

Prospects for diffractive and forward physics at the LHC: Standard optics running



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Carry out a program of diffractive and forward physics as integral part of the routine data taking at the LHC, i.e. at nominal beam optics and up to the highest available luminosities.

Shorter term aspects:
CMS program for the 2008 LHC running



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

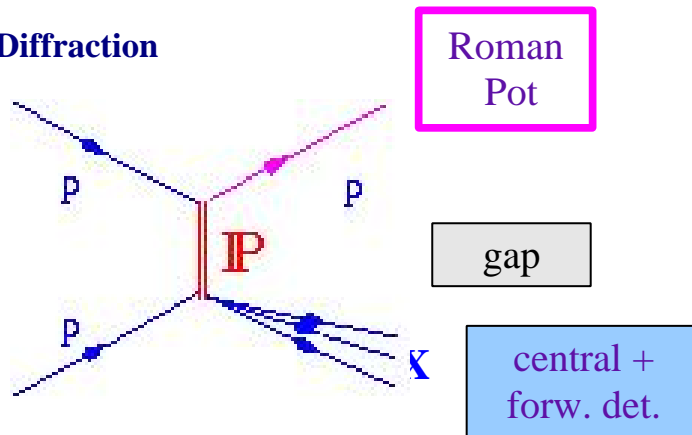
Prospects for
Diffractive
and Forward Physics
at the LHC

The CMS and TOTEM
diffractive and forward physics
working group

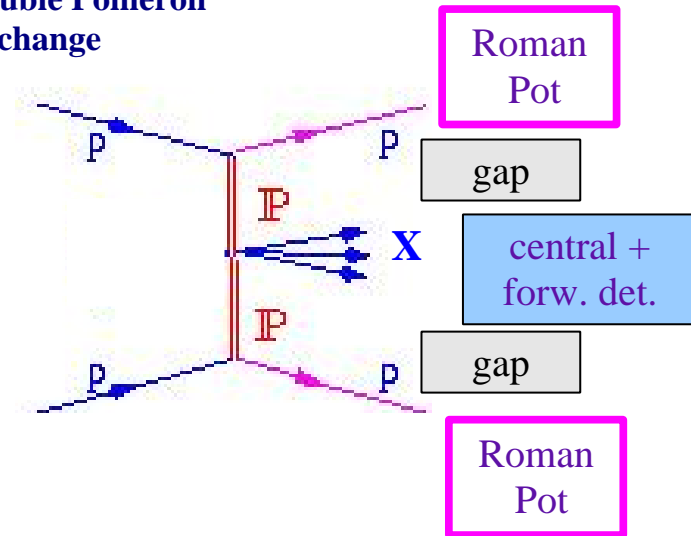
Program on diffractive and forward physics

1. Diffraction

Single Diffraction



Double Pomeron Exchange



X=anything : dominated by soft physics

- Measure fundamental quantities of soft QCD:
SD and DPE inclusive cross sections, their s , t , M_X dependences are fundamental parameters of non-perturbative QCD.
- Contributes to the pile up.

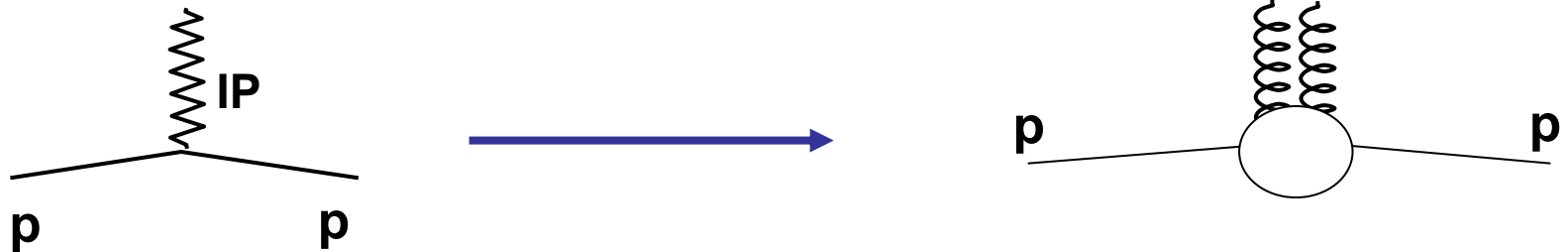
see previous talk,
by K. Osterberg

X includes jets, W's, Z's, Higgs (!): hard processes calculable in pQCD

- Give info on proton structure (dPDFs and GPDs), QCD at high parton densities, multi-parton interactions, discovery physics

Diffraction ? - A way to probe the proton

In diffractive events look at the proton constituents through a lens that filters out all parton combinations except those with the vacuum quantum numbers



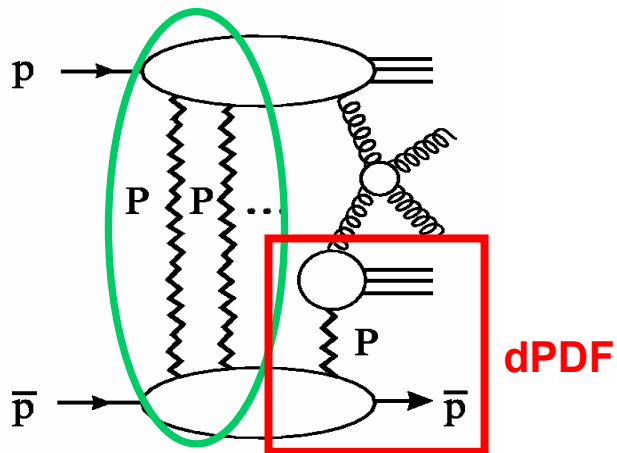
**2-gluon exchange:
LO realisation of vacuum
quantum numbers in QCD**

- Tool to investigate low- x partons through diffractive PDFs and generalized parton densities (GPDs)
- Window on QCD at high parton densities (saturation, AA)
- Diffractive production may be a discovery channel for a light Higgs boson

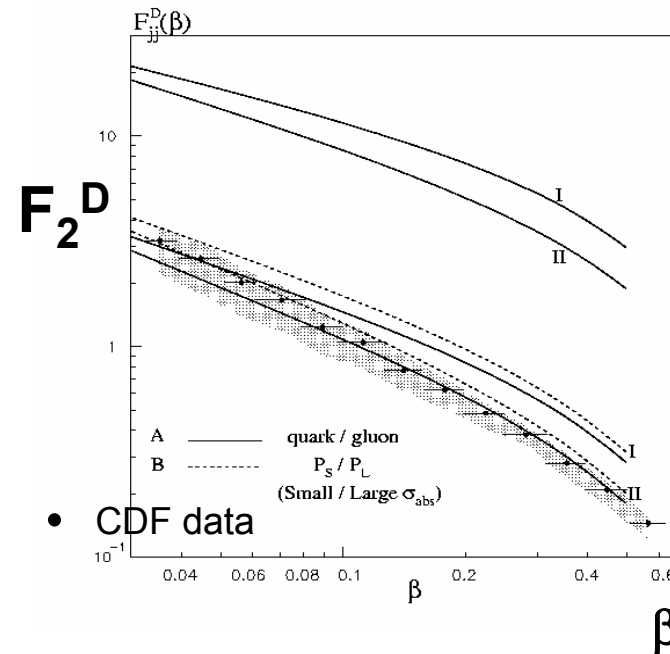
Program on diffractive and forward physics

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.
 - Fill rapidity gap & slow down outgoing protons → Hence reduce the rate of diffractive events.
- Quantified by **rapidity gap survival probability**.



Closely related to the underlying event at the LHC



without and with rescattering effects

Predictions based on HERA diffractive PDFs

Experimental issues in selecting diffractive events at the LHC

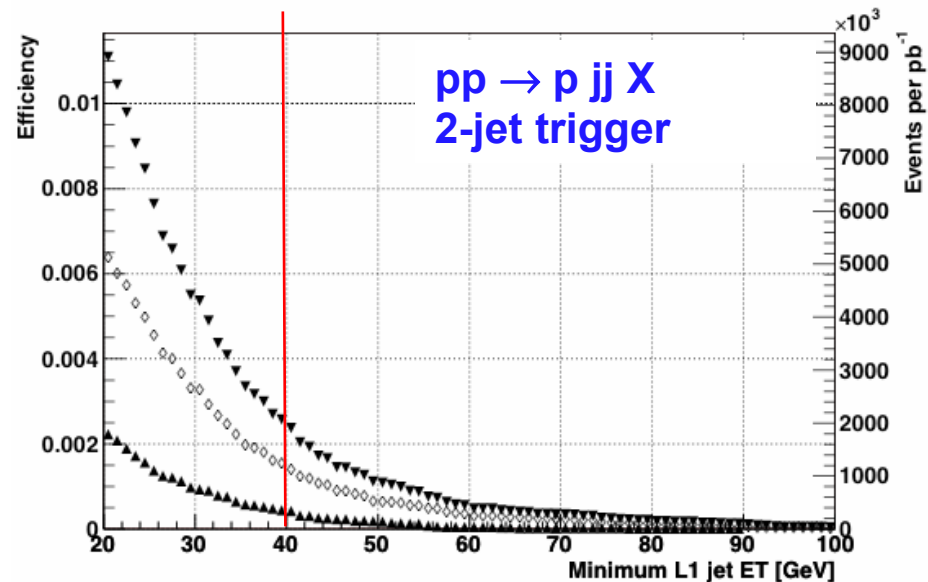
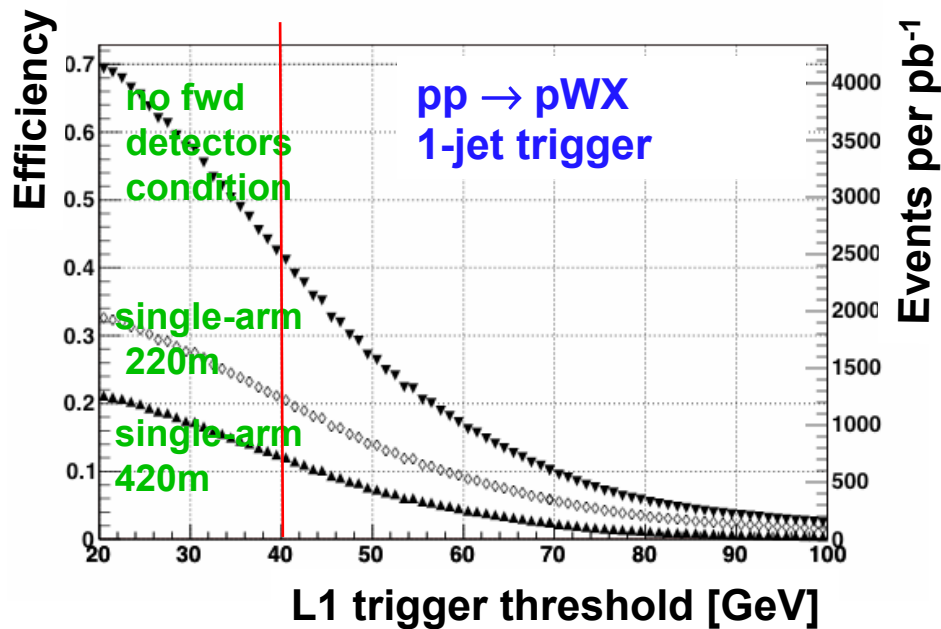
1. **Trigger** is a major limiting factor for selecting diffractive events
2. Background from non-diffractive events that mimic diffractive events because of **protons from pile-up events**

Exercised these issues at a number of exemplary processes

Note: Took into account as an option also near-beam detectors at 420 m from the IP
(R&D project)

“Prospects for diff and fwd physics at the LHC” - Part I: Diffractive part

Trigger (I)



Attention: Gap survival probability not taken into account
 Normalized to number of events with $0.001 < \xi < 0.2$
 for proton and, in 2-jet case, with jets with $p_T > 10 GeV$

At $2 \times 10^{33} cm^{-1} s^{-1}$ without any additional condition on fwd detectors:

L1 1-jet trigger threshold $O(150 GeV)$

L1 2-jet trigger threshold $O(100 GeV)$

“Prospects for diff and fwd physics at the LHC” - Part I: Diffractive part

Trigger (II)

- CMS trigger thresholds for nominal LHC running too high for diffractive events
- Use information of forward detectors to lower in particular CMS jet trigger thresholds
- The CMS trigger menus now foresee a **dedicated diffractive trigger stream with 1% of the total bandwidth on L1 and HLT** (1 kHz and 1 Hz)

Lumi nosity [cm ⁻² s ⁻¹]	# Pile-up events per bunch crossing	L1 2-jet rate [kHz] for $E_T > 40\text{GeV}$ per jet	Total reduc tion needed	Reduction when requiring track in RP detectors	
				at 220 m $\xi < 0.1$	
1×10^{32}	0	2.6	2	370	
1×10^{33}	3.5	26	20	7	15
2×10^{33}	7	52	40	4	10

**single-sided
220m condition
without and with
cut on ξ**

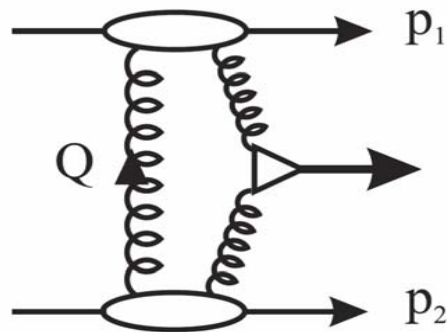
Achievable total reduction: 10 (single-sided 220m) x 2 (jet iso) x 2 (2 jets same hemisphere as p) = 40

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 $2 \times 10^{33} \text{ cm}^{-1} \text{ s}^{-1}$

Much less of a problem is triggering with muons, where L1 threshold for 2-muons is 3 GeV

“Prospects for diff and fwd physics at the LHC” - Part I: Diffractive part Trigger (III)

Central exclusive production $pp \rightarrow pHp$ with $H(120\text{GeV}) \rightarrow bb$



- In non-diffractive production hopeless, signal swamped with QCD dijet background
- Selection rule in CEP (central system is $J^{PC} = 0^{++}$ to good approx) improves S/B for SM Higgs dramatically
- In certain MSSM scenarios the signal cross section is three order of magnitude higher than for the SM case

Trigger is a major limiting factor !

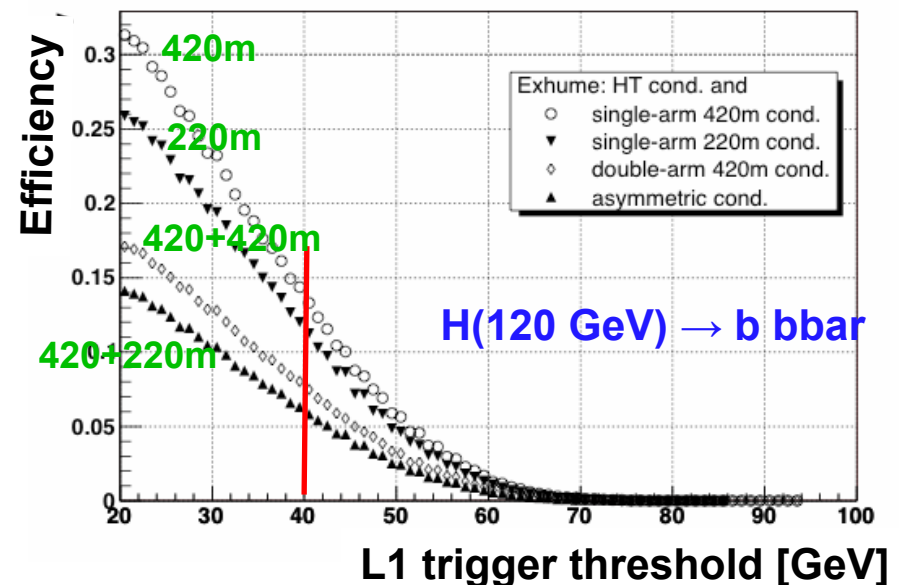
Level-1:

~12% efficiency with 2-jets ($E_T > 40\text{GeV}$) & single-sided 220 m condition

HLT: Jet trigger efficiency ~7%

To stay within 1 Hz output rate, needs to either prescale b-tag or add 420 m detectors in trigger

Additional ~10% efficiency by introducing a 1 jet & 1 μ (40GeV, 3GeV) trigger condition



Pile-up background

Number of PU events with protons within acceptance of near-beam detectors on either side:

~2 % with p @ 420m

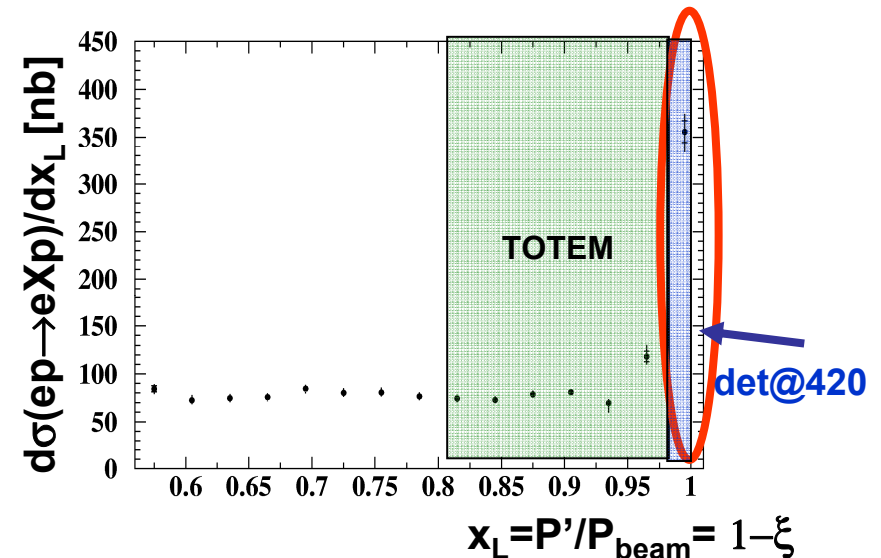
~6 % with p @ 220m

Translates into a probability of obtaining a fake DPE signature caused by protons from PU:

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

Eg at $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ 10% of any signal event one wants to select have a fake DPE signature
This is independent of the type of signal.

Depends critically on the leading proton spectrum at the LHC which in turn depends on size of soft rescattering effects (rapidity gap survival factor) !



Pile-up background (II)

Can be reduced by:

Requiring correlation between ξ , M measured in the central detector and ξ , M measured by the near-beam detectors

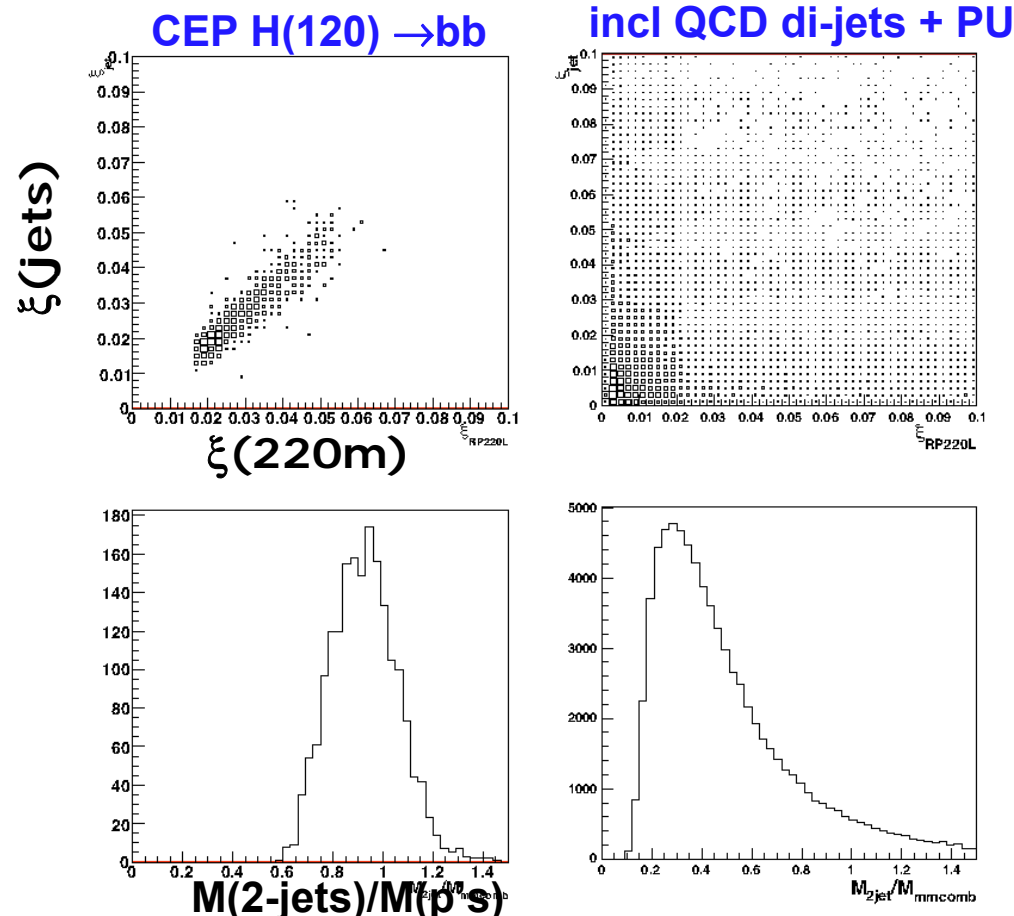
Fast timing detectors that can determine whether the protons seen in the near-beam detector came from the same vertex as the hard scatter (currently R&D project)

$$\xi_{1,2} = \frac{1}{\sqrt{s}} \sum_{\text{particles}} E_T e^{\pm\eta} \quad ; \quad \xi_1 \xi_2 s = M^2$$

CEP of **H(120 GeV) → b bbar**:

Possible to retain O(10%) of signal up to $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ in a special forward detectors trigger stream

S/B in excess of unity for a SM Higgs and up to 1000 for a MSSM Higgs appears achievable



2. Forward physics

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

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 condensate

Photon-photon and photon-proton physics:

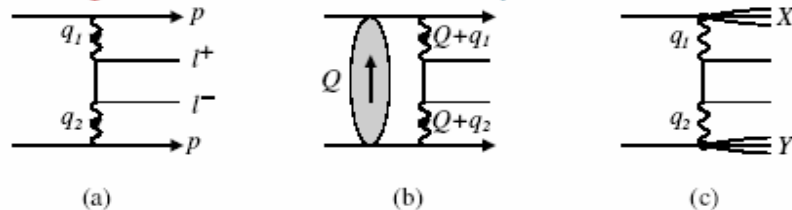
Also there protons emerge from collision intact and with very low momentum loss

Multiple connection points to other areas in High-Energy-Physics !

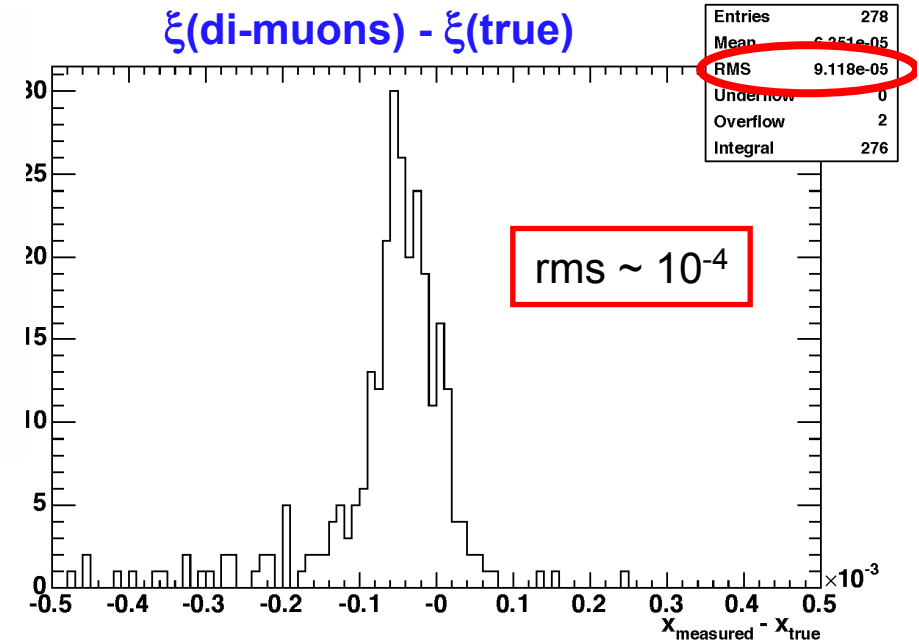
Photon-mediated processes: Exclusive $\mu\mu$ production

- QED process (a) production σ precisely known

event generator LPAIR based on ME by Vermaseren



- Hadronic corrections [(b) (c)] small.

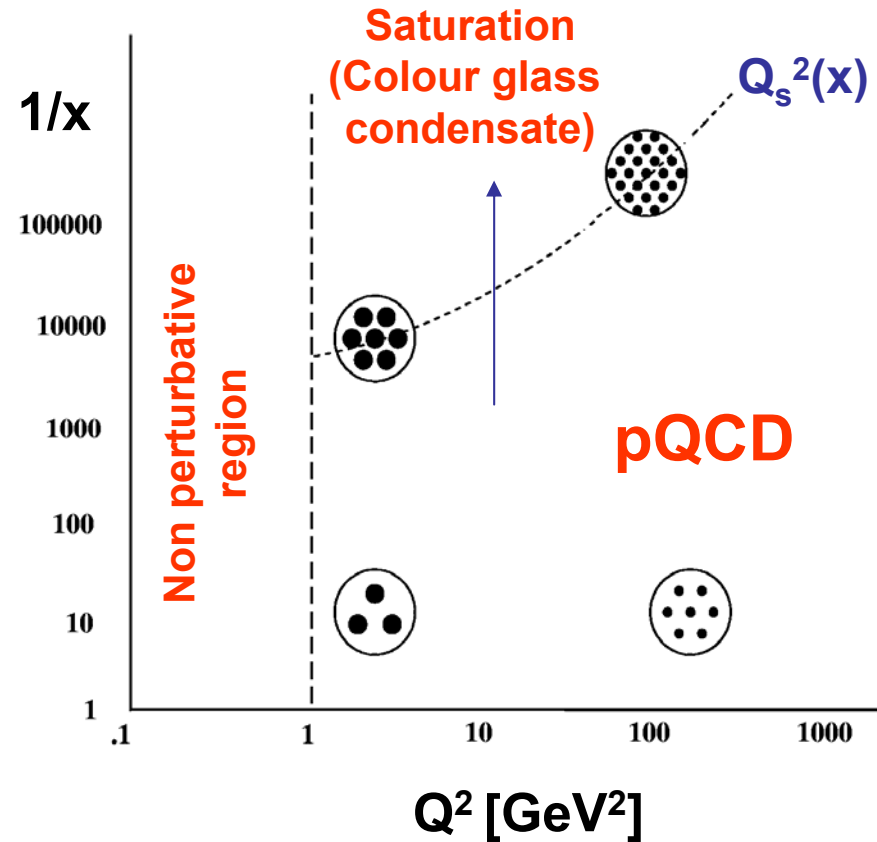


- **Calibration process** both for luminosity and energy scales of near-beam detectors
- Striking signature: acoplanarity angle between leptons
- Allows reco of proton ξ values with resolution of 10^{-4} , i.e. smaller than beam dispersion
- Expect ~ 300 events/100 pb $^{-1}$ after CMS muon trigger

Low-x QCD

- When $x \rightarrow 0$ at $Q^2 >$ a few GeV^2 DGLAP predicts steep rise of parton densities
- At small enough x , this violates unitarity
- Growth is tamed by gluon fusion: saturation of parton densities at $Q^2 = Q_s^2(x)$

So far not observed in pp interactions

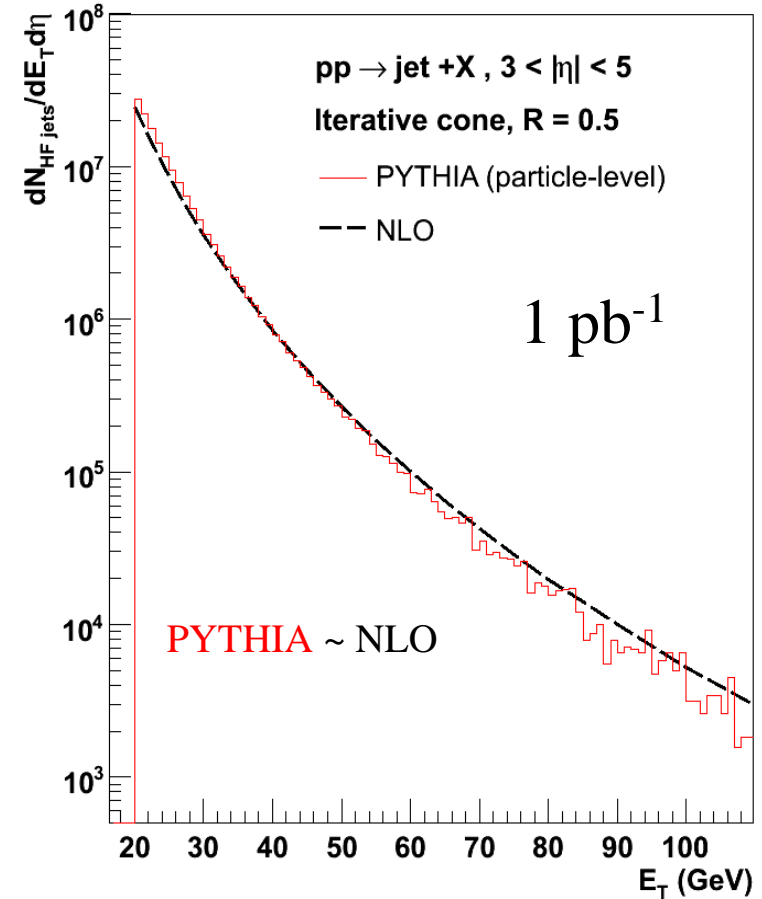
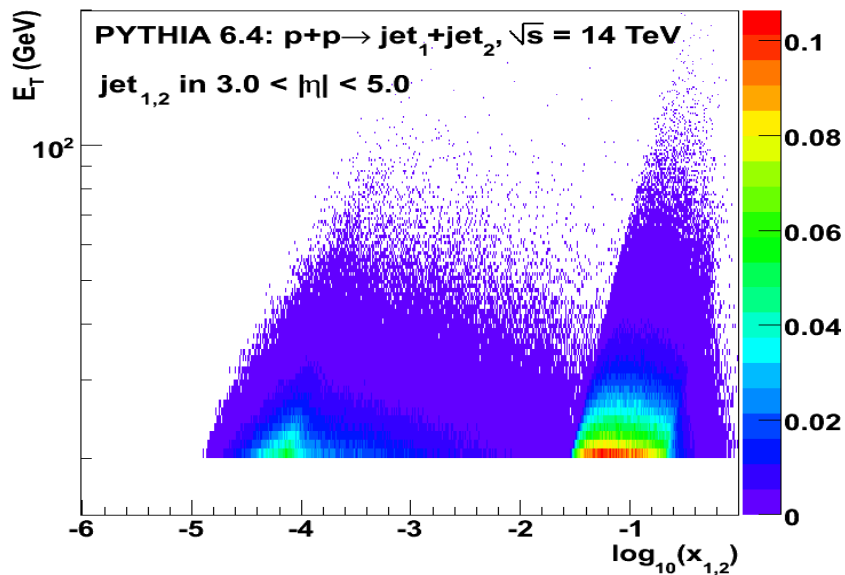


Low-x QCD: Forward jets

Inclusive forward “low- E_T ” jet
($E_T \sim 20-100$ GeV) production:

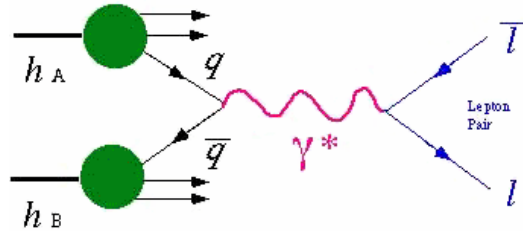
$$p + p \rightarrow jet1 + jet2 + X$$

Sensitive to gluons with: $x_2 \sim 10^{-4}$, $x_1 \sim 10^{-1}$



Large expected yields ($\sim 10^7$ at ~ 20 GeV) !

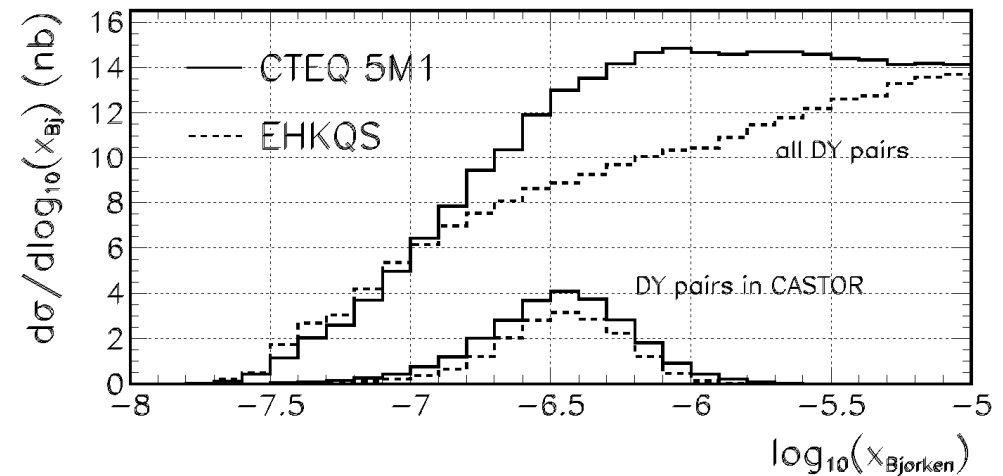
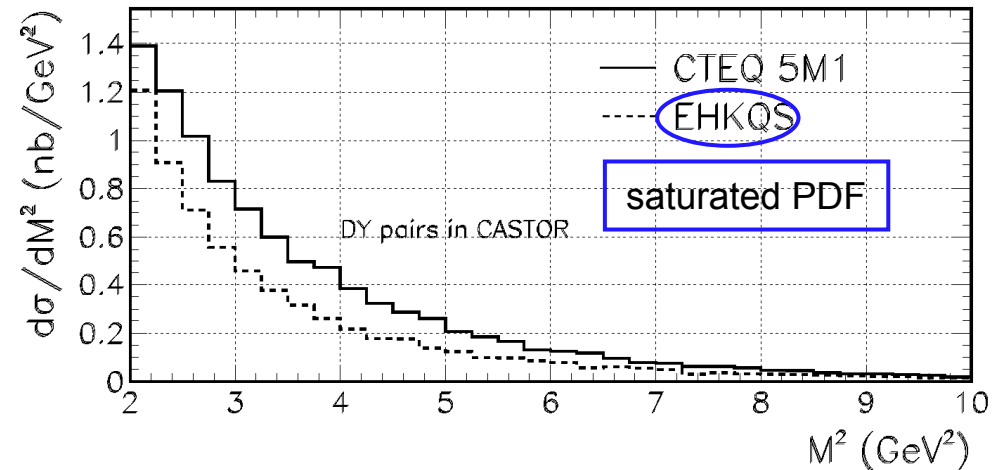
Low-x QCD: Forward Drell-Yan



Gives access to low- x_{BJ} quarks in proton in case of large imbalance of fractional momenta $x_{1,2}$ of electrons, which are then boosted to large rapidities

→ CASTOR with $5.3 \leq |\eta| \leq 6.6$ gives access to $x_{BJ} \sim 10^{-7}$

→ Measure angle of electrons with T2

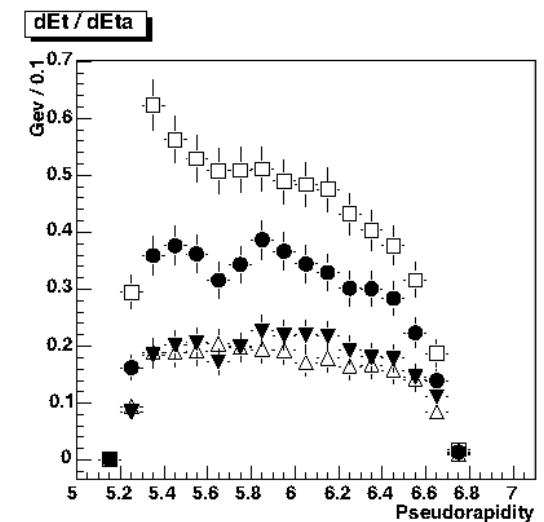
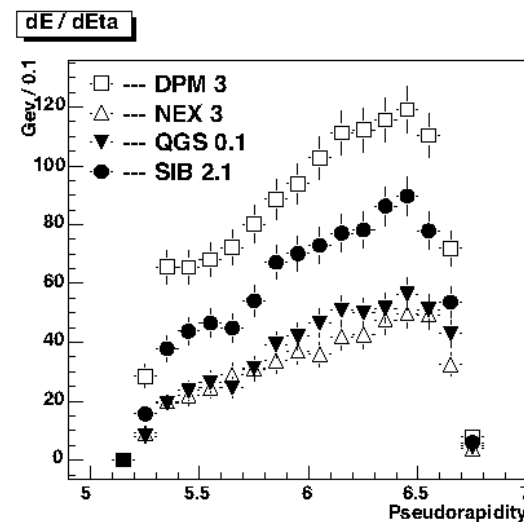
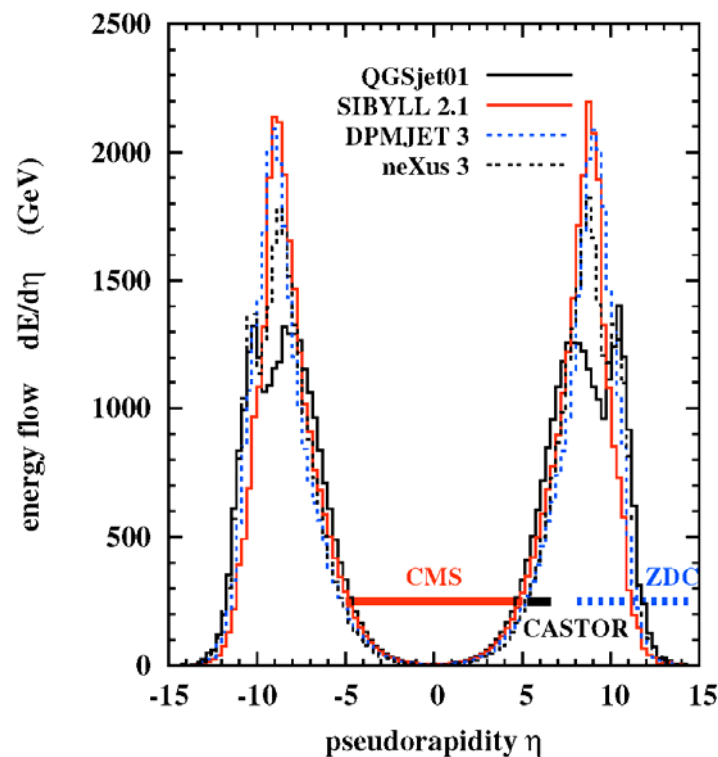


DY pairs suppressed in saturated PDF

“Prospects for diff and fwd physics at the LHC” - Part 2: “Forward physics” part

Validation of hadronic shower models in 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 shower models by comparing to measurements with T1/T2, CASTOR, ZDC



see also multiplicity plots in K.Osterberg's talk

Conclusions I

Low Luminosity ($\leq 10^{32} \text{ cm}^{-2}\text{s}^{-1}$): low & high β^*

- Measure inclusive SD and DPE cross sections and t , M_x dependence
- Rapidity Gap selection possible

- Muller-Navelet dijets
- Forward Drell-Yan
- Validation of Cosmic Ray generators

High Luminosity ($> 10^{32} \text{ cm}^{-2}\text{s}^{-1}$): low β^*

- Measure SD and DPE in presence of hard scale (dijets, vector bosons, heavy quarks): dPDF, GPD

- $\gamma\gamma$ and γp physics

Highest Luminosity ($> 10^{33} \text{ cm}^{-2}\text{s}^{-1}$): low β^*

- Discovery physics in central exclusive production (SM or MSSM Higgs, other exotic processes)

The CMS and TOTEM collaborations intend to carry out a joint diffractive and forward physics program with an unprecedented rapidity coverage. The document outlines some aspects of this physics program.

The document addresses, for the first time at the LHC, the central experimental issues in measuring fwd and diffractive physics by way of a number of exemplary processes

A worthwhile program !

CMS Program for the 2008 LHC running

First analyses of the 2008 data will have to be based on **large rapidity gap (LRG) selection**. Even if Totem RP detectors at 220m are available, need time to understand them (alignment !)
Hence: For 2008 first concentrate on those data samples for which pile-up is negligible.

The program:

Measurement of the ratio of events with LRG and a hard scale (W, Z, dijets, heavy quarks) at 14TeV

Measurement of rapidity gap survival probability from SD and DPE dijet events at 14TeV

“Rediscover” hard diffraction at the LHC

Measurement of the ratio of di-jet events with a LRG between the two jets

Study of the underlying event in diffractive topologies

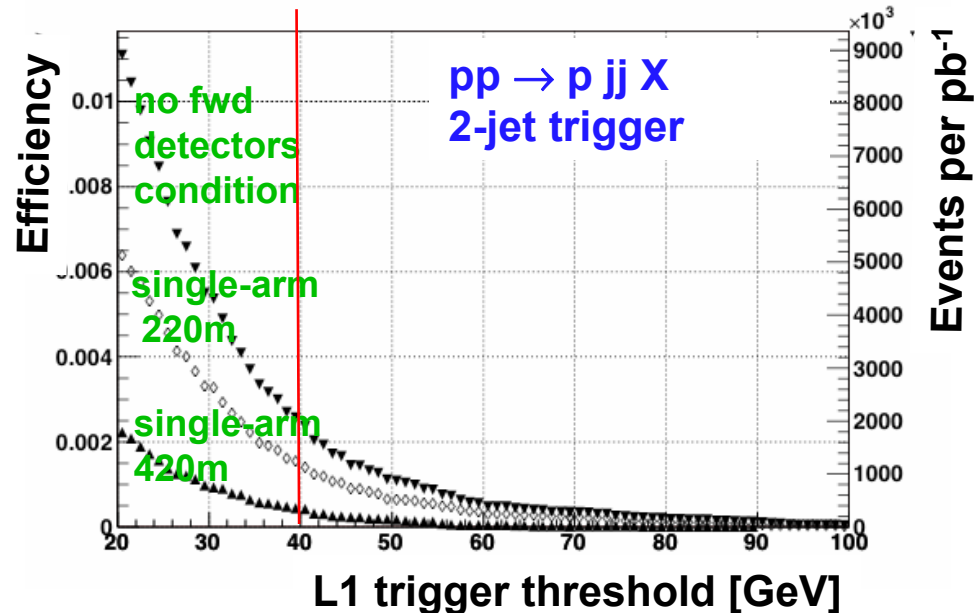
Measurement of forward energy flow and multiplicities(CASTOR, ZDC, possibly T1, T2)

Measurements of forward jets and forward Drell-Yan electrons

Study of gamma-gamma and gamma-proton interactions

CMS Program for the 2008 LHC running (II)

In order to make a LRG-based program possible, need to work on **rap gap trigger** with forward detectors (HF, CASTOR, ZDC)



Combination of 2-jet trigger with condition on fwd detectors allows to lower jet thresholds substantially while still staying within the trigger bandwidth limits

Need to establish how much thresholds can be lowered in combination with LRG condition instead

With thresholds at 40 GeV:

$O(10^6)$ $pp \rightarrow p jj X$ events in 100 pb^{-1} data

Exciting times ahead !

Grand summary:

Carry out a forward and diffractive physics program as integral part of the routine data taking at the LHC, with nominal LHC optics and up to the highest possible luminosities. This program spans the full lifetime of the LHC.

→ At the lowest luminosities, fundamental aspects of soft QCD can be studied via inclusive single diffraction and inclusive double Pomeron exchange.

→ With increasing luminosity, diffraction in the presence of a hard scale comes into reach and will render possible the investigation of fundamental aspects of the proton structure.

→ At the highest LHC luminosities, central exclusive production (i.e. double Pomeron exchange) may become a tool for the discovery of a Higgs Boson with mass close to the current exclusion limit, an area that poses a special challenge to the LHC experiments.

Map to diffraction and fwd physics in CMS

Low lumi

Rapidity gap selection possible
HF, Castor, BSCs, T1, T2
Proton tag selection optional
RPs at 220m and 420 m

Diffraction is about 1/4 of σ_{tot}
High cross section processes

“Soft” diffraction

Interesting for start-up running
Important for understanding pile-up

Low lumi

High lumi

No Rapidity gap selection possible
Proton tag selection indispensable
RPs at 220m and 420 m

Central exclusive production

Discovery physics:

Light SM Higgs
MSSM Higgs
Extra dimensions

High lumi

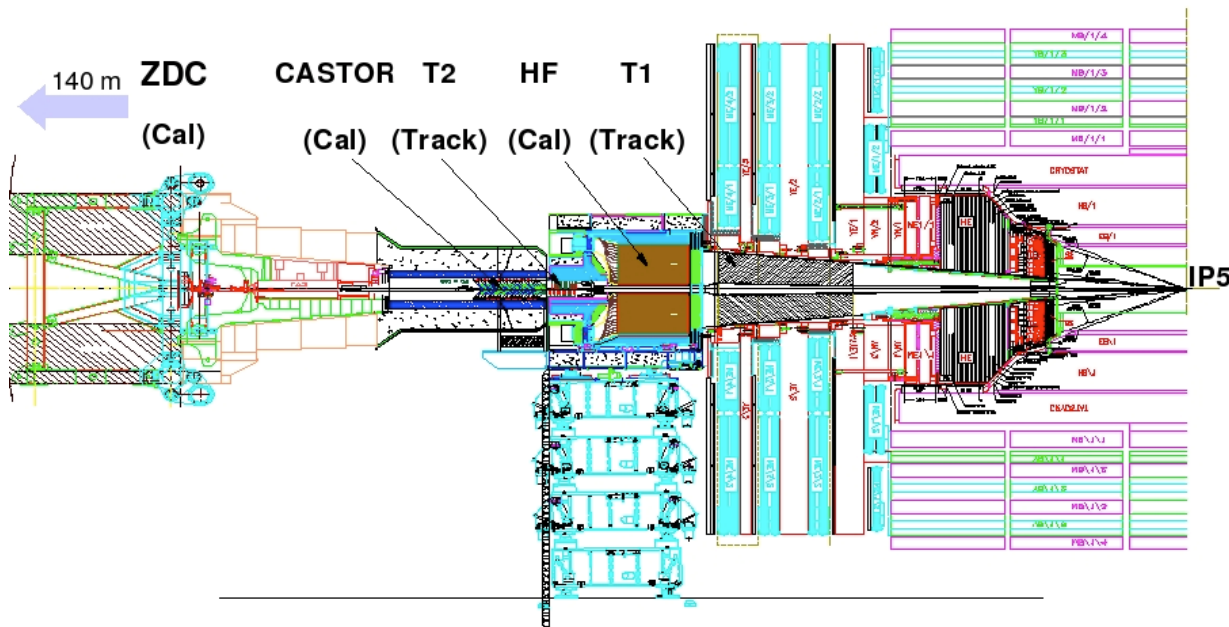
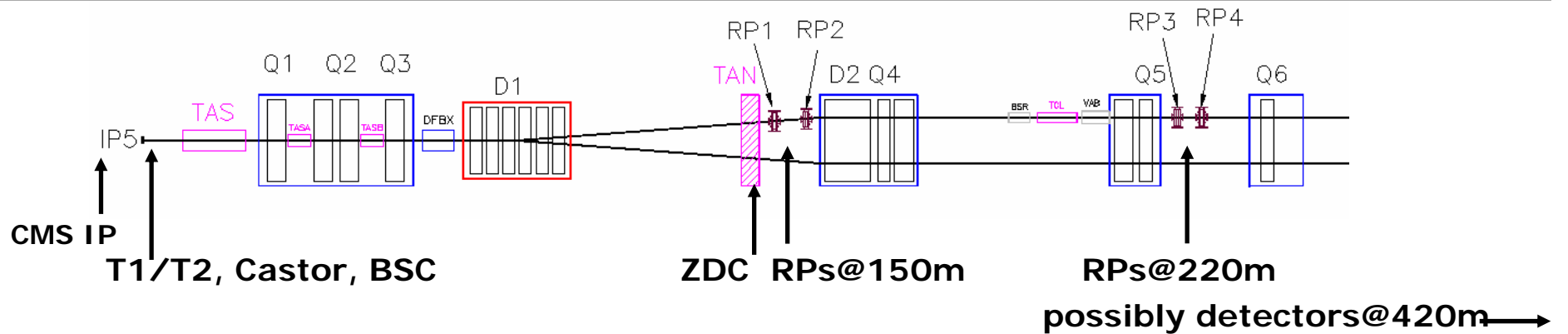
Gamma-gamma and gamma-proton interactions
Forward energy flow - input to cosmic shower simulation
QCD: Diffraction in presence of hard scale
Low-x structure of the proton
High-density regime (Color glass condensate)
Diff PDFs and generalized PDFs
Diffractive Drell-Yan

CMS alone

CMS with Totem and/or FP420

BACKUP

CMS + TOTEM: Unprecedented Coverage in η

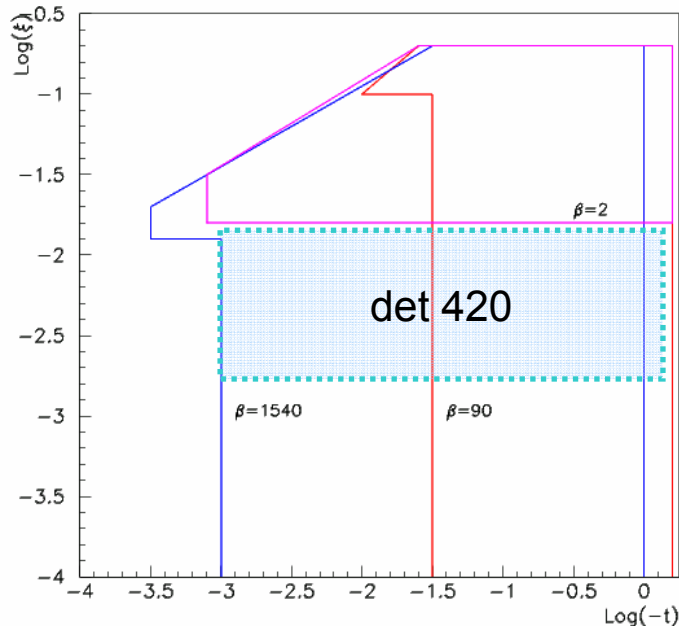


T1 (CSC) $3.1 \leq |\eta| \leq 4.7$
HF $3 \leq |\eta| \leq 5$
T2 (GEM): $5.3 \leq |\eta| \leq 6.6$
Castor $5.3 \leq |\eta| \leq 6.6$

Possible addition FP420:
Near-beam detectors at 420 m

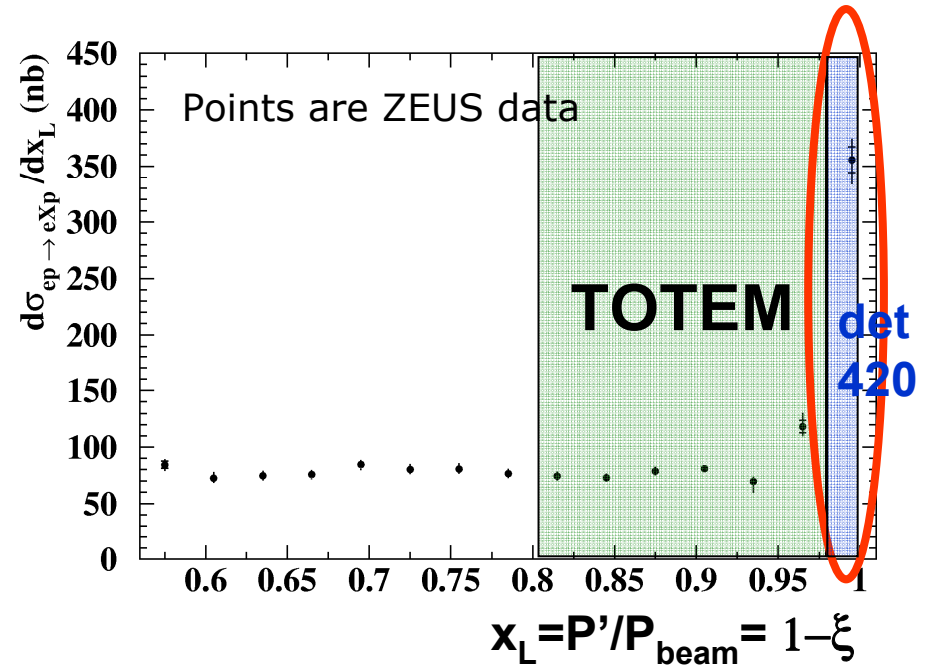
CMS + TOTEM: Coverage in ξ

Depends on value of β^*



ξ : fractional momentum loss of proton
 t : 4-momentum transfer squared at proton vertex

At nominal LHC optics, $\beta^*=0.5\text{m}$

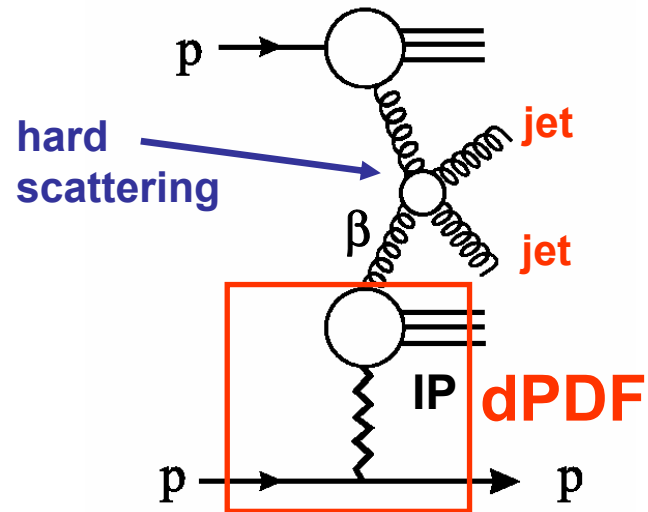


diffractive peak

Note: Totem RP's optimized for special optics runs at high β^*
 β^* is measure for transverse beam size at vertex
 Consider 3 different optics, at $\beta^*=0.5\text{m}$, 90m and 1540m

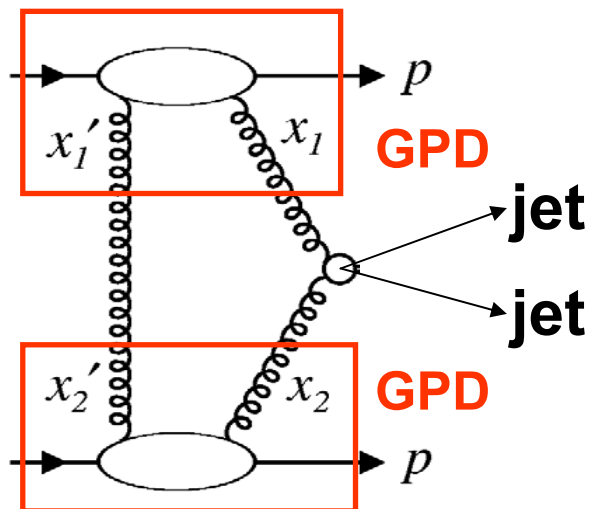
Program on diffractive and forward physics

Diffractive PDFs and GPDs



- **Diffractive PDFs:**

probability to find a parton of given x under condition that proton stays intact – sensitive to low- x partons in proton, complementary to standard PDFs



- **Generalised Parton Distributions (GPD)**

quantify correlations between parton momenta in the proton
 t -dependence sensitive to parton distribution in transverse plane

When $x'=x$, GPDs are proportional to the *square* of the usual PDFs

“Prospects for diff and fwd physics at the LHC” - Part I: Diffractive part

Detecting 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

All studies in document use these acceptance calculations

