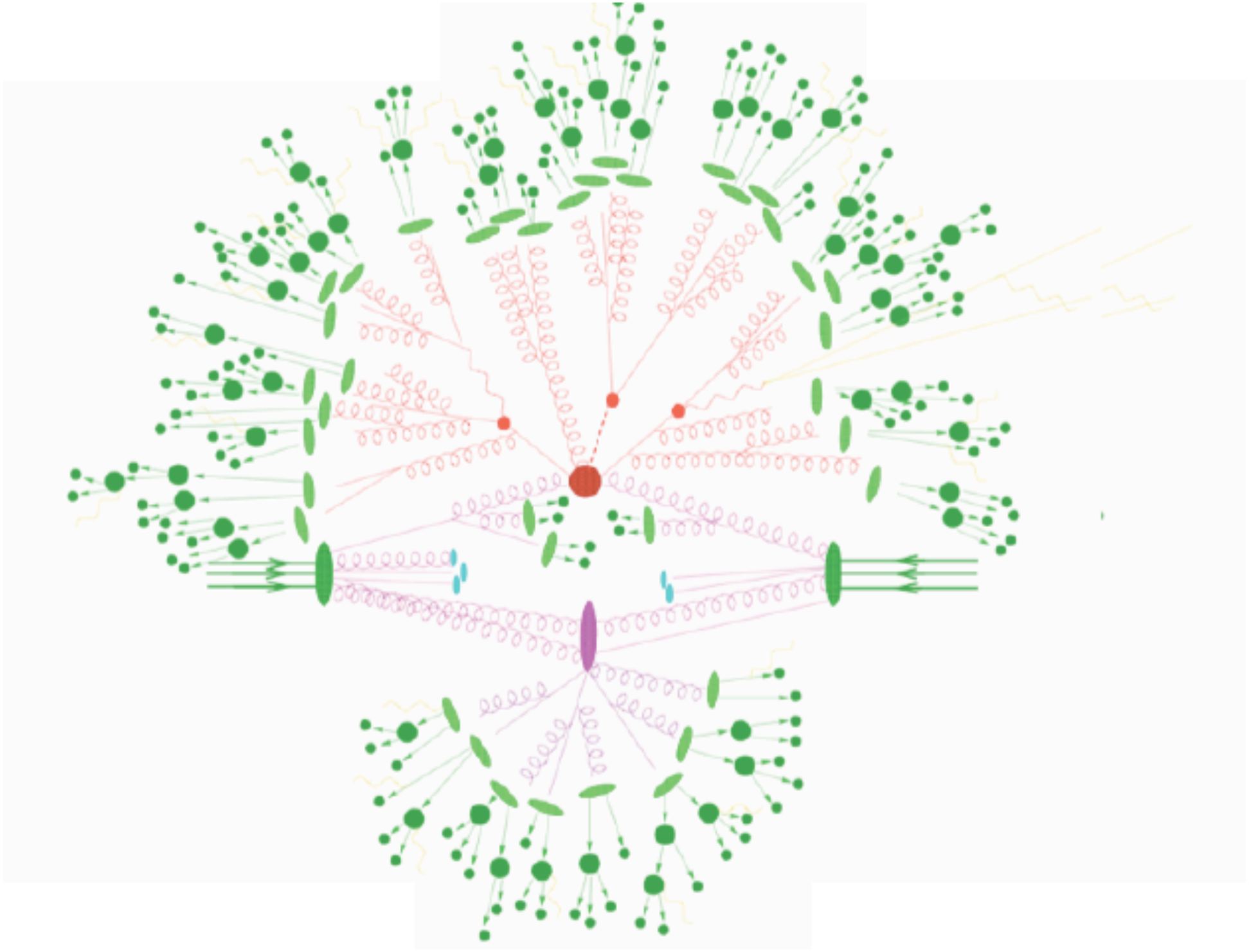
Forward and Small-x QCD Physics with CMS

A. Vilela Pereira on behalf of the CMS Collaboration
Universidade do Estado do Rio de Janeiro

LISHEP 2015 - Manaus - Brazil
2-8 August 2015

Forward & Low-x Physics



Forward & Low-x Physics

The understanding of proton-proton collisions depends on a wide range of phenomena which manifest themselves by looking at low transverse momentum, or forward rapidities:

Small-x QCD

Underlying event, MPI & DPS

Soft and hard diffraction, exclusive processses, γγ interactions, etc.

In this presentation some selected results on these subjects from the CMS collaboration will be shown.

For a full list of results and publications see:

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

Forward & Low-x Physics

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See D. Damião's talk for results on diffractive and exclusive physics.

Outline

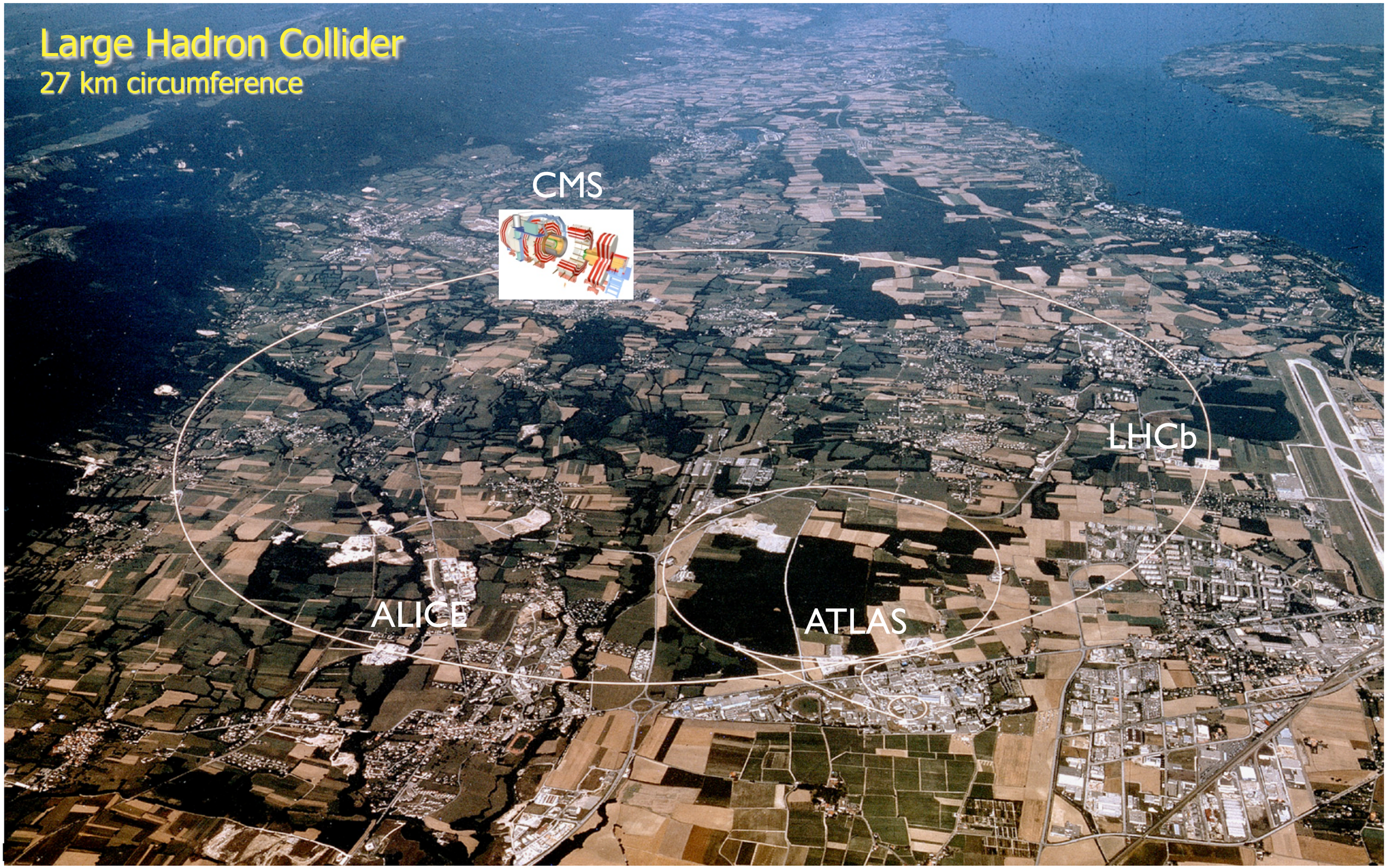
The CMS detector and forward instrumentation

Underlying event in pp collisions and DPS

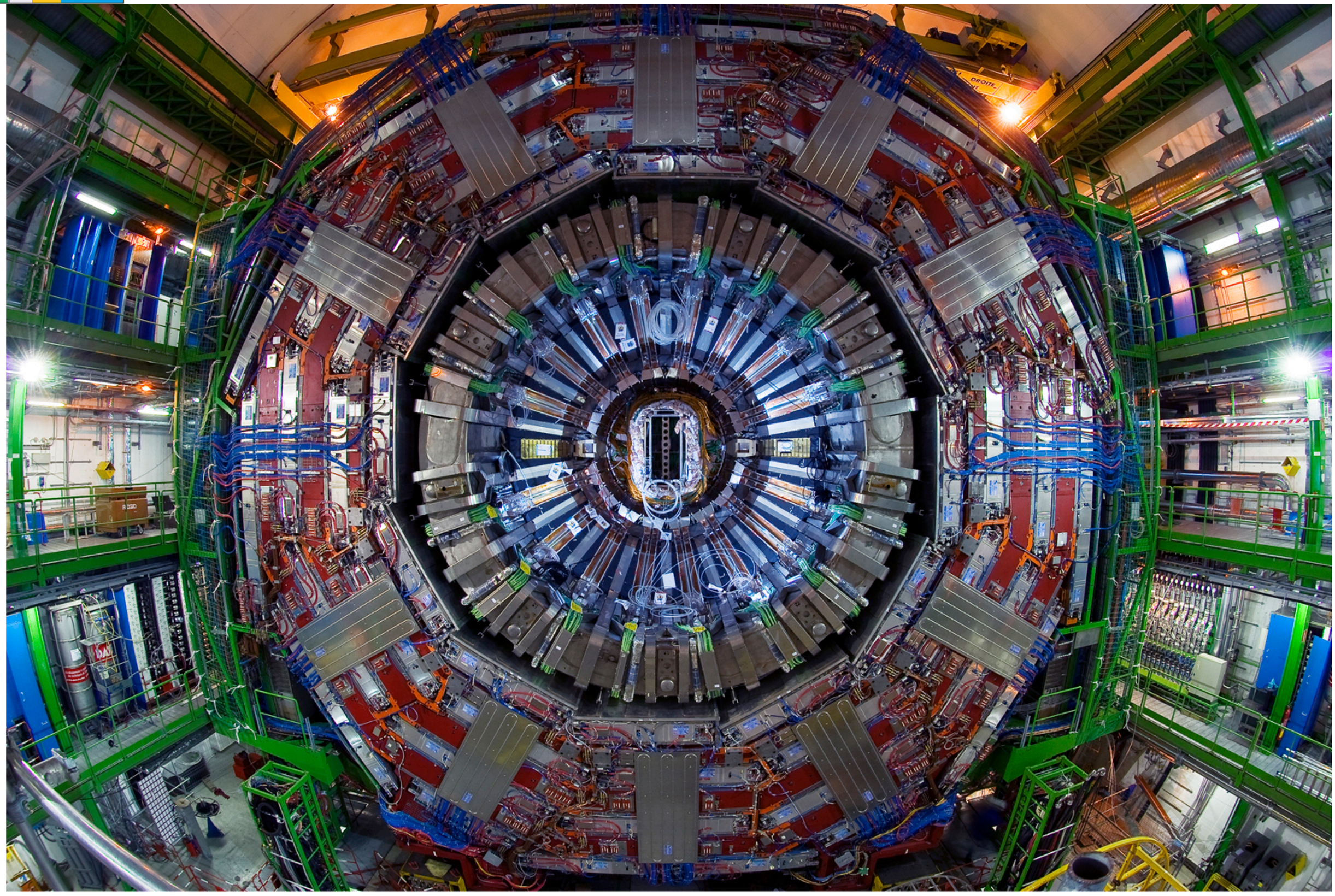
Low-x jet production

Forward energy flow & particle production and inelastic cross section

The CMS detector



The CMS detector



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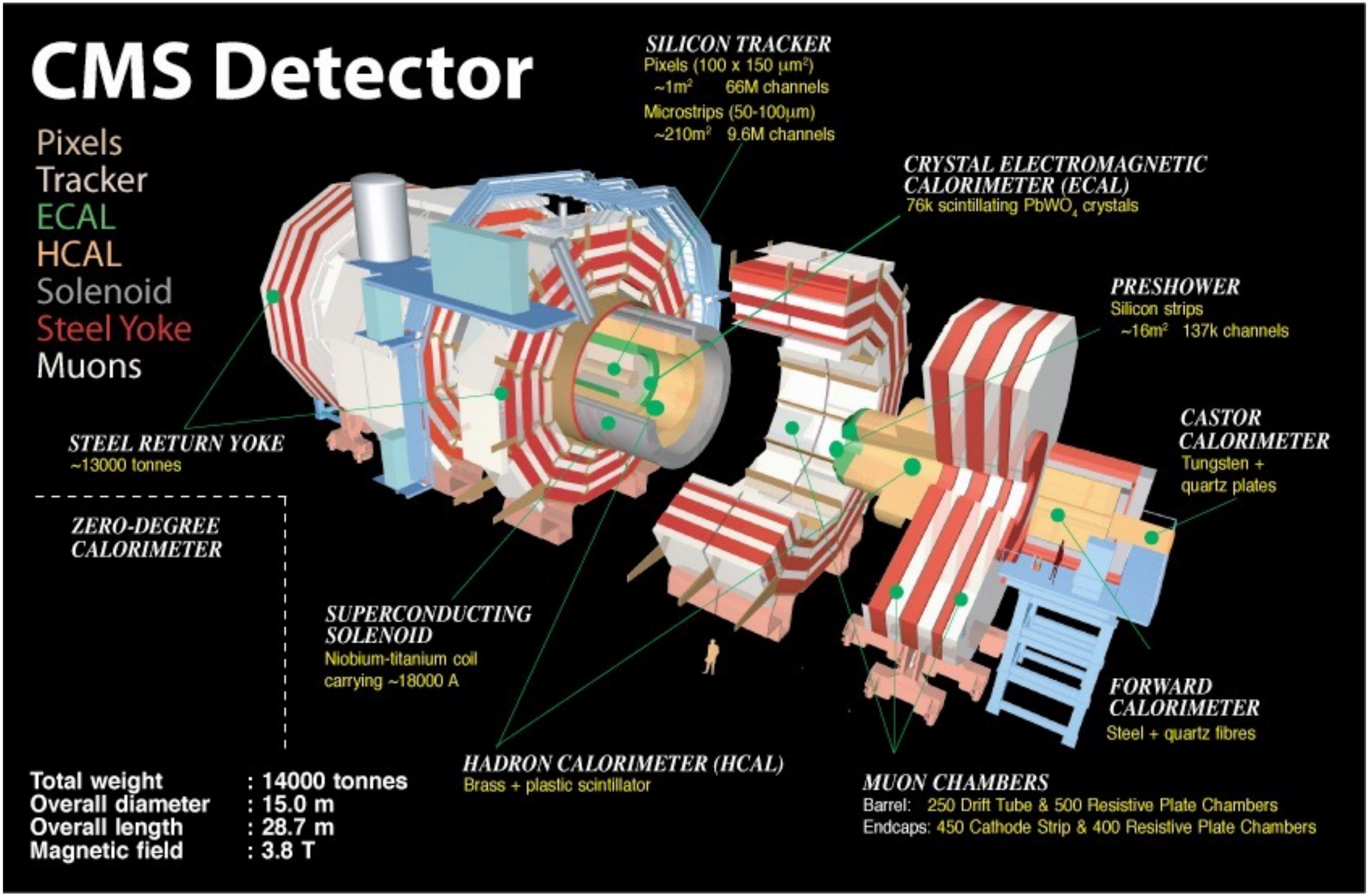
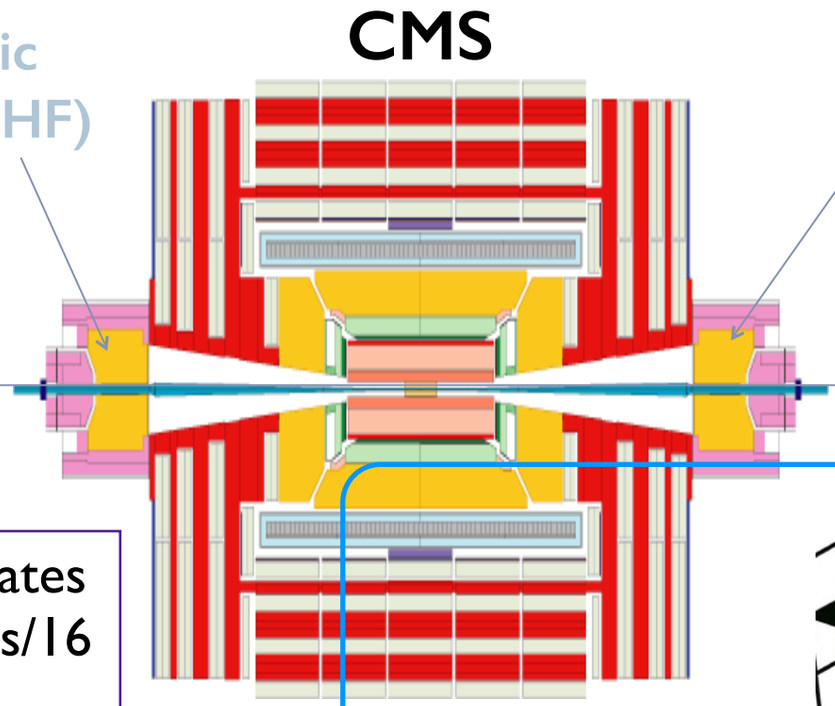
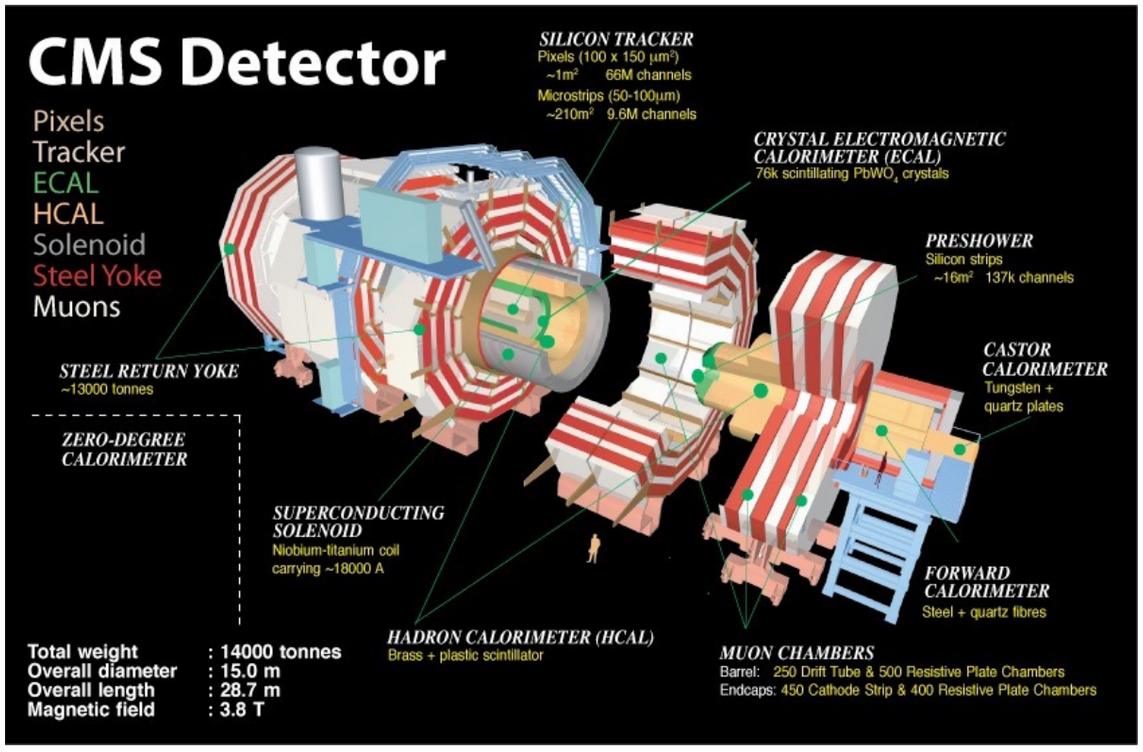


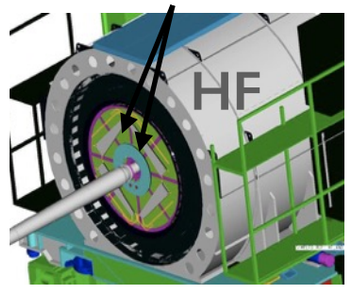
Forward detectors at CMS

Detector configuration during 2010 - 2011



W-absorbers/quartz plates
12 longitudinal modules/16 azimuthal sectors





Hadron Forward:

11.2m from interaction point

Rapidity coverage: $3 < |\eta| < 5$

Steel absorbers/quartz fibers (Long+short fibers)

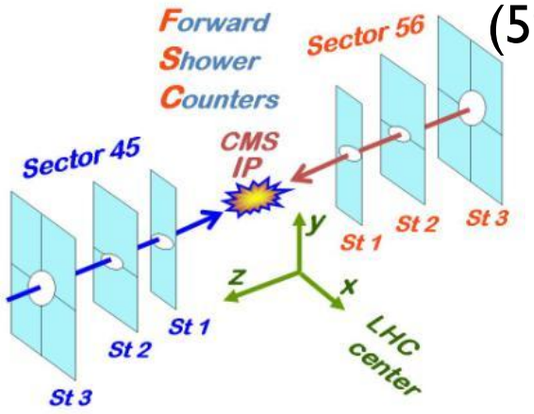
0.175x0.175 η/φ segmentation

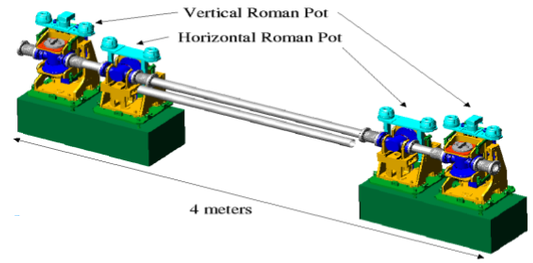
Acceptance limited to $|\eta| < 4.9$ at analysis level

CMS-TOTEM detectors

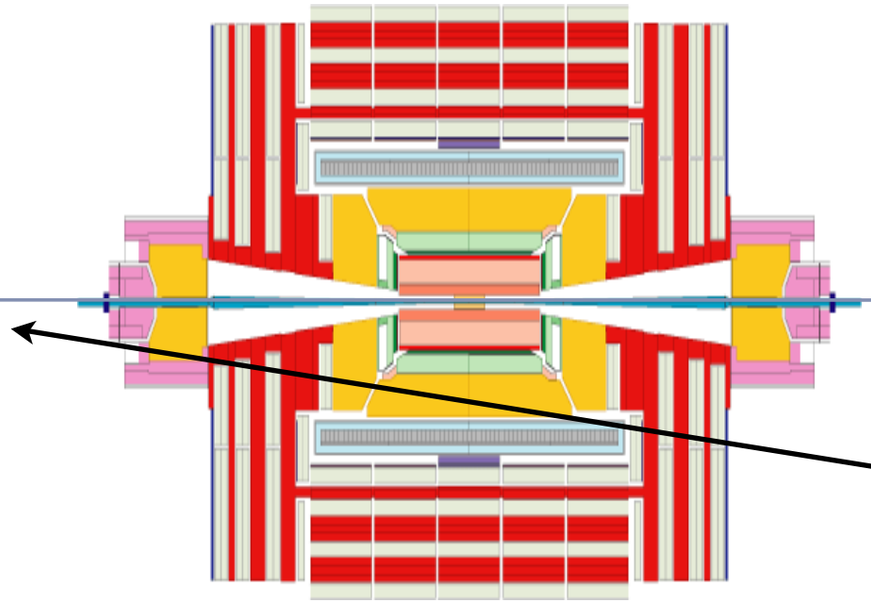
Prospects for Diffractive and Forward Physics at the LHC
CERN-LHCC-2006-039-G-124

Forward Shower Counters
(59-114m)





TOTEM RPs
(147, 220m)



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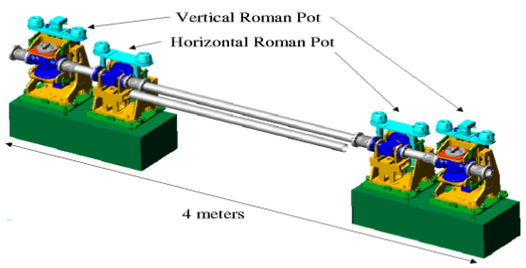

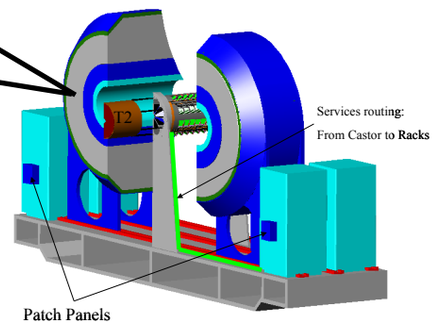

TOTEM T2
(In front of
CASTOR position)

Common data taking during low-PU runs in 2012

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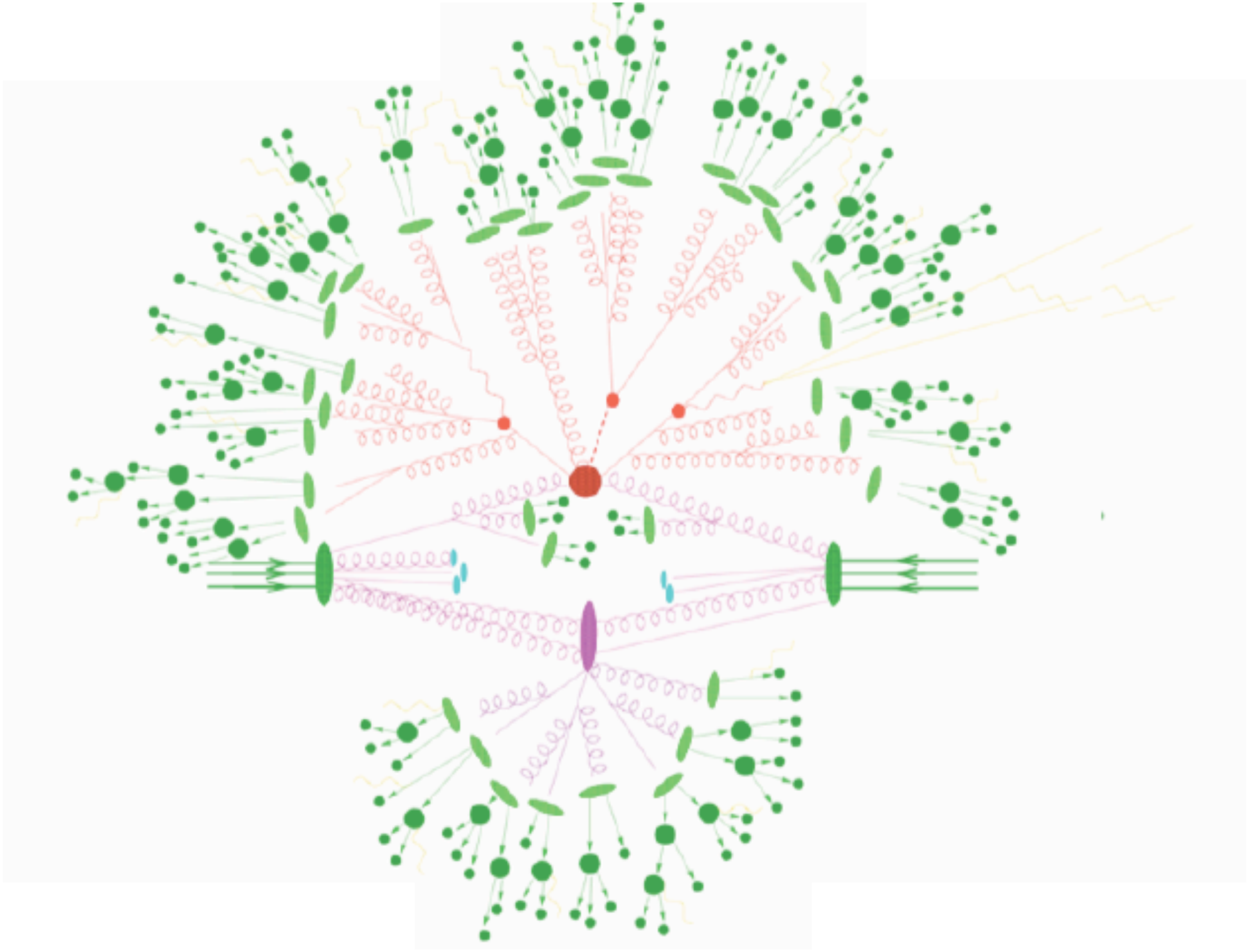
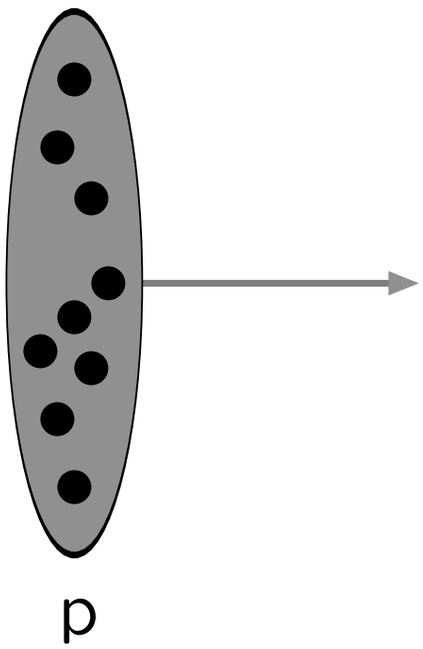
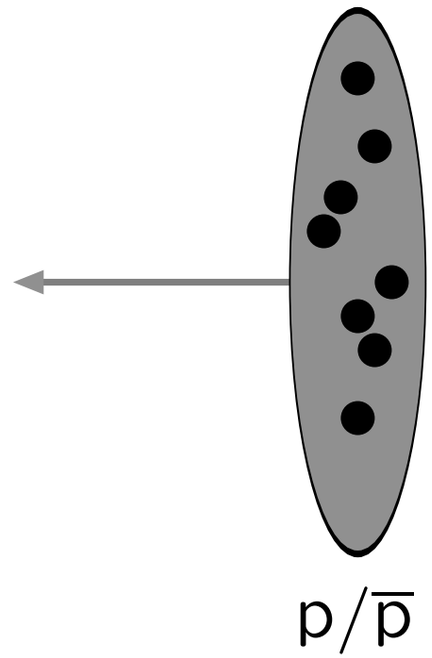
Underlying Event in pp collisions



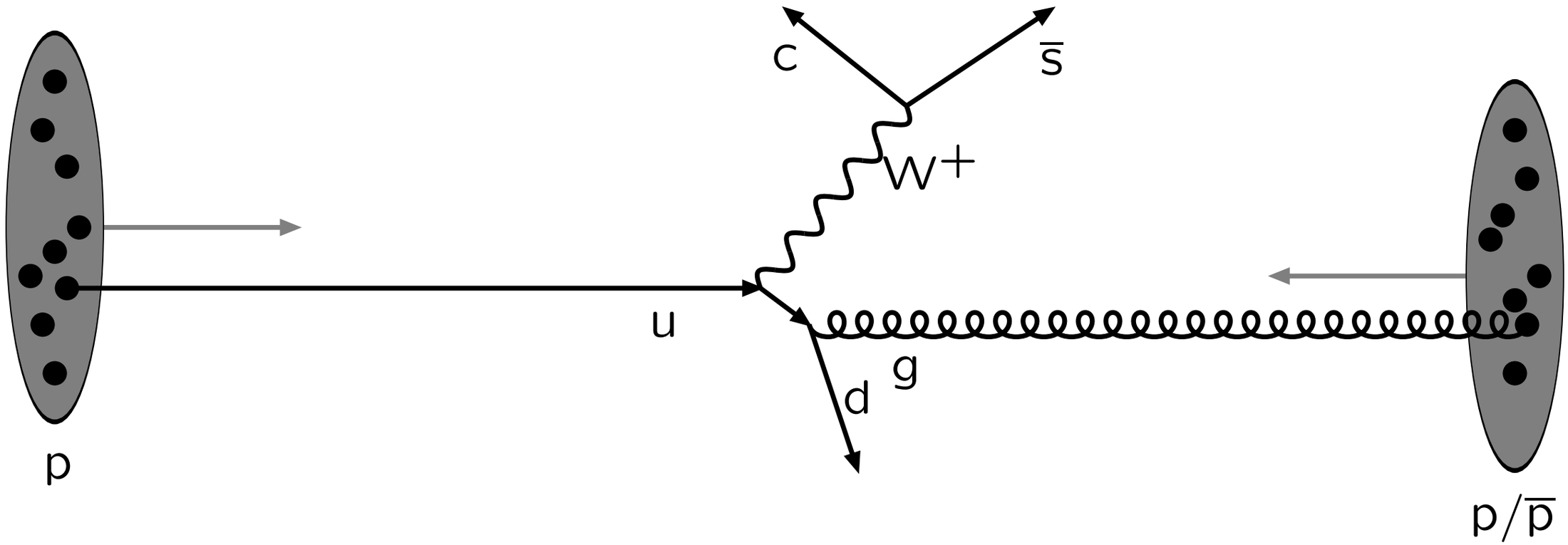
Underlying Event in pp collisions



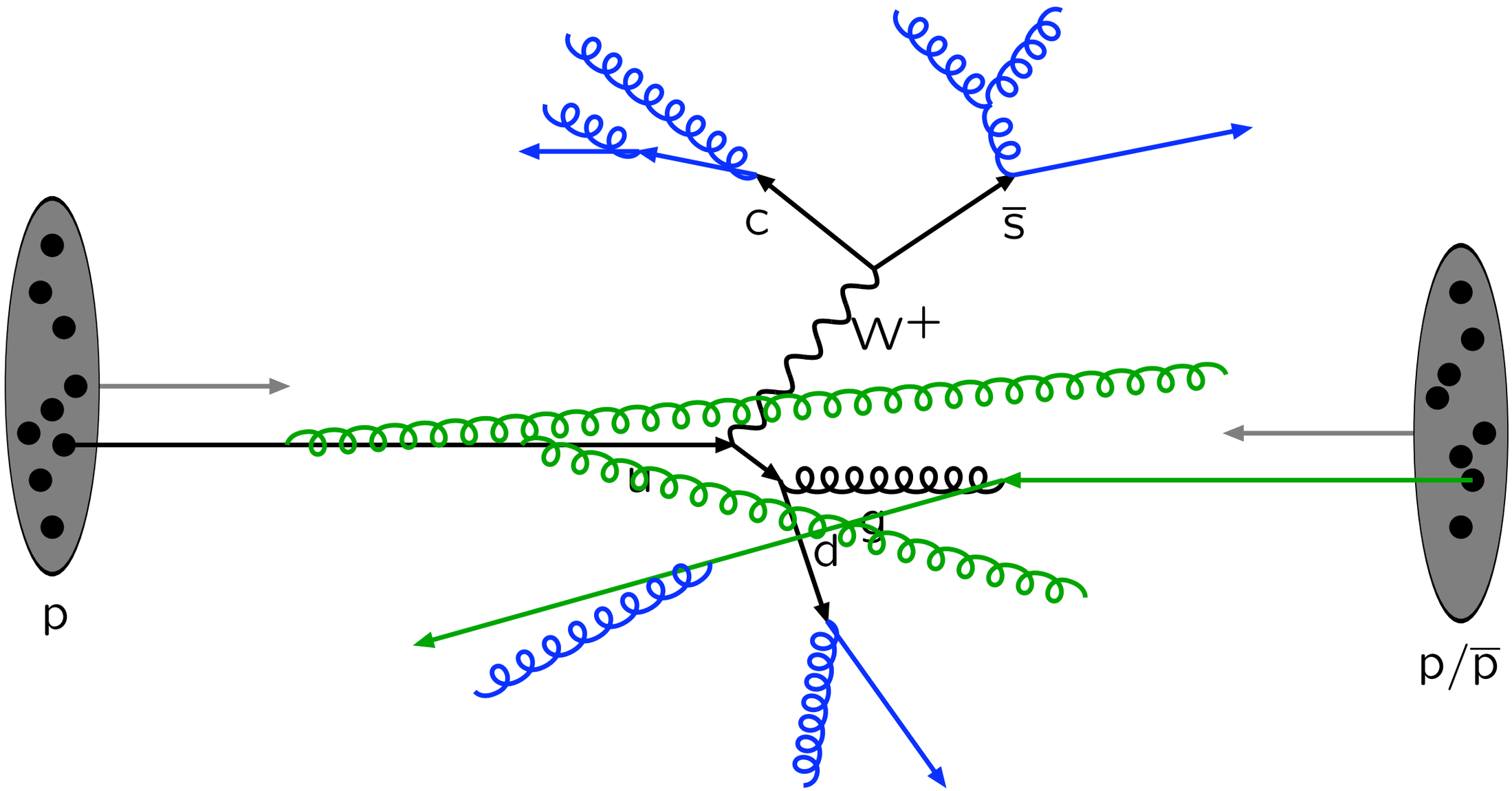


T. Sjostrand

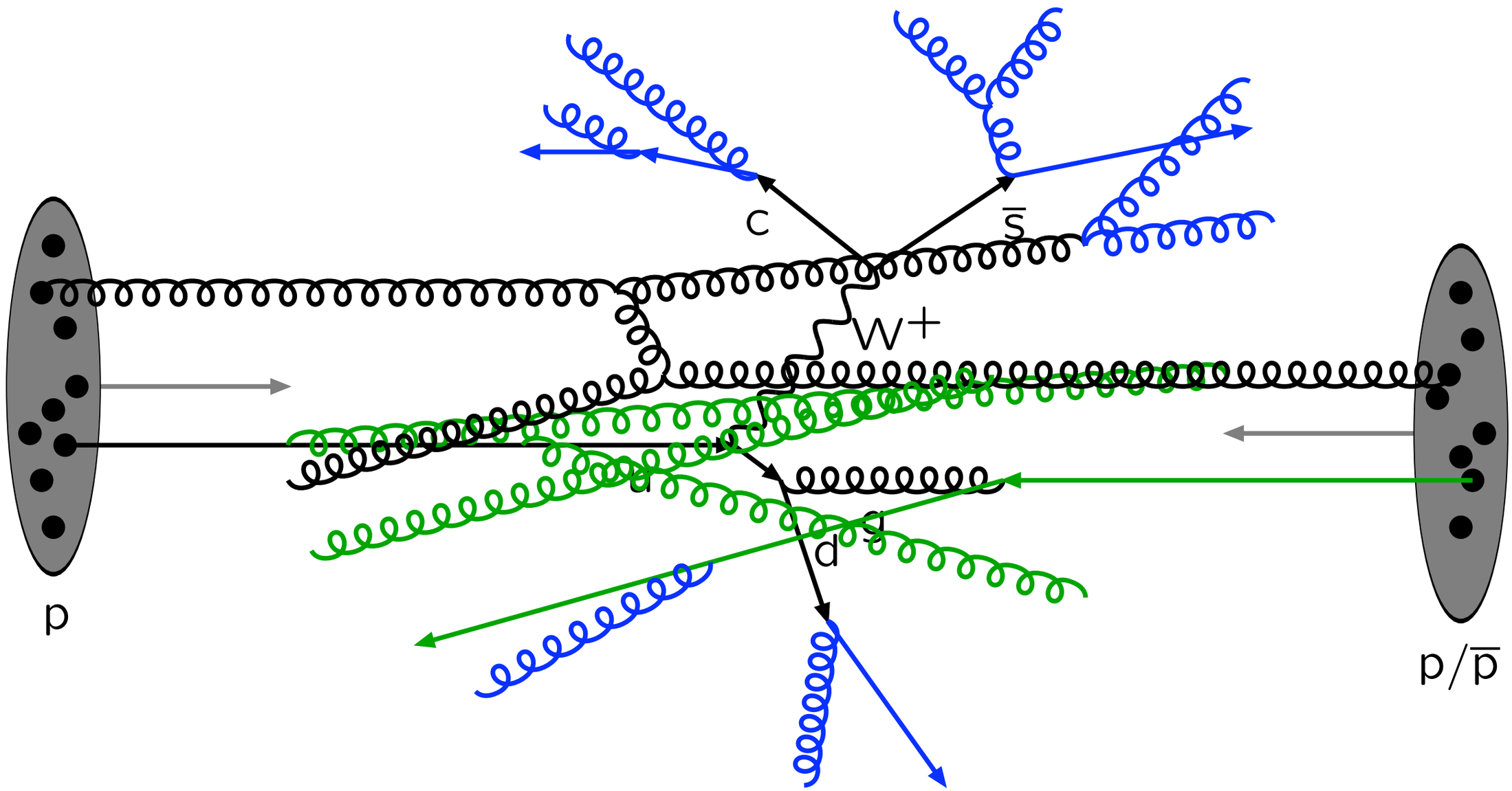
Underlying Event in pp collisions



Underlying Event in pp collisions



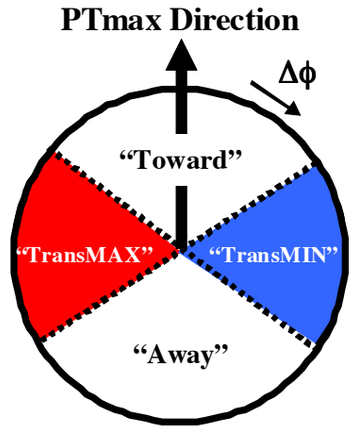
Underlying Event in pp collisions

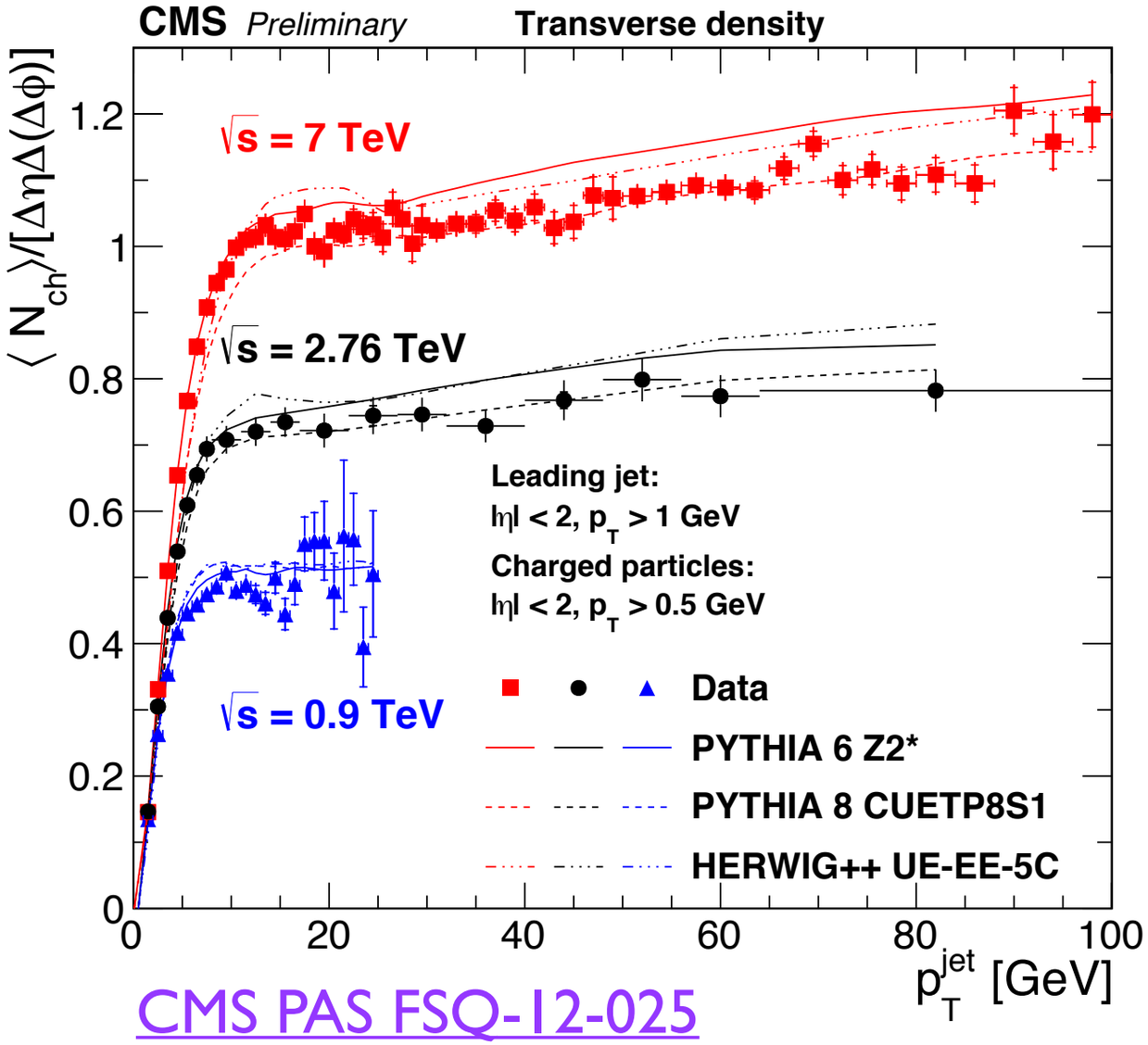


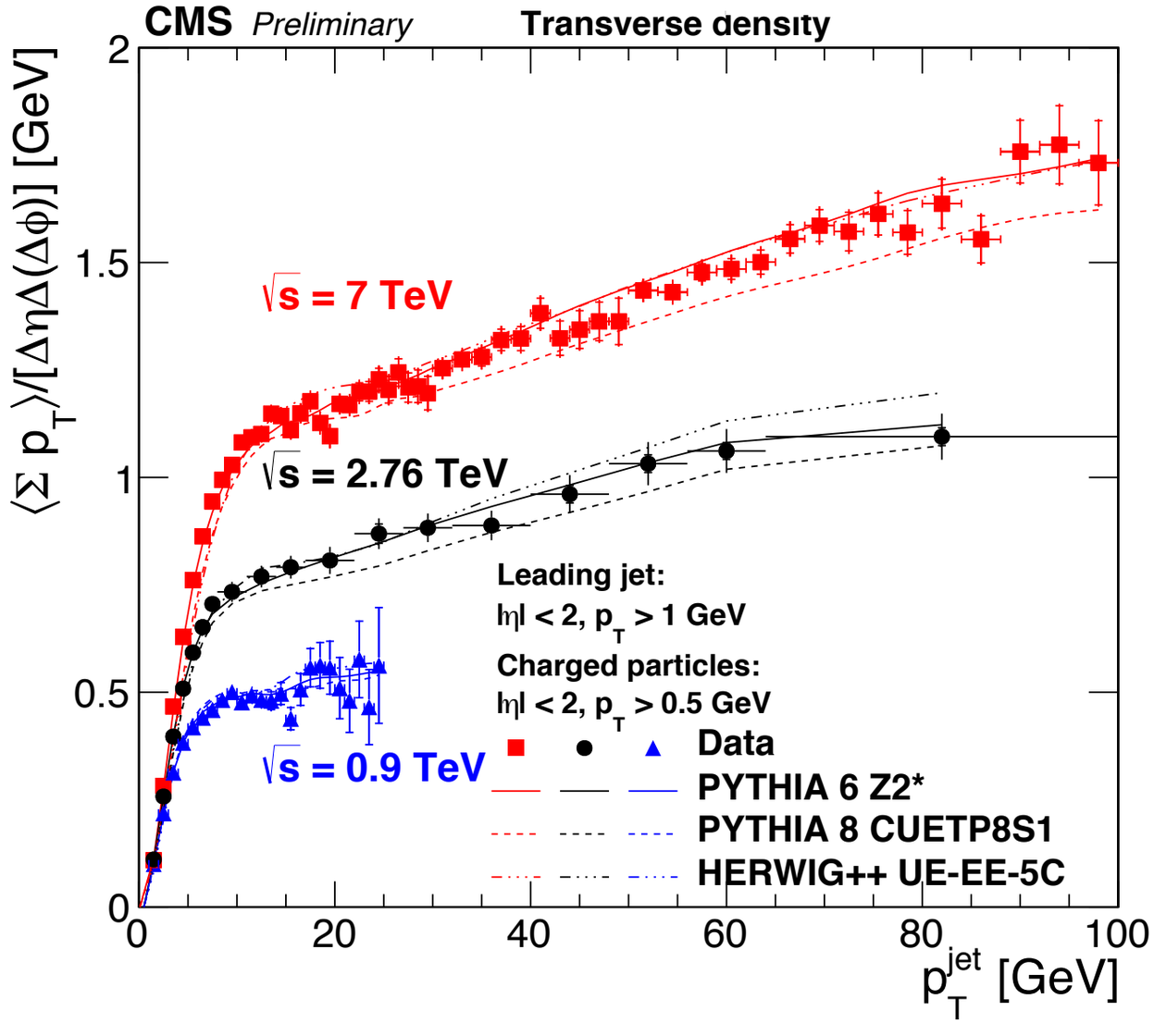
Underlying Event (0.9, 2.76, 7 TeV)

Charged particle and p_T sum density in transverse region to highest p_T jet well described by PYTHIA & HERWIG tunes.

Good description of energy dependence.



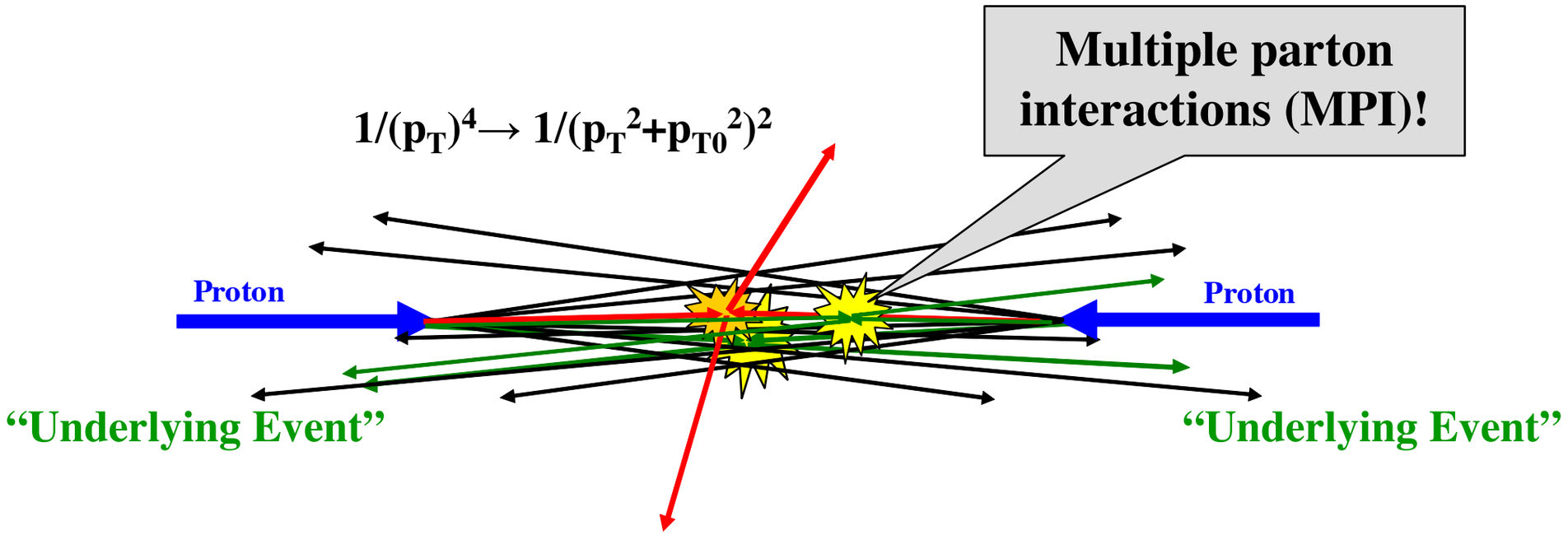




CMS PAS FSQ-12-025

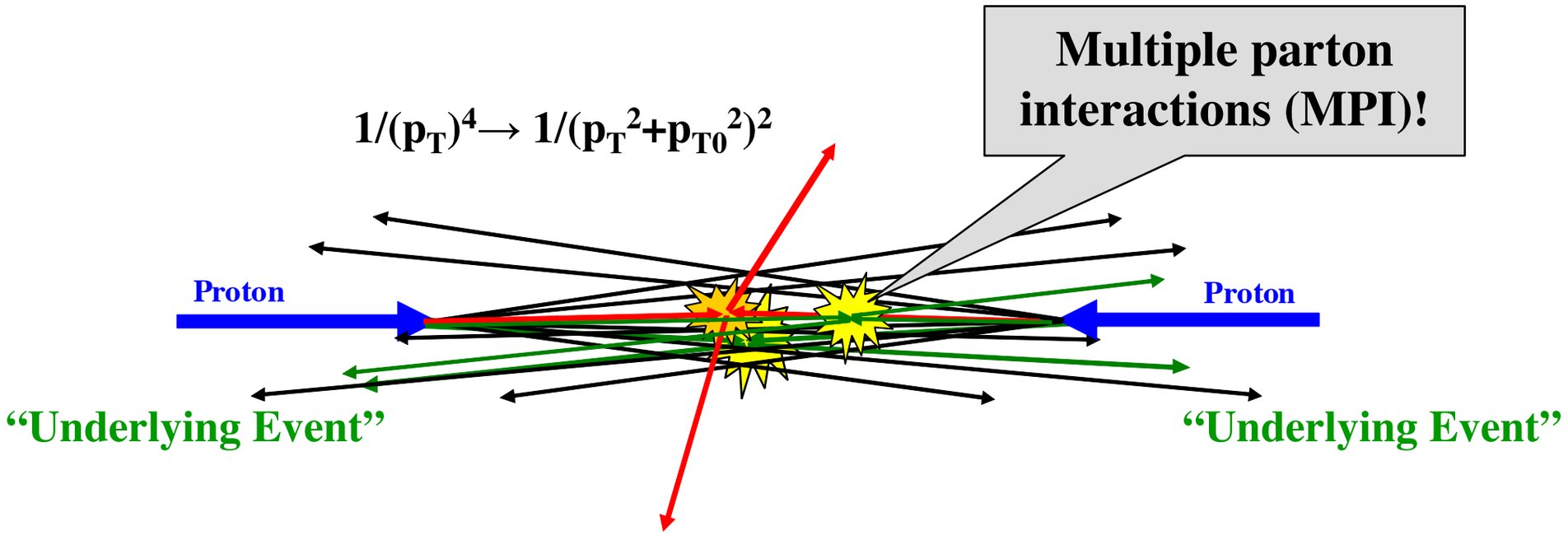
Underlying Event, MPI and DPS

Underlying Event, MPI and DPS



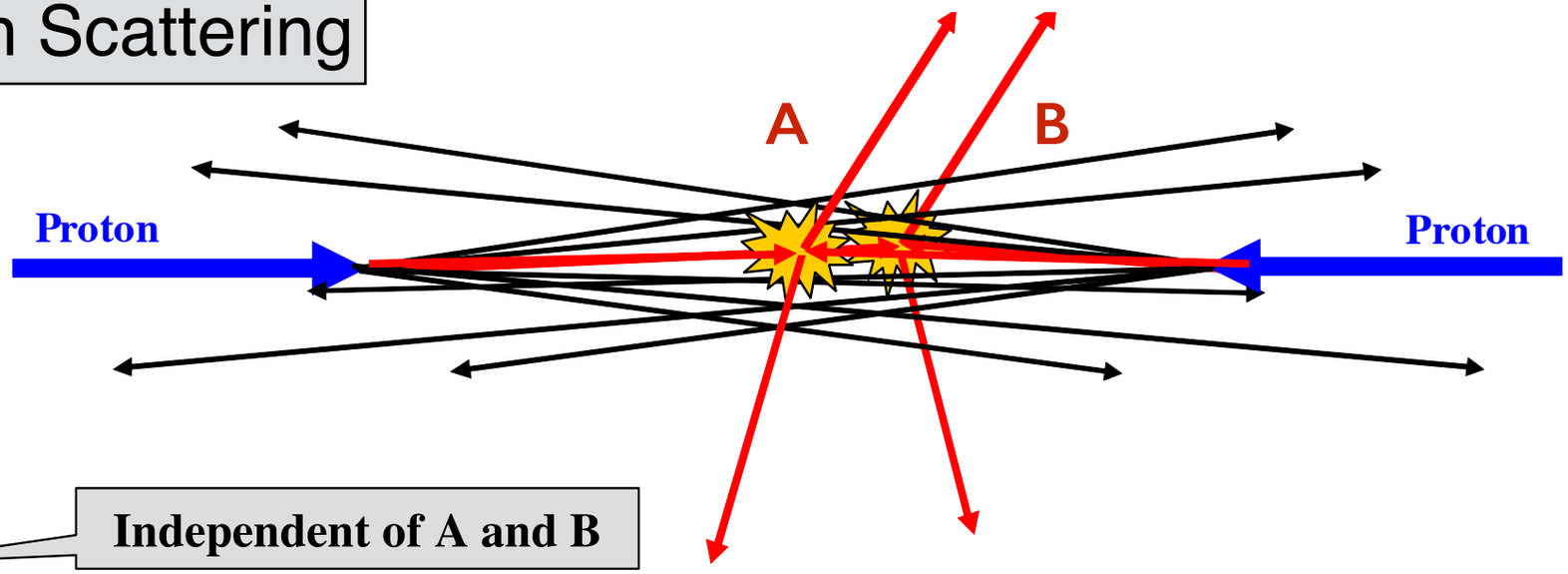
R. Field

Underlying Event, MPI and DPS



R. Field

Double Parton Scattering

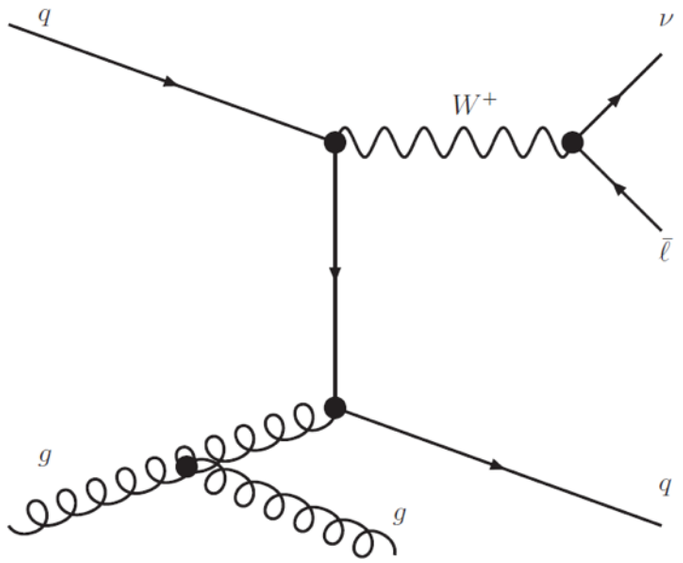


$$\sigma_{AB} = \frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

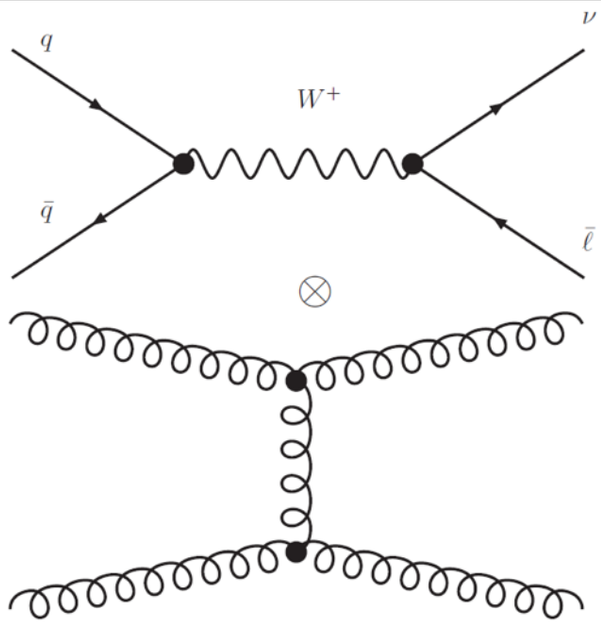
Independent of A and B

Double Parton Scattering: W + jets

Single Parton Scattering (SPS)



Double Parton Scattering (DPS)

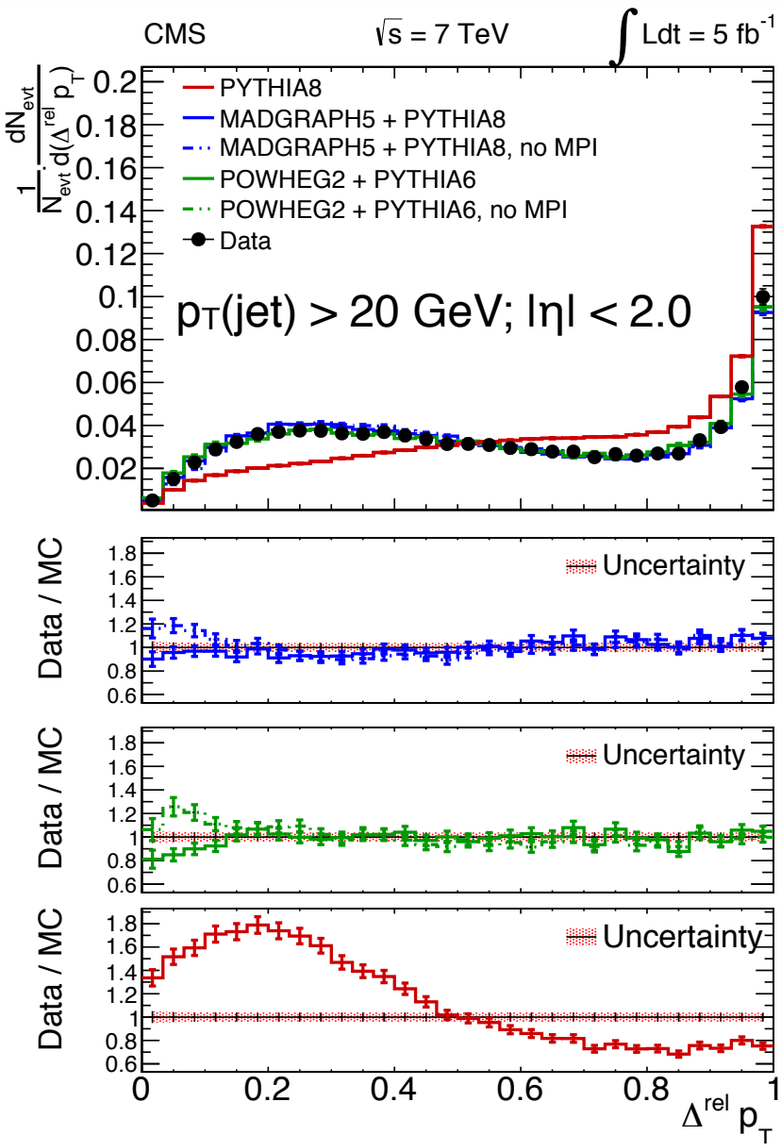


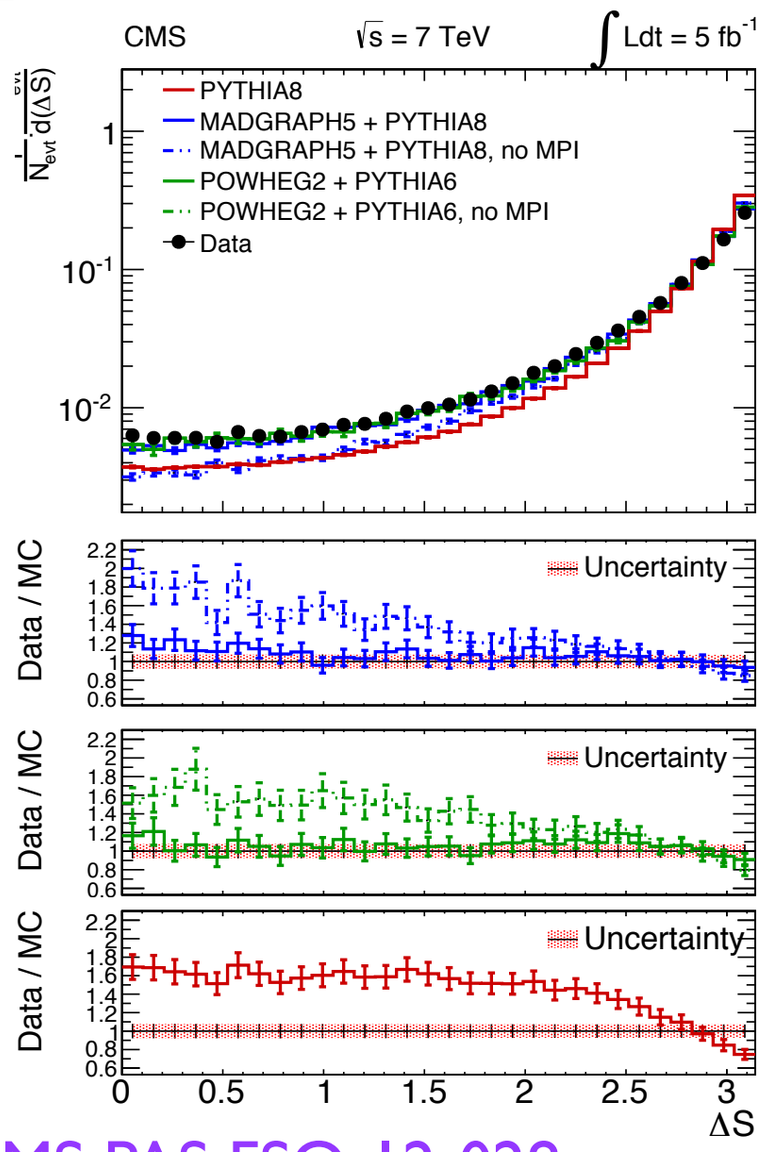
Predictions both at LO and NLO without MPI cannot describe the data.

PYTHIA8 does not account for higher order contributions.

$$\Delta^{\text{rel}}\,\mathrm{p_T} = \frac{|\vec{p}_T(j1) + \vec{p}_T(j2)|}{|\vec{p}_T(j1)| + |\vec{p}_T(j2)|}$$

$$\Delta S = arccos\left(\frac{\vec{P}_T(\mu, \not{E}_T).\vec{P}_T(j1, j2)}{|\vec{P}_T(\mu, \not{E}_T)|.|\vec{P}_T(j1, j2)|}\right)$$



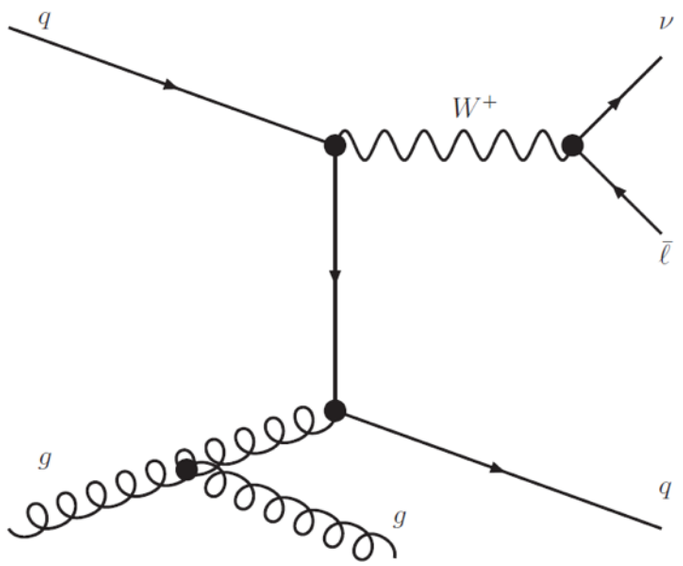


CMS PAS FSQ-12-028

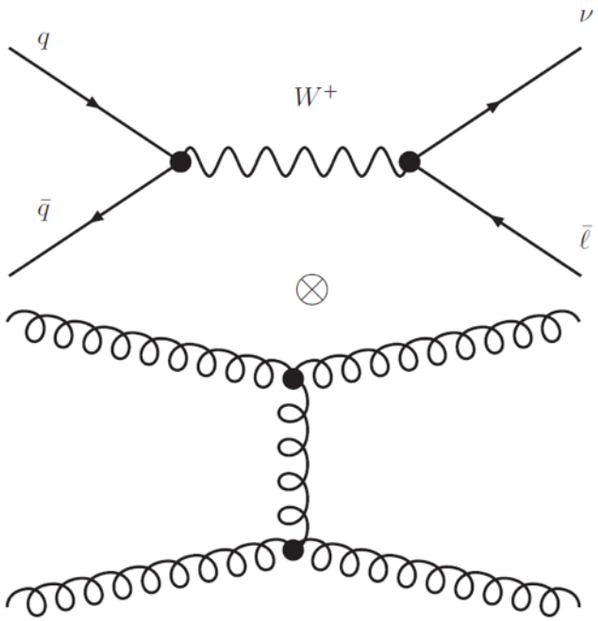
J. High Energy Phys. 03 (2014) 032

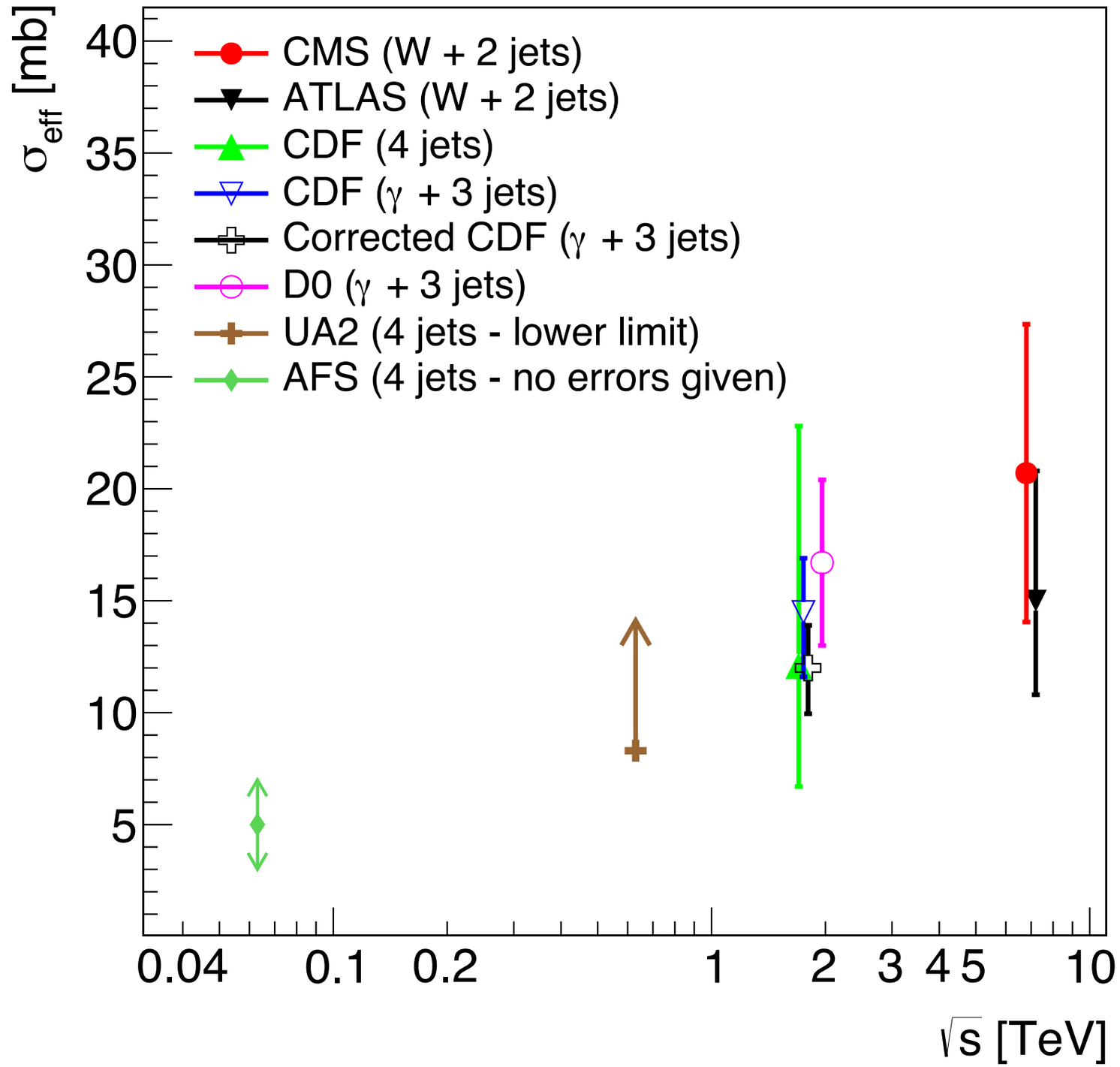
Double Parton Scattering: W + jets

Single Parton Scattering (SPS)



Double Parton Scattering (DPS)





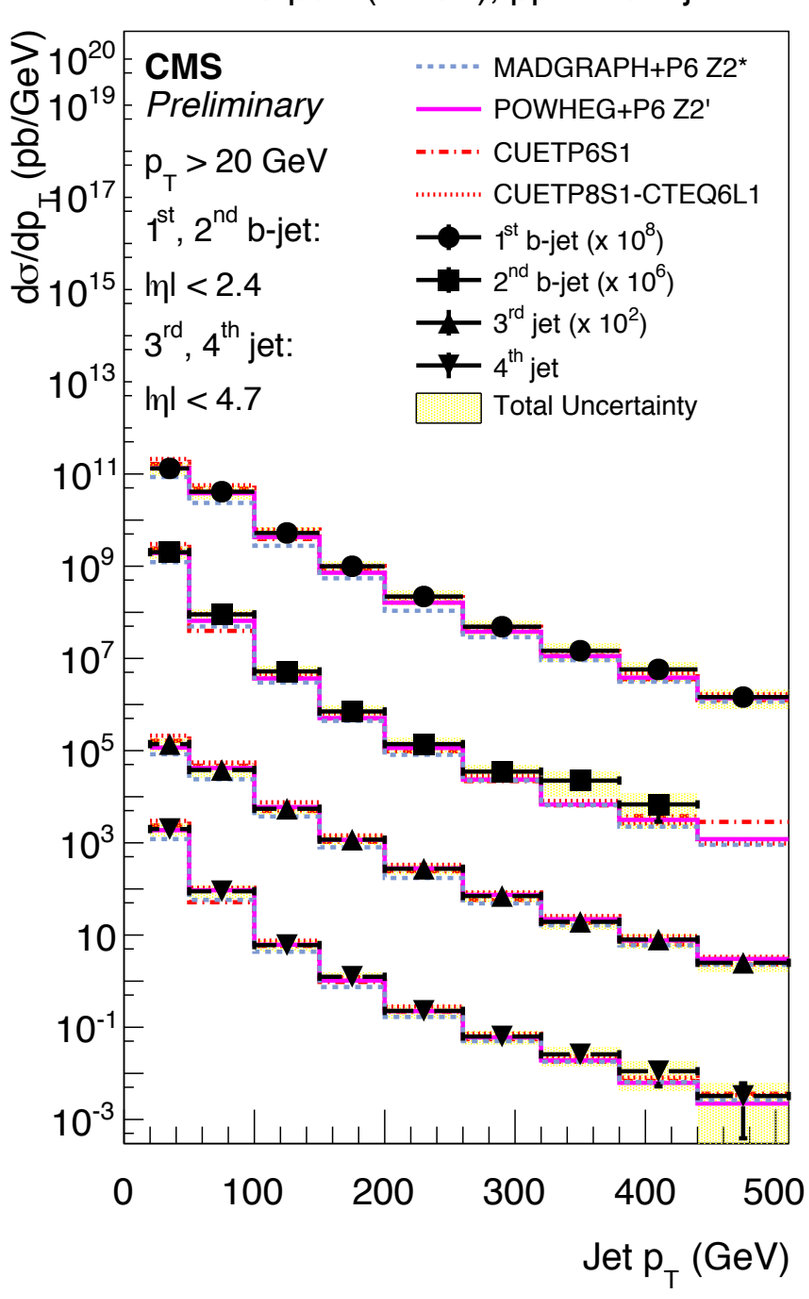
CMS PAS FSQ-12-028

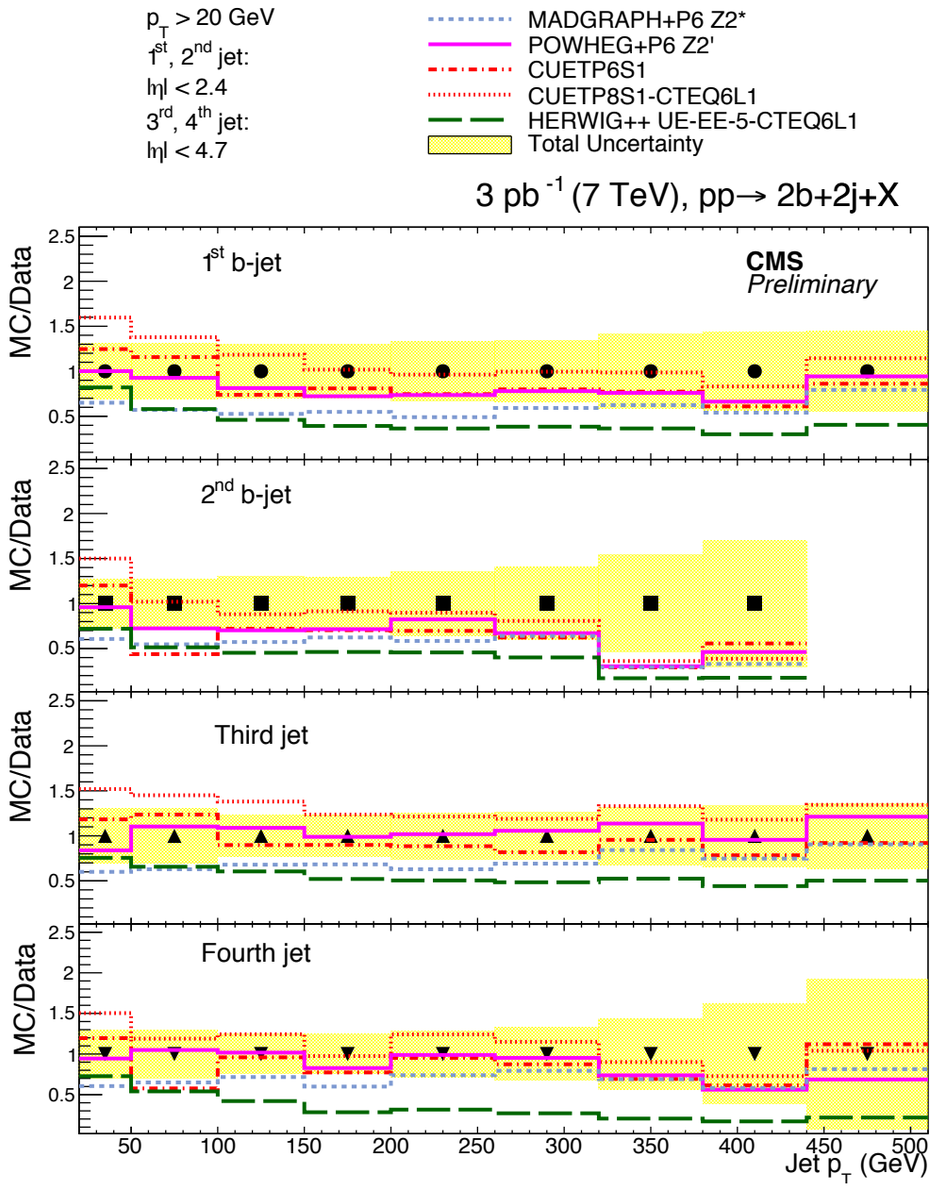
J. High Energy Phys. 03 (2014) 032

2 b-jets + 2 jets production and DPS

At least 4 jets with p_T > 20 GeV (2 leading b-jets with $|\eta|$ < 2.4 and 2 lights-jets with $|\eta|$ < 4.7);

Predictions are in general able to describe well jet spectra, besides Herwig++;





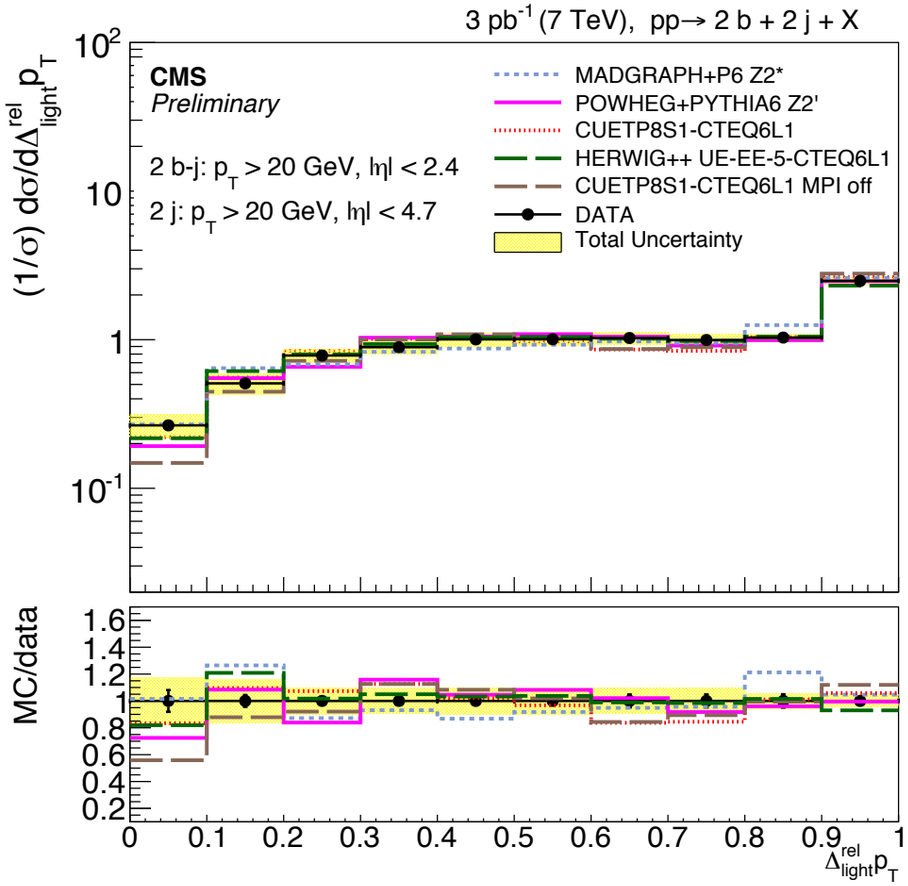
CMS PAS FSQ-13-010

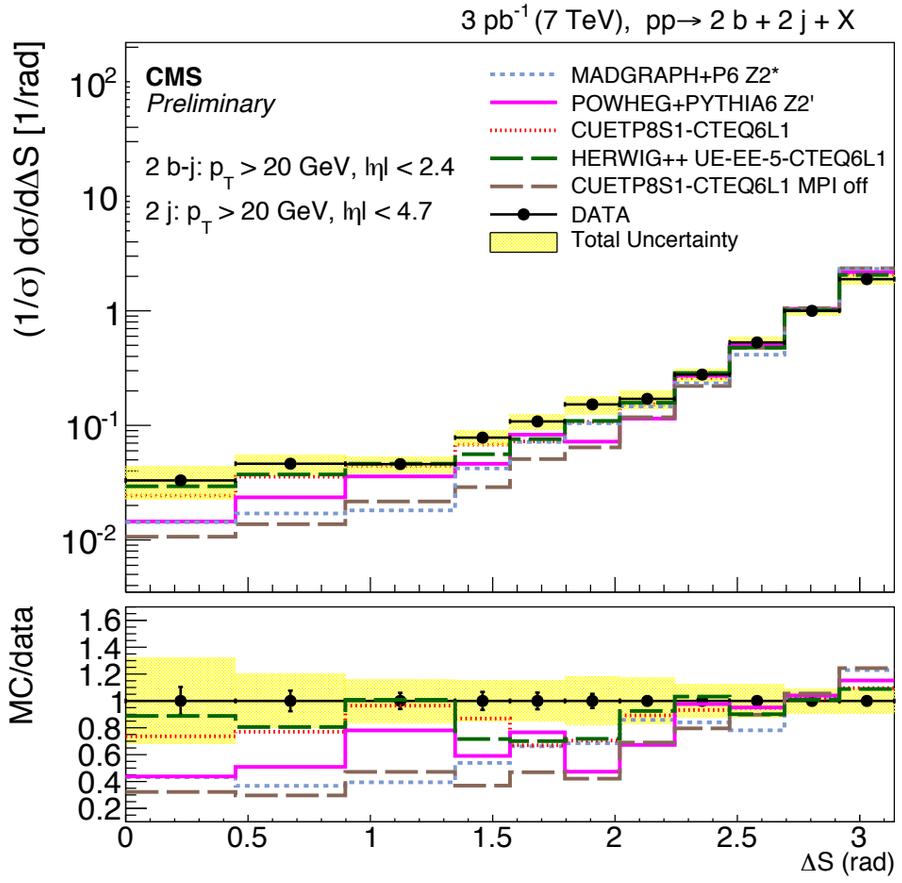
2 b-jets + 2 jets production and DPS

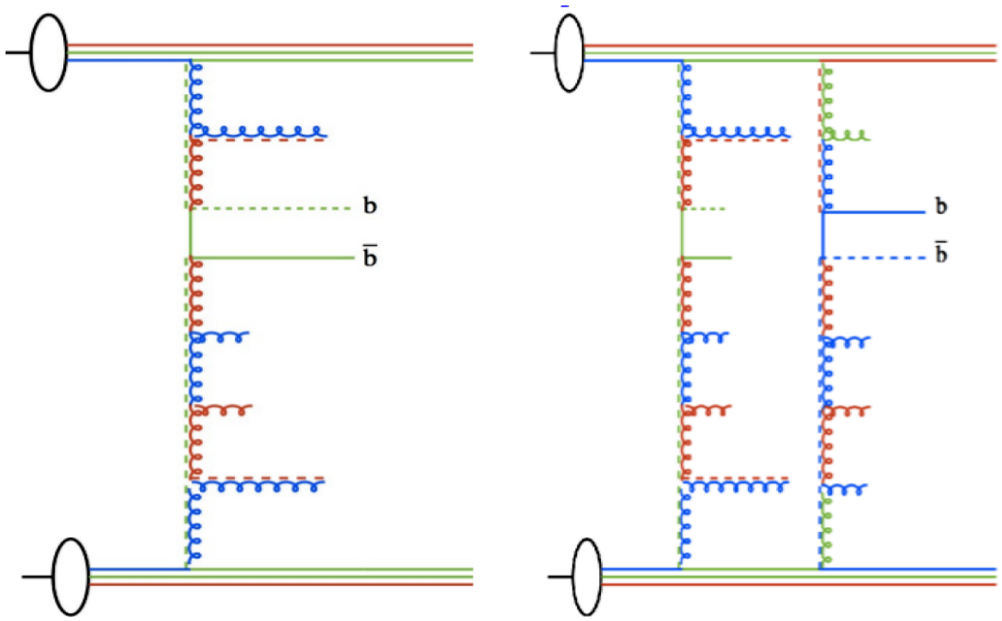
At least 4 jets with p_T > 20 GeV (2 leading b-jets with |η| < 2.4 and 2 lights-jets with |η| < 4.7);

Predictions are in general able to describe well jet spectra, besides Herwig++;

Distributions of correlation observables not fully described by any of the theoretical models (simulation of UE tuned to soft MPI).

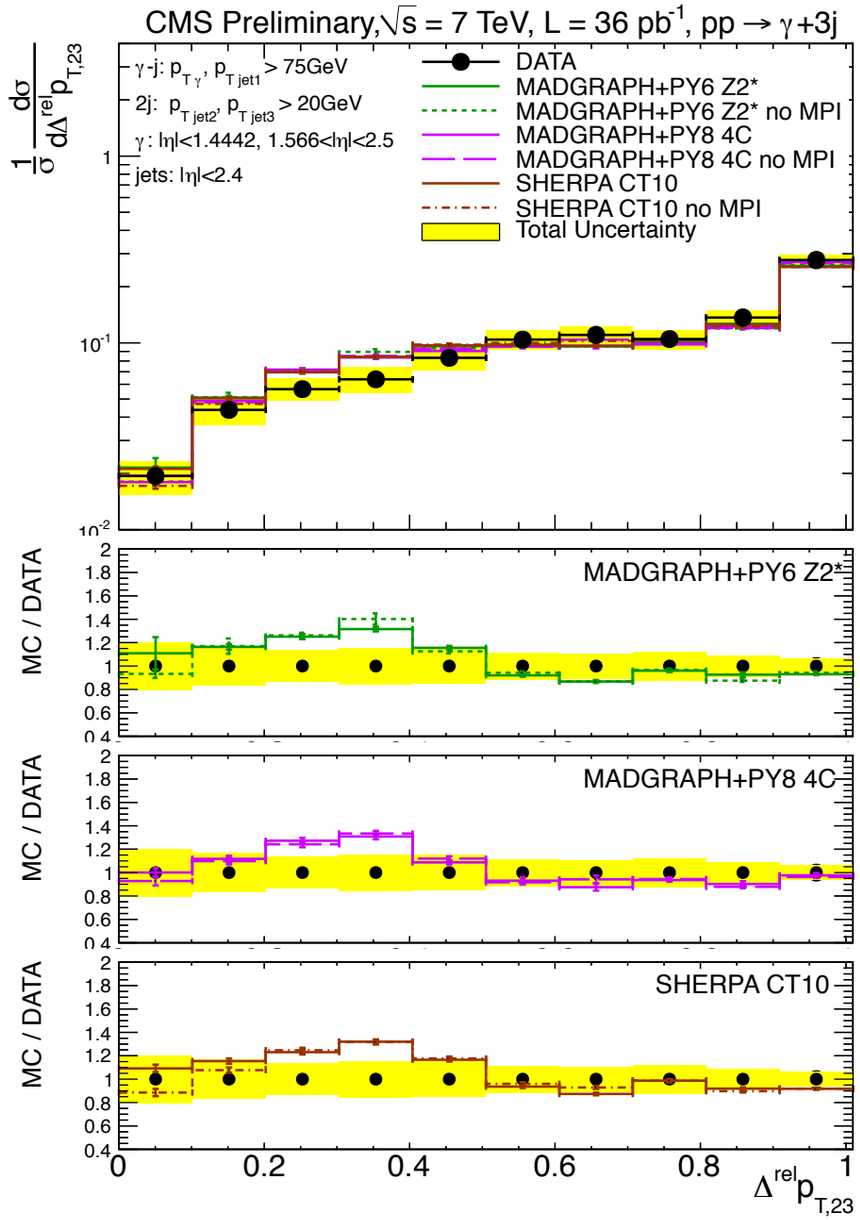


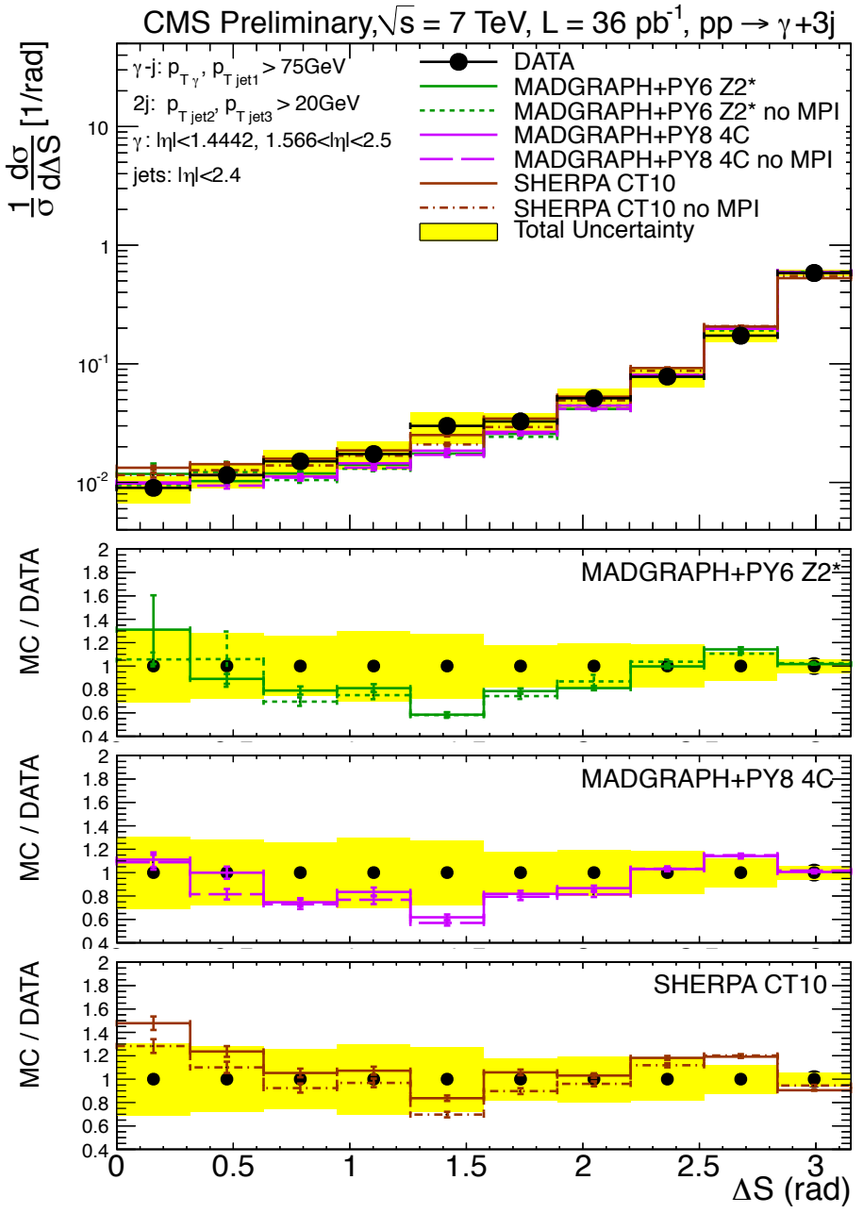


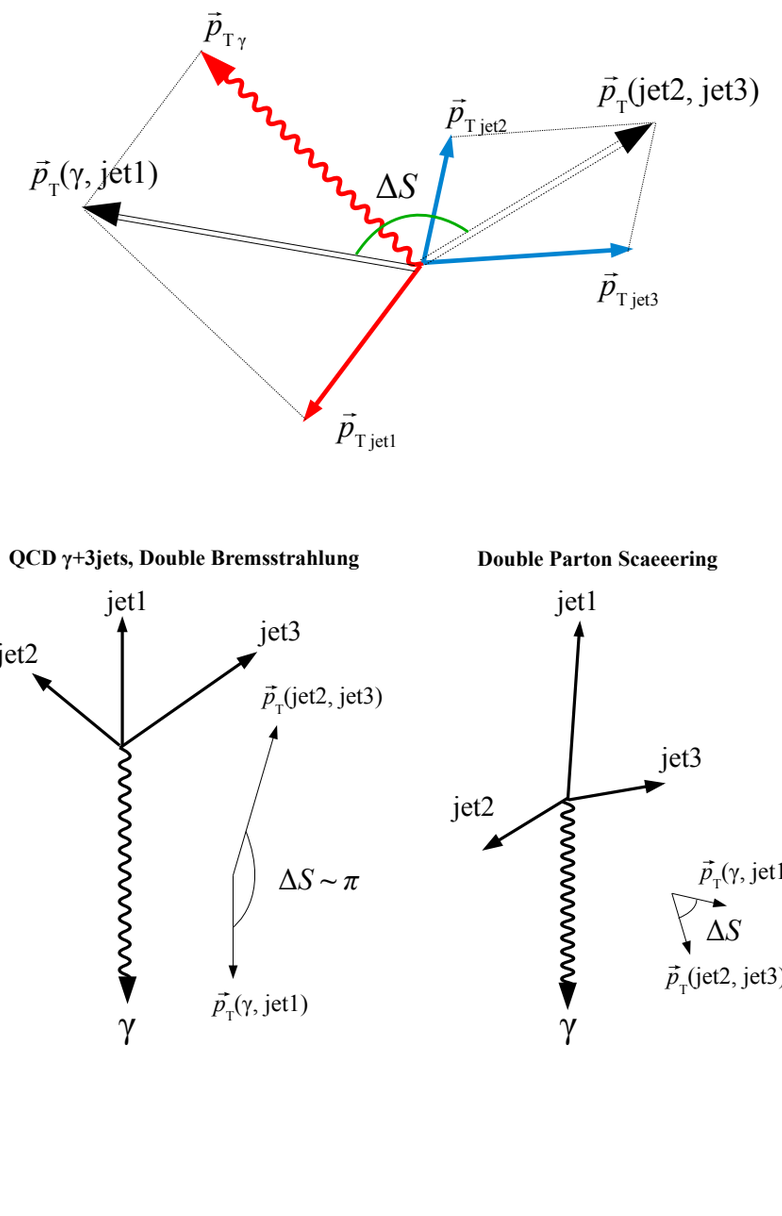


[CMS PAS FSQ-13-010]

DPS: γ + 3 jets

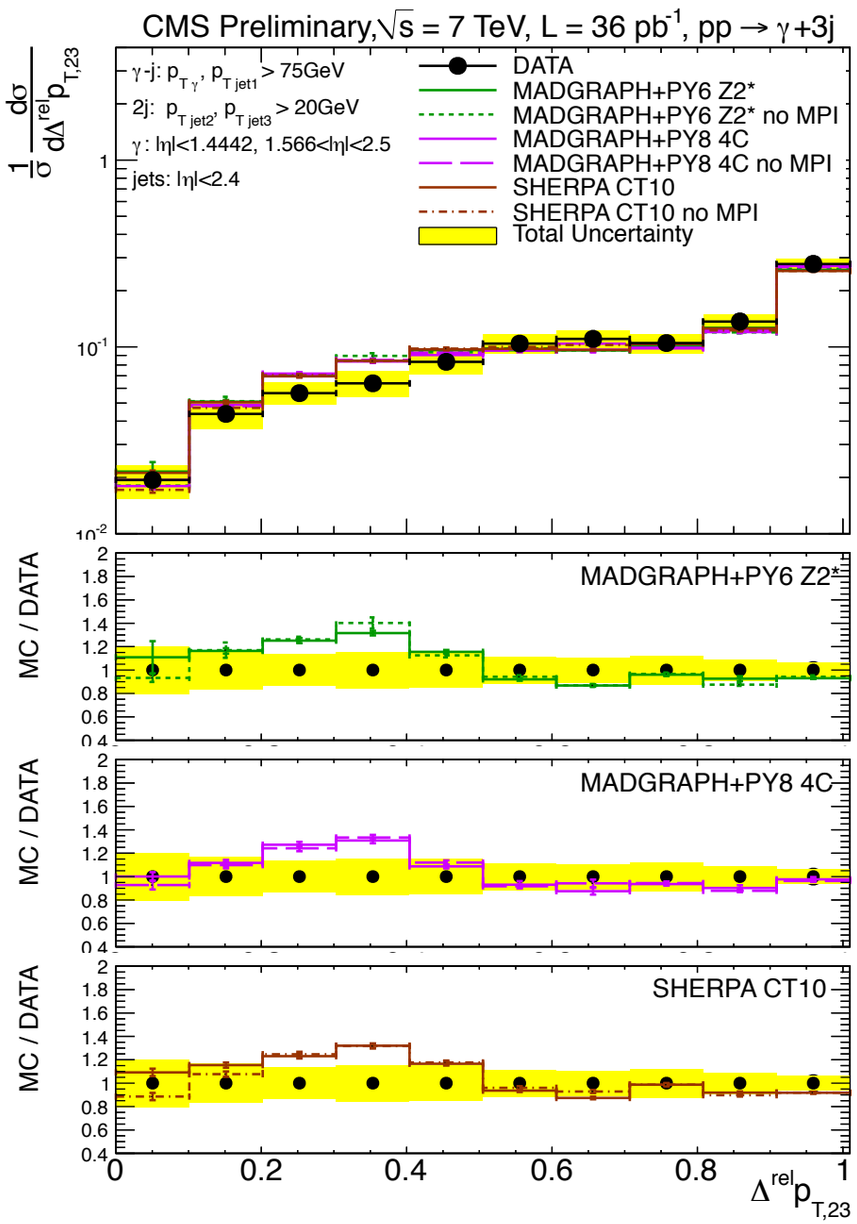


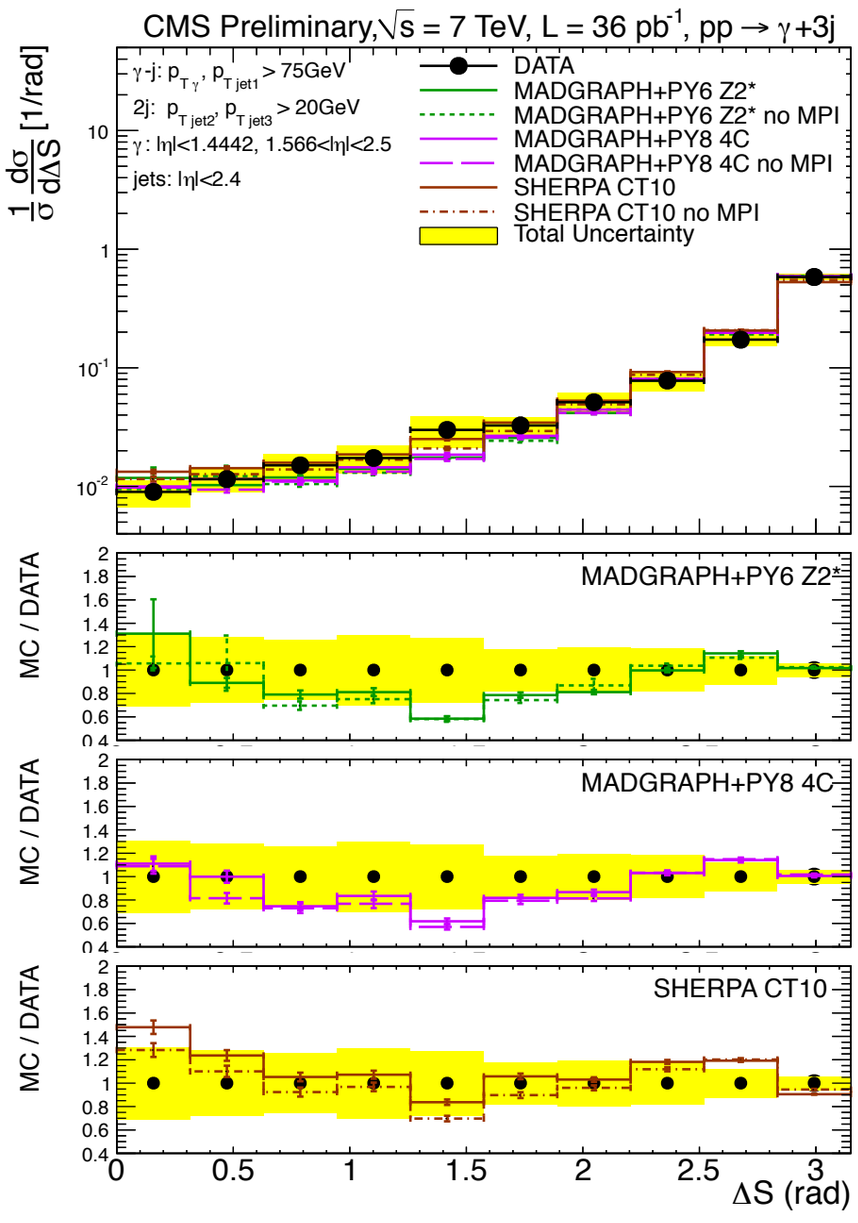




CMS PAS FSQ-12-017

DPS: γ + 3 jets





γ + 1 jet in central region with p_T > 75 GeV and 2 jets with p_T > 20 GeV;

Data overall well described by different models;

Measurement not very sensitive to MPI (note high p_T cuts).

[CMS PAS FSQ-12-017]

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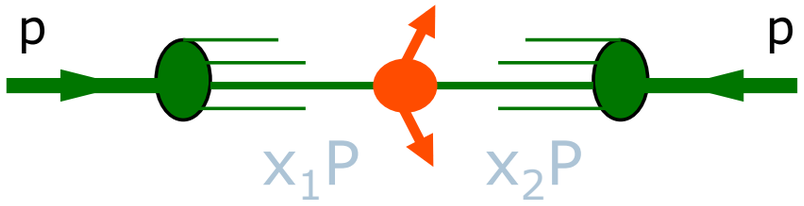
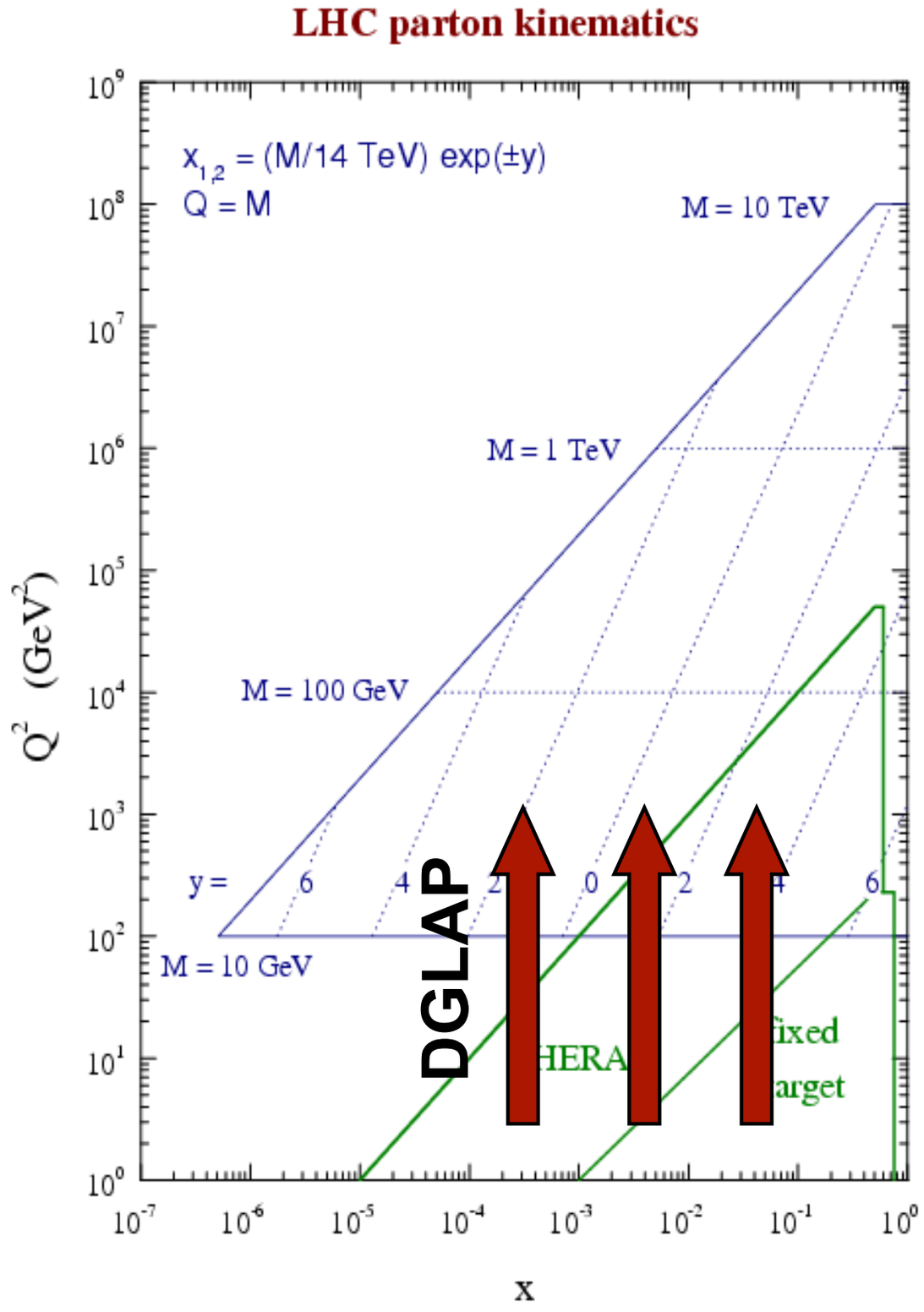
Low-p_T and forward jets



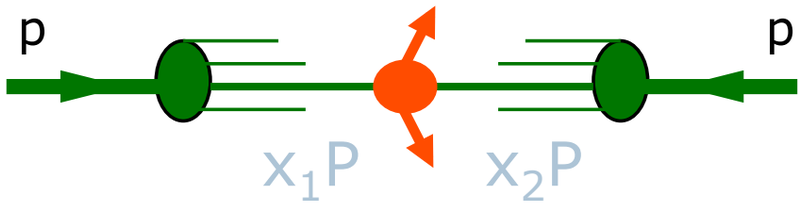
$$x = \frac{Q}{\sqrt{s}} e^{-y}$$

Low-x region can be accessed with low-p_T or very forward jets;

Test of perturbative QCD evolution (DGLAP vs BFKL dynamics);



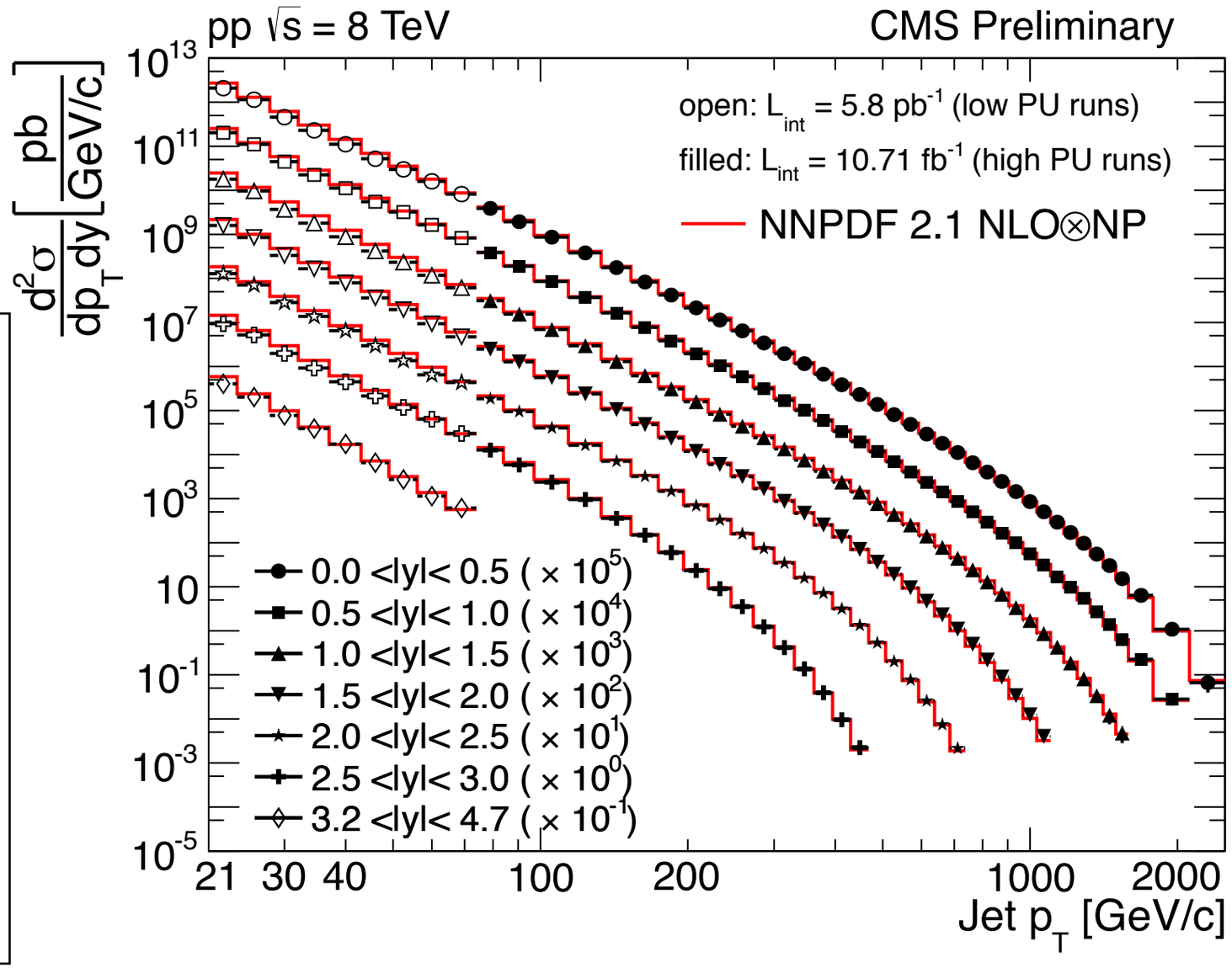
Low-p_T and forward jets



Low-x region can be accessed with low-p_T or very forward jets;

Test of perturbative QCD evolution (DGLAP vs BFKL dynamics);

Inclusive jet production cross section at rapidities $|y| < 4.7$ with $21 < p_T < 74$ GeV (Anti-k_T, R = 0.7 jets), combined with high-p_T measurements.



CMS PAS FSQ-12-031

Forward-central jet correlations

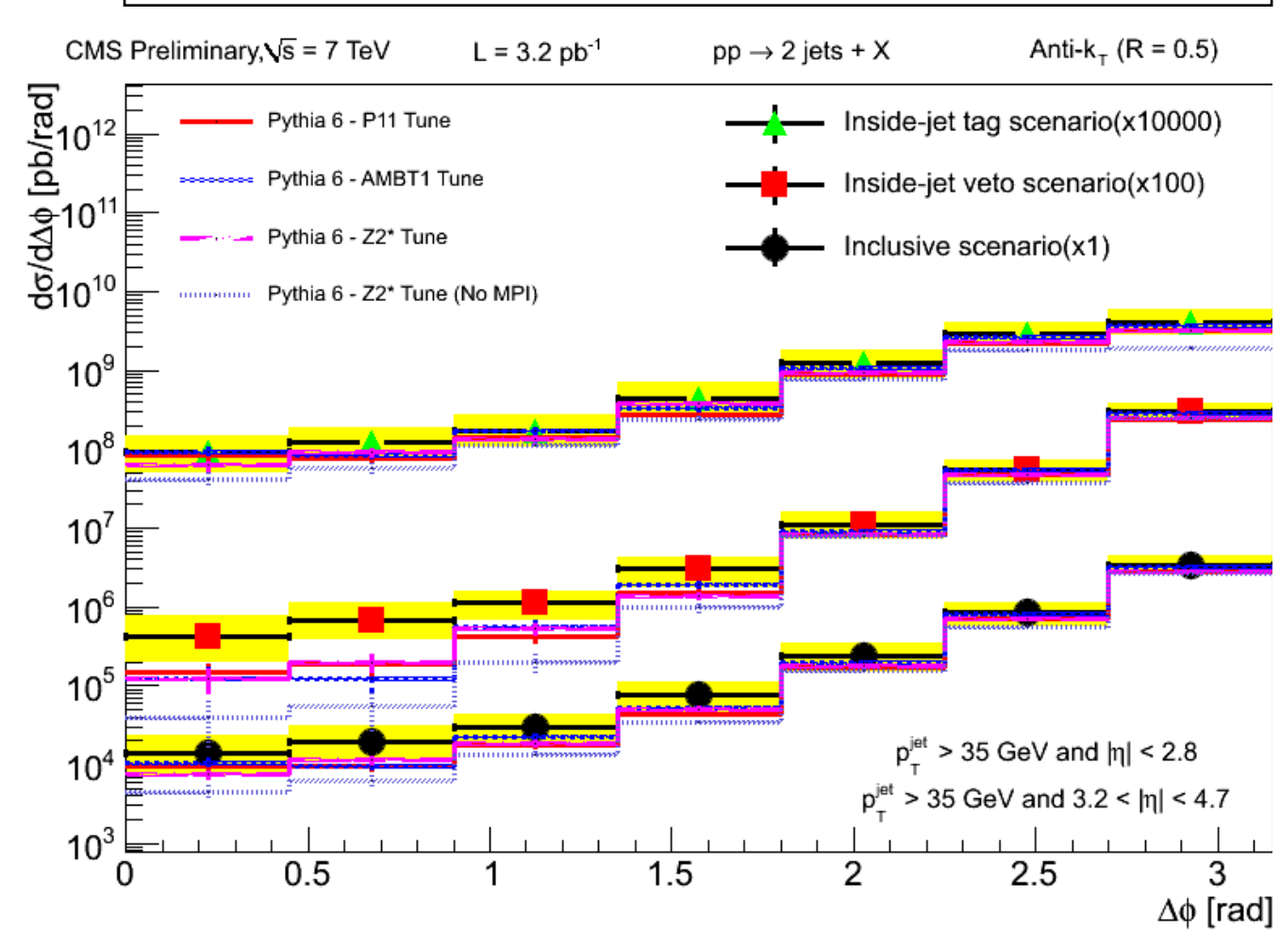
Azimuthal correlations between forward ($3.2 < \eta < 4.7$) and central ($|\eta| < 2.8$) jets with $p_T > 35$ GeV;

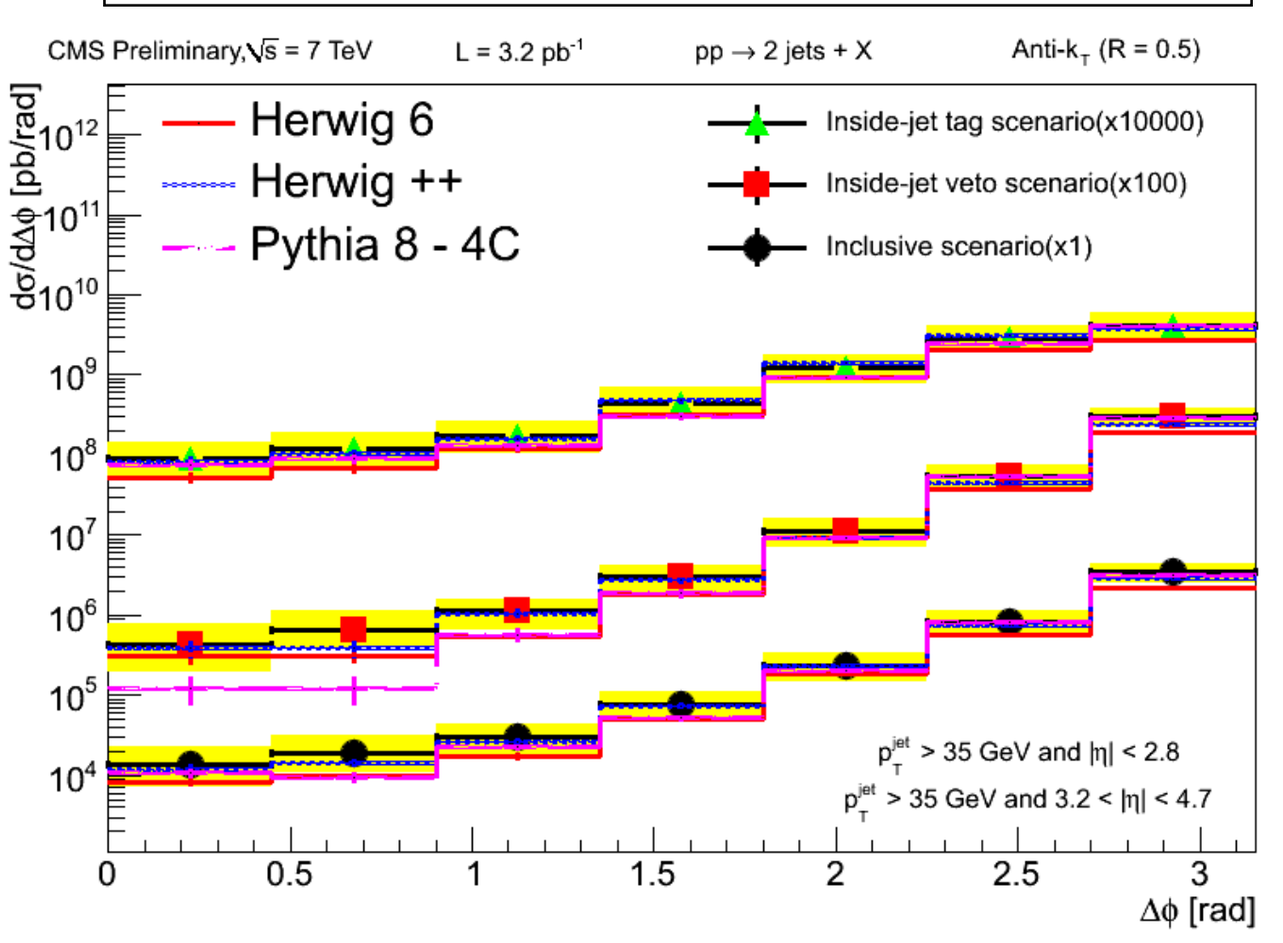
Jets with large rapidity separation;

Topologies with extra jet and vetoing extra jet between central/forward jets.

DGLAP-based MC predictions are able to describe observables considered;

When MPI is turned off correlations are worse.





CMS PAS FSQ-12-008

Forward-central jet correlations

Azimuthal correlations between forward ($3.2 < \eta < 4.7$) and central ($|\eta| < 2.8$) jets with $p_T > 35$ GeV;

Jets with large rapidity separation;

Topologies with extra jet and vetoing extra jet between central/forward jets.

DGLAP-based MC predictions are able to describe observables considered;

When MPI is turned off correlations are worse.

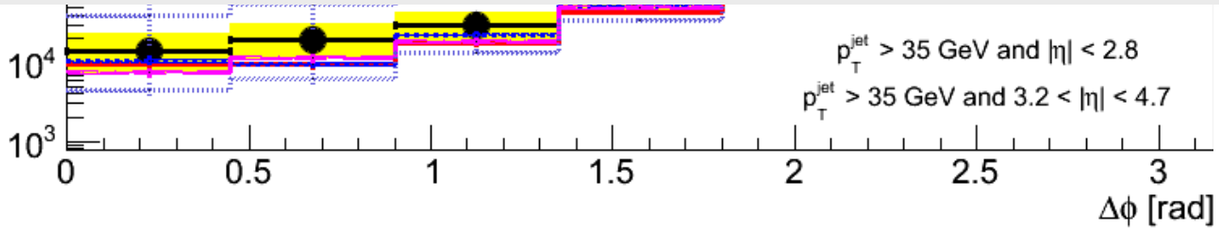
See also:

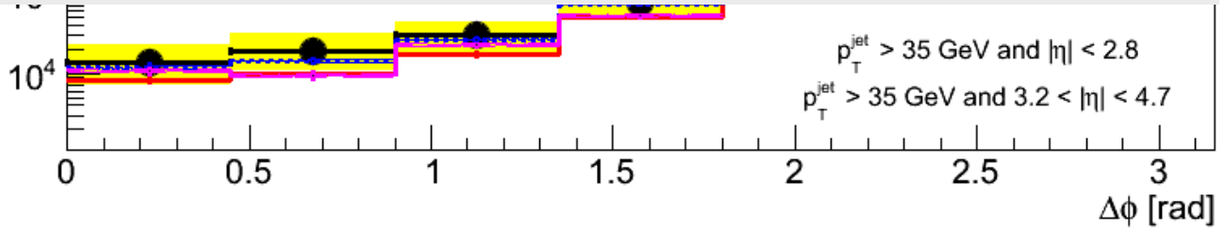
Azimuthal angle decorrelations of jets widely separated in rapidity in pp collisions at $\sqrt{s}$ = 7 TeV

CMS-PAS-FSQ-12-002

Dijet production with a large rapidity gap between the jets

CMS-PAS-FSQ-12-001



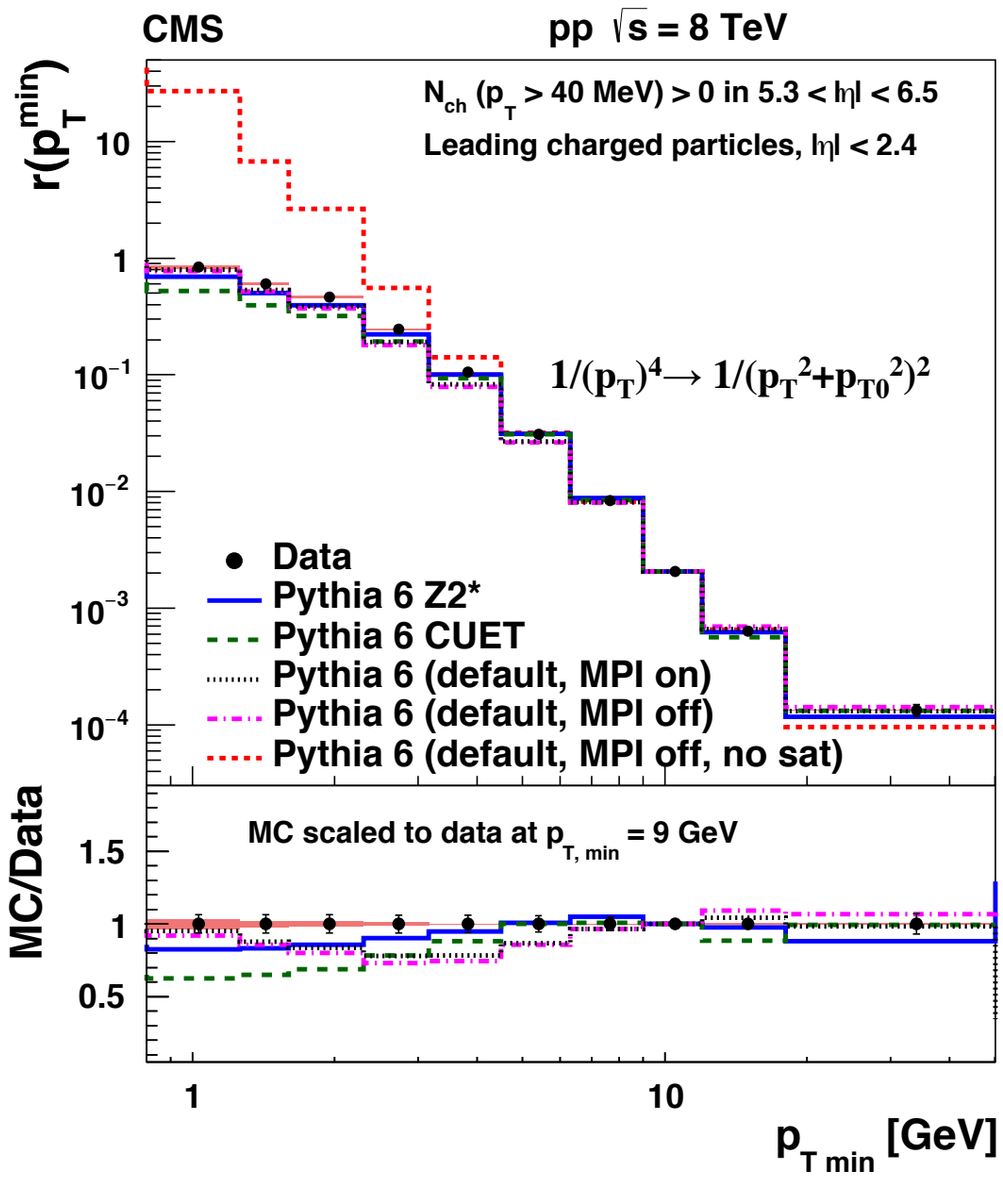


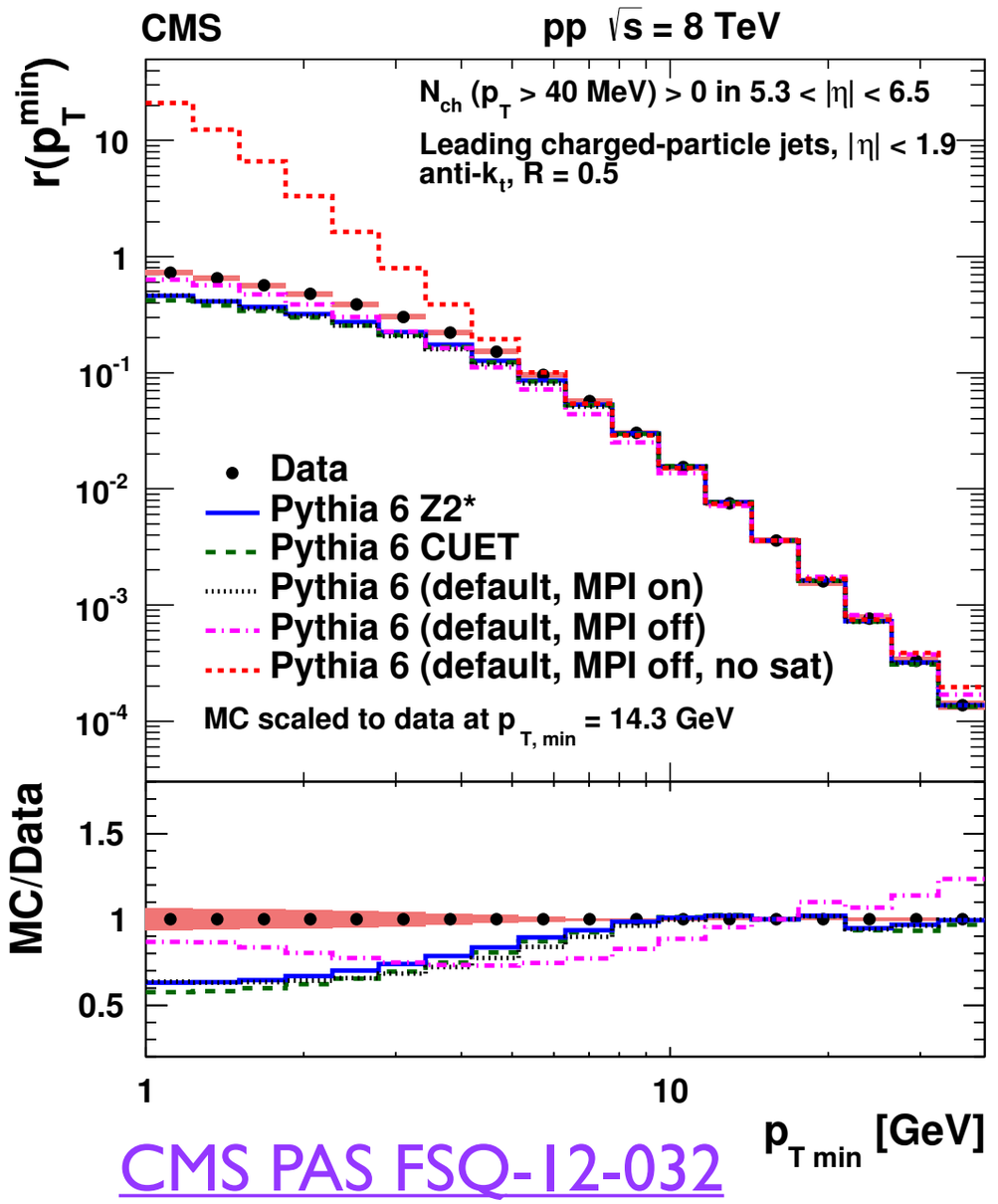
CMS PAS FSQ-12-008

Leading charged particles/jets at small p_T

Leading charged particles ($|\eta| < 2.4$, $p_T > 0.8$ GeV) and leading charge-particle jets ($|\eta| < 1.9$, $p_T > 1.0$ GeV);

Transition from perturbative to non-perturbative region. Saturation of parton-parton cross section visible at p_T values of O(1 GeV).





CMS PAS FSQ-12-032

arXiv:1507.00233

Outline

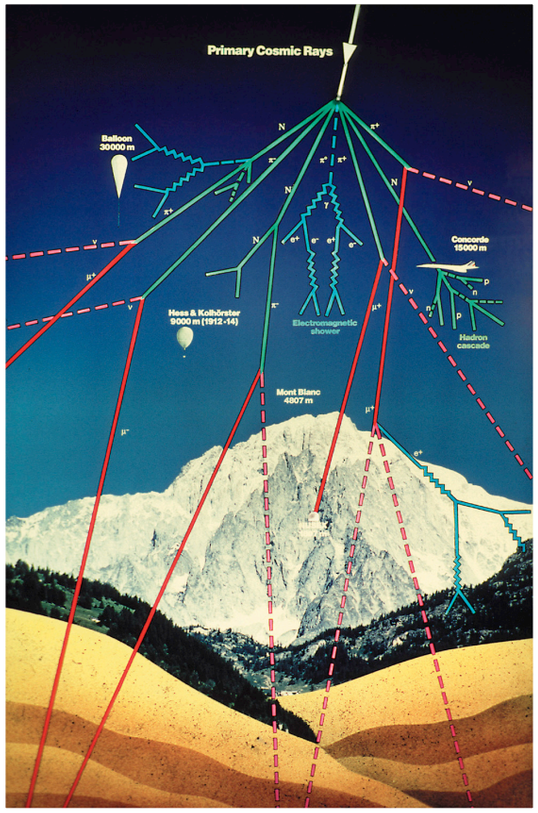
The CMS detector and forward instrumentation

Underlying event in pp collisions and DPS

Low-x jet production

Forward energy flow & particle production and inelastic cross section

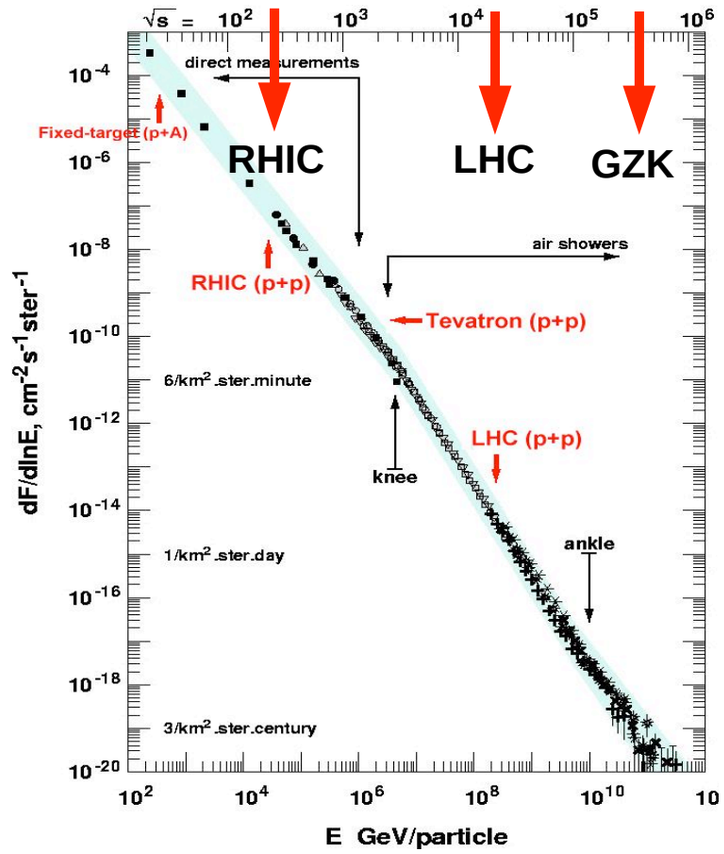
dE/dη and cosmic rays



Regge-based Monte Carlo generators for cosmic ray (proton) interactions in the atmosphere (EPOS, QGSJET, SIBYLL);

LHC data important for model extrapolations to ultra high energies;

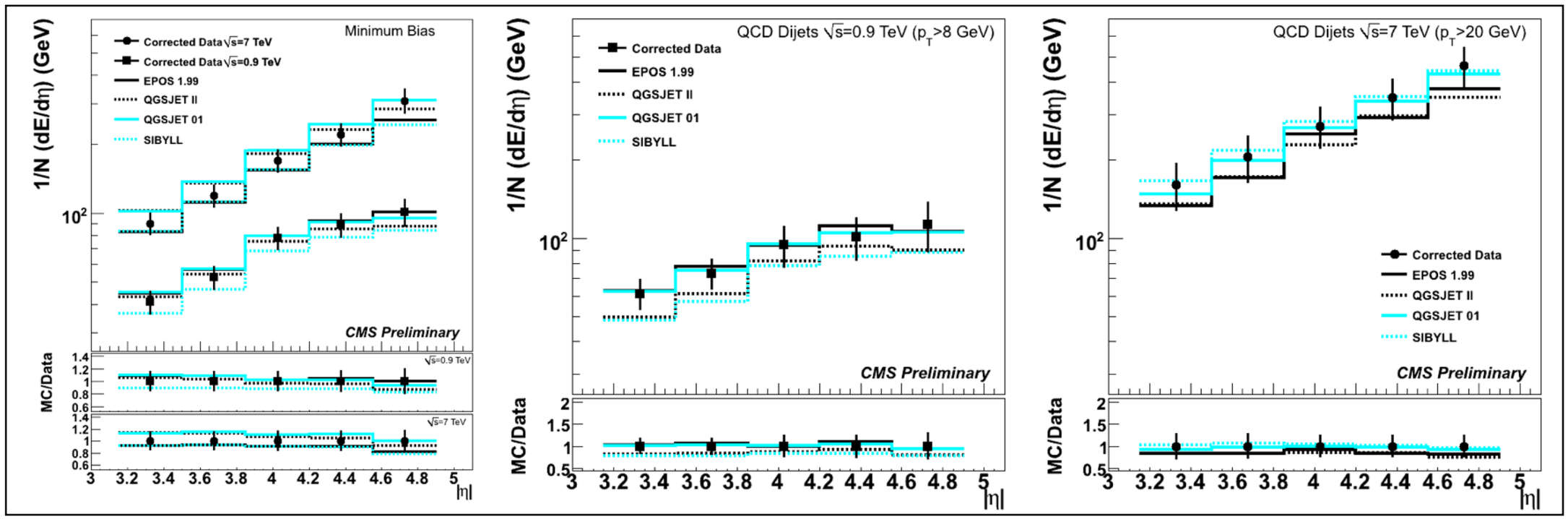
Good agreement with dE/dη data.



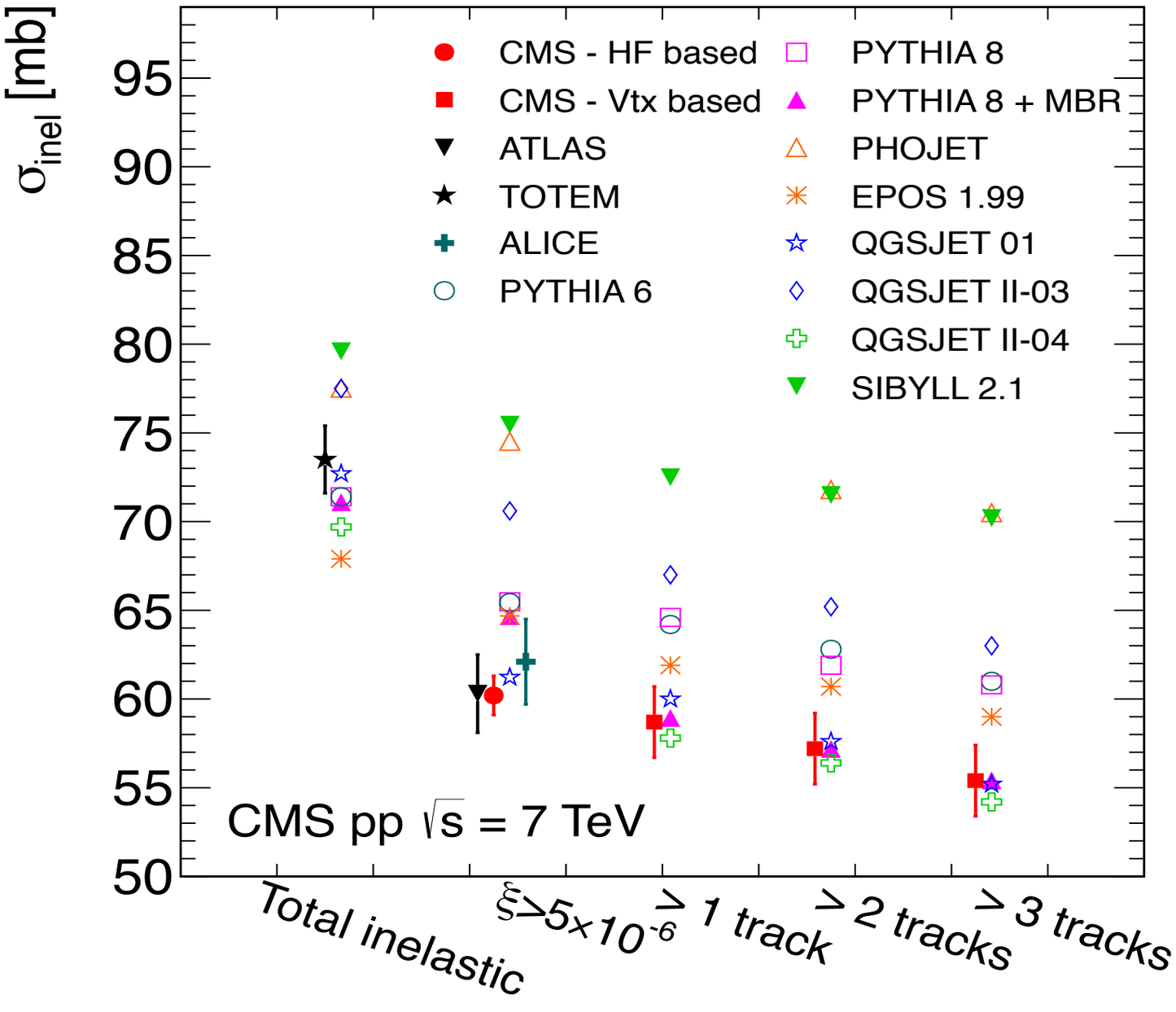
CMS PAS FWD-10-011

J. High Energy Phys. 11 (2011) 148

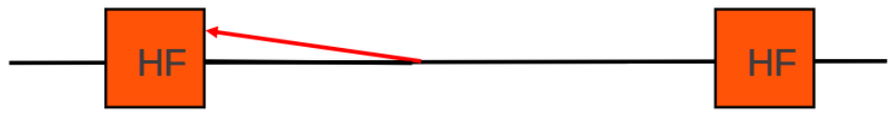
J. High Energy Phys. 02 (2012) 055 (Erratum)



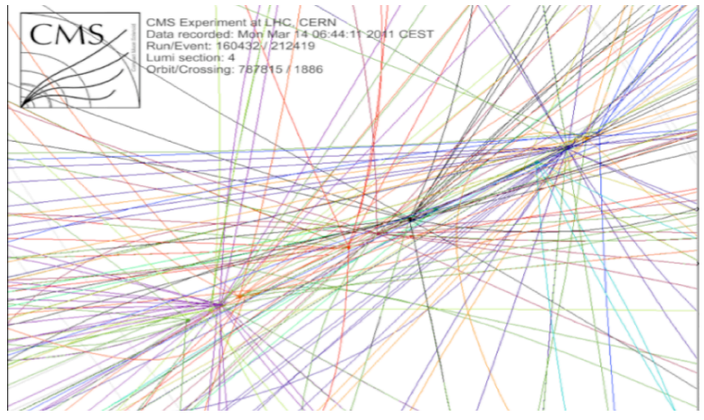
Total inelastic cross section

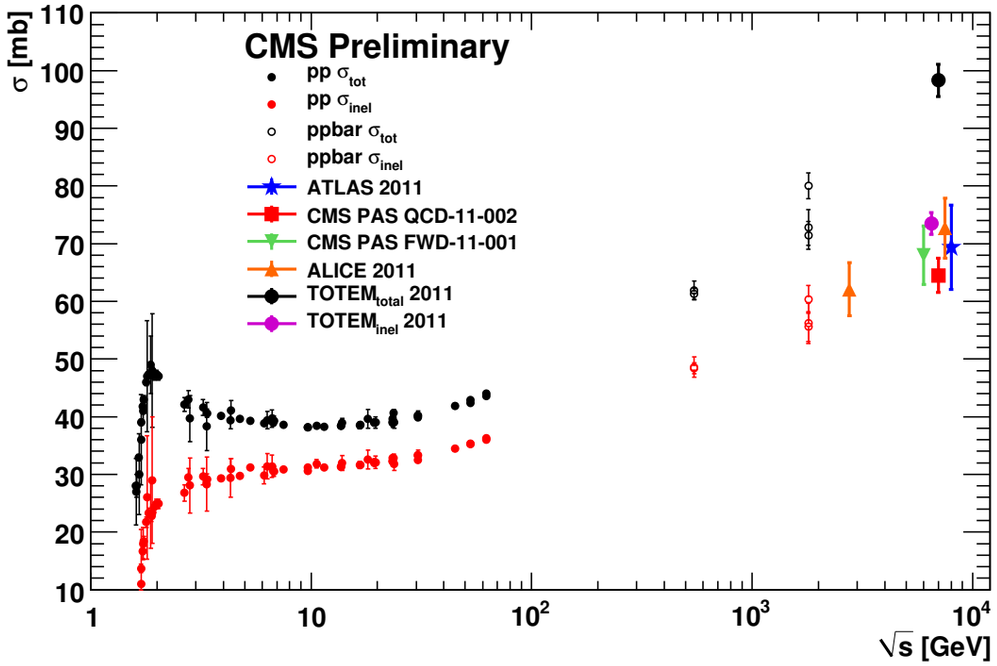


HF based: count events within acceptance:



Vertex based: count extra vertices (pile-up):



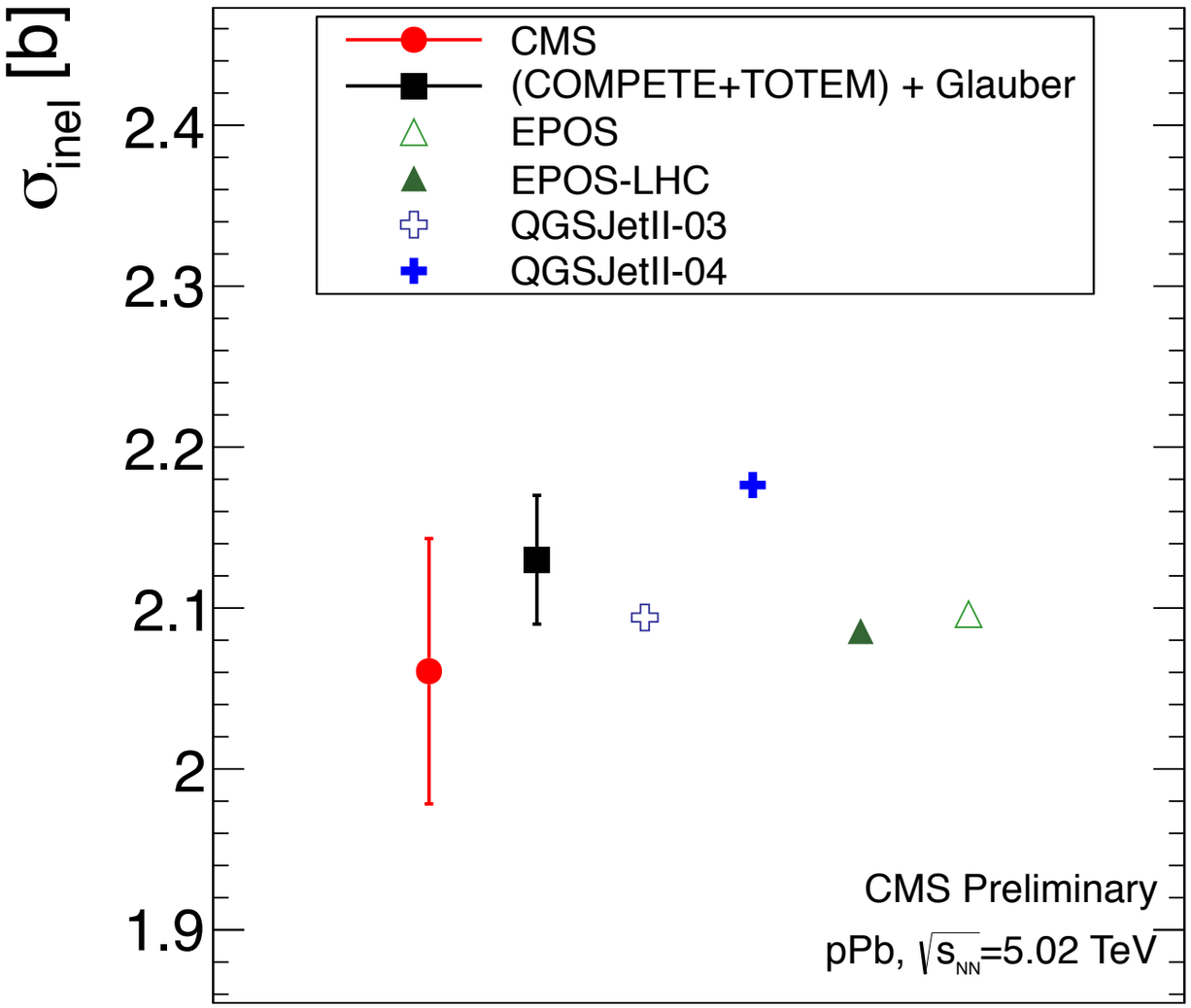


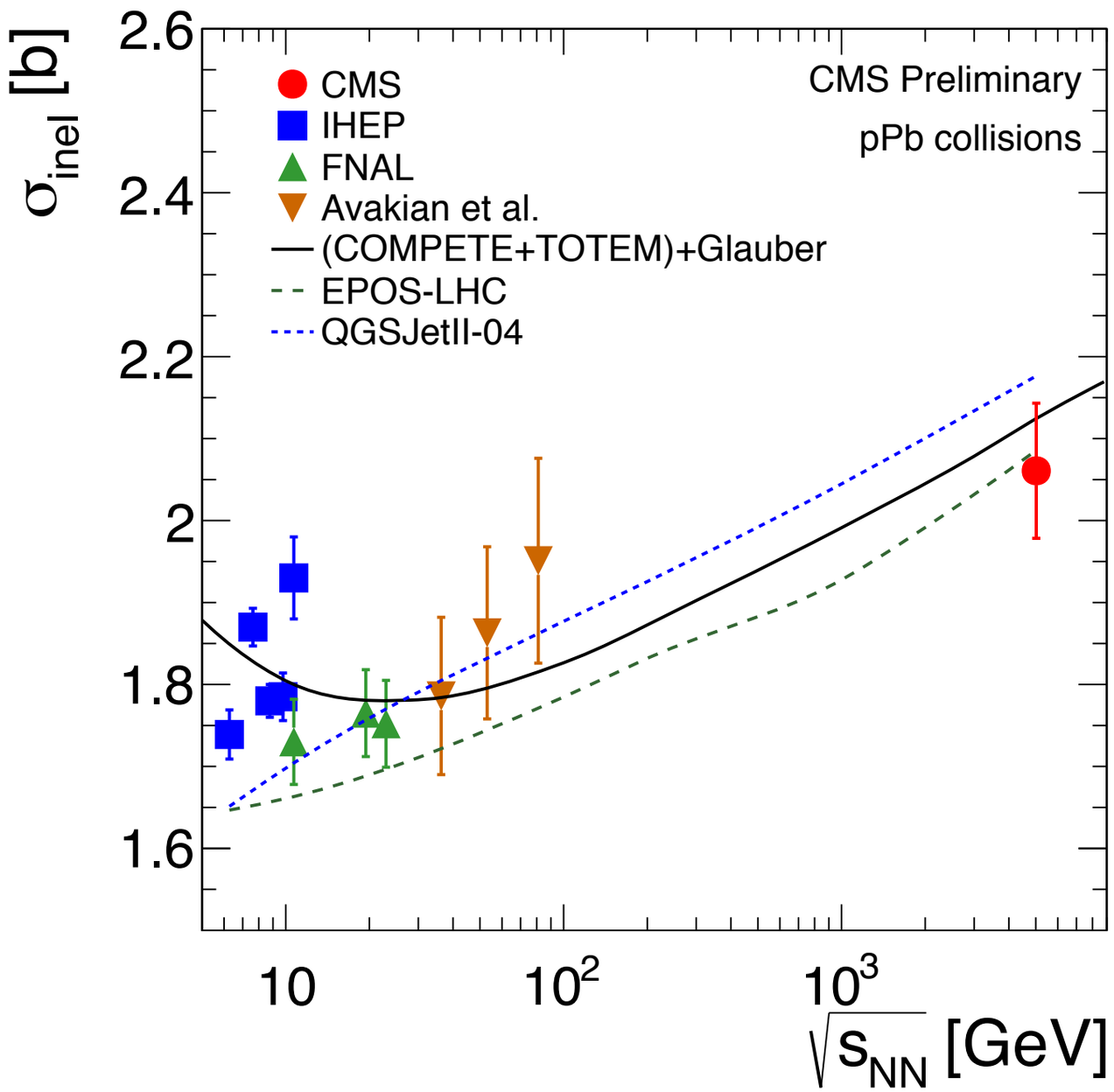
CMS FWD-11-001

CMS QCD-11-002

Phys. Lett. B 722 (2013) 5-27

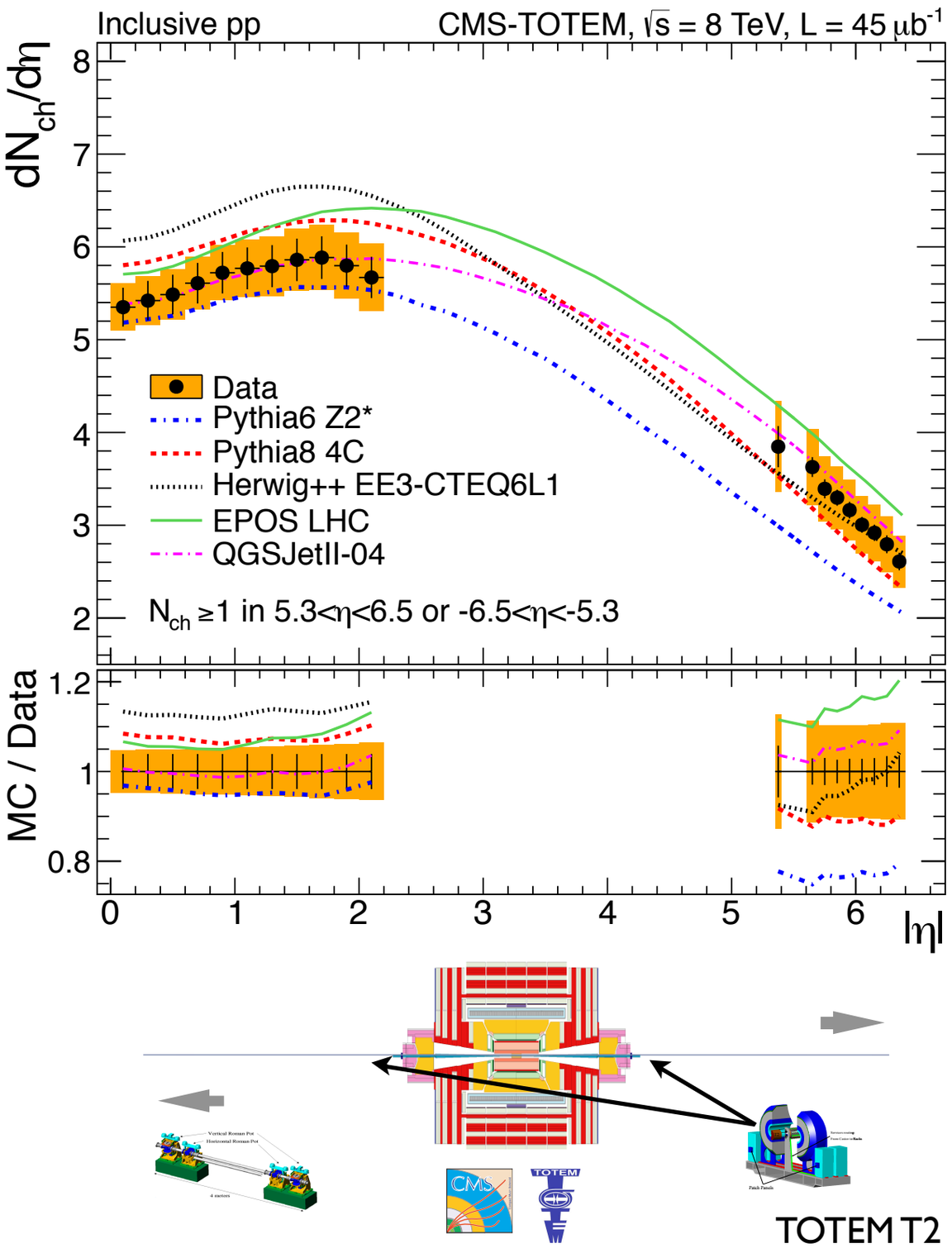
Inelastic pPb cross section (5.02 TeV)

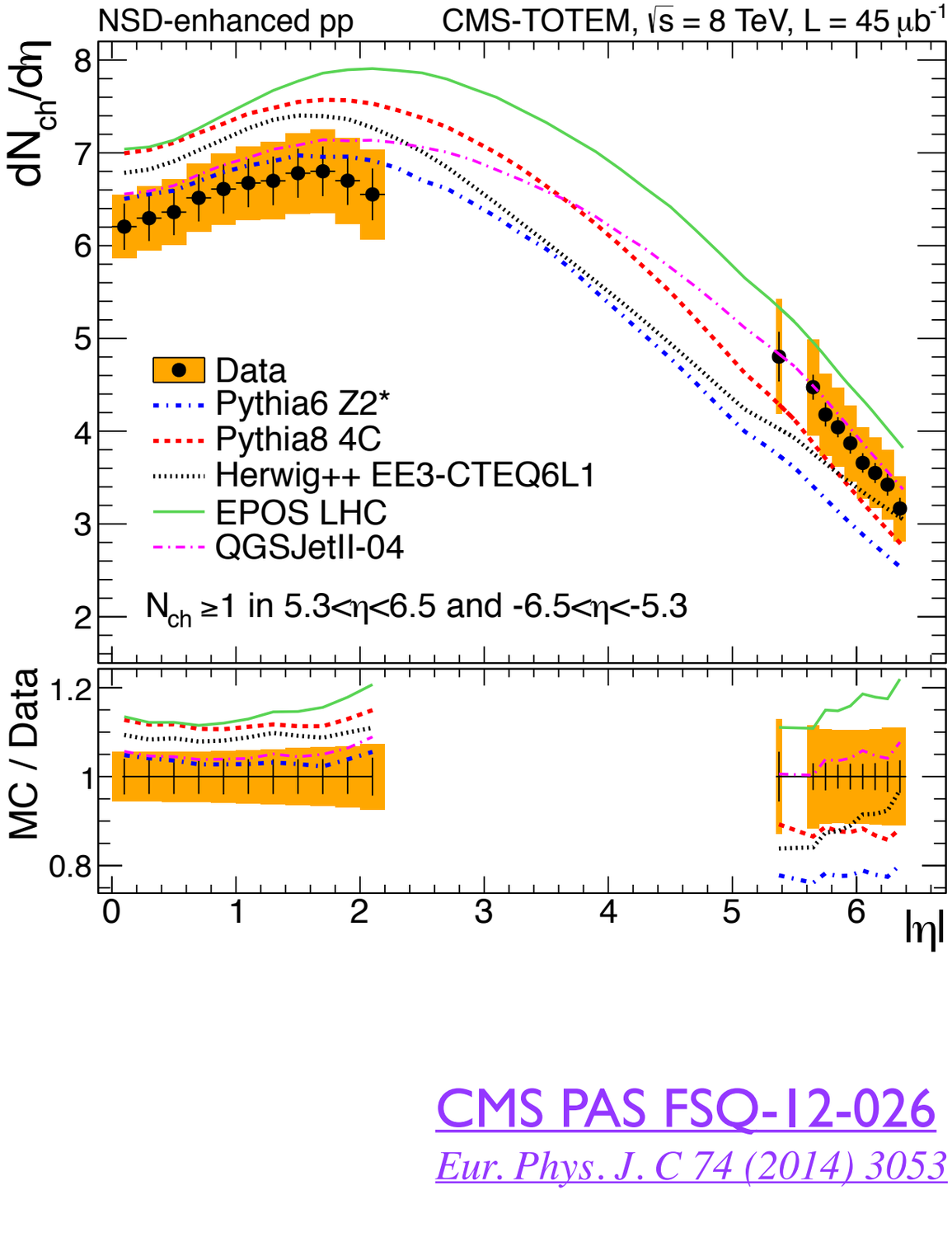




[CMS PAS FSQ-13-006]

$dN_{ch}/d\eta$ in central + forward region

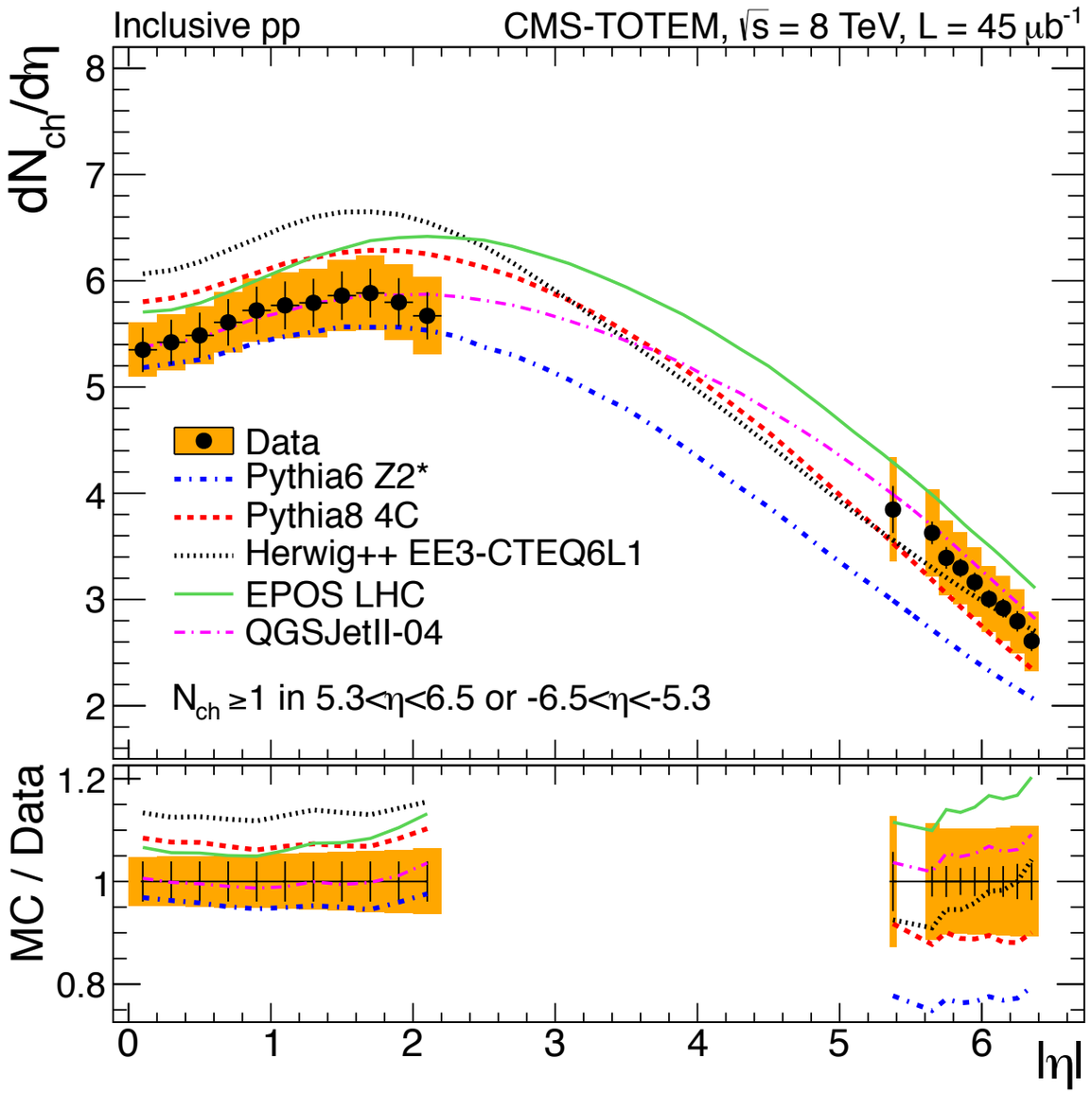


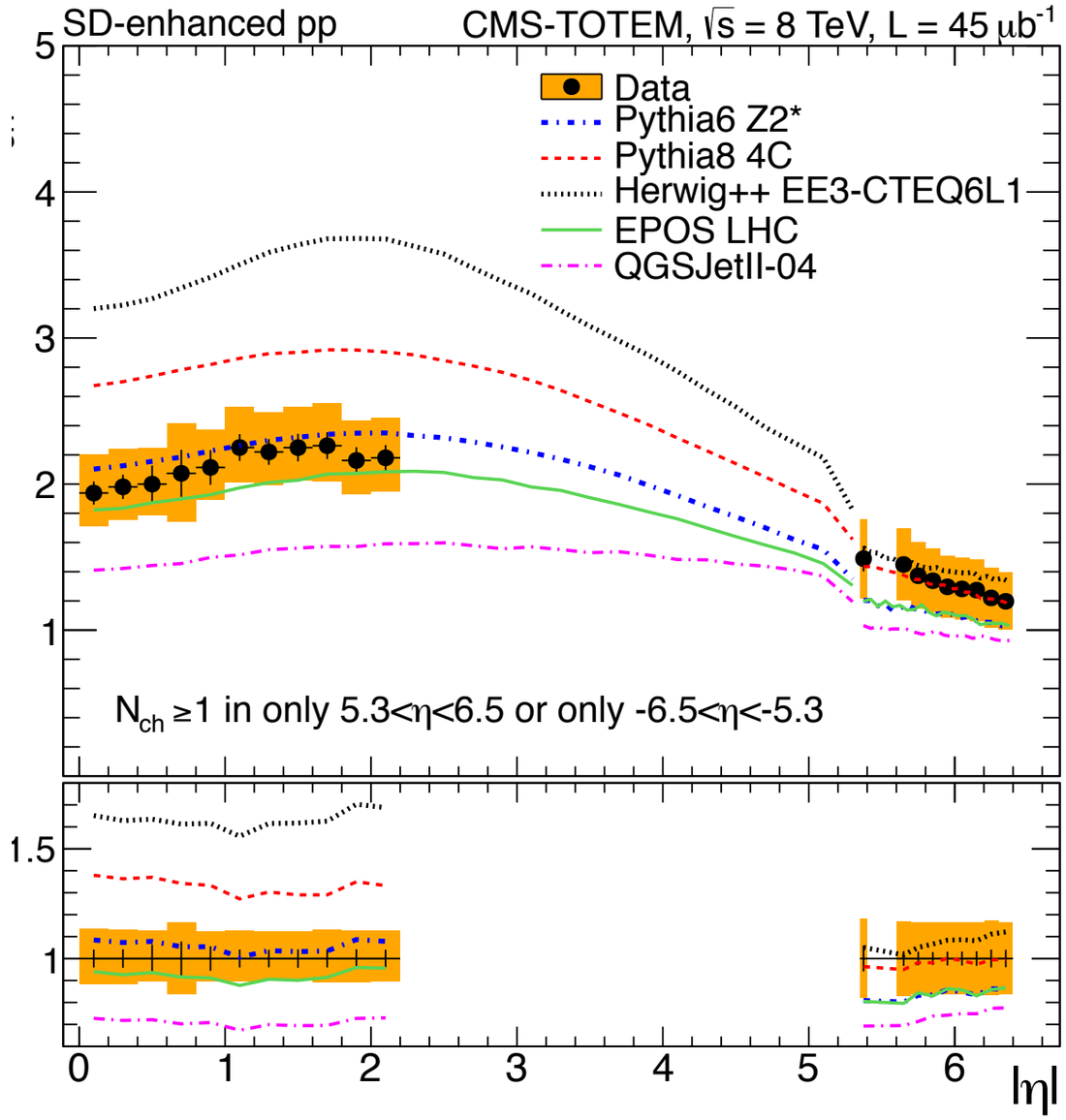


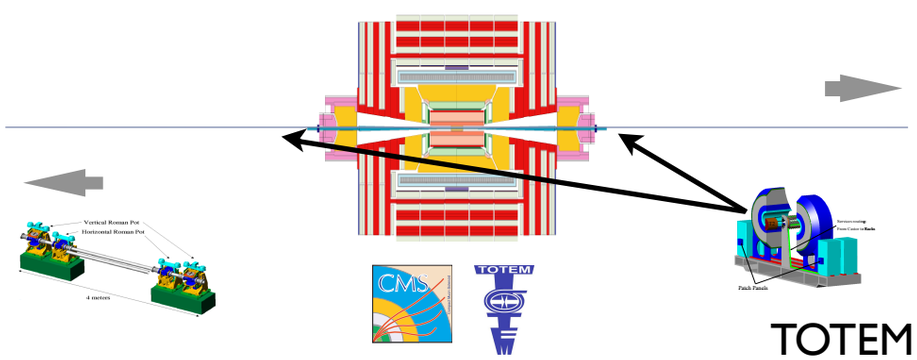
[CMS PAS FSQ-12-026](#)

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

$dN_{ch}/d\eta$ in central + forward region







[CMS PAS FSQ-12-026](#)

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

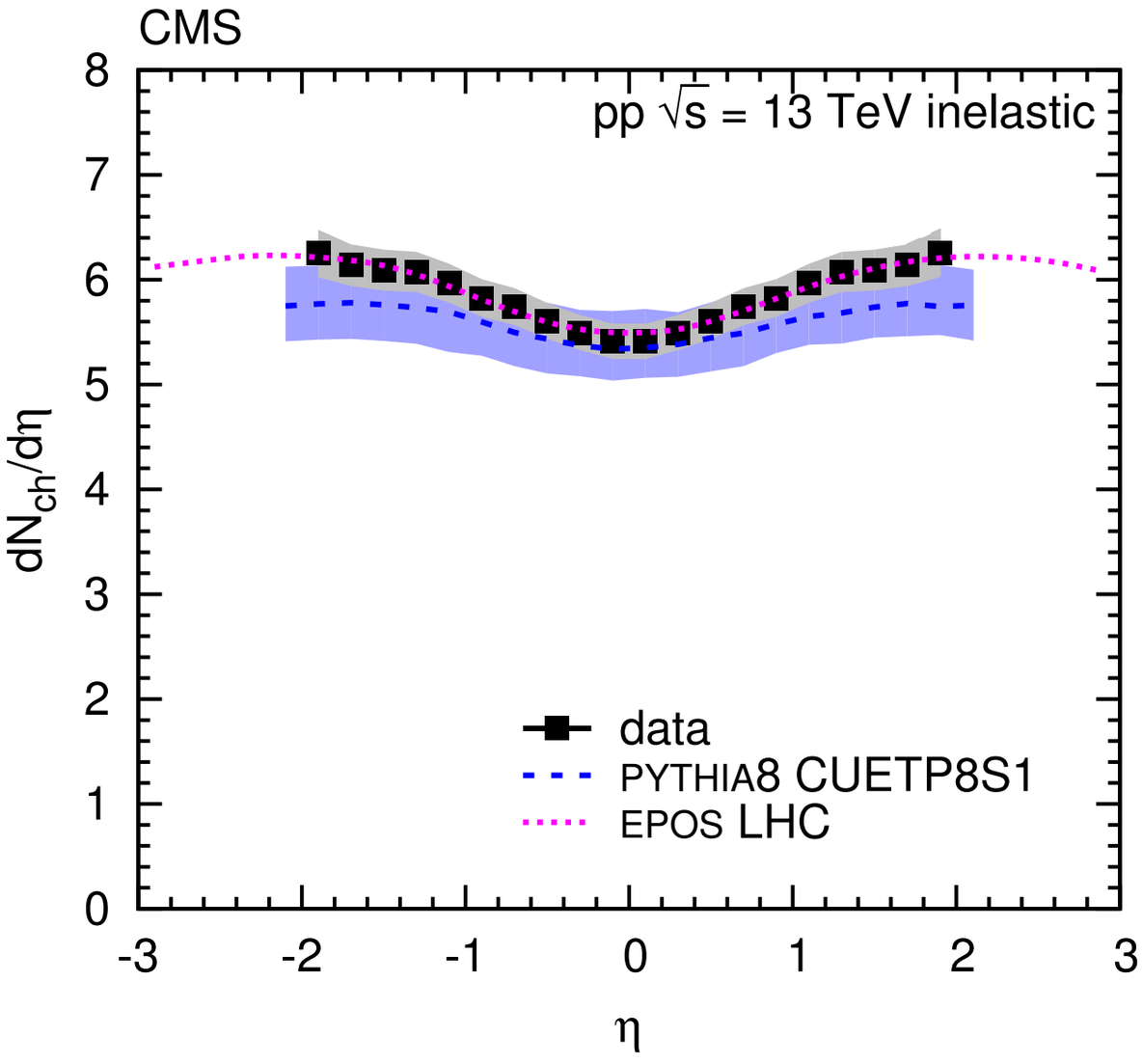
dN/dη of charged hadrons at 13 TeV

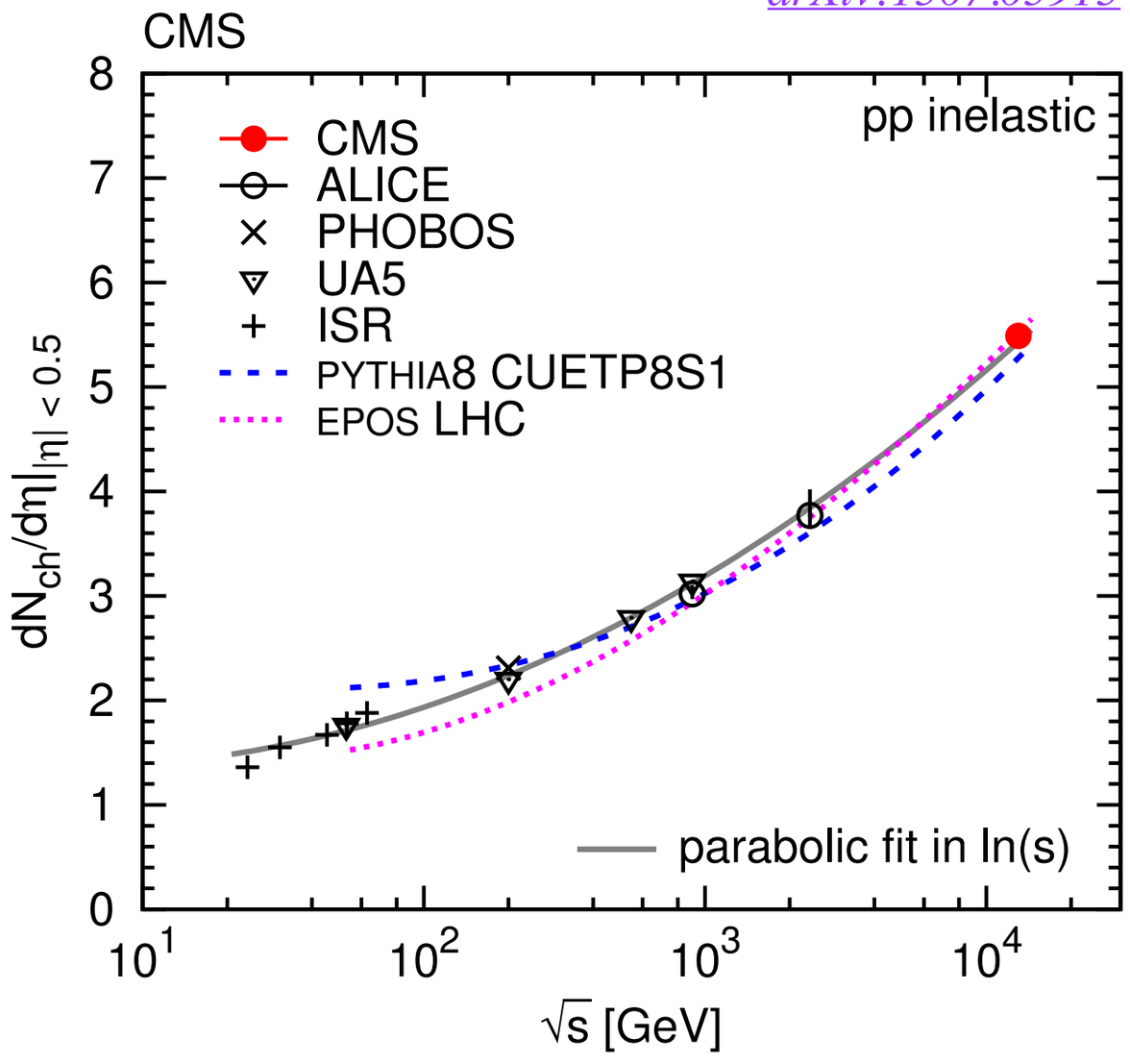
Charged hadron pseudorapidity density in inelastic pp collisions at 13 TeV;

Central value: 5.49 ± 0.01 (stat.) ± 0.17 (syst.);

First LHC paper at 13 TeV.

arXiv:1507.05915





Summary

CMS has a unique forward detector instrumentation, especially complemented by the TOTEM experiment.

Joint physics programme with TOTEM at high luminosity (See João Varela's talk on CT-PPS).

Total inelastic cross section measured in pp and pPb.

Underlying event measured at different collision energies and well modelled.

Double Parton Scattering studied at different topologies (W+jets, 4 jets, 2 b-jets + 2 jets, γ + 3 jets).

New kinematic regions of QCD explored using forward and low-p_T final states (MPI, DGLAP vs BFKL dynamics, non-perturbative domain, etc.).

Connection with cosmic ray physics and models studied.

First paper at 13 TeV: dN/dη of charged hadrons.


Obrigado

Extra slides

CMS Tune CUETP8S1-CTEQ6L

➡ **PYTHIA 8 Tunes:** Corke & Sjöstrand Tune 4C-CTEQ6L and CMS Tune CUETP8S1-CTEQ6L (CMS1).

	4C	CMS1
PDF	CTEQ6L	CTEQ6L
ecmRef	1800	1800
pT0Ref	2.085	**2.1006**
ecmPow	0.19	**0.21057**
expPow	2.0	**1.60889**
reconnectRange	1.5	**3.31257**
MultipartonInteractions:alphaSvalue	0.135	0.135
SigmaProcess:alphaSvalue	0.135	0.135
SpaceShower:alphaSvalue	0.137	0.137
TimeShower:alphaSvalue	0.1383	0.1383
TimeShower:pTmin	0.4	0.4
TimeShower:pTminChgQ	0.4	0.4
BeamRemnants:halfScaleForKT	1.0	1.0
BeamRemnants:primordialKThard	2.0	2.0
BeamRemnants:primordialKTsoft	0.50	0.50
Tune:ee	3	3

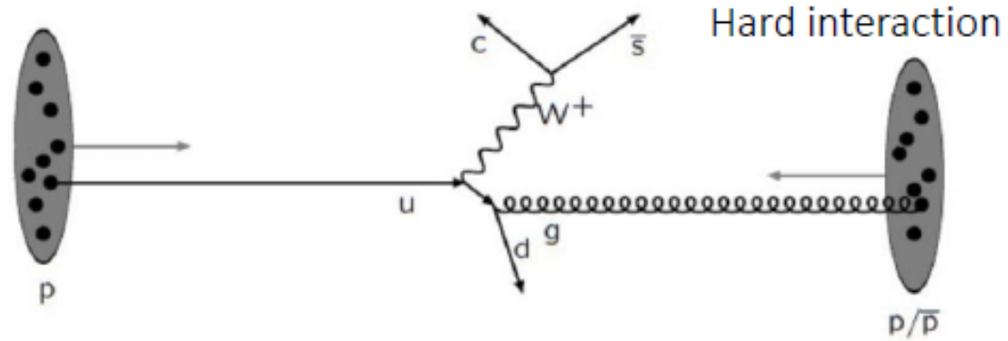
Start with Tune 4C and vary 4 parameters!

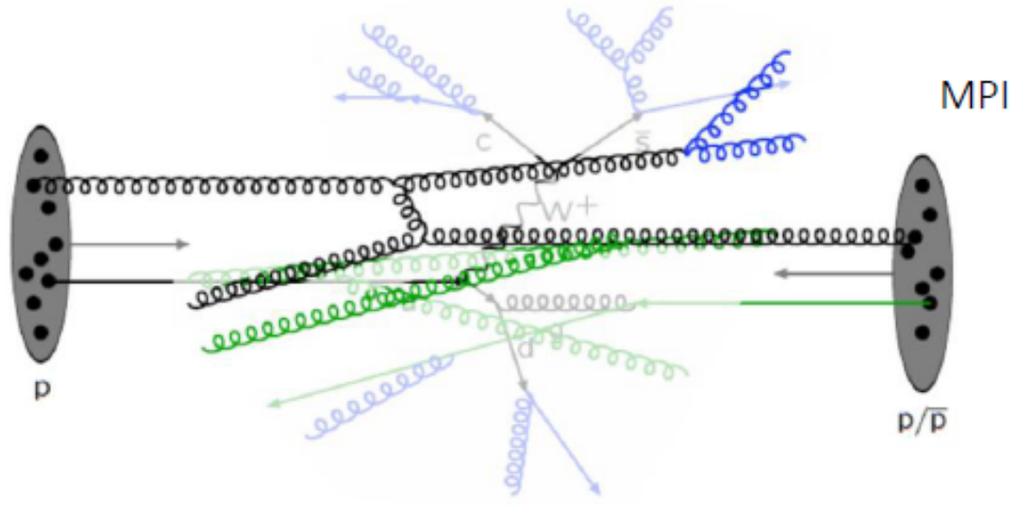
CMS Tune CUETP8S1-CTEQ6L
pT0Ref = 2.1006
ecmPow = 0.21057
ecmRef = 1800

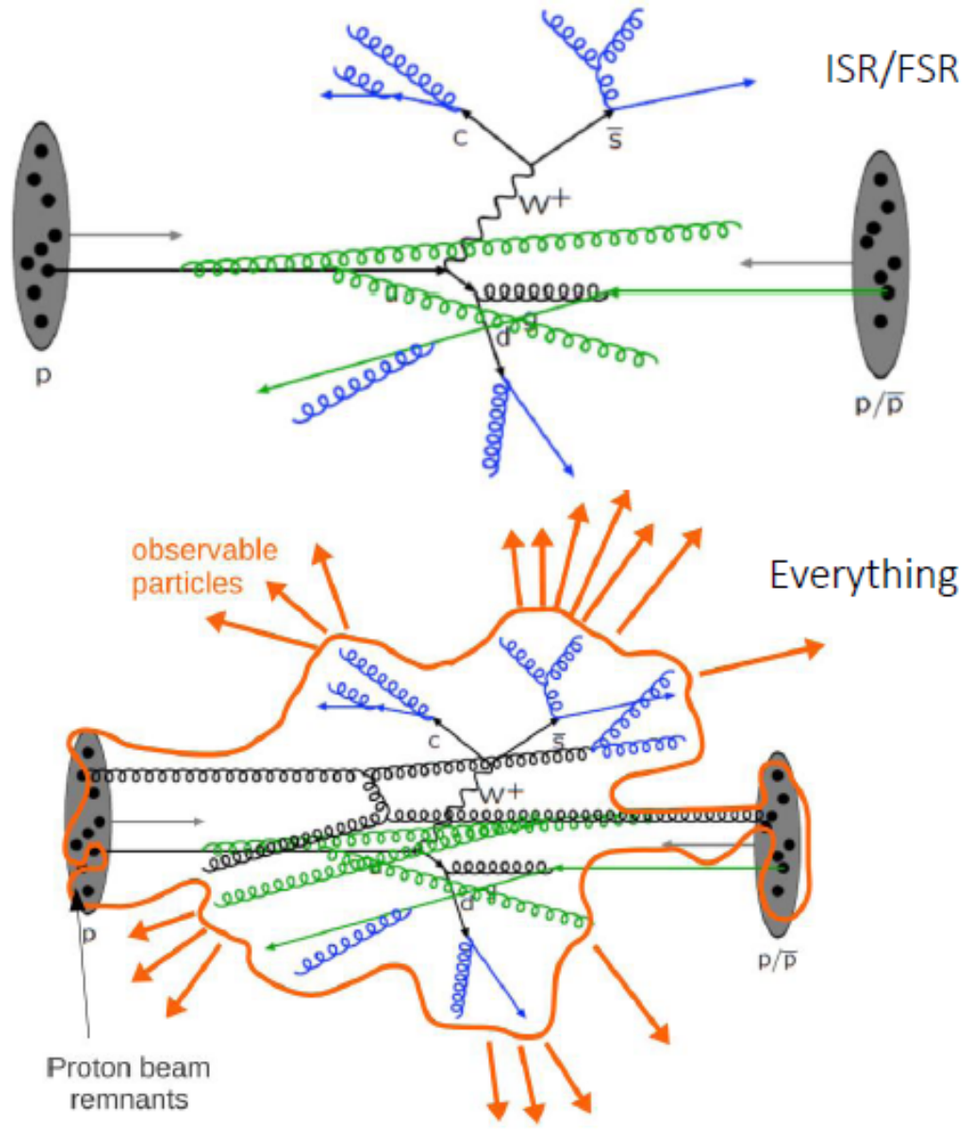
Ecm (TeV)	pT0 (GeV/c)
0.3	1.440
0.9	1.815
1.96	2.139
7	2.796
13	3.185

$$pT0(E_{cm}) = pT0Ref \times (E_{cm}/ecmRef)^{ecmPow}$$

Underlying Event in pp collisions





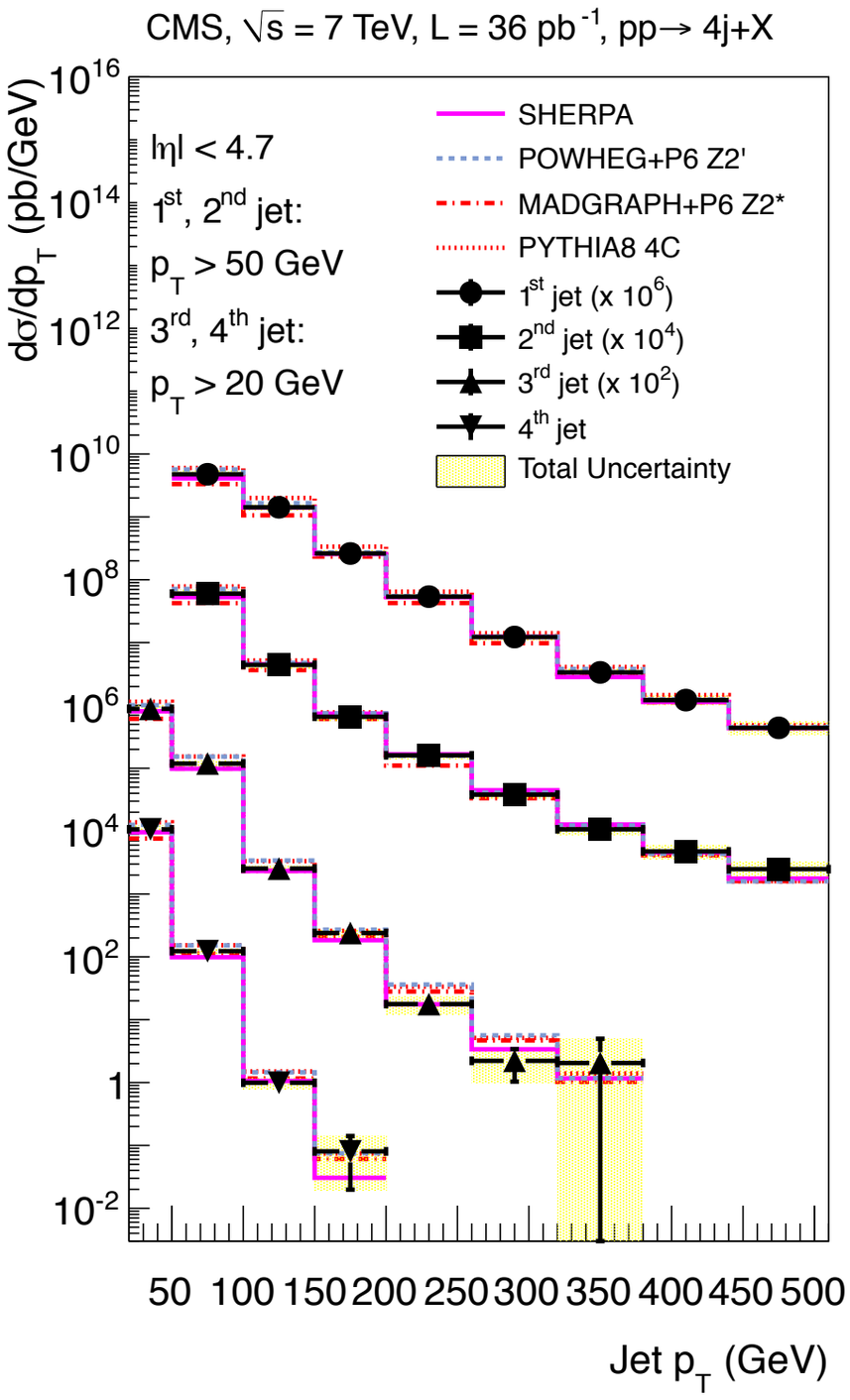


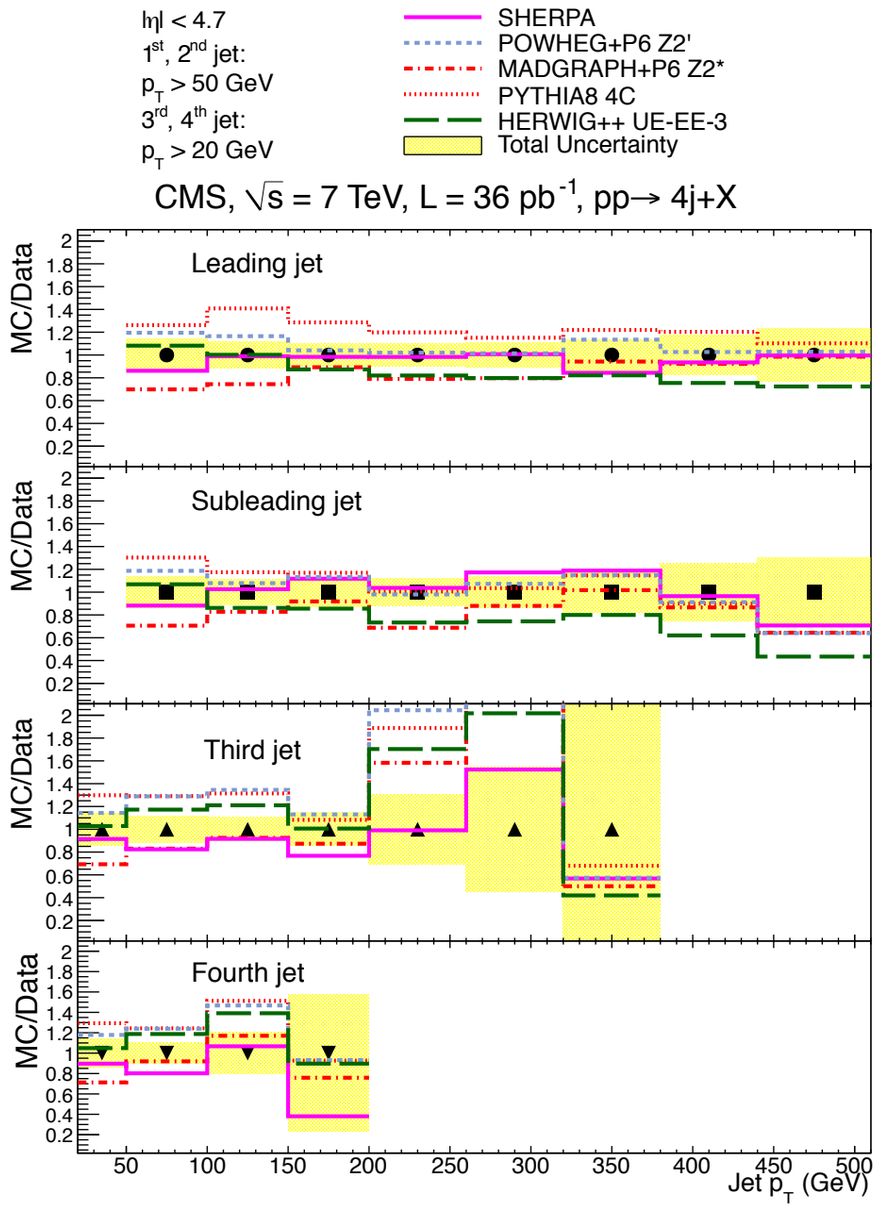
MPI, ISR/FSR, hadronisation, colour reconnections, beam remnants, soft rescattering of beam remnants etc...

4 jet production

2 hard jets with p_T > 50 GeV and two soft jets with p_T > 20 GeV ($|\eta|$ < 4.7);

Discrepancies with some predictions (e.g. PYTHIA8 Tune 4C, MadGraph + PY6 Z2*), especially at low p_T;





CMS PAS FSQ-12-013

Phys. Rev. D 89 (2014) 092010

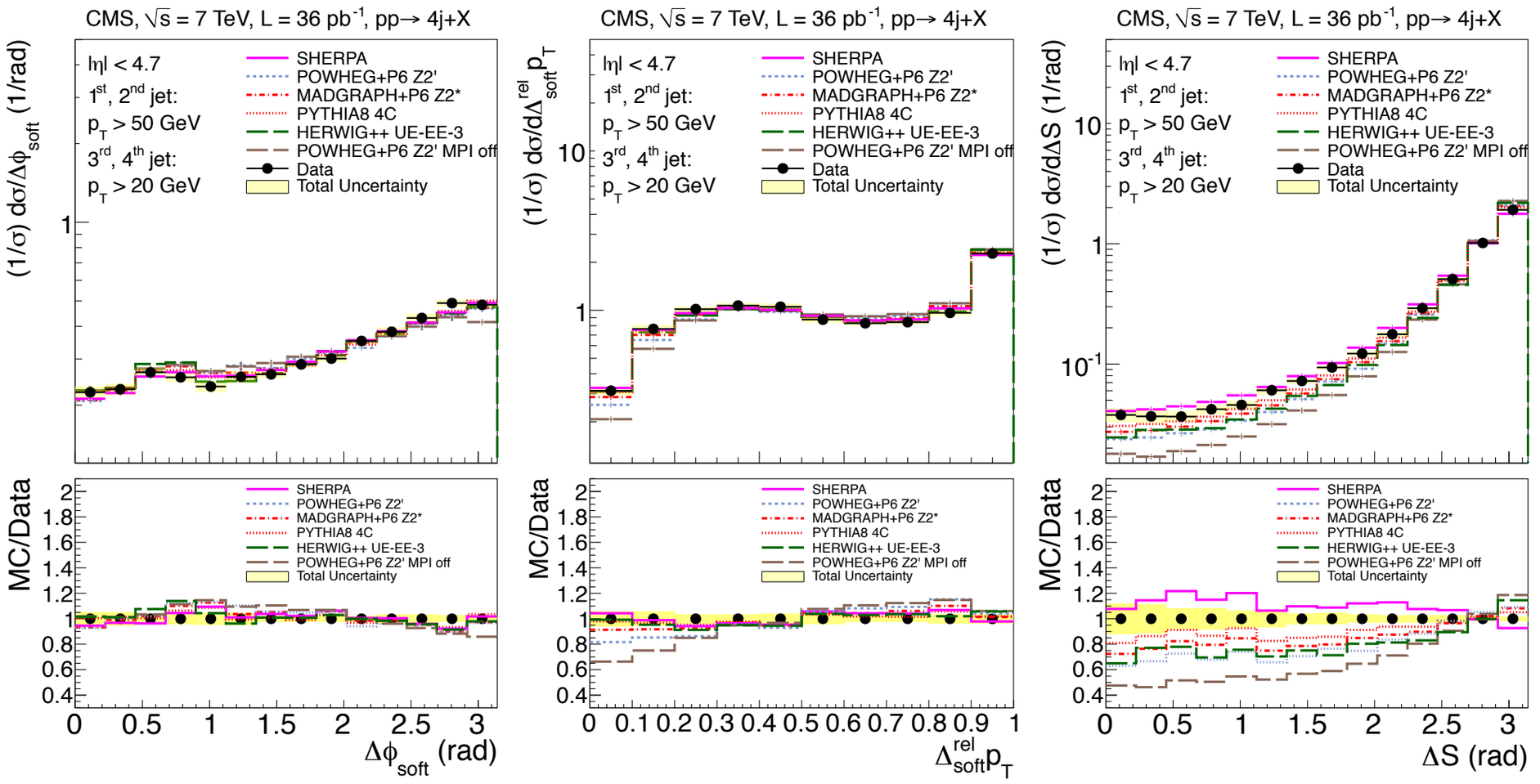
4 jet production

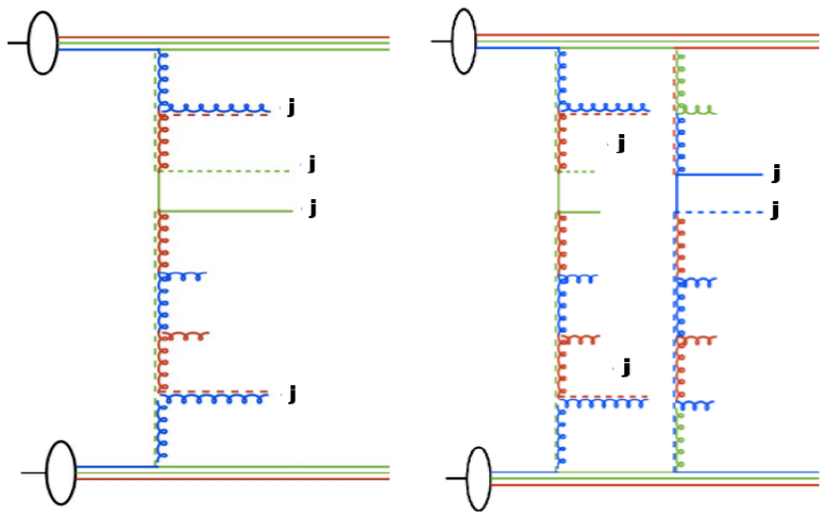
2 hard jets with p_T > 50 GeV and two soft jets with p_T > 20 GeV ($|\eta|$ < 4.7);

Discrepancies with some predictions (e.g. PYTHIA8 Tune 4C, MadGraph + PY6 Z2*), especially at low p_T;

Models (including MPI) agree only in some regions if the phase space;

Possible indication of the need of DPS in the models.





$$\Delta\phi_{\text{soft}} = |\phi(\text{j}^{\text{soft}_1}) - \phi(\text{j}^{\text{soft}_2})|;$$

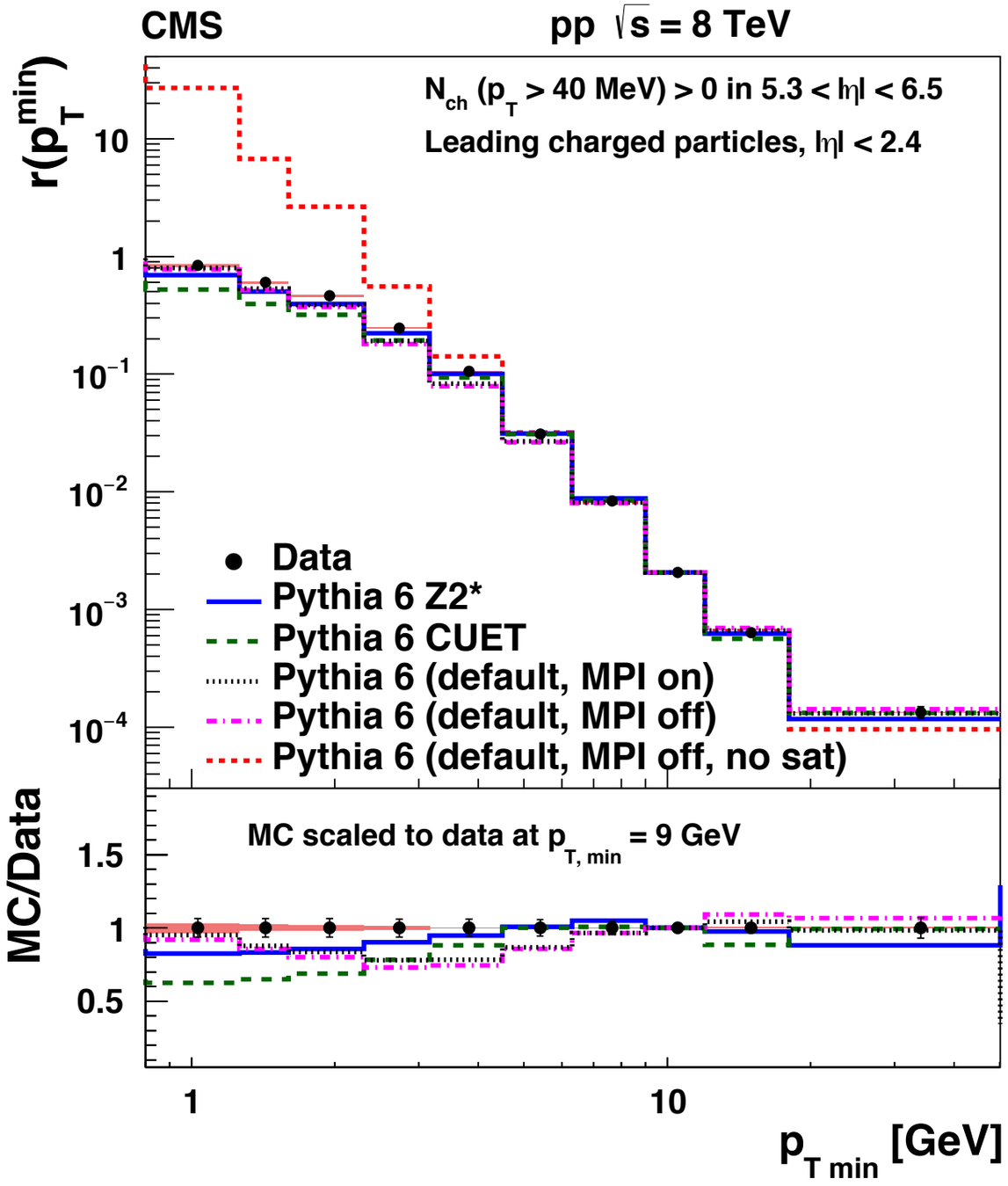
$$\Delta^{\text{rel}}_{\text{soft}} p_{\text{T}} = \frac{|\vec{p}_{\text{T}}(\text{j}^{\text{soft}_1}) + \vec{p}_{\text{T}}(\text{j}^{\text{soft}_2})|}{|\vec{p}_{\text{T}}(\text{j}^{\text{soft}_1})| + |\vec{p}_{\text{T}}(\text{j}^{\text{soft}_2})|};$$

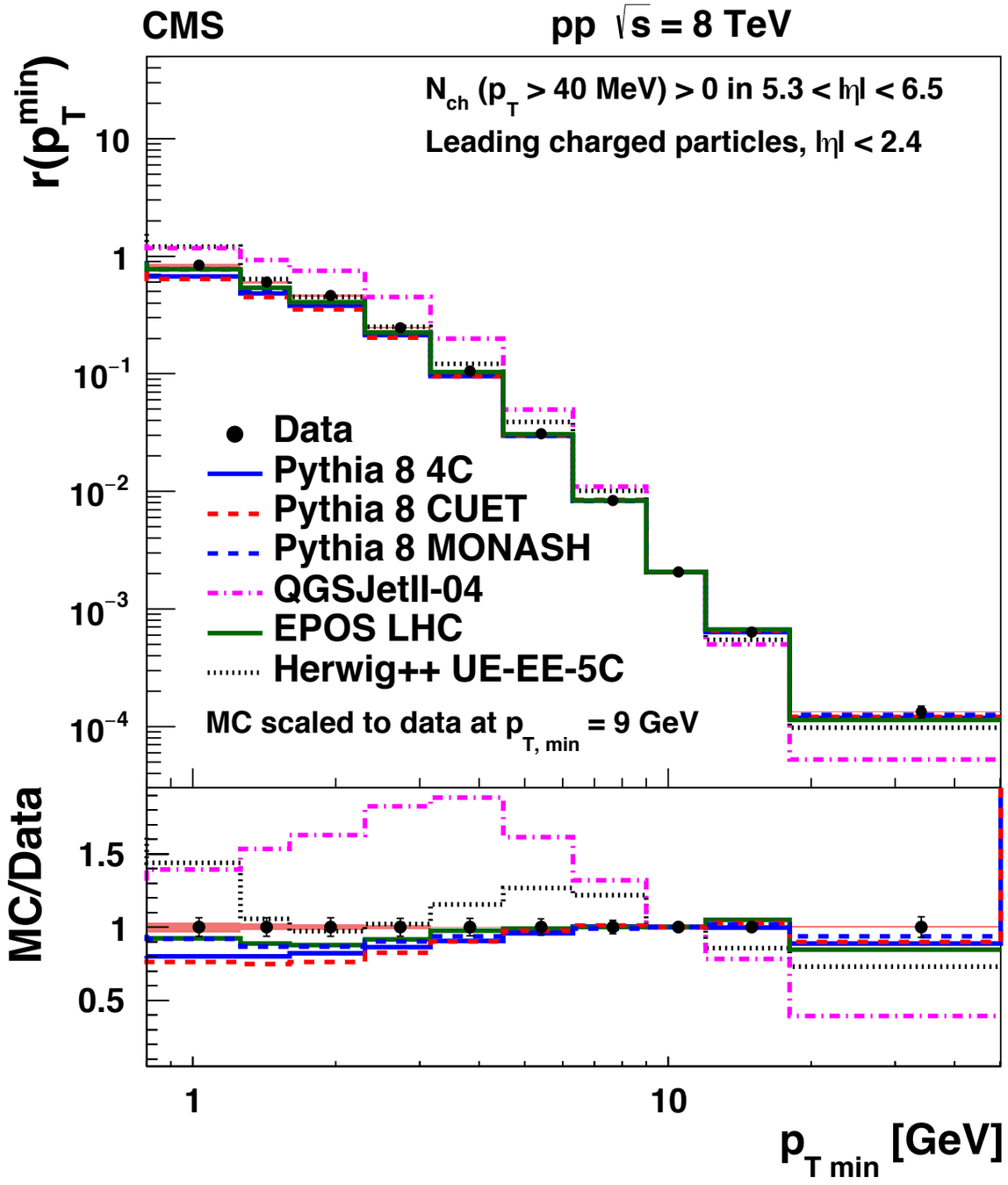
$$\Delta\text{S} = \arccos\left(\frac{\vec{p}_{\text{T}}(\text{j}^{\text{hard}_1}, \text{j}^{\text{hard}_2}) \cdot \vec{p}_{\text{T}}(\text{j}^{\text{soft}_1}, \text{j}^{\text{soft}_2})}{|\vec{p}_{\text{T}}(\text{j}^{\text{hard}_1}, \text{j}^{\text{hard}_2})| \cdot |\vec{p}_{\text{T}}(\text{j}^{\text{soft}_1}, \text{j}^{\text{soft}_2})|}\right)$$

CMS PAS FSQ-12-013

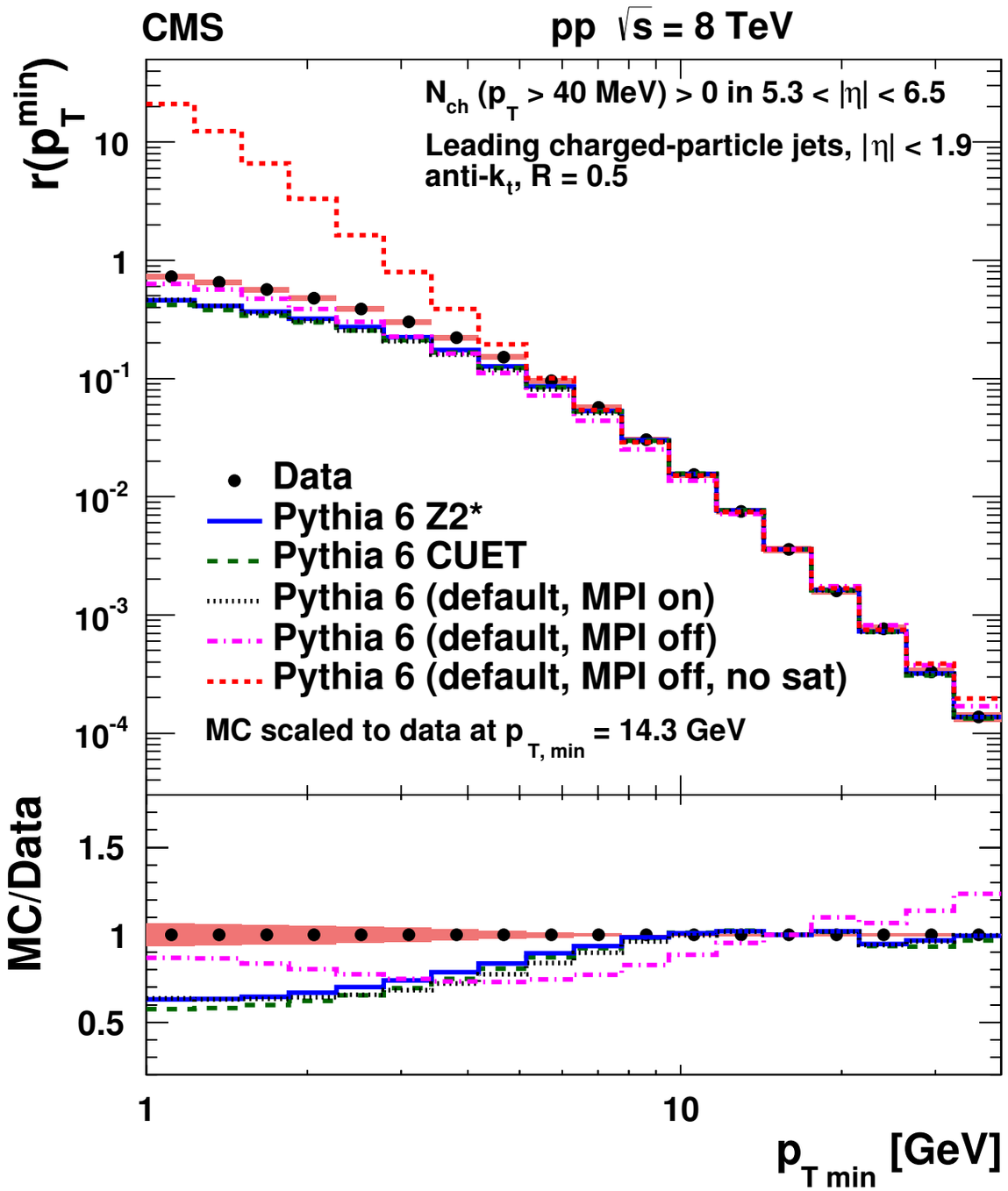
Phys. Rev. D 89 (2014) 092010

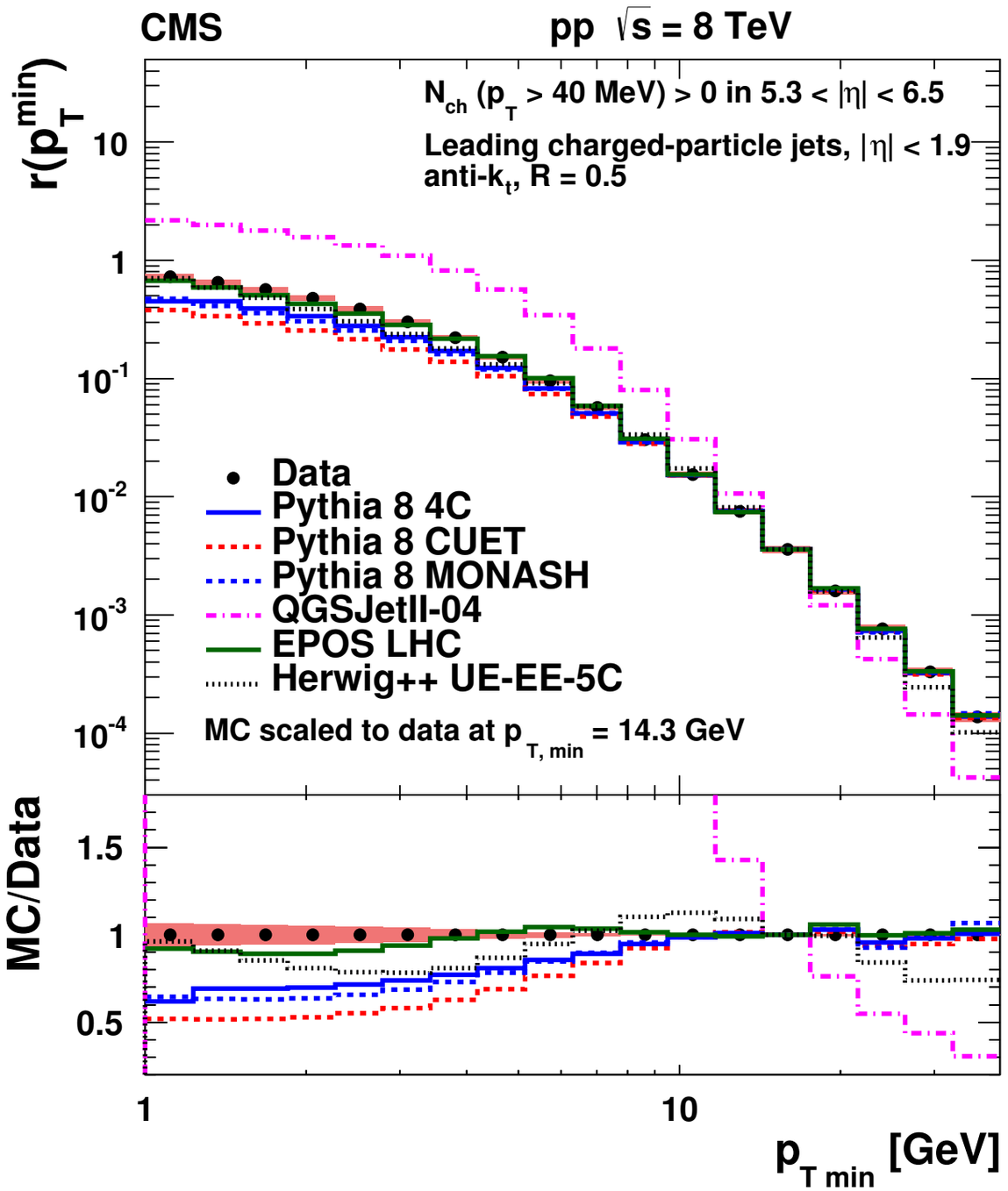
Leading charged particles/jets at small p_T



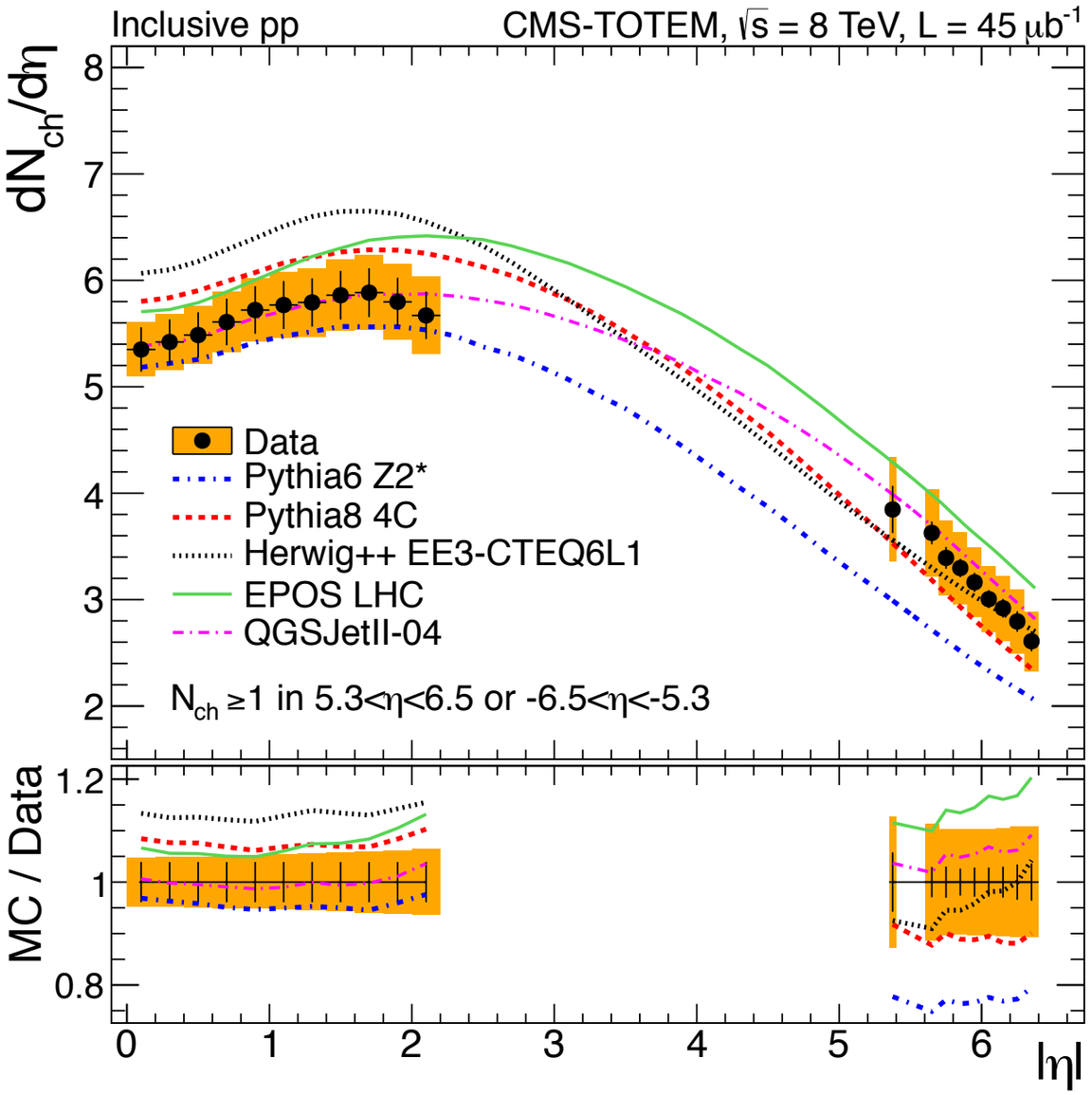


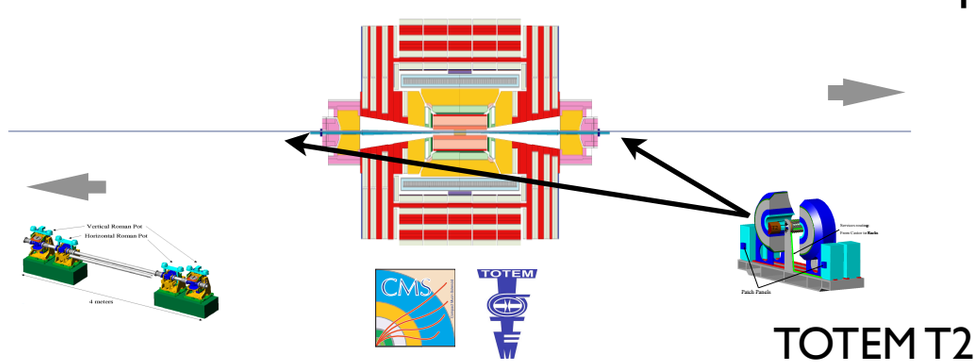
Leading charged particles/jets at small p_T

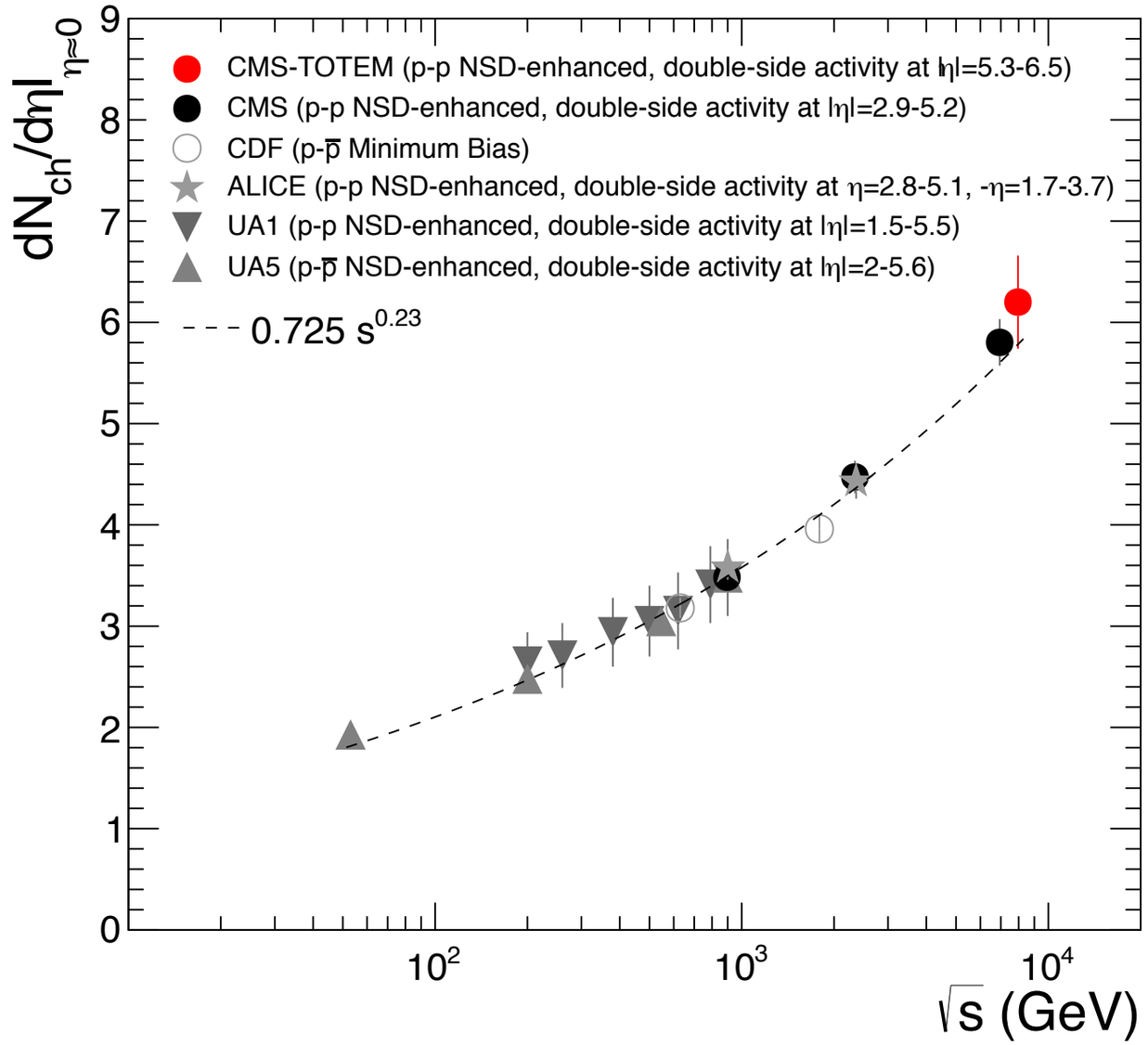




$dN_{ch}/d\eta$ in central + forward region



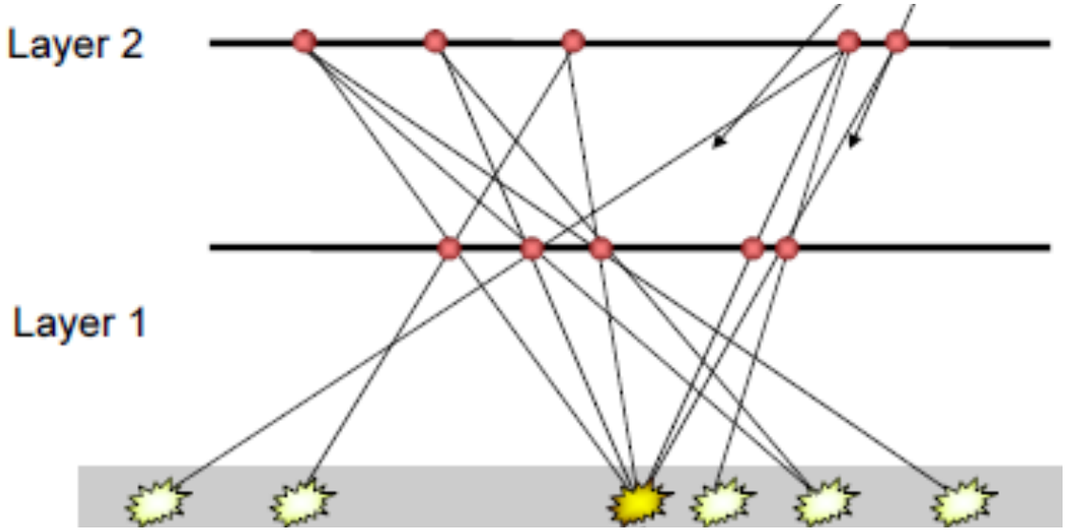


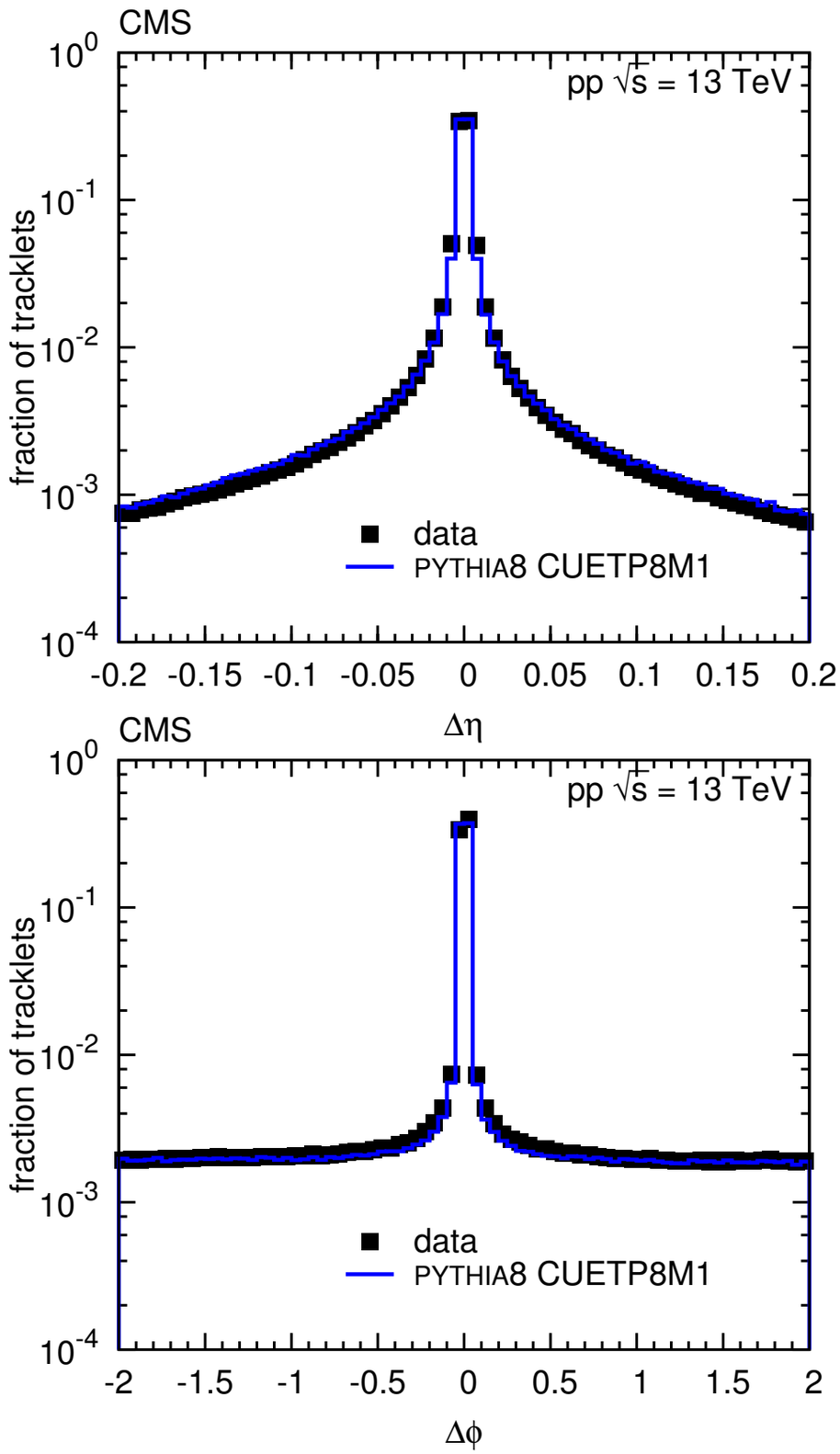


[CMS PAS FSQ-12-026](#)

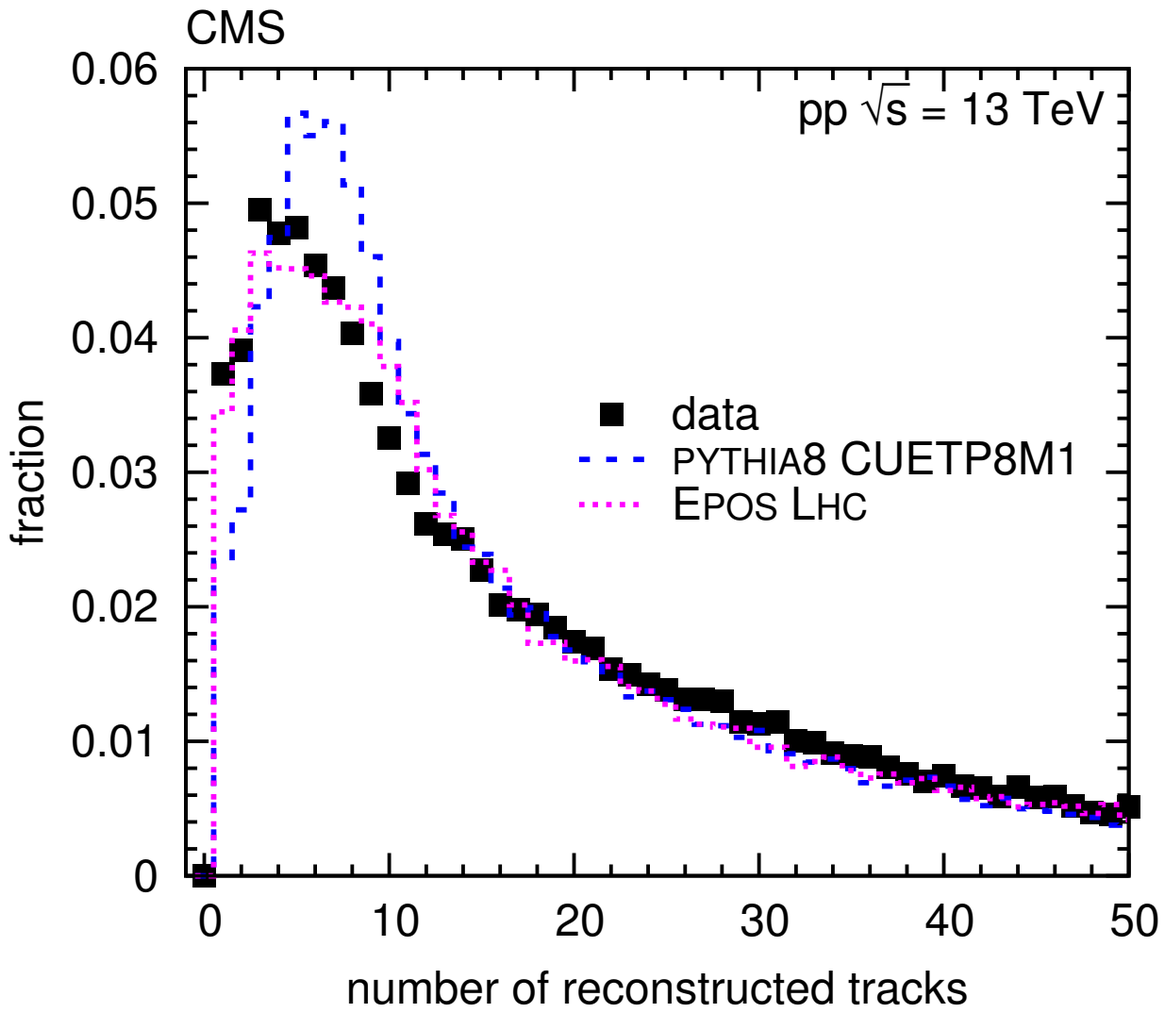
Eur. Phys. J. C 74 (2014) 3053

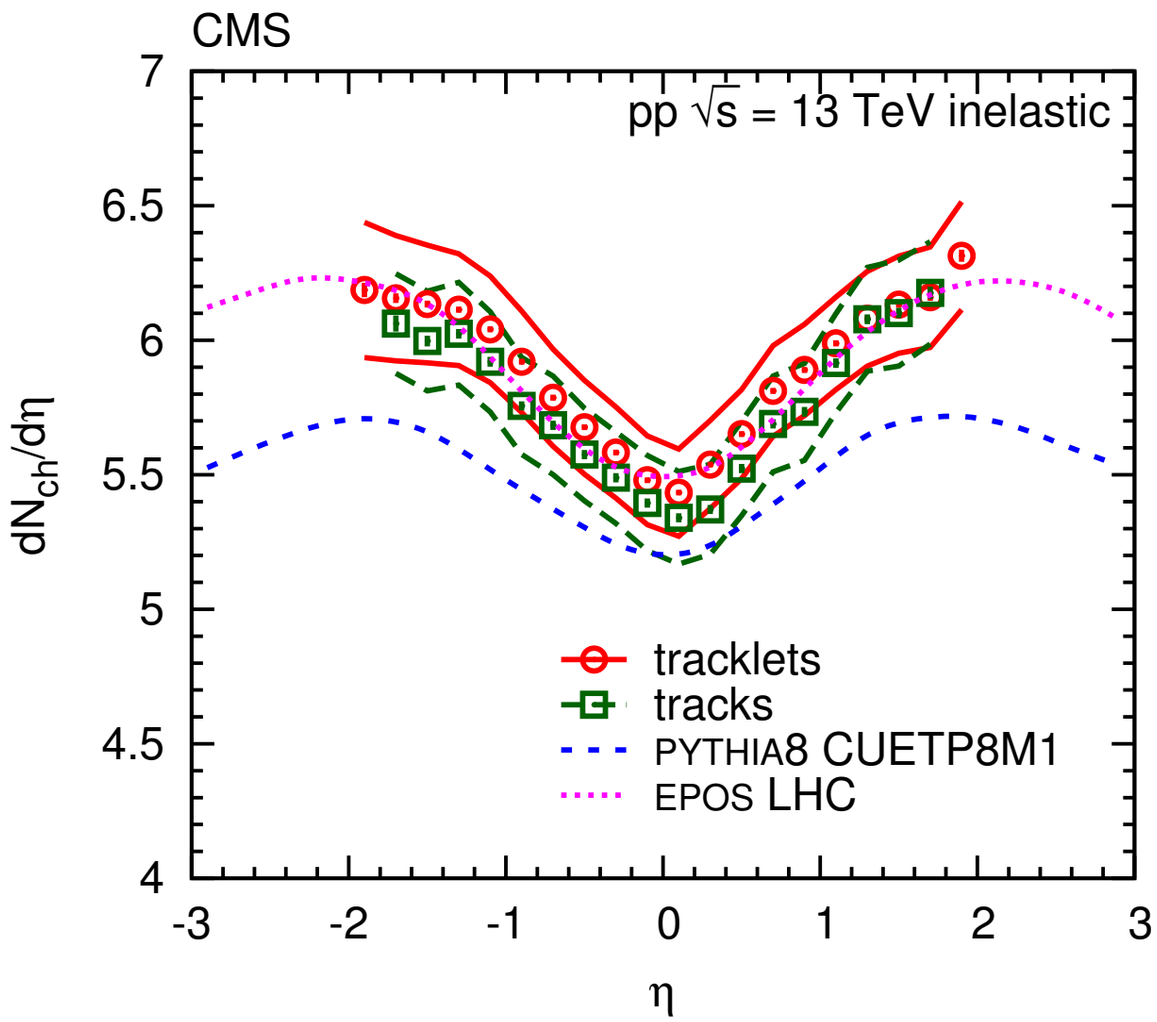
$dN_{ch}/d\eta$ at 13 TeV (tracklets)





$dN_{ch}/d\eta$ at 13 TeV (tracks)





Forward energy flow

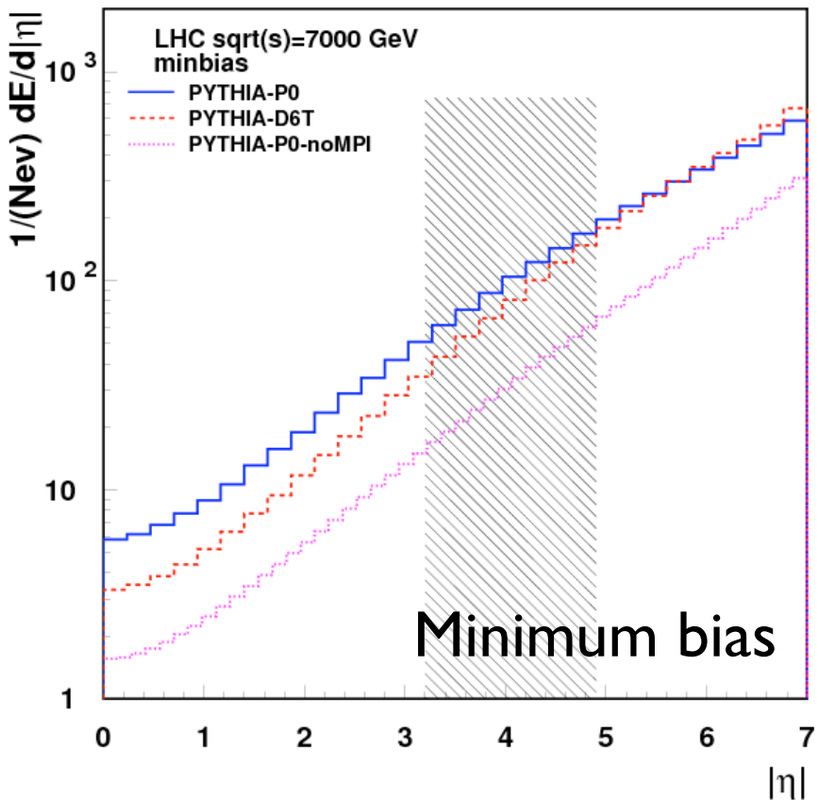
Energy flow in the forward region particularly sensitive to the underlying event (UE) dynamics

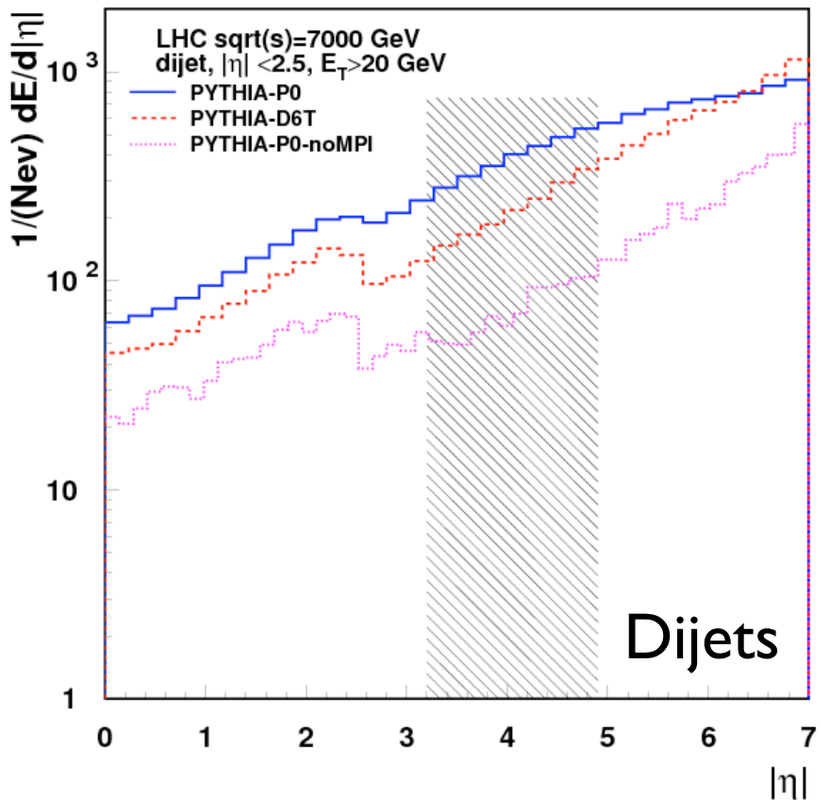
Important input in the tuning of multi-parton interactions (MPI) models at the LHC

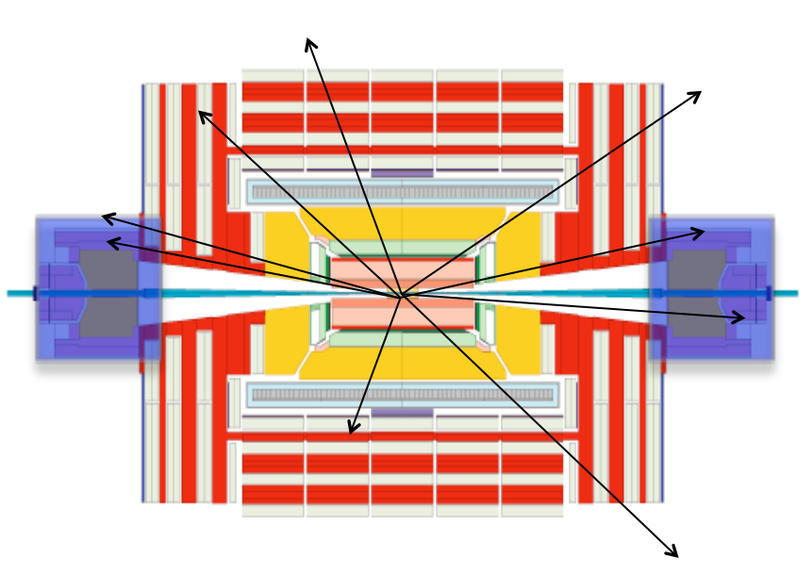
Measurement of the forward energy flow (dE/dη) in minimum bias and dijet events

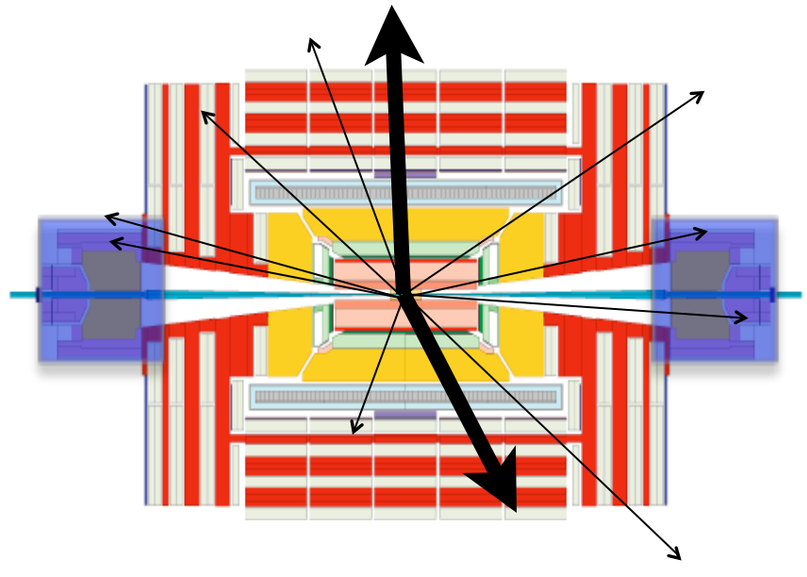
Performed in the range covered by the HF calorimeter ($3 < |\eta| < 5$)

$\sqrt{s}$ dependence from results at both 0.9 and 7 TeV









Generator level

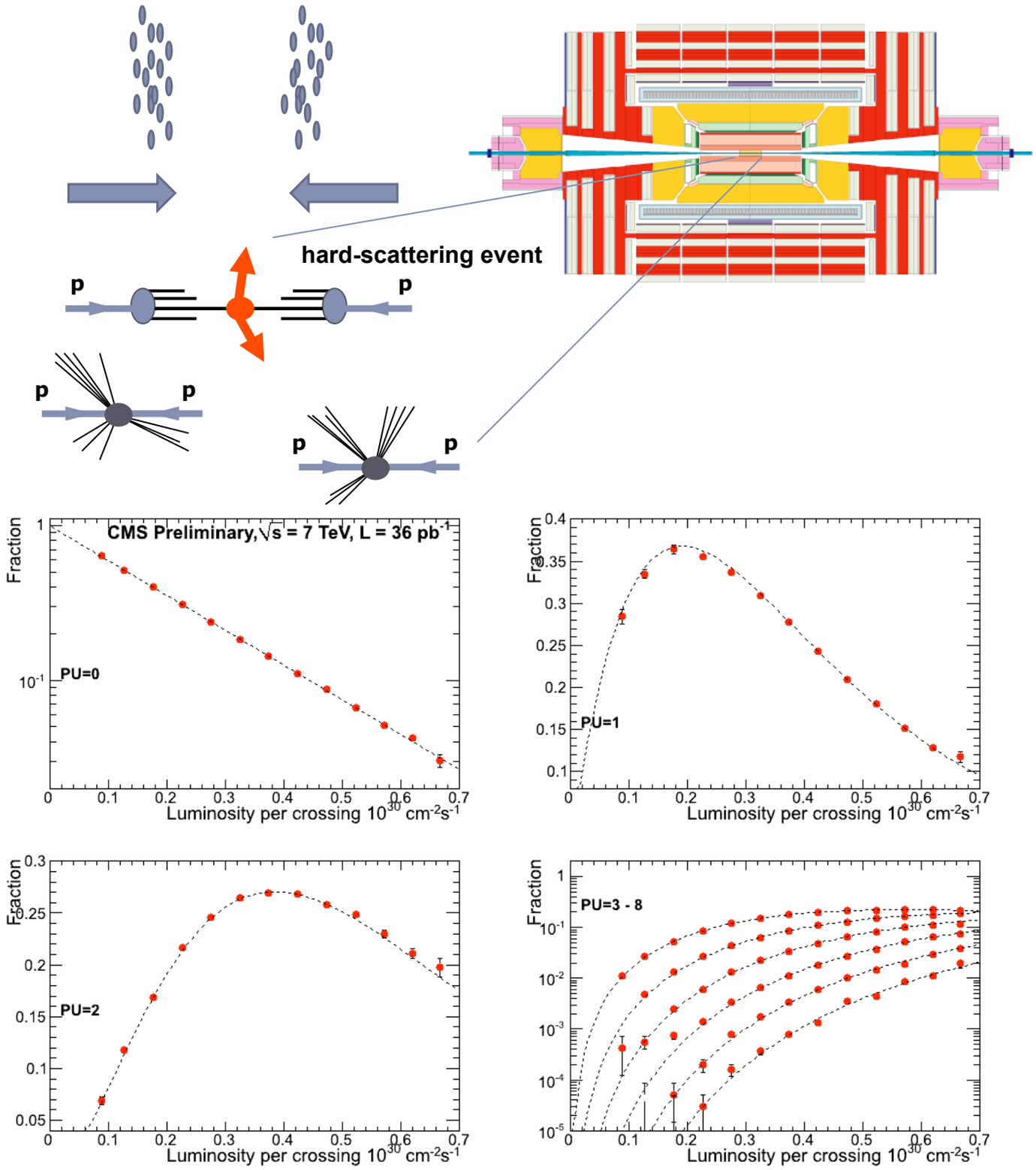
Total inelastic cross section

Additional (pile-up) interactions in a bunch crossing give an unbiased source of inelastic events

Probability follows a Poisson distribution that depends on the bunch luminosity and total cross section:

$$P(n) = \frac{(L\sigma)^n}{n!} \exp^{-L\sigma}$$

From the number of extra interactions versus luminosity the total (visible) cross section can be extracted



[CMS PAS FWD-11-001]

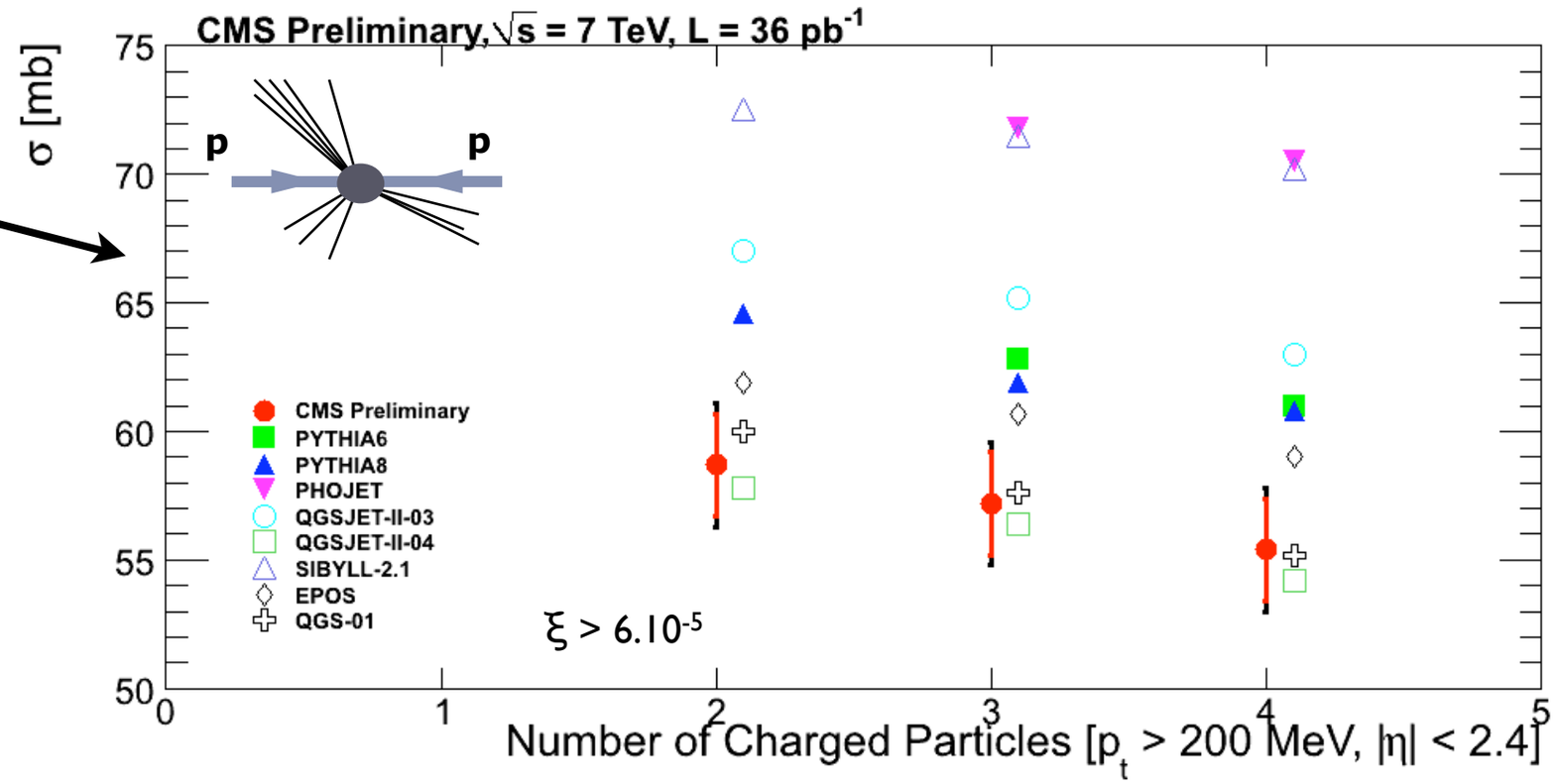
Total inelastic cross section

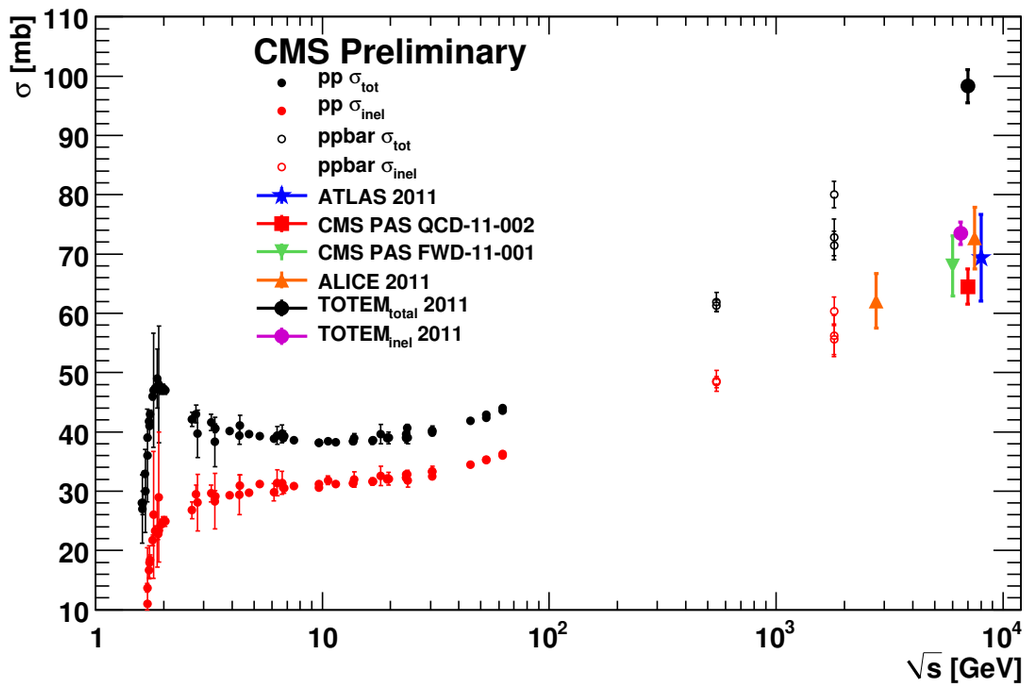
Procedure counts only (extra) events for which a vertex is reconstructed

Correct for the inelastic cross section for events with a minimum number of charged particles in the central region (p_T > 200 MeV, $|\eta|$ < 2.4)

Minimum number of (2) charged particles is roughly equivalent to a cut-off at $\xi \sim 6.10^{-5}$

MC dependent extrapolation to total inelastic cross section



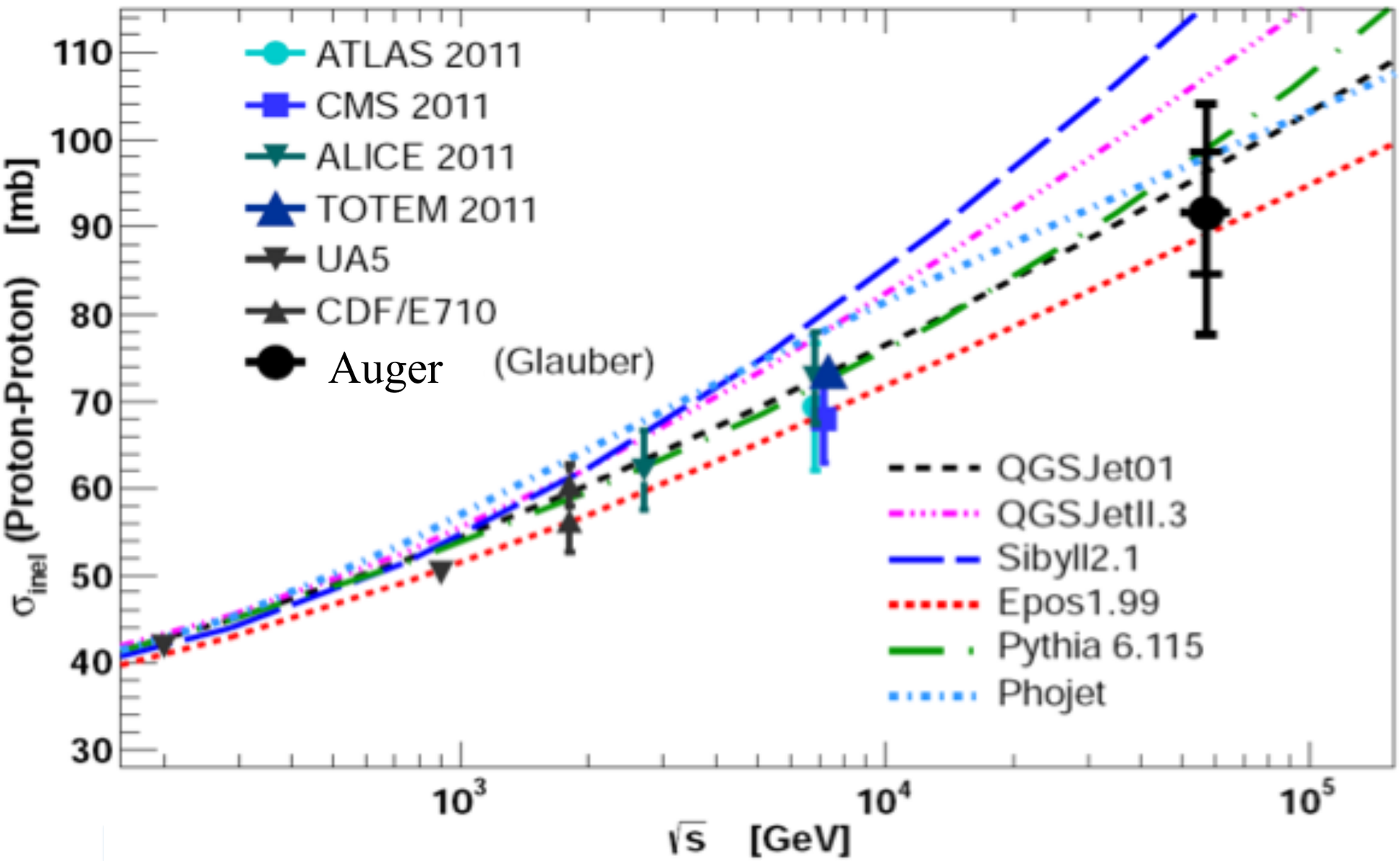


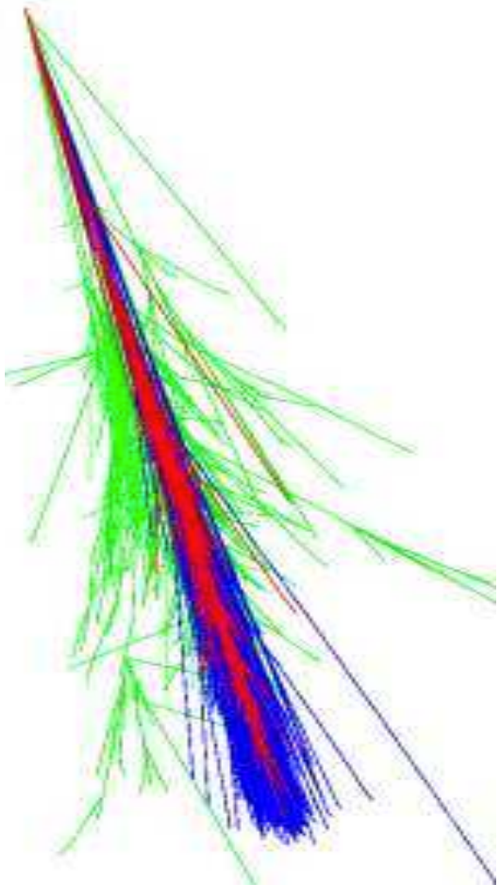
CMS (ext.)

$\sigma(pp) = 68 \pm 2.0$ (Syst.)
± 2.4(Lum.)
± 4(Ext.) mb

CMS PAS FWD-11-001

Total inelastic cross section





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