Recent QCD Results from the Tevatron

LHCP 2016, Lund, Sweden

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1) Gauge bosons

2) Hadrons

3) Multiple Parton Scatters

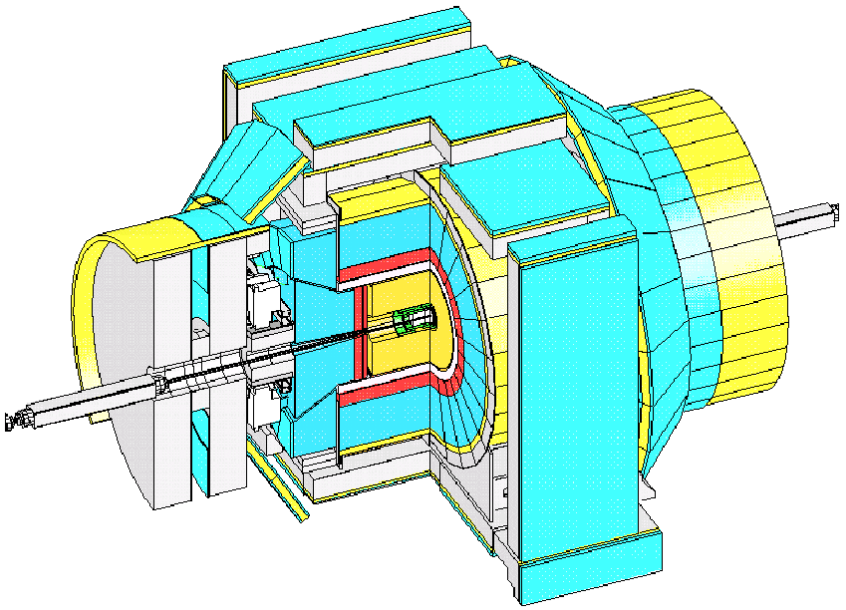
The Royal Society

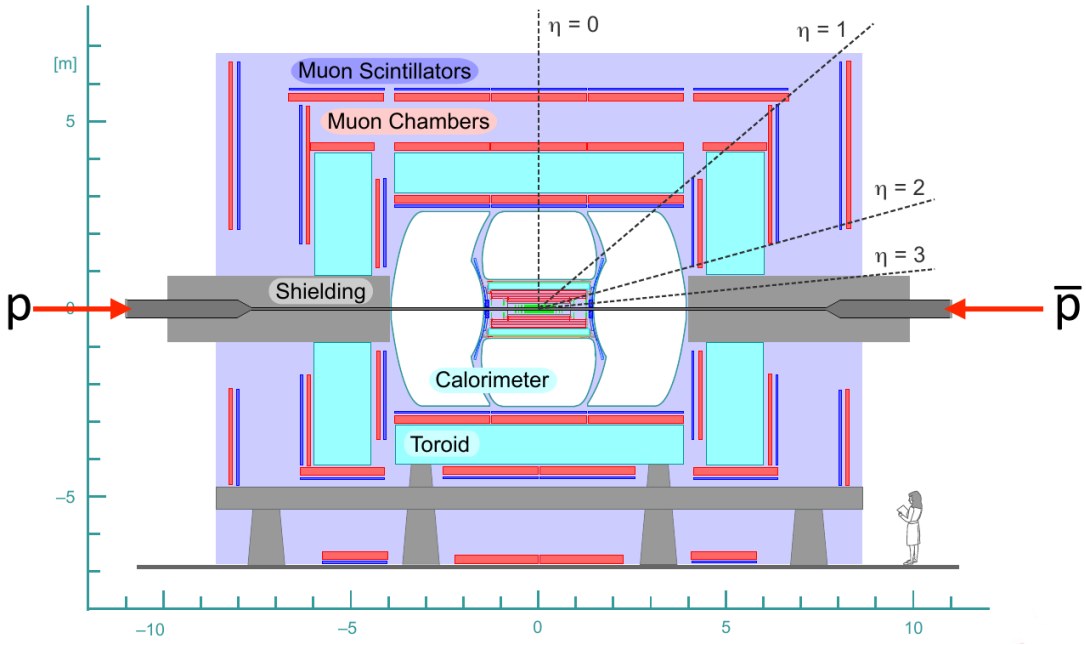
Science & Technology Facilities Council

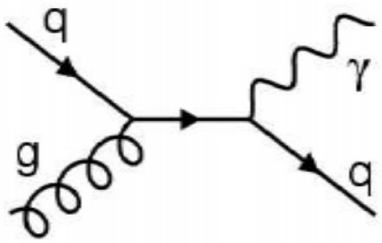
Tevatron

Tevatron Run II: 2001-2011
- collide protons and antiprotons
- c.o.m. energy 1.96 TeV

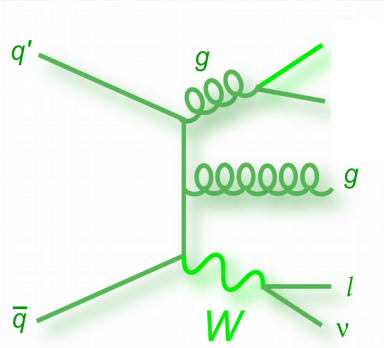
CDF & D0:
- general purpose experiments
- Integrated lumi ~ 10fb^{-1} each







Part 1: gauge bosons



Use colourless objects:

- photons, leptonic decays of W

Probe the underlying QCD in a range of different processes:

- exclusively, differentially, high multiplicity, ….

Gauge bosons

Trigger on & select isolated EM clusters:

- p_T > 30 GeV, $|\eta|$ < 1.0
- trigger thresholds 25 – 70 GeV
- low p_T triggers pre-scaled!

Photon ID based on:

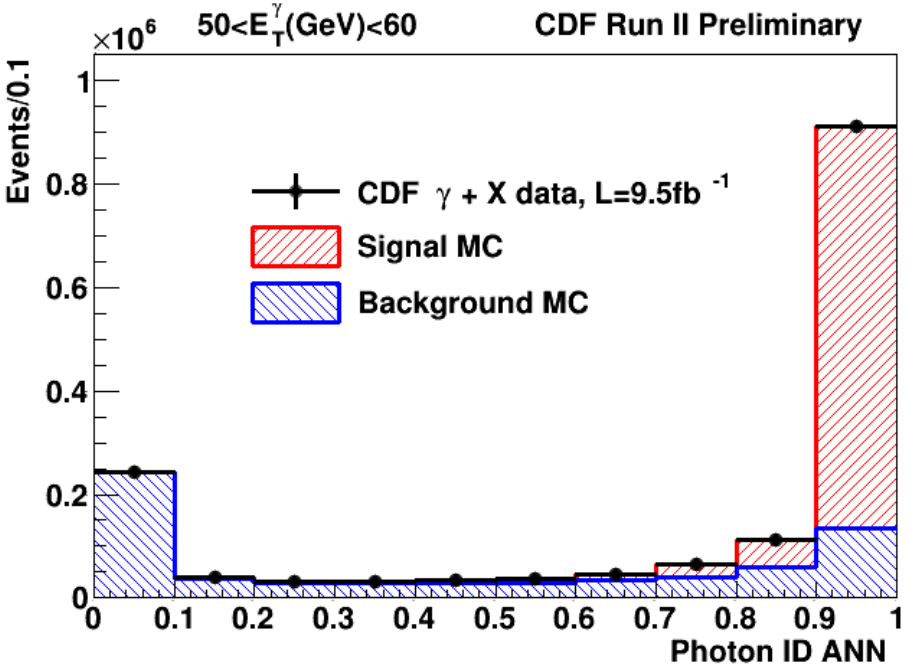
- shower shapes, isolation, tracking
- photon fraction varies from 50-80%

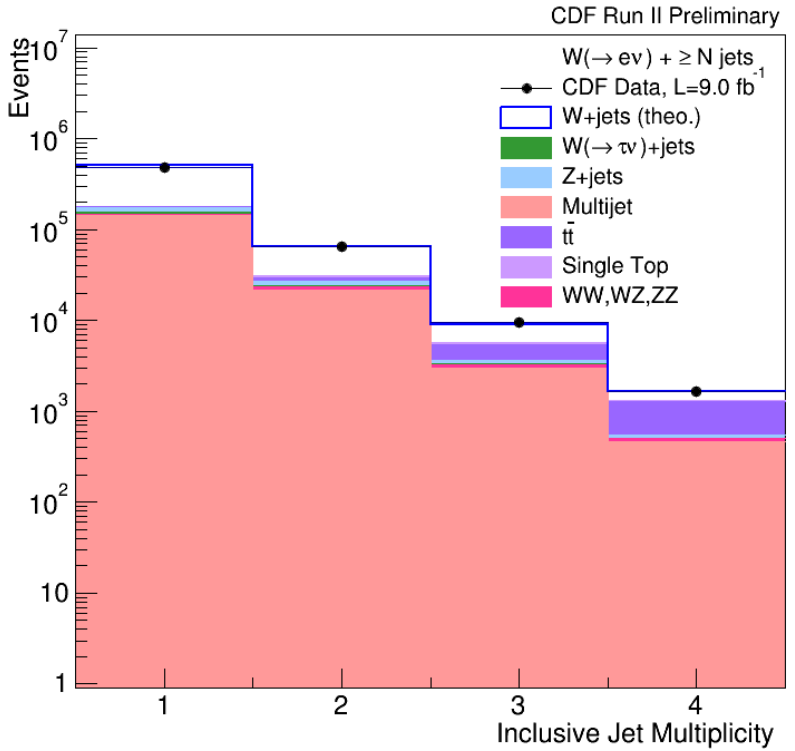
Leptonic W decays

- electron or muon with pT> 25 GeV
- transverse mass > 40 GeV
- jets with E_T > 25 GeV

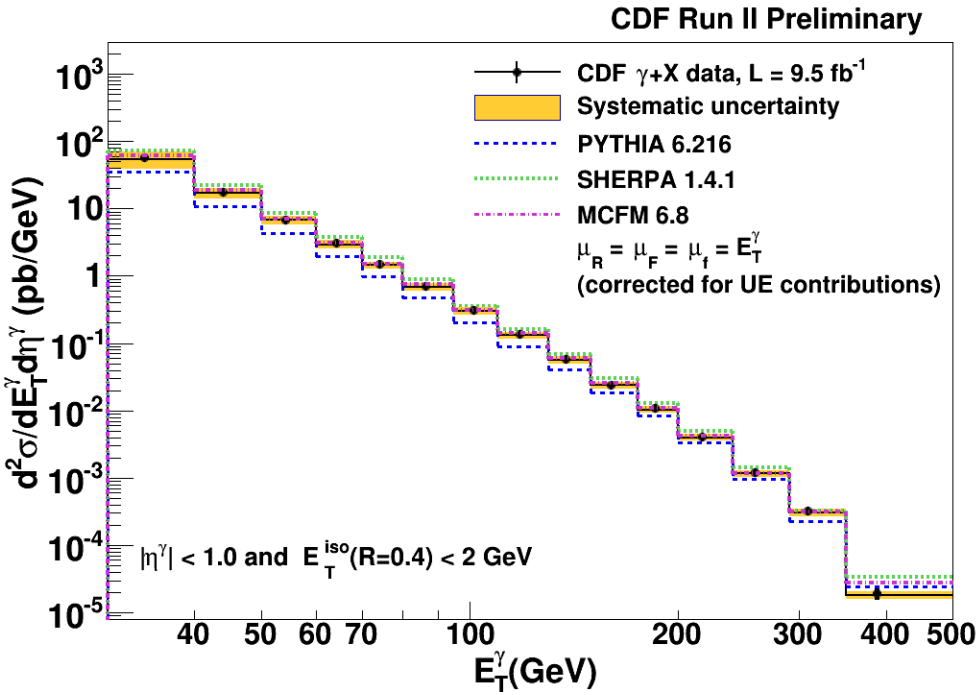
Unfold to particle level using SVD method

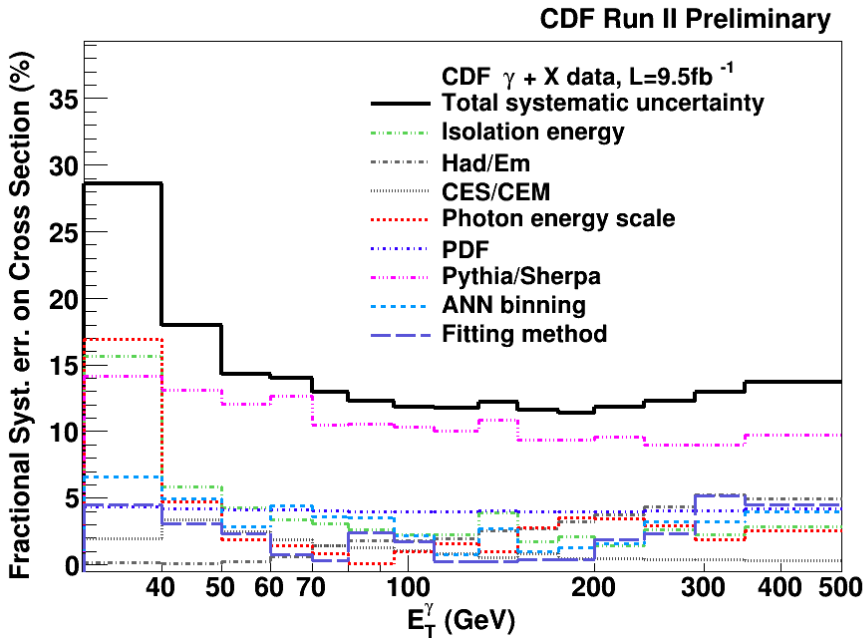
- channels then combined using BLUE





Inclusive Photon

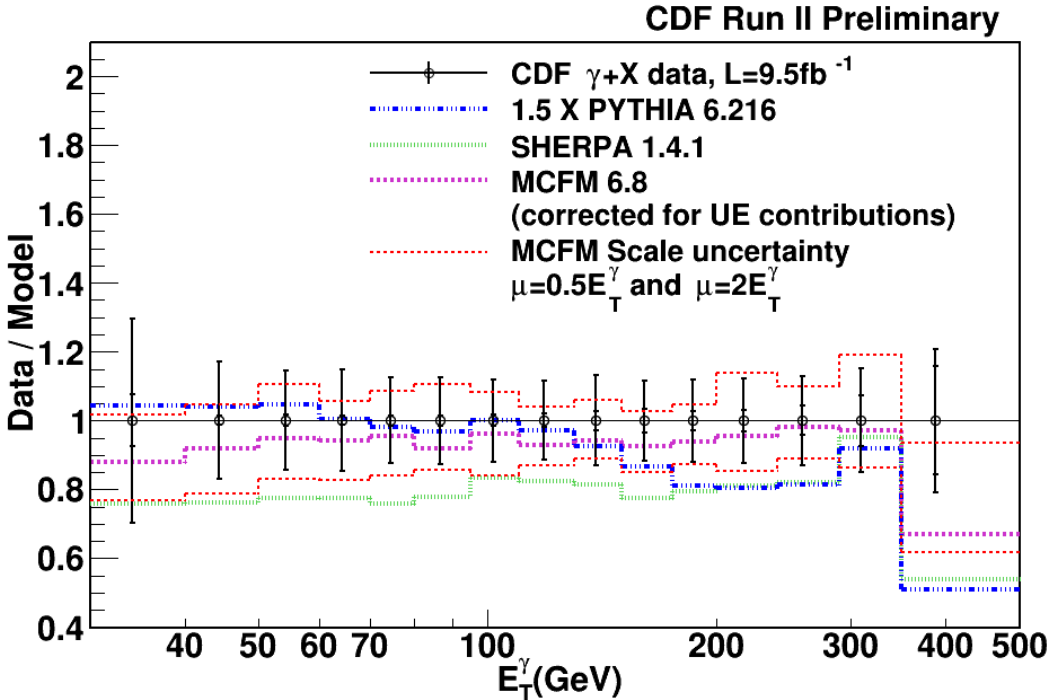




Comparison with:

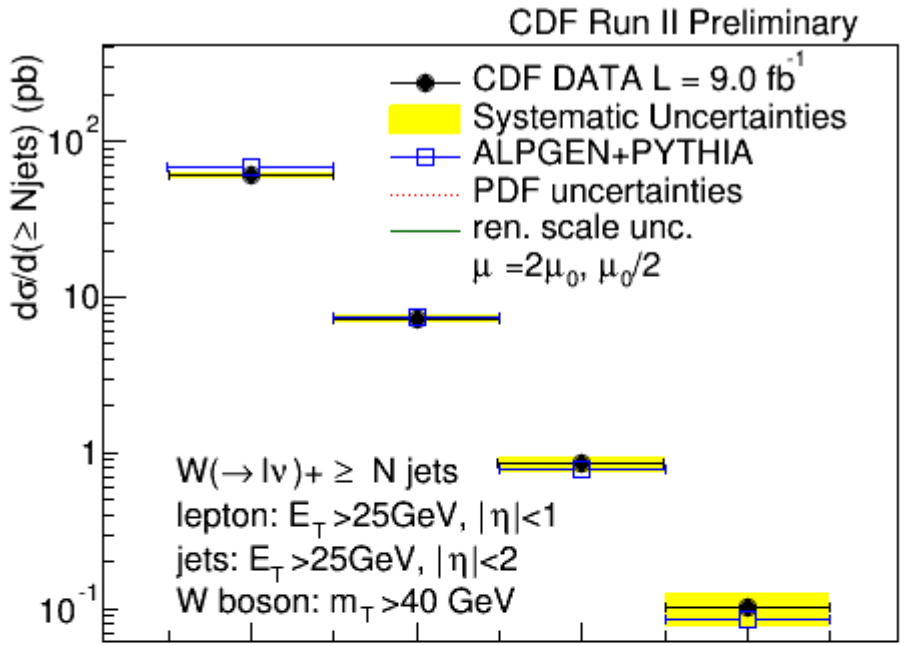
- Pythia 6.216 (LO), CTEQ5L PDF
- Sherpa 1.4.1, CT10 PDF
  - 0-3 jets @ LO
- MCFM NLO, fragmentation at LO
  - underlying event correction ~0.91
  - derived using Pythia 6.216

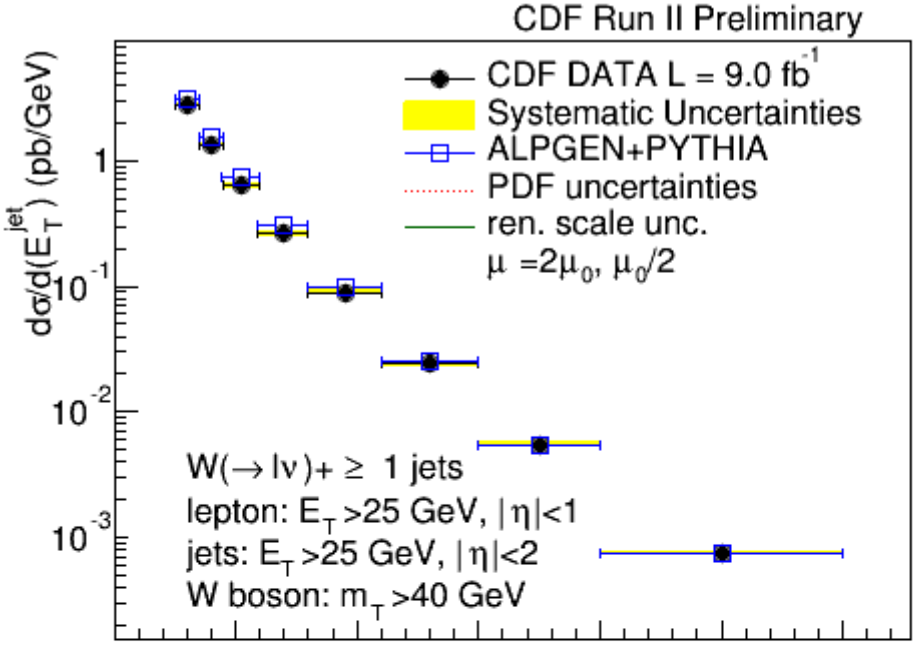
CDF Note 11180

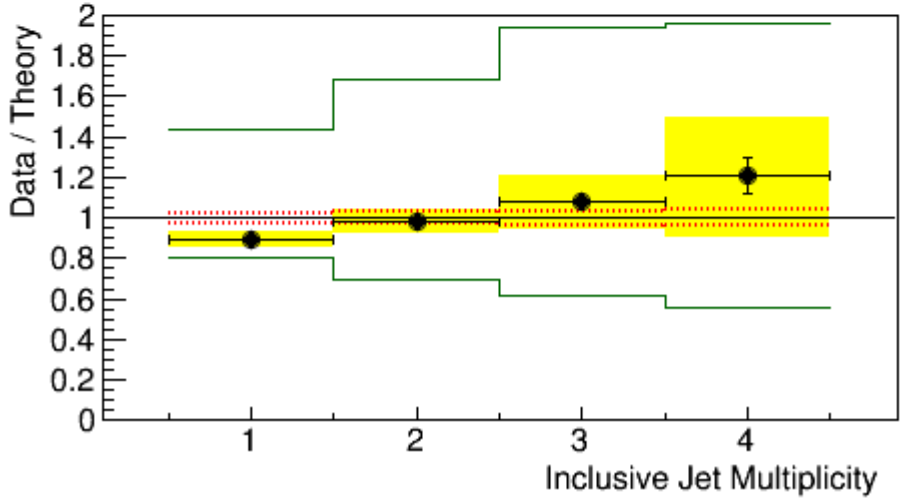


W+jets

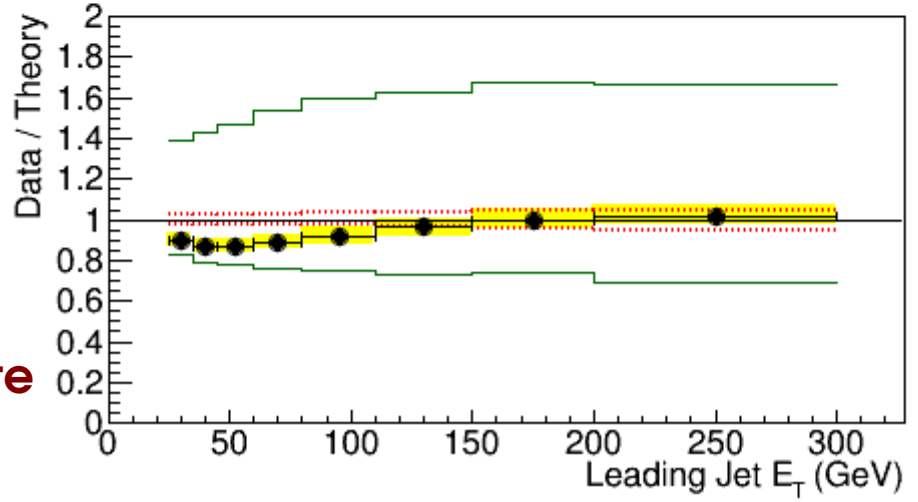
Result compared to Alpgen+Pythia6, using CTEQ5L PDF
- ren & fact scale = mW2 + pTW2, varied up and down by a factor of 2

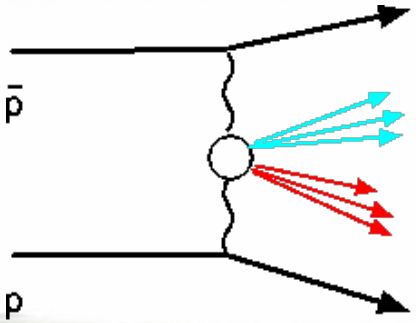






CDF Note 11167





Part 2: identified hadrons

Exclusive $\pi\pi$ production:
- sensitive to double pomeron exchange

Λ, Ξ & Ω Asymmetry:
- testing hadron production models

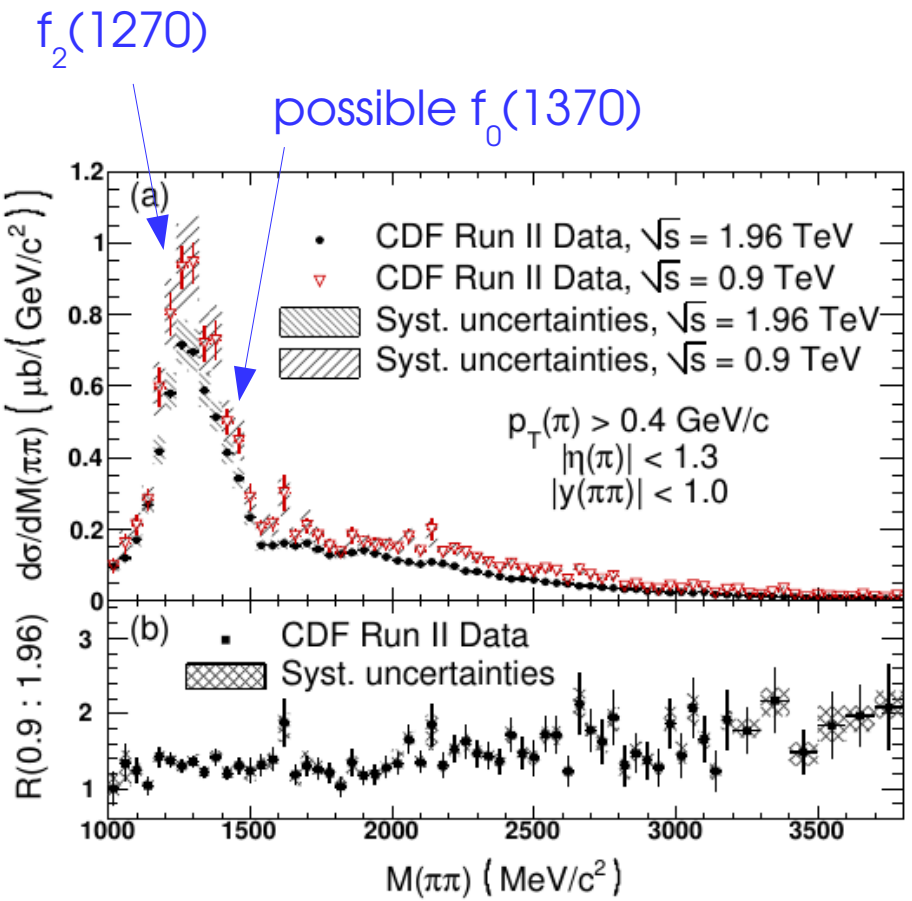
Exclusive $\pi^+\pi^-$

Sensitive to double pomeron exchange:

- IP IP $\rightarrow \pi^+\pi^-$
- IP = pomeron: colour singlet, mainly gluons; test scalar and tensor glueballs

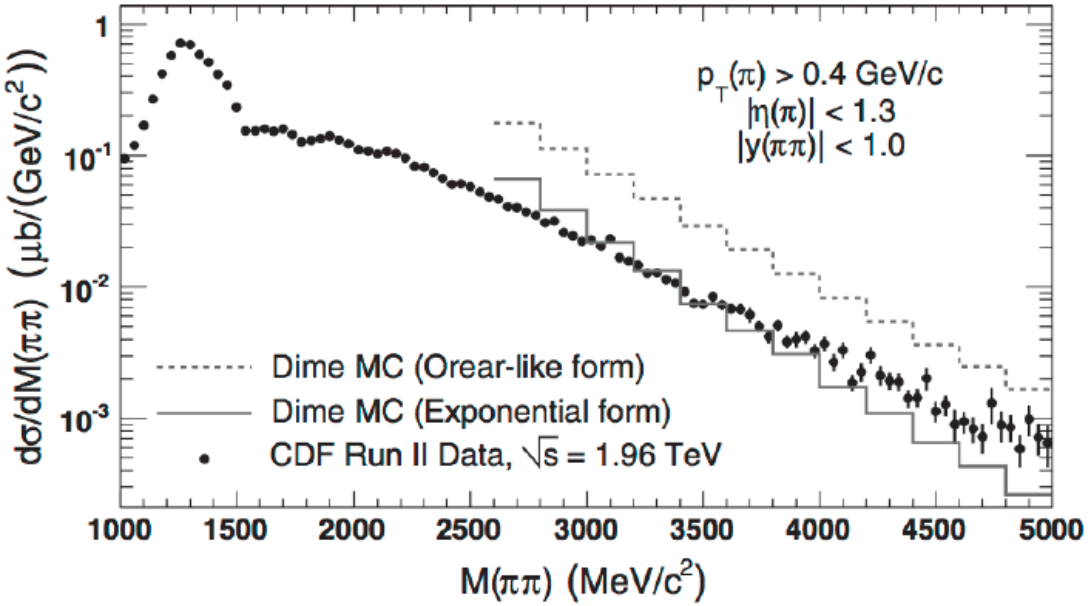
Select two charged particles with $|\eta|<1.3$, pT>0.4 GeV

- rapidity gap $1.3<|\eta|<5.9$
- analysis carried out at 1.96 and 0.9 TeV



Exclusive $\pi^+\pi^-$

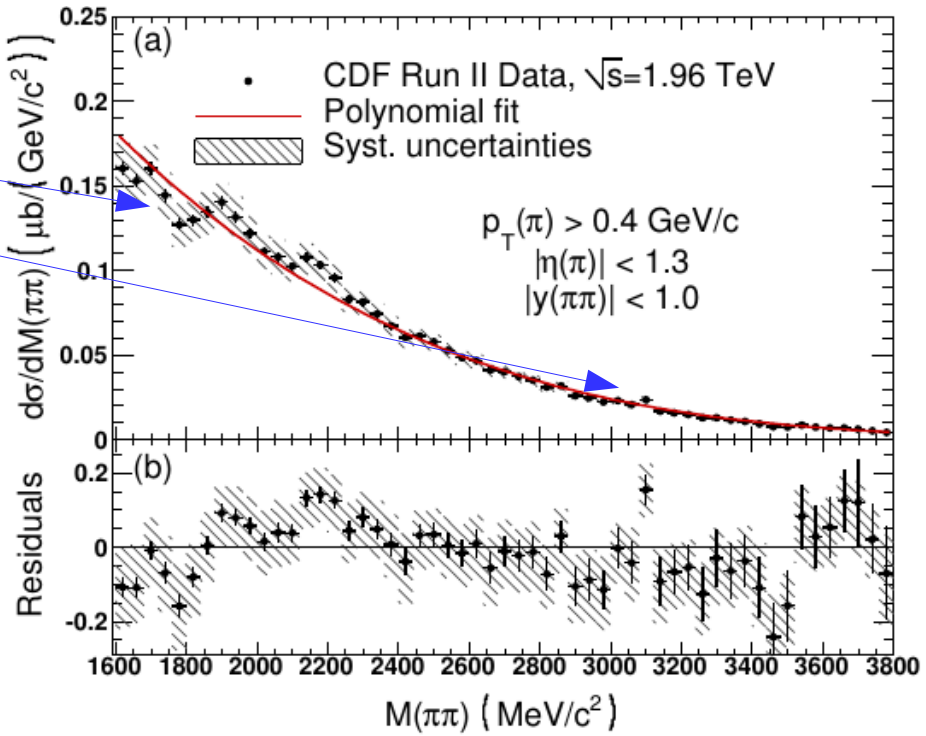
Prediction from DIME MC
- exponential form factor favoured



Structures up to 2400 MeV

Peak consistent with γ + IP → J/ψ → e^+e^-

No sign of χ_c^0(3415)
- set 90% CL limit on exclusive production:
  $d\sigma/dy\,|_{y=0} < 35.5\ (23.4)$ nb
  in the $\pi\pi$ (KK) decay modes



Λ Asymmetry

Asymmetry of Λ production:

- are Λ ($\bar{\Lambda}$) produced favourably close to the p (anti-p) beam direction?
- measure "rapidity loss" = y(proton) – y(Λ) or y(antiproton) - y($\bar{\Lambda}$)

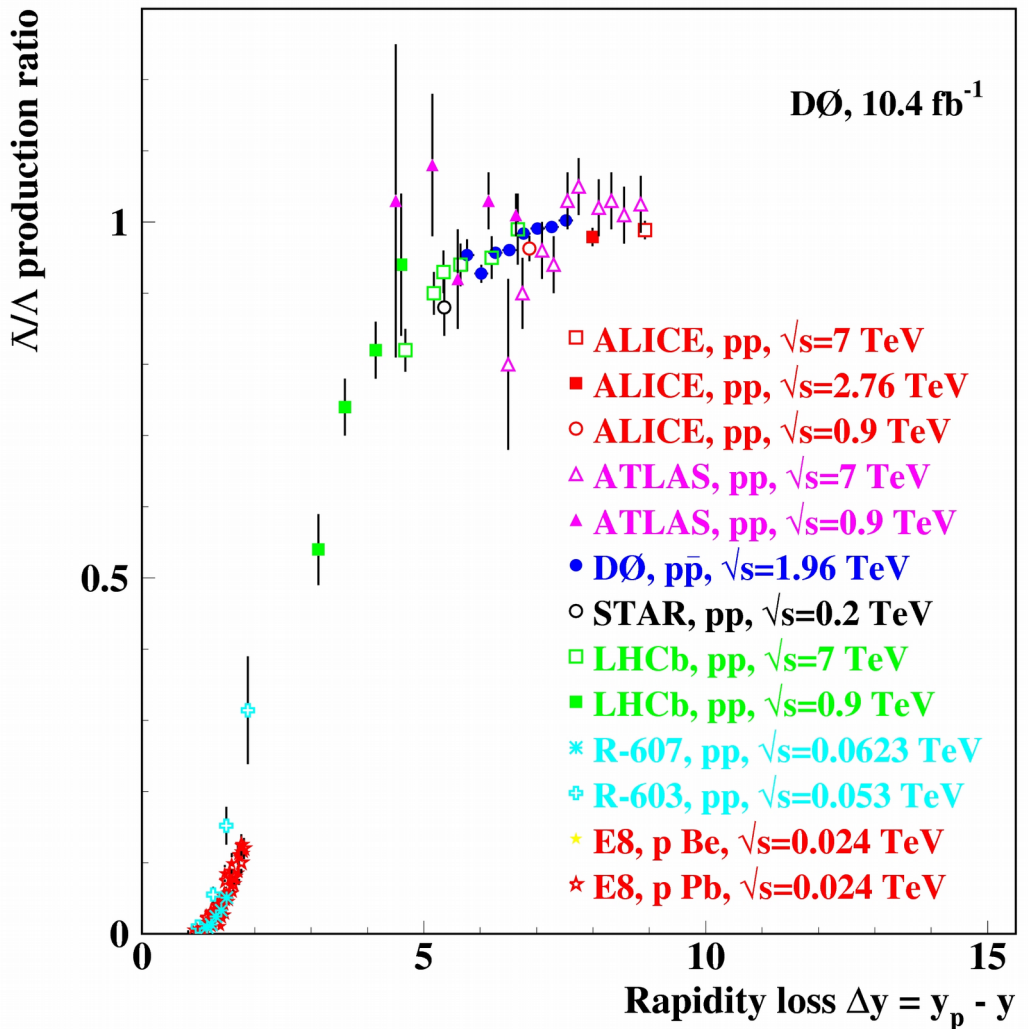
Measurement in three channels

- pp → $\Lambda(\bar{\Lambda})$X
- pp → J/$\psi\Lambda(\bar{\Lambda})$X
- pp → $\mu\Lambda(\bar{\Lambda})$X

Reconstruct $\Lambda \rightarrow p\pi$ at displaced vertex

New D0 result consistent with picture:

- real asymmetry
- appears independent of beam energy
- may result for strange quark coalescing with diquark from proton remnants



Phys. Rev. D93, 032002 (2016)

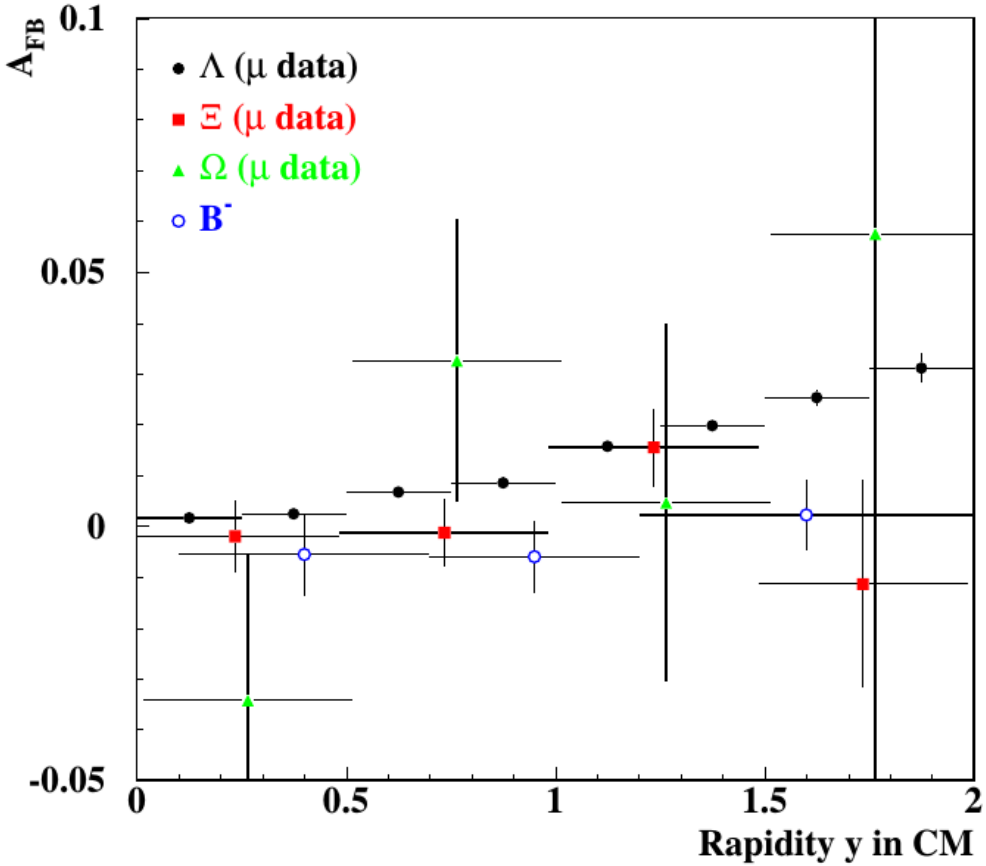
Ξ & Ω Asymmetry

Ξ (dss) and Ω (sss)

- don't share diquark with proton
- do not expect asymmetry

$$A_{FB} \equiv \frac{N_F - N_B}{N_F + N_B}$$

Ξ^- and Ω^- forward in p beam direction

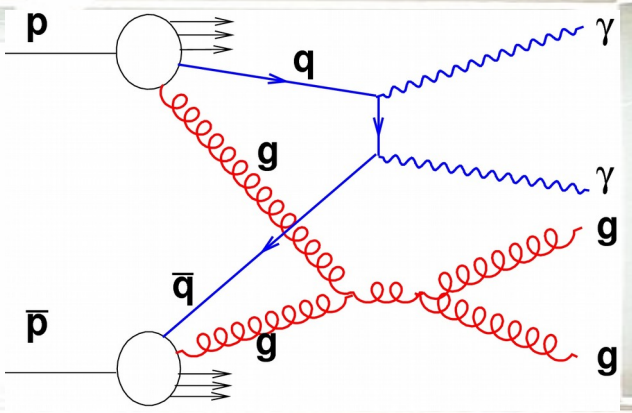


Phys. Rev. D 93, 112001 (2016)

For AFB (B^-, B^+) see Phys. Rev. Lett. 114, 051803 (2015).

For AFB (Λ_b , $\overline{\Lambda}_b$) see Phys. Rev. D 91, 072008 (2015).

Part 3:
double parton interactions



$$\sigma_{\mathrm{DP}}^{(1,2)} = \frac{m}{2}\frac{\sigma^{(1)}\sigma^{(2)}}{\sigma_{\mathrm{eff}}}$$

m = 2 for distinguishable processes

σ_{eff} depends on distribution of quarks and gluons in the proton
- should transfer to any process

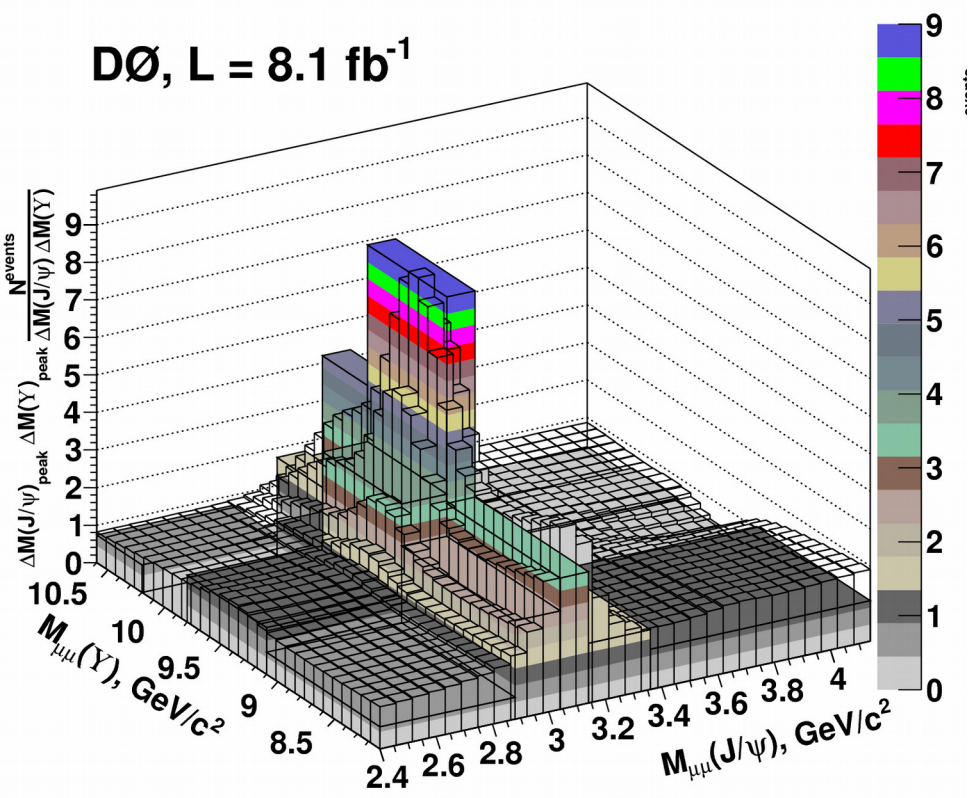
J/ψ + ϒ

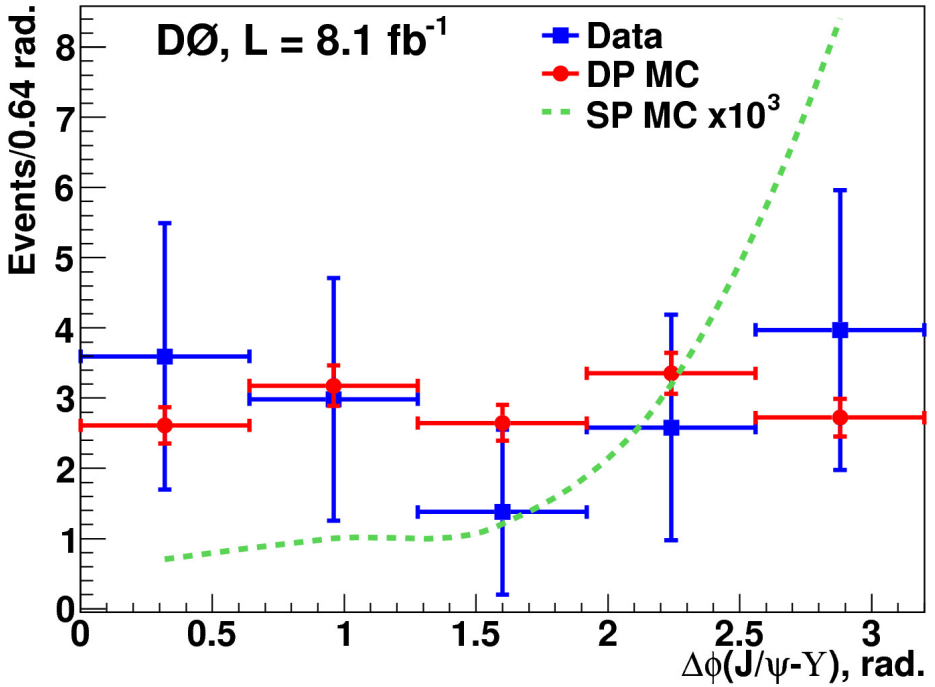
Select J/ψ and ϒ decaying to muons (muon pT>2, |η|<2)

- and require mass windows: 2.4 – 4.2 GeV, and 8 – 12 GeV

Fit 2D mass plot to extract simultaneous J/ψ + ϒ cross section:

- 12.0 ± 3.8 (stat) ± 2.8 (syst) events
  - first evidence of simultaneous production (3.2σ) !
- σ(J/ψ + ϒ) = 27 ± 9 (stat) ± 7 (syst) fb





J/ψ + ϒ

Extract σ_{eff}:

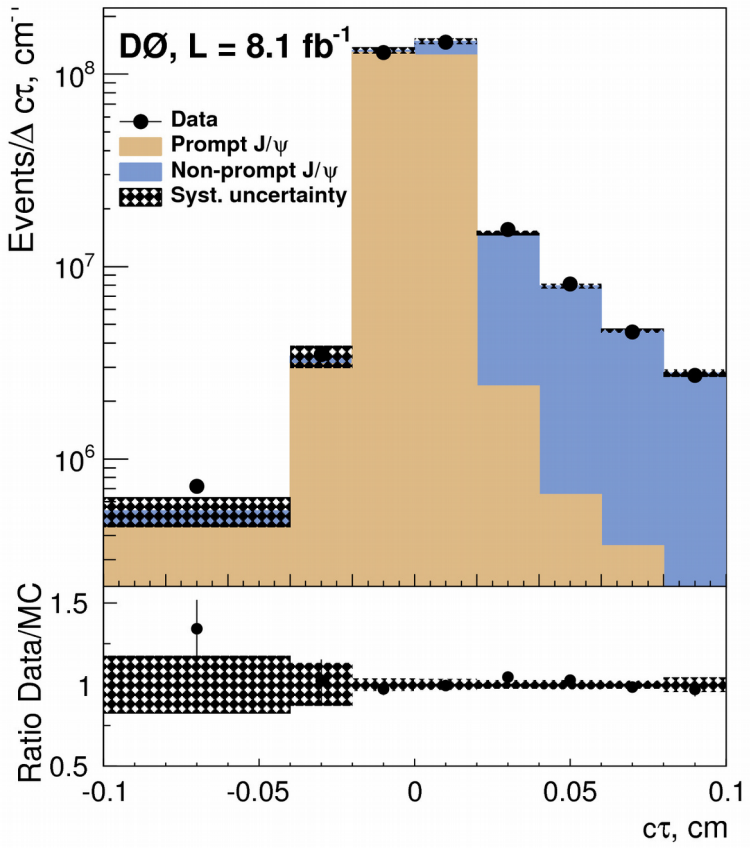
$$\sigma_{\rm eff} = \frac{\sigma(J/\psi)\sigma(\Upsilon)}{\sigma_{\rm DP}(J/\psi + \Upsilon)}$$

Fit non-prompt J/ψ, extract cross section:

σ(J/ψ) = 28 ± 7 (syst.) nb

Extrapolate σ(ϒ) from previous D0 measurement:

σ(ϒ) = 2.1 ± 0.3 (syst) nb



$$\sigma_{\rm eff} = 2.2 \pm 0.7(\text{stat.}) \pm 0.9(\text{syst.})\ \text{mb}$$

Phys. Rev. Lett. 116, 082002

Diphoton + dijet

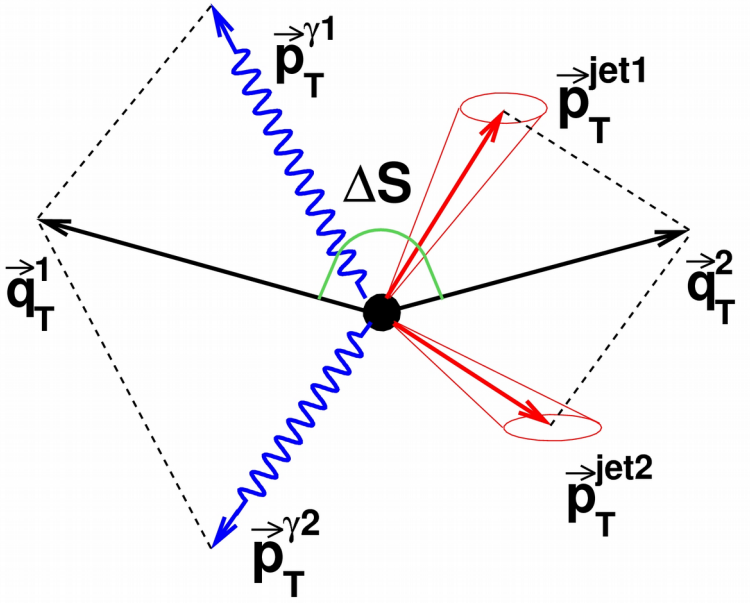
First measurement of DPI in diphoton + dijet

- extra background from separate $p\bar{p}$ interactions

Extract fraction of DPI using ΔS

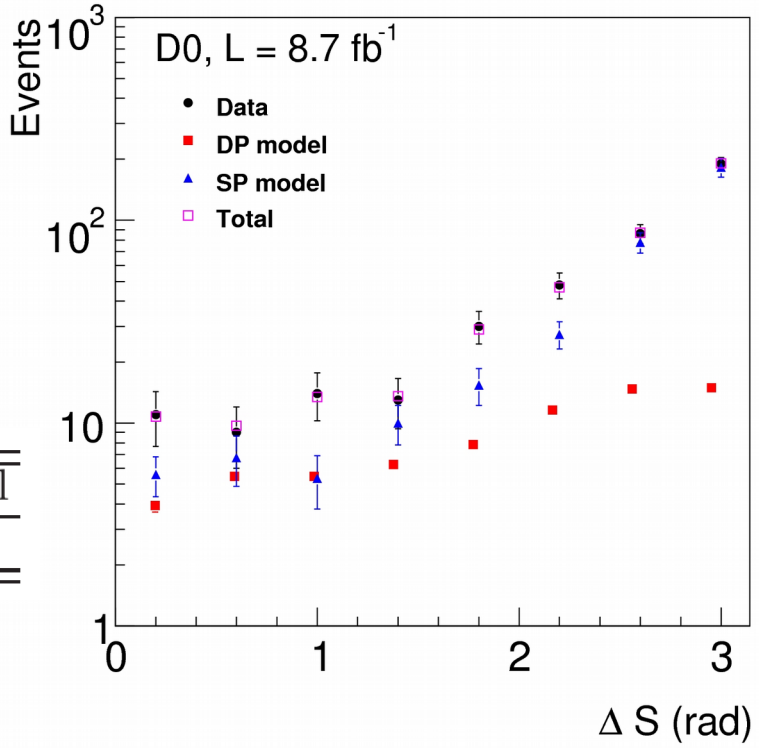
- require ΔS < X, for 7 values of X
- average:

$$f_{\mathrm{DP}}^{\mathrm{avg}} = 0.213 \pm 0.061(\mathrm{stat}) \pm 0.028(\mathrm{syst})$$



$$\sigma_{\mathrm{eff}} = 19.3 \pm 1.4(\mathrm{stat}) \pm 7.8(\mathrm{syst})\mathrm{mb}$$

f_{DP}	f_{DI}	EffRatio	Purity	JES	$R_c\sigma_{\mathrm{hard}}$	SystTotal	StatTotal	Total
31.0	18.7	7.1	7.2	13.2	2.6	40.2	6.9	40.8

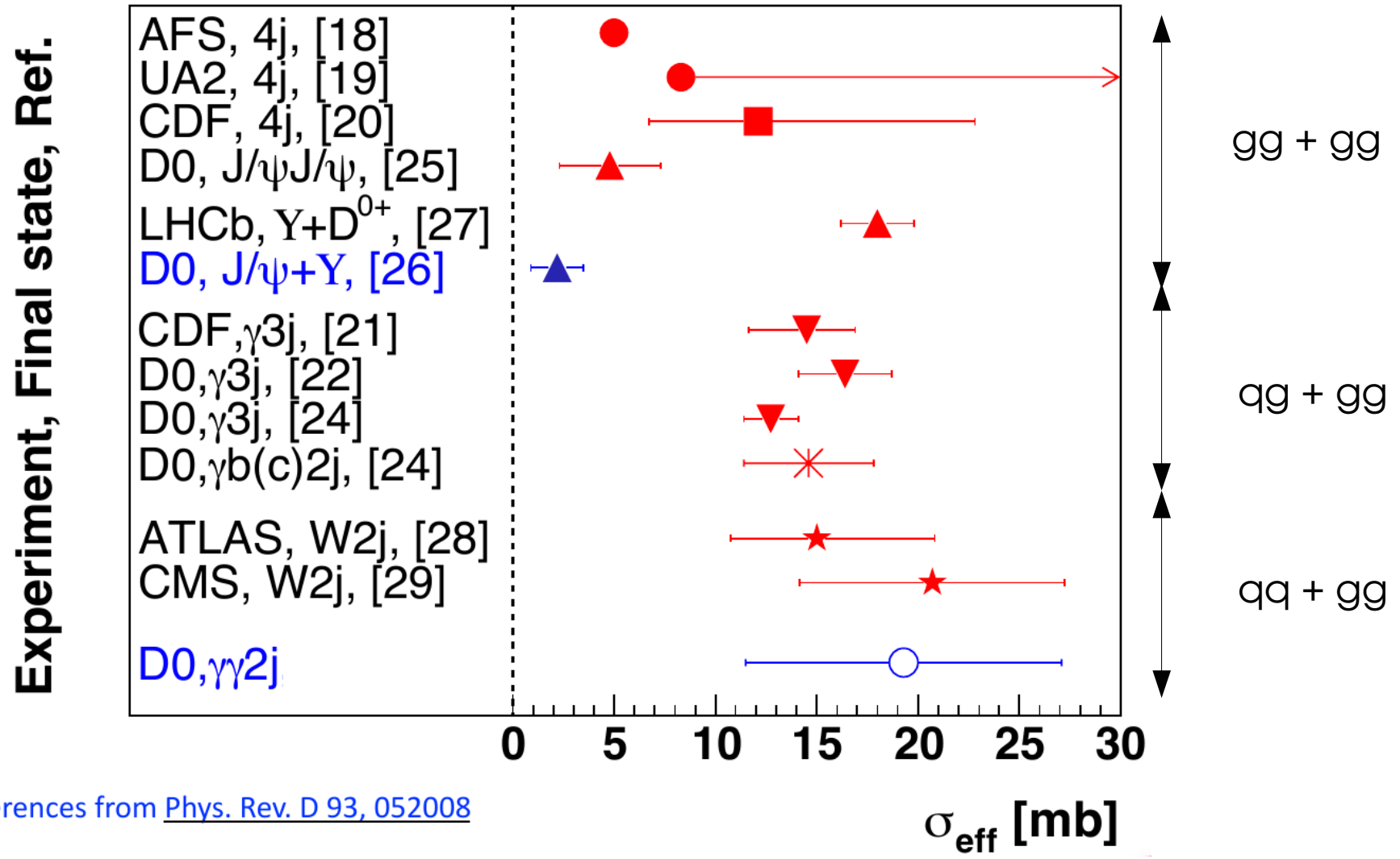


Phys. Rev. D. 93, 052008

DPI Summary

$J/\psi + \Upsilon$ consistent with $J/\psi J/\psi$, significantly lower than other processes

- dominated by gg initial state, others dominated by qq/qg
- indication gluons occupy smaller spacial region than quarks?



References from Phys. Rev. D 93, 052008

Conclusion

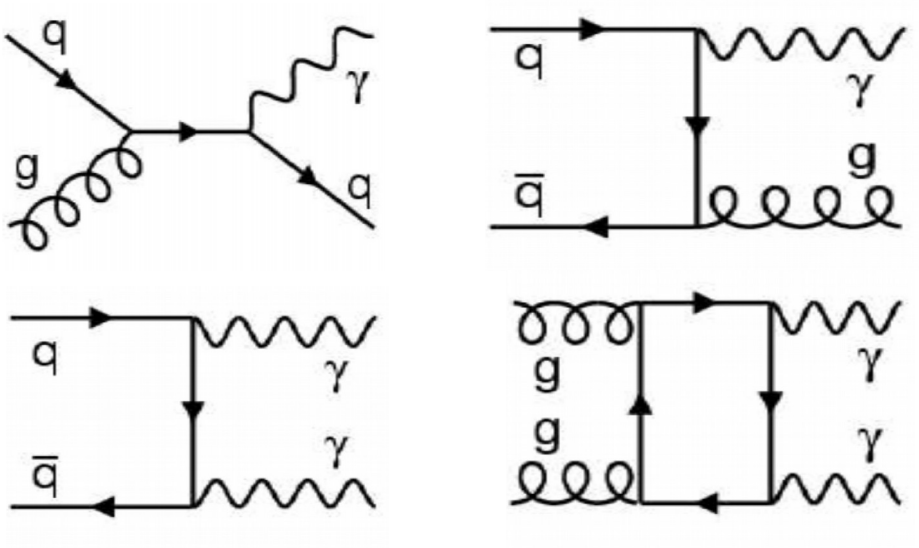
New results:

- inclusive photon CDF Note 11180
- W+jets CDF Note 11167
- exclusive $\pi\pi$ production PRD 91, 091101, 2015
- Λ asymmetry Phys. Rev. D93, 032002
- Ξ and Ω asymmetry Phys. Rev. D 93, 112001, 2016
- DPI in J/ψ + Υ Phys. Rev. Lett. 116, 082002
- DPI in $\gamma\gamma$ + dijet Phys. Rev. D. 93, 052008

Many "legacy" Tevatron QCD results available

- http://www-d0.fnal.gov/Run2Physics/WWW/results/qcd.html
- http://www-cdf.fnal.gov/physics/new/qcd/QCD.html

Inclusive Photon

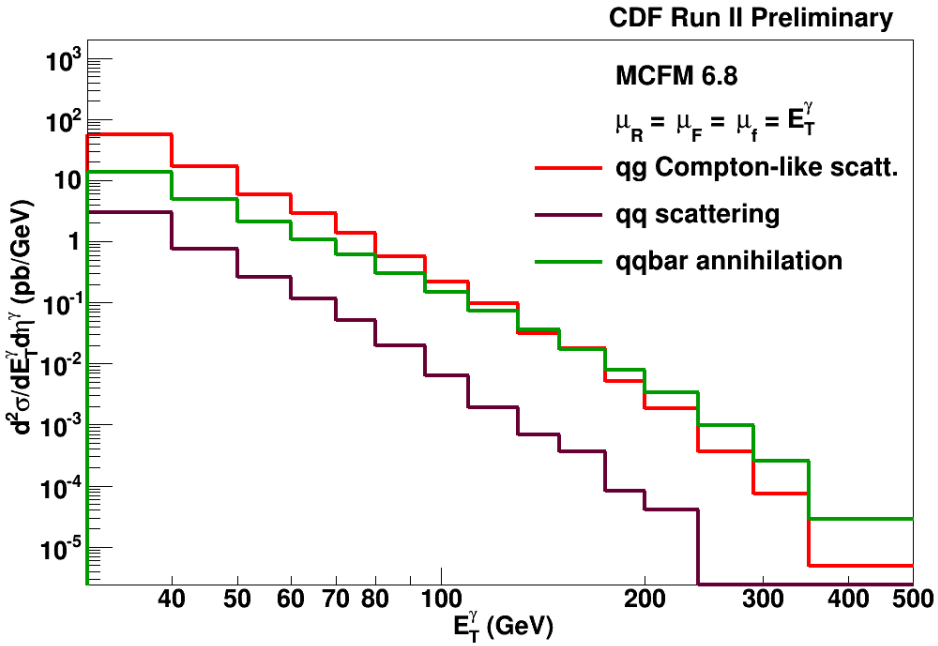


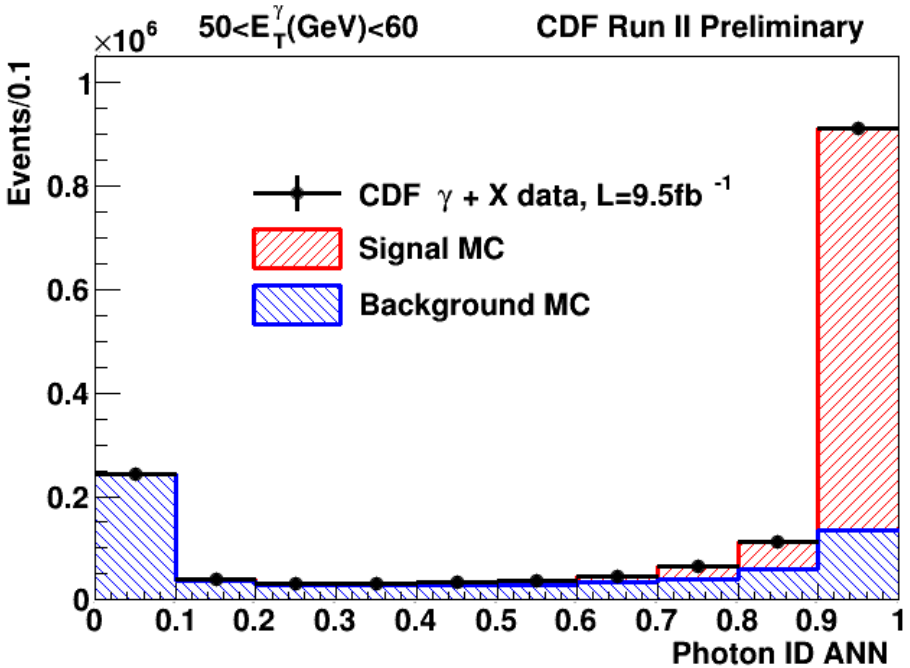
Trigger on & select isolated EM clusters:

- trigger thresholds 25 – 70 GeV
- low p_T triggers pre-scaled!

Photon ID based on:

- shower shapes, isolation, tracking
- $p_T > 30$ GeV, $|\eta| < 1.0$
- photon fraction varies from 50-80%





W+jets

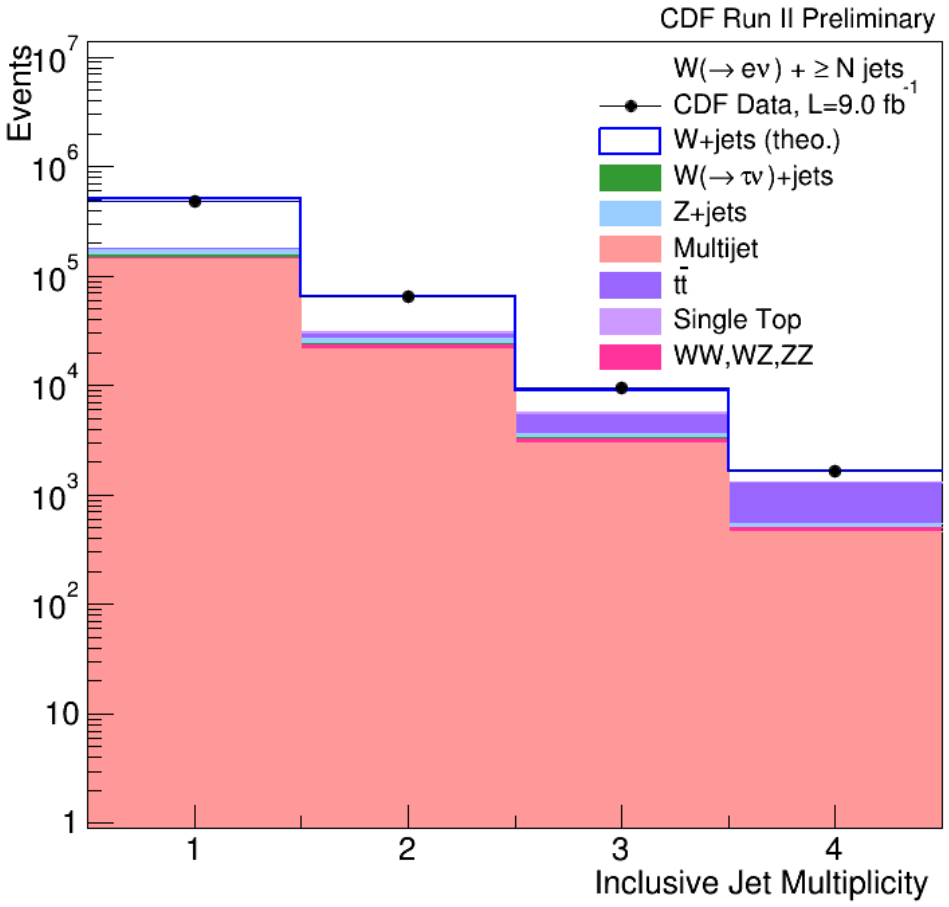
Use leptonic W decays to probe more complex final states

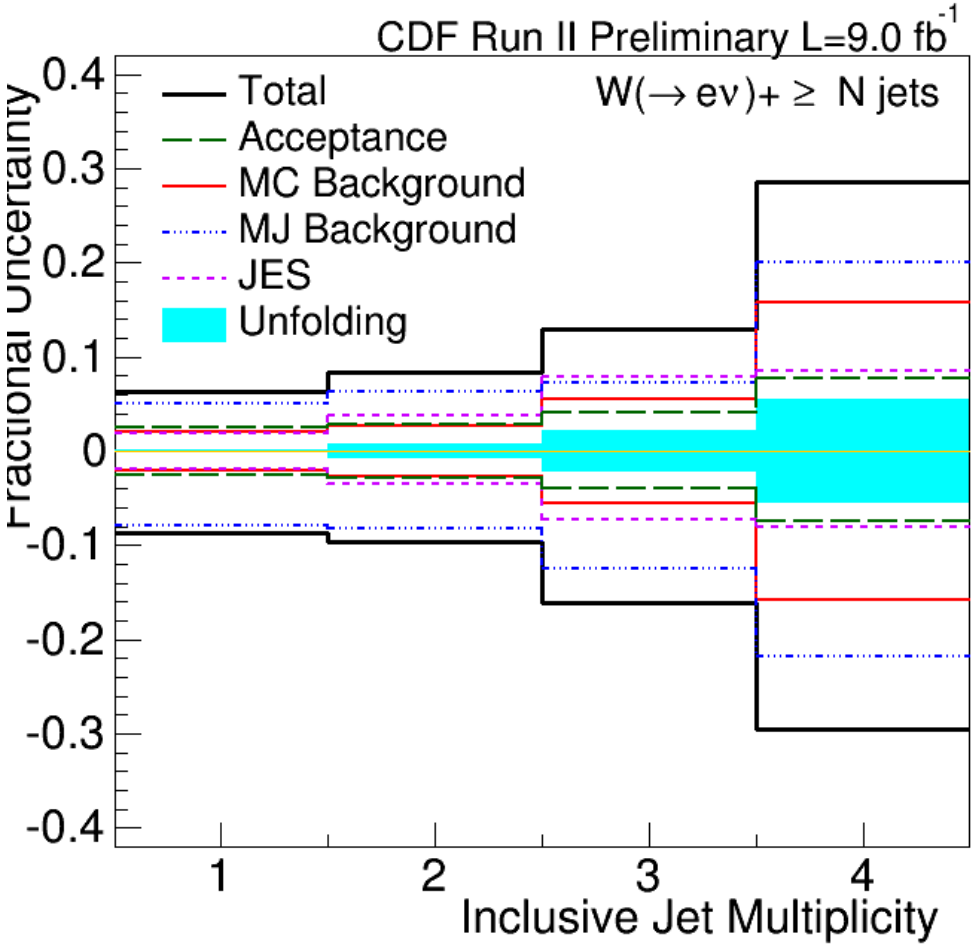
- select electron or muon with pT> 25 GeV, transverse mass > 40 GeV
- jets with E_T > 25 GeV

CDF Note 11167

Unfold to particle level using SVD method

- electron and muon channel then combined using BLUE





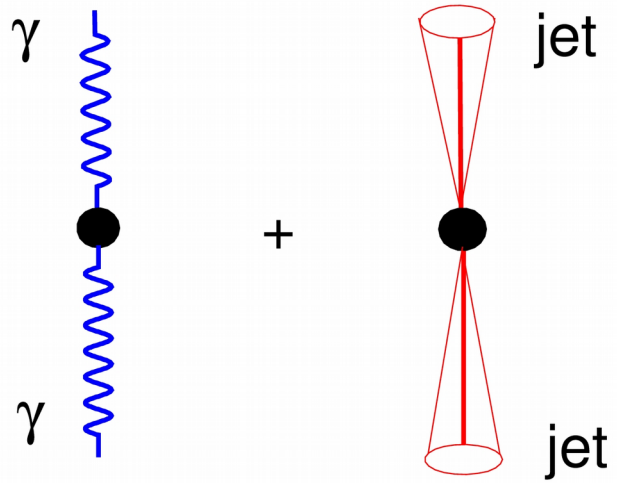
Diphoton + dijet

First measurement of double parton interactions (DP) in diphoton + dijet

- with diphotons, extra background from separate pp interactions (DI)

Use ratio instead of individual cross sections:

$$\sigma_{\text{eff}} = \frac{N_{\text{DI}}}{N_{\text{DP}}} \frac{A_{\text{DP}}}{A_{\text{DI}}} \frac{\epsilon_{\text{DP}}}{\epsilon_{\text{DI}}} \frac{\epsilon_{1\text{vtx}}}{\epsilon_{2\text{vtx}}} R_c \, \sigma_{\text{hard}}$$



where R_c = Nc(1)/2Nc(2)

- Nc(n) is the number of crossings with n hard scatters

Number of double interactions (DI) and number of double-parton scatters (DP) :

$$N_{\text{DI}} = f_{\text{DI}} P_{\text{DI}}^{\gamma\gamma} N_{2\text{vtx}}$$

$$N_{\text{DP}} = f_{\text{DP}} P_{\text{DP}}^{\gamma\gamma} N_{1\text{vtx}}$$

Photon purities ($P^{\gamma\gamma}$) essentially cancel. N_{DI} estimated using photon direction:

$$f_{\text{DI}} = 0.193 \pm 0.021 \ (\text{stat}) \pm 0.030 \ (\text{syst})$$

DPI

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

$F(\beta) = \int f(b) f(b-\beta) d^2 b$,
β is the impact parameter for the two colliding hadrons,
$f(b)$ is a function describing the spatial distribution of the parton matter inside a hadron.

$$\sigma_{\mathrm{DP}}^{(1,2)} = \frac{m}{2} \frac{\sigma^{(1)} \sigma^{(2)}}{\sigma_{\mathrm{eff}}}$$