Prospects for Diffractive and Forward Physics at the LHC

6th Small-x and Diffraction Workshop

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On behalf of the CMS and TOTEM
Diffractive and Forward Physics Working Group

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Outline

1. Introduction
2. Diffractive Physics
   - Experimental Capabilities
   - Forward and near beam detectors
     - Acceptance
     - Background (pile-up)
     - Triggering
3. Forward Physics
4. Final Remarks

CERN/LHCC 2006-039/G-124
CMS Note xxx
TOTEM Note 06-5
21 December 2006

Prospects for
Diffractive
and Forward Physics
at the LHC

The CMS and TOTEM
diffractive and forward physics
working group

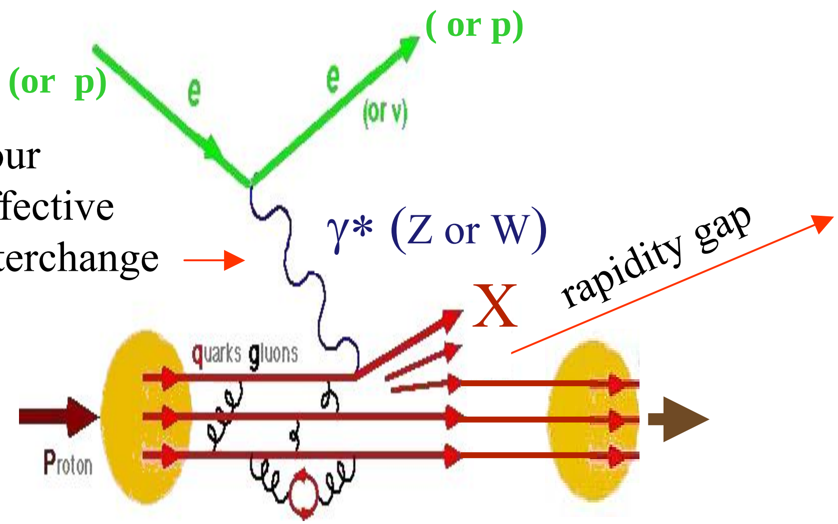
- Complemented by F. Ferro talk

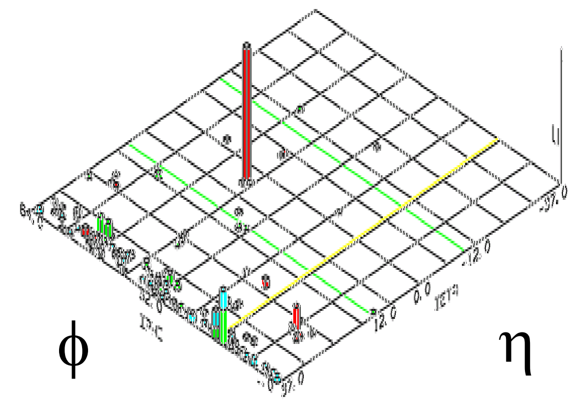
Total Cross section, proton acceptance and reconstruction, and soft diffraction (low luminosity)

- RP420 talk by M. Albrow

Introduction

no colour
~ no effective
spin interchange





D0 Run I sample

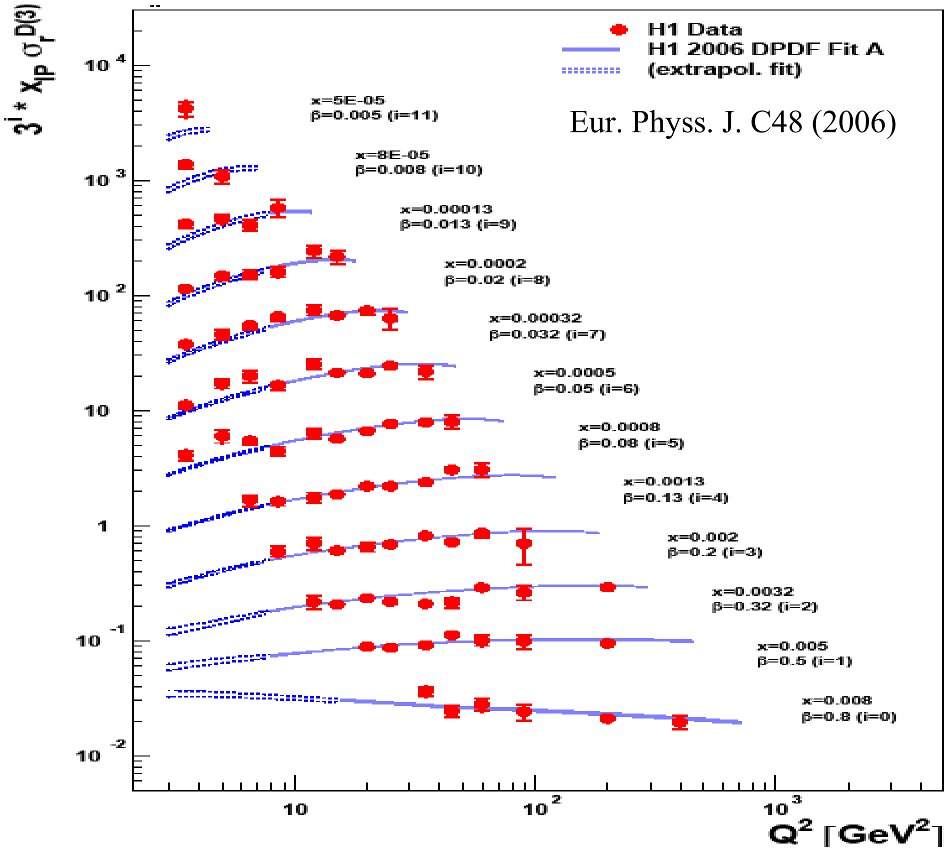
HERA: ep→eXp diffractive deep inelastic scattering

$$\frac{d\sigma^{ep\to eXp}}{d\beta dQ^2 dx_p dt} = \frac{4\pi\alpha^2}{\beta Q^4}\left[\left(1 - y + \frac{y^2}{2}\right)F_2^{D(4)}(\beta, Q^2, x_p, t) - \frac{y^2}{2}F_L^{D(4)}(\beta, Q^2, x_p, t)\right]$$

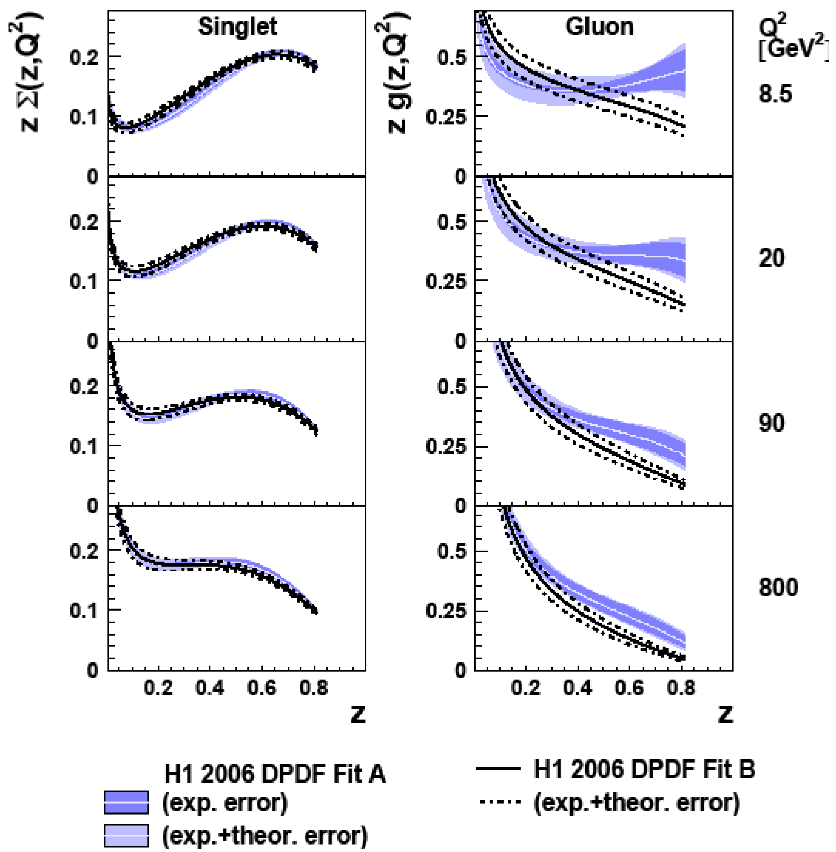
$F_2^{D(4)}$, $F_L^{D(4)}$ diffractive structure functions

Proton Structure Probe

$x_{I\!P} = 0.01 \qquad \sigma_2^{D(3)} = F_2^{D(3)}$ for $F_L^{D(4)} \approx 0$



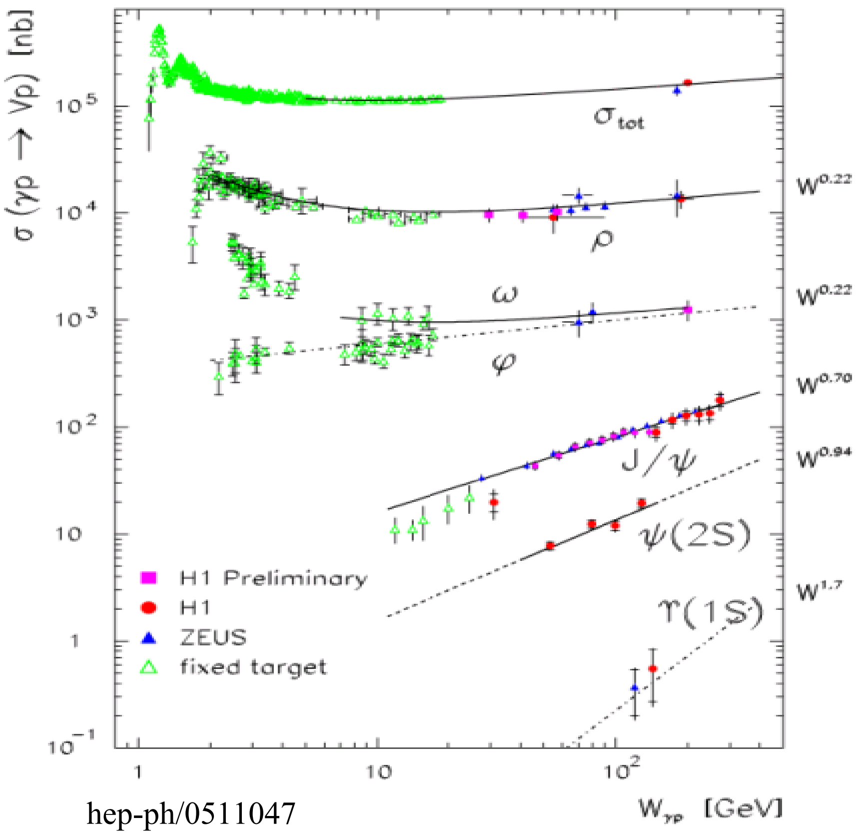
Eur. Physs. J. C48 (2006)



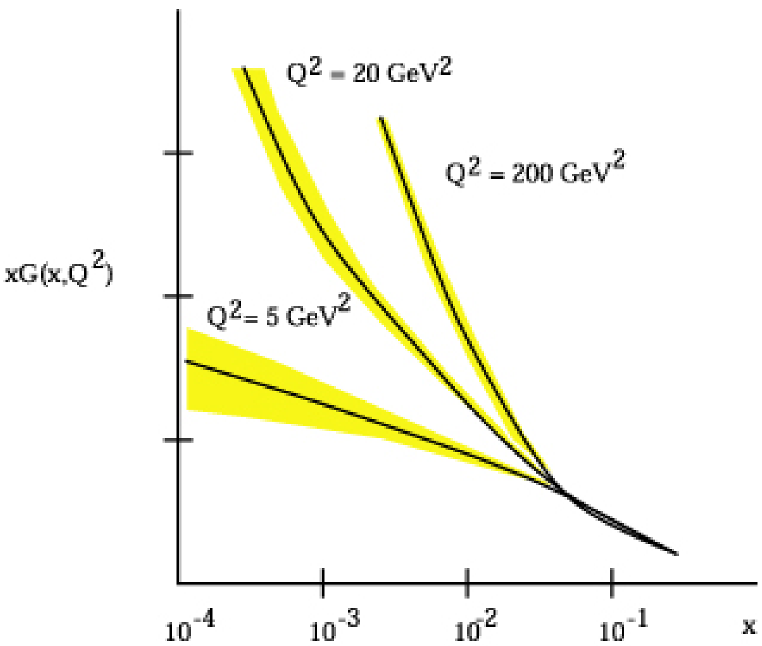
- Strong rise at low-x: partons resolved ~ gluons (+ quark singlets).
- Hard scattering obeys QCD factorization at HERA energies.
- ~ 70% of exchanged momentum carried by gluons

Exclusive Diffractive processes

HERA: $\gamma^* p \rightarrow Vp$ "elastic" vector meson production and $\gamma^* p \rightarrow \gamma p$ deeply virtual Compton scattering



hep-ph/0511047



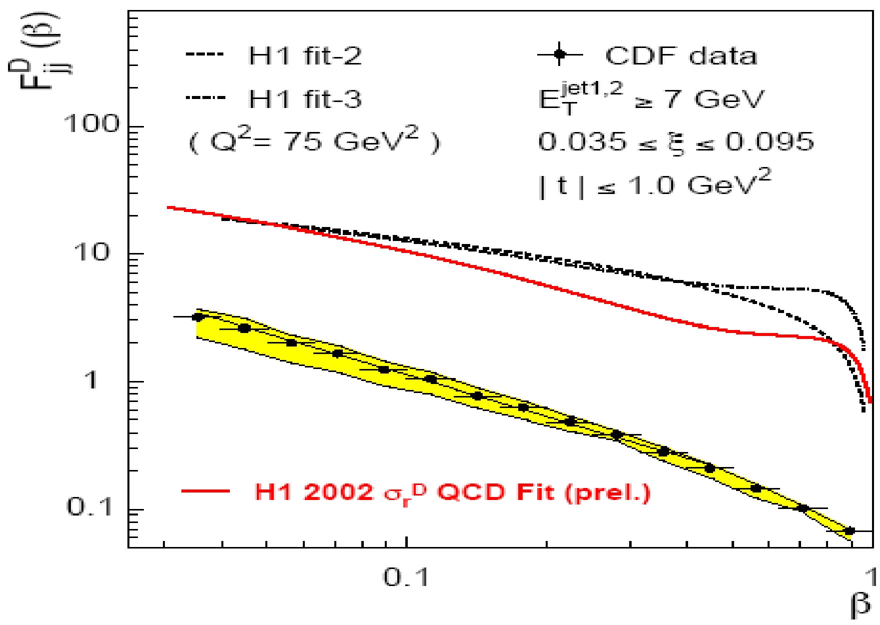
hep-ph/0311028. ZEUS Data

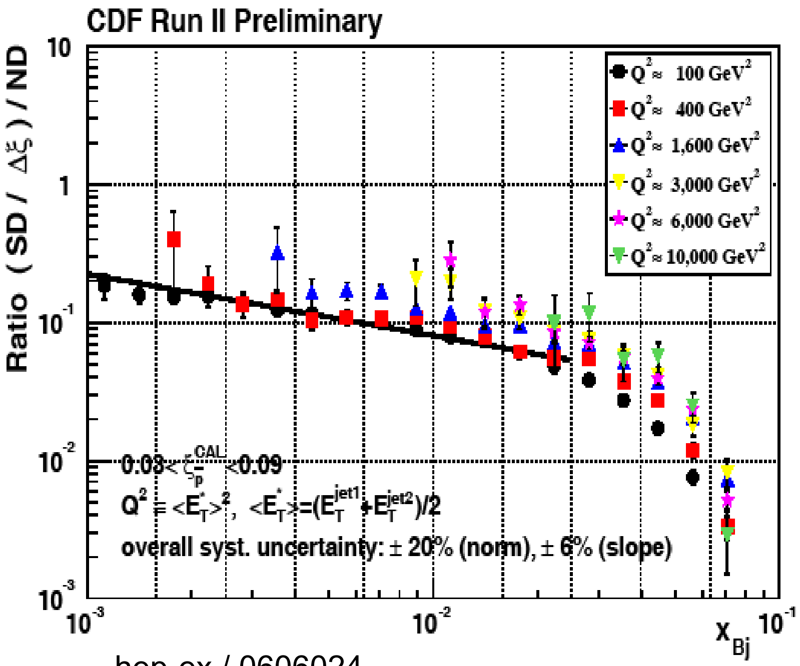
- Energy dependence of these processes becomes steep in the presence of hard scale
- This reflects the x scale dependence of the gluon density in the proton.
- Cross section of these processes is ~ proportional to the square of gluon density.

Diffractive Physics at the Tevatron

- SD rates of *W* and *Z*- bosons, dijet, b-quark and J/ψ meson production in the Tevatron are about 10 times lower than expectations based diffractive parton distribution functions determined at HERA

Phys. Rev. Lett. 84 (2000) 5043





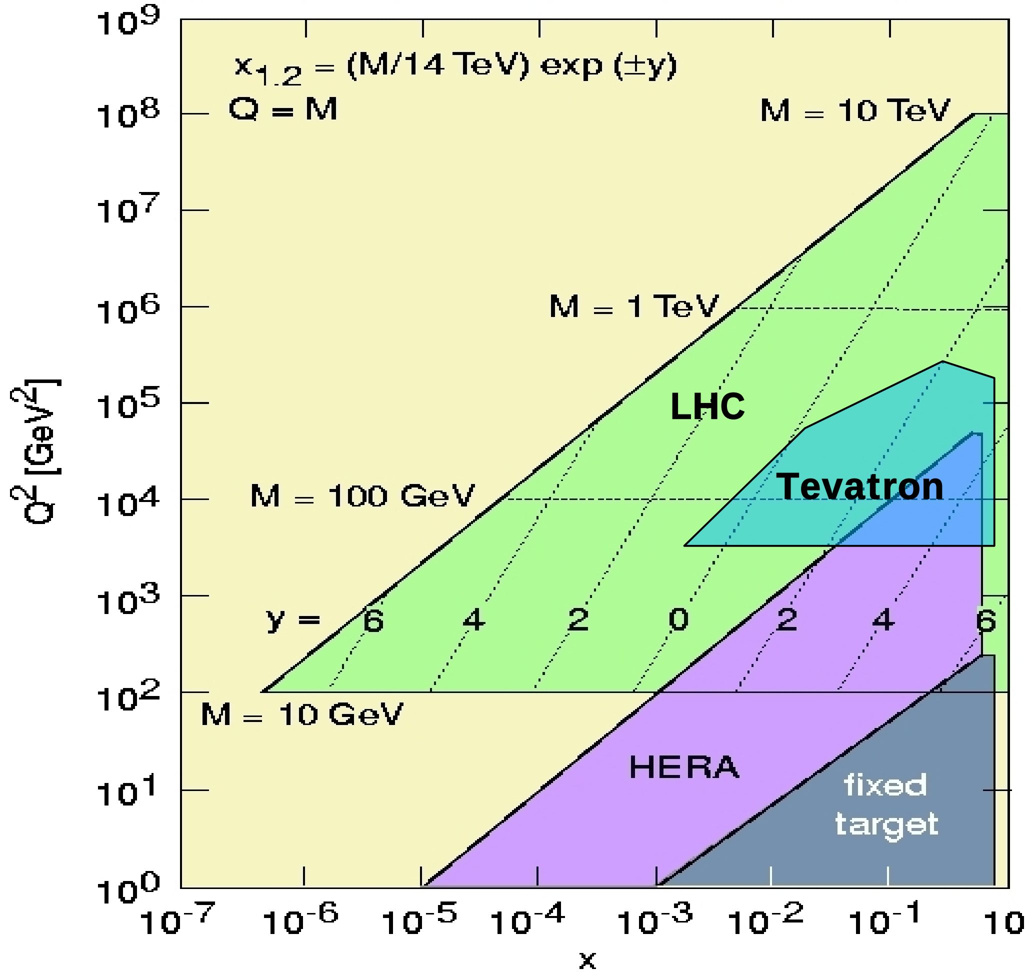
hep-ex / 0606024

- Breakdown of QCD factorization for diffractive processes
- Likely due to the filling of the rapidity gap and slowing (breaking) of the proton due to soft scattering of the two interacting hadrons (quantified by rapidity gap survival probability)

From the Tevatron to the LHC

- LHC will probe forward rapidities y ~ 5, Q^2 ~ 100 GeV and x down to ~10^{-5}
- Some of the available processes:

Inclusive single diffraction (SD) and double "pomeron" exchange (DPE)	pp→pX pp→pXp
production of dijets, vector bosons and heavy quarks	pp→pjjX pp→p*W*(*Z*) pp→p$q\bar{q}$
Central exclusive production	pp →p*H*p with *H* (120GeV)→ $b\bar{b}$
High energy photon interactions	pp→pWX pp→(pγp)→p*WHX*



Based on Stirling's Eur. Phys. J. C 14, 133 (2000)

Program on Diffractive Physics

The accessible physics is a function of the instantaneous and integrated luminosity

Low Luminosity:

- Low enough that pile-up is negligible, i.e <10^{32} $cm^{-2}s^{-1}$, and integrated lumi a few 100pb^{-1} to <1 fb^{-1}
- Measure inclusive SD and DPE cross sections and their Mx dependence

Intermediate Luminosity (β*=0.5m)

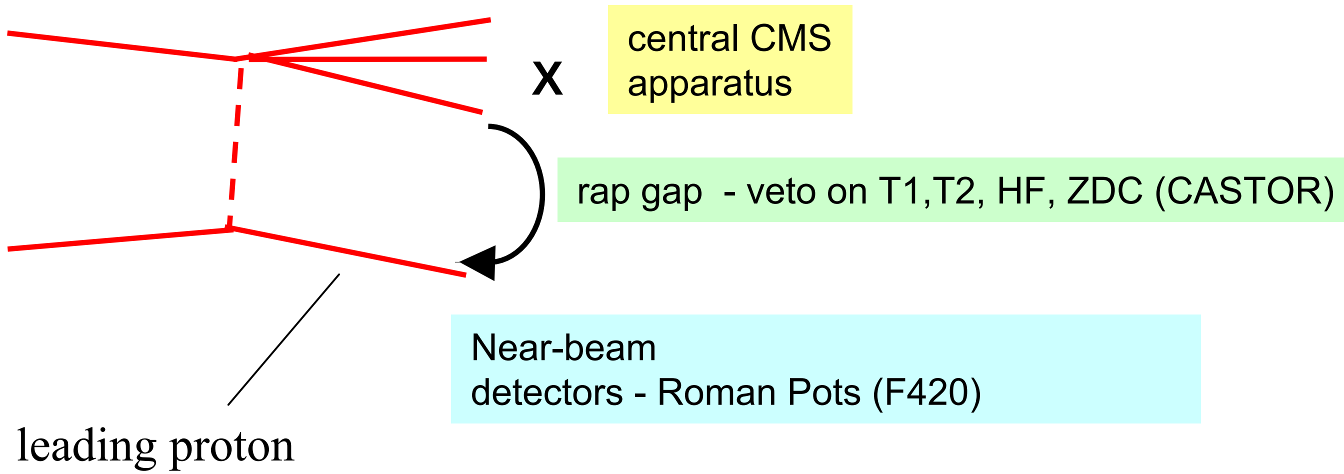
- Lumi < 10^{33} $cm^{-2}s^{-1}$, pile-up starts becoming an issue, integrated lumi 1 to a few fb^{-1}
- Measure SD and DPE in presence of hard scale (dijets, vector bosons, heavy quarks)
- Follow the Tevatron program

High Luminosity:

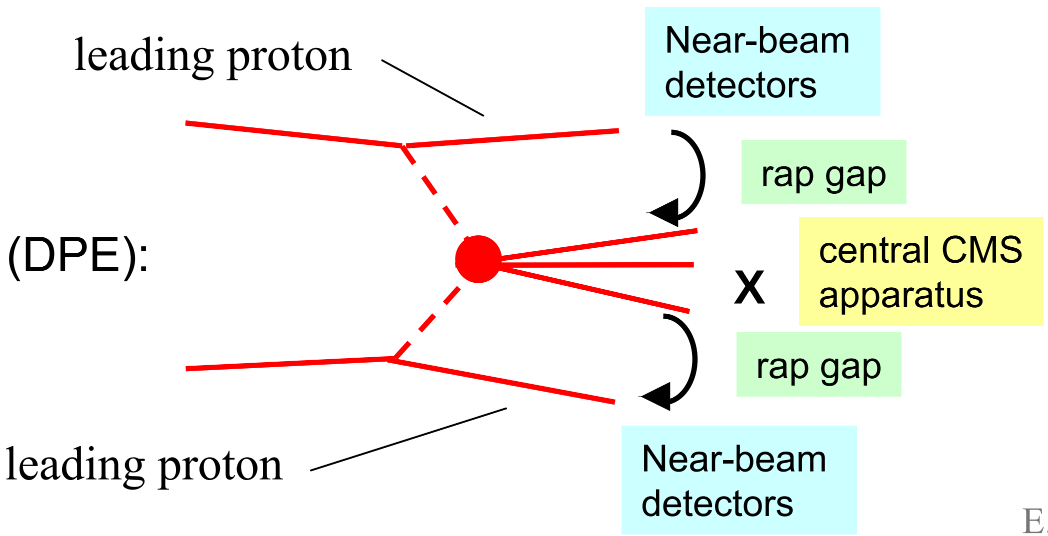
- Lumi_> 10^{33} $cm^{-2}s^{-1}$, pile-up substantial and integrated lumi several tens of fb^{-1}
- Discovery physics comes into reach in central exclusive production

Diffractive Physics with CMS, Totem, and the Forward Detectors

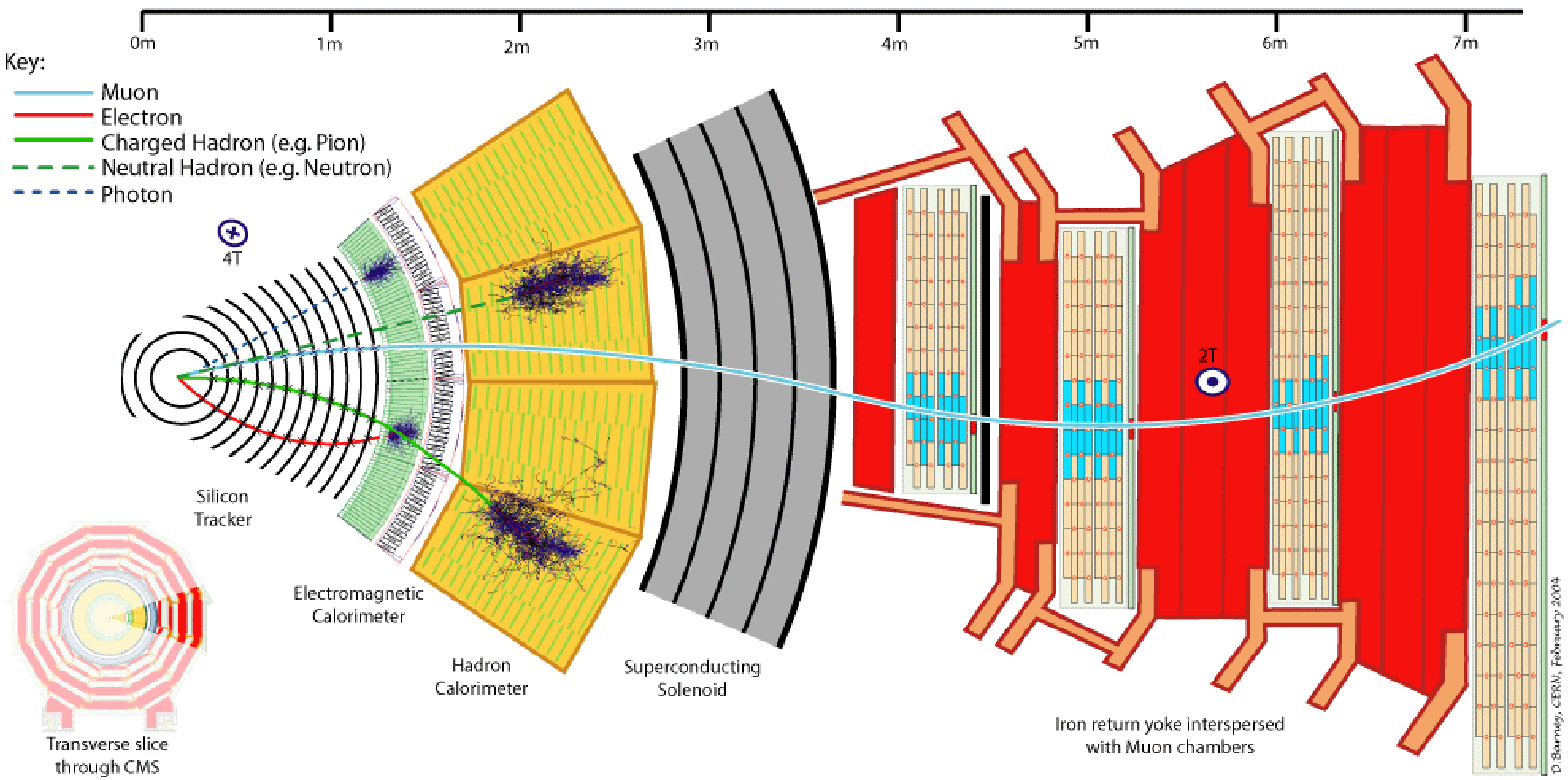
Single diffraction (SD):



Double Pomeron exchange (DPE):



Central CMS detector - $|\eta|<2.4$



CALORIMETERS

MUON BARREL

Si TRACKER

Silicon Microstrips and Pixels

ECAL

Scintillating $PbWO_4$ crystals

HCAL

Plastic scintillator/brass sandwich

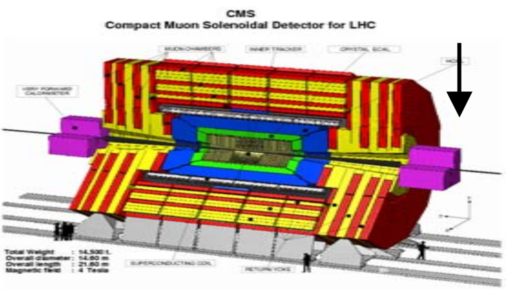
Drift Tube Chambers (**DT**)

Resistive Plate Chambers (**RPC**)

Forward Region

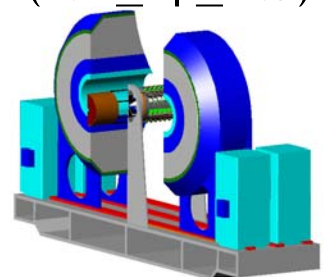
Forward Cal

$(3 \leq |\eta| \leq 5)$



Totem T1,T2

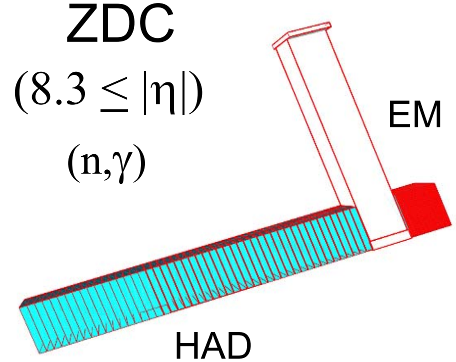
$(5.2 \leq \eta \leq 6.7)$



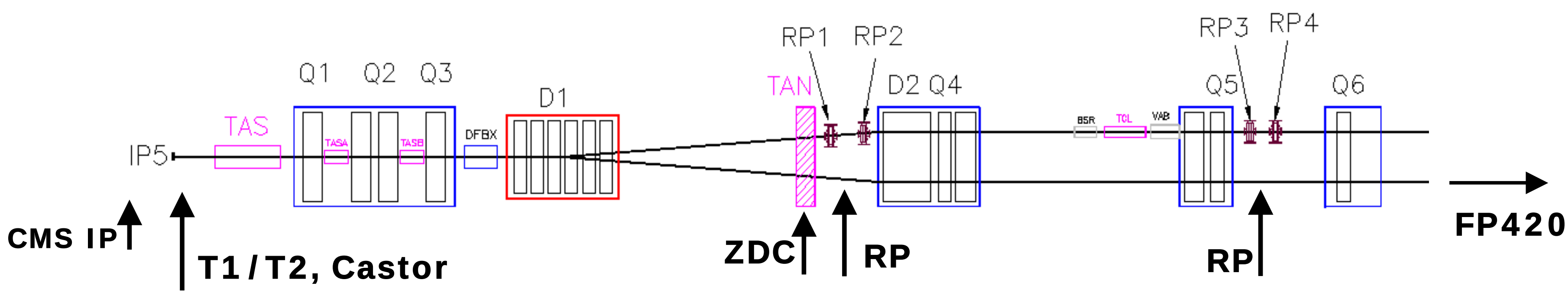
ZDC

$(8.3 \leq |\eta|)$

(n,γ)

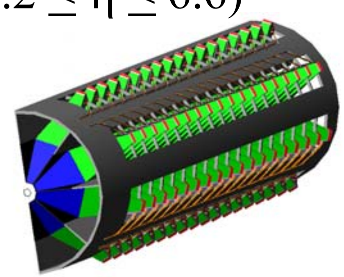


$(z = \pm\, 140$ m)



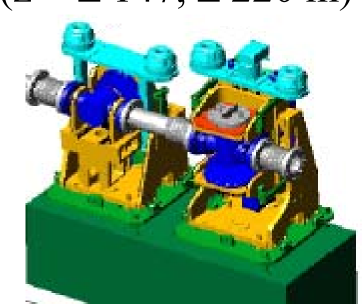
CASTOR

$(5.2 \leq \eta \leq 6.6)$



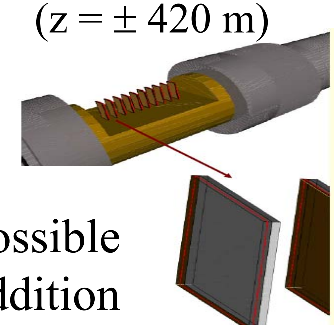
Totem Roman Pots

$(z = \pm\, 147, \pm\, 220$ m)



FP420

$(z = \pm\, 420$ m)



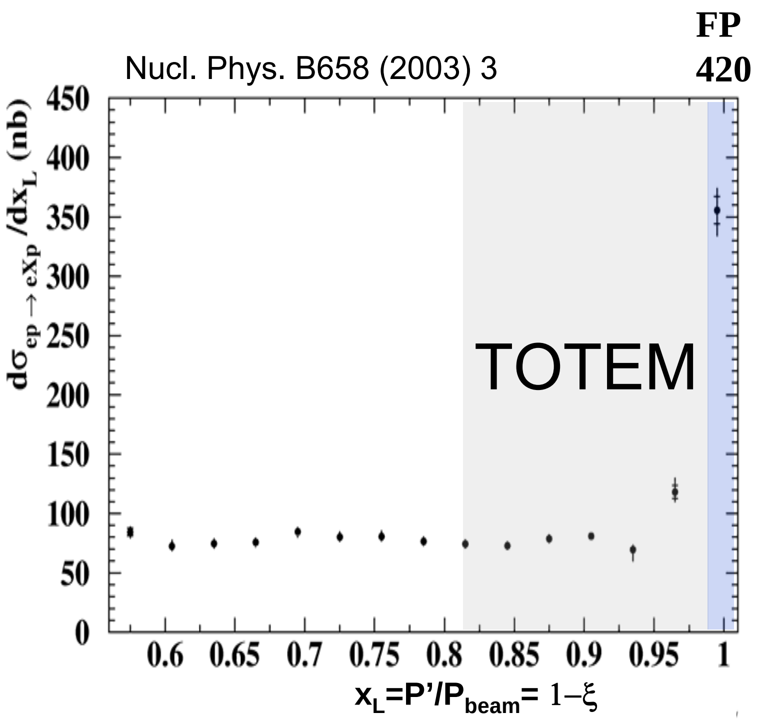
possible addition

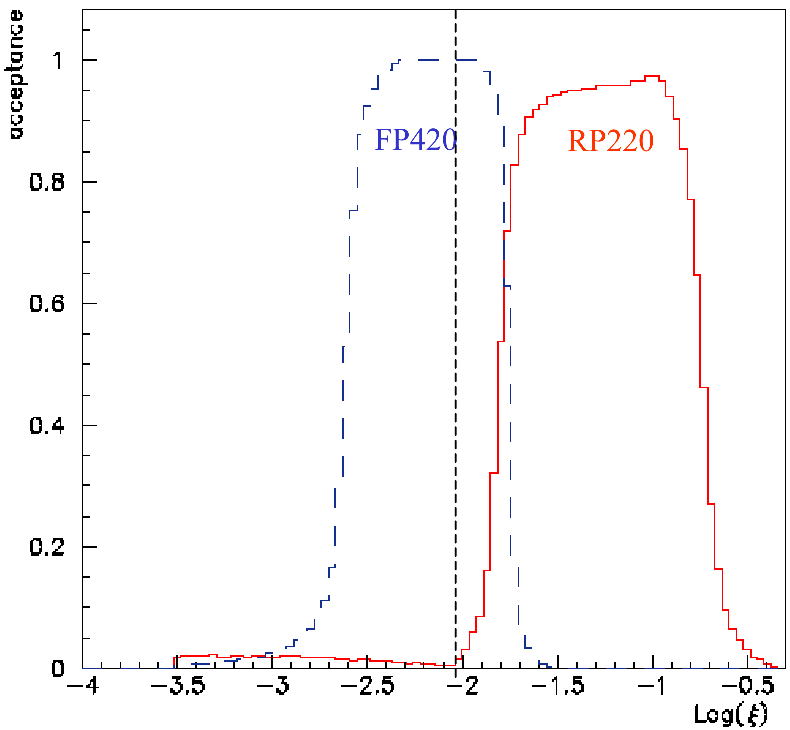
TOTEM (+ FP420): coverage for leading protons

At nominal LHC optics:
β^*=0.5m and L = 10^{33}-10^{34} cm^{-2} s^{-1}

ξ fractional momentum loss of the proton.

at 220m: $0.02 < \xi < 0.2$
at 420m: $0.002 < \xi < 0.02$



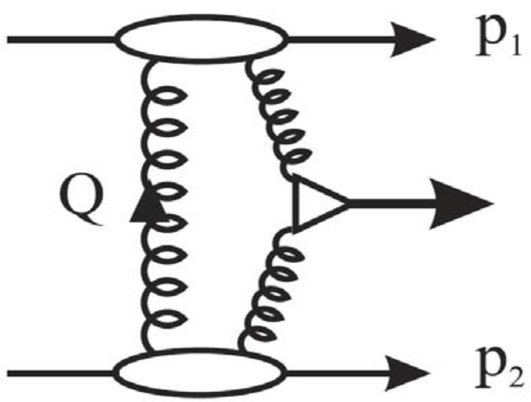


For example:

$$\xi_1 \xi_2 s = M^2$$

With $\sqrt{s}$=14TeV, M=120GeV on average:
$\xi \approx 0.009 \approx 1\%$

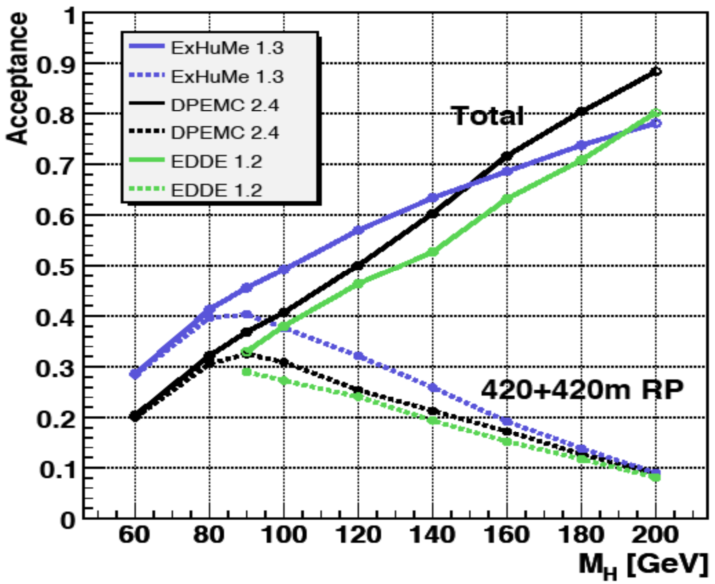
TOTEM (+ FP420): coverage for leading protons



Example: Central exclusive production

pp →p*H*p with *H* (120GeV) → $b\bar{b}$

- In non-diffractive production very hard, signal swamped with QCD dijet background
- Selection rule in central exclusive production (CEP) ~ $J^{PC} = 0^{++}$ improves S/B for SM Higgs dramatically
- Key: Detection of diffractively scattered protons inside of beam pipe. Plus: two collimated jets in central detector with consistent values mass from central detectors



$$\xi_1 \xi_2 s = M^2$$

- Acceptance for events in which both protons are measured in the 420 m detectors or in combination of 420 m + 220 m detectors ("Total")
- M. Albrow talk will be on the 420 m detectors.

Pile-up Background

- Using a mixed sample of events and pile-up one can extract probability of obtaining a fake DPE signature in the near beam detectors caused by protons from pile-up events:

CMS-2006/054 and TOTEM-2006/01

lumi	$\langle N^{PU} \rangle$	420+420	220+220	220+420	Total
$1 \cdot 10^{33}$	3.5	0.003	0.019	0.014	0.032
$2 \cdot 10^{33}$	7.0	0.008	0.052	0.037	0.084
$5 \cdot 10^{33}$	17.5	0.033	0.205	0.153	0.300
$7 \cdot 10^{33}$	25.0	0.063	0.280	0.246	0.417
$1 \cdot 10^{34}$	35.0	0.101	0.480	0.380	0.620

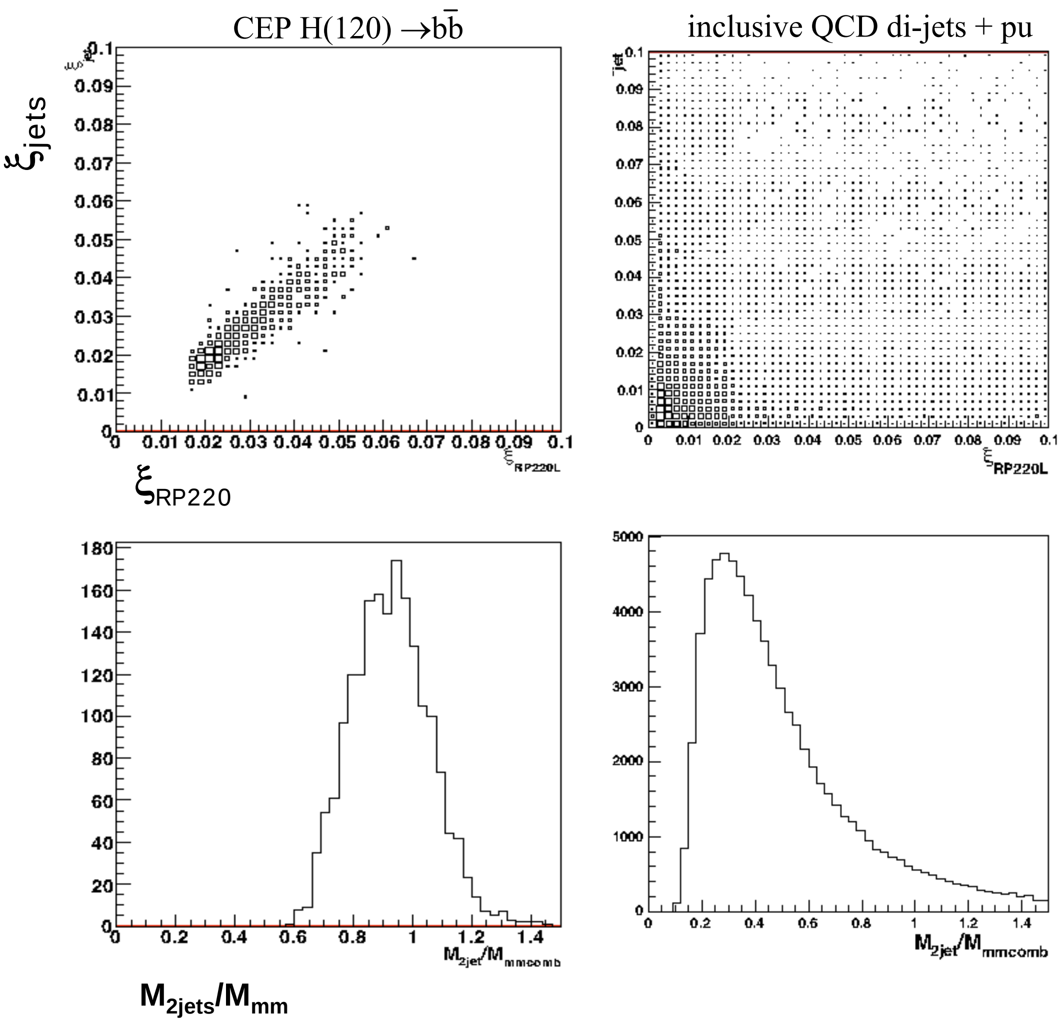
- Eg at 2 x10^{33} $cm^{-2}s^{-1}$ with an average of 7 pileup events per beam crossing, ~10% of the non-diffractive background in the central detector appear to have DPE signature
- This is independent of the type of signal.
- S/B_PU hence depends on the relative cross section of diffractive signal and non-diffractive background that looks like the signal in the central detector

Pile-up Background

- Reduced by correlation between ξ_{jets} measured in the central detector and ξ_{RP} measured by the near-beam detectors
- Reduced by fast timing detectors that can determine whether the protons seen in the near-beam detector came from the same vertex (current R&D project)

$$\xi_1 \xi_2 s = M^2$$

$$\xi_{jets} = \frac{1}{\sqrt{s}} \sum_i E_{T,i} \exp(\eta_i)$$



Triggering

- Diffractive/forward processes typical values of p_T lower than most hard processes suited for CMS.
- The CMS trigger menus now foresee a dedicated diffractive trigger stream with 1% of the total bandwidth on L1 and HLT

CMS-2006/054 and TOTEM-2006/01

Luminosity $[cm^{-2}s^{-1}]$	# Pile-up events per bunch crossing	L1 2-jet rate [kHz] for $E_T > 40$GeV per jet	Total reduction needed	Reduction when requiring track in RP detectors: at 220 m	at 220 m, $\xi < 0.1$	at 420 m	at 220 m & 420 m (asymmetric)	at 220 m & 420 m (asymmetric), $\xi < 0.1$
1×10^{32}	0	2.6	2	370				
1×10^{33}	3.5	26	20	7	15	27	160	380
2×10^{33}	7	52	40	4	10	14	80	190
5×10^{33}	17.5	130	100	3	5	6	32	75
1×10^{34}	35	260	200	2	3	4	17	39

The 420 m detectors won't make it to the L1 trigger within latency

Achievable total reduction: 10 x 2 (H_T cond) x 2 (topological cond) = 40

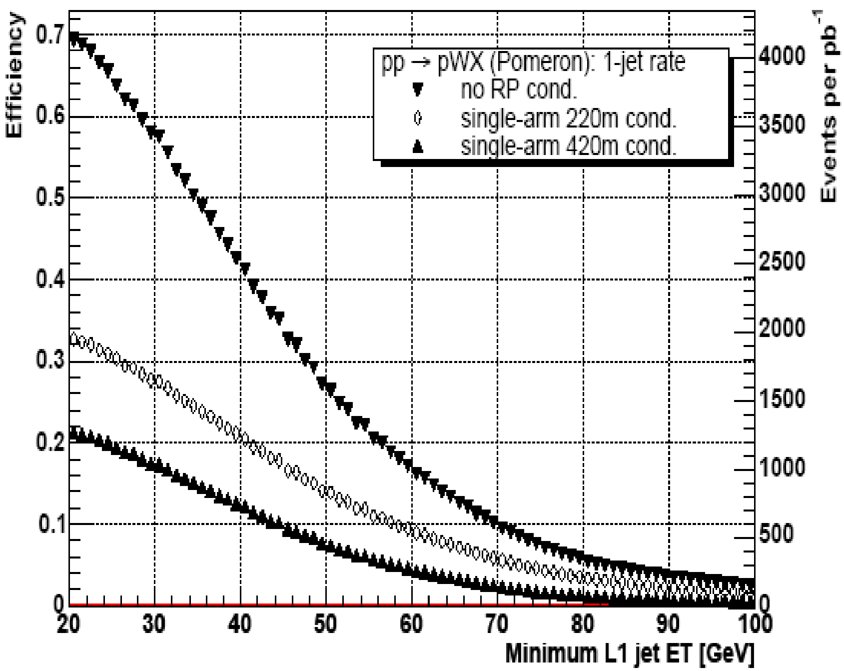
Jet isolation criterion

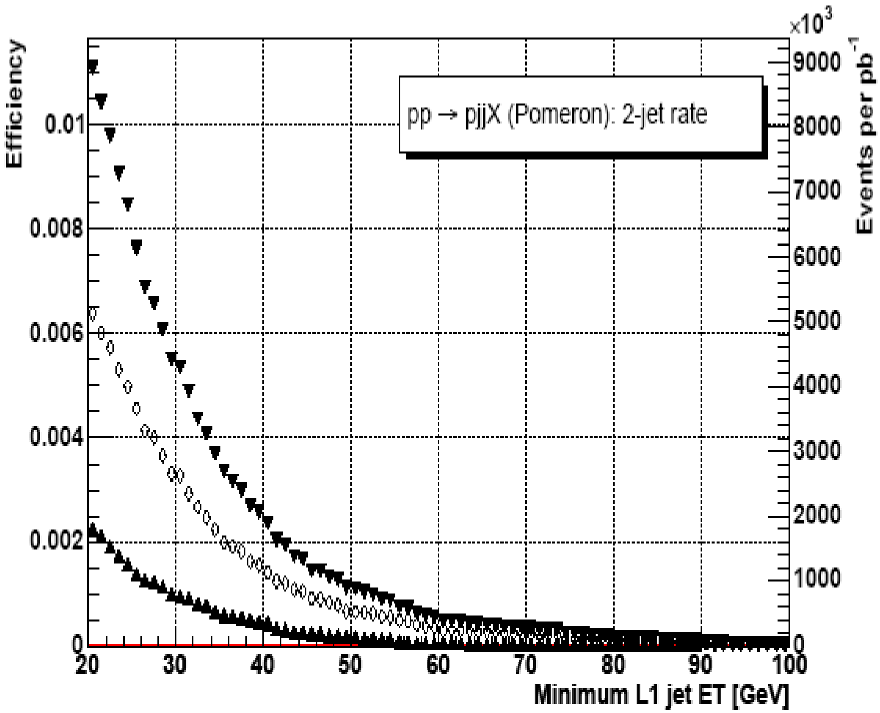
reduction requiring 2 jets in the same η hemisphere as the RP detectors that see the proton

Adding L1 conditions on the near-beam detectors provides a rate reduction sufficient to lower the 2-jet threshold to 40 GeV per jet while still meeting the CMS L1 bandwidth limits for luminosities up to 2 x 10^{33} cm^{-1} s^{-1}

Trigger efficiencies for Single Diffraction

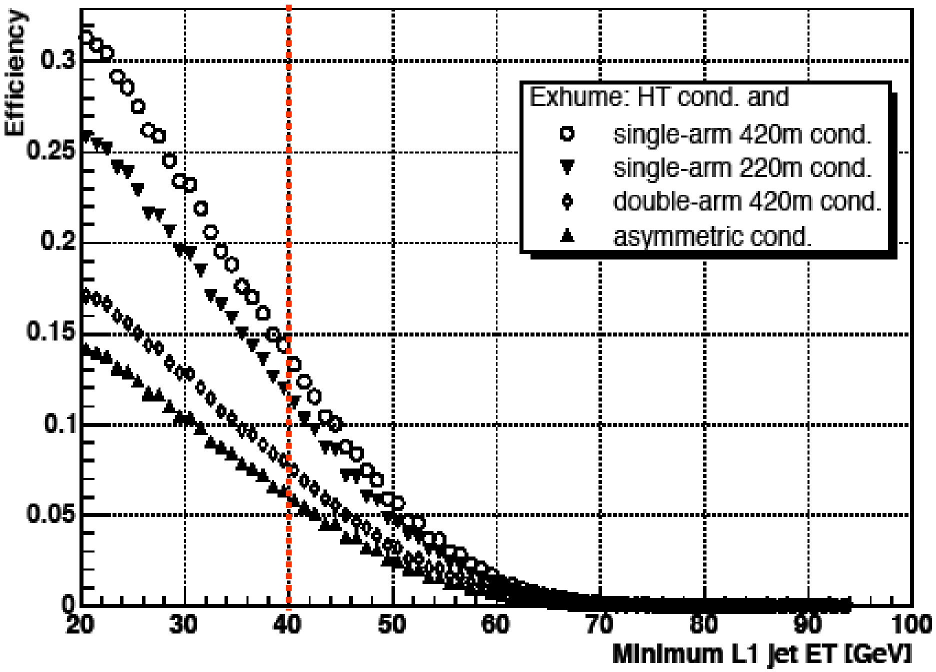
- pp→p*W*x: one L1 jet with E_T above threshold required
- pp→p*jj*X: at least two L1 jets with E_T above threshold required
- No pile-up case, three different conditions studied:
  - Trigger in central detectors alone
  - With single arm 220 m condition (proton signal detected on near-beam 220 m detectors)
  - With single arm 420 m condition (for completeness)





Trigger Efficiencies DPE

Example: Central exclusive production
pp →p*H*p with *H* (120GeV) → $b\bar{b}$



Level-1:

- H_T condition ~ rapidity gap of 2.5 with respect to beam direction
- 2-jets (E_T>40GeV) & single-sided 220m, efficiency ~ 12%
- Add another ~10% efficiency by introducing a 1 jet & 1 μ (40GeV, 3GeV) trigger condition

HLT: Efficiency ~7%
To stay within 1 Hz output rate, needs to either prescale b-tag or add 420 m detectors in trigger

- Possible to retain about ~10% of the signal events up to 2 x 10^{33} cm^2 s^1 in a special forward detectors trigger stream
- Reduction of the pile-up background by $O(10^9)$ can be obtained with relatively simple cuts, further requirements (vertex position) can give a further 10-100 suppression or larger.
- Yield S/B in excess of unity for a SM Higgs

Program on Forward Physics

Study of the underlying event at the LHC:

- Multiple parton-parton interactions and rescattering effects accompanying a hard scatter
- Closely related to gap survival and factorization breaking in hard diffraction

Heavy-ion and high parton density physics:

- Proton structure at low x_{BJ} → saturation → Color glass condensates

Photon-photon and photon-proton physics:

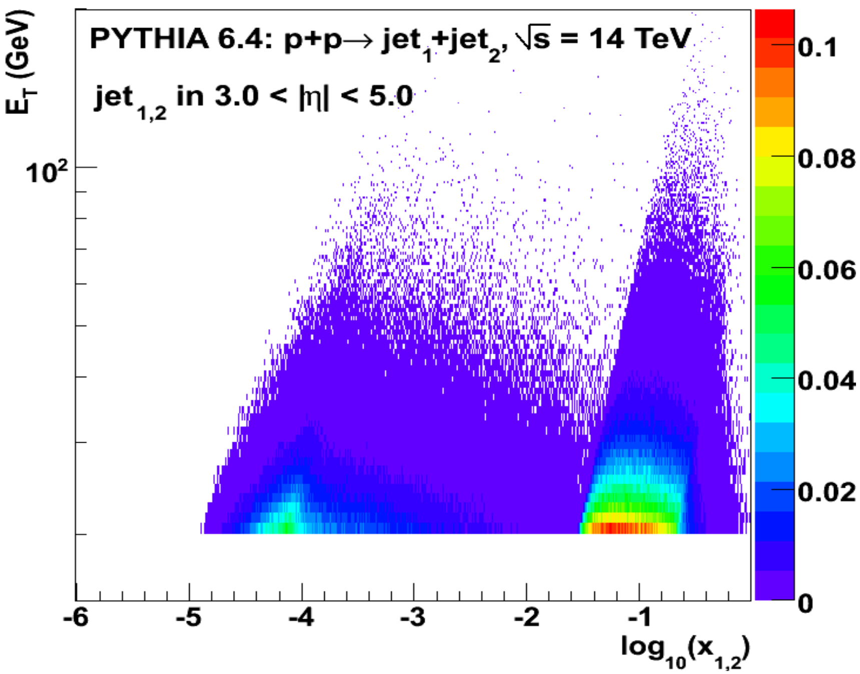
- Also there protons emerge from collision intact and with very low momentum loss

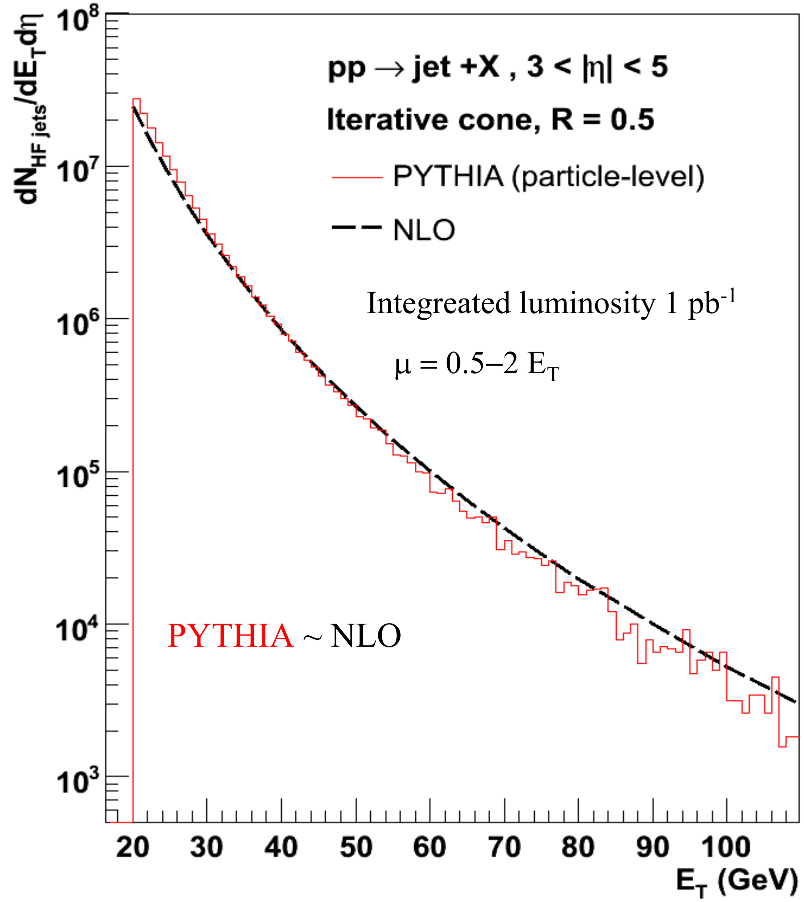
Cosmic ray physics

- Models for showers caused by primary cosmic rays (PeV = 10^{15} eV range) differ substantially
- Fixed target collision in air with 100 PeV center-of-mass E corresponds to pp interaction at LHC
- Hence can tune cosmic ray shower models at the LHC

Forward Jets

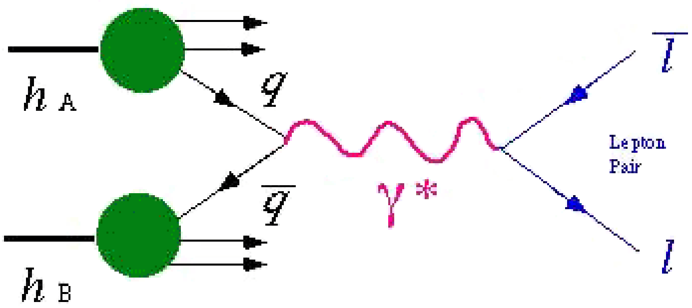
- At Tevatron is the standard tool to study PDFs in global fit analysis
- At CMS (E_T ~20-100 GeV) dijet detection will be possible in HF for $3<\eta<5$ and $-3<\eta<-5$
- This allows to probe values as low as $x_2 \sim 10^{-4}$ (even further with Castor $\sim 10^{-6}$)

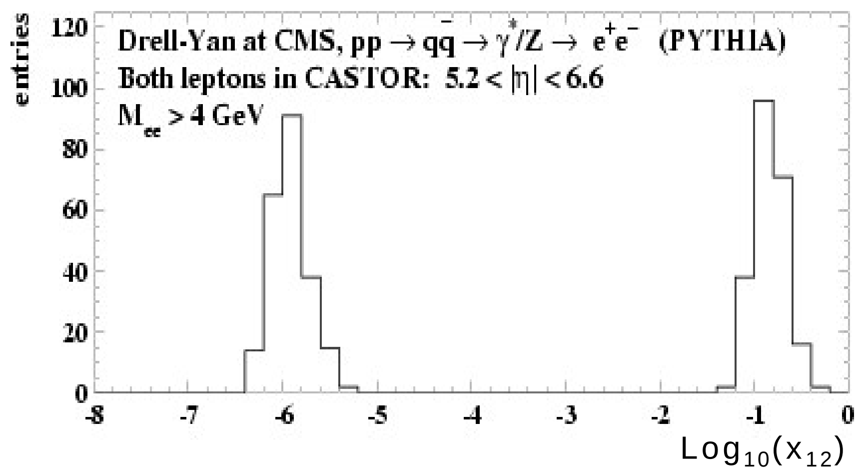




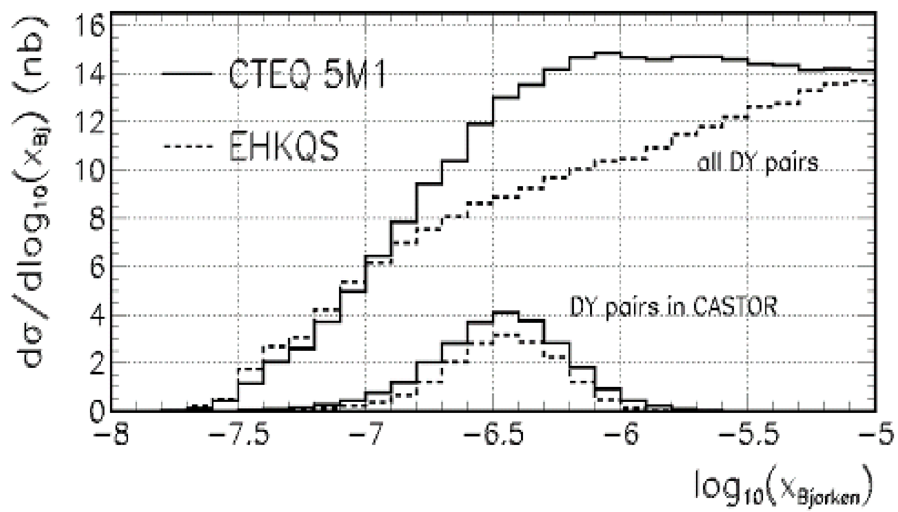
Single inclusive jet measurement
Generator level estimates: No detector response, underlying event and hadronization corrections included for spectrum

Forward Drell-Yan





$$M^2 = s x_1 x_2 \quad \text{and} \quad x_{1,2} = \frac{M}{\sqrt{s}} e^{\pm y}$$

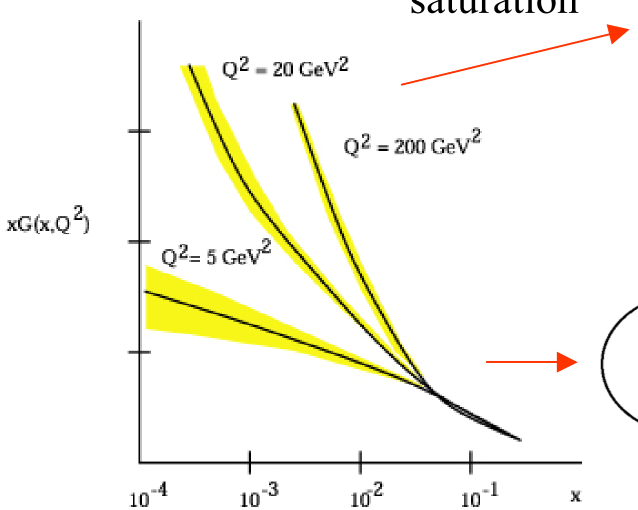


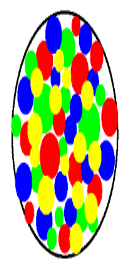
- Access to the low x regime of the quark (antiquark) distributions requires imbalance of fractional momenta → $x_{1,2}$ boosted to large rapidities
- CASTOR with 5.3 ≤ |η| ≤ 6.6 gives access to x_{BJ}~10^{-7}
- Measure angle of electrons with T2

Forward Physics: Gluon saturation region

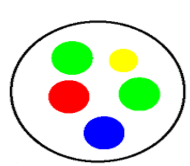
- New regime of QCD is expected to reveal at small x due to effects of large gluon density
- So far not observed in pp interactions
- Field of common interest with Heavy Ions Physics

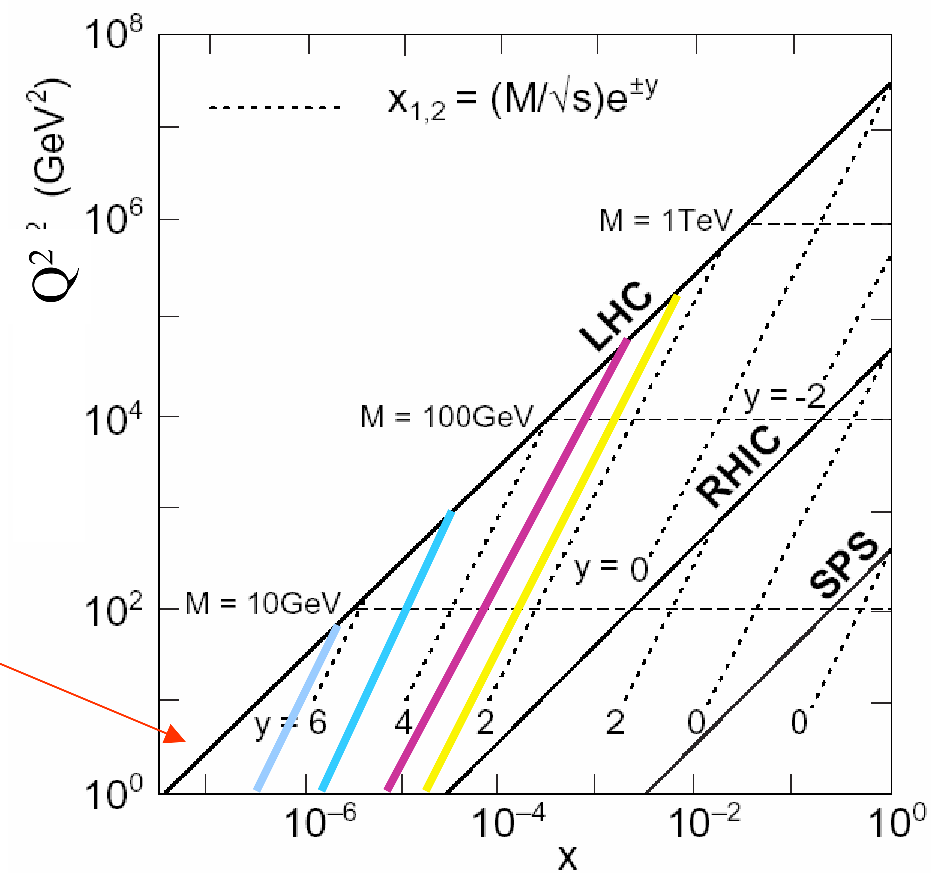
ZEUS data for gluon distribution
In partons





CGC

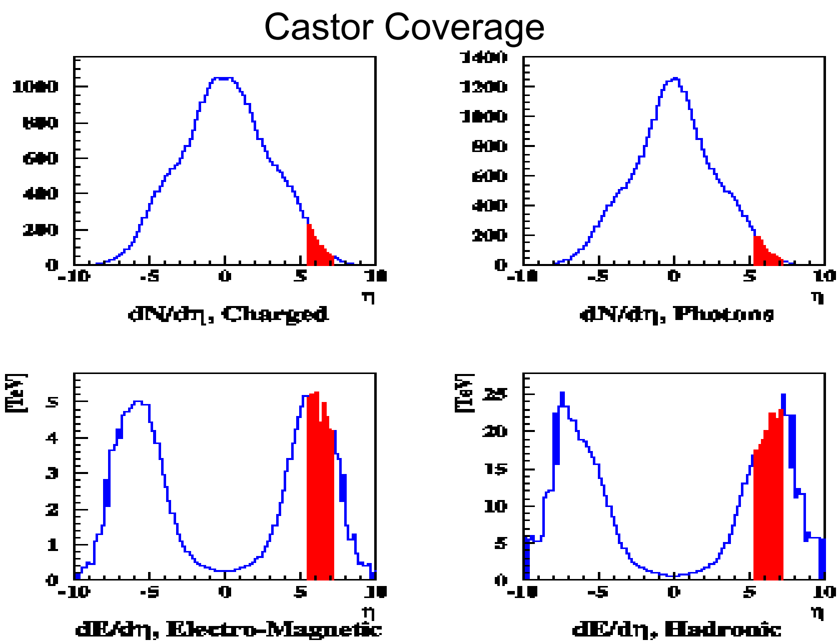


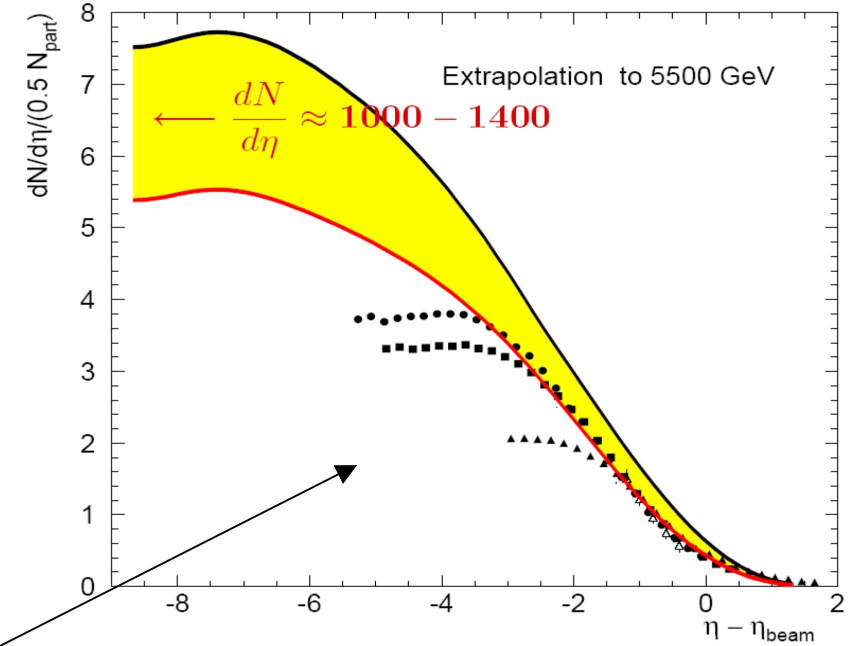


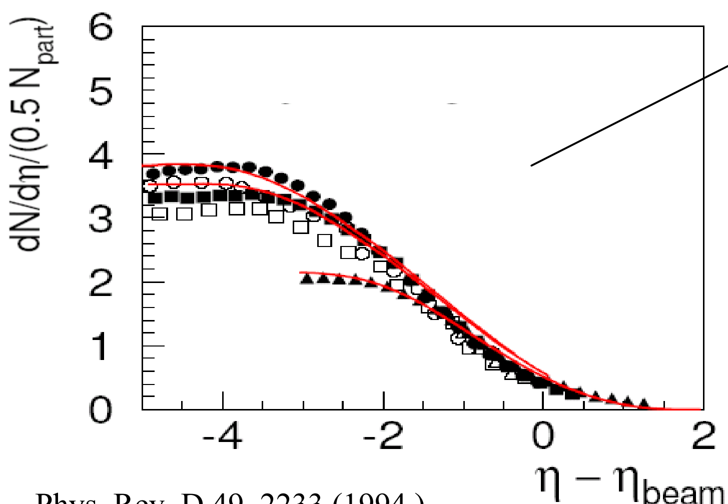
Sub detector	Coverage
Forward HCAL	3 .0< | η | < 5.2
CASTOR	5.2 < | η | < 6.6
ZDC	8.3 < |η|

McLerran, hep-ph/0311028

Limiting Fragmentation





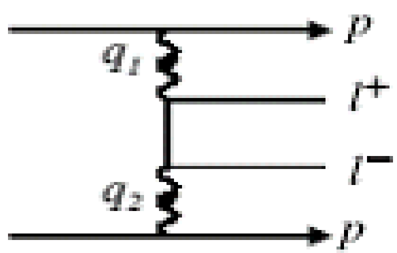


Phys. Rev. D 49, 2233 (1994)

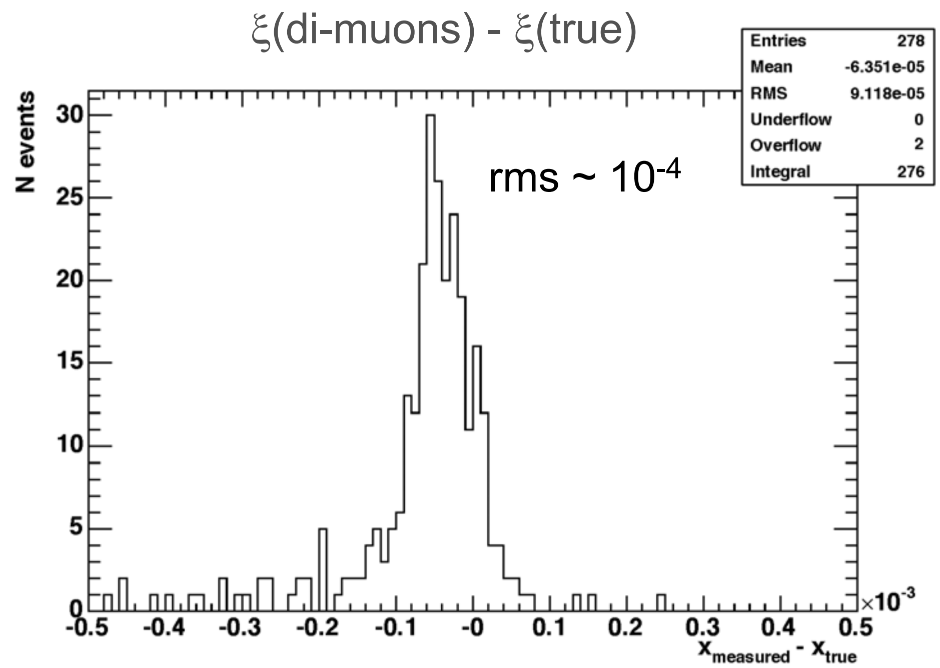
- At RHIC limited fragmentation can be explained by gluon saturation (Colour Glass Condensate) model.
  - Data PHOBOS 200, 130 and 62 GeV AuAu
  - Model McLerran-Venugopalan
- This can be measured also at LHC for larger gluon density region

Photon-mediated processes

$$p + p \rightarrow (p\gamma\gamma p) \rightarrow pl\bar{l}$$



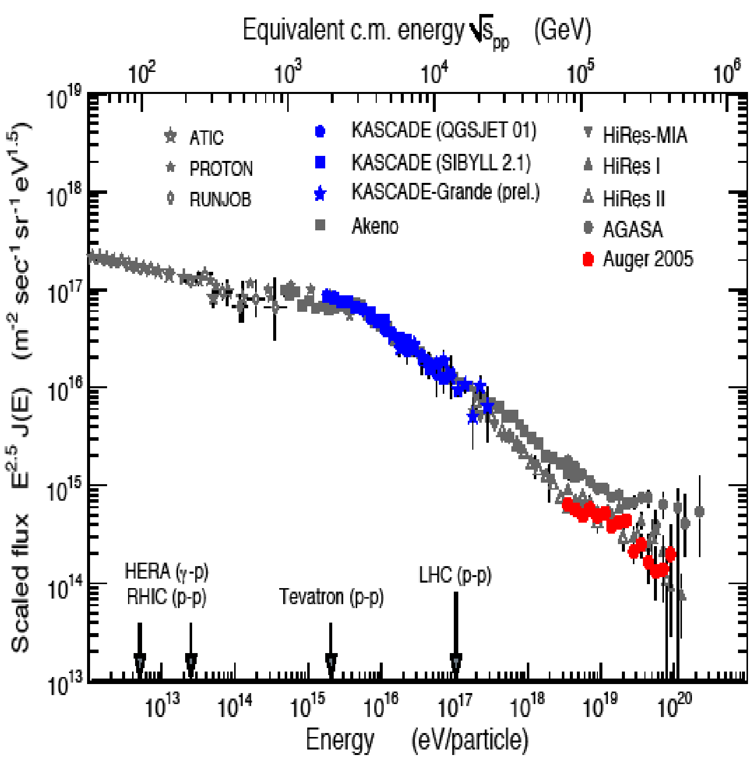
- QED theoretical cross section for this process is precisely known
- Reaction can then be used to calibrate the pp-luminosity provided that events can be identified above pile-up
- The calibration for the forward proton's energy measurement can be achieved
- Expect ~300 events/100 pb^{-1} after CMS muon trigger

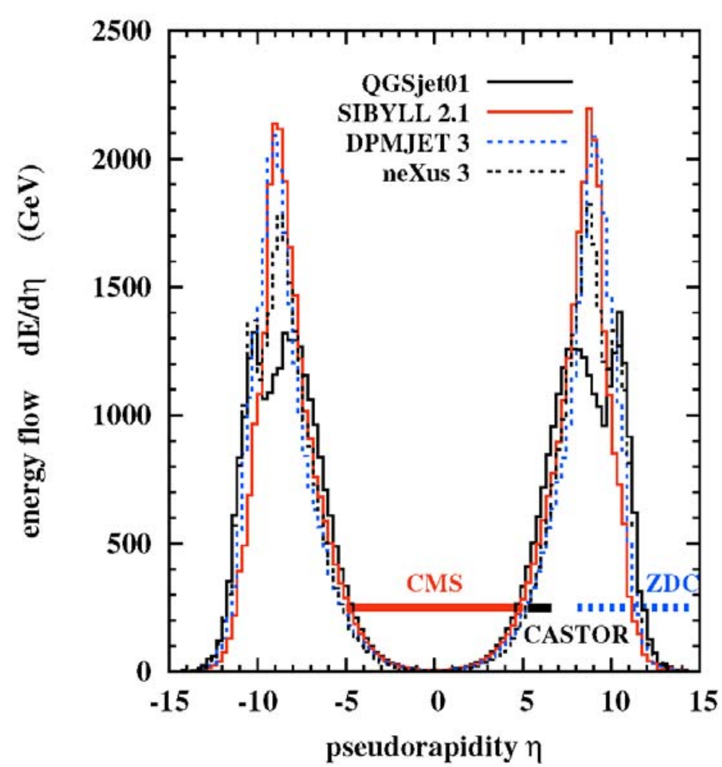


- Resolution of the reconstructed forward proton momentum using exclusive pairs in CMS
- Reconstruction of proton ξ values with resolution of 10^{-4}, i.e. smaller than beam dispersion

Validation of Hadronic Shower Models

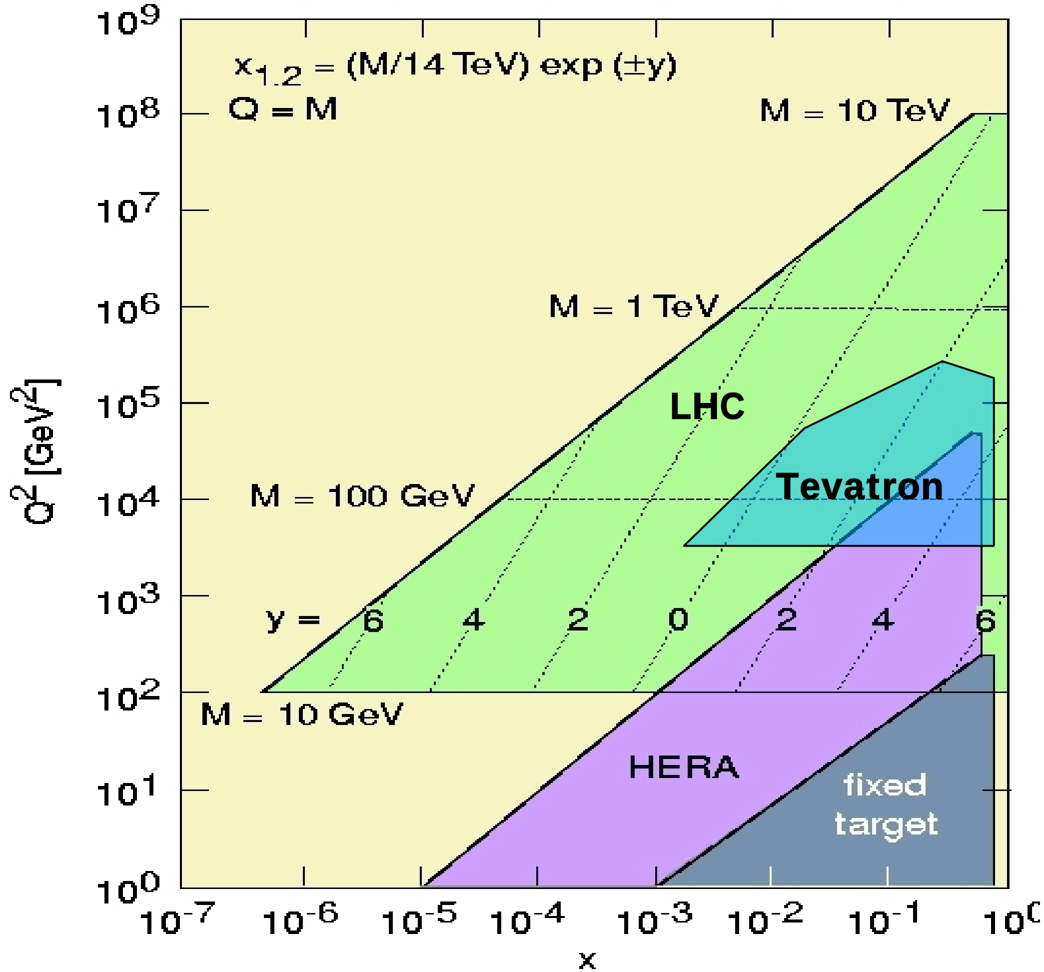
- Models for showers caused by primary cosmic rays differ substantially
- Fixed target collision in air with 100 PeV center-of-mass E corresponds to pp interaction at LHC
- Hence can tune shower models by comparing to measurements with T1/T2, CASTOR, ZDC





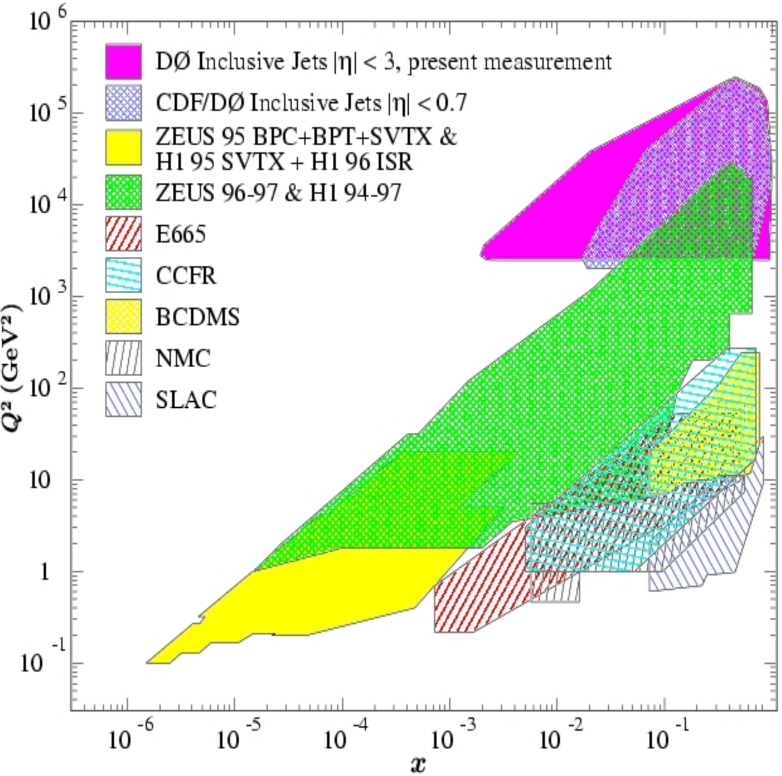
Final Notes

- CMS and Totem will carry out a joint program for physics
- The two experiments together will provide coverage in η unprecedented in a hadron collider.
- Will have the opportunity to review the diffractive physics program of the Tevatron, and probe the also unprecedented low-x physics provided by the LHC.

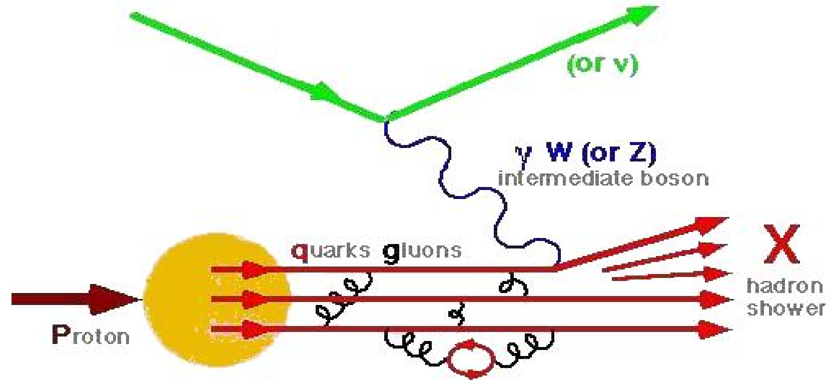


Based on Stirling's Eur. Phys. J. C 14, 133 (2000)

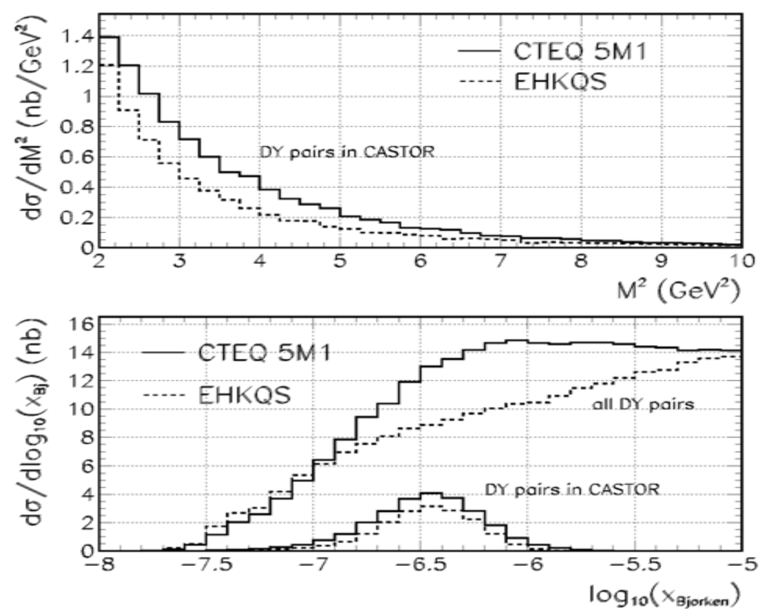
Backup Transparencies



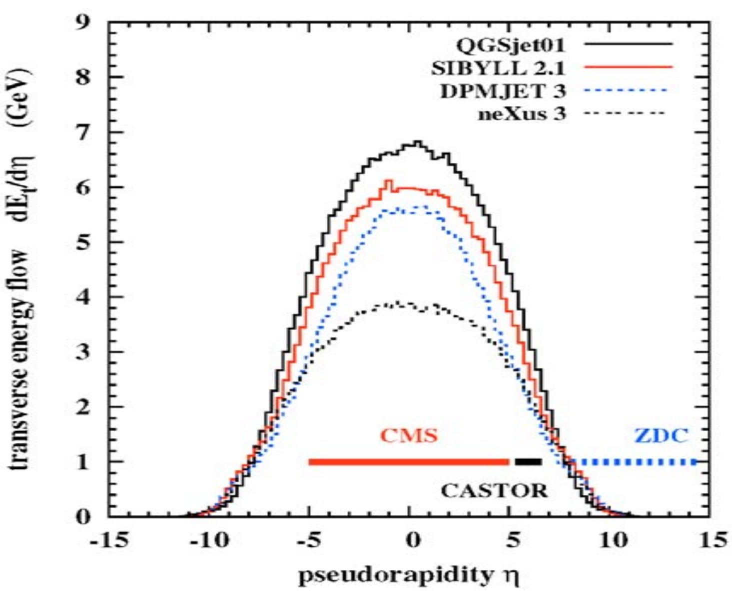
DØ Inclusive Jets |η| < 3, present measurement
CDF/DØ Inclusive Jets |η| < 0.7
ZEUS 95 BPC+BPT+SVTX &
H1 95 SVTX + H1 96 ISR
ZEUS 96-97 & H1 94-97
E665
CCFR
BCDMS
NMC
SLAC
Q² (GeV²)
x



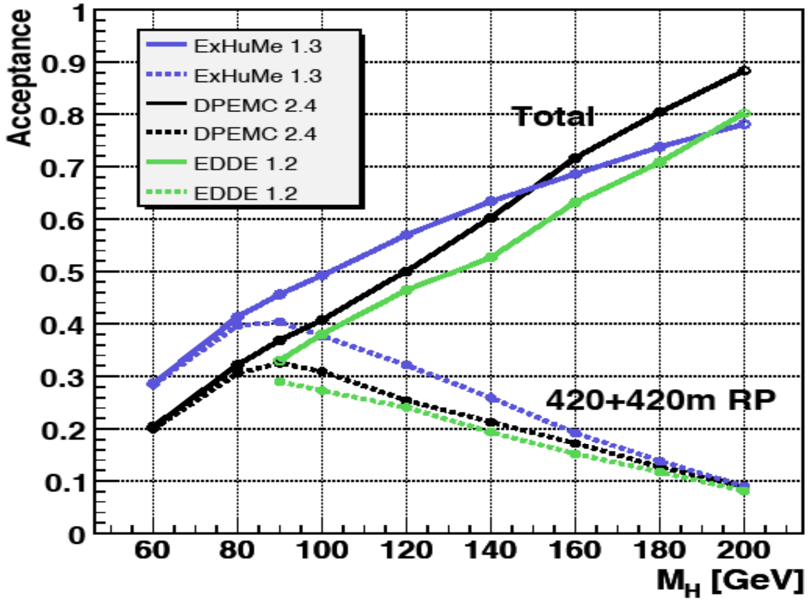
(or ν)
γ W (or Z)
intermediate boson
quarks gluons
Proton
X
hadron
shower



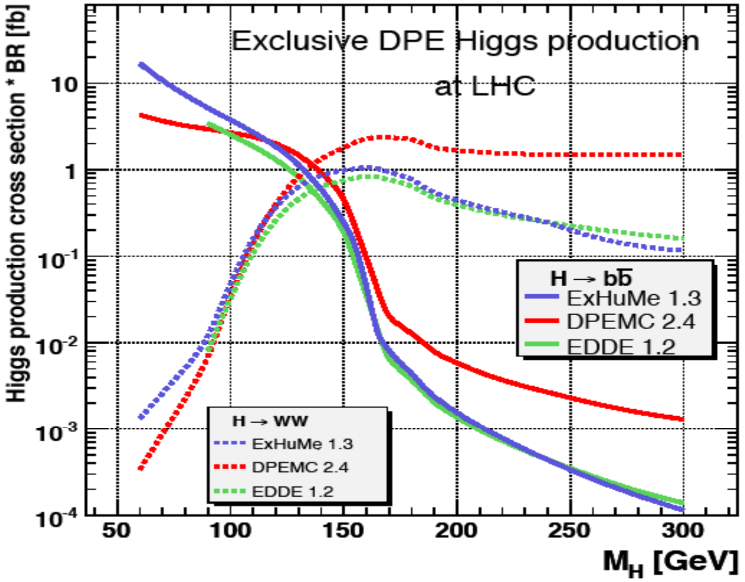
CTEQ 5M1
EHKQS
DY pairs in CASTOR
dσ/dM² (nb/GeV²)
M² (GeV²)
CTEQ 5M1
EHKQS
all DY pairs
DY pairs in CASTOR
dσ/dlog10(xBj) (nb)
log10(xBjorken)



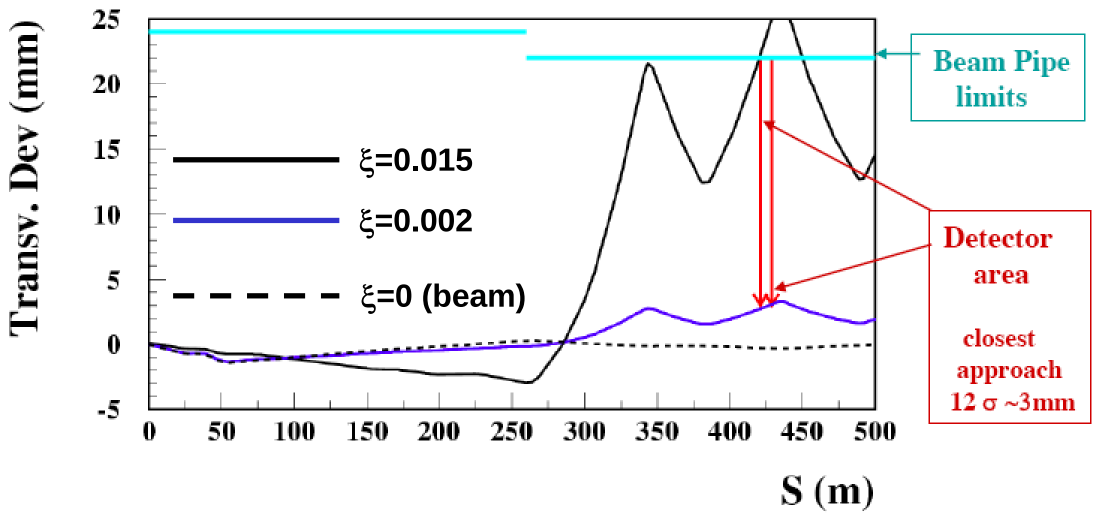
QGSjet01
SIBYLL 2.1
DPMJET 3
neXus 3
CMS
ZDC
CASTOR
transverse energy flow dEt/dη (GeV)
pseudorapidity η



Acceptance
ExHuMe 1.3
ExHuMe 1.3
DPEMC 2.4
DPEMC 2.4
EDDE 1.2
EDDE 1.2
Total
420+420m RP
M_H [GeV]



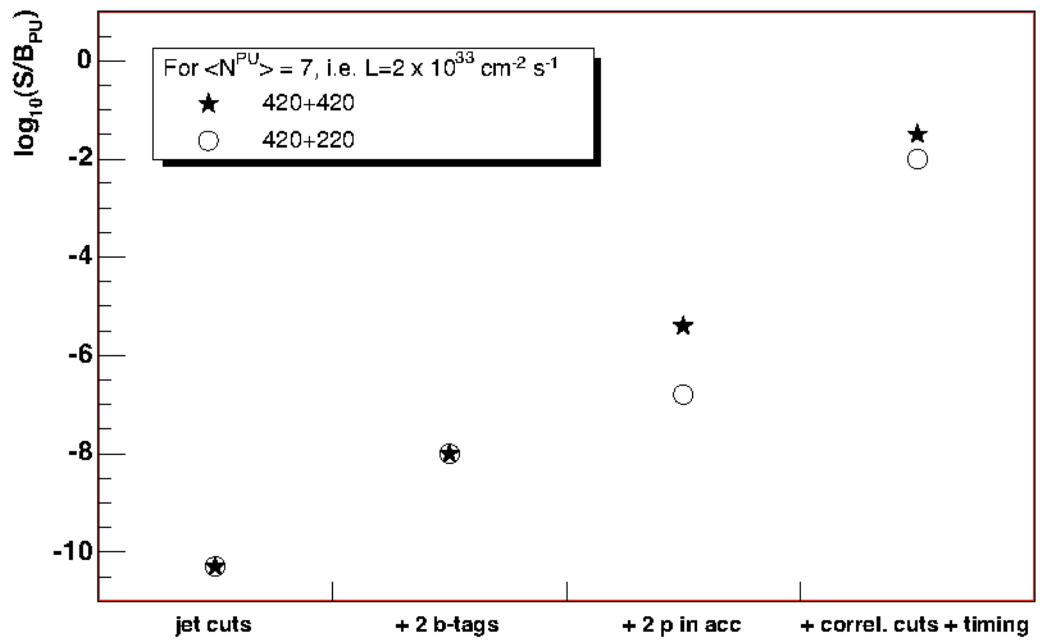
Exclusive DPE Higgs production
at LHC
Higgs production cross section * BR [fb]
H → bb̄
ExHuMe 1.3
DPEMC 2.4
EDDE 1.2
H → WW
ExHuMe 1.3
DPEMC 2.4
EDDE 1.2
M_H [GeV]



Transv. Dev (mm)
ξ=0.015
ξ=0.002
ξ=0 (beam)
Beam Pipe
limits
Detector
area
closest
approach
12 σ ~3mm
S (m)

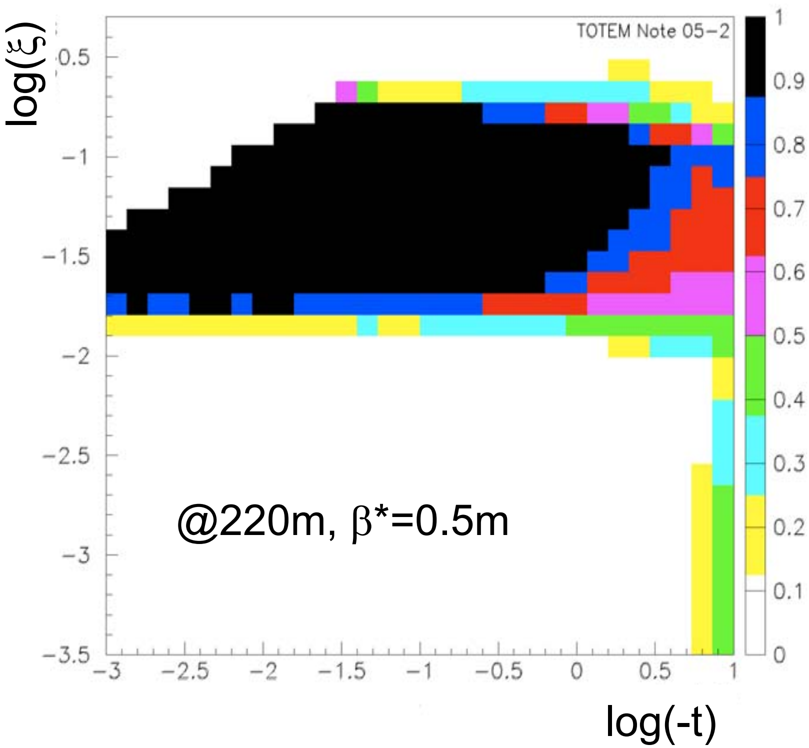
Example:
Central exclusive production
pp →p*H*p with *H* (120GeV) → bb

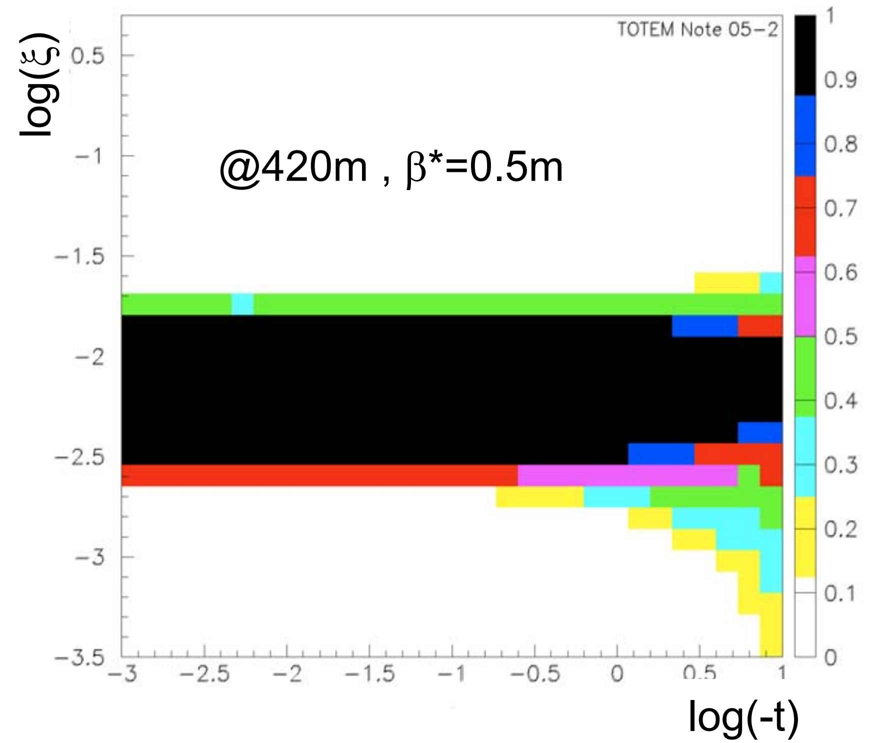
Selection cuts:
Jet cuts: >2 jets E_T>30/45 GeV
both jets b-tagged
2 protons in near-beam detectors,
either 220+420 or 420+420

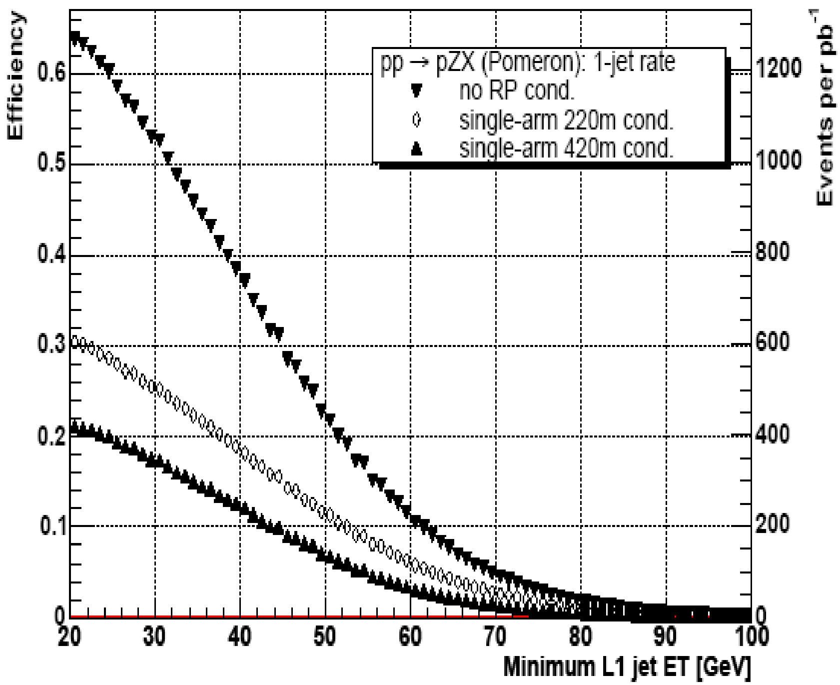


Leading Protons Acceptance

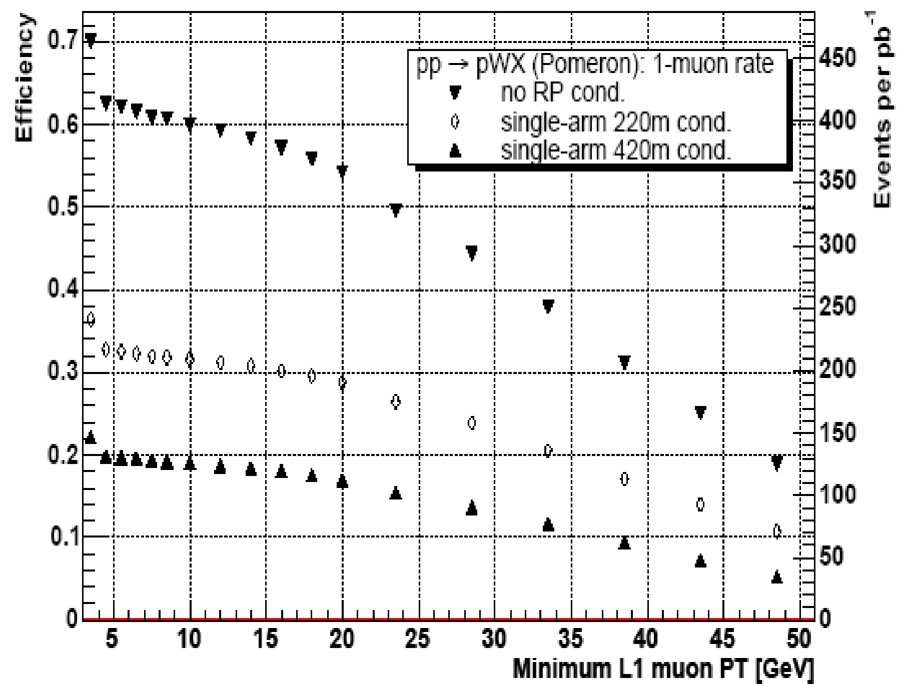
- Determined by tracking protons through the LHC accelerator lattice with the program MAD-X
- Smearing of both transverse vertex position and scattering angle at the IP according to transverse beam size and beam momentum divergence
- Assume that near-beam detectors are 100% efficient, i..e. assume all protons that reach 220/420m location outside of cutout for beam (1.3mm @220m, 4mm @420m) are detected







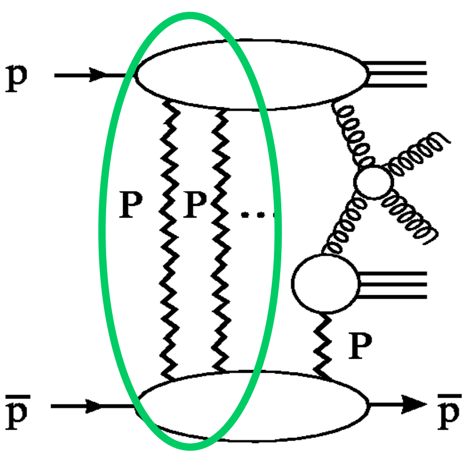
pp → pZX (Pomeron): 1-jet rate
no RP cond.
single-arm 220m cond.
single-arm 420m cond.
Efficiency
Events per pb⁻¹
Minimum L1 jet ET [GeV]



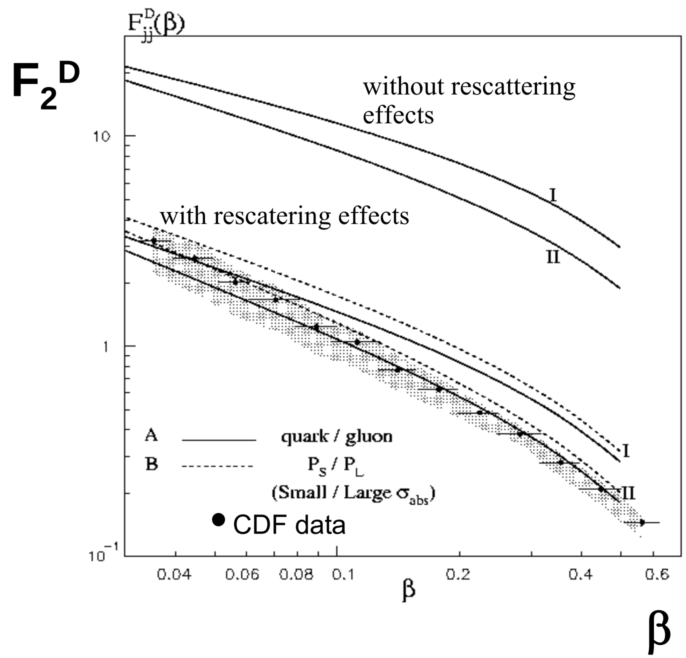
pp → pWX (Pomeron): 1-muon rate
no RP cond.
single-arm 220m cond.
single-arm 420m cond.
Efficiency
Events per pb⁻¹
Minimum L1 muon PT [GeV]

Rapidity gap survival probability

- Proton and anti-proton are large objects, unlike pointlike virtual photon
- In addition to hard diffractive scattering, there may be soft interactions among spectator partons. They fill the rapidity gap and slow down the outgoing protons hence reduce the rate of diffractive events.
- Quantified by rapidity gap survival probability.



Kaidalov, Khoze, Martin, Ryskin (2000)



Predictions based HERA diffractive PDFs

Beam Halo Background

- T1 and T2 → beam gas interactiosn + small muaon halo (rough calculation leads to an average suppresion factor of .6)
- Roman Pts→ Beam halo, beam gas, pp background by inellastic pp colission in IP5
- Reliable estimations at this point of machine background are very difficult, and with large uncertainties.

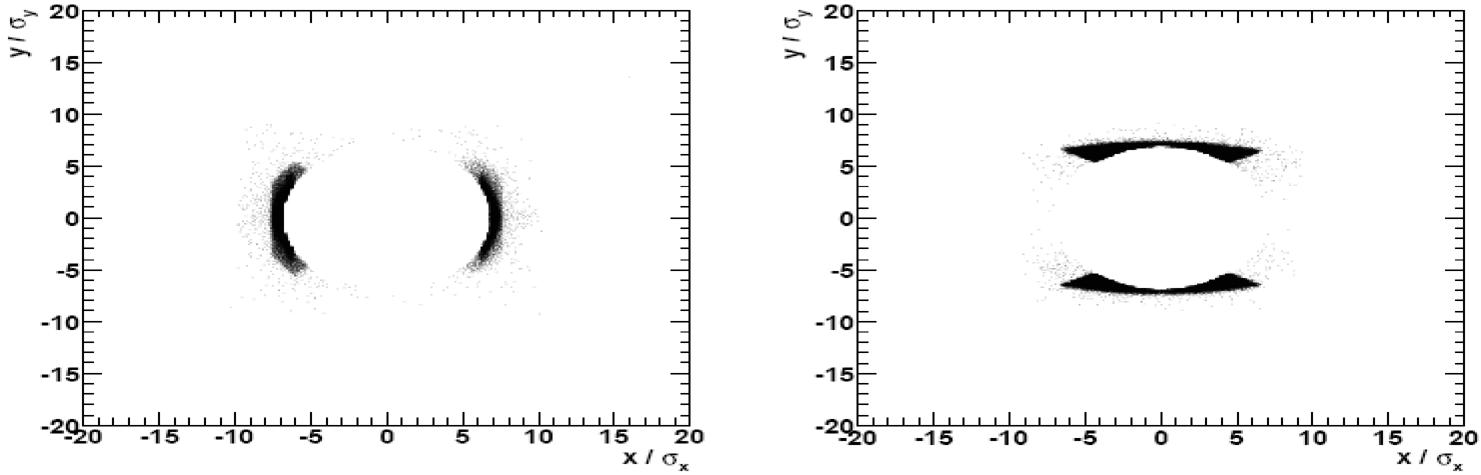


Figure 4.1: Beam-halo profiles for $\beta^* = 0.5\,\mathrm{m}$ at 220 m for horizontal and vertical proton losses. The coordinates are normalised by the beam width.

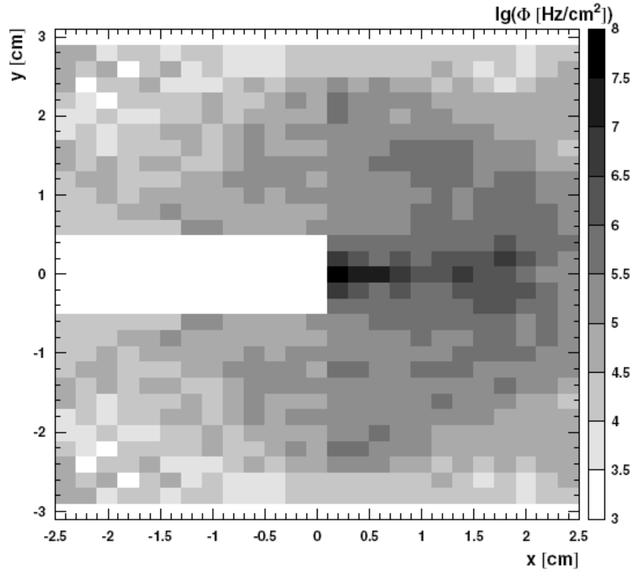


Figure 4.4: Map of the flux of charged hadrons (adapted from [81]) over an area correspond-
ing approximately to the RP d

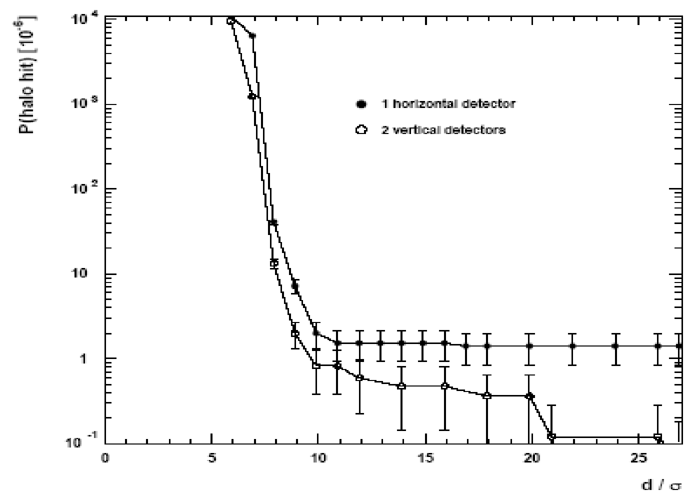


Figure 4.2: Halo hit probability per lost proton for the horizontal and the vertical detectors in the RP station at 220 m, evaluated for $\beta^* = 0.5$ m and not expected to depend strongly on the optics until availability of more simulation results. To obtain the halo hit rate, these numbers have to be multiplied by f_{loss} in Table 4.3.

Background due to central exclusive production on bbar jets and inclusive DPE dijets

In order to quantify the S/B ratio in the region of interest, we define mass windows and consider the 420+420 and the 220+420 configurations separately, since the mass resolution is different in the two cases. So for $M_H = 120$ GeV, where the resolutions are about 1.6% and 5.6%, respectively, the mass windows chosen are 4 and 10 GeV.

Table 7.2: Cross section and event yield for 30 fb^{-1}. For the signal, $H \to b\bar{b}$, ExHuME 1.3.1 was used. The first of the two background numbers corresponds to $pp \to pb\bar{b}p$, the second to $pp \to pjjXp$, obtained with DPEMC with the Cox and Forshaw model.

M_H[GeV]	σ^S[fb]	$N^S_{ev}/N^B_{ev}(\Delta M)$	
		420+420	220+420
120	1.87	0.6/(1+6)	0.9/(8+8)

- The contribution from inclusive DPE dijets has a significant theoretical uncertainty.
- The b-tag requirement will be important for suppressing the pp→pjjXp background, it provides a large reduction factor (~500)