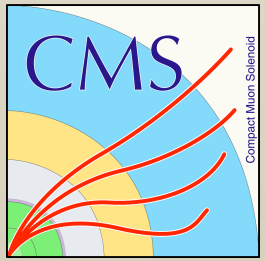


SOFT QCD AT CMS AND ATLAS

INCLUDING MIN BIAS, INELASTIC, TOTAL X-SECTIONS

Alessia Bruni, INFN Bologna, on behalf of the ATLAS and CMS Collaborations

30th Rencontres de Blois, Particle Physics and Cosmology, 3-8 June 2018

Overview

This talk presents recent ATLAS and CMS results on

- inelastic cross section, CMS arXiv:1802.02613; ATLAS Phys. Rev. Lett. 117 (2016) 182002
- exclusive $\gamma\gamma \rightarrow l^+l^-$ production, ATLAS Phys. Lett. B 777 (2018) 303; CMS+TOTEM arXiv:1803.04496
- diffractive processes – forward photons, ATLAS+LHCf ATLAS-CONF-2017-075
- underlying event, CMS arXiv:1711.04299
- double parton scattering, CMS-PAS-FSQ-16-009, CMS JHEP 02 (2018) 032
- hadronisation, CMS arXiv:1706.10194; CMS arXiv:1712.07198; ATLAS Phys. Rev. D 96 (2017) 092008

More results:

- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
- https://cms-results.web.cern.ch/cms-results/public-results/publications/FSQ/index.html

Inelastic proton-proton cross section @ 13 TeV

CMS arXiv:1802.02613; ATLAS Phys. Rev. Lett. 117 (2016) 182002

Inclusive hadronic cross sections are fundamental observable in high energy particle, nuclear, and cosmic ray physics.

ATLAS: events tagged in Minimum Bias counters, $2.07<|\eta|<3.86$, corresponding to $M_X> 13$ GeV

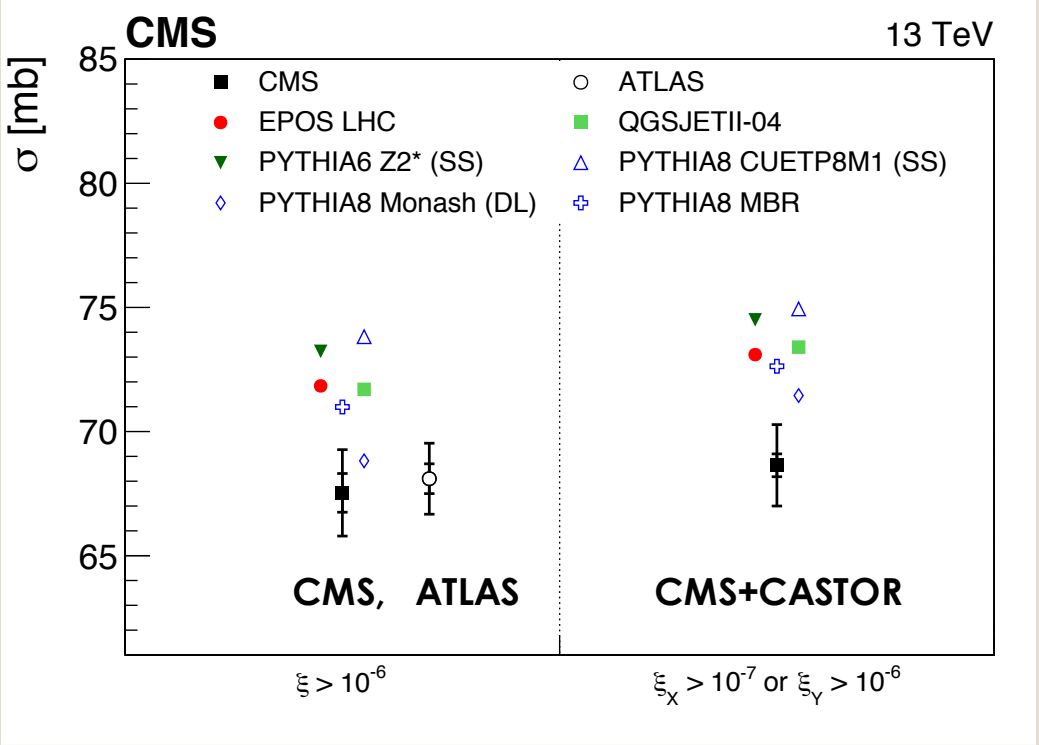
$\sigma_{inel}(\xi=M_X^2/s>10^{-6})=68.1 \pm 0.6$ (syst) ± 1.3 (lumi) mb

CMS: events tagged in Hadron Forward (HF) calorimeter $3.0<|\eta|<5.2$

$\sigma_{inel}(\xi>10^{-6})=67.5 \pm 0.8$ (syst) ± 1.6 (lumi) mb

CMS: events tagged in HF or CASTOR calorimeter $-6.6<\eta<-3.0$ and $+3.0<\eta<+5.2$, extending phase space to $M_X> 4.1$ GeV and/or $M_Y>13$ GeV

- $\sigma_{inel}(\xi_X>10^{-7}$ or $\xi_Y>10^{-6})=68.6 \pm 0.5$ (syst) ± 1.6 (lumi) mb



The total inelastic cross sections measured inside the fiducial region are smaller than those predicted by the majority of the models

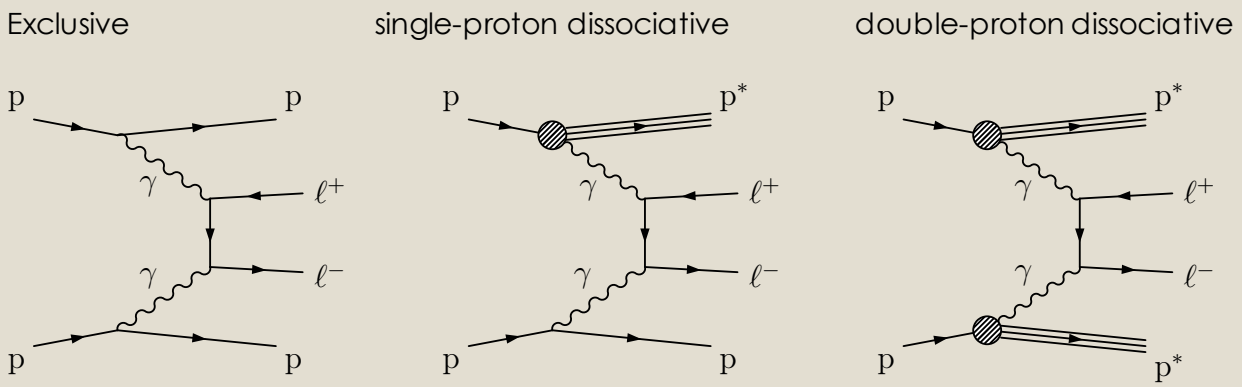
Exclusive γγ production of lepton pairs in pp @ 13 TeV

ATLAS Phys. Lett. B 777 (2018) 303; CMS+TOTEM arXiv:1803.04496

$\gamma\gamma$ induced interactions provide unique opportunity to study electroweak high energy processes

Equivalent Photon Approximation (EPA): beam of quasi-real photons with a small virtuality of $Q^2 < 0.1$ GeV^2

Small corrections due to the finite size of protons reduce the EPA cross section



- Photon induced production of lepton pairs is up to a few percent of the inclusive dilepton production at LHC energies
- Exclusive γγ → l^+l^- production process competes with the two-photon interactions involving single- or double-proton dissociation
- Proton-dissociative processes have different kinematic distributions (i.e. l^+l^-acoplanarity) and can be separated from exclusive reactions

Exclusive γγ production of lepton pairs in pp @ 13 TeV

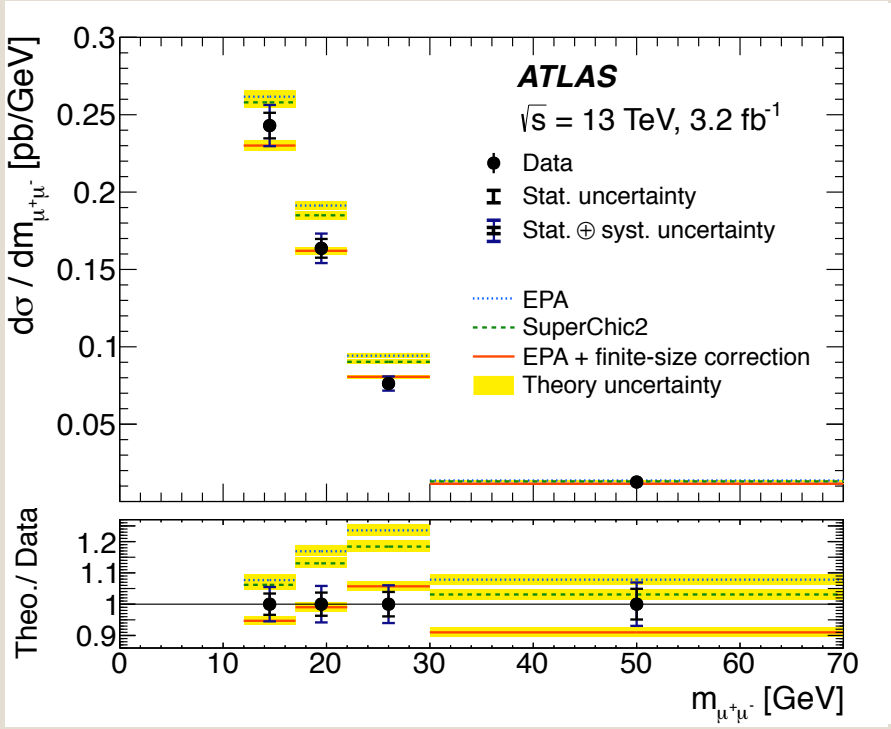
ATLAS Phys. Lett. B 777 (2018) 303

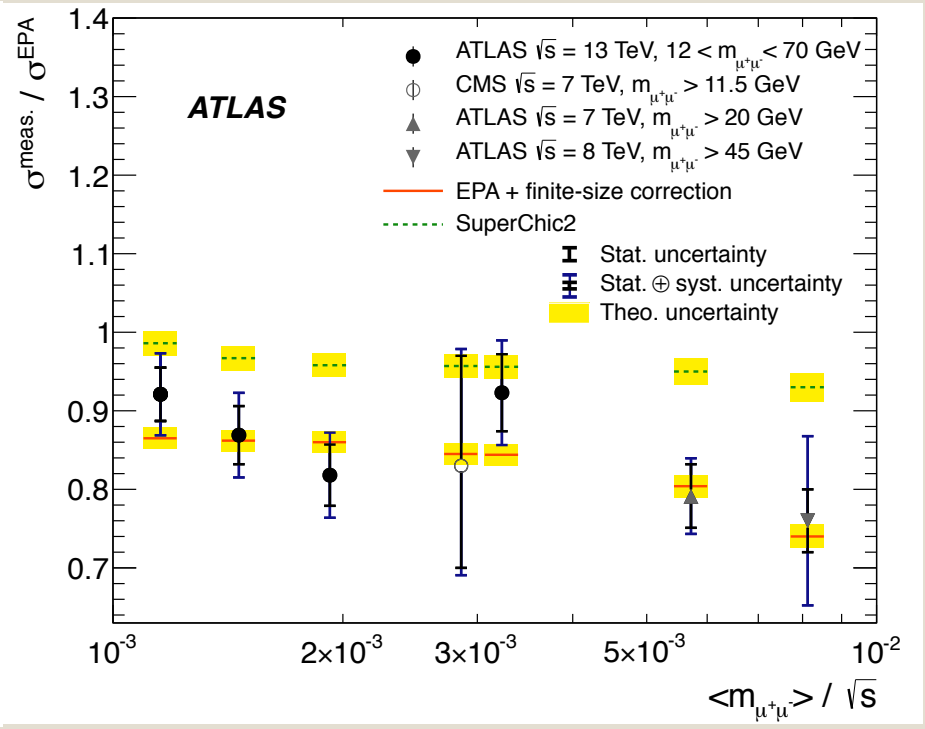
- Data: 3.2 fb^{-1} in 2015 @ 13 TeV, exactly one pair of μ+μ−

Cross sections measured in the fiducial region:

- $\sigma_{\gamma\gamma\to\mu^+\mu^-} = 3.12 \pm 0.07\ (stat.) \pm 0.14\ (syst.)$ pb
- $d\sigma/dm_{\mu^+\mu^-}$ compared to models

Invariant mass range	p_T^μ requirement	$\lvert\eta^\mu\rvert$ requirement
$12\ GeV < m_{\mu^+\mu^-} < 30\ GeV$	$> 6\ GeV$	< 2.4
$30\ GeV < m_{\mu^+\mu^-} < 70\ GeV$	$> 10\ GeV$	< 2.4





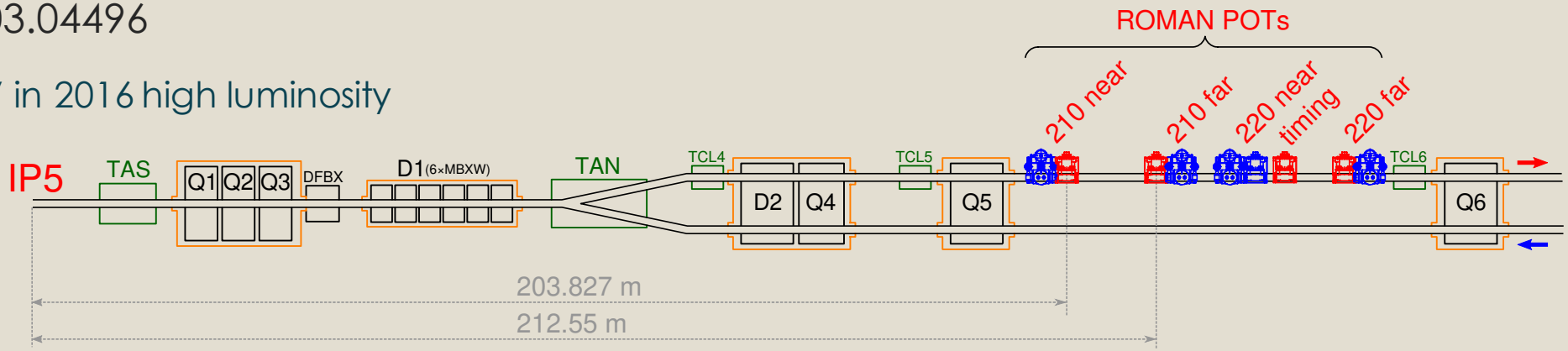
correction to the EPA cross sections measured vs the average $\langle m_{\mu^+\mu^-} \rangle$ scaled by a given *pp* centre-of-mass energy

size of absorptive corrections tends to increase with $\langle m_{\mu^+\mu^-} \rangle/\sqrt{s}$.

(semi) exclusive γγ production of lepton pairs in pp @ 13 TeV

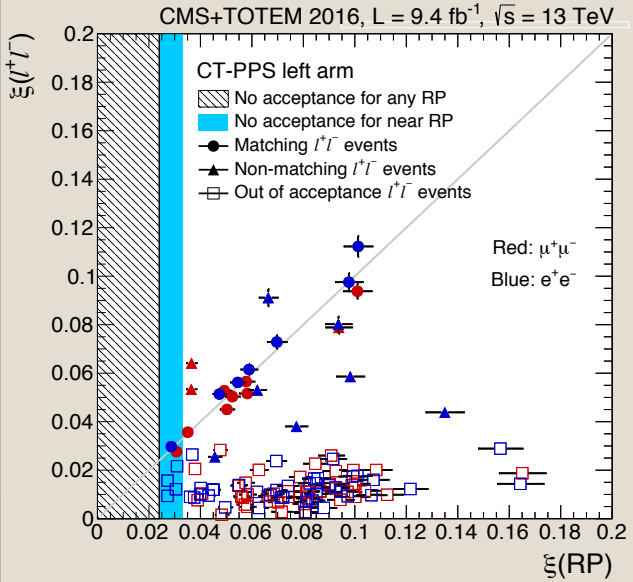
CMS+TOTEM arXiv:1803.04496

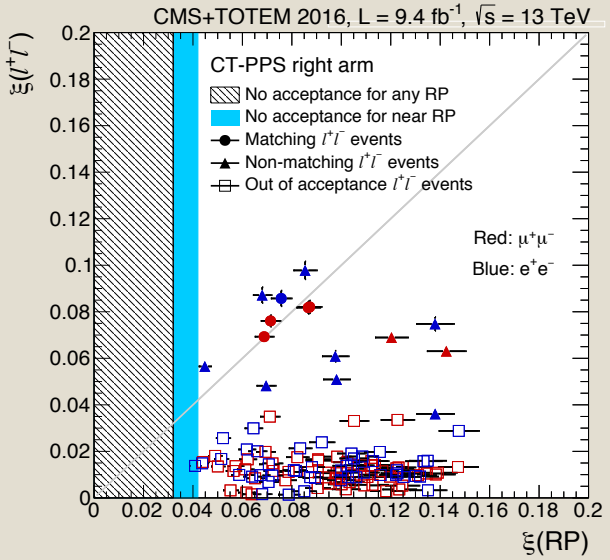
Data: 9.4 fb^{-1} @ 13 TeV in 2016 high luminosity



One proton reconstructed in CMS-TOTEM precision proton spectrometer (CT-PPS)

12 μ+μ− and 8 e+e- reconstructed in CMS with m_{ll}> 110 GeV , expected background (double-dissociative or Drell-Yan events) of 1.49 ± 0.07 (stat) ± 0.53 (syst) and 2.36 ± 0.09 (stat) ± 0.47 (syst





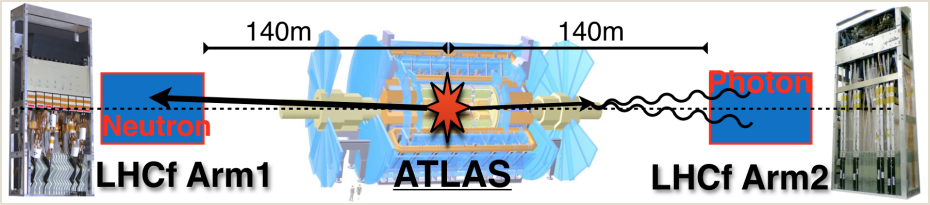
fraction of proton momentum loss $\xi = \Delta p/p$ measured in central dilepton system and the Roman Pots

First observation of proton tagged $\gamma\gamma$ collisions at electroweak scale

=> prove of feasibility of operating a near-beam spectrometer at high-luminosity

Forward photon in diffractive processes in pp @ 13 TeV

ATLAS+LHCf ATLAS-CONF-2017-075 First joint analysis of the ATLAS and LHCf collaborations



LHCf goal is to verify hadronic interaction models by measuring the forward neutral particle production at LHC. Significant discrepancies for inclusive energy spectra of forward photons between model predictions and pp data at 13 TeV were found

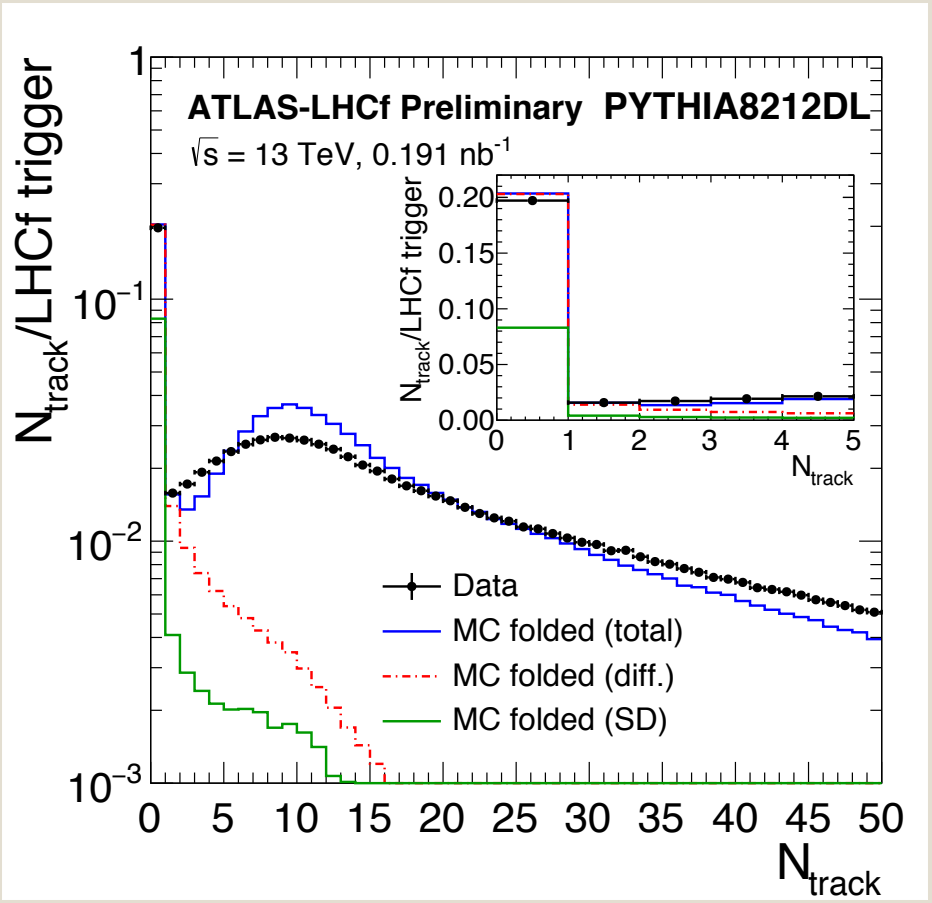
Strategy: investigate photon energy spectrum separately for diffractive and non-diffractive processes

Data: a dedicated run in 2015, at low μ~0.01, 2M events triggered by LHCf and matched with ATLAS

Photons measured in LHCf calorimeters at ±140 m from ATLAS IP, for 200 GeV < Eγ < 6 TeV and η > 10 and 8.5 < η < 9.5

Events classified according to the presence of at least one charged-particle track with p_T > 100 MeV and |η| < 2.5 in ATLAS central tracker

For N_{track} = 0 the contribution of non-diffractive events is less than 2% in all models. The ratio of N_{track} = 0 events to the total number of events is 20% in the data, whereas the same ratio predicted by the MC models varies between 6% and 20%.



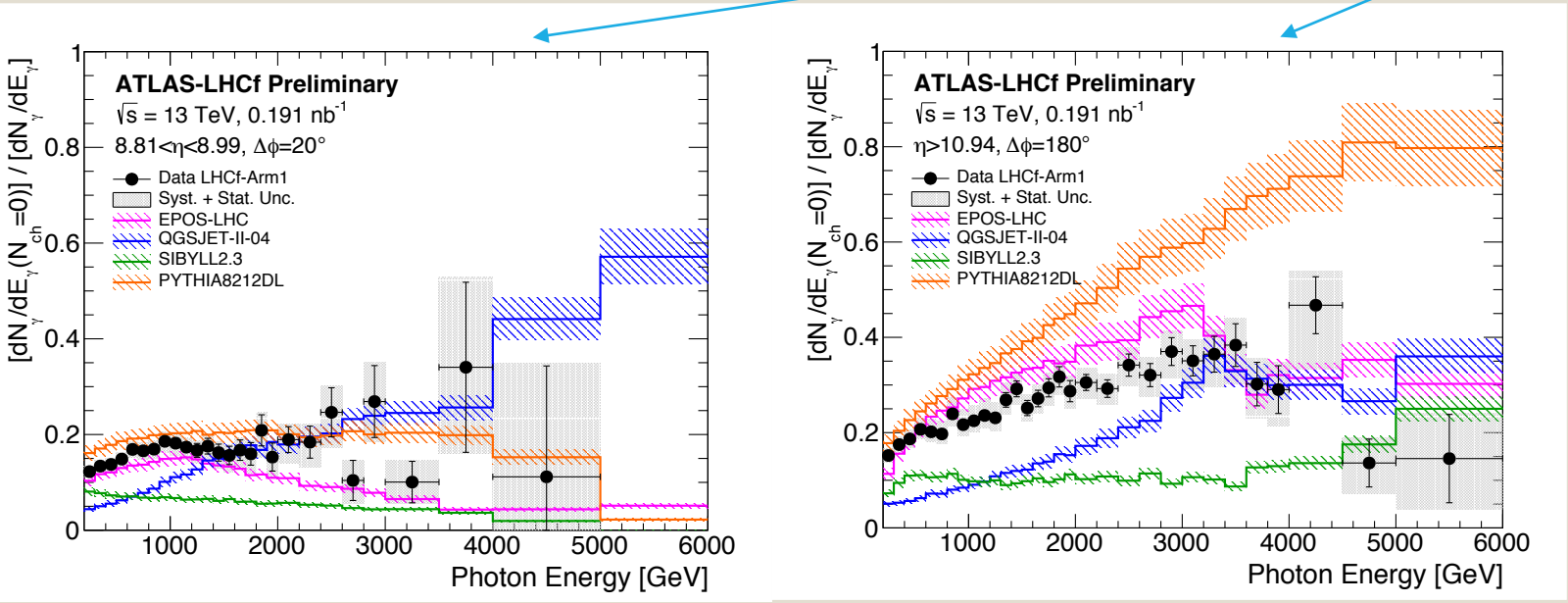
Forward photon in diffractive processes in pp @ 13 TeV

ATLAS+LHCf ATLAS-CONF-2017-075

The inclusive-photon spectra is compared to spectra for events with no extra charged particles with $p_T > 100$ MeV and $|\eta| < 2.5$.

ratio between the diffractive enriched $N_{nch}=0$ and inclusive photon spectra in different η regions:

- increases from 0.15 to 0.4 with increasing photon energy up to 4 TeV at $\eta > 10.94$
- is relatively constant (around 0.15) at $8.81<\eta<8.99$.



PYTHIA 8 predicts significantly higher diffractive fraction than observed in data

EPOS-LHC describes the data

QGSJET-II-04 and SYBILL 2.3 predict a too small contribution of low-mass diffractive events

Joint analysis of LHCf and ATLAS to validate hadronic interaction models helps in addressing open questions form ultra-high energy cosmic-ray events

Underlying event measured in Z production pp @ 13 TeV

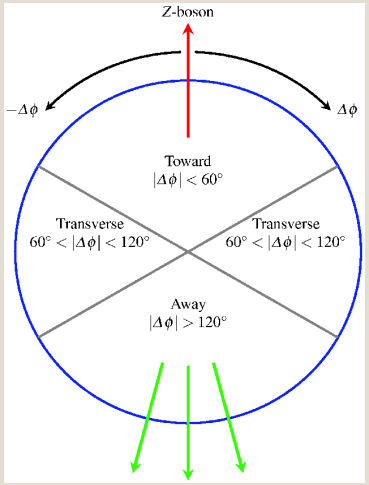
CMS arXiv:1711.04299

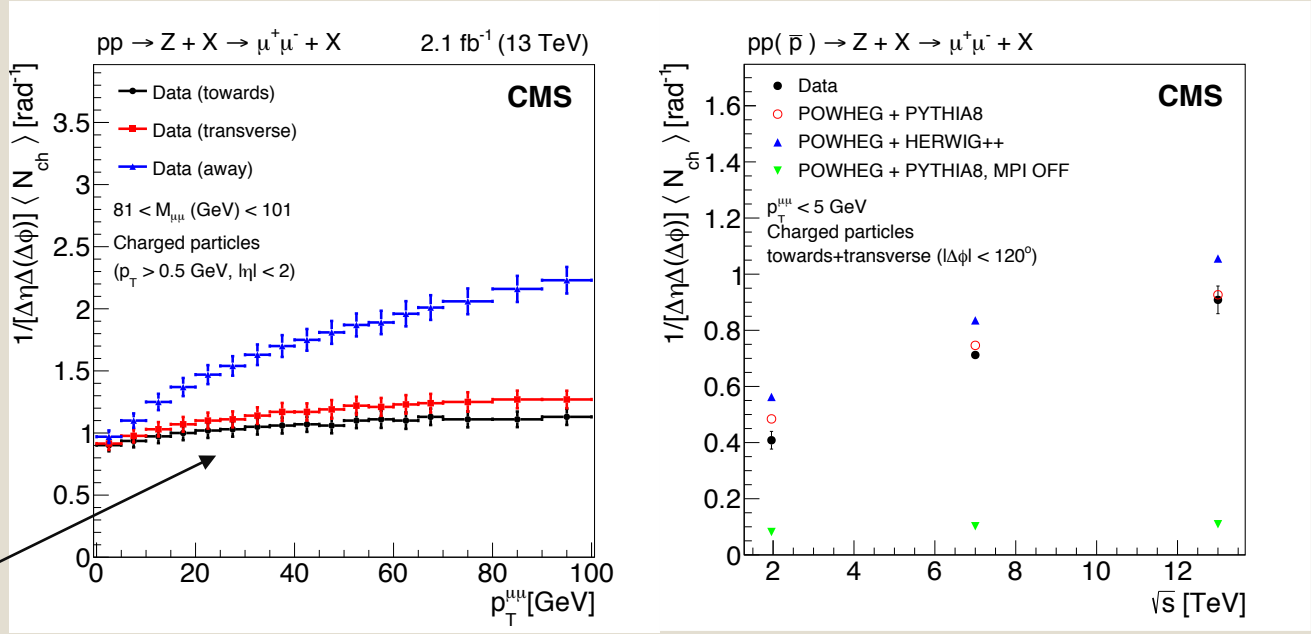
Data: 2.1 fb^{-1} pp @ 13 TeV in 2015; Z →μ+μ−

The activity accompanying the hard scattering is defined as UE. It includes beam-beam remnant interactions, multiple parton interactions (MPI)

Measurements relevant for better understanding of the mechanism involved and MC tuning.

Strategy: Azimuthal plane of the event segmented into distinct regions with respect to the leading particle (toward, away and transverse) that have different sensitivity to UE





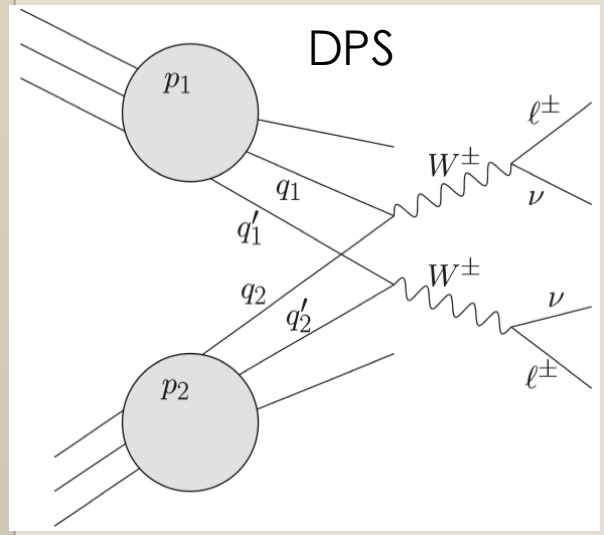
particle density, plateau in **towards** and **transverse** region

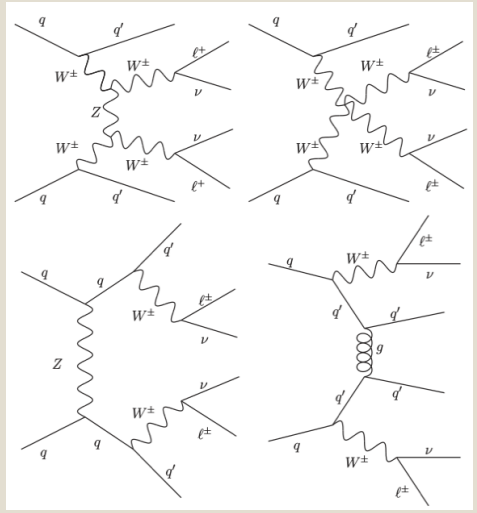
The UE activity almost doubles as the collision energy increases from 1.96 (CDF)to 13 TeV

MC generators, tuned on different processes, provide a reasonable description of the evolution of the UE activity as the collision energy rises from 1.96 to 13 TeV and confirm universality of the physical processes producing the underlying event in pp collisions at high energies

Double parton scattering investigated for same-sign WW production @ 8 and 13 TeV CMS JHEP 02 (2018) 032, CMS-PAS-FSQ-16-009

At LHC, significant probability of multiple parton-parton scattering same signWW->μμ or eμ





	$\mu^+\mu^+$	$\mu^-\mu^-$	$e^+\mu^+$	$e^-\mu^-$
fakes	151.1 ± 26.6	132.7 ± 23.4	412.7 ± 47.2	341.4 ± 39.0
WZ	277.2 ± 28.1	164.5 ± 16.7	355.9 ± 36.1	228.1 ± 23.2
ZZ	24.8 ± 7.0	18.7 ± 5.3	57.8 ± 16.4	55.8 ± 15.8
$W\gamma*$	85.9 ± 27.5	73.1 ± 23.4	142.8 ± 45.7	127.7 ± 40.9
other rare	39.7 ± 15.0	20.2 ± 7.7	83.7 ± 31.7	49.4 ± 18.8
charge flips	—	—	20.4 ± 0.0	21.5 ± 0.0
background	578.6 ± 50.3	409.2 ± 38.2	1073.3 ± 83.0	824.0 ± 65.8
DPS WW	41.1 ± 1.0	20.6 ± 0.5	48.7 ± 1.2	24.1 ± 0.6
observed	604	411	1091	869

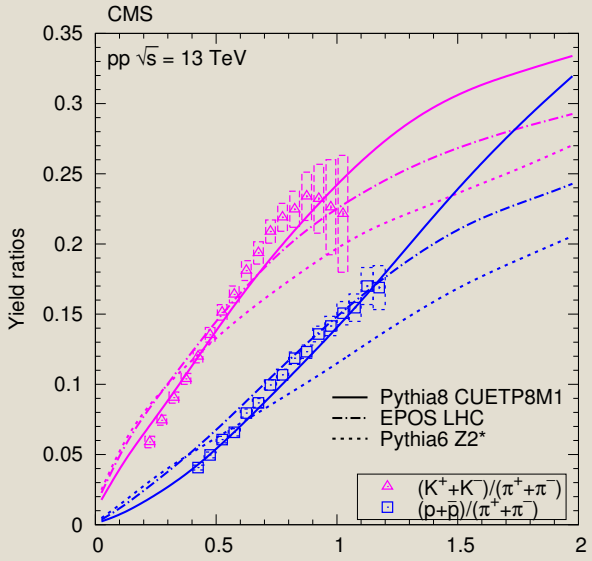
two leptons: $e^\pm\mu^\pm$ or $\mu^\pm\mu^\pm$
$p_T^{\ell 1} > 25$ GeV , $p_T^{\ell 2} > 20$ GeV
$|\eta_e| < 2.5$, $|\eta_\mu| < 2.4$
$E_T^{miss} > 15$ GeV
$N_{jets} < 2$ ($p_T > 30$ GeV)
$N_{b\text{-}jets} = 0$ ($p_T > 25$ GeV)
veto on additional leptons
veto on hadronic τ lepton decays

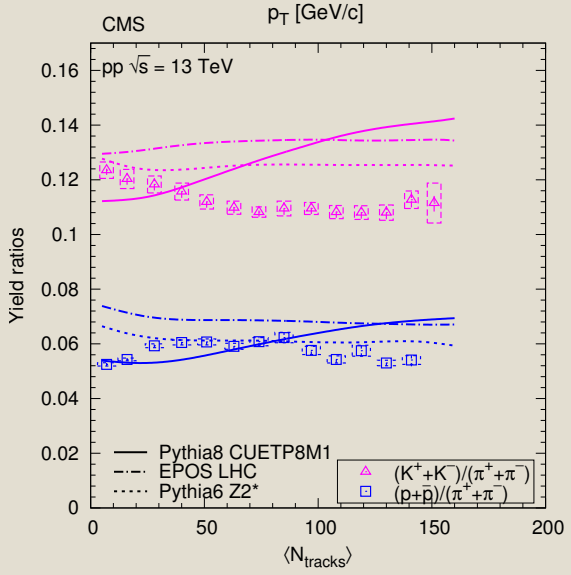
	expected	observed
σ_{DPSWW}^{pythia}	1.64 pb	$1.09^{+0.50}_{-0.49}$ pb
$\sigma_{DPSWW}^{factorized}$	0.87 pb	
significance for σ_{DPSWW}^{pythia}	$3.27\,\sigma$	$2.23\,\sigma$
significance for $\sigma_{DPSWW}^{factorized}$	$1.81\,\sigma$	
UL in the absence of signal	< 0.97 pb	< 1.94 pb

Data: 19.7 fb^{-1} in 2012 @ 8 TeV
no significant excess observed

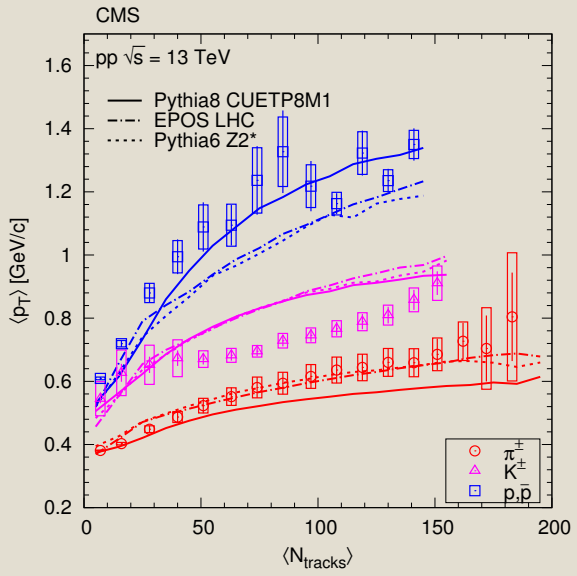
Data 35.9 fb^{-1} in 2016 @ 13 TeV
Extracted cross section: σ =1.09± 0.50 pb, compatible with MC predictions

Production of charged pions, kaons and protons in pp @ 13 TeV CMS arXiv:1706.10194





- Data: special run with low pileup @ 13 TeV, minimum bias trigger
- Particles identified via energy loss in silicon tracker, p<0.15 GeV electrons, p<1.2 GeV pions, p<1.05 GeV kaons, p<1.7 GeV protons, $|\eta|<2.4$. Measured for $0.1<p_T<1.7$ GeV and rapidity $|y|<1$
- Goal: investigate hadron generation, ie. sensitivity to multiple gluon minijets.
- Ratio of particles described by MC, increases with p_t, const. with N_{trk}



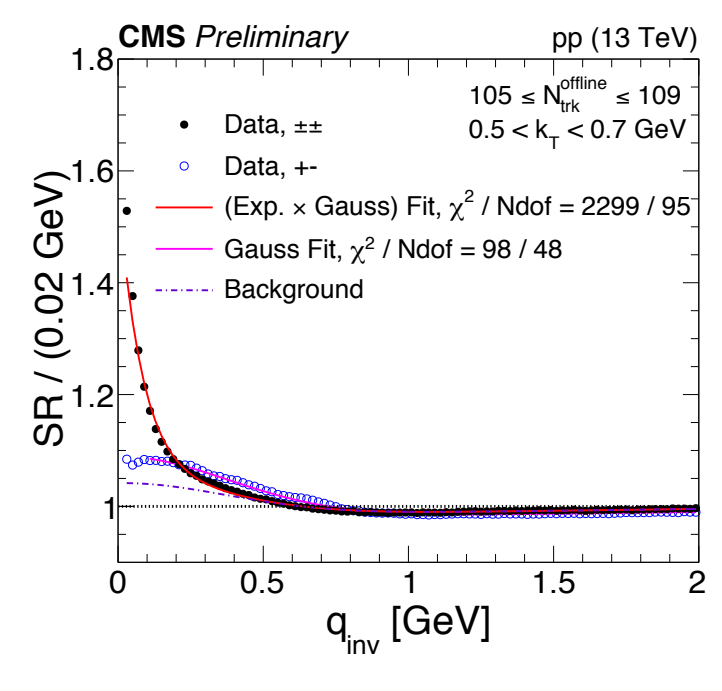
- $\langle p_T \rangle$ is strongly correlated with particle multiplicity N_{trk}, that is related to the number of underlying parton-parton interactions
- MC parameters that control the strangeness and baryon production vs parton multiplicity, need additional fine-tuning
- Small or no dependence on CM energy of pp collisions

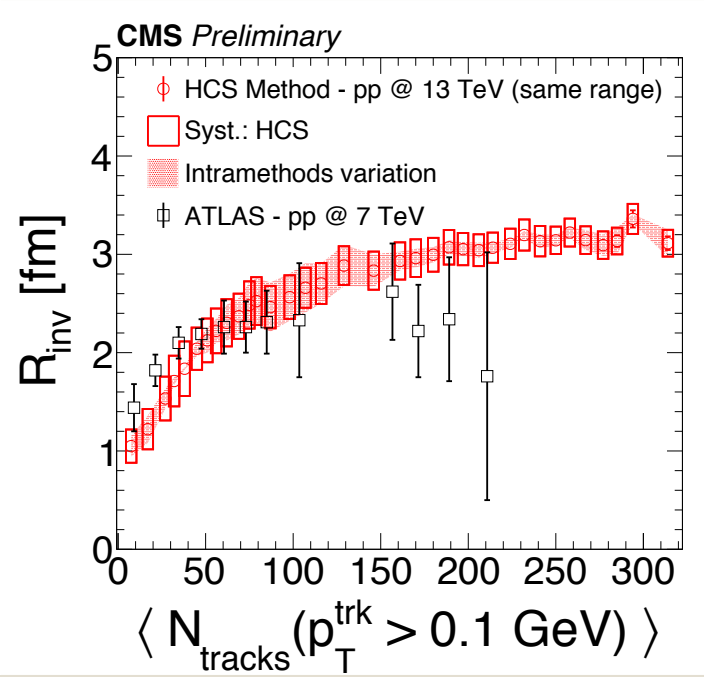
Bose-Einstein correlations in pp @ 13 TeV
CMS-PAS-FSQ-15-009

Correlation phenomena in hadron production give info about early stage of hadron formation not yet understood from first principle

BEC effect = higher emission probability of two identical bosons with very similar momenta.

BEC investigated at 13 TeV in minimum bias events





2 particle correlation function SR(q_{inv}): probability to observe pair of particles of same sign / reference sample investigated vs

- q_{inv}, the 4-momentum difference of the 2 partons
- Multiplicity of charged particles N_{tracks}

parameter R is a measurement of emitting source effective radius.

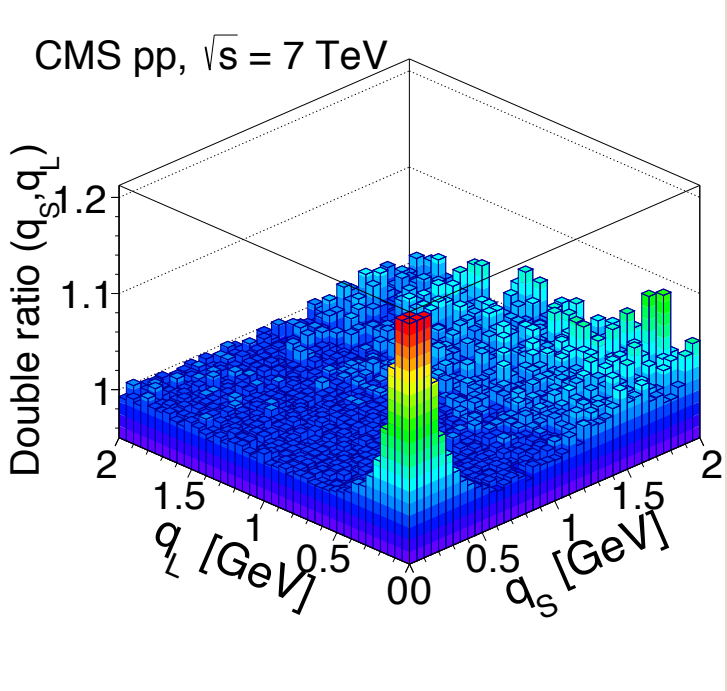
R increases as $N_{tracks}^{1/3}$ up to Ntrack~100
For larger multiplicity there is a saturation effect indicating a constant size of the emitting source

Bose-Einstein correlations in pp, pPb, and PbPb collisions at LHC

CMS arXiv:1712.07198 (up to 7 TeV), CMS-PAS-FSQ-15-009 (13 TeV)

Correlation phenomena in hadron production give info about early stage of hadron formation not yet understood from first principle

BEC effect = higher emission probability of two identical bosons with very similar momenta.



BEC investigated in minimum bias events:

- for 3 colliding systems: pp collisions 0.9, 2.76, and 7 TeV, pPb and peripheral PbPb collisions at nucleon-nucleon center-of-mass energies of 5.02 and 2.76 TeV

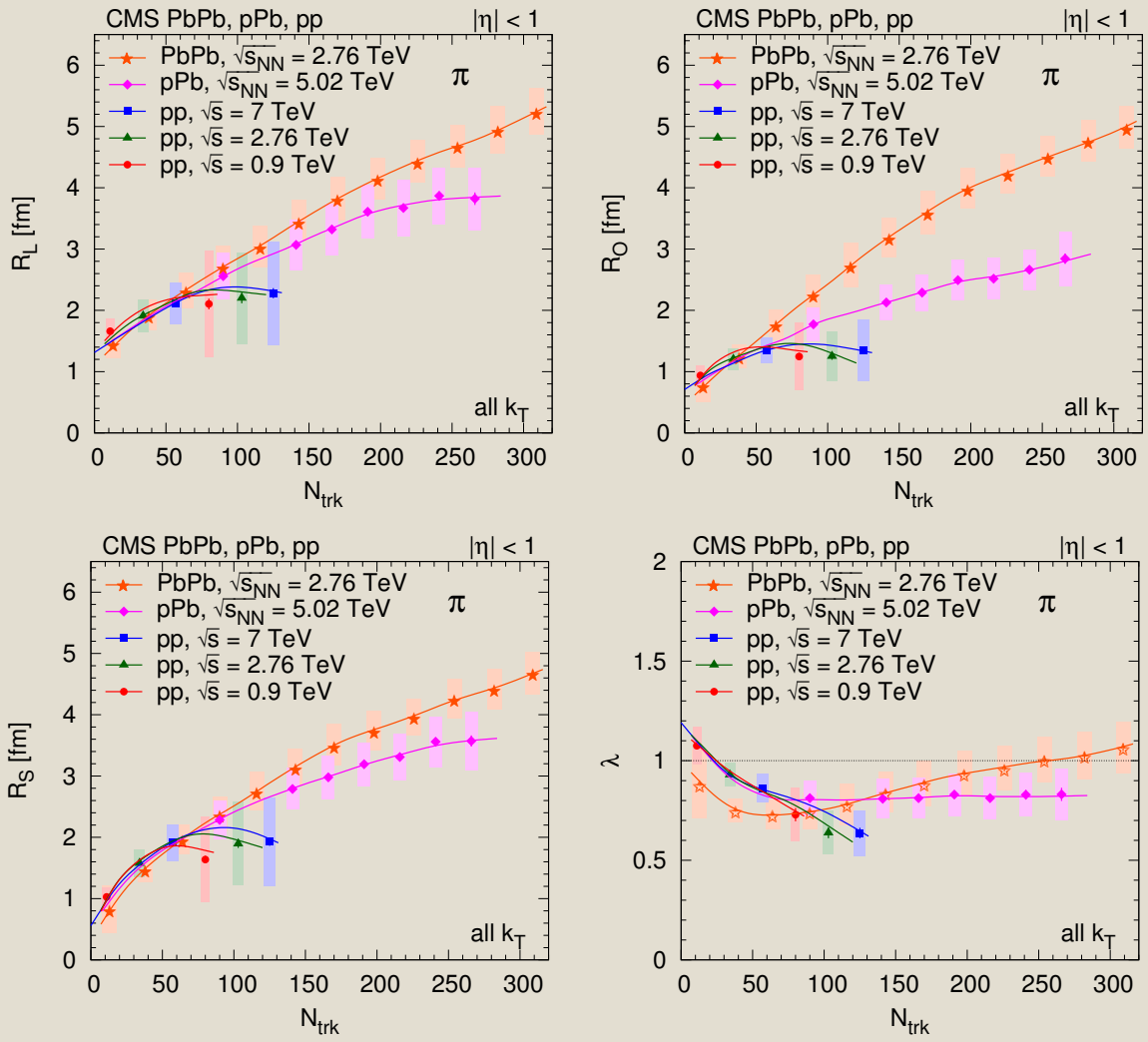
- using 2 methods: i) double ratio: probability to observe pair of particles of same sign / reference sample; data / MC
  ii) identification of π and K and cluster subtraction.

- in more dimensions: 1D (R_{inv}), 2D (R_T,R_L), and 3D (R_L,R_S,R_O) investigating correlations as a function of the k_T, q_T, q_L, q_0, q_S of the particle's pair, give info on size and shape of the emitting system.

Quantum correlation well described by exponential parameterization as a function of the relative momentum of the particle pair, both in 1D, 2D and 3D, consistent with a Cauchy-Lorentz spatial source

Bose-Einstein correlations in pp, pPb, and PbPb collisions at LHC

CMS arXiv:1712.07198



Radii investigated as functions of charged multiplicity N_{trk} and pair average transverse momentum k_T

The fitted radius parameters R increase with charged-particle multiplicity N_{trk} for all colliding systems

Radii are in the range 1-5 fm, max for PbPb collisions at high multiplicity
Sources are elongated for pp and pPb, while they are more symmetric for peripheral PbPb
Small differences between π and K

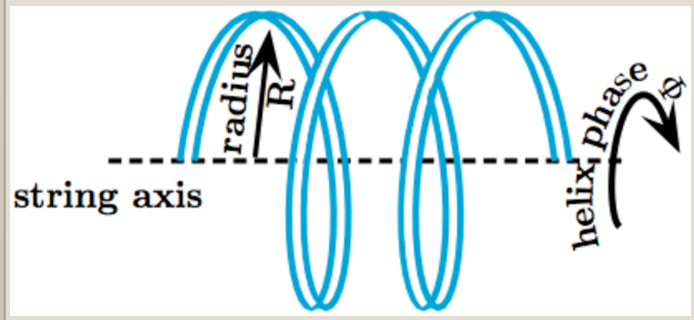
Radii are approx. Independent from CM energy; the dependence on N_{trk} and k_T factorize

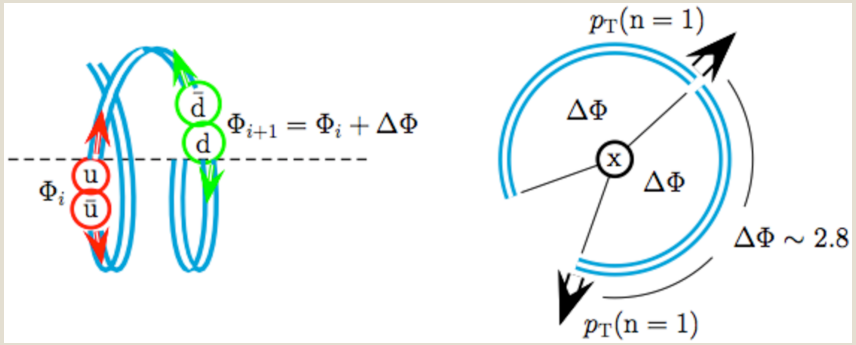
Study of ordered hadron chains at LHC and QCD string fragmentation models ATLAS Phys. Rev. D 96 (2017) 092008, arXiv:1709:07384

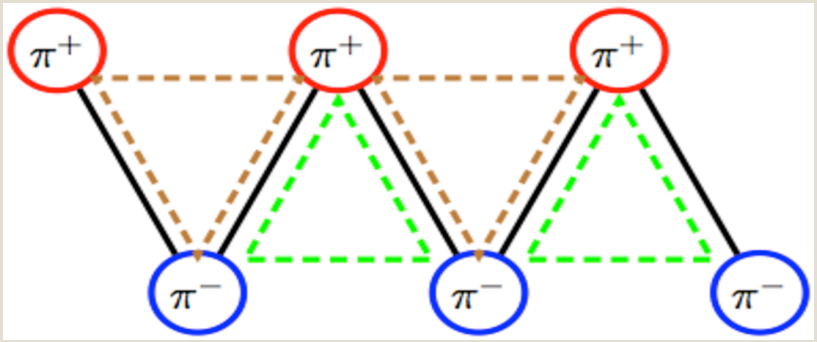
Correlation phenomena in hadron production used to investigate QCD

Quark confinement: for large charge separation, QCD field lines seem to be compressed to tubelike regions => QCD field approximated by strings (i.e. 1D string in Pythia Lund model)

- Quantized string fragmentation models: 3D string with helicity conservation in gluon emission => helix shaped string. An effective quantization is imposed







Observables are related to string parameters: the quantized helix phase ΔΦ and the transverse shape of string R radius and string tension k (~1 GeV/fm)

$$E_T(n) = n\kappa R \Delta\Phi \qquad p_T(n) = 2\kappa R \,|\sin(n\Delta\Phi/2)|$$

Pseudoscalar meson (π, η, η')can be seen as string pieces fragmenting in ground state hadrons with n=1,3,5. Their mass spectrum is used to extract the helical QCD field parameters

Search of chains of correlated adjacent hadrons

ATLAS Phys. Rev. D 96 (2017) 092008, arXiv:1709:07384

- 4-momentum difference Q between ground state pions can be predicted according their "rank" (position in the chain)

	OS	LS	OS	LS	OS
Pair rank difference r	1	2	3	4	5
Q expected [MeV]	266 ± 8	91 ± 3	236 ± 7	171 ± 5	178 ± 5

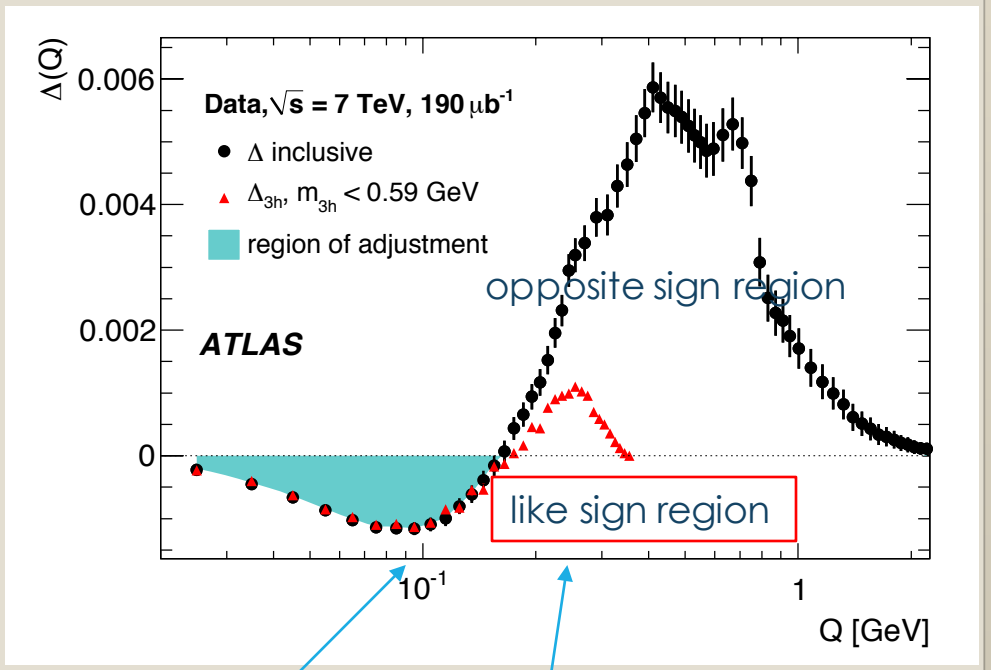
Strategy:

1) construct chains of 3 pions (choosing the like'sign partner (LS) giving the minimal momentum difference, and adding an opposite charge hadron (OS) producing the overall minimum mass)

2) construct a correlation function $\Delta Q=[N(Q)^{OS}- N(Q)^{SS}]/N_{CH}$

and ΔQ_{3h} from pairs belonging to the exclusive particle chains selection

correlation function vs Q



Enhanced like sign distribution at low Q can be entirely attributed to 3 –hadron chains

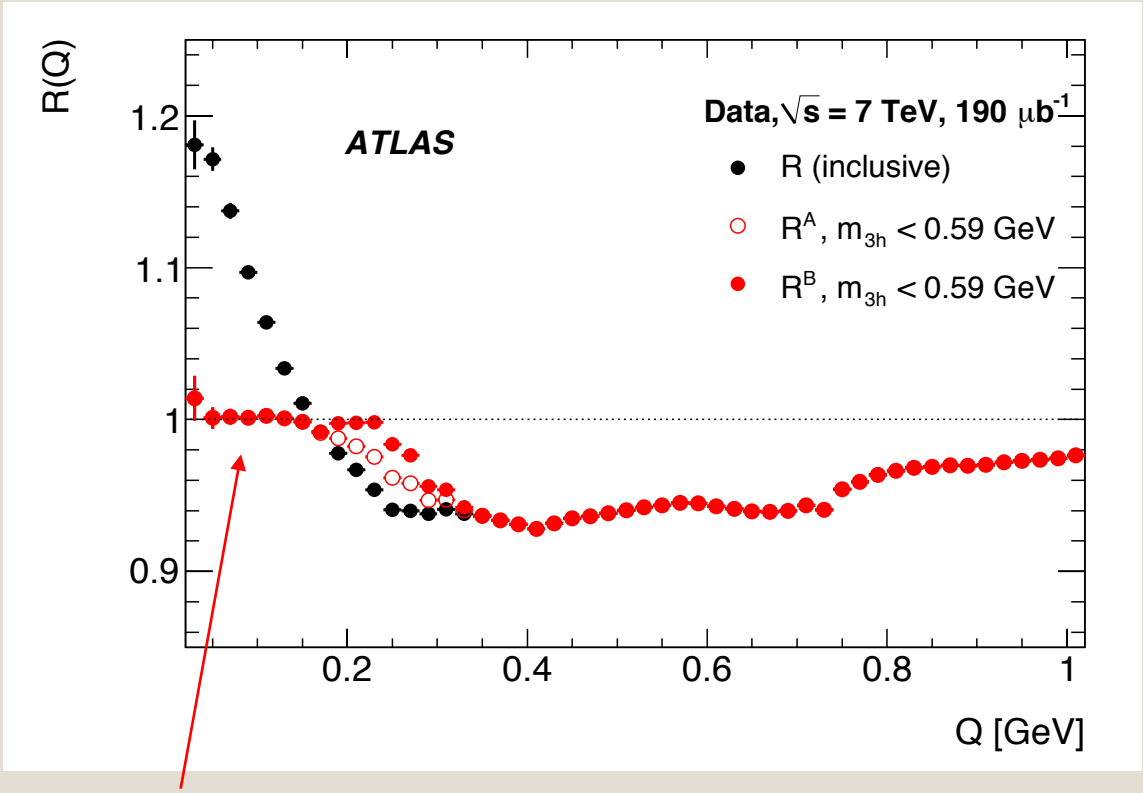
as predicted by the model, 3-hadron chains is asymmetric with peaks at:
91 MeV (like sign) and 266 MeV (opposite sign)

Study of ordered hadron chains at LHC and QCD string fragmentation models ATLAS Phys. Rev. D 96 (2017) 092008, arXiv:1709:07384

Enhanced production of pairs of like-sign charged hadrons is traditionally attributed to the Bose-Einstein effect originating in the symmetrization of the quantum-mechanical amplitude with respect to the exchange of identical bosons

Ratio of inclusive like-sign and opposite-sign pair spectra inclusive and after the subtraction of the 3-hadron chains (for chains of different lenght) investigated $R=N(Q)^{LS}-N(Q)^{OS}$ before and after the subtraction of contribution from ordered hadron chains, R^A, R^B

Enhanced like-sign pair production compatible with the hadron chains



after subtraction of pairs belonging to the exclusive particle chains selection

BEC find a coherent explanation within the helical QCD string model

Summary

- Recent LHC results for ATLAS, CMS, in collaboration with TOTEM, LHCf
- inelastic cross section measured at 13 TeV, $\sigma_{inel}(\xi_X>10^{-7}$ or $\xi_Y>10^{-6})=68.6 \pm 0.5$ (syst) $\pm$ 1.6 (lumi) mb
- exclusive and semi-exclusive production of yy has been measured, also with forward p tagged
- forward photon in diffractive processes can validate hadronic interactions models
- Double parton scattering of WW has been investigated, at 13 TeV an excess has been reported
- Underlying event measured in association with Z production confirms universality of such processes
- Minimum bias at 13 TeV: studied for tracks at low $p_T>100$ MeV
- Particle correlation studies:
  - Bose Einstein Correlations of same sign particles investigated in 3D
  - Study of ordered hadron chains support model of quantized fragmentation of a QCD string with helical structure: this model emerge as a powerful concept unifying previously disconnected aspects of hadron production