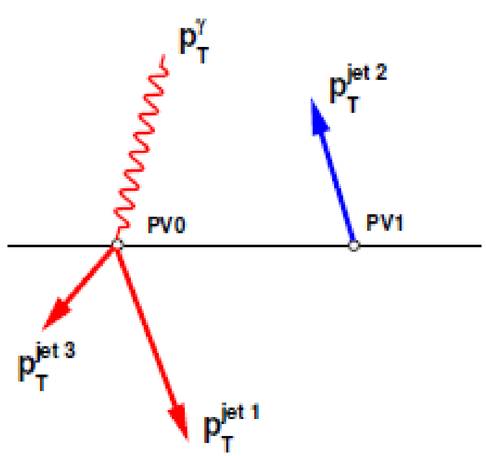
Double Interaction: at least one jet (2nd or 3rd) should originate from PV1

- $f_{DI} = 0.135 \pm 0.002$ (Inclusive sample)
- $f_{DI} = 0.131 \pm 0.010$ (HF sample)

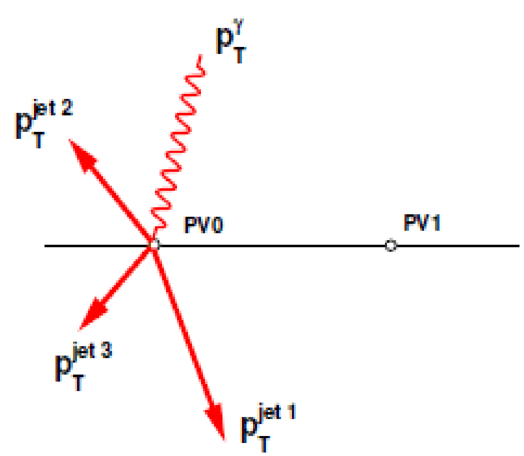
Charged particle fraction

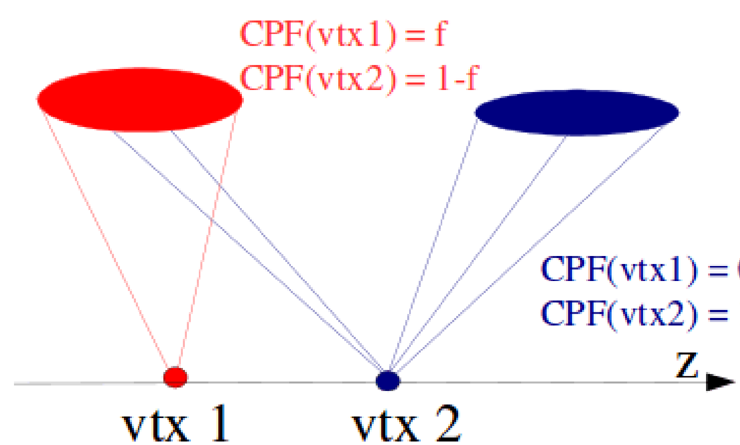
$$\mathrm{CPF}(\mathrm{jet}_i, \mathrm{Vtx}_j) = \frac{\sum_k p_T(\mathrm{trk}_k^{\mathrm{jet}_i}, \mathrm{Vtx}_j)}{\sum_n \sum_l p_T(\mathrm{trk}_l^{\mathrm{jet}_i}, \mathrm{Vtx}_n)}$$

2-vtx Signal



2-vtx Background





Double interaction: jet – vertex matching

1. $\Delta Z(jet, PV0)$ resolution is found using 1PV vertex data sample;
2. $\sigma \approx 1.2\ cm$ for all jets;
3. we require 3σ cut for all 3 jets in 2PV data sample.

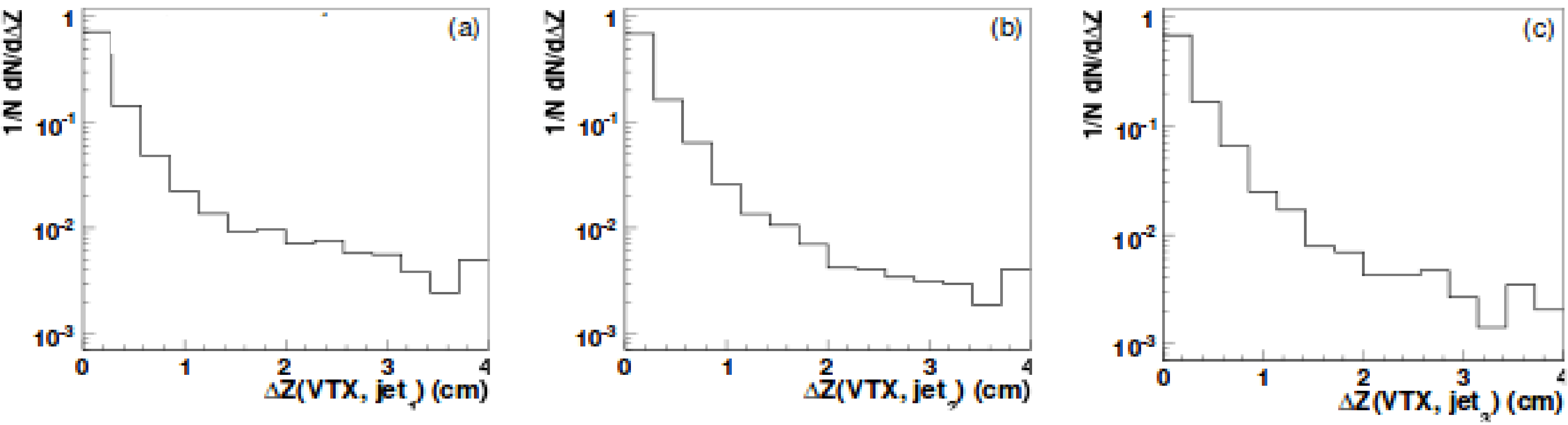
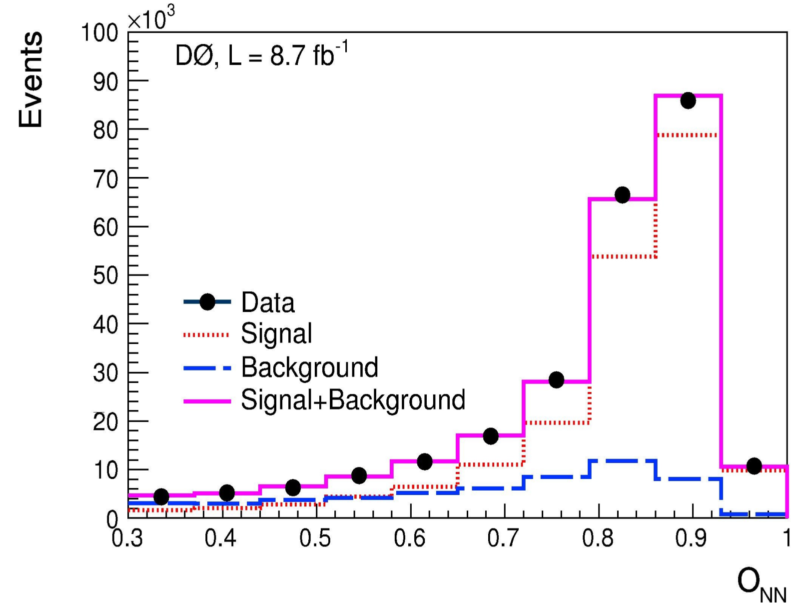


TABLE IV: DI event fraction with respect to Δz(PV0, PV1).

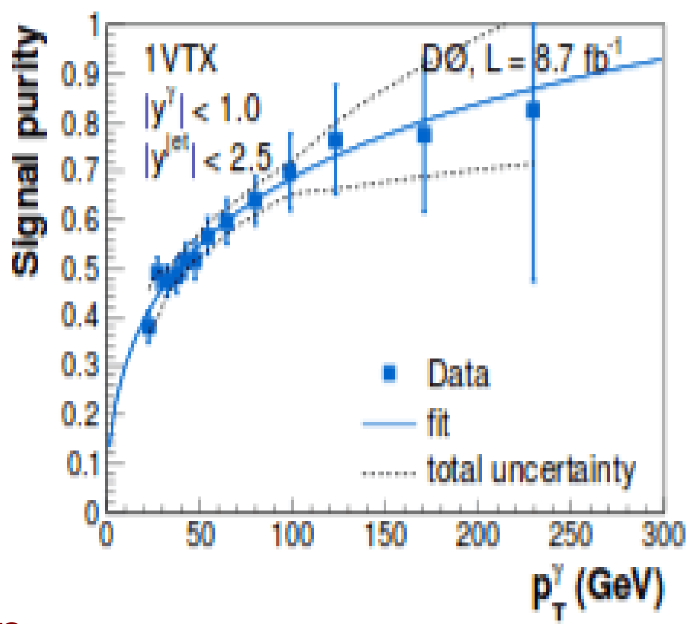
Δz(PV0, PV1)	Inclusive sample	HF sample
No cut	0.135 ± 0.002	0.131 ± 0.010
$> 5\sigma_z$	0.129 ± 0.002	0.122 ± 0.011

Photon fraction: Double Parton vs Double Interaction

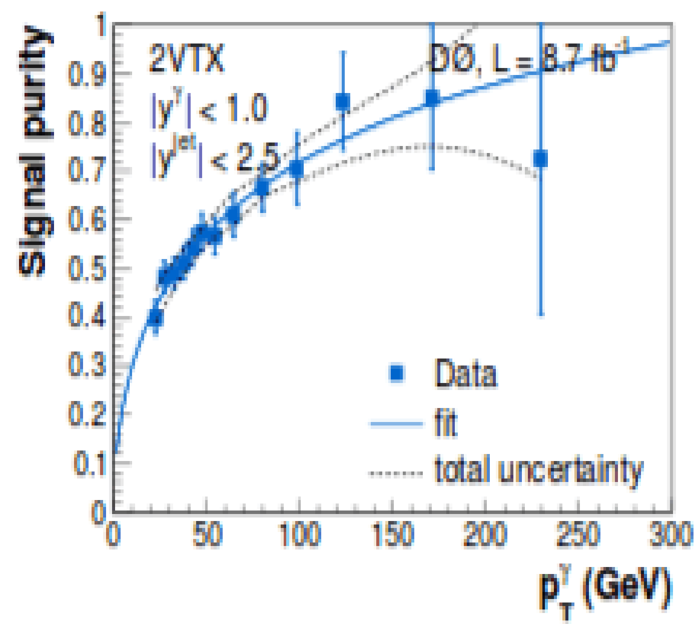
Fractions are found using signal and background photon ANN templates fitted to data



DP



DI



Photon fractions 0.447+/- 0.025 0.459+/- 0.025 (CC)

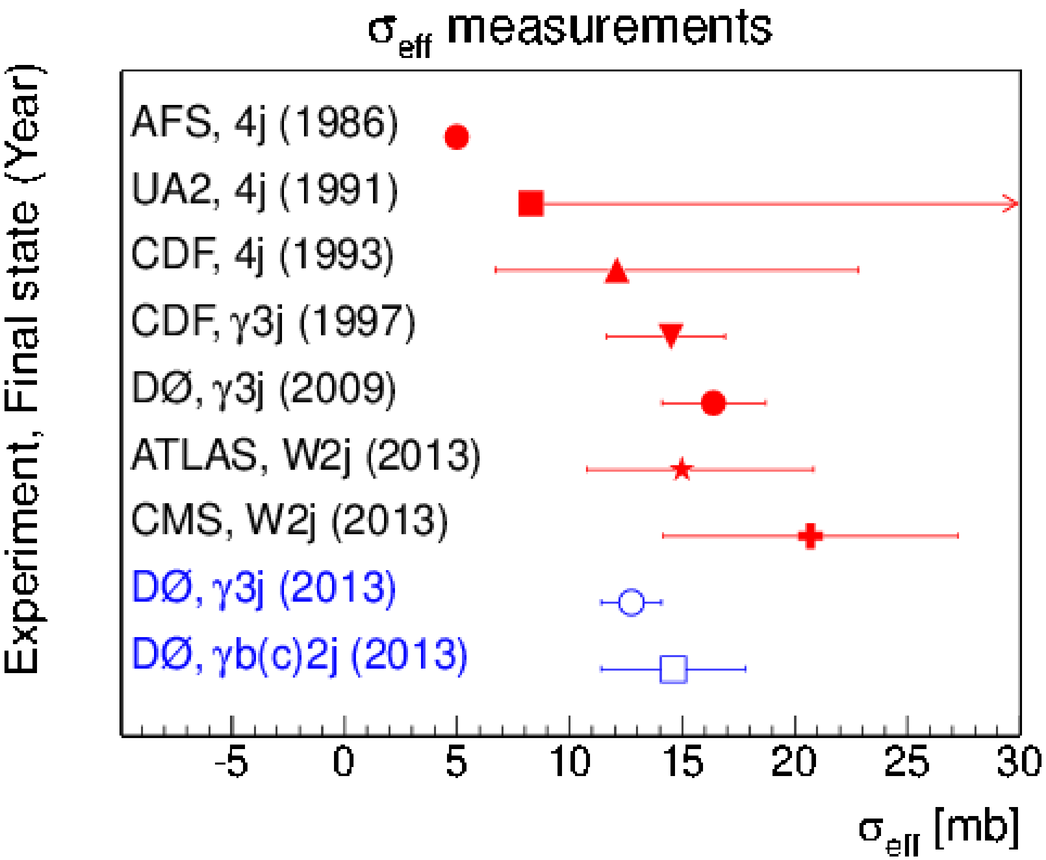
Effective cross section

Phys.Rev.D89, 072006 (2014), arXiv:1402.1550

- Having measured number of DP events and corresponding acceptances and efficiencies one can calculate **σ_{eff}** for both final states.

- Measured σ_{eff} is in agreement with all Tevatron and LHC measurements, but the new values is more precise.

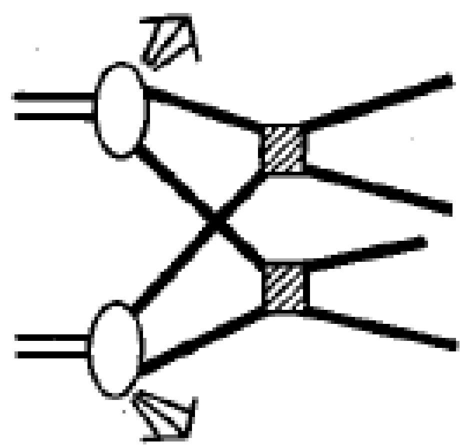
- No dependence of **σ_{eff}** on initial quark flavor has been observed.



Final state	γ+HF+dijet	γ+3 jet
$\sigma_{eff}\,(mb)$	14.6 ± 3.26	12.7 ± 1.32

Double Parton Interactions in double J/psi production

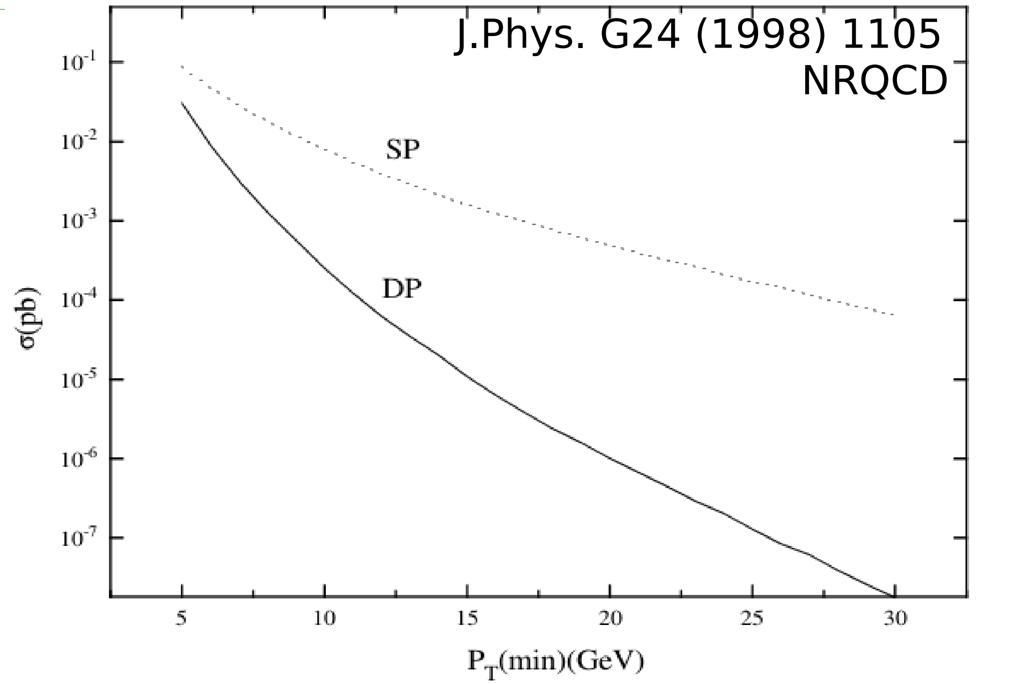
- Almost fully gluon initial state
- Low energy range

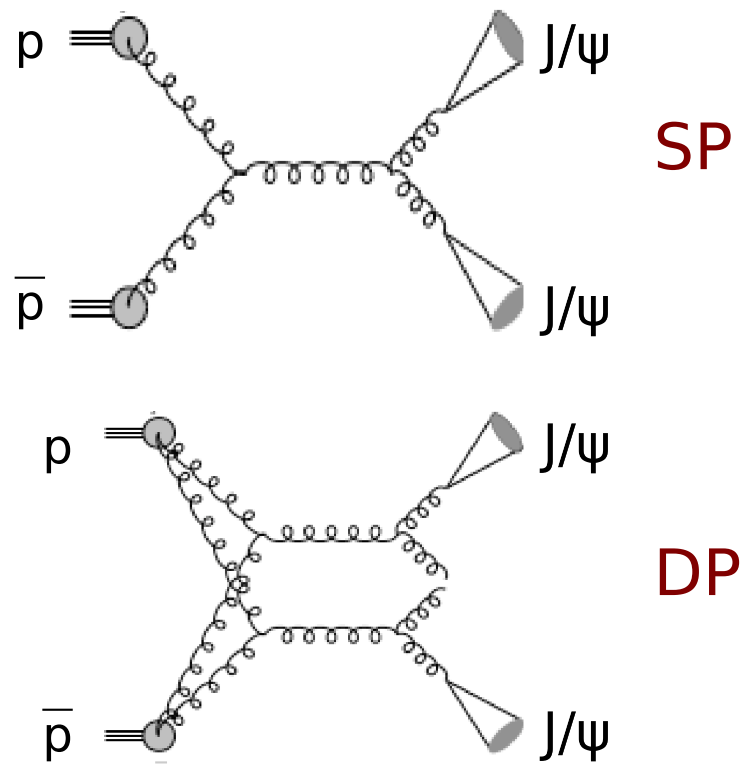


Double J/psi production

- Dominant production channel: gg → J/ψ J/ψ
- Signal: prompt direct J/ψ (S-wave) and (P-waves) χ_{1c} and χ_{2c}, $\chi_{1(2)c}$ → J/ψ+γ
- Background: non-prompt B-hadron decays, non-resonant DY, π/K decays.
- Single and Double parton scatterings may contribute
  => Test of σ_{eff} energy dependence: from high energies to 4-5 GeV, with gg initial state only

Prediction for the Tevatron at pT(J/ψ)>4 GeV, |η|<0.6:
expected DP fraction is ~15%





Data selection

- L = 8.1 fb-1 statistics

- Logical OR of low pT unprescaled di-muon triggers

- $p_T(\mu)>2$ GeV if $|\eta|<1.35$, $|p|>4$ GeV if $1.35<|\eta|<2.0$
  $p_T(J/\psi)>4.0$ GeV, $|\eta|<2.$

- exclude muons having hits just outside of toroid

- veto cosmic muons by timing cut

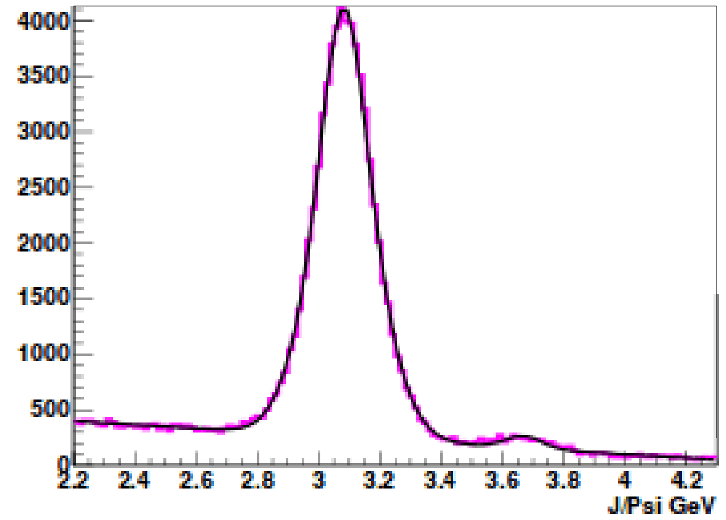
- muon track segment is matched to the central tracker

- track with at least 3 hits

- opposite charge μ

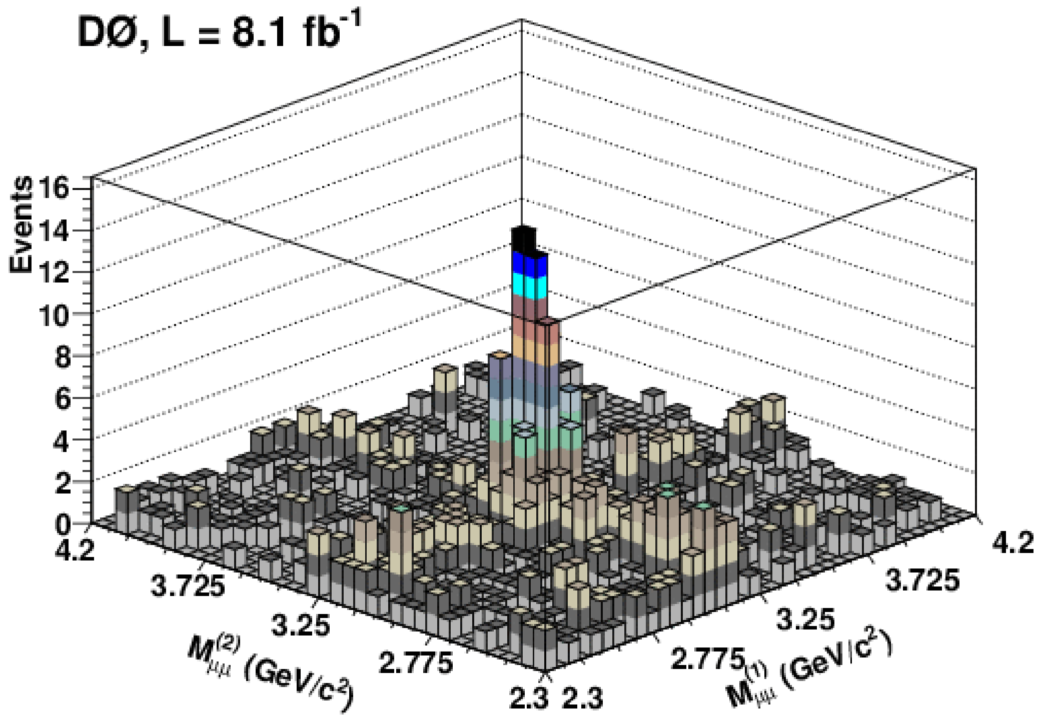
- r-DCA (transverse distance of closest approach of the track to the primary vertex point) < 0.5 cm; z-DCA < 2 cm

- Muon pair is in $2.85 < M_{\mu\mu} < 3.35$ GeV



Single J/ψ candidates:
7.2 M events selected

Double J/ψ candidates



902 events in 2.3 < $M_{\mu\mu}$ < 4.2 GeV
242 events in 2.85 < $M_{\mu\mu}$ < 3.35 GeV
($M_{\mu\mu}$ cuts are for both dimuon pairs)

Signal and Background Models

Non-prompt: b+bbar events simulated with Pythia

SP-1: NRQCD implemented in DJpsiFDC generator. It is interfaced to Pythia (Tune A and Perugia UE models) to simulate the parton shower. Contains CS (~90%) and CO (~10%).

SP-2: Herwig++, CS only.

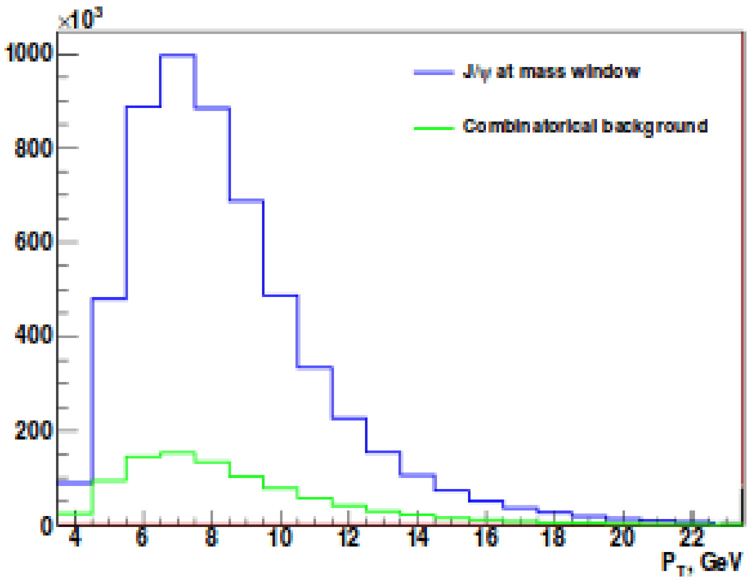
DP-1: Pythia8 with CS and CO contributions

DP-2: two J/ψ candidates randomly selected from two single J/ψ events in data

Background subtraction

Accidental contribution from pi/K decays, DY events Is estimated by fitting data in a wide mass range 2.3 – 4.2 GeV

with double Gaussian + line (or exp) for Single J/ψ events: 20x20 martix in (pT,η)
with double Gaussian + plane (or exp) for Double J/ψ events



$f_{acc,DY}$ (Single J/ψ) = 0.126 $\pm$ 0.013

$f_{acc,DY}$ (Double J/ψ) = 0.132 $\pm$ 0.025

The uncertainty is derived from variation of the fit parameters in the signal and background models

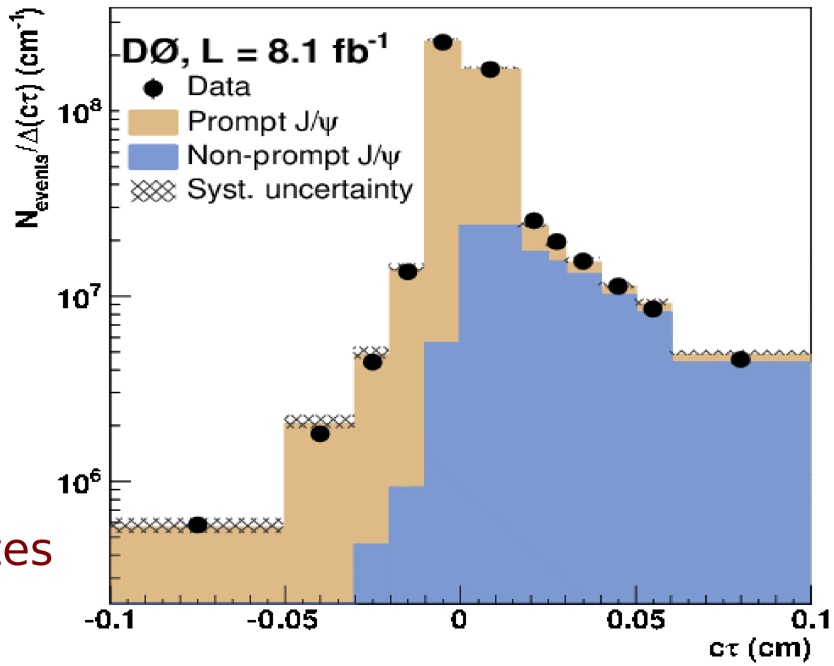
Background subtraction

Non-prompt background:
– Estimated using the decay length from primary ppbar interaction vertex to the J/ψ production vertex

$$c\tau = L_{xy} m_{pdg}^{J/\psi} p_T^{J/\psi}$$

L_{xy} is the distance between intersection of muon tracks and the hard scattering vertex in the plane transverse to the beam.

– $c\tau$ templates for signal and background events are fitted to data:



Single J/ψ: fit to data using prompt and non-prompt templates

$F_{prompt} = 0.814 \pm 0.009$

Double J/ψ: fit to data using double prompt, non-prompt and prompt+non-prompt templates:

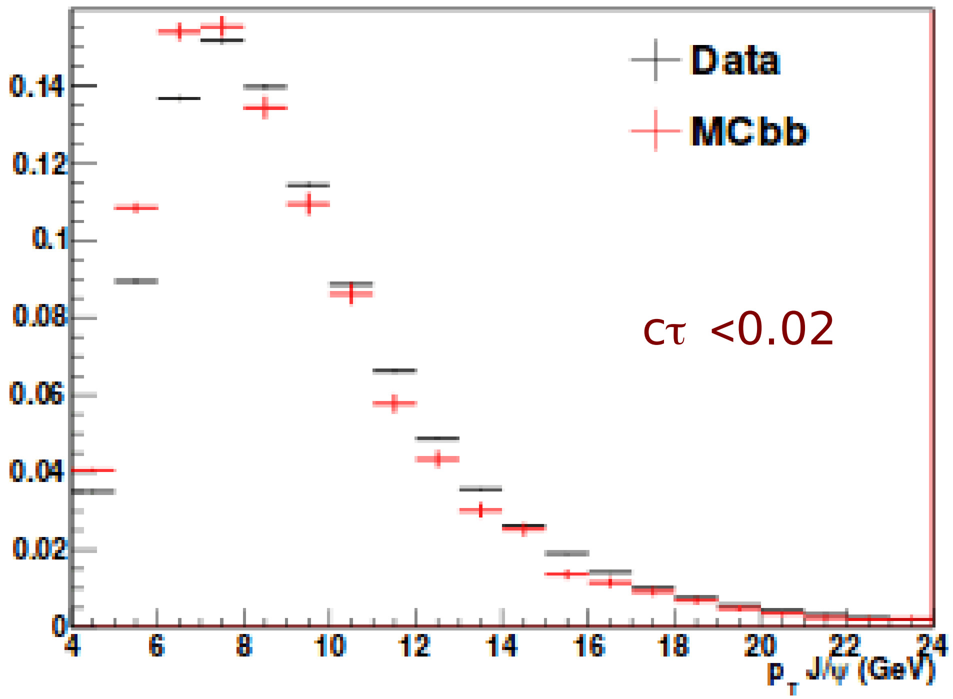
$F_{prompt} = 0.604 \pm 0.084$

($F_{np} = 0.303 \pm 0.065$, $F_{p+np} = 0.090 \pm 0.057$)

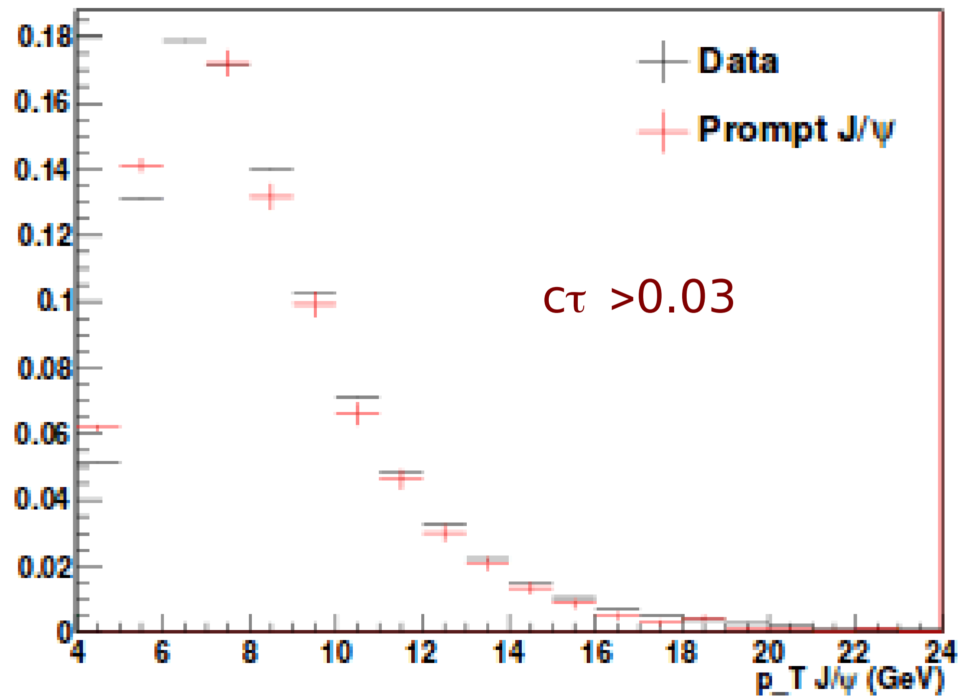
Cross checks for signal and background models

Comparison of pT shapes for Jpsi events in MC and D0 data

Non-prompt data vs MC



Prompt data vs MC



Good agreement with the default MC samples.
Remaining small defeerences are used to reweight MC and get systematics.

Single J/ψ cross section

$$\sigma(J/\psi) = \frac{N_{data} f_{prompt} \left(1 - f_{acc,DY}\right)}{\epsilon_{trig} L A \epsilon_{sel}}$$

– Acceptance and selection efficiencies are calculated using MC events corrected by data/MC (pT,eta)dependent correction factors (~0.9)
– Trigger efficiency is calculated using events passed zero-bias and zero-bias+dimuon trigger

Measured cross section (with pT and η cuts on slide 41):

$$23.9 \pm 4.6 (stat) \pm 3.7 (syst)\, nb$$

Predicted cross section using the ”kT factorization”:

$$23.0 \pm 8.6\, nb$$

Uncertainties in theory: gluon PDF (A0 to A+-) and scale variation by factor 2 around $\mu_R = \mu_F = \hat{s}/4$.

Single Parton and Double Parton contributions

– We measure the Double J/ψ production cross section for Double Parton and Single Parton scatterings separately. To discriminate between the two mechanisms, we use $\triangle\eta(J/\psi, J/\psi)$ difference.

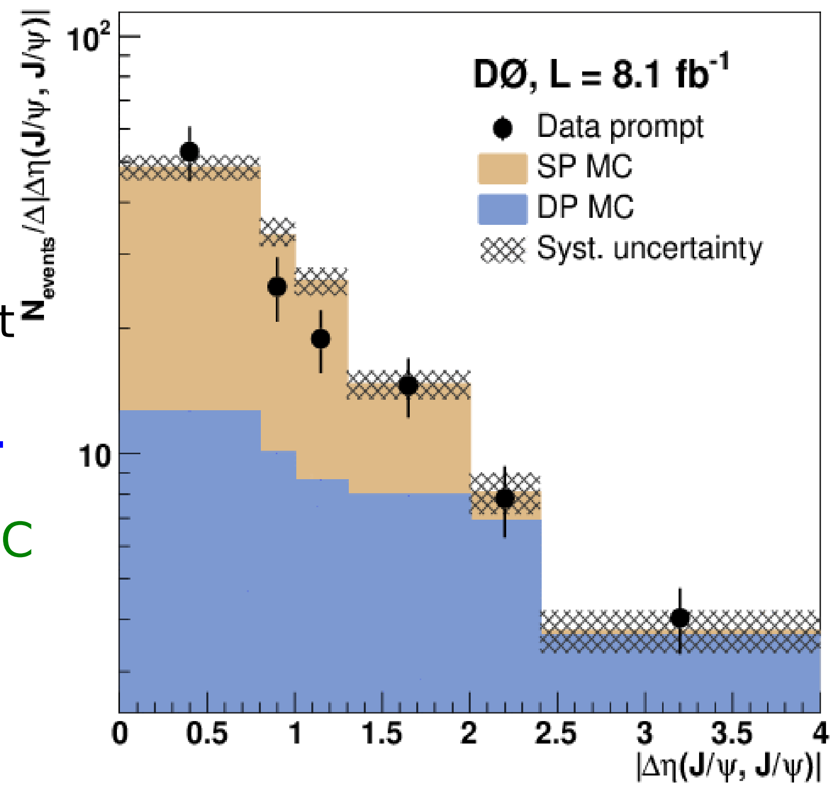
– Contributions from double non-prompt, prompt+non-prompt and accidental backgrounds are subtracted from data
=> data should contain just prompt SP and DP events.

SP template: DJ events simulated with Herwig++ /DJPsiFDC
DP template: Pythia-8 or data-like DP model.

$f_{SP} = 0.70 \pm 0.11, \ f_{DP} = 0.30 \pm 0.10$

Systematics: fit and variation between the 2+2 models; prompt+non-prompt origin (either 100% SP- or DP-like).

DP double non-prompt is highly suppressed to 0.7–2 fb.



DP dominates at $|\triangle\eta(J/\psi\ J/\psi)| > 2$

Double J/ψ SP cross section

$$\sigma_{SP}(J/\psi\, J/\psi)=\frac{N_{data} f_{SP} f_{prompt}(1-f_{acc,DY})}{\epsilon_{trig,SP} L (A\epsilon_{sel})_{SP}}$$

Measured fiducial cross section (with pT and η cuts on slide 41):

$$\sigma_{SP}=112.0\pm9.8(stat)\pm29.8(syst)\, fb$$

Predicted cross section using the ”kT factorization”:

$$\sigma_{SP}^{kT}=55.1^{+28.5}_{-15.6}(PDF)^{+31.0}_{-17.0}(scale)\, fb$$

Predicted cross section using NRQCD (LO):

$$\sigma_{SP}^{NRQCD}=51.9\, fb$$

Since μ_R and μ_F rely on m_c, the prediction is very sensitive to its value.

Double J/ψ SP cross section

$$\sigma_{SP}(J/\psi\, J/\psi) = \frac{N_{data} f_{SP} f_{prompt} (1 - f_{acc,DY})}{\epsilon_{trig,SP} L (A \epsilon_{sel})_{SP}}$$

Measured fiducial cross section (with pT and η cuts on slide 41):

$$\sigma_{SP} = 112.0 \pm 9.8 (stat) \pm 29.8 (syst)\ fb$$

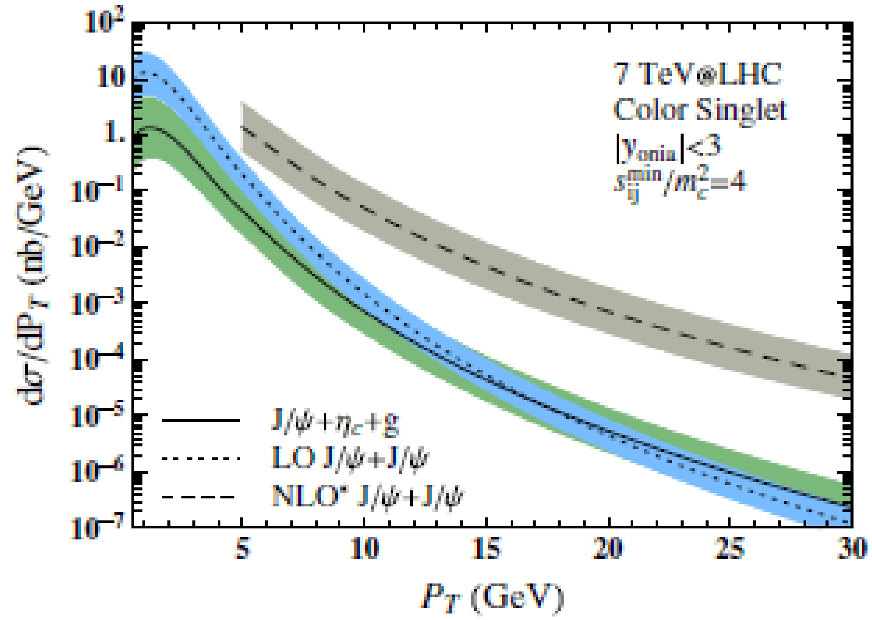
Predicted cross section using the ”kT factorization”:

$$\sigma_{SP}^{kT} = 55.1^{+28.5}_{-15.6} (PDF)^{+31.0}_{-17.0} (scale)\ fb$$

Predicted cross section using NRQCD (LO):

$$\sigma_{SP}^{NRQCD} = 51.9\ fb$$

However, NLO corrections have become recently for LHC: Phys.Rev.Lett.111,122001 (2013).
At pT>4 GeV, the NLO cross section is almost twice larger than LO!
To some extent it should be true for the Tevatron.



Double J/ψ Double Parton cross section

$$\sigma_{DP}(J/\psi\, J/\psi) = \frac{N_{data}\, f_{DP}\, f_{prompt}\,(1 - f_{acc,DY})}{\epsilon_{trig,DP}\, L\, (A\,\epsilon_{sel})_{DP}}$$

Measured fiducial cross section (with pT and η cuts on slide 41):

$$\sigma_{DP} = 56.6 \pm 5.8\,(stat) \pm 23.2\,(syst)\; fb$$

Predicted cross section using the ”kT factorization”:

$$\sigma_{SP}^{kT} = 1/2\,(\sigma_0 + \sigma_1 + \sigma_2)^2 / \sigma_{eff}^0$$

Taking σ_{eff}^0 = 15 mb

$$\sigma_{DP}^{kT} = 17.6 \pm 13\; fb$$

Double J/ψ DP cross section

$$\sigma_{DP}(J/\psi\, J/\psi) = \frac{N_{data}\, f_{DP}\, f_{prompt}\left(1 - f_{acc,DY}\right)}{\epsilon_{trig,DP}\, L\, (A\,\epsilon_{sel})_{DP}}$$

Measured fiducial cross section (with pT and η cuts on slide 53):

$$\sigma_{DP} = 56.6 \pm 5.8\,(stat) \pm 23.2\,(syst)\ fb$$

Predicted cross section using the "kT factorization":

$$\sigma_{SP}^{kT} = 1/2\,(\sigma_0 + \sigma_1 + \sigma_2)^2 / \sigma_{eff}^0$$

Taking σ_{eff}^0 = 15 mb

$$\sigma_{DP}^{kT} = 17.6 \pm 13\ fb$$

And consequently, using

$$\sigma_{eff} = \frac{\sigma(J/\psi)^2}{\sigma(J/\psi\, J/\psi)}$$

we get

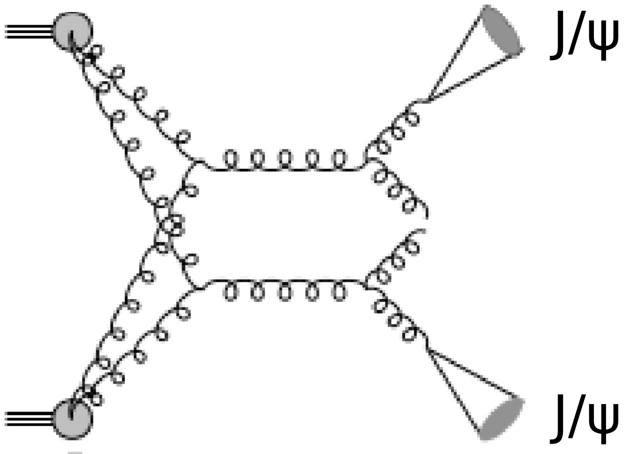
$$\sigma_{eff} = 5.0 \pm 0.5\,(stat) \pm 2.7\,(syst)\ fb$$

Some discussion

– The measured σ_{eff} in double J/ψ events (5.0±2.8 mb) within 2 σ_{exp} uncertainty agrees with that measured in γ+3jet events (12.7±1.3 mb). However, the central value is still noticeably lower. Why can it be?

– The initial state in the DP double J/ψ production is very similar to 4-jet production at low pT which is dominated by gluons, while γ(W)+jets events are produced in quark interactions, $q\bar{q}, qg, q\bar{q}'$.

=> The measured σ_{eff} may indicate a smaller average distance between gluons than between quarks, or between a quark and a gluon, in the transverse space.



Summary

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

- They provide a better description of complex final states in hadron-hadron collisions.

- In D0 we have studied production of DP events in γ+b/c +dijet and γ+3-jet final states using (L=8.7 fb^{-1}):

• Fraction of DP events in γ+b/c +dijet: 0.17±0.02, in γ+3-jet: 0.20±0.01

• Effective cross section

$\sigma_{eff}^{HF} = 14.6 \pm 0.6(stat) \pm 3.2(syst)\, mb$ $\qquad$ $\sigma_{eff}^{incl} = 12.7 \pm 0.2(stat) \pm 1.3(syst)\, mb$

- We have also studied production of double J/ψ events and found that

• Fraction of DP events is 30±10%

• Effective cross section:

$$\sigma_{eff} = 5.0 \pm 0.5(stat) \pm 2.7(syst)\, fb$$

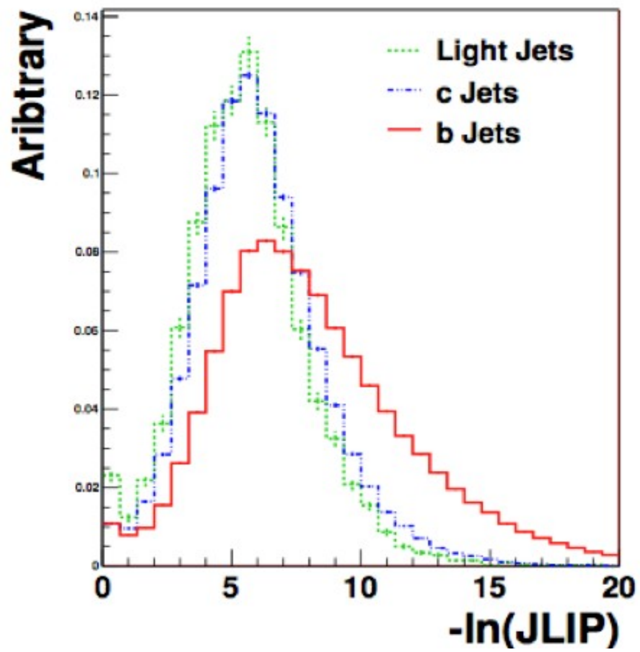
The size of σ_{eff} may indicate a smaller average distance between gluons than between quarks.
This result is in a qualitative agreement with the pion cloud model predicting a smaller nucleon's average gluonic transverse size than that for singlet quarks.

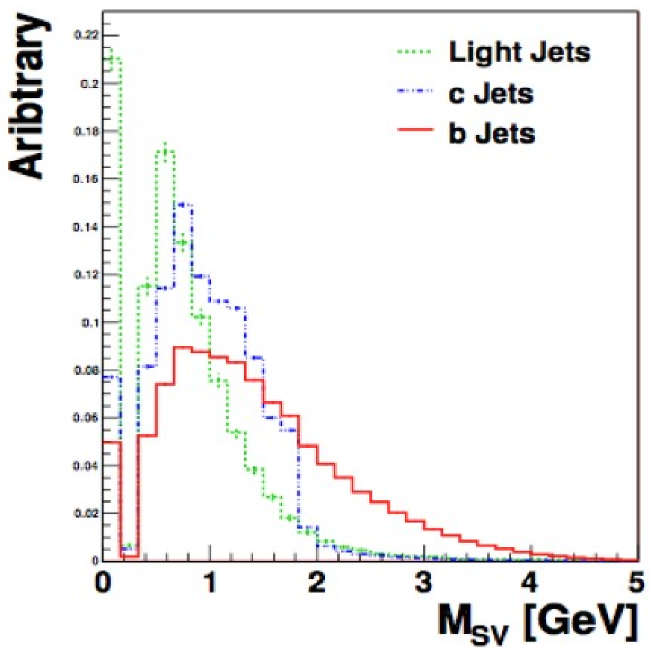
Estimation of Heavy Flavor fraction

- The tagged sample still has some fraction of misidentified jets
- To further separate jets of different flavors, use a discriminant
  - M_{SVT} is invariant mass of tracks associated to secondary vertex
  - JLIP is jet lifetime impact parameter

$$D_{\mathrm{MJL}} = \frac{M_{\mathrm{svt}}/5 - ln(\mathrm{JLIP})/20}{2}$$

  - JLIP takes into account the geometry of the tracks in the event and M_{svt} takes into account event kinematics, providing pronounced discrimination
  - Stable performance with jet kinematics





Estimation of Heavy Flavor fraction

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$$D_{\mathrm{MJL}} = \frac{M_{\mathrm{svt}}/5 - ln(\mathrm{JLIP})/20}{2}$$

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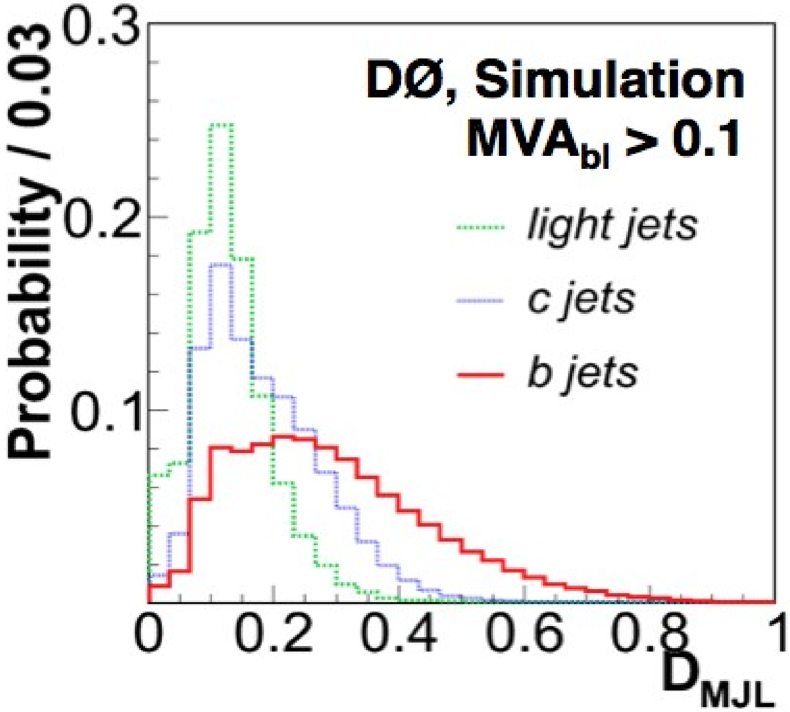

Fractions of Double Parton events

A few reweightings for most critical variables have been done to check stability of DP fractions (best results are with SP model in Sherpa):

TABLE III: DP event fraction with respect to different reweighting procedures.

f_{DP}	Inclusive sample	HF sample
Default	0.202 ± 0.007	0.171 ± 0.020
$\Delta\phi(\gamma, \mathrm{jet1})$ reweighted	0.195 ± 0.007	0.169 ± 0.020
p_T^{jet2} and p_T^{jet3} reweighted	0.216 ± 0.007	0.177 ± 0.020
Reweighted average	0.206 ± 0.007	0.173 ± 0.020

(see also Backup)