Exclusive Central Production in Proton-Proton Collisions: from the ISR to the Tevatron to the LHC

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Fermilab
1) Introduction

2) Diffractive Excitation of High Masses (Jets, W, Z) – CDF/D0

3) Central Exclusive Production:

\[(\pi^+\pi^-, K^+K^-, pp) \rightarrow e^+e^-, \mu^+\mu^-, J/\psi/\psi(2S), Y, JJ\]

4) LHC: Study of Higgs through p+H+p, WW and ZZ, Excl.Z?

FP420: R&D project; proposing extensions to ATLAS & CMS.
ISR = Intersecting Storage Rings, started 1971
First colliding proton beams.

Centre of mass energy = 63 GeV
Centre of mass energy = 7.4 GeV

Equivalent to beam of 2110 GeV + fixed p target
“Into the realm of cosmic rays!”

First collisions ... no detectors installed! ... put in 4 counters!

Emulsions on a toy train set!
$2008: LHC = \text{Large Hadron Collider}$

7 TeV = 7000 GeV

$\equiv 10^8 \text{GeV} = 10^{17} \text{eV}$

cf. cosmic cut off $\approx 10^{20} \text{eV}$

ATLAS $\sim 2500$ physicists!

One of four experiments.

Meanwhile, back at the ISR in 1972 ...

Intersection I-2:

Nobody knew what to do with complete multi-particle (~ 10+) final states. Study “inclusive” particle production: \( pp \rightarrow e, \mu, \pi, K, p \ldots + \) “anything”.

Muon Detector: Looking for \( W(\sim3-4 \text{ GeV}) \) ... missed \( J/\psi \)

Wide Angle Spectrometer: co-discovered high \( p_T \) (quark scattering)

Small Angle Spectrometer: discovered high mass (14 GeV) diffraction

\[
p \times \sim 0.95 \Rightarrow x = \frac{p_{\text{OUT}}}{p_{\text{IN}}} \}
\]

\( M \sim 14 \text{ GeV} \)
Small Angle Spectrometer: Forward proton spectra

\[ x_{\text{Feynman}} = \frac{p_L}{p_{\text{beam}}} \]

Feynman scaling:

\[ E \frac{d^3 \sigma}{dp^3} = f(x_F, p_T) \text{ not } \sqrt{s} \]

Discovery of high-x, scaling peak

\[ x > 0.95 \]

M \{ 
\begin{align*}
M &< \sqrt{0.05} \sqrt{s} = 0.22 \sqrt{s} \\
M &\text{ up to about 1.6 GeV at AGS/PS} \\
&14 \text{ GeV at ISR} \\
&440 \text{ GeV at Tevatron} \\
&3100 \text{ GeV at LHC}
\end{align*}
\]

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Forward Proton Spectrometers: ISR \( \rightarrow \) LHC

**ISR (1971)**
- Small Angle Spectrometer
- Gas Cerenkovs and tracking
- \( p \) (beam)
- \( p \) (scattered)
- \( \sim 15m, \ dp/p \sim 0.5\% \)
- SEPTUM
- 30 GeV/c

**LHC (2009 – FP420 2011)**
- 120m of 8T dipoles
- QUADS, SEPs
- FP420
- 420m, \( dp/p \sim 0.01\% \)
- High Precision (5-10 \( \mu \)m) tracking
- 20 mm x 6 mm
- 7000 GeV/c
- 3-24 mm
- 10m
Central Diffractive Excitation

Theoretically (Regge theory) if:

\[ x > 0.95 \]

\[ M < \sqrt{0.05\sqrt{s}} = 0.22\sqrt{s} \]

happens, so should:

\[ x > 0.95 \]

\[ M < 0.05\sqrt{s} \]

\[ \text{…both protons coherently scattered} \]

Exchanged 4-momentum must have no electromagnetic charge or strong charge (colour), & spin \( \geq 1 \)

\[ \gamma \text{ or } g \ ( + \ g \ , \ g \\ g ) = \text{IP (pomeron)} \]

Central state Quantum Numbers restricted.

W/Z exchange allowed, but \( p \) would break up.

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Central Exclusive Production

$$pp \rightarrow p \ X \ p$$ where X is a simple system completely measured

At CERN ISR
Glueball Search

At Tevatron & LHC

$$\gamma \gamma \rightarrow \mu^+ \mu^-$$
$$\gamma IP \rightarrow \psi, Y \rightarrow \mu^+ \mu^-$$

$$gg \rightarrow \gamma \gamma$$ through q-loops (box) + colour bleaching (g)

$$\gamma \gamma \rightarrow WW; H \rightarrow WW, H \rightarrow ZZ$$
$$H \rightarrow b\bar{b}; BSM \rightarrow WW, SUSY etc$$
**Central Exclusive Production in Different Machines**

**In $e^+e^-$ collisions** (through LEP energies $\rightarrow$ ILC):
\[ \gamma\gamma \rightarrow l^+l^-, q\bar{q} \rightarrow \text{hadrons}, \text{and at high (ILC) energy:} \]
WW $\rightarrow$ WW, WW $\rightarrow$ Z,H ; WZ $\rightarrow$ W

**In ep collisions** (HERA):
\[ \gamma \gamma \rightarrow l^+l^- \ (q\bar{q} \text{ too but buried?}) \]

**In pp ($p\bar{p}$) (ISR $\rightarrow$ Tevatron and LHC):**
\[ \text{IP IP $\rightarrow$ hadrons (can be single hadron), q-loop $\rightarrow$ Higgs, } \gamma \gamma \gamma \text{-IP $\rightarrow$ vector mesons (.. $\psi, \psi', Y, Z$(allowed but tiny)?)} \]
\[ \gamma\gamma \rightarrow l^+l^- \ (q\bar{q} \text{ too but buried?}) \]

**New in CDF**

In AA (RHIC, LHC) mainly
\[ \gamma\gamma \rightarrow l^+l^- \ (E\text{-fields}) \]
$\gamma$ -IP and IP+IP
**ISR: Axial Field Spectrometer (R807)**

First sophisticated high-pT spectrometer in pp. Forerunner of p-pbar collider experiments.

**Axial Field Magnet**

(≈Helmholtz coils)

Uranium-scintillator full-azimuth calorimeter

37%/sqrt(E) hadron showers

**Jets in hadron-hadron**

co-discovered with UA2, UA1 (1982 Paris)


**Circularity (2D-sphericity)**
**Low Mass Central Exclusive Production**

\[ pp \rightarrow p \ X \ p \]

X fully measured

\[ \text{ISR} \ \sqrt{s} = 63 \ \text{GeV} \]

Search for “Glueballs”

\( \{gg\} \) as distinct from \( \{q\bar{q}\} \)

Axial Field Spectrometer (R807)

Added very forward drift chambers
Central Exclusive $\pi^+\pi^-$ Production (AFS)

3500 events/25 MeV

Also $K^+K^-$ and $p\bar{p}$

$\alpha\alpha$ elastic scattering on-line dip!

No $\rho$

$f_0(980)$

G(1710)??

Structures not well understood beyond $f(980)$. Not studied at higher $\sqrt{s}$.

Pity: $\phi\phi$ would be great for G-spectroscopy

$M(\pi^+\pi^-)$

Exclusive Central Hadron States at ISR

Birmingham did much of this at Omega facility, lower $\sqrt{s}$.

Axial Field Spectrometer:

$\sqrt{s} = 63$ GeV, $\Delta y \leq 3$

$\pi^+\pi^-, K^+K^-, p\bar{p}, 4\pi$

Q.No. Filter: $I^GJ^{PC} = 0^+$ even $^{++}$

What about, among others:

$K^0_S\bar{K}^0_S, D^0\bar{D}^0, D_s\bar{D}_s, \ldots \Lambda\bar{\Lambda}, \Sigma\bar{\Sigma}, \Omega\bar{\Omega}, \ldots$

Pomeron $\sim gg$ is flavor-blind, mostly depends on masses.

CDF detector equal to best in world, Tevatron to best place!

Hope to do it, but …
CDF Detector at Fermilab Tevatron

Time-of-Flight Detector

End Wall Hadron Cal.

End Plug Hadron Calimeter

Solenoid

COT

SVX II

5 Layers

Intermediate Silicon Layers

BEYOND 3 deg:
Luminosity Counters
Beam Shower Counters
Roman Pots
MiniPlugs

980 GeV pbar

980 GeV p
Installed very forward **Beam Shower Counters** (BSC) for rapidity gaps and scintillating fiber trackers in **Roman pots** for pbar detection.

Not at all to scale!

Roman pot detectors 20mm x 20mm
55 m downstream.
Not used for most of this (acceptance).

Beam Shower Counters BSC tight around pipe.
Full coverage $-7.4 < \eta < +7.4$

\[ p \rightarrow n\pi; \ p\pi\pi, \text{etc vetoed} \]
Central tracking: Silicon strips & Drift Chamber

\(~ 720,000\) strips,
\(25\ \mu\text{m}\) with \(50\ \mu\text{m}\) readout

- Drift chamber
  - 96 layers \(\rightarrow\) 30,240 sense wires
  - 40 \(\mu\text{m}\) gold-plated tungsten
  - ADC and TDC each end
  - Resolution \(~ 150\ \mu\text{m}/\text{wire}\)

Surrounded by lead/iron scintillator sandwich calorimeter for energy measurement
**Diffractive W and Z Production**

W produced but p “stays intact”

CDF: \[ \frac{\text{Diff. W}}{\text{Non-Diff W}} = (1.15 \pm 0.55)\% \]

D0 also sees diffractive W and Z all consistent with 1% diffractive

Should be much larger at LHC

\[ \eta(LO) = 2.3 - 4.3 \]
\[ \eta(CAL) = 3.0 - 5.2 \]

**M(\mu\nu): no p_\perp(\nu) ambiguity**

Central Exclusive Production in CDF

\[ p + p \rightarrow p \ X \ p \] where X is a simple system completely measured

\[ \sqrt{s} = 63 \quad 1960 \quad 14000 \ \text{GeV} \]

\[ \Delta y = 2 \ln \frac{\sqrt{s}}{m_p} = 8.4 \quad 15.3 \quad 19.2 \ (-6 \text{ for gaps}) \]

CDF: e^+e^-, \gamma\gamma, \mu^+\mu^-, J/\psi, \psi(2S), \chi_c, \Upsilon \ldots Z? JJ

LHC: Z, H, W^+W^-, \tilde{\ell}\tilde{\ell} \ldots
Rapidity (Tevatron)

3 possibilities: $\gamma + \gamma$, $\gamma + \text{IP}$, $\text{IP} + \text{IP}$

We have now seen all 3 in h-h!

$t(\gamma) \ll t(\text{IP})$

$\sigma \approx \Delta y^{\alpha(t)-1}$, where $\alpha(t)$ is (complex) spin of exchange.

$a(0) \equiv$ spin $J$ for massless exchange:

$J \geq 1$ for large $\Delta y$ ⇒ only photon or "pomeron" IP

$a(0) \sim 1.1$ for IP → rising elastic and $\sigma(\text{tot})$.

IP modeled as gg for many situations.

+(?) O = ggg
Also in e+e- and ep
Also in ep
Only in hadron-hadron

FIG. 1: Feynman diagrams for (a) $\gamma\gamma \rightarrow \mu^+\mu^-$, (b) $\gamma p \rightarrow J/\psi(\psi(2S))$, and (c) $IP IP \rightarrow \chi_c$.

$J/\psi/\psi'(2S) \rightarrow \mu^+\mu^-$

$\chi_c \rightarrow J/\psi + \gamma \rightarrow \mu^+\mu^- + \gamma$

Odderon can replace photon in p+pbar, not in e+p

We cannot detect p and pbar ... require all CDF in noise, to $|\eta| = 7.4$
**Exclusive Electron-Positron Production**

\[ E_T(e^\pm) > 5 \text{ GeV}; \mid \eta(e^\pm) \mid < 2.0 \]

\[ e^+ e^- : \Delta \phi = 180^0 \pm 2^0 \]

\[ M(e^+ e^-) 10 \rightarrow 38 \text{ GeV} \]

\[ \Delta p_T \text{ small (} \cong \text{ resolution) } \]

16 events

Estimated background = 1.9 ± 0.3 (mostly p-dissociation)

\[ \sigma_{\text{MEAS.}} = 1.6^{+0.5}_{-0.3} \text{ (stat)} \pm 0.3 \text{ (syst) pb} \]

p-value = \[1.3 \times 10^{-9}(\geq 5\sigma)\]

\[ \sigma_{\text{QED}} = (1.711 \pm 0.008) \text{ pb} \]

QED process: \( \gamma \gamma \) collisions in pp

Monte Carlos: LPAIR, GRAPE, STARLIGHT
Exclusive 2-Photon Production

KMR+Stirling hep-ph/0409037

\[ \sim 40 \text{ events per } fb^{-1} \text{ with } p_T(\gamma) > 5 \text{ GeV/c \& } |\eta| < 1.0 \]

Claim factor \sim 3 \text{ uncertainty \& Correlated to } p+H+p

\[ \gamma\gamma \to \gamma\gamma \text{ \& } q\bar{q} \to \gamma\gamma \text{ much smaller} \]
Exclusive $\gamma\gamma$ Production in Hadron-Hadron Collisions

3 candidates observed: $E_T(\gamma) > 5 \text{ GeV}; |\eta(\gamma)| < 1.0$

2 events are "perfect" $\gamma\gamma$

candidates and 1 may be a $\pi^0\pi^0$


$\sigma$ (our cuts) = $(36 + 72 - 24) \text{ fb} = 0.8 + 1.6 - 0.5 \text{ events.}$

Cannot yet claim “discovery” as b/g study a posteriori, 2 events corresponds to $\sigma \sim 90 \text{ fb}$, agreeing with Khoze et al.

If really $\gamma\gamma \to H$

It means exclusive $H$ must happen (if $H$ exists) and probably $\sigma \sim 5 \text{ fb}$ within factor $\sim 3$.

$\sigma$ is higher in MSSM

Note: $\sigma_{MEAS} \approx 2 \times 10^{-12} \sigma_{INEL}$!
Central Exclusive $\mu^+\mu^-$ Production

Why interesting?

Among other things:

Two-photon production: $\gamma\gamma \rightarrow \mu^+\mu^-$ continuum (QED + FF).

Cross section very well known (QED) so can calibrate LHC luminosity (??).
Can come through photo-production of $\psi,\psi', Y, Y', Y''$.

Forward proton momenta precisely known:
calibrate momentum scale of forward spectrometers for $p + p \rightarrow p + H + p$ at LHC.
New Results “approved” Sept 4\textsuperscript{th}:

\[ p + \bar{p} \rightarrow p + \mu^+ \mu^- + \bar{p} \]

\[ 3 \text{ GeV}/c^2 < M_{\mu\mu} < 4 \text{ GeV}/c^2 \]

Region rich in physics.
First observations in (elastic) hadron-hadron:

1) \( \gamma + \gamma \rightarrow \mu^+ \mu^- \)
2) \( \gamma + \mathrm{IP} \rightarrow \mathrm{J/\psi} \ & \psi(2S) \)
3) \( \mathrm{IP} + \mathrm{IP} \rightarrow \chi_c \)

1 & 2) \text{Forward proton momenta precisely known:}
\text{calibrate momentum scale of forward spectrometers for } p + p \rightarrow p + H + p \text{ at LHC.}

3) \text{Calibrate theory (x-sn) of } p + H + p
Luminosity (Good Runs) = 1.48/fb (+/- 6%)
Trigger = muon + track + BSC1 gaps → 2 muons
Number of events on tape: ~ 1.6 million

Fiducial “box”:  

\[ |\eta(\mu)| < 0.6, \, p_T(\mu) > 1.4 \text{ GeV}/c, \, 3.0 < M(\mu^+\mu^-) < 4.0 \text{ GeV}/c^2 \]

Reject cosmic ray events (ToF, colinearity) … 100% efficient
Exclusivity: Require all detectors < noise cuts except in and around muons.

Example, BSC1, Period 9:
402 events, final sample

\[ \text{CDF Run II Preliminary} \]

\[ L_{\text{effective}} = 139 \text{ pb}^{-1} \]

\[ p + \bar{p} \rightarrow p + \mu^+ \mu^- + \bar{p} \]

\[ J/\psi \rightarrow \mu^+ \mu^- \]

\[ \psi' \]
Observation of Exclusive Charmonium Production
and $\gamma\gamma \rightarrow \mu^+\mu^-$ in $p\bar{p}$ Collisions at $\sqrt{s}=1.96$ TeV.

$p + \bar{p} \rightarrow p + \mu^+\mu^- + \bar{p}$

Fit: 2 Gaussians + QED continuum.
Masses 3.09, 3.68 GeV == PDG
Widths 15.8, 16.7 MeV = resolution.
QED = generator x acceptance
3 amplitudes floating
\( J / \psi \) \hspace{1cm} \( \psi'(2S) \)

**QED continuum**: \( \gamma + \gamma \rightarrow \mu^+\mu^- \)

**CDF Run II Preliminary**

\[ L_{\text{effective}} = 139 \text{ pb}^{-1} \]

- **CDF Run II Preliminary**

\[ F_{AE} = 0.6 - 0.5 \cdot e^{-3.22(M-3.05)} \]

\( \times \) QED spectrum

\[ \sim F_{\text{QED}} = A \cdot e^{-0.852 \times M} \]

Only normalization A floating

\[ A \rightarrow \sigma(\gamma\gamma \rightarrow \mu^+\mu^-) : \]

\[ \sigma(|\eta| < 0.6, 3 \text{ GeV/c}^2 < M_{\mu\mu} < 4 \text{ GeV/c}^2) = 2.6 \pm 0.5 \text{ pb} \]

STARLIGHT & LPAIR QED: 2.18 pb

**STARLIGHT \& LPAIR MCs**

**Good description**: v. low pT
**J/ψ Photoproduction**
(or possible odderon exchange)

**Kinematics well described by**
STARLIGHT MC
also $\psi(2S)$

Much broader

$\Delta\phi(\mu^-\mu^+), p_T(\mu^+\mu^-)$ than

QED continuum: $\gamma + \gamma \rightarrow \mu^+\mu^-$

---

Non-inclusive b/g?
Odderon component?
Some $\chi_c$?
Now allow photons: EmEt spectrum with J/psi mass cut:

J/ψ have photons: 286 → 352
ψ(2S) do not: 39 → 40

χ_c → J/ψ + γ

Empirical functional form

65 events above 80 MeV cut.
3 events below (estimated from fit)
→1% background under J/psi
→# χ_c = 68 +/- 8

MC also estimates only few % of χ_c → J/ψ + γ under the cut

(But CDFSIM not reliable for such low ET)
Kinematic fits on $J/\psi : \Delta \phi (\mu \mu)$ and $p_T (J/\psi)$

Events with EM shower

Good fits to $\mu^+ \mu^-$ kinematics with only $\chi_c$, if EM shower

⇒ No photoproduced $J/\psi$ above 80 MeV cut

Confirms $\chi_c$ assignment
Summary of Results

\[ p + \bar{p} \rightarrow p + \mu^+ \mu^- + \bar{p} \]

\[ M = 3-4 \text{ GeV/c}^2 \]

<table>
<thead>
<tr>
<th>Quantity</th>
<th>This analysis</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{d\sigma}{dy} (y = 0)J/\psi ) (nb)</td>
<td>3.96±0.64</td>
<td>(3.0±0.8) nb</td>
</tr>
<tr>
<td>( \frac{d\sigma}{dy} (y = 0)\psi(2S) ) (nb)</td>
<td>0.53±0.15</td>
<td>0.46±0.11</td>
</tr>
<tr>
<td>( \frac{d\sigma}{dy} (y = 0)\chi_c^\circ ) (nb)</td>
<td>66±13</td>
<td>130±50</td>
</tr>
<tr>
<td>( \sigma_{box, QED, pb} )</td>
<td>2.6±0.5</td>
<td>2.18±0.02</td>
</tr>
<tr>
<td>( Q\gamma )</td>
<td>&lt;0.38(95% c.l.)</td>
<td>0.3 - 0.6</td>
</tr>
<tr>
<td>( \sigma_{P\rightarrow J/\psi} )</td>
<td>&lt;0.06 (95% c.l.)</td>
<td>No Prediction</td>
</tr>
<tr>
<td>( \sigma_{P\rightarrow \chi_c} )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Assumed

\( \chi_c(3415), J = 0, B \rightarrow (J/\psi + \gamma) = 0.013 \)

\( \chi_c(3516), J = 2, B \rightarrow (J/\psi + \gamma) = 0.202 \)

Suppressed by \( J_z = 0 \) rule
Some predictions for J/psi photoproduction:

e.g. Schafer and Szczurek:

Machado, Goncalves 3.0 nb
Motyka and Watt: 3.4 nb
Schafer & Szczurek ~ 2.8 nb
Nystrand 2.2 nb

Our result: 3.96 ± 0.64 nb

Take 3.0 ± 0.8

We are consistent, & so we can put a limit on odderon exchange. If theory gets more precise, our limit can change.
**Odderon Limits and ratios**

In QCD but not yet observed.

- \( R\left(\frac{\text{data}}{\text{theory}}\right)(J/\psi) = 1.32 \pm 0.41 \)
- \( R\left(\frac{\text{data}}{\text{theory}}\right)(\psi') = 1.15 \pm 0.21 \)
- \( R\left(\frac{\text{data}}{\text{theory}}\right)(V, \text{combined}) = 1.19 \pm 0.19 \)
- \( \left(\frac{O + \gamma}{IP \rightarrow J/\psi}{IP + IP \rightarrow \chi_{c0}(3415)}\right) = 0.060 \pm 0.015 \)

Our limits on O-exchange are close to, and constrain, theoretical predictions.
**Dimuons: Upsilon Region**

**Trigger:** $\mu^+\mu^- |\eta|<0.6$, $p_T(\mu) > 4$ GeV/c

**Search for/measurement of photo-production of Y, Y’ (not before seen in hadron-hadron)**

**Invariant Mass**
(n_assoc_tracks = 0)
$p_T(\mu\mu) < 6$ GeV/c

**Status:** have data, analysis in progress.
**Exclusive Upsilon(1S) candidate**

M ~ 9.4 GeV

Plugs, Miniplugs, CLC, BSC empty

Run/Event: 204413/8549136
Search for Exclusive $Z$, and observation of high mass lepton pairs.

Have 12 exclusive candidate events $e^+e^-$ and $\mu^+\mu^-$ $M = 40 – 91$ GeV$^2$
11 have $\Delta\phi < 0.02$ rad and good QED candidates. Cross section $\sim$ right.
91 GeV$^2 = M(Z)$ has larger $\Delta\phi$ & $p_T$ … may be non-exclusive b/g (?)

Total = 12 $\ell^+\ell^-$ pairs

CLC and BSC empty in 8/12 events, others $p \rightarrow p^*$ dissociation.
Paper in draft.

E not ET!

218658  6083168 ($e^+e^-$)
Double Diffractive Di-Jets in CDF

Jet <ET> spectra ~ same in SD and DPE

“Almost” exclusive di-jet, Two jets and nothing else

\[ \frac{M_{JJ}}{M_{CEN}} > 0.8 \]
**Exclusive Dijets (2 central jets + “nothing”) : CDF**

\[ R_{jj} = \frac{M_{jj}}{M_X} \approx 1.0 \]

\[ M_X = \text{total central mass} \quad M_{jj} \approx 40 - 150 \text{ GeV} \]

**ExHuME**: MC with exclusive di-jets.

**Cross section comparison not yet done**

**Apparent b-jet suppression as they become exclusive?**

(Theoretically → 0 as \( R_{jj} \rightarrow 1, J_z=0 \) rule)

Greatly reduces QCD background
Exclusive DiJet cross section

\[ p + \bar{p} \rightarrow p + JJ + \bar{p} + \sim \text{nothing else} \]

Cross section agrees with ExHuME / 3 (inside uncertainty)
FP420: Forward Protons 420m downstream of CMS & ATLAS

CMS: Inner Vacuum Tank insertion
Very Forward Proton Detectors (& Momentum Measurement)

& FP420

Roman pot acceptances

\[ M^2 = \xi_1 \xi_2 S \]

Where \( \xi_{1,2} \) are the fractional momentum losses of the outgoing protons

\( \xi = \text{fractional momentum loss} \)

Low \( \beta^* \): (0.5m): Lumi \( 10^{33-10^{34}} \text{cm}^{-2}\text{s}^{-1} \)

220m: \( 0.02 \times \xi \times 0.2 \)

300/400m: \( 0.002 \times \xi \times 0.2 \)

3D Si Tracking, Cerenkov Fast Timing

σ_{TOF}(z) \approx 4.2 \rightarrow 2.1 \text{ mm}

cf \sigma_z(\text{interactions}) \approx 52 \text{ mm}

Resolution
Rad hardness
Edgelessness
Speed, S/N
Availability
Enthusiasts!

6\text{mm}(y) \times 24\text{mm}(x)

covers distribution

\sim 8 \text{ layers}
10\text{um} \times y \text{-y pixels}

BPM

GASTOF

QUARTIC

MCP

\? 

\sim 8 \text{ m} 

Measure distance of track from beam (5-10 um) and slope (~5-10 um over 10 m) $\Rightarrow$ fractional momentum loss $\xi$

Protons, in x and y at detector

Normal Low-$\beta$ operation

Note: detector
6mm(y) x 24mm (x) covers distribution.
Fast Timing Counters: GASTOFs and QUARTICs

Pile-Up background: p’s, JJ or WW from different collisions

Counters with ~10 ps timing resolution behind tracking

\[
10 \text{ ps} = \frac{3 \text{ mm}}{\sqrt{2}} = 2.1 \text{ mm}
\]

1) Check both p’s from same collision (reduce background)
2) Get z(vertex) to match with central track vertex
3) Tell what part of bunches interacting protons were (F-M-B)

Solution:
Cerenkov light in gas or quartz (fused silica) bars \(\rightarrow\)
MCP-PMT (Micro-Channel Plate PMT)
Oct 07 test beam at CERN:
“Hamburg pipe”, 3D Si tracking, GASTOF & QUARTIC timing
Central Exclusive Production of Higgs

Higgs has vacuum quantum numbers, vacuum has Higgs field. So \( pp \rightarrow p+H+p \) is possible.

Allowed states: \( I J^{PC} = 0 \text{ even}^{++} \)

\( J \geq 2 \) strongly suppressed at small \( p \) angle (t)

Process is \( gg \rightarrow H \) through t-loop as usual with another g-exchange to cancel color and even leave p’s in ground state. If measure p’s:

\[
M_{\text{CEN}} = \sqrt{(p_1 + p_2 - p_3 - p_4)^2}
\]

\( \sigma(M_H) \approx 2 \text{ GeV per event} \)

Even for \( H \rightarrow W^+W^- \rightarrow l^\pm \nu JJ \)

\( \gamma\gamma \rightarrow \tilde{l}\tilde{l} \text{ etc...} \)

MGA+Rostovtsev: hep-ph/0009336

http://www.fp420.com
What is exclusive H cross section?

\[ \sigma[pp \rightarrow p+H+p](M_H), \sqrt{s} = 14 \text{ TeV} \]

Calculation involves:
- \( gg \rightarrow H \) (perturbative, standard, NLO)
- Unintegrated gluon densities \( g(x_i)g(x_i') \)
- Prob.(no other parton interaction) (“Gap survival”)
- Proton form factor
- Prob.(no gluon radiation \( \rightarrow \) no hadrons) Sudakov Suppression

\[ \sigma \sim 3 \text{ fb} \ (M(H)=125 \text{ GeV}) \]

“factor \sim 3 uncertainty”

\[ 30 \text{ fb}^{-1} \rightarrow \sim 100 \text{ Ae events} \]

(Ae = acceptance, efficiency)

But other estimates differ by “large” amounts!

Need to “calibrate” theory!
**What is H Signal:Background? (not pile-up)**

- **H(120–135 GeV) → b\bar{b}**
  - Inclusively, gg → b\bar{b} background overwhelming
  - Exclusively, pp → p + qq + p (q = quark jet)

- Strongly suppressed at LO \( \sim \frac{M^2}{M_H^2} \) by

- Spin selection rule \( J_z = 0 \).

- Most "exclusive dijets" are gg

- Need b-tagging, then \( \frac{S}{B} \) (SMH) \( \sim 3 \times \frac{1 \text{ GeV}}{\sigma(M)} \)

- \( q\bar{q} \) dijets strongly suppressed
  - \( J = 1 \) forbidden, \( J = 0 \) strongly favored
  - \( J = 0,2 \) discrimination possible

- Trigger is issue:
  - Probably need asymmetric 220m + 420m and:
  - Eventual trigger upgrade??

**Kinematic constraints:**

- \( E_{T,1} \approx E_{T,2}; \phi_1 = -\phi_2 \)

- \( \xi_{3(4)} = \frac{1}{\sqrt{s}} \sum_{1,2} E_T e^{-(+)\eta} \)

\[
\xi = 1 - \frac{p_{out}}{p_{beam}}
\]
Cross section for $p+p \rightarrow p + SMH + p$ at LHC, $x$ branching fractions:

Small ($\sim$ fb) but S:B can be high.

ExHuMe “verified” by 2-photon, $\chi_c$ & JJ

$< 140$ GeV : bbar,

$> 140$ GeV, WW(*)
Simulations of SMH \rightarrow b\bar{b} signals & background
Cox, Loebinger and Pilkington arXiv:0709.3035 (JHEP t.b.p.)

(a) 300/fb = 3 years at $10^34$, 420+420, L1 trigger on jets, muons, 25 kHz
(b) Same with no pile-up background – super-high resolution p-timing

SMH significance, 120 GeV SMH, vs L(E33)
3 years with no pile-up b/g. JET + mu trigs

... and if 420+420 in L1 trigger

future upgrade in latency?
MSSM

Can have \{h, A, H\} close together in mass (few GeV)
Hard to resolve by inclusive production.
Exclusive advantages: higher production than SM, A highly suppressed
Excellent mass resolution could separate h and H (unique)
Excellent mass resolution might even measure H widths (if ~ few GeV)

Durham Group (KMRS)


Figure 4: The hadronic level cross section $\mathcal{M}_{\text{Higgs, had}}^2 \frac{\partial \sigma}{\partial y} \,(y = 0)$ when the produced Higgs bosons decay into $b$ quarks, calculated using CTEQ6M PDFs. Tri-mixing scenarios have been taken with $\phi_3 = -90^\circ$ (solid lines) and $\phi_3 = -10^\circ$ (dotted lines). The vertical lines indicate the three Higgs boson pole mass positions.
Non-SM cases: no Higgs? MSSM Higgses?

1) No SMH? Can we exclude? Suppose measure 100 exclusive $\gamma\gamma$ in CMS. ($\sim 0.1$ fb$^{-1}$ effective S.I.Lum) $\rightarrow$ predict $p+\text{SMH}+p$ to $\sim 20\%$

Expect (say) 100 pHp events in 30 fb$^{-1}$, see $< 50$. Conclusion?

2) No SMH or MSSM-Hs? WW physics becomes very interesting!

$$pp \rightarrow p + W^+ W^- + p \text{ via } \gamma\gamma \rightarrow W^+ W^- \quad \sigma \approx 50\text{fb} \text{ (precisely known in SM)}$$

$W^+ W^-$ Final State Interactions distort $\frac{d\sigma}{dM_{WW}}$, visibly? New physics?

Preview of ILC physics!

3) In case of SUSY, Forward $p$-tagging can be crucial! Cross section can be much higher than SMH. Decays to $b\bar{b}$ enhanced. $A(\text{CP }-\text{ve})$ highly suppressed.

Kaidalov Khoze Martin Ryskin
hep-ph/0307064

MSSM SUSY: cross section x BR $\rightarrow$ b-bbar larger than SM
Heinemeyer et al., arXiv:0708.3052

Ratio (MSSM/SM) $h \rightarrow WW(\ast)$ vs M(A) and tan(beta). M(h) $\sim$ 120 GeV.

Excluded by LEP $Z^\ast \rightarrow Z+h/H$

In [tan $\beta$ : M$_A$ ] plane, 5$\sigma$ contours (top) and 3$\sigma$ (bottom); H $\rightarrow$ b$\bar{b}$, 60/fb & 600/fb
M(H) contours: dashed lines
Exclusiveness brings many rewards. H \rightarrow \text{Jet Jet case}

\[ M_{\text{CEN}} = \sqrt{(p_1 + p_2 - p_3 - p_4)^2} \]

Two jets' \( E_T \) are the same to \( \sim 1 \) GeV, \( \Delta \phi=180^0 \)
and, knowing that and \( \eta_1, \eta_2 \) and \( \xi_1(220) \)
in L1 trigger (fast look-up) can use correlation
to reduce L1 trigger rate.

\[ \xi = 1 - \frac{p_z(\text{out})}{p_z(\text{beam})} \]

(fractional momentum loss)

\[ \xi(1,2) = \frac{1}{\sqrt{S}} \sum_{\text{jets}} E_T \text{e}^{+(-)\eta_i} \]

420m just too far for L1 trigger. 420 + 220 + Jet info.
**What is Signal:Background? H(135–200) (not pile-up)**

H(135 – 200 GeV) → W⁺W⁻

\[ \sigma_{\text{incl}} (W^+W^- \text{ non-H}) \sim 100 \text{ pb}; \sigma (H) \sim 20 \text{ pb} \]

& M(WW) resolution v.poor (ν(s) and/or jets)

Exclusive B/G is \( \gamma\gamma \rightarrow W^+W^- \), \( \sigma \sim 50 \text{ fb, continuum} \)

Mass resolution \( \sigma_M (WW^{(*)}) \sim 2 \text{ GeV any decay} \)

Exclusive H → ZZ, negligible B/G

**Examples:** \( WW \rightarrow l\nu l\nu, l = e, \mu \)

NO OTHER TRACKS ON VERTEX!

(But only 4.6% of WW)

\[ H(160) \rightarrow W^+W^- \rightarrow p \ e^+\mu^- \not{\ell}_T \ p \]

\[ MM^2 = (p_1 + p_2 - p_3 - p_4)^2 = M_H^2 \]

Always : \( \sigma(M_{WW} \approx 2 \text{ GeV})! \)

Prob. ZERO BACKGROUND in ZZ!

~ 4 events ➜ DISCOVERY!
**What is Signal:Background?** \( H(135-200) \rightarrow WW(*) \)

\[ WW \rightarrow l\nu JJ, \; l = e, \mu, \tau \]

Durham Gp: Khoze, Martin, Ryskin, Stirling hep-ph/0505240

![Graph: \( M_{JJ} \) vs. \( M_{\nu} \)]

\[ \text{Can use } \approx 50\% \text{ of WW (all but JJJJ)} \]

\[ H(180) \rightarrow ZZ \rightarrow l^+l^-\nu\bar{\nu} \; (BR \sim 10 \times l^+l^-l^+l^-) \]

\[ MM(12-34l^+l^-) = M(Z_{\nu\bar{\nu}}), \; \sigma_M \sim 2 \text{ GeV}! \]

\[ MM(12-34JJ) \approx 0(M_{\nu}) \]

\[ MM(12-34JJ) = M_w^* \text{ (even for } \tau\nu) \]

\[ M(JJ) = M_w^* \]

**In WW/ZZ case, central trigger effective (420+420 OK)**

Unfortunately very few events (SM)
Determining Quantum Numbers of Central State (H?)

Is it J = 0, CP = ++?

In gg → X only CP = ++ is allowed.
(a CP –ve A (MSSM) is highly suppressed)

gg → vector (J = 1) forbidden, Yang’s theorem.

J = 0, 2 can be distinguished by angular distributions
→ partial wave analysis. Can even see states hidden in overall M distribution!
   Of course this needs many events.

Moments H(LM) of the cos(φ) distributions → M(J=0), M(J=2).

e.g. ISR/R807 glueball search in pp → p + π⁺π⁻ + p\ NPB264 (1986) 154
BSM: The White Pomeron

Mike Albrow  Univ. Birmingham Oct 2008
Central Exclusive Production in Proton Proton Collisions: ISR-Tevatron- LHC

Asymptotic freedom $\rightarrow$ 16 color triplet q’s
Only 6 known (duscbt)
But (!) 1 color sextet Q counts 5 times, so
\{ud\}+\{cs\}+\{tb\} + \{UD\} works!

\[ \Pi = U\overline{D} \text{ etc, } \eta_0 \ldots \text{EWSB, role of Higgs} \]
“composite higgs”

Can be dark matter (N = DDU ~ TeV)

Pomeron couples strongly to WW through U,D loops

$\rightarrow$ Anomalous (quasi-diffractive) production of WW, ZZ
(not WZ) production at LHC (M(DPE@LHC) $\sim$ 700 GeV).

Dramatic effects at LHC, especially in pp $\rightarrow p + WW/ZZ + p$
& pp $\rightarrow p + Z + p$
Summary

Any states with vacuum quantum numbers and strong or electromagnetic couplings can be produced at LHC by **Central Exclusive Production**

This includes **Higgs boson(s), W-pairs**, lepton and photon pairs.

Cross section $pp \rightarrow p+\text{SMH}+p$ known to factor $\sim 3$ ($\sim 5$ fb)

If protons well measured, can get mass of central state to $\sim 2$ GeV per event, Quantum numbers (J, CP) and couplings to gg.

need both 220m and 420m detectors.

R&D on S:B can be good – excellent in BSM scenarios.

For good acceptance/resolution **FP420**: tiny but v.high precision tracking, timing, BPM

Best particle spectrometer ever, using part of LHC

We have proposed this as extensions to CMS and ATLAS

for installation in 2010-2011 shutdown
BACK-UPs
\( \psi(2S) \) photoproduction (or possible odderon exchange)

Kinematics well described by STARLIGHT MC

Again much broader

\[ \Delta \phi(\mu^- \mu^+), p_T(\mu^+ \mu^-) \] than

QED continuum: \( \gamma + \gamma \rightarrow \mu^+ \mu^- \)