Diffractive and Exclusive Physics with CMS

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Universidade do Estado do Rio de Janeiro

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Outline

CMS detector & forward instrumentation

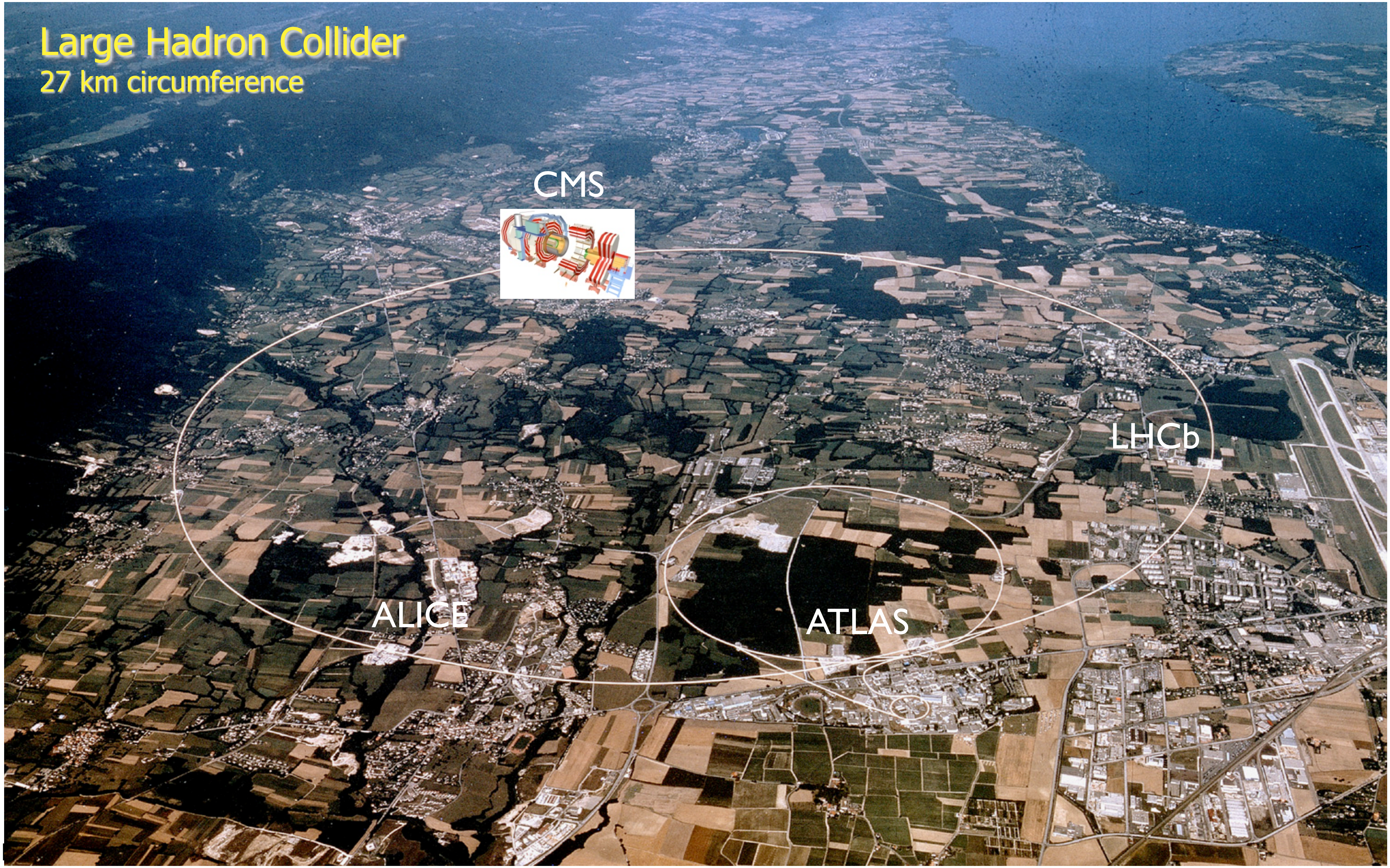
Probing hard diffraction

- Diffractive dijet production
- W/Z events with (pseudo-)rapidity gaps

Exclusive processes

- Exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ / $\gamma\gamma \rightarrow e^+e^-$
- Exclusive $\gamma\gamma \rightarrow W^+W^-$
- Central Exclusive Production

The CMS detector



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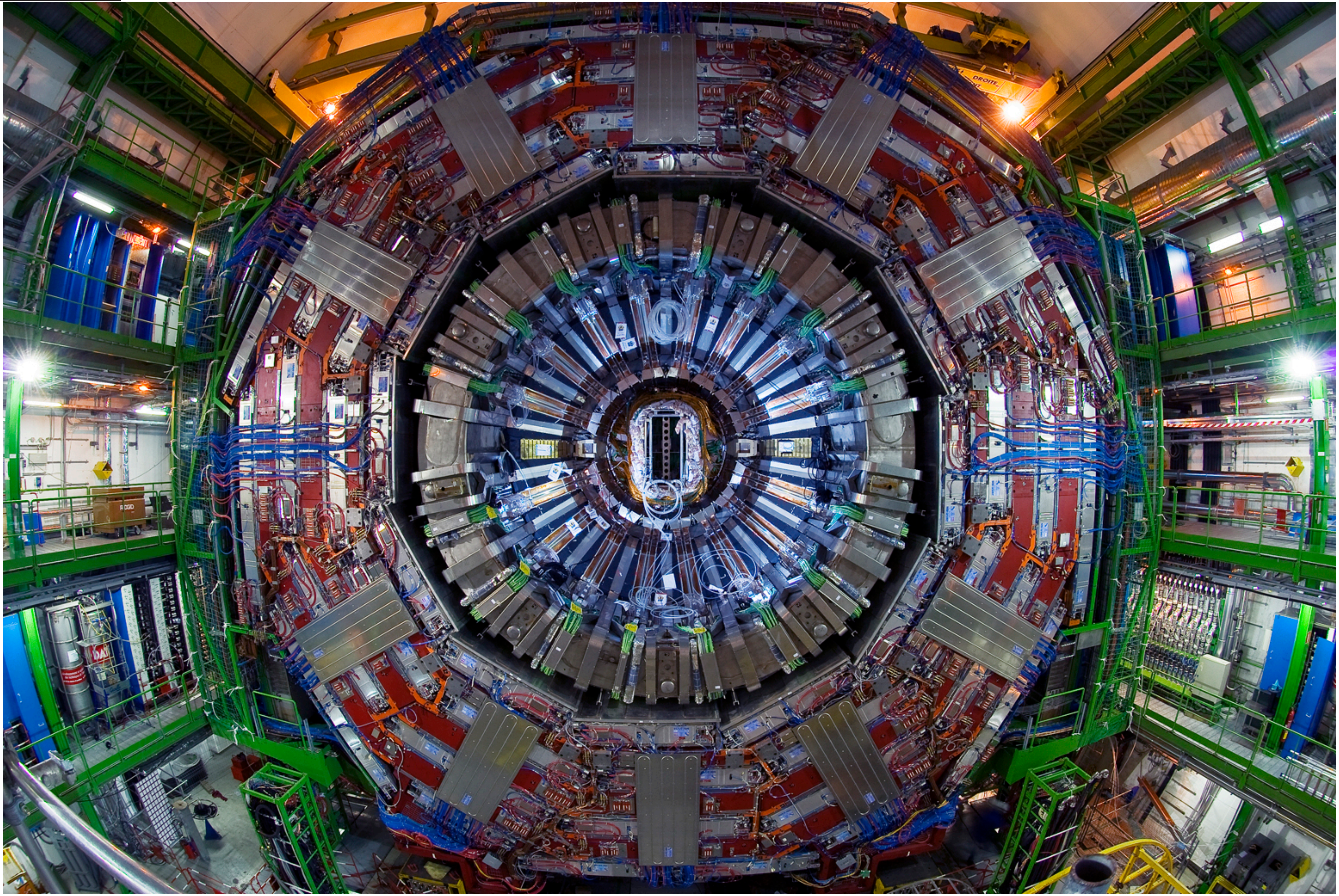

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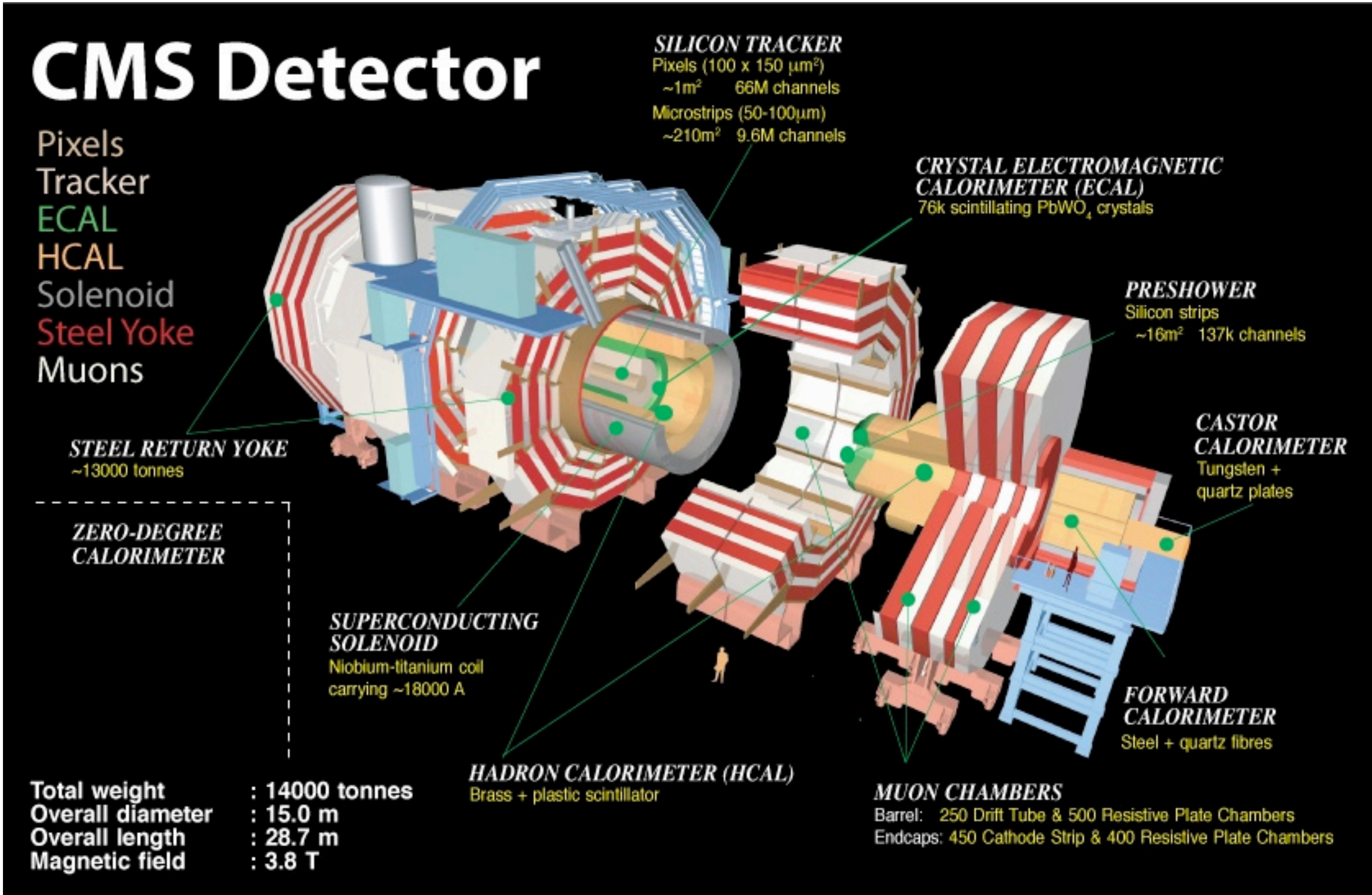
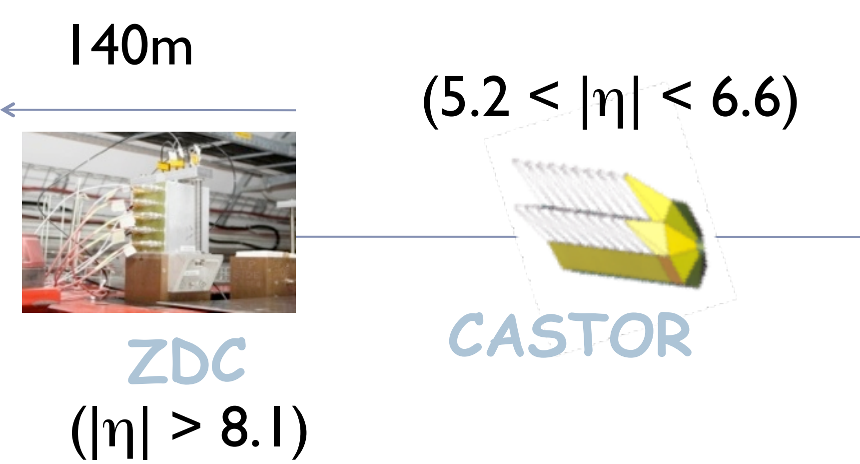
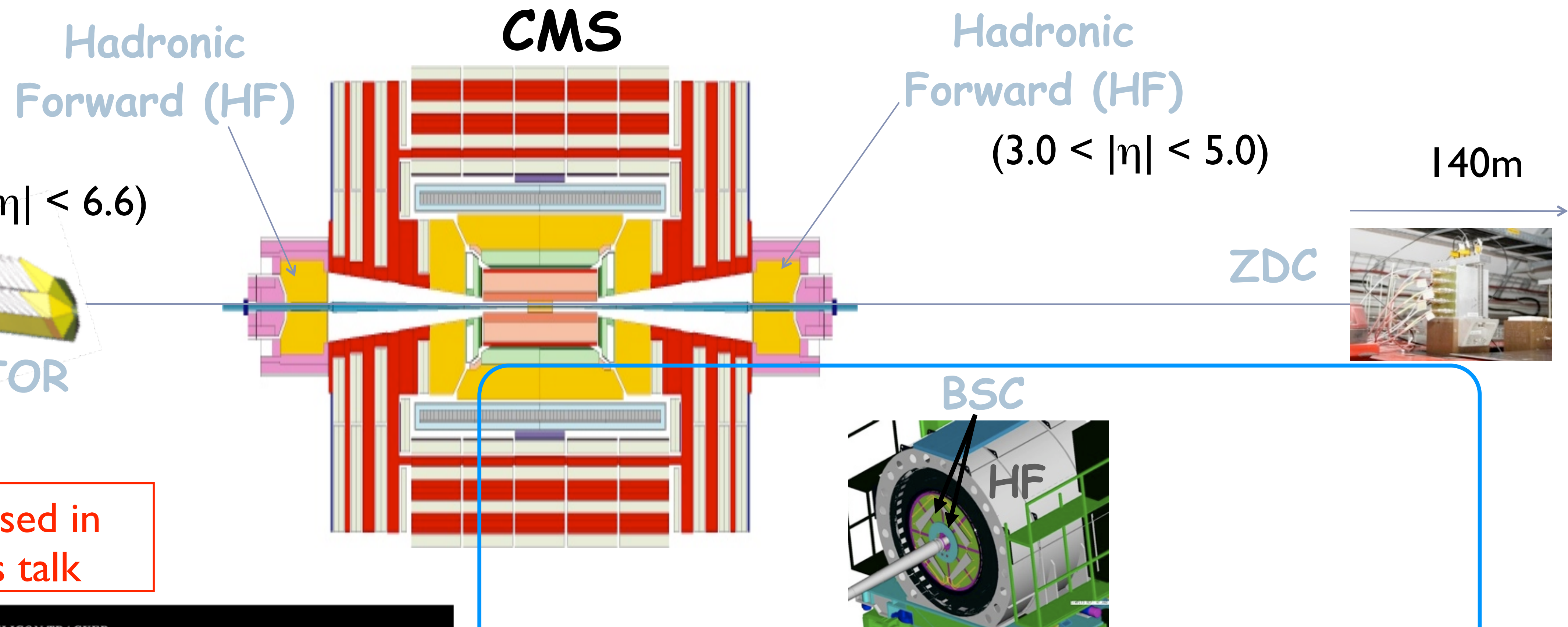


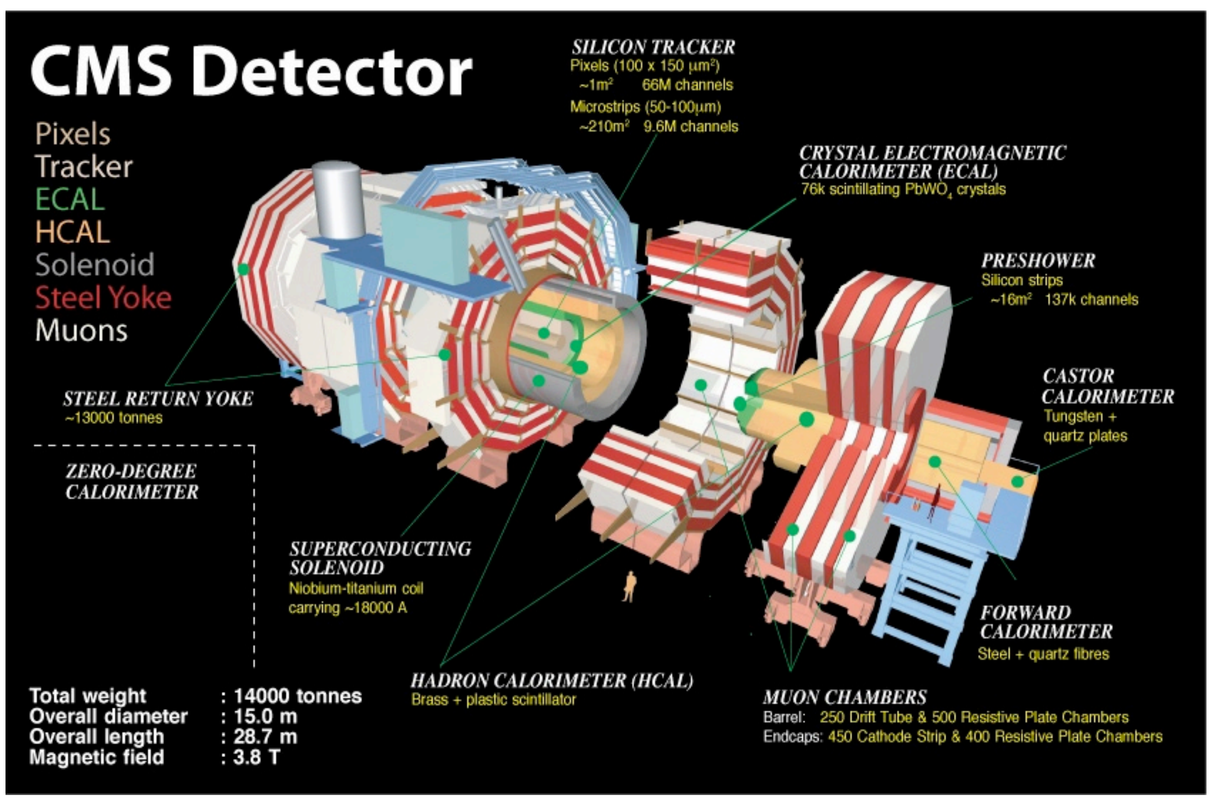
Forward detectors @ CMS

Detector configuration during 2010 - 2011





CASTOR & ZDC not used in results presented in this talk



Hadron Forward:

@11.2m from interaction point

Rapidity coverage: 3 < |η| < 5

Steel absorbers/quartz fibers (Long+short fibers)

0.175x0.175 η/φ segmentation

Acceptance limited to |η| < 4.9 at analysis level

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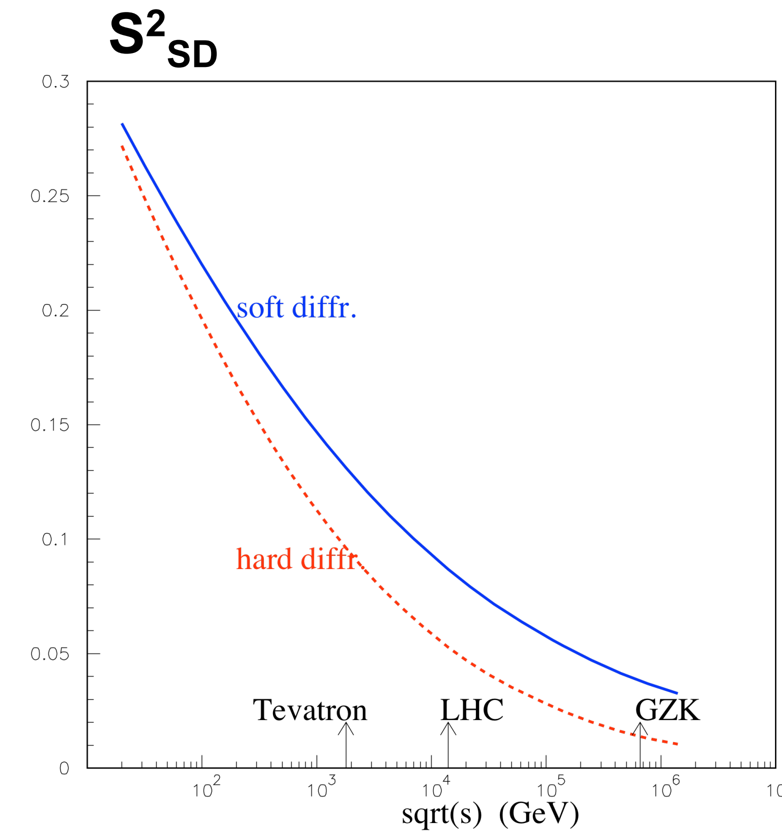
Probing hard diffraction

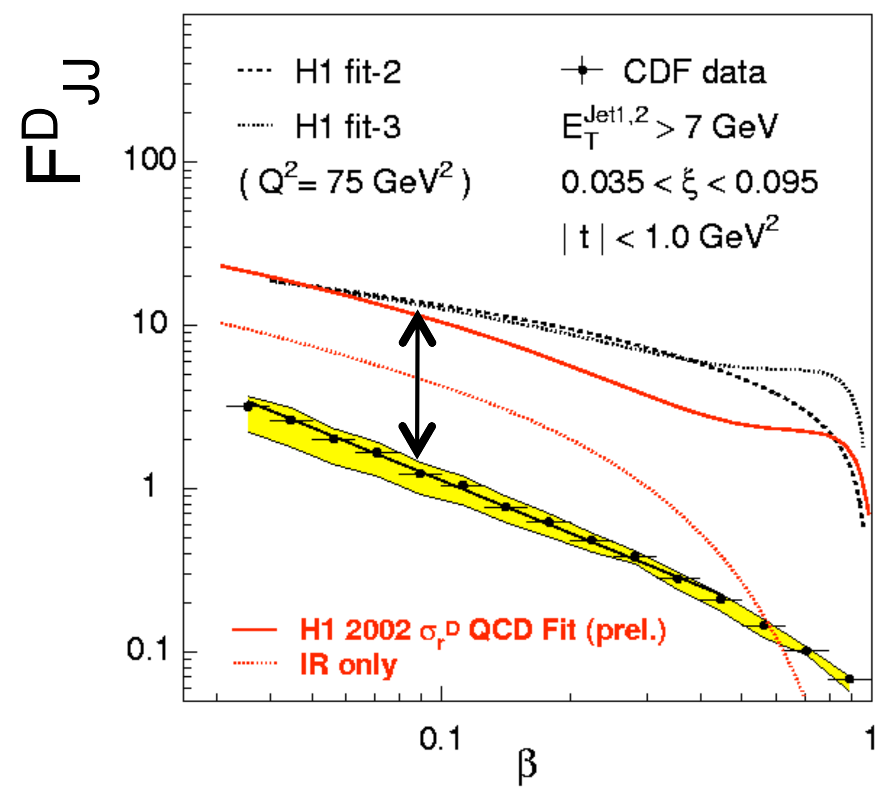
Diffractive events where a hard scale is present: high-p_T jets, W/Z's, ...

Extension of HERA/Tevatron studies on diffractive PDFs (dPDFs), rapidity gap survival probability (<S^2>) & exclusive processes

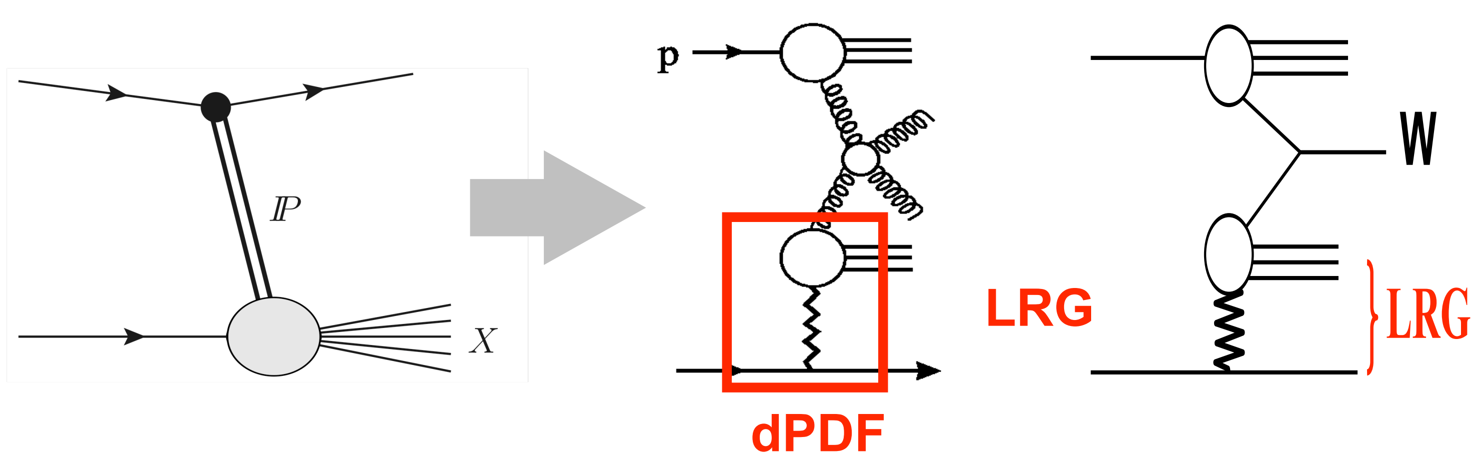
Set the framework for future searches with proton tagging at high luminosity



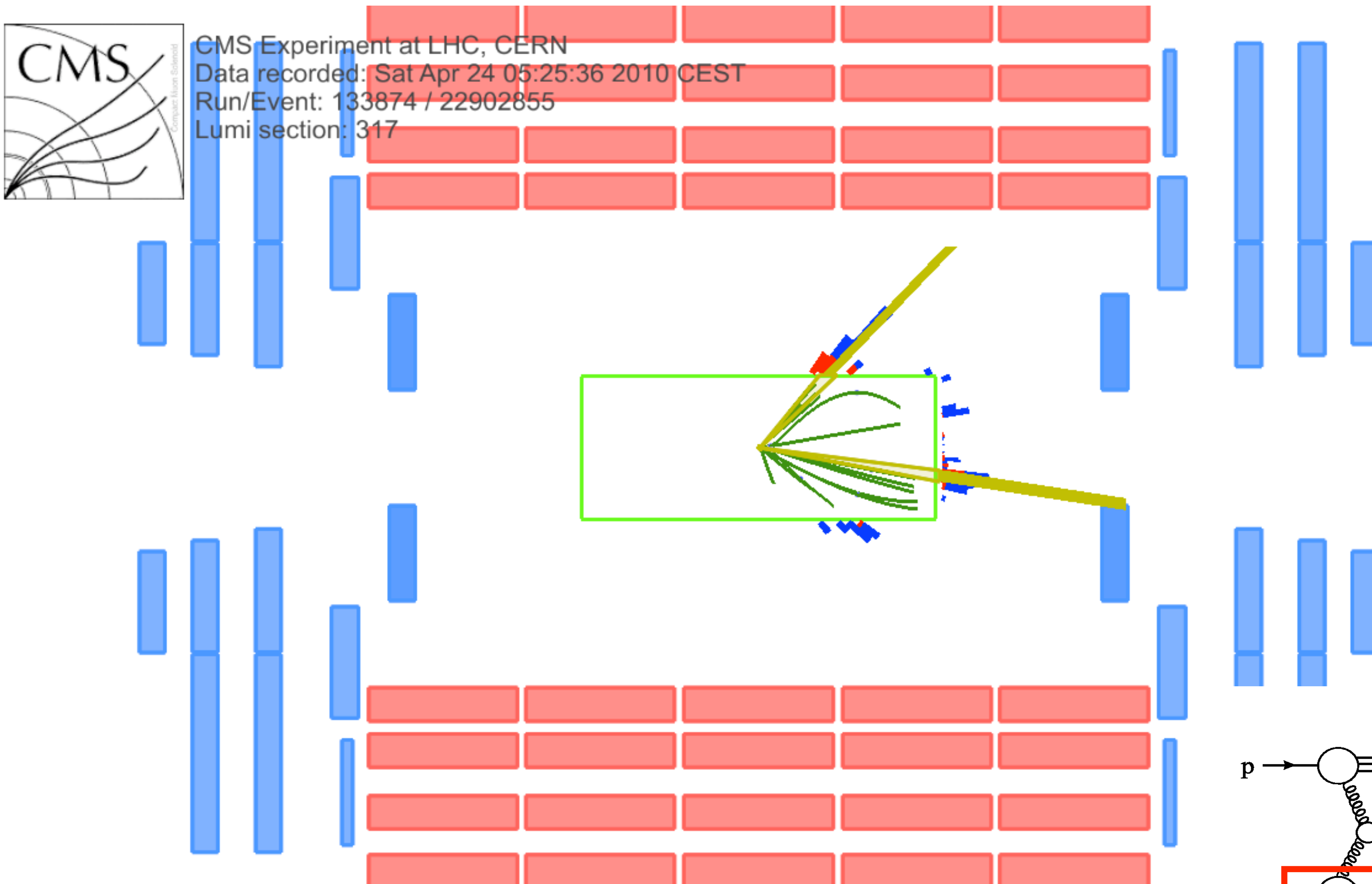
V.A.Khoze et al, Phys. Lett. B 643 (2006)

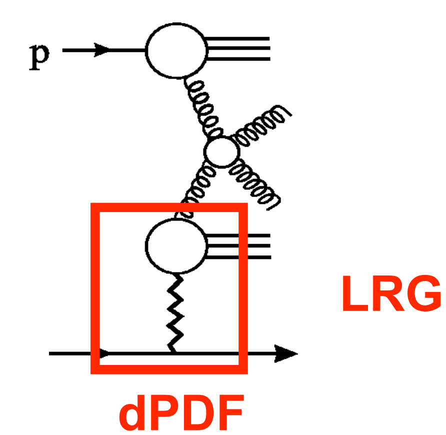


CDF Collaboration, Phys. Rev. Lett. 84, 5043 (2000)

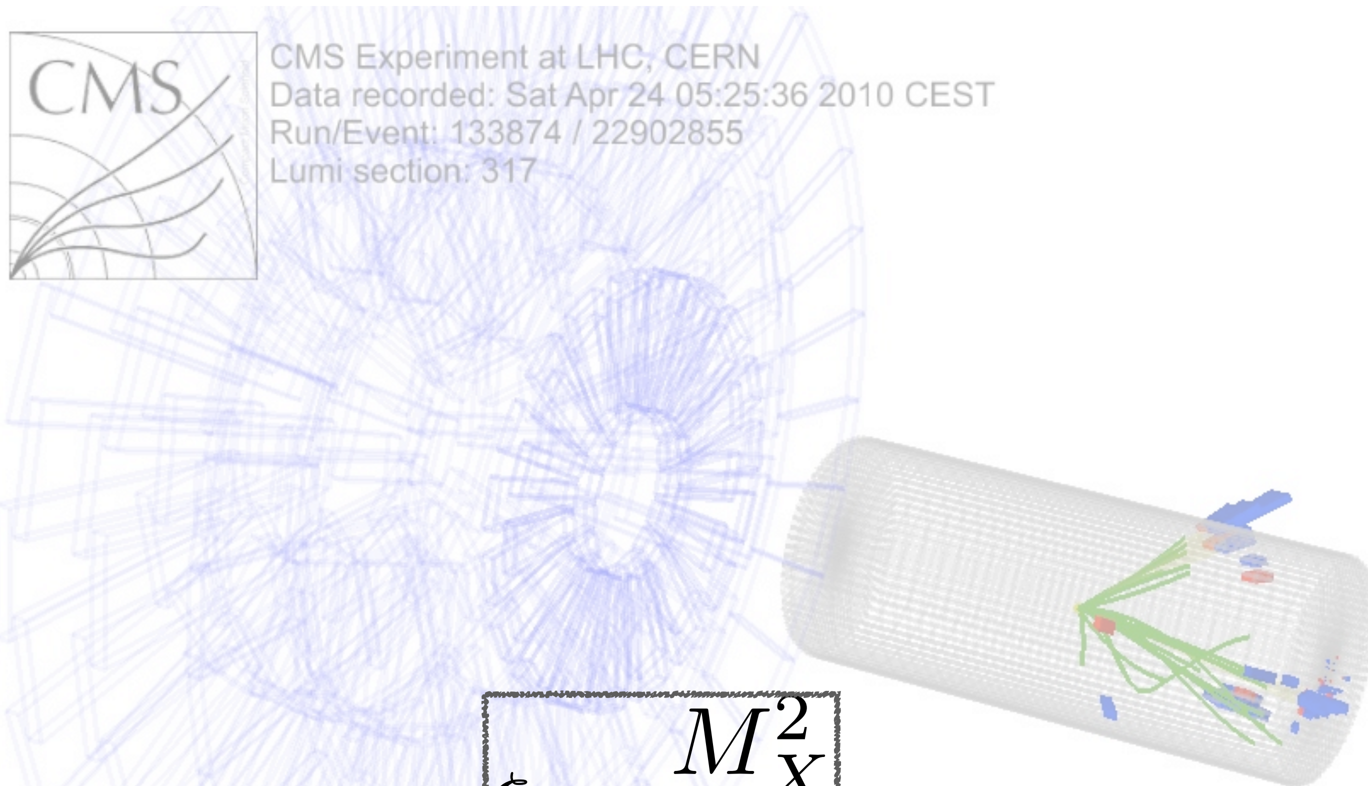


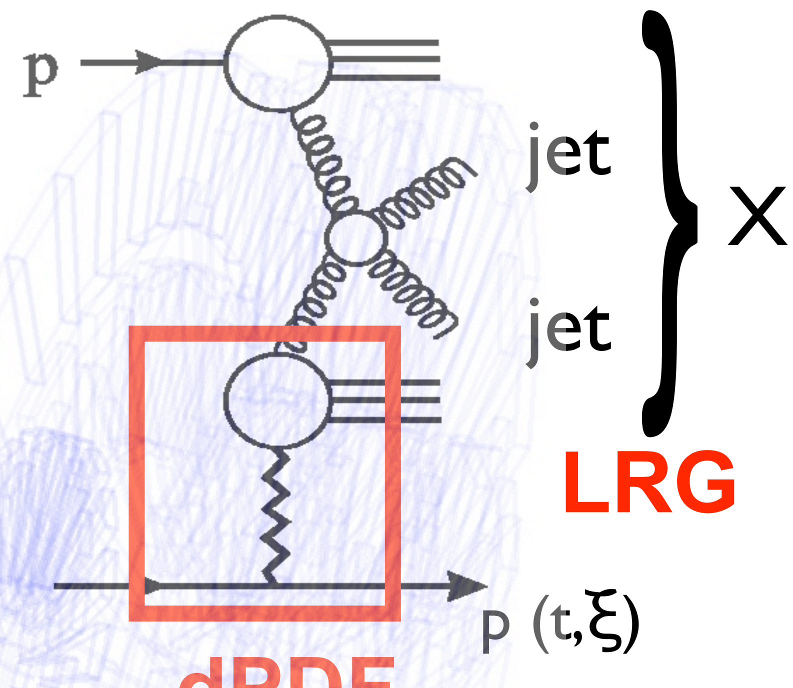
Diffractive dijet candidate





Kinematics & cross section





$$\xi = \frac{M_X^2}{s}$$

diffractive pdf: "pomeron" flux ⊗ pdf

partonic cross section

$$\frac{d^2\sigma}{d\xi dt} = \sum \int dx_1 dx_2 \, f(\xi, t) \, f_{I\!P}(x_1, \mu) \, f_p(x_2, \mu) \, \hat{\sigma}$$

proton pdf

$$f(\xi, t) = \frac{e^{Bt}}{\xi^{2\alpha_{I\!P}(t)-1}}$$

Implemented in "hard-diffractive" MC's: POMPYT, POMWIG, PYTHIA8, etc.

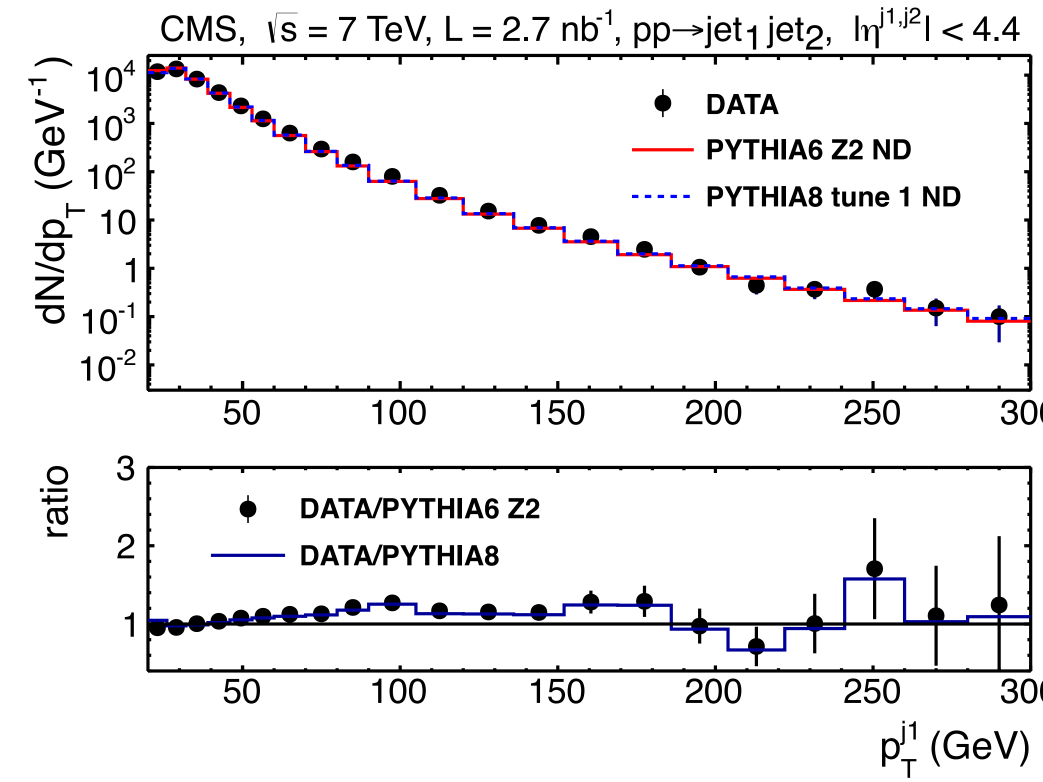
Event selection

Low-p_T trigger at 6 GeV (uncorrected)

High quality vertex + beam background and noise rejection

At least two jets with p_T > 20 GeV and within $-4.4 < \eta < 4.4$

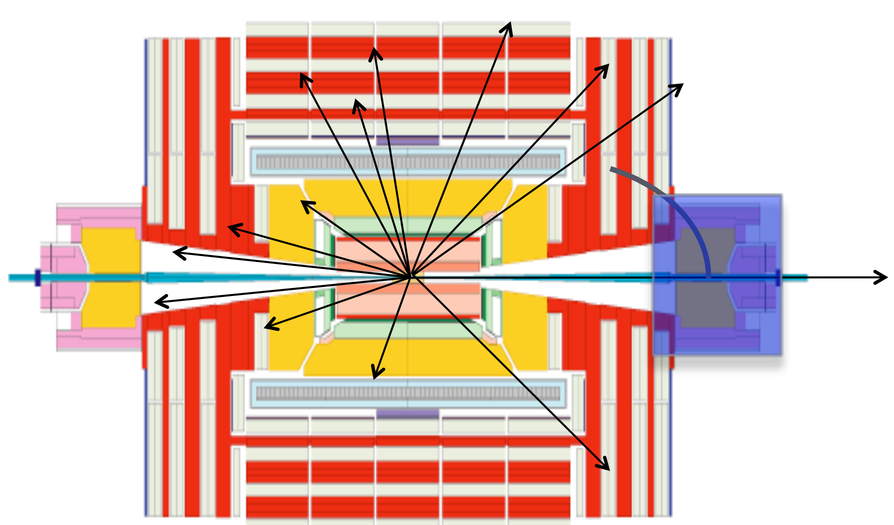
$\eta_{max(min)}$: most forward (backward) particle in the detector



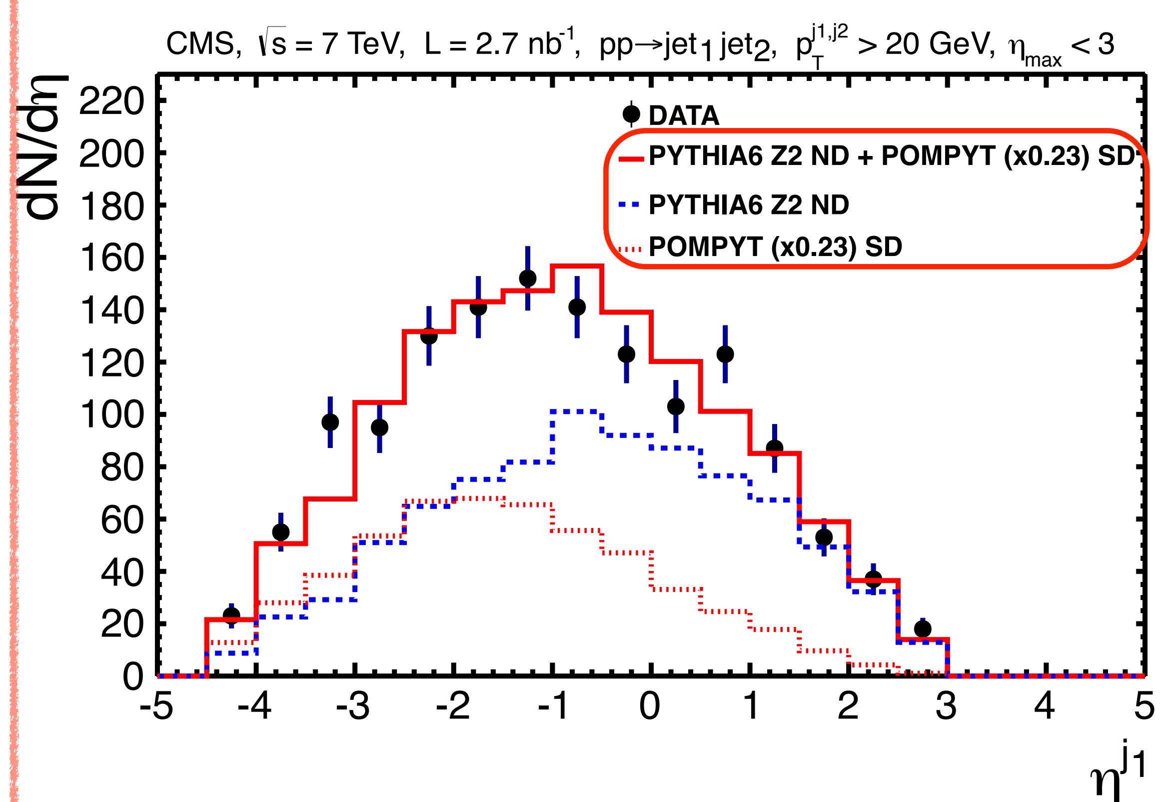
CMS FWD-10-004

Phys. Rev. D 87 (2013) 012006

Forward η-gap selection



Selection comprising Δη ~ 1.9 in forward calorimeter (HF) acceptance



Normalised to fit of PYTHIA6 + POMPYT

Event distributions

Distributions are obtained as a function of ξ^+ and ξ^-, and averaged

A combination of PYTHIA6 (Tune Z2) and POMPYT is used to describe the data, where their relative contributions are obtained from a fit to the ξ distribution

Note that different MC tunes would imply considerable variations in relative yields

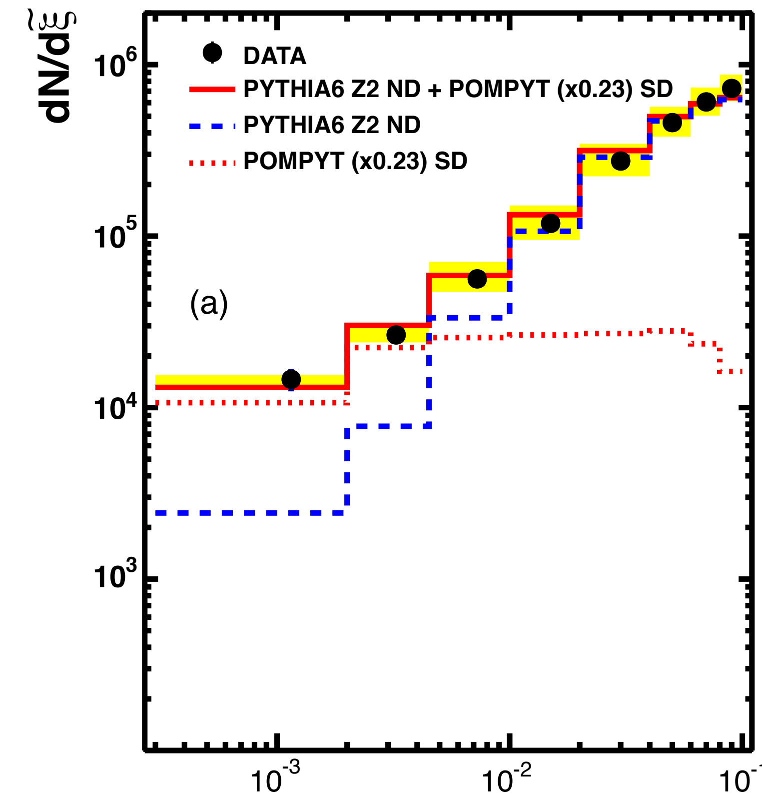
Suppression of events with high ξ values after $\eta_{max} < 3$ (or $\eta_{min} > -3$) selection, while low-ξ region is mostly unaffected

Results in three ξ bins: (0.0003,0.002); (0.002,0.0045); (0.0045,0.01)

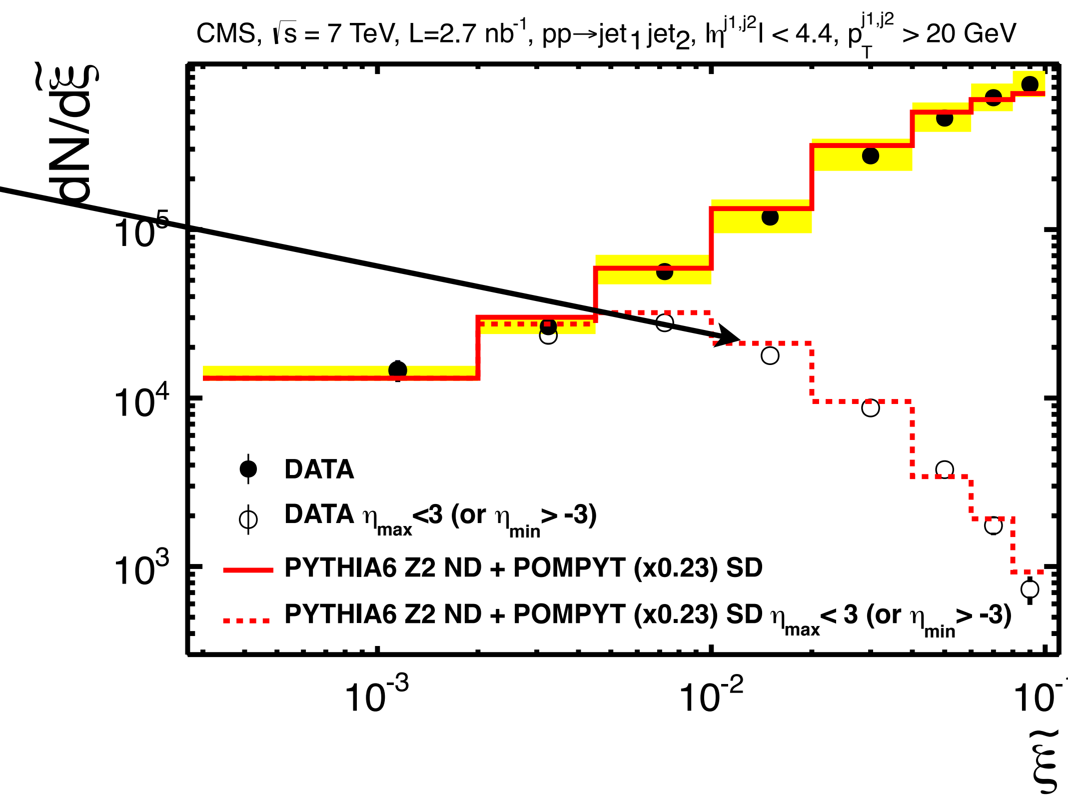
See Diego Figueiredo's poster at LISHEP2013 for more details

$$\tilde{\xi}^{\pm} = C \frac{\sum (E \pm p_z)}{\sqrt{s}}$$

(See Backup)



Energy scale uncertainties



CMS FWD-10-004

Phys. Rev. D 87 (2013) 012006

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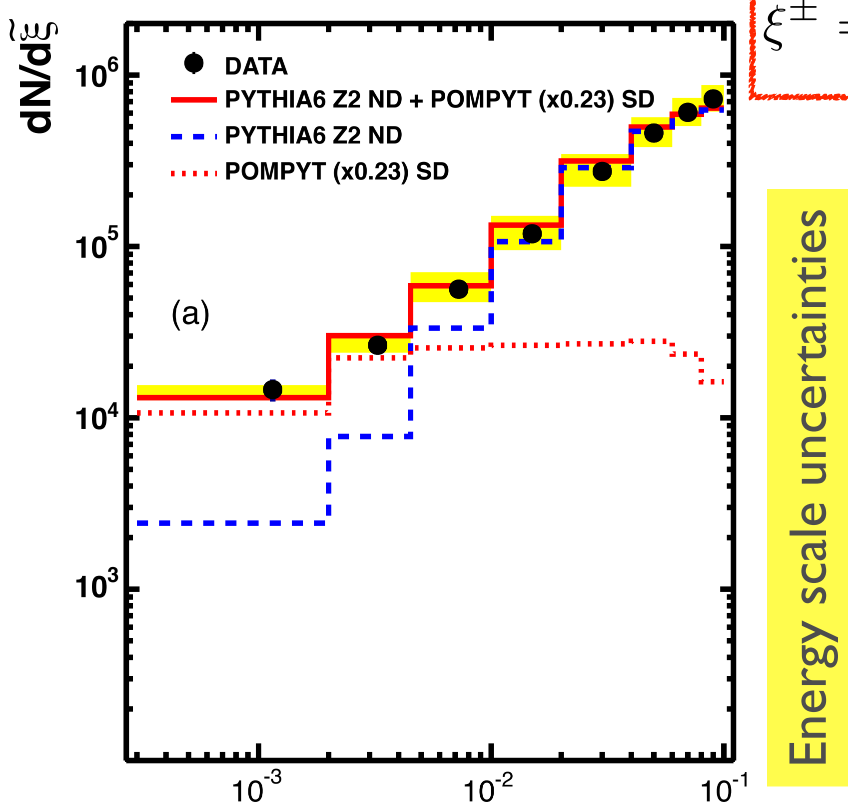

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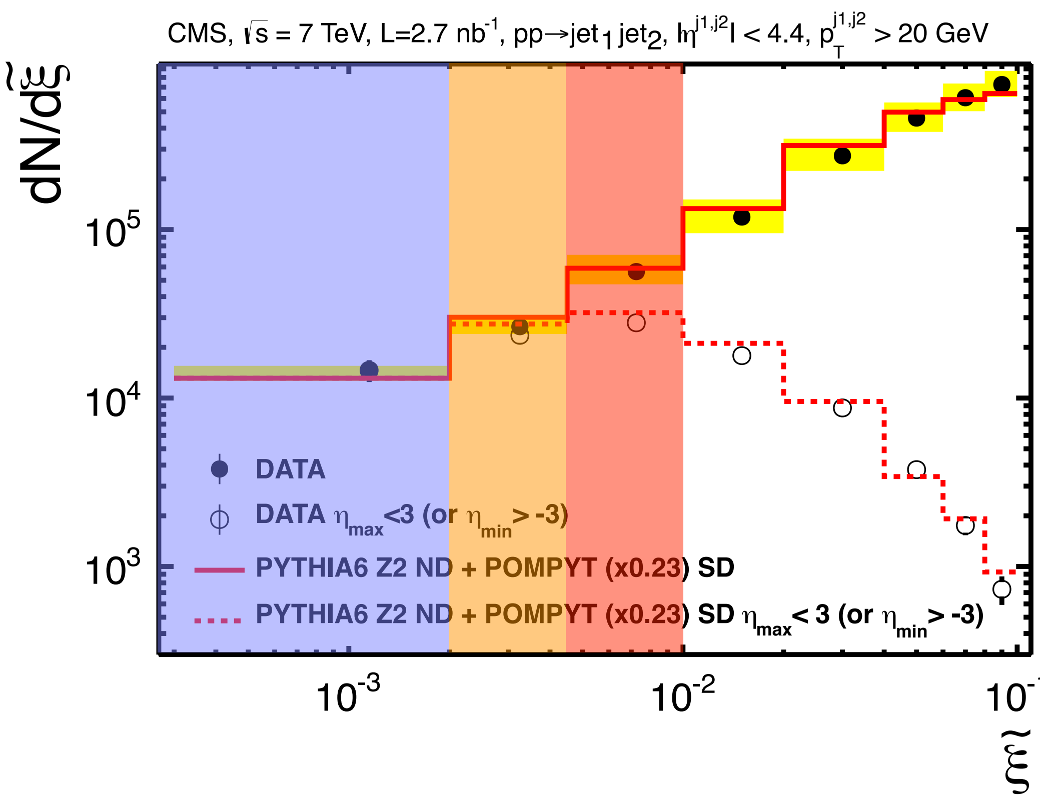

CMS FWD-10-004

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Dijet cross section

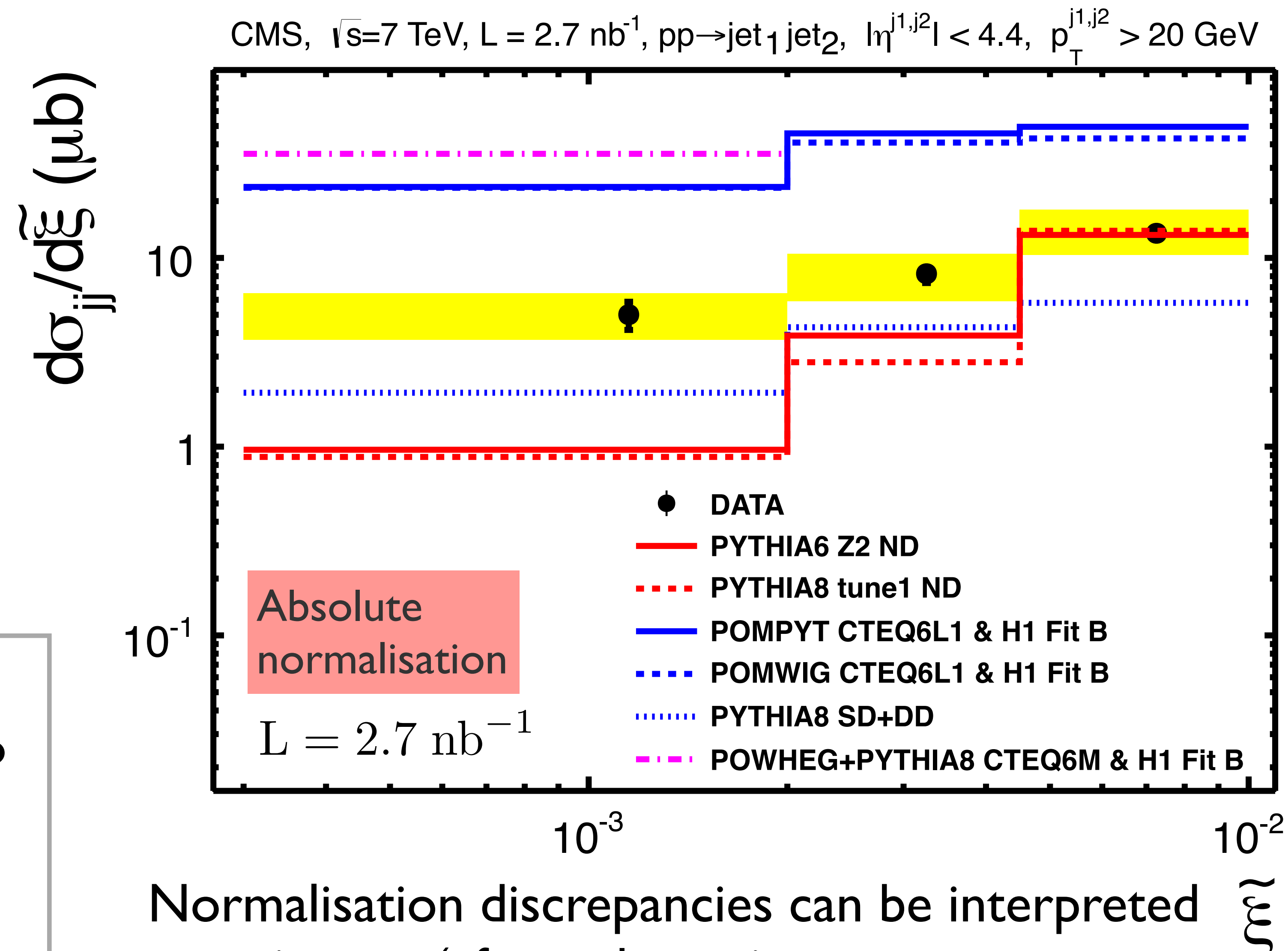
$$\frac{d\sigma_{jj}}{d\tilde{\xi}} = \frac{N^i_{jj}}{L \cdot \epsilon \cdot A^i \cdot \Delta\tilde{\xi}^i}$$

$$A^i_{MC} = \frac{N^i(\tilde{\xi}_{Rec})}{N^i(\tilde{\xi}_{Gen})}$$

Excess of events in low-ξ region with respect to non-diffractive MC's PYTHIA6 and PYTHIA8

POMPYT and POMWIG (LO) diffractive MC's as well as the NLO calculation from POWHEG, using diffractive PDFs, are a factor ~5 above the data in lowest ξ bin

PYTHIA8 diffractive cross sections are considerably lower due to different pomeron flux parametrisation

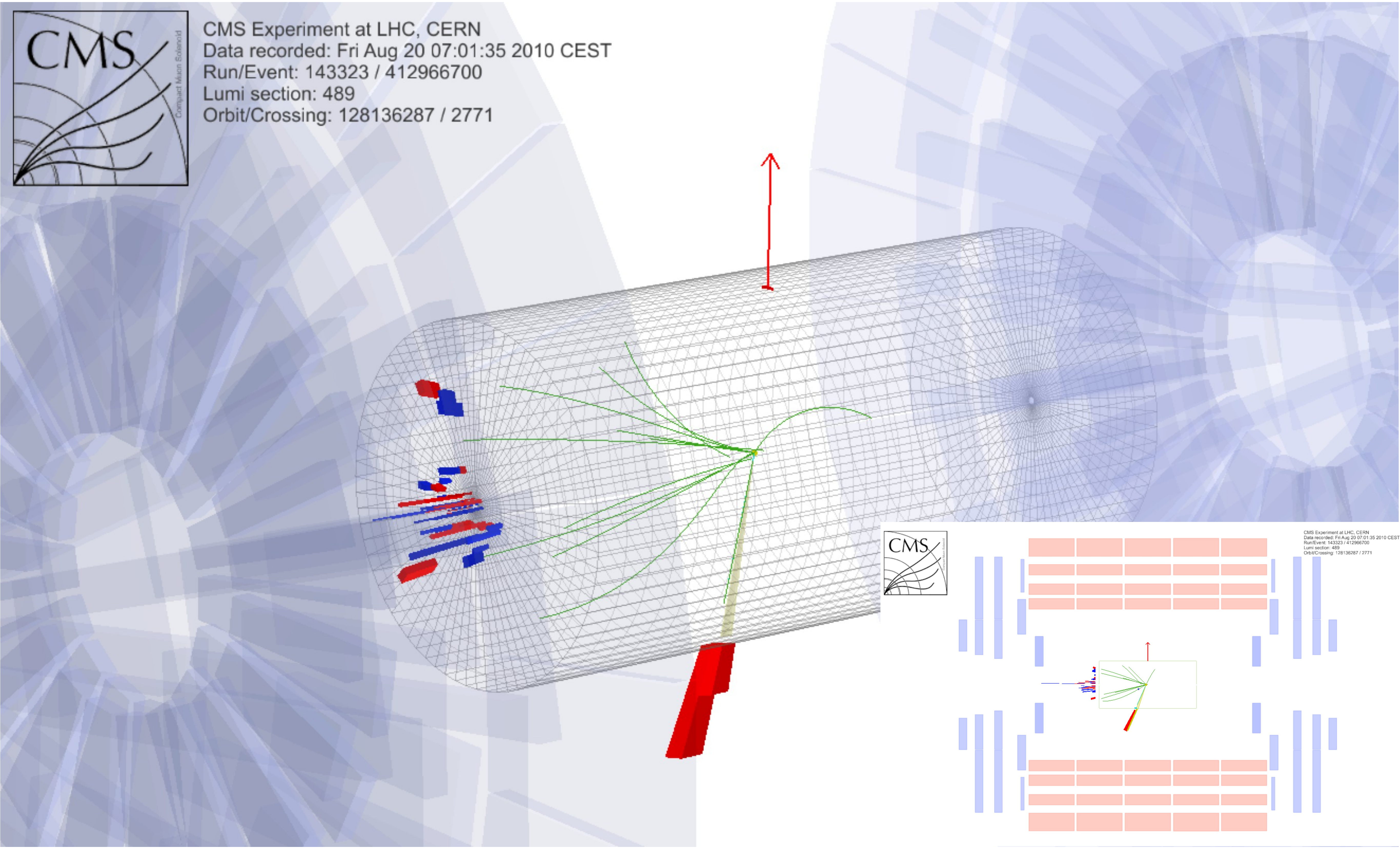


Normalisation discrepancies can be interpreted as estimates (after subtracting proton dissociation) of rapidity gap survival probability:

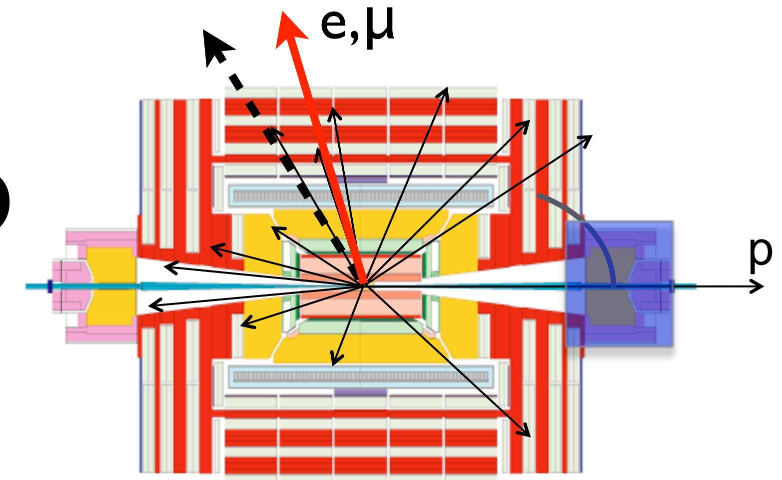
$$S^{2\,(*)}_{data/MC} = 0.12 \pm 0.05 \text{ (LO MC)}$$
$$S^{2\,(*)}_{data/MC} = 0.08 \pm 0.04 \text{ (NLO MC)}$$

(*) MC based subtraction of proton dissociation

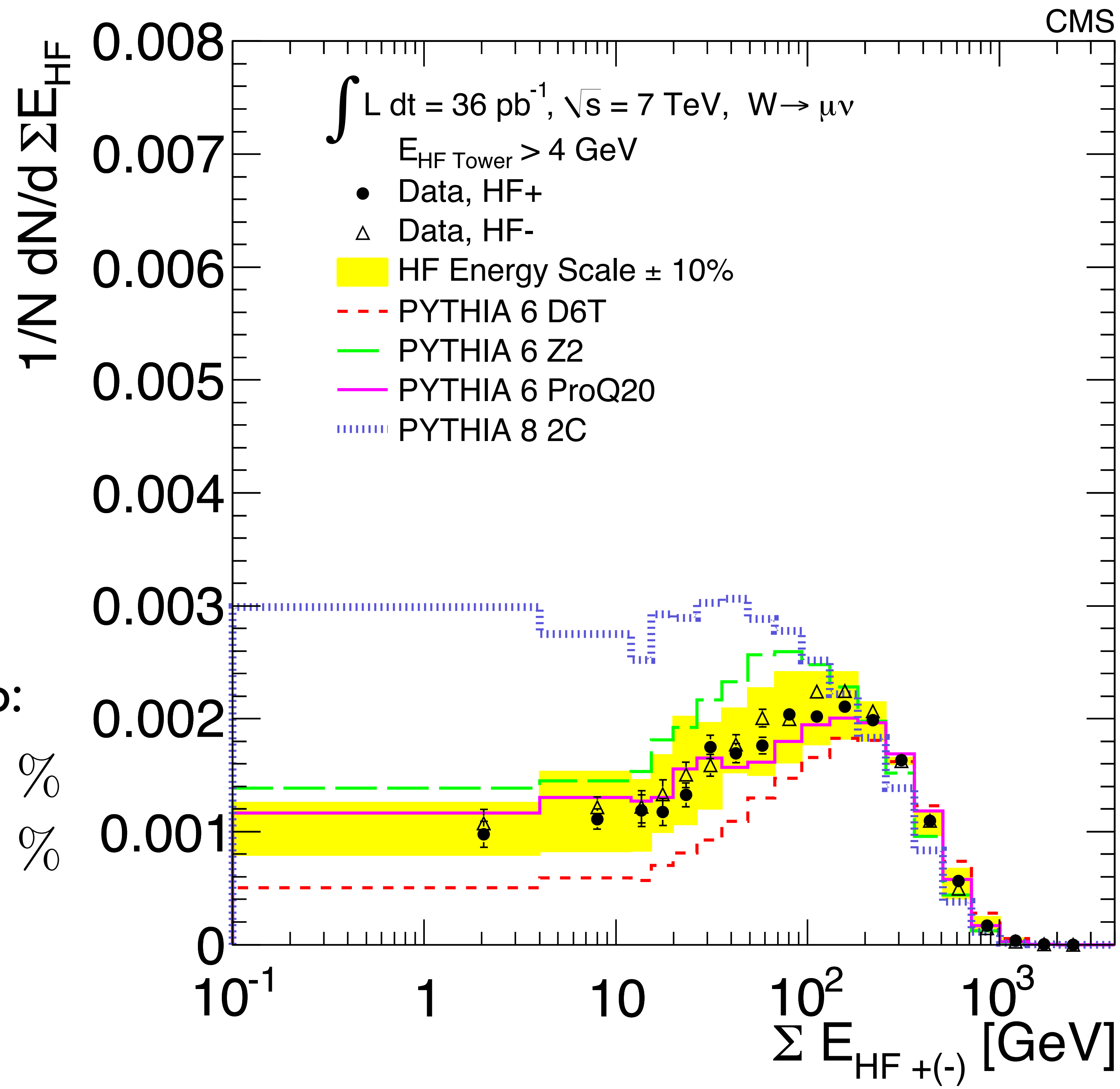
W/Z events with pseudorapidity gaps



W/Z events with an η-gap



- Diffractive component in W/Z data set
- Events with low energy deposits at the forward calorimeters
- Monte Carlo generators cannot describe the data (extensive studies on overall energy flow and correlations)



Fraction of W/Z events with a forward gap:

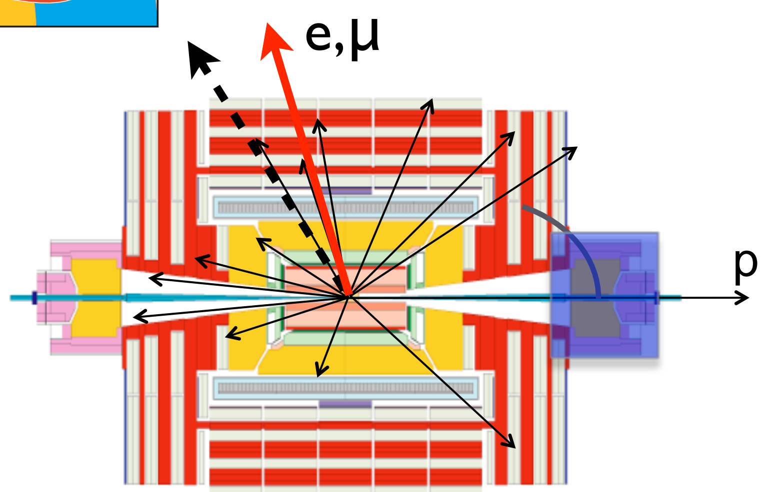
$W\rightarrow l\nu$: $1.46 \pm 0.09(\text{stat.}) \pm 0.38(\text{syst.})\ \%$

$Z\rightarrow ll$: $1.60 \pm 0.25(\text{stat.}) \pm 0.42(\text{syst.})\ \%$

CMS FWD-10-008

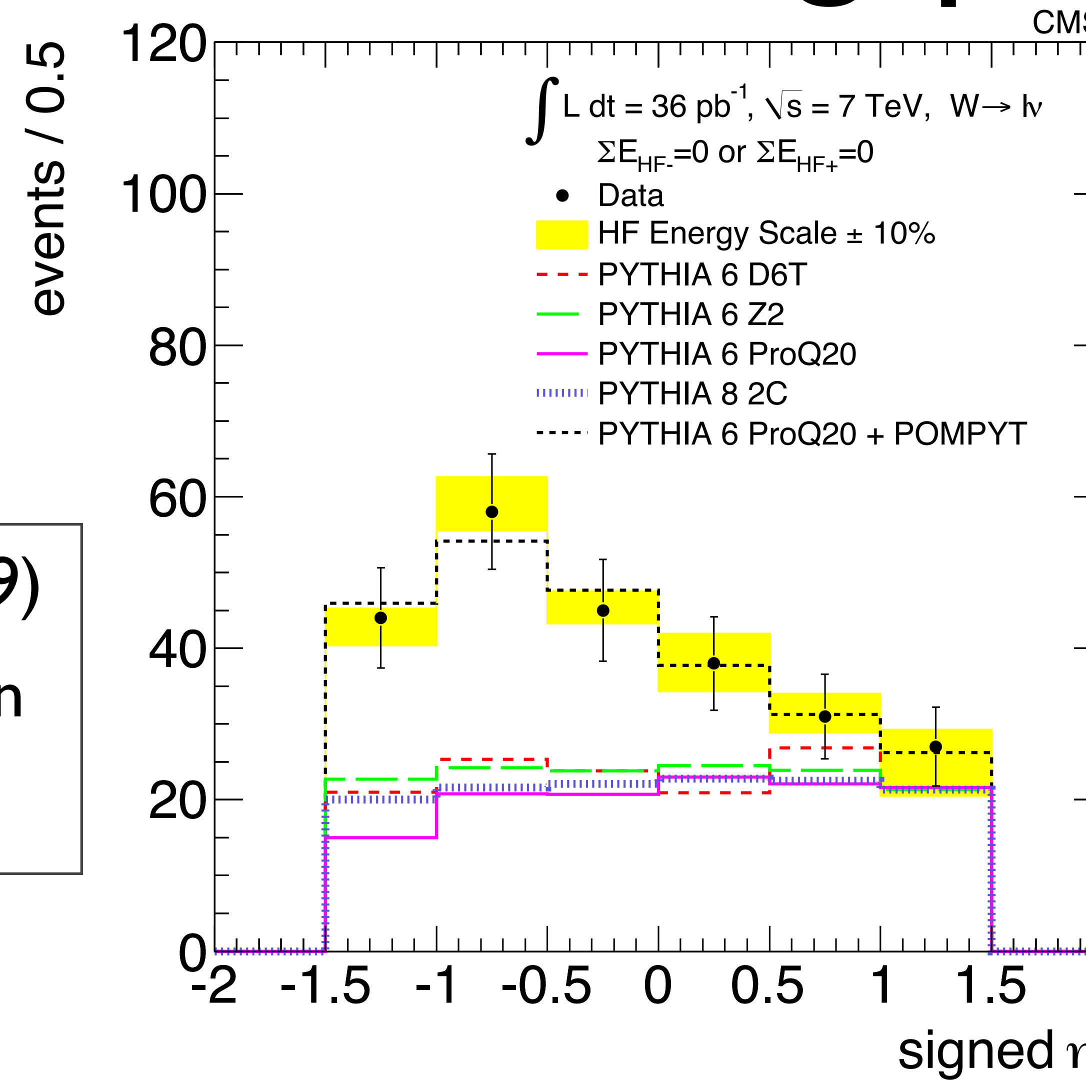
Eur. Phys. J. C (2012) 72:1839

W→eν(μν) events with a gap



Forward gap selection in HF (3 < |η| < 4.9)

Signed η_{lepton} distribution (η_{lepton} < 0 when e,μ opposite to the pseudorapidity gap)



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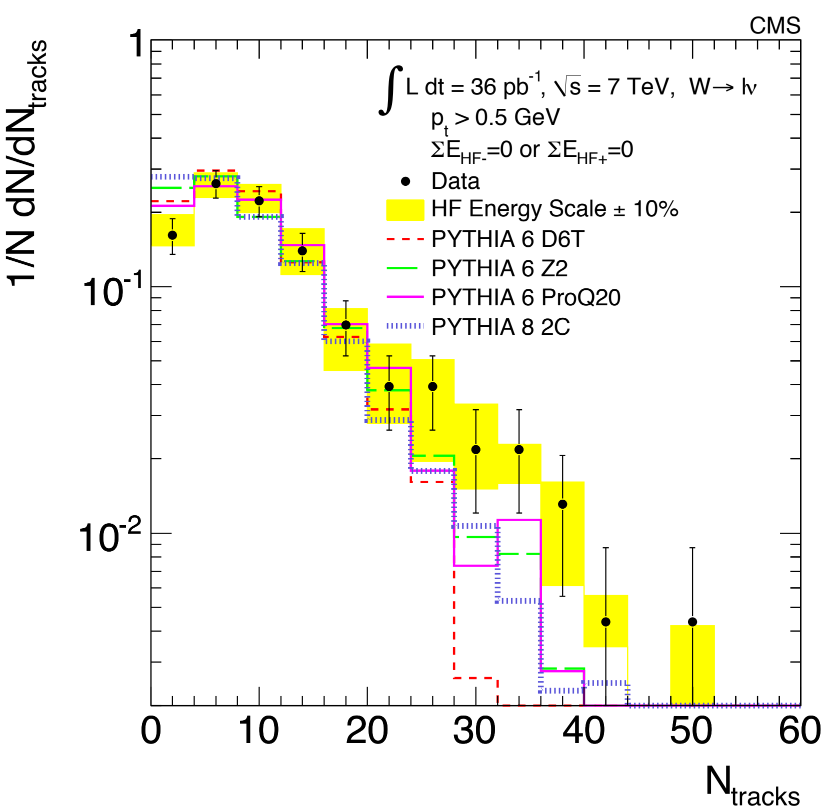

Flat for non-diffractive, asymmetric for diffractive events

Evidence of diffractive W production in the data

Fit for PYTHIA (ND) + POMPYT (SD):

$$f_{\rm SD} = 50.0 \pm 9.3({\rm stat.}) \pm 5.2({\rm syst.})\ \%$$

(η-gap sample)

CMS FWD-10-008

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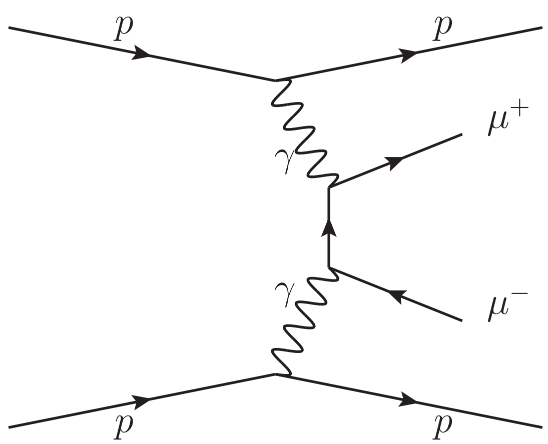
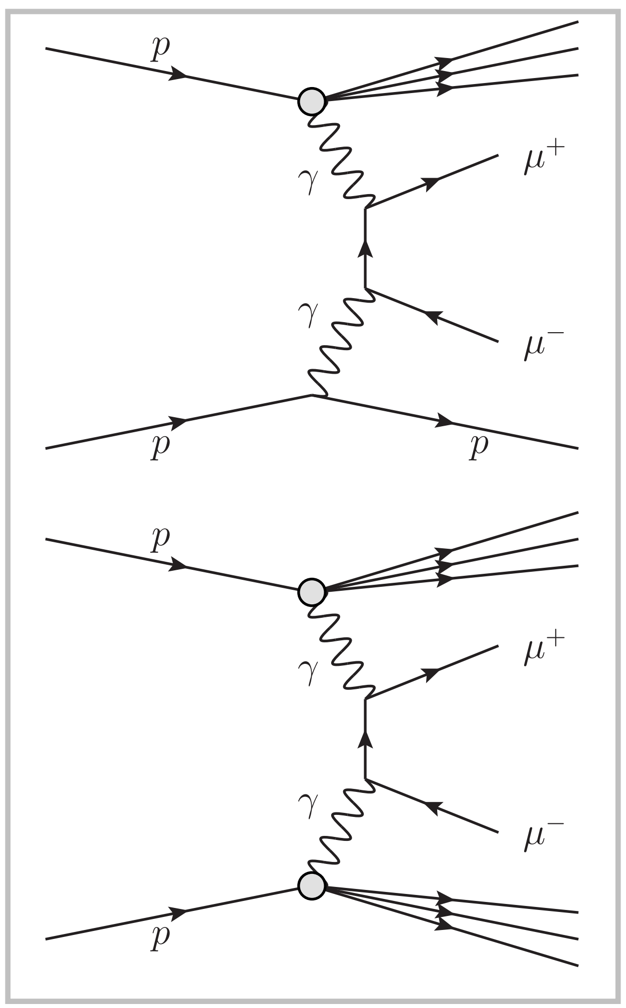
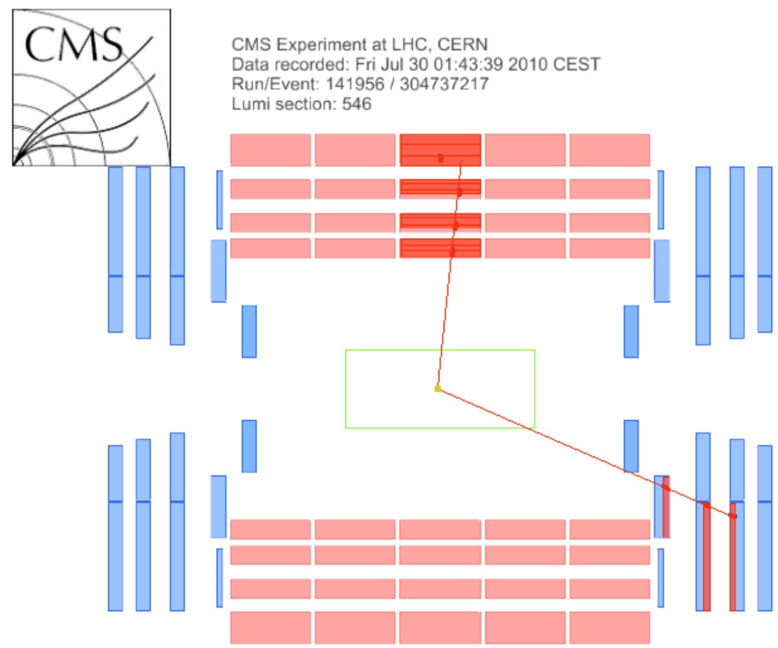
Exclusive production: $\gamma\gamma \rightarrow \mu^+\mu^-/e^+e^-$

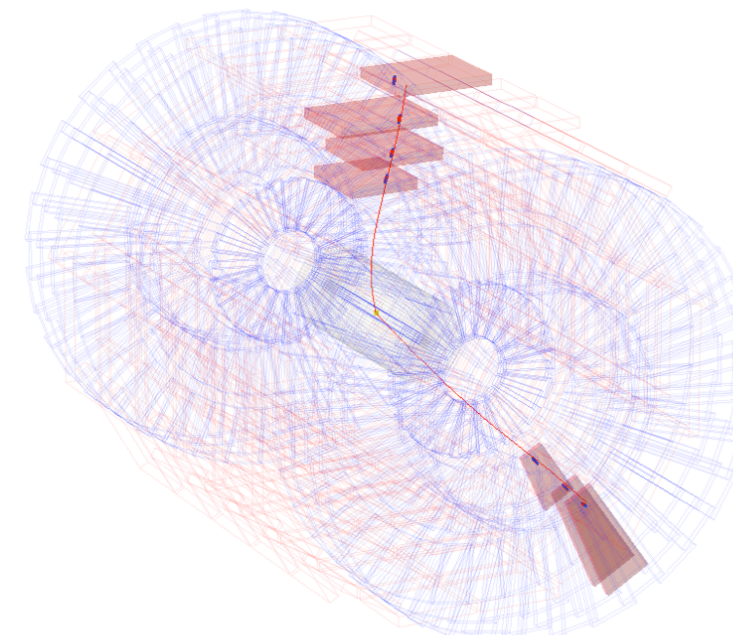
[CMS FWD-10-005](#)

[*J. High Energy Phys.* 01 (2012) 052](#)









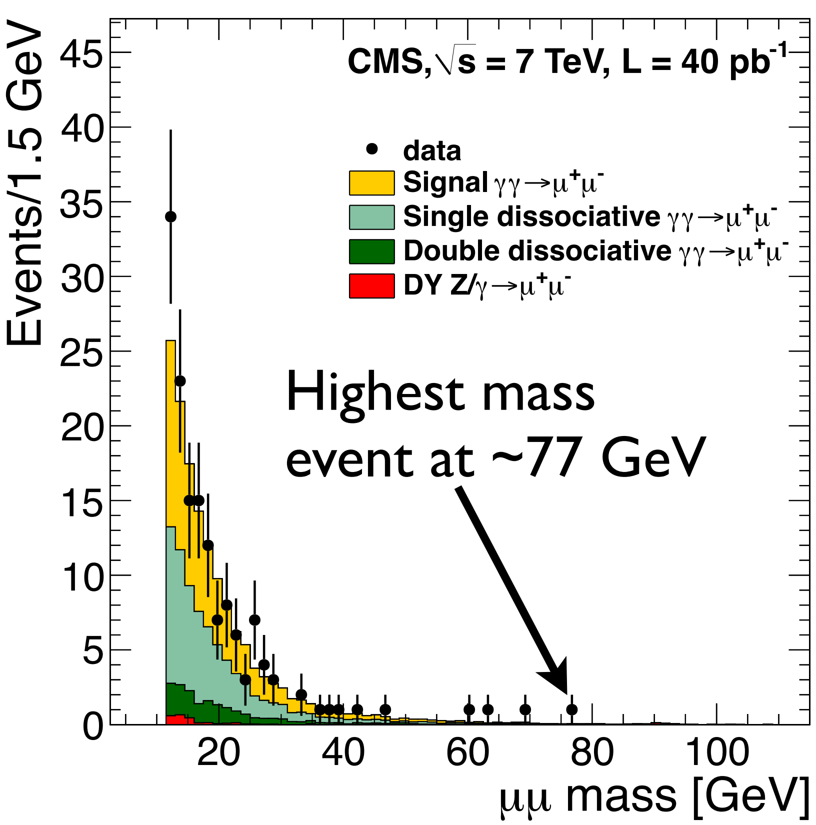
- Exclusive two-photon events: 2 muons/electrons and *nothing else*
- Main background to pure QED process from single and double proton dissociation processes, where the proton fragments in a low mass state
- Standard candle for exclusive processes at the LHC

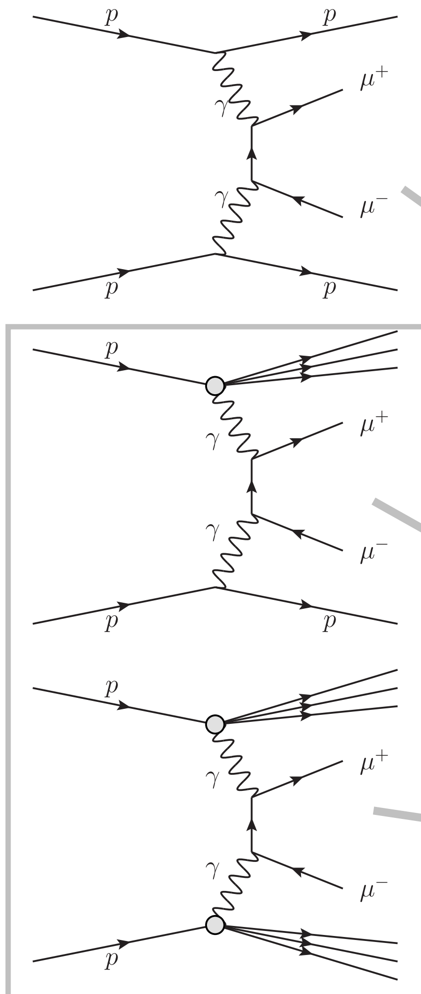
Exclusive $\gamma\gamma \to \mu^+\mu^-$ production

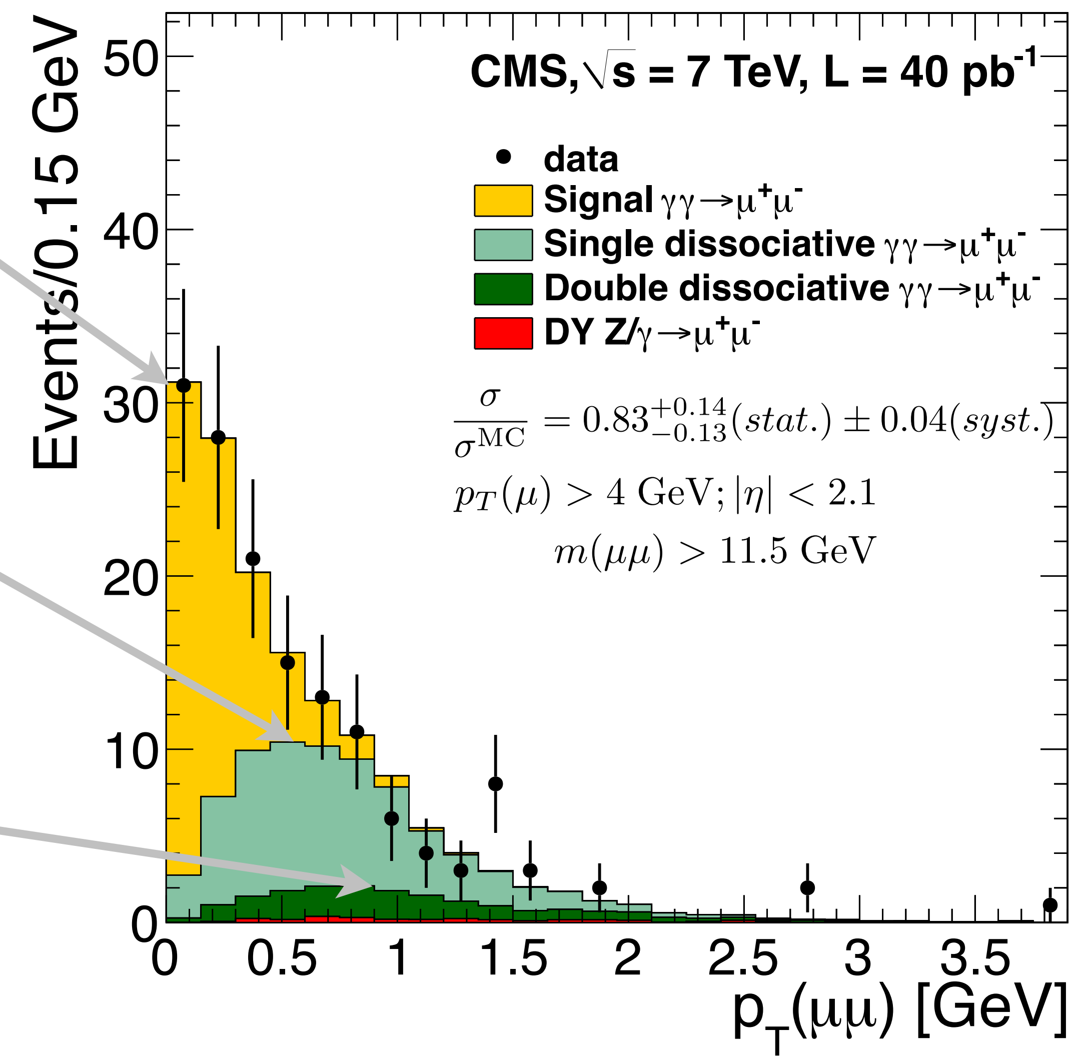
Measurement restricted to well controlled kinematic region ($p_T(\mu) > 4$ GeV, $|\eta| < 2.1$, $m(\mu\mu) > 11.5$), rejecting Υ photo-production

Exclusivity condition requires a primary vertex with exactly 2 muons and no other track within 2 mm

Signal extracted with a binned maximum likelihood fit to the $p_T(\mu\mu)$ distribution







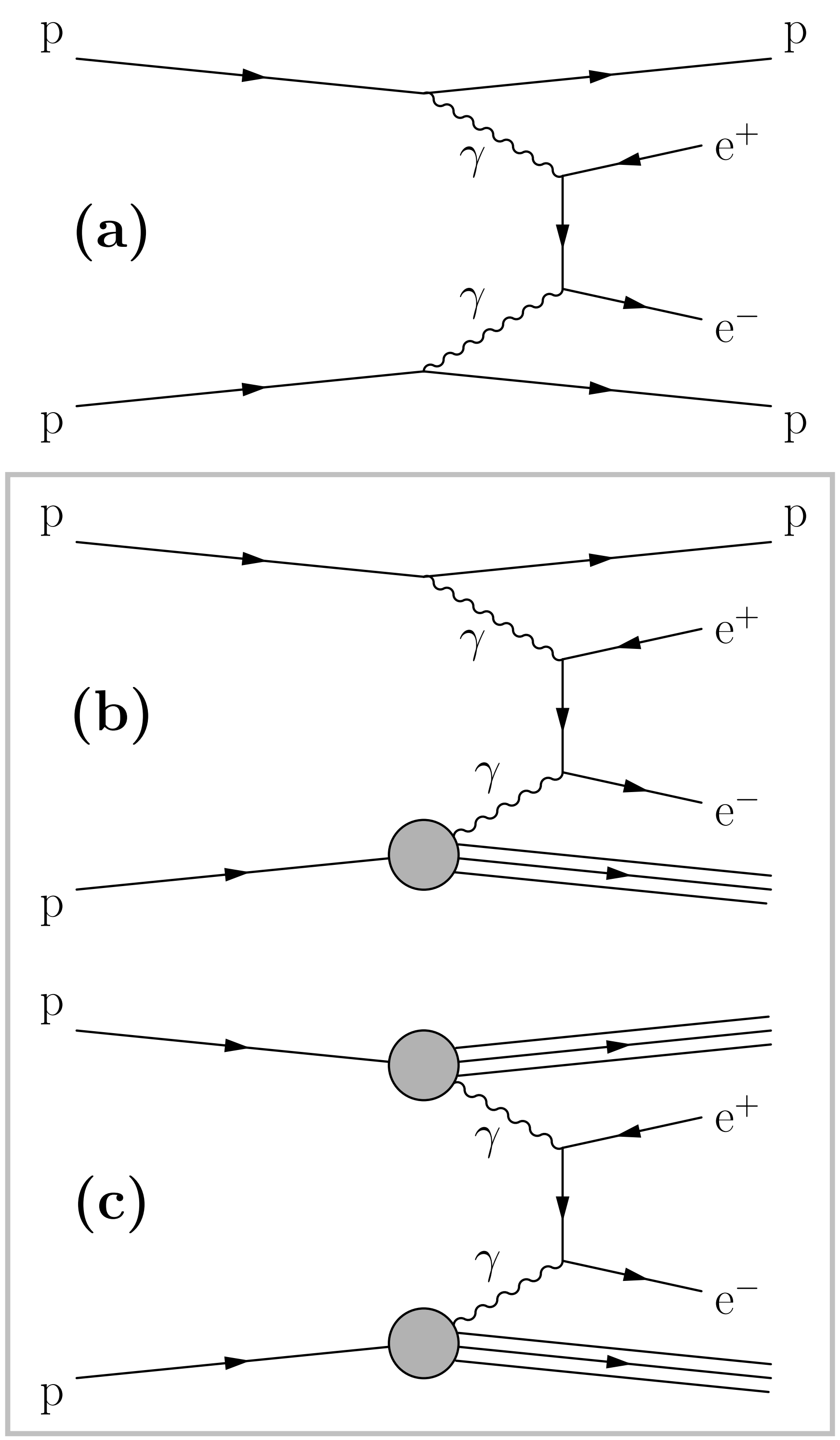
$$\sigma\,(p + \mu\mu + p) = 3.38^{+0.58}_{-0.55}(stat.) \pm 0.16(syst.) \pm 0.14(lum.)\text{pb}$$

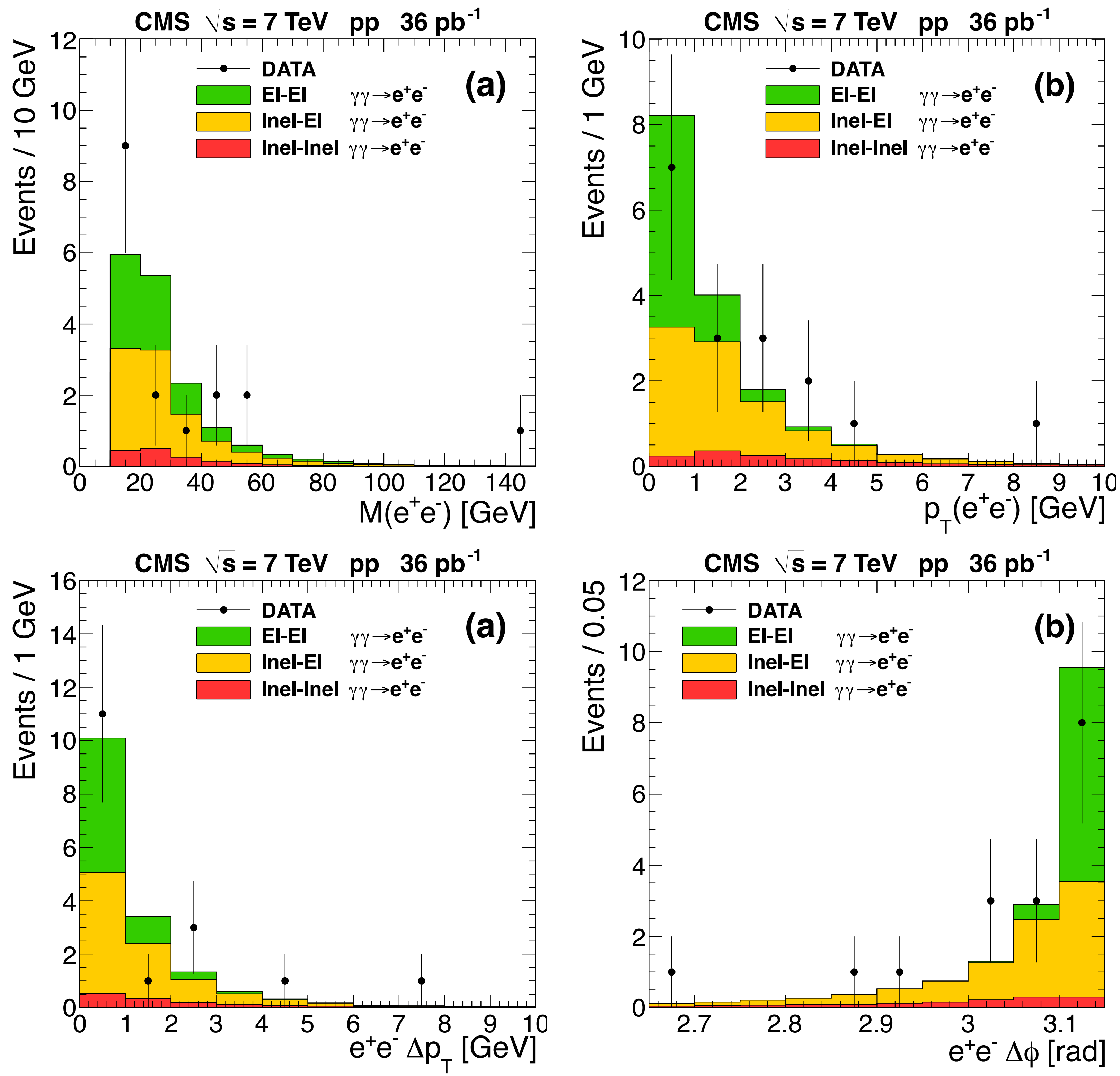
Largest systematics from track veto efficiency (data driven - pile-up sensitive)

Good agreement between data and LPAIR MC (signal and proton dissociation)

Potential for luminosity monitor at the LHC

Exclusive $\gamma\gamma \to e^+e^-$ production





CMS FWD-11-004

J. High Energy Phys. 11 (2012) 080

Good agreement between data and LPAIR MC (signal + proton dissociation)

Exclusive $\gamma\gamma \to W^+W^-$ production

Data sample corresponding to $5.05\ fb^{-1}$ integrated luminosity, from 2011, at 7 TeV

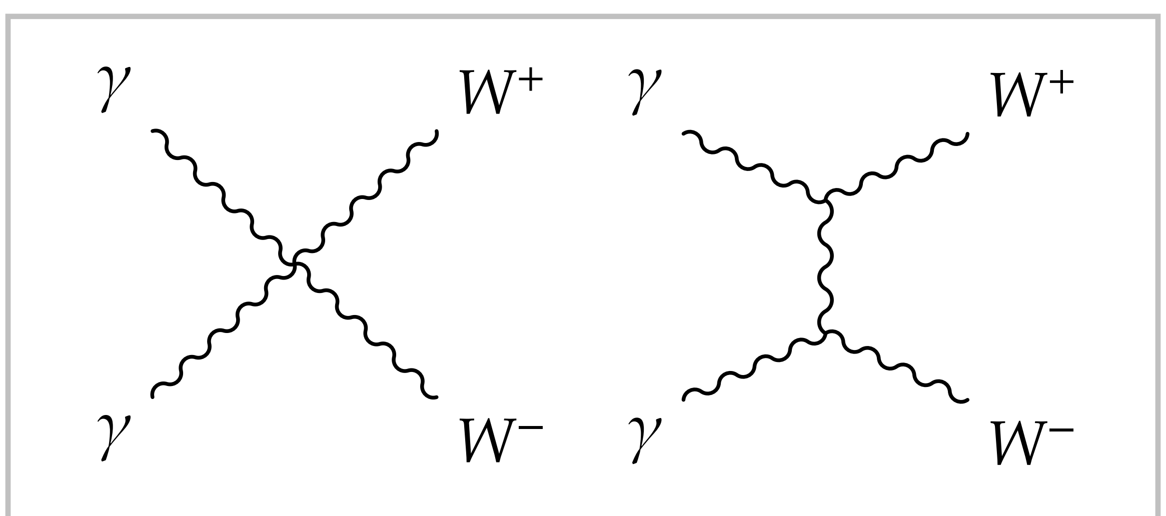
Only μe decay channel used to suppress same sign background; $\mu^+\mu^-$ used as benchmark for efficiency determination and pile-up dependence

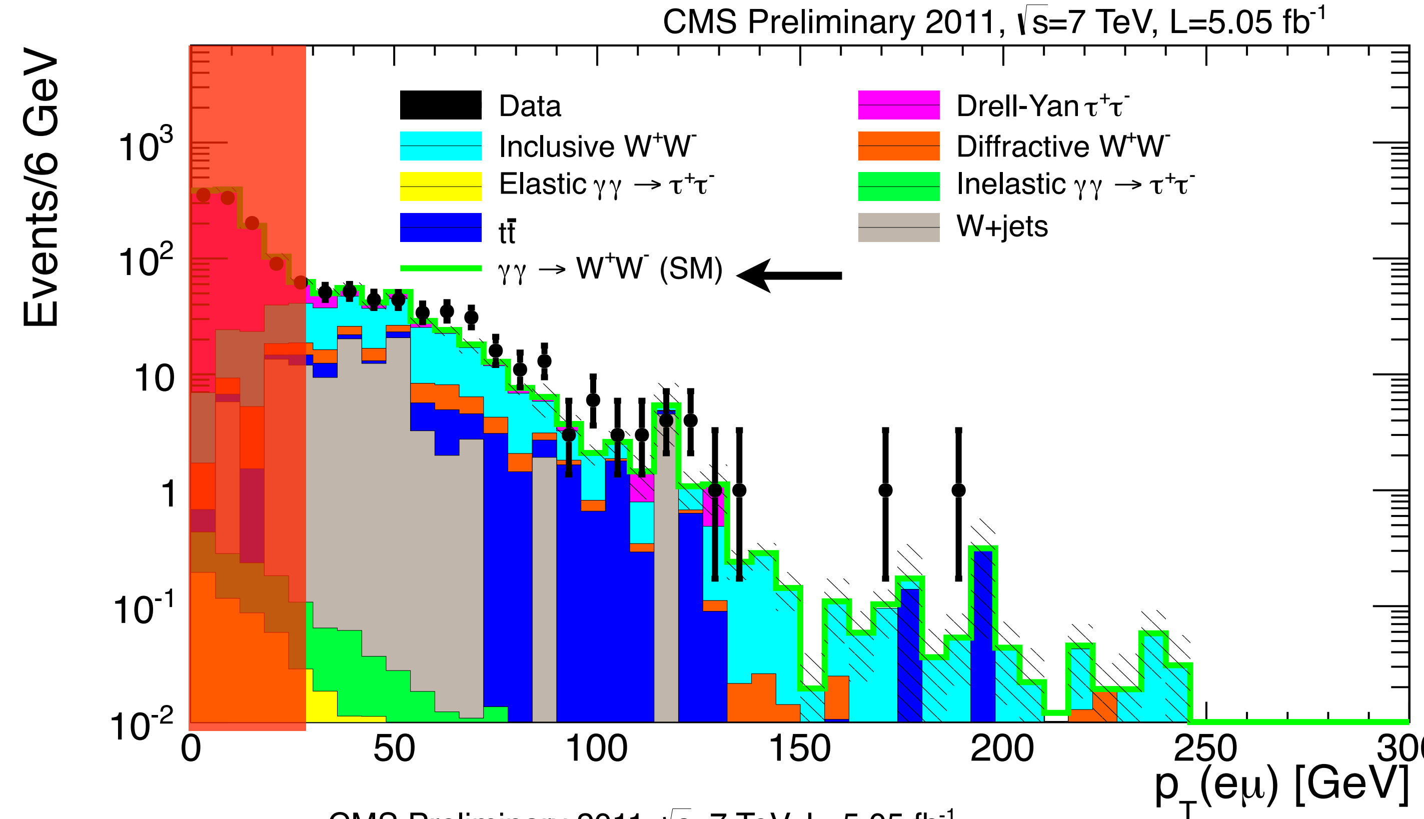
Exclusivity requirement: no extra tracks associated to μe vertex

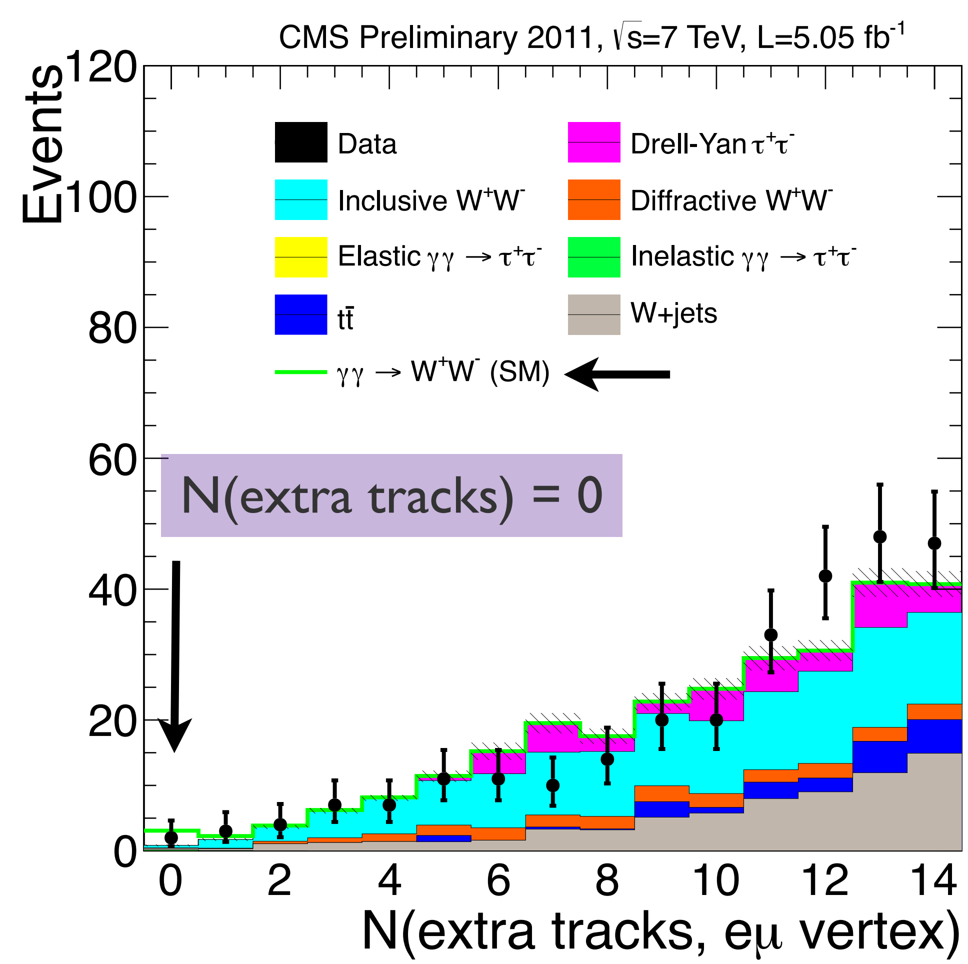
SM signal region defined with:

$p_T(\mu e) > 30$ GeV, N(extra tracks) = 0

Search for deviations from SM - anomalous quartic gauge couplings (AQGC) - look at region with $p_T(\mu e) > 100$ GeV where SM is small



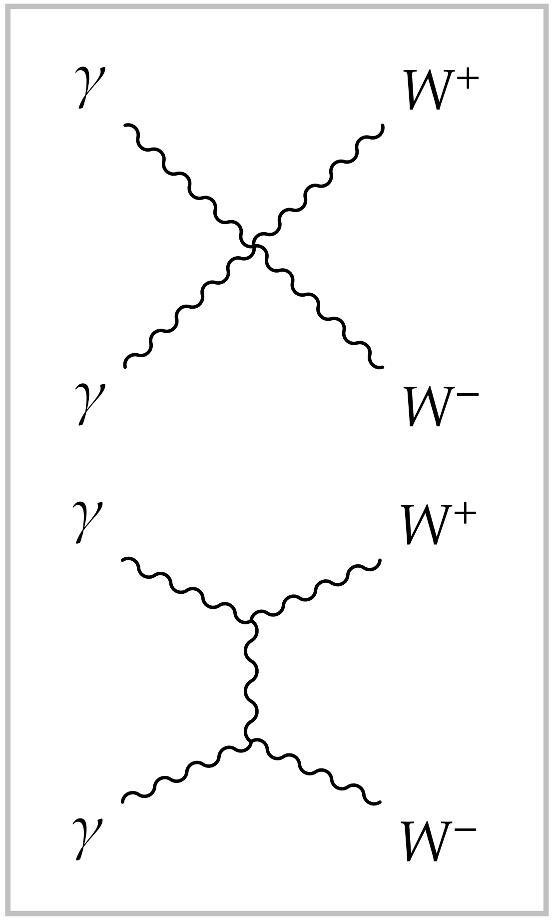


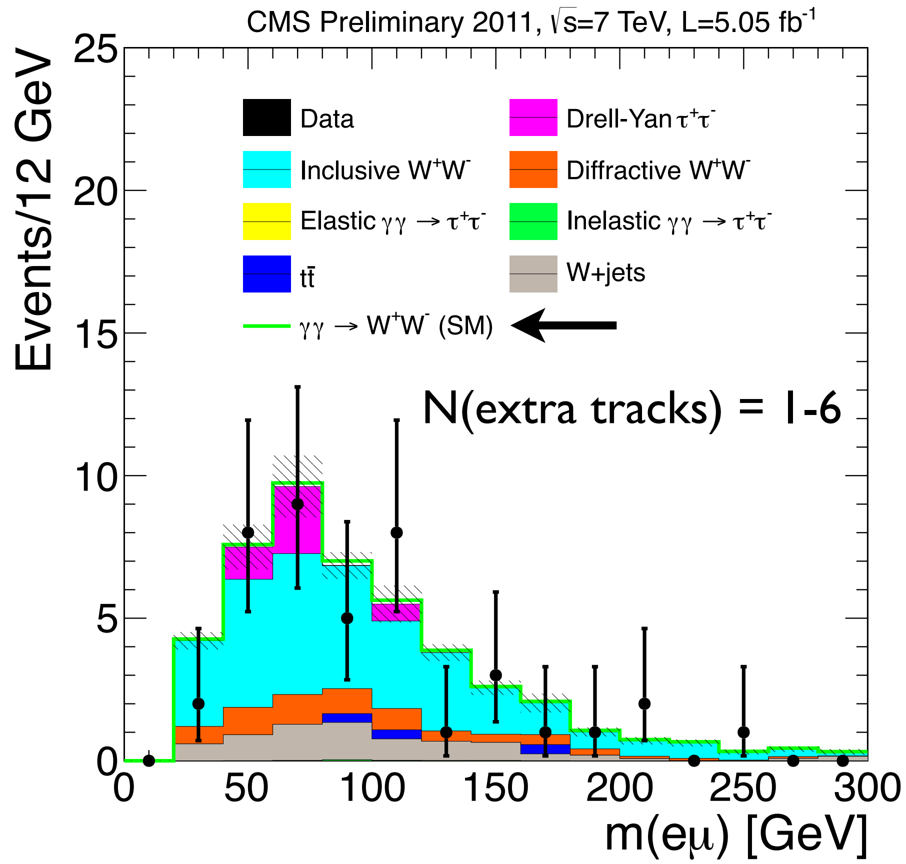


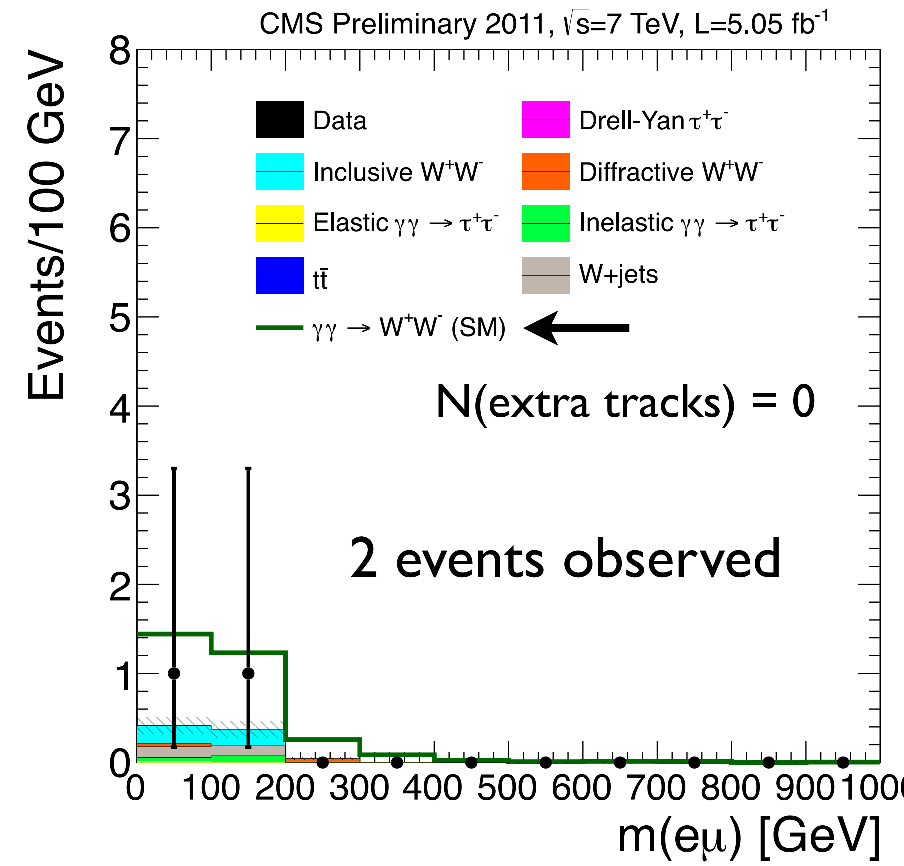
$p_T(\mu e) > 30$ GeV

CMS FSQ-12-010

Exclusive $\gamma\gamma \to W^+W^-$ production







CMS FSQ-12-010

Signal includes contribution from proton dissociative (inelastic) two-photon production

Expected 2.2 ± 0.5 signal, with 0.84 ± 0.13 background events in signal region. The corresponding upper limit and observed cross section for a SM signal are:

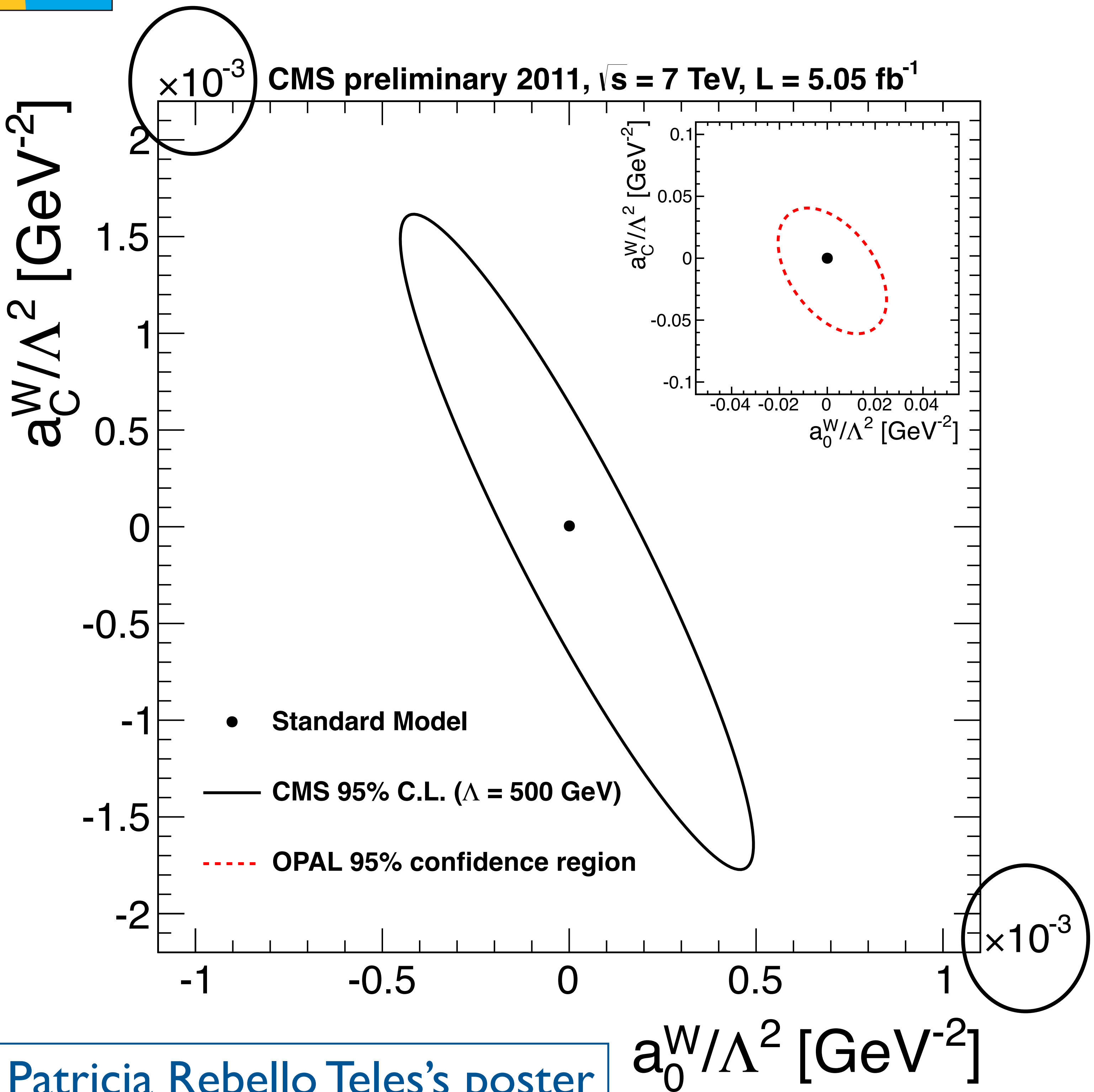
$$\sigma\left(pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^\pm e^\mp p^{(*)}\right) < 8.4 \text{ fb}$$ **(95% CL)**

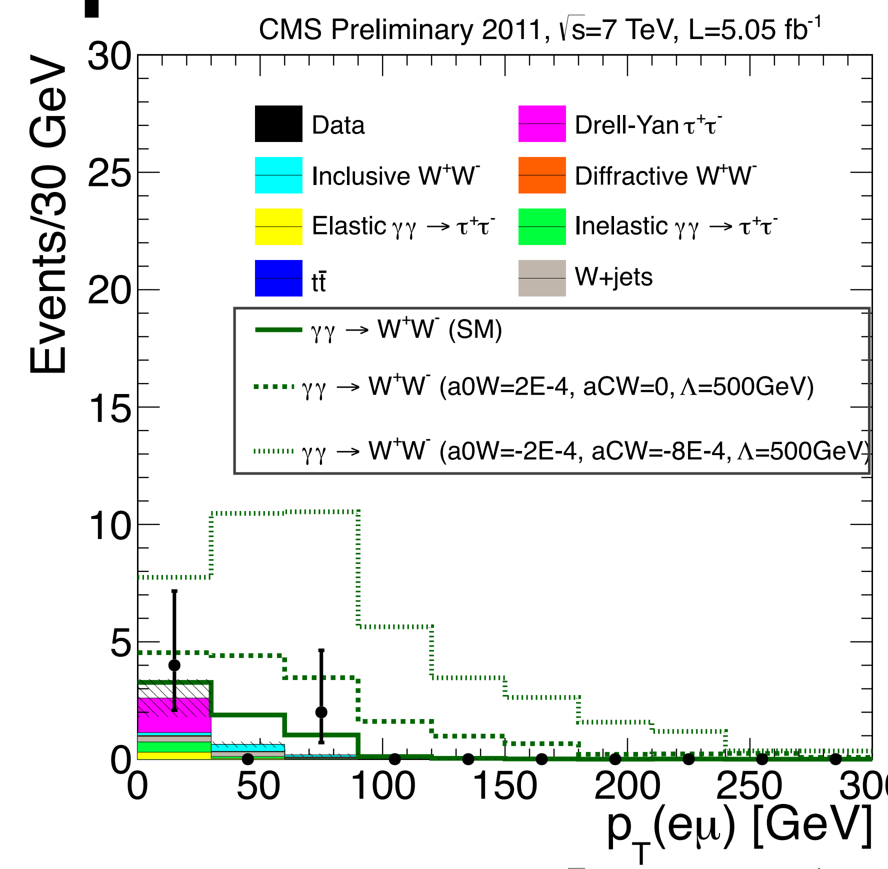
$$\sigma\left(pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^\pm e^\mp p^{(*)}\right) = 2.1^{+3.1}_{-1.9} \text{ fb}$$

(Obs. - 1.1σ)

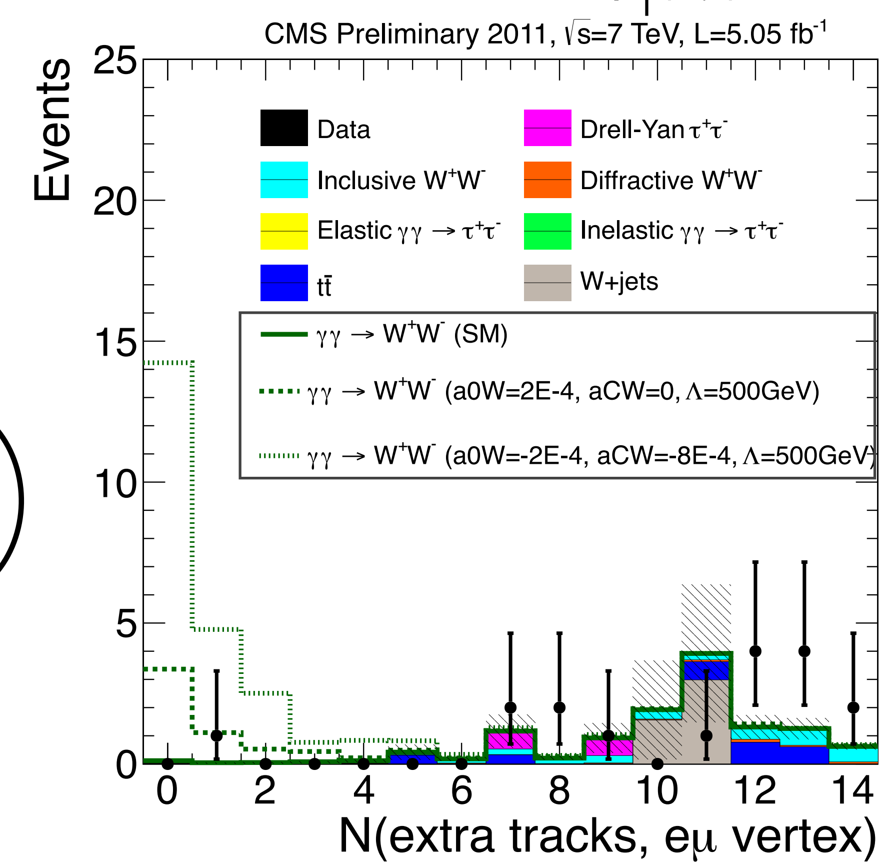
SM: 3.8 ± 0.9 fb

Exclusive $\gamma\gamma \to W^+W^-$ production





N(extra tracks) = 0



$p_T(\mu e) > 100$ GeV

See Patricia Rebello Teles's poster at LISHEP2013 for more details

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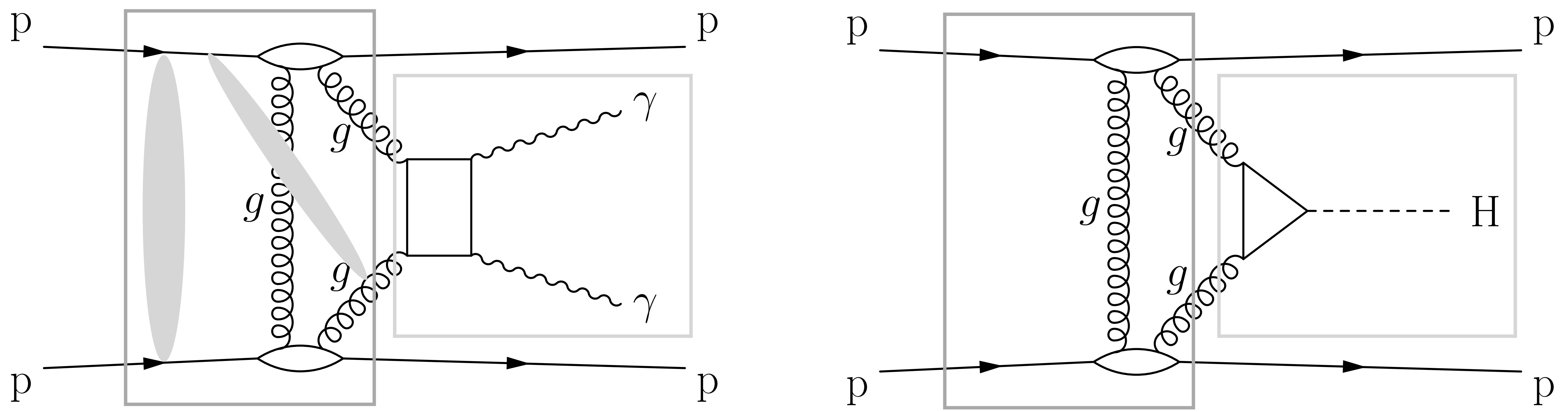
“Central Exclusive” production

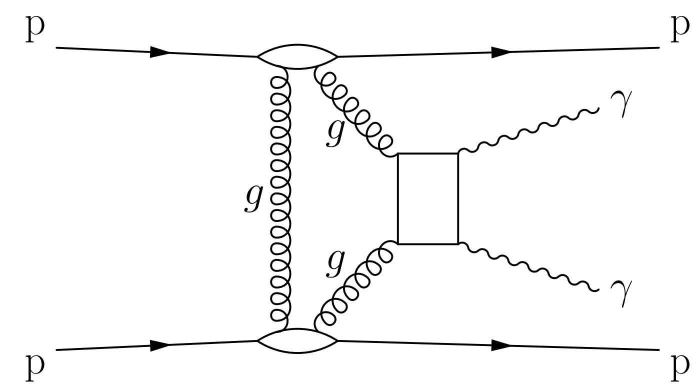


Exclusive channel through exchange of color singlet, lowest order given by gluon-gluon fusion, plus *screening* low-Q^2 gluon

Protons remain intact as in QED process, or dissociate in a low mass system, and are separated from the central system (γγ, H, etc.) by rapidity gaps

Main theoretical uncertainties common among different final states. Higher cross section channels, such as γγ or dijets, can test predictions for central exclusive production of a Higgs boson, and other states.

Central Exclusive γγ production



No candidate events observed with an expected background of 1.79 ± 0.40 events

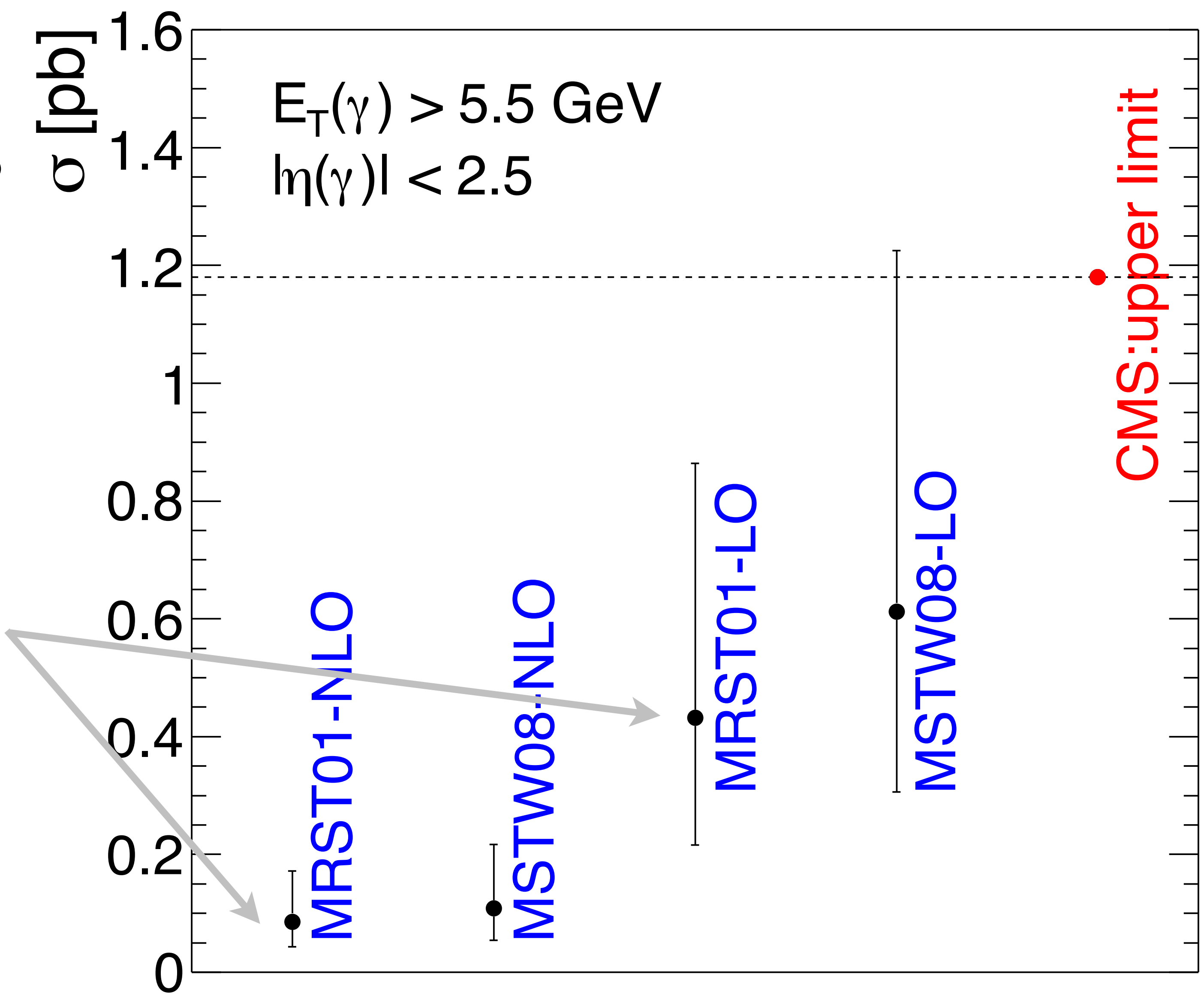
95% confidence level upper limit:

$\sigma\,(E_T(\gamma) > 5.5GeV, |\eta(\gamma)| < 2.5) < 1.18$ pb

Upper limit on the sum of exclusive (el-el) and semi-exclusive (inel-el + inel-inel) where the proton dissociation leaves no signal in the detector acceptance

Theoretical predictions for exclusive (el-el) cross section

Difference from LO and NLO cross sections mostly from low-x gluon density



CMS FWD-11-004

J. High Energy Phys. 11 (2012) 080

Outlook: ongoing/future analyses

July 2012: (β* = 90 m, 8 TeV)

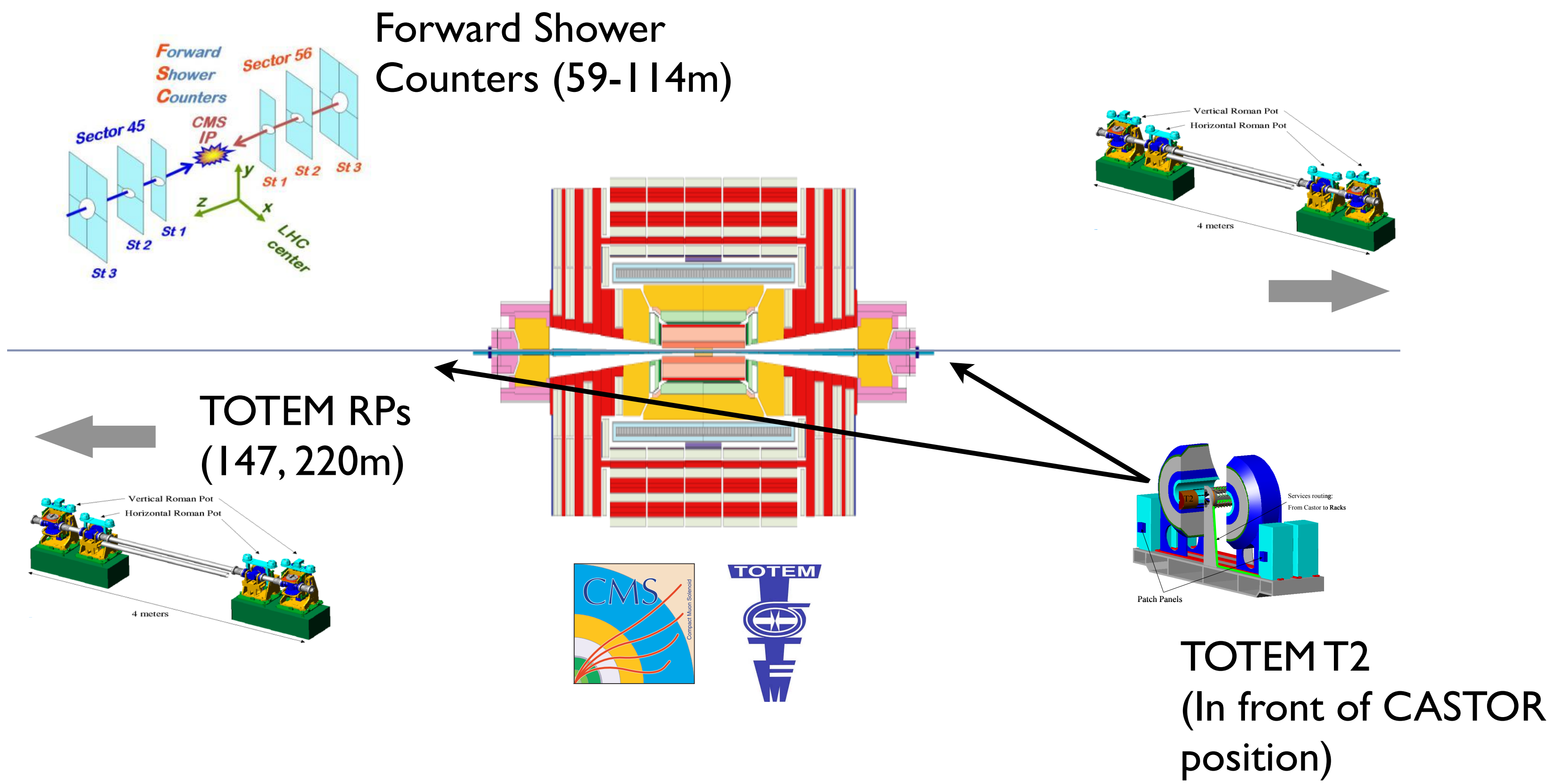
Common CMS-TOTEM data taking at low pile-up with around 50 nb^{-1}

HI Run: pPb and pp (at 2.76 TeV - low pile-up)

TOTEM Roman Pots (RPs): detect protons scattered from diffractive and photon induced processes

TOTEM T1/T2 tracking stations at very forward angles

Forward Shower Counters (FSC) covering |η| ~ 6-8



First "forward proton spectrometer" associated with complete central coverage at the LHC

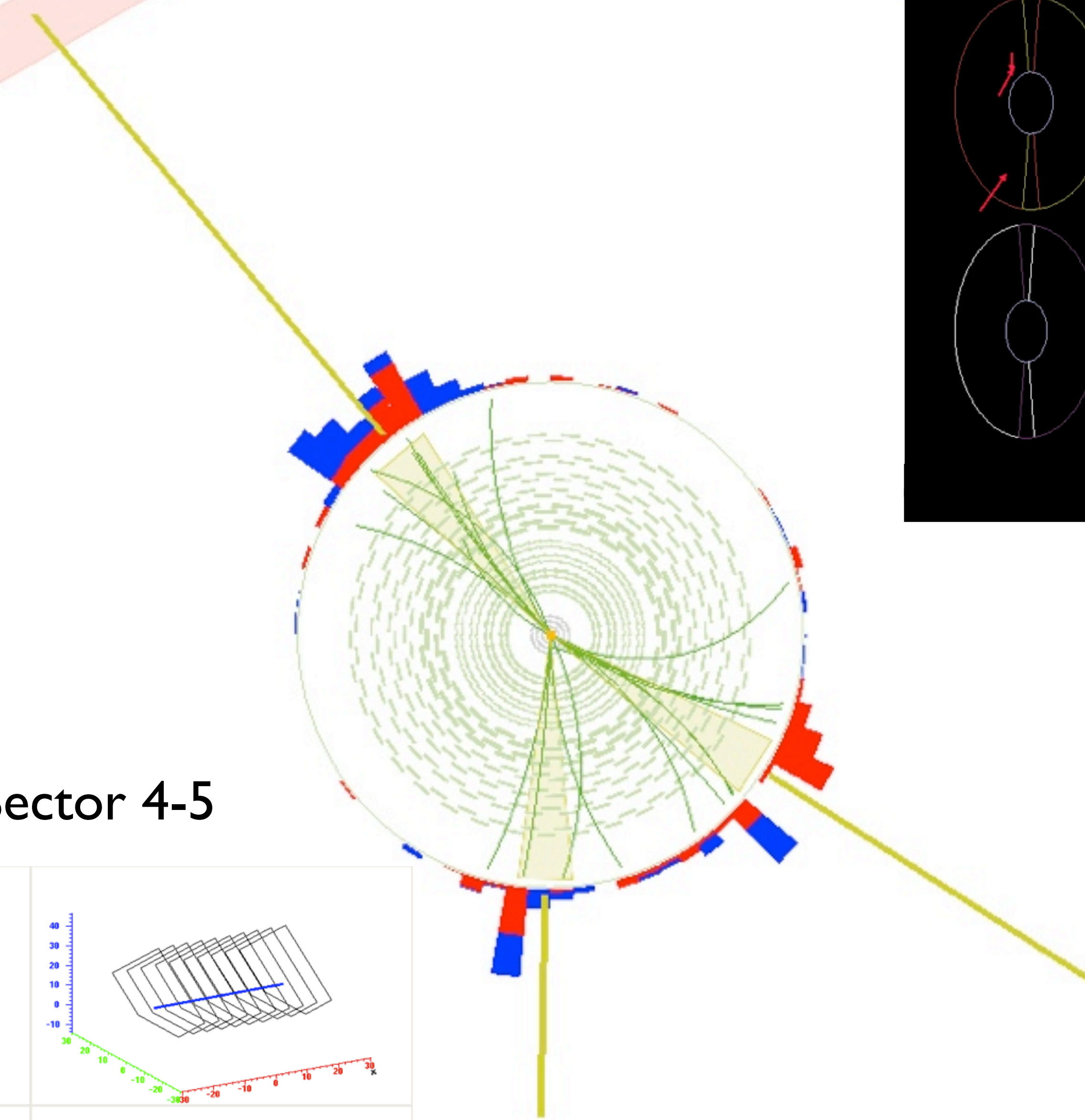
CMS and ATLAS ongoing projects for the installation of proton detectors at high luminosity (not covered here)

(See related talk by C. Royon)

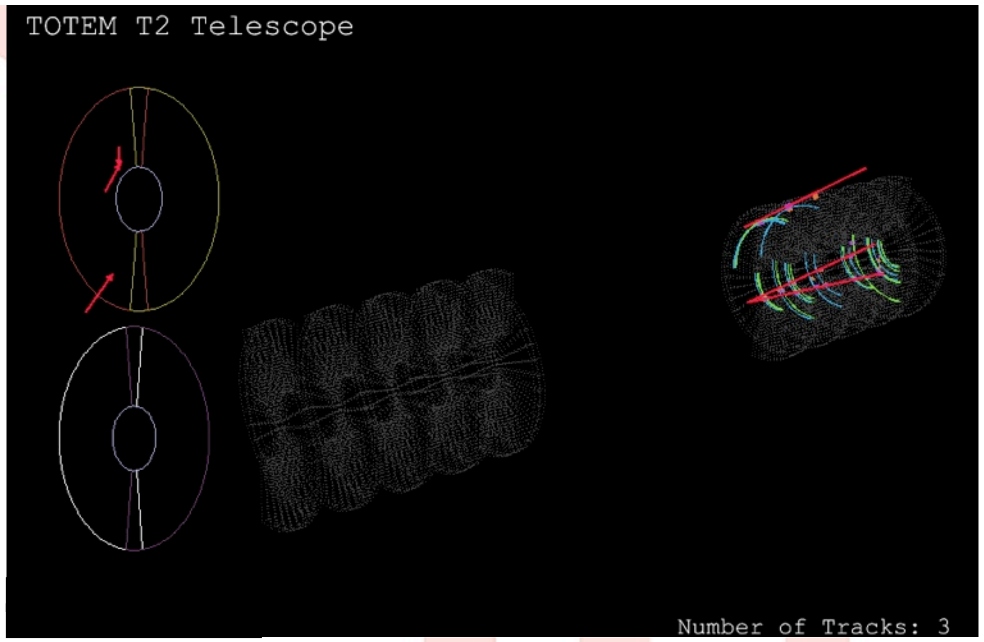
Central dijet event candidate with two leading protons

CMS Experiment at LHC, CERN
Data recorded: Thu Jul 12 22:40:03 2012 BRST
Run/Event: 198903 / 3478279
Lumi section: 166
Orbit/Crossing: 43375975 / 1789

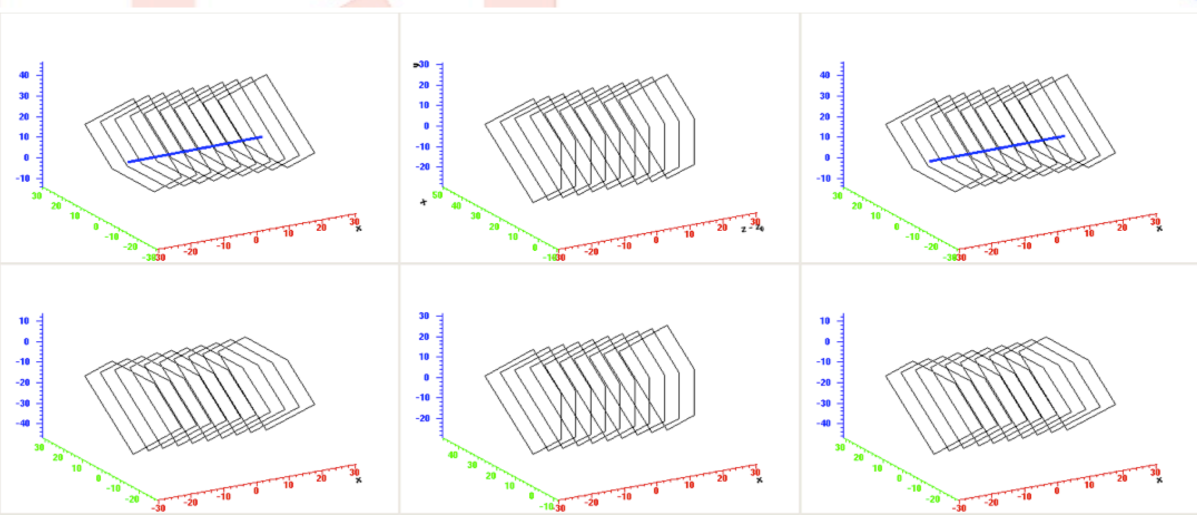
CMS DP-2013-004
CMS DP-2013-006



TOTEM T2



TOTEM Roman Pot stations - Sector 4-5



Leading three jets E_T = 65, 45, 27 GeV
proton $\Delta p/p$ = -0.01 (z+)
proton $\Delta p/p$ = -0.1 (z-)
M(pp, TOTEM) = 244 GeV
M(CMS) = 219 GeV
$\Sigma\, p_T$ (CMS) = 3.4 GeV
FSC empty in both sides

ECAL/HCAL E_T > 200 MeV
Track p_T > 1 GeV

Summary

First measurements of hard diffraction at the LHC, associated with high-p_T jets and W/Z bosons

The differential dijet cross section has been measured, as a function of a variable (ξ) that approximates the momentum loss of protons in diffractive events

Diffractive dijet events dominate the low-ξ region. Comparing the measured cross section to diffractive MC predictions based on dPDFs from HERA, an estimate of the survival probability was obtained

A large asymmetry is observed with the charged lepton in the opposite or same hemisphere as the pseudorapidity gap signature, in a W/Z data set, consistent with diffractive W/Z production

These measurements give constraints on hard-diffractive processes at the LHC, diffractive PDFs, and especially estimates of the survival probability

Summary

Exclusive events induced by photon-photon interactions have been observed. The exclusive dimuon and dielectron yields are in agreement with theoretical predictions

Exclusive two-photon W+W- production has been observed and its cross section measured. A search for anomalous quartic gauge couplings (AQGC) has been performed. Limits were obtained which are two orders of magnitude more stringent than at LEP

An upper limit on the central exclusive diphoton production has been given. It is the first search for such events at a center-of-mass energy of 7 TeV, at the LHC

Result gives already some constraint on the theoretical predictions of central exclusive production cross sections

Future measurements will give further information on the predictions of central exclusive processes associated with a Higgs boson, and other states

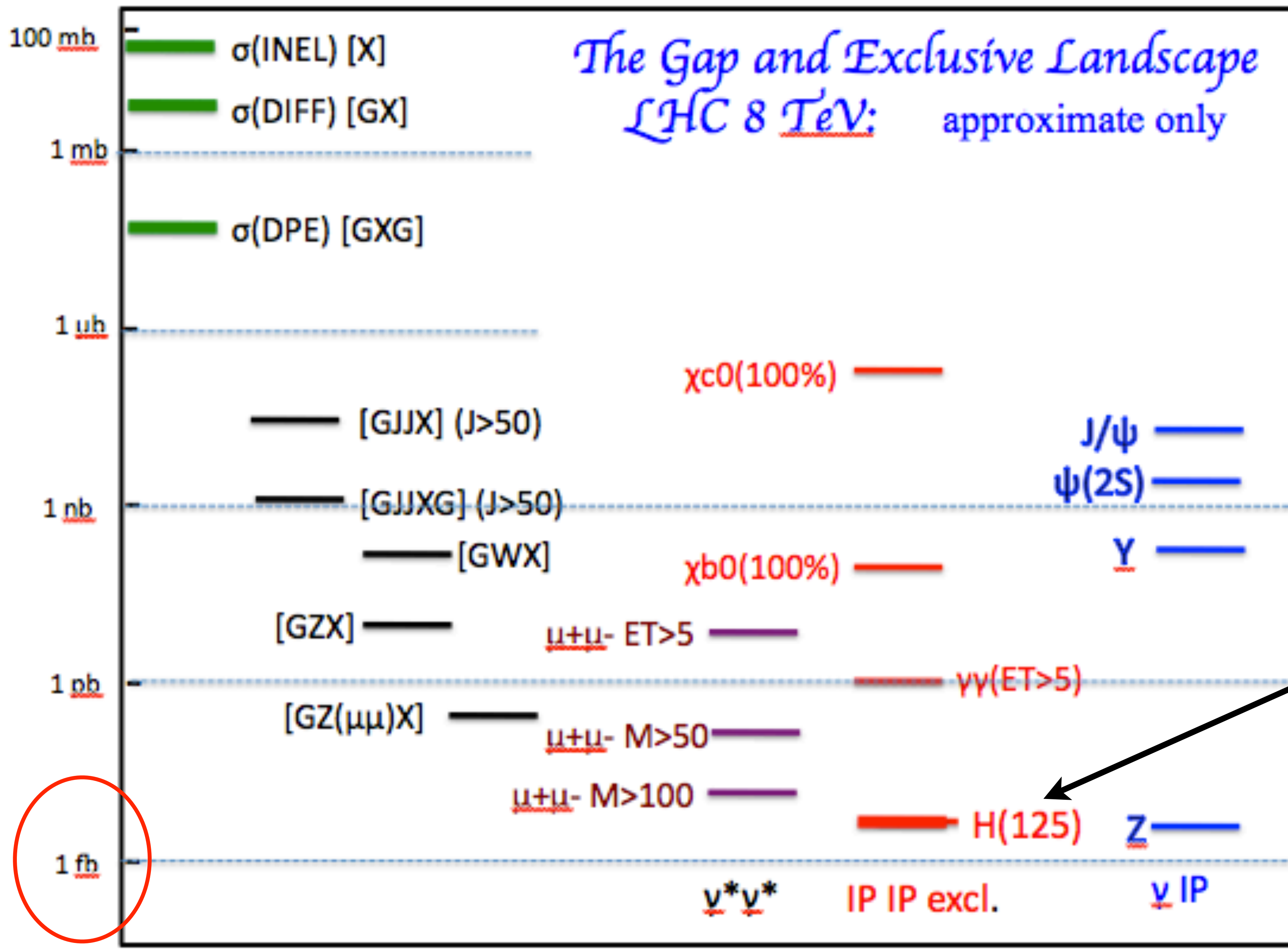
Extra slides

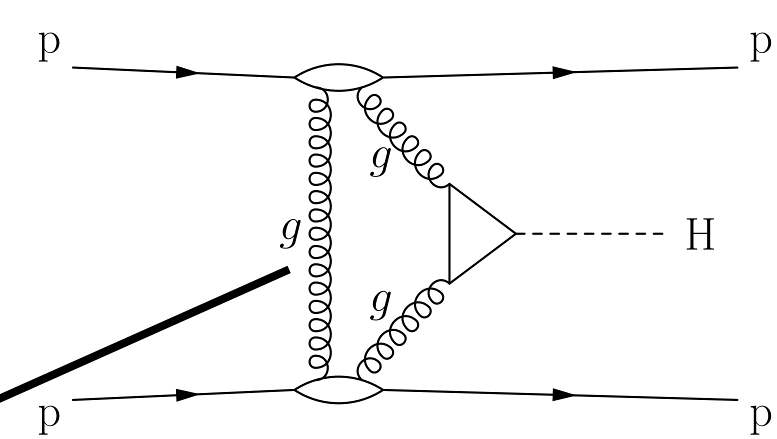
Forward physics results at CMS

- Low-x QCD & PDFs
- Soft and hard diffraction
- Exclusive processes, $\gamma\gamma$ interactions
- Underlying event & MPI, etc.

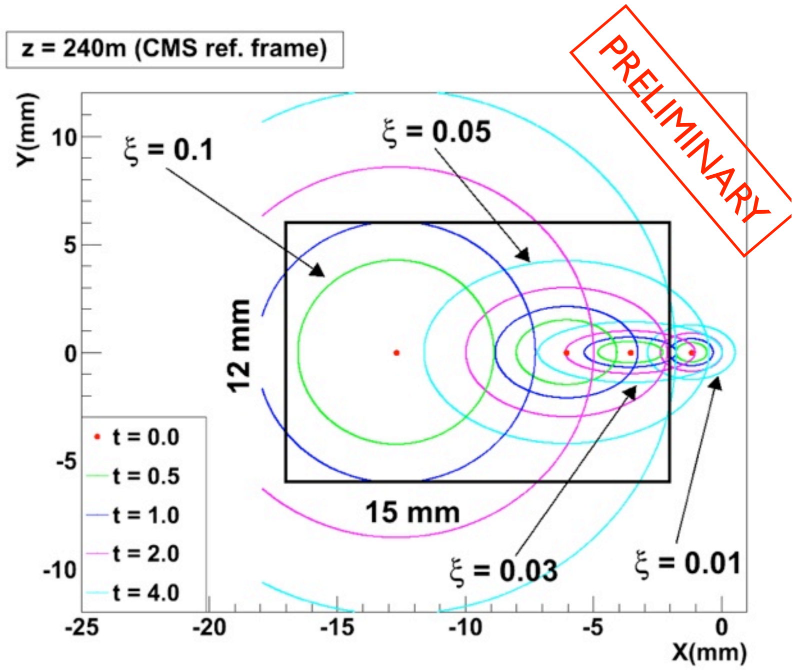
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ

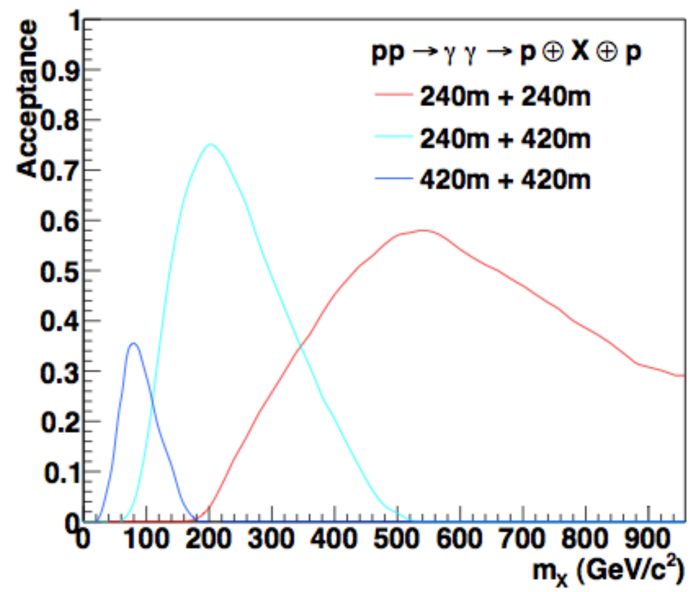
Exclusive/diffractive cross sections

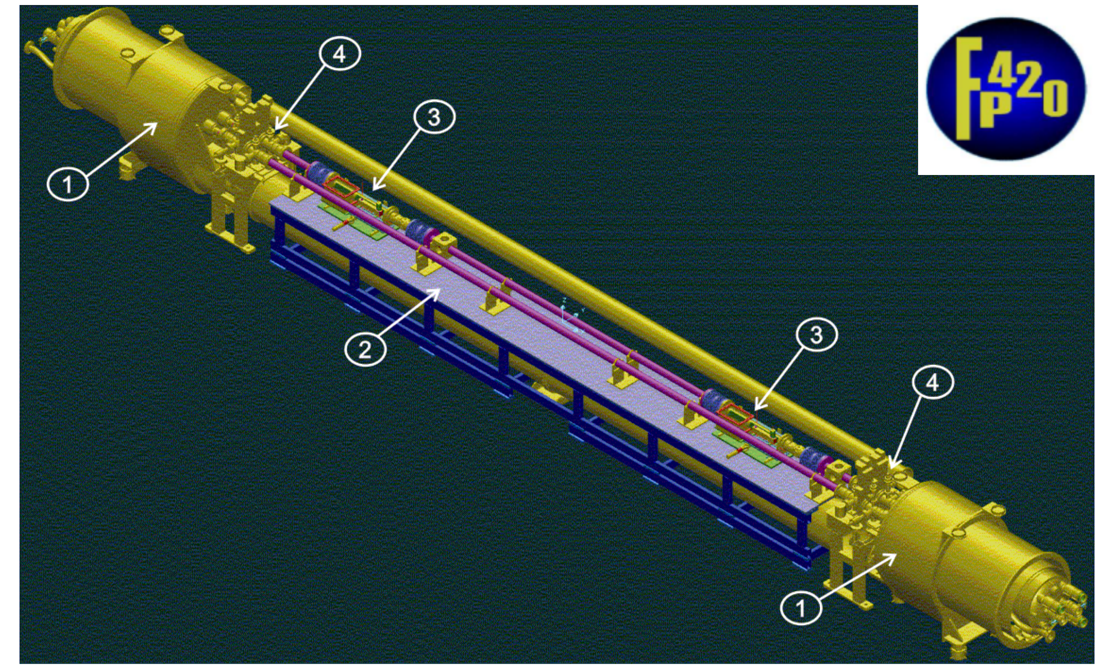


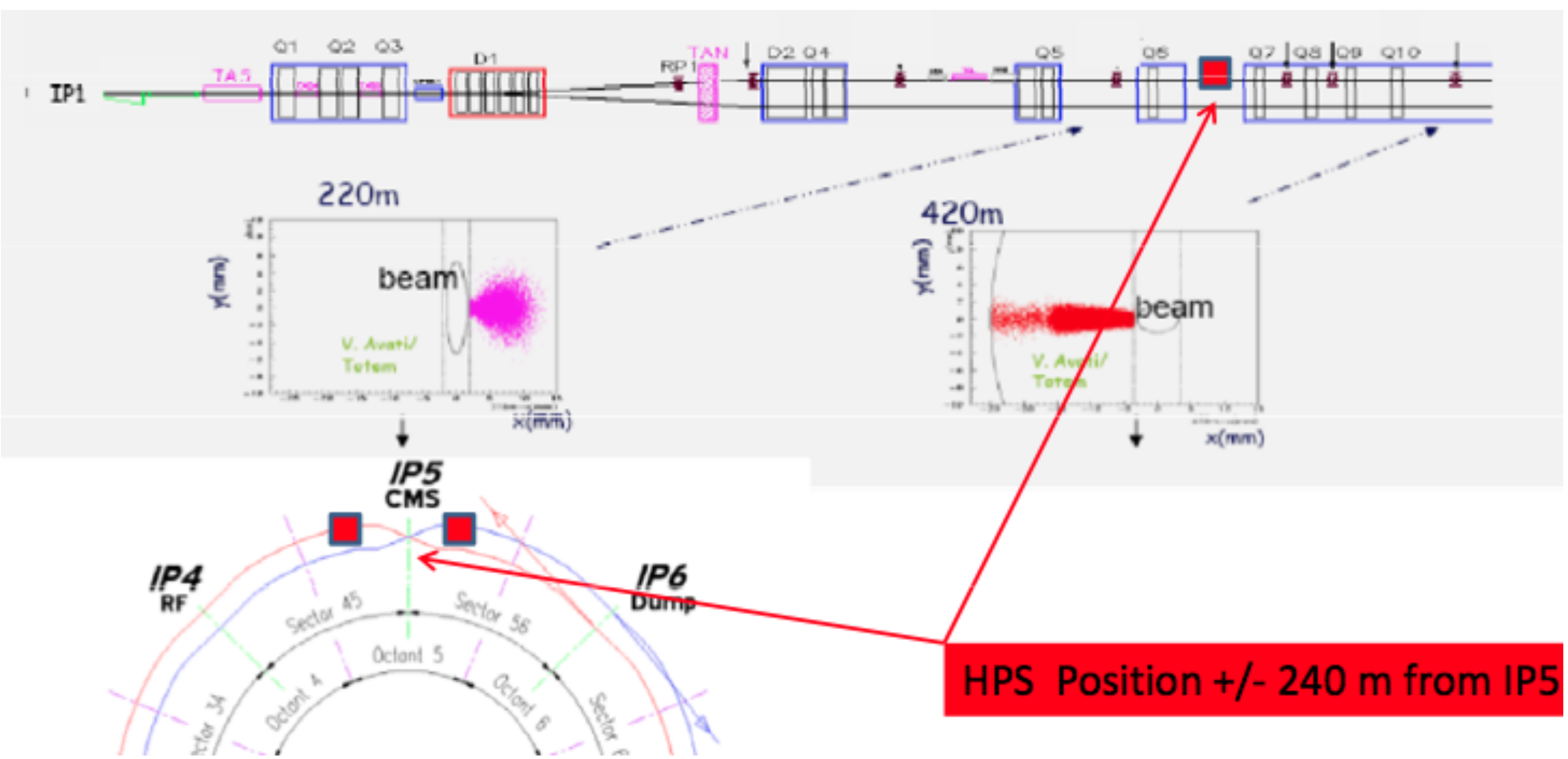


HPS and protons at high luminosity





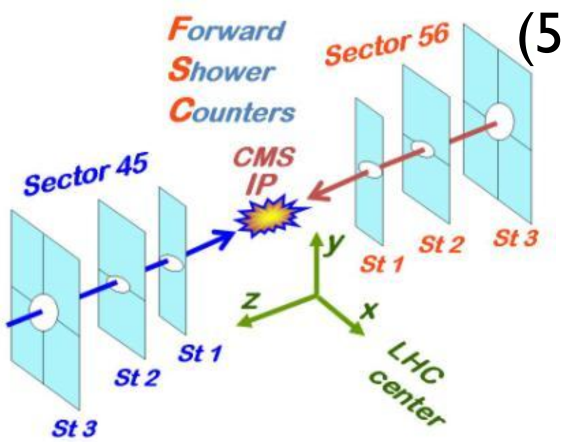


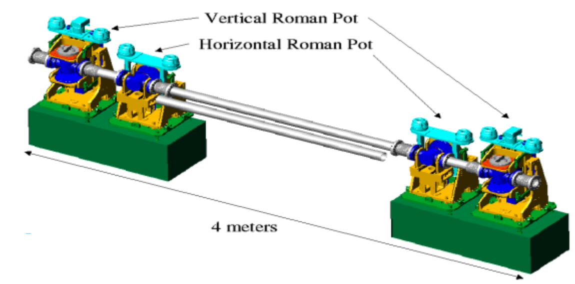


CMS-TOTEM detectors

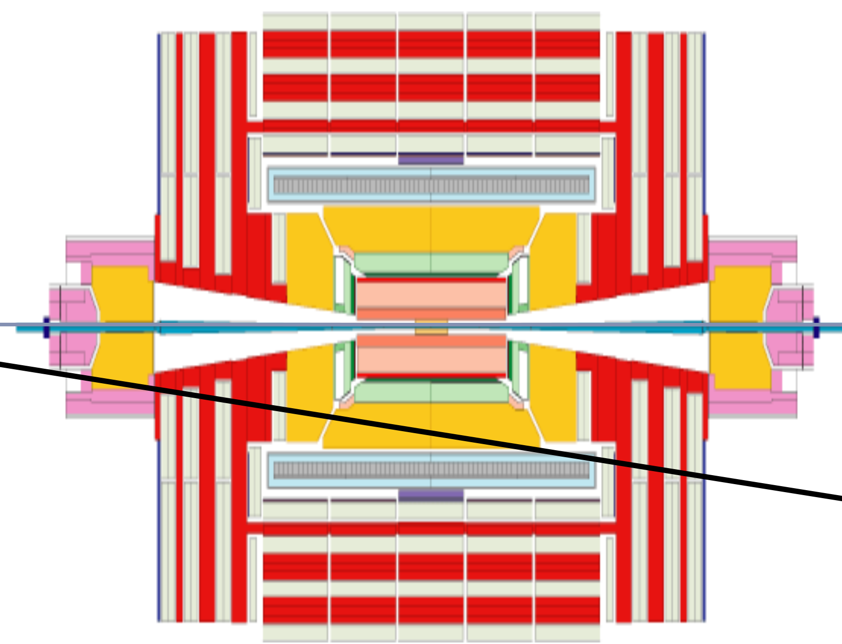
Prospects for Diffractive and Forward Physics at the LHC
[CERN-LHCC-2006-039-G-124]

Forward Shower Counters
(59-114m)

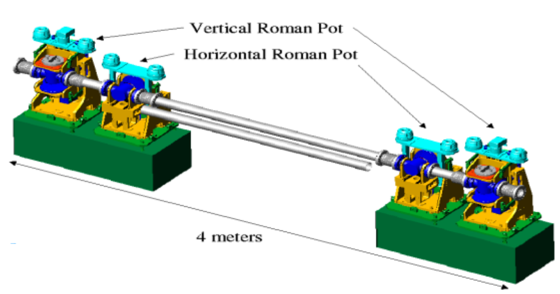


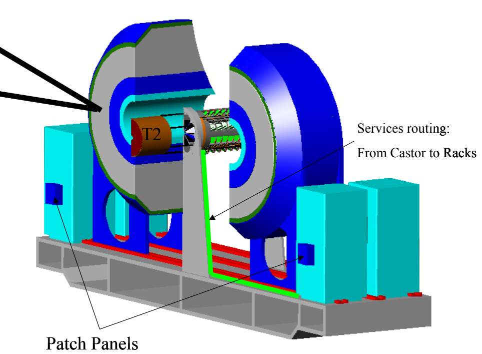


TOTEM RPs
(147, 220m)



TOTEM RPs
(147, 220m)

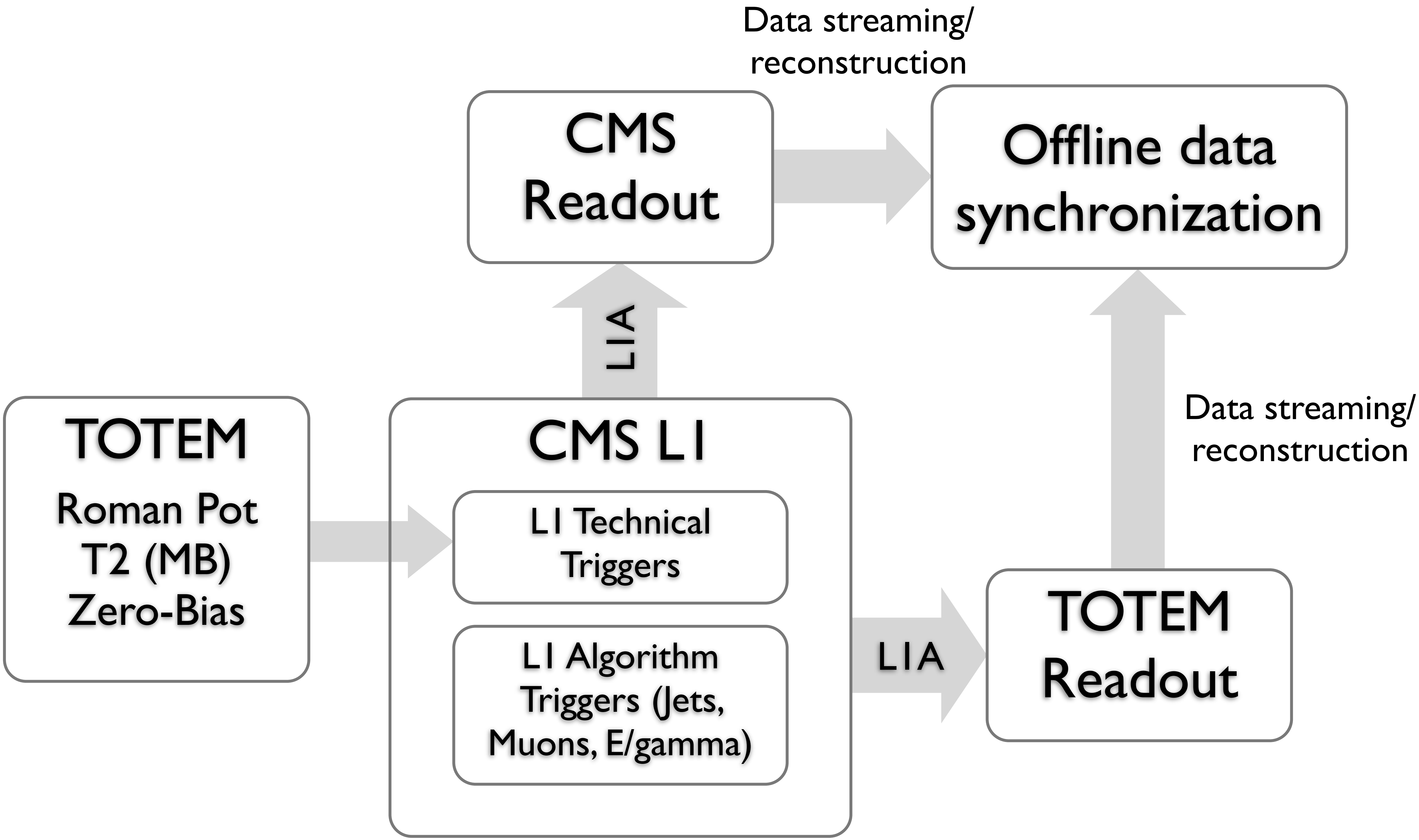




TOTEM T2
(In front of
CASTOR position)

Common data taking during low-PU
runs in 2012

CMS-TOTEM common data taking



CMS-TOTEM central dijet events: Event selection

Low-PU β^* = 90 m Run with common CMS-TOTEM triggers

Data sample recorded with 'L1_DoubleJet20' trigger (CMS)

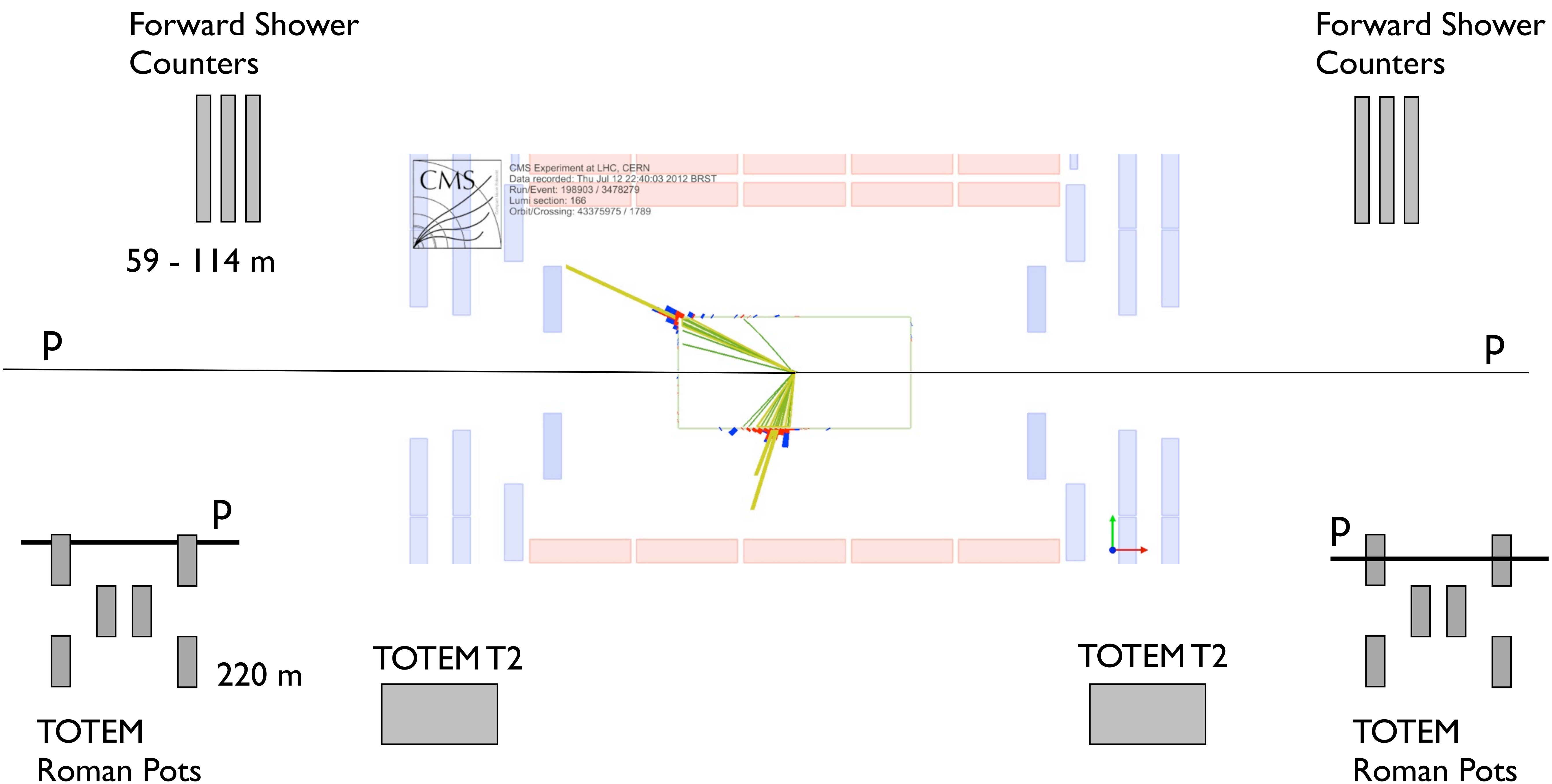
Event selection required at least two jets with p_T greater than 20 GeV (Anti-k_T R = 0.5 - Particle-Flow Jets)

Forward Shower Counters (FSC) empty ($|\eta| \sim 6$-8)

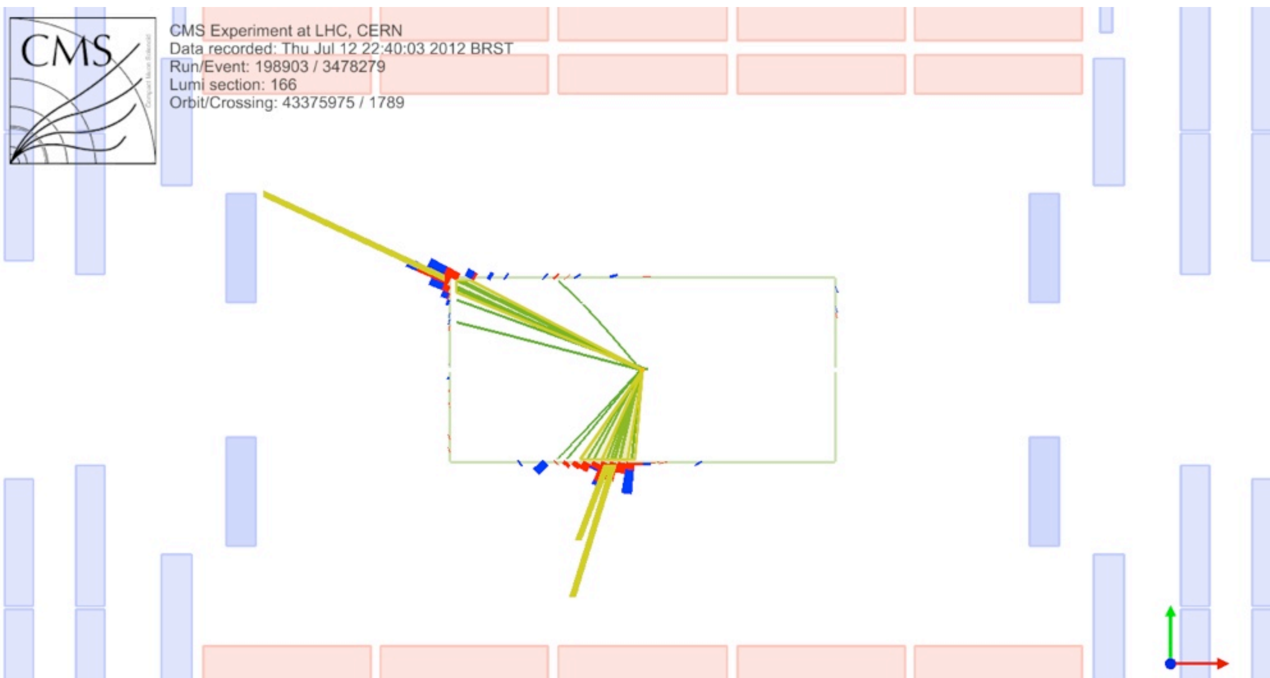
Reconstructed proton tracks (TOTEM Roman Pots) in both sides of IP (non-elastic)

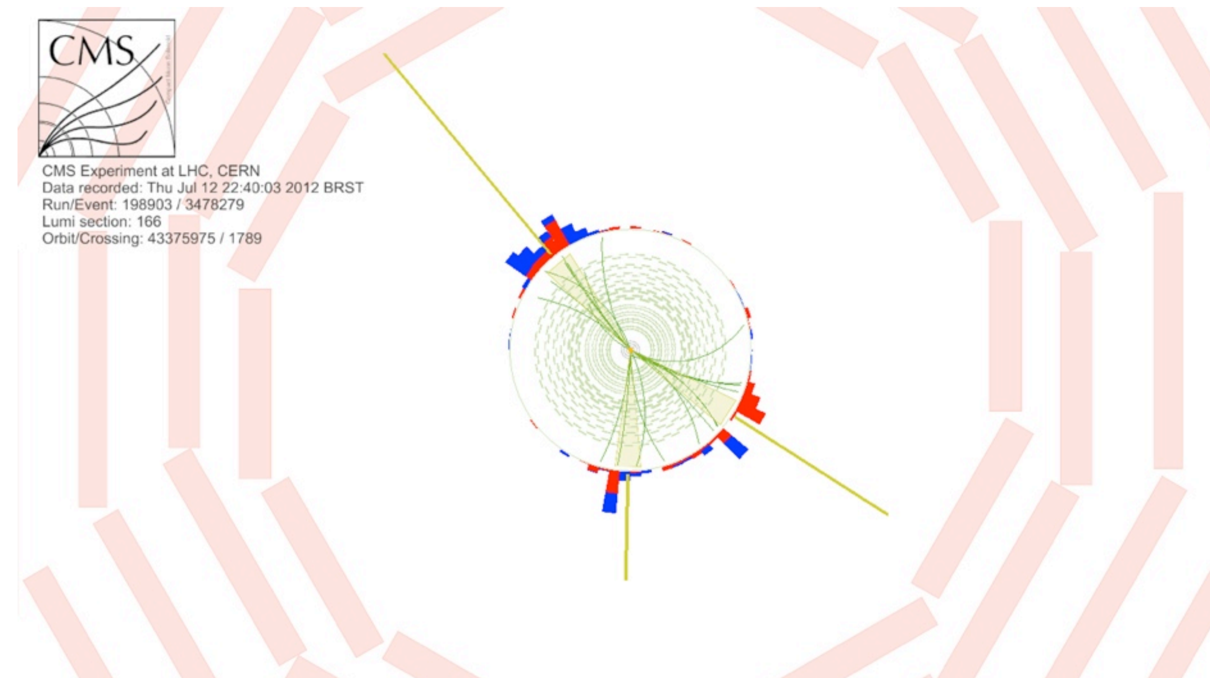
Best event candidates selected according to compatibility of CMS and TOTEM kinematical properties

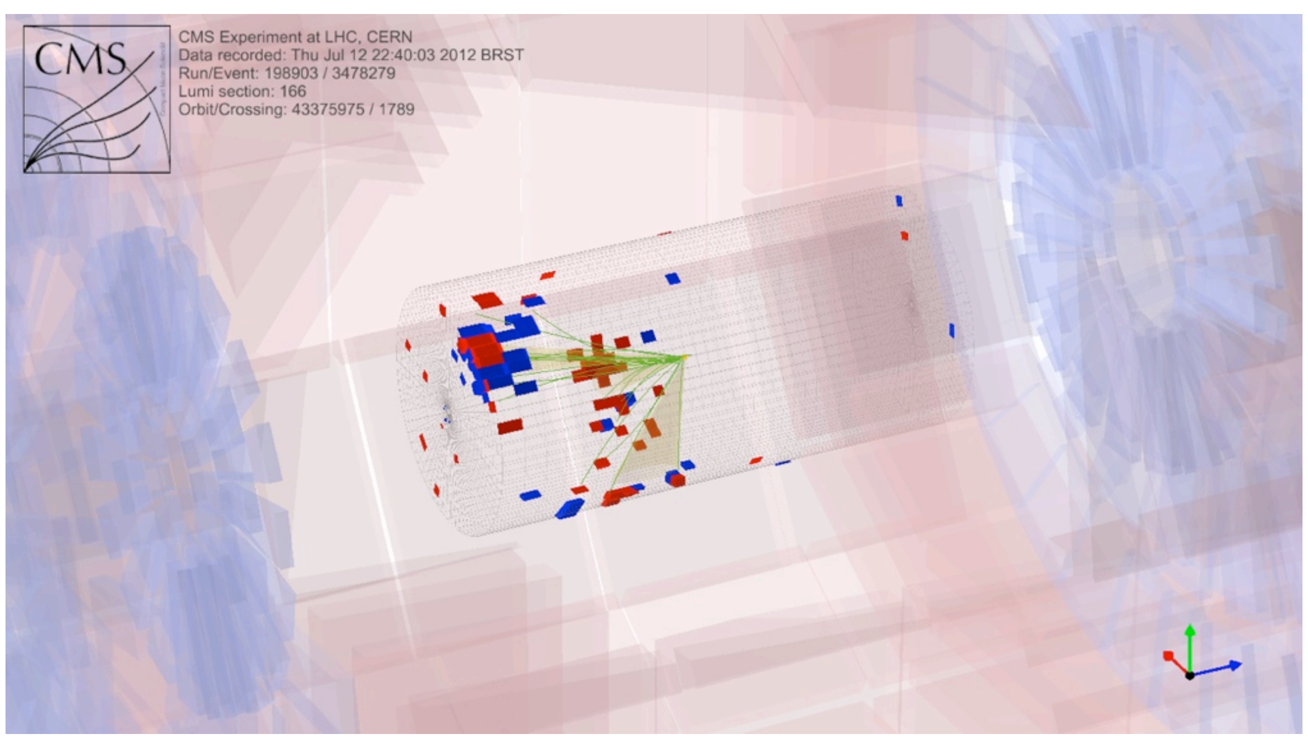
CMS-TOTEM central dijet events: Event topology

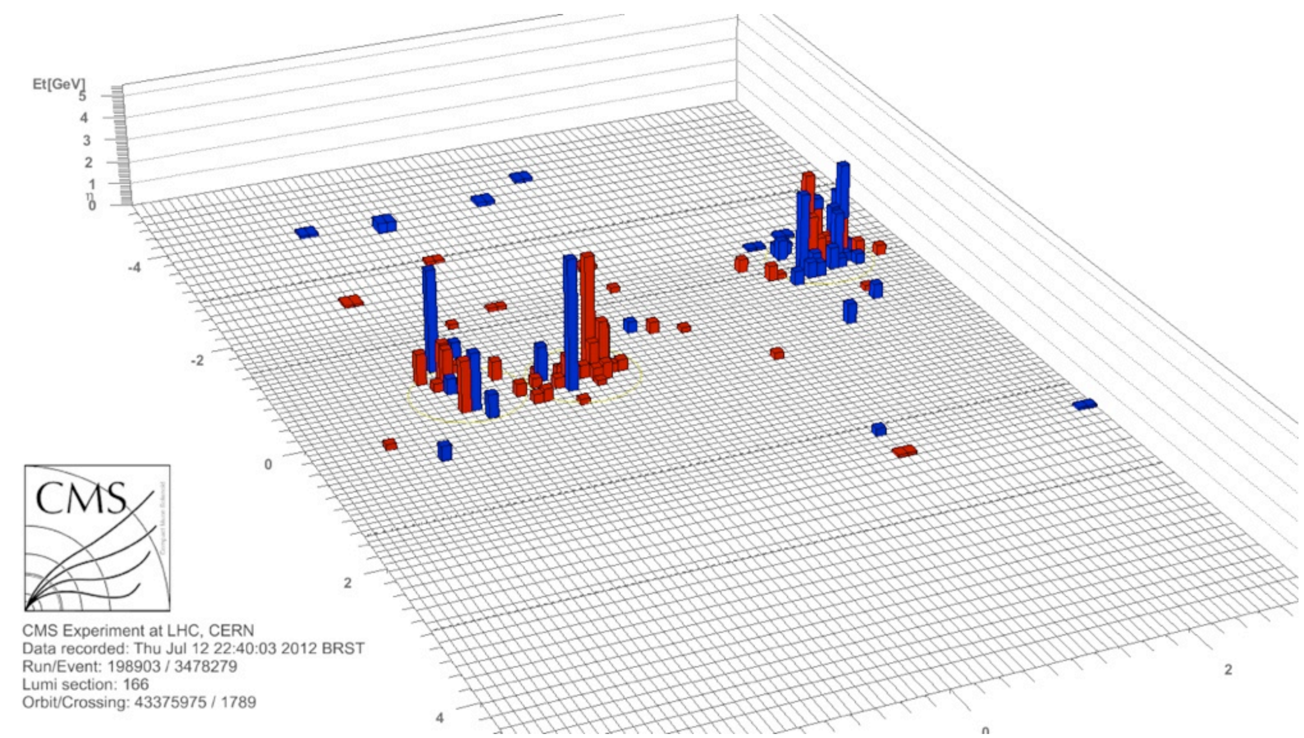


Run 198903 - Event 3478279



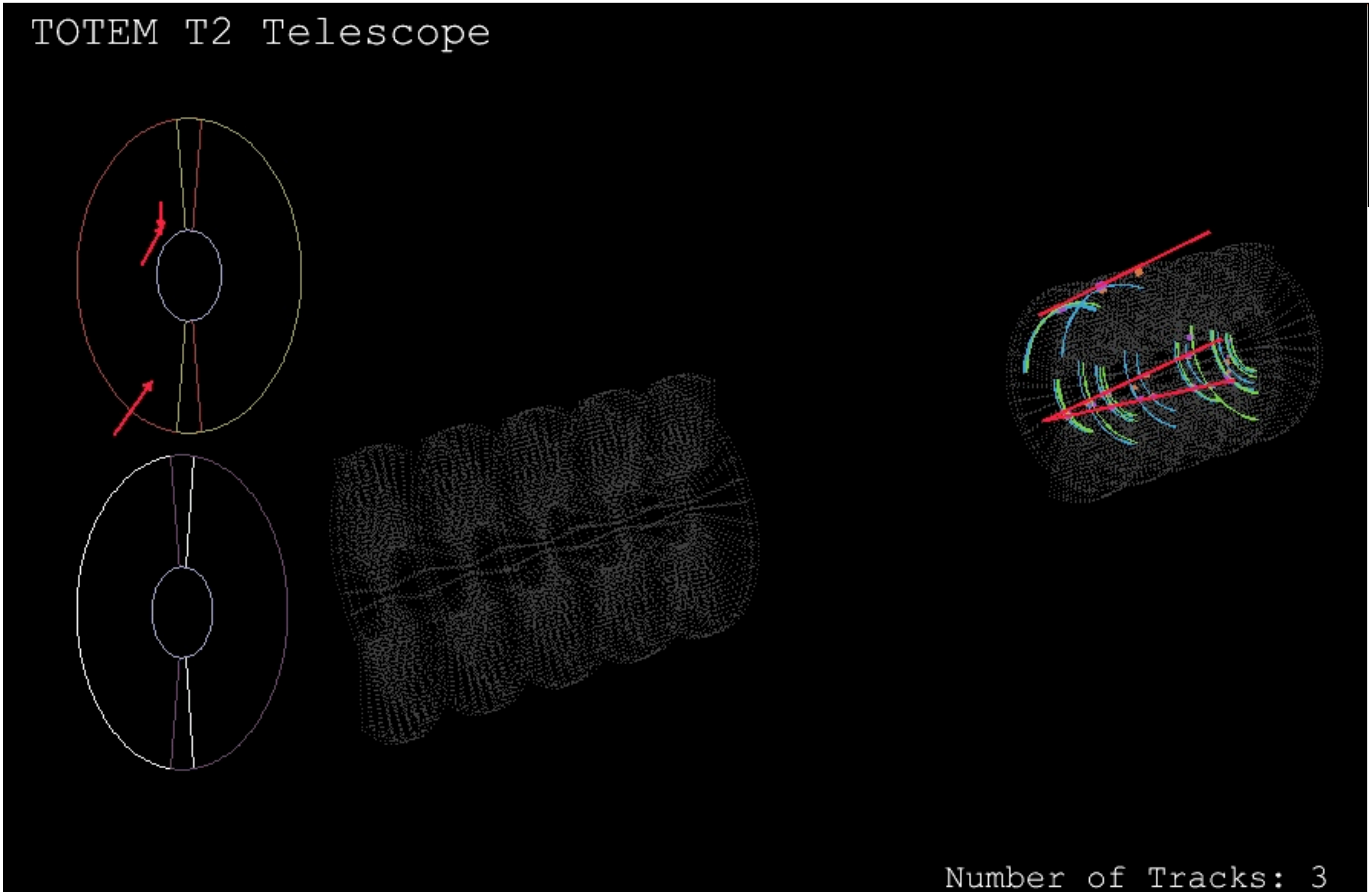






Run 198903 - Event 3478279

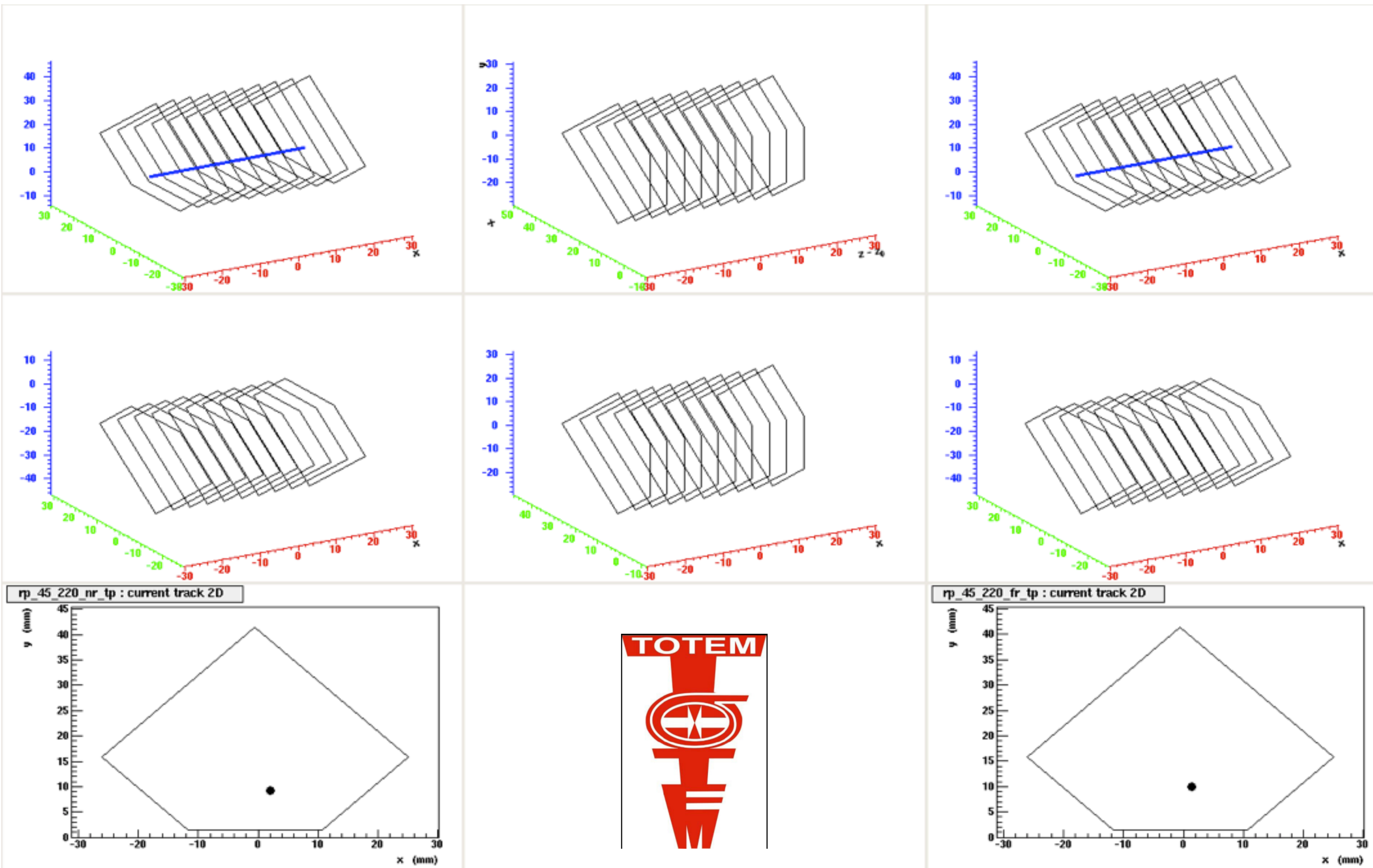
TOTEM Event 15322



CMS-TOTEM event display: high-p_T jets with leading protons

Run 198903 - Event 3478279

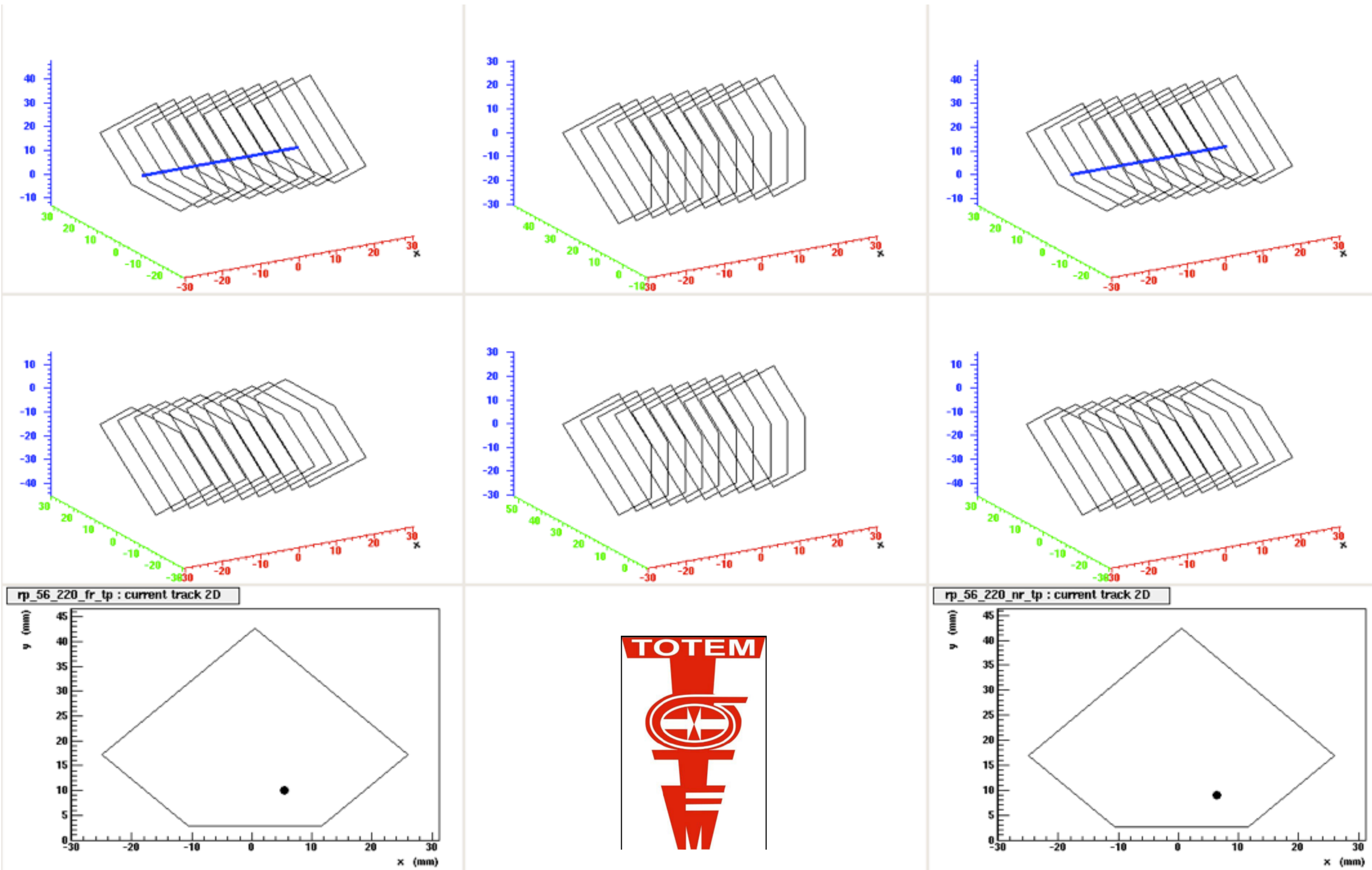
TOTEM Event 15322



RP stations - Sect 4-5

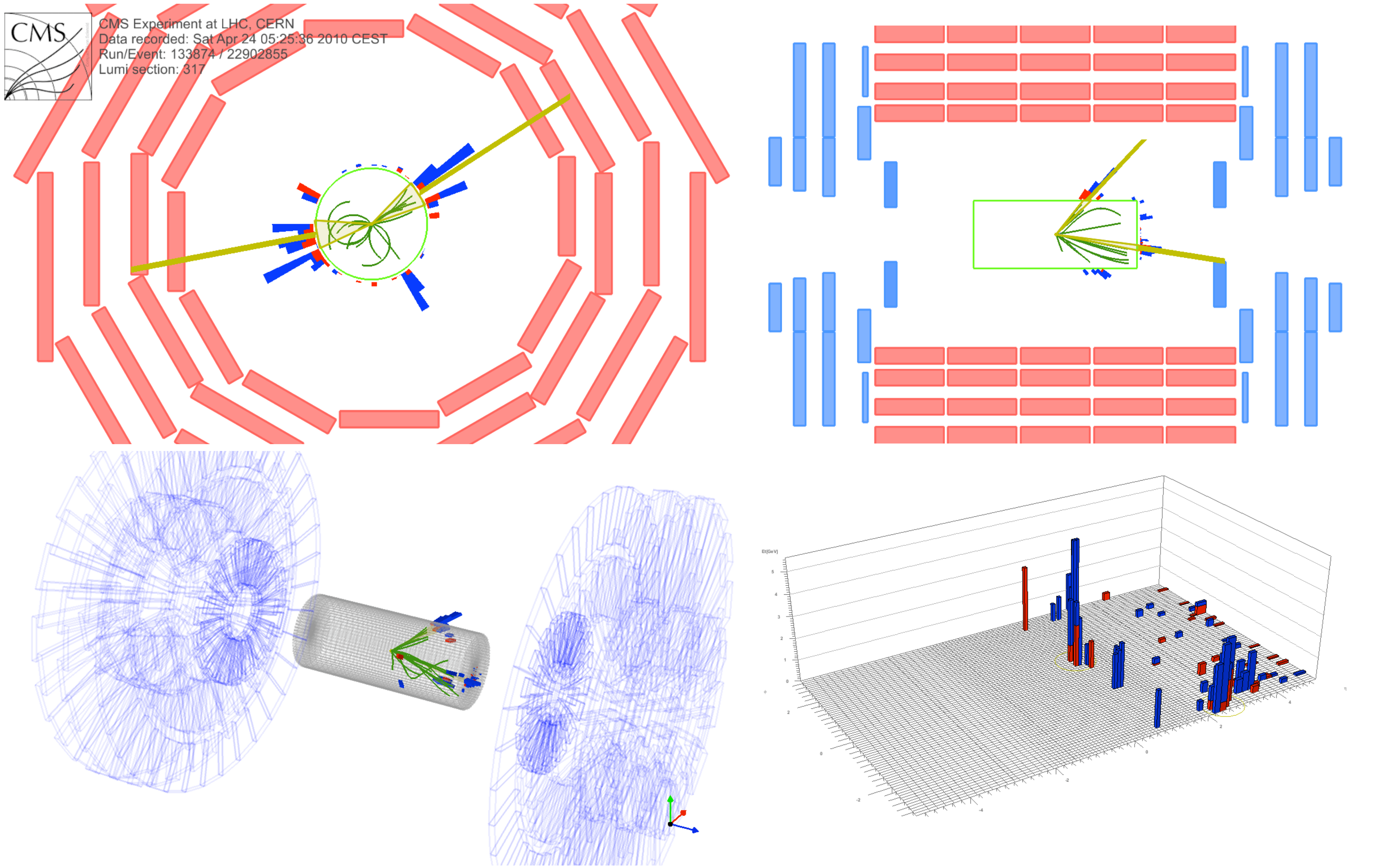
Run 198903 - Event 3478279

TOTEM Event 15322



RP stations - Sect 5-6

Diffractive dijet candidate



$E(\eta < 3.0) > 1.5$ GeV $\quad p_T(\text{track}) > 0.5$ GeV
$E(\eta \geq 3.0) > 2.0$ GeV

p_T (jet1) = 43.5 GeV, p_T (jet2) = 36.9 GeV
η (jet1) = 0.83, η (jet2) = 2.55

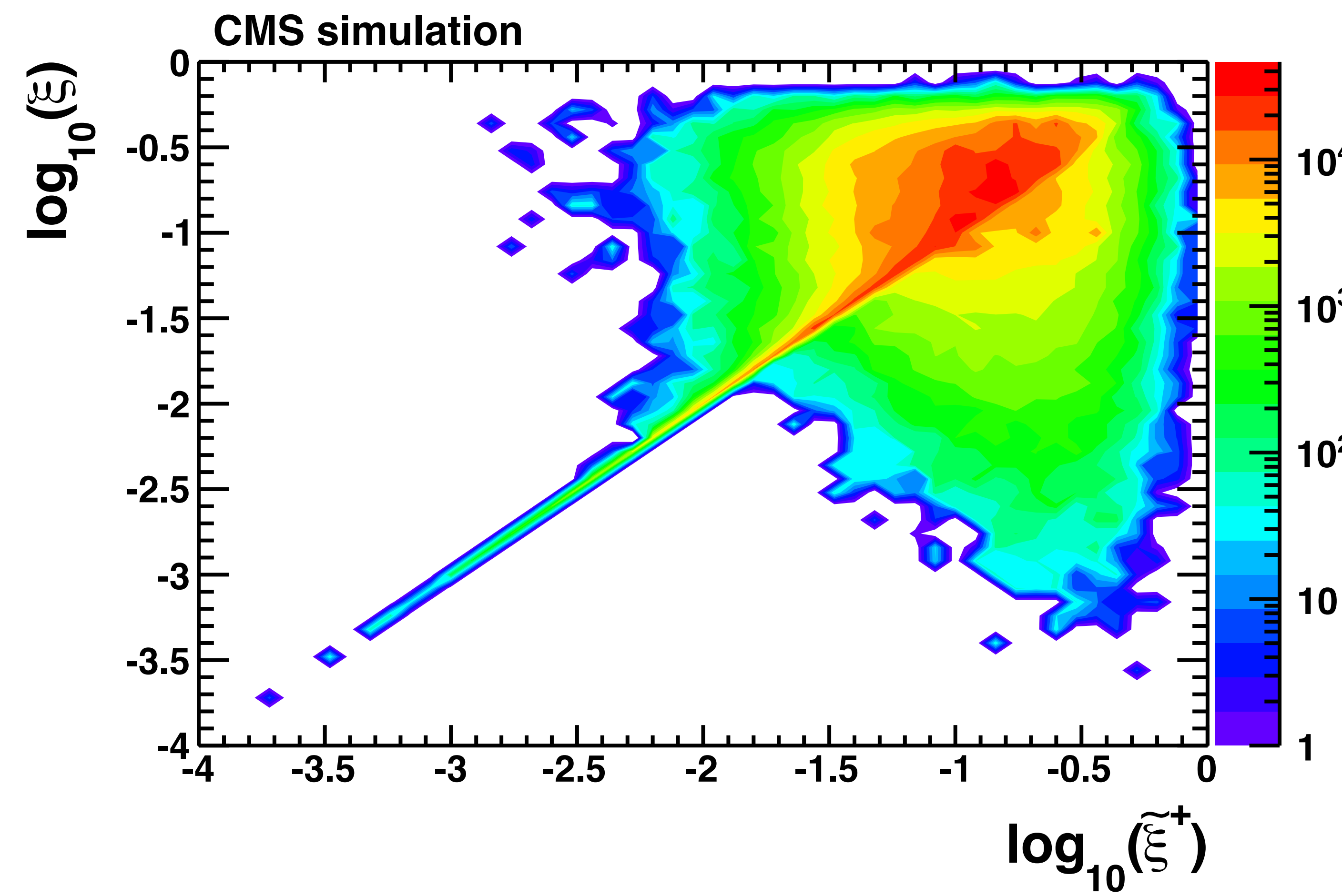
Diffractive dijets: ξ definition

Sum over all final state particles with $\eta < 4.9$ (ξ^+) or $\eta > -4.9$ (ξ^-):

$$\tilde{\xi}^+ = \frac{\sum (E + p_z)}{\sqrt{s}} \approx \frac{M_X^2}{s}$$

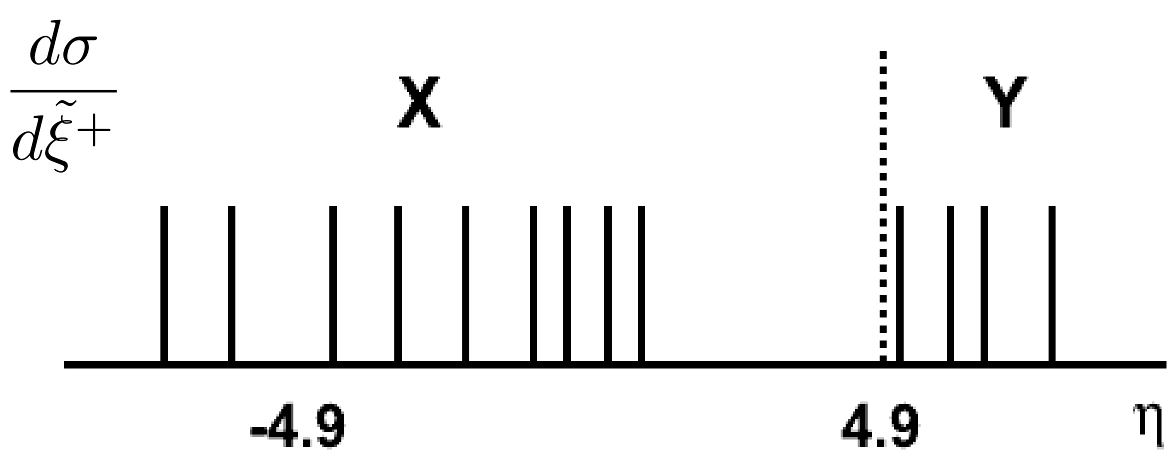
$$\tilde{\xi}^- = \frac{\sum (E - p_z)}{\sqrt{s}} \approx \frac{M_X^2}{s}$$

Defnition converges to "true" ξ (M_X^2/s) for SD events in low-ξ region



System X defined in acceptance region of CMS

System Y is undetected (M_Y mostly below ~ 12 GeV)



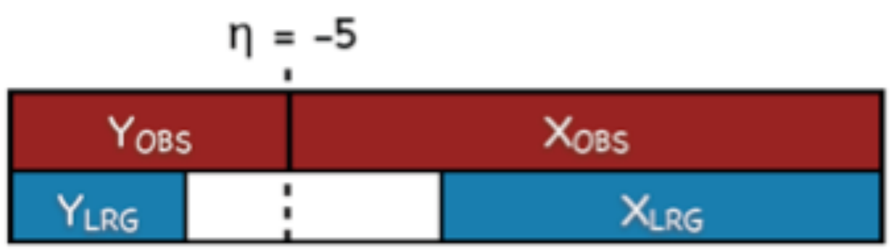
At reconstruction level, ξ is defined from all particles (using a particle-flow algorithm) above threshold, and a scale correction factor (resolution ~25%):

$$\tilde{\xi}^{\pm} = C \frac{\sum (E \pm p_z)}{\sqrt{s}}$$

Diffractive dijets: ξ definition

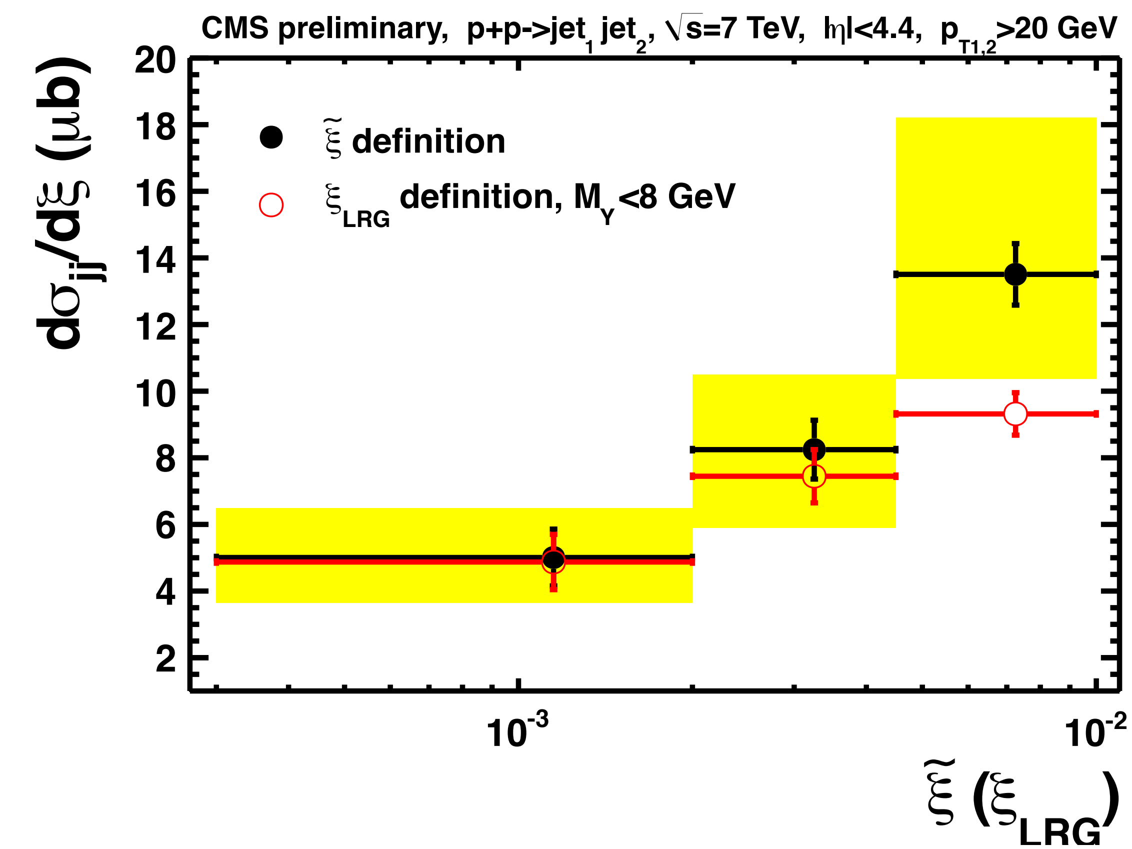
$$\tilde{\xi}^{\pm} = \frac{\sum (E \pm p_z)}{\sqrt{s}} \approx \frac{M_X^2}{s}$$

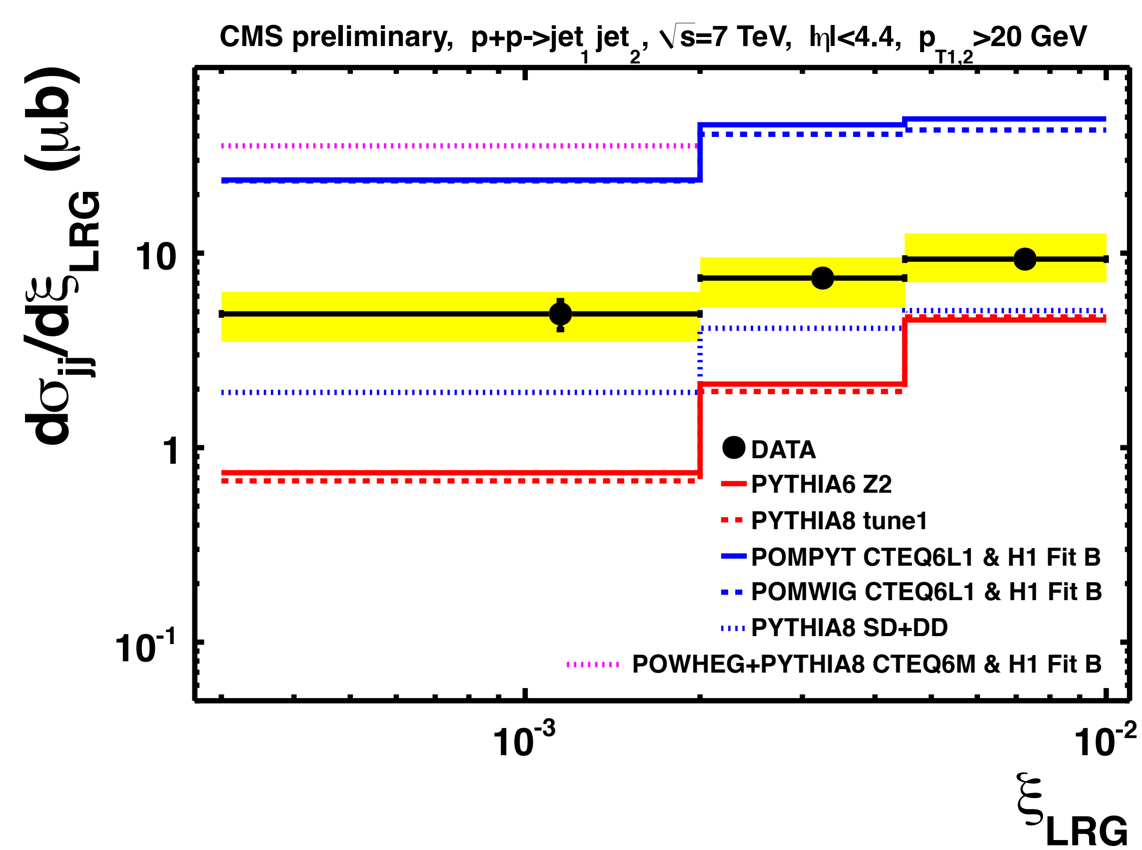
- ideal topology
  $M_{X,OBS} = M_{X,LRG}$



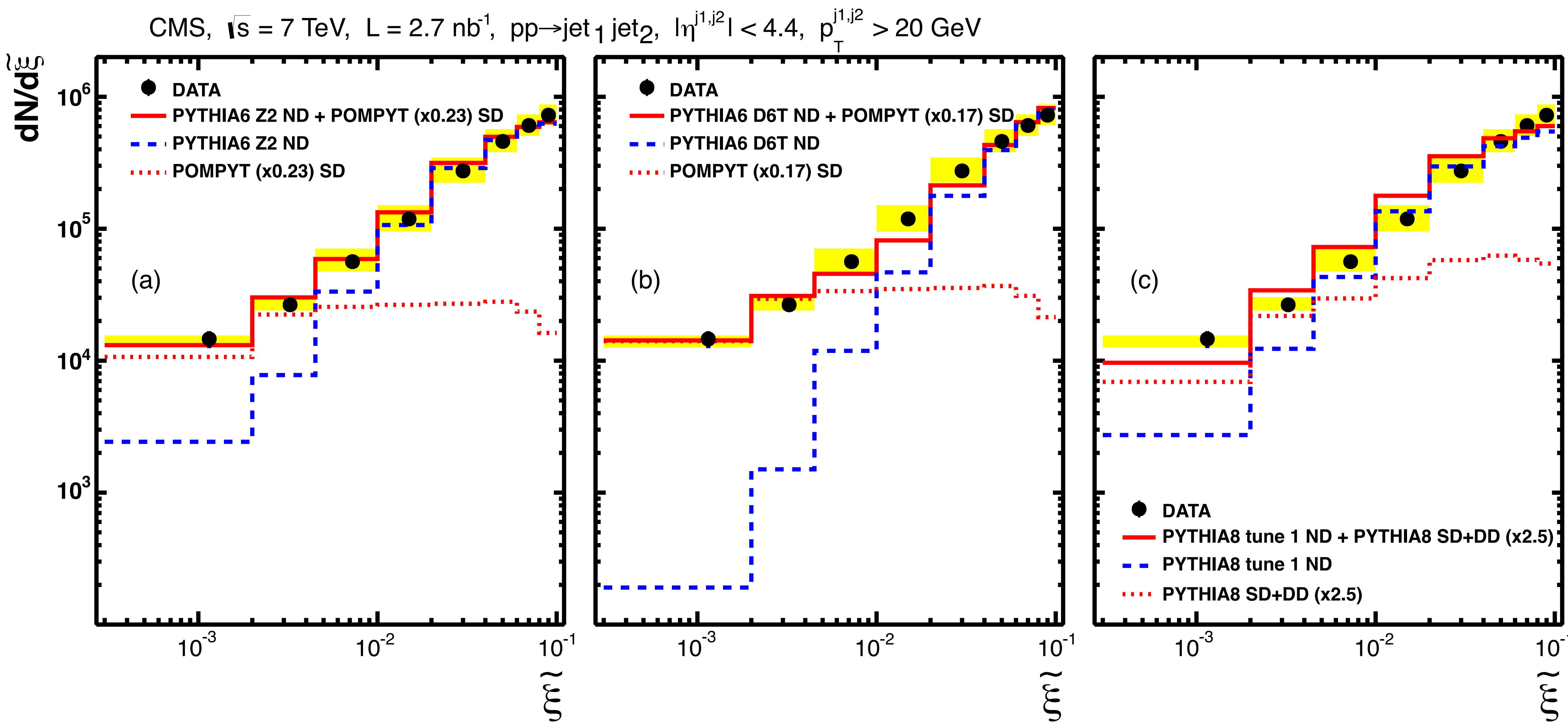
- X_{LRG} extends beyond detector acceptance
  $M_{X,OBS} \neq M_{X,LRG}$

- Y_{LRG} penetrates detector acceptance
  $M_{X,OBS} \neq M_{X,LRG}$





Diffractive dijets: Event distributions



Systematic uncertainties

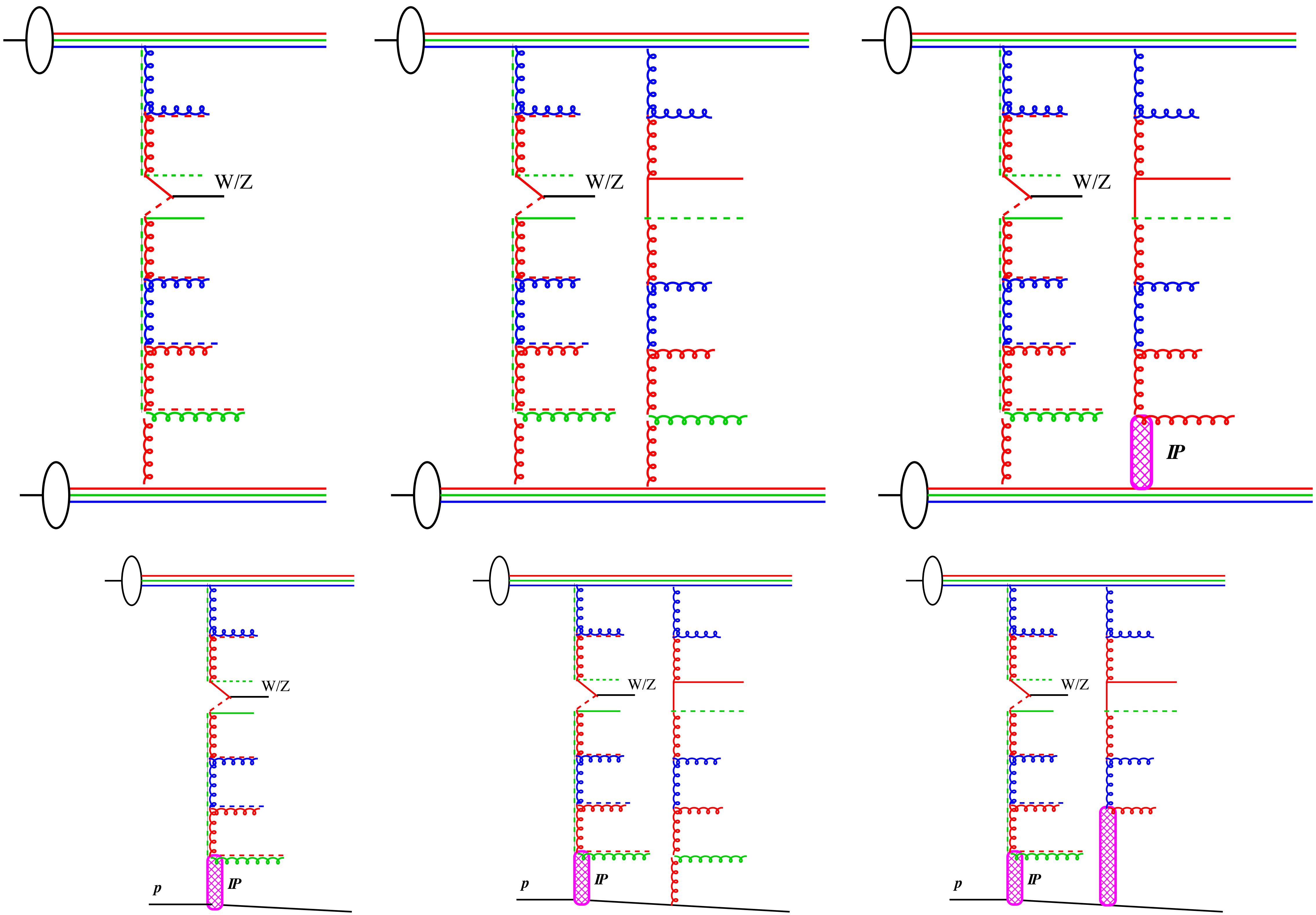
Largest contribution from Jet Energy Scale uncertainty

Average systematic error around 30%

$\tilde{\xi}$ bin	$\Delta\sigma_{jj}/\Delta\tilde{\xi}$ (μb)
$0.0003 < \tilde{\xi} < 0.002$	$5.0 \pm 0.9(\text{stat.})^{+1.5}_{-1.4}(\text{syst.})$
$0.002 < \tilde{\xi} < 0.0045$	$8.2 \pm 0.9(\text{stat.})^{+2.3}_{-2.3}(\text{syst.})$
$0.0045 < \tilde{\xi} < 0.01$	$13.5 \pm 0.9(\text{stat.})^{+4.7}_{-3.1}(\text{syst.})$

Uncertainty source	$0.0003 < \tilde{\xi} < 0.002$	$0.002 < \tilde{\xi} < 0.004$	$0.0045 < \tilde{\xi} < 0.01$
1. Jet energy scale	$(+26/-19)\%$	$(+21/-20)\%$	$(+28/-16)\%$
2. Jet energy resolution	$(+5/-3)\%$	$(+2/-1)\%$	$(+3/-1)\%$
3. Calorimeter energy scale	$(+7/-14)\%$	$(+14/-8)\%$	$(+12/-10)\%$
4. MC uncertainty	$(+5/-6)\%$	$(+3/-14)\%$	$(+3/-3)\%$
5. HF threshold	$(+0/-6)\%$	$(+2/-0)\%$	$(+2/-0)\%$
6. Tracks p_T threshold	$(+0/-1)\%$	$(+1/-0)\%$	$(+0/-2)\%$
7. One vertex selection	$(+6/-0)\%$	$(+0/-1)\%$	$(+1/-0)\%$
8. Calorimeter jets	$(+0/-4)\%$	$(+0/-4)\%$	$(+2/-4)\%$
9. $\tilde{\xi}^+$, $\tilde{\xi}^-$ difference	$\pm 8\%$	$\pm 8\%$	$\pm 11\%$
10. η_{max} (η_{min}) cut	$(+0/-0)\%$	$(+3/-0)\%$	$(+9/-0)\%$
11. Trigger efficiency	$\pm 3\%$	$\pm 3\%$	$\pm 3\%$
12. Luminosity	$\pm 4\%$	$\pm 4\%$	$\pm 4\%$

Underlying event in hard interactions

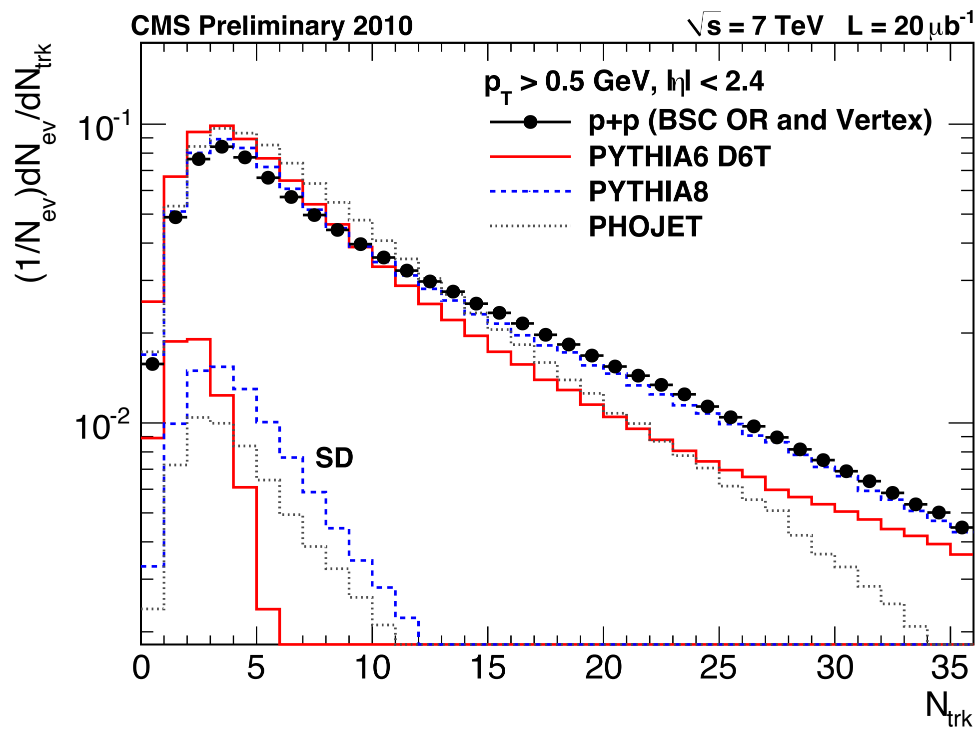


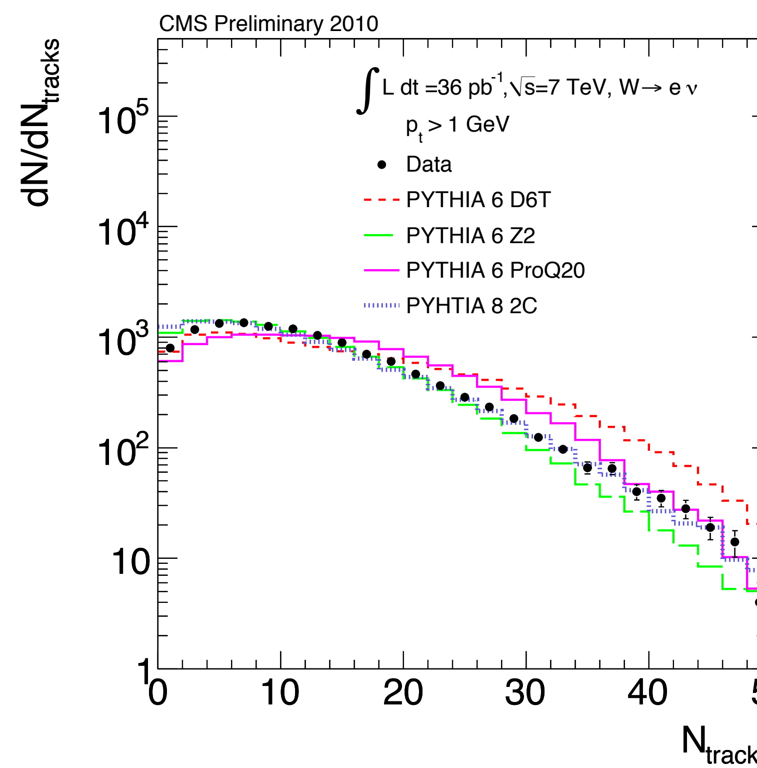
Central vs Forward energy flow

Minimum bias

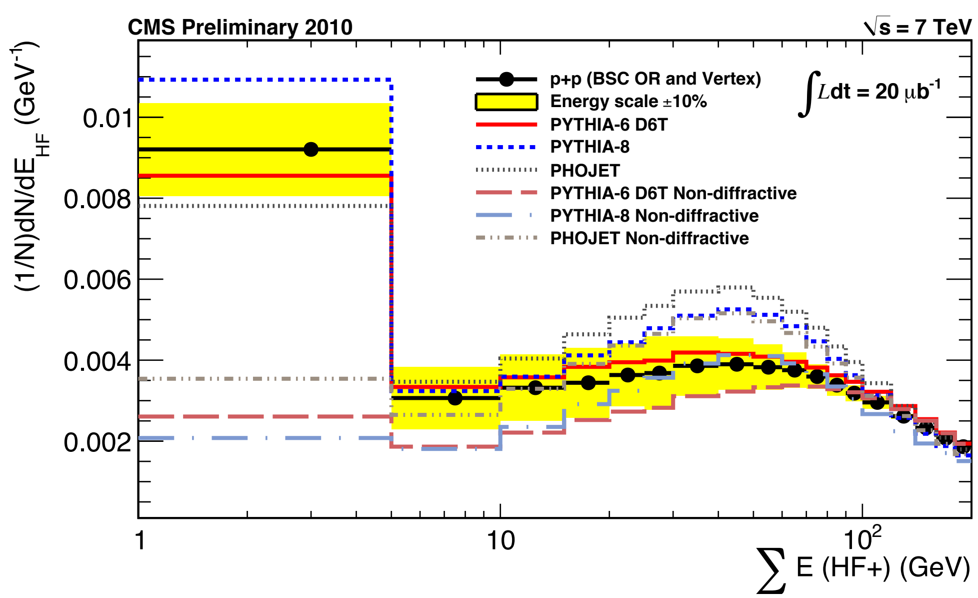
$pp \to W X$

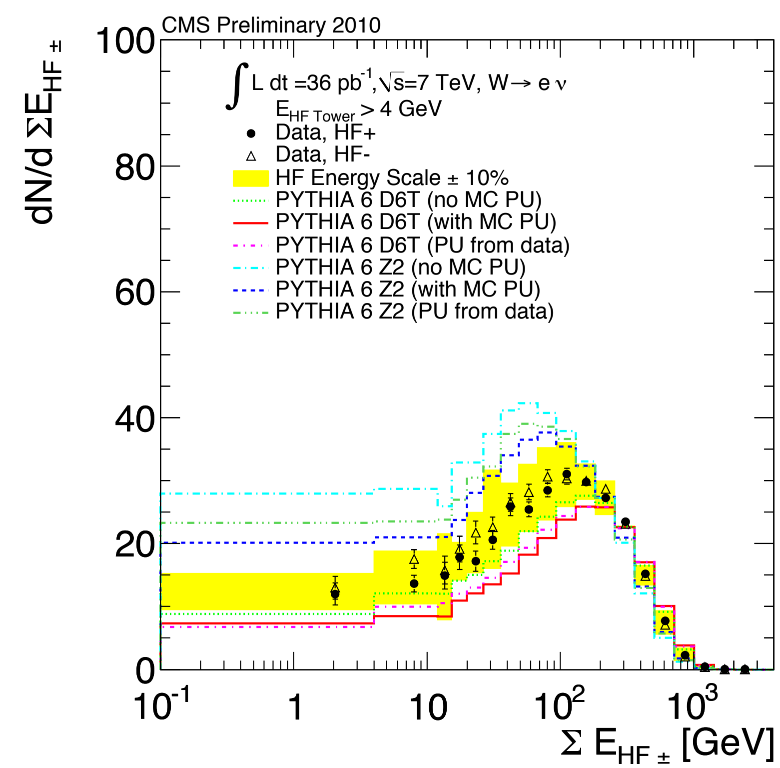
Central track multiplicity





Forward energy



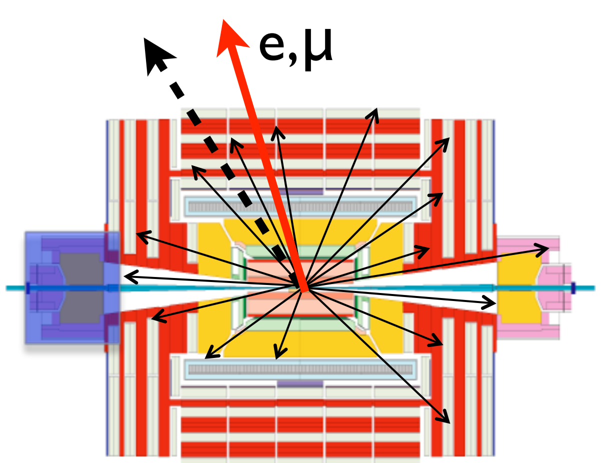


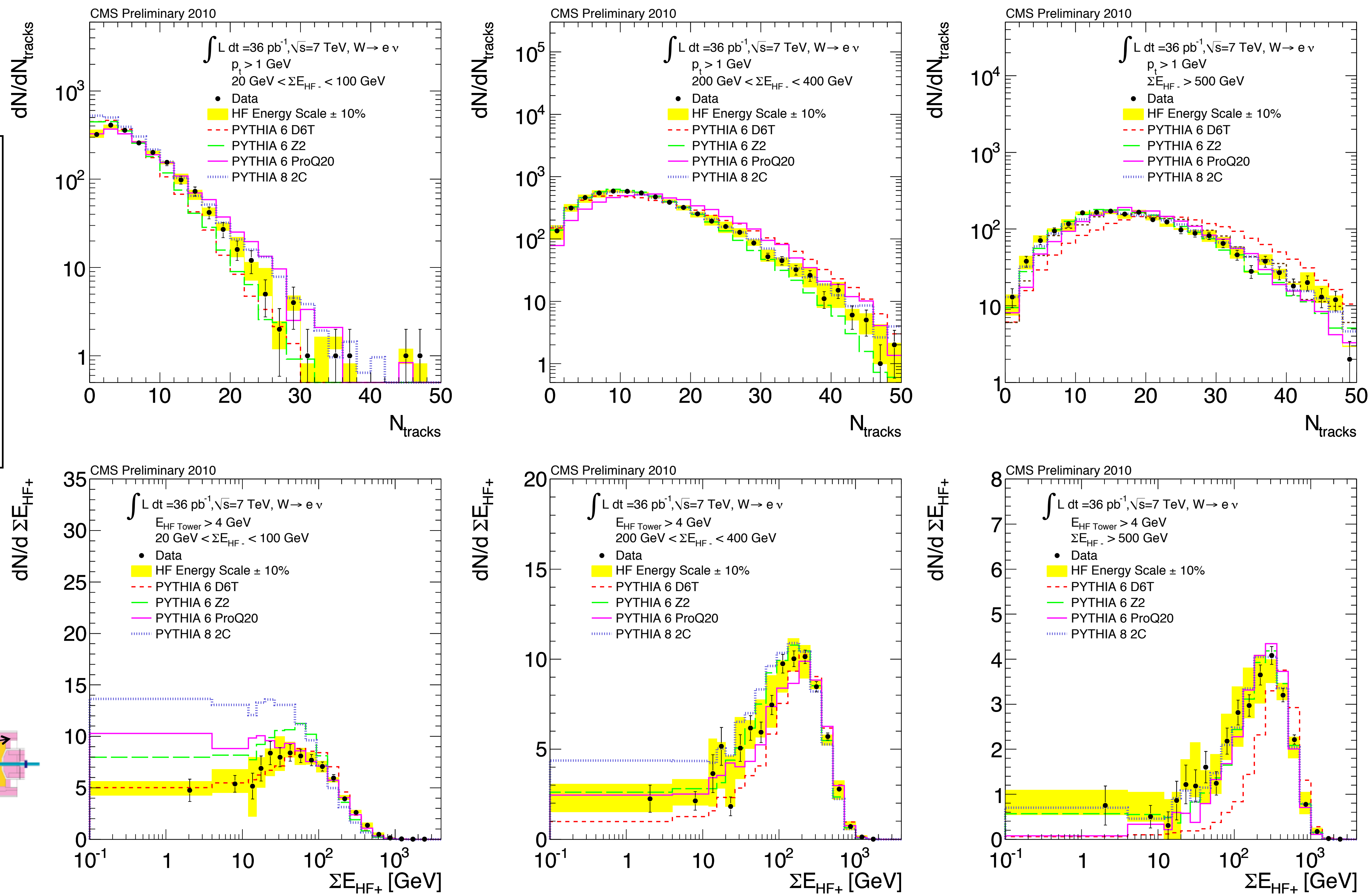
CMS FWD-10-008

Eur. Phys. J. C (2012) 72:1839

Central vs Forward energy flow

Central and forward activity with increasing forward deposition in the opposite side



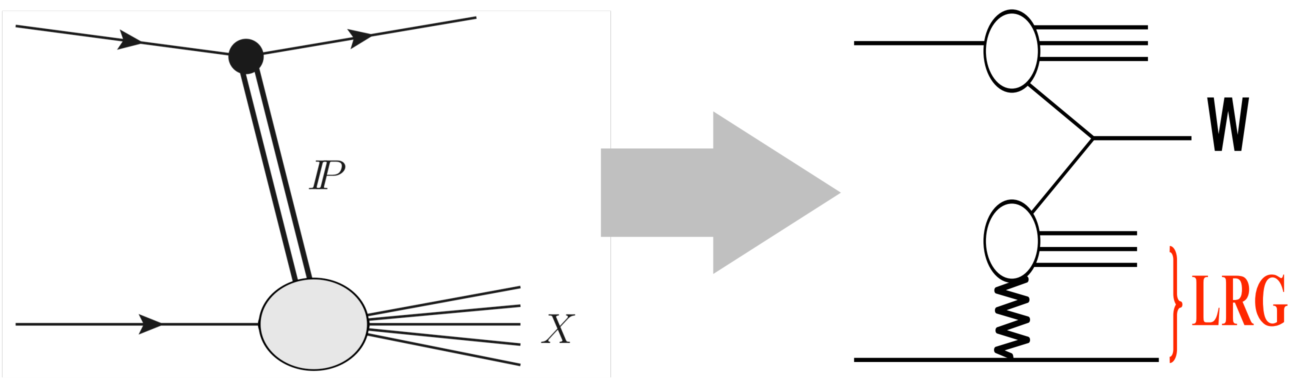


$\sum E_{HF-}$

[CMS FWD-10-008](#)

[Eur. Phys. J. C (2012) 72:1839](#)

W→eν(μν) gap distributions

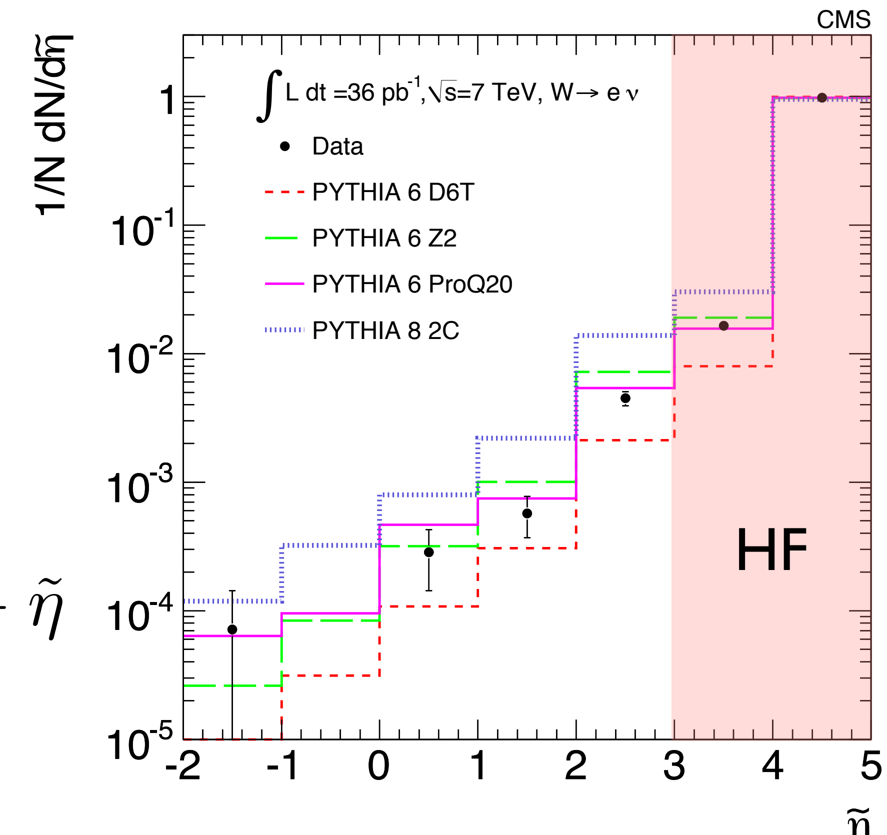


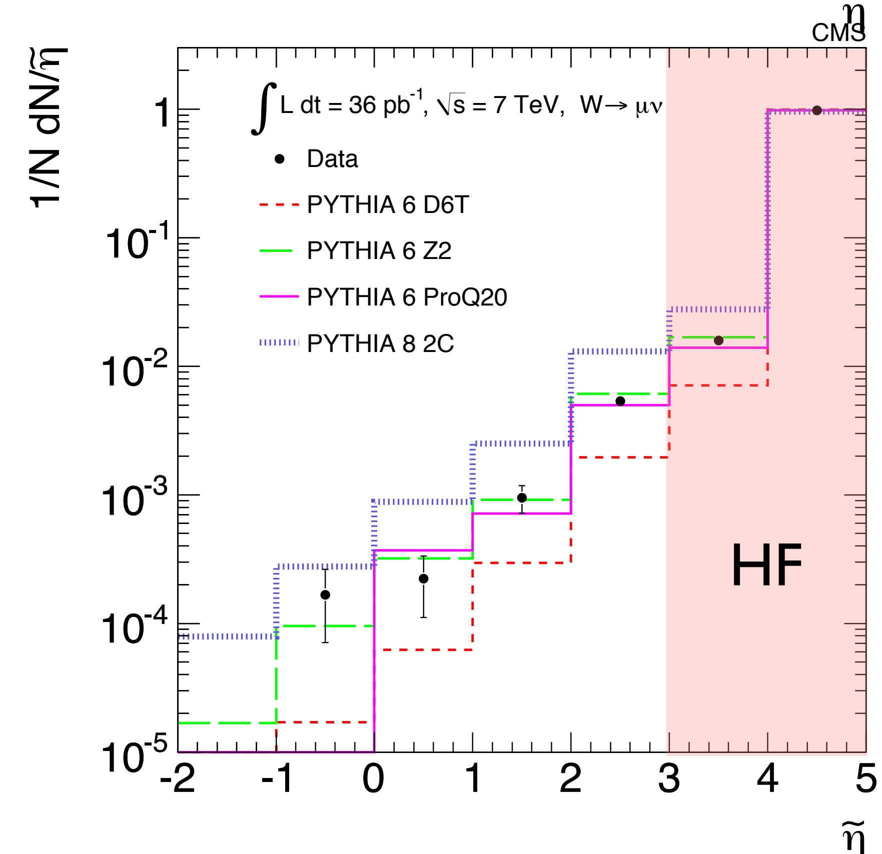
$$\Delta\eta^{\mathrm{Gap}} \equiv 4.9 - \tilde{\eta}$$

- Single-vertex events to reject pile-up
- Gap size (Δη) distributions for W candidate events
- Note that large gap events from non-diffractive MC events as well as data
- Large dependence on MC tune

[CMS PAS FWD-10-008](#)

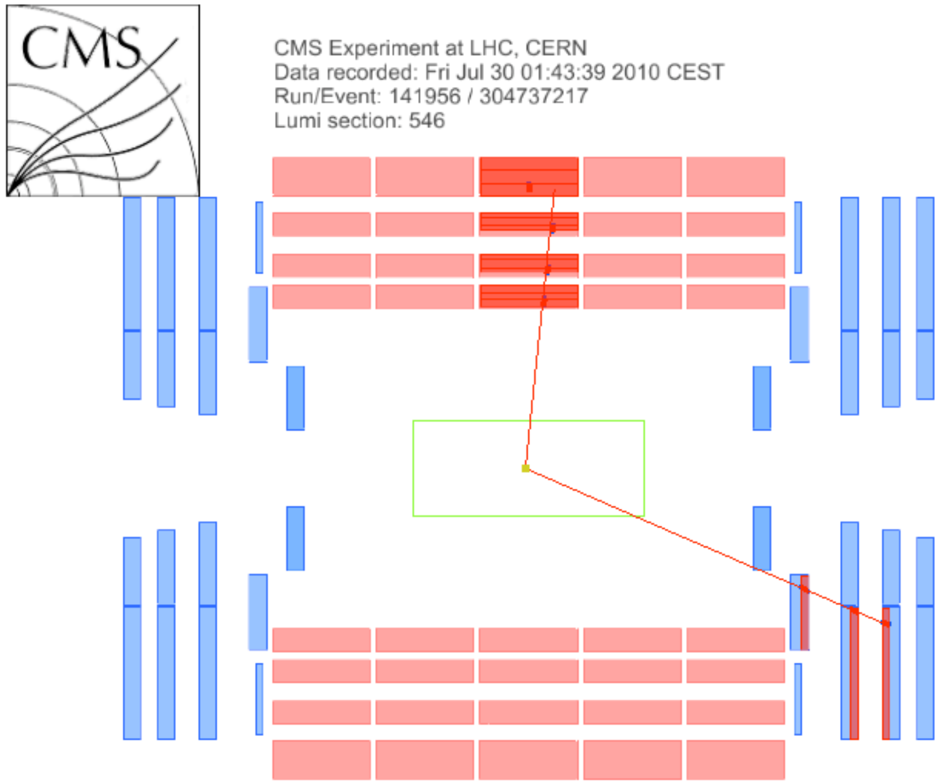
[Eur. Phys. J. C (2012) 72:1839](#)

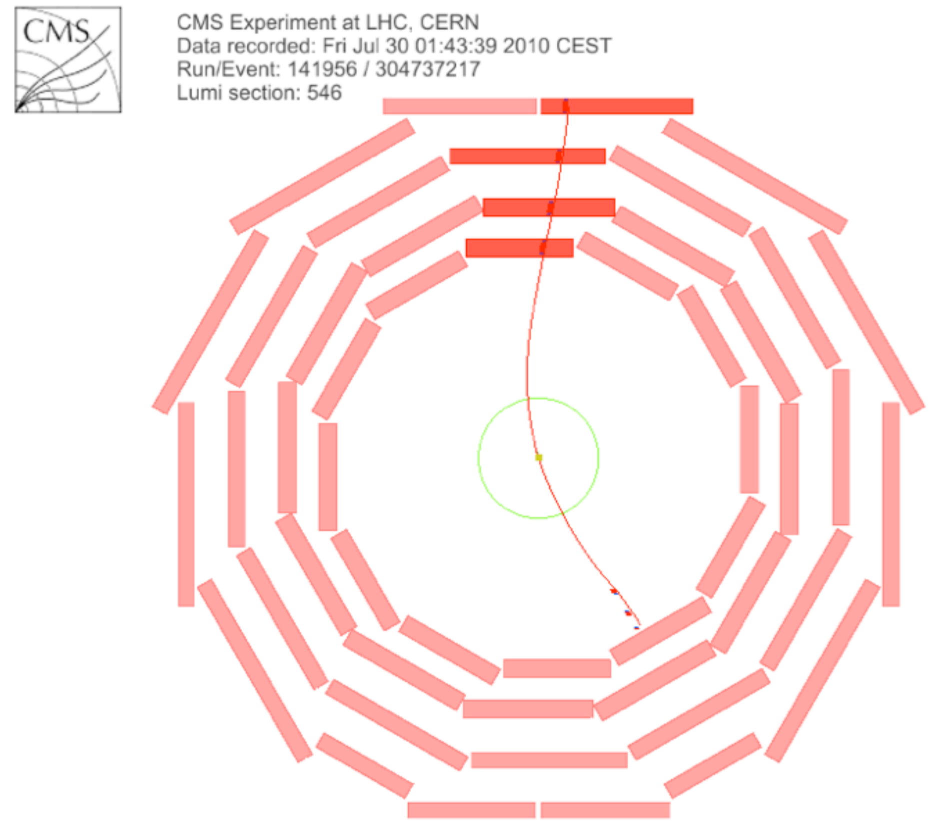


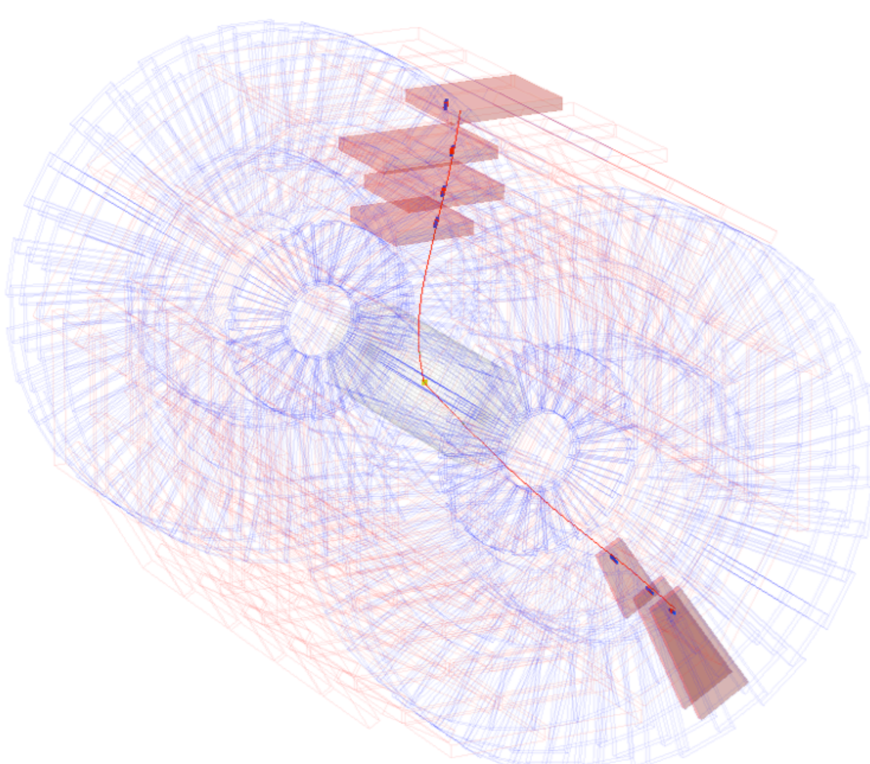


$\sum E_{HF} = 0 \Leftrightarrow \eta_{max,min} < 3$

Exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ production

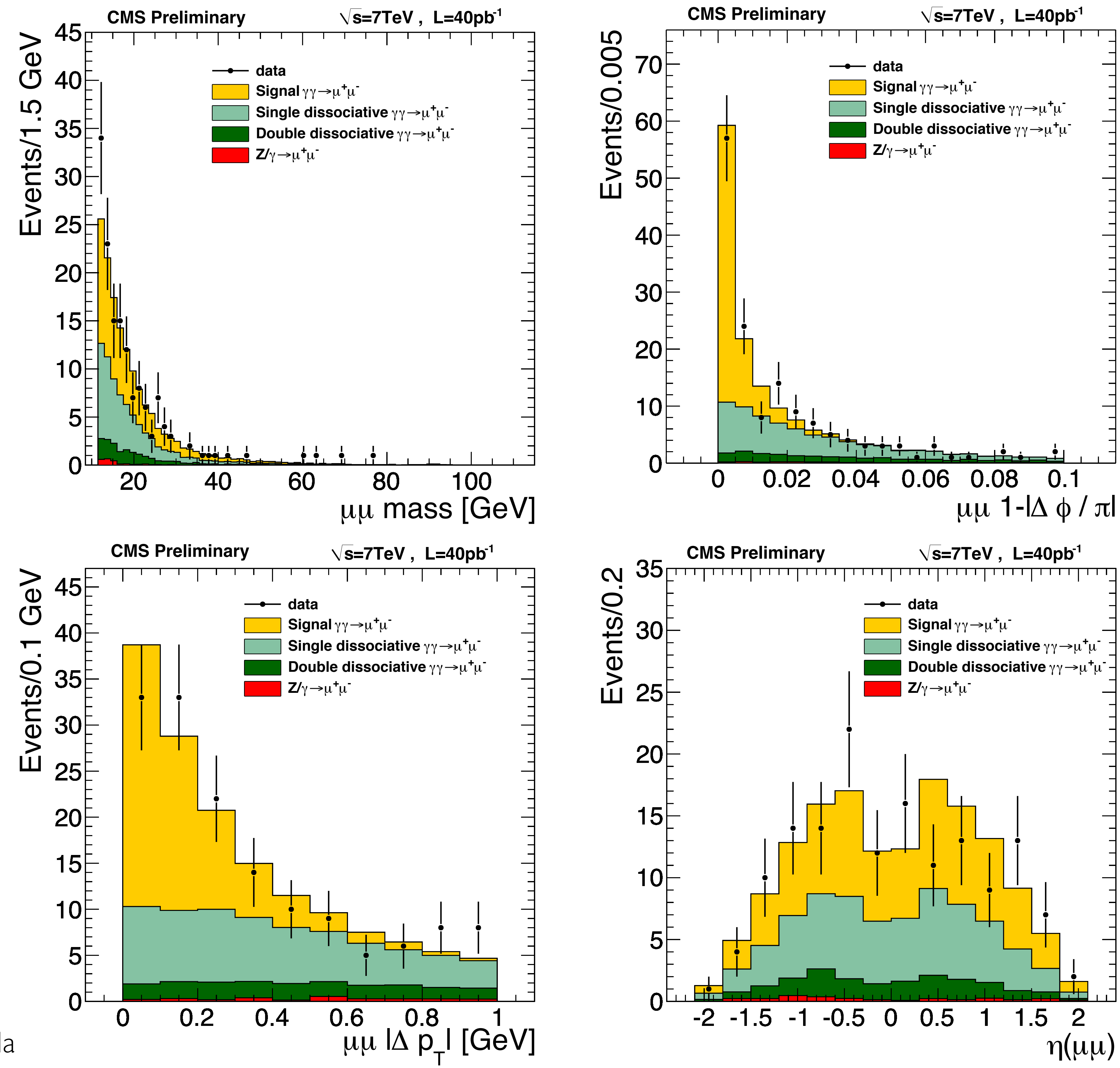




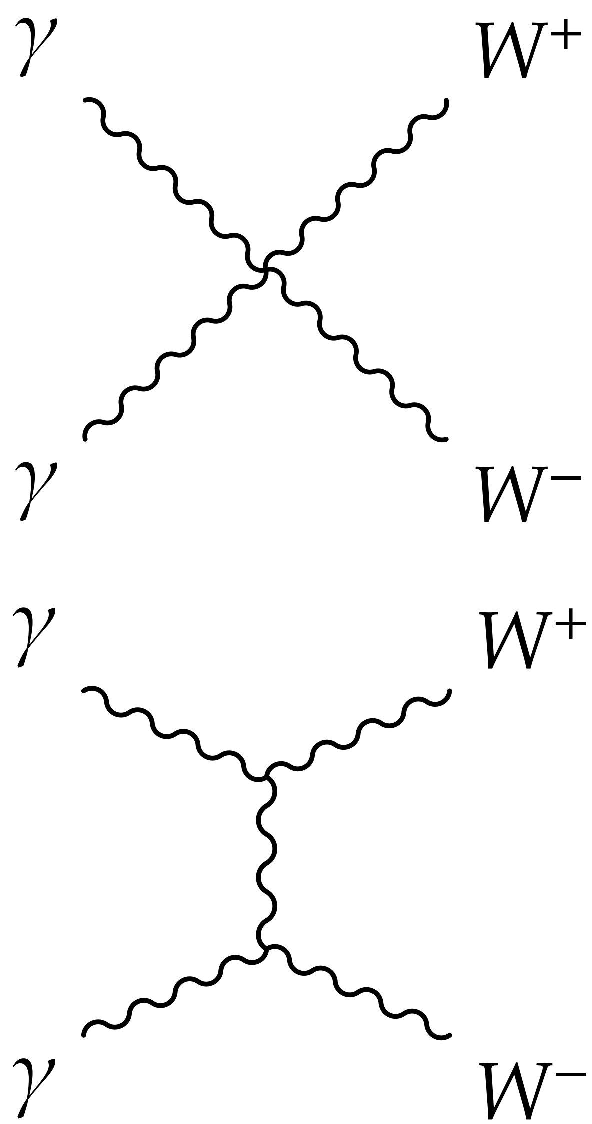


$$m = 20.51 \pm 0.2 \text{ GeV}$$
$$\frac{\Delta\phi}{\pi} = 0.98$$
$$\Delta p_T = 0.48$$
$$\text{track: } p_T > 0 \text{ GeV}$$
$$\text{HCAL: } E > 4 \text{ GeV}$$
$$\text{ECAL: } E > 2.5 \text{ GeV}$$

Exclusive γγ→μ⁺μ⁻ production

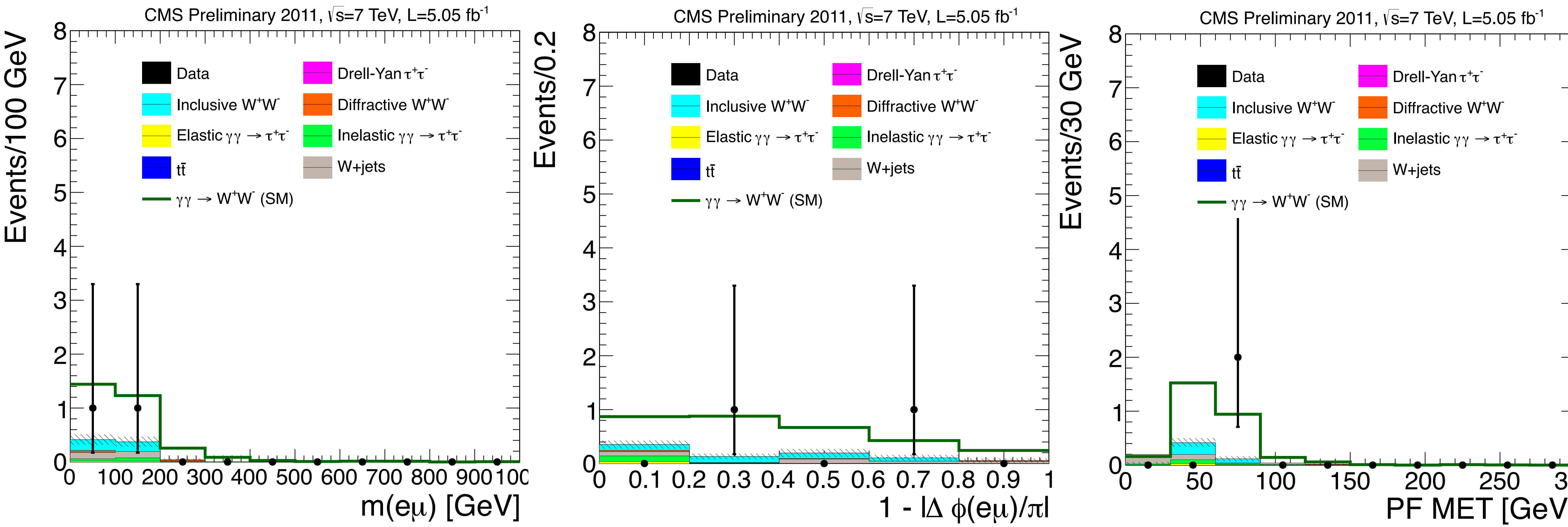


Exclusive γγ→W⁺W⁻ production



$$\begin{aligned}\mathcal{L} = a_1\ & F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W^{-}_{\alpha} \\ + a_2\ & F_{\mu\nu}F^{\mu\nu}Z^{\alpha}Z_{\alpha} \\ + a_3\ & F_{\mu\alpha}F^{\mu\beta}Z^{\alpha}Z_{\beta} \\ + a_4\ & F_{\mu\alpha}F^{\mu\beta}(W^{+\alpha}W^{-}_{\beta} + W^{-\alpha}W^{+}_{\beta})\end{aligned}$$

Exclusive $\gamma\gamma \to W^+W^-$ production



Exclusive IPIP → γγ & γγ → e$^+$e$^-$

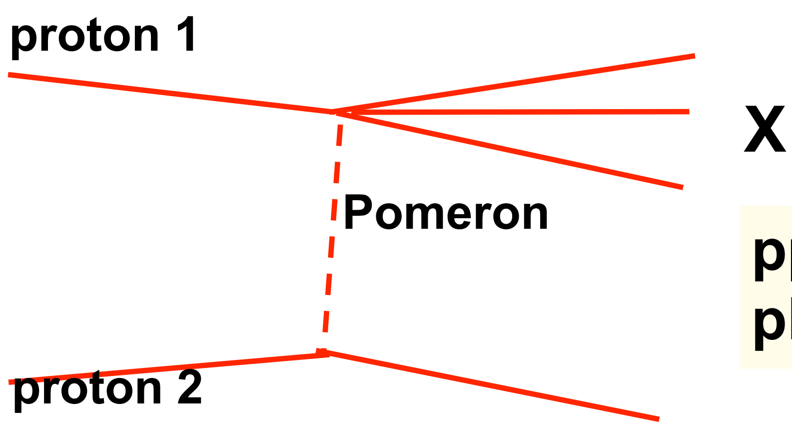
Table 1: Number of diphoton and dielectron candidates remaining after each selection step.

Diphoton analysis		Dielectron analysis	
Selection criterion	Events remaining	Selection criterion	Events remaining
Trigger	3 023 496	Trigger	3 023 496
Photon reconstruction	1 683 526	Electron reconstruction	132 271
Photon identification	40 692	Electron identification	1 668
Cosmic-ray rejection	34 234	Cosmic-ray rejection	1 321
Exclusivity requirement	0	Exclusivity requirement	17

Table 4: Background event yields expected for both the diphoton and the dielectron analyses. The quoted uncertainties are statistical.

Diphoton analysis		Dielectron analysis	
Background	Events	Background	Events
Non-exclusive	1.68 ± 0.40	Non-exclusive	0.80 ± 0.28
Exclusive e^+e^-	0.11 ± 0.03	Exclusive Υ(1S,2S,3S) $\rightarrow e^+e^-$	Negligible
Cosmic ray	Negligible	Cosmic ray	0.05 ± 0.01
Exclusive $\pi^0\pi^0$ and $\eta\eta$	Negligible	Exclusive $\pi^+\pi^-$	Negligible
Total	1.79 ± 0.40	Total	0.85 ± 0.28

Meaning of $E \pm p_z$



pp --> pX
pPomeron --> X

- $\Sigma(E \pm p_z)$ runs over all calo towers
- Measure for the momentum of the Pomeron = momentum loss of the proton

Momentum and energy conservation:
E(Pomeron) + E(proton 1) = E(X)
p_z(Pomeron) + p_z(proton 1) = p_z(X)

Recall: in SD events proton loses almost none of its initial momentum.

If proton 1 moves in positive z direction: E(proton 1) - p_z(proton 1) $\approx$ 0 (and proton 2, and Pomeron, move in the negative z direction)

Hence:
E(Pomeron) - p_z(Pomeron) $\approx$ 2E(Pomeron) $\approx$ E(X) - p_z(X)

i.e. $\xi = 2E(\text{Pomeron})/\sqrt{s} \approx (E(X) - p_z(X))/\sqrt{s}$

Conversely, if proton 1 moves in the negative z direction (and proton 2, and Pomeron, in the positive z direction), E(proton 1) + p_z(proton 1) $\approx$ 0, hence:

E(Pomeron) + p_z(Pomeron) $\approx$ 2E(Pomeron) $\approx$ E(X) + p_z(X)

i.e. $\xi = 2E(\text{Pomeron})/\sqrt{s} \approx (E(X) + p_z(X))/\sqrt{s}$