Exclusive central particle production in CDF at $\sqrt{s}$ = 1960 GeV and 900 GeV

Mike Albrow (Fermilab) on behalf of the CDF Collaboration

p(*) + X + pbar(*)

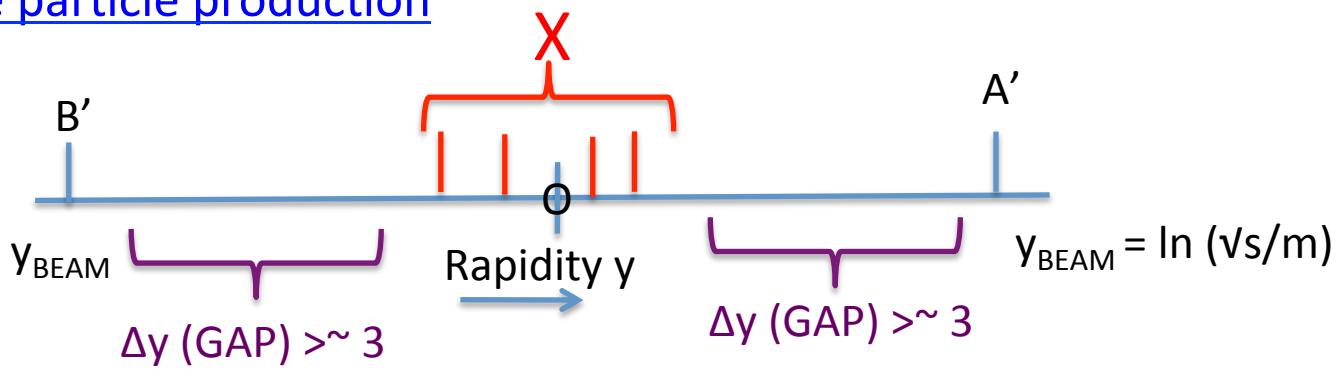
Introduction & different classes: $\gamma + \gamma$, $\gamma + P$, $P + P$ (P = pomeron)

Collider Detector at Fermilab (CDF) Detector

Exclusive $\pi^+ \pi^-$: Triggers, data sets, cuts

Mass distributions, corrections and cross sections:
mass M($\pi\pi$), p_T- & s-dependence, and χ_c limits.

Central exclusive particle production



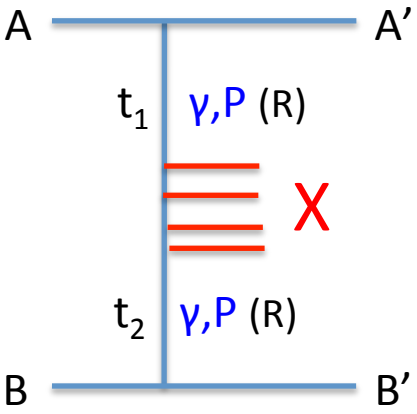
Generic definition: A + B → A' + X + B'

X is a "simple" system fully measured (= exclusive)

Two large rapidity gaps Δy with no hadrons

A' and B' may be the beam particles (quasi-elastic scattering) or low mass systems (pππ etc.)

Rotate diagram for t-channel view:



4-momentum transfer^2 |t| is small , typically < 2 GeV^2

Feynman x_F = p(A')/p(A) = 1 – ξ >~ 0.95 ≅ Δy ≥ 3 (>4 is better!)

t_1, t_2 carried by either photon γ or pomeron P

as spin J(=1) or pomeron intercept $\alpha_P(t=0) > 1$

Reggeon R, e.g. "ρ" with $\alpha_R(t=0) \sim 0.5$ dies like 1/√s or $e^{-0.5\Delta y}$

Therefore: γ + γ → X or γ + P → X or P + P → X

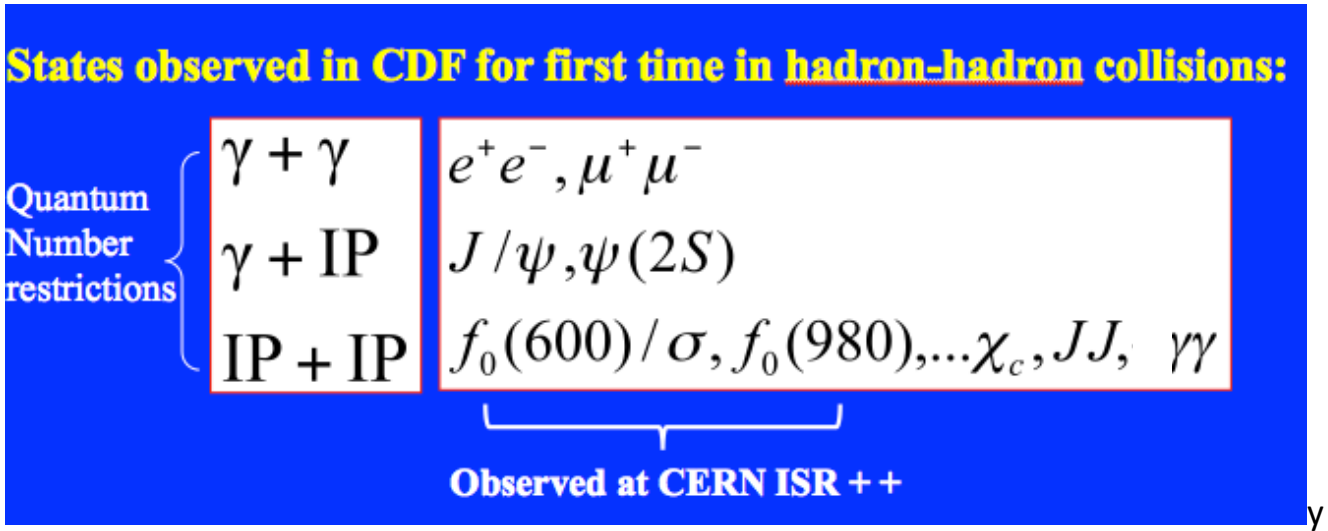
e+ e- (E.g.LEP) → e+ X + e- is purely γ + γ → X,
& at higher energy can have W, and Z exchange too, not P

e p (e.g. HERA) γ + γ & also γ + P (photoproduction)

pp(ppbar) (e.g. LHC, Tevatron) : γ + γ & γ + P & P + P (double pomeron exchange)
σ(P+P) >> σ(γ+P) >> σ(γ + γ)

Different Quantum Numbers for X : $I^G J^{PC} = 0^+ \text{even}^{++}$ for DPE; $J^{PC} = 1^{--}$ for photoproduction
& γ + γ favours quarks and P + P favours gluons
So for M(X) < ~ 3 GeV excellent tool for hadron (meson) spectroscopy.
& for M(X) >~ 3 GeV perturbative QCD can be applied (g + g → X with spectator gluon)

Photon is long range, large impact parameter (can be 4 fm), so |t| very small
P is strongly interacting, impact parameter <~ 1 fm and |t| ~ several hundreds MeV^2



CDF: *The Collider Detector at Fermilab*

CENTRAL:

Silicon tracker

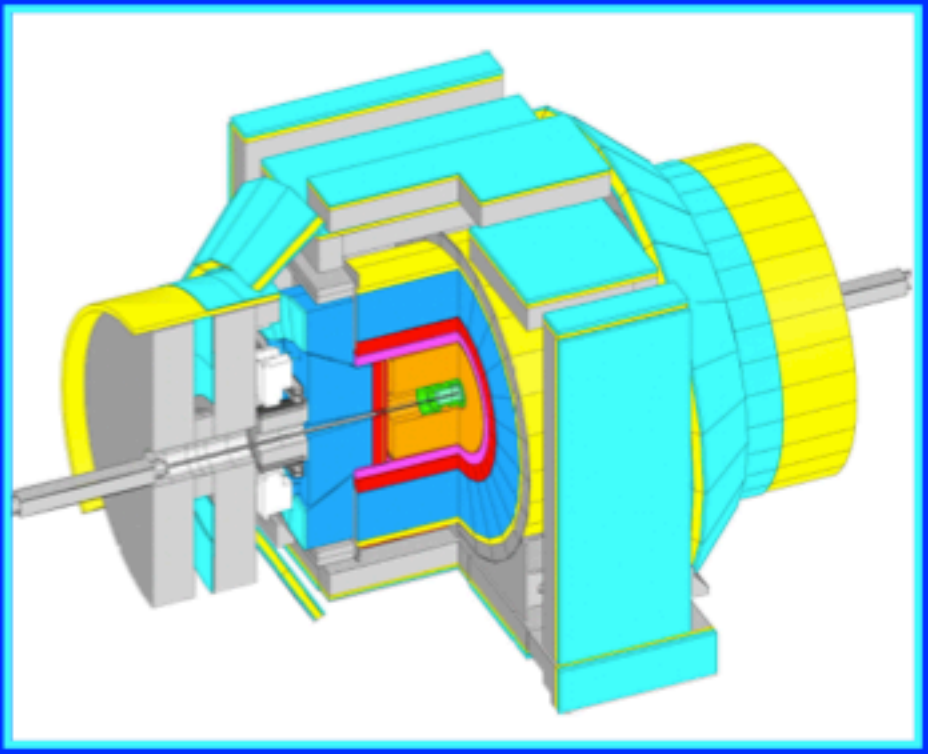
Drift chamber tracker

Time-of-Flight barrel

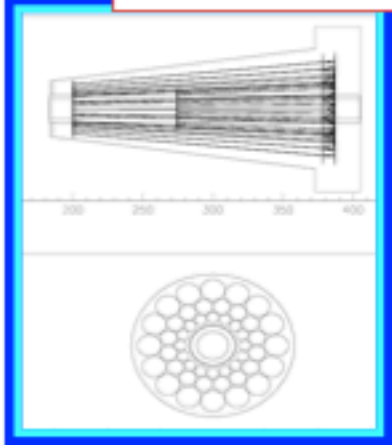
EM calorimeters

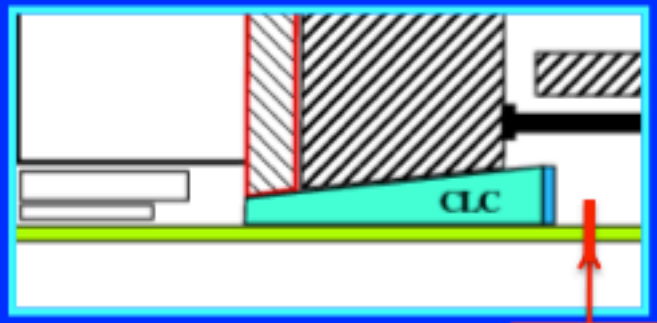
Hadron Calorimeters

Muon chambers



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





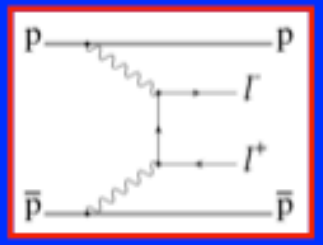
BSC1 counters
$|\eta| = 5.4 - 5.9$
Pb in front.
4 PMTs/side

Earlier: BSC2,3 to $|\eta| = 7.4$

Photon "beams" radiated from electrons and protons

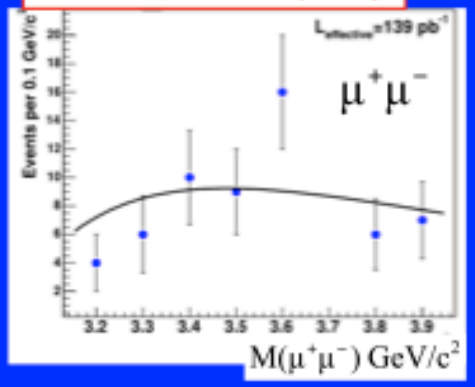
e,p → γ

LEP etc: e+e- (~ background free)
HERA: e p (more background, little done) (γγ)
pp/ ppbar: Very high b/g … Seen in CDF, LHC

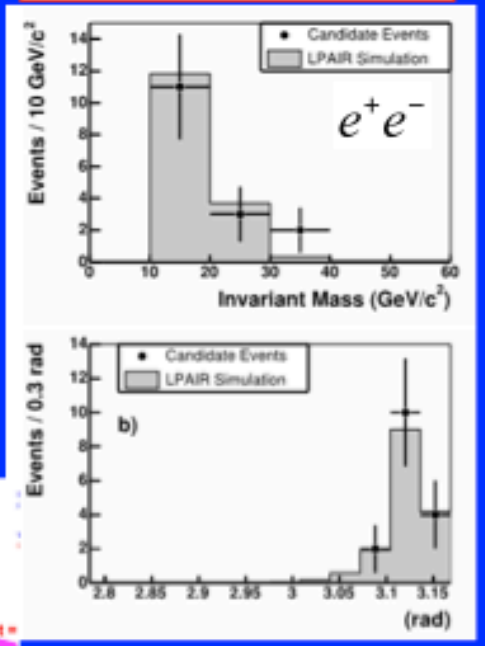


Tevatron, LHC as γγ colliders!

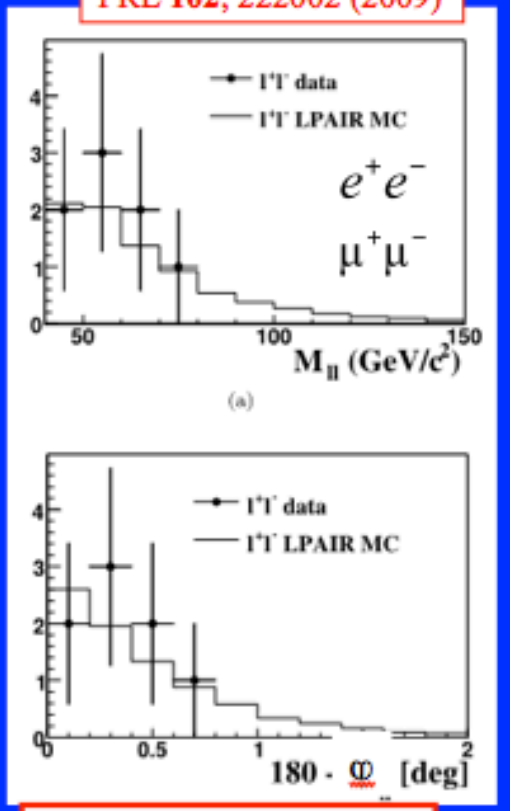
PRL **102**, 242001 (2009)

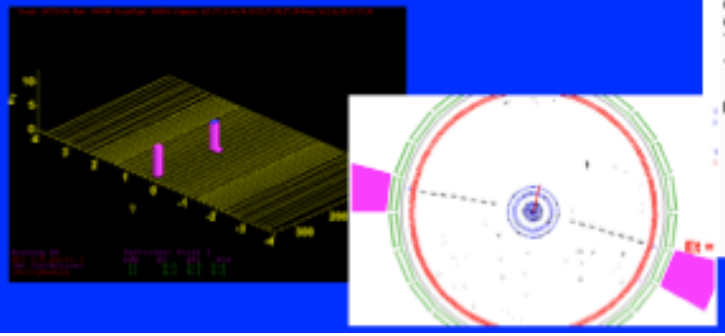


Phys.Rev.Lett 98,112001(2007)



PRL **102**, 222002 (2009)





$\sigma \sim 0.24$ pb $\sim 3\times10^{-12}\sigma_{inel}$

P + P

P = pomeron = strongly interacting color singlet t-channel exchange, in leading order {gg}, at higher Q^2 gluons and q-qbar pairs evolve in.

P + P → X has selection rules:

Q = S = C = B = 0 (of course), $I^G = 0^+$, $J^{PC} = 0^{++}$ or 2^{++} DOMINANT

Interesting for hadron spectroscopy, and for understanding pomeron (> 25% of p-pbar collisions have pomeron exchange!)

Higgs boson obeys all selection rules (vacuum) GHG expected at LHC (~ 2 -3 fb

We already did some, and they importantly tested the theory for p + H + p:

PHYSICAL REVIEW D **77,** 052004 (2008)

Observation of exclusive dijet production at the Fermilab Tevatron $\bar{p}p$ collider

X = JJ

PRL **108,** 081801 (2012) PHYSICAL REVIEW LETTERS week ending 24 FEBRUARY 2012

Observation of Exclusive $\gamma\gamma$ Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

X = γγ

PRL **102,** 242001 (2009) PHYSICAL REVIEW LETTERS week ending 19 JUNE 2009

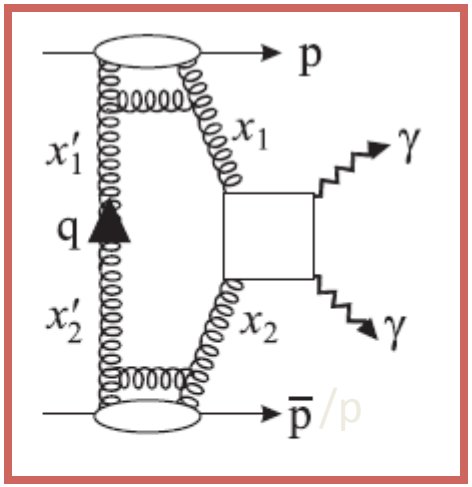
Observation of Exclusive Charmonium Production and $\gamma\gamma \to \mu^+\mu^-$ in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

X = J/Ψ, Ψ(2S) & χ_c 0/1/2

Exclusive γγ Production in CDF and at LHC

$p + p \rightarrow p + \gamma\gamma + p$

with two high p_T central photons and no produced hadrons



Ingredients for calculation:

Khoze, Martin, Ryskin & Stirling
Eur.Phys. J.C38 (2005) p.475

$\sigma(g + g \rightarrow \gamma + \gamma)$
Unintegrated $g(x,x')$ $\sigma \sim g^4$
Loop integral over quarks
No gluon/hadron radiation (Sudakov)
No other parton-parton interaction
(Gap survival factor)

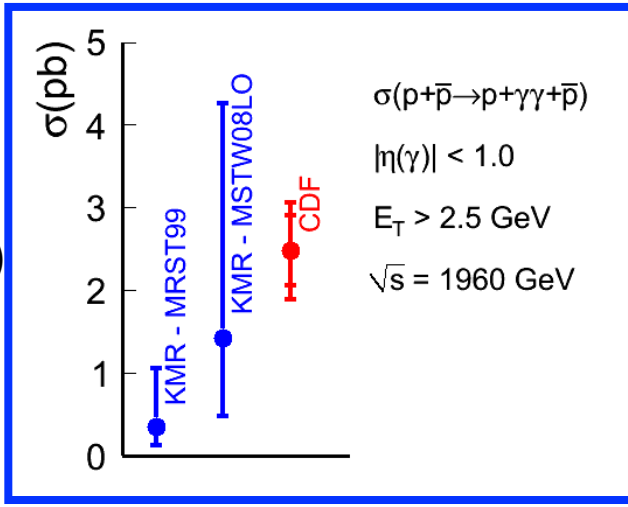
Interesting QCD physics
Understanding pomeron {gg}
from perturbative direction

Quark loops (box/triangle), mostly u and c

ALSO: c-loop → χ_c, b-loop → χ_b, t-loop → Higgs!

γγ is cleanest, like the H (no strong interactions in final state).

Observed at Tevatron (CDF) : PRL 99 (2007) 242002 (search: 3 candidates)
PRL 108 (2012) 081801 (observation, 43 events)



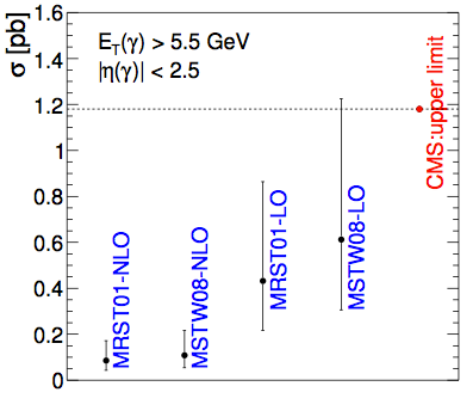
Could not detect protons, but rap gaps to $|\eta| = 7.4$
Beams had $y = 7.64$.

When p's not detected, diffraction dissociation allowed: $p + p \rightarrow p(*) + \gamma\gamma + p(*)$

@ LHC: CMS search : JHEP 11 (2102) 080

36 pb^{-1}, ε(exclusive) = 0.145, L(eff, 1) ~ 5 pb^{-1}

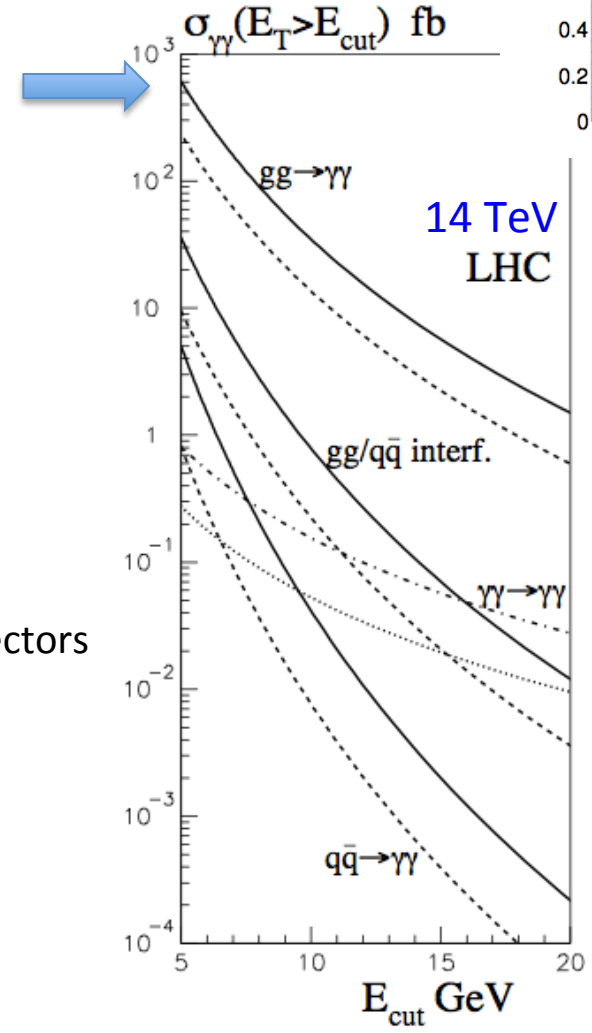
No candidates, upper limit. →



What *could* we do? Goal: 5% stat.error

KMRS (Durham): Eur.Phys.J C38 (2005) 475

Lines: |η(γ)| < 2 and 1



Suppose:

250 hours (can do in 2 weeks)

PU (μ) = 1/crossing (max # single ints./hour)

2800 bunches → L(eff,1) ~ 200 pb^{-1}

0.8 pb^{-1}/hour

Trigger = 2 EM > 2 GeV (cut offline at 3 GeV) in |η| < 3 (EE+EB)

Veto on hadron calorimeters and forward detectors

Off-line: < = 2 tracks (want e+e- also)

σ(>5 GeV, |η| < 2) = 0.6 pb

→ σ(>5 GeV, |η| < 3) ~ 1.8 pb (extrapolated)

If 60% efficiency: 200x1.8x0.6 = 180 events

E_T (γ) > 5 GeV (& more > 3 GeV)

>> ~7% statistical error

Backgrounds small:

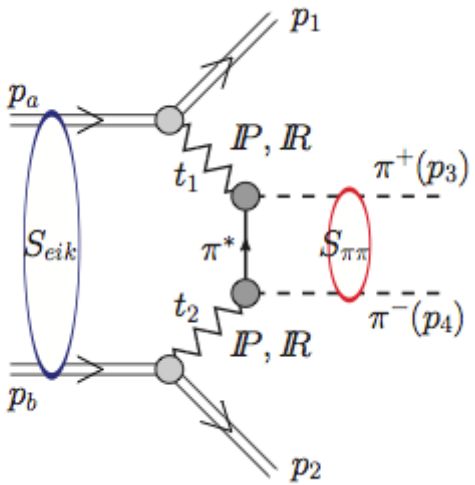
Δφ ~ π

p_{T1} ~ p_{T2}

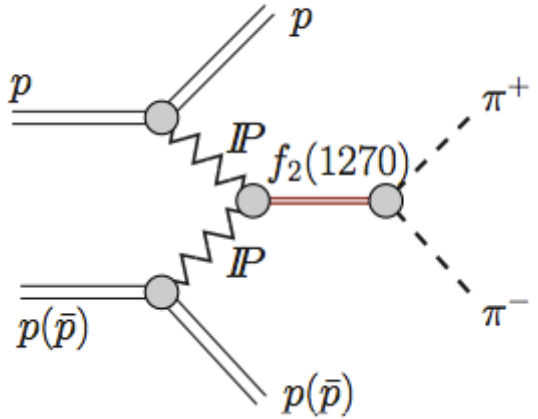
e^+e^- can be measured too.

At low masses, **Double Pomeron** region, non-perturbative and difficult to calculate. New predictions (Harland-Lang et al, Antoni Szczurek et al.)

Diagram from P.Lebiedowicz & A.Szurek
arXiv:12120166



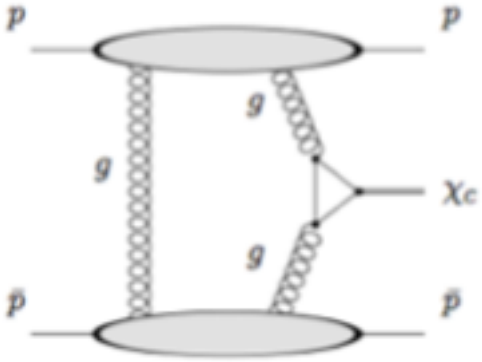
a)



b)

or f0(600)/σ or f0(980) etc.

Into perturbative regime:
"Durham" diagram



e.g. χ_c, χ_b, γγ, Higgs !!

Review:

Central Exclusive Particle Production at High Energy Hadron Colliders.
M.G. Albrow (Fermilab), T.D. Coughlin (University Coll. London), J.R. Forshaw (Manchester U.). Jun 2010. 64 pp.
Published in **Prog.Part.Nucl.Phys. 65 (2010) 149-184** arXiv:1006.1289 [hep-ph]

Now: Preliminary results on double pomeron:
p + pbar → p(*) + [π+π-] + pbar(*)

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)

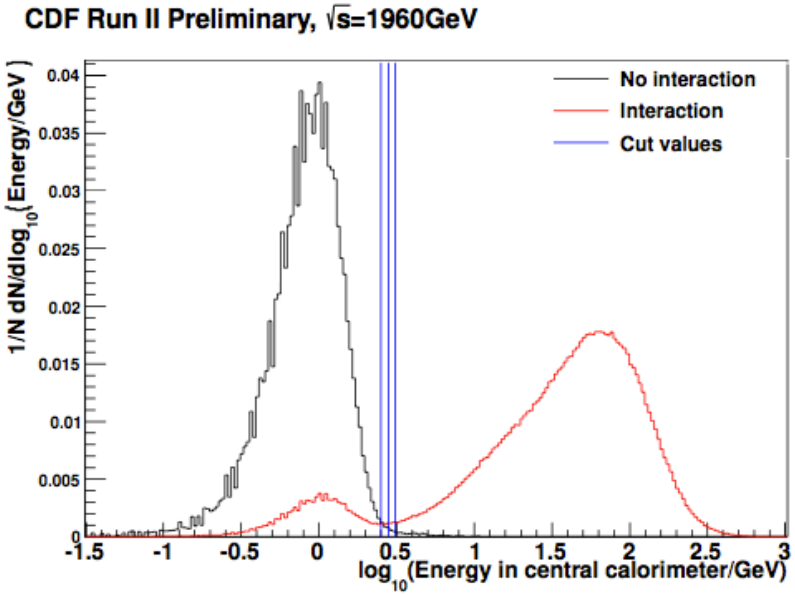
Data summary

Vs	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

s-scan!

38 hours

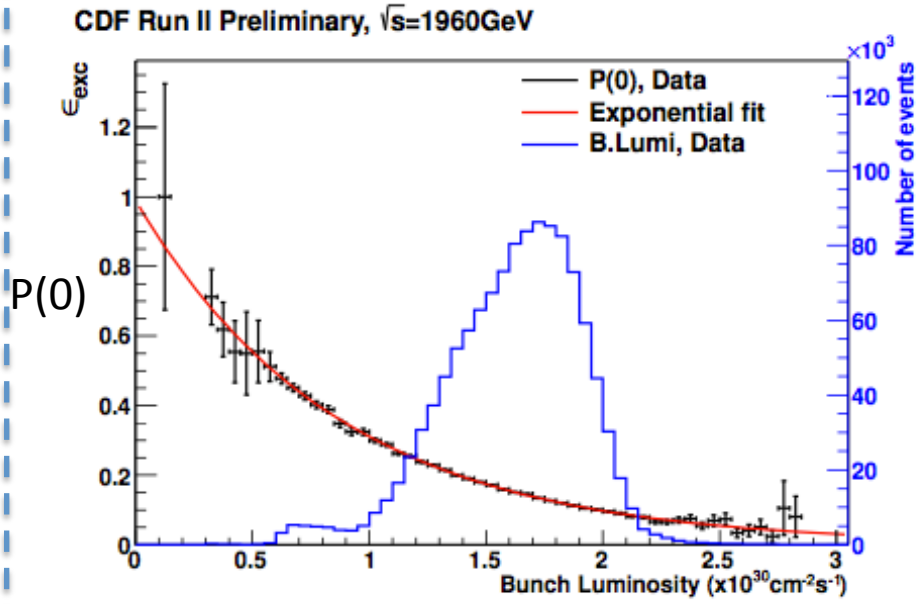
Noise levels → empty detector, exclusivity cuts and σ(vis), example:



Energy in Central Calorimeter

Cuts well defined; noise well separated from interactions.

0-bias (bunch crossing) data (critical)
2 classes:
No interaction = no tracks, no μ stubs, no CLC hits
>= 1 Interaction = all other bunch crossings.



P(0)

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

Note: above plot, 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)

$\sqrt{s}$ =	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}

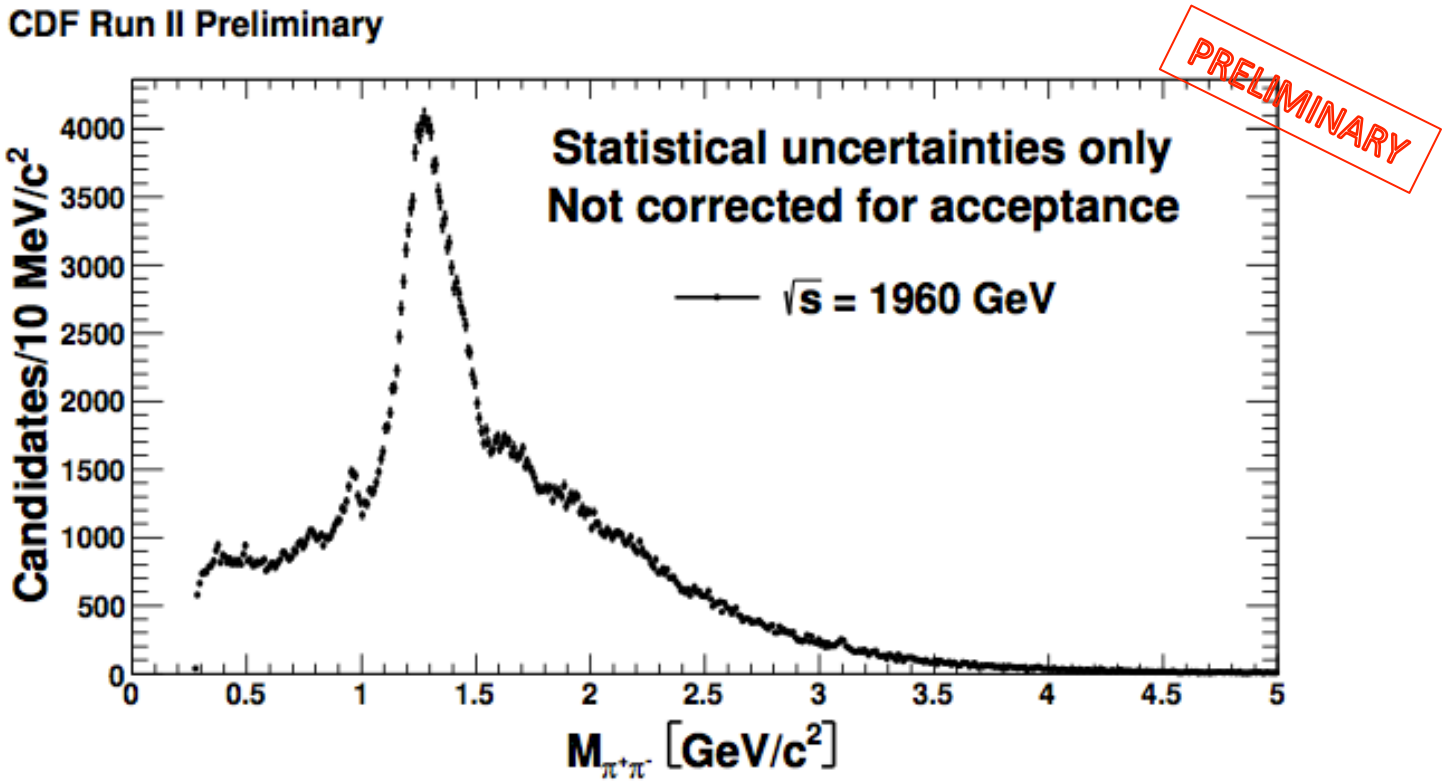
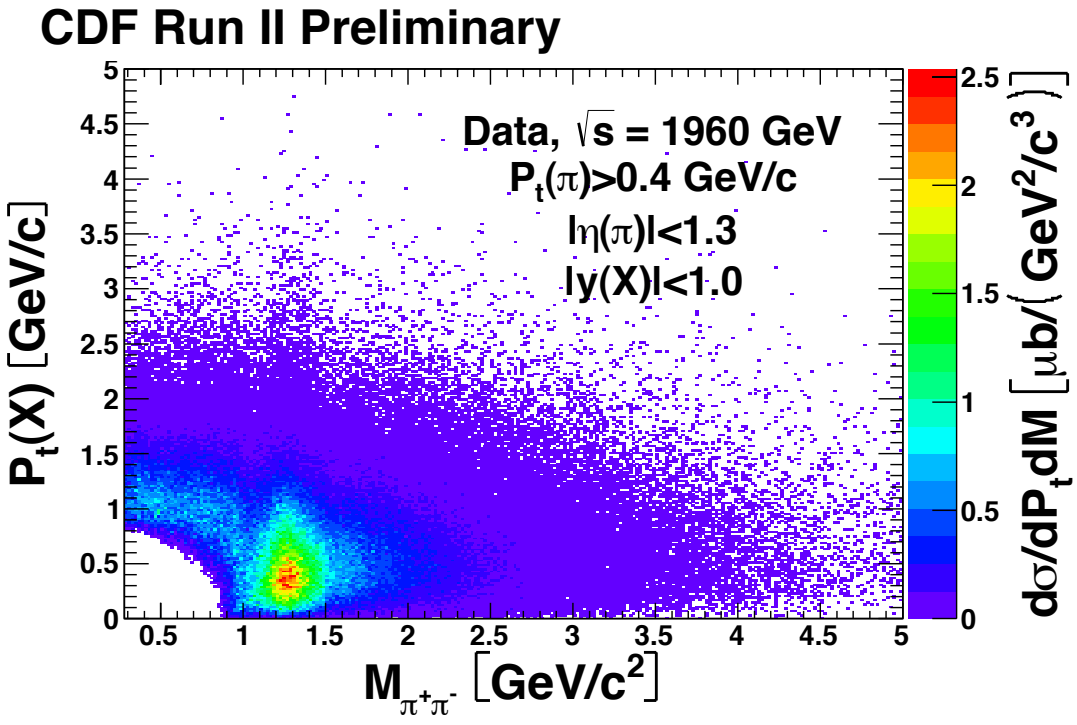


Figure 23: Invariant mass distribution of two particles assuming pion mass - not corrected for acceptance at $\sqrt{s} = 1960$ GeV.

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

Cross section in M, p_T plane after all corrections



Gaps Δy > = 4.6 both sides

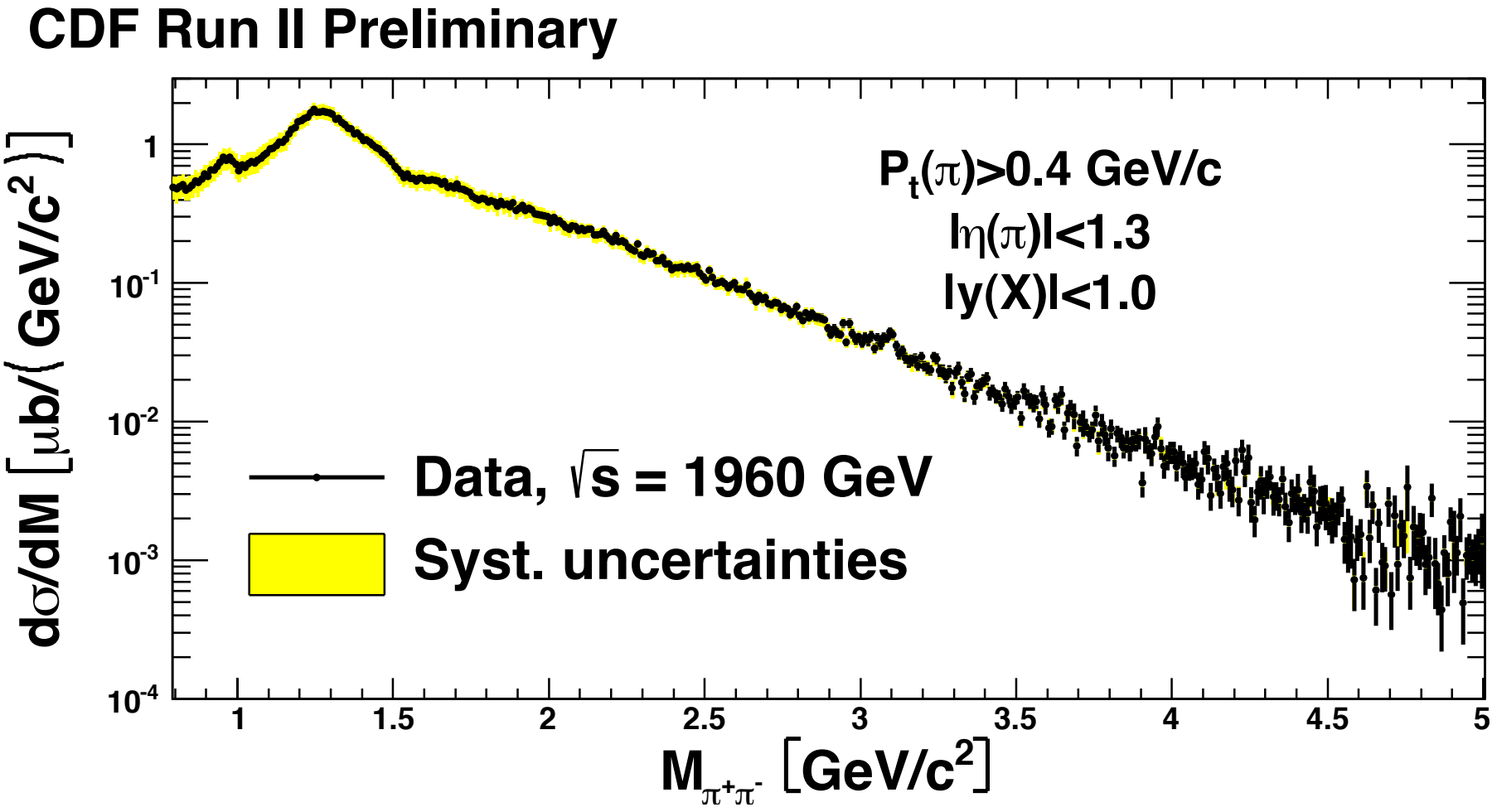


Figure 29: Invariant mass distribution of two particles assuming pion masses - corrected for acceptance, on a logarithmic scale, $\sqrt{s} = 1960$ GeV.

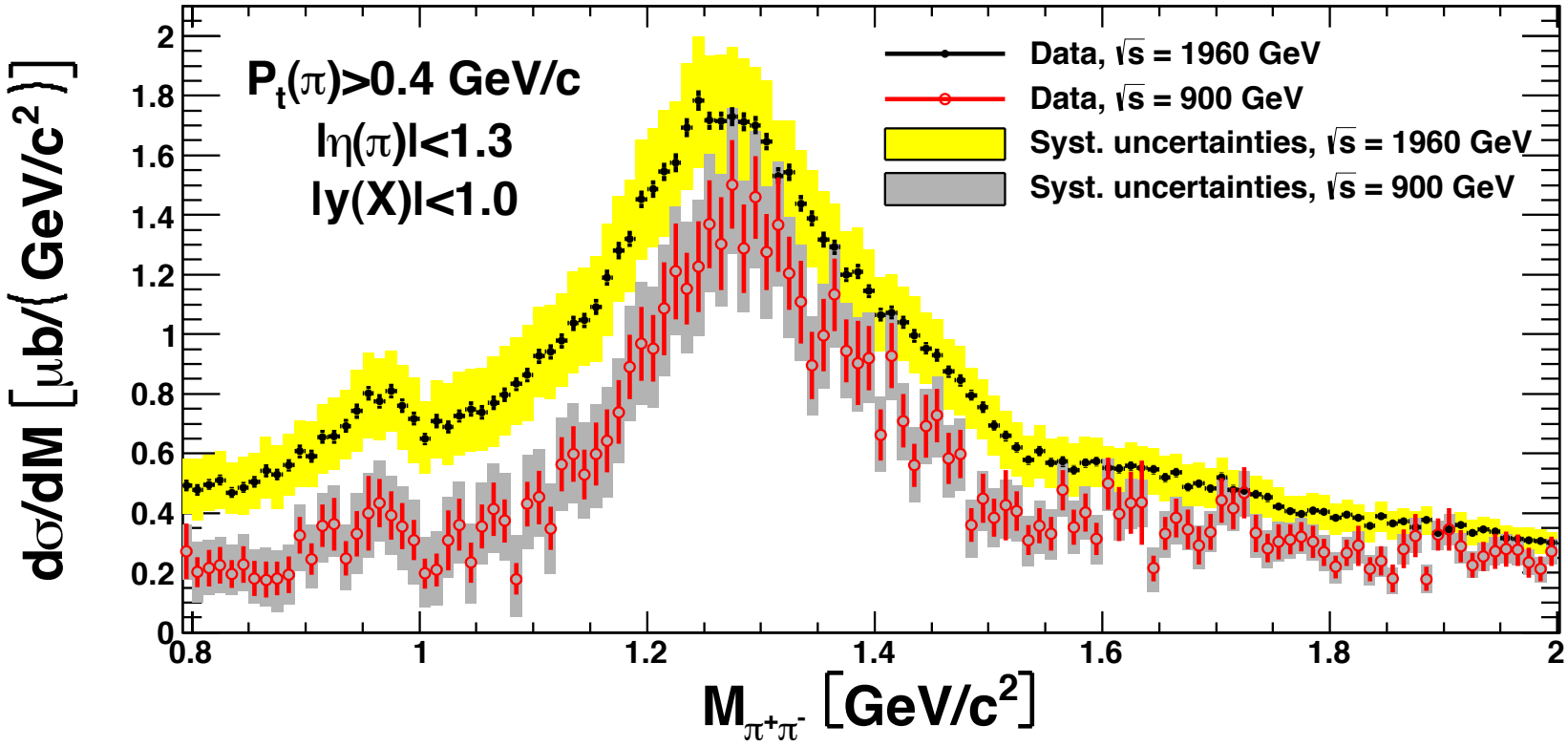
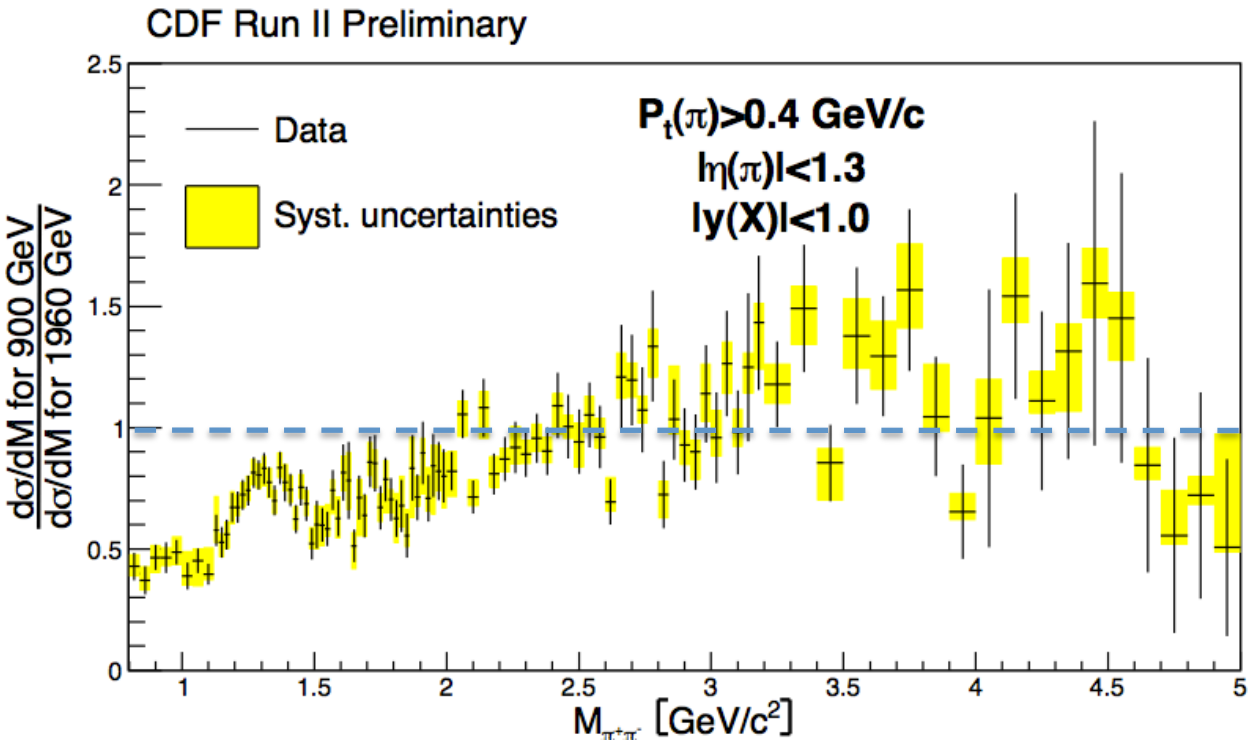


Figure 31: Comparison of invariant mass distribution of 2 particles assuming pion masses - corrected for acceptance, for two $\sqrt{s}$ energies, 1960 GeV - black and 900GeV - red.

At ISR (R807) :
with p +(3) ππ +(+3) p low mass σ(0.8 – 0.95 GeV) >> σ(980, 1270 etc.)
(also at SPS, Tevatron FT energies)
Is this (a) √s (b) gaps 4.6 cf 3 (c) p not p* (d) ppbar cf pp (ω or O?)



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

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

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

Search for J/ψ → e+e- (seen, photoproduction) and $\chi_{c0} \rightarrow \pi^+\pi^-$, K^+K^-

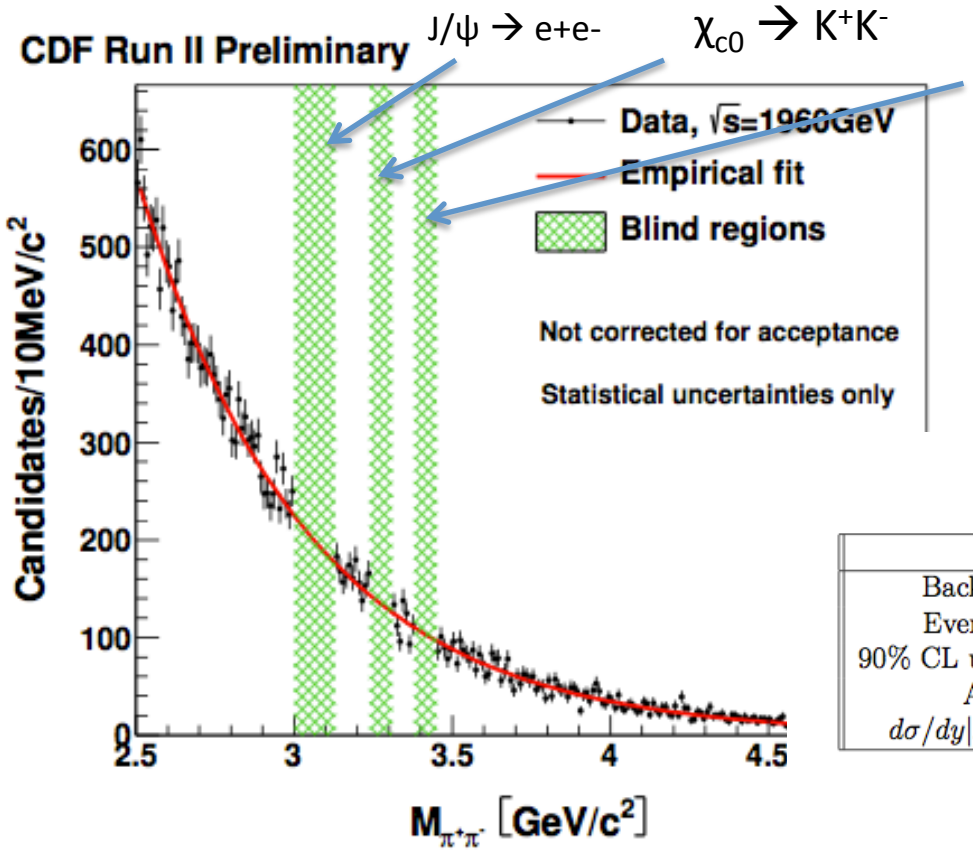


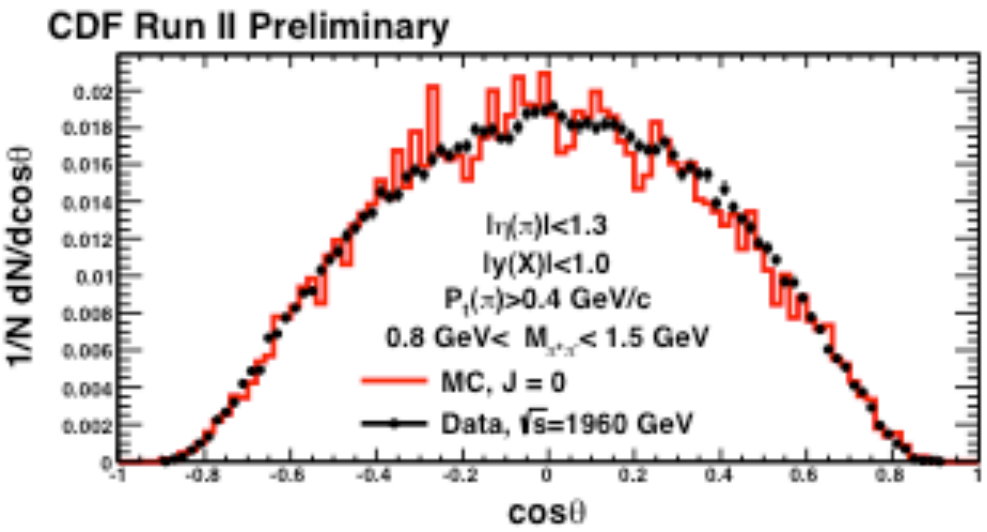
Table 8: Upper limits on χ_{c0} cross sections.

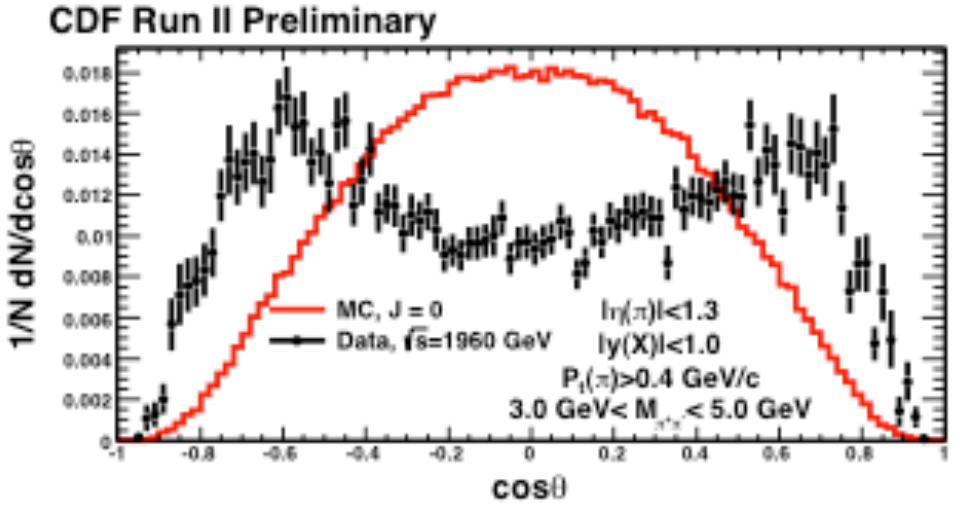
State:	$\chi_{c0} \to \pi^+\pi^-$	$\chi_{c0} \to K^+K^-$
Background (est.)	722.9	940.0
Events in window	754	951
90% CL upperlimit (events)	69.6	59.2
Acceptance	24.2%	21.8%
$d\sigma/dy\|_{y=0}$, 90% CL UL	21.4±4.2 (syst.) nb	18.9±3.8 (syst.) nb

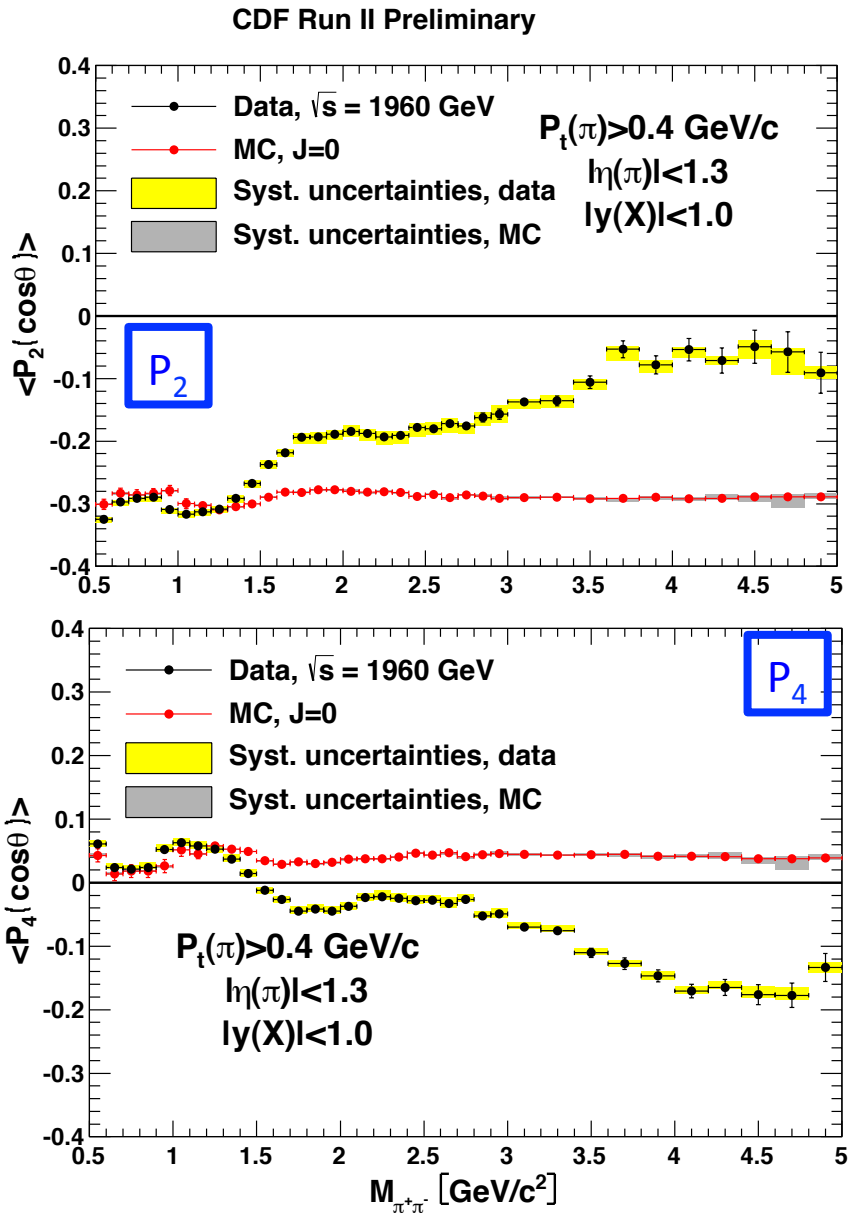
Figure 36: Invariant mass distribution of two particles, assumed to have $m(\pi)$, in the charmonium region at $\sqrt{s} = 1960GeV$. The regions of the J/psi and χ_{c0} (in both $\pi^+\pi^-$ and K^+K^- modes) are excluded from the fit.

Previous observation in J/ψ + γ included all 3 states (not resolved)
Results consistent if >~ 70% of those were χ_{c1} , χ_{c2} . LHCb agrees with that, but...
Also previous had gaps to |η| = 7.4, new results to |η| = 5.9

Angular distributions (not corrected for A)

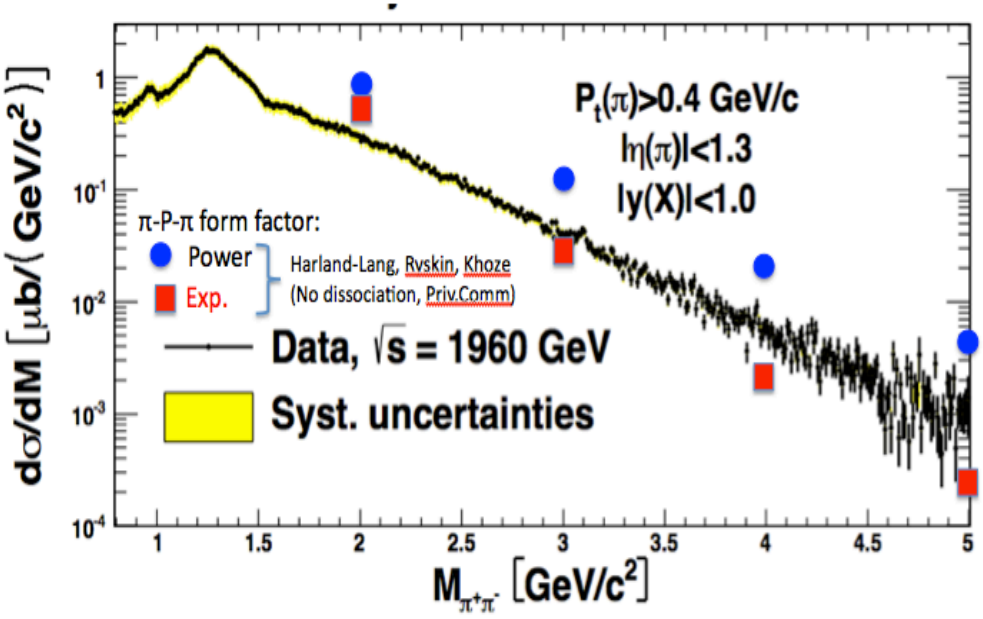






P_{even} : Non-zero because sculpted by acceptance. Data agrees with S-wave MC → isotropic.
J = 0 ? Difference above M = 1.3 GeV → Higher waves (J = 2, 4, ...) present.

Data are test of central exclusive/double pomeron models in NP-QCD = PQCD transition.
Challenge to theorists.
Lucien Harland-Lang, Misha Ryskin and Valery Khoze:
Private Communication, “upper” and “lower” bounds, depending on π-pom-π form factor.
But not including proton dissociation.



Antoni Szczurek and Piotr Lebiedowicz:
AIP Conf Proc. 1523 (2012) 132
arXiv:1212.0166
... with these cuts, results coming

More to come from CDF on "GXG"

$X = \pi^0\pi^0, \eta^0\eta^0, \eta'\eta'$?

$X = K^+K^-, K^0s\ K^0s$ .... $\rho\rho$, K^*K^* ?

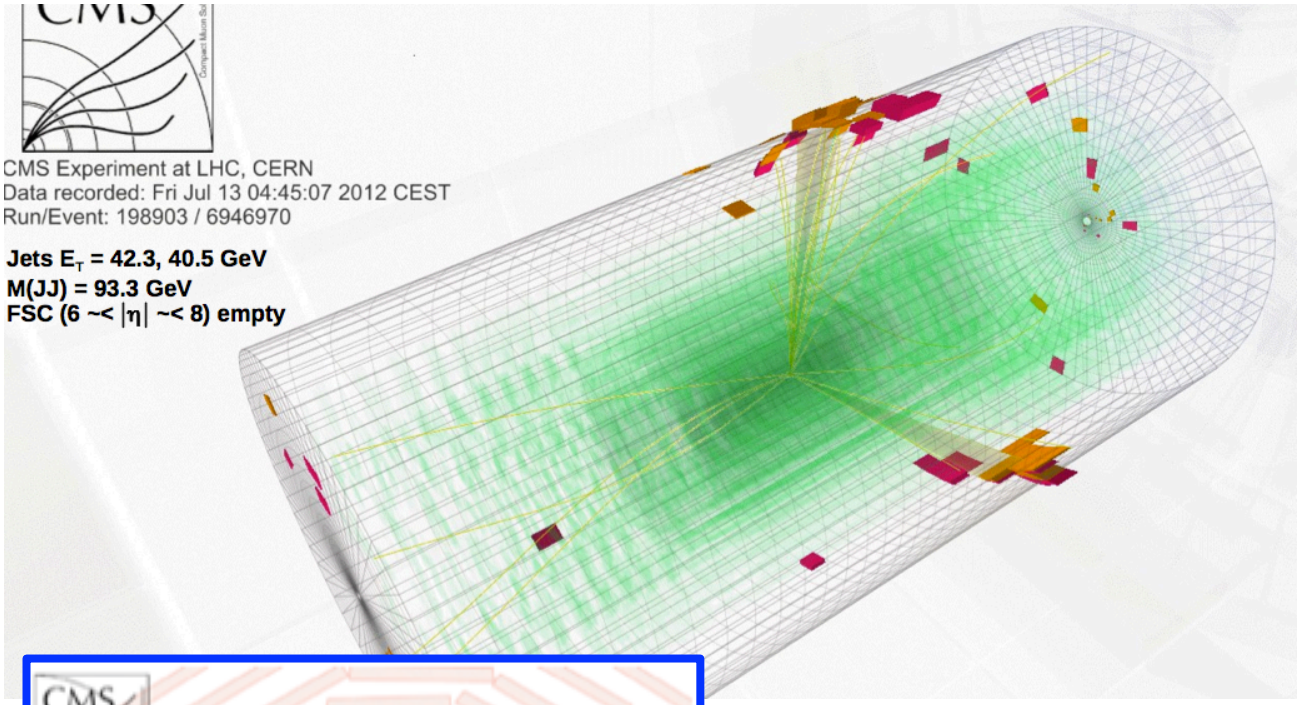
Moving on to LHC:

Exclusive hadrons (DPE): Pile-up limitations in CMS & ATLAS (short runs only)
LHCb leads the field (but no fwd p's, no BSC yet)

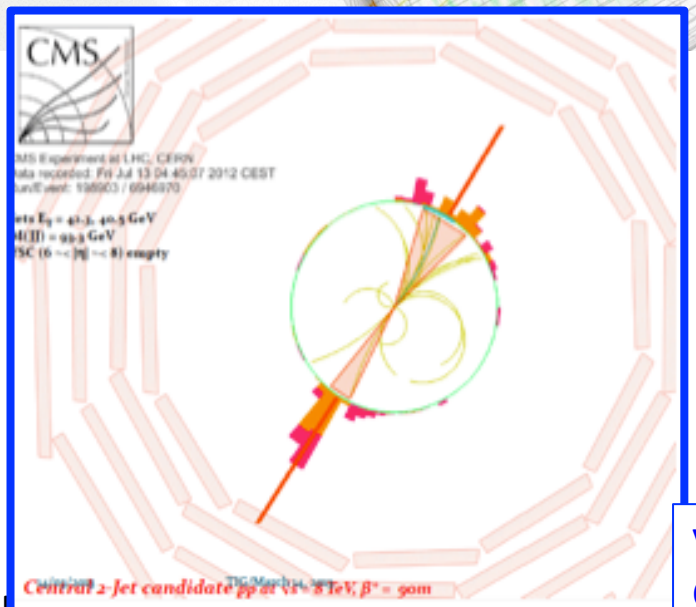
High mass exclusives **X = W+W-, Higgs (!), BSM ?** In high pile-up, high-L runs.
Precision proton tracking near beams, and timing (10 ps) for pile-up rejection
PPS (CMS + TOTEM) project approved by Collaboration Boards.
Low- pileup start up in 2015 → High-lumi running in 2016 & beyond.

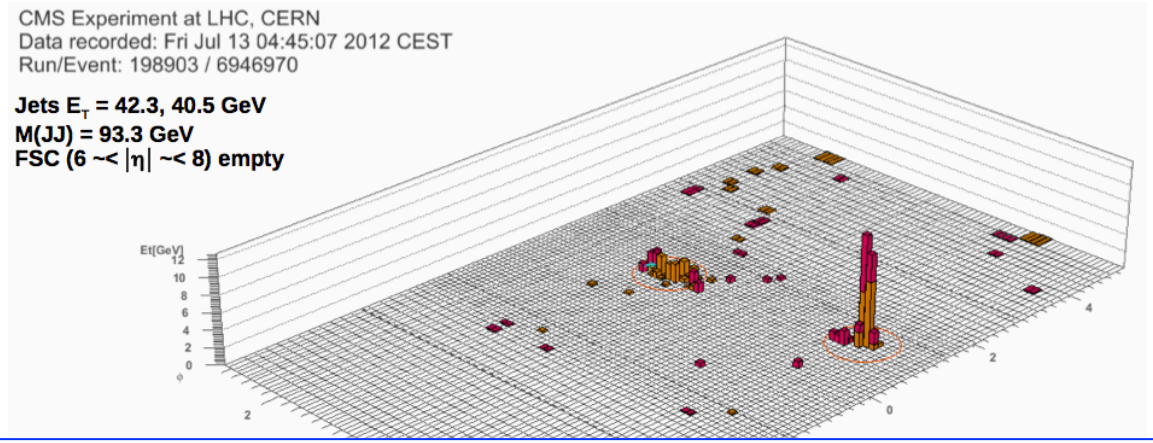
A taste of things to come:

From 90 m β* Run with TOTEM: p + JJ + p



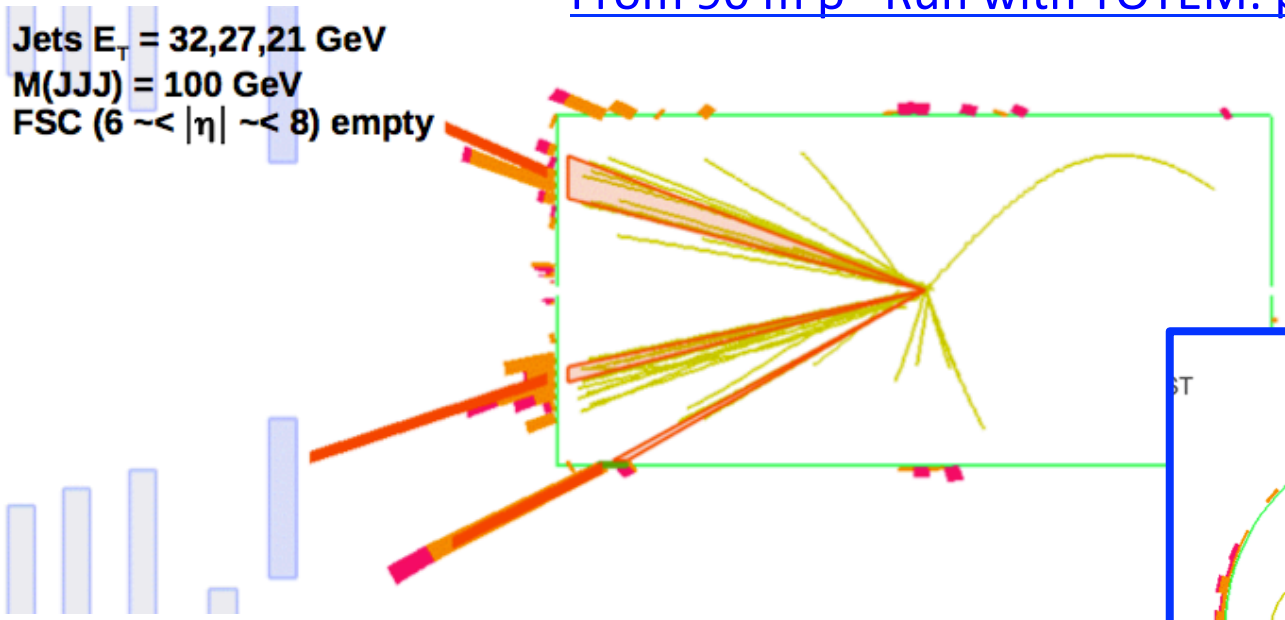
REAL CMS+TOTEM EVENTS!



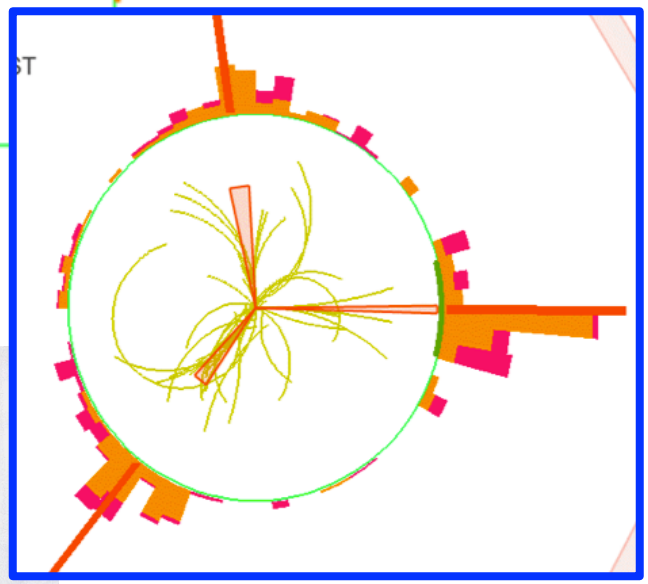


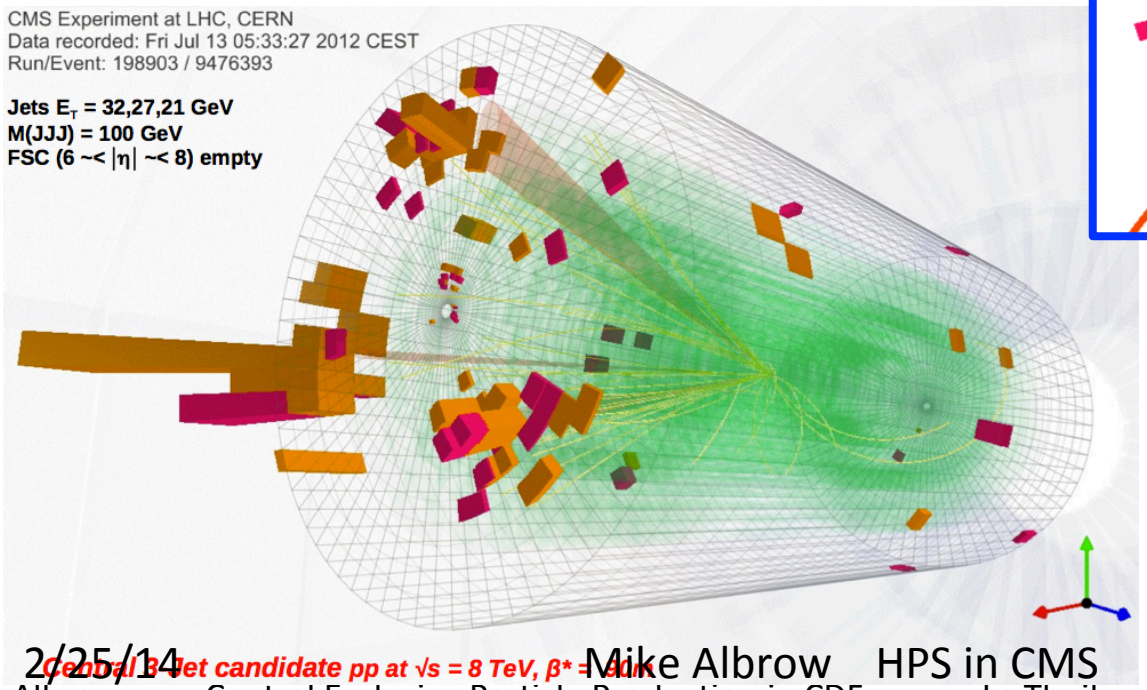
Very low pile-up, only 100 bunches, short run → ~ few dozen events
Could get ~ 5000 in < 2 weeks with μ ~ 1, 2800 bunches, 13 TeV

From 90 m β* Run with TOTEM: p + JJJ + p



> = 2 jets E_T > 20 GeV
2 protons & FSC gaps





Exclusive 3-jet events, theory (not detailed):
Mostly ggg
Some qqg ... more open
20% each bb, cc, ss, uu, dd
If one b, 2 b's!

Thank You

and thanks to the La Thuile Organizers for the invitation