Physics with the CT-PPS project

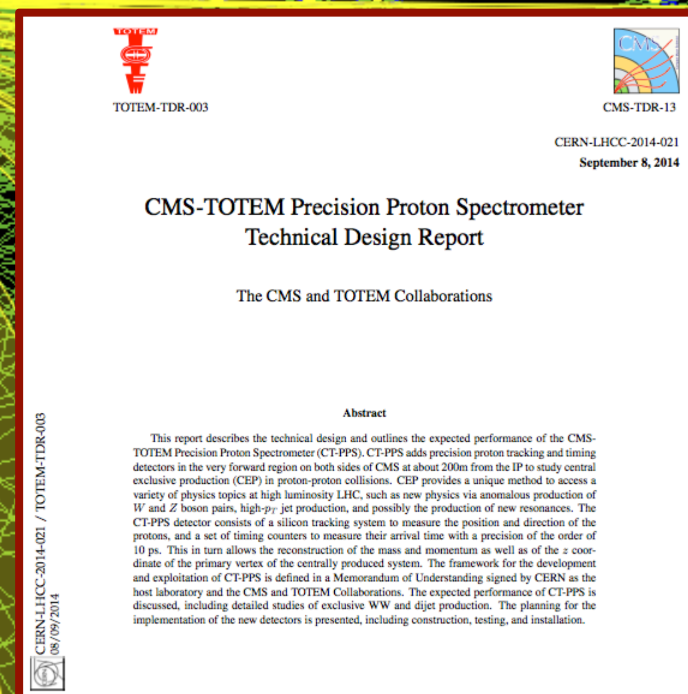
Michele Gallinaro

LIP Lisbon

(on behalf of the CMS and TOTEM collaborations)

CERN-LHCC-2014-021
08/09/2014

- ✓ Introduction
- ✓ Exclusive dijets
- ✓ Exclusive WW



TOTEM-TDR-003

CMS-TDR-13

CERN-LHCC-2014-021
September 8, 2014

CMS-TOTEM Precision Proton Spectrometer
Technical Design Report

The CMS and TOTEM Collaborations

Abstract

This report describes the technical design and outlines the expected performance of the CMS-TOTEM Precision Proton Spectrometer (CT-PPS). CT-PPS adds precision proton tracking and timing detectors in the very forward region on both sides of CMS at about 200m from the IP to study central exclusive production (CEP) in proton-proton collisions. CEP provides a unique method to access a variety of physics topics at high luminosity LHC, such as new physics via anomalous production of W and Z boson pairs, high-p_T jet production, and possibly the production of new resonances. The CT-PPS detector consists of a silicon tracking system to measure the position and direction of the protons, and a set of timing counters to measure their arrival time with a precision of the order of 10 ps. This in turn allows the reconstruction of the mass and momentum as well as of the z coordinate of the primary vertex of the centrally produced system. The framework for the development and exploitation of CT-PPS is defined in a Memorandum of Understanding signed by CERN as the host laboratory and the CMS and TOTEM Collaborations. The expected performance of CT-PPS is discussed, including detailed studies of exclusive WW and dijet production. The planning for the implementation of the new detectors is presented, including construction, testing, and installation.

CERN-LHCC-2014-021 / TOTEM-TDR-003
08/09/2014

Introduction

EWK

LHC used as a photon-photon collider

- Measure $\gamma\gamma \rightarrow W^+W^-$, e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$
- Search for AQGC with high sensitivity
- Search for SM forbidden $ZZ\gamma\gamma$, $\gamma\gamma\gamma\gamma$ couplings

QCD

QCD physics

- Exclusive two and three jet events, M up to ~ 700-800 GeV.
- Test of pQCD mechanisms of exclusive production.

Gluon Jet Factory

- Gluon jet samples with small component of quark jets

BSM

Search for new resonances in CEP

- Clean events (no underlying pp event)
- Independent mass measurement from pp system
- J^PC quantum numbers 0++, 2++

Introduction

EWK

LHC used as a photon-photon collider

- Measure $\gamma\gamma \rightarrow W^+W^-$, e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$
- Search for AQGC with high sensitivity
- Search for SM forbidden $ZZ\gamma\gamma$, $\gamma\gamma\gamma\gamma$ couplings

QCD

QCD physics

- Exclusive two and three jet events, M up to ~ 700-800 GeV.
- Test of pQCD mechanisms of exclusive production.

Gluon Jet Factory

- Gluon jet samples with small component of quark jets

BSM

Search for new resonances in CEP

- Clean events (no underlying pp event)
- Independent mass measurement from pp system
- J^PC quantum numbers 0++, 2++

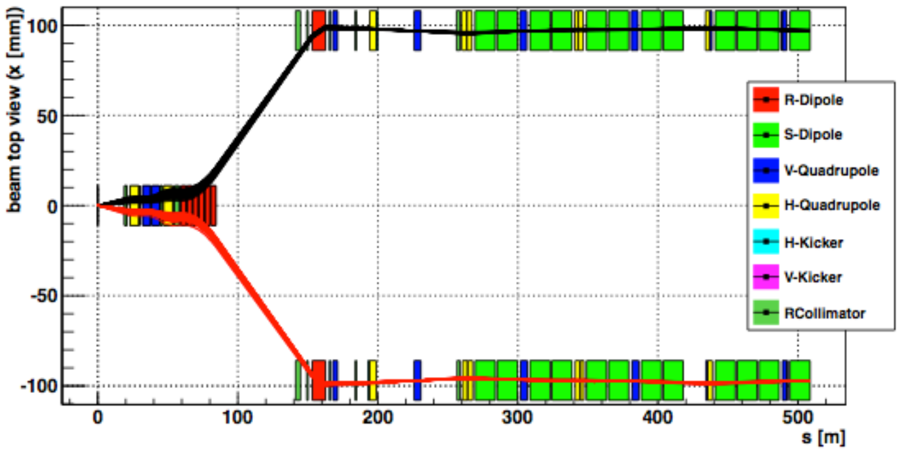
Simulation

- Generated events are processed through GEANT4 simulation of CMS central detector, and standard reconstruction chain
- Protons are tracked through the beam-line to tracking and timing detector position
  - Simulation includes beam energy dispersion, beam crossing angle, smearing due to beam divergence, vertex smearing
- Fast simulation of PPS detectors takes into account detector segmentation and resolution
  - Time resolution of 10ps (baseline) and 30ps (conservative) considered
  - Tracking detectors: position resolution of 10μm at z=204-214m
- Beam induced background is included
  - Simulated event-by-event simulation based on data at PU=9 and extrapolated to PU=(25) 50

Simulated samples

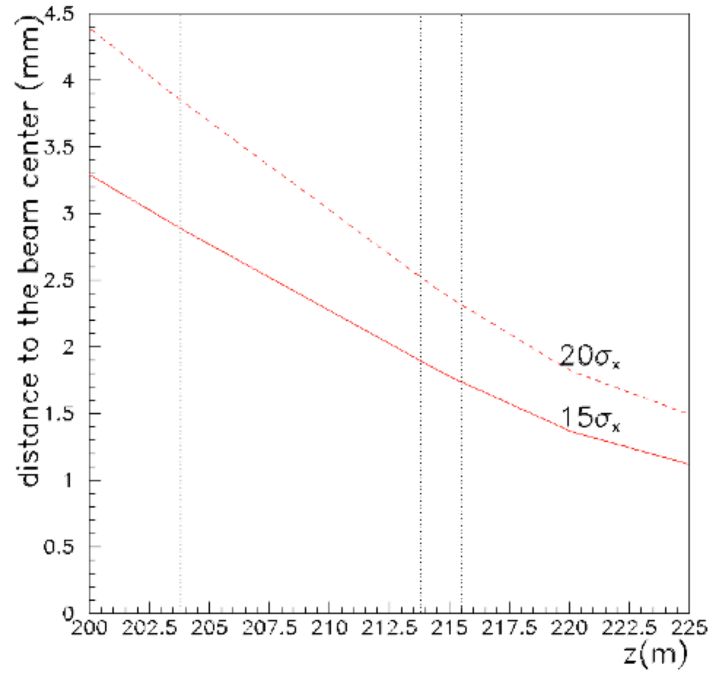
- Signal
  - Exclusive dijets: ExHuME generator interfaced with PYTHIA
  - Exclusive WW: FPMC with HERWIG to simulate decay of WW pair
- Background
  - WW inclusive events: PYTHIA, normalized to 13 TeV xsection
  - SD and DPE use POMWIG interfaced with HERWIG
  - Multijet QCD events simulated with PYTHIA
  - Exclusive $\gamma\gamma/\tau\tau$ events generated with FPMC
- Pileup
  - PYTHIA to generate minimum bias samples (incl. diffractive events)
  - 25 and 50 pileup event samples

Beam optics



- HECTOR, a fast simulator for particle transport in a beam-line
- good agreement with MADx
- Full transport line simulation in CMSSW

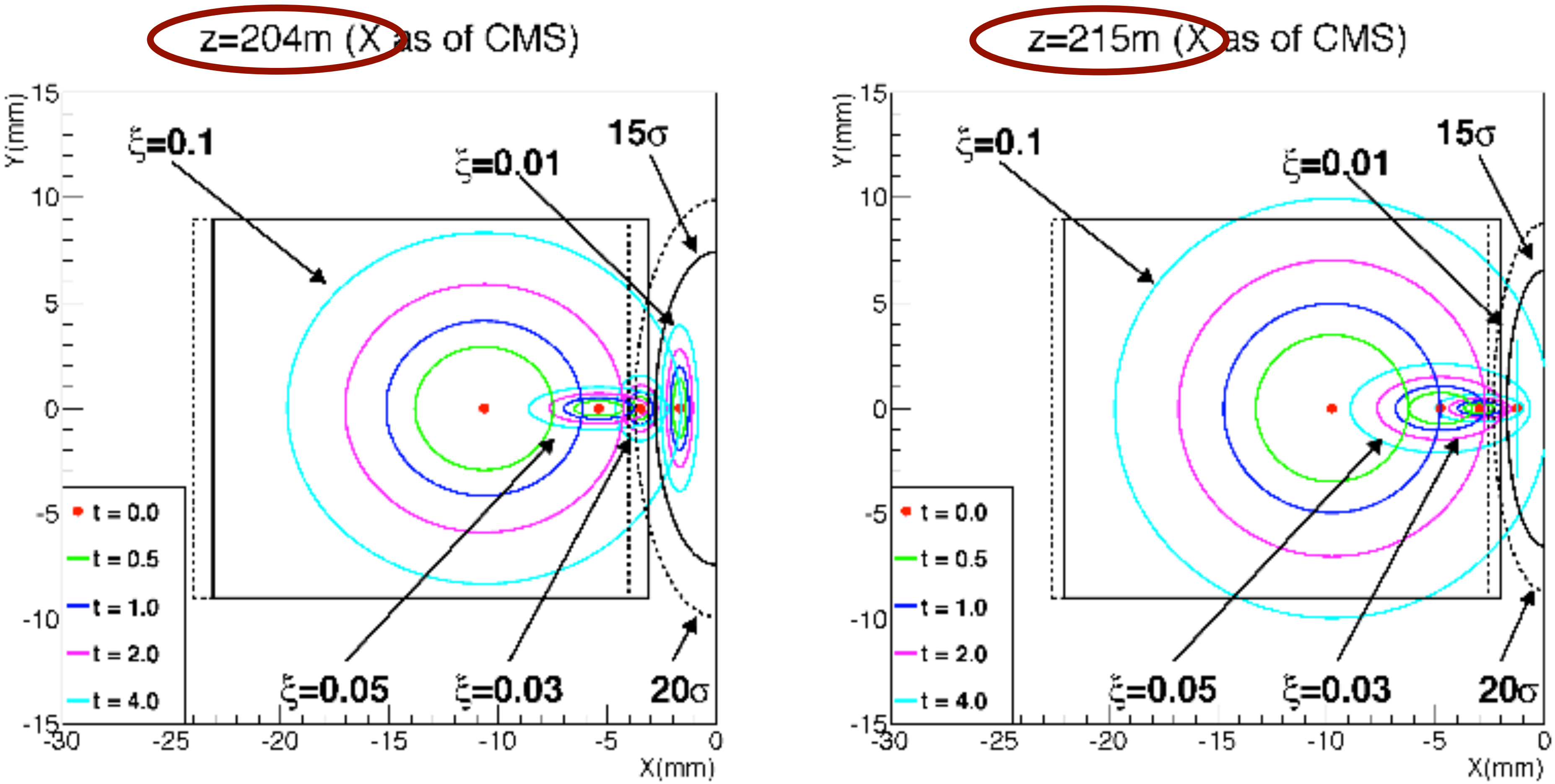
Horizontal distance to beam center in the z-range of the PPS detectors



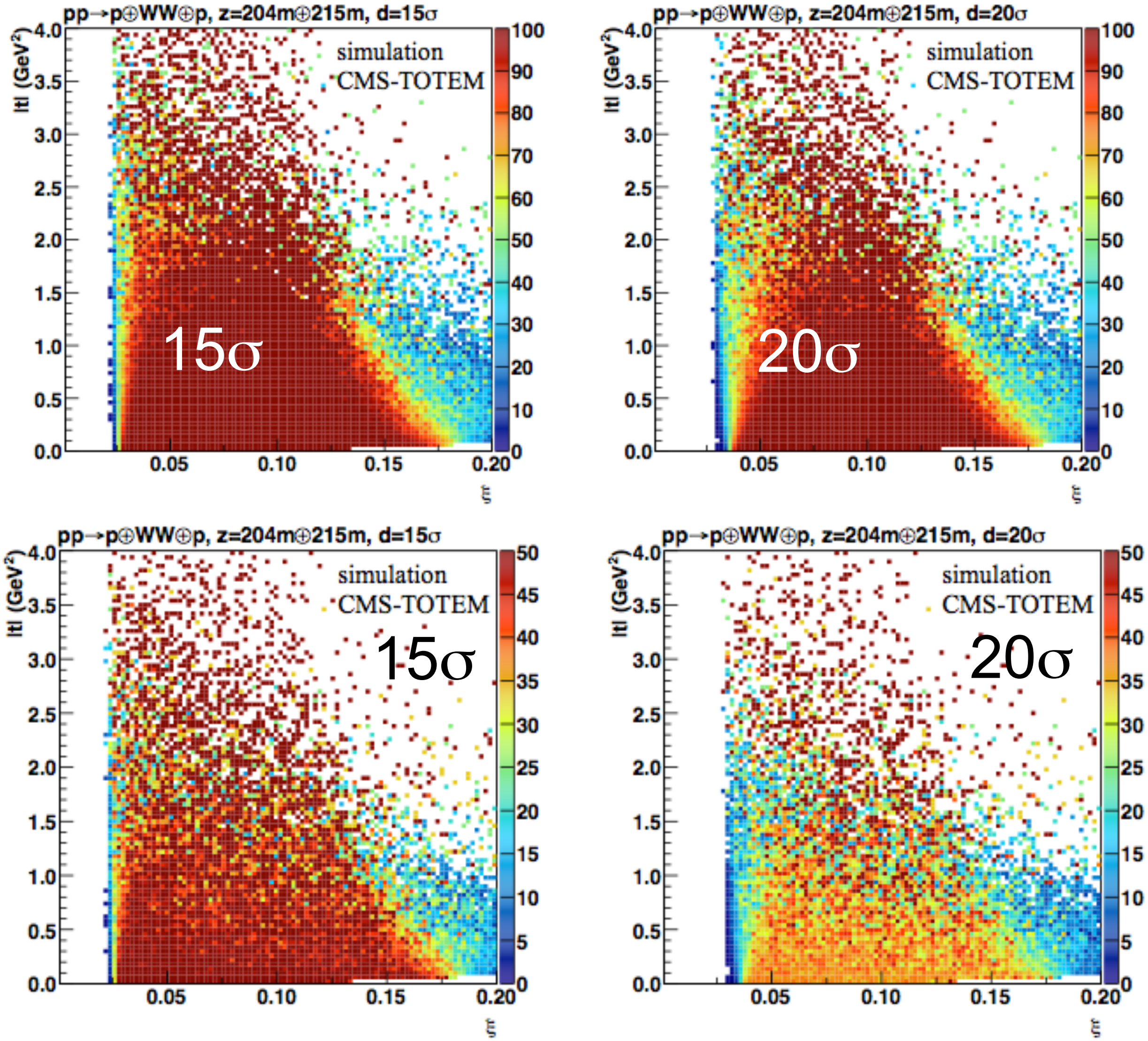
Detector acceptance

Acceptance: X vs Y (includes ξ,t ellipses)

- Particle gun (t,ξ,φ) based on HECTOR at √s = 13 TeV



WW detector acceptance: ξ vs t

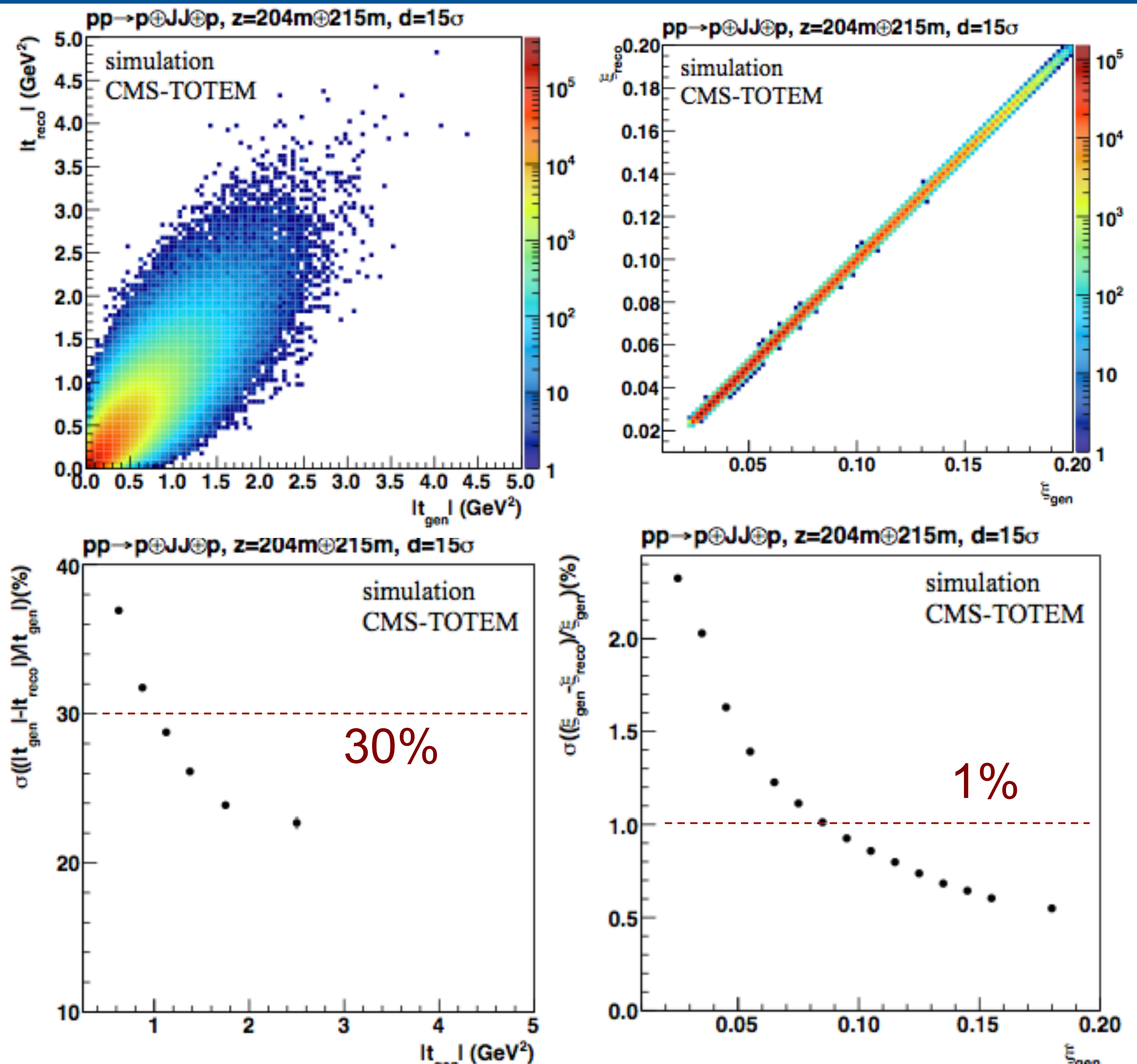


- Single arm acceptance: ⇒ ~55% @15σ

- Double arm acceptance: ⇒ ~28% @15σ
- acceptance in one arm (z>0) when requiring other proton to be inside the acceptance of the other arm (z<0)

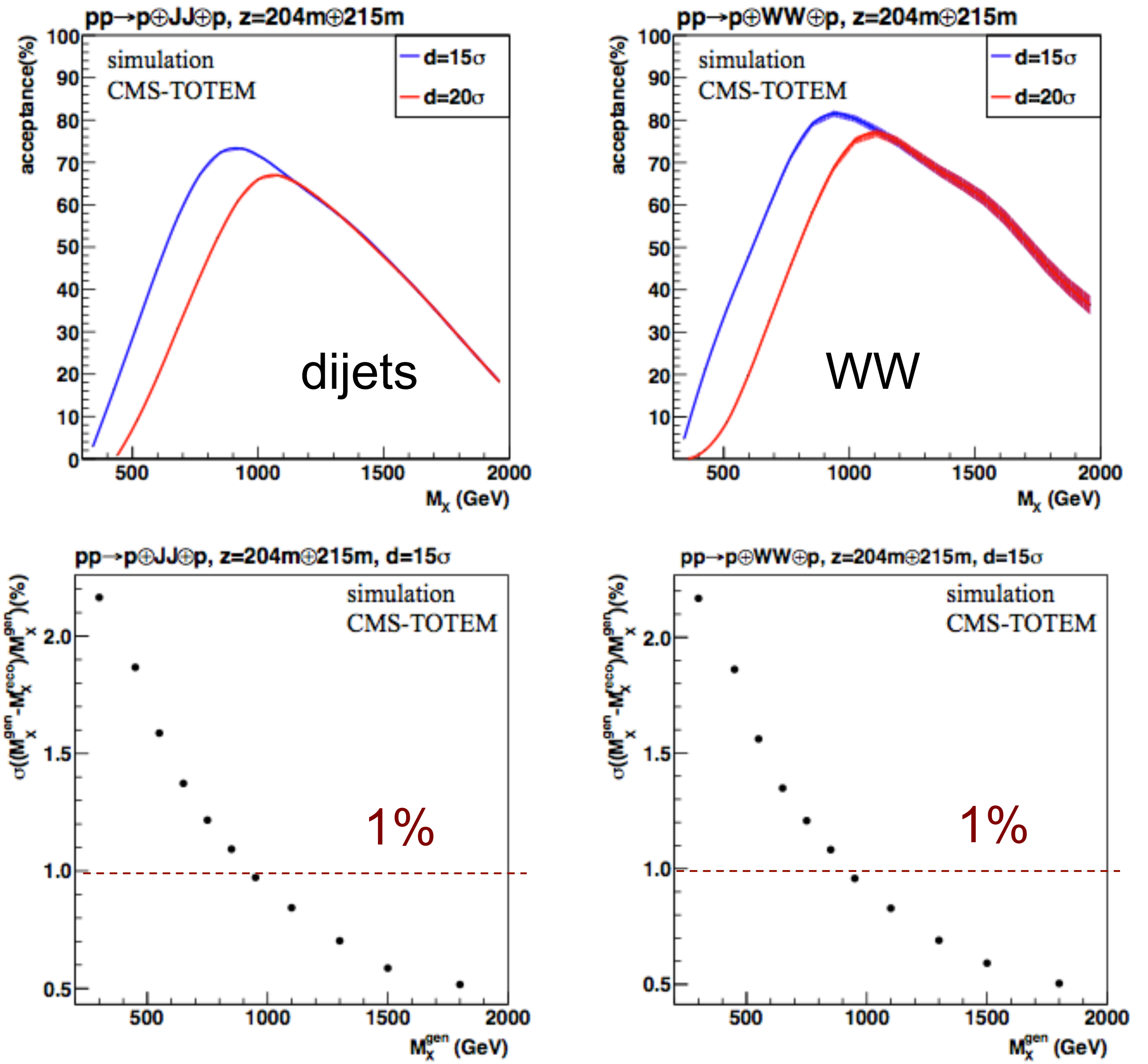
WW detector resolution: t, ξ

- Compare generated and reconstructed values
- Resolution of the t and ξ variables



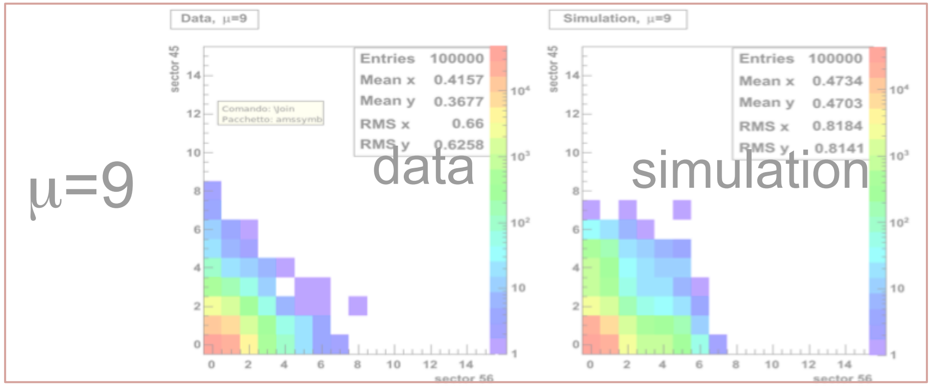
Detector resolution: mass

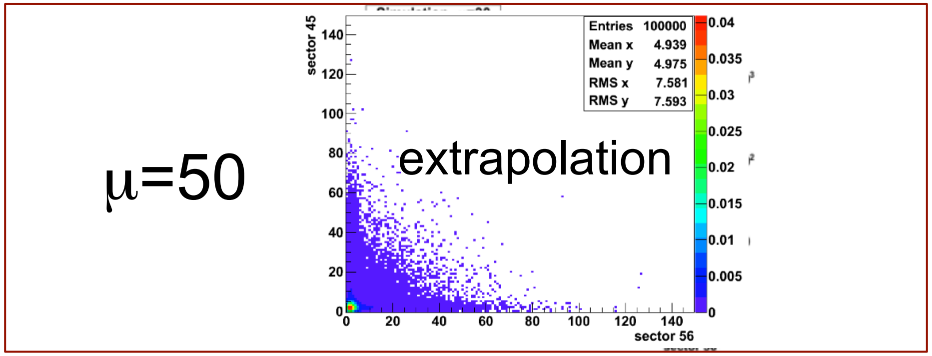
- Mass acceptance and resolution vs M_X
- PPS selects exclusive systems in 300-1700 GeV range (ε>5%)
- At 15σ acceptance larger by a factor of two (wrt 20σ) for lower masses
- Mass resolution ~1.5% at 500 GeV



Machine induced backgrounds

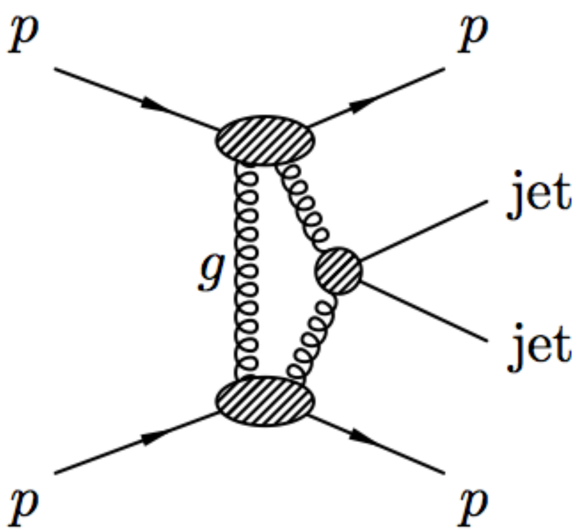
- Use TOTEM data at μ=9
- Account for pileup protons (from simulation) to estimate beam background only
- Extrapolate from μ=9 to μ=50





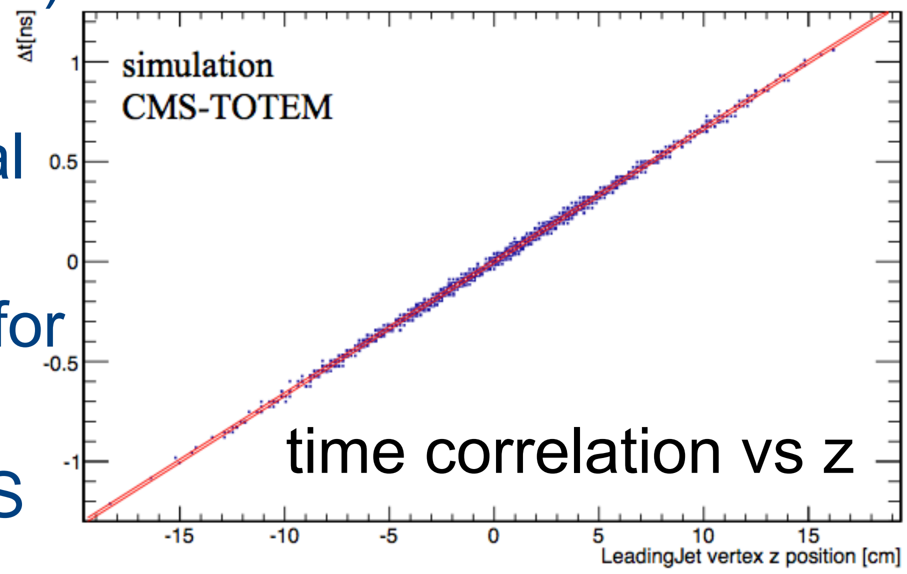
Physics processes

- Exclusive dijets
  - high jet p_T events (M_{jj} up to~400-500 GeV)
  - test of pQCD mechanism of exclusive production
- Exclusive WW
  - quartic gauge boson coupling $WW\gamma\gamma$
  - sensitivity to anomalous couplings

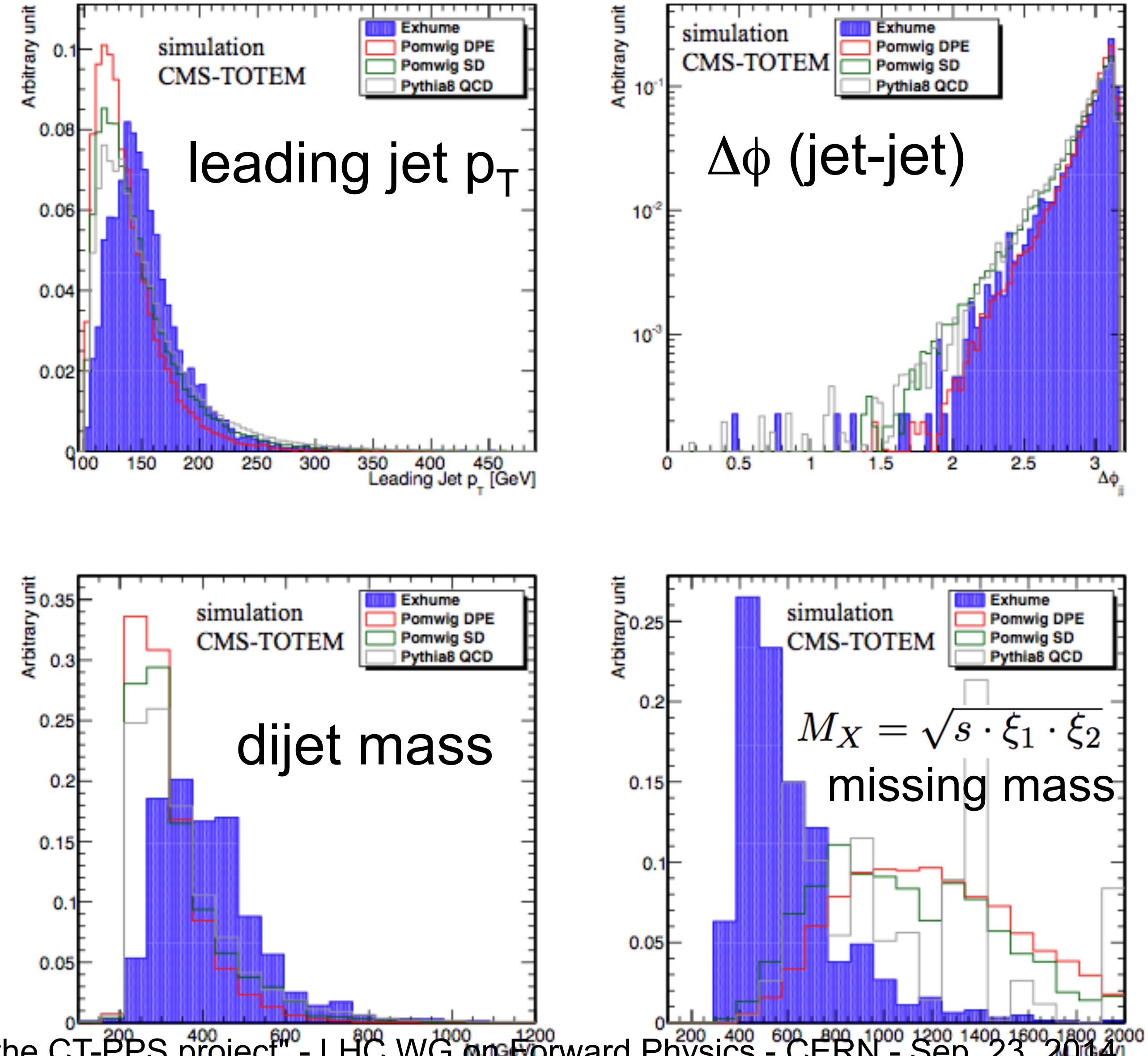


Exclusive dijets

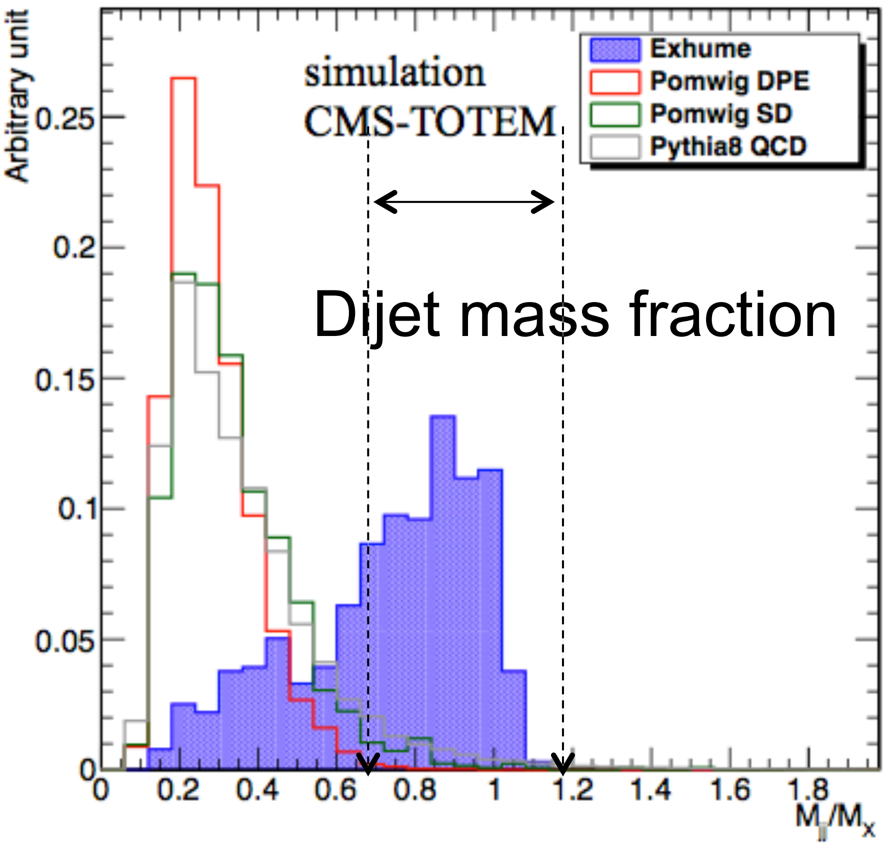
- Require 2 jets (p_T>100 GeV, $|\eta|$<2)
- Leading protons tagged by PPS
- Sensitivity to high mass of central system M_X (from PPS)
- Timing as powerful discriminant for exclusive states
- Kinematical constraints from PPS measurements
- Signal: ExHuME (pp→gg→dijets)
- PU: Pythia 8 (MB, PU50, PU25)

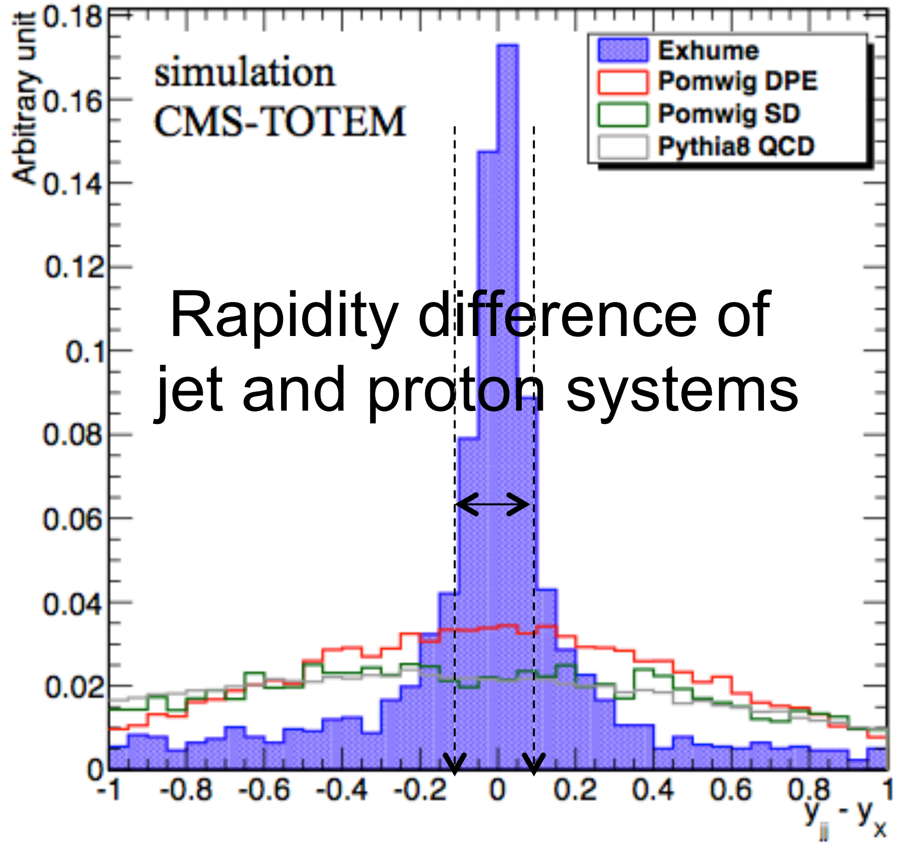


Kinematical distributions



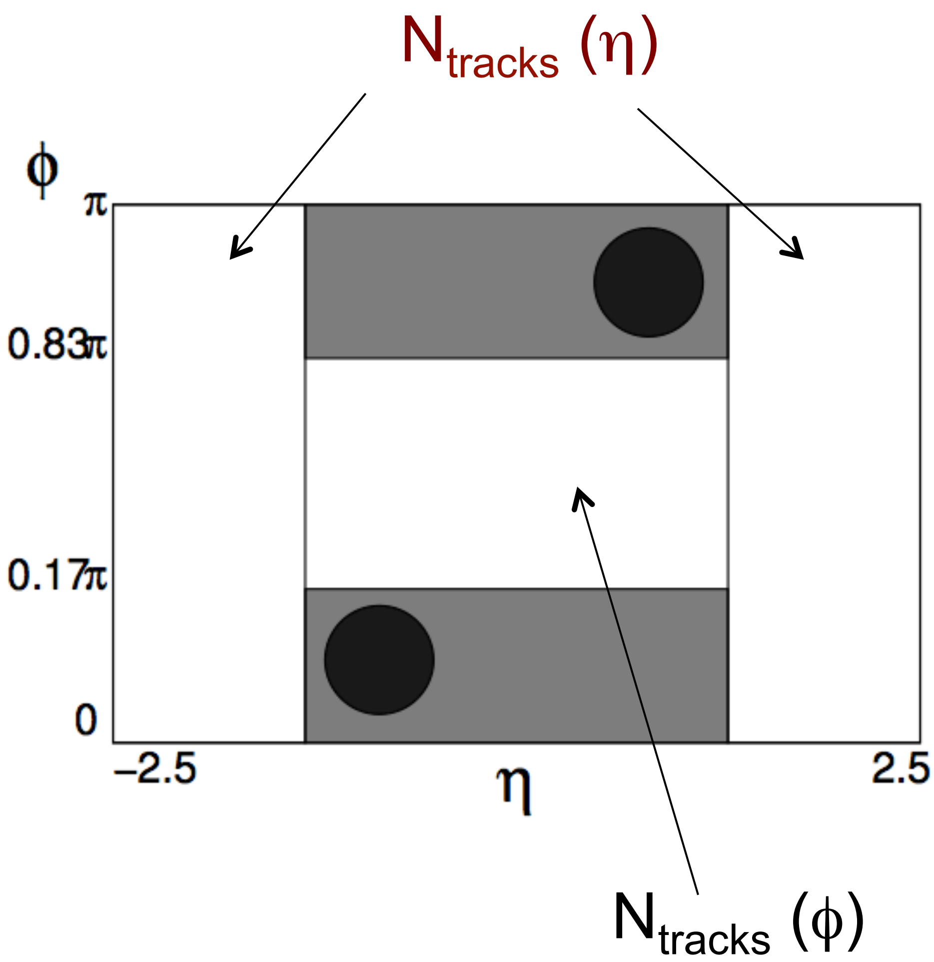
Kinematical distributions (cont.)



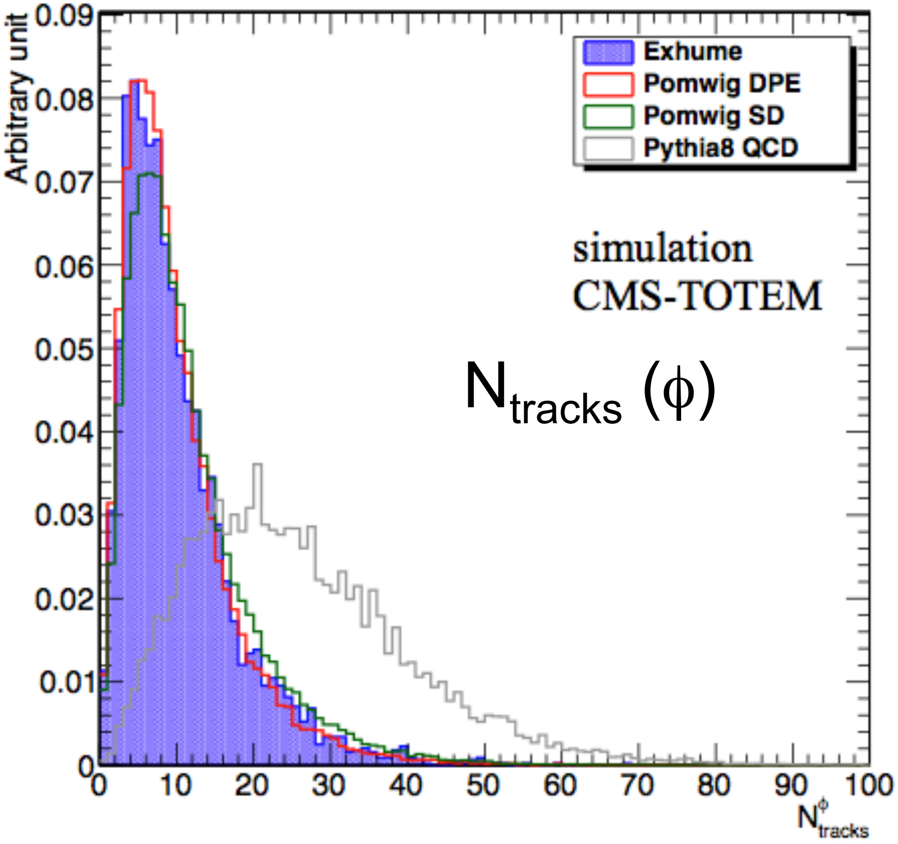


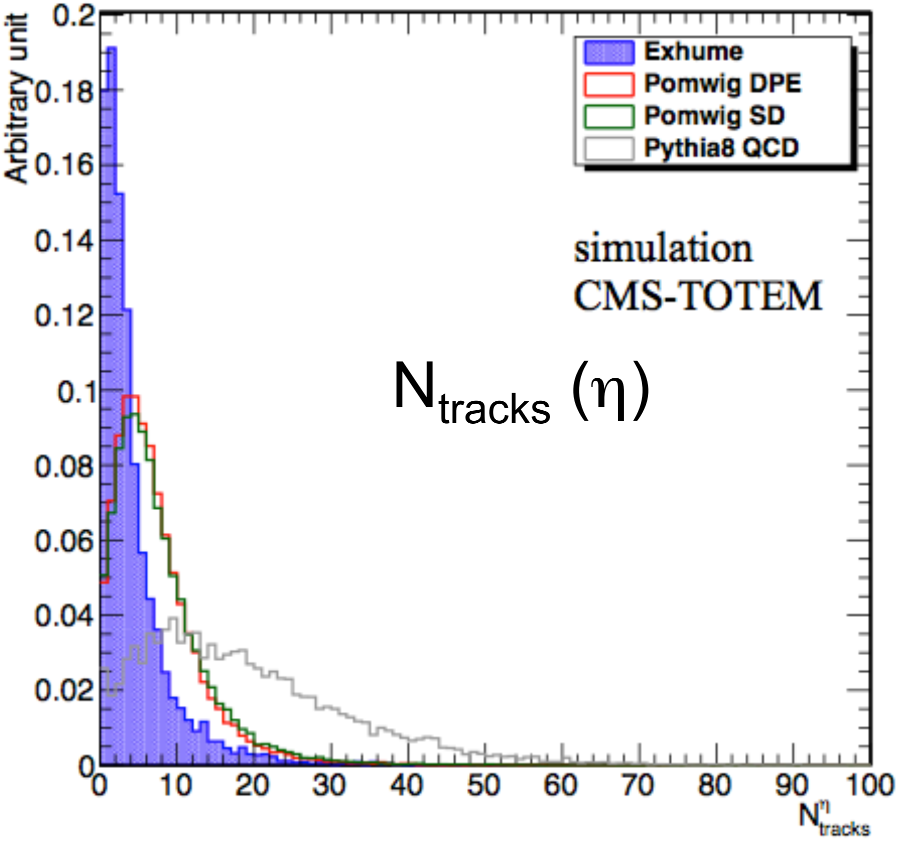
Track multiplicity

- Exploit the exclusivity of signal events to discriminate against large QCD multijet background
- Count number of tracks in regions of η/ϕ around the jet system

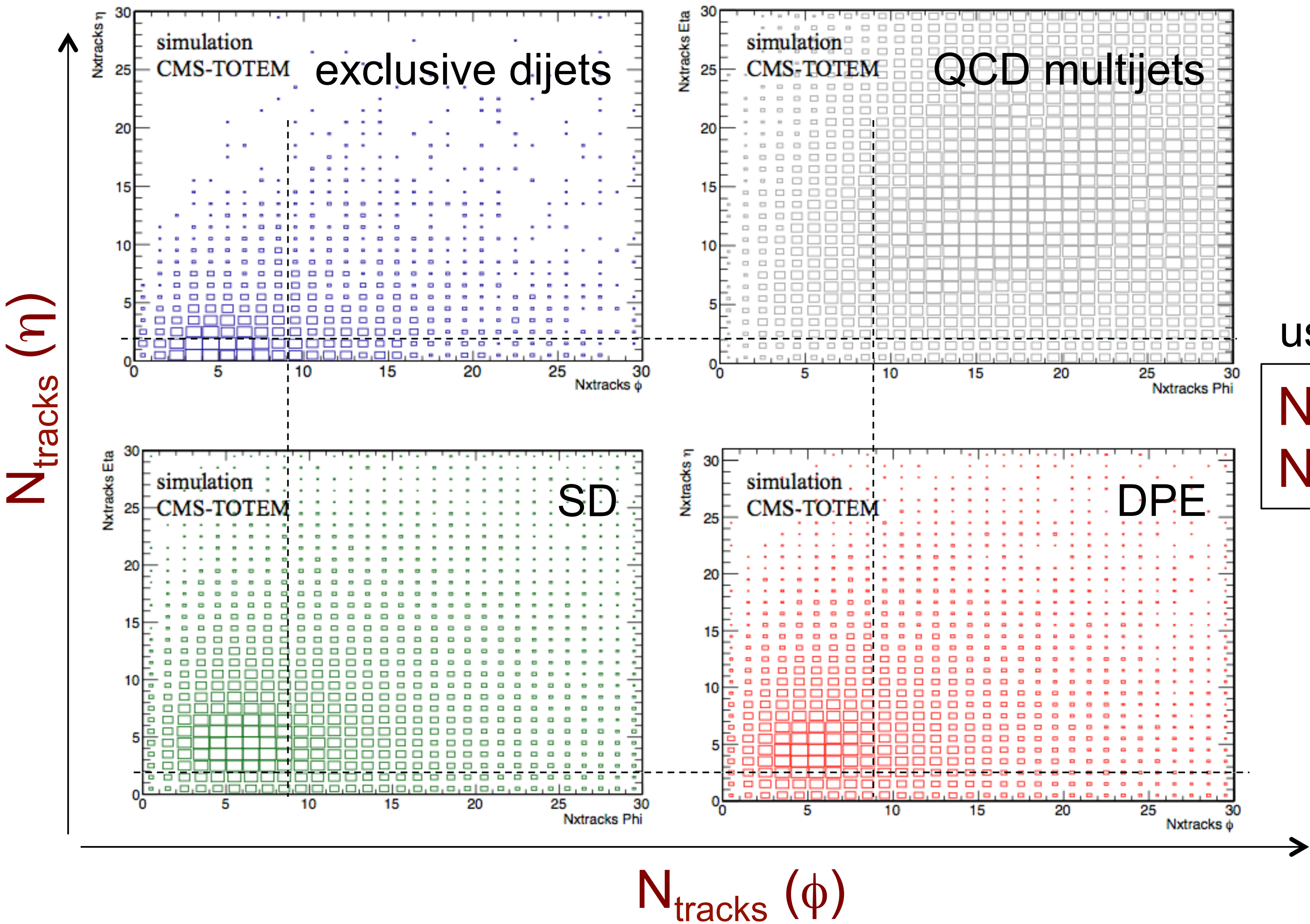


Track multiplicity (cont.)





Track multiplicity (cont.)



use:

$N_{tracks}(\eta) \leq 2$
$N_{tracks}(\phi) \leq 9$

Yields per 1/fb – Pileup=50

Selection	Exclusive dijets		DPE		SD		Inclusive dijets	
	events	ϵ (%)	events	ϵ (%)	events	ϵ (%)	events	ϵ (%)
total number of events	652±7	100	290×10^3	100	2.6×10^6	100	2.4×10^{10}	100
≥ 2 jets (p_T >100 GeV, $\lvert\eta\rvert < 2.0$)	287±5	44	36×10^3	12.2	270×10^3	10	4.4×10^8	1.8
PPS tagging (fiducial)	77±3	12	23×10^3	7.8	39×10^3	1.5	0.5×10^8	0.2
no overlap hits in ToF detectors	54±2	8	18×10^3	6.3	25×10^3	1.2	0.3×10^8	0.12
ToF difference, Δt	32 (27)±2	5	$14\ (11) \times 10^3$	4.8	6×10^3	0.3	$95\ (180) \times 10^4$	4×10^{-3}
$0.70 < [R_{jj} = (M_{jj}/M_X)] < 1.15$	20 (16)±1	3.1	43 (39)±8	0.01	200 (250)±40	0.01	$45\ (85) \times 10^3$	2×10^{-4}
$\Delta(y_{jj} - y_X) < 0.1$	15 (12)±1	2.3	10 (11)±4	-	12±10	-	$5\ (9) \times 10^3$	-
N_{tracks}	5 (4)±1	0.8	1.3 (1.5)±0.5	-	1±1	-	40 (77) ± 1	-
≥ 2 jets (p_T > 150 GeV, $\lvert\eta\rvert < 2.0$)	2.5 (1.9)±0.2	0.4	0.4±0.2	-	0±1	-	20 (36) ± 1	-

⇒ S/B ~ 1/8

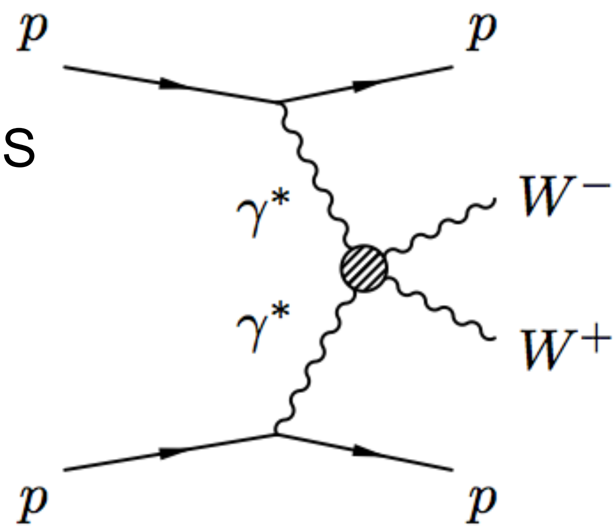
Yields per 1/fb – Pileup=25

Selection	Exclusive dijets		DPE		SD		Inclusive dijets	
	events	ϵ (%)	events	ϵ (%)	events	ϵ (%)	events	ϵ (%)
total number of events	652±5	100	290×10^3	100	2.6×10^6	100	2.4×10^{10}	100
≥ 2 jets (p_T >100 GeV, $\|\eta\| < 2.0$)	250±4	38	25×10^3	8.7	190×10^3	7.6	3.4×10^8	1.4
PPS tagging (fiducial)	50±2	8	15×10^3	5.1	12×10^3	0.5	0.1×10^8	0.05
no overlap hits in ToF detectors	43±2	7	14×10^3	4.8	$10\ (18) \times 10^3$	0.4	0.1×10^8	0.04
ToF difference, Δt	30 (23)±2	4.6	$11\ (9) \times 10^3$	3.8	3×10^3	0.1	$0.3\ (0.6) \times 10^6$	1×10^{-3}
$0.70 < [R_{jj} = (M_{jj}/M_X)] < 1.15$	20 (15)±1	3.1	15 (14)±3	0.01	85 (110)±15	-	$16\ (30) \times 10^3$	1×10^{-4}
$\Delta(y_{jj} - y_X) < 0.1$	15 (12)±1	2.4	6 (4)±2	-	3 (11)±3	-	$1.8\ (3.4) \times 10^3$	-
N_{tracks}	7.4 (5.8)±0.4	1.1	0.8 (0.6)±0.3	-	1±1	-	19 (35) ± 1	-
≥ 2 jets (p_T > 150 GeV, $\|\eta\| < 2.0$)	3.5 (2.6)±0.2	0.5	0.2 (0.1)±0.1	-	1±1	-	9 (17) ± 1	-

⇒ S/B ~ 1/3

WW production

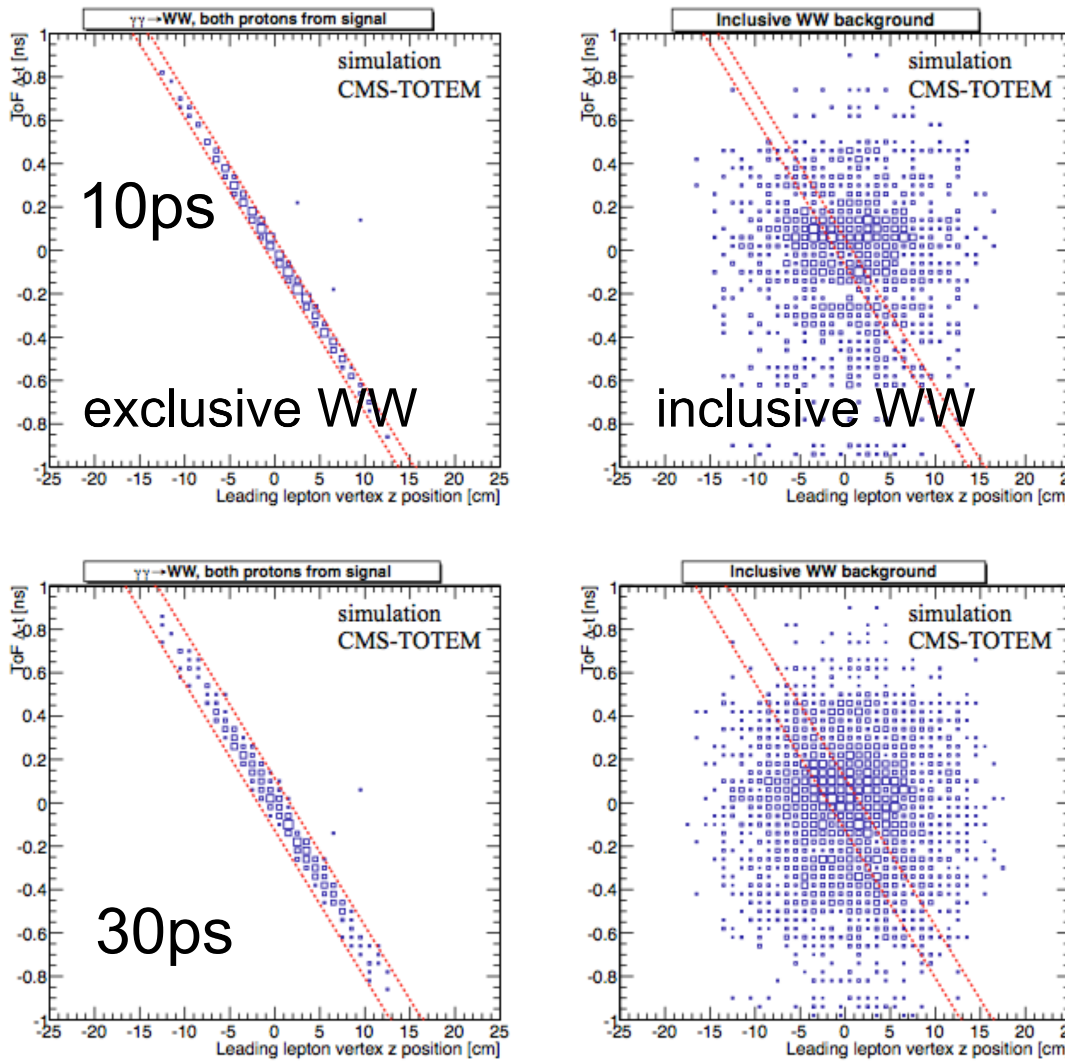
- Study of process: pp→pWWp
  - Clean process: W in central detector and “nothing” else, intact protons can be detected far away from IP
  - Exclusive production of W pairs via photon exchange: QED process, cross section well known
- Events:
  - WW pair in central detector, leading protons in PPS
  - Study only eμ final state



- SM observation of WW events
  - σ_{WW}=95.6 fb, σ_{WW} (W>1TeV)=5.9 fb
- Anomalous coupling study
  - AQGCs predicted in BSM theories
  - Two points: $a_0^W/\Lambda^2=5\times10^{-6}$, $a_C^W/\Lambda^2=5\times10^{-6}$

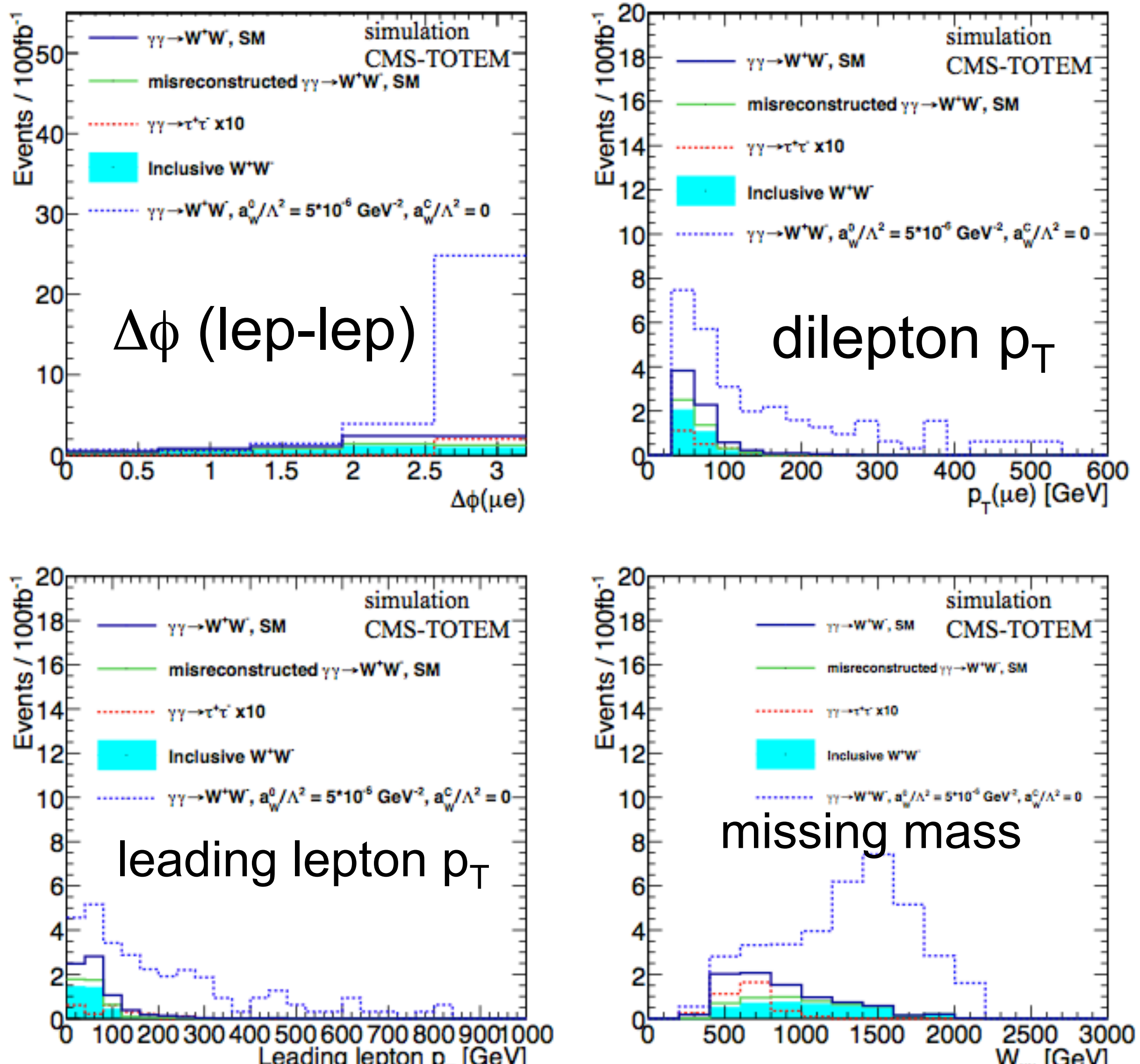
PPS timing vs. z-vertex

- Use timing to reject background
- Keep:
  - ~99% of signal events
  - ~10% of inclusive WW
- Two scenarios: 10ps and 30ps

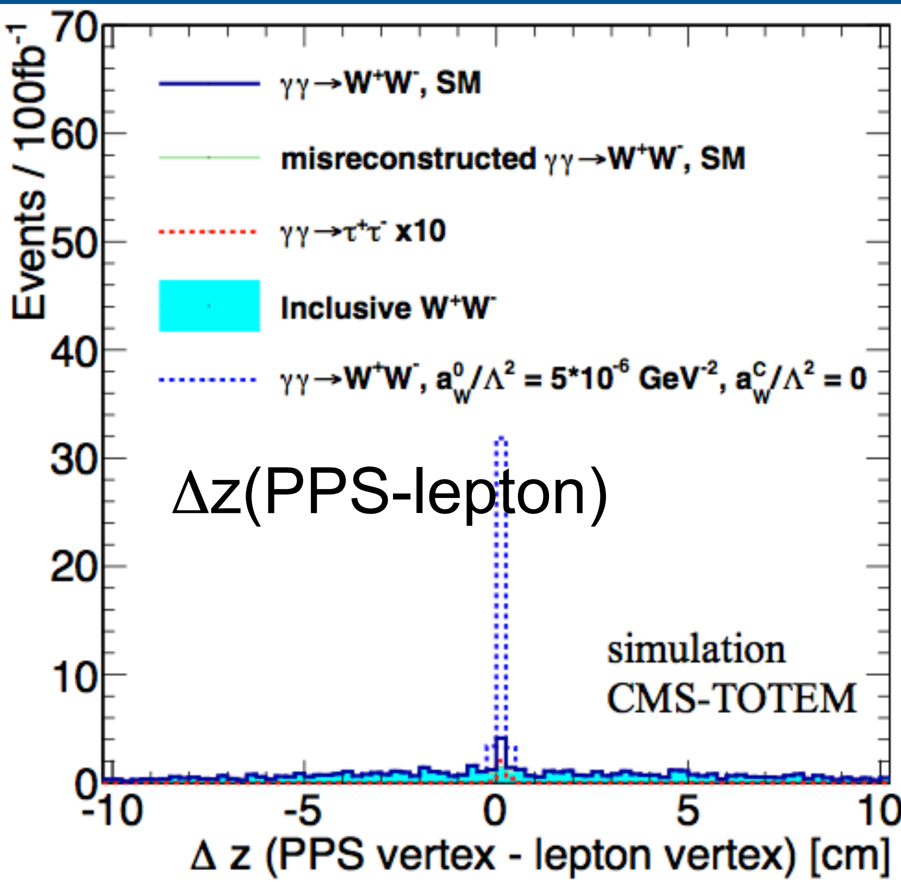


Kinematical distributions

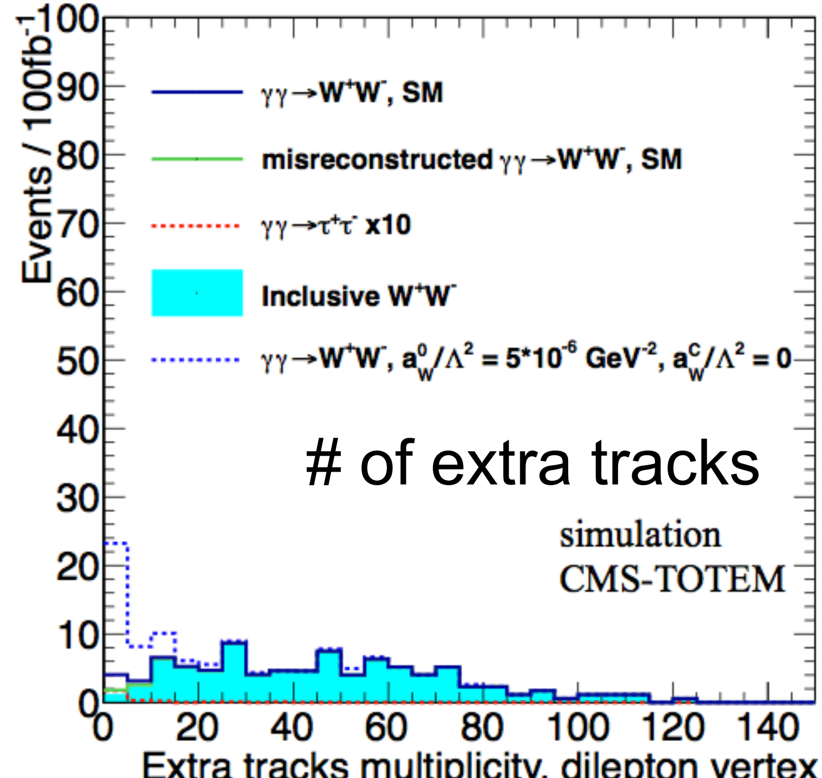
- SM vs AQGC: missing mass provides good separation
- Information from PPS



PPS and central detector



- Multiplicity of “extra tracks” associated to dilepton vertex
- Requiring <10 tracks keeps 80% of signal, 5% of bkg

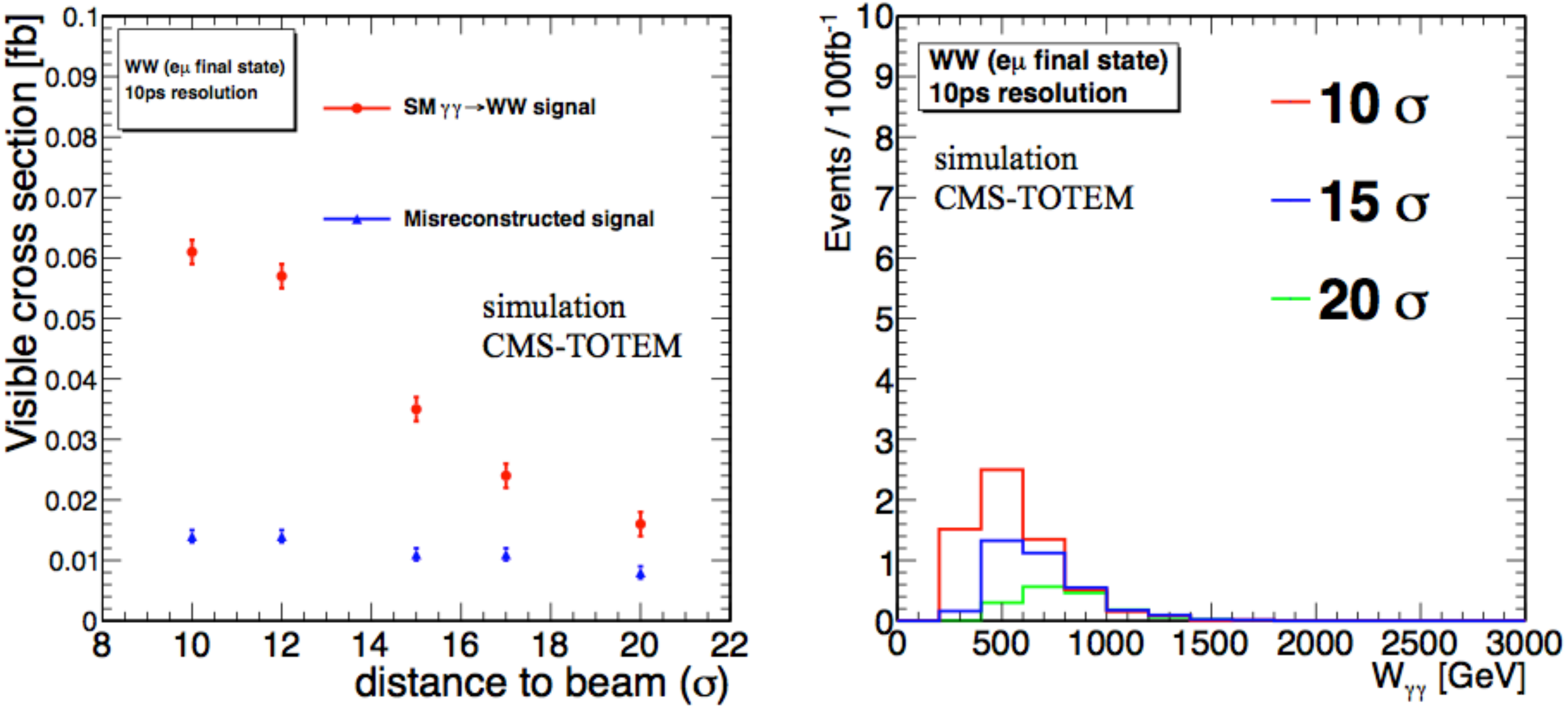


Yields (in fb)

- Select WW events
- Apply central lepton and PPS acceptance cuts
- Additional timing and track multiplicity cuts
- Inefficiency due to overlapping hits in timing detectors is taken into account
- Number in parenthesis are for time resolution of 30ps

Selection	Cross section (fb)			
	exclusive WW	exclusive WW (incorrectly reconstructed)	inclusive WW	exclusive $\tau\tau$
generated $\sigma \times \mathcal{B}(WW \to e\mu\,\nu\bar{\nu})$	0.86±0.01	N/A	2537	1.78±0.01
≥ 2 leptons ($p_T > 20$ GeV, $\eta < 2.4$)	0.47±0.01	N/A	1140±3	0.087±0.003
opposite sign leptons, "tight" ID	0.33±0.01	N/A	776±2	0.060±0.002
dilepton pair $p_T > 30$ GeV	0.25±0.01	N/A	534±2	0.018±0.001
protons in both PPS arms (ToF and TRK)	0.055 (0.054)±0.002	0.044 (0.085)±0.003	11 (22)±0.3	0.004±0.001
no overlapping hits in ToF + vertex matching	0.033 (0.030)±0.002	0.022 (0.043)±0.002	8 (16)±0.2	0.003 (0.002)±0.001
ToF difference, $\Delta t = (t_1 - t_2)$	0.033 (0.029)±0.002	0.011 (0.024)±0.001	0.9 (3.3)±0.1	0.003 (0.002)±0.001
$N_{\mathrm{tracks}} < 10$	0.028 (0.025)±0.002	0.009 (0.020)±0.001	0.03 (0.14)±0.01	0.002±0.001

Yields vs distance to beam



Potential enhancement of sensitivity with closer approach:

- Signal yield grows by ~x2 when going from 15σ to 10σ
- Background is more or less flat

AQGC yields (in fb)

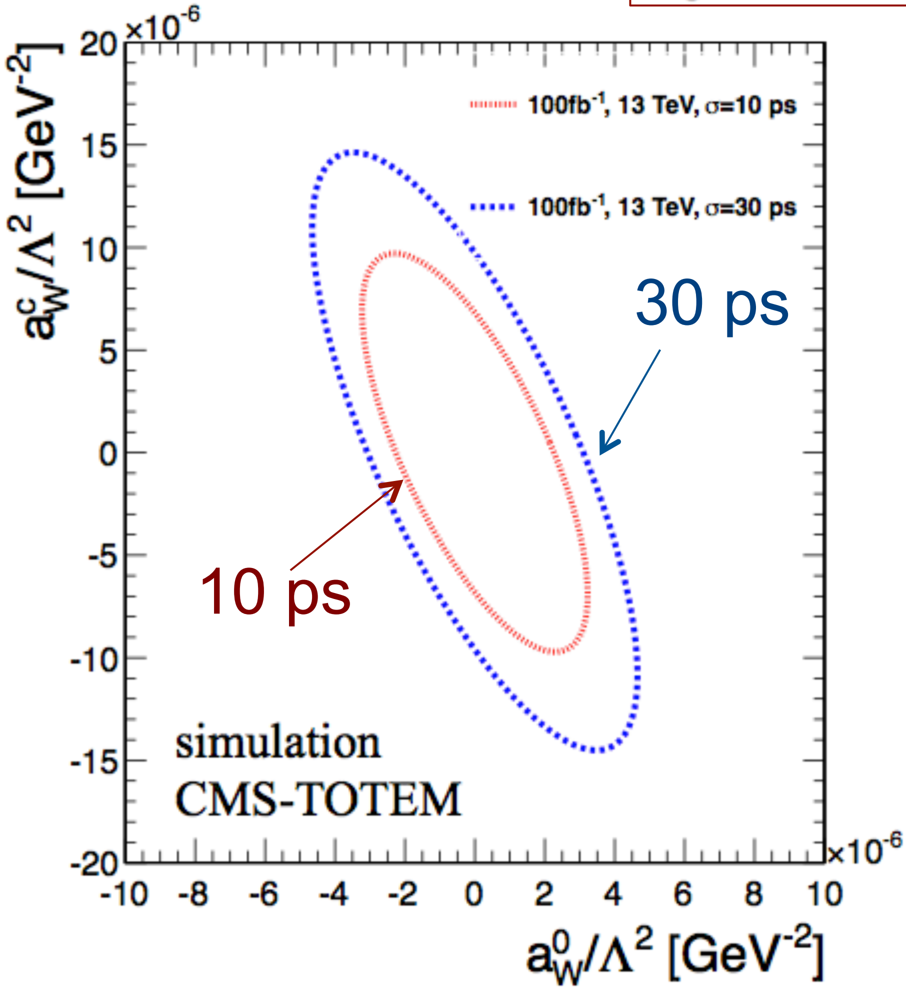
Table 7: Cross section (in fb) for the expected exclusive WW events due to anomalous quartic gauge couplings, for different values of anomalous coupling parameters (a_0^W and a_C^W) after each selection cut (for a timing resolution of 10 ps). In case of different values, numbers in parentheses are for a timing resolution of 30 ps. Only the $e\mu$ final state is considered. Statistical uncertainties are shown.

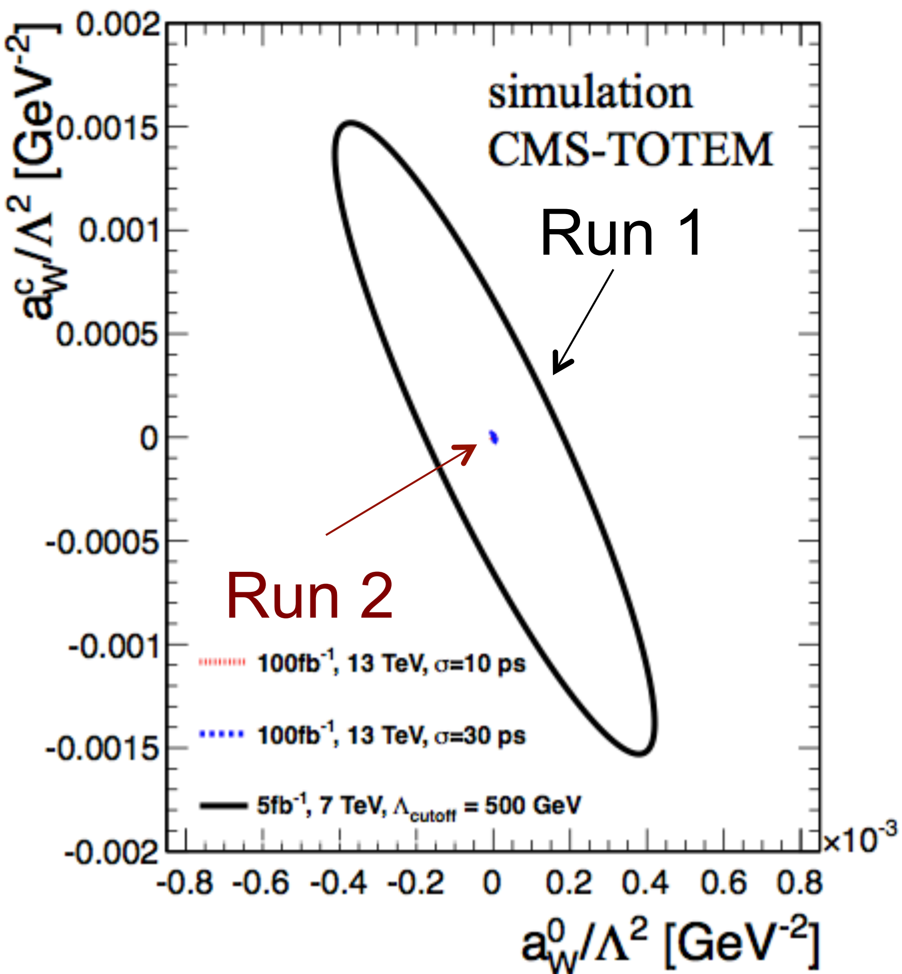
Selection	Cross section (fb)	
	$a_0^W/\Lambda^2 = 5 \cdot 10^{-6}\text{GeV}^{-2}$ ($a_C^W = 0$)	$a_C^W/\Lambda^2 = 5 \times 10^{-6}\text{GeV}^{-2}$ ($a_0^W = 0$)
generated $\sigma \times \mathcal{B}(WW \to e\mu\, \nu\bar{\nu})$	3.10±0.14	1.53±0.07
≥ 2 leptons ($p_T > 20$ GeV, $\eta < 2.4$)	2.33±0.08	1.00±0.04
opposite sign leptons, "tight" ID	1.82±0.08	0.78±0.03
dilepton pair $p_T > 30$ GeV	1.69±0.07	0.68±0.03
protons in both PPS arms (ToF and TRK)	0.52 (0.50)±0.04	0.18 (0.17)±0.02
no overlapping hits in ToF detectors	0.35 (0.32)±0.03	0.12 (0.11)±0.01
ToF difference, $\Delta t = (t_1 - t_2)$	0.35 (0.32)±0.03	0.12 (0.11)±0.01
$N_{\text{tracks}} < 10$	0.27 (0.24)±0.03	0.11 (0.10)±0.01

AQGC expected limits

Expected limits @95%CL:

$$a_0^W/\Lambda^2 = 2 \times 10^{-6}\ (3 \times 10^{-6}),$$
$$a_C^W/\Lambda^2 = 7 \times 10^{-6}\ (10 \times 10^{-6}),$$



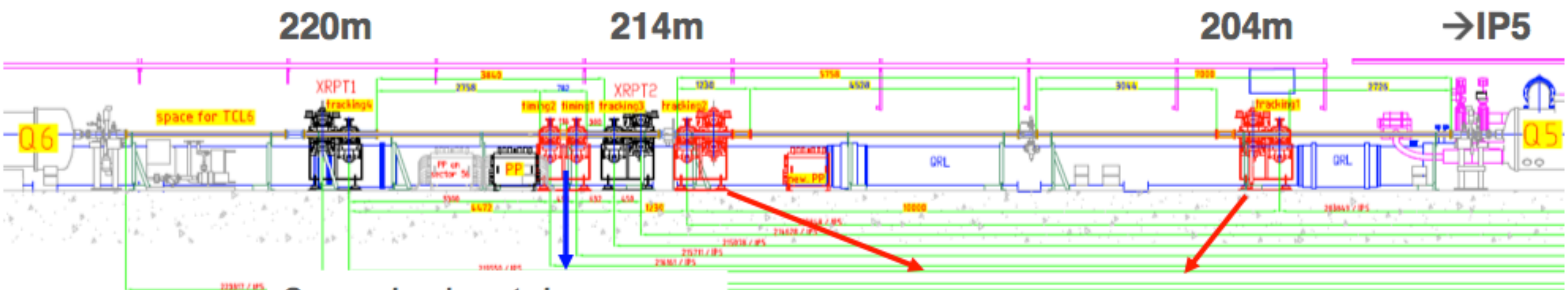


Summary

- Studied physics and detector performance
  - Timing resolutions of 10ps and 30ps
  - Distance from beam at 15σ and 20σ
- Physics case and impact of PPS
- Exclusive dijets
  - test of pQCD mechanism of exclusive production
  - S/B~1/8 for PU=50, and S/B~1/3 for PU=25
- Exclusive WW
  - Exclusive WW via photon-photon interaction (S/B~2:1)
  - Search for anomalous couplings (S/B~6:1)
- PPS improves sensitivity to SM and BSM physics

backup

Detector concept



2 new horizontal cylindrical RPs (1in LS1)

Equipped with timing detectors, for PU rejection

2 horizontal box-shaped RPs

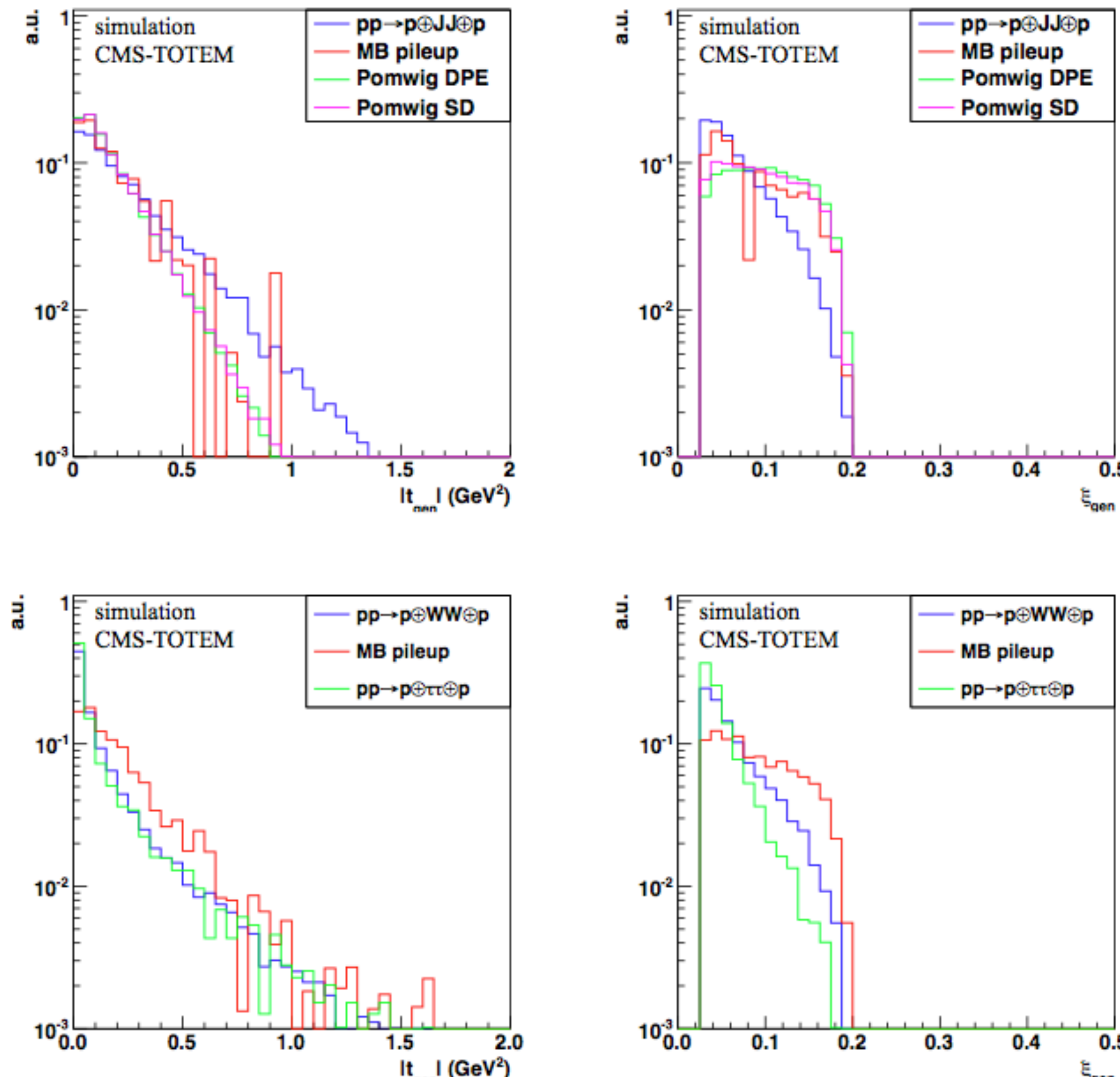
Equipped with tracking detectors to measure the displacement of the scattered protons w.r.t. the beam

Distributions of ξ, t

- In PPS acceptance information for signal and background

dijets

WW

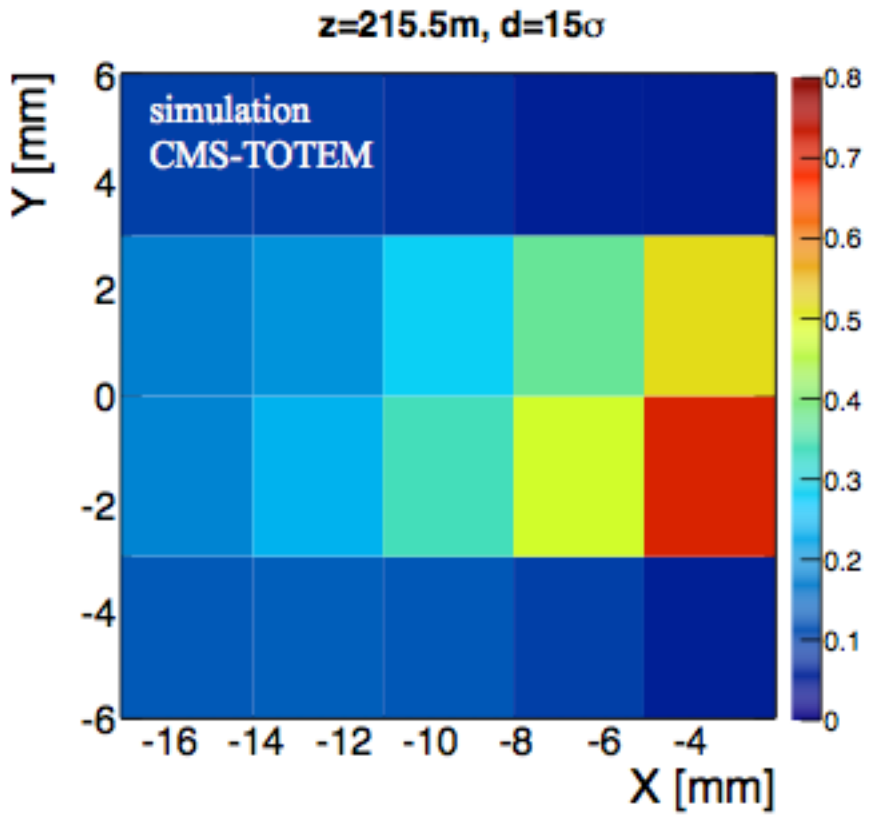


Dijets: yields in separate mass bins

	Exclusive dijets	DPE	SD	Inclusive dijets	S:B
pileup $\mu = 25$					
$M_X \leq 500$ GeV	4.0±0.2	0.2±0.1	0±1	1 ± 1	3:1
$500 < M_X \leq 800$ GeV	3.1±0.2	0.3±0.1	0±1	15 ± 1	1:5
$M_X > 800$ GeV	0.3±0.1	0.3±0.1	1±1	4 ± 1	1:18
pileup $\mu = 50$					
$M_X \leq 500$ GeV	2.8±0.2	0.6±0.2	0±1	5 ± 1	1:2
$500 < M_X \leq 800$ GeV	2.3±0.2	0.7±0.3	1.3±1.0	26 ± 1	1:12
$M_X > 800$ GeV	0.3±0.1	0±1	0±1	9 ± 1	1:30

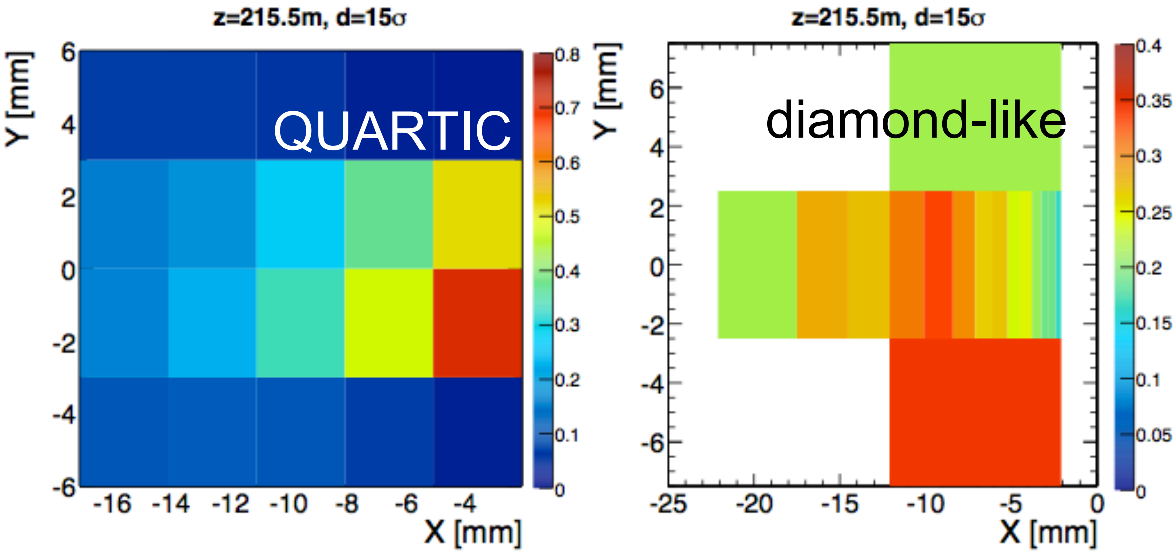
Detector inefficiency

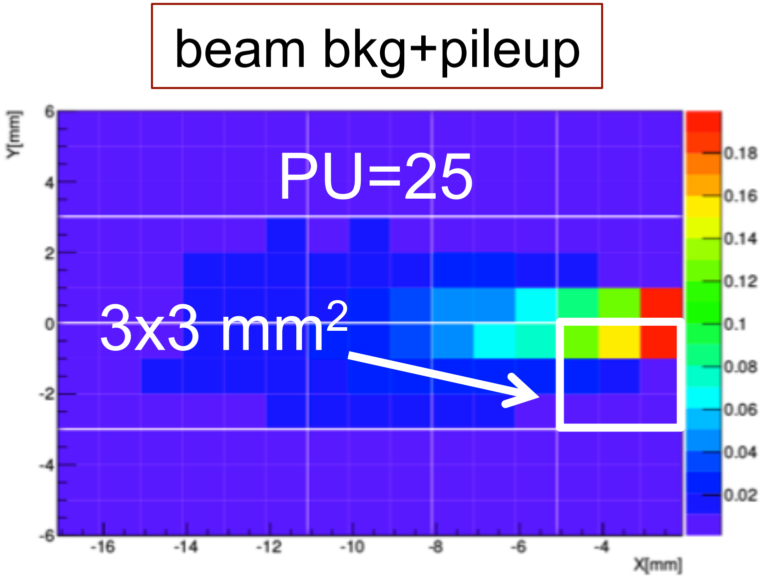
- High occupancy in baseline timing detector
  - Quartic: segmentation $3x3mm^2$
- Inefficiency due to overlapping hits ~40%
  - Motivation for R&D on new technologies



Timing detector occupancy

- Studied occupancy with beam bkg+pileup
- High occupancy in current Quartic design
- Studied alternative segmentation





Running conditions

- β~0.5-0.6m
- $N_{bunches}$~2800
- N_p~1.5 x 10^{11}
- E_{beam}=6.5 TeV
- μ=50
- L=1-100 fb^{-1}

- RP position wrt beam: 15 (20) σ
- RP tracking position: z= 204/214 m
- RP timing position: z=216 m
- RP timing resolution: σ=10 (30) ps

Anomalous WWγγ gauge coupling

- Quartic anomalous couplings parametrized by a_0^W, a_C^W
  - anomalous parameters =0 in SM
- Cross section enhanced at high mass

$$\mathcal{L}_6^0 \sim \frac{-e^2}{8}\frac{a_0^W}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W^-_\alpha - \frac{e^2}{16\cos^2(\theta_W)}\frac{a_0^Z}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}Z^\alpha Z_\alpha$$

$$\mathcal{L}_6^C \sim \frac{-e^2}{16}\frac{a_C^W}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}(W^{+\alpha}W^-_\beta + W^{-\alpha}W^+_\beta) - \frac{e^2}{16\cos^2(\theta_W)}\frac{a_C^Z}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}Z^\alpha Z_\beta$$

- Different behavior of cross section as function of anomalous coupling
- Measurement of WW events: 2W and protons tagged in forward detectors