Recent developments in the area of SoftQCD and Diffractive Physics at the ATLAS Experiment

Róbert Astaloš

(Comenius University Bratislava)

on behalf of the ATLAS Collaboration

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Overview

- Measurement of the Inelastic Proton-Proton Cross Section at $\sqrt{s} = 13\ \mathrm{TeV}$ with the ATLAS Detector at the LHC

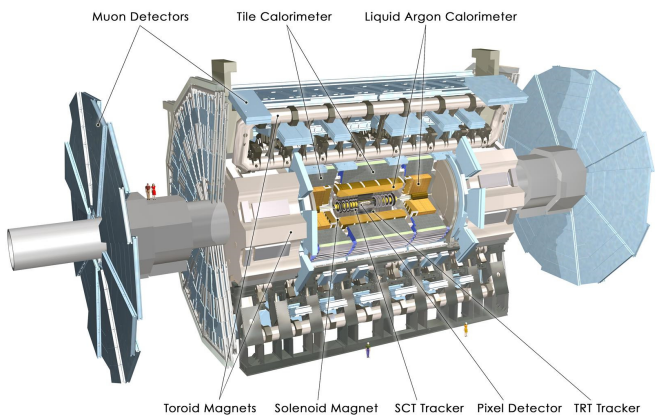
  Phys. Rev. Lett. 117 (2016) 182002, arXiv:1606.02625

- Measurement of the exclusive $\gamma\gamma \to \mu^+\mu^-$ process in *pp* collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector at the LHC

  Phys. Lett. B 777 (2018) 303, arXiv:1708.04053

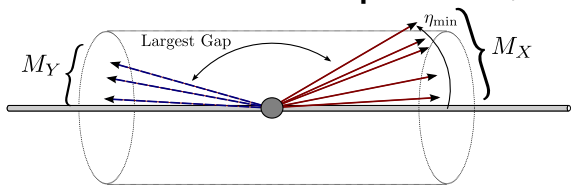
- Study of ordered hadron chains with the ATLAS detector

  Phys. Rev. D 96 (2017) 092008, arXiv:1709.07384



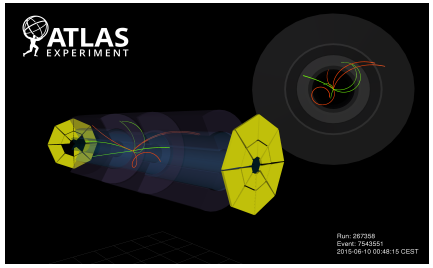
Inelastic Proton-Proton Cross Section at $\sqrt{s} = 13$ TeV

- rise of total *pp* cross section with center-of-mass energy predicted by Heisenberg $\rightarrow$ probes the nonpertubative regime of QCD
  $\rightarrow$ confirmed by many experiments
- two sets of scintillation counters, elastic *pp* scattering out of their acceptance;
  $M_X > 13$ GeV (fiducial region $\xi = M_X^2/s > 10^{-6}$)
  $\rightarrow$ then extrapolated to total inelastic cross-section

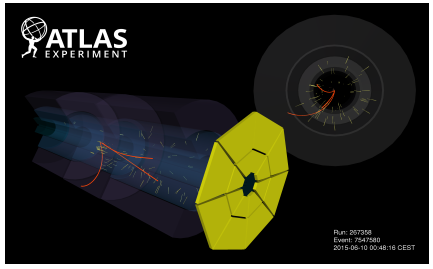


- minimum-bias trigger scintillators (MBTS):
  installed on the frontface of each endcap calorimeter ($z = \pm 3.6$ m)
  cover region: $2.07 < |\eta| < 3.86$; $149 < r < 445$ & $445.5 < r < 895$ mm
- two other forward detector used to measure trigger efficiency ϵ_{trig}:
  - forward Cherenkov detector LUCID ($z = \pm 17$ m): $5.6 < |\eta| < 5.9$
  - tungsten-scintillator calorimeter det. LHCf ($z = \pm 140$ m): $|\eta| > 8.4$

- **inclusive** selection: at least 2 MBTS counters
  with charge above 0.15 pC ($n_{\text{MBTS}} \geq 2$)
  4 159 074 events passing



- **single-sided** selection: hits in ≥ 2 counters on one side of the detector and no hits on the other to constrain diffractive component
  442 192 events passing



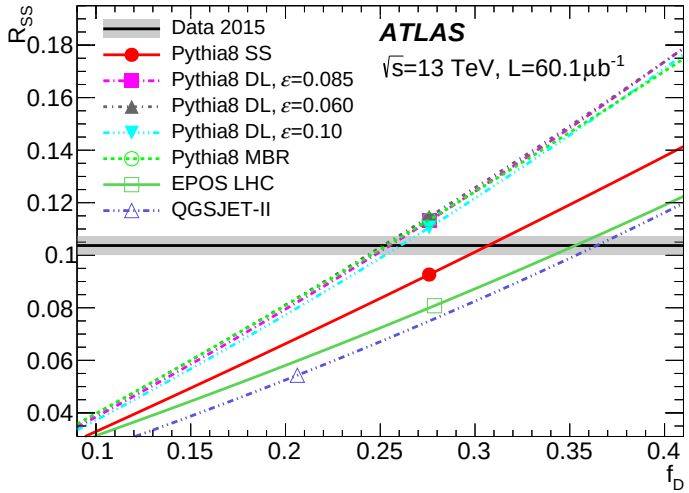
Monte Carlo models

$$R_{SS} = \frac{\text{number of events passing the singlesided selection}}{\text{number of events passing the inclusive selection}}$$

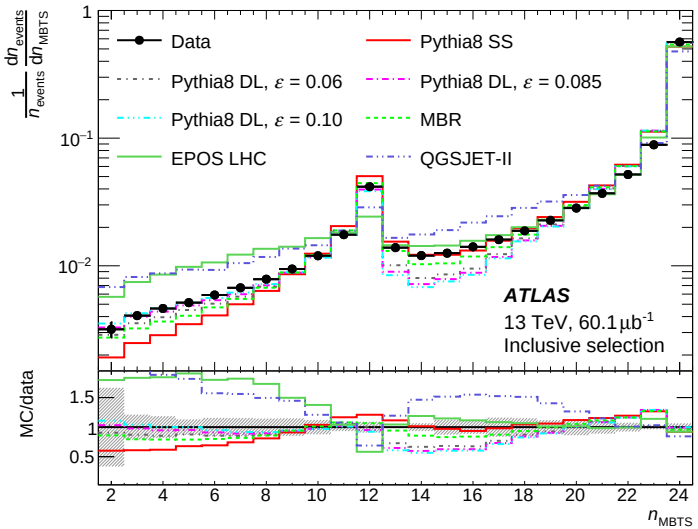
used to adjust for each MC the fraction:

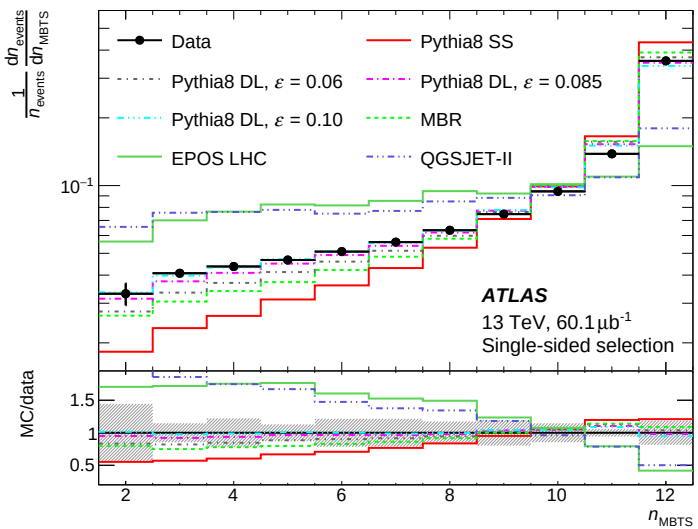
$$f_D = (\sigma_{SD} + \sigma_{DD})/\sigma_{inel}$$

obtained $R_{SS} = 10.4 \pm 0.4\%$ (stat + syst)



n_{MBTS} distributions in data compared to ones from MC utilizing the fitted f_D value:





best agreement with DL and MBR-based models; other do not describe data well

Pythia8 DL with $\varepsilon = 0.085$ chosen as the nominal MC model

only DL and MBR models considered for MC systematics

Fiducial inelastic cross section

fiducial cross section $\sigma^{\text{fid}}_{\text{inel}}(\xi > 10^{-6}) = \frac{N - N_{\text{BG}}}{\epsilon_{\text{trig}} \times \mathcal{L}} \times \frac{1 - f_{\xi < 10^{-6}}}{\epsilon_{\text{sel}}}$

Factor	Value	Rel. uncertainty
Number of events passing the inclusive selection (N)	4159074	–
Number of background events (N_{BG})	51187	$\pm 50\%$
Integrated luminosity [μb^{-1}] ($\mathcal{L}$)	60.1	$\pm 1.9\%$
Trigger efficiency (ϵ_{trig})	99.7%	$\pm 0.3\%$
MC correction factor (C_{MC})	99.3%	$\pm 0.5\%$

$C_{\text{MC}} = \frac{1 - f_{\xi < 10^{-6}}}{\epsilon_{\text{sel}}}$ – migration of events with $\xi < 10^{-6}$ into the fiducial region

– event selection efficiency

systematic uncertainties include: counter efficiency variations impact of the material uncertainty, uncertainty in the fitted value of f_{D}, and variations in C_{MC} found by comparing Pythia8 DL and MBR models

measured fiducial cross section: $\sigma^{\text{fid}}_{\text{inel}} = 68.1 \pm 0.6(\text{exp}) \pm 1.3(\text{lum})$ mb

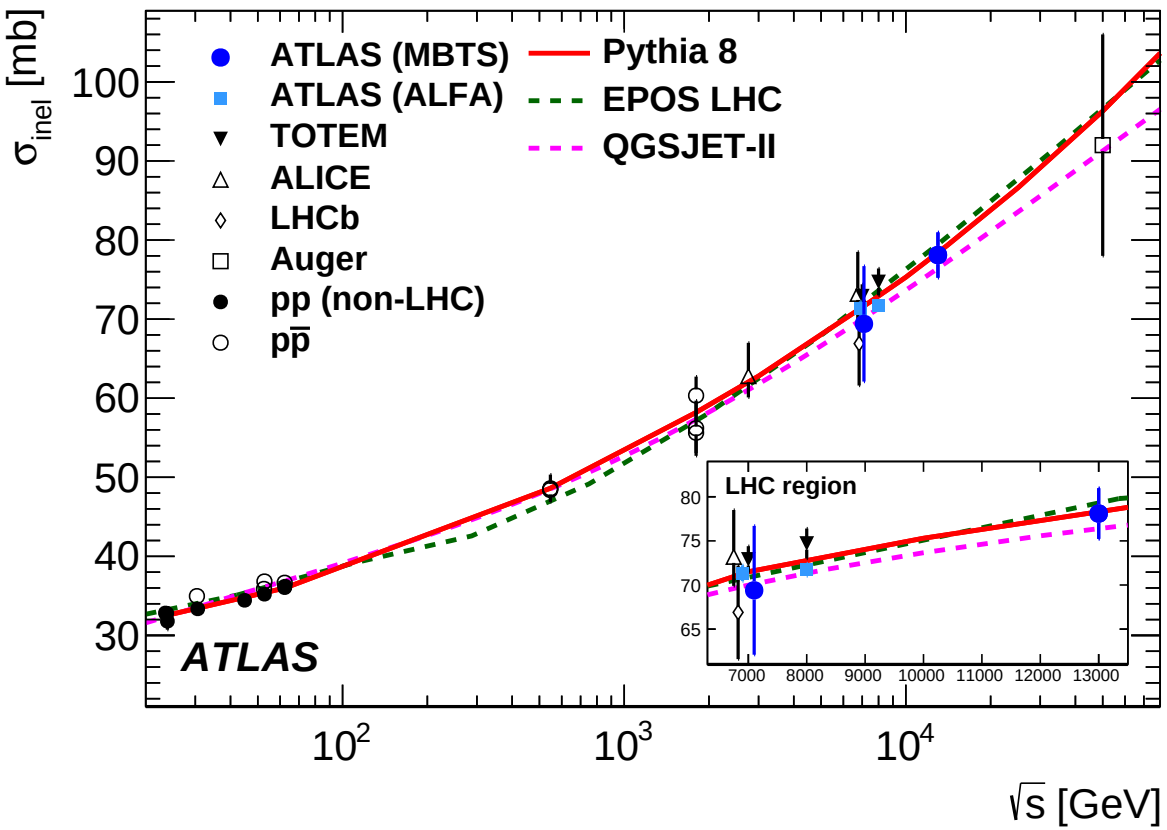
MC predictions: Pythia8 DL: 71.0 mb (ε=0.06); 69.1 mb (ε=0.085); 68.1 mb (ε=0.1)
Pythia8 MBR: 70.1 mb
EPOS LHC: 71.2 mb
QGSJet-II: 72.7 mb
Pythia8 SS: 74.4 mb

Total inelastic cross section

total cross section $\sigma_{\text{inel}} = \sigma_{\text{inel}}^{\text{fid}} + \sigma^{7\text{TeV}}(\xi < 5 \times 10^{-6}) \times \frac{\sigma^{\text{MC}}(\xi < 10^{-6})}{\sigma^{7\text{TeV,MC}}(\xi < 5 \times 10^{-6})}$

$\sigma^{7\text{TeV}}(\xi < 5 \times 10^{-6})$ is difference between $\sigma_{\text{inel}}^{7\text{TeV}}$ measured using ALFA detector and $\sigma^{7\text{TeV}}(\xi > 5 \times 10^{-6})$ measured using MBTS

measured total cross section: $\sigma_{\text{inel}} = 78.1 \pm 0.6(\text{exp}) \pm 1.3(\text{lum}) \pm 2.6(\text{extrap})$ mb



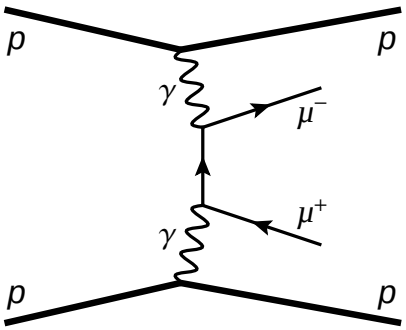
measured cross section agrees well with variety of theoretical predictions

is consistent with the inelastic cross section increasing with $\sqrt{s}$

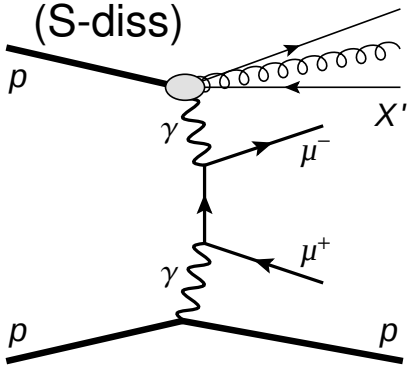
Exclusive $\gamma\gamma \to \mu^+\mu^-$ production

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

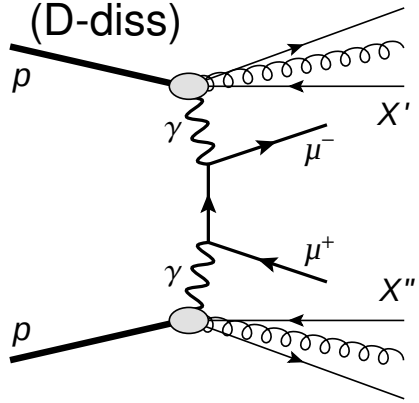
exclusive production



single-proton dissociation (S-diss)

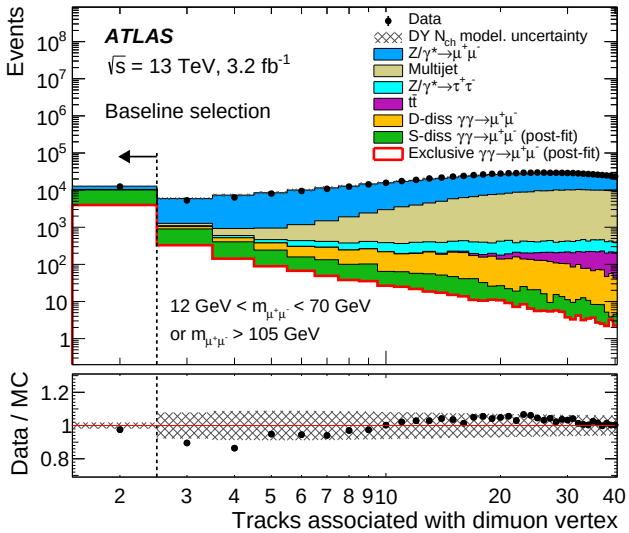


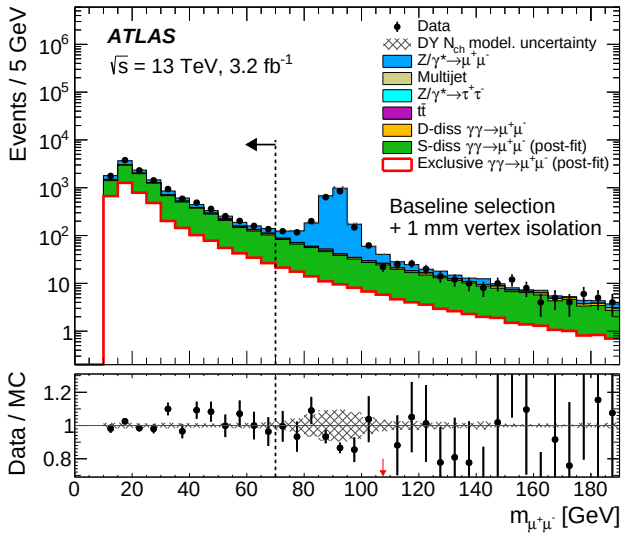
double-proton dissociation (D-diss)

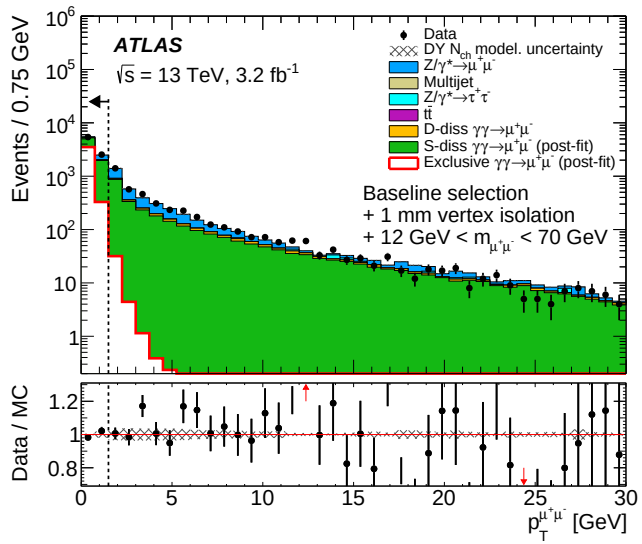


- data set: *pp* collisions at $\sqrt{s} = 13$ TeV, dimuon trigger, integrated luminosity 3.2 fb^{-1}
- cross section calculations based on Equivalent Photon Approximation (EPA): colliding protons produce quasi-real photons with small virtuality of $Q^2 < 0.1$ GeV $\to$ convolving the photon fluxes with elementary cross section of $\gamma\gamma \to \mu^+\mu^-$
- muon candidates identified by matching complete tracks in MS to tracks in the ID muons required to be isolated, info from ID and calorimeters transverse and longitudinal impact parameters: $|d_0|/\sigma_{d_0} < 3.0$; $|z_0| \sin\theta < 0.5$ mm
- events required to have exactly 1 pair of opposite-sign charged muons
- background contributions: S-diss, D-diss, $Z/\gamma^* \to \mu^+\mu^-$, $Z/\gamma^* \to \tau^+\tau^-$

Exclusive selection







	Data	Signal	Total background	S-diss	D-diss	$Z/\gamma^* \to \mu^+\mu^-$	$Z/\gamma^* \to \tau^+\tau^-$	Multijet	$t\bar{t}$
Baseline selection	2 933 384	5740	2 897 000	8640	8000	226 8000	10 900	590 000	12 200
1 mm vertex isolation	14 759	4560	11 100	6840	300	3900	30	50	0
$m_{\mu^+\mu^-} < 70\ GeV$	12 395	4420	8800	6420	300	2000	30	50	0
$p_{\mathrm{T}}^{\mu^+\mu^-} < 1.5\ GeV$	7952	4370	4300	3550	60	670	7	10	0

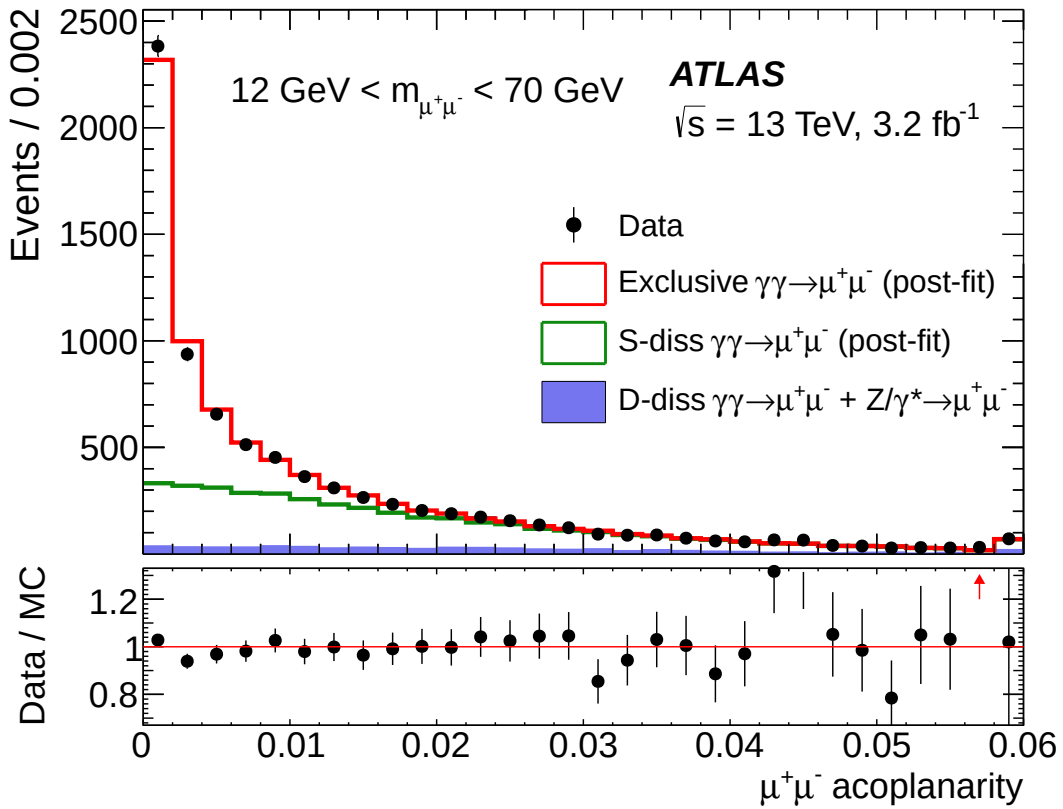
typical signature of exclusive events: absence of other charged-particle tracks
→ a veto on additional charged-particle applied: no additional tracks with $p_{\mathrm{T}} > 400$ MeV and $|\eta| < 2.5$ near the dimuon vertex with $|z_0^{\mathrm{trk}}| < 1$ mm

definition of the fiducial region:

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

Fiducial cross section

exclusive $\gamma\gamma \to \mu^+\mu^-$ contribution extracted performing a binned maximum-likelihood fit to the measured dimuon acoplanarity distribution: $1 - |\Delta\Phi_{\mu^+\mu^-}|/\pi$



fiducial cross section:

$$\sigma^{\text{excl.fid.}}_{\gamma\gamma\to\mu^+\mu^-} = \frac{N_{\text{excl.}}}{L_{\text{int}} \times C}$$

$N_{\text{excl.}}$ – total number of signal events extracted using LL

L_{int} – integral luminosity

C – corr. factor for efficiencies and resolution effects

differential fid. cross section as funct. of dimuon invariant mass:

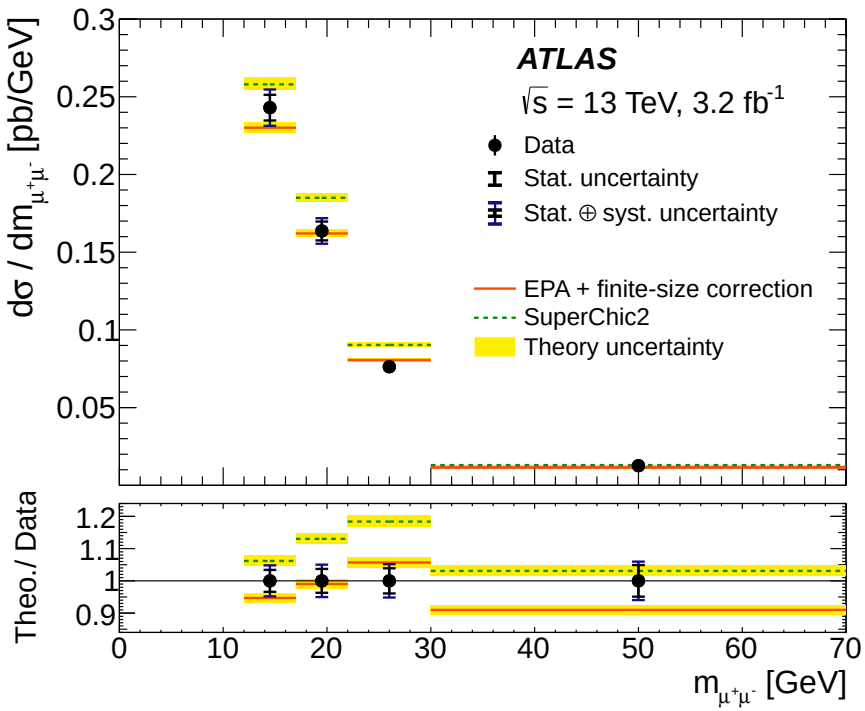
$$\left(\frac{\mathrm{d}\sigma^{\text{excl.}}_{\gamma\gamma\to\mu^+\mu^-}}{\mathrm{d}m_{\mu^+\mu^-}}\right) = \frac{N^i_{\text{excl.}}}{L_{\text{int}} \times C_i \times (\Delta m)_i}$$

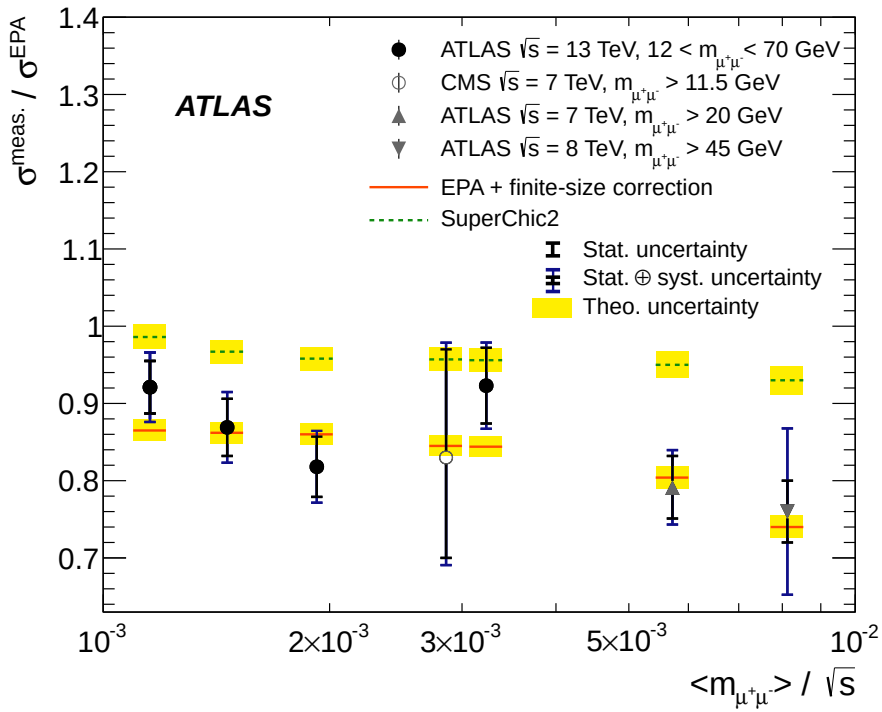
$(\Delta m)_i$ – width of the bin

the fiducial cross section in the dimuon invariant mass range of 12 GeV < $m_{\mu^+\mu^-}$ < 70 GeV is: $\sigma^{\text{excl.fid.}}_{\gamma\gamma\to\mu^+\mu^-} = 3.12 \pm 0.07(\text{stat}) \pm 0.14(\text{syst})$ pb

Differential cross section and absorptive corrections

$m_{\mu^+\mu^-}$ [GeV]	$N^i_{\text{excl.}}$	C_i	$d\sigma/dm_{\mu^+\mu^-}$ [pb/GeV]	$\delta^{\text{stat.}}$ [%]	$\delta^{\text{syst.}}$ [%]
12–17	1290± 50	0.333±0.007	0.243 ± 0.011	3.4	3.2
17–22	1040± 40	0.398±0.008	0.164 ± 0.008	3.7	3.1
22–30	830± 30	0.428±0.009	0.076 ± 0.004	3.9	3.1
30–70	690± 30	0.416±0.008	0.013 ± 0.001	4.9	2.9
12–70	3850±100	0.387±0.008	0.054 ± 0.002	2.1	3.2





expected that absorptive effects in two-photon interactions depend on the proton energy fractions passed to quasi-real photons → survival factor = ratio of measured cross section and to the bare EPA predictions → absorptive corrections tend to increase with energy fraction of protons passed to the initial-state photons

Ordered hadron chains

Correlation phenomena in hadron production:

important source of information about early stages of hadron formation

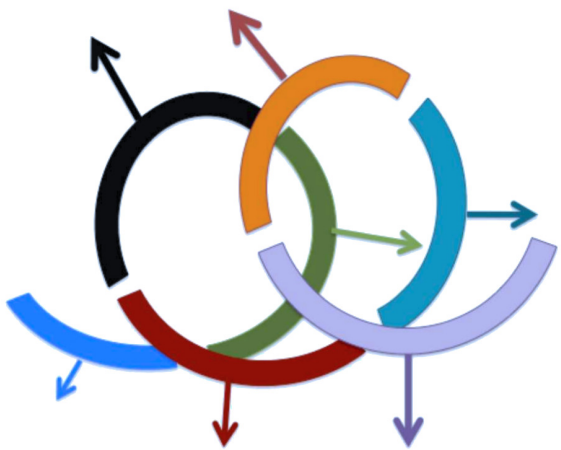
not yet understood from first principles

3D QCD string (helix-like shaped) fragmentation model & coherent emission of adjacent hadrons:

- cross-talk (causal constraint) between breakup vertices is imposed
- transverse shape of the string generates both the transverse momentum and the mass of the hadron
- quantization enables the build-up of the hadron mass spectrum

assuming local homogenity of the fragmenting QCD field, Q between ground state pion can be predicted as function of their rank:
($Q(r) = 2p_{\mathrm{T}}^{thr}|\sin(r\Delta\Phi/2)|$, $p_{\mathrm{T}}^{thr} \simeq 134$ MeV, $\Delta\Phi \simeq 2.82$)

Phys. Rev. D 89, 015002 (2014)

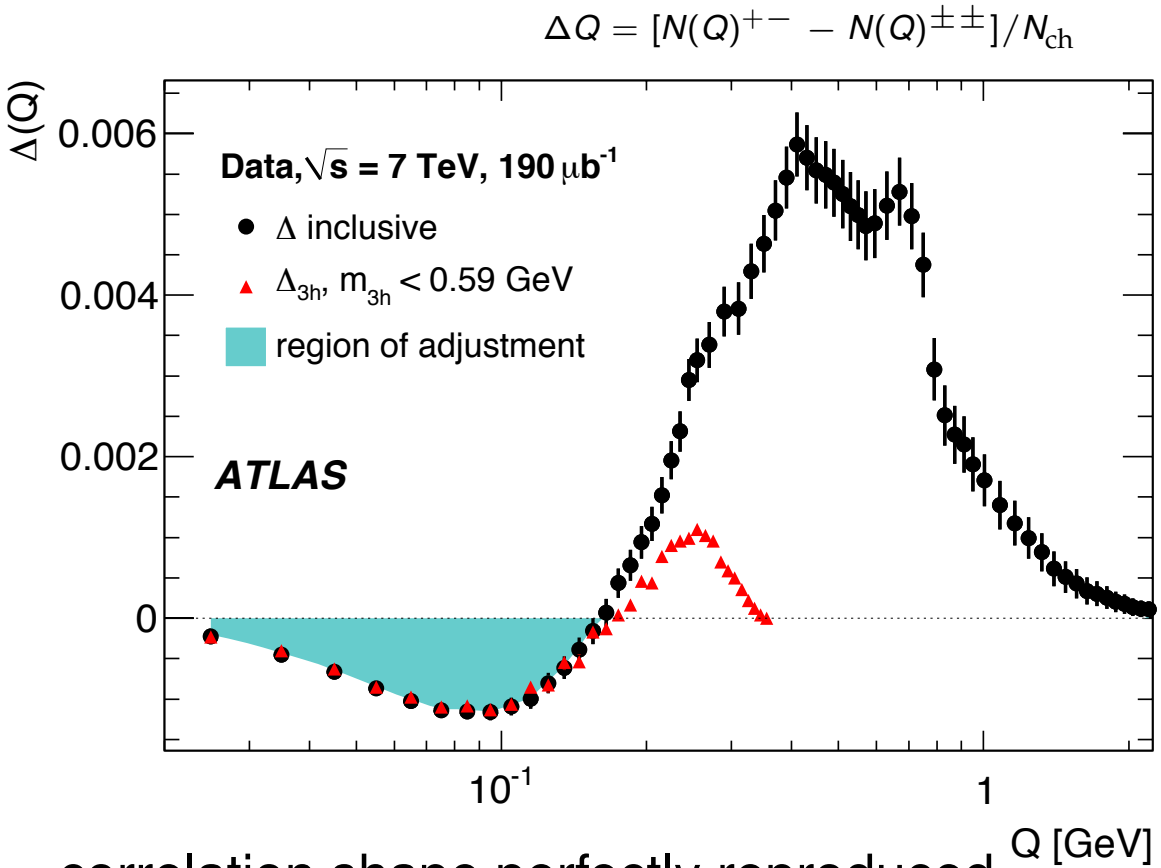


Pair rank difference	1	2	3	4	5
Q expected [MeV]	266±8	91±3	236±7	171±5	178±5

Search of chains of correlated adjacent hadrons

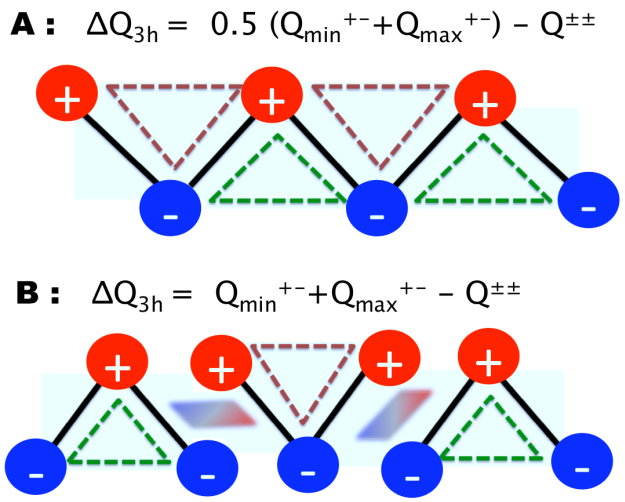
based on minimization of mass of the shortest hadron chain containing a pair of like-sign hadrons, a 3-hadron chain composed of 3 pairs

- choosing the like-sign partner giving the minimal momentum difference
- adding an opposite charge hadron producing the overall minimum mass



charge conservation constraint/ordering

$\rightarrow [+ - +]$ or $[- + -]$



correlation shape perfectly reproduced by selection of low mass hadron chains!

Low-mass three-hadron chains

upper limit on the mass of the triplet chain m_{3h} obtained from the region of adjustment:

Parameter [MeV]	m_{3h}^{cut} (input) 580	590	600	interpolation
CCS/CS $\pm\sigma$(stat)	0.88 ± 0.02	0.99 ± 0.02	1.09 ± 0.02	1.00 ± 0.02 (stat) ± 0.07 (syst)
m_{3h}^{cut} adjusted				591 ± 2 (stat) ± 7 (syst)

$$\Delta_{3h}(Q) = f_{LS}(Q; Q_{LS}, \sigma_{LS}) + f_{OS}(Q; Q_{OS}, \sigma_{OS}) = n_{LS} \exp\left(\frac{-(Q-Q_{LS})^2}{2\sigma_{LS}^2}\right) + n_{OS} \exp\left(\frac{-(Q-Q_{OS})^2}{2\sigma_{OS}^2}\right)$$

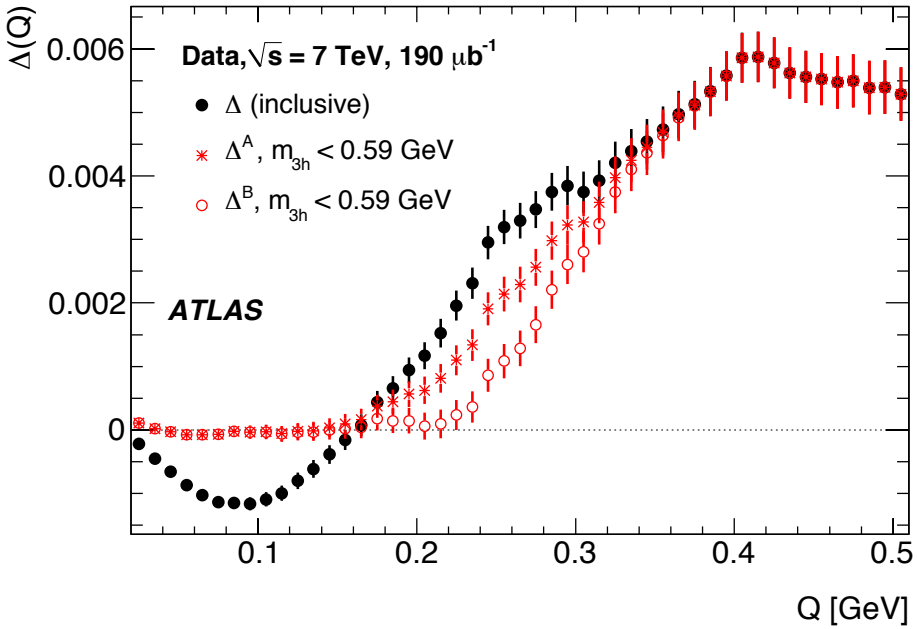
Measured parameter	Central value [MeV]	Systematic uncertainty (by source) [MeV] stat	reconstruction	unfolding	acceptance	combined
m_{3h}^{cut}	591	± 2	± 6	± 4	−10	+7.5/−13
Q_{LS}	89.7	± 2.1			−2.8	+2.1/−3.3
σ_{LS}	44.3	± 0.8			−1.0	+0.8/−1.3
Q_{OS}	256.4	± 5.5			−7.3	+5.5/−9.1
σ_{OS}	44.2	± 1.9			−2.6	+1.9/−3.2

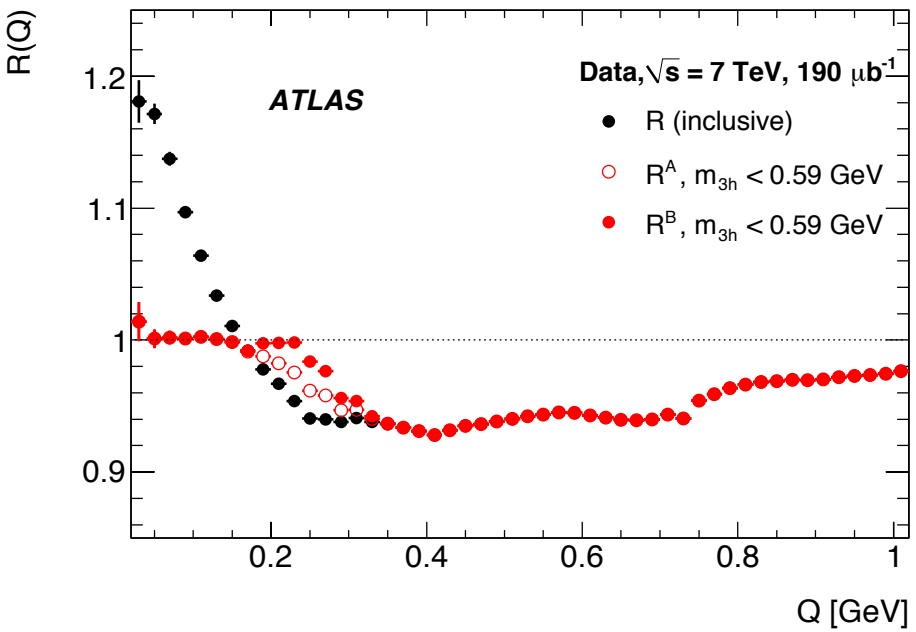
variations of multiplicity and correlation strength with change of acceptance region:

Acceptance variations	p_T >100 MeV $\lvert\eta\rvert$ < 2.5	p_T >100 MeV $\lvert\eta\rvert$ < 1	p_T >200 MeV $\lvert\eta\rvert$ < 2.5
N_{ch}/N_{ch}^{main}	1 (by construction)	0.33	0.78
$-\int_{\Delta Q<0} d\Delta Q$ [%]	$1.07\pm0.03(\text{stat})^{+0.05}_{-0.17}(\text{syst})$	$1.24\pm0.07(\text{stat})^{+0.06}_{-0.21}(\text{syst})$	$0.56\pm0.03(\text{stat})^{+0.03}_{-0.10}(\text{syst})$

correlation strength: stable within restricted $|\eta|$ region; reduced by a factor of 2 with p_T threshold increased → in MB sample strings oriented mainly along the beam axis → correlated hadrons have small intrinsic p_T → quantized fragm. model: ∼134 MeV

Subtraction of selected three-hadron chains





$$\Delta^{\mathrm{A}}(Q) = \Delta(Q) - \Delta_{3\mathrm{h}}(Q)$$
$$\Delta^{\mathrm{B}}(Q) = \Delta(Q) - \Delta_{3\mathrm{h}}(Q) - f_{\mathrm{OS}}(Q; Q_{\mathrm{OS}}, \sigma_{\mathrm{OS}})$$

data in agreement with the prediction of a thresholdlike behavior: after substraction of selected three-hadron chains from inclusive $\Delta(Q)$ no adjacent pairs up to a certain value

B scenario: threshold value up to ~0.25 GeV
→ coincides with threshold predicted by helical QCD string fragmentation model & fits position of the peak formed by closest oppo-sign pairs

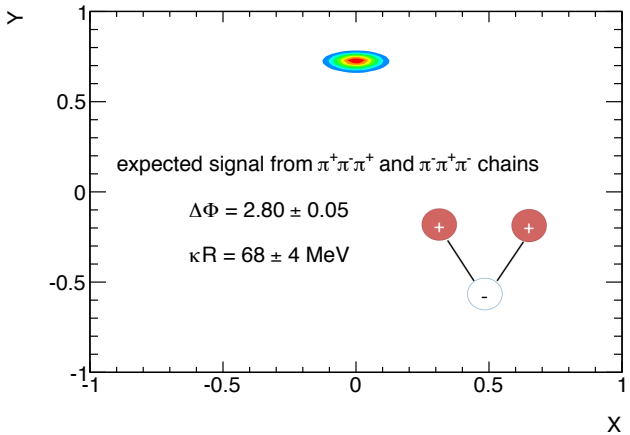
enhanced production of like-sign charge pairs traditionally atributed to Bose-Einstein effect

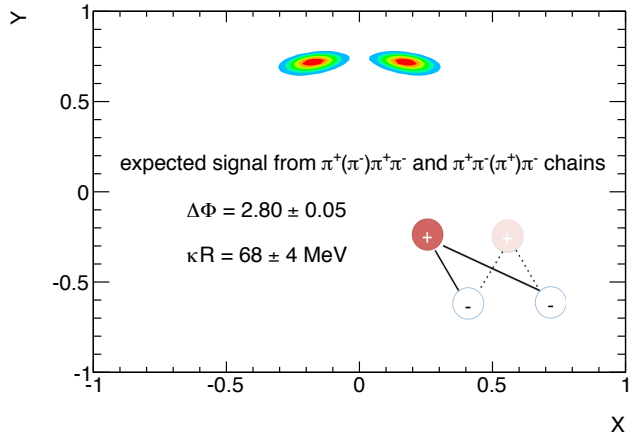
$$R = N(Q)^{\mathrm{LS}} / N(Q)^{\mathrm{OS}}$$

substraction of estimated contribution from ordered hadron chains from both LS and OS

in both scenarios: the chain selection contains source of enhanced like-sign pair production
→ alternative explanation of the data

Contribution of quadruplet chains

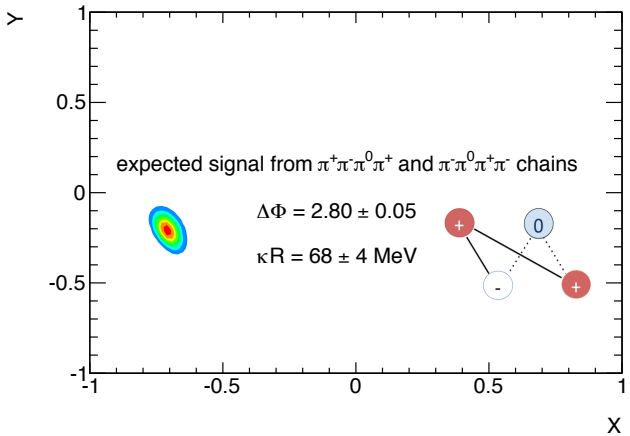


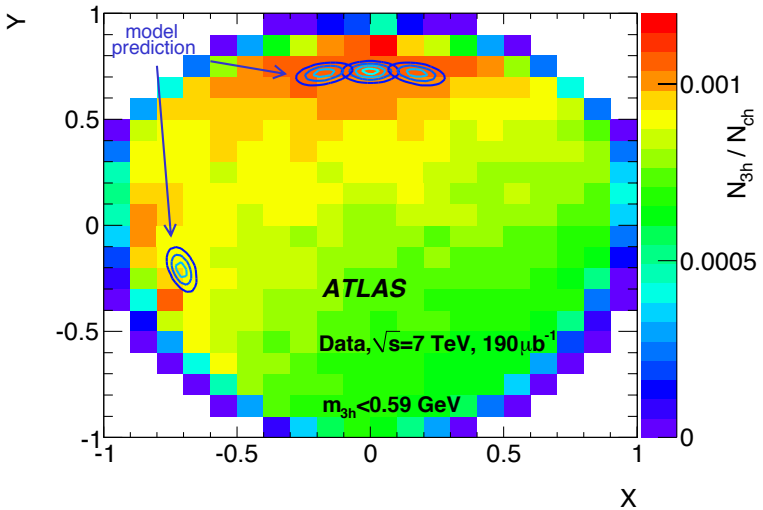


$$X = \sqrt{3}\frac{T_0 - T_2}{\sum_{i=0}^{2} T_i}$$

$$Y = \frac{3T_1}{\sum_{i=0}^{2} T_i} - 1$$

T_i - kinetic energy
0 and 2 form like-sign pair





significant admixture of opposite-sign pairs with rank difference 3 ($Q \sim 0.236$ GeV) → bias taken into account -9±5 MeV

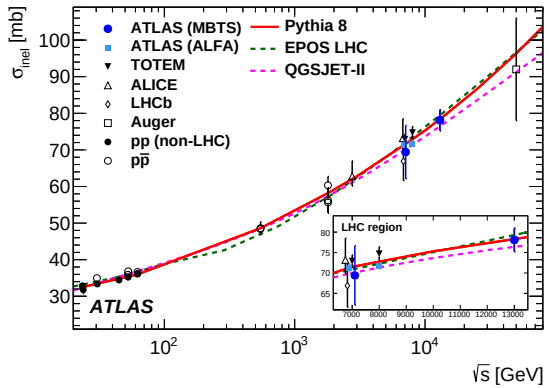
inclusive two-particle correlation pattern is reproduced by three-hadron chains below a mass limit of $m_{3h}^{cut} = 591 \pm 2(stat)^{+7.5}_{-13}(syst)$ MeV

data show a threshold effect in the production of adjacent hadron pairs, it coincides with preferred momentum difference between opposite-sign pairs in the selected chains $Q_{OS} = 256.4 \pm 0.5(stat) \pm 1.8(rec)^{+5.5}_{-9.1}(chain\ selection)$ MeV

Summary

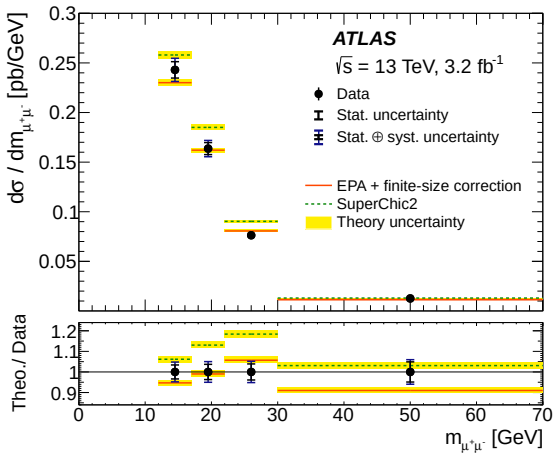
- total inelastic *pp* cross section at $\sqrt{s} = 13$ TeV:
  $\sigma_{\text{inel}} = 78.1 \pm 0.6(\text{exp}) \pm 1.3(\text{lum}) \pm 2.6(\text{extrap})$ mb

  Phys. Rev. Lett. 117 (2016) 182002



- the fiducial cross section for exclusive $\gamma\gamma \to \mu^+\mu^-$ production in the dimuon invariant mass range of 12 GeV < $m_{\mu^+\mu^-}$ < 70 GeV is:
  $\sigma^{\text{excl.fid.}}_{\gamma\gamma\to\mu^+\mu^-} = 3.12 \pm 0.07(\text{stat}) \pm 0.14(\text{syst})$ pb

  Phys. Lett. B 777 (2018) 303



- inclusive two-particle correlation pattern reproduced by three-hadron chains below a mass limit of:
  $m^{\text{cut}}_{3\text{h}} = 591 \pm 2(\text{stat})^{+7.5}_{-13}(\text{syst})$ MeV

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