Exclusive central $\pi^+\pi^-$ production in CDF a.k.a. double pomeron exchange DPE at $\sqrt{s}$ = 1960 GeV and 900 GeV

Collider Detector at Fermilab (CDF) Detector

Triggers and data sets

Exclusivity cut and luminosity normalization

Mass distributions before correcting for acceptance and efficiency

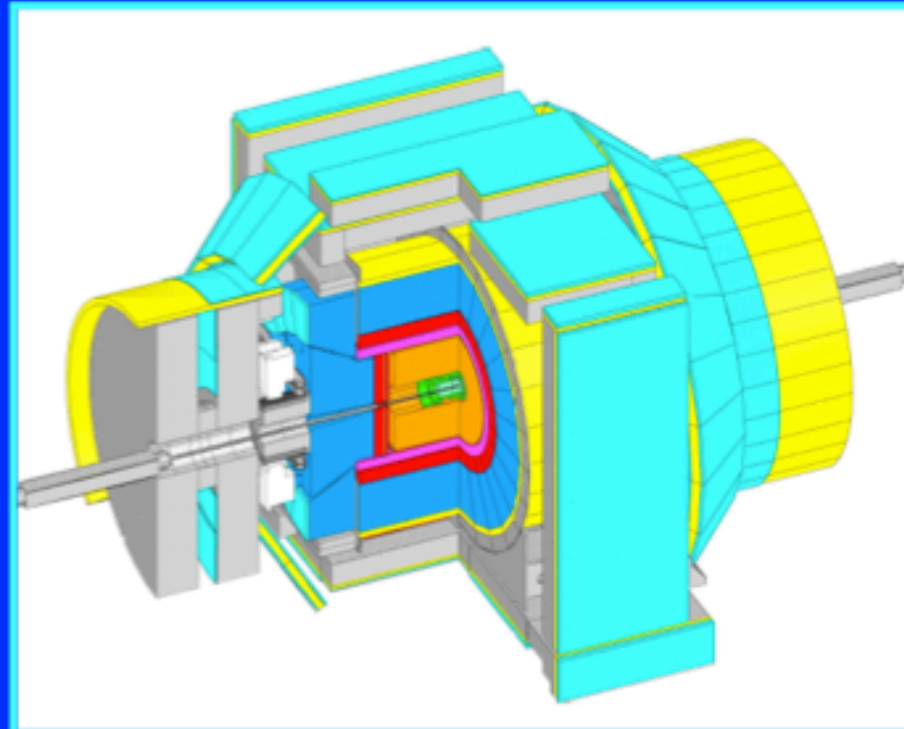
Corrections and cross sections: Mass $M(\pi\pi)$, p_T, s-dependence
J/ψ and χ_c limits.

Future studies

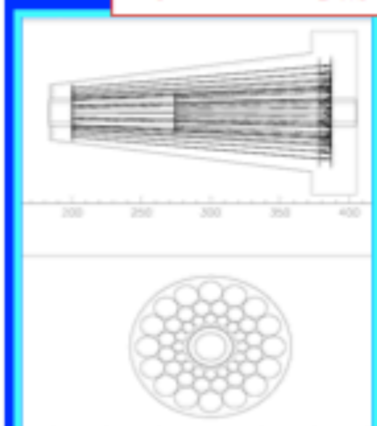
CDF: *The Collider Detector at Fermilab*

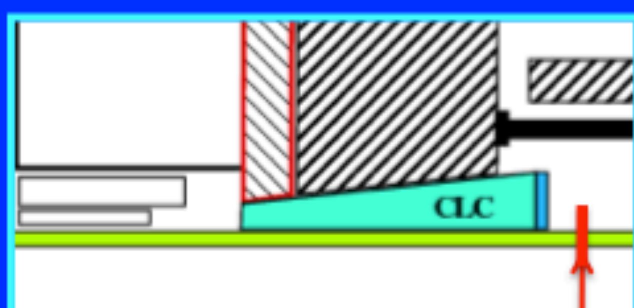
CENTRAL:

Silicon tracker
Drift chamber tracker
Time-of-Flight barrel
EM calorimeters
Hadron Calorimeters
Muon chambers



CLC = Cherenkov Luminosity Counters.
48 PMT + Gas cones / side





BSC1

BSC1 counters
$|\eta| = 5.4 - 5.9$
Pb in front.
4 PMTs/side

Triggers: BSC1veto & Plug veto
& [2 TOW > 0.5 GeV (or JET > 5 GeV or Track > 2 GeV/c)]

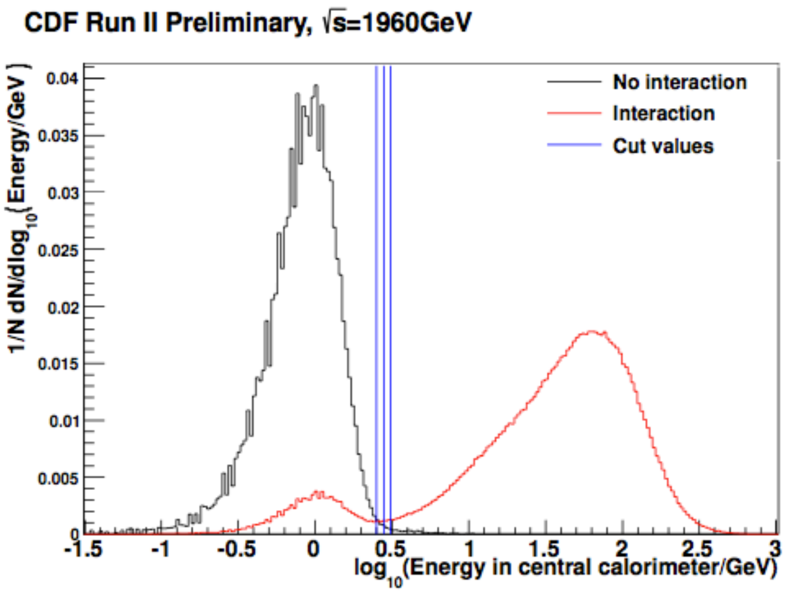
Trigger as soft as possible: 2 TOW > 0.5 GeV in $|\eta| < 1.3$
Veto on BSC1 both sides: kills most pile-up and is a "gap seed".
Level 2 Veto on Plug both sides.
Little pile-up left. Trigger comes in at end of stores.
90 million GXG triggers at 1960 GeV!
Off-line require all CDF detectors in noise except for 2(4) tracks (& their clusters)

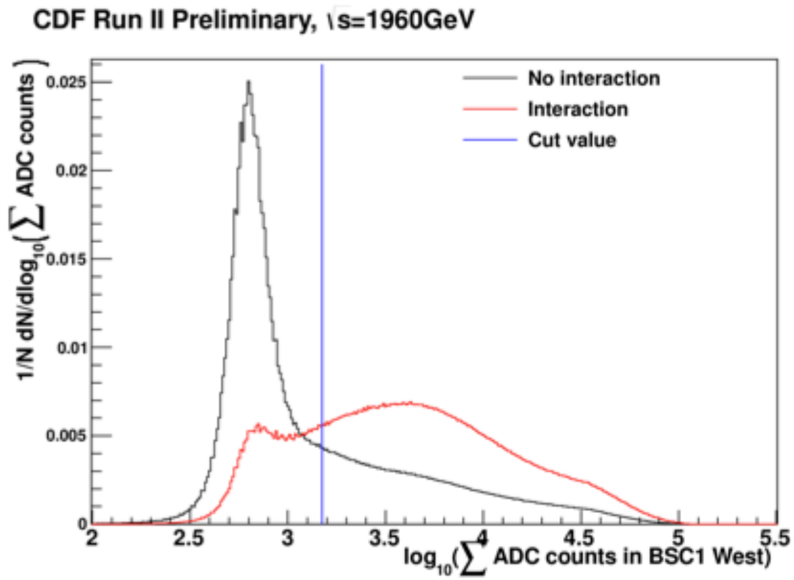
Data summary

√s	0-bias (E)	minbias (G)	Gap-X-Gap (C)	Jets (J)	e,μ,γ (B)	Total # events
300	1.89 M	12.1 M	9.2 M	8.3 K	352	23.2 M
900	8.0 M	54.3 M	21.8 M	550 K	16 K	84.7 M

← 38 hours

Noise levels → empty detector, exclusivity cuts and σ(vis) : examples





Energy in Central Calorimeter

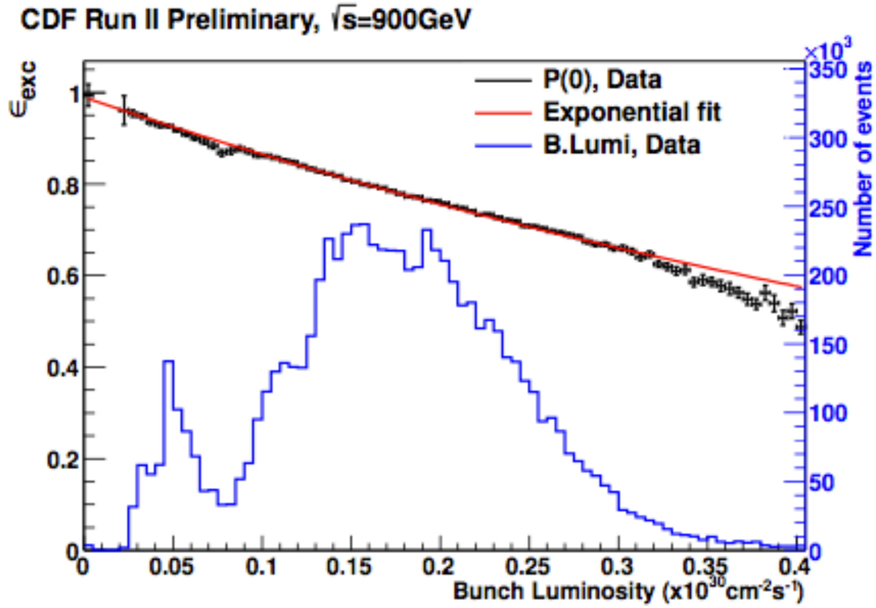
Sum ADC counts in BSC (west)

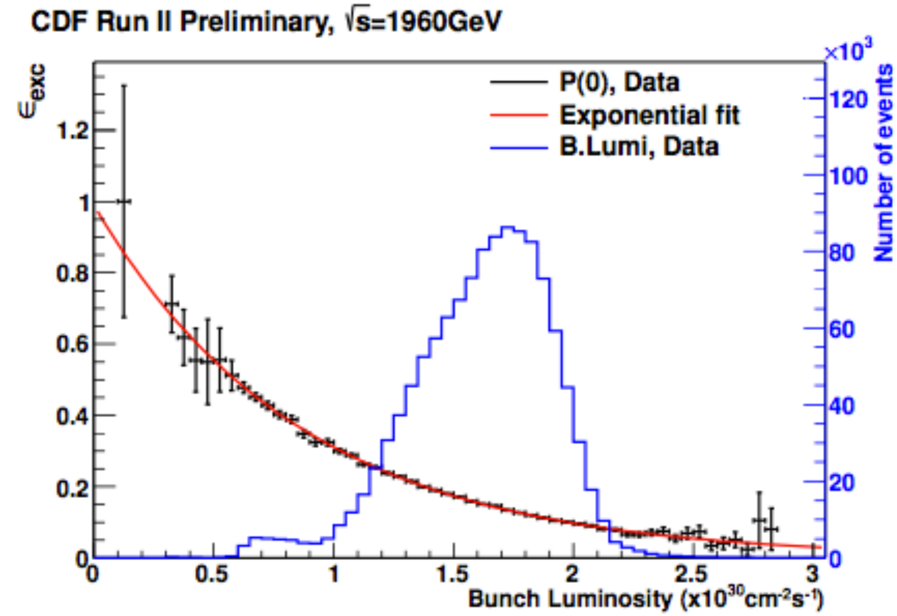
Cuts well defined; noise well separated from interactions.

0-bias data (critical)
2 classes:
No interaction = no tracks, no μ stubs, no CC hits
Interaction = all other bunch crossings.

Cuts values for 1960/900 GeV

Cut	1960 GeV	900 GeV
Sum of ADC counts in Bsc1 West	<1260 counts	<1260 counts
Sum of ADC counts in Bsc1 East	<1260 counts	<1260 counts
Sum of ADC counts in CLC West	<4170 counts	<4000 counts
Sum of ADC counts in CLC East	<4170 counts	<4200 counts
Sum of Em Energy in West Plug	<4.0 GeV	<3.0 GeV
Sum of Em Energy in East Plug	<4.0 GeV	<3.5 GeV
Sum of Had Energy in West Plug	<4.5 GeV	<2.1 GeV
Sum of Had Energy in East Plug	<4.5 Gev	<3.8 Gev
Energy in Central Calorimeter	< 2.8 GeV	<0.8 GeV





Take 0-bias events, measure P(0) = probability all CDF in noise |η| < 5.9 = ε(exclusive) vs bunch luminosity (from CLC). Intercept = 1.0, slope = σ(vis) = σ(|η| < 5.9)

We choose to use σ(vis) to calibrate the absolute luminosity at 900 GeV as CLC not calibrated. At 1960 GeV methods agree. 10% syst unc. on L(900).

Note: above plots, divide BL by 47,747 to get BL per crossing (not /sec)

$\sqrt{s}$ (GeV)	900	1960
$\sigma(inel)$ (TOTEM fit) (mb)	52.7±1.6	61.0±1.8
$f(vis)$ (MBR)	0.90±0.05	0.85±0.05
$\sigma(vis)$ (mb)	47.4±3.0	51.8±3.4

p + pbar → p(*) + [π+π-] + pbar(*)

Data at √s = 1960 GeV (standard) and 900 GeV (special, 38 hours at low luminosity)

Trigger:

2 Central |η| < 1.3 Calorimeter towers with ET (EM + HAD) > 0.5 GeV
Veto on signals in Beam Shower Counters, BSC, 5.4 < |η| < 5.9 (scint. + 1.7 X_0 rad.)
Veto on Cherenkov Luminosity Counters, CLC, 3.75 < |η| < 4.75 (48 gas tubes + PMTs)
Veto on Forward Plug Calorimeter (EM + HAD), 2.11 < |η| < 3.64 (Pb + Fe/scint.)

Off-line:

Require exactly two tracks, ΣQ = 0, |η| < 1.3, pT > 0.4 GeV/c, on vertex, good quality.
Require all CDF -5.9 < η < +5.9 detectors < noise level cuts except two track hits.
Assume pions, |y(ππ)| < 1.0, M(ππ) > 0.8 GeV/c

All sub-detector noise levels determined from 0-bias (bunch crossing) events taken simultaneously. Two classes: (A) No interaction

$\sqrt{s}$ =	1960 GeV	900 GeV
Triggered events	90230×10^3	21737×10^3
After Forward exclusivity cuts	59538×10^3	18749×10^3
Exactly 2 tracks	4721×10^3	271×10^3
Quality, exclusivity, cosmic rejection	415603	10362
Opposite sign	350243	9349
Luminosity	7.12 pb^{-1}	0,056 pb^{-1}
Exclusive efficiency	0.166	0.797
Effective (no-PU) luminosity	1.18 pb^{-1}	0.0435 pb^{-1}

Table 4: Numbers of 2-track events after sequential requirements.

2 tracks candidates selection

Cut	Value	Variation
$\|\eta(\text{track})\|$	<1.3	1.297-1.303
$\|y(X)\|$	<1.0	0.998 – 1.002
Muon stubs	= 0	No systematics
3D angle	<3.1 rad	No systematics
d0	< 0.1 mm	0.095 – 0.105 mm
Pt	>0.4 GeV/c	0.39 – 0.41 GeV/c
Tracks matching triggered tower		No systematics
ΔZ0	1.0 cm	0.8 – 1.2 cm
Z0	60 cm	59.85 – 60.15 cm
Number of COT hits	≥ 25 axial and ≥ 25 stereo	24 – 26 hits
$\chi 2$/Ndof of track fit	>2.5	2.4 – 2.6
Q=0		No systematics

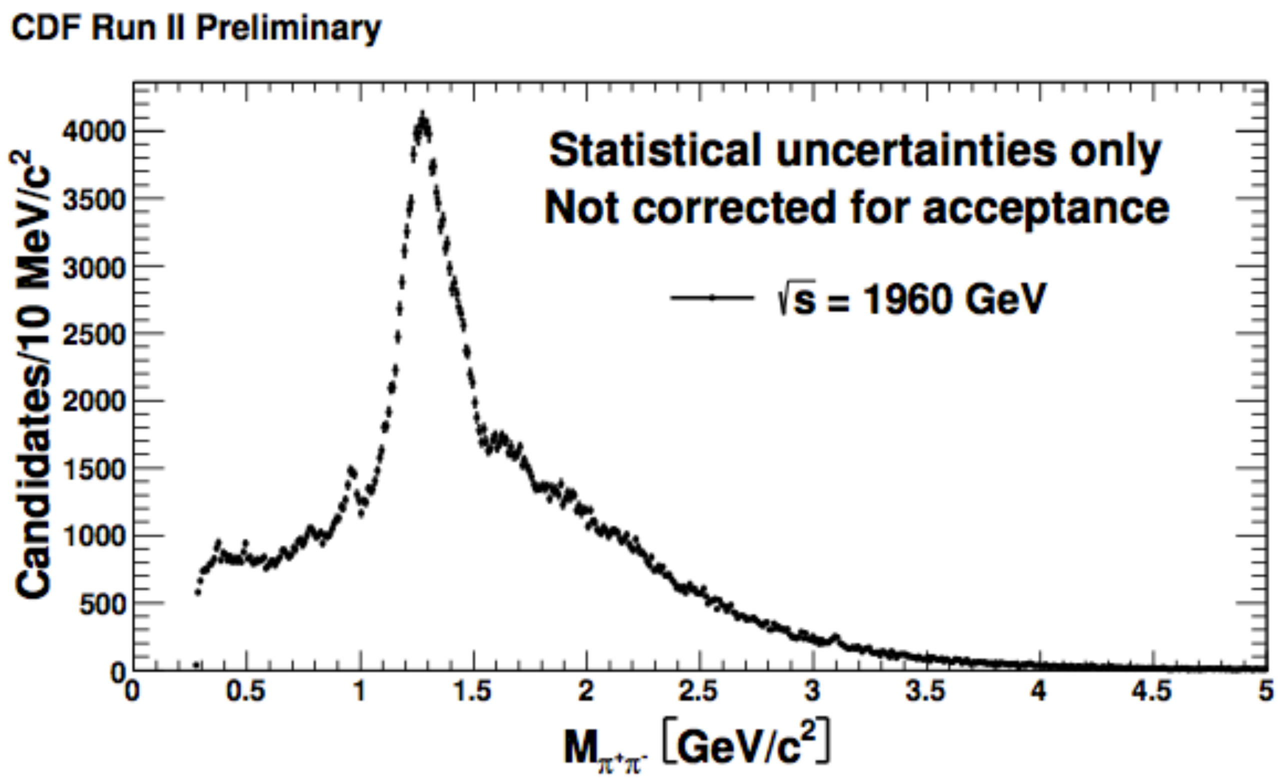
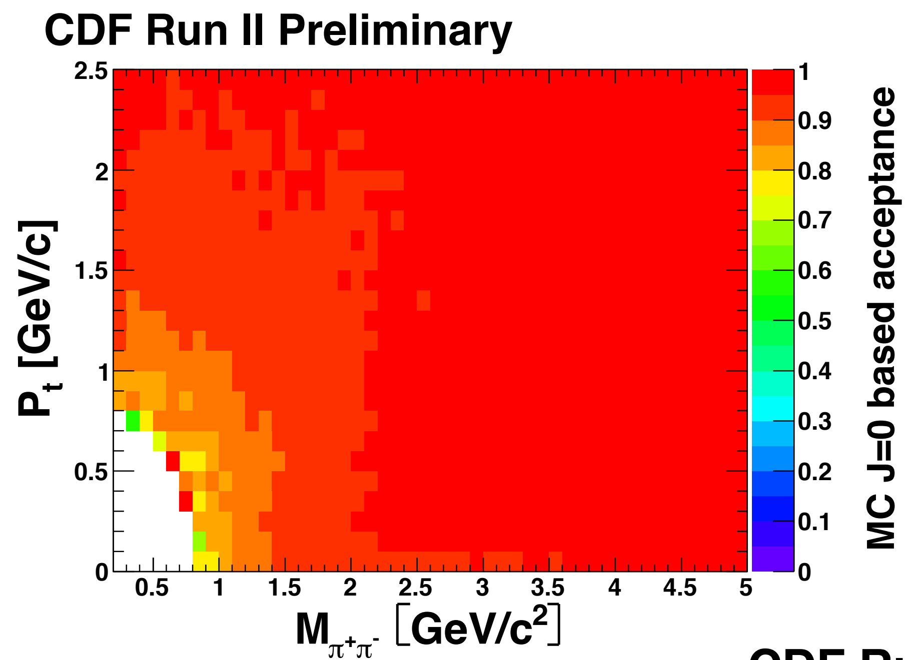


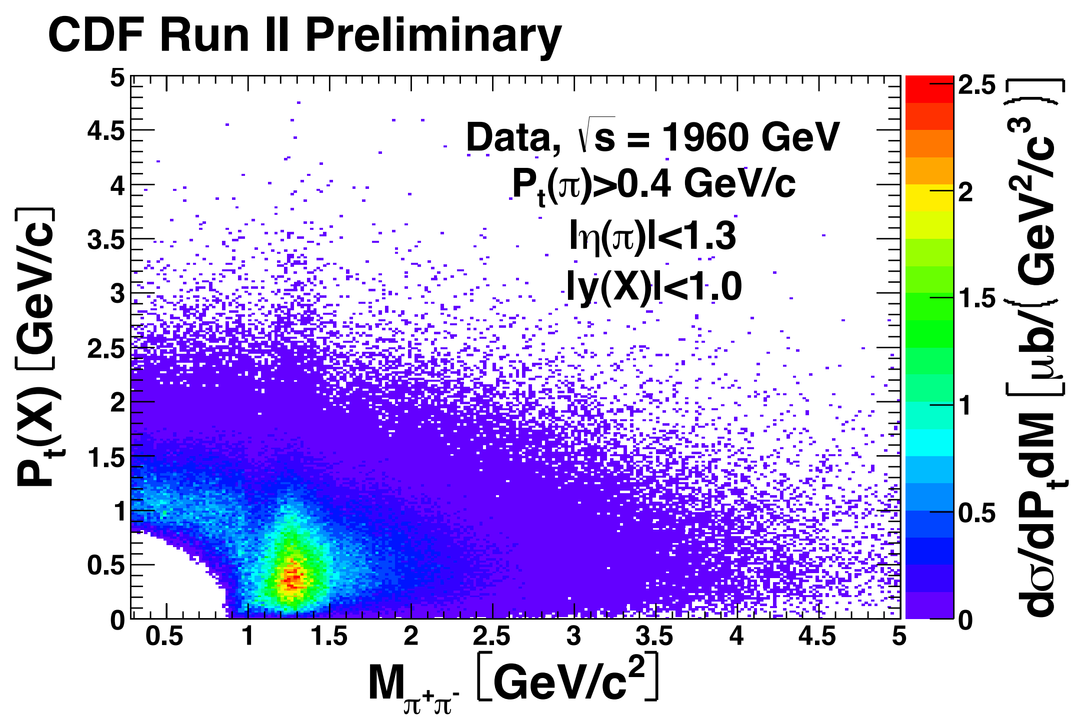
Figure 23: Invariant mass distribution of two particles assuming pion mass - not corrected for acceptance at $\sqrt{s} = 1960$ GeV.

Raw data, uncorrected. At M < 0.8 GeV, small p_T not accepted.
Small Φ → K+K- (with π mass) at ~ 0.34 GeV
Small K^0_S → π+π- (non-exclusive background)
f0(980) – fX(1200-1500) --- 1.5 "mini-dip" --- J/ψ → e+e- (μμ?) at 3.1 GeV



Acceptance, given tracks η, p_T and y(ππ) ... VDF simulation

Cross section in M, p_T plane after all corrections



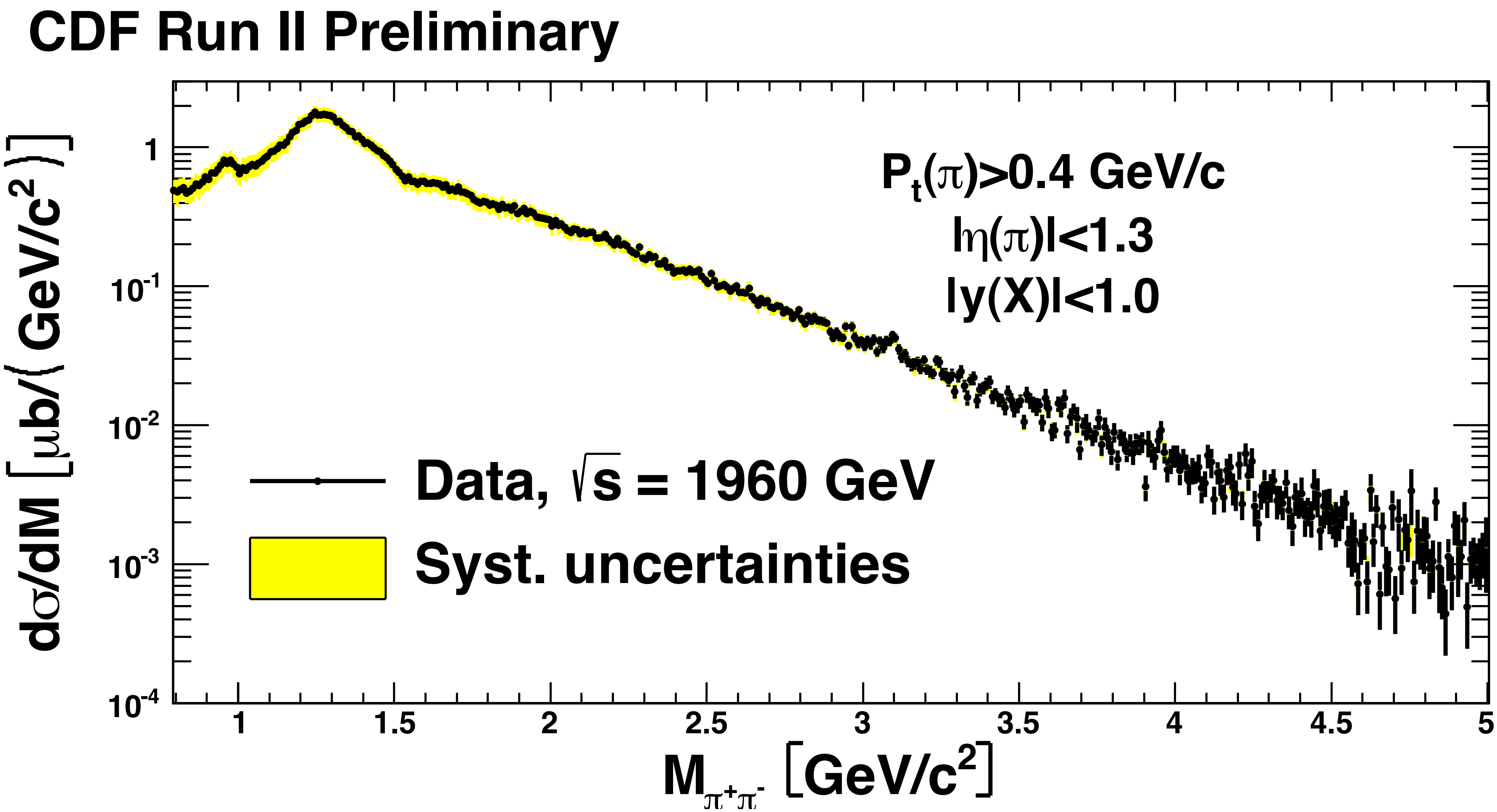


Figure 29: Invariant mass distribution of two particles assuming pion masses - corrected for acceptance, on a logarithmic scale, $\sqrt{s} = 1960$ GeV.

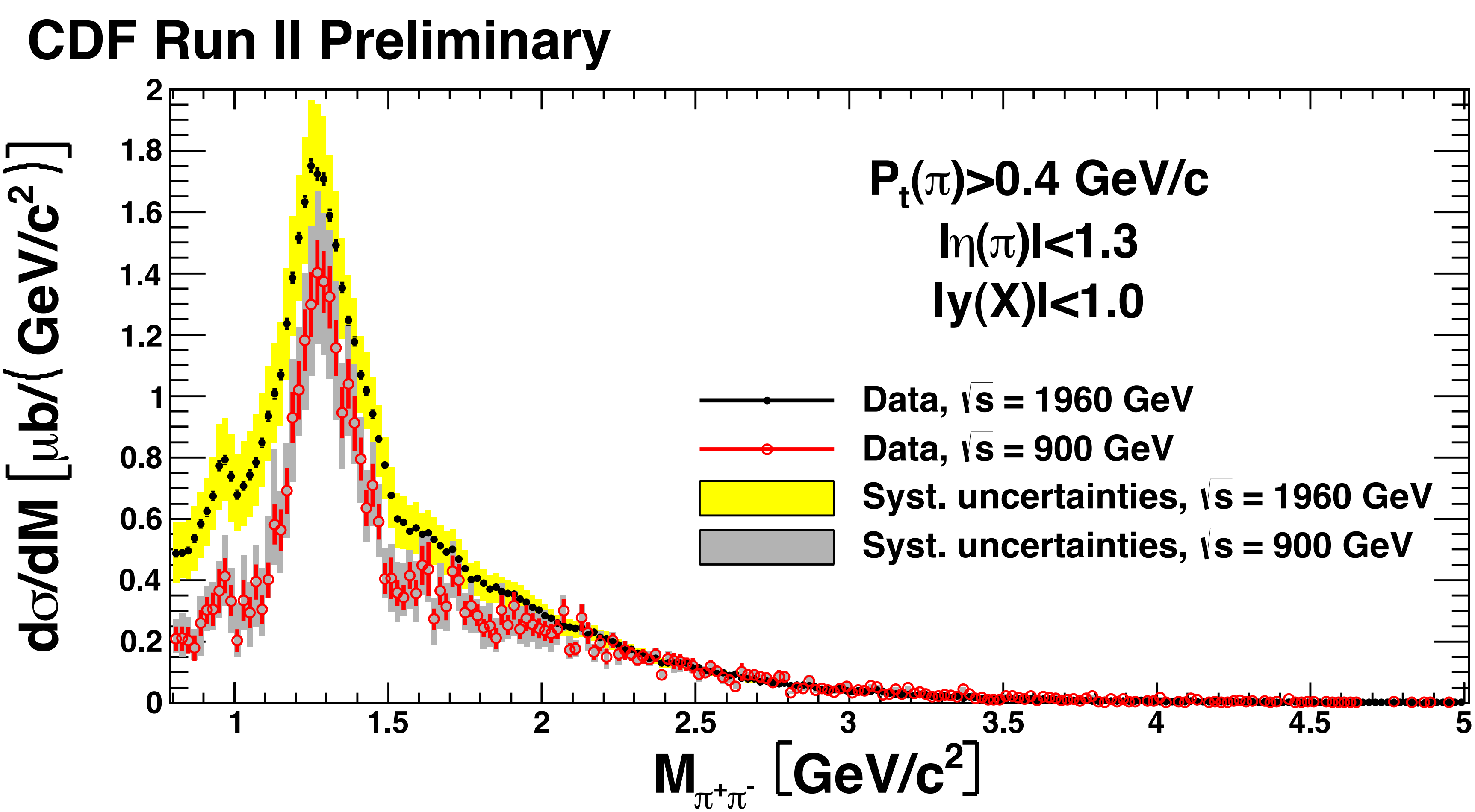


Figure 30: Comparison of invariant mass distribution of two particles assuming pion masses - corrected for acceptance, for two $\sqrt{s}$ energies, 1960 GeV - black and 900 GeV - red.

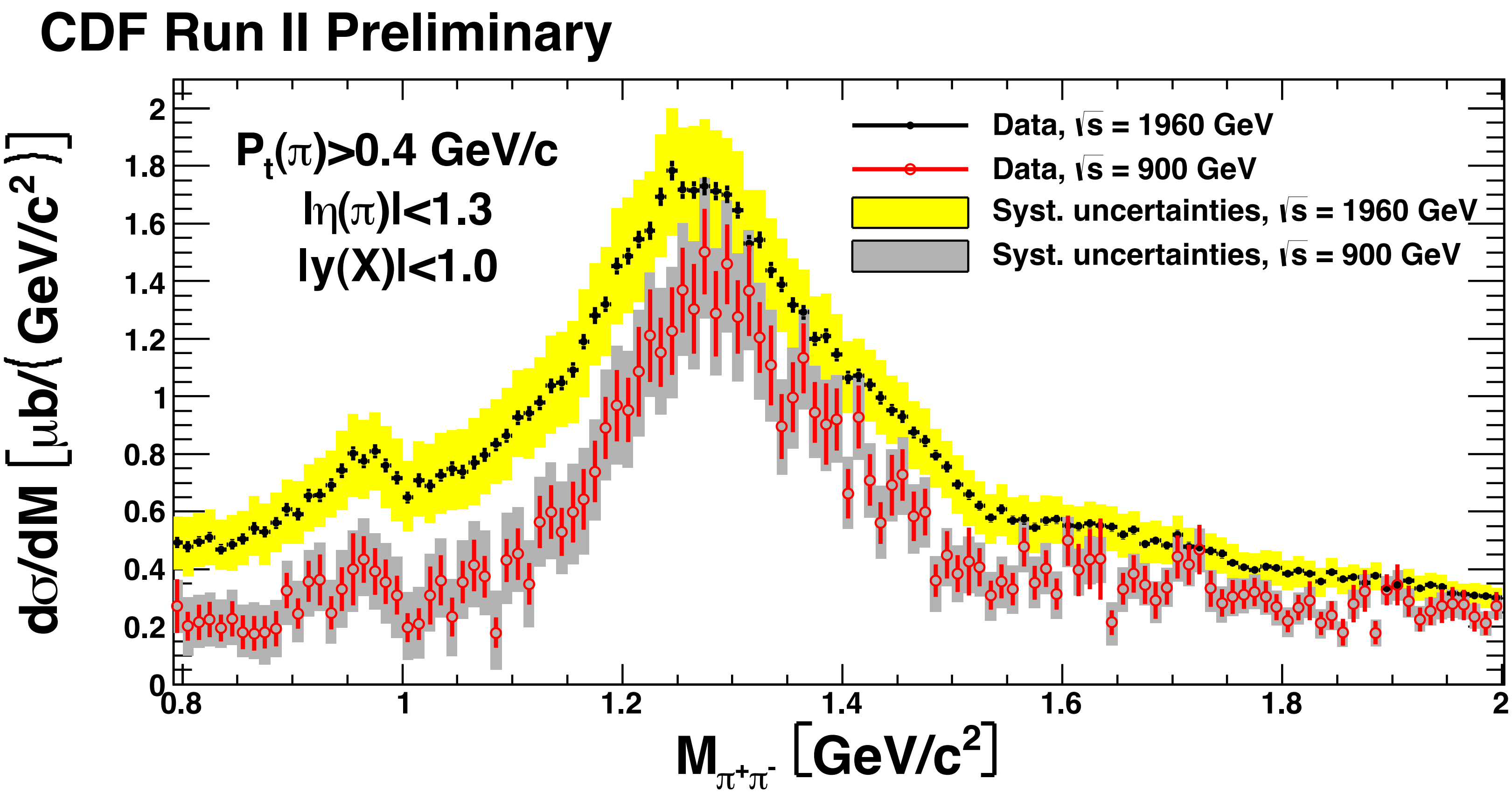
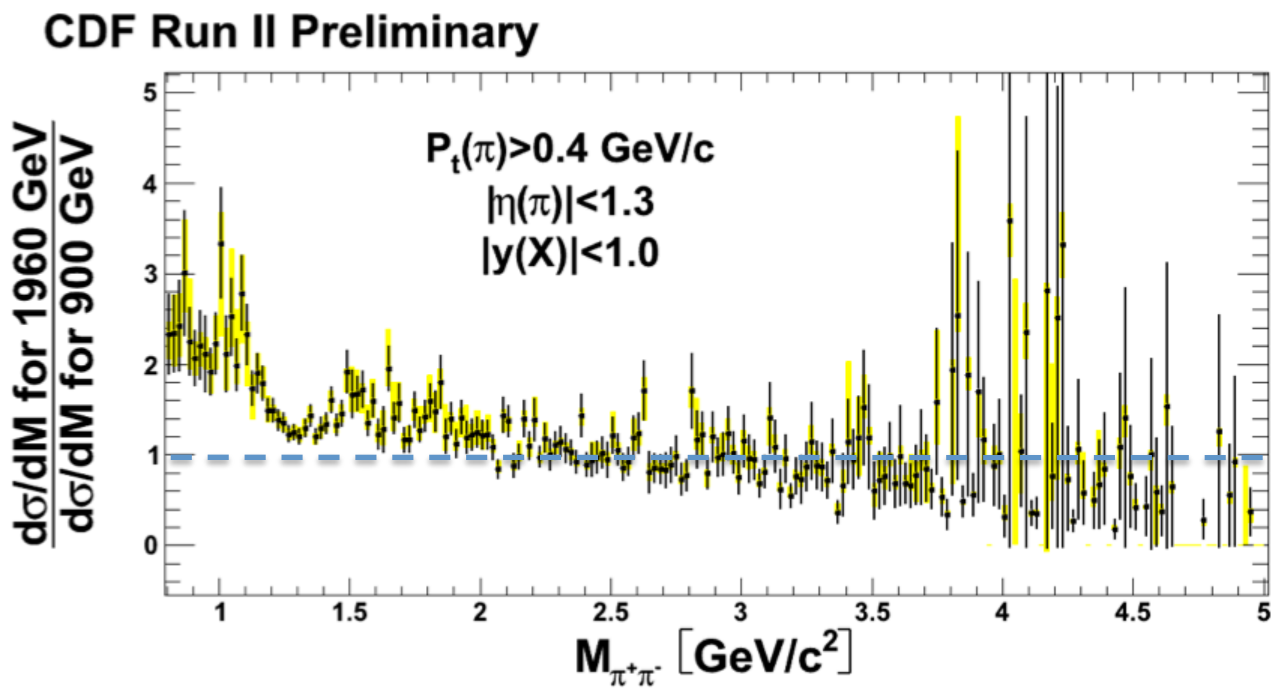


Figure 31: Comparison of invariant mass distribution of 2 particles assuming pion masses - corrected for acceptance, for two $\sqrt{s}$ energies, 1960 GeV - black and 900GeV - red.

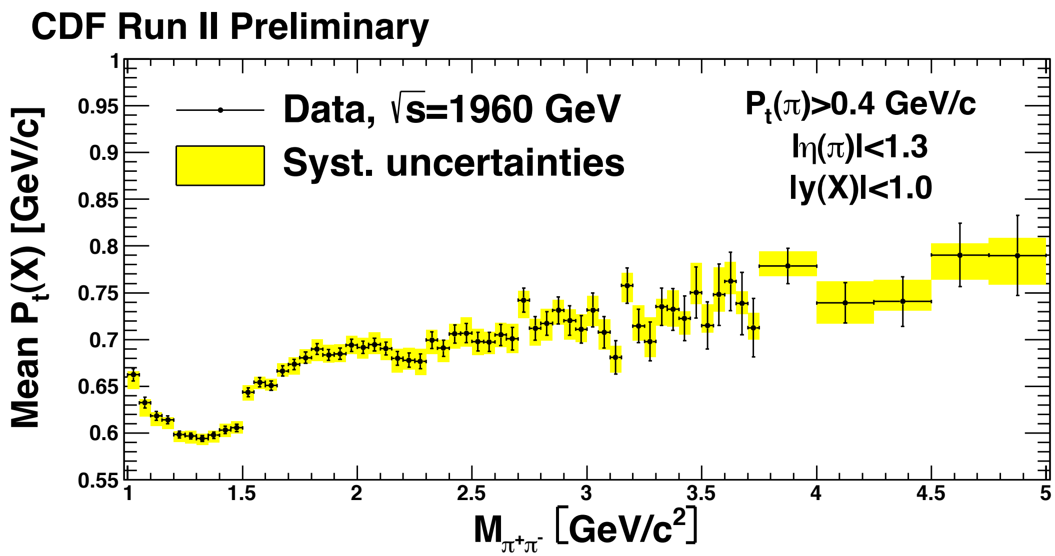


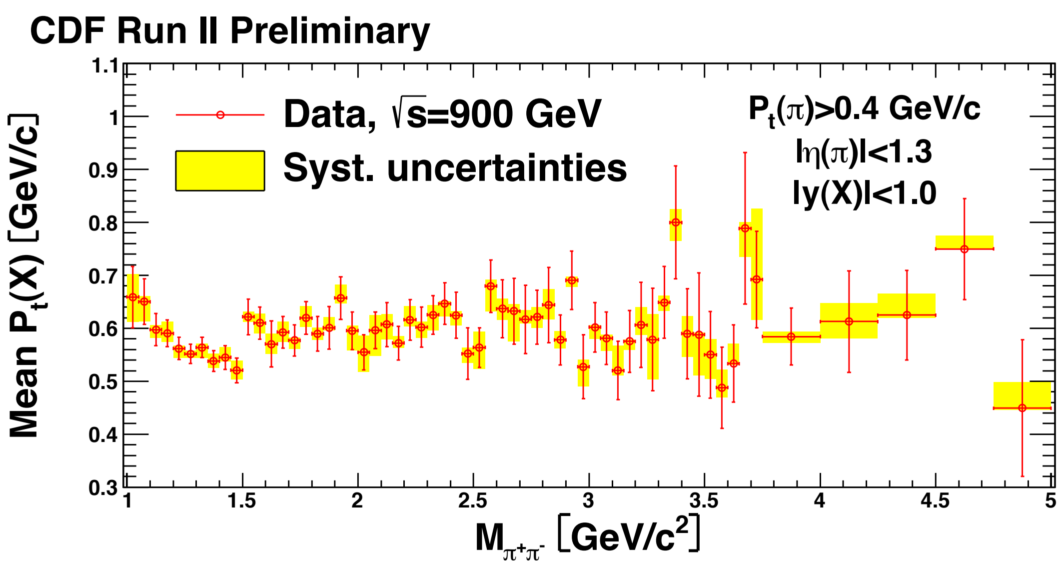
Ratio of cross sections at √s = 1960 GeV/900 GeV vs M(ππ).

Note: At 900 GeV, less rapidity space for proton dissociation:
Rap Gap to η = 5.9 at both √s

$$y_{beam} = \ln(\sqrt{s}/m(p)) = 6.87 \text{ and } 7.64$$

If no dissociation : p + X + p, 1960 GeV cross section lowers more than 900 GeV





Corrected for acceptance
Note different scales.

Abrupt rise at 1.5 GeV

Figure 34: Mean value of the P_t distribution of central state decaying to two central pions as a function of invariant mass.

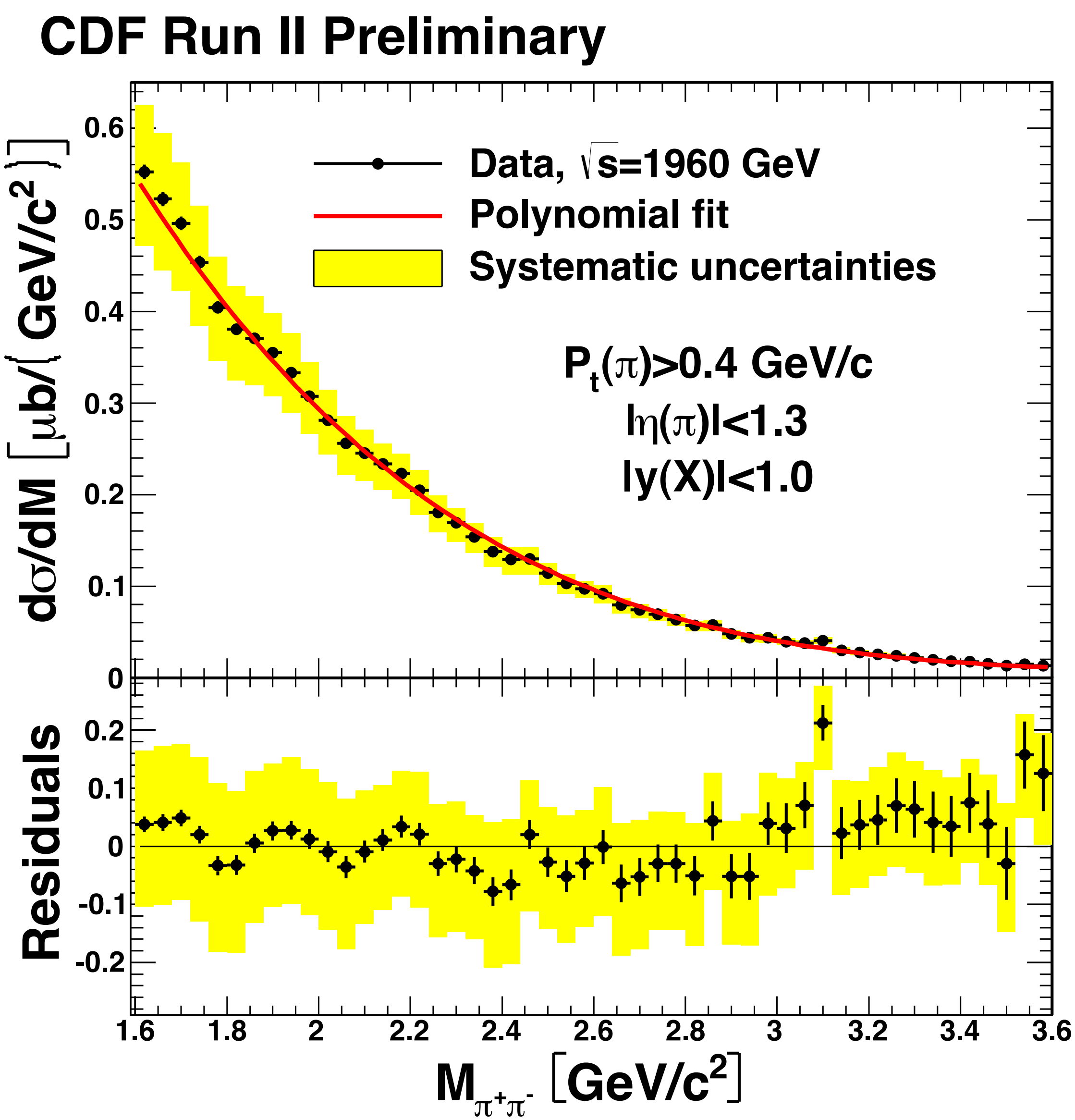


Figure 32: Invariant mass distribution of 2 particles assuming pion masses - corrected for acceptance with 4th order polynomial fit together with residuals of the fit, $\sqrt{s} =$ 1960 GeV.

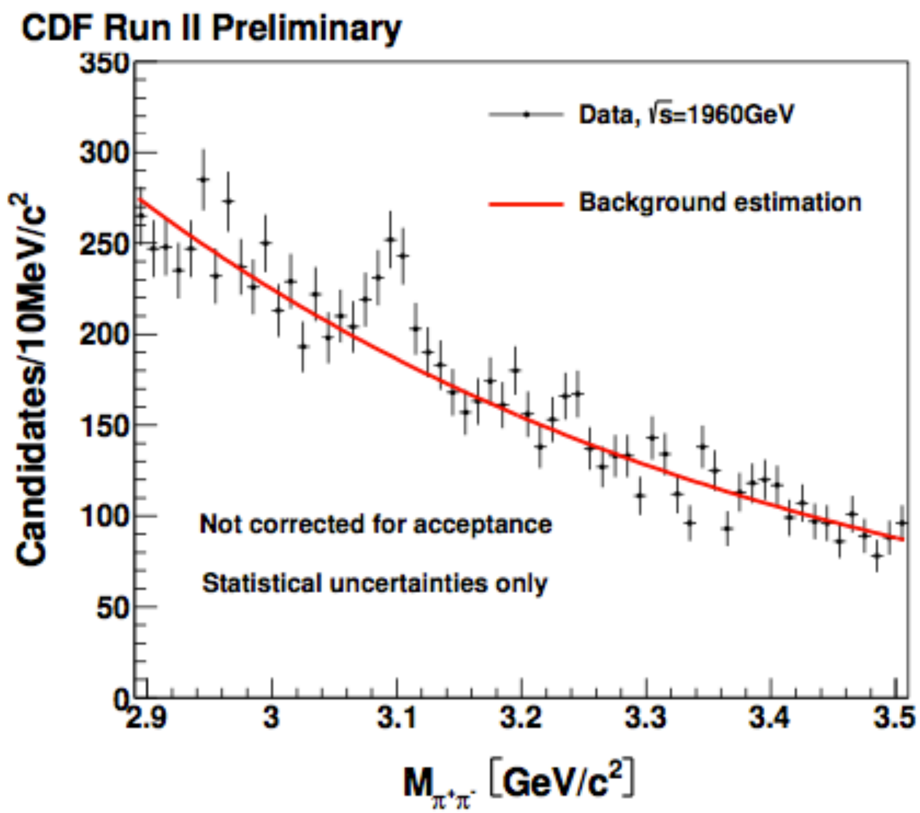


Figure 37: Invariant mass distribution of 2 particles in the J/ψ region. with the same fit as in Fig. 36, which excludes $M(J/\psi) \pm 3\sigma$.

Size of signal "compatible" with photoproduced J/ψ → e+e- (measured in μ+μ- channel)
(Can include some μ+μ- if no muon stubs in outer detectors)

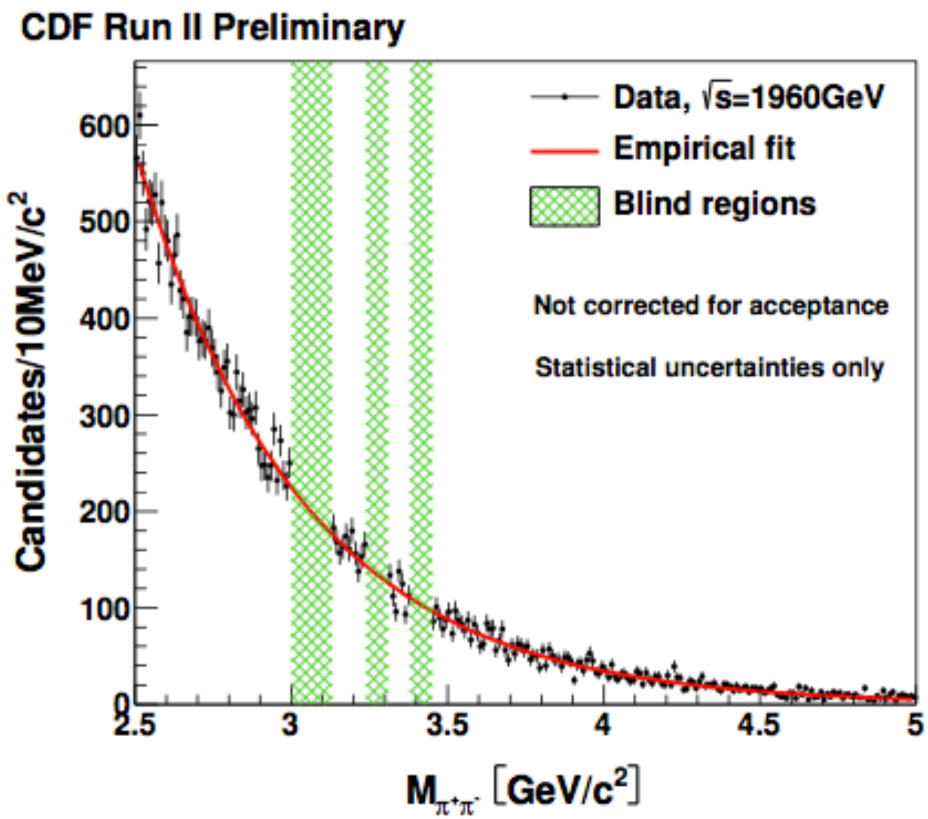


Figure 36: Invariant mass distribution of two particles, assumed to have $m(\pi)$, in the charmonium region at $\sqrt{s} = 1960GeV$. The regions of the J/psi and χ_{c0} (in both $\pi^+\pi^-$ and K^+K^- modes) are excluded from the fit.

Table 9: Branching fractions (BF in %) of χ_c states, for decays to all charged particles with BF > 0.1%.

State $I^G J^{PC}$	$\chi_{c0}(3415)$ 0^+0^{++}	$\chi_{c1}(3511)$ 0^+1^{++}	$\chi_{c2}(3556)$ 0^+2^{++}
Mass(MeV):	3414.76±0.35	3510.66±0.07	3556.20±0.09
Width (MeV):	10.4±0.7	0.89±0.05	2.06±0.12
BF(Channel)			
$J/\psi + \gamma$	1.16±0.08	35.6±1.9	20.2±1.0
Above with $J/\psi \to \mu^+\mu^-$	0.077	0.021	0.012
$\pi^+\pi^-\pi^+\pi^-$	2.27±0.19	0.76±0.26	1.11±0.11
$\pi^+\pi^-K^+K^-$	1.80±0.15	0.45±0.10	0.92±0.11
$3(\pi^+\pi^-)$	1.20±0.18	0.58±0.14	0.86±0.18
$\pi^+\pi^-$	0.56±0.03	<0.1	0.159±0.009
K^+K^-	0.60±0.03	<0.1	0.11±0.008
$\pi^+\pi^-K_s^0K_s^0$	0.58±0.11	<0.1	0.92±0.11
Above with $K_S^0 \to \pi^+\pi^-$	0.27±0.05	<0.1	0.43±0.05
$K^+K^-K^+K^-$	0.28±0.03	0.06±0.01	0.18±0.02
$\pi^+\pi^-p\bar{p}$	0.21±0.07	<0.1	0.13±0.03
Total %	7.2	1.9	4.7

Table 8: Upper limits on χ_{c0} cross sections.

State:	$\chi_{c0} \to \pi^+\pi^-$	$\chi_{c0} \to K^+K^-$
Background (est.)	722.9	940.0
Events in window	754	951
90% CL upperlimit (events)	69.6	59.2
Acceptance	24.2%	21.8%
$d\sigma/dy\vert_{y=0}$, 90% CL UL	21.4±4.2 (syst.) nb	18.9±3.8 (syst.) nb

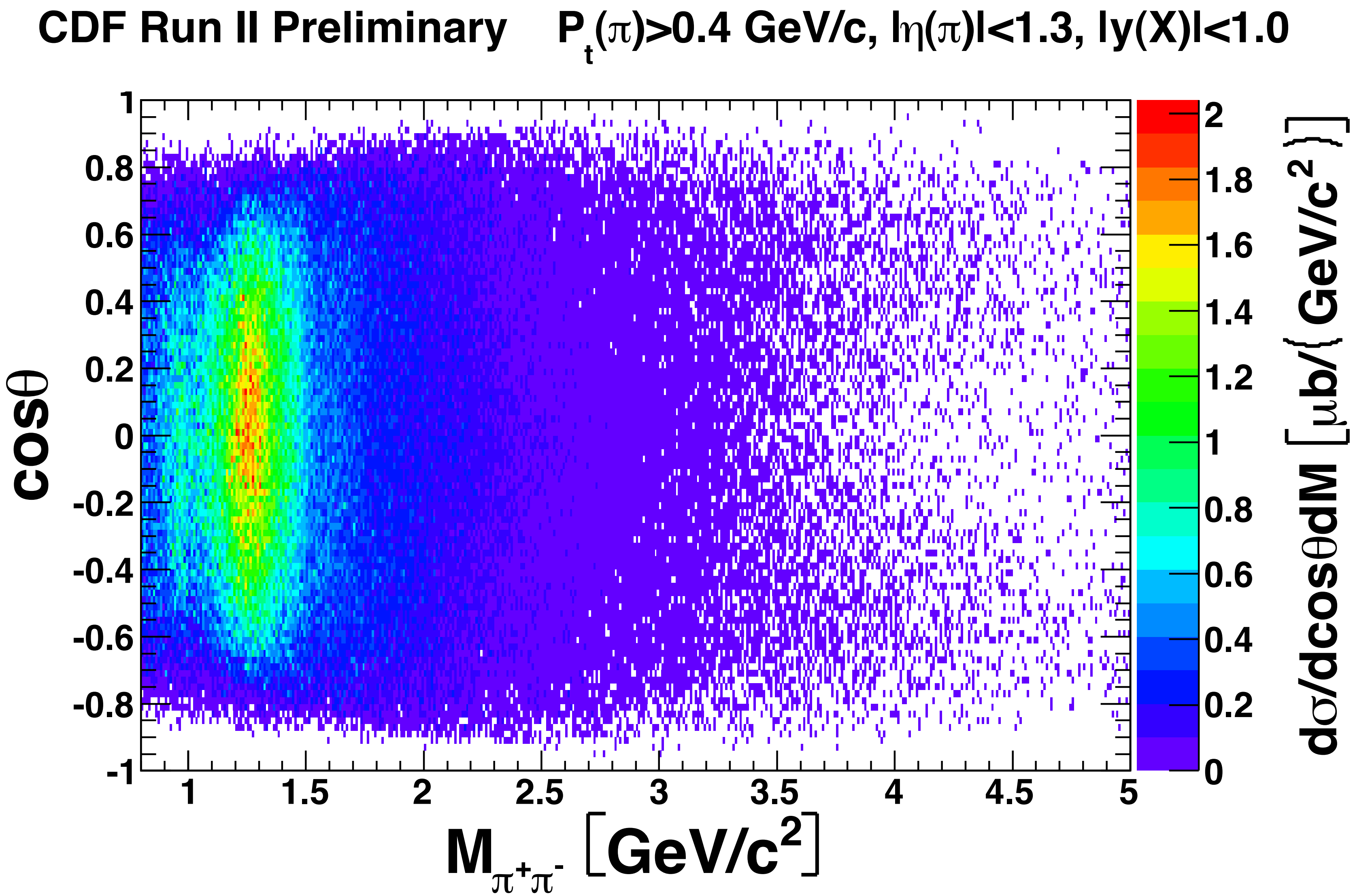


Figure 39: The differential cross section as a function of invariant mass and $\cos\theta$ for $\sqrt{s}$ = 1960 GeV. **BLESS**

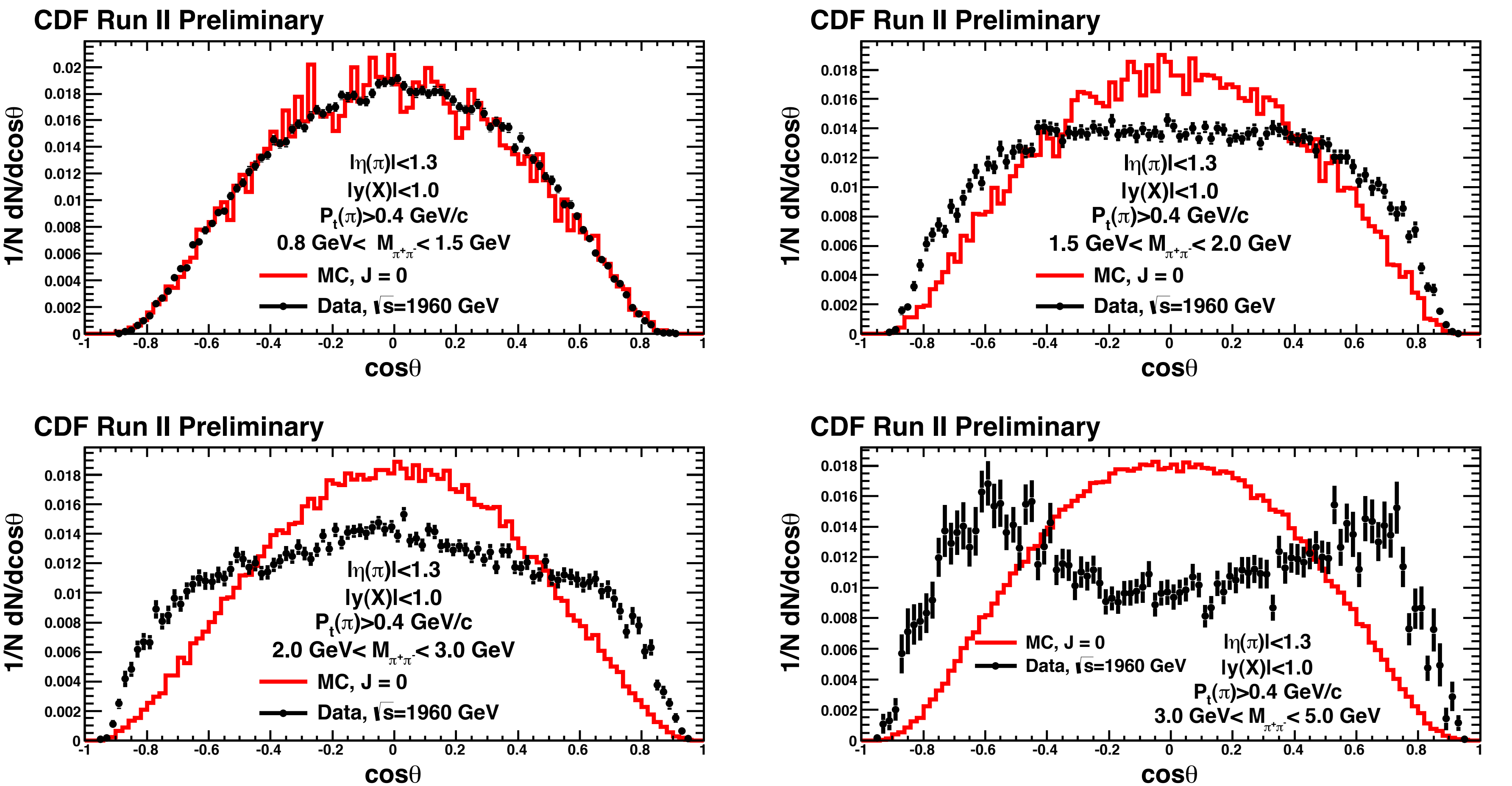


Figure 41: Normalized $\cos\theta$ distribution in several mass bins for our data compared to MC sample with isotropic decay mode (pure S-wave). **BLESS**

P$_0$ (should = 1.0)

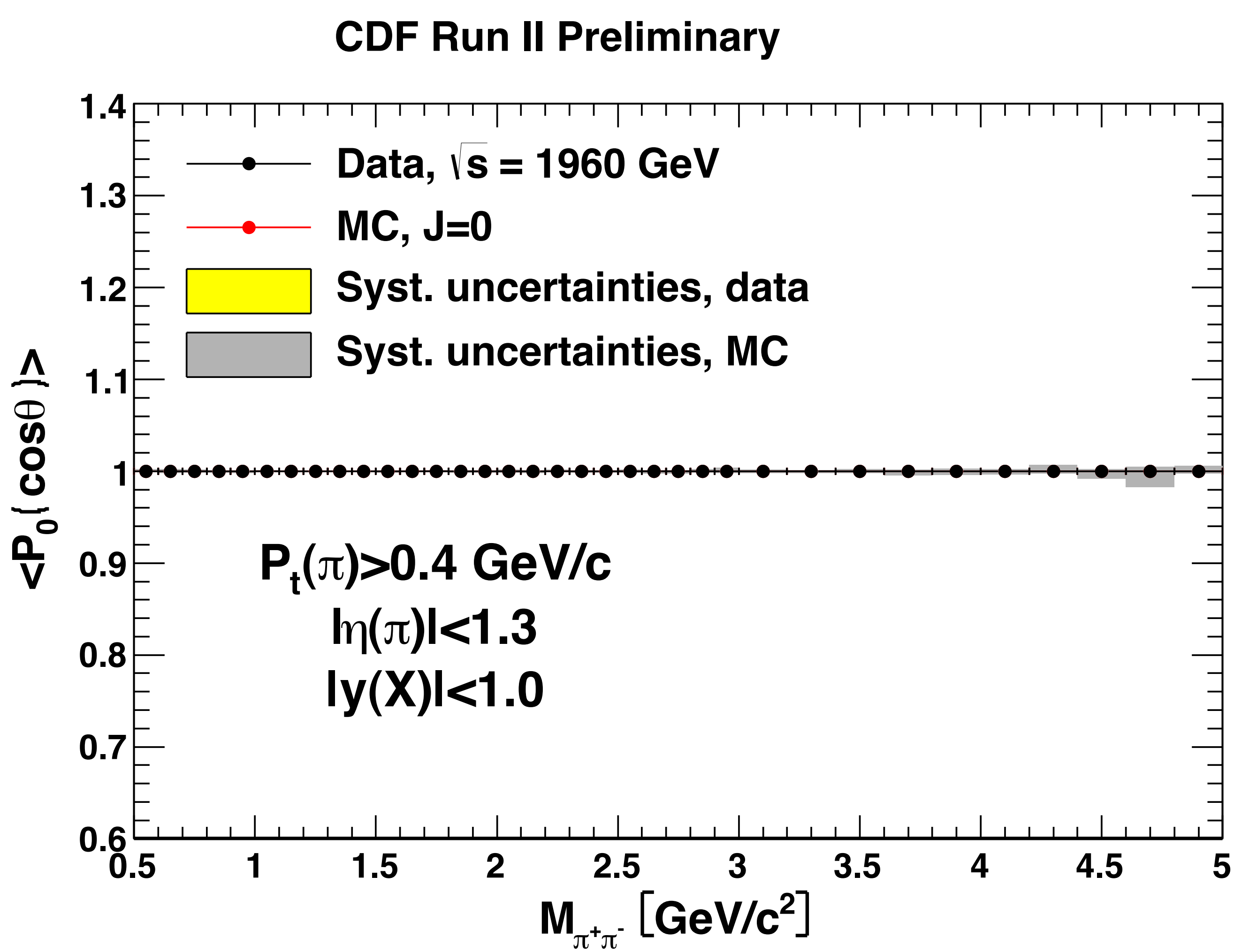
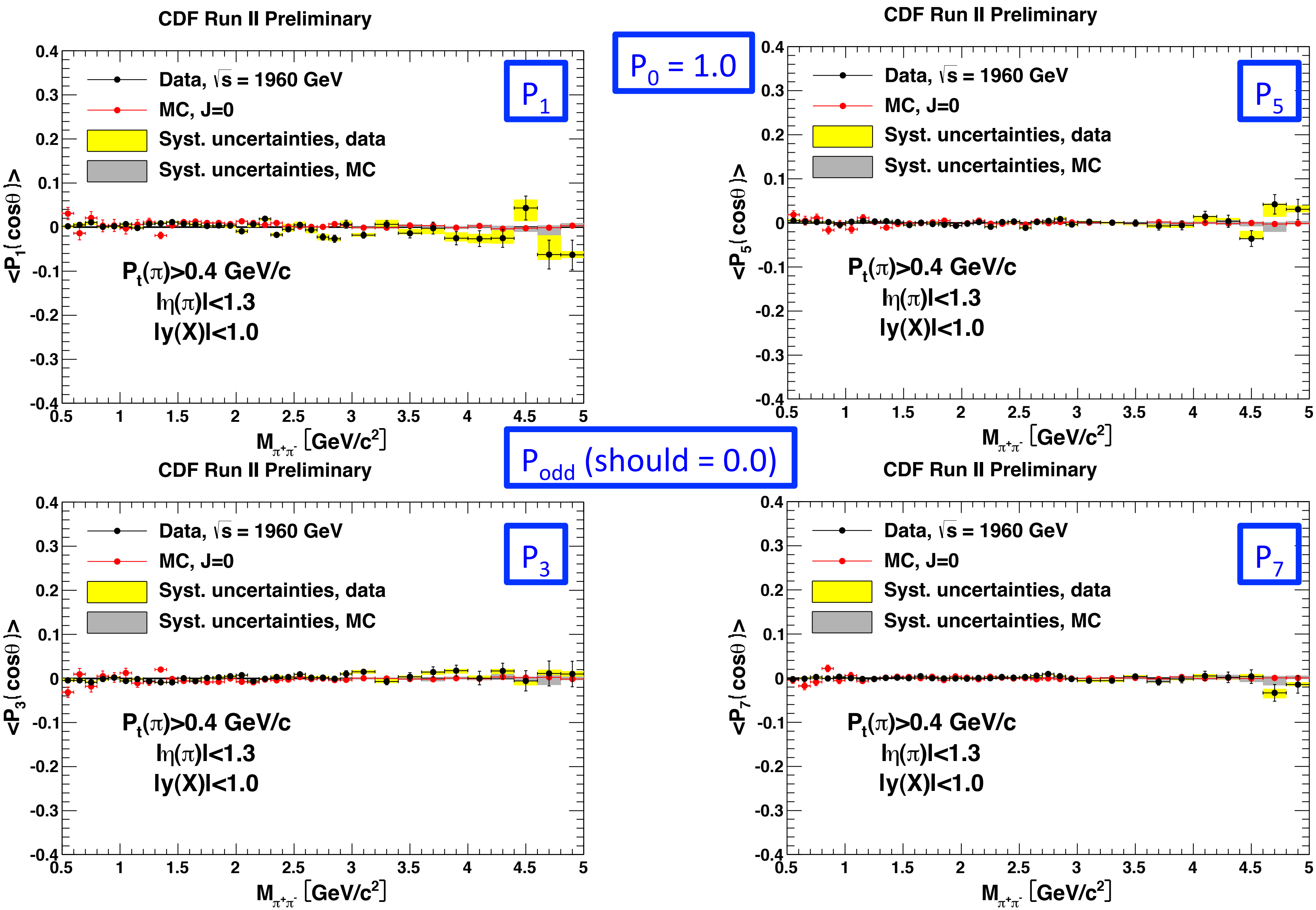
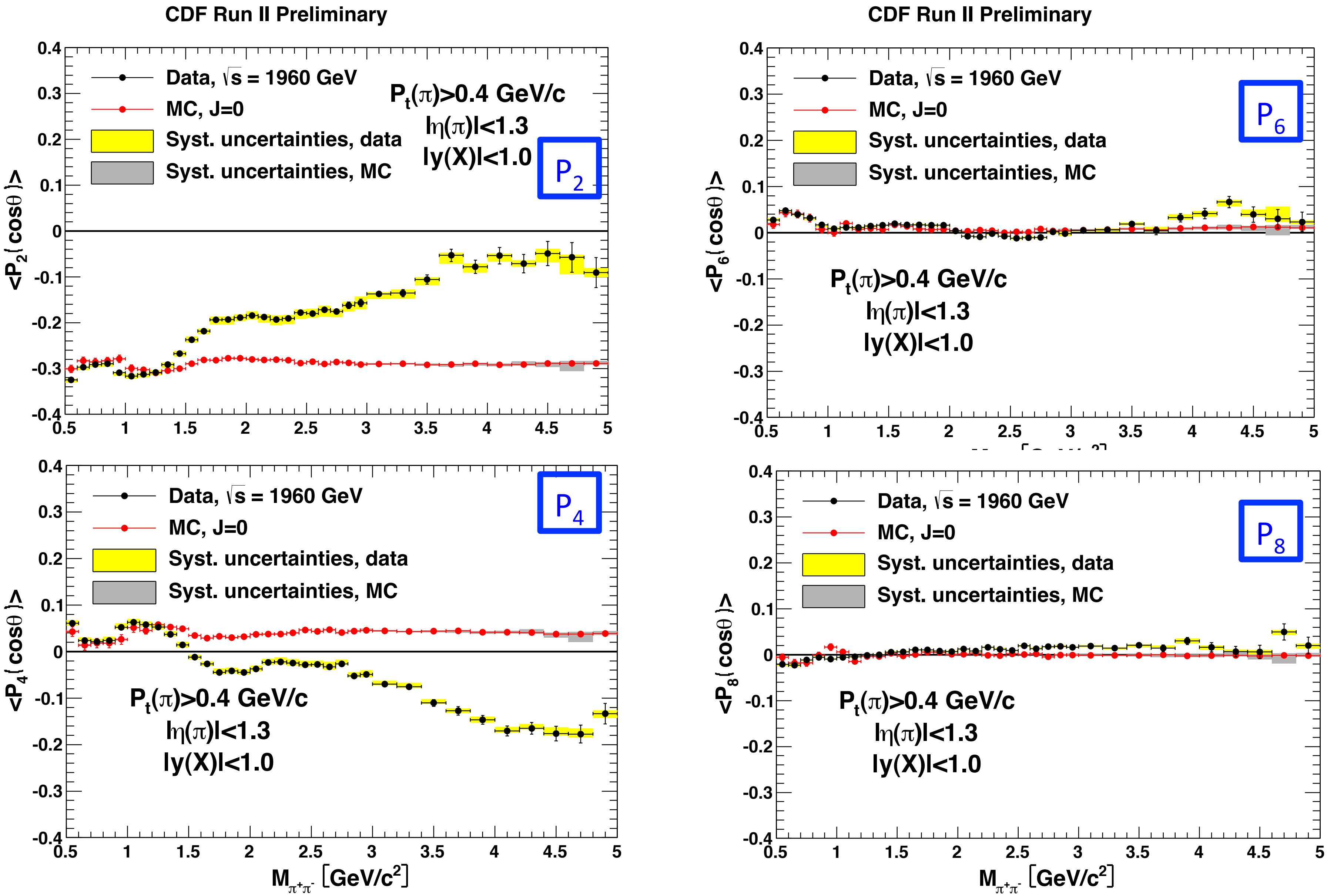


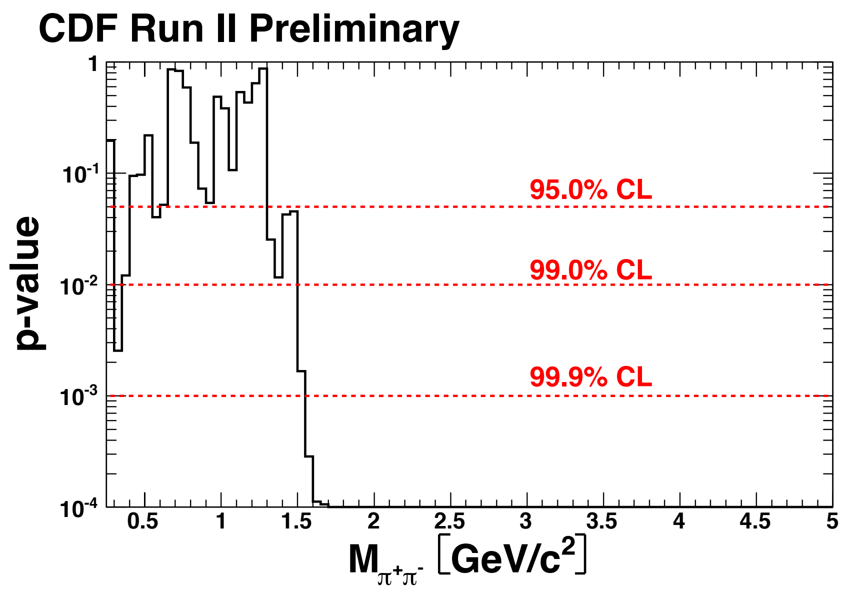
Figure 42: First ten Legendre coefficients as a function of mass for selected sample of two tracks events for $\sqrt{s} = 1960$ GeV data and for MC sample (isotropic decay model) of two tracks events. **BLESS**

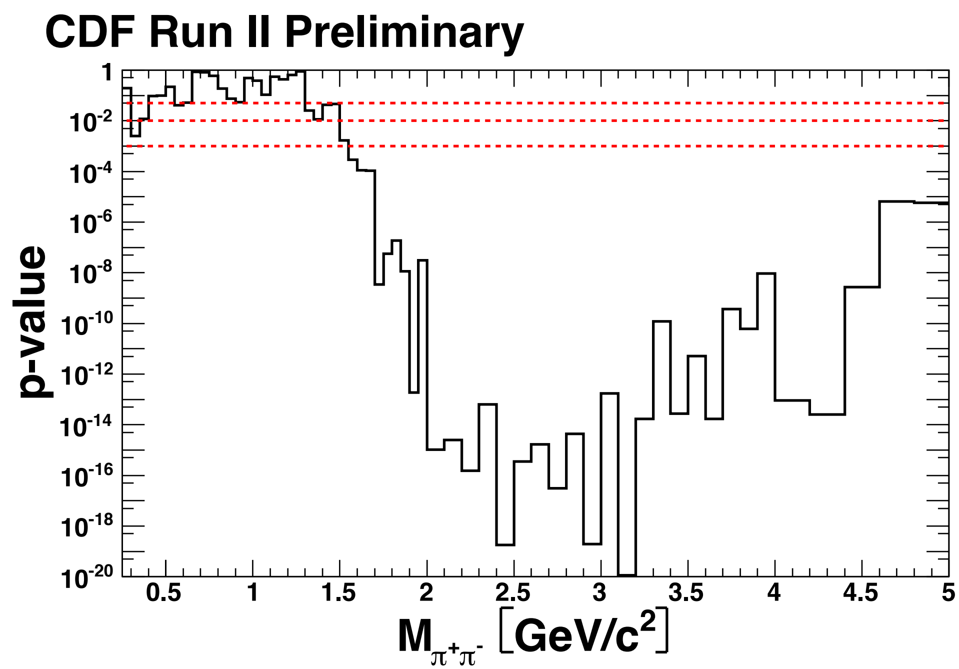


Legendre coefficients vs Mass for 1960 GeV data and isotropic decay simulation.
Odd coefficients should all be zero as detector and physics left-right symmetric



P_{even} : Non-zero because sculpted by acceptance. Data agrees with S-wave MC means J = 0.
Difference above M = 1.3 GeV → Higher waves (J = 2, 4, ...) present.

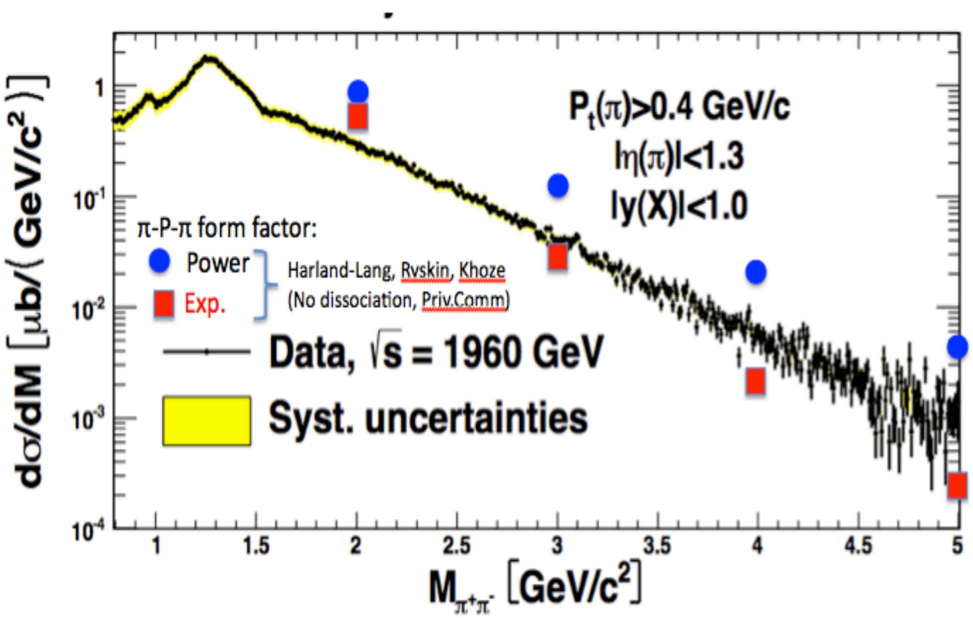




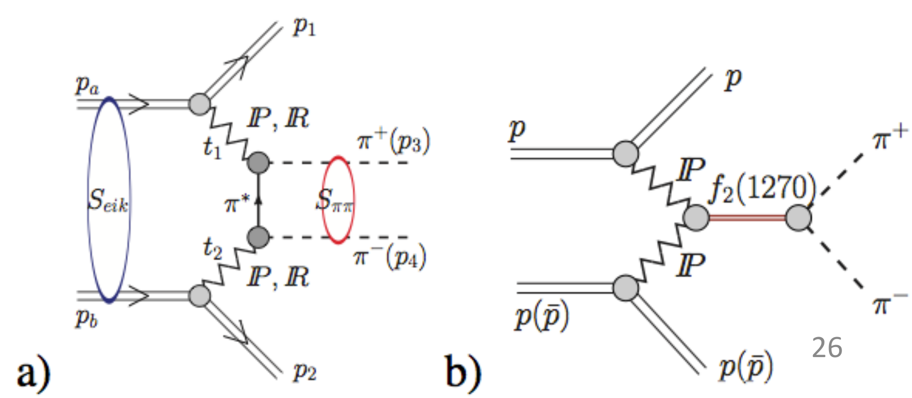
p-value of Smirnov test of S-wave-only hypothesis as a function of Mass for 1960 GeV data. Above 1.51 GeV the S-wave-only hypothesis is excluded at 99.9% C.L.

We are not sensitive enough (limited η) to distinguish J = 2 and 4.

Data are test of central exclusive/double pomeron models in NP-QCD = PQCD transition.
We ask (challenge) theorists to predict our results.
Lucien Harland-Lang, Misha Ryskin and Valery Khoze are working on this.
Private Communication, "upper" and "lower" bounds, depending on π-pom-π form factor.
But not including proton dissociation.



Anton Szczurek and Piotr Lebiedowicz:
AIP Conf Proc. 1523 (2012) 132
arXiv:1212.0166



4-track data: Many exclusive channels to study:
Good statistics at 1960 GeV, then look at 900 GeV for s-dependence

$K^+ - K^-$ $K_s^0 - K^\pm \pi^\mp$ $\Lambda^0 - pK$

$p - \bar{p}$ $\Lambda - \bar{\Lambda}$ $\Sigma - \bar{\Sigma}$

$K^* - K^*$ $\rho - \rho$

$\phi - \phi$ Helicity correlations?

Other potential studies in G-X-G data:
Charm production D*-D e.g.
Double parton scattering (enhanced?)
Bose-Einstein correlations (small source?)

Thank You

Back Ups

Cut	syst. uncertainty in % for $M_{\pi^+\pi^-} < 1.5$ GeV/c^2	syst. uncertainty in % for $M_{\pi^+\pi^-} > 1.5$ GeV/c^2
BSC gap cut	2	2
CLC gap cut	0.1	0.1
Fwd Plug gap cut	4	2
$\eta(\pi)$	0.2	0.2
y(X)	0.1	0.1
3D opening angle	0.1	0.1
d_0	1	1
$P_t(\pi)$	8	2
exclusivity cut	12	9
Δz_0	2	2
COT hits	4	4
χ^2/DoF of track fit	3	3
trigger efficiency	0.4	0.6
stat. error of acceptance	2	4
luminosity	6	6

Table 6: Systematic uncertainties in cross sections distribution for $\sqrt{s} = 1960$ GeV data for low and high invariant mass regions. **BLESS**

Cut	systematic uncertainty in % for $M_{\pi^+\pi^-} < 1.5$ GeV/c^2	systematic uncertainty in % for $M_{\pi^+\pi^-} > 1.5$ GeV/c^2
BSC gap cut	2	2
CLC gap cut	0.1	0.1
Fwd Plud gap cut	4	2
$\eta(\pi)$	0.2	0.2
y(X)	0.1	0.1
3D opening angle	0.1	0.1
d_0	1	1
$P_t(\pi)$	12	2
exclusivity cut	15	10
Δz_0	3	3
COT hits	4	4
χ^2/DoF of track fit	4	4
trigger efficiency	0.4	0.6
stat. Error of acceptance	2	4
luminosity	10	10

Table 7: Systematic uncertainties in cross sections distribution for $\sqrt{s} = 900$ GeV data for low and high invariant mass region. **BLESS**

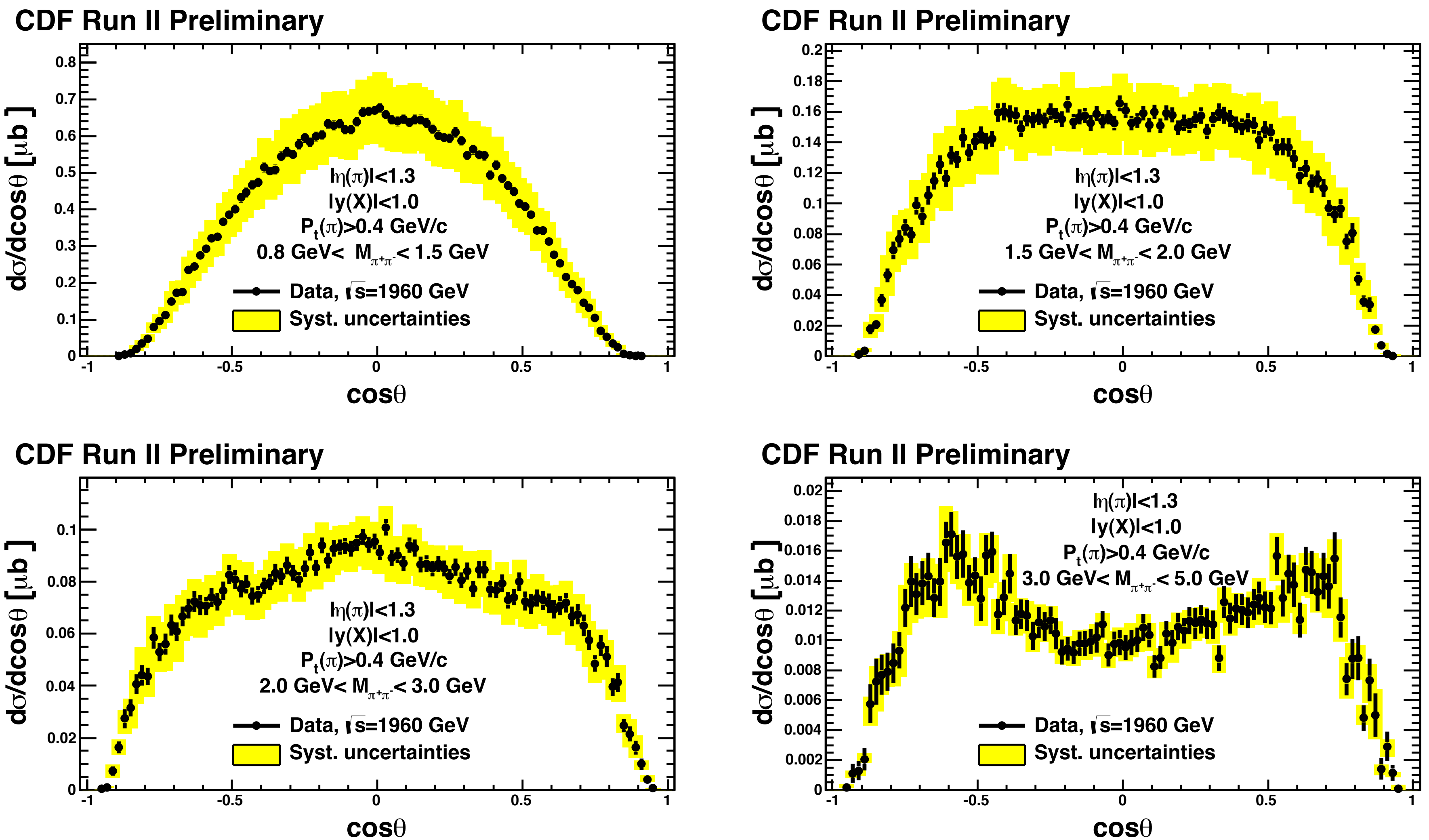
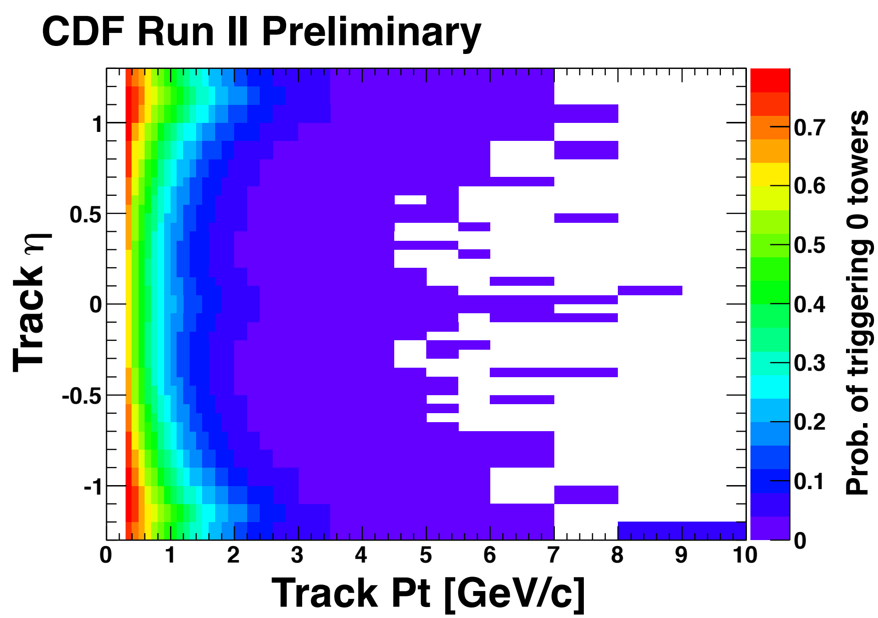
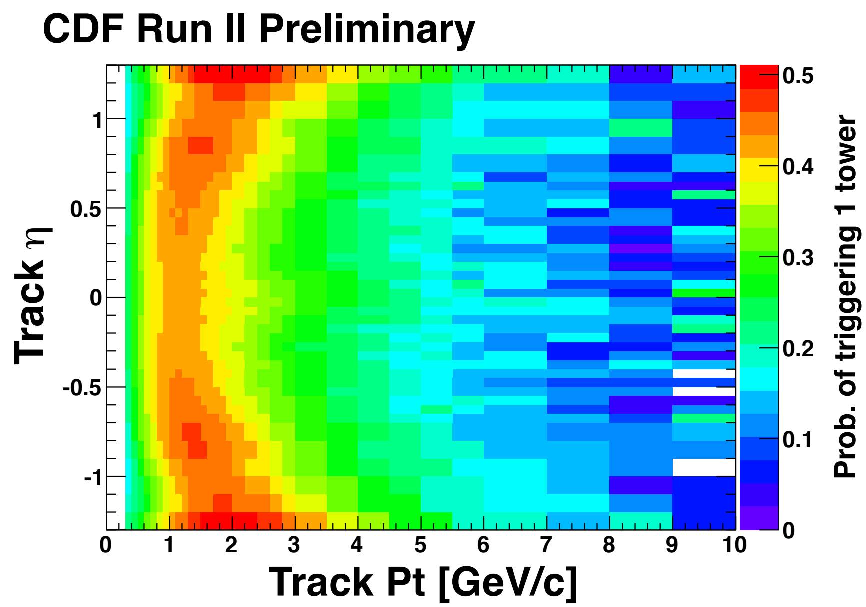
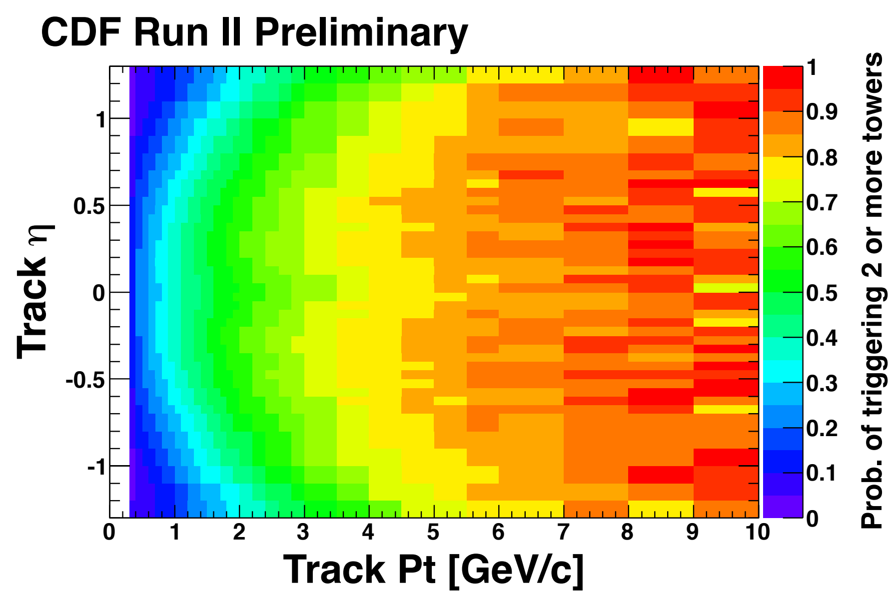


Figure 40: Differential cross section as a function of $\cos\theta$ in several mass bins. **BLESS**







The probability of a track triggering
0, 1, or >2 trigger towers
as a function of track pT and η

Input for cross sections

From CDFSIMulation (GEANT)

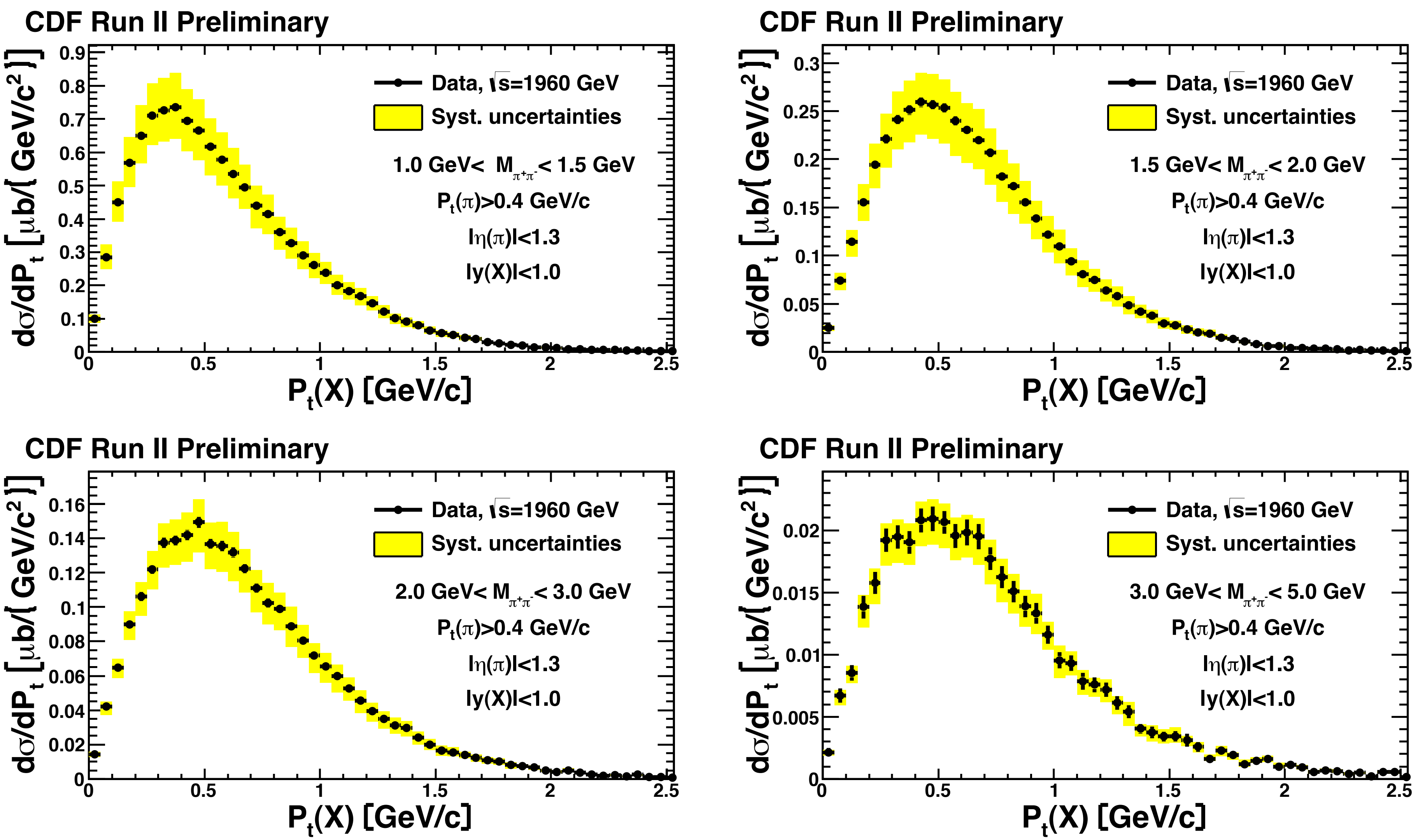


Figure 35: P_t distribution of central state decaying to two central pions in few mass windows, $\sqrt{s}$ =1960 GeV.