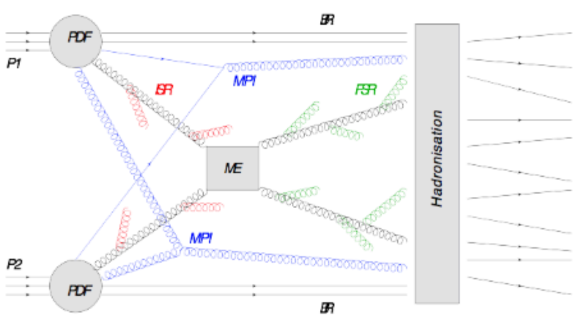
Forward Physics Measurements with CMS Experiment

Sunil Bansal
Panjab University

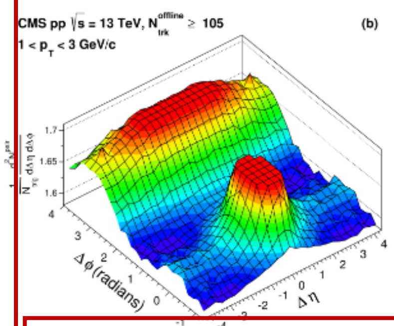
International Workshop on Forward and Jet Physics at LHC
11-12 February 2019, Bose Institute

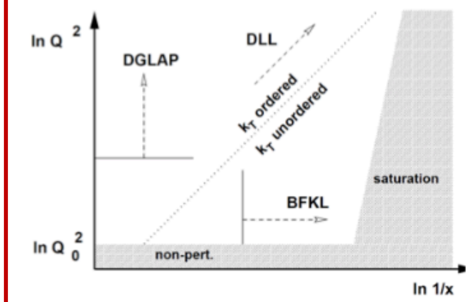
Forward Physics @ CMS

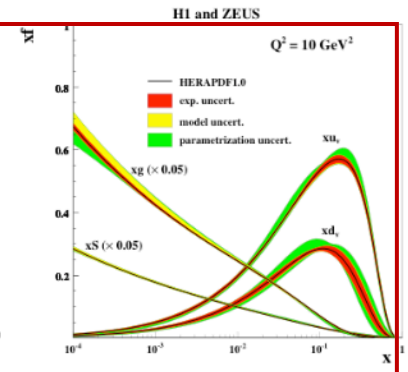
Soft QCD
(particle spectra; underlying event)



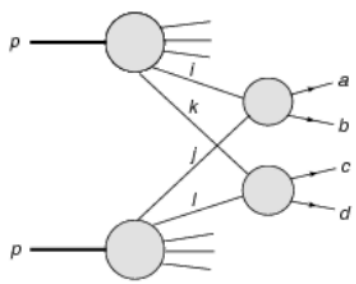
Small-x QCD
(forward jets)



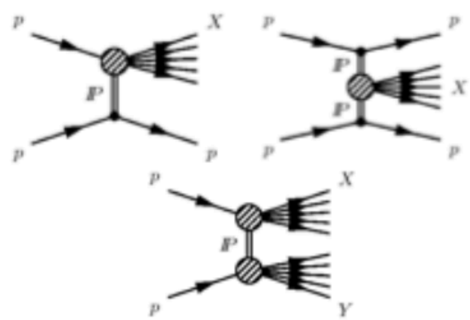




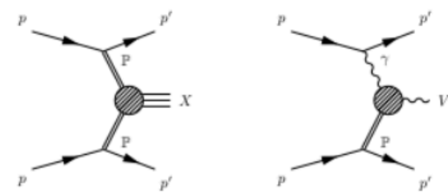
Double parton scattering



Diffraction

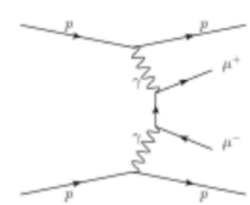


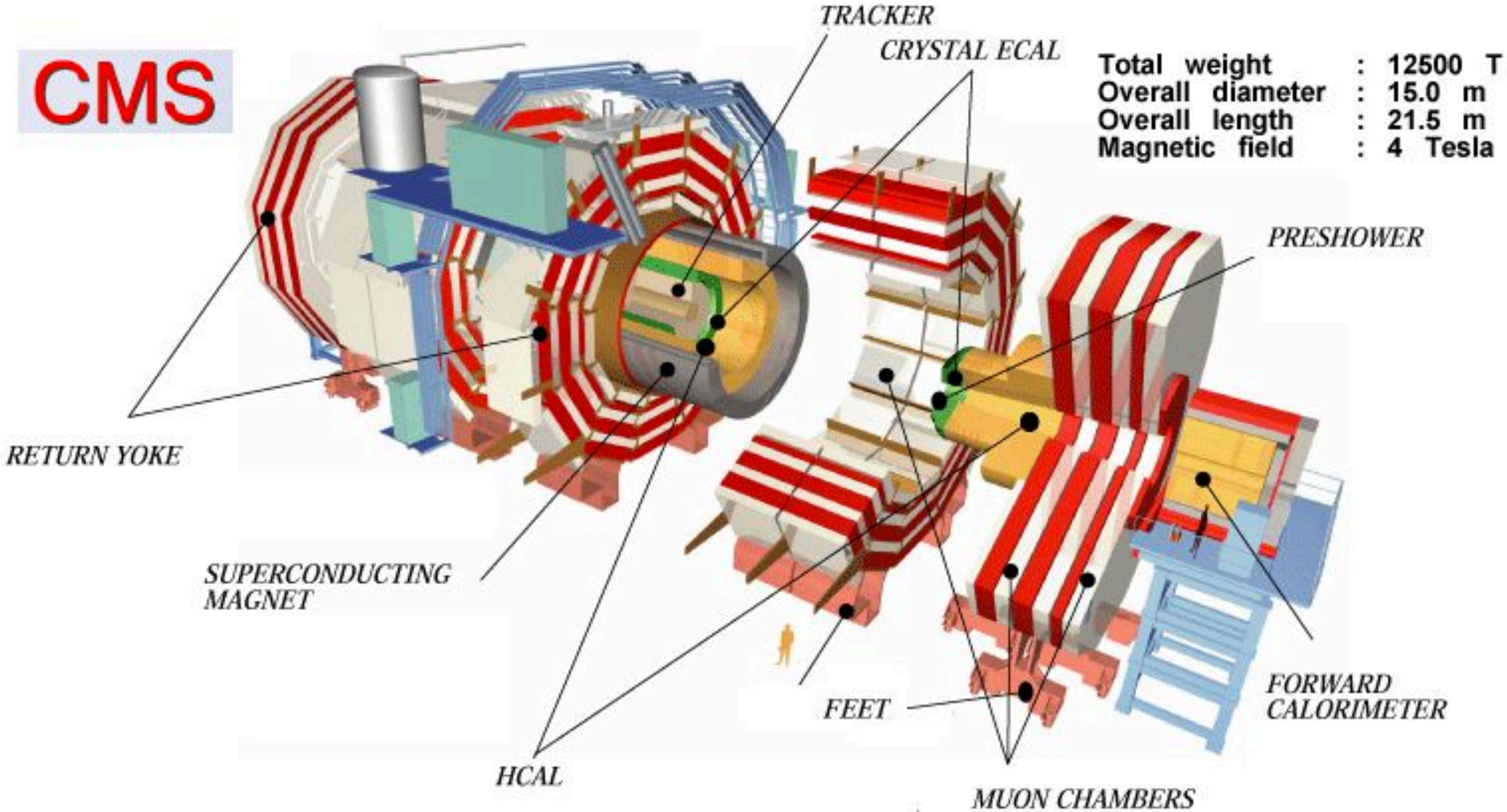
Central exclusive production

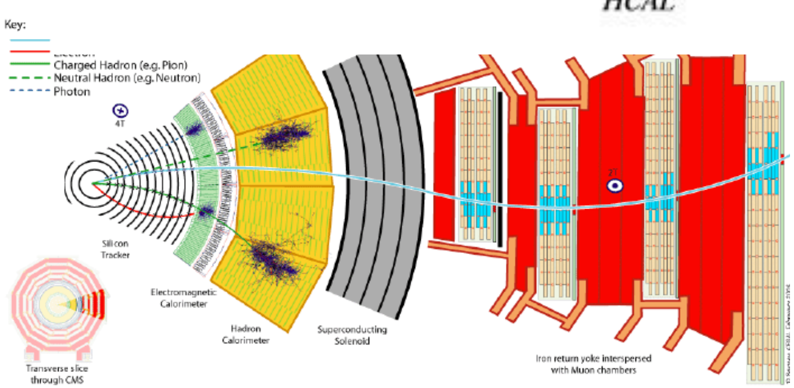


Low mass

High mass





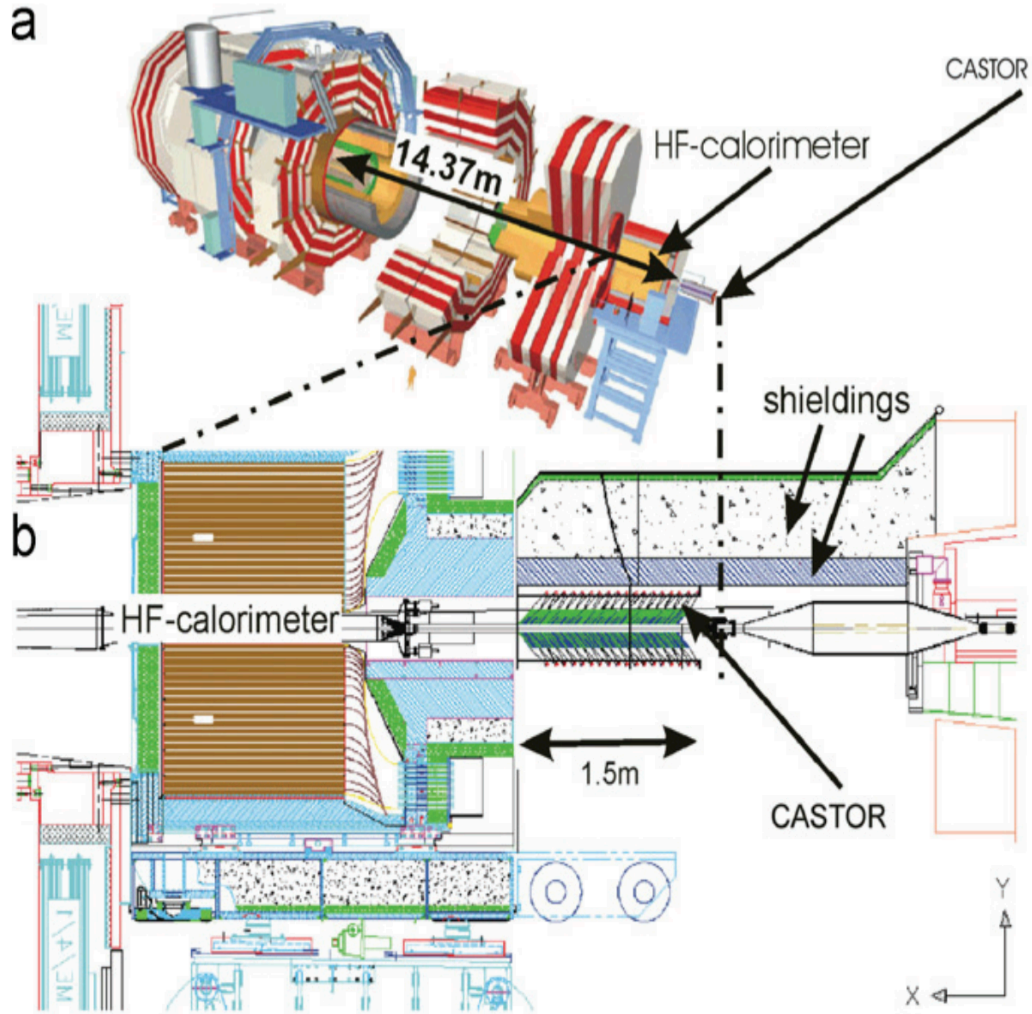


Forward Physics uses:

- Forward Calorimeter (HF)
- CASTOR Detector
- TOTEM
- CT-PPS

Hadron Forward Calorimeter & CASTOR

The CMS experiment has forward sub-detectors to enhance its pseudorapidity coverage:



Hadronic Forward (HF):

✓ Coverage $3.0 < |\eta| < 5.2$

CASTOR: (not always installed)

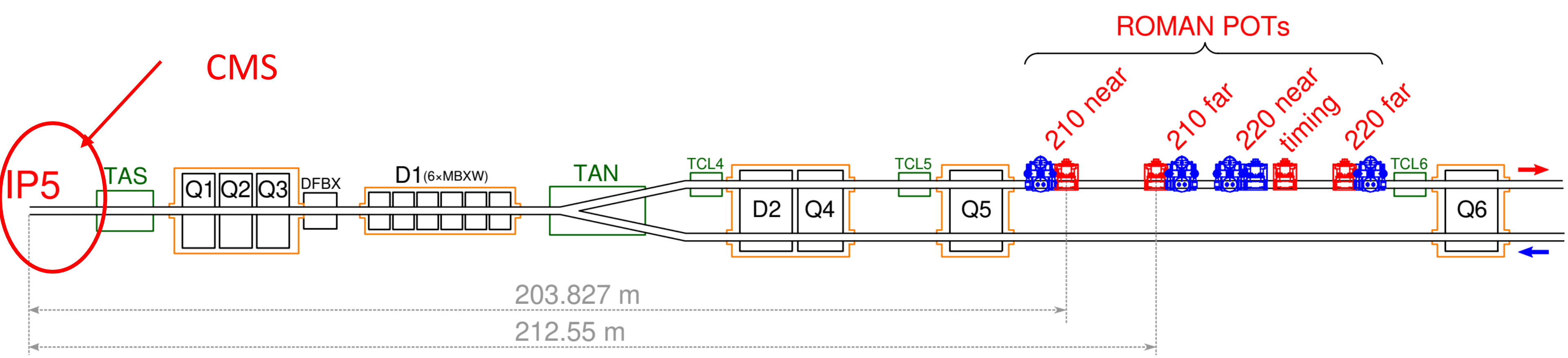
✓ Coverage $-6.6 < \eta < -5.2$

TOTEM & CT-PPS: Proton Tagger

- ✓ TOTEM, CT-PPS are tracking and timing measurements of protons.
- ✓ Detect proton at 220 m from CMS
- ✓ CMS-TOTEM combined data need special optics.

  Low mass Exclusive/Diffractive processes
- ✓ CT-PPS is combined CMS-TOTEM project. Deliver data with standard run conditions.

  High mass Exclusive/Diffractive processes

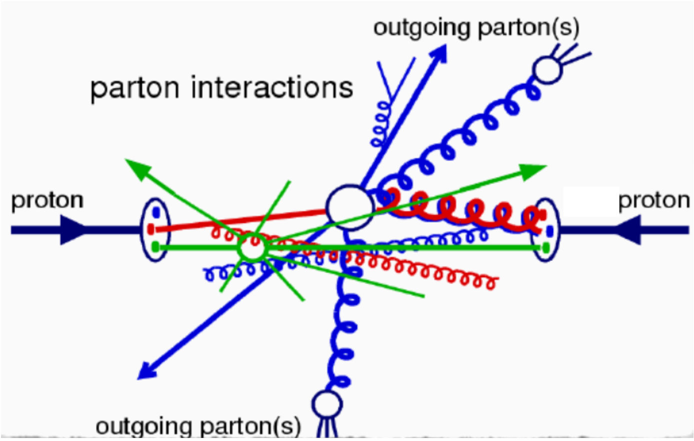


Pool of Data

- Various Collision Scenario:
  - ✓ p-p, p-Pb, Pb-Pb
  - ✓ C.O.M Energy 0.9 – 13 TeV: opportunity to understand evolution with energy
  - ✓ Special Conditions i.e. very low PU to high PU
  - ✓ Special Optics i.e. 90 m β^* for combined CMS-TOTEM data

Particle Production in Forward Rapidities

- ❑ The production of particles at large rapidities (typically $|\eta| > 5$) are used to investigate:



- ✓ multiparton interactions (MPI);
- ✓ initial- and final-state radiation;
- ✓ fragmentation of beam remnants; and
- ✓ diffraction.

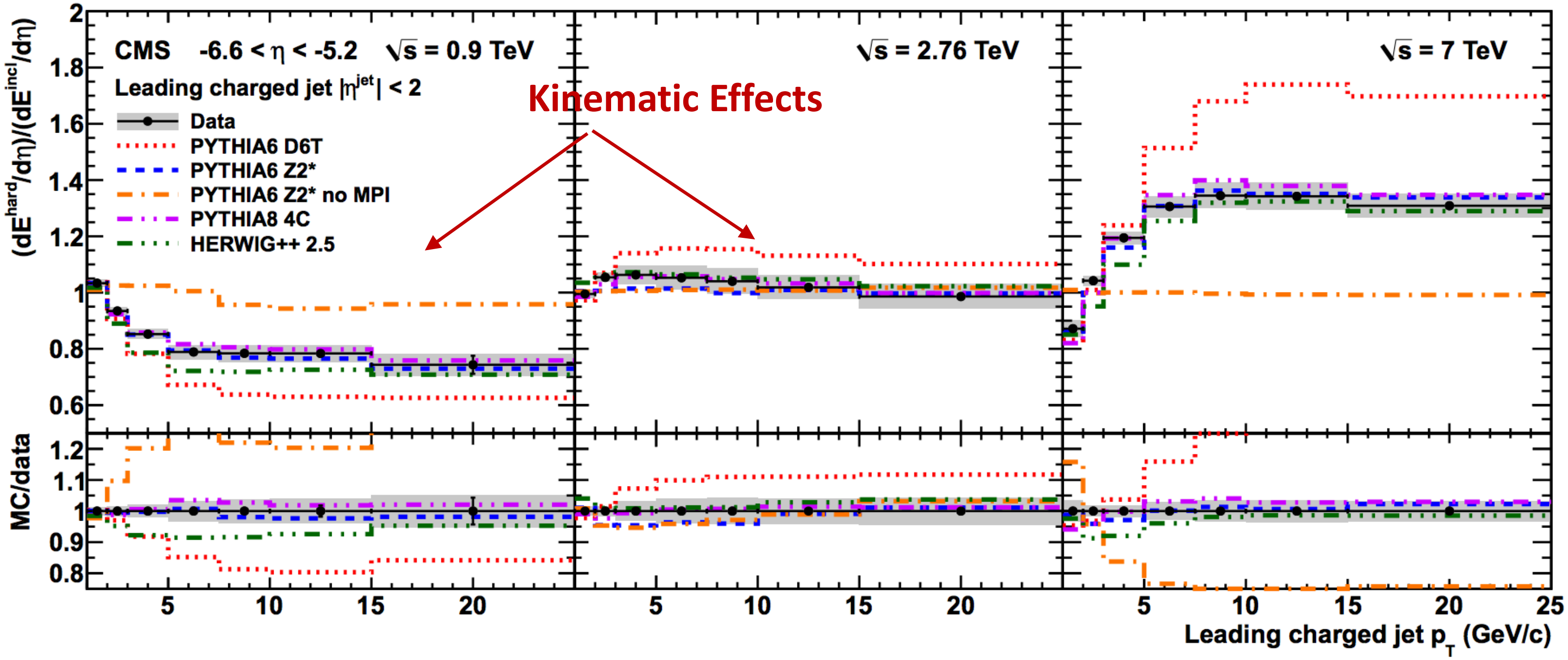
- ❑ CASTOR/HF data is used in this analysis

– Few reports on proton-proton (proton-Ion) collisions at various energies.

Underlying Event in Forward Rapidity

JHEP 04 (2013) 072

- proton-proton collision @ 0.9, 2.76 and 7 TeV
- Observable: energy deposit, in CASTOR, as function of central jet p_T

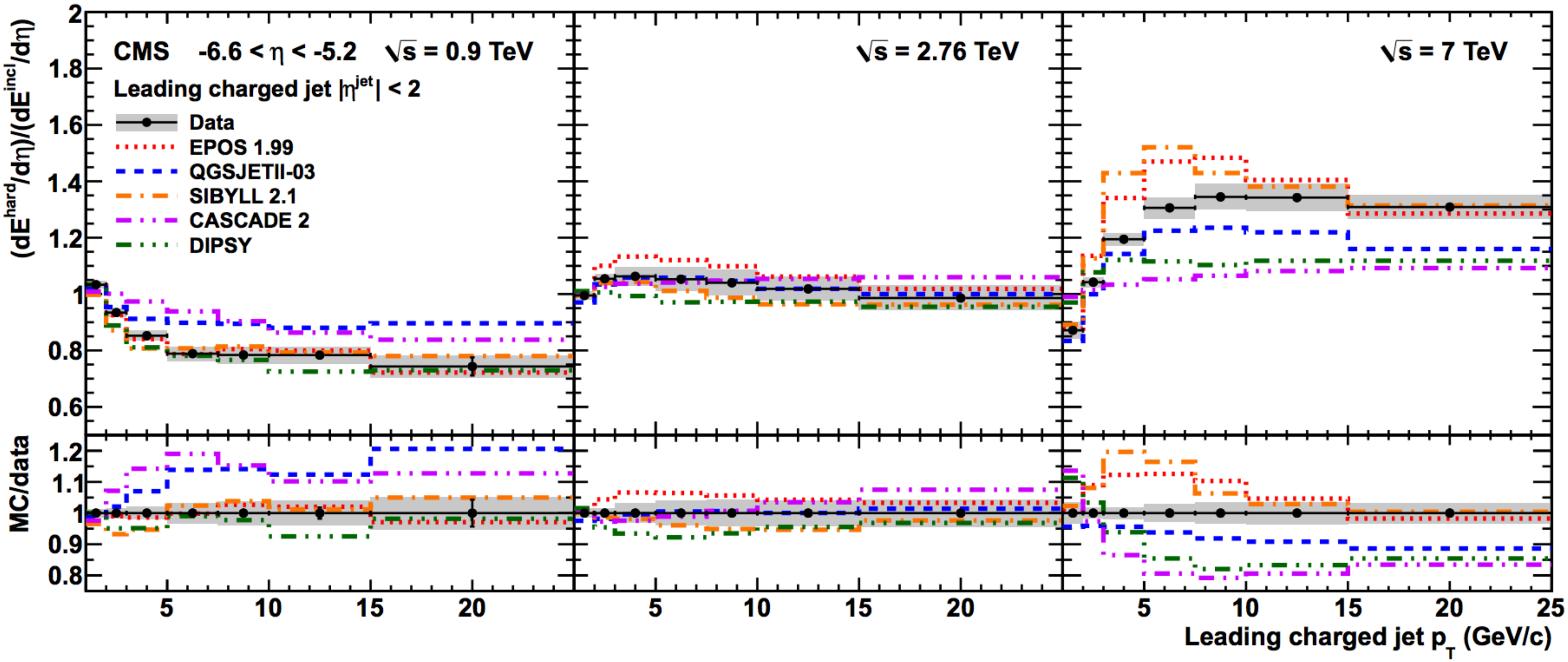


✓ Forward UE, qualitatively, similar as in central region.

✓ None of pre-LHC tune successful in describing the measurements. Pythia8 -4C does a decent job.

Underlying Event in Forward Rapidity

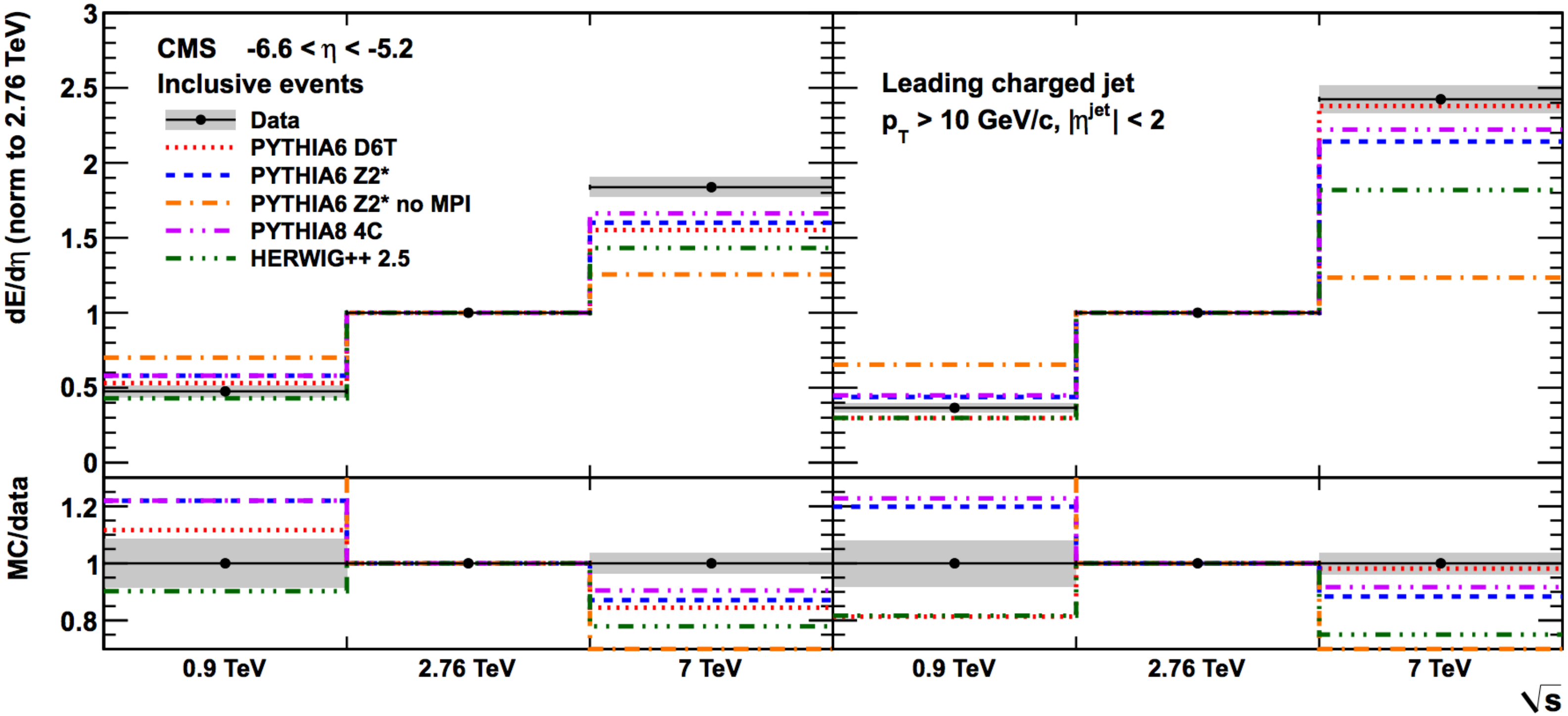
JHEP 04 (2013) 072



- ✓ Forward UE, qualitatively, similar as in central region.
- ✓ None of pre-LHC tune successful in describing the measurements. Pythia8 -4C does a decent job.
- ✓ Cosmic ray event generators do not describe measurements at all energies simultaneously.

Underlying Event in Forward Rapidity

JHEP 04 (2013) 072



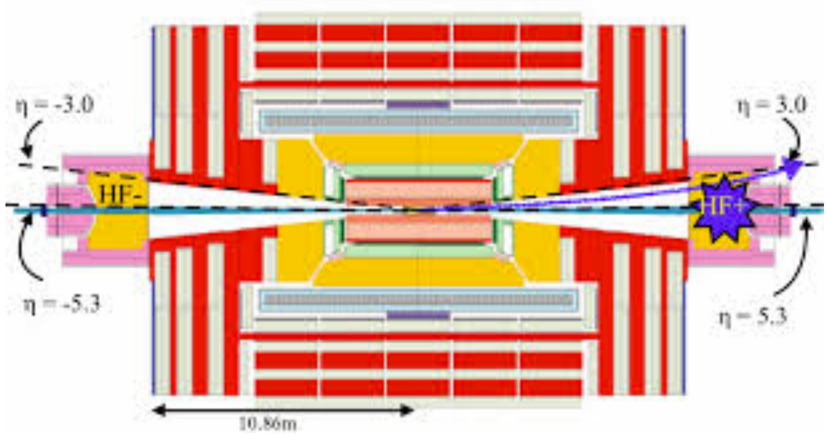
- ✓ Rise in forward UE with √s is consistent as in the central rapidity
- ✓ pre-LHC tune describes √s dependence but Pythia8 -4C does a decent job.
- ✓ Cosmic ray event generators also provide a reasonable description.

Energy Density as a Function of Pseudo-rapidity

arXiv:1812.04095

- Proton-proton collision @ 13 TeV
- Observable: total energy deposit (in HF/CASTOR) as function of Pseudo-rapidity

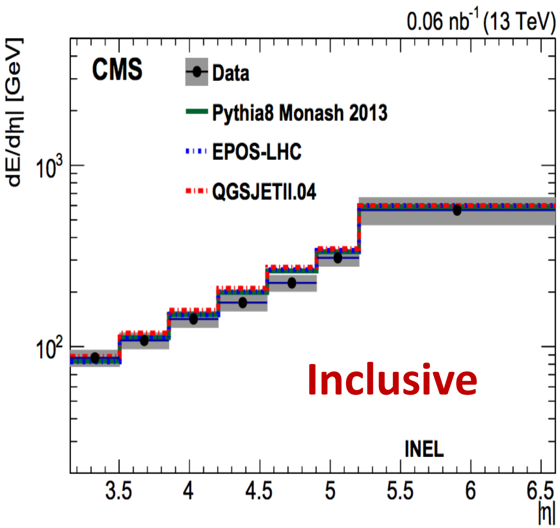
- Event Class :
  - ✓ Inelastic (Energy deposit in either side HF)
  - ✓ Non-Single Diffractive (Energy deposit in both side HF)
  - ✓ Signal Diffractive Enhanced (Energy deposit in one HF but veto on others)

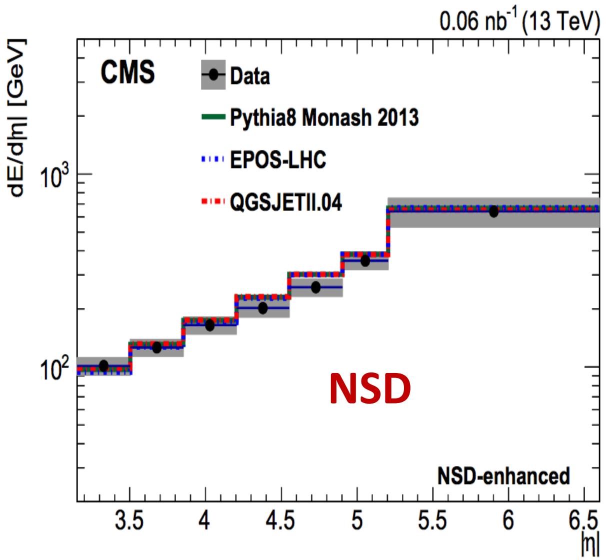


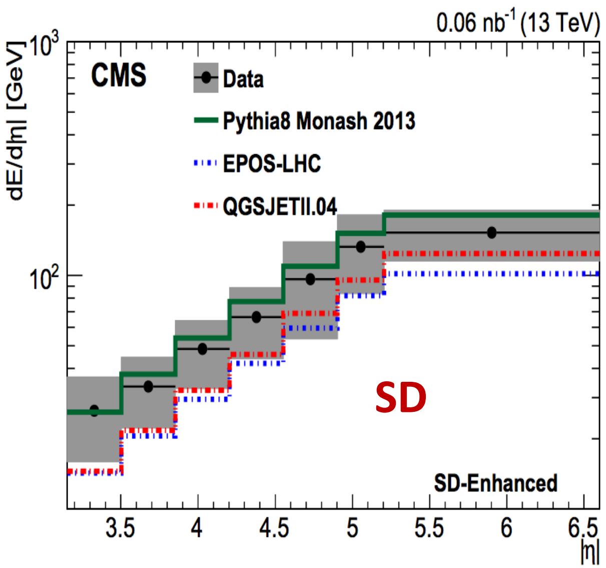
Energy Density as a Function of Pseudo-rapidity

arXiv:1812.04095

- ➢ Corrected for detector effects for comparison with model predictions
- ➢ Limited by energy scale uncertainty.



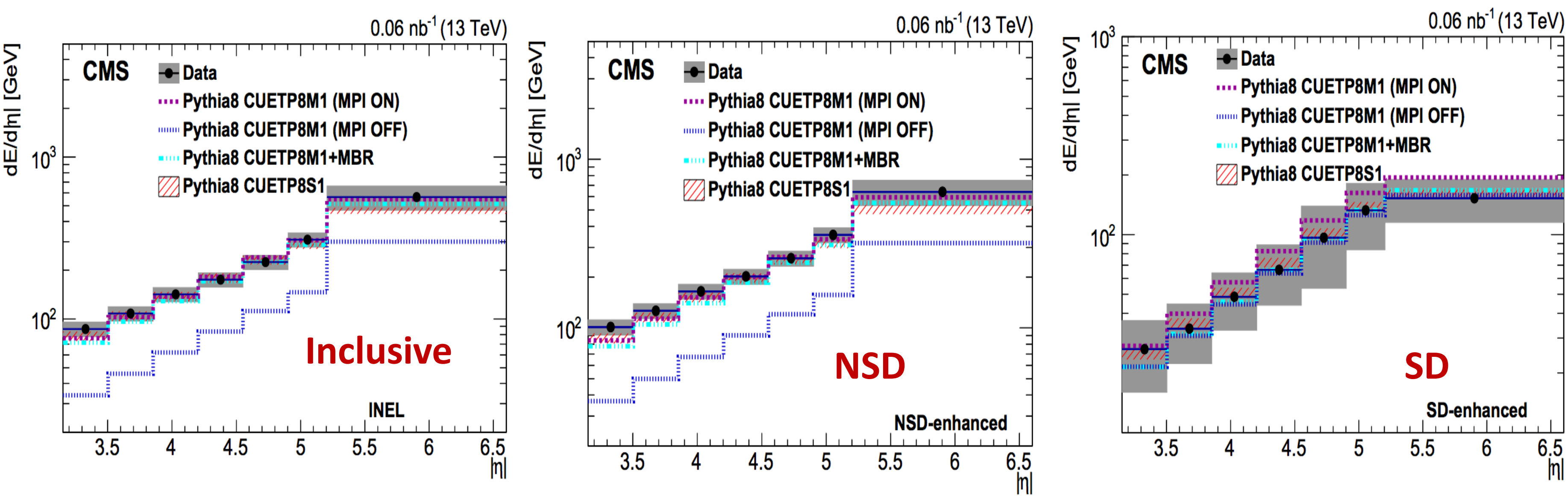




- ❑ Energy density in SD-Enhanced events is 20-30% of Inclusive.
- ❑ Simulations give good description energy density except tension for the SD-Enhanced events.

Energy Density as a Function of Pseudo-rapidity

arXiv:1812.04095



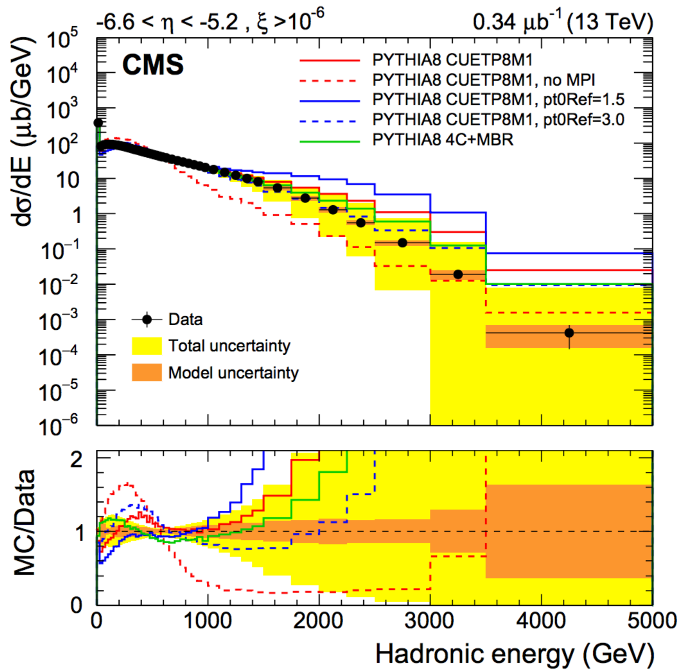
- ❑ Pythia8 CMS tunes give a nice description.
- ❑ MPI has significant effect on energy density for the Inclusive and NSD-Enhanced events.
- ❑ Diffractive (SD-Enhanced) events have less sensitivity to the presence of MPI.

Inclusive Energy Spectrum with CASTOR

JHEP 08 (2017) 046

- proton-proton collision @ 13 TeV
- Observable: total energy, Electromagnetic and Hadronic, deposit in CASTOR

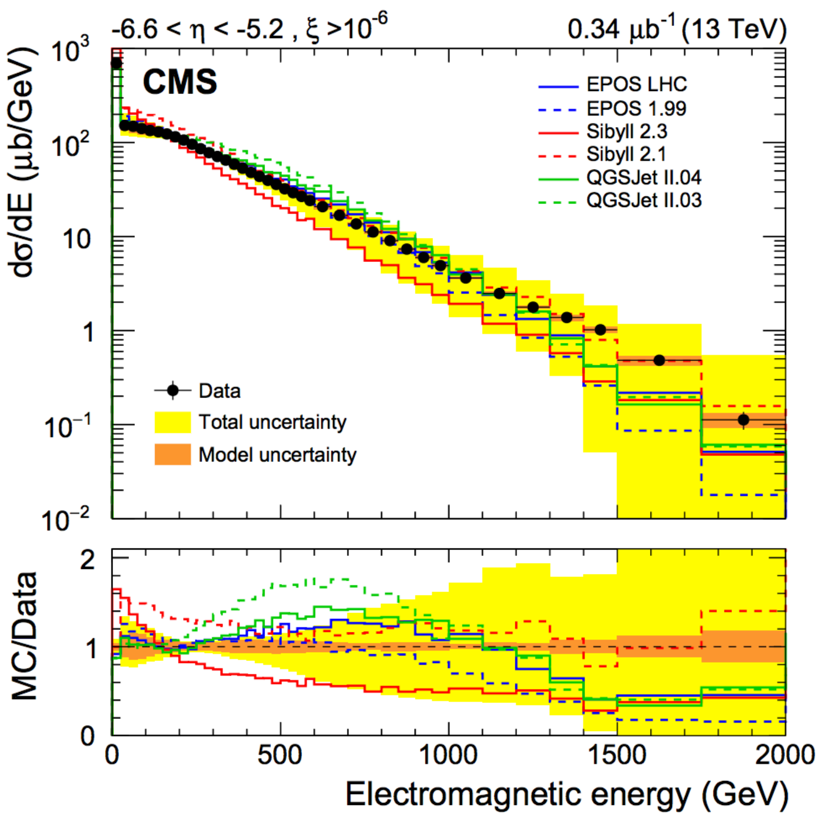
- Corrected detector effects for comparison with model predictions
- Limited by energy scale uncertainty.

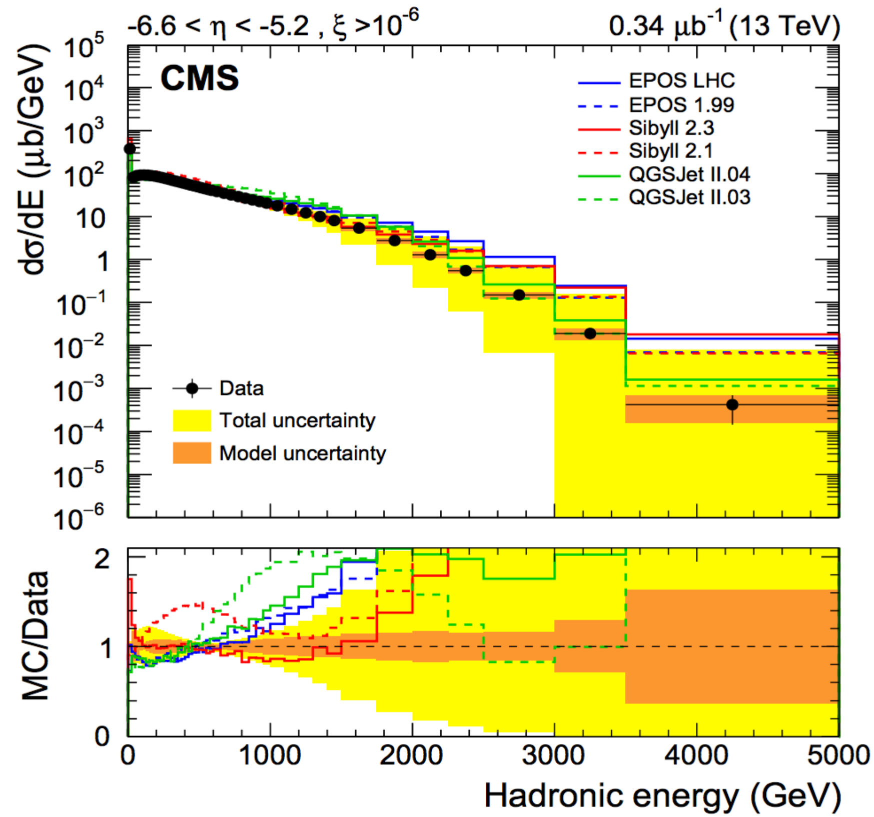


- ✓ Pythia8 MBR give good description of the measurement.
- ✓ Measurement is sensitive to MPI.

Inclusive Energy Spectrum with CASTOR

JHEP 08 (2017) 046



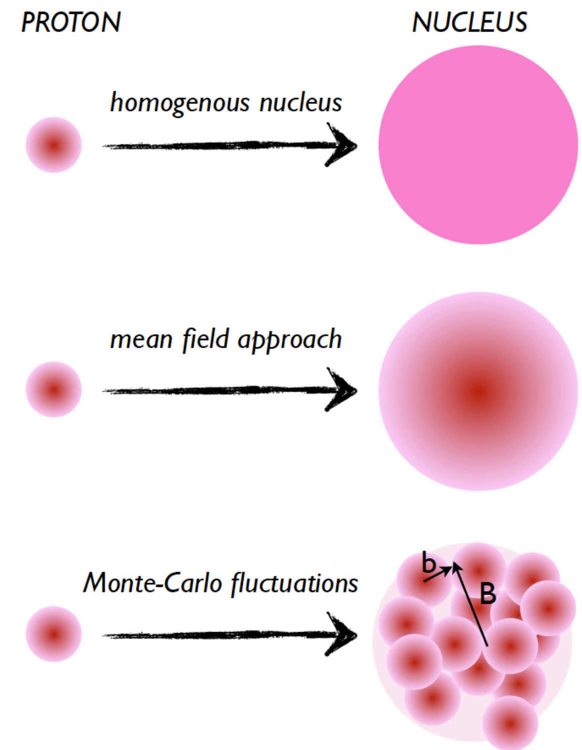


- Good description by Cosmic Ray Monte-Carlo generator i.e. Sibyll, QGSJet tuned with LHC data.
- EPOS also gives reasonable description of the measurement.

Inclusive Jet Spectrum with CASTOR

arXiv:1812.01691

- Studies in proton-Nucleus collisions are suitable for searchers of signals of gluon saturation;
- This goal leads to the investigation of nonlinear effects and alternatives for the description of parton evolution equations;
- Nonlinear effects can be studied with low x partons by measuring low p_T jets in p-Pb collisions

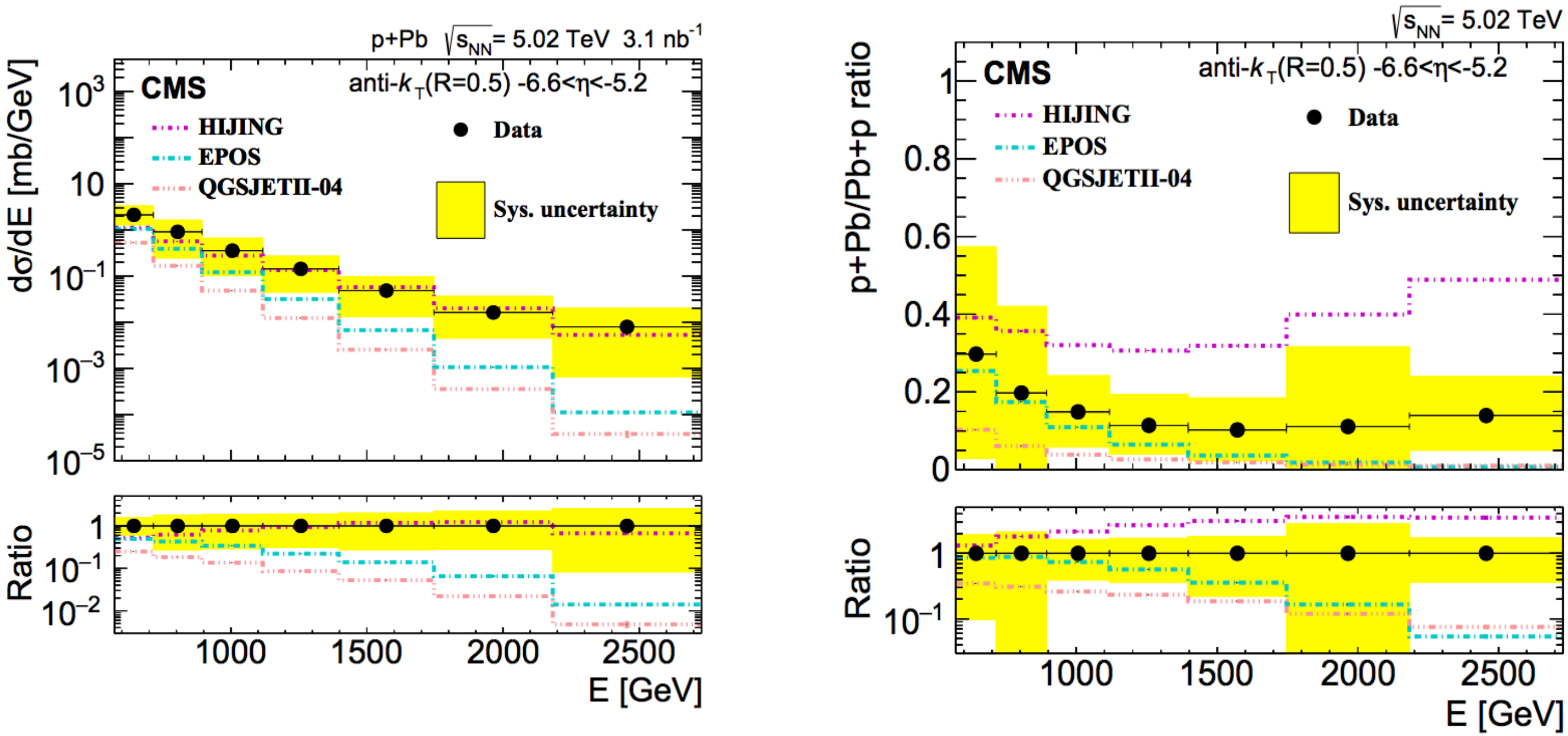


- proton-Pb collision @ 5.02 TeV
- Observable: Differential (in energy) jet production cross-section

Inclusive Jet Spectrum with CASTOR

arXiv:1812.01691

➢ Corrected detector effects for comparison with model predictions



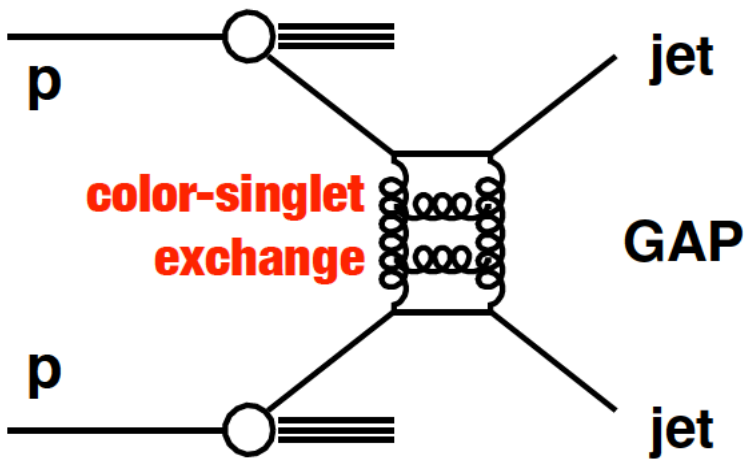
✓ HIJING describes reasonably the jet cross-section but fails to describe ratio.

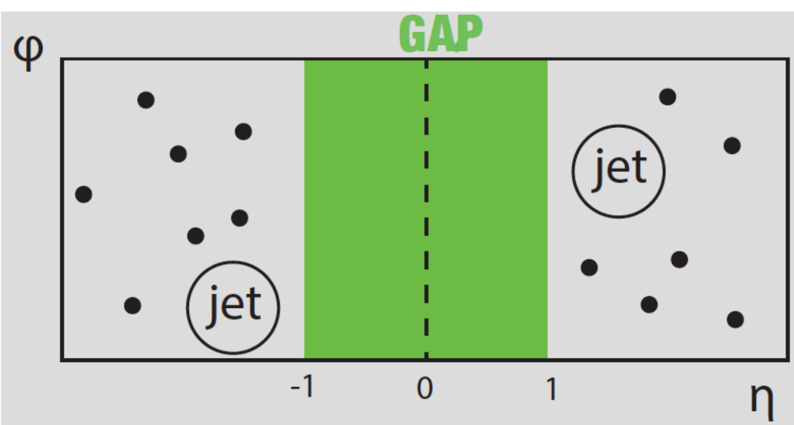
✓ Cosmic ray generator QGSJET fails in prediction.

Jet-gap-Jet Events

Eur. Phys. J. C 78 (2018) 242

➢ There is a probability to have an interaction with large momentum transfer to produce a pair of jets with large gap in pseudo-rapidity η;

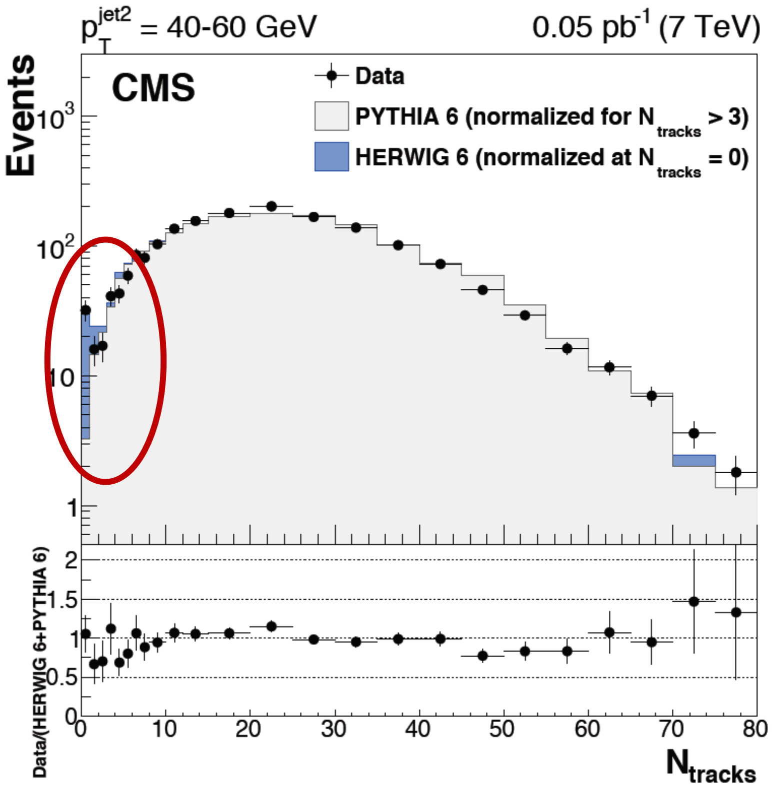




- ❑ GAP: no QCD radiation fills the gap, i.e., a color-singlet exchange (CSE) (a.k.a. diffractive event);
- ❑ Dijet production is in general well described by the DGLAP equation;
- ❑ The presence of a large interval in pseudorapidity [Δη(jj)] is better described by the BFKL equation.

Jet-gap-Jet Events

Eur. Phys. J. C 78 (2018) 242

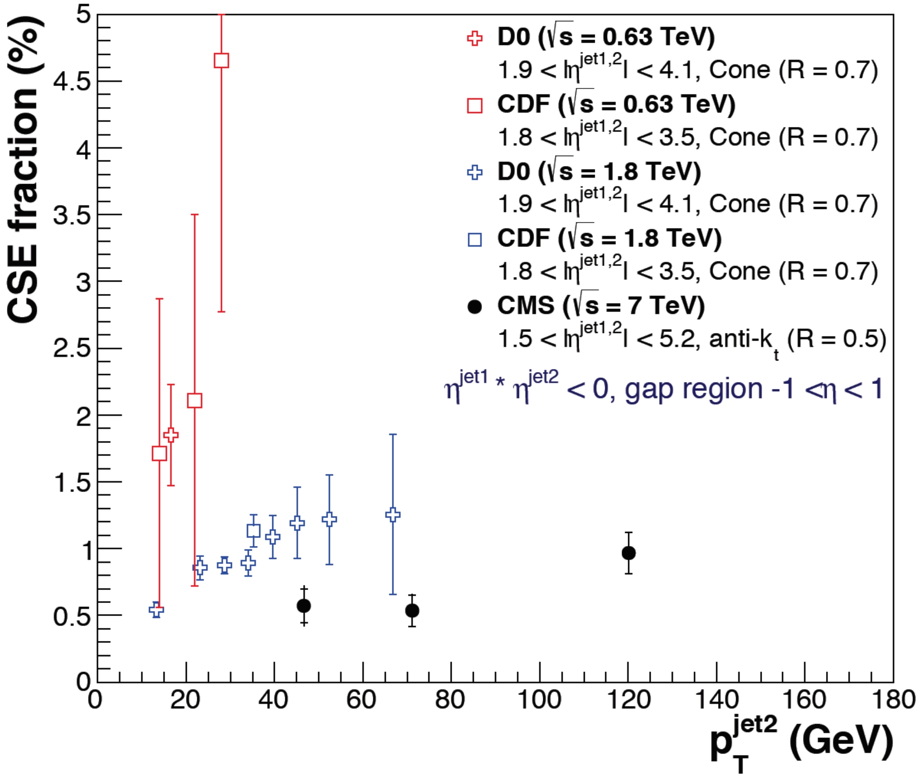


- ✓ To ensure pseudorapidity gaps, conditions required:
  1. two leading jets (p_T > 40 GeV) with 1.5 < |η(j)| < 4.7;
  2. two leading jets in opposite hemispheres: η(j1)*η(j2) < 0.
- ✓ The N_{tracks} is obtained from a distribution of charged-particle multiplicity,
  1. N_{tracks}, with |η(all)| < 1 for p_T(all) > 0.2 GeV, between the 2 jets;

❑ Pythia (DGLAP) fails to describe 0 track event but BFKL predictions (Herwig) do a nice job.

Jet-gap-Jet Events

Eur. Phys. J. C 78 (2018) 242



- The fraction of diffractive events is defined as:

$$f_{\mathrm{CSE}} = \frac{N^{\mathrm{F}}_{\mathrm{events}} - N^{\mathrm{F}}_{\mathrm{non\text{-}CSE}}}{N_{\mathrm{events}}}$$

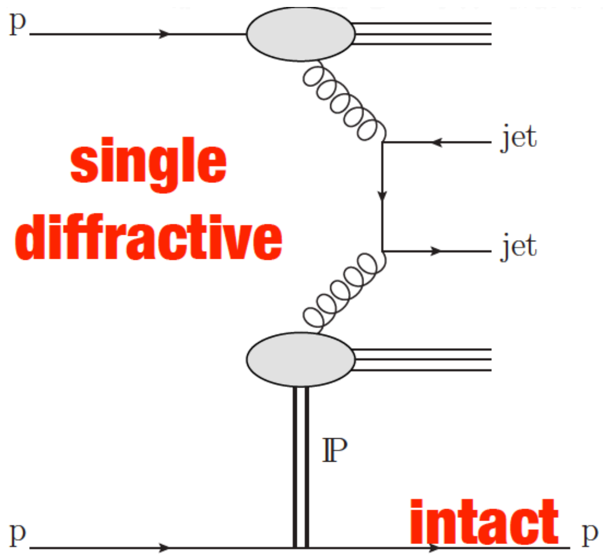
✓ CSE fraction increases with rapidity gap.

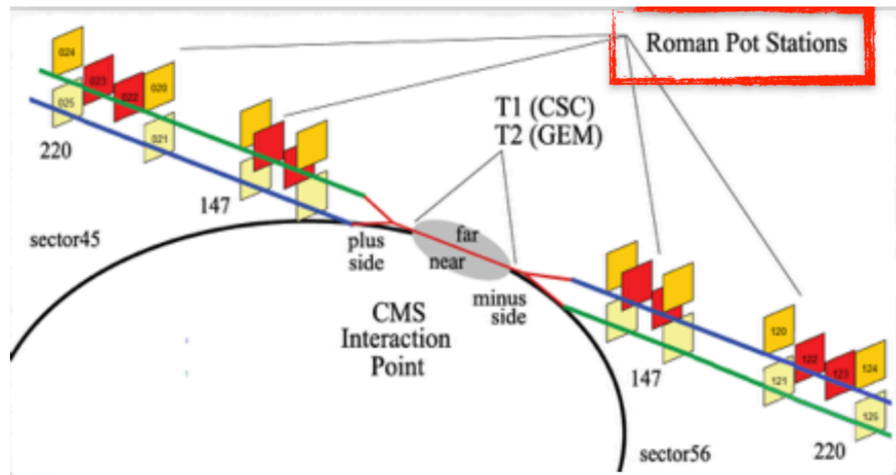
✓ Gap-fraction decreases with the collision energy. Due to stronger contribution of re-scattering process of spectator partons.

Dijets with leading proton

CMS-PAS-FSQ-12-033

- Both CMS and TOTEM detectors are employed to detect a scattered proton from a diffractive event;





- In a diffractive interaction, the intact proton is scattered at small angles;
  - TOTEM Roman Pots are used to collect this information.
  - TOTEM acceptance increases the CMS coverage.

Dijets with leading proton

CMS-PAS-FSQ-12-033

TOTEM only Selection

fractional momentum loss $\xi = 1 - \frac{|\mathbf{p}_f|}{|\mathbf{p}_i|}$,

4-momentum transfer squared $t = (p_f - p_i)^2$.

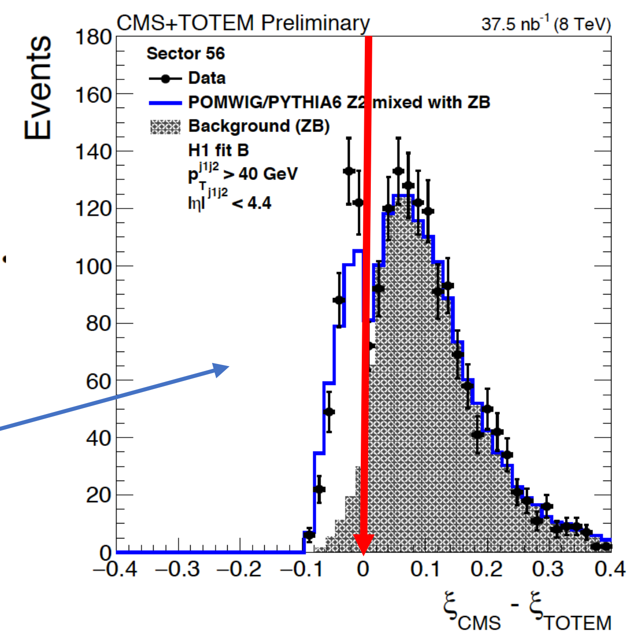
CMS only Selection

$$\xi^{\pm}_{\text{CMS}} = \frac{\sum (E^i \pm p^i_z)}{\sqrt{s}}$$

- Proton selection requires

$$\xi_{\text{CMS}} - \xi_{\text{TOTEM}} \leq 0.$$

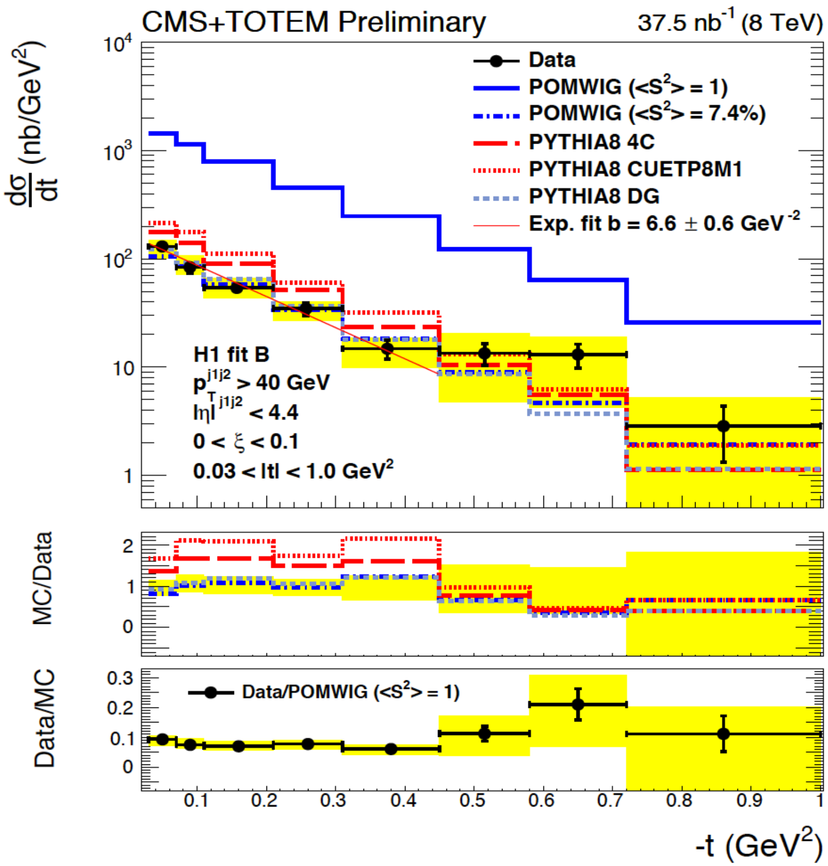
Measurement is well reproduced by MC with Diffraction included

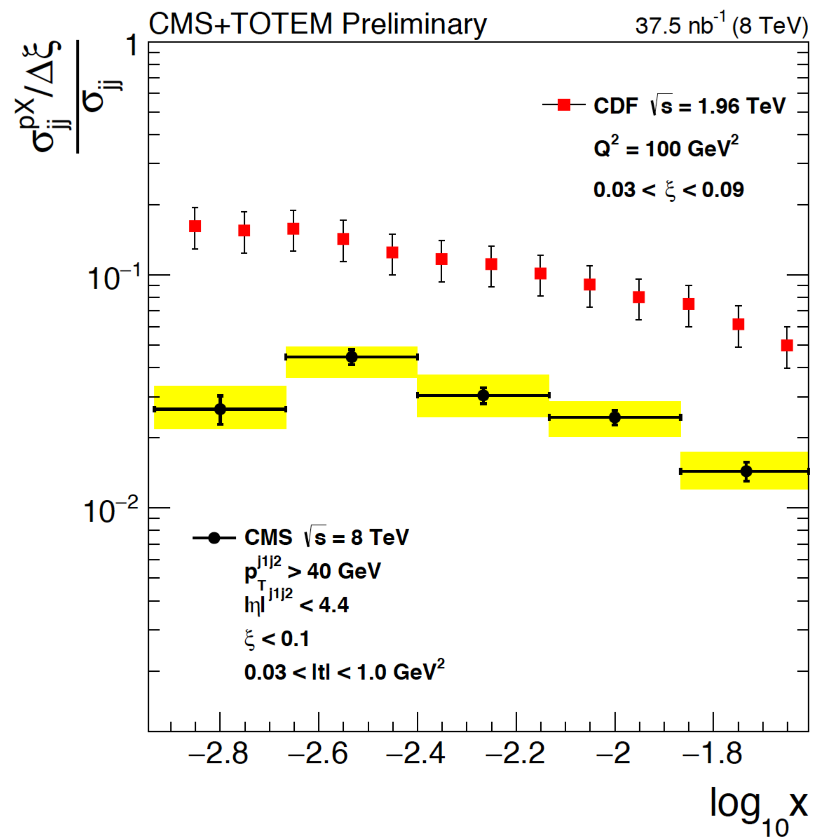


Dijets with leading proton

CMS-PAS-FSQ-12-033

- ✓ Pythia 8 fails by 50-100%.
- ✓ POMWIG fails but retuning of <S^2> make it predict in the agreement with the measurement.



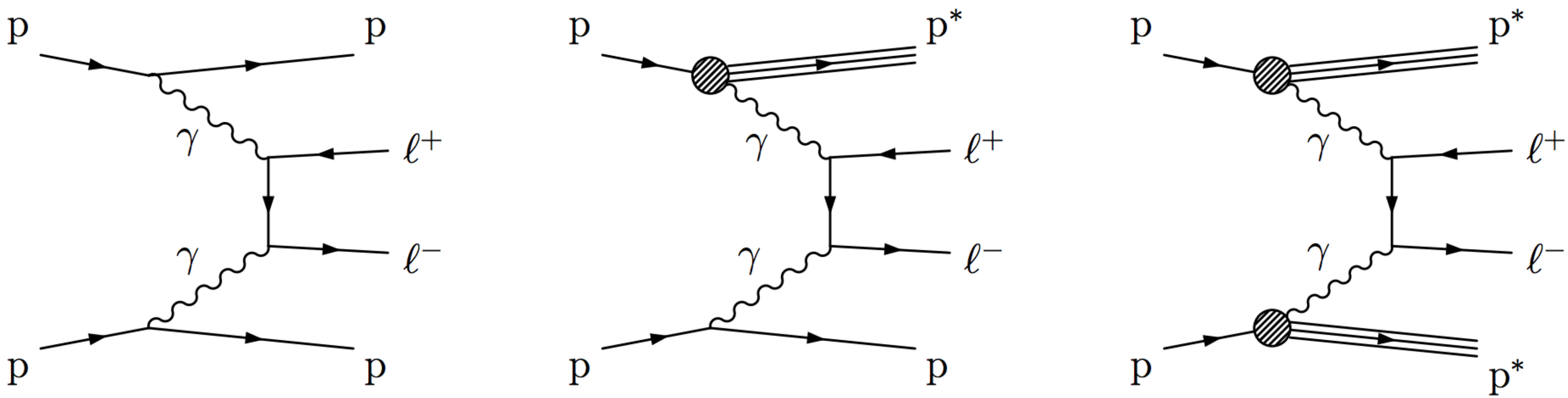


- ✓ Decrease in diffraction with collision energy observed by CDF as well.
- ✓ Can be attributed to increased contribution of rescattering process

Exclusive WW ($\gamma\gamma \rightarrow$ WW)

JHEP 07 (2018) 153

- Apart of diffractive production, the two-photon interaction is also an elastic collision with intact protons scattered at small angles;



- The Precision Proton Spectrometer is meant to measure the forward protons of the elastic interaction at a high-luminosity regime;
  – Acceptance for protons detected in both arms start at M(ll) $\gtrsim$ 400 GeV;
  – Adding semi-exclusive events can increase data sample.

Exclusive WW (γγ → WW)

JHEP 07 (2018) 153

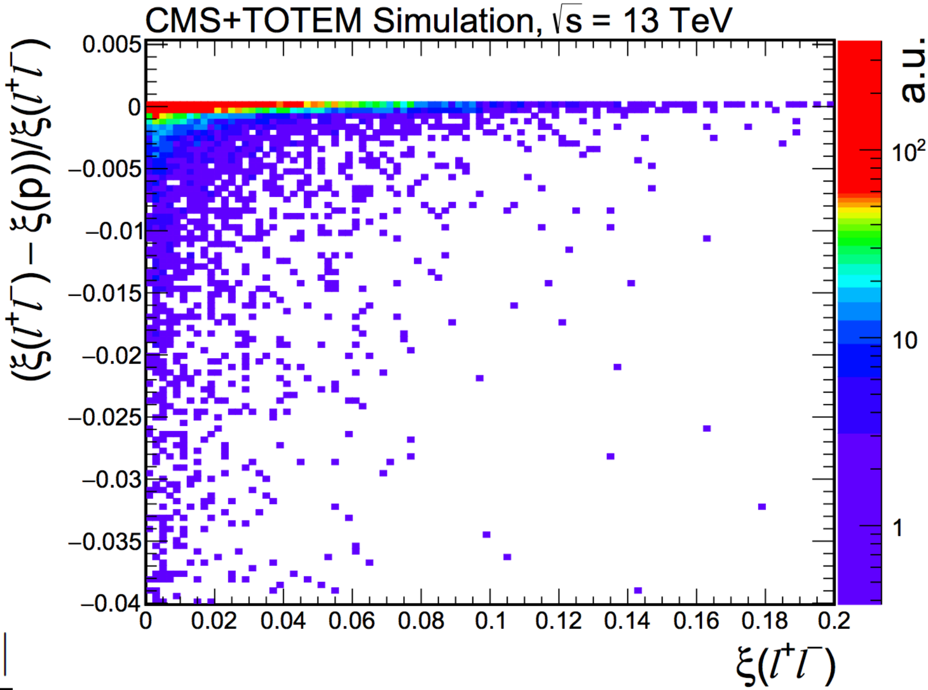
➢ The analysis considers 9.4/fb of 2016 data to search for (semi-)exclusive dilepton production;

✓ 1. Leptons are selected with $p_T > 50$ GeV with opposite charge;

✓ 2. No tracks from the vertice given a veto distance;

✓ 3. Consistent back-to-back leptons based on acoplanarity;

✓ 4. Dilepton with invariant mass above 110 GeV.



fractional momentum loss $\xi = 1 - \frac{|\mathbf{p}_f|}{|\mathbf{p}_i|}$,

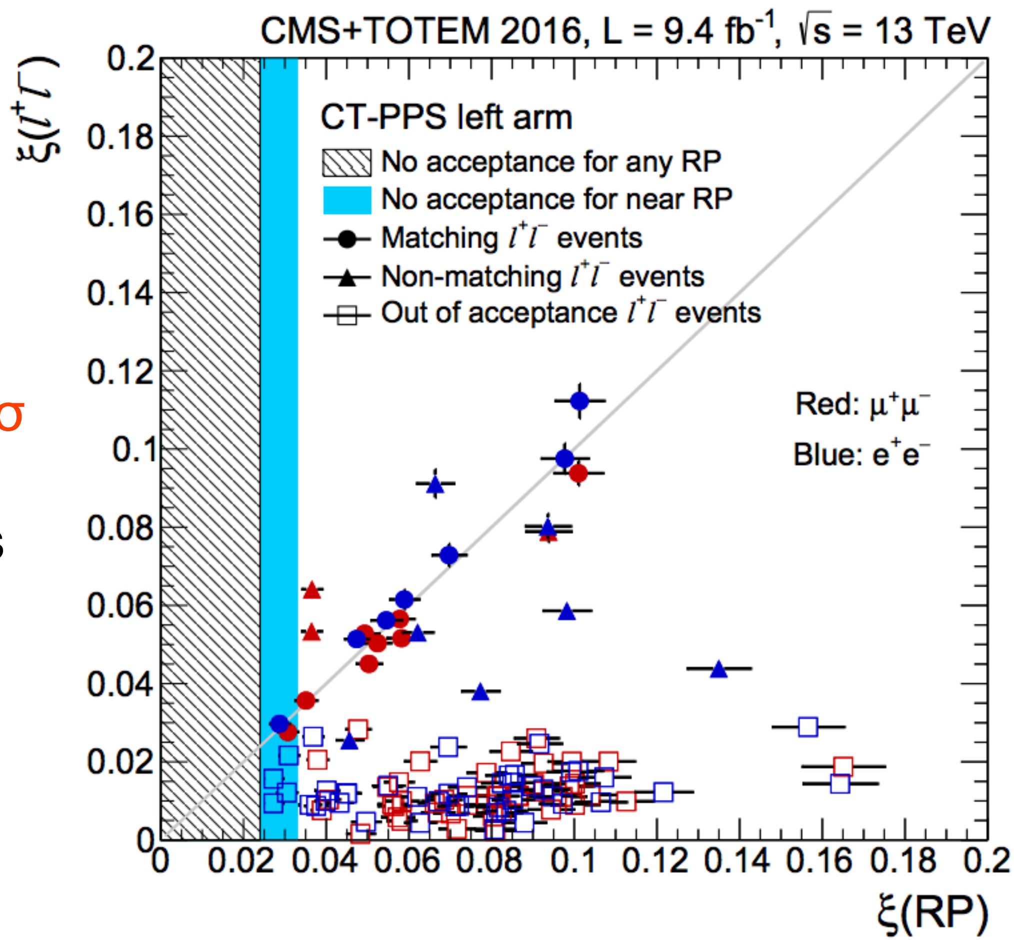
$$\xi(\ell^+\ell^-) = \frac{1}{\sqrt{s}}\left[p_{\mathrm{T}}(\ell^+)\mathrm{e}^{\pm\eta(\ell^+)} + p_{\mathrm{T}}(\ell^-)\mathrm{e}^{\pm\eta(\ell^-)}\right]$$

Exclusive WW (γγ → WW)

JHEP 07 (2018) 153

A total of 12 events (μ+μ−) and 8 events (e+e−) are observed;

- ✓ Significances are 4.3σ (μ+μ−) and 2.6σ (e+e−): combined >5σ
- ✓ Consistent with MC predictions within acceptance and overall efficiency.



Summary

- CMS has forward detectors with capabilities to cover interesting physics;

forward particles, jet production, exclusive and diffractive processes.

- Many interesting measurements, vast possibilities to explore range of collected data.
- Welcome new ideas!!