## DIS 2009 – Madrid

# Observation of hard diffraction with early CMS data

## (feasibility studies)

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On behalf of the CMS Collaboration

# Outline

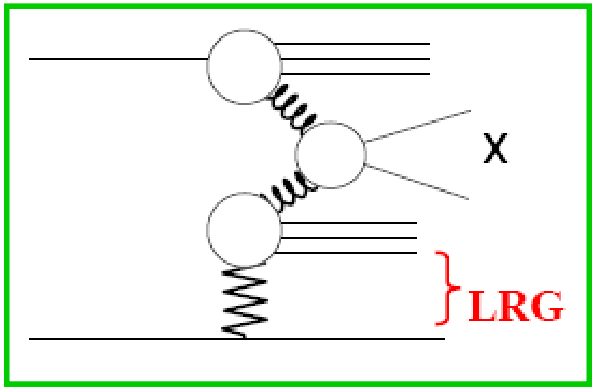
1. **Hard diffraction at CMS: possible studies with early data**

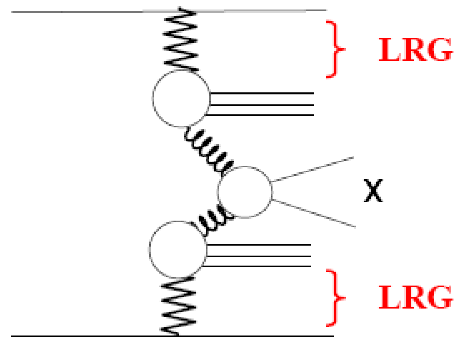
2. **Single diffractive dijet production – Single diffractive W production**
   a. **Selection**
   b. **Observation of single-diffractive (SD) signal**
   c. **Sensitivity to gap survival probability**

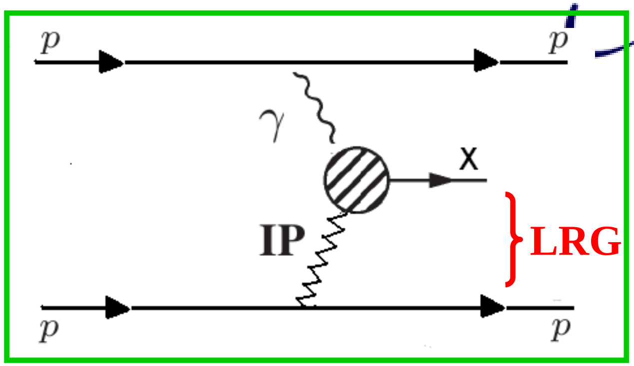
3. **Exclusive Y photoproduction**
   a. **$\Upsilon \rightarrow \mu^+ \mu^-$ selection**
   b. **Invariant mass spectrum**
   c. **Studies of the $\Upsilon$ production dynamics**

**Analyses planned for the first LHC data.**

# Hard diffraction




....

**SINGLE DIFFRACTION** **DOUBLE DIFFRACTION** **PHOTOPRODUCTION** **....**

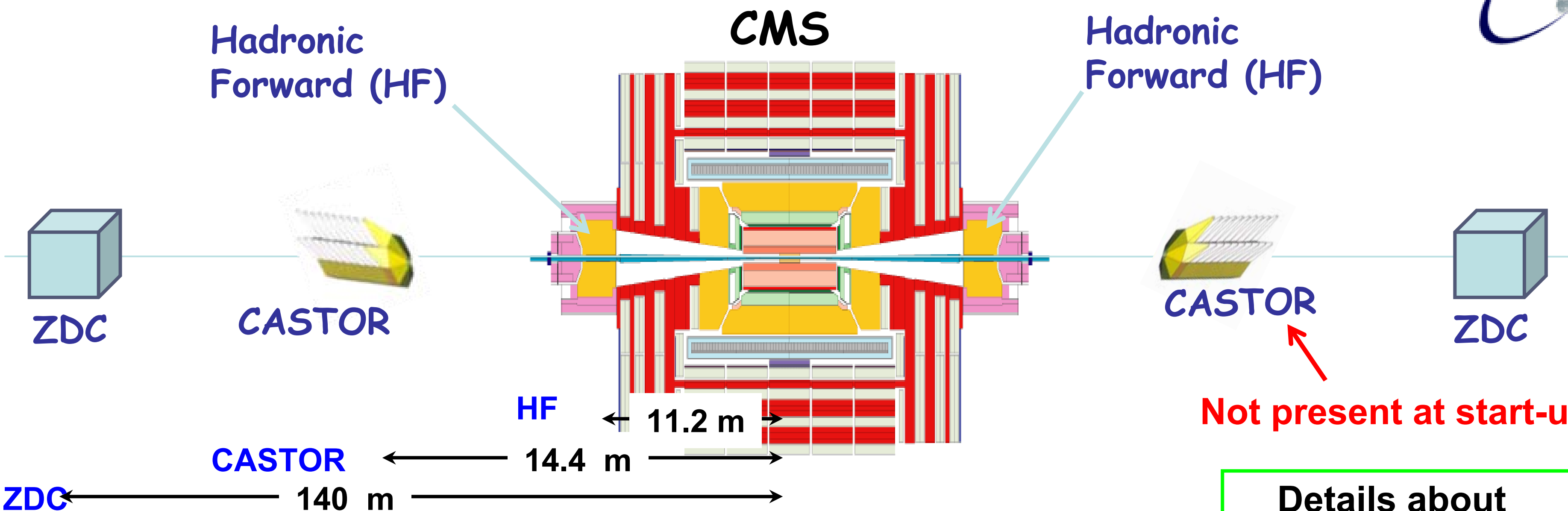
**Events characterized by:**

- **the presence of a system X resulting from a hard scattering**
- **a proton escaping the collision intact, losing a small momentum fraction**
- **Large Rapidity Gap: $\eta$ region devoid of particles due to absence of colour flow between the proton and the system X**

**SIGNATURE OF DIFFRACTIVE EVENTS**

- **small fractional energy loss of the leading proton** — PROTON TAGGERS
- **Large Rapidity Gap** — NO PILE-UP

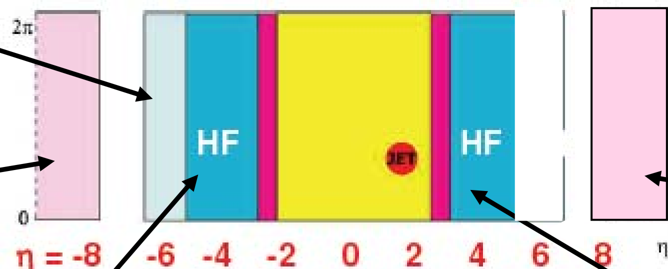
# CMS detectors in forward region




Not present at start-up

Details about CASTOR and ZDC in B. Roland's talk

CASTOR [$-6.6 < \eta < -5.2$]




ZDC [$\eta < -8.1$]

ZDC [$\eta > 8.1$]

HF-minus [$-5.0 < \eta < -3.0$]

HF-plus [$3.0 < \eta < 5.0$]

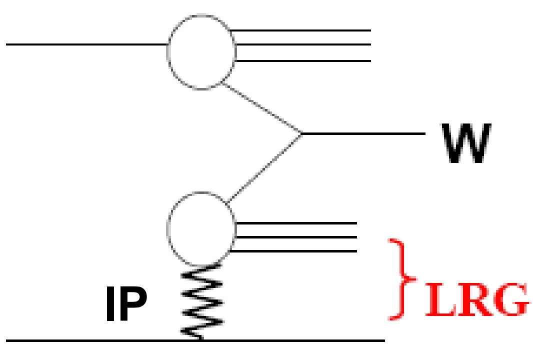
**In early LHC running no proton taggers available**

**For future plans see K. Piotrzkowski's talk**

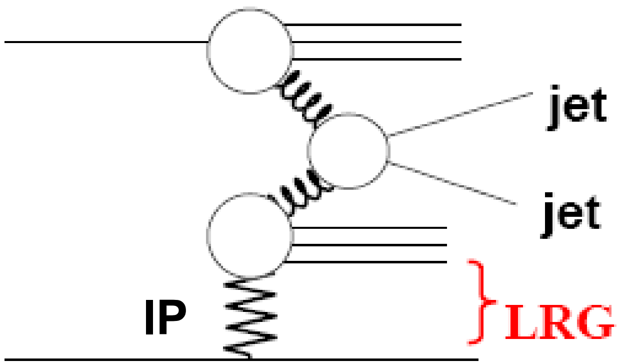
# Hard Diffraction at CMS

**Three processes have been studied so far at CMS**

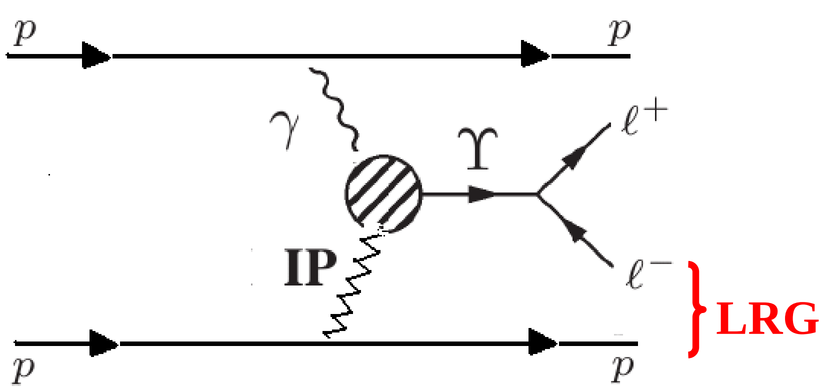
**SINGLE DIFFRACTIVE W PRODUCTION**




**SINGLE DIFFRACTIVE DIJET PRODUCTION**




**Υ EXCLUSIVE PHOTOPRODUCTION**




**MC studies → Full detector simulation and reconstruction (except CASTOR)**

**$E_{CM}$ = 14 TeV**

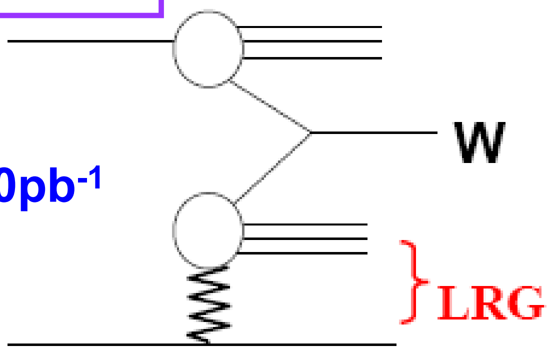
**No pile-up scenario → selection based on Large Rapidity Gap (LGR) / exclusive final state**

# SINGLE DIFFRACTIVE DIJET and W PRODUCTION

*Available from https://twiki.cern.ch/twiki/bin/view/CMS/PhysicsResults*

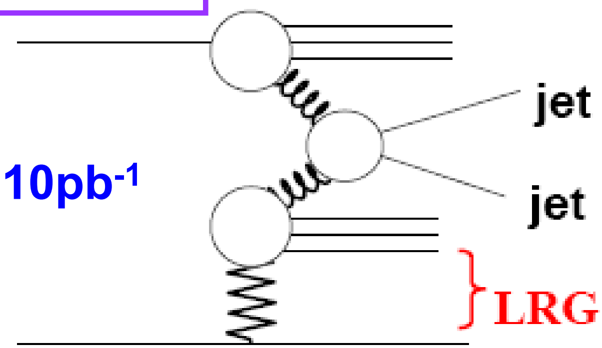
**CMS PAS DIF-07-002**

$L_{INT}$=100pb$^{-1}$




**CMS PAS FWD-08-002**

$L_{INT}$=10pb$^{-1}$




***Same analysis method***

**Assume:**
- **Rapidity gap survival probability: <|S|$^2$>=0.05**
- **Diffractive PDF: NLO H1 2006 Fit B**
- **Inclusive PDF: CTEQ61**
- **SD MC: POMWIG; non-diffr. generator: PYTHIA / MADGRAPH**

# Possible measurements at CMS

## SD DIJET (W) PRODUCTION

**Time ordered:**

- **observe SD – dijet (W) events with rapidity gap**
- **measure $R_{JJ(W)} = N^{DIFF}_{JJ(W)} / N^{TOT}_{JJ(W)}$**
- **probe the diffractive parton distribution functions (dPDFs)**
- **measure the rapidity gap survival probability $<|S|^2>$ at LHC energy:**

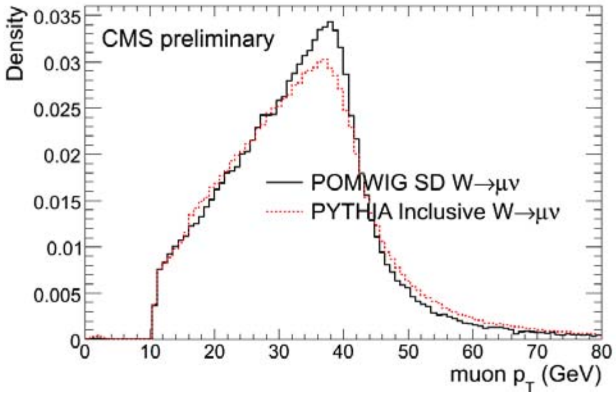
  **→ values $<|S|^2>$ as low as 0.4% and as high as 23% have been proposed (J. S. Miller, EPJC 56 (2008) 39)**

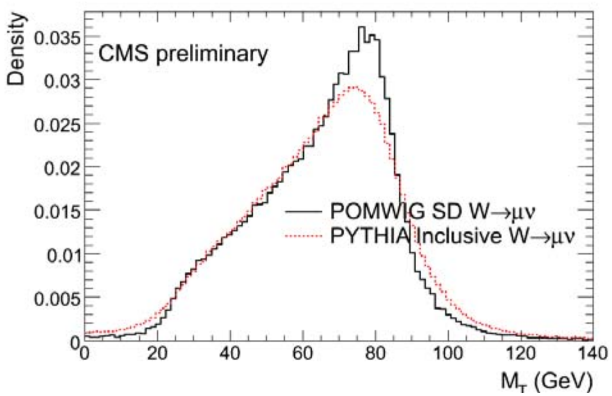
  **→ some consensus on hard diffractive processes $<|S|^2>= 5\%$**

**Simple measurement of SD yields may give early information on $<|S|^2>$**

***At Tevatron $<|S|^2> \sim 10\%$***

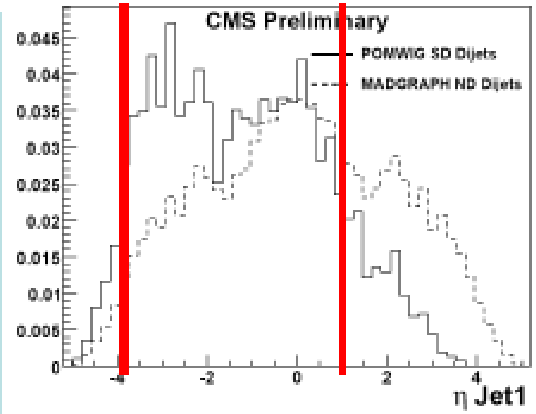
# Event selection



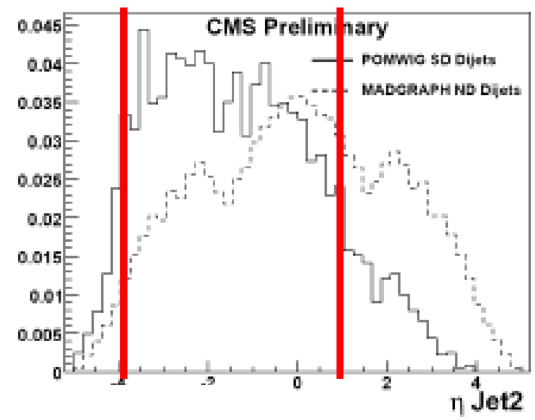



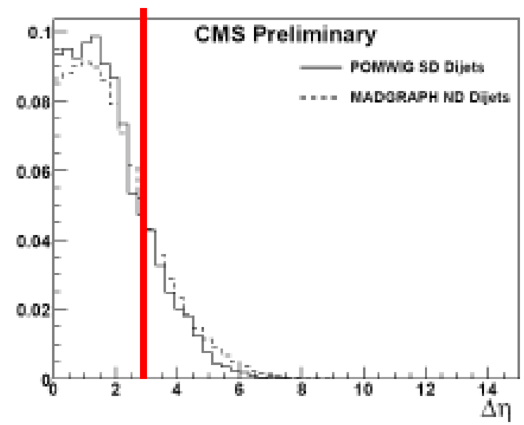

**W → νμ**

**Dijet**




At least 2 jets with $E_T^{JET} > 55$ GeV



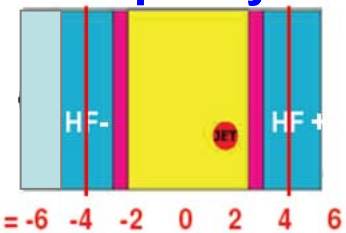




- 1 isolated μ ($p_T > 25$ GeV and $|\eta| < 2.0$)
- $50 < M_T < 200$ GeV
- $\zeta = \pi - \Delta\varphi(\mu, E_T^{miss}) < 1$ rad
- n jets($E_T > 40$ GeV) $\leq 3$
- n muons($p_T > 20$ GeV) $< 2$

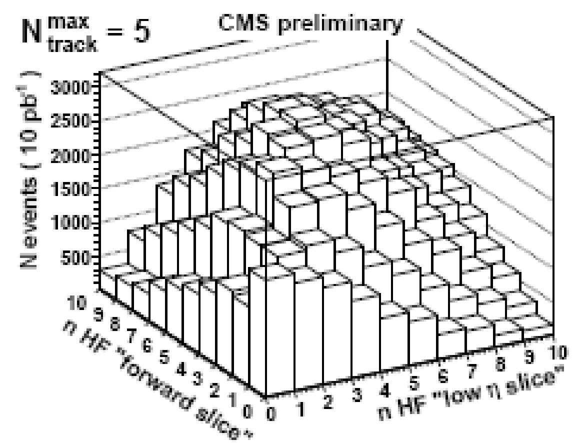
# Selecting diffractive events

1. **Determination of Rapidity Gap side**: **side with lower energy sum in HF**
   → Probability of selecting the gap side incorrectly is ~10% for dijet and ~30% for W.

2. **Multiplicity in forward calorimeters (HF, CASTOR) <u>for the gap side only</u>**

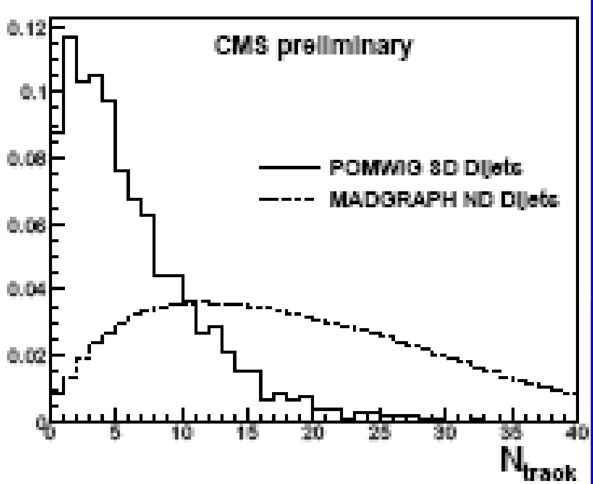



**a. HF tower multiplicity in "low η" region (3.0 < |η| < 4.0) vs**
**HF tower multiplicity in "high η" region (4.0 < |η| < 5.0),**




**b. HF tower multipl. vs CASTOR sector multiplicity**

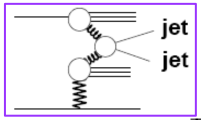
→ Generator level information used for CASTOR :
number of φ-sectors with energy above threshold (E > 10 GeV)
→ only event with gap in the z-minus side .



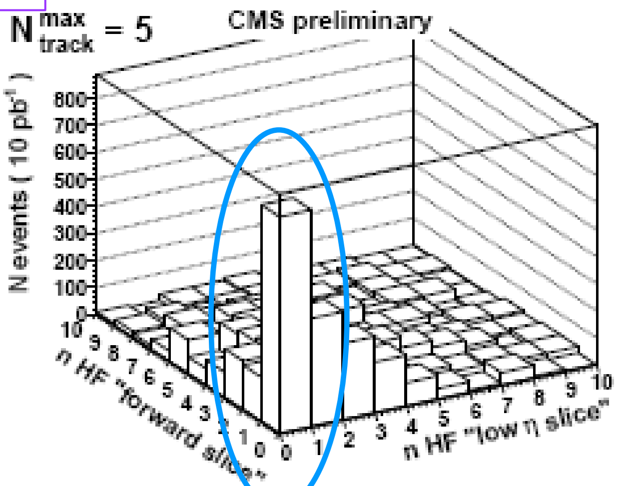

**Analysis repeated for different central Track Multiplicity: $N_{TRACK}$ ≤1, ≤5, no cut**

Number of reconstructed tracks in central tracker (|η| < 2.0) with $p_T$ > 0.9 GeV.
Tracks associated to the two jets (μ) excluded.

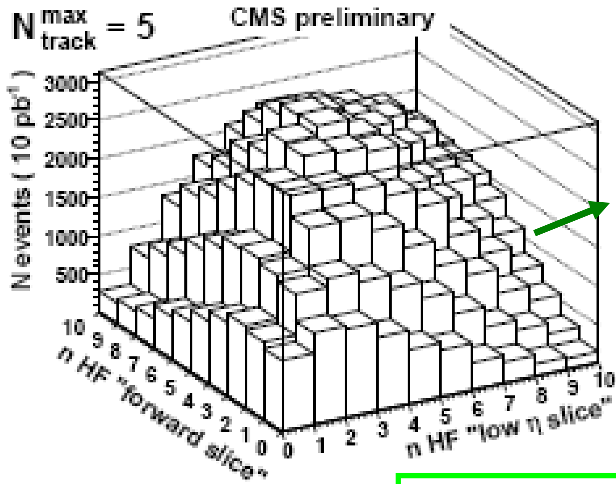
# Multiplicity Plot: LRG




**DIFFRACTIVE (SIGNAL)**



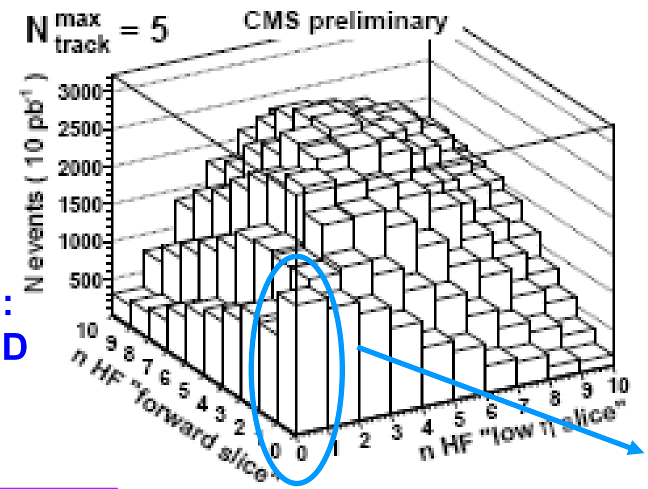

**NON-DIFFRACTIVE (BACKGROUND)**




**Shape sensitive to underlying event simulation**

**See Nick van Remortel's talk**

**Clear peak at zero multiplicity**




**SIGNAL+BACKGROUND: DISTRIBUTION EXPECTED FROM THE DATA**

**<u>Multiplicity plot – HF only:</u>**

**"low η": 3.0 < |η| < 4.0**

**"high η": 4.0 < |η| < 5.0**

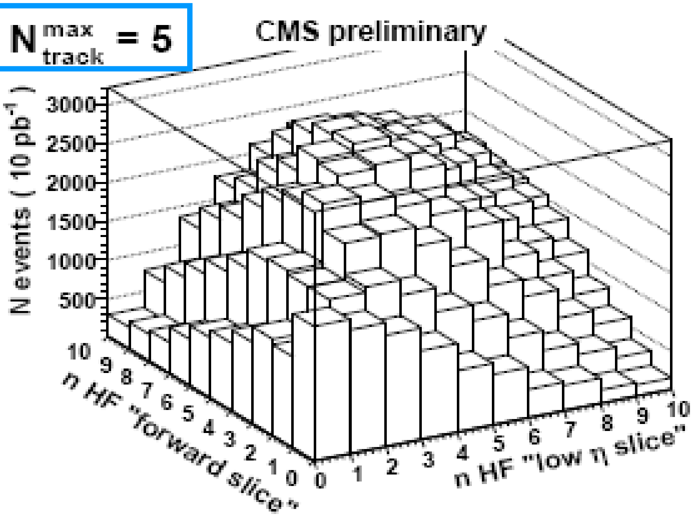
**Excess in low multiplicity visible**

**SAME METHOD USED AT TEVATRON – RUN1**

# SD Dijet/W production: results

$N_{track}^{max} = 5$

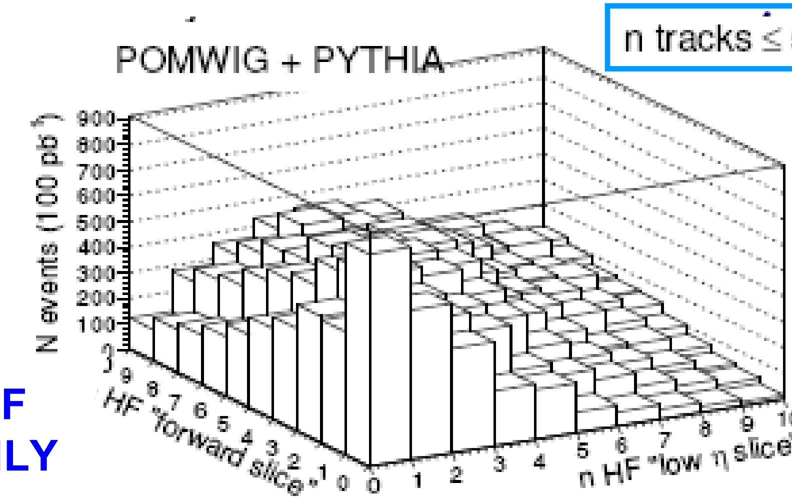
**DIJET**




**HF ONLY**

n tracks ≤ 5

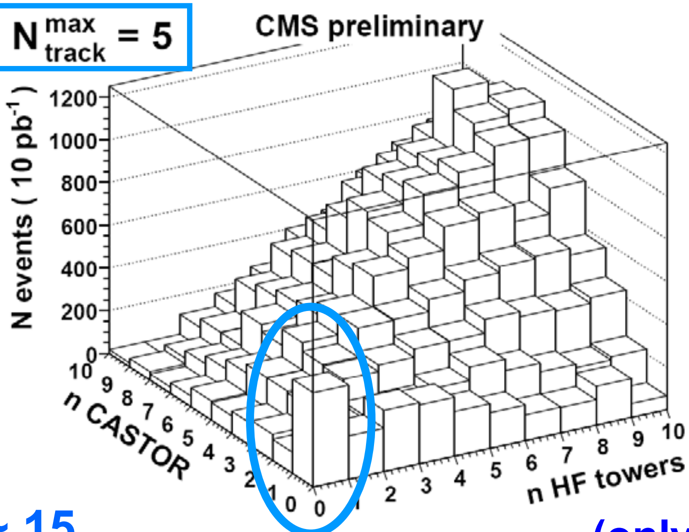
**W**




**O(300) evts/10 pb$^{-1}$** ← **[n(Castor), n (HF)] = [0,0] bin** → **O(100) evts/100 pb$^{-1}$**

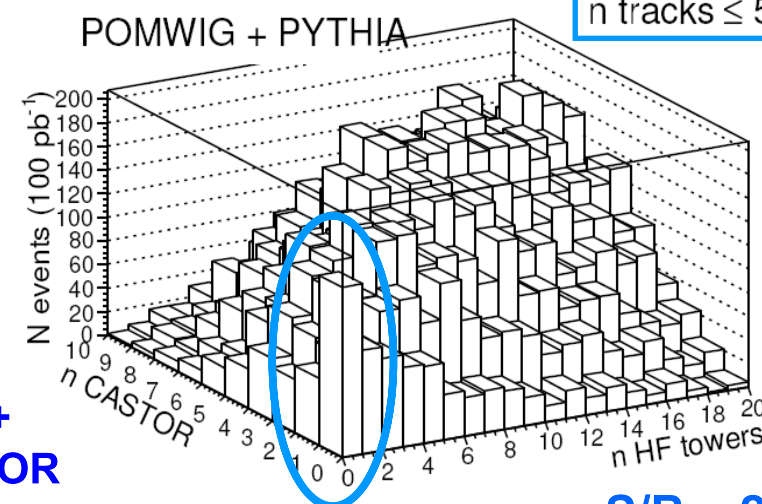
$N_{track}^{max} = 5$

**DIJET**




n tracks ≤ 5

**W**




**S/B ~ 15**

**HF+ CASTOR (only negative η side)**

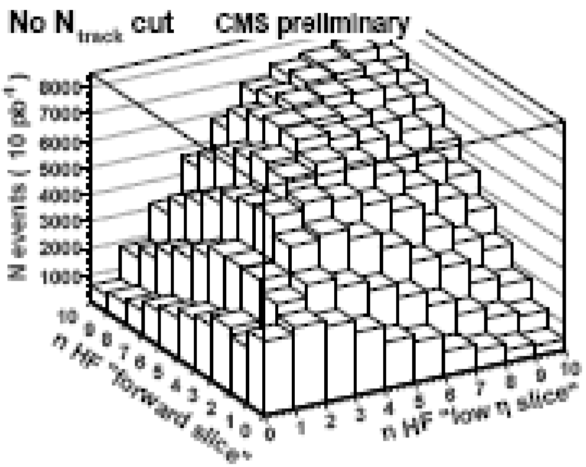
**S/B ~ 20**

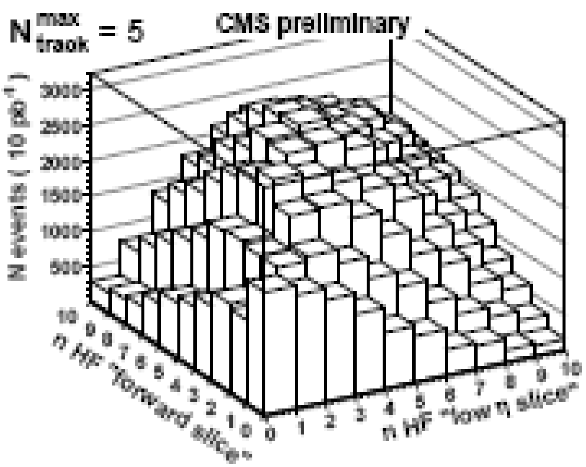
# Establishing diffractive signal in data

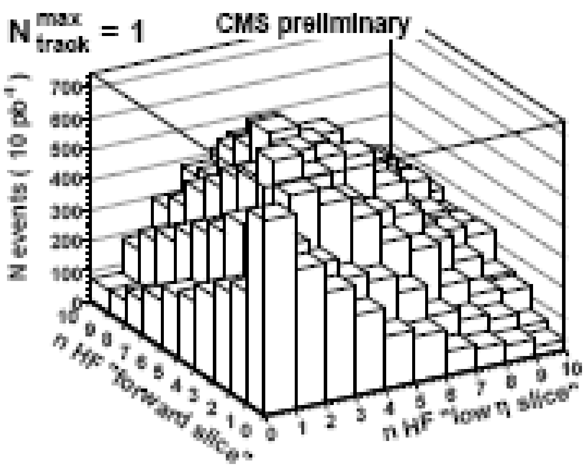
**Size of SD signal can be controlled in a predictable way when changing diffractive selection cuts → enhancement in [0,0] bin is not a statistical fluctuation.**

**For example:**

| NO Ntrack cut | Ntrack ≤ 5 | Ntrack ≤ 1 |
|---|---|---|




***Significance is higher when the $N_{TRACK}$ cut is stricter***

DIJET - HF-ONLY plots

# Sensitivity to <|S|$^2$>

**So far assumed rapidity gap survival probability <|S|$^2$> = 0.05**

**Evaluated diffractive dijet yields in (0,0) bin for <|S|$^2$>=0.004 and 0.23:**

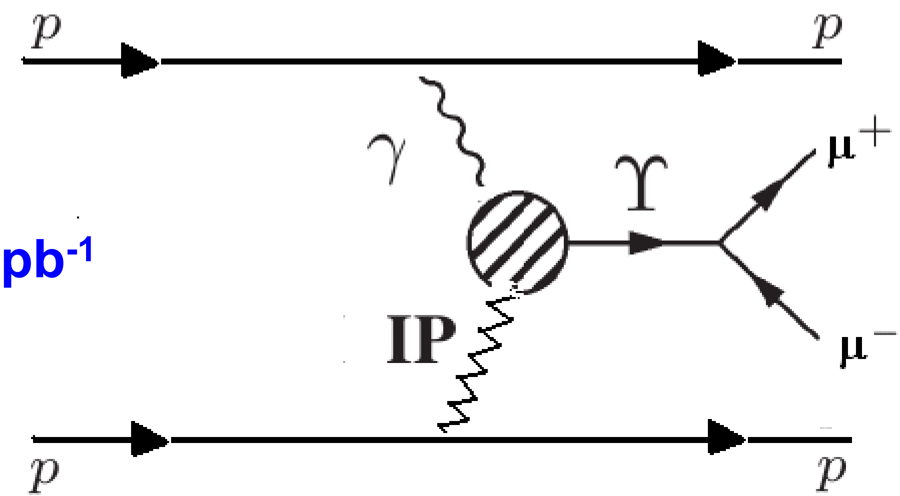
| | $N_{HF}=0$ | $N_{track}^{max}$ | $N_{diff}$ $\langle \|S\|^2\rangle = 0.05$ | $N_{diff}$ $\langle \|S\|^2\rangle = 0.004$ | $N_{diff}$ $\langle \|S\|^2\rangle = 0.23$ | $N_{non-diff}$ |
|---|---|---|---|---|---|---|
| **HF ONLY** | | no cut | $1047 \pm 32$ | $84 \pm 9$ | $4816 \pm 69$ | $1719 \pm 41$ |
| | | 5 | $803 \pm 28$ | $64 \pm 8$ | $3694 \pm 61$ | $943 \pm 31$ |
| | | 1 | $362 \pm 19$ | $29 \pm 5$ | $1665 \pm 41$ | $276 \pm 16$ |
| | $N_{HF}=0, N_{CASTOR}=0$ | | | | | |
| **HF+ CASTOR** | | no cut | $504 \pm 22$ | $40 \pm 6$ | $2318 \pm 48$ | $67 \pm 8$ |
| | | 5 | $409 \pm 20$ | $33 \pm 4$ | $1881 \pm 43$ | $31 \pm 6$ |
| | | 1 | $236 \pm 15$ | $19 \pm 4$ | $1086 \pm 33$ | $8 \pm 3$ |

- **<|S|$^2$> = 0.004 marginal observable signal**
- **<|S|$^2$> = 0.23 → very prominent signal**

**Observation of eg 409 ± 20(stat.)$^{+200}_{-160}$(syst.) would exclude <|S|$^2$> = 0.004, for which no signal is visible.**

# EXCLUSIVE Υ PHOTOPRODUCTION

$L_{INT}$=100 pb$^{-1}$




LRG

http://cms-physics.web.cern.ch/cms-physics/public/DIF-07-001-pas.pdf

**Assume:**

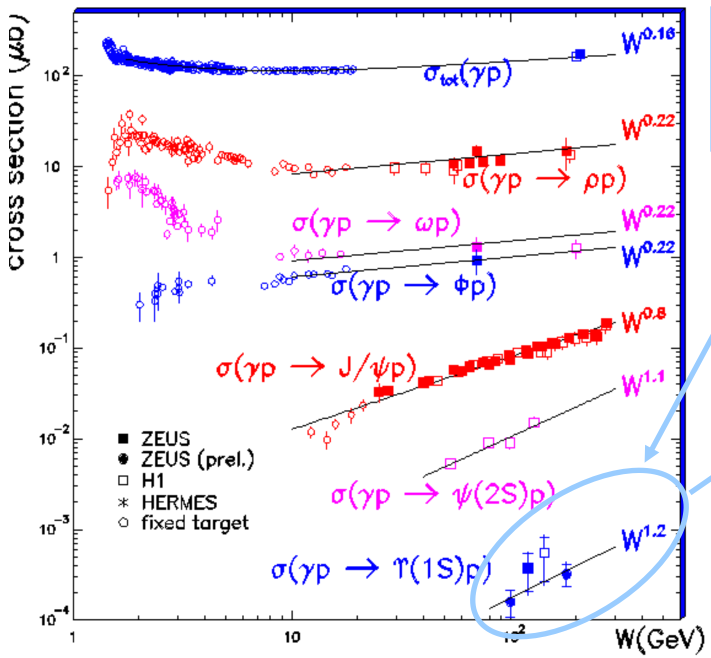
- **For Y photoproduction (STARLIGHT)**
  - **$\sigma$ x BR[Y(1S)→$\mu^+\mu^-$] = 39 pb**
  - **$\sigma$ x BR[Y(2S)→$\mu^+\mu^-$] = 13 pb**
  - **$\sigma$ x BR[Y(3S)→$\mu^+\mu^-$] = 10 pb**

  **Gap survival factor taken to be $<|S|^2> = 1$**

- **Background generator: PYTHIA/LPAIR**

# Possible measurements at CMS

**Extract the exclusive Υ photoproduction signal from the dilepton invariant mass spectrum**



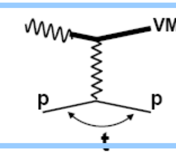

**Measure the photoproduction cross-section (W~500 GeV).**

***Constraint on cross section slope, sensitive to rise in gluon density***
***( $\sigma \propto [xg(x)]^2$ )***

W = γp CENTRE-OF-MASS ENERGY ( proportional to $\frac{1}{\sqrt{x}}$ )

**Measure the t distribution**

- t cannot be measured directly but $p_T^2$ of the Υ is an effective estimator



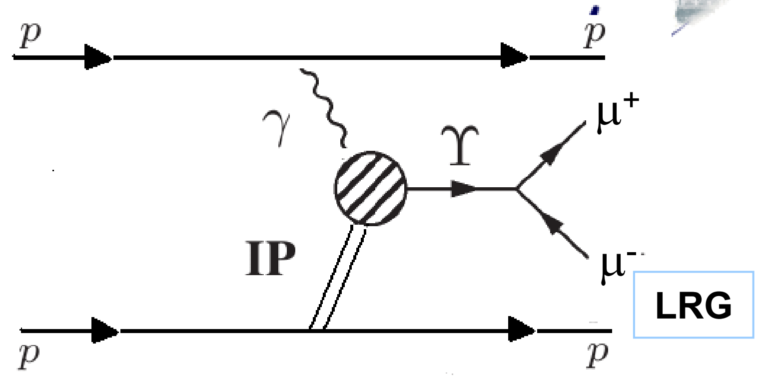

***These measurements give information on the gluon density and in particular on the GPDs (parton-parton correlation) of the proton.***

# Event signature

**Production mechanism:**

**1° Quasi-real photon fluctuates into a $q\bar{q}$ pair**

**2° The pair interacts diffractively with the other proton**

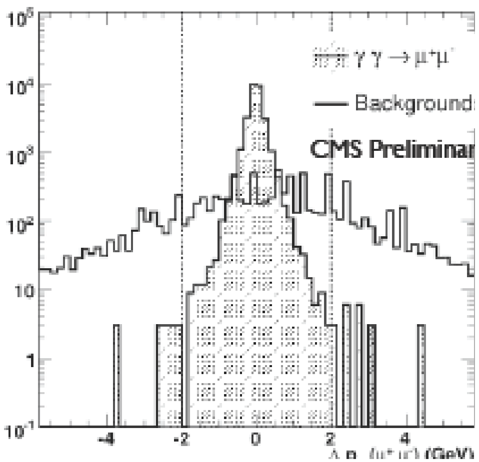



**Event signature (zero pileup assumed):**

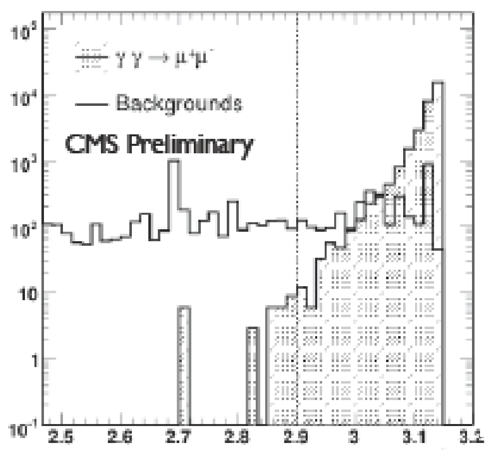
- **2 central muons detected in CMS**
  - **with nearly equal $p_T$**
  - **back-to-back in $\phi$**

**High trigger thresholds required by CMS running conditions kill the signal in the $e^+e^-$ channel**

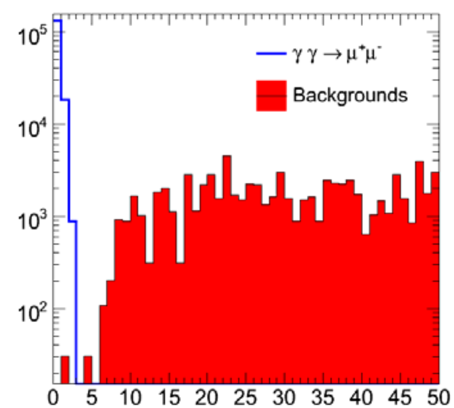
- **No other activity expected in CMS : → exclusive final state**



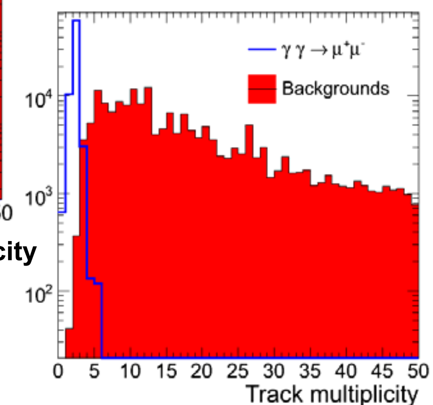

**$\Delta p_T$ (μμ) [GeV ]**




**|Δφ(μμ)|**

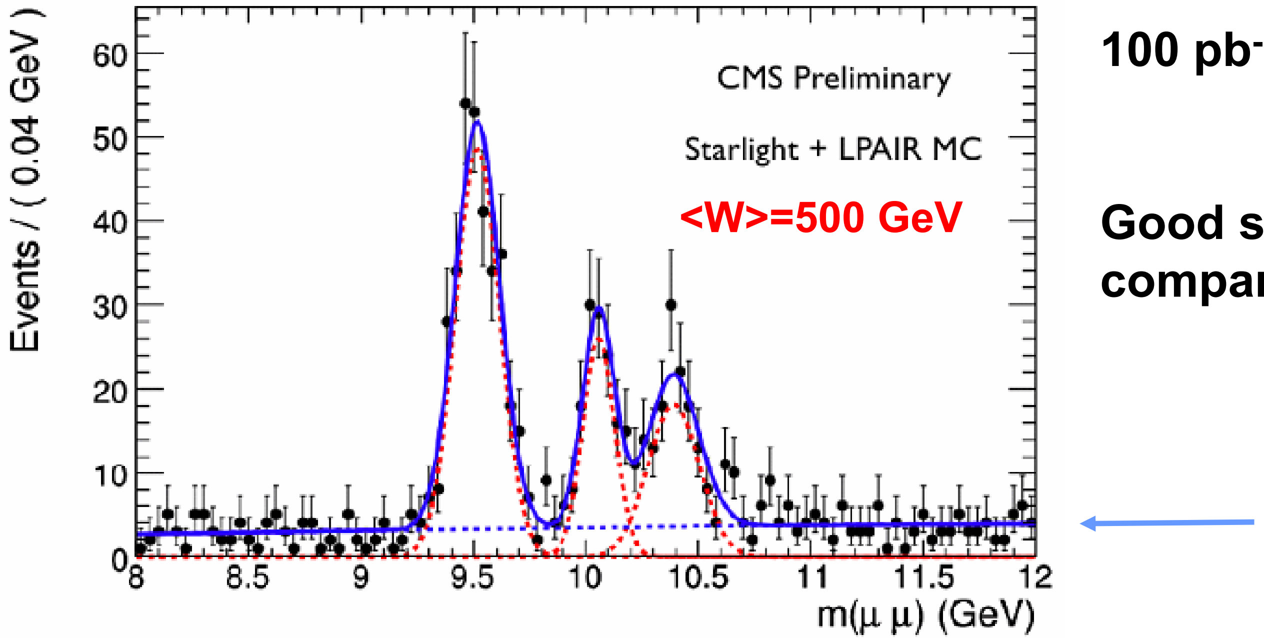



**Calorimeter ExtraTower multiplicity**



# Dimuon invariant mass spectrum

**After all selections are applied, the signal yields for Υ(1S), Υ(2S), Υ(3S) are extracted by performing a fit to the dimuon invariant mass spectrum**




**100 $pb^{-1}$ → Few months of data taking.**

**Good statistics and resolution compared to HERA.**

**The γγ continuum is modelled with a second order polynomial, the 3 Υ resonances are fit to 3 single gaussians with floating mean and width.**

# Studies of the Υ production dynamics

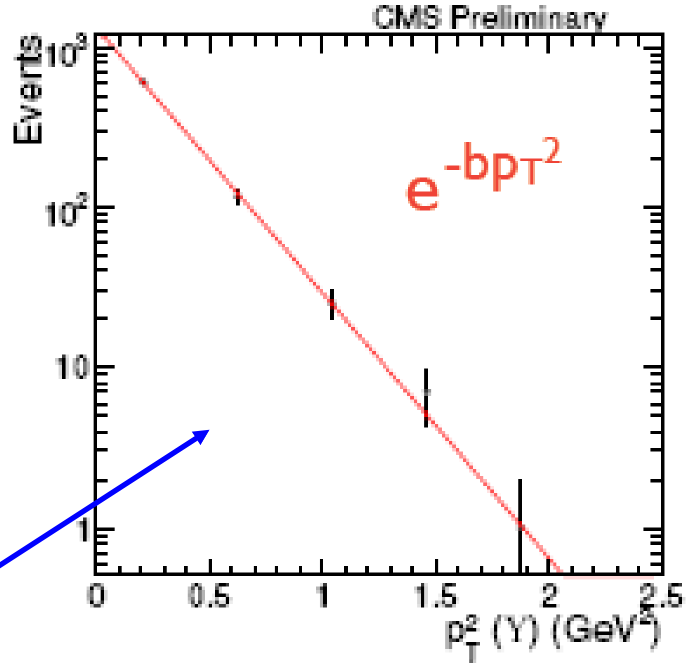
**The $p_T^2$ distribution of the Υ(1S) has been studied**

**Exponential fit ( $e^{-bp_T^2}$ ) to the reconstructed $p_T^2$ distribution:**

- **b = (3.82 ± 0.16) $GeV^{-2}$**

**Exponential fit to the true t distribution:**

- **b = (4.03 ± 0.04) $GeV^{-2}$**




Uncertainties due to statistics of the simulated sample.

**The study of the t dependence of the cross-section in these events is possible using $p_T^2$ distribution of the Υ, with appropriate corrections for the small bias involved in this approximation.**

# Summary

- Detailed studies to re-discover hard diffraction at the LHC with CMS early data using rapidity gap/exclusivity of the final state (no pile-up).

**10pb$^{-1}$** → **Expected O(300) reconstructed signal events for SD-dijets. Simple measurement of SD-dijet yields may give early information on $<|S|^2>$.**

**100pb$^{-1}$** → **Expected O(100) reconstructed signal events for SD-Ws.**

→ **First three $\Upsilon$ resonances visible. Study the rates and dynamics of exclusive $\Upsilon$ photoproduction.**

- Important to have proton tagging as soon as possible: CMS & TOTEM (see H. Niewiadomski's talk) and later FP420 (see K. Piotrzkowski's talk).

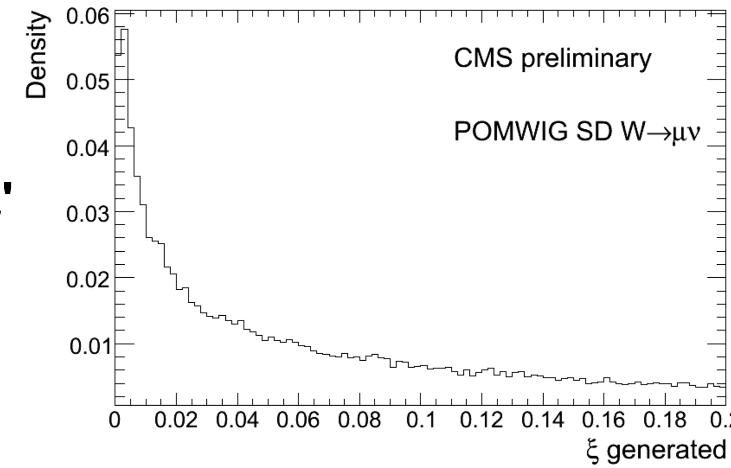
# Backup slides

# SD-W MC samples

**Diffractive $W\rightarrow\mu\upsilon$ samples (~200k evt):**

- **Pomwig v2.0beta**
- **Proton PDF: CTEQ6M**
- **dPDF: NLO H1 2006 Fit B ($\alpha_{IP(0)}$ = 1.111, $\alpha'$ = 0.06 GeV$^{-2}$, $B_{IP}$ = 5.5 GeV$^{-2}$)**

Generated ξ




ξ = the fractional momentum loss of the scattered proton

**Non-diffractive samples (~1M evt):**

- **Pythia $W\rightarrow\mu\upsilon$**
- **Pythia Inclusive QCD ($\mu$-enriched)**

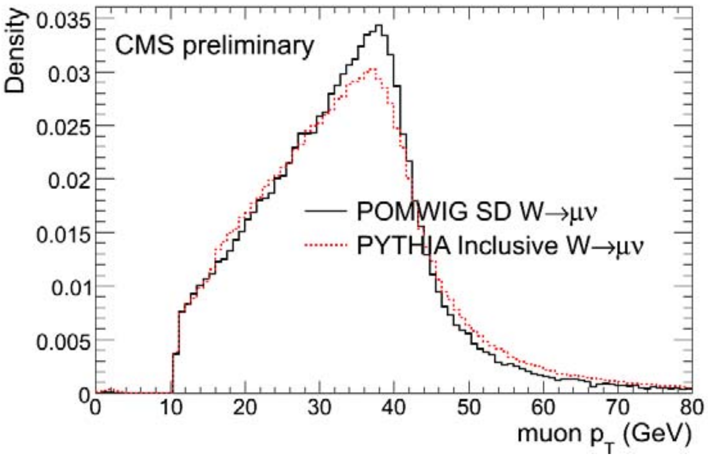
**Cross sections:**

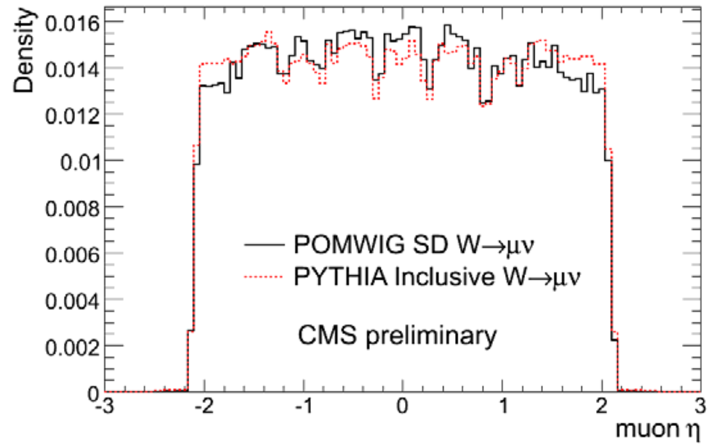
**- Diffractive $W\rightarrow\mu\upsilon$: $\sigma$ ~ 69 pb (NLO PDFs) (assumes $S^2$ = 5%)**

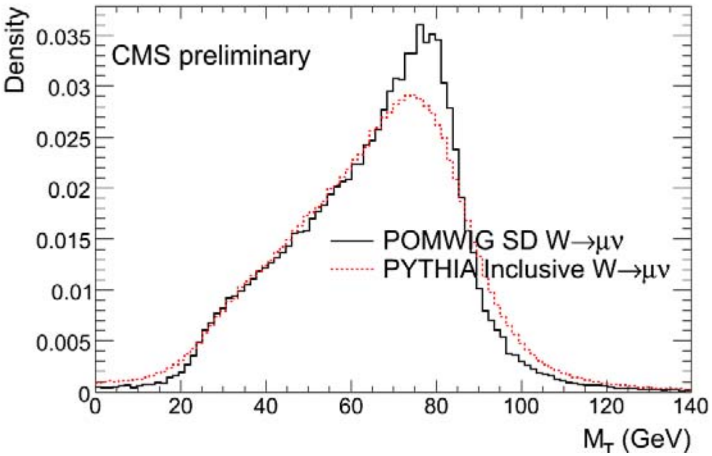
**- Non-difractive $W\rightarrow\mu\upsilon$: $\sigma$ ~ 21 nb (NLO cross section)**

**This gives a ratio of diffractive to inclusive cross sections of ~0.3%**

# W → μυ selection



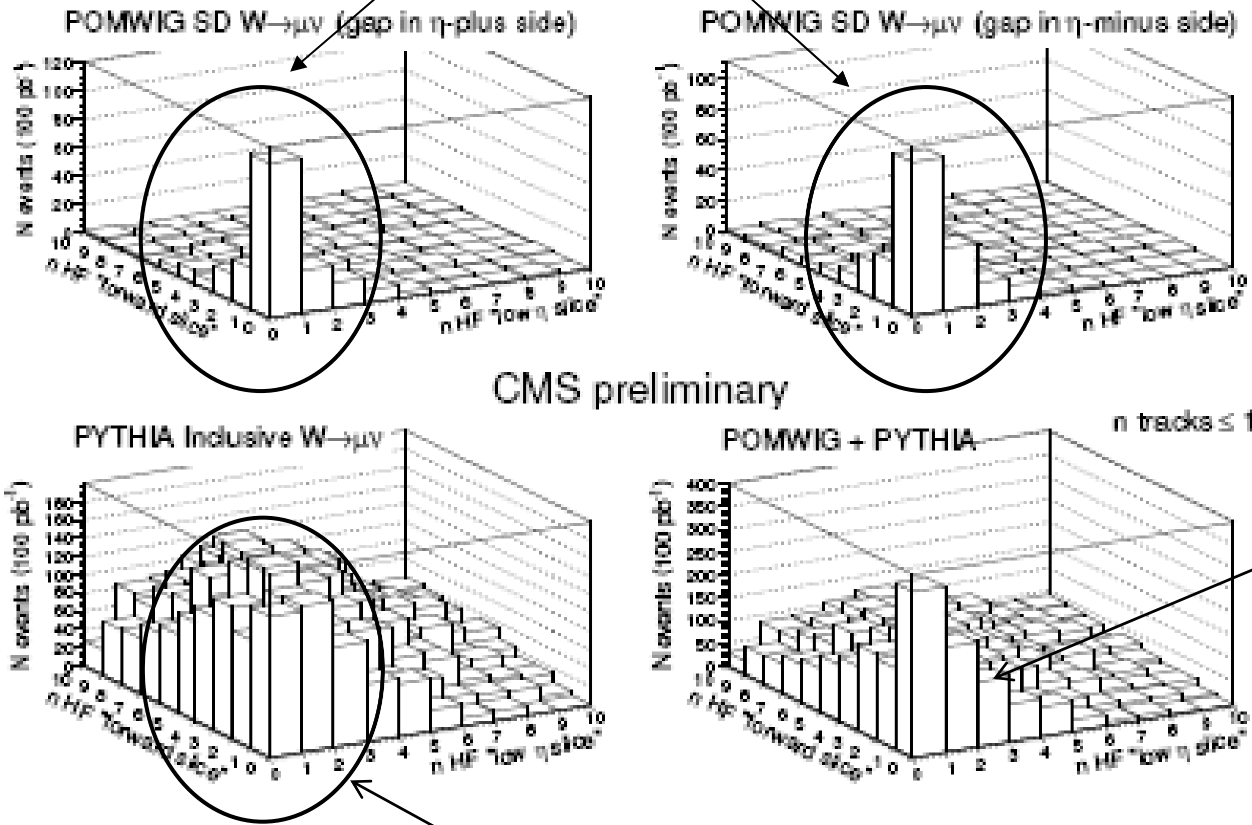

**W → μυ selection (same as inclusive analysis)**

- 1 isolated μ ( $p_T$ > 25 GeV and $|\eta| < 2.0$)
- $50 < M_T < 200$ GeV
- $\zeta = \pi - \Delta\varphi(\mu, E_T^{miss}) < 1$ rad
- n jets($E_T$ > 40 GeV) ≤ 3
- n muons($p_T$ > 20 GeV) < 2

**Overall efficiency**: Pomwig SD W→μυ: 34% (2.4k evts/100pb$^{-1}$)
Pythia W→μυ: 28% (600k evts/100pb$^{-1}$)

# HF multiplicity : “low η” vs “high η”

**Clear peak at zero multiplicity**




“low η”: 3.0 < |η| < 4.0

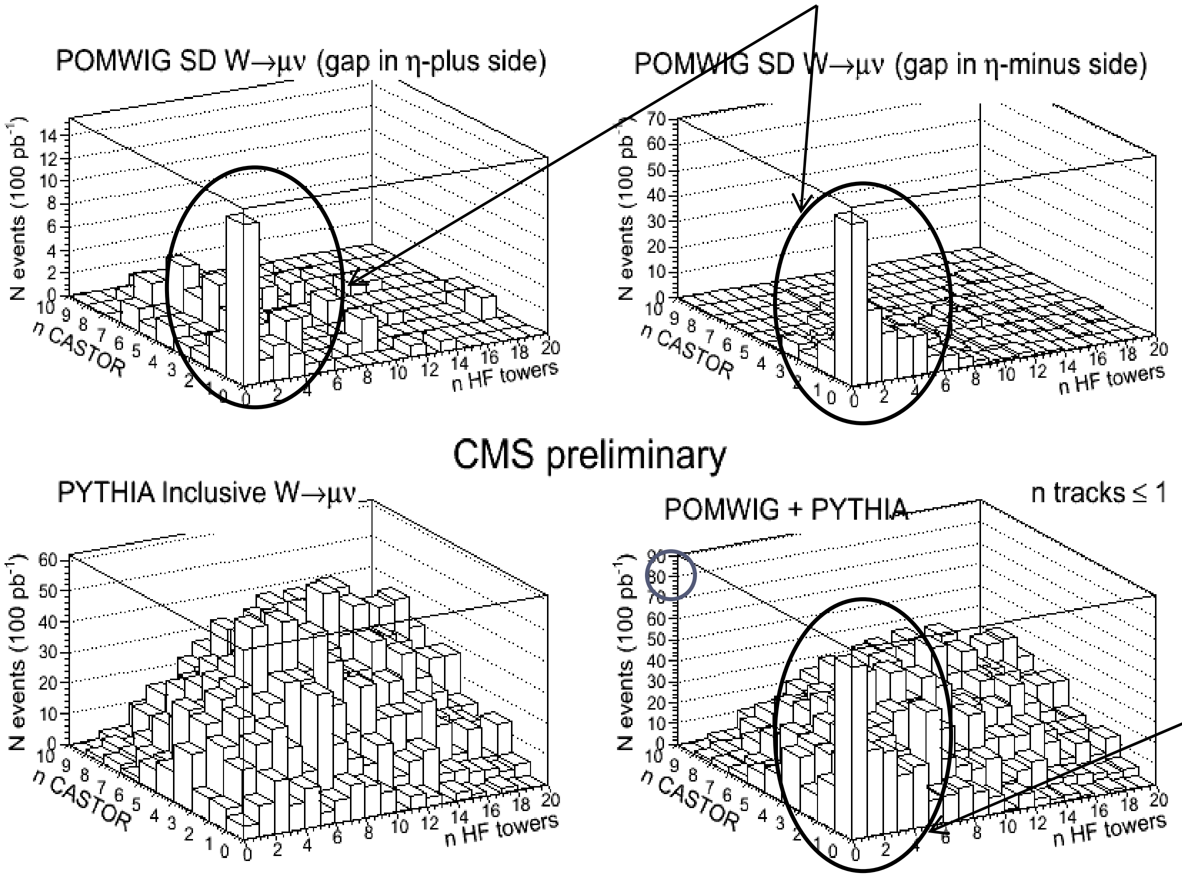
“high η”: 4.0 < |η| < 5.0

**Excess in low multiplicity visible**

**Non-diffractive background clusters in the low multiplicity (signal) region**

# HF tower vs CASTOR φ-sector multiplicity

**Potential signal increase by factor ~2 with CASTOR in both sides**



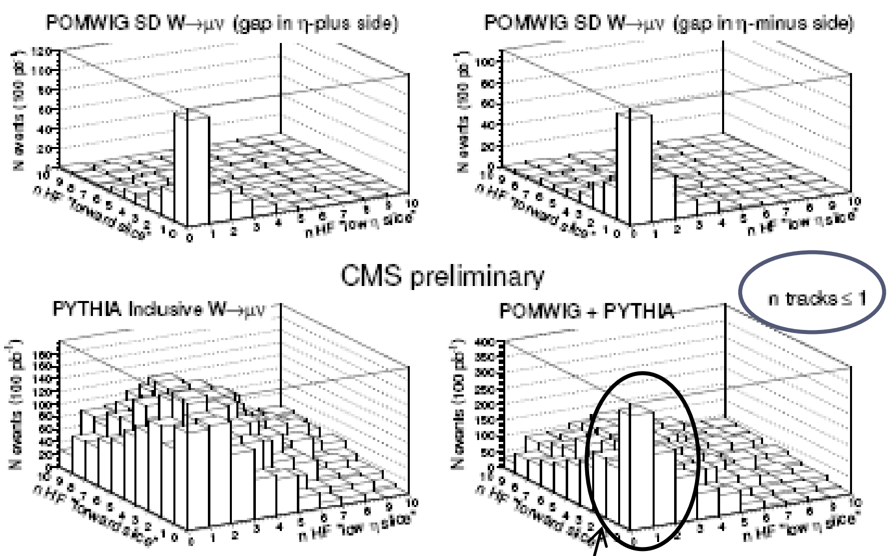

- CASTOR: (5.2 < |η| < 6.6)
- no η segmentation, 16 φ-sectors

**Clear peak at low multiplicity**

**~ 100 events in zero multiplicity bin (S/B ~ 20)**

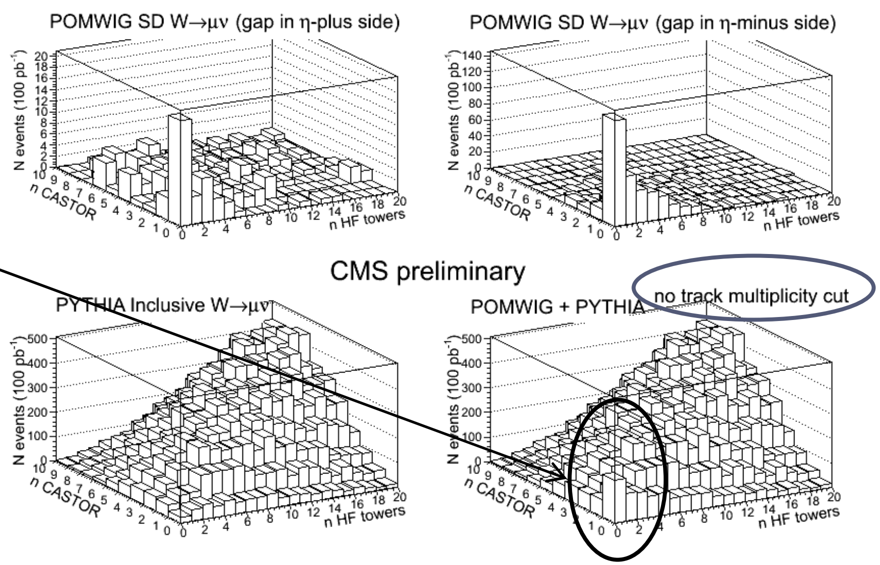
# Effect of central track pre-selection

W




**Increased non-diffractive background when loosening the track pre-selection**

**Diffractive signal less visible when no track pre-selection is present – but still visible**




**~ 100 – 200 events in zero multiplicity bin (S/B ~ 6 - 20)**

# Other sources of background

i) QCD events with muons from hadron decays or tracks misidentified as muon

- Studied applying full selection to a "μ-enriched" QCD sample (Pythia)

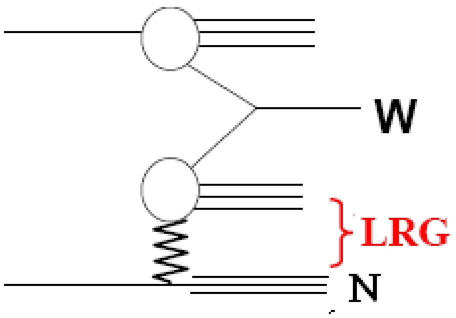
  Number of events in the low multiplicity region increased by less that 1% of the yields

ii) Proton-dissociative events

- Cross section expected to be of the same order as signal
- If N escapes detection (limited forward coverage), it's an irreducible background

  (but it's also diffraction)

- About 50% can be rejected by vetoing on ZDC
- Expect enhancement in signal region by ~ 30%




*N* IS A LOW MASS STATE INTO WHICH THE PROTON DIFFRACTIVELY DISSOCIATES

# SD-W systematics

i. **Rapidity Gap Survival Probability (<|S|²>), assumed 5%** (as indicated by theory)

- $N_{diff} \alpha <|S|^2>$

**Extraction of diffractive yields provides <|S|²> measurement**

ii. **Uncertainties related to the W selection and reconstruction** (uncertainties on μ selection efficiency, including μ momentum scale and misalignment )

- Same for diffractive and non-diffractive

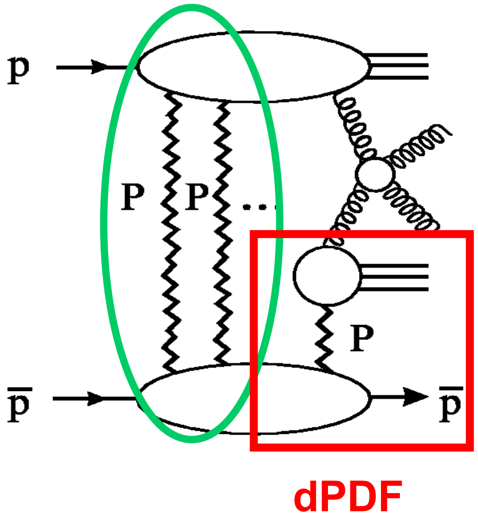
**Negligible effect on acceptance**

iii. **UE description:**

- Generator level study: Pythia Tune DWT (default) vs Tune A
- Selection applied on full simulated Alpgen $W \rightarrow \mu\upsilon$ events

**Potential background enhancement by factor 3 – 5 in signal region**

# Factorisation breaking in pp, $p\bar{p}$




At hadron colliders soft interactions/rescatterings among spectator partons

→ Fill rapidity gap & slow down outgoing hadron

→ Hence suppress visible $\sigma_{diffr}$

• Quantified by rapidity gap survival probability $<|S|^2>$

→ $\sigma_{diffr}$ proportional to $<|S|^2>$

At Tevatron $<|S|^2> \sim 0.1$, ie suppression by O(10) compared to HERA

At LHC:

$<|S|^2> = 5\%$ the most quoted prediction for hard diffractive processes

Values $<|S|^2>$ as low as 0.4% and as high as 23% have been proposed

# SD-dijet MC samples

**Diffractive Dijet sample:**

- Pomwig v2.0 beta
- Proton PDF: CTEQ6M
- dPDF: NLO H1 2006 Fit B ($\alpha_{IP(0)}$) = 1.111, $\alpha$' = 0.06 GeV2, $B_{IP}$ = 5.5 $GeV^{-2}$)
- $P_T \geq$ 40 GeV (214 Kevt, 168 nb, assumes $<|S|^2>$ = 0.05)

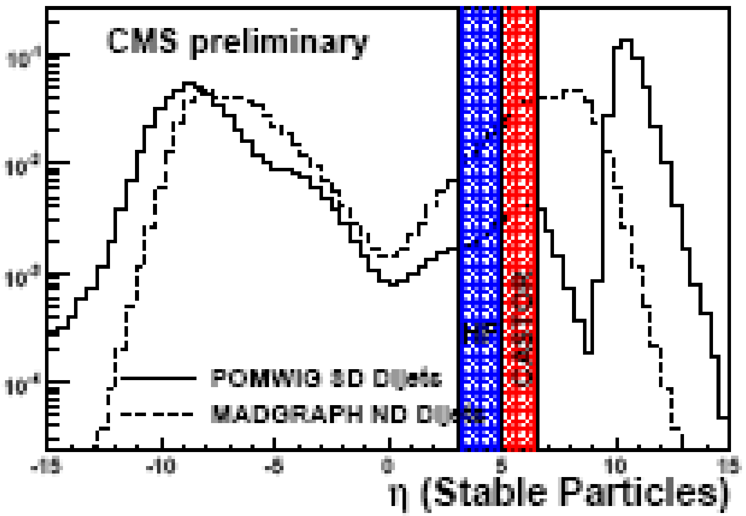
**Non-diffractive samples:**

- MadGraph:
  - 100 < $H_T$ < 250 GeV (125 Mevts, 23850 nb)
  - 250 < $H_T$ < 500 GeV (50 Mevts, 770 nb)
  - 500 < $H_T$ < 1000 GeV (20 Mevts, 37 nb)
  - $H_T$ > 1000 GeV (5 Mevts, 1 nb)
  - $p_T \sim H_T/2$

**With the given cross sections, the ratio of diffractive/inclusive yields~ 0.5%.**

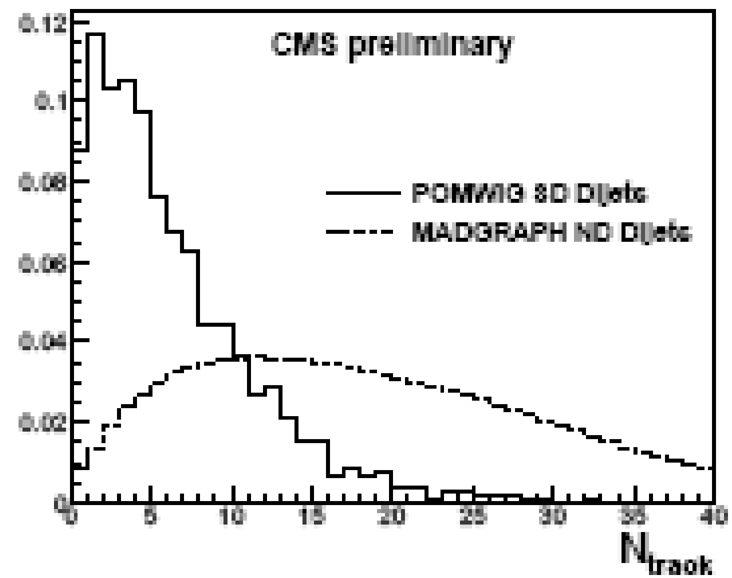
# Selecting diffractive events

**GENERATED PARTICLES – ENERGY WEIGHTED**




Diffractive sample generated with gap in η–plus side

**TRACK MULTIPLICITY :**
number of reconstructed tracks in central tracker ($|\eta| < 2.0$) with $p_T > 0.9$ GeV

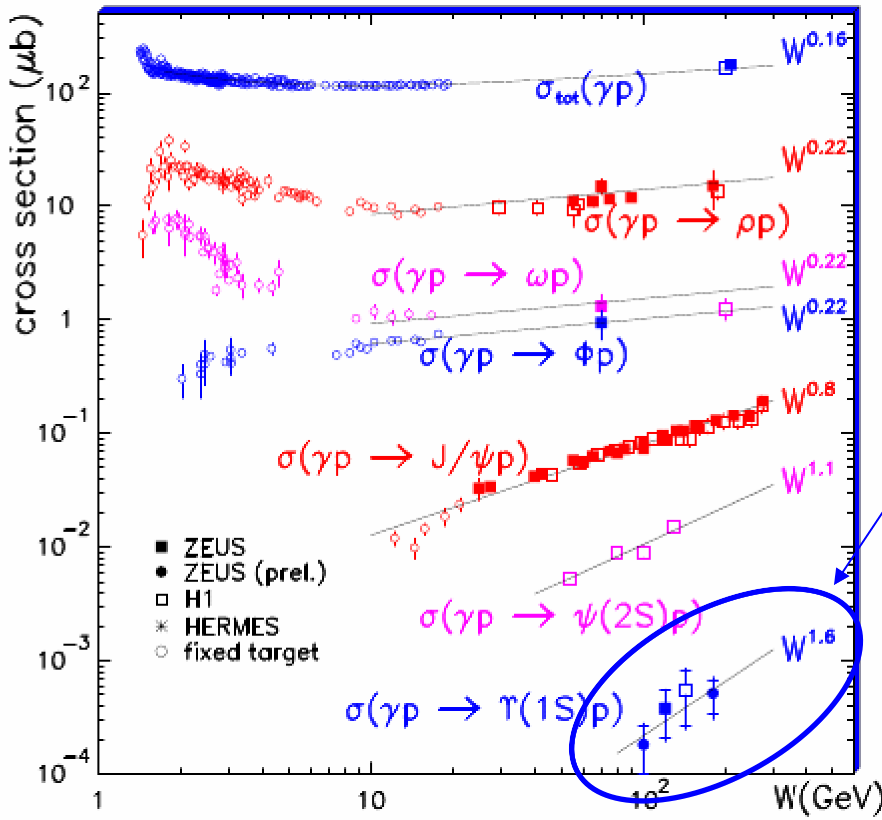



**Diffractive event candidates selected on the basis of different multiplicity distribution:**

- **in the central tracker**
- **in the HF and/or CASTOR [in the gap side]**

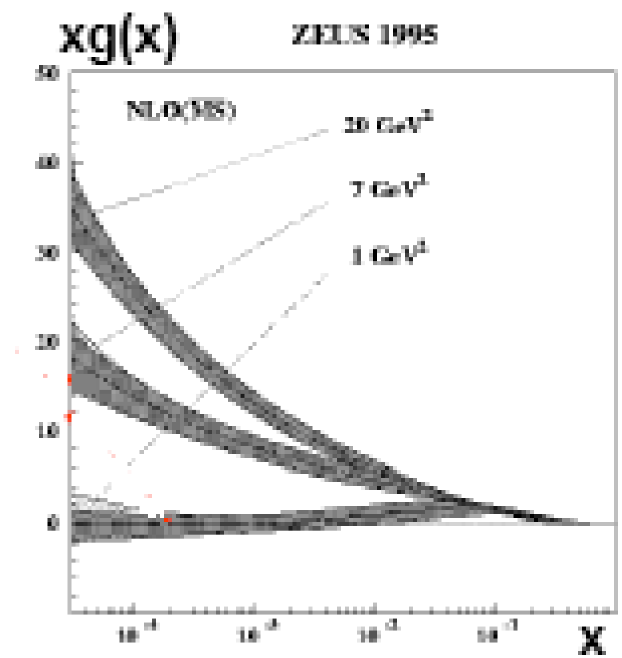
# Photoproduction cross section

**At CMS measurement of Υ photoproduction cross-section for W~500 GeV.**




W = γp CENTRE-OF-MASS ENERGY
( proportional to $\frac{1}{\sqrt{x}}$ )

**Constraint on cross section slope, sensitive to rise in gluon density.**



# Υ photoproduction: MC samples

GENERATORS

For Υ photoproduction (~16k evt) → **STARLIGHT**

- Υ forced to decay into muon pair
- $\sigma \times BR[\Upsilon(1S) \rightarrow \mu^+\mu^-] = 39$ pb
  $\sigma \times BR[\Upsilon(2S) \rightarrow \mu+\mu-] = 13$ pb
  $\sigma \times BR[\Upsilon(3S) \rightarrow \mu+\mu-] = 10$ pb
- The gap survival factor for the Upsilons not included

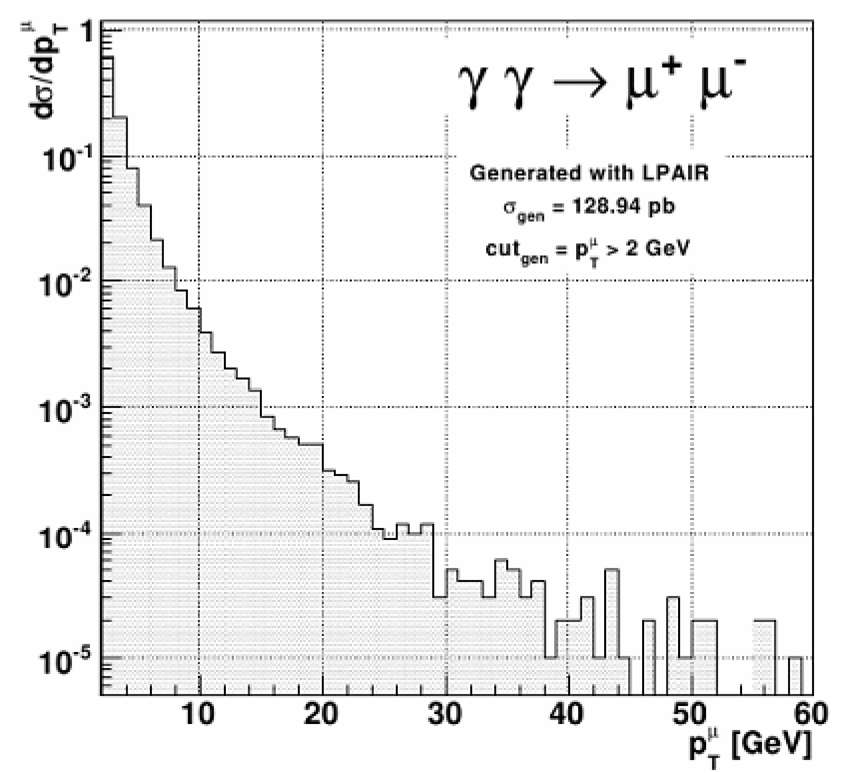
OTHER MODELS VARY IN THEIR CROSS-SECTION PREDICTIONS BY UP TO A FACTOR OF 3.

For non-exclusive background: Drell-Yan, quarkonium decay, heavy flavour jets (~50M evt) → **PYTHIA**

For elastic $\gamma\gamma \rightarrow \mu^+\mu^-$ (100k evt) and two-photon inelastic (20k evt) background → **LPAIR**

**All samples processed through the full detector simulation and reconstruction**

# Υ Trigger selection




Spectrum peaked at very low $P^{\mu}_T$ values

**Low trigger threshold necessary to retain as many event as possible**

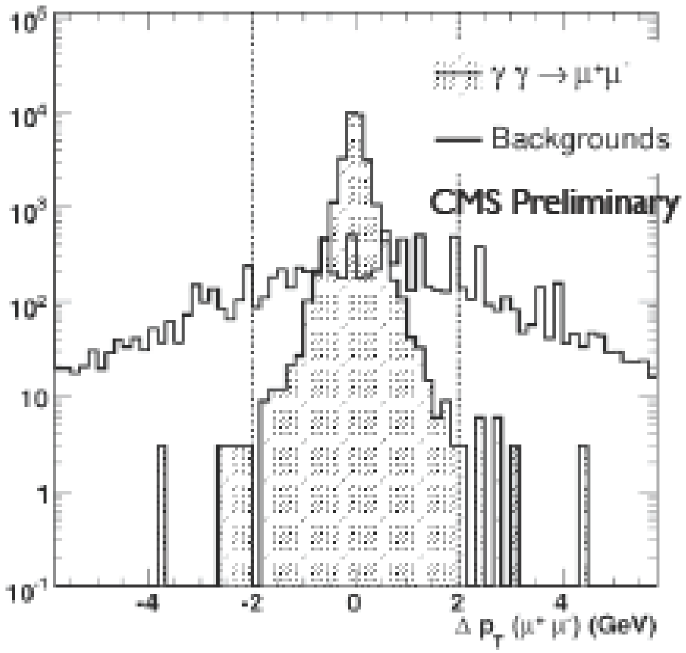
**L1 and HLT:**

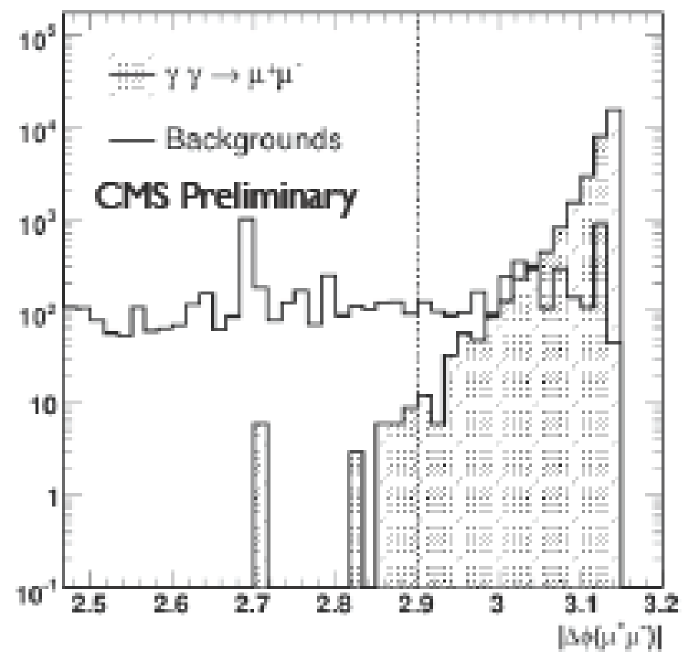
**Standard CMS start-up dimuon trigger:**

- **two muons with $p_T$ > 3 GeV**

**Efficiency for triggering on Υ photoproduction events: (8.7 ± 0.5)% (L1 and HLT triggers).**

# Dilepton selection



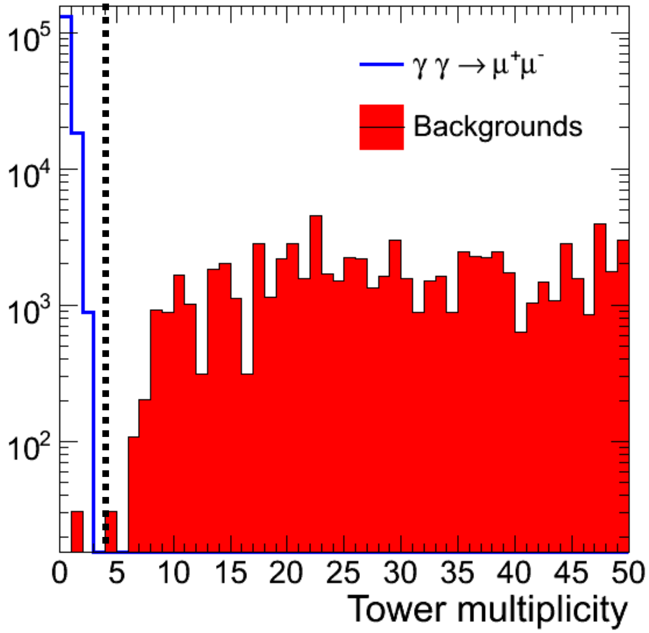




**SIGNAL IS SHARPLY PEAKED AT $|\Delta\phi| = \pi$ AND $\Delta P_T = 0$**

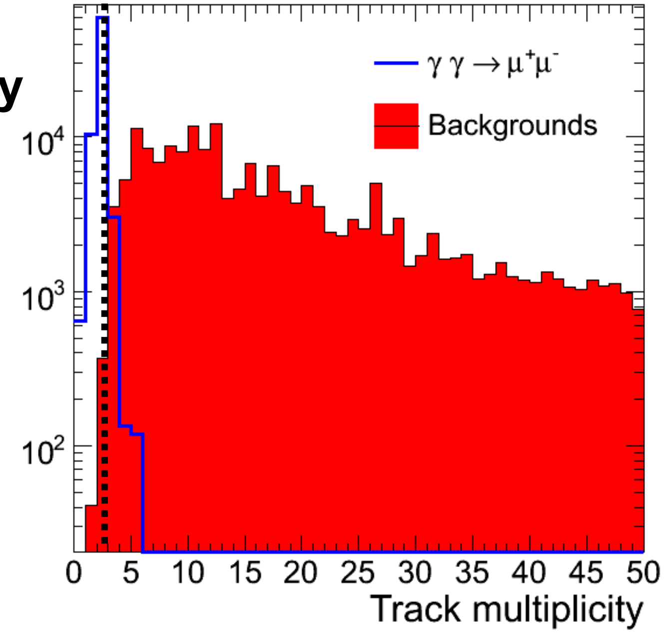
**Offline analysis selection:**

- **Exactly 2 reconstructed opposite-sign muons**
- **$\Delta p_T$ ($\mu\mu$) < 2.0 GeV**
- **$|\Delta\varphi(\mu\mu)| > 2.9$**

# Exclusivity




**CMS preliminary**



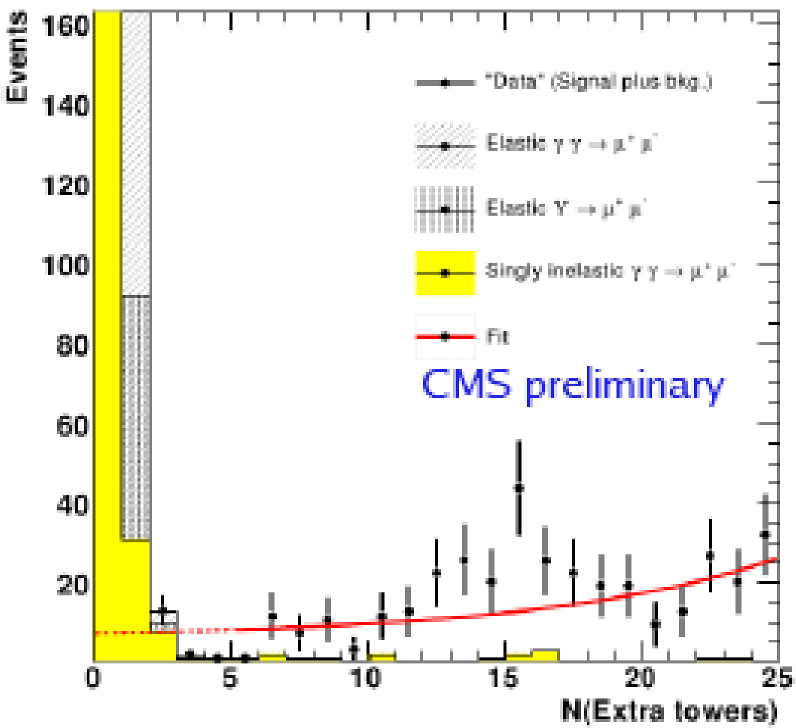

"Extra" towers: E > 5 GeV, isolated from either of the $\mu$ candidates by $\Delta R > 0.3$ in the $\eta$-$\phi$ plane

N. of tracks with $p_T > 0.9$ GeV in central region ($|\eta| < 2.5$)

**Select events with:**
- **Number of extra towers < 5**
- **Number of tracks < 3**

# Non-exclusive background

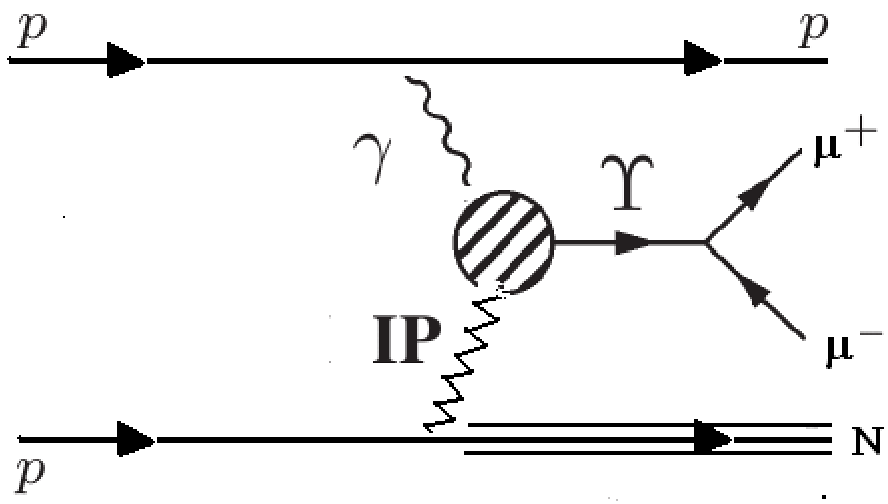
**The presented selection is highly effective at reducing non exclusive backgrounds (rejection > 99%)**




**Remaining non-exclusive background estimated from data by fitting the sideband of the extra calorimeter tower distribution.**

# Background (Υ)

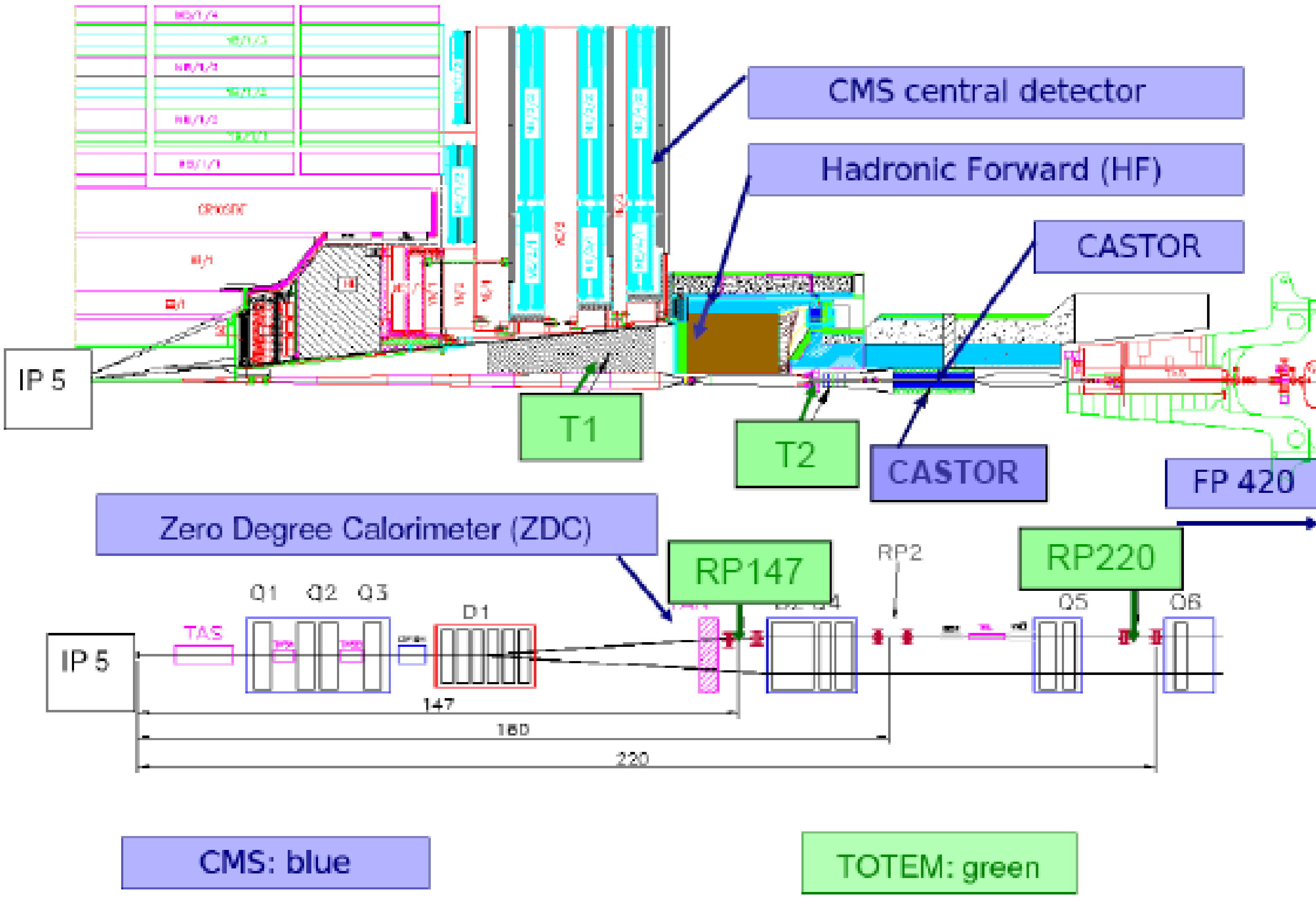
The presented selection doesn't allow to distinguish  proton-dissociative events




N  IS A LOW MASS STATE INTO WHICH THE PROTON DIFFRACTIVELY DISSOCIATES

- 25% of the events produce activity in the region covered by the calorimeter
- Based on acceptance, 2/3 of remaining proton-dissociative events could be rejected using ZDC (2 directions) + Castor (1 direction)

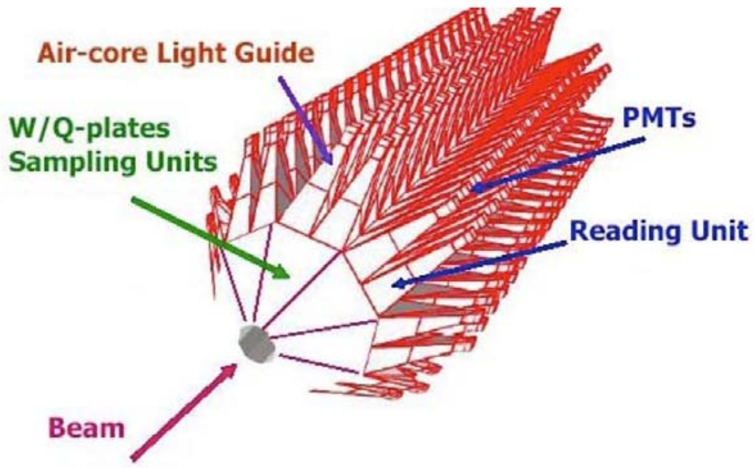
# Forward detector @ IP5



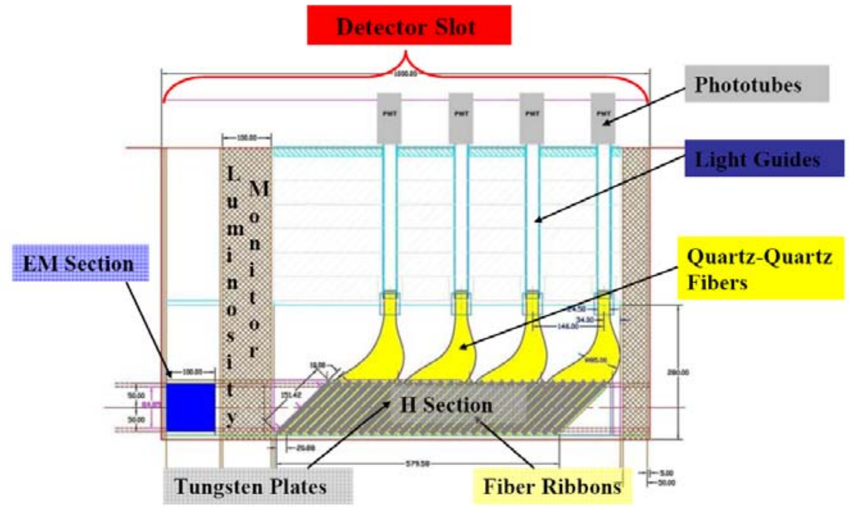
# Hadron Forward calorimeter

- @11.2m from interaction point
- Rapidity coverage: $3 < |\eta| < 5$
- $0.175 \times 0.175$ segmentation in $\eta$, $\varphi$
- Steel absorbers and embedded radiation-hard quartz fibers for fast collection of Cherenkov light
- Long (1.65m) and short (1.43m) fibers are placed alternately and run parallel to the beam axis along the iron absorbers.

# CASTOR and ZDC calorimeters




- -6.6<η<-5.3, 14 m from interaction point
- Octagonal cylinder with outer radius 14cm, depth 10.5 $\lambda$
- W absorber & quartz plates, 45° wrt beam
- Cherenkov photons transmitted through aircore lightguides
- 16 segments in *φ*, 2 (EM)+12(HAD) in *z*
- No segmentation in *η*




- 140 m from interaction point in TAN absorber
- Tungsten/quartz Cherenkov calorimeter with separate EM and HAD sections
- Acceptance for neutrals (γ, $\pi^0$, n) from $\eta$ > 8.1, 100% for $\eta$ > 8.4