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Double Parton Scattering in $p\bar{p}$ Interactions

Simultaneous J/ψ and ϒ production
Diphoton + Dijet events

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for the D0 Collaboration
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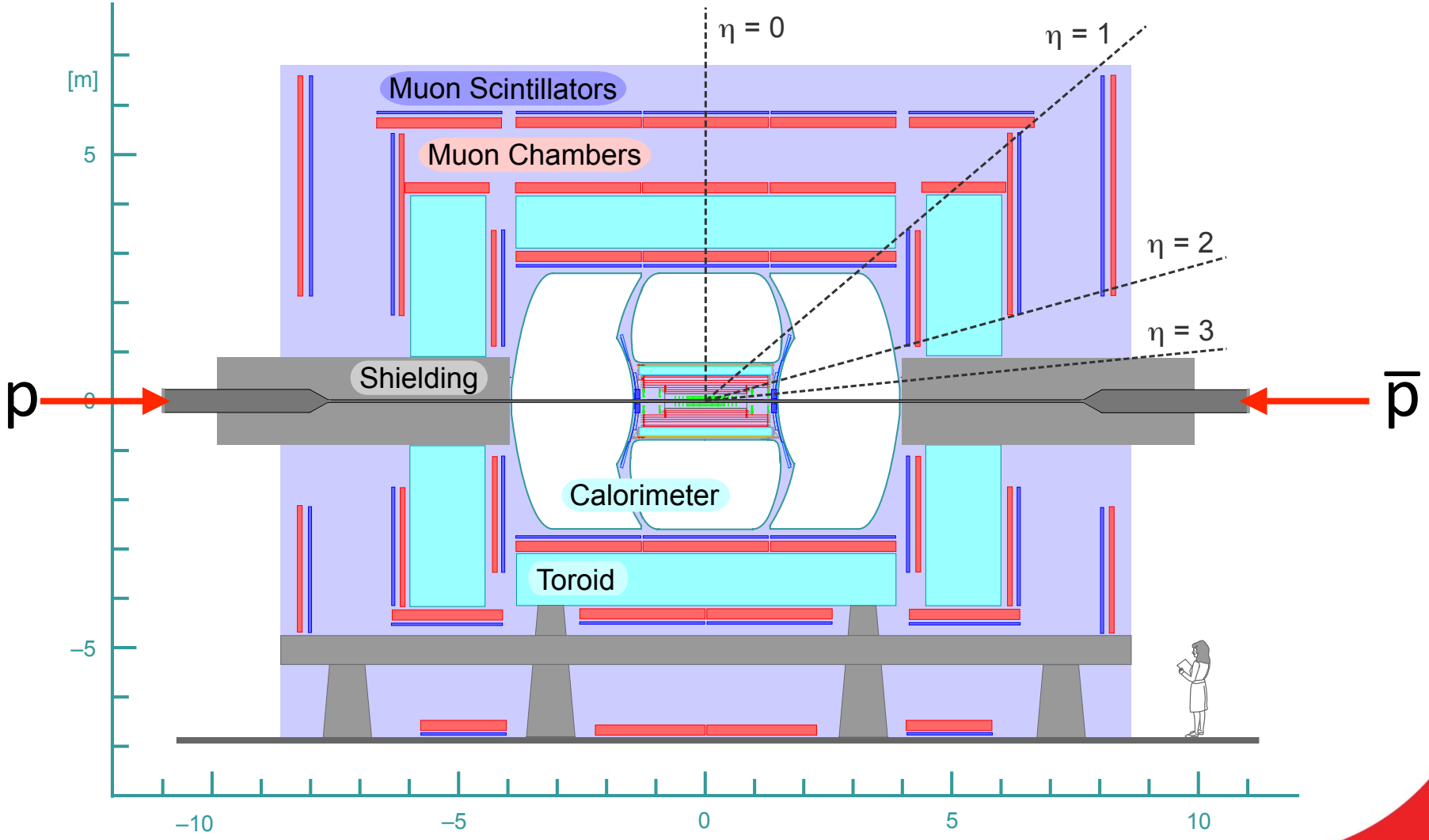
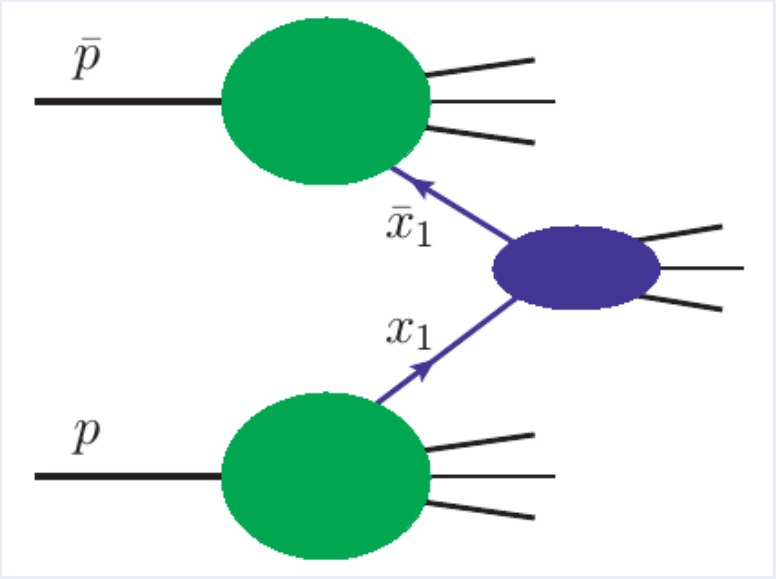
The D0 Detector

- Multi-purpose, high acceptance, well understood detector.
  Excellent jet reconstruction, muon id and acceptance. $\int \mathscr{L} dt \sim 10\ fb^{-1}$

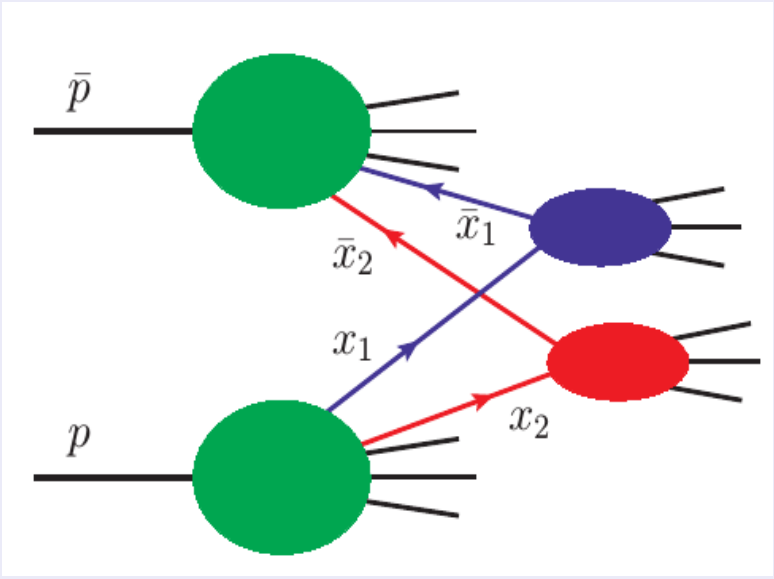


Double Parton Scattering

Single Parton Scattering(SPS,SP)



Double Parton Scattering(DPS,DP)



Double Parton Scattering

dominated by $q\bar{q}$ + gg

$\gamma\gamma + 2jets$, $W + 2jets$

dominated by qg + gg

$\gamma + 3jets$

dominated by gg + gg

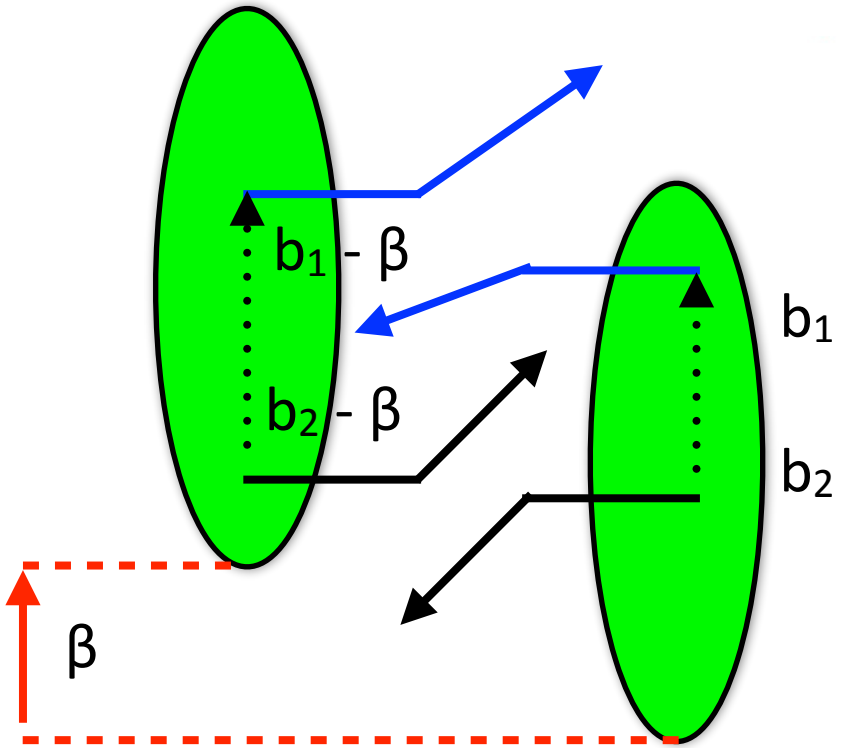
$4jets$, $J/\psi J/\psi$, $J/\psi\Upsilon$

Effective Cross Section

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

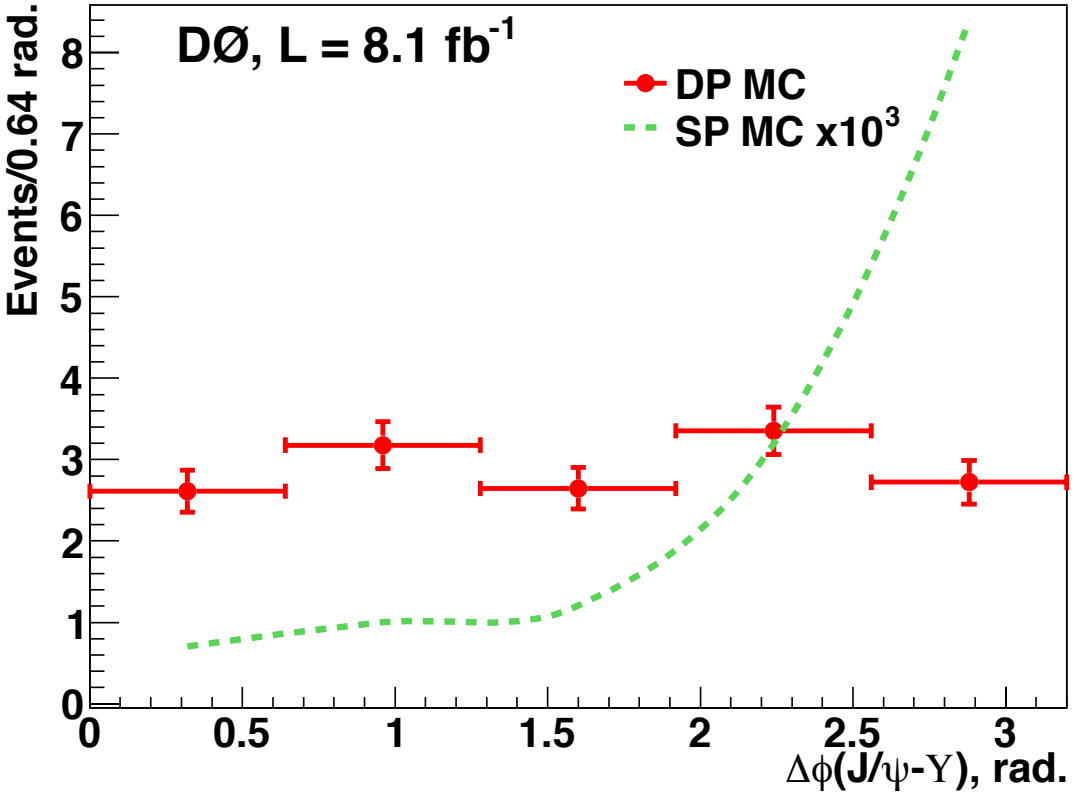
$F(\beta) = \int f(b) f(b-\beta) d^2 b$,
β is the impact parameter for the two colliding hadrons,
$f(b)$ is a function describing the spatial distribution of the parton matter inside a hadron.

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



Simultaneous J/ψ and ϒ production

- Double parton scattering is expected to dominate at the Tevatron.
  - J/ψ and ϒ should be produced in gluon-gluon interactions.
- Measure
  - Single J/ψ cross section
  - Double parton J/ψ and ϒ cross section
- Estimate
  - Single ϒ cross section
- Calculate



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

Simultaneous J/ψ and ϒ production

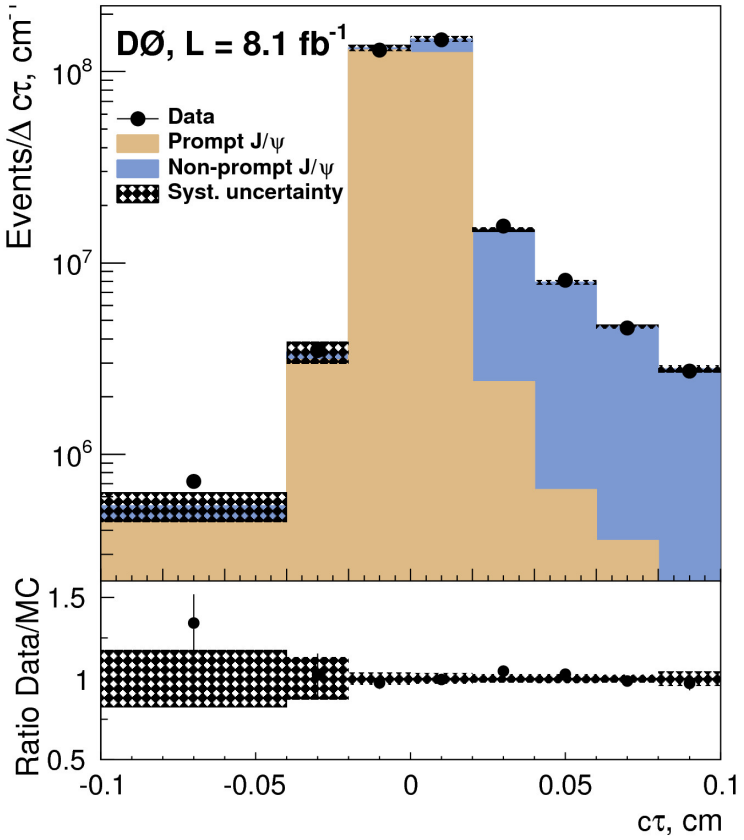
- Data Selection: J/ψ (ϒ) → $\mu^+\mu^-$
  - $p_T^{\mu} > 2$ GeV, $|\eta^{\mu}| < 2.0$
  - For J/ψ select candidates with $2.88 < M_{\mu\mu} < 3.36$ GeV
  - For ϒ select candidates with $9.1 < M_{\mu\mu} < 10.2$ GeV

- Prompt J/ψ Cross section
  - Maximum likelihood fit of cτ

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

  - Single J/ψ prompt fraction is 0.83 ± 0.03 (syst.)

$$\sigma(J/\psi) = 28 \pm 7(\text{syst.})\ \text{nb}$$

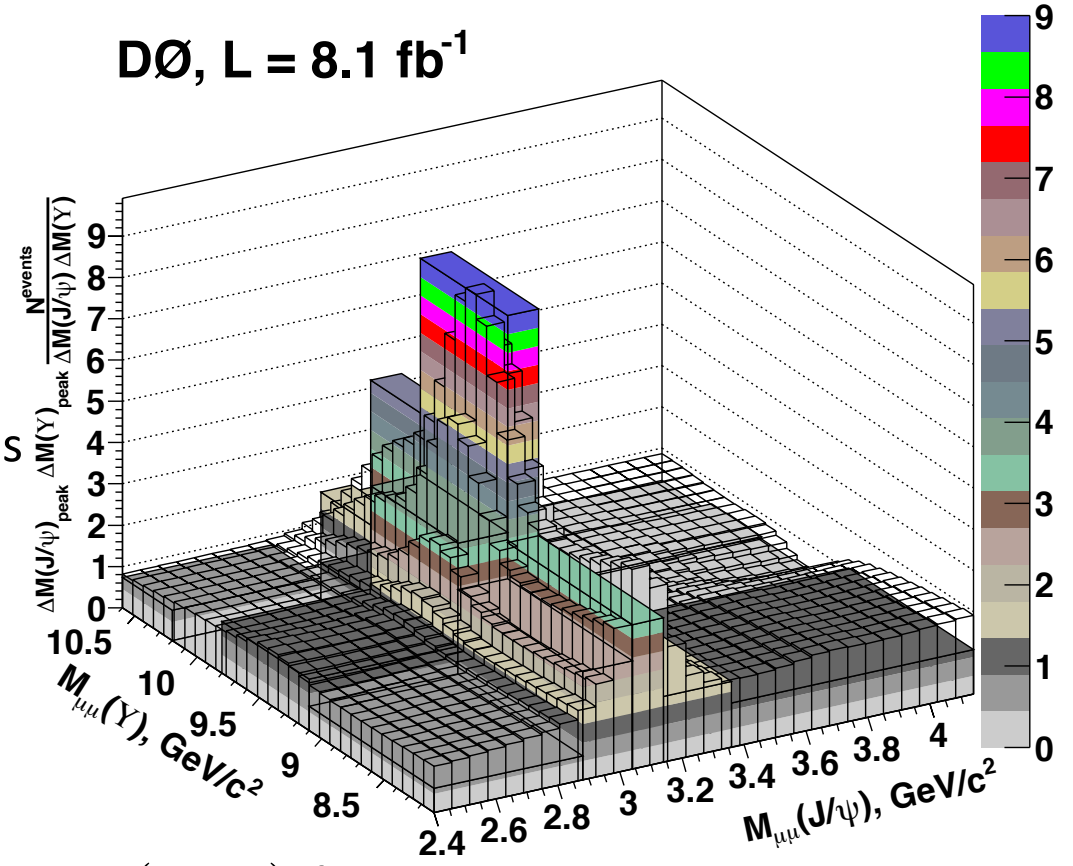


Simultaneous J/ψ and ϒ production

- Cross section for single ϒ production extrapolated from previous D0 measurements to the fiducial region of this analysis

$$\sigma[\Upsilon(1S;2S;3S)] = 2.1 \pm 0.3(\text{syst.})\ \text{nb}$$

- Extract prompt number J/ψ and ϒ events
  - fit of 2D distribution
  - Number of J/ψ+ϒ events is 12.0 ± 3.8 (stat) ± 2.8 (syst).
  - First evidence of simultaneous production (3.2 σ)
  - Extract Cross section



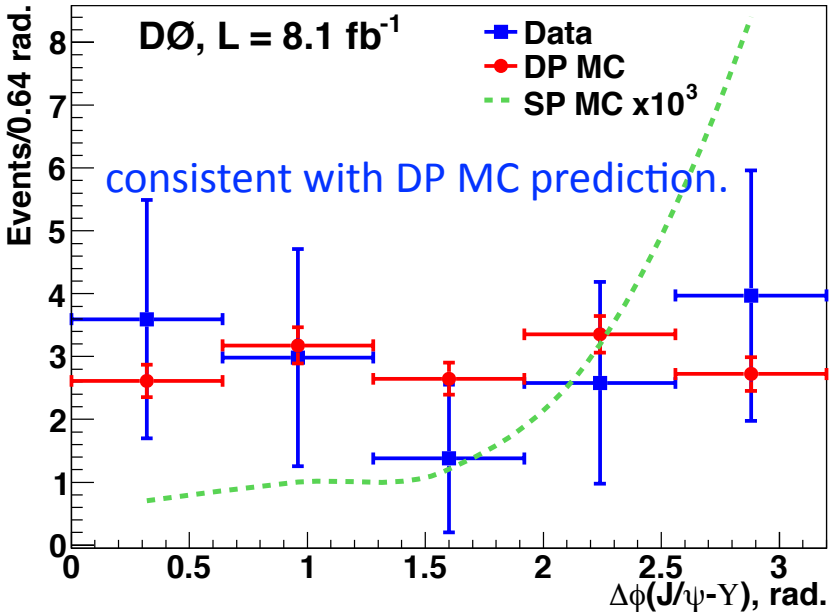
$$\sigma[J/\psi + \Upsilon] = 27 \pm 9\,(\text{stat}) \pm 7\,(\text{syst})\,\text{fb}$$

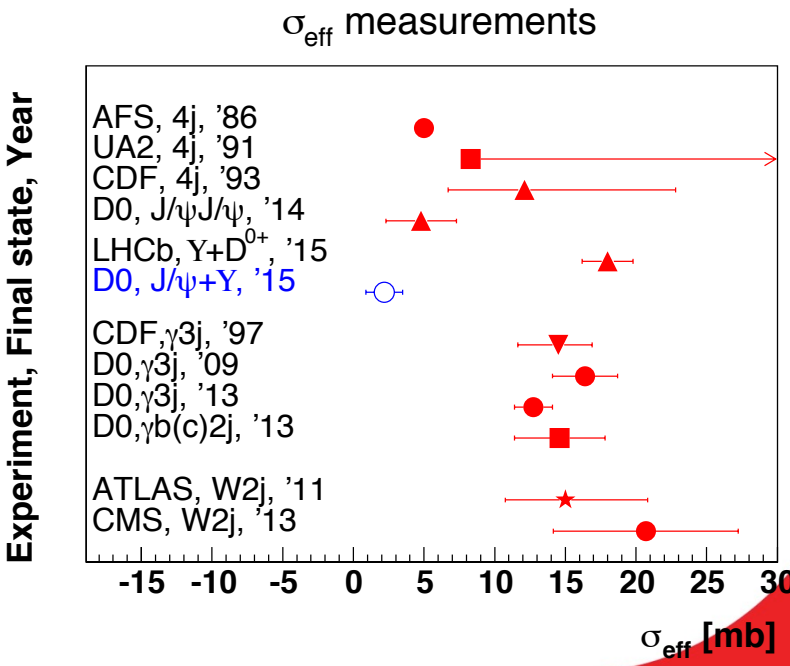
Simultaneous J/ψ and ϒ production

- Extract σ_{eff}

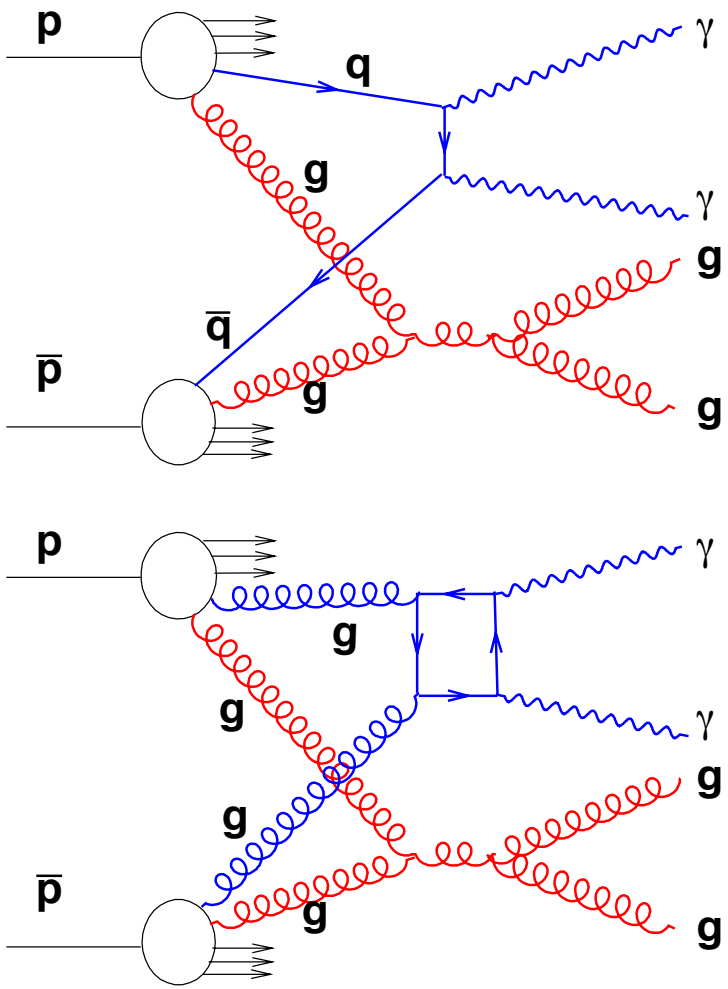
$$\sigma_{\rm eff} = 2.2 \pm 0.7(\rm stat.) \pm 0.9(\rm syst.)\ \rm mb$$

  - Measurement consistent with D0's J/ψJ/ψ value of σ_{eff} .
  - **σ_{eff}** much smaller than previously measured qq and qg dominated processes.
  - possible indication that spatial region occupied by gluons smaller than that occupied by quarks





Diphoton + Dijet events



- First measurement of double parton scattering in diphoton plus dijet events
  - Need to measure the number of dijets and diphotons produced in different $p\bar{p}$ interactions in same crossing (DI).
    - Events with 2 vertices
  - Also measure double parton (DP) fraction from data using ΔS (see later).
    - Events with 1 vertex

Diphoton + Dijet events

- Extract σ_{eff} using

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

where $R_c = N_c(1)/2N_c(2)$

$N_c(n)$ is the number of beam crossings with n hard collisions

- where

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

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

and $f_{DI(DP)}$ is the fraction of DP(DI) events in the sample, $P^{\gamma\gamma}$ is the diphoton purity and N_{nvtx} is the number of events with exactly 1 or 2 reconstructed primary vertices,

- Note the γγ and jj cross sections cancel in this ratio.
  - the ratios reduce systematic uncertainties.

Diphoton + Dijet events

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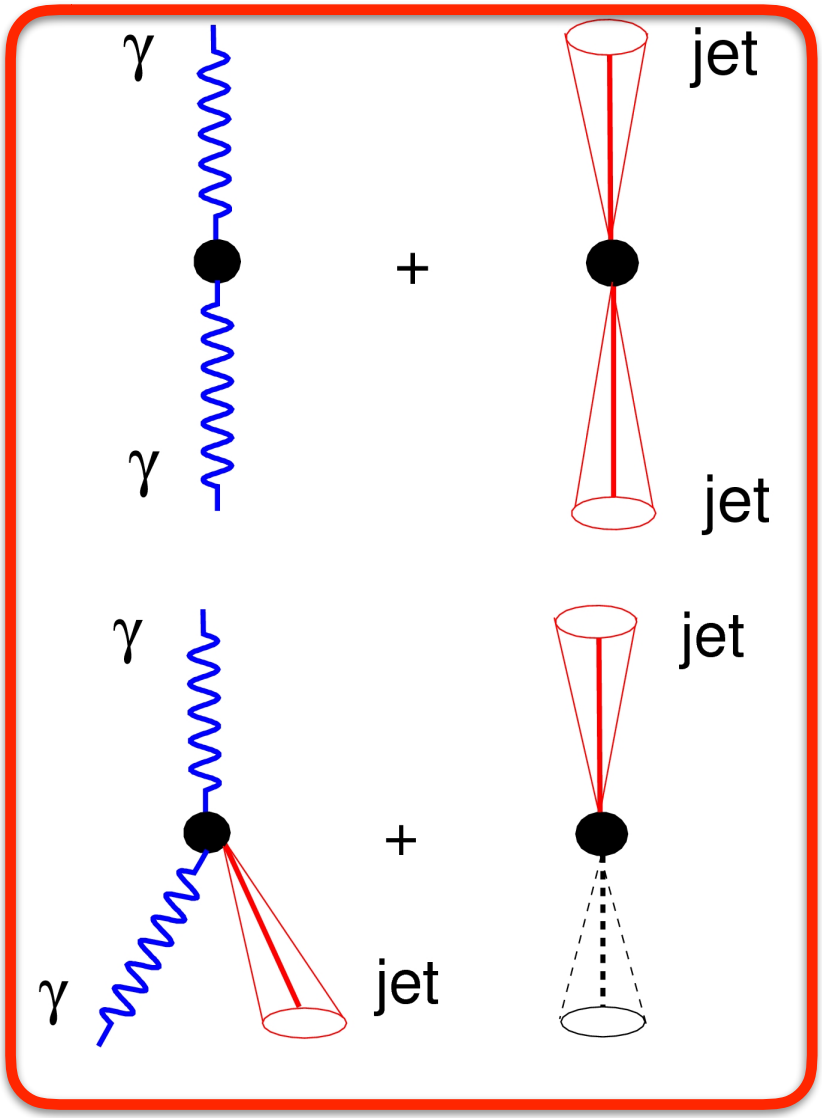
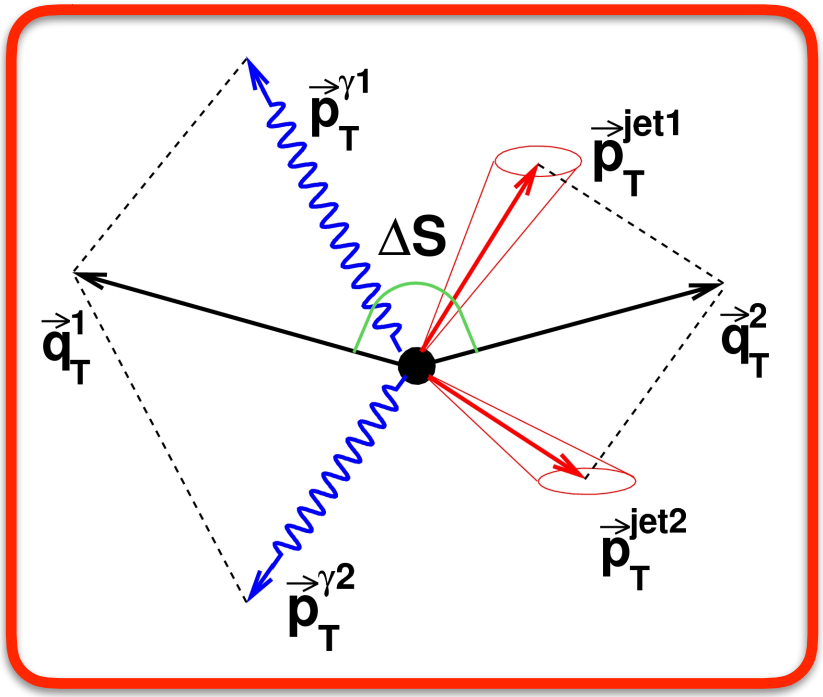
Signal



Background



$$\Delta S \equiv \Delta\phi\left(\vec{q}_{\mathrm{T}}^{\,1},\ \vec{q}_{\mathrm{T}}^{\,2}\right),$$

Use ΔS to model fraction of SP and DP events

Diphoton + Dijet events

- DP fraction is found
  - As a function of ΔS

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

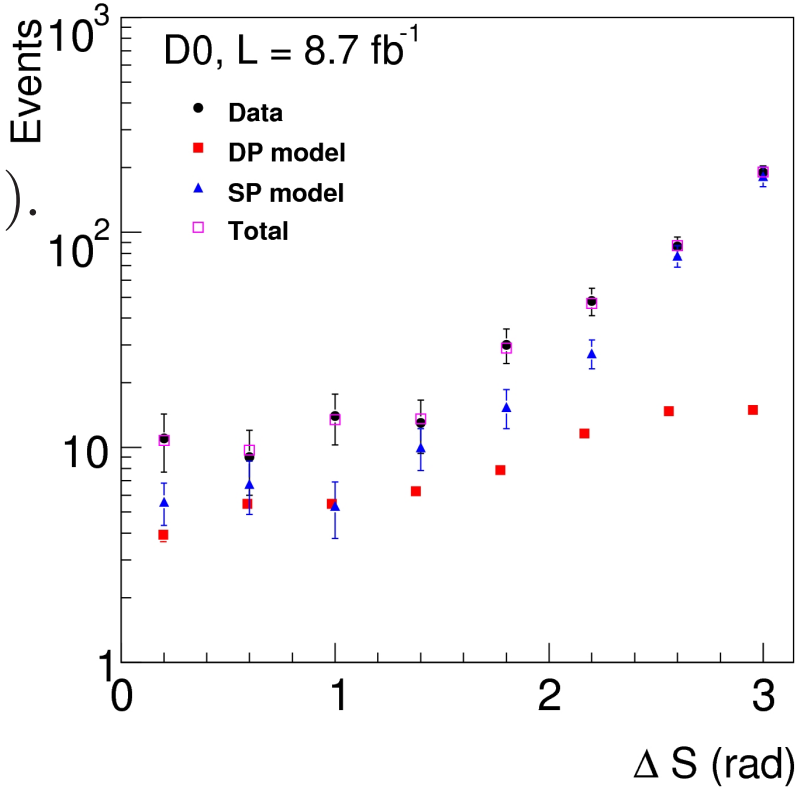
  - as a cross check for SP and DP model to data: $f_{DP} = 0.18 \pm 0.11$

- DI fraction calculated using charged particle fraction and photon direction.

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

- Photon purities
  - Max likelihood fit using MC templates for jets (Pythia) and photons (pythia and sherpa)

$$P_{\mathrm{DI}}^{\gamma\gamma} / P_{\mathrm{DP}}^{\gamma\gamma} = 1.002 \pm 0.039$$



Diphoton + Dijet events

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

- We determine that $R_c\sigma_{\rm hard} = 18.92 \pm 0.49$ mb.
- giving

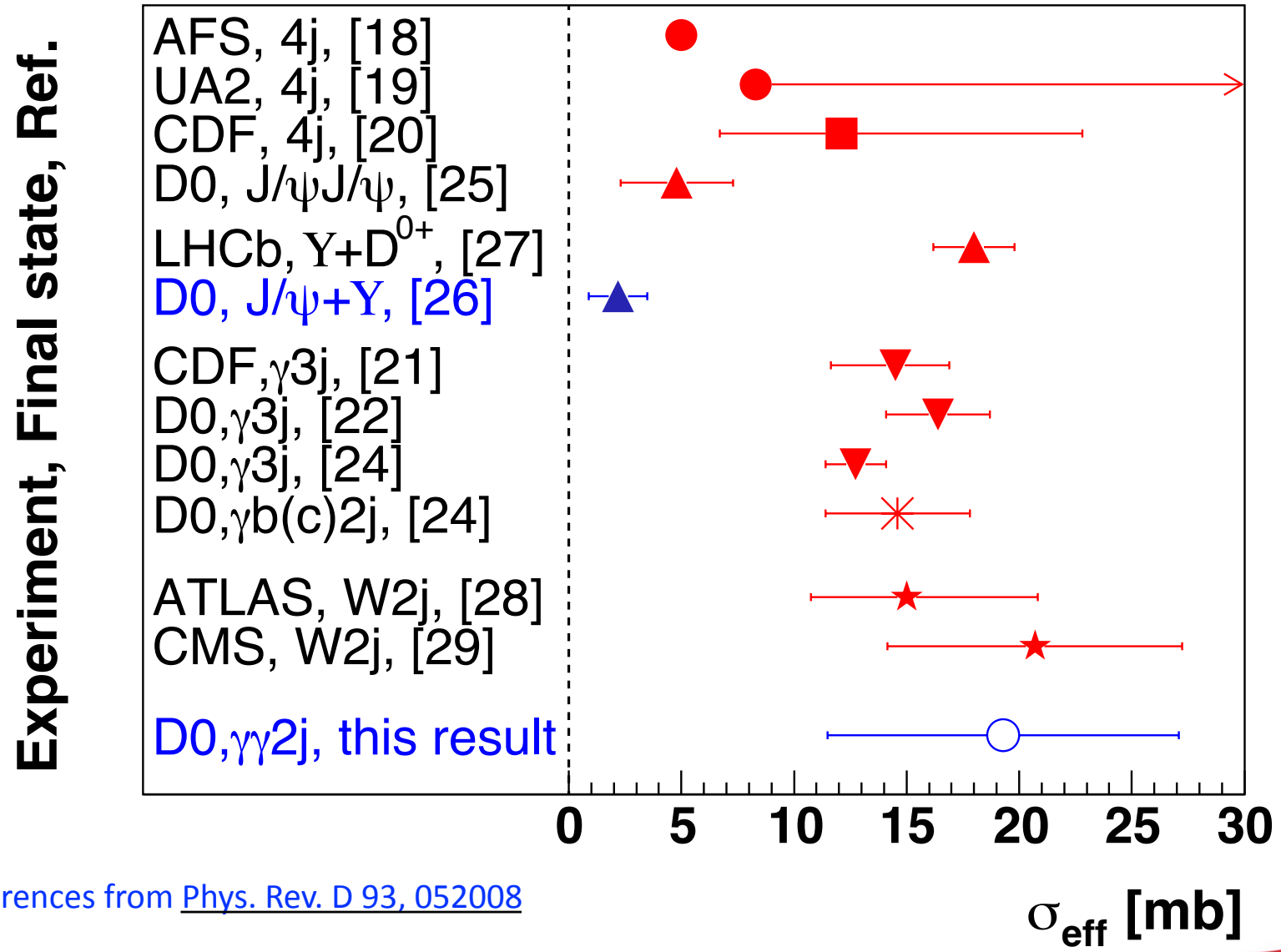
$$\sigma_{\rm eff} = 19.3 \pm 1.4({\rm stat}) \pm 7.8({\rm syst}){\rm mb}.$$

- and the percentage uncertainties are

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

Summary of Results

σ_{eff} measurements



References from Phys. Rev. D 93, 052008

Conclusions

- First evidence of simultaneous production of J/ψ and ϒ mesons and measurement if the effective cross section.
  - Phys. Rev. Lett. 116, 082002

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

- First measurement of double parton scattering in diphoton plus dijet events.
  - Phys. Rev. D 93, 052008

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

Diphoton + Dijet events

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

	DP	DI	Ratio
A_{DP}/A_{DI}	0.429 ± 0.008	0.826 ± 0.019	0.521 ± 0.015
$\varepsilon_{DP}/\varepsilon_{DI}$ (sherpa)	0.477 ± 0.035	0.333 ± 0.021	1.372 ± 0.039
$\varepsilon_1/\varepsilon_2$ (vertex)	0.944 ± 0.003	0.922 ± 0.003	1.021 ± 0.005
$P^{\gamma\gamma}_{DI} / P^{\gamma\gamma}_{DP}$			1.002 ± 0.039

$$R_c \sigma_{\rm hard} = 18.92 \pm 0.49 \text{ mb}.$$

- and the percentage uncertainties are

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

- giving

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