Results from combined CMS-TOTEM data

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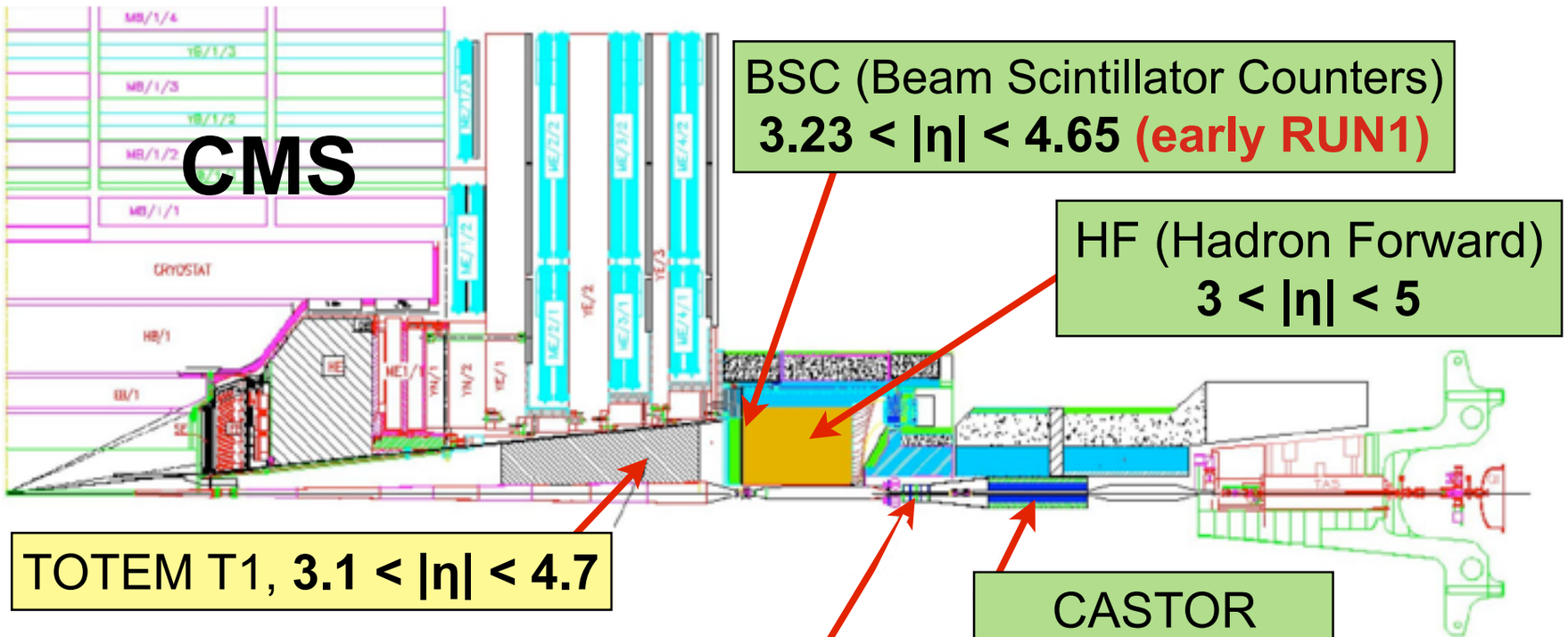
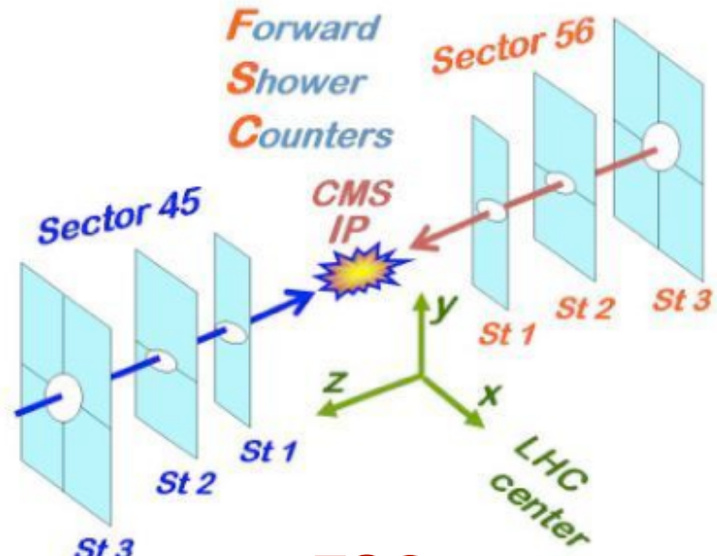
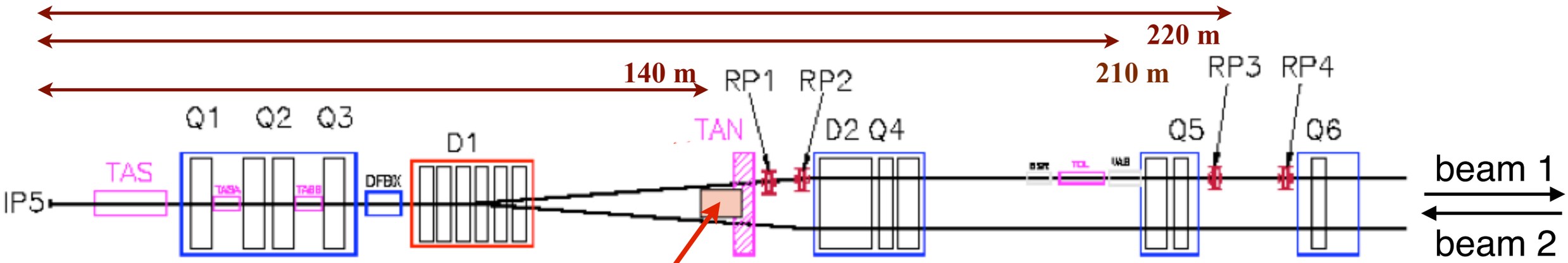
Outline

- CMS-TOTEM detectors @ IP5
- CMS-TOTEM 2015 joint data taking at high β*
- CMS-TOTEM physics objectives at RunII (β* = 90 m)
- Physics Highlights of RunI / CMS-TOTEM 2012
  - The CMS and TOTEM Collaborations, Measurement of pseudorapidity distributions of charged particles in proton-proton collisions at sqrt(s) = 8 TeV by the CMS and TOTEM experiments, EPJC 74 (2014) 3053.
  - The CMS Collaboration, Production of leading charged particles and leading charged-particle jets at small transverse momenta in pp collisions at √s = 8 TeV, Phys. Rev. D 92, 112001.
  - The CMS and TOTEM Collaborations, CMS+TOTEM event displays of high-p_T jets with two leading protons at √s = 8 TeV, CMS-DP-2013-004, CMS-DP-2013-006 (2013).
- Summary

CMS-TOTEM Detectors @ IP5







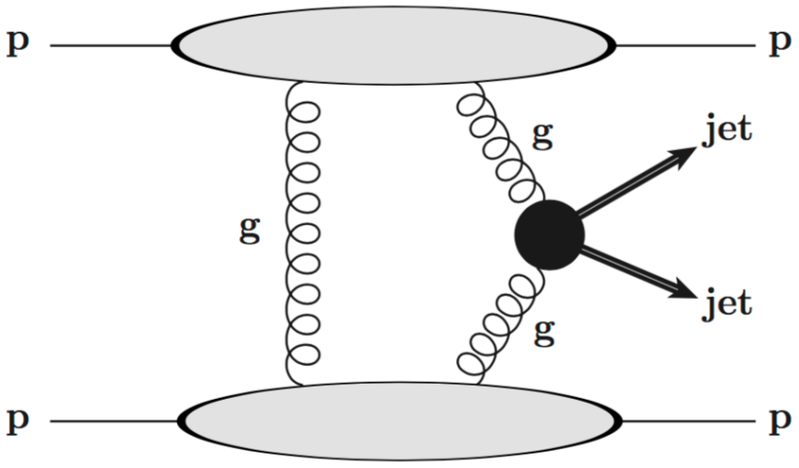
Forward Shower Counters
6 < |η| < 8

Zero Degree Calorimeter
|η| > 8.1

TOTEM Roman Pots
±210m, ±220m

CMS-TOTEM physics objectives at RunII (β* = 90 m)

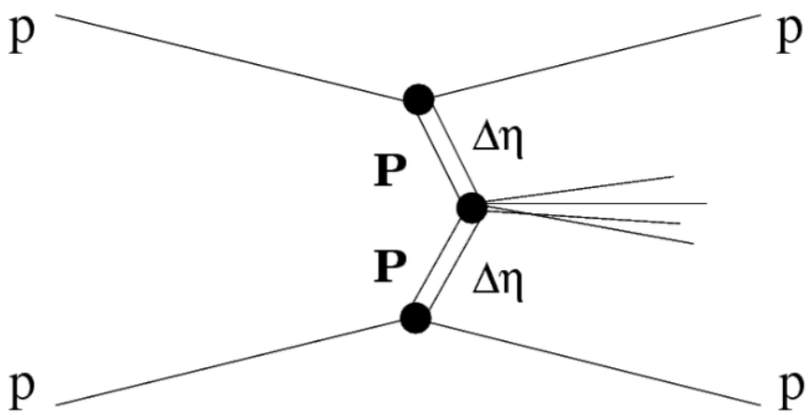
Central exclusive dijet production



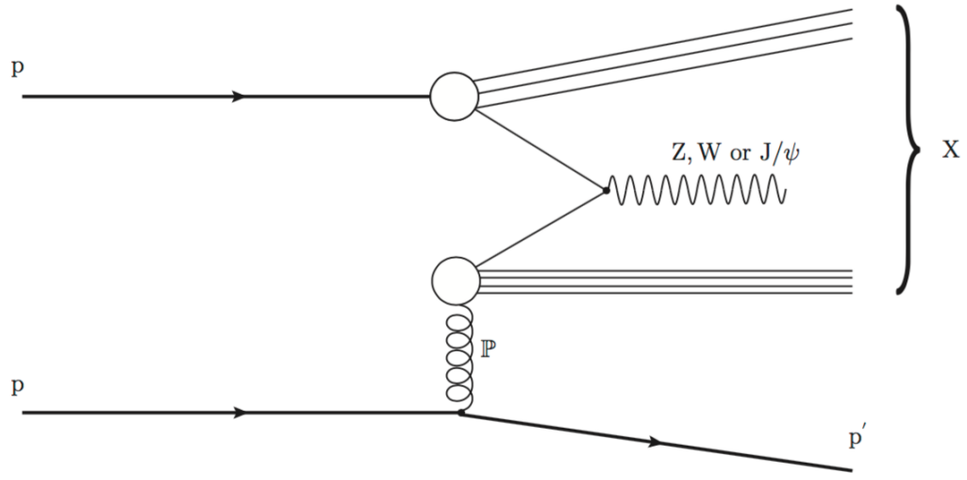
- Central exclusive production
  - low-mass resonances & glueball candidates
  - ccbar production X_c, J/Ψ..
  - missing mass searches
- Single- and central-diffractive jet production
- Single diffractive J/ψ, W and Z production

…

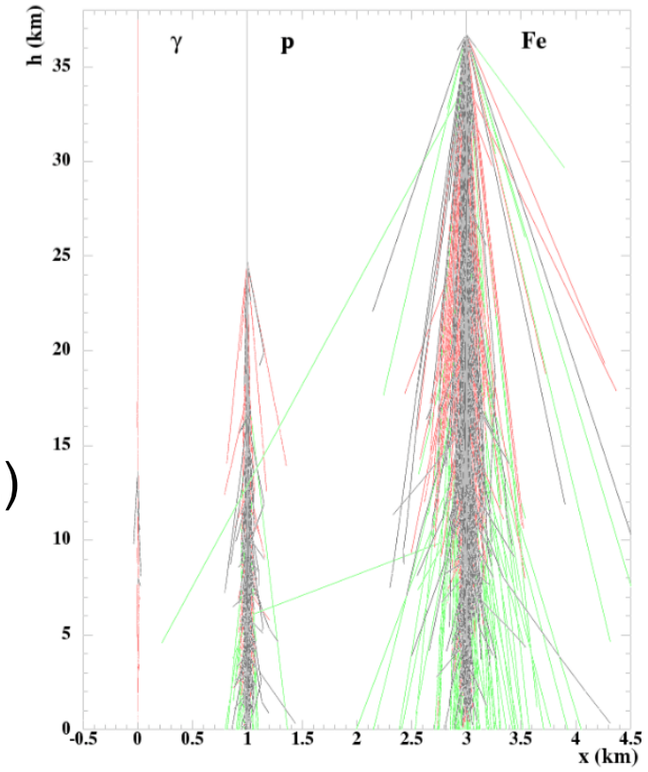
Soft central diffraction



Single diffractive Z, W and J/ψ production



Forward Particle production



@ RunI:

- Inclusive diffraction
- total cross sections (SD/CD..)
- SD dijet production
- forward particle/energy flow

…

CMS-TOTEM joint data taking in 2015 (β* = 90 m)

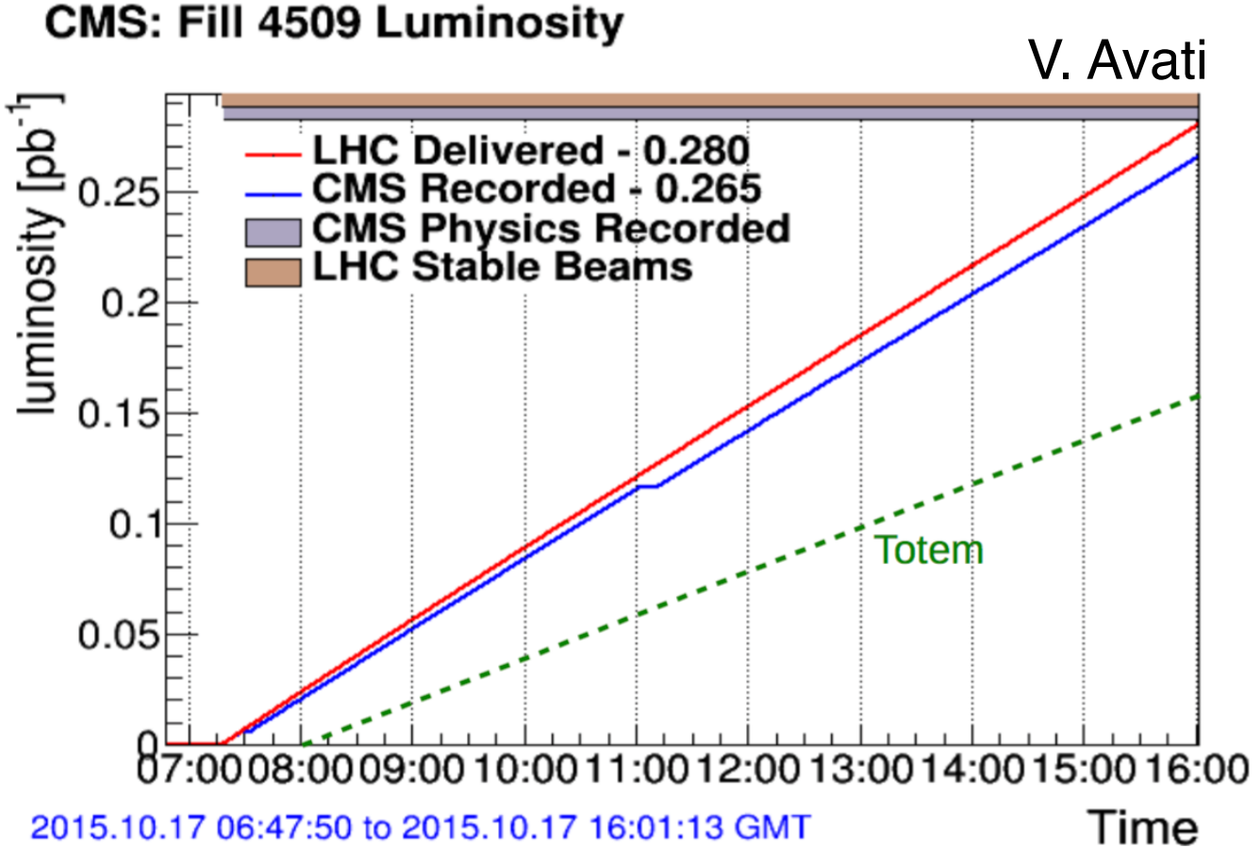
- CMS-TOTEM Runs, **Oct 15-17, 2015**
- B = 3.8 T, 13 TeV, low-PU
- β* = 90m, to reach low ltl independent of ξ.
- No CMS CASTOR.

* Independent DAQs
* L1 Trigger exchange
* Offline merging

x10 larger statistics compared to 2012

Physics Runs

Bunches	Duration (h)	Luminosity $(\mu b\ s)^{-1}$	Pileup
42	3.6	0.7	0.15
240	2.6	3.9	0.09
671	4.2	6.9	0.065
"	2.7	10.6	0.095
"	8.8	9.0	0.085
"	3.3	7.6	0.07
"	5.5	9.8	0.096



Integrated Luminosity
LHC delivered : 0.74/pb
CMS recorded : 0.68/pb
Totem recorded : 0.4/pb

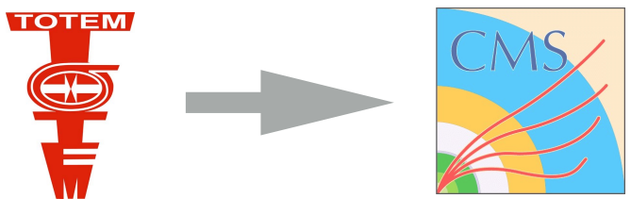
Effective Luminosity
Totem Trigger & CMS : 0.55/pb
CMS-TOTEM : 0.4/pb

CMS-TOTEM Triggers in 2015

TOTEM L1 Rate ~ 50 kHz recorded, ~ 3 x 10^9 events collected

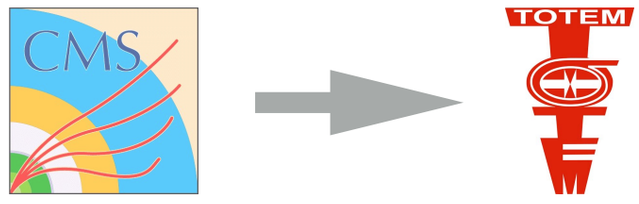
CMS HLT Rate ~ 10 kHz recorded

After the DAQ upgrade in Aug 2015, can save 80 kHz (before it was 1 kHz)



Triggers from TOTEM to CMS L1 GT

1. L1_TOTEM_0 double arm RP
2. L1_TOTEM_1 MB (track in T2)
3. L1_TOTEM_2 ZeroBias
4. L1_TOTEM_3 top/top or bottom/bottom coincidence in +/- RP.



Triggers from CMS to TOTEM

1. Total L1 decision (OR of all triggers)
2. Total L1SA decision (OR of all triggers in the special partition)

Content of L1SA: L1_DoubleJet*, L1_DoubleMuOpen triggers.

Large rate for TOTEM RP coincidence due elastic events. Tracker-based selection at HLT level in CMS.

Normally all CMS-TOTEM L1 triggered events are saved w/o any further processing at HLT. (The same events must be saved by CMS and by TOTEM).

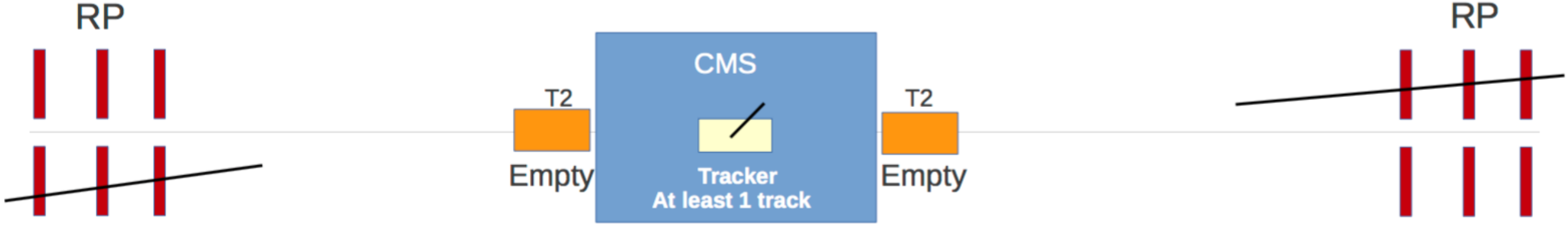
Offline merging by requiring the same LHC orbit number and bunch ids.

✓worked very well

CMS-TOTEM Triggers in 2015

Totem Rate ~ 45 kHz, CMS HLT rate ~ 1.5-2 kHz

RP double-arm + T2 Veto (L1) + CMS track (HLT)



x500-750 larger statistics compared to 2012!

$L \sim 0.4\ pb^{-1}$

$\sim 10^8$ low mass DPE candidate events

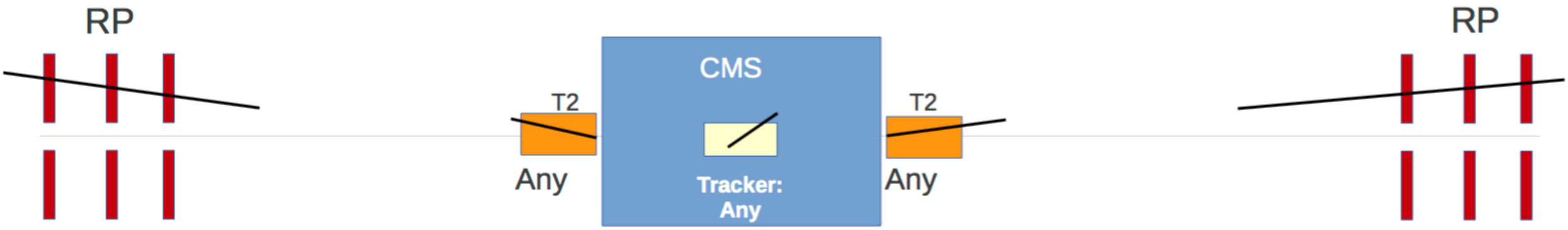
3 RP units/arm
improved acceptance
New in 2015!

Physics channels:
Low mass central diffraction (DPE),
Exclusive charmonium production
(Exclusive) CD production of meson pairs or any low mass state
Various exclusive channels; J/ψ, $\pi^+\pi^-$,…
glueballs searches
...

CMS-TOTEM Triggers in 2015

Totem Rate ~ 5 kHz, CMS HLT rate ~ 5 kHz

RP double-arm Top-Top OR Bottom-Bottom, T2 any (L1), CMS track any (HLT)



High mass central diffraction, missing mass searches

No elastic background

Exchange of color singlets with vacuum quantum numbers

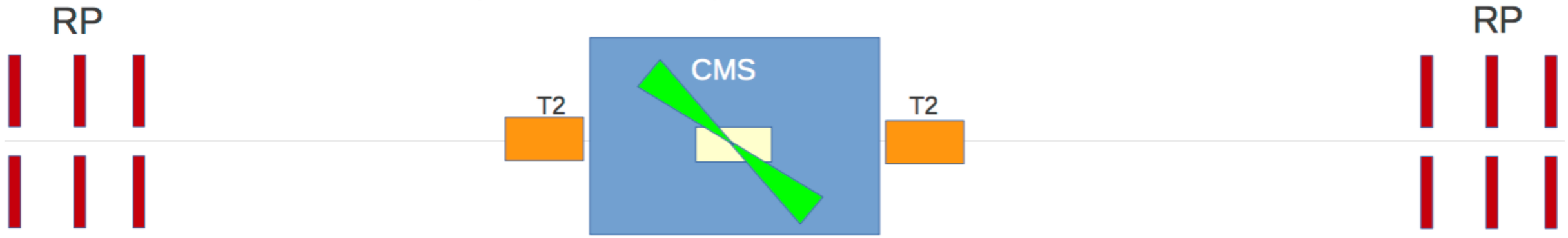
X: $J^{PC} = 0^{++}, 2^{++},\ldots$

CMS-TOTEM Triggers in 2015

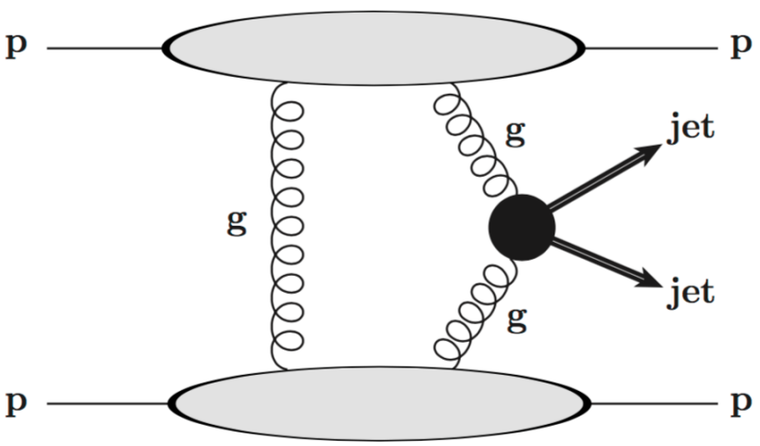
CMS HLT rate ~ 0.5-1 kHz

CMS only (L1): DoubleJet20, DoubleJet32, DoubleMuon

(Single Muon with HF gap, MinBias (T2), ZeroBias)



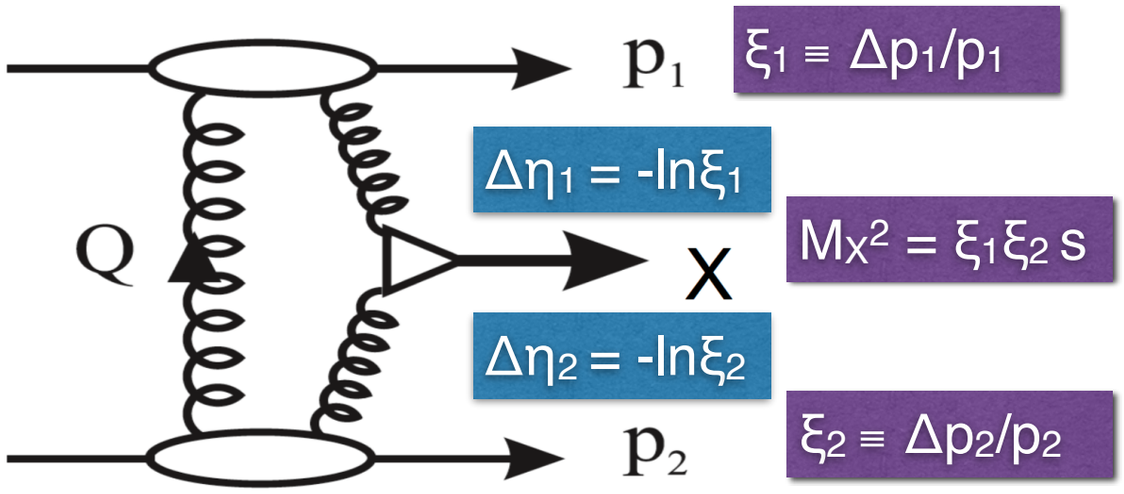
Single Diffractive Dijets, Exclusive Dijets



- detect both protons (TOTEM), object reconstruction at central detector (CMS).
- pileup removal is crucial.
- compare ξ values.
- require empty CMS FSC.

jj and jjj event candidates in 2012 data (next slides)

Central Exclusive Production (CEP)



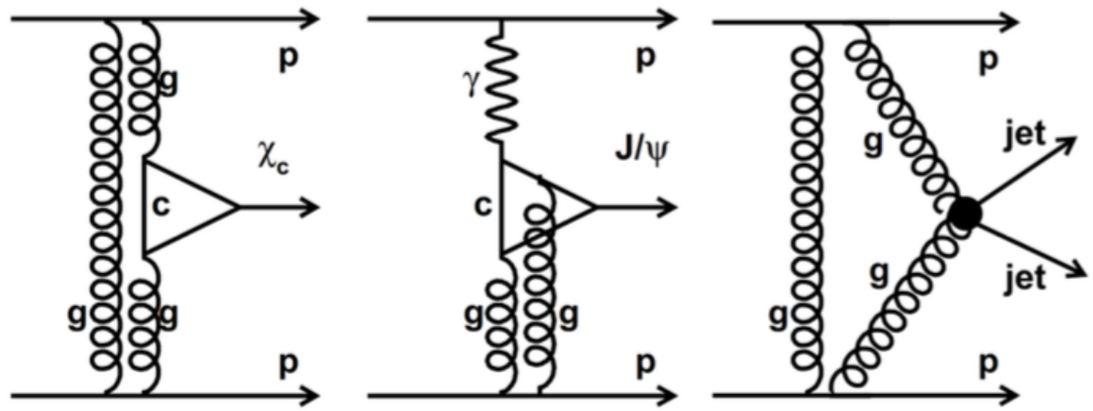
Exchange of color singlets → rapidity gaps (Δη)

X: $J^{PC} = 0^{++}, 2^{++},\ldots$

Event selection by kinematic comparison:

M(pp) =? M(central) (similarly for $p_{T,z}$ and vertex)

Many exclusive states can be measured using high β* data:
χ_C, charmonium, J/Ψ, jets…

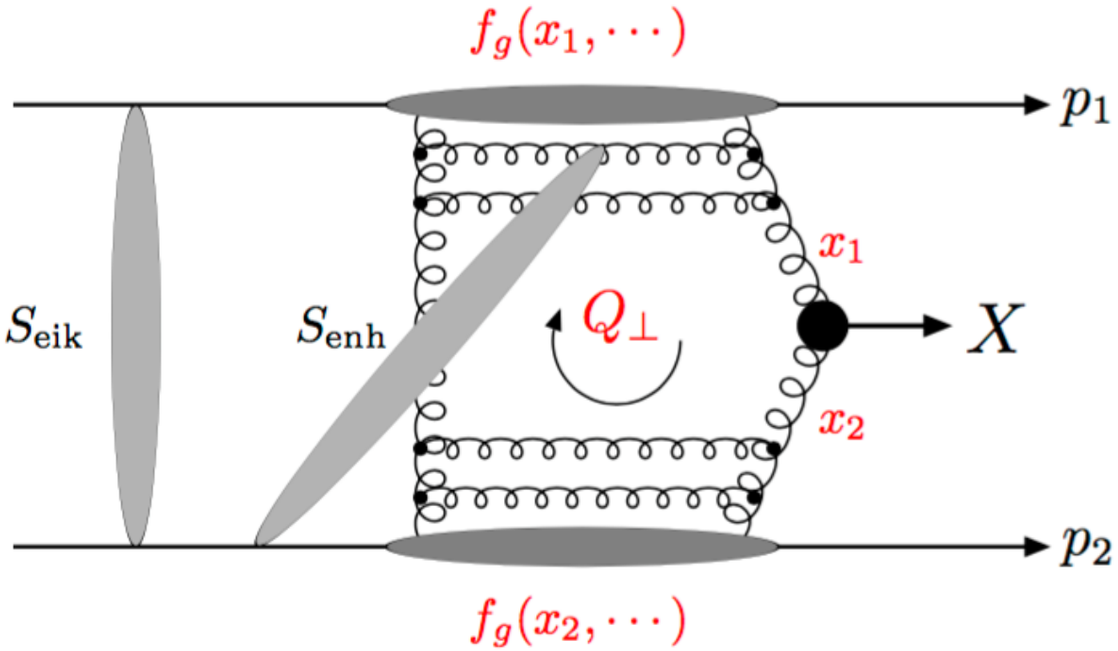


* Missing Mass & Momentum (large mass): x 100 statistics (2012)
* Low mass (non-exclusive) central diffractive dijets (pTjet > 30, 40 GeV): x 100 statistics (2012)
* Exclusive central diffractive dijets ($p_T^{jet} > 40$ GeV) ~ O(10) events

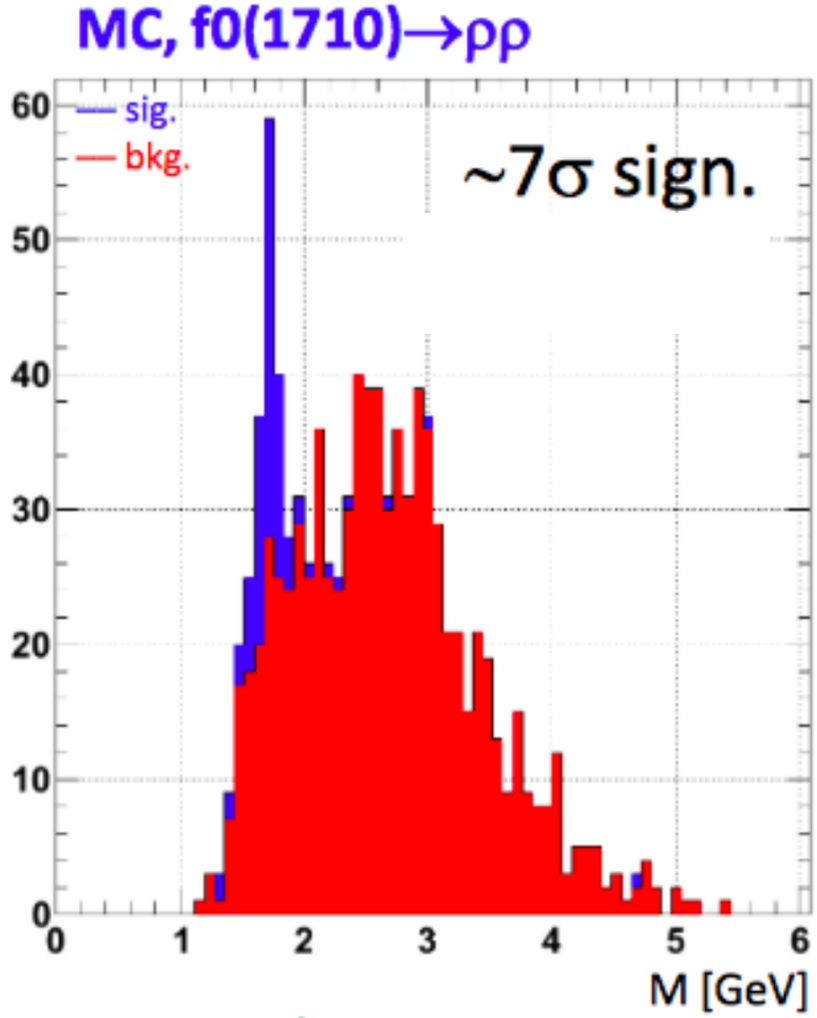
With 1 pb^{-1}: confirmation of unobserved possible **$f_0(1710)$** and $f_0(1500)$ decay modes.
With 5-10 pb^{-1}: $\sigma \times BR$ for all $\chi_{C,0,1,2}$ states and comparison with pQCD.

CEP low-mass states and Glueball candidates

Pomeron ~ colorless gluon pair / ladder, likely to produce glueballs



X = low-mass resonances / meson pair
$\pi^+\pi^-$, $\rho^0\rho^0$, K^+K^-…



M_X ~ 1-4 GeV masses can be probed diffractively ($\xi \sim 10^{-4}$ - 10^{-3})

Check the $f_0(1500)$ or $f_0(1710)$ glueball candidates

Gen level study: (in CMS and TOTEM acceptances, DIME MC) signal and non-resonant $\rho^0\rho^0$ background

Need 0.6 pb-1 of data to have feasible decay characterization

CEP low-mass states and Glueball candidates

Check the $f_0(1500)$ or $f_0(1710)$ glueball candidates

☑ **Lattice QCD** predicts 0^{++} glueball with 1.7 ± 0.1 GeV (**favors $f_0(1710)$**)

☑ CMS-TOTEM 2012 data ($L \sim 1$ nb^{-1} of double arm RP trigger) show sensitivity to:

$f_0(1710) \rightarrow \pi^+\pi^-$

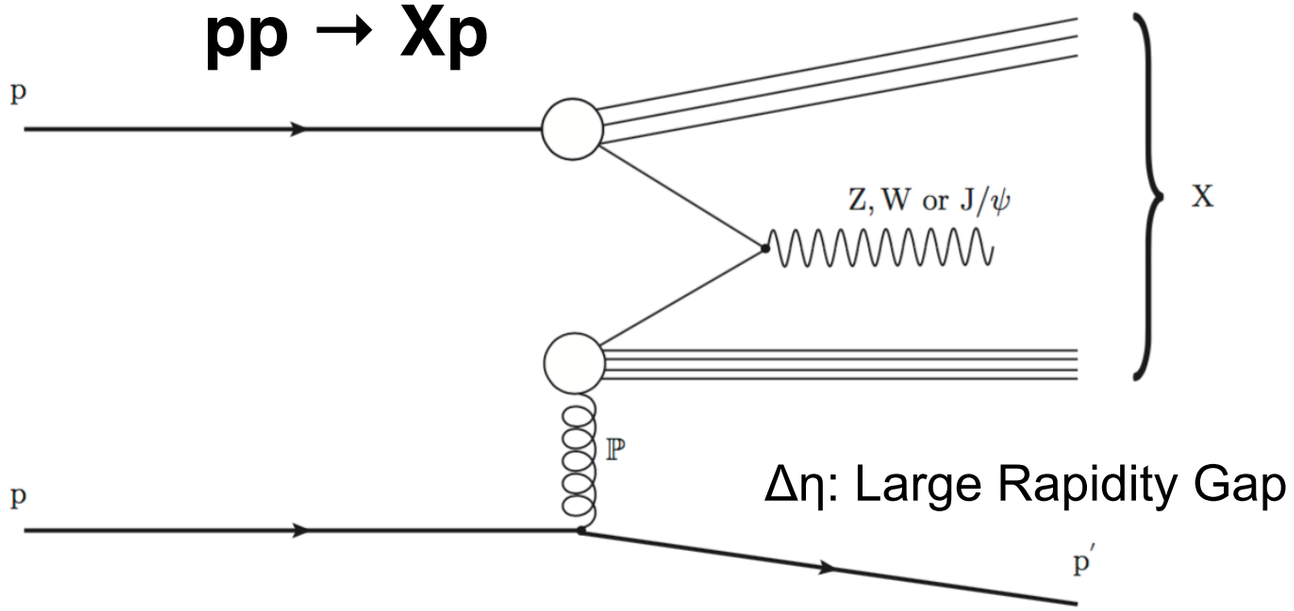
$f_0(1710) \rightarrow \rho^0\rho^0 \rightarrow 4\pi$ (not yet reported by PDG)

- Measure & tag both protons with TOTEM RP.
- Reconstruct charged particle mass at CMS, e.g., 4 charged particles with invariant mass ~ 20 - 30 MeV for $f_0(1710) \rightarrow \rho^0\rho^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$.
- Spin determination from decay angles & proton azimuthal correlations

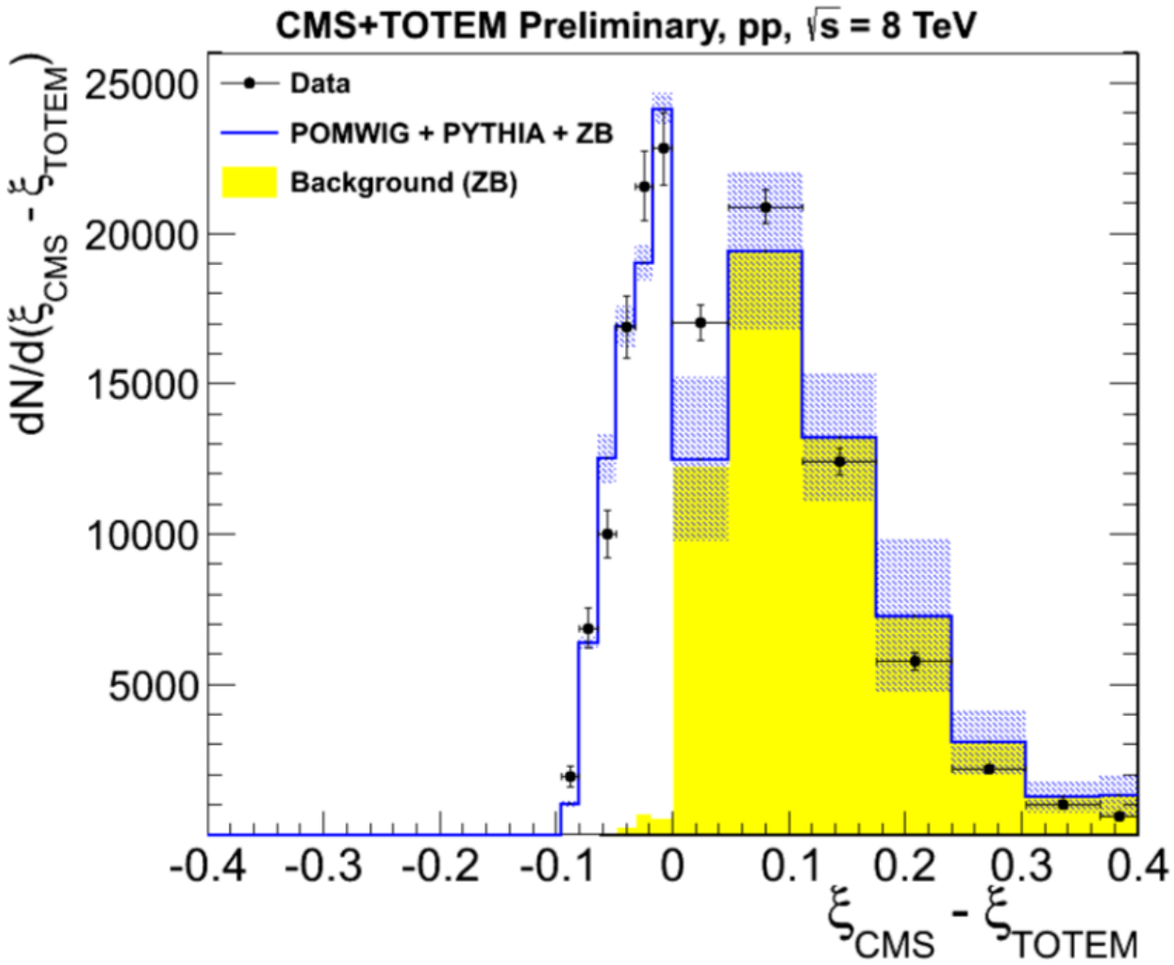
Low-mass CD trigger in 2015: $\mathcal{L}$ = ~0.4 pb^{-1} (x 500-750 statistics compared to 2012).

Allows to study the decay characterization up to some extent.
More data is needed for full spin analysis ($\mathcal{L}$ = ~5 pb^{-1}).

Single Diffractive Processes with Proton Tagging at High β*



Δη: Large Rapidity Gap



- Studying different SD processes with **Z, W, J/ψ,** and jets.
- Measurement of gap survival probability for different SD hard processes.
- Triggering with CMS lepton & jets triggers.

$$\xi^{\pm}_{\mathrm{CMS}} = \frac{1}{\sqrt{\mathrm{s}}} \sum_{\mathrm{i}}^{\mathrm{N}} E_{T,i} e^{\pm \eta_{\mathrm{i}}}$$

Pileup and beam-halo backgrounds can be removed by reconstructing ξ at CMS and TOTEM. Already studied with 2012 data!

The CMS and TOTEM Collaborations, CMS-TOTEM feasibility studies for single diffractive Z, W, J/ψ and central exclusive dijet production in pp collisions at \sqrt(s) = 13 TeV, CMS PAS FSQ-14-001, TOTEM-NOTE-2014-002.

Physics Highlights of RunI / CMS-TOTEM 2012

- 8 TeV, July 2012 data, low-PU, $\beta^* = 90$ m
- Minimum bias events triggered by TOTEM T2 and contributed to the CMS global trigger decision:

  At least one charged track with $p_T > 40$ MeV in $5.3 < |\eta| < 6.5$.

- The data collected concurrently with the CMS and TOTEM detectors.
- Events are combined offline (LHC orbit number and bunch numbers).

Also low pileup $\beta^* = 0.6$ m Runs in May 2012.

Charged Particles Distribution

- Measurement of pseudorapidity distributions of charged particles in proton-proton collisions at sqrt(s) = 8 TeV by the CMS and TOTEM experiments, EPJC 74 (2014) 3053.

low-p_T and large rapidity!

Event Selection and Observables

Eur. Phys. J. C (2014) 74:3053

Trigger:

- Minimum bias events triggered by TOTEM T2 (charged track with $p_T > 40$ MeV in $5.3 < |\eta| < 6.5$)

Vertex requirements:

- Primary vertex reconstruction at CMS. Multiple vertices events are removed.

Tracks selection:

- Primary tracks with $p_T > 100$ MeV in $|\eta| < 2.2$.
- Tracks with $p_T > 40$ MeV in T2.

Observables:

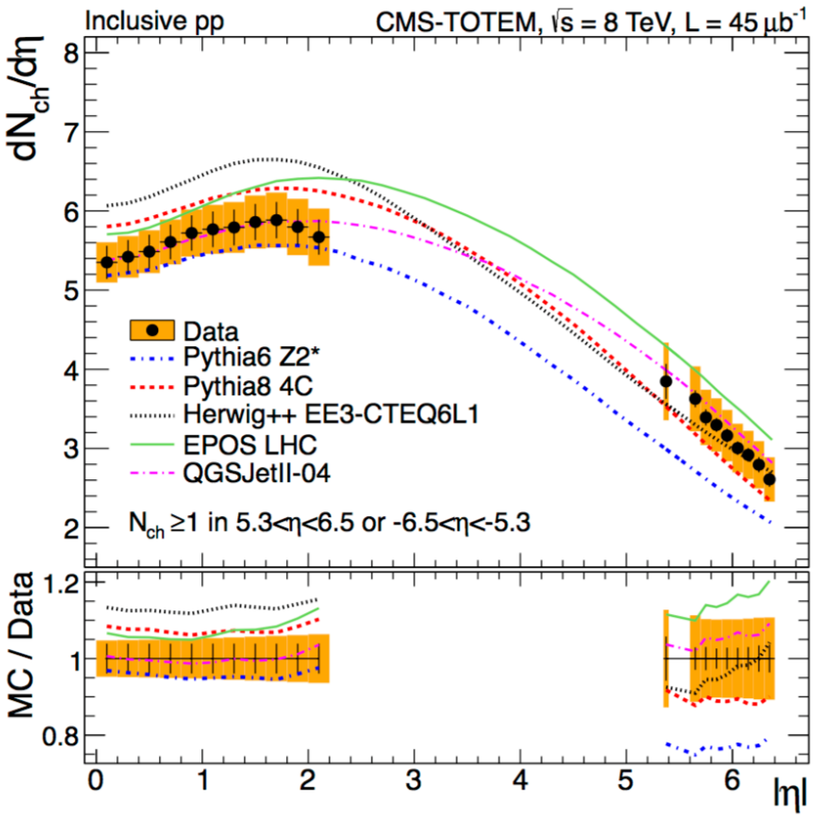
- $dN_{ch}/d\eta$ in three different event samples (offline selection):
  - Inclusive inelastic sample: at least one track in either side of T2.
  - NSD-enhanced: at least one track in both T2.
  - SD-enhanced: at least one track in one T2 and no track in the other T2.

NSD: non-single diffractive dissociation
SD: single diffractive dissociation

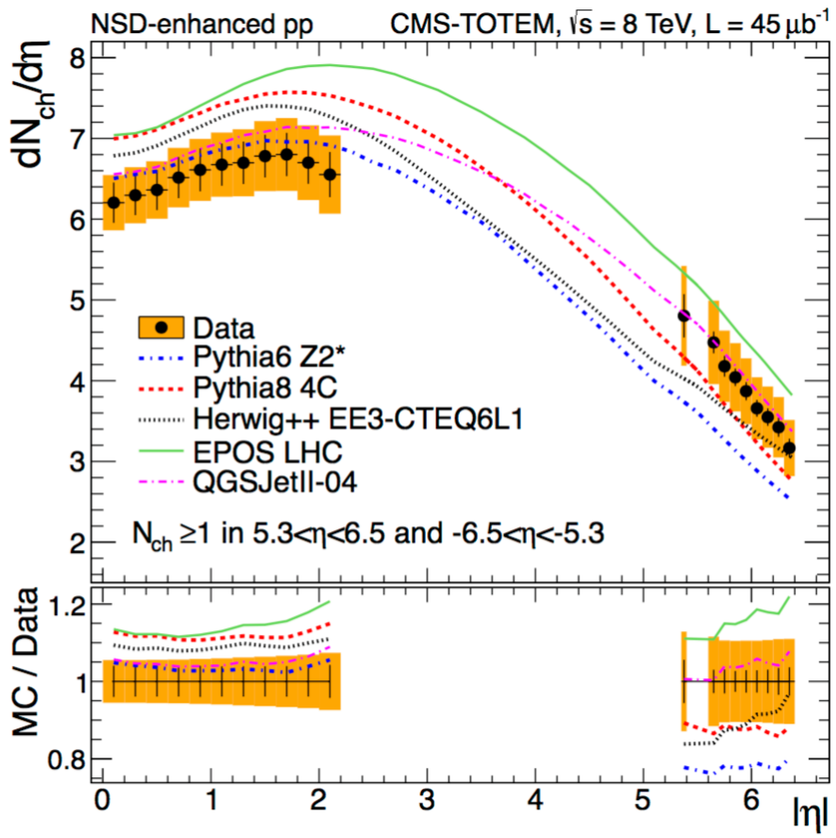
Charged Particles Distribution

Eur. Phys. J. C (2014) 74:3053

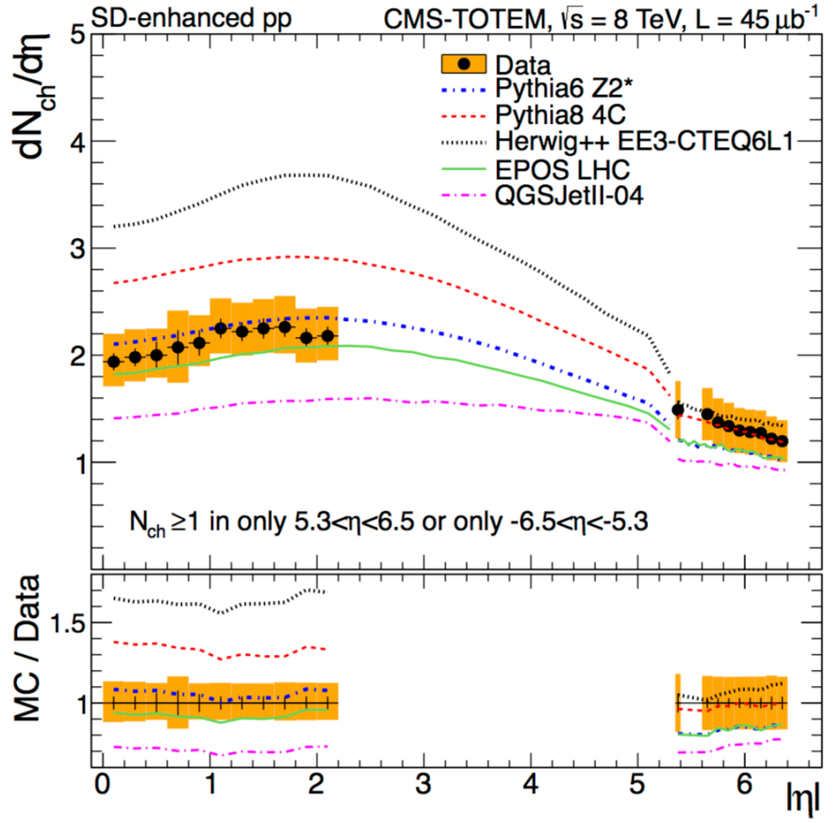
Inclusive



NSD-enhanced



SD-enhanced



Stable-particle level definitions:

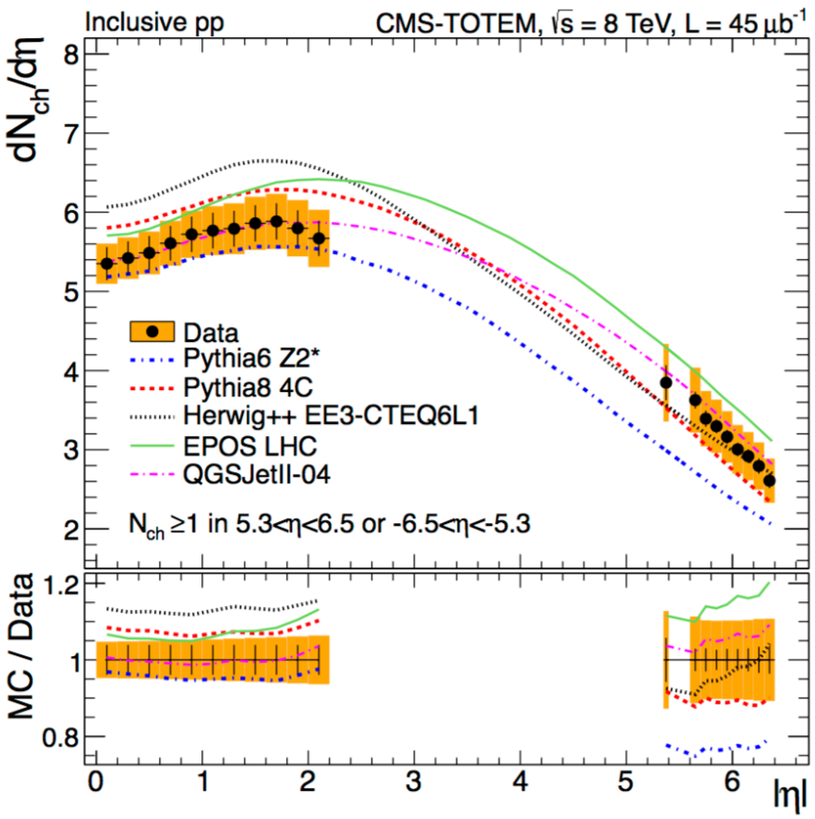
Charged particles with $p_T > 0$ in $|\eta| < 2.2$ and $5.3 < |\eta| < 6.5$

- **Inclusive inelastic:** $N_{ch} > 0$ in $-6.5 < \eta < -5.3$ **or** $5.3 < \eta < 6.5$, $p_T > 0$
- **NSD-enhanced:** $N_{ch} > 0$ in $-6.5 < \eta < -5.3$ **and** $5.3 < \eta < 6.5$, $p_T > 0$
- **SD-enhanced:** $N_{ch} > 0$ in **only** $-6.5 < \eta < -5.3$ **or only** in $5.3 < \eta < 6.5$, $p_T > 0$

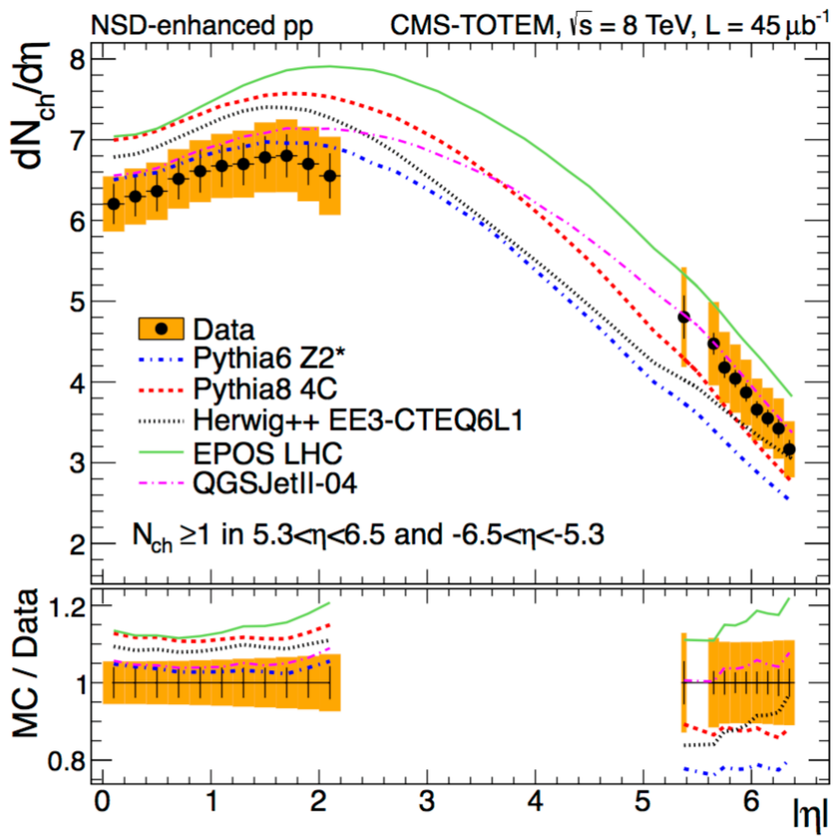
Charged Particles Distribution

Eur. Phys. J. C (2014) 74:3053

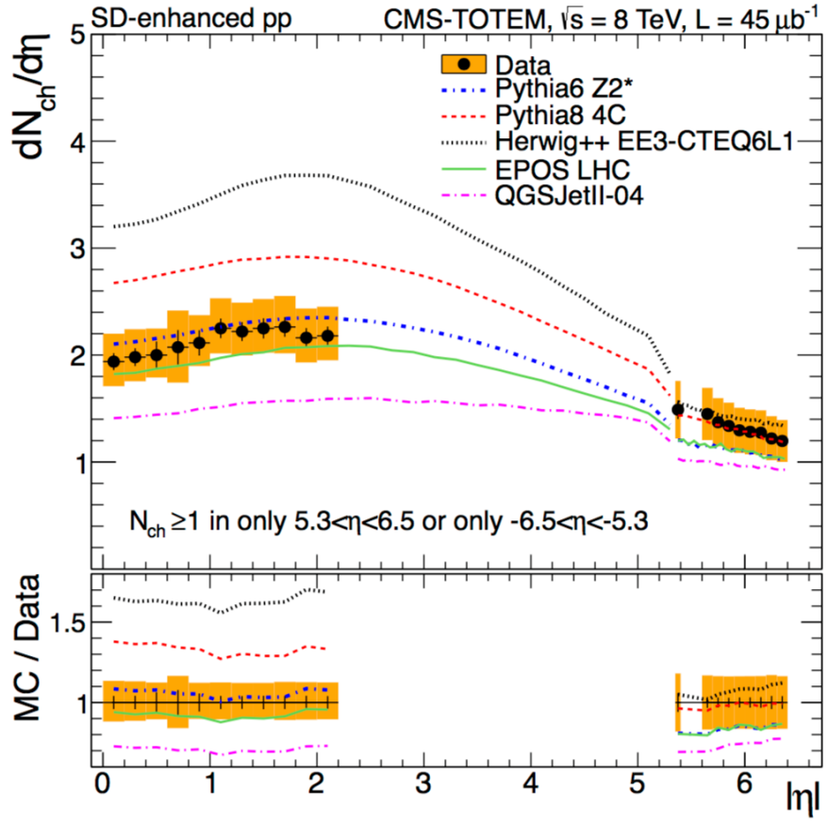
Inclusive



NSD-enhanced



SD-enhanced

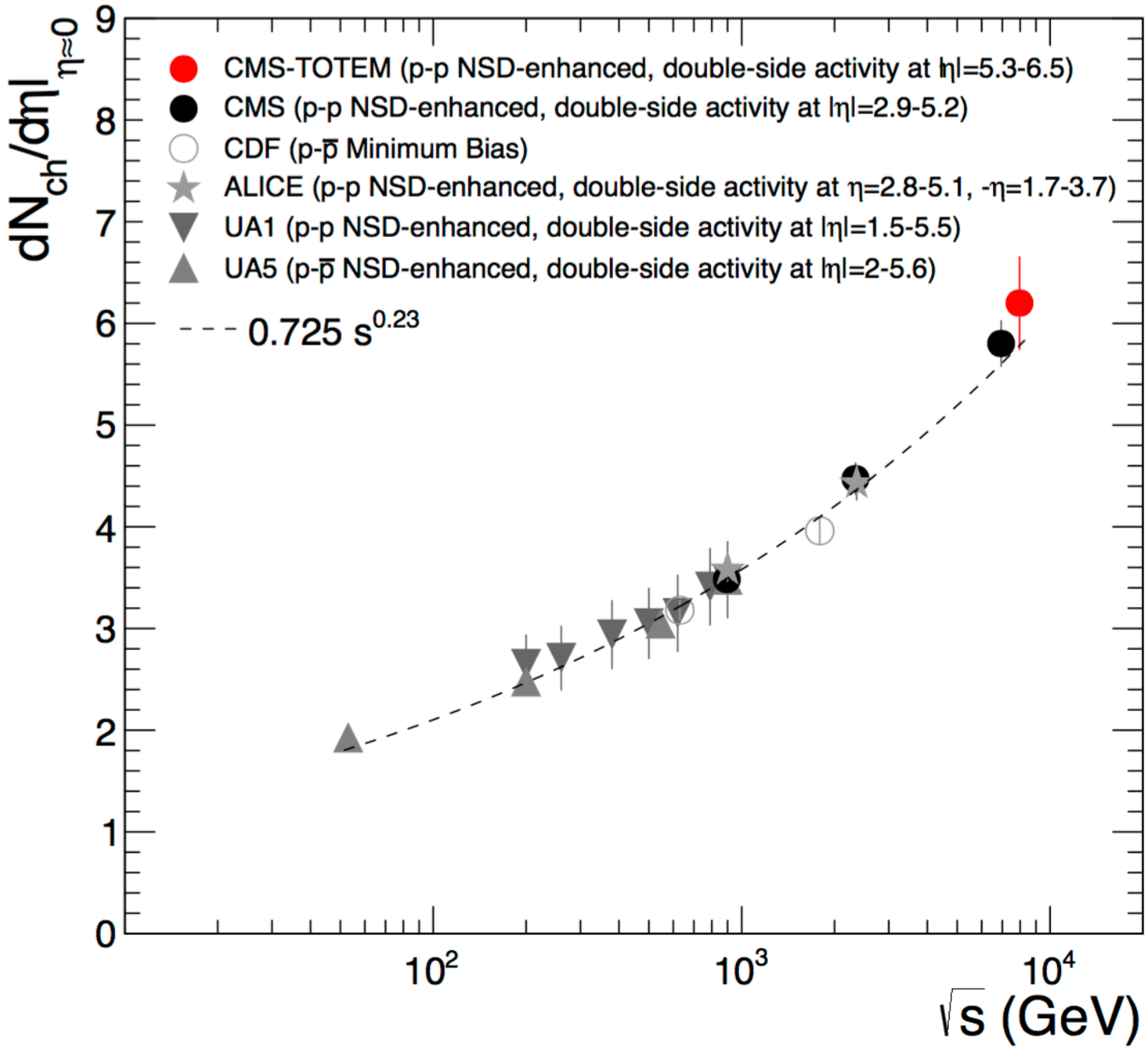


- Large discrepancies between models.
- The predictions differ from the data by up to 20 % and even larger for SD-enhanced sample.
- None of the models are able to describe the data in full-η range and for all event topologies.
- Only QGSJet describes the full-η range for inclusive and NSD-enhanced samples but underestimates the SD-enhanced data.

Charged Particles Distribution

Eur. Phys. J. C (2014) 74:3053

The center-of-mass energy dependence of $dN_{ch}/d\eta$ at $\eta \approx 0$.



expected to follow
a power-law dependence

$$dN_{ch}/d\eta\,\big|_{\eta=0} \propto s^{\epsilon}$$

power-law fit

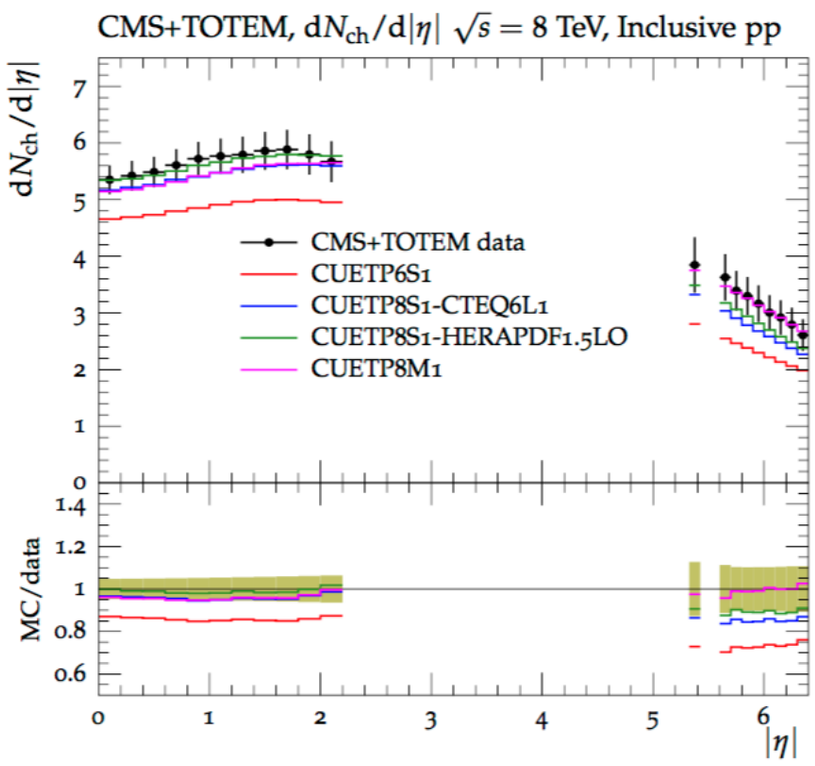
$$\epsilon = 0.23 \pm 0.01$$

Data from various experiments for NSD events in pp and ppbar; √s = 0.53 TeV - 8 TeV

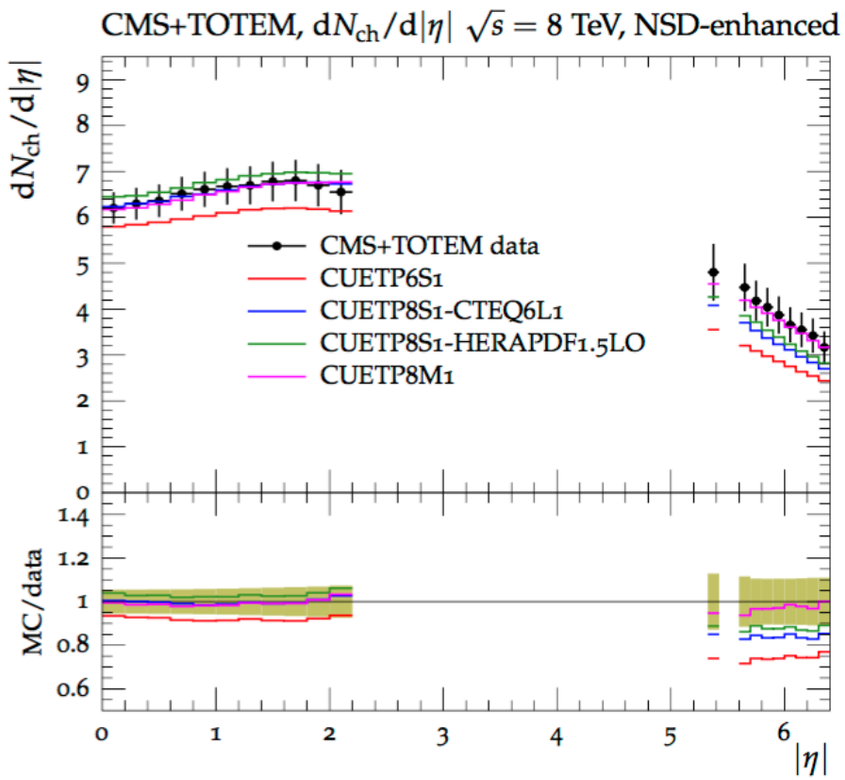
Charged Particles Distribution – Tuning Forward Data

The CMS Collaboration, CMS-GEN-14-001, **Eur. Phys. J. C 76 (2016) 155**

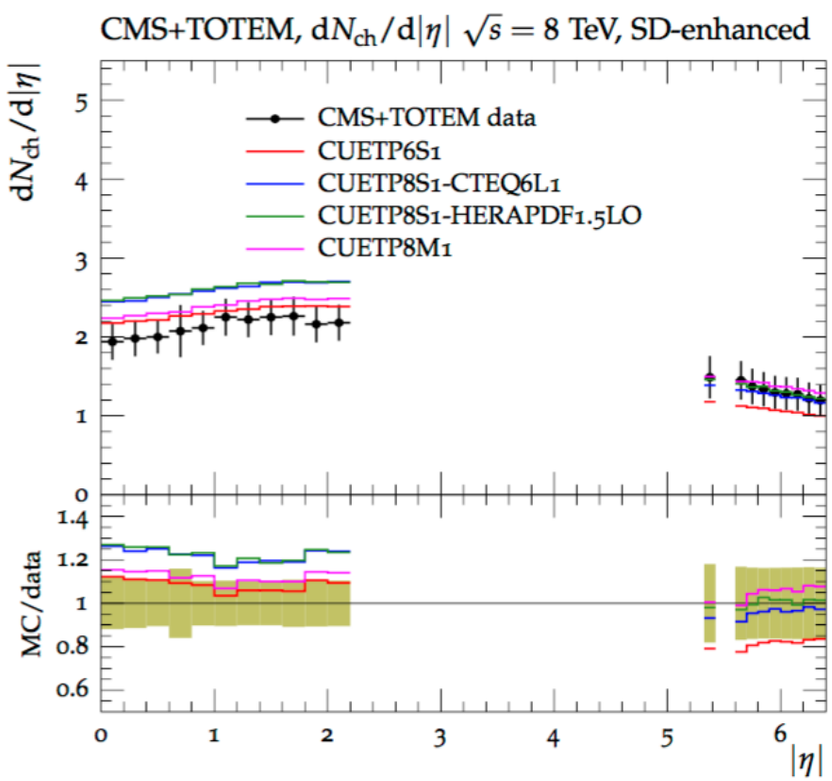
Inclusive



NSD-enhanced



SD-enhanced



- The precise measurements in the forward region from CMS-TOTEM provide great inputs for tuning studies.
- Improved low-x gluon distribution. NNPDF2.3LO PDF.
- CUETP8M1 (recent CMS tune) describes the data well both at central and at forward regions and also for all event topologies.

Leading Charged Particles and Leading Jets at low-p_T

- Production of leading charged particles and leading charged-particle jets at small transverse momenta in pp collisions at $\sqrt{s}$ = 8 TeV, Phys. Rev. D 92, 112001.

Motivation

Jet production with pT > 20 GeV in |η| < 3 well described by NLO pQCD.

- At low-pT values, total 2→2 cross section becomes larger than total inelastic cross section, σ_{inel}

$$\sigma(p_{\mathrm{T}}^{\min}) = \int_{p_{\mathrm{T}}^{\min}} dp_{\mathrm{T}}^2 d\sigma/dp_{\mathrm{T}}^2$$

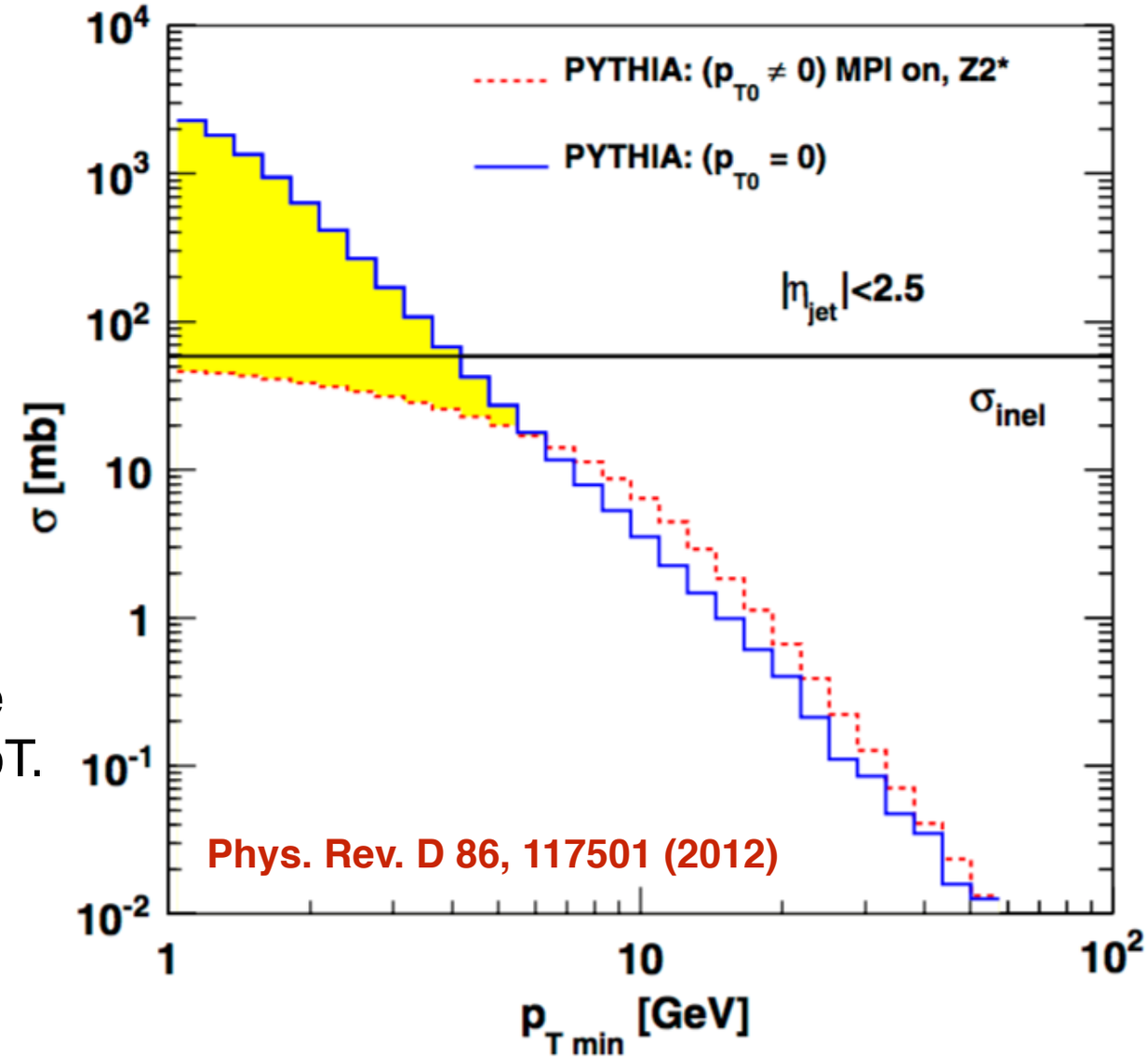
- In PYTHIA, the rise of the 2→2 cross section is controlled by the parameters, p_{T0} and $\langle n_{MPI} \rangle$.

$$\sigma(p_{T\,min}) \propto \frac{1}{p_{T\,min}^2 + p_{T0}^2}$$

$$\langle n_{MPI} \rangle = \sigma(p_{T\,min})/\sigma_{inel}$$

- The per-event yields with a leading charged particle or leading jet are sensitive to the saturation at low-pT.

$$r(p_{\mathrm{T}}^{\min}) = \frac{1}{N_{\mathrm{evt}}} \int_{p_{\mathrm{T}}^{\min}} dp_{\mathrm{T}}^{\mathrm{lead}} \left(\frac{dN}{dp_{\mathrm{T}}^{\mathrm{lead}}} \right)$$



Event Selection and Observables

Trigger:

- Minimum bias events triggered by TOTEM T2 (charged track with $p_T > 40$ MeV in $5.3 < |\eta| < 6.5$)

Vertex requirements:

- Primary vertex reconstruction at CMS. Events with multiple vertices are removed.

Tracks selection:

- $|\eta| < 2.4$ with $p_T > 0.4$ GeV/c.

Track-jets selection:

- Anti-kT, 0.5
- Leading track-jet in $|\eta| < 1.9$ with $p_T > 1$ GeV — input tracks $|\eta| < 2.4$ with $p_T > 0.4$ GeV

Observable: The per-event yields, $r(p_{T,min})$

Normalized integrated charged particle or charged-particle jet event cross sections as a function of $p_{T,min}$ where $p_{T,lead} > p_{T,min}$.

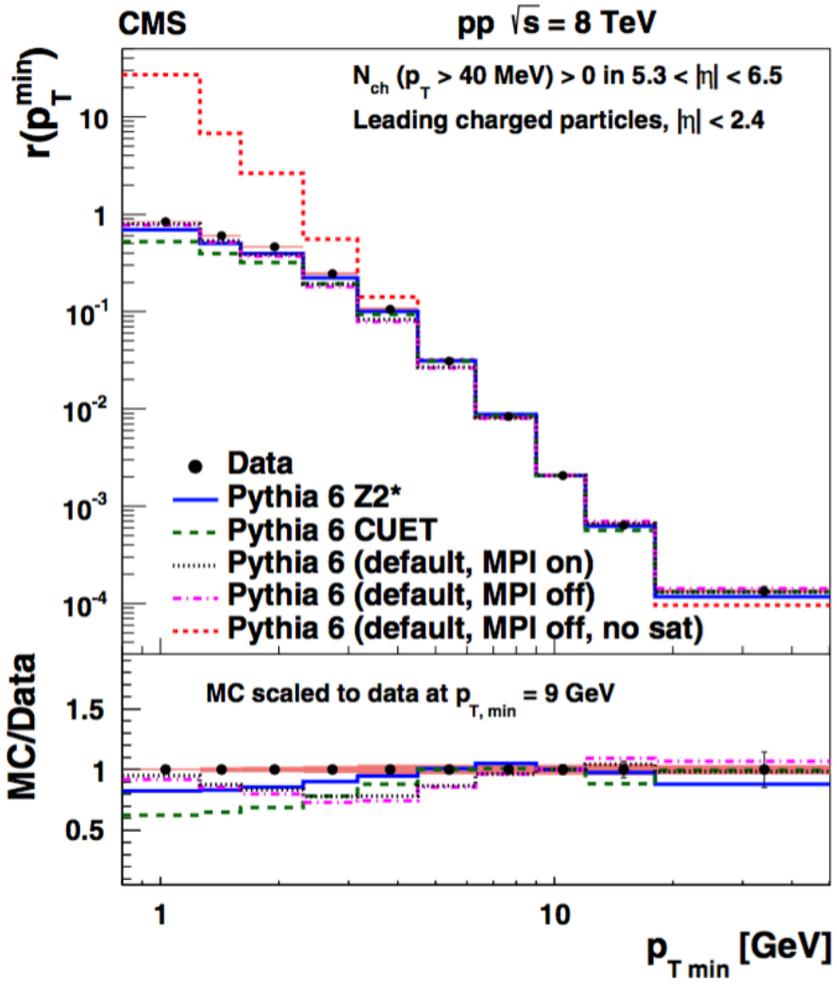
$$r(p_{\mathrm{T}}^{\mathrm{min}}) = \frac{1}{N_{\mathrm{evt}}} \sum_{p_{\mathrm{T}}^{\mathrm{lead}} > p_{\mathrm{T}}^{\mathrm{min}}} \Delta p_{\mathrm{T}}^{\mathrm{lead}} \left(\frac{\Delta N}{\Delta p_{\mathrm{T}}^{\mathrm{lead}}} \right)$$

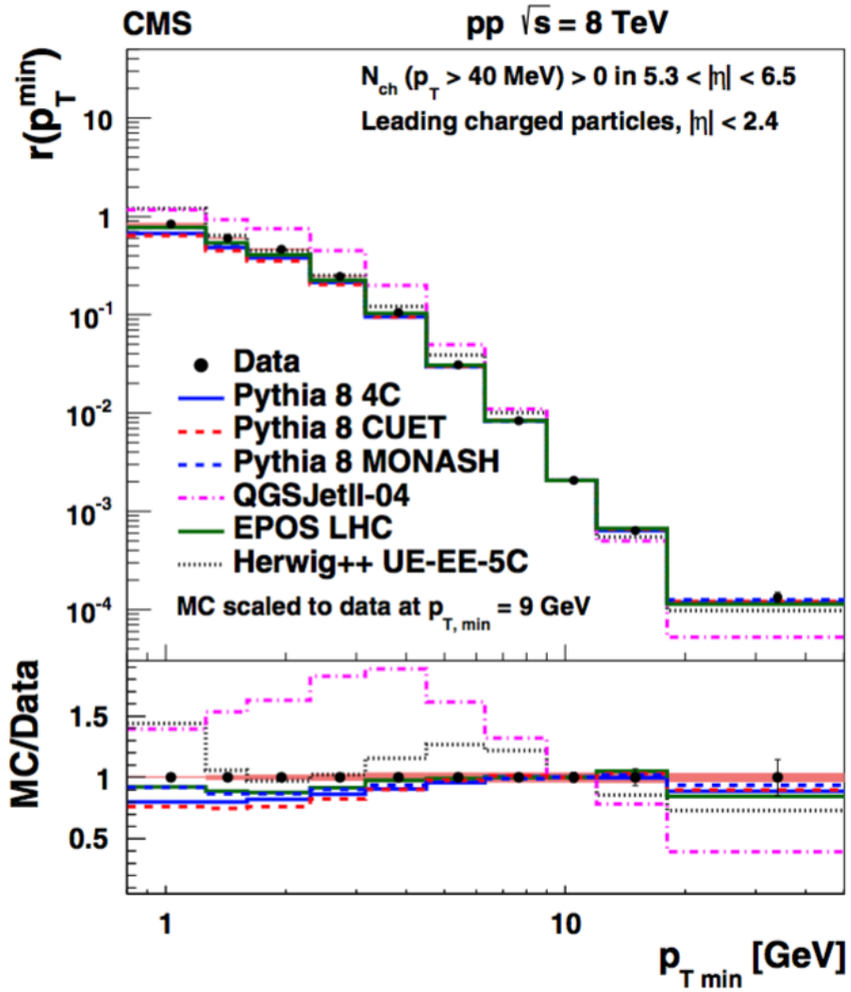
Both the leading charged particle and leading charged-particle jets measurements are normalized to events (N_{evt}) with a leading track in $|\eta| < 2.4$ with $p_T > 0.4$ GeV.

Leading Charged Particles

Phys. Rev. D 92, 112001

Normalized integrated distributions for leading charged particles for events with $p_{T,min} > 0.8$ GeV



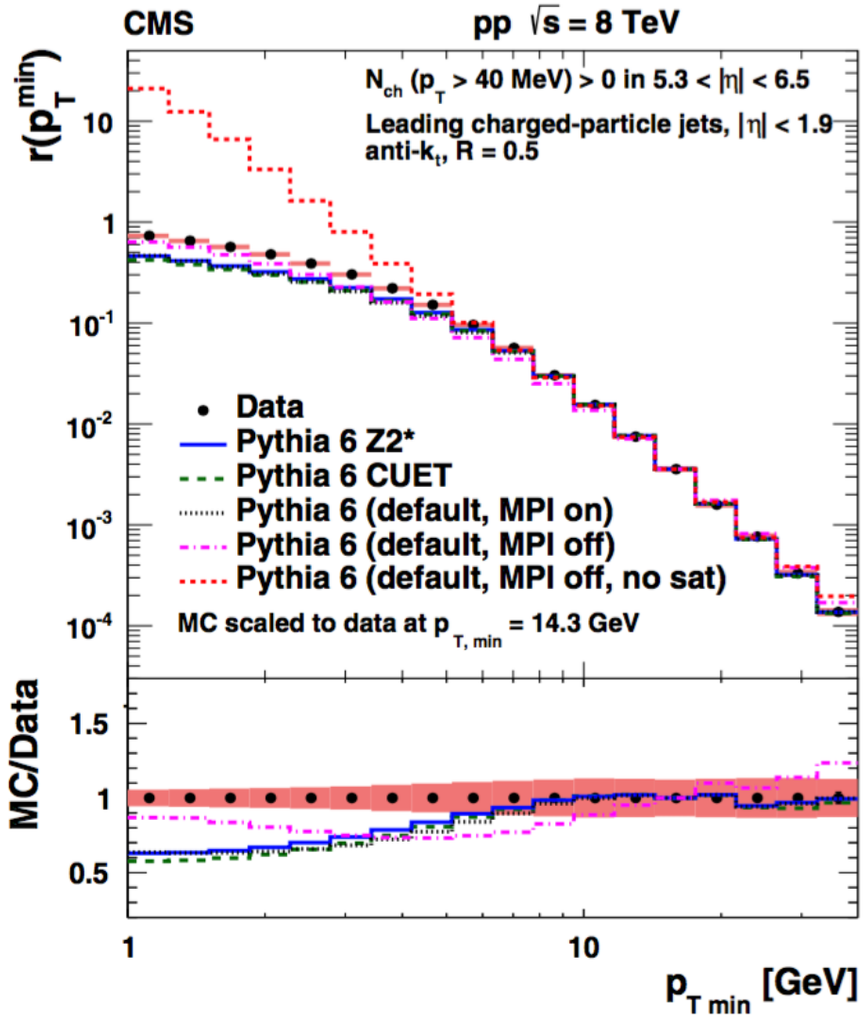


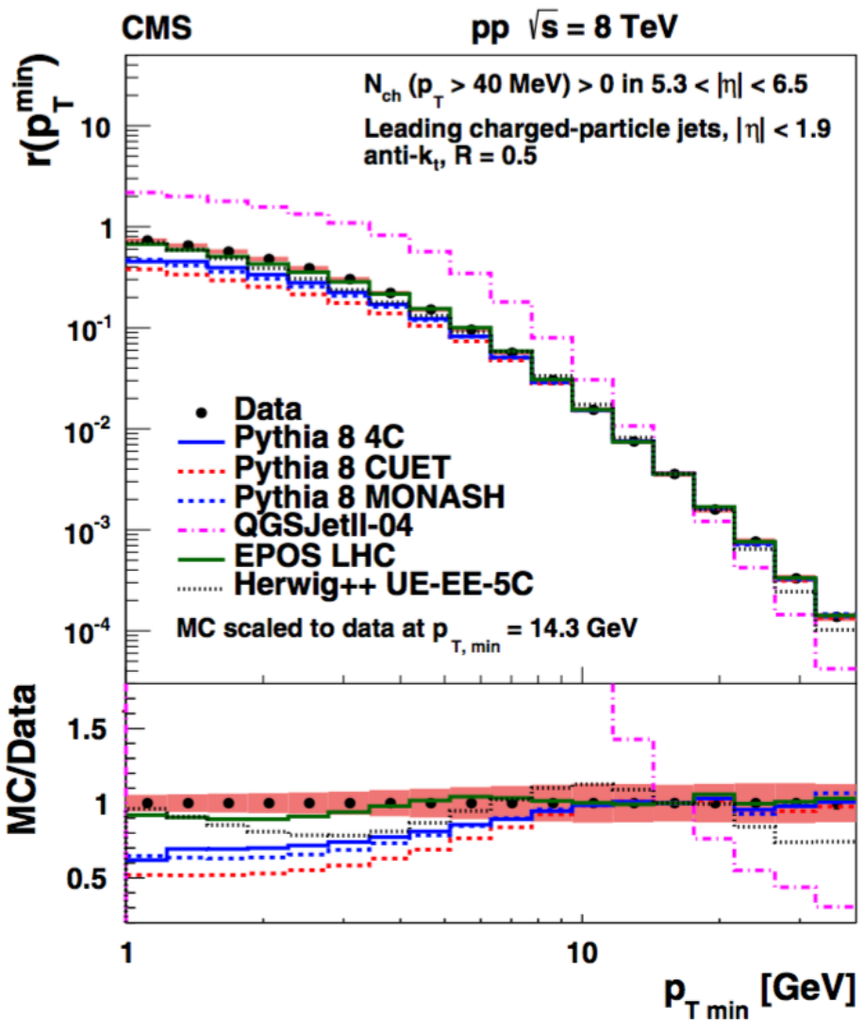
- MC is rescaled to the data at $p_{T,min} = 9$ GeV.
- The distributions fall steeply at high-p_T. Relatively flat between 1-10 GeV.
- MPI has not a big effect. (When clustering particles into jets MPI becomes more important).
- A large deviation from the data at low-p_T if both MPI and saturation turned off.
- Described well by EPOS. QGSJet fails.

Leading Charged Particle Jets

Phys. Rev. D 92, 112001

Normalized integrated distributions for leading charged-particle jets for events with $p_{T,min} > 1$ GeV

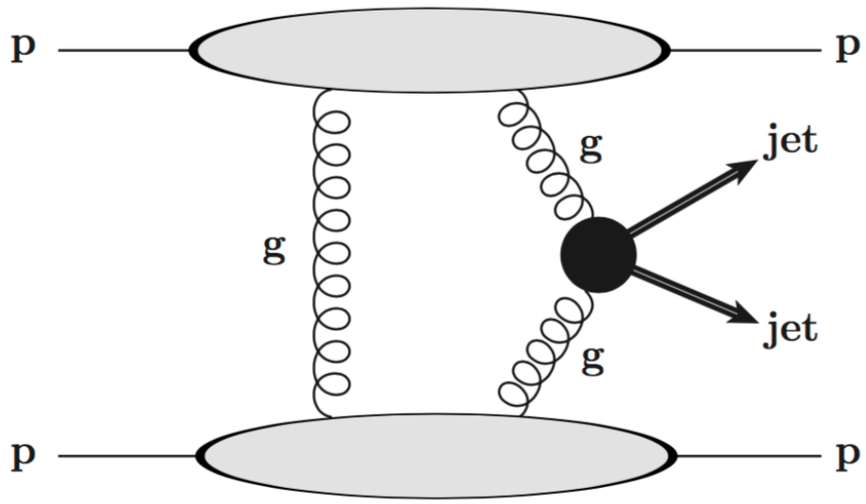




- MC is rescaled to the data at $p_{T,min}$ = 14.3 GeV.
- The turnover point is different: when clustering the particles into jets more energy is collected in the jet cone.
- The PYTHIA6 has a better description of data at low-p_T when MPI is off.
- EPOS has the best description. Large discrepancies between the models.

High-p_T jets with two leading protons

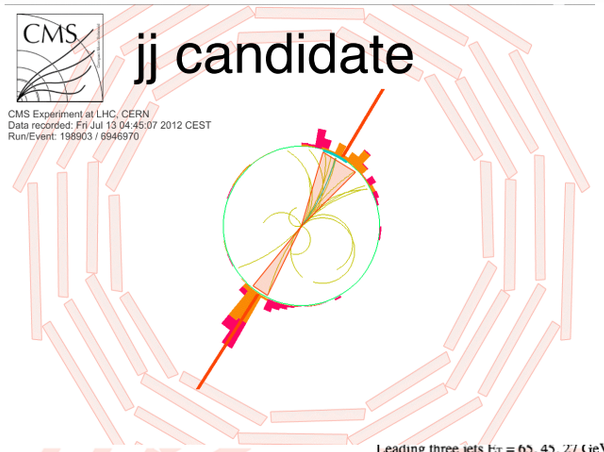
- CMS+TOTEM event displays of high-p_T jets with two leading protons at $\sqrt{s}$ = 8 TeV, CMS-DP-2013-004, CMS-DP-2013-006 (2013).

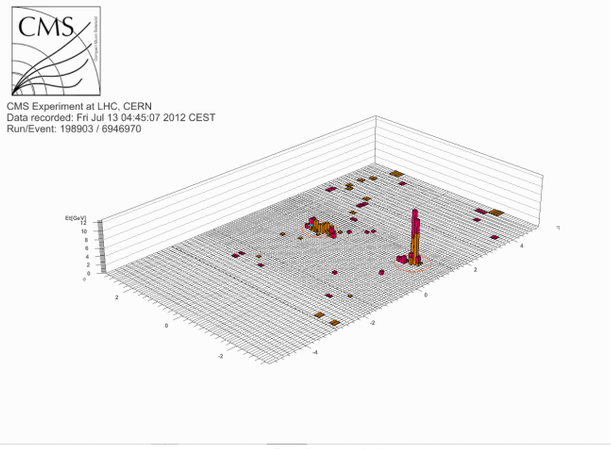


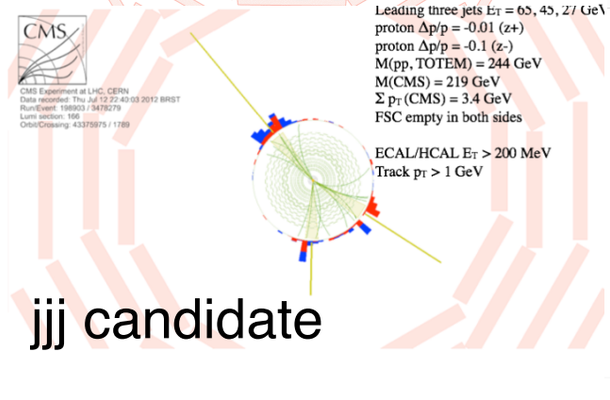
- 8 TeV, July 2012 data, low-PU, β* = 90m
- At least two jets with p_T > 20 GeV.
- Forward Shower Counters (FSC) empty.
- Proton tracks (non-elastic) at TOTEM Roman Pots on both sides of IP.

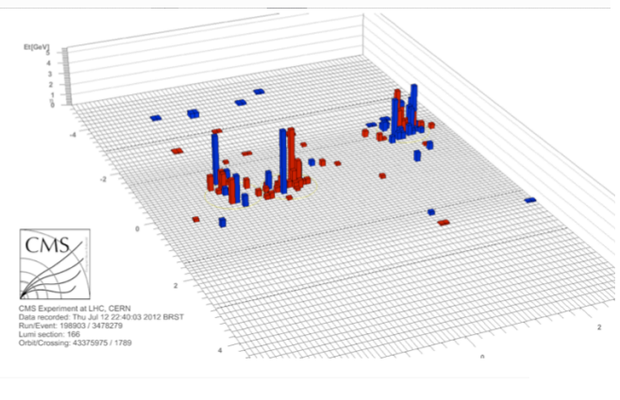
CMS: |η| < 5 **T2: 5.3 < |η| < 6.5** **FSC: 6 < |η| < 8** **TOTEM RP** **very large rapidity coverage !**

High-p_T jets with two leading protons



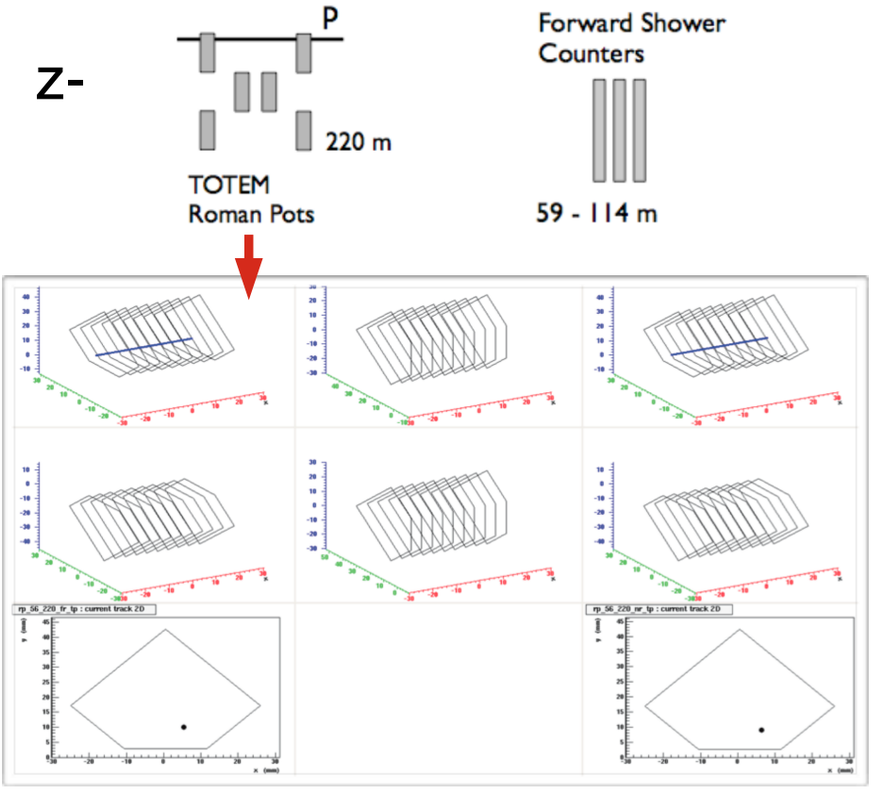


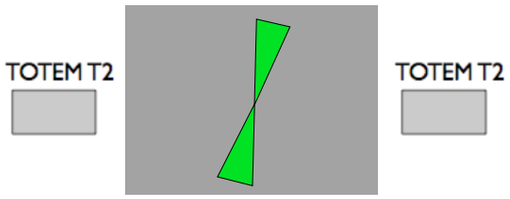


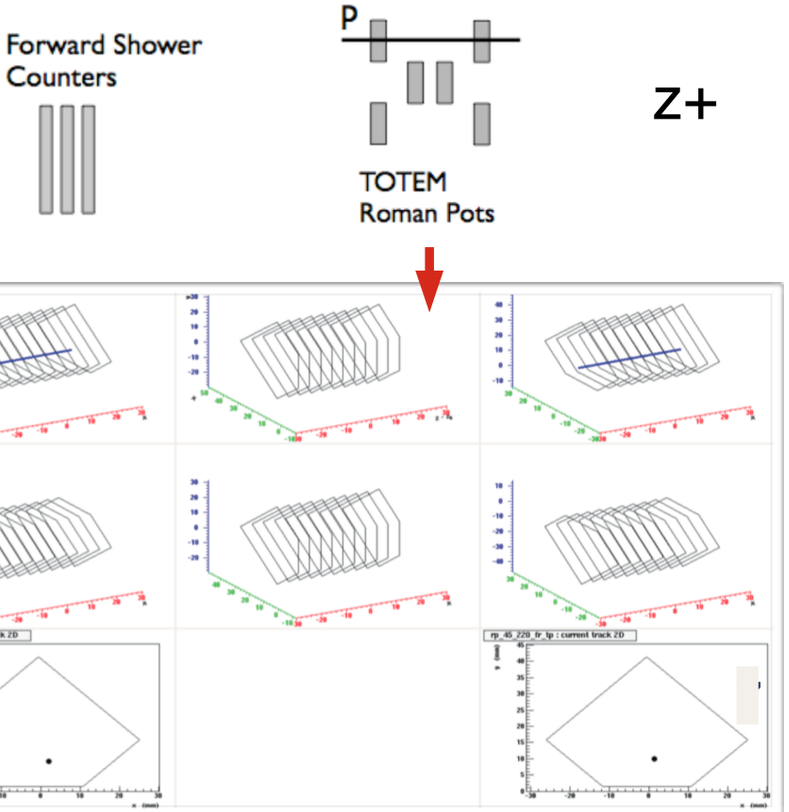


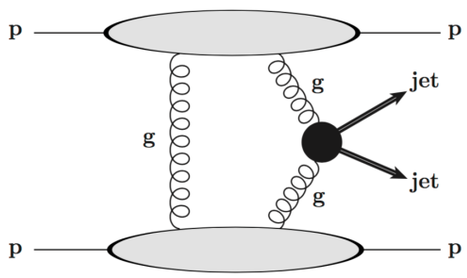
Leading three jets E_T = 65, 45, 27 GeV
proton Δp/p = -0.01 (z+)
proton Δp/p = -0.1 (z-)
M(pp, TOTEM) = 244 GeV
M(CMS) = 219 GeV
Σ p_T (CMS) = 3.4 GeV
FSC empty in both sides

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









Summary

- **CMS and TOTEM** detectors provide **unique pseudorapidity coverage** and **unprecedented measurement possibilities**.
- CMS-TOTEM the charged-particle density measurements, span the **largest pseudorapidity interval ever measured at the LHC!** It provides great details between central & forward particle correlations and extremely useful in particular for tuning efforts in the forward region.
- Leading jets at low-pT is another unique measurement for a better understanding of the transition **from perturbative to non-perturbative QCD**.
- Now the overall **statistics** for β* = 90 m Runs **in 2015** is an order of magnitude **larger with respect to 2012**. Acceptance at very low |t| for any ξ. Allows to follow well-established medium luminosity physics program.
- For the reprocessing of 2015 data, the CMS-TOTEM common software **tools updated & validated** successfully.
- RP alignment and proton reconstruction already performed by TOTEM.
- All CMS data processed for the merging step.
- **A huge part of the dataset already merged and physics analyses started**.
- Some of the analyses with RunI data are at their final stages. New results soon!

Backup

Charged Particles Distribution – Uncertainties

Eur. Phys. J. C (2014) 74:3053

Central region

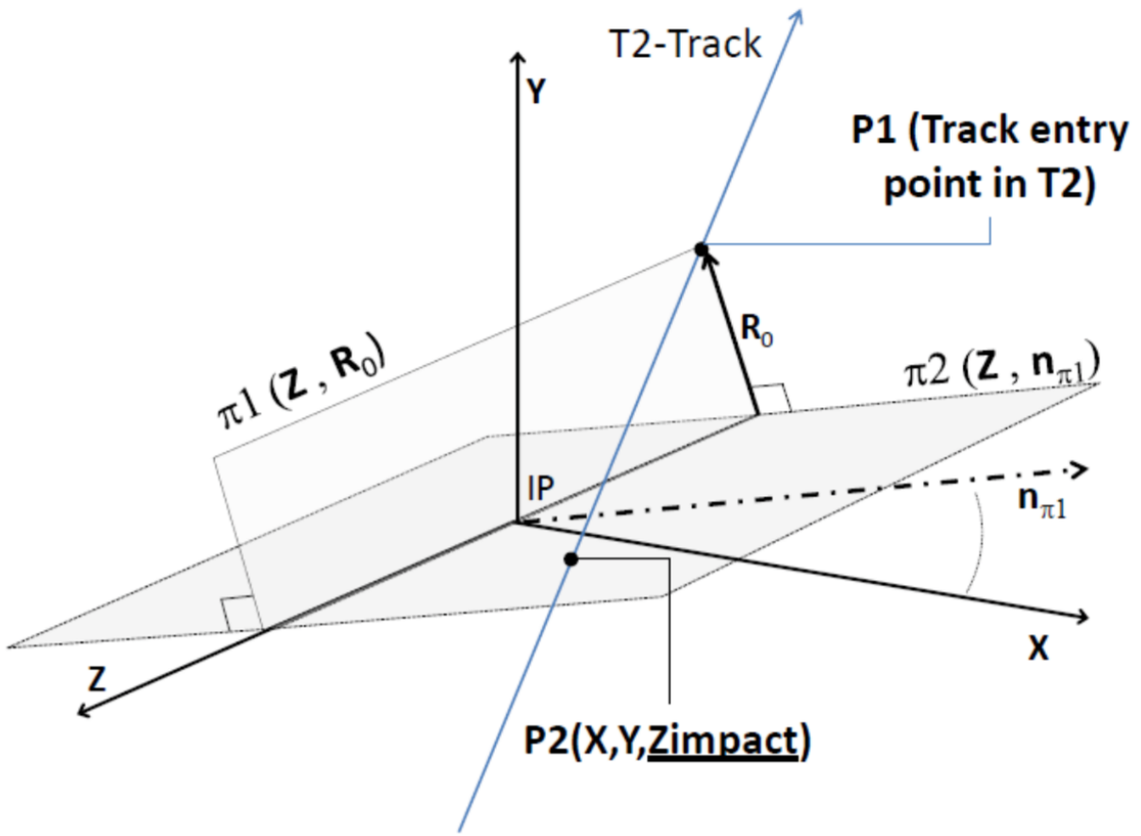
The given ranges indicate the η dependence of the uncertainties.

Source	Inclusive	NSD-enhanced	SD-enhanced
Event and primary track selection ($C_{sel}(\eta)$)	3–5%	4–6%	9–16%
Tracking efficiency	3.9%	3.9%	3.9%
Trigger efficiency	0.1%	0.1%	0.1%
Model dependence of track corrections (ω_{trk})	1–4%	1–4%	1–4%
Correction to $p_T = 0$	0.2%	0.2%	0.2%
Statistical	0.1%	0.1%	0.1%
Total	5–7%	6–8%	10–17%

Forward region

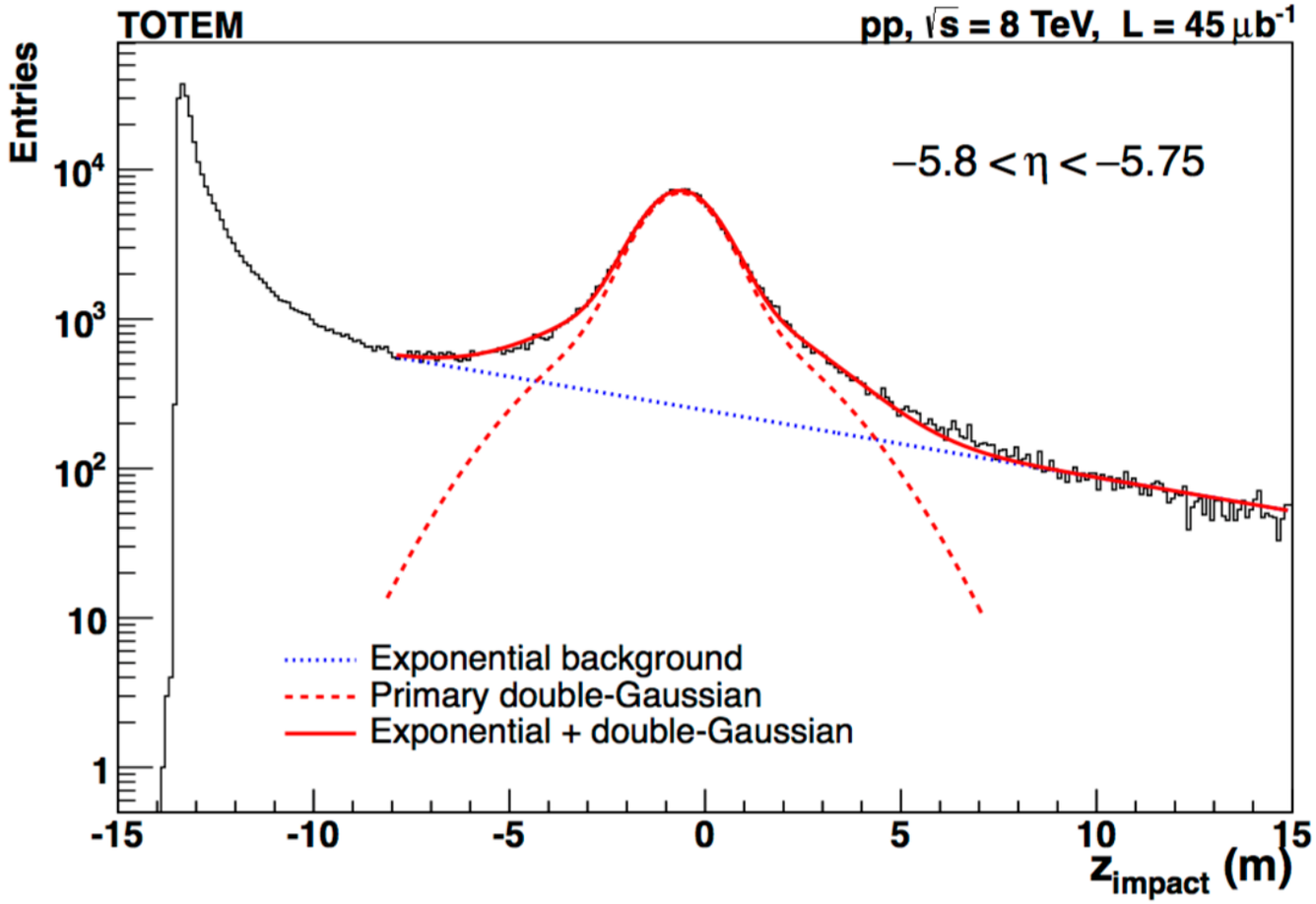
Source	Inclusive	NSD-enhanced	SD-enhanced
Tracking efficiency data-MC discrepancy	5–6%	5–6%	5–6%
Primary selection (including alignment)	4–5%	4–5%	4–5%
Non-primaries in the double-Gaussian peak	5%	5%	5%
Material effects	3–6%	3–6%	3–6%
High-multiplicity events	3%	3%	3%
Event selection	2–3%	2–3%	13–15%
Tracking efficiency dependence on energy spectrum and magnetic field	2%	2%	2%
Track quality criterion	1%	1%	1%
Correction to $p_T = 0$	0.5%	0.5%	0.5%
Trigger efficiency	0.2%	0.2%	0.2%
Statistical	0.1%	0.1%	0.1%
Total (after averaging half-arms)	10–12%	10–12%	16–18%

Primary and secondary tracks at T2



About 80% of the reconstructed tracks in T2 are due to non-primary (secondary) particles, that are mainly electrons and positrons. generated by photon conversions

At the edge of the CMS HF calorimeter In the conical section of the beam pipe at |η| ≈ 5.5

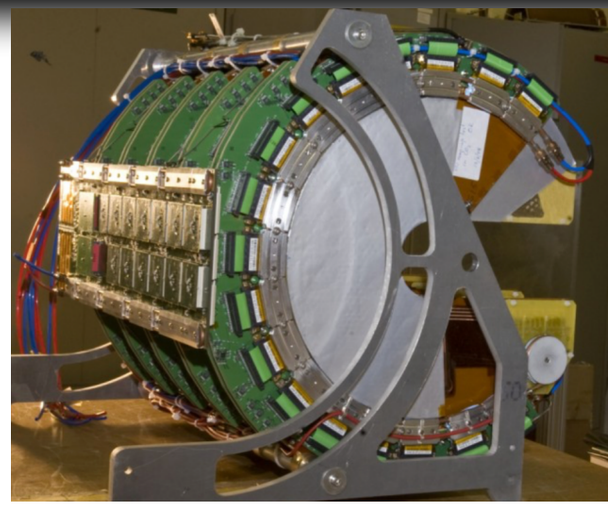


The dotted curve represents the **exponential** component from **secondary particles**, while the dashed curve is the **double-Gaussian component, mainly due to primary tracks.**

TOTEM T2 Detector

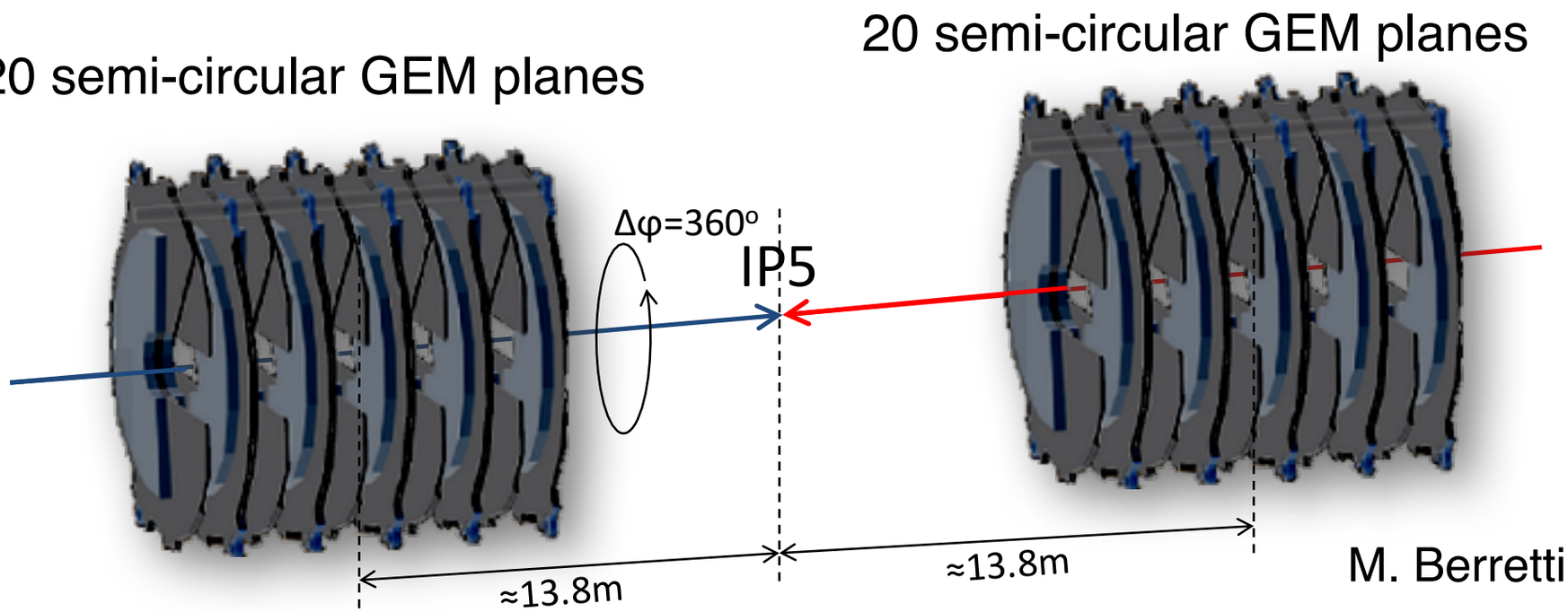
Based on GEM (**G**as **E**lectron **M**ultiplier) technology

- Provides a full azimuthal acceptance around the beam line
- Tracks of the charged particles coming out from the pp collision



An assembled quarter of one T2 Telescope

20 semi-circular GEM planes



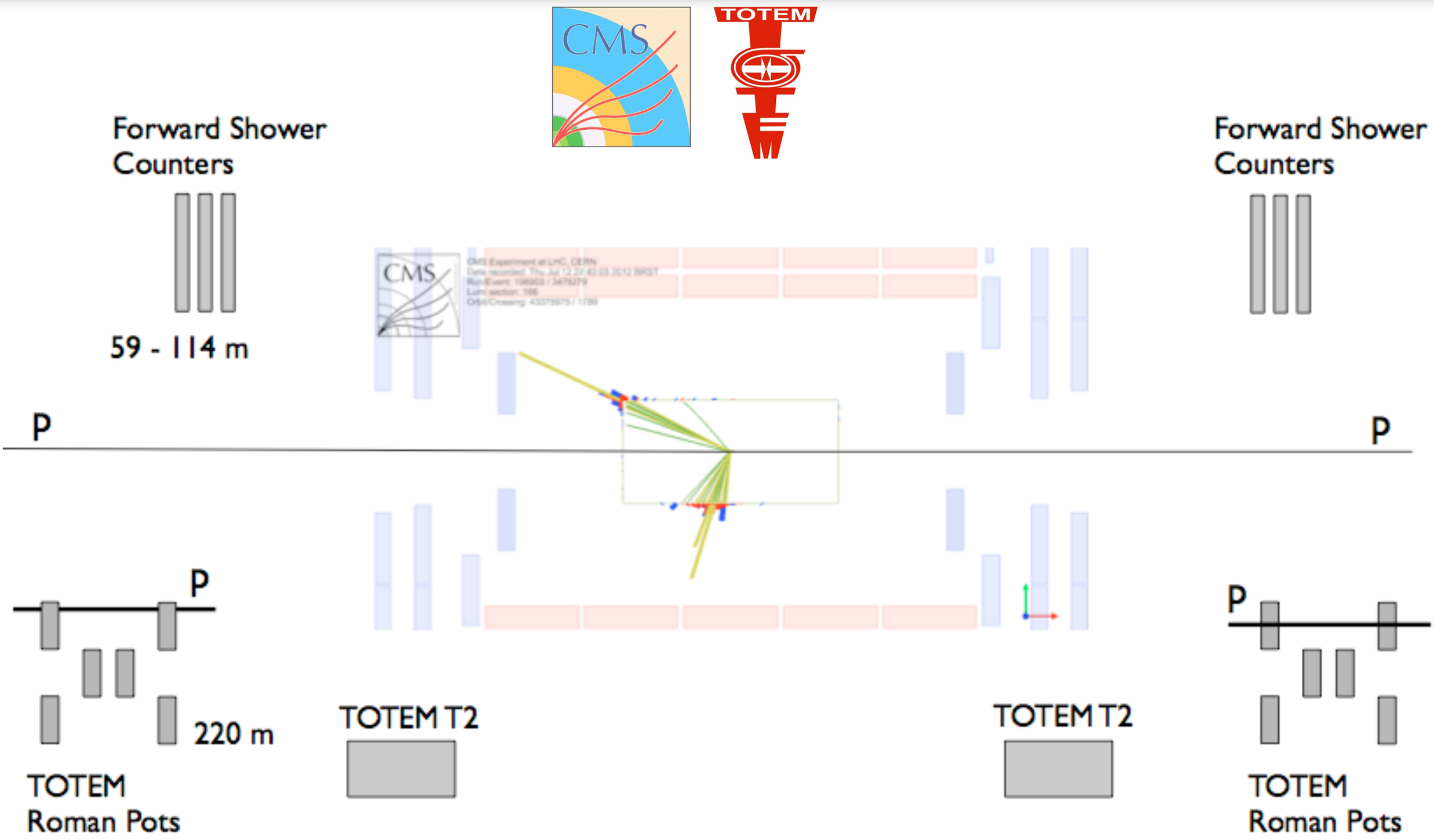
20 semi-circular GEM planes

$5.3 < |\eta| < 6.5$

M. Berretti

The efficiency is 80 % at $\sqrt{s}$ = 8 TeV for $p_T > 40$ MeV/c. Efficiency increases with p_T.

High-p_T jets with two leading protons



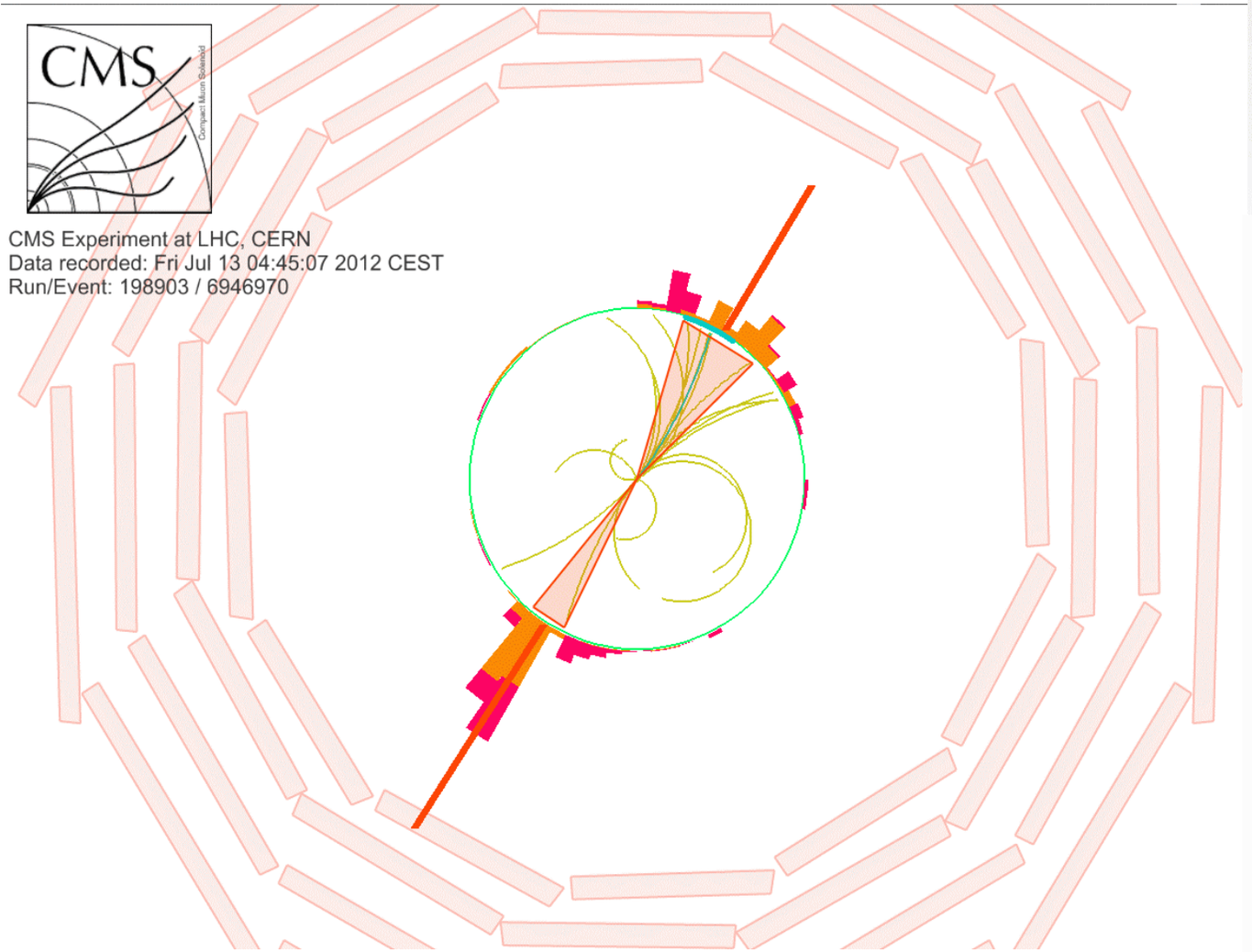
CMS: $|\eta| < 5$ **T2: $5.3 < |\eta| < 6.5$** **FSC: $6 < |\eta| < 8$** **TOTEM RP**

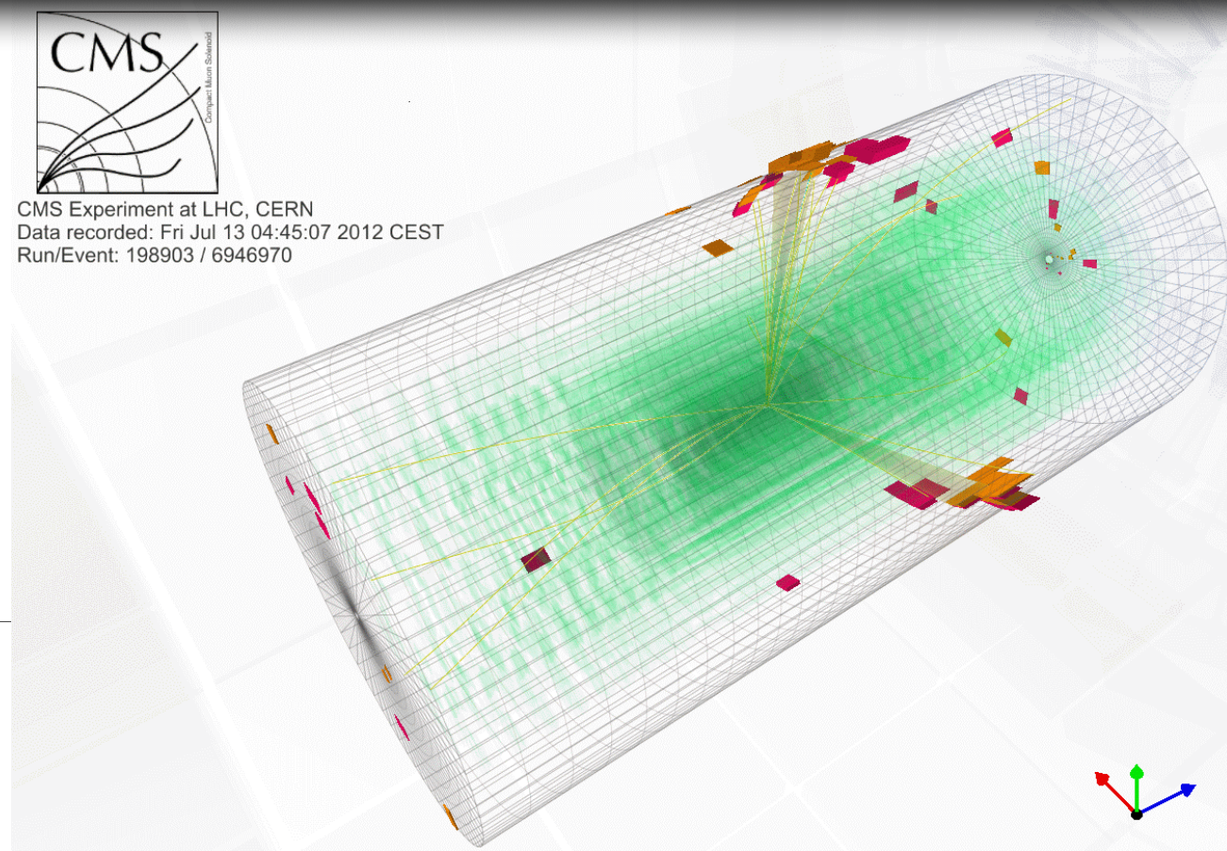
very large rapidity coverage !

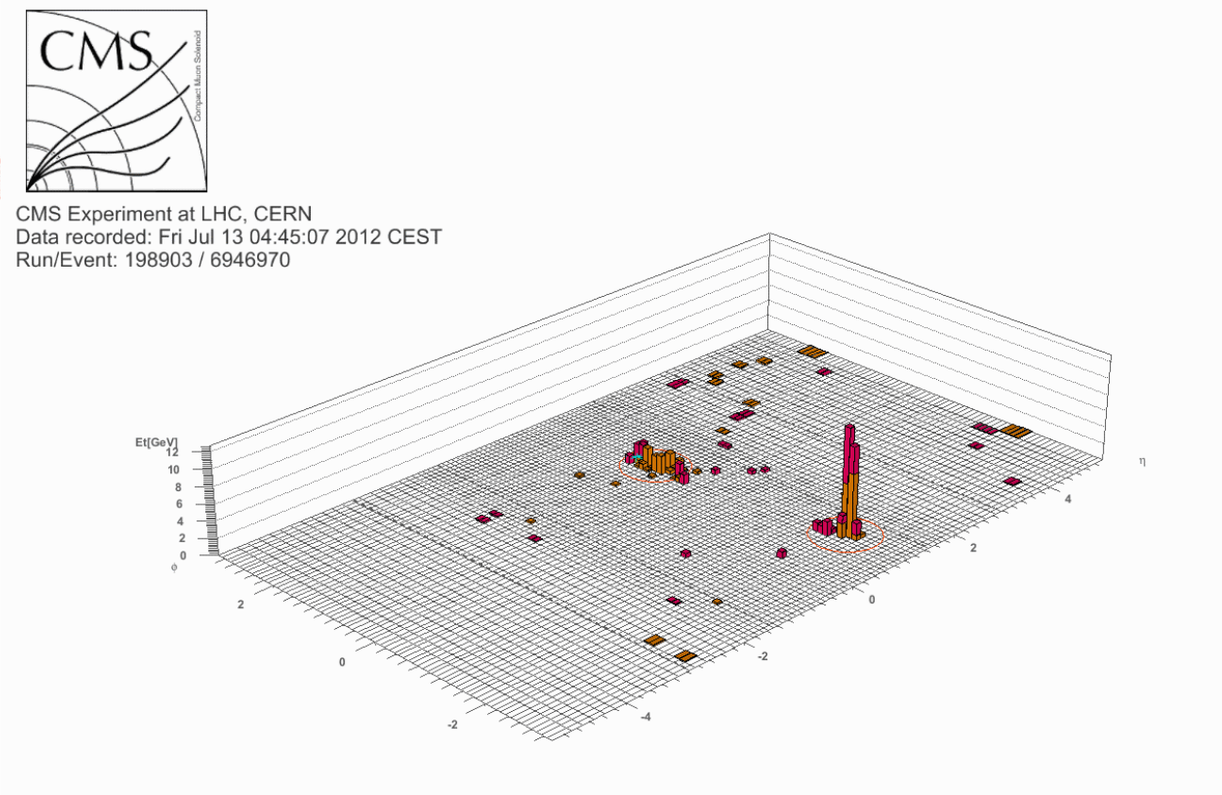
Dijet Event Display - CMS

Run 198903
CMS Event 6946970

Central dijet event.
Forward protons in TOTEM RPs.

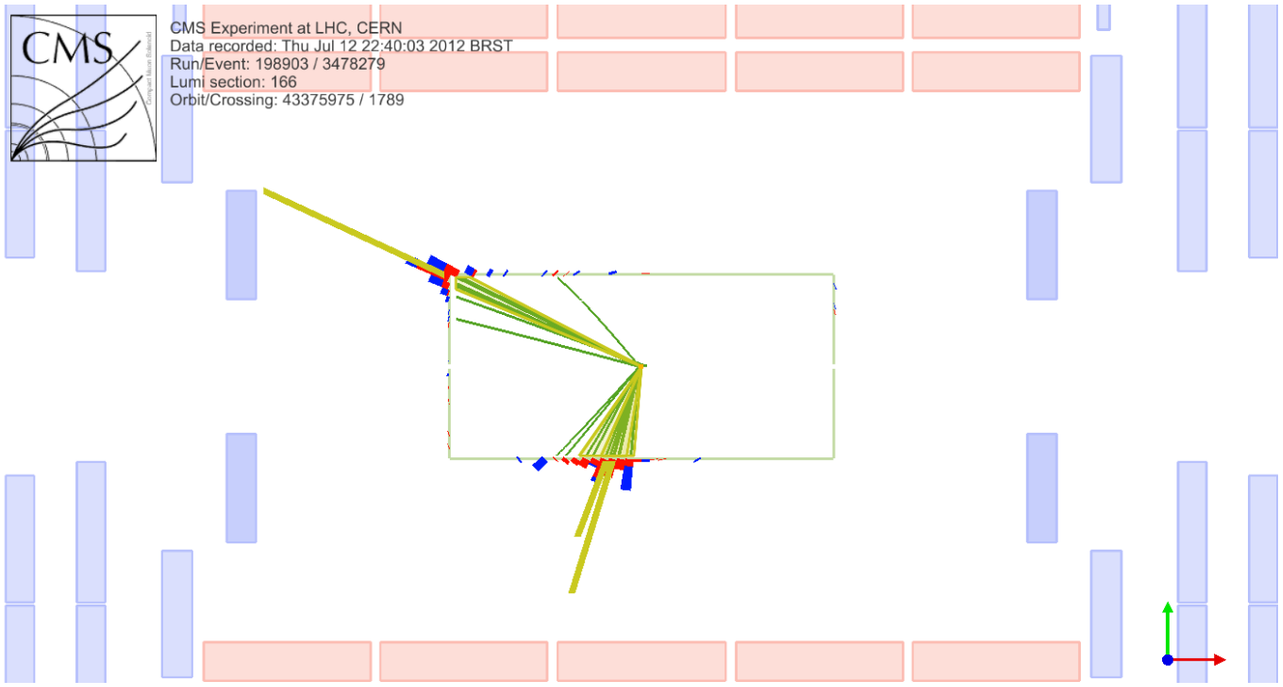


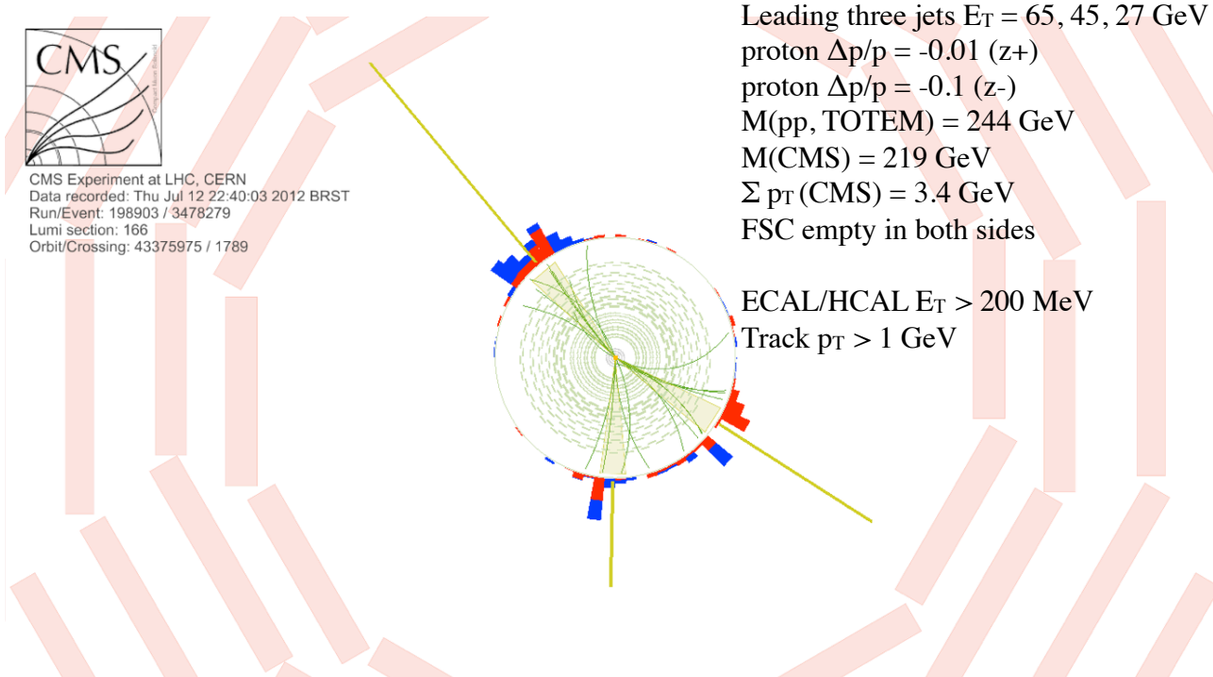




3 Jets Event Display – CMS

Run 198903 - CMS Event 3478279





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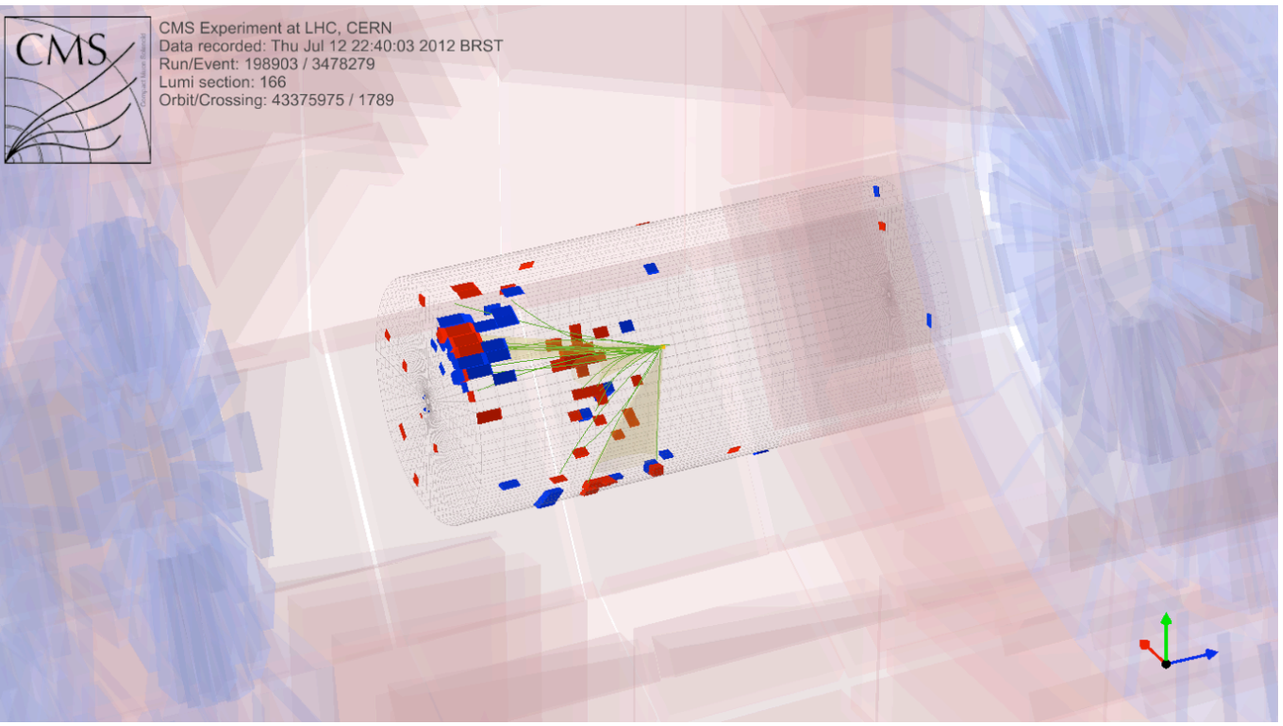
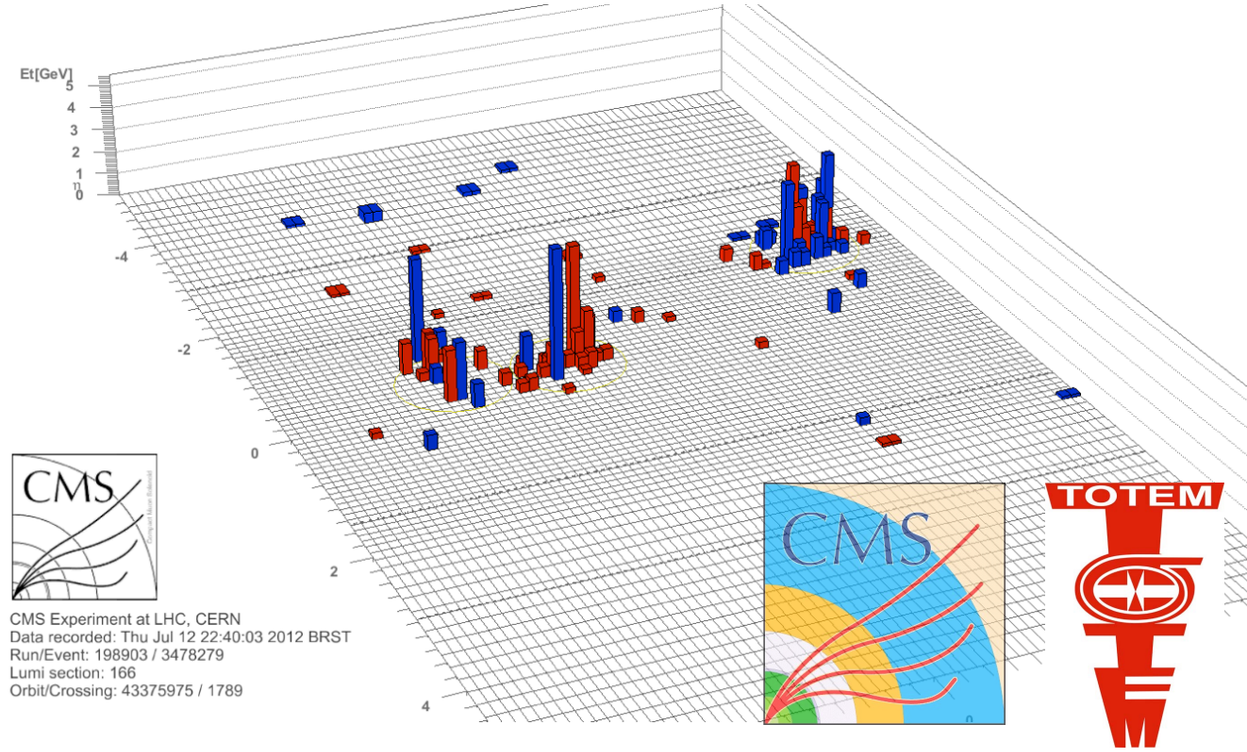
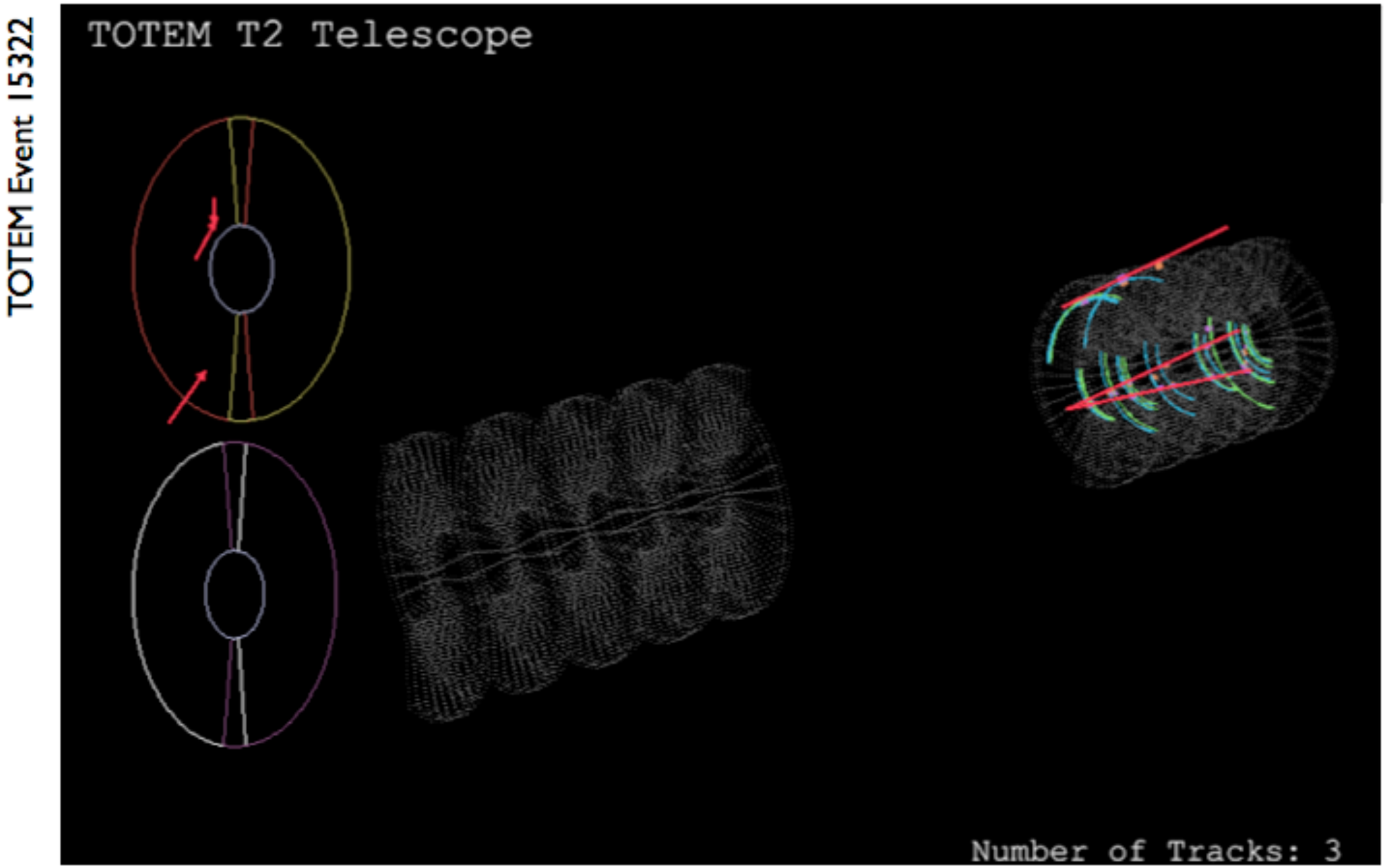




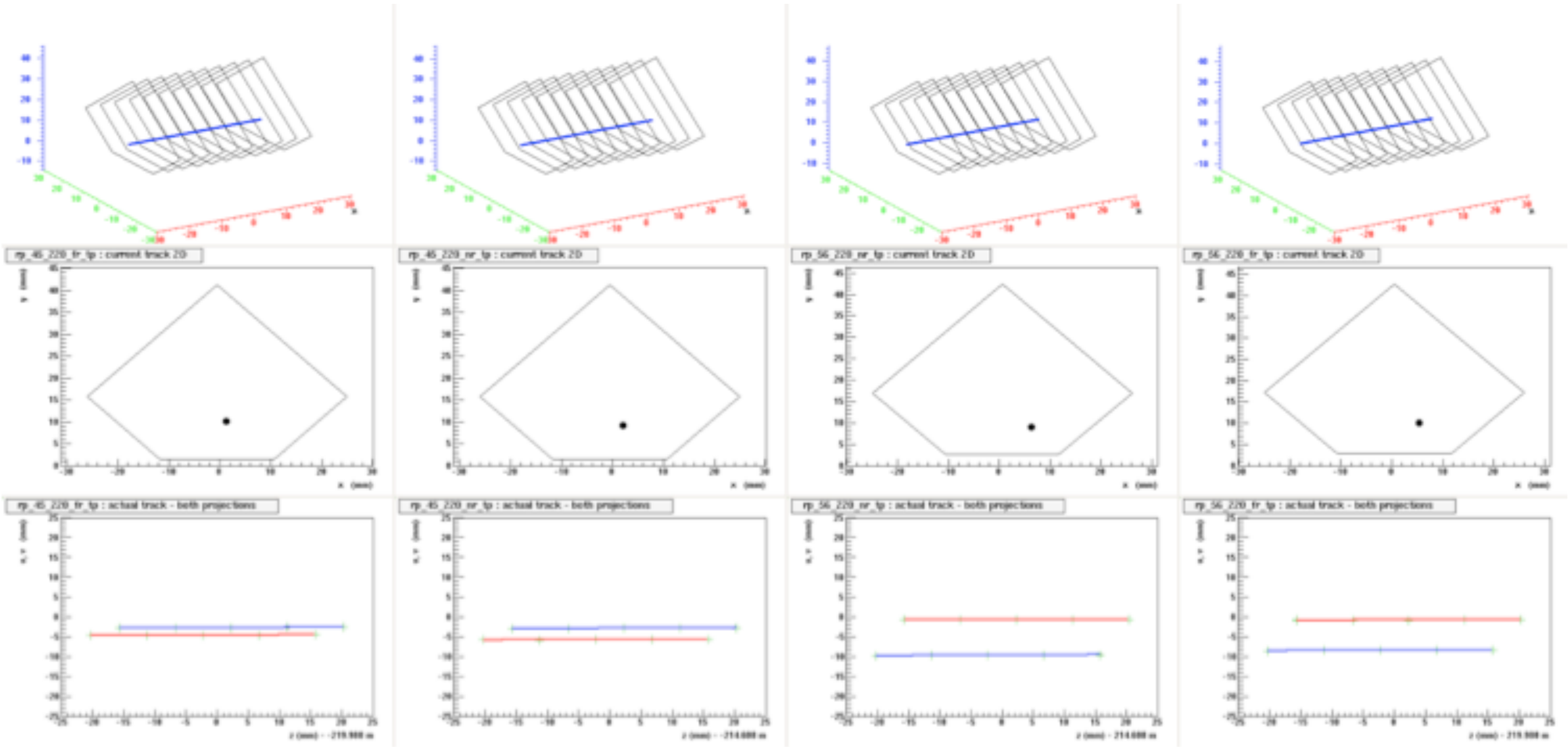
3 Jets Event Display - TOTEM T2

Run 198903 - CMS Event 3478279



3 Jets Event Display – TOTEM Roman Pots

Run 198903 - CMS Event 3478279



TOTEM Event 15322