Measurements of low energy observables in proton-proton collisions with the ATLAS Detector

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On behalf of the ATLAS Collaboration

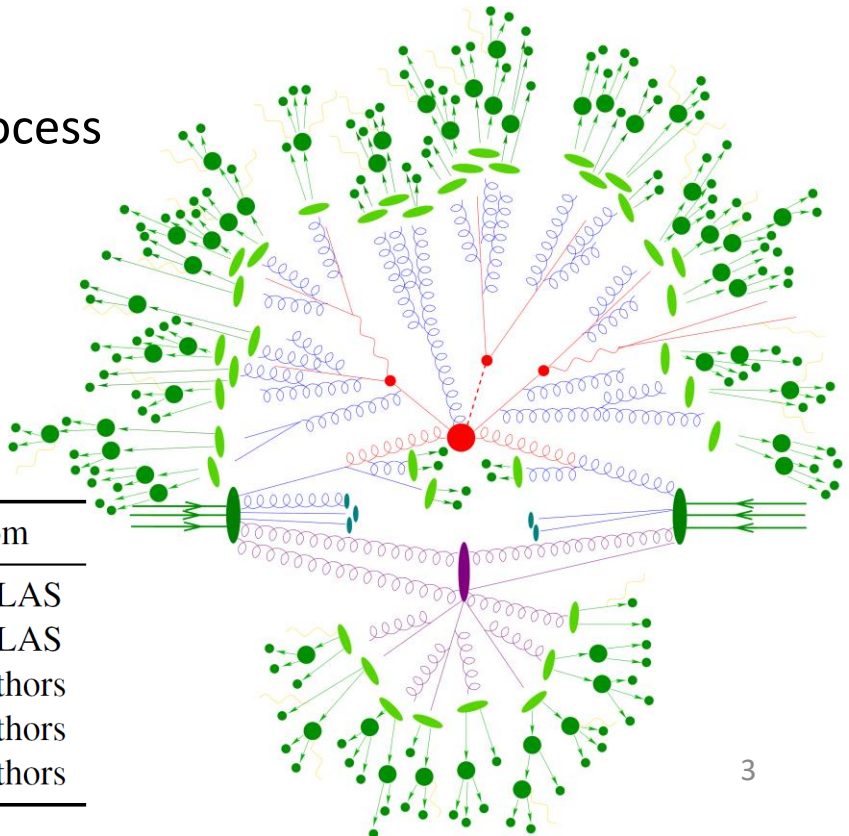
Track-based Underlying Event @ 13 TeV

JHEP 03 (2017) 157
https://arxiv.org/abs/1701.05390

Track-based Underlying Event @ 13 TeV

- Measurement of angular distribution of energy and of particle flow with respect to leading particle – as a function of p_T^{lead} , $\Delta\phi$, and of track multiplicity (33 distributions)
- 2 goals:
  - challenge the Monte Carlo predictions for new energy (average 5% accuracy)
  - provide corrected data for new tuning/UE model development (Rivet)

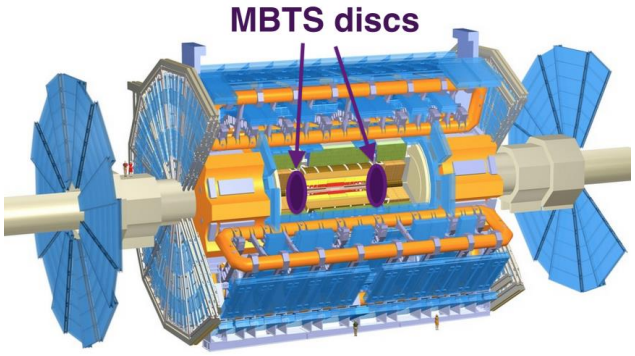
    (highly precise measurement < 1%)
- Phenomenology of UE – on top of "hard" process
  - shower algorithms (initial/final)
  - semi-hard MPI
  - soft MPI / remnant scattering
  - color evolution and reconnection

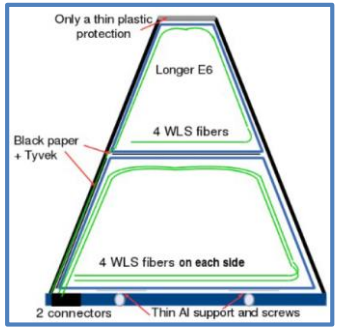


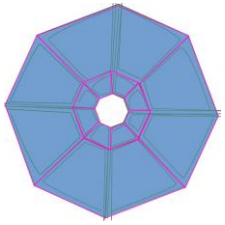
Generator	Version	Tune	PDF	Focus	From
Pythia 8	8.185	A2	MSTW2008 LO	MB	ATLAS
Pythia 8	8.185	A14	NNPDF2.3 LO	UE	ATLAS
Pythia 8	8.186	Monash	NNPDF2.3 LO	MB/UE	Authors
Herwig 7	7.0.1	UE-MMHT	MMHT2014 LO	UE/DPS	Authors
Epos	3.4	LHC	—	MB	Authors

Track-based UE @ 13 TeV

- New measurement of Underlying Event (UE) using the Minimum Bias (MB) data
  - 2015 data, 1.6 nb^{-1} ; MBTS trigger (> 1 hit) 99-100% efficient
  - Inner tracking detector $|\eta| < 2.5$ (Run II – new pixel „B“ layer; r = 25 mm)
  - low luminosity run – multiple vertex events removed (> 3 tracks above 100 MeV)
  - track $p_T > 500$ MeV, “primary“ (impact parameter below 1.5 mm)
  - 66 M events with at least one track $p_T > 1000$ MeV







8 segments in the inner octagonal ring, 4 segments in the outer ring

- Connected measurements: Track-based Minimum bias at 13 TeV

  Eur.Phys.J.C76 (2016) 502, Phys. Lett. B758 (2016) 67
  - corresponding low luminosity measurements of low-p_T charged particles ($p_T > 500$, later 100 MeV)
  - focus on variables describing the entire event – mean p_T , inclusive spectra of track transverse momentum and pseudorapidity

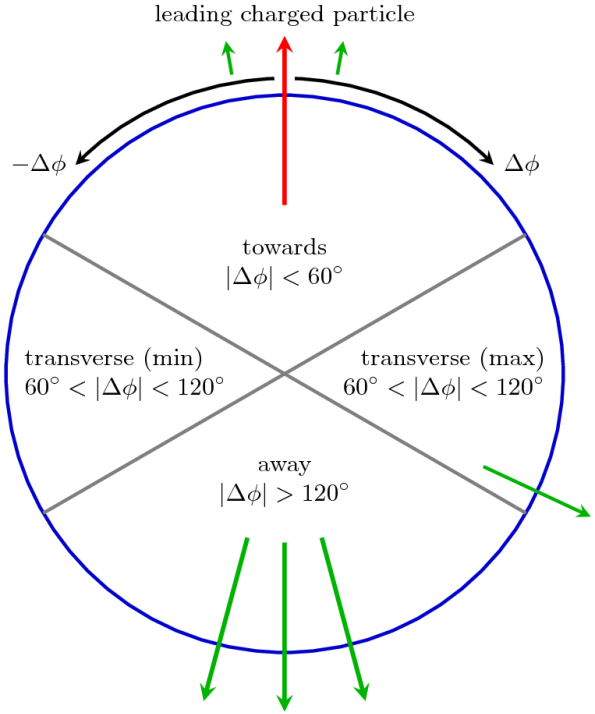
Track-based UE @ 13 TeV

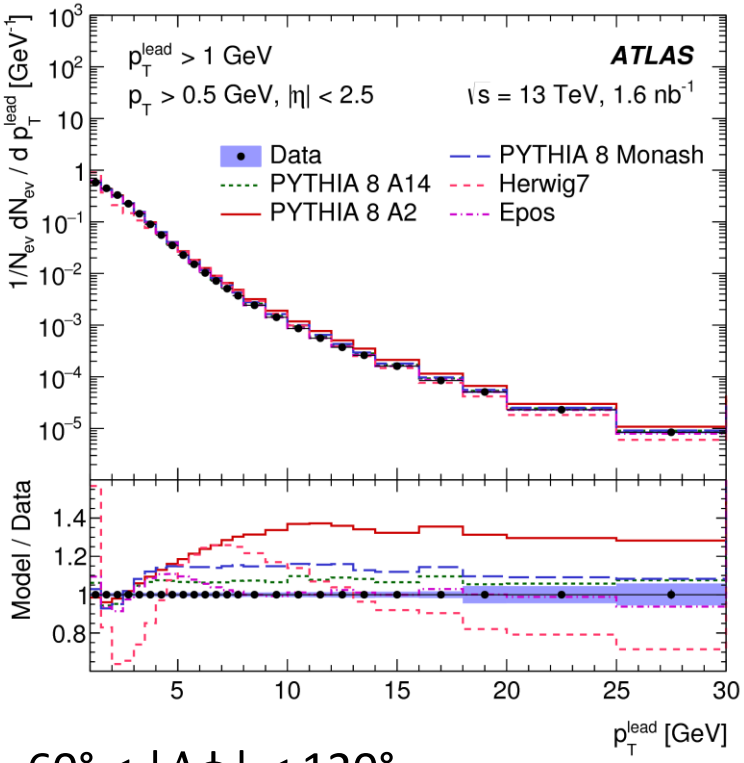
Measurement strategy: divide the phase space to discriminate the UE sources

Regions in the azimuthal plane
(track ϕ wrt leading particle)

- Towards $|\Delta\phi| < 60°$
- Away $|\Delta\phi| > 120°$

main flow of hard process energy insensitive to UE

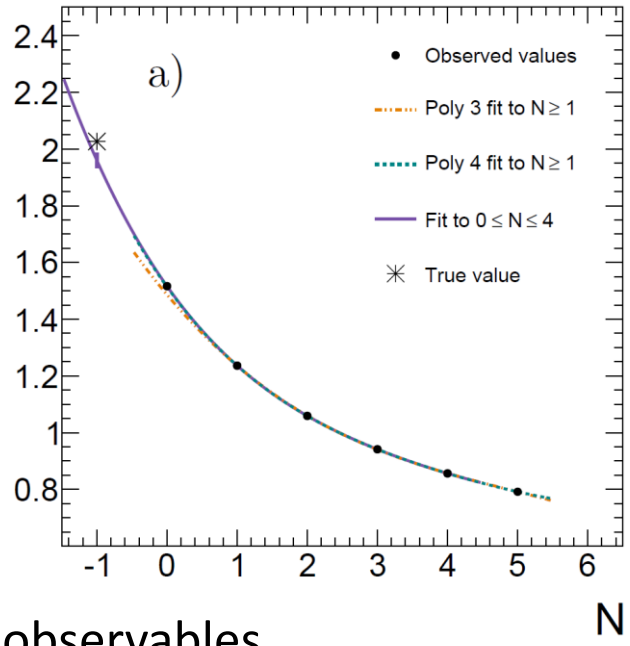




- Transverse $60° < |\Delta\phi| < 120°$
  - sensitive to UE, according to $\sum p_T$ divides into
  - "Trans-max" – occasional occurrence of hard emission
  - "Trans-min" – only UE (MPI)
  - "Trans-diff" – wide angle emissions without UE (Trans-min subtracted from trans-max)
- all regions have to be filled to accept event

Track-based UE @ 13 TeV

Nucl. Instrum. Meth. A 701 (2013) 17



Classical correction to particle level (N_{ch}, $\sum p_T$, $\langle p_T \rangle$):

- Event weighting:
  - trigger efficiency
  - data-driven vertex reconstruction efficiency ~100%
- Track weighting: (MC based)
  - track matching 65 – 85 % wrt track η and p_T
  - non-primary track fraction – up to 2.3% for p_T = 500 MeV
  - out-of-kinematic-range fraction

Correction to particle level – for |Δϕ| region dependent observables

- effect of "reorientation" may disrupt the measurement – few per-cent level effect
- HBOM method (Hit Backspace Once More):

  Smoothly varying observable value in a bin when "track reconstruction" is applied (track reco efficiency is known)

  Let's apply it 4 times to data (for each bit each observable) and extrapolate it back to "-1" step (2nd order polynomial) → get the distribution as there would be 100% efficiency

Compared to MC unfolding

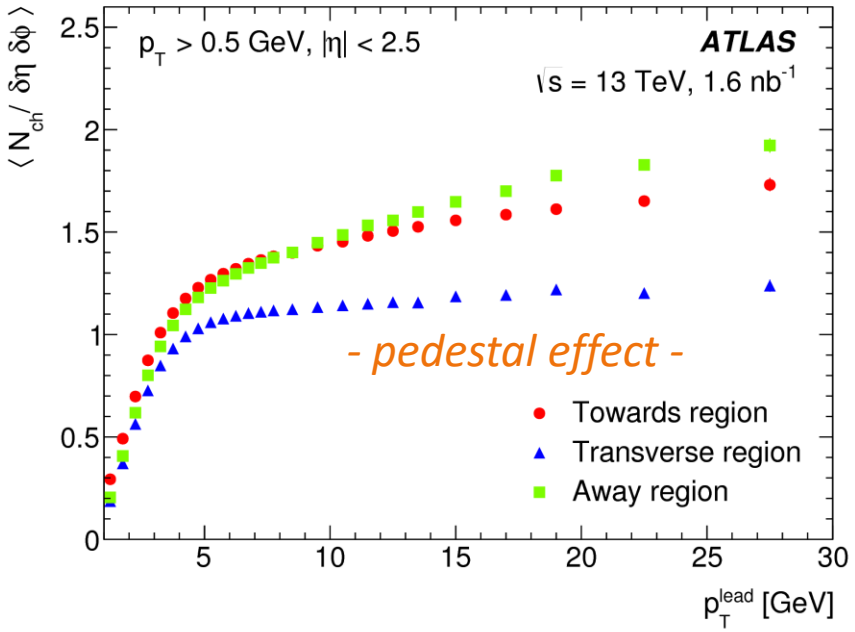
Track-based UE @ 13 TeV

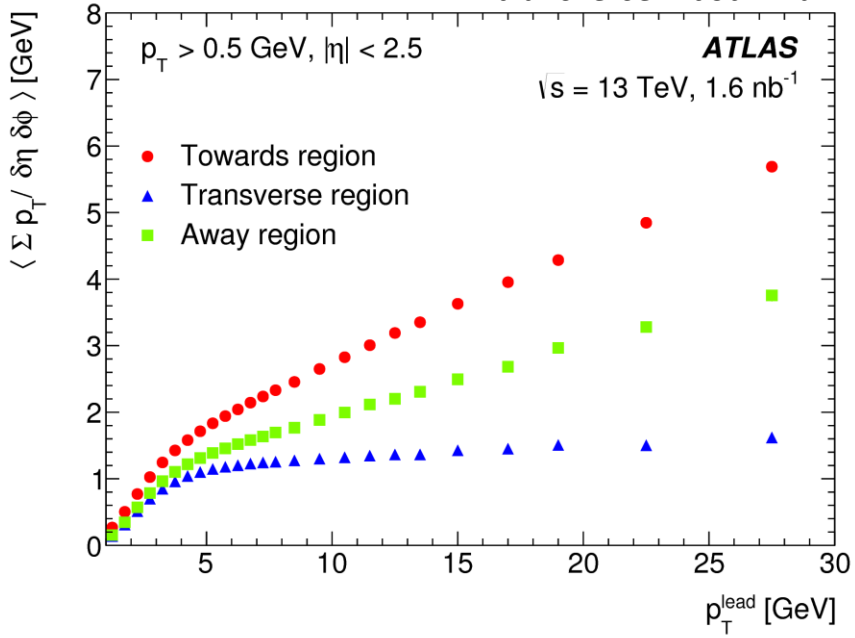
- observables insensitive to diffraction (by construction), max 2%
- non-collision background events negligible

- 2D event/track distributions measured → mean value 1D distributions (profiles)
  - number of charged particles N_{ch}
  - scalar sum of transverse momenta $\sum p_T$
  - average transverse momentum of particles $\langle p_T \rangle$
  - all as densities per $\delta\eta\delta\phi$ unit ($\delta\eta = 5$, $\delta\phi = 2\pi/3$ …)

As a function of
- leading track p_T
- N_{ch} (in different regions)
- $|\Delta\phi|$

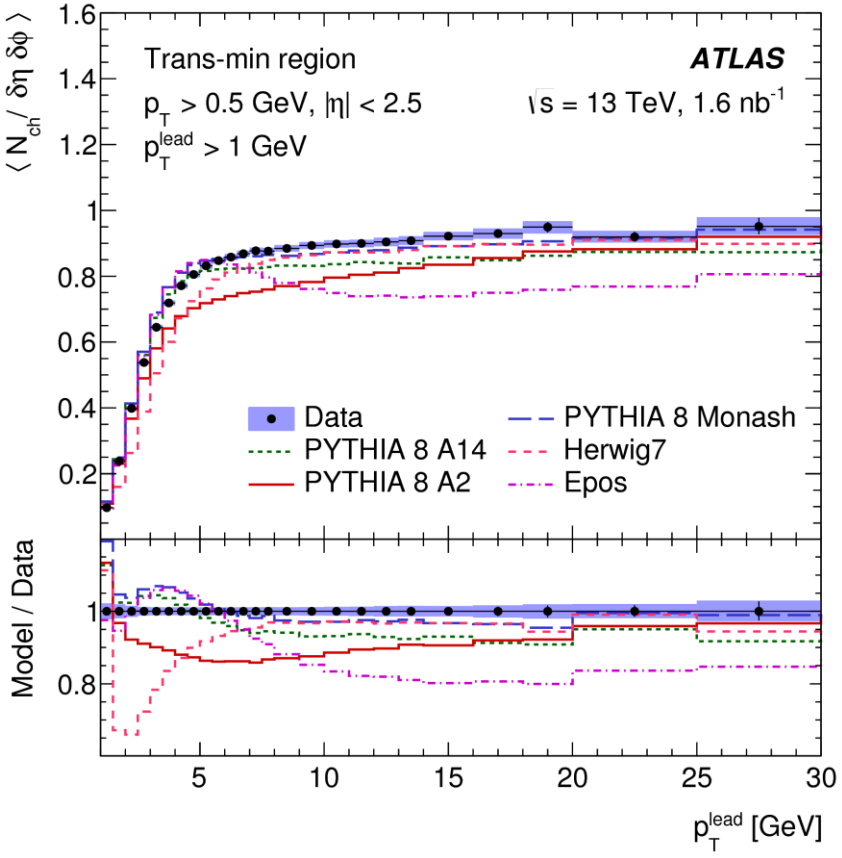
transverse = both max + min

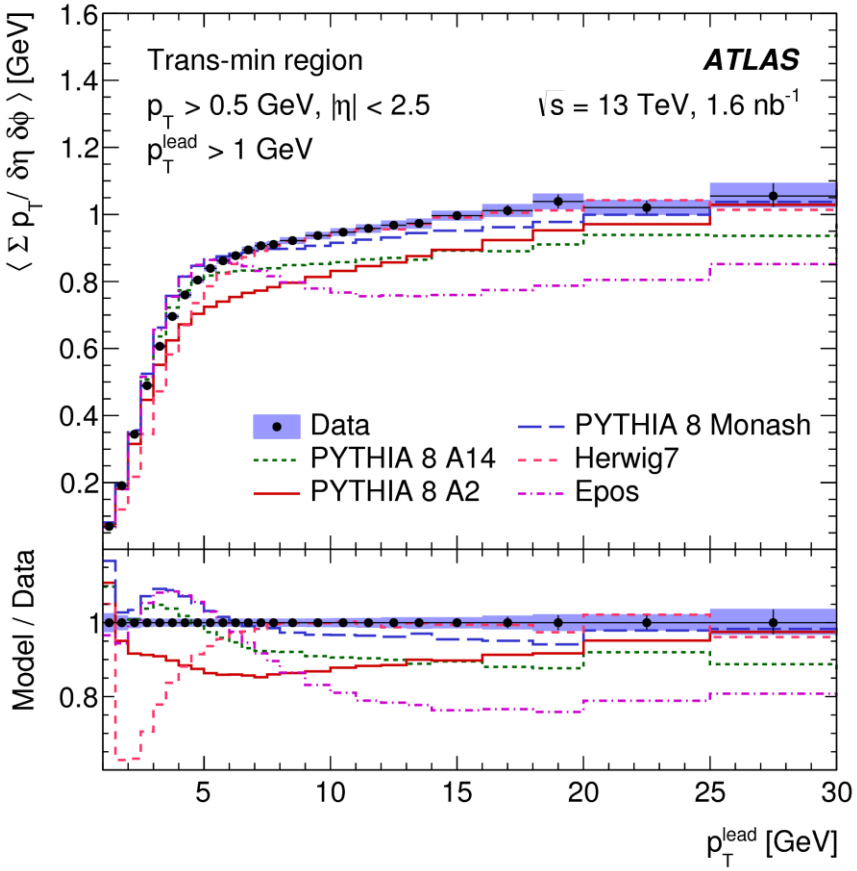




Track-based UE @ 13 TeV

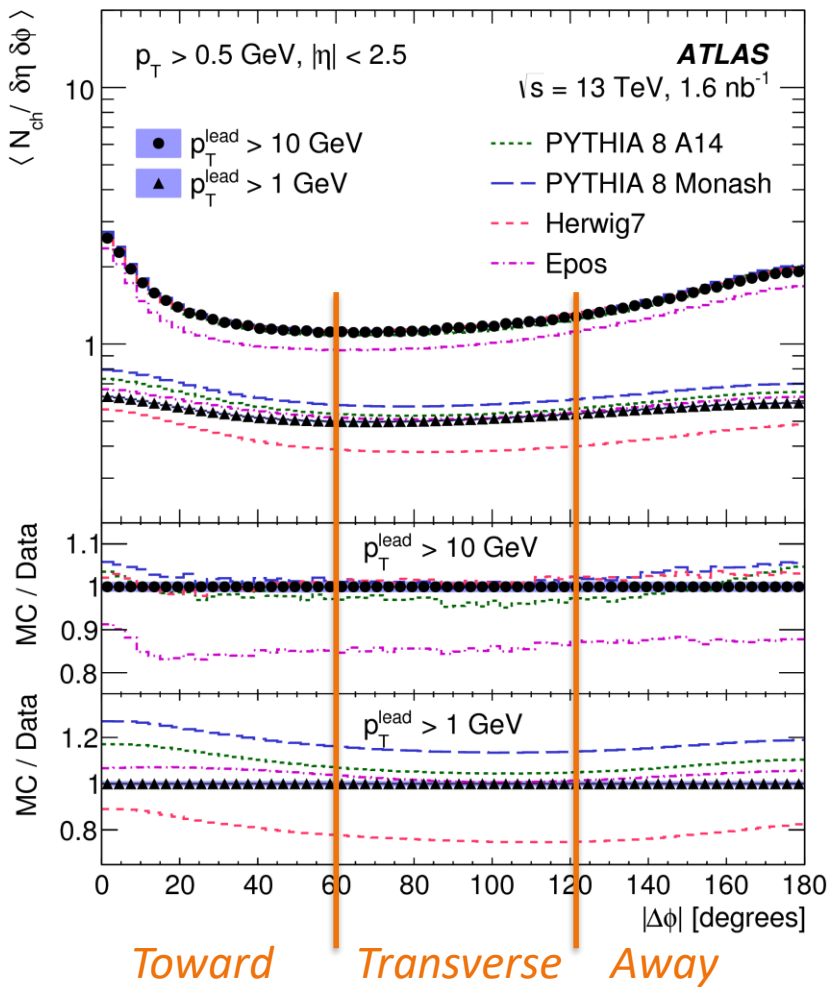
Transverse region with lower $\sum p_T$ – MPI enhanced

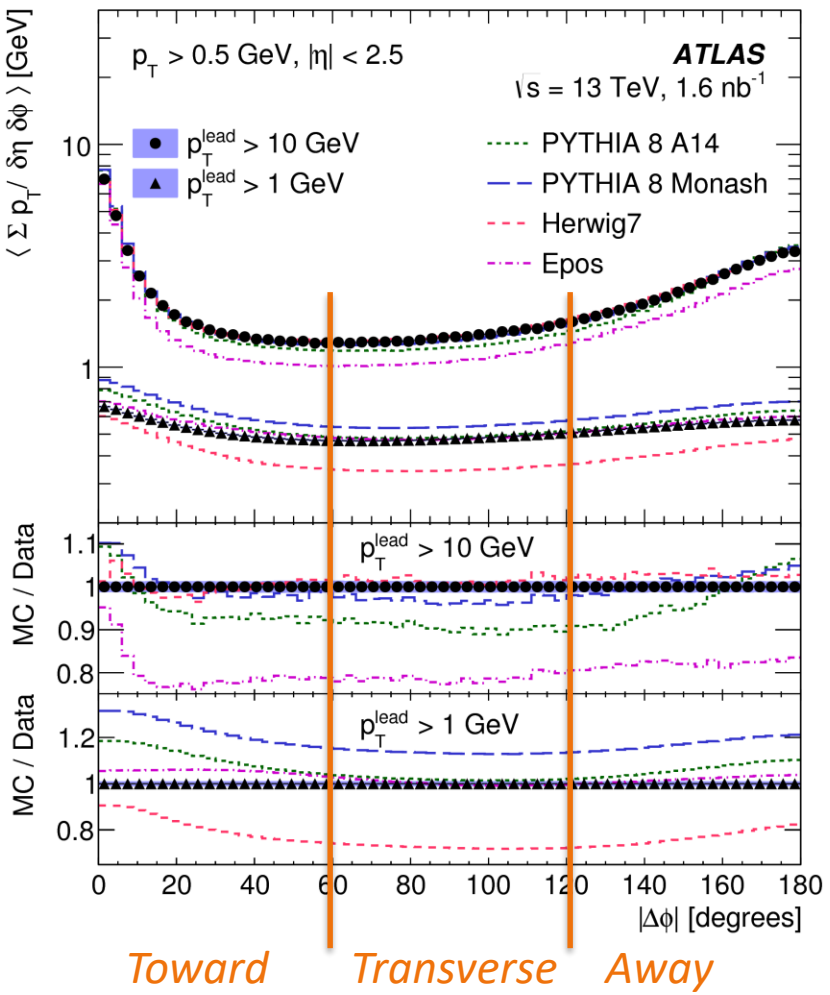




- the strongest pedestal effect among the regions
- Plateau - best Pythia8 Monash and Herwig7
  - Pythia8 A2 and A14 off by 10%; Epos by 20%

Track-based UE @ 13 TeV



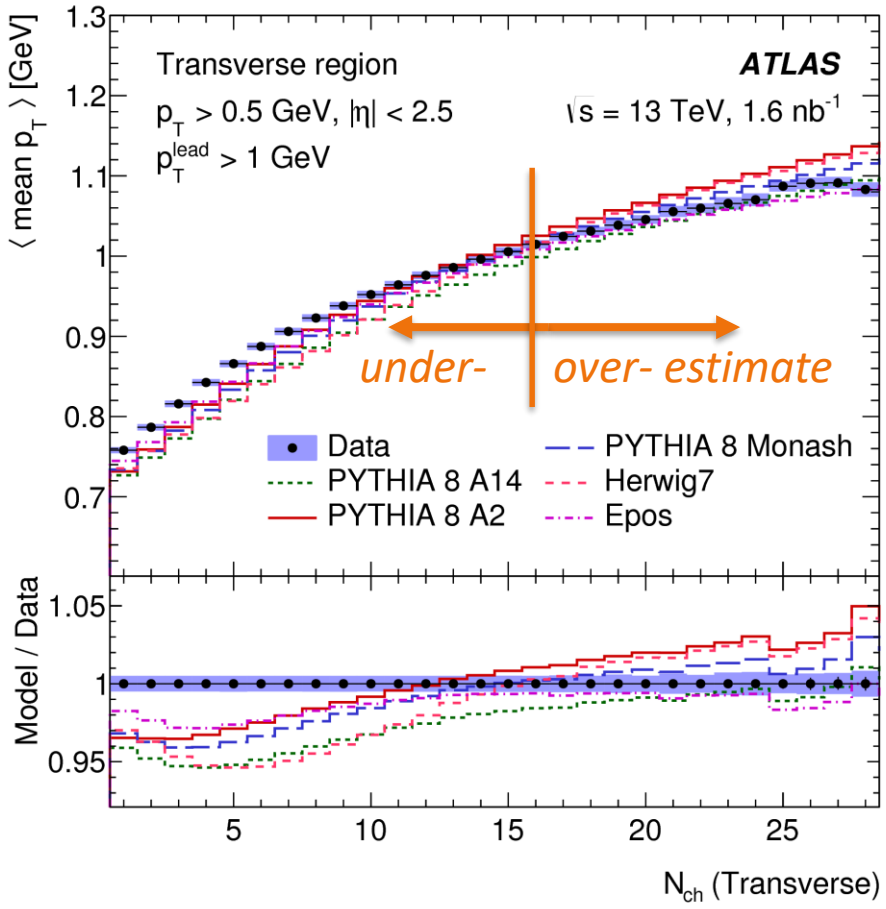


- Epos stands for 1 GeV but looses for 10 GeV selections
- No model describes both N_{ch} and $\sum p_T$

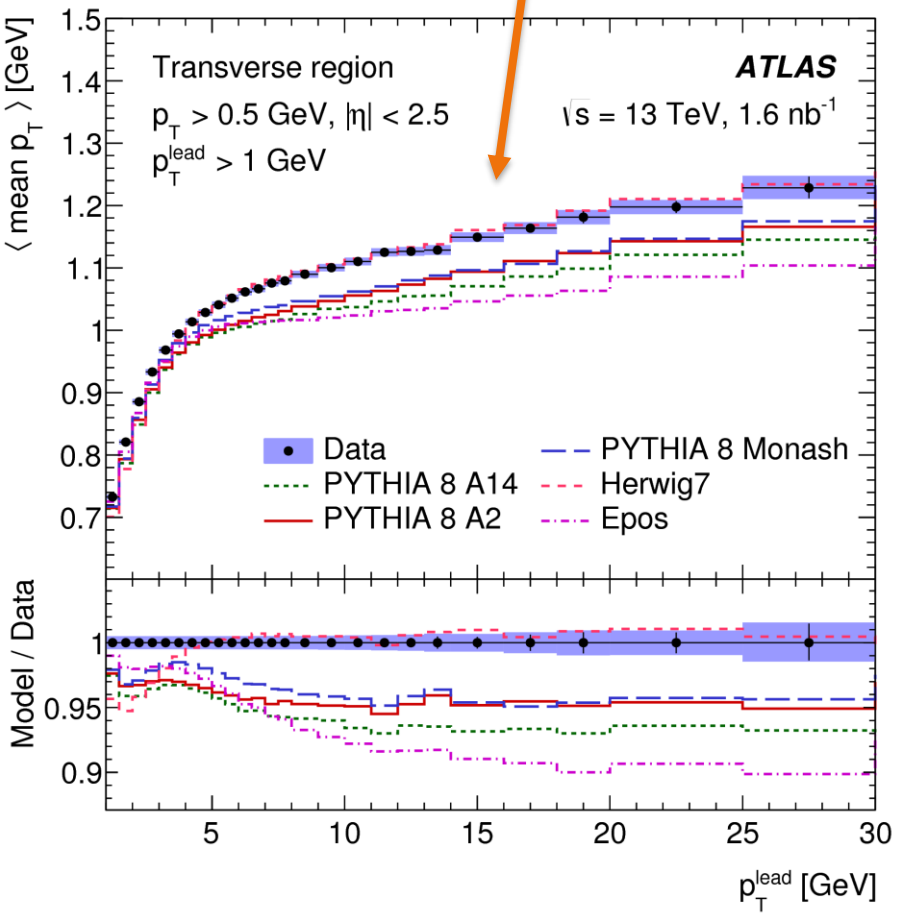
Track-based UE @ 13 TeV

not as flat as N_{ch} and $\sum p_T$

Transverse region



Best: Epos < 3%



Best: Herwig7 < 1% (above 5 GeV)

- Connections between p_T and N_{ch}
- Sensitive to color re-connection

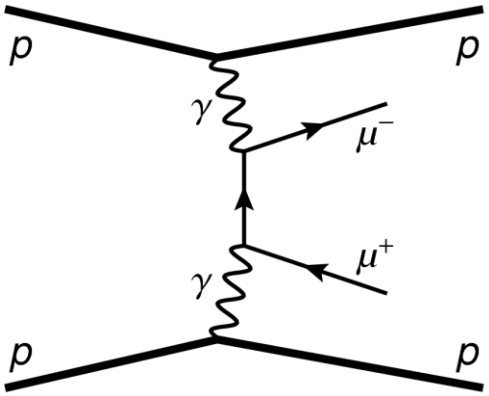
Exclusive $\gamma\gamma \to \mu^+\mu^-$ @ 13 TeV

submitted to Phys. Lett. B

http://inspirehep.net/record/1615866

https://arxiv.org/abs/1708.04053

Exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ @ 13 TeV



- Pure electroweak process in *pp* collision
- Protons remain unbroken – elastic scattering
- Measurement without forward proton detectors
  - exclusive track selection and specific kinematics employed
- Connected ATLAS measurements:
  - exclusive dilepton production @ 7TeV: Phys. Lett. B 749 (2015) 242
  - exclusive WW production @ 8 TeV: Phys. Rev. D 94 (2016) 032011

Signal modeling:

- Equivalent Photon Approximation (EPA)

interacting photons ≈ quasi-real photons around the proton

low virtuality ($Q^2 < 0.01$ GeV^2) → back-to-back muons

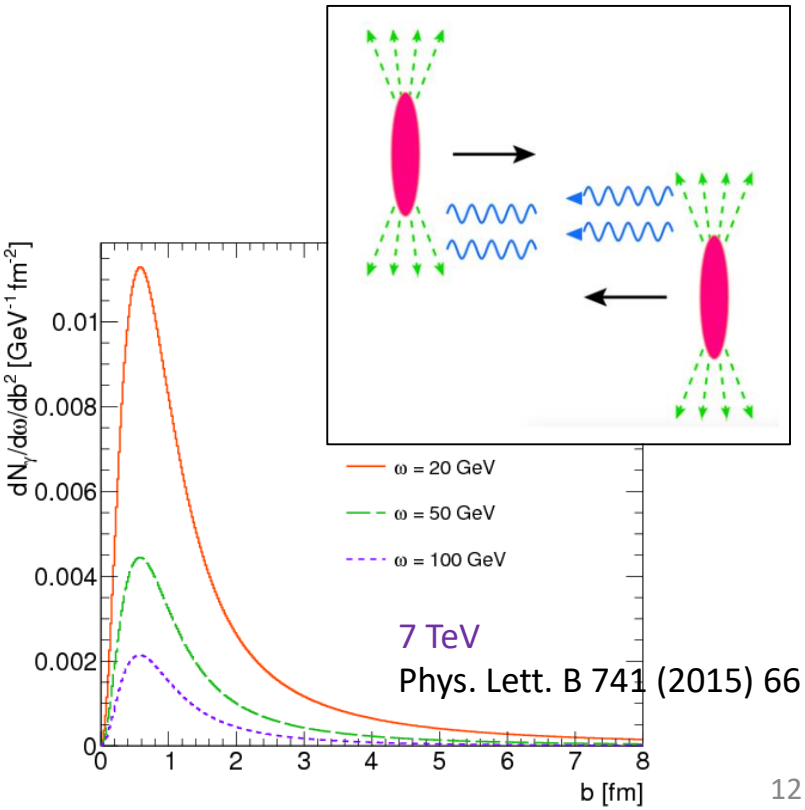
Main data sample:

Herwig7 generator as LO $\gamma\gamma \rightarrow \mu^+\mu^-$

using EPA initial photon flux input

Second data sample:

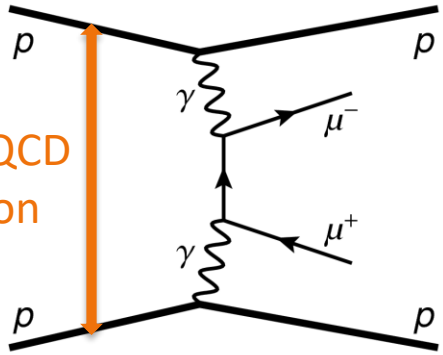
SuperChic2 generator

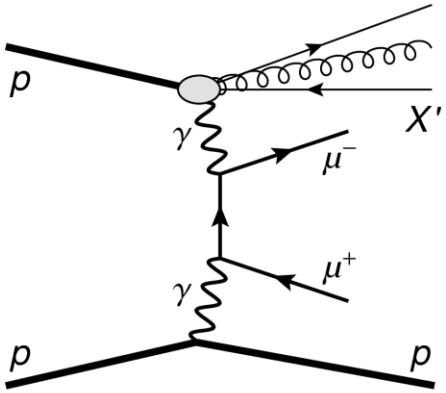


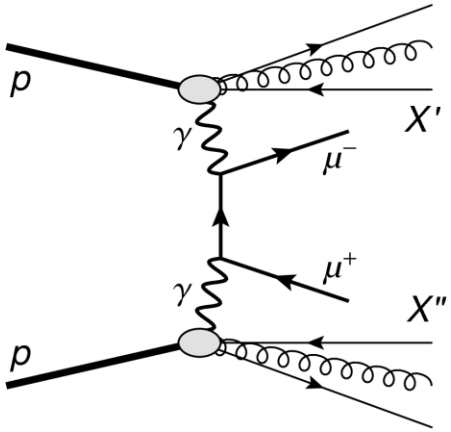
Exclusive $\gamma\gamma \to \mu^+\mu^-$ @ 13 TeV

Background processes:

parallel QCD interaction







Proton absorptive effects
- measured via "Survival factor"
- EPA corrected by finite-size parametrization photons have to be outside proton, r > 0.64 fm

Drell-Yan (+ ttbar)
- Powheg-Box + Pythia8 + Photos for FSR QED

Single- and double-proton dissociation
Single: Lpair + JetSet
(Brasse and Suri-Yennie structure functions)
Double: Pythia8
- also include absorptive effects

	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
$p_T^{\mu^+\mu^-} < 1.5\ GeV$	7952	4370	4300	3550	60	670	7	10	0

76% of signal remains

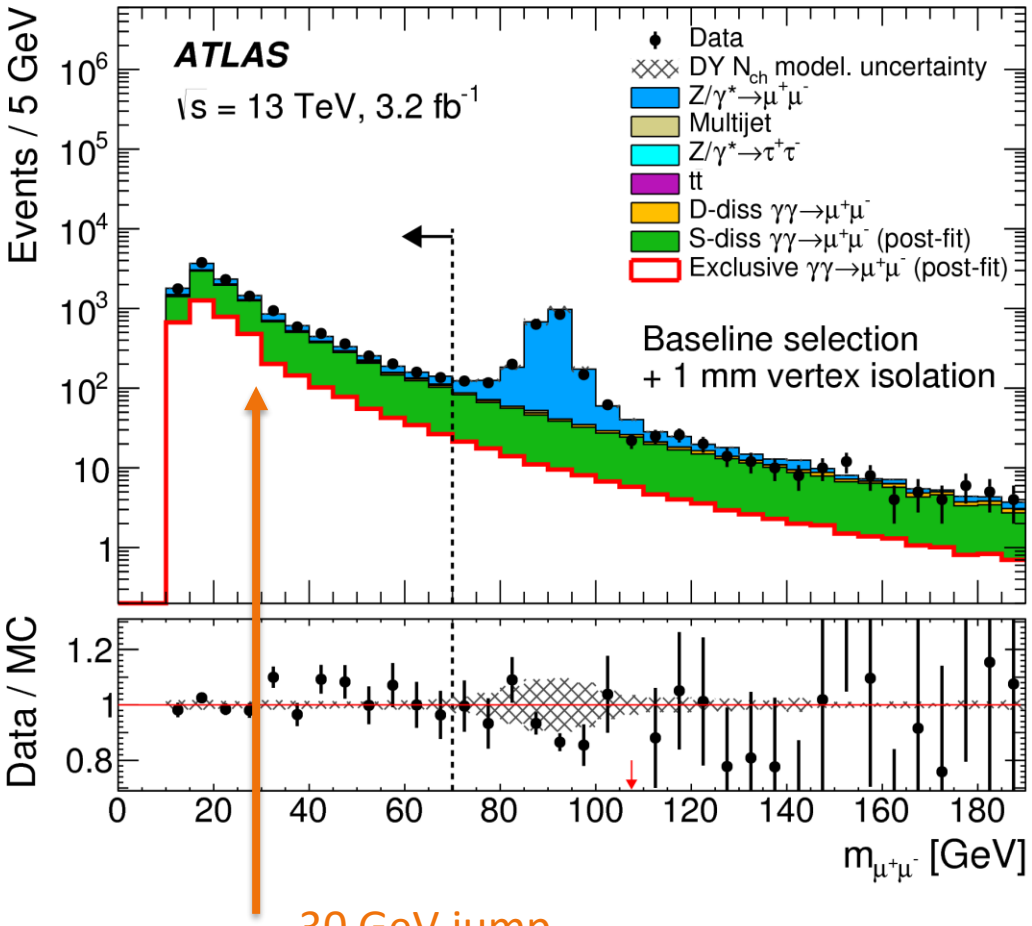
41% of bkg single-dissociation remains

Exclusive $\gamma\gamma \to \mu^+\mu^-$ @ 13 TeV

Baseline selection: *3M candidate events*

2015 data, 13 TeV, 3.2 fb^{-1}

2 kinematical selections merged into one fiducial region (two triggers)



- $p_T(\mu) > 6$ GeV
  → $12 < m_{\mu\mu} < 30$ GeV
- $p_T(\mu) > 10$ GeV
  → $m_{\mu\mu} > 30$ GeV
- $|\eta(\mu)| < 2.4$
- standard muon track quality and isolation requirements applied;

Common di-muon vertex reconstructed
→ both muons have to satisfy:

$$|z_0| * \sin\theta < 0.5 \text{ mm}$$

wrt the dimuon vertex

15k candidate events

Exclusive $\gamma\gamma \to \mu^+\mu^-$ @ 13 TeV

Exclusive selection: 12k *candidate events*

- remove event if there is a track:

  $p_T > 400$ MeV

  $|\eta| < 2.5$

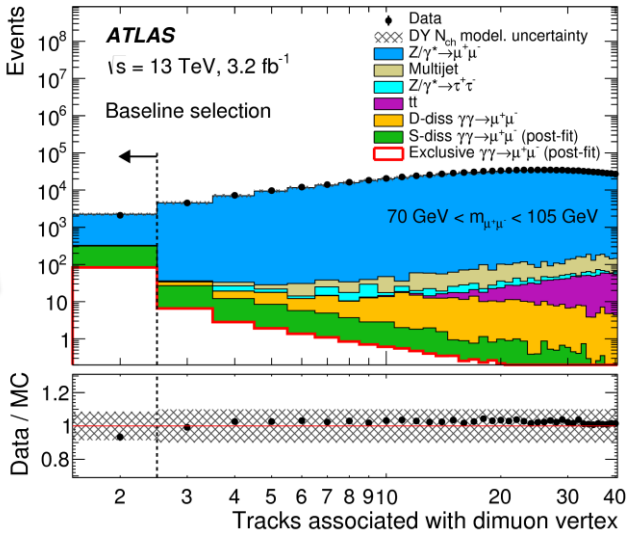
  $|z_0^{trk}| < 1$ mm - wrt the muon vrtex

- **$m_{\mu\mu} < 70$ GeV**

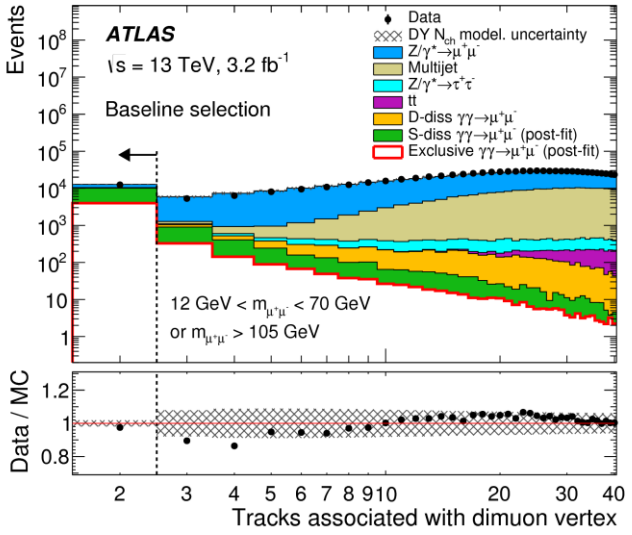
DY modeling overestimates the track spectrum

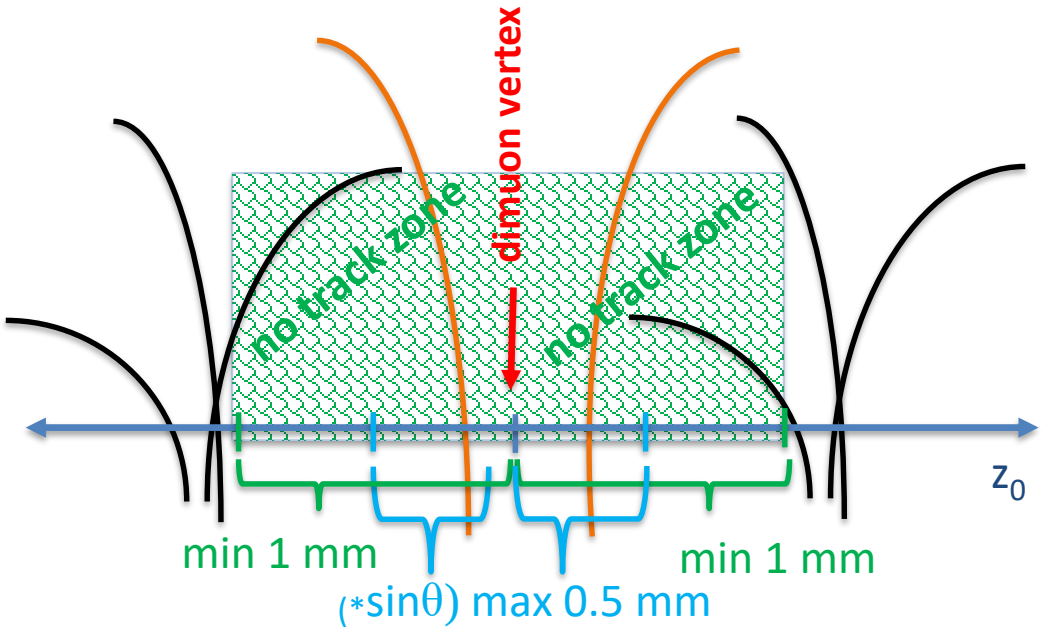
correction applied based on control region data

DY control region



signal region





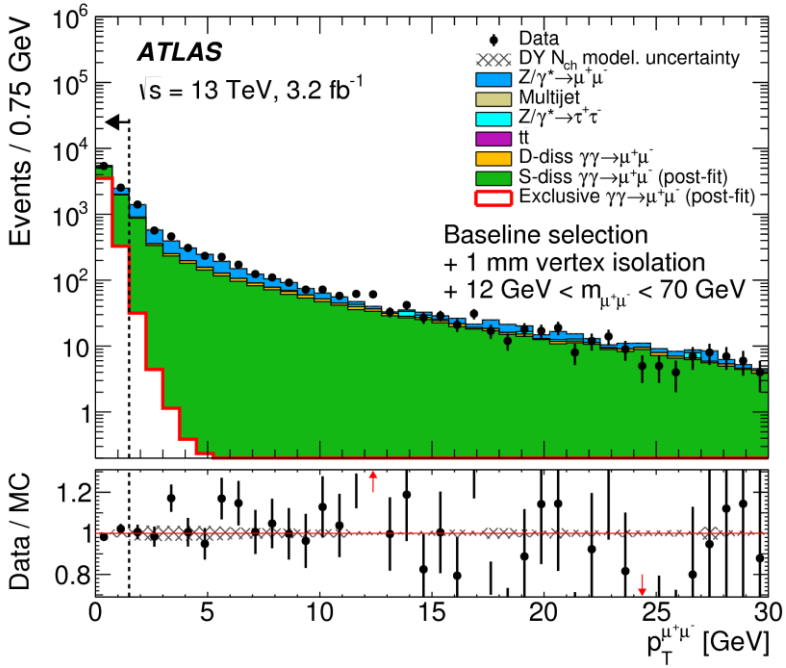
Exclusive $\gamma\gamma \to \mu^+\mu^-$ @ 13 TeV

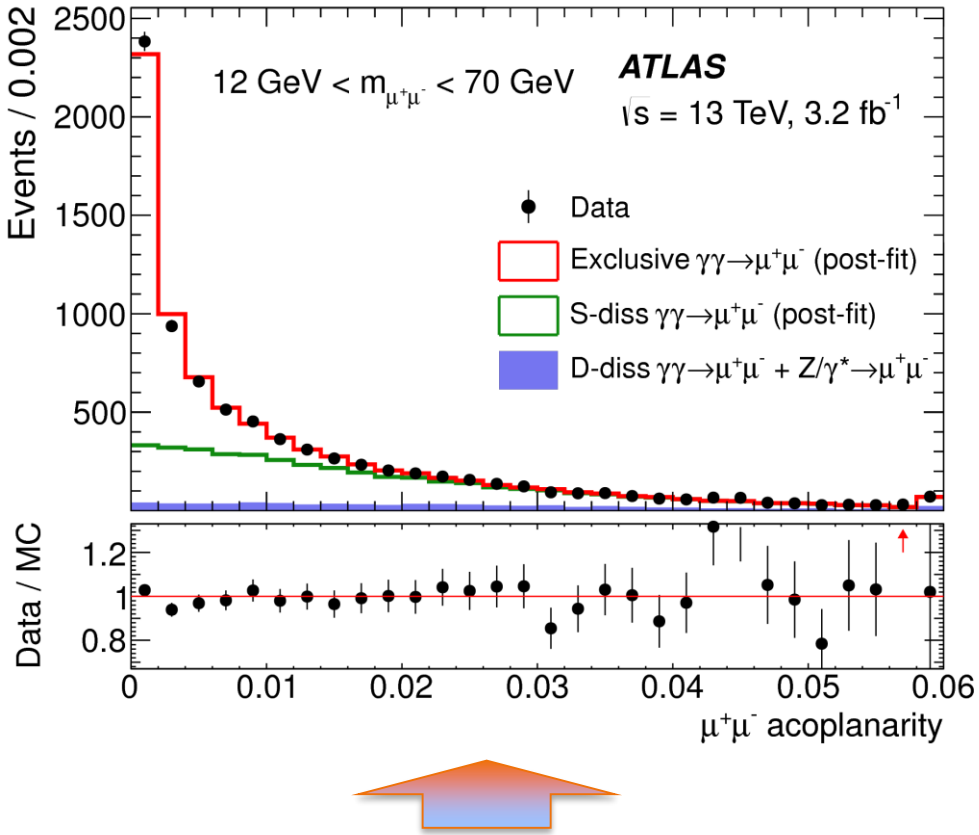
Exclusive selection:

12k *candidate events*

- signal signature: back-to-back in transverse space

  → **$p_T^{\mu\mu} < 1.5$ GeV**





Acoplanarity: $1-|\Delta\phi_{\mu\mu}|/\pi$

- used for binned max-log-likelihood fit
- Double-dissociation and DY fixed

(data corrected bin-by-bin)

Exclusive $\gamma\gamma \to \mu^+\mu^-$ @ 13 TeV - results

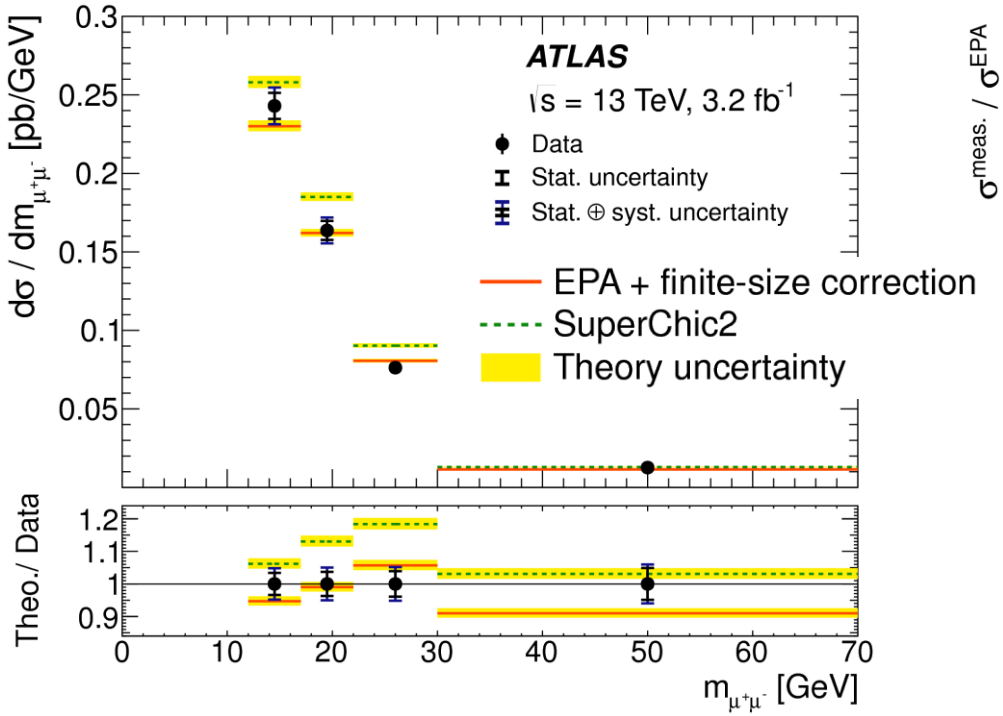
Integrated fiducial cross section

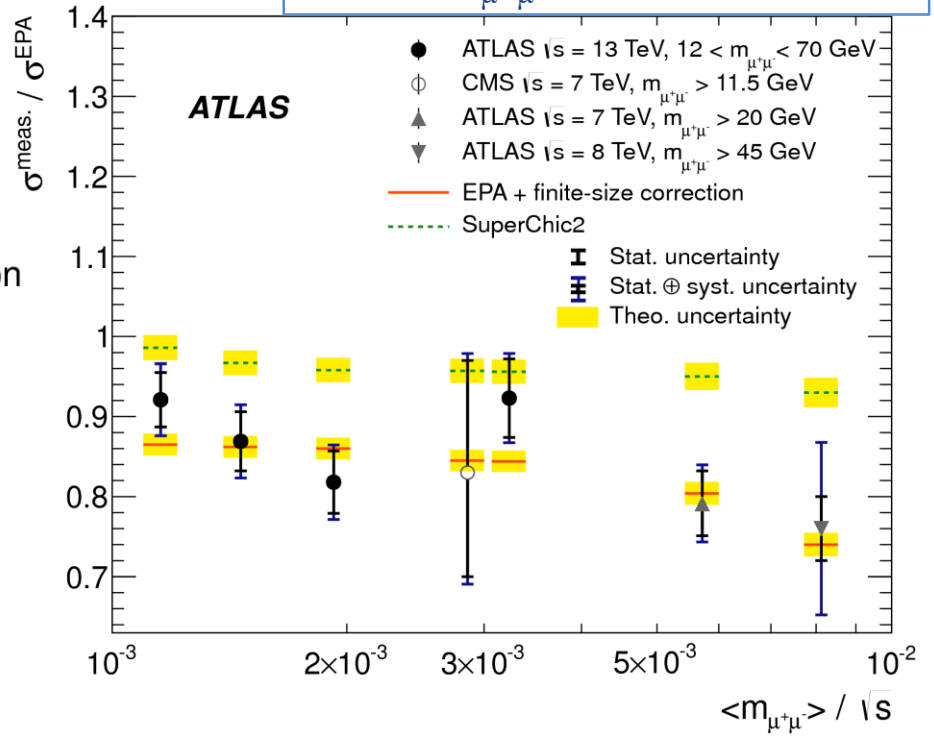
measured: $\sigma_{\gamma\gamma\to\mu^+\mu^-} = 3.12 \pm 0.07\ (\text{stat}) \pm 0.10\ (\text{syst})$ pb (~4%)

EPA + corr. $\sigma_{\gamma\gamma\to\mu^+\mu^-} = 3.06 \pm 0.05$ pb

SuperChic2 $\sigma_{\gamma\gamma\to\mu^+\mu^-} = 3.45 \pm 0.05$ pb

x = fractional energy of photon
$\langle x \rangle \approx \langle m_{\mu^+\mu^-} \rangle / \sqrt{s}$





- Finite-size parametrization describes data
- SuperChic2 overestimates data by 10-20%

- Survival factor = data/bare EPA ≈ 80-90%
- Does exhibit mass dependency

Correlations in ordered hadron chains @ 7 TeV

to be published

Ordered hadron chains - motivation

- How are the early stages of hadronization?

- Is there screwiness at the end of the QCD cascades?

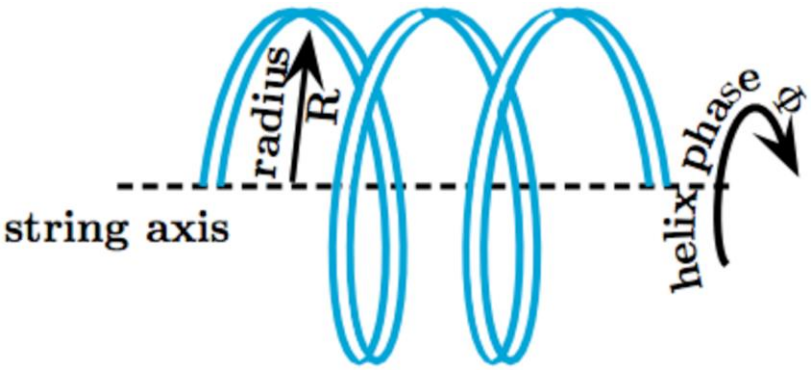
  B. Andersson et al., JHEP 9809 (1998) 014

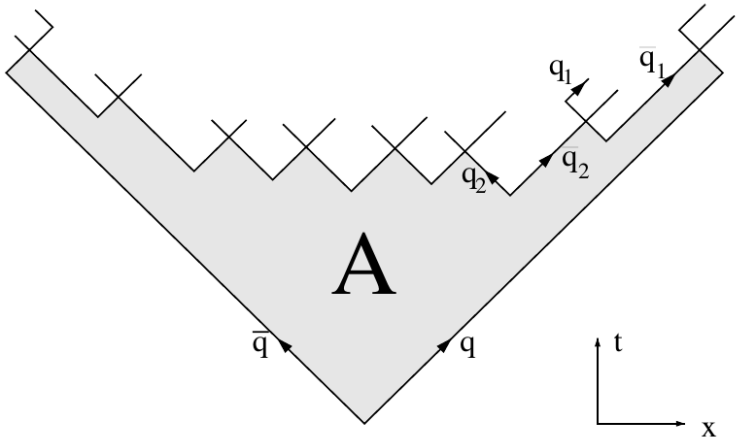
  - "emission of soft gluons is constrained to produce an ordered field in the form of a helix"
  - e.g. meant as a modification of Lund string fragmentation model
  - collinear gluon emissions are absent

- Quantization of the helix string

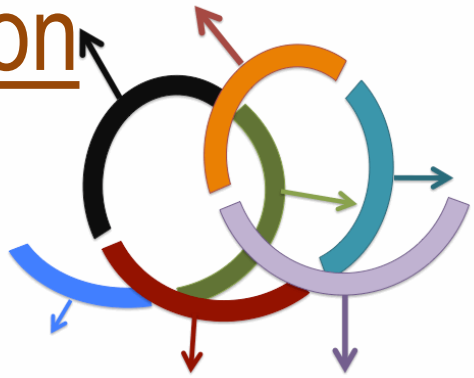
  S. Todorova-Nova, Phys. Rev. D 89 (2014) 015002

  – string of tension κ (~ 1 GeV/fm) is described by radius R and phase ϕ





Quantized helical string fragmentation



- String quantization assumed in transverse coordinate

  $R\,\phi \Rightarrow n\,R\,\Delta\phi$ (n = 1, 2, 3, ...)

- Mass spectrum of light mesons (π,η,η‘) fit

  → string breaks at regular Δϕ intervals, $\kappa R = 68 \pm 2$ MeV

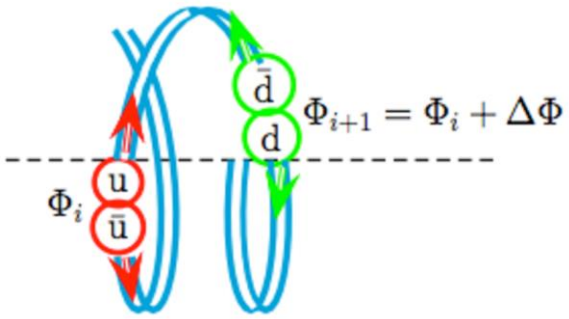
n = 1 for pions → $\Delta\phi = 2.82 \pm 0.06$ ← almost back-to-back!

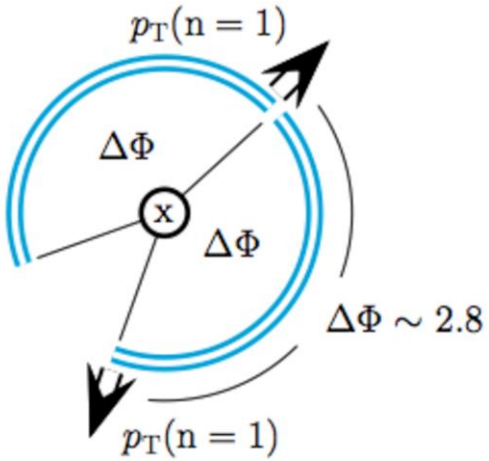
(analysis focus on „ground state pions“ – lack of particle identification)

- Model predicts: minimal momentum difference Q for adjacent hadrons!

  → minimal mass of *n* hadron chain

$$Q = \sqrt{-(p_i - p_j)^2}$$





Quantized helical string fragmentation

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

Phys. Rev. D 89 (2014) 015002

- Hadron pairs are ordered along the string (ranking)

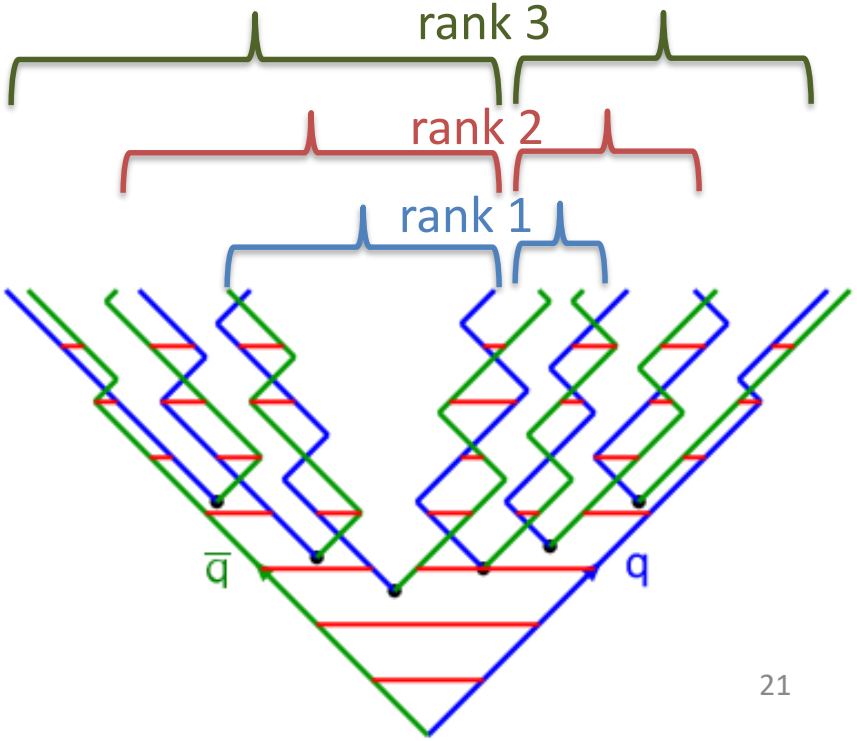
- Local charge conservation

→ rank 1 pairs always + –

→ rank 2 pairs always + + or – –

- Helicity conservation

→ momentum difference constrained



Ordered hadron chains - strategy

- Two-particle correlation function of 4-momentum difference Q

$$\Delta(Q) = \frac{1}{N_{ch}}(N(Q)^{+-} - N(Q)^{++/--})$$

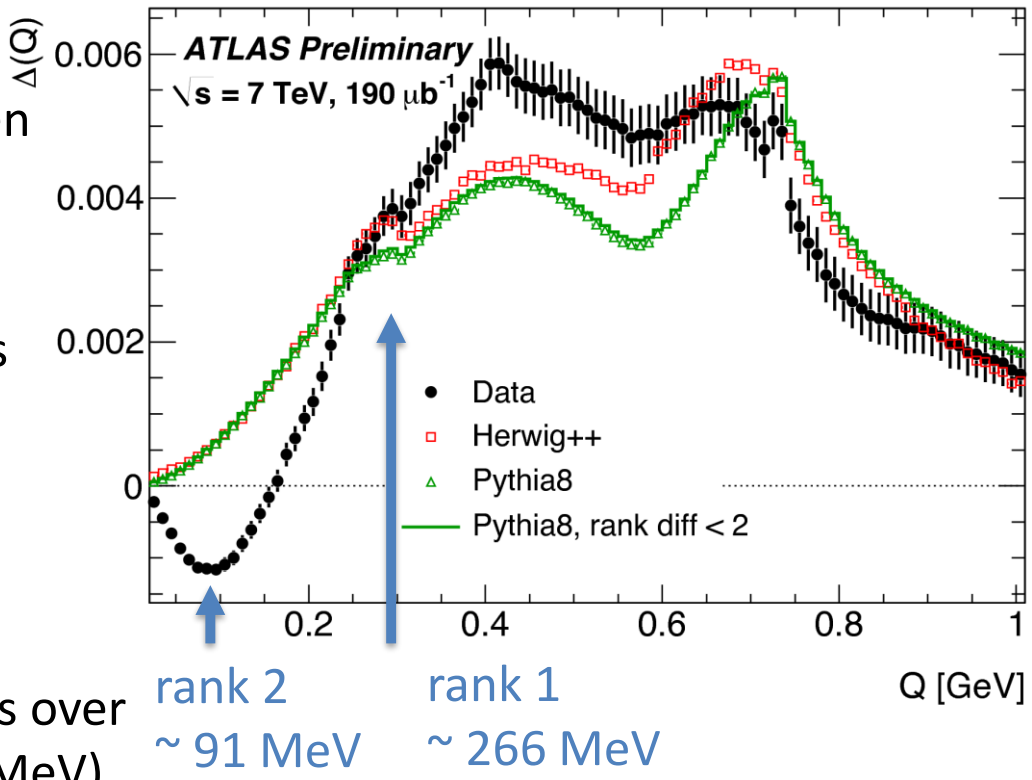
$$Q = \sqrt{-(p_i - p_j)^2}$$

showing the average difference between opposite- and same–sign hadron pairs

Subtraction (instead of ratio) eliminates the combinatorial background (distant pairs mostly $\Delta(Q) \sim 0$)

Full-event MC do not even indicate the enhanced production of same-sign pairs over the opposite-sign pairs at low Q (<200 MeV)

Well, rank is not known – what to do?



nicely confirmed qualitative predictions for rank 1 and 2 hadron pairs

Ordered hadron chains - strategy

- Novel approach: let's measure pairs within hadron triplets: $\pi^+\pi^-\pi^+$ or $\pi^-\pi^+\pi^-$

triplets are designed to best correspond to the hadron chain from the same string breakup = powerful probe of the correlation between particles (ranks 1 or 2)

→ small 3h chain mass expected: $m_{3h} < 570 \pm 20$ GeV ($m_{nh} < n\,\kappa\,R\,\Delta\phi$)

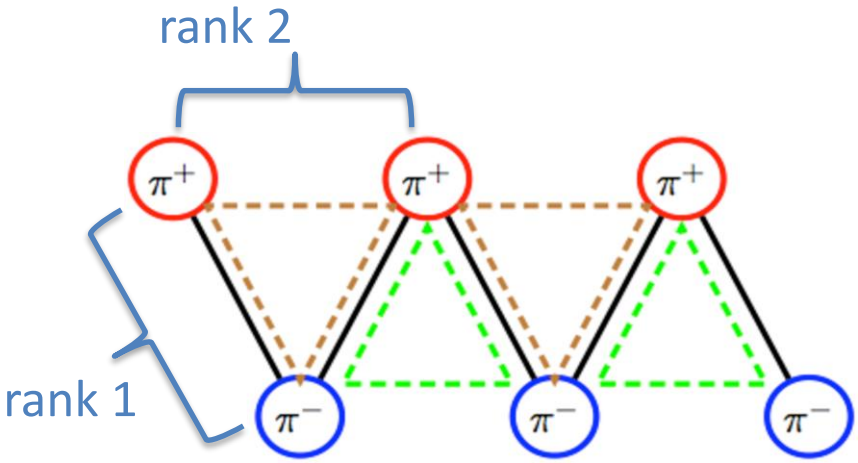
Rivet routine provided!

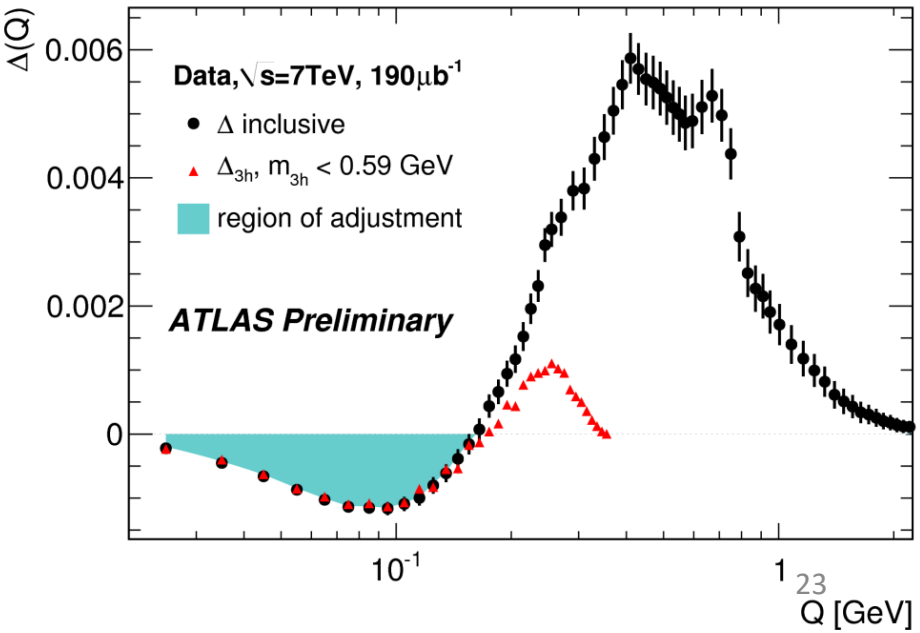
How much $\Delta_{3h}(Q)$ describes the inclusive $\Delta(Q)$?

- actually it agrees fully up to 200 MeV

-> fitted to get the 3h chain mass limit

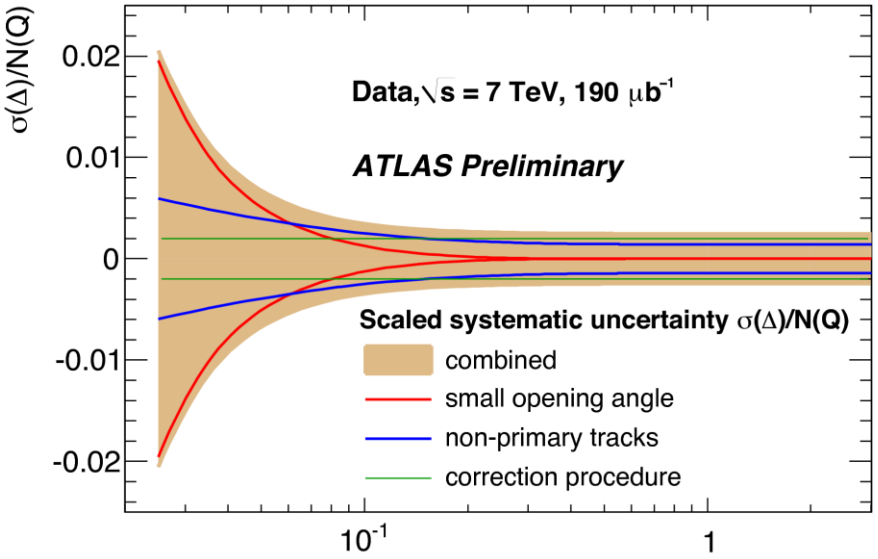
-> result: $m_{3h} < 590$ GeV



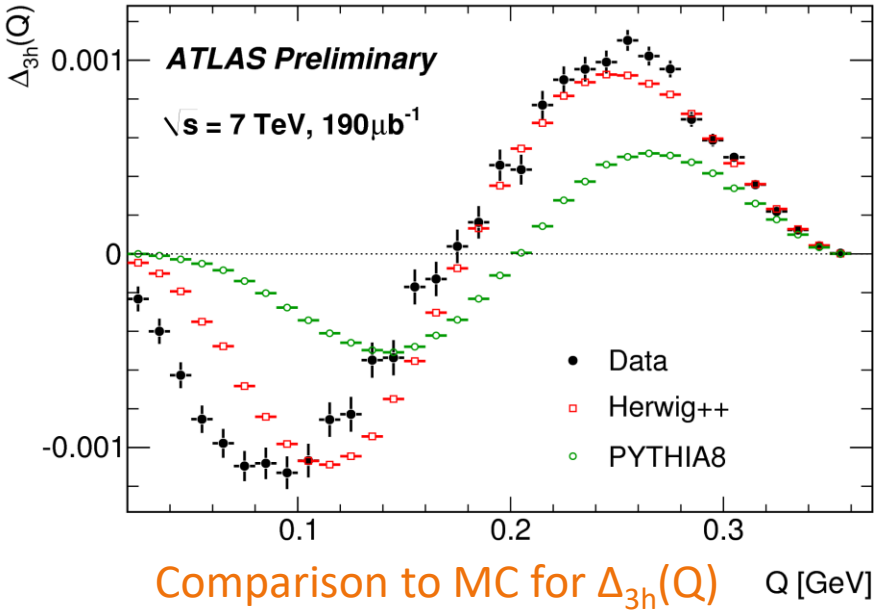


Ordered hadron chains – measurement

- Event selection
  - 7 TeV Minimum Bias 2010 data, $7\mu b^{-1}$, low luminosity run
  - Low-p_T enhanced track selection: $p_T > 100$ MeV, $|\eta| < 2.5$, $n_{ch} > 1$
  - HBOM semi-data driven unfolding
  - Additional correction (+ systematics) for track pairs reconstructed with small opening angle (low Q)
  - MC: 86% pions, 9.5% kaons, 4% protons/antiprotons, 0.5% leptons. ~ 2.3% non-primary particles



Systematics for Δ(Q)

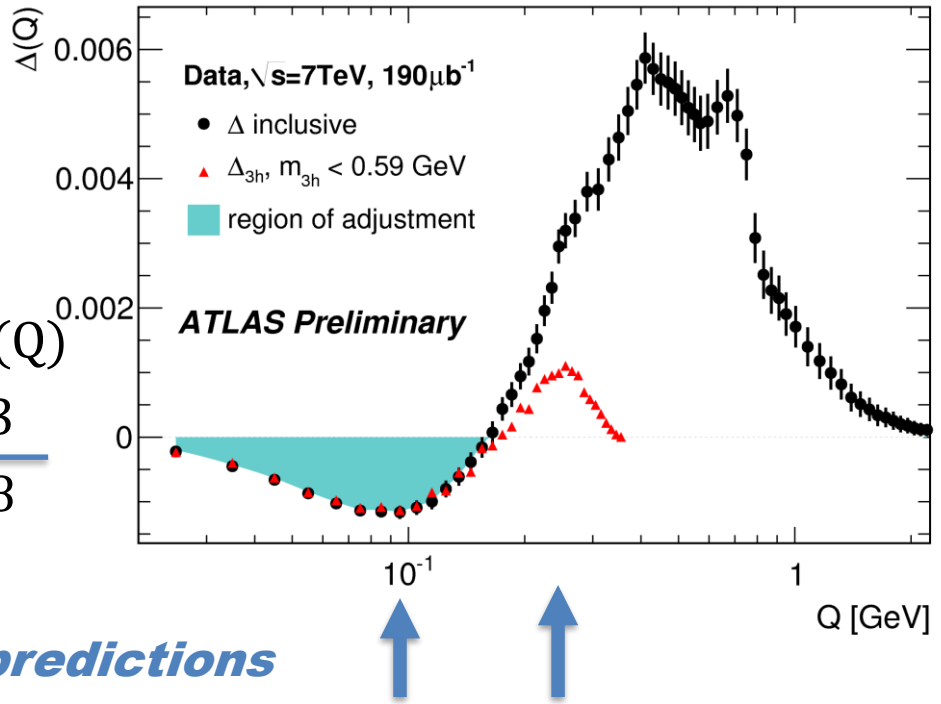


Comparison to MC for $\Delta_{3h}(Q)$

Ordered hadron chains – results

- triplet hadron chain (3h) measurement does reproduce the observed abundance of same-sign hadron pairs when upper mass (m_{3h}^{cut}) of the chain is adjusted!
  (by interpolation from 0.58, 0.59 and 0.60 values)

$$\mathbf{m_{3h}^{cut} = 591 \pm 2\ (stat) \pm 7\ (syst)\ MeV}$$



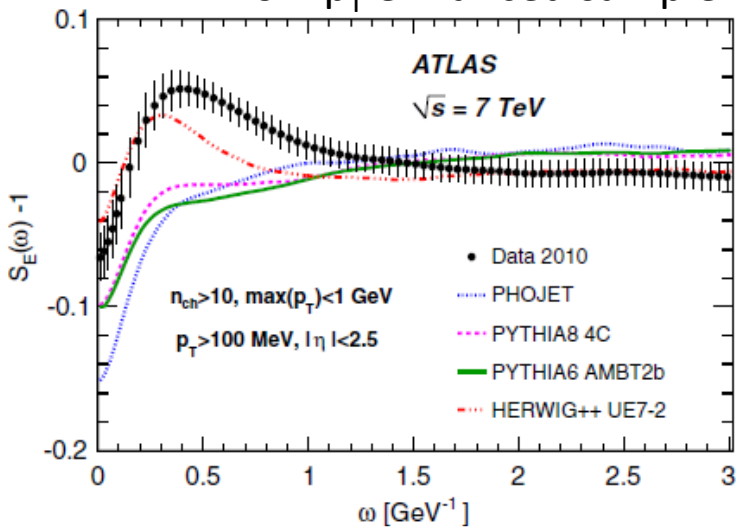
- Double-Gaussian parametization of $\Delta_{3h}(Q)$

	measured	model predictions
$Q(++ \text{ or } --) = 89.4 \pm 0.4$	91 ± 3	
$Q(+-) = 255.8 \pm 0.5$	266 ± 8	

Existence of these thresholds is a fundamental feature of the quantized helical model of fragmentation!

Ordered hadron chains

low p_T enhanced sample



- New measurement connections:

"Measurement of the azimuthal ordering of charged hadrons with the ATLAS detector"

- Phys. Rev. D 86 (2012) 052005

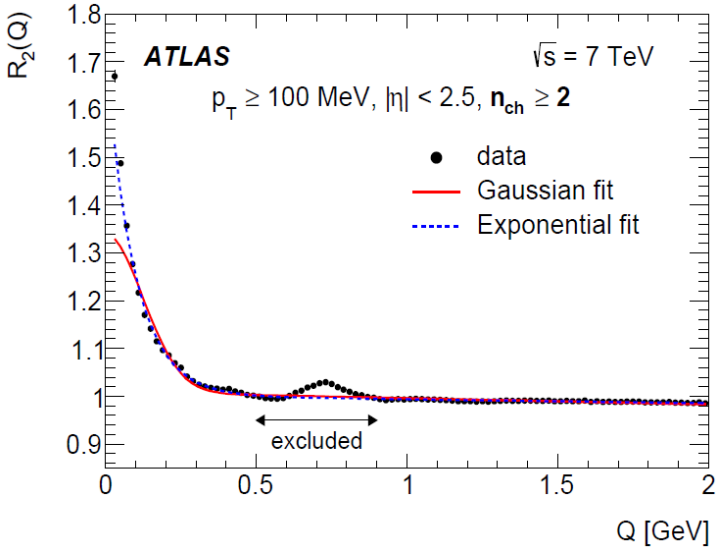
$$S_E(\omega) = 1 + \frac{1}{N_{\text{ev}}} \sum_{\text{event}} \frac{1}{n_{\text{ch}}} \sum_{i \neq j} \cos(\omega \Delta X_{ij} - \Delta \phi_{ij})$$

power spectrum; hadron with azimuth ϕ and position X along the chain $X_j = 0.5E_j + \sum_{k=0}^{k<j} E_k$

"Two-particle Bose–Einstein correlations in pp collisions at √s = 0.9 and 7 TeV measured with the ATLAS detector"

- Eur. Phys. J. C 75 (2015) 466
- incoherence/chaoticity parametrized model
- the very same data as new measurement - compared

$$R_2(Q) = \frac{\rho(++,--)}{\rho(+-)} \Big/ \frac{\rho^{\text{MC}}(++,--)}{\rho^{\text{MC}}(+-)}$$



Summary

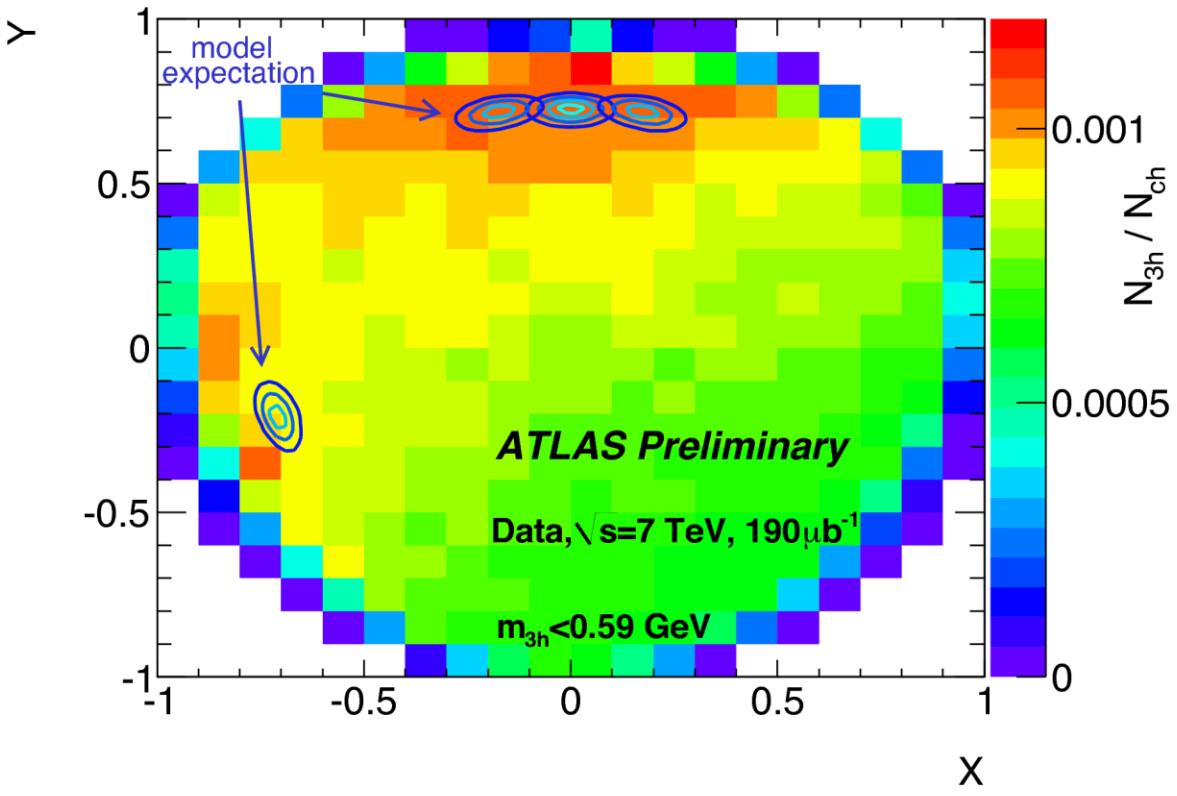
- Track-based UE @ 13 TeV:
  - new track-based measurement reaching lower p_T^{lead} and higher precision (1%)
  - roughly 20% increase in UE activity wrt 7 TeV
  - MC predictions within total 5% accuracy – systematic mismodeling shown

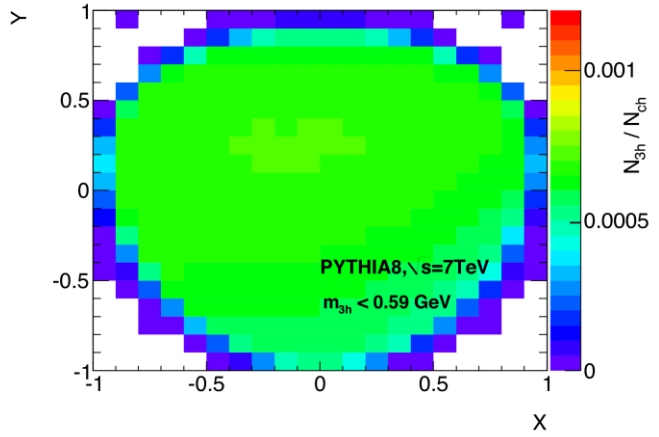
- Exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ @ 13 TeV
  - production cross section measured – integrated & differential in dimuon mass
  - survival through additional QCD interaction approx. 80-90%, tend to decrease with dimuon mass

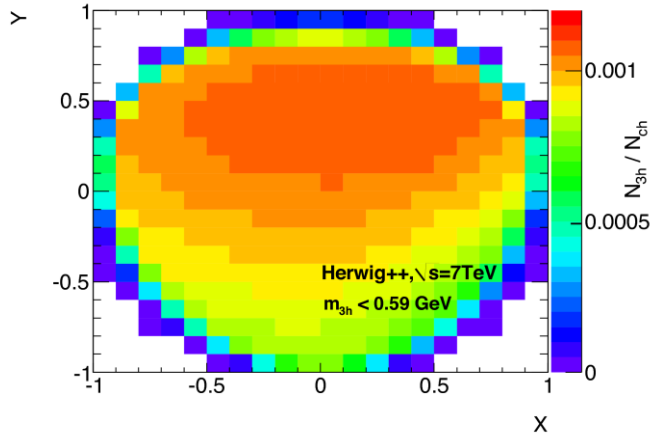
- Helical string fragmentation @ 7 TeV
  - two-particle correlation spectra in Minimum Bias data
  - unique observation of "adjacent" hadrons – via 3h mass restriction
  - 4mom. difference: same-sign pairs at 89.7 MeV, oposite-sign pairs at 266 MeV

Back-up

Ordered hadron chains – Dalitz plots



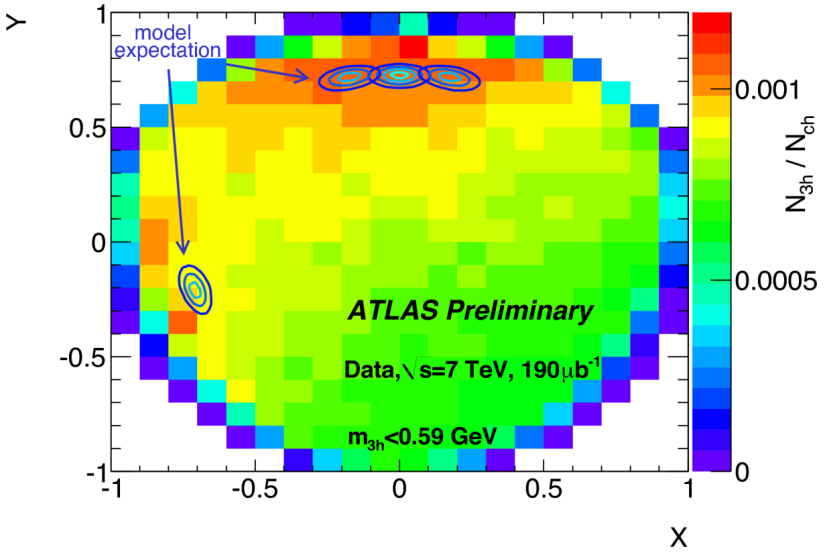


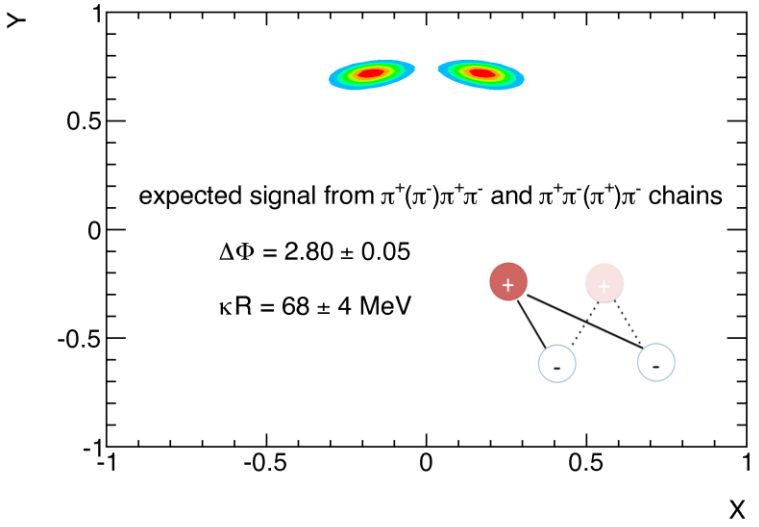


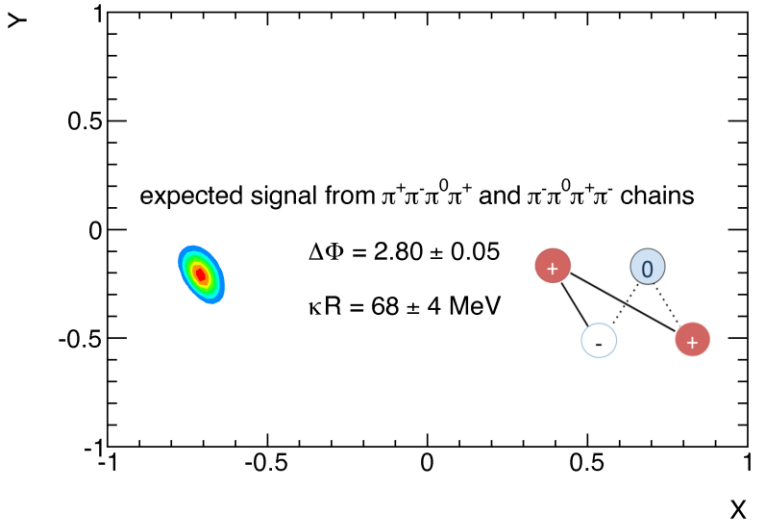
$$X = \sqrt{3}\,\frac{T_0 - T_2}{\Sigma_{i=0}^{2} T_i}, \qquad Y = \frac{3T_1}{\Sigma_{i=0}^{2} T_i} - 1$$

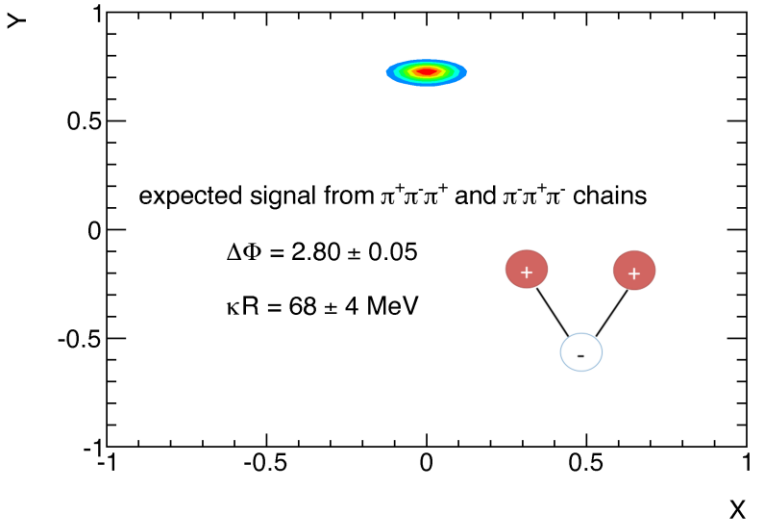
T_i = kinetic energy of *i*-th hadron in the 3h chain

Ordered hadron chains – Dalitz plots



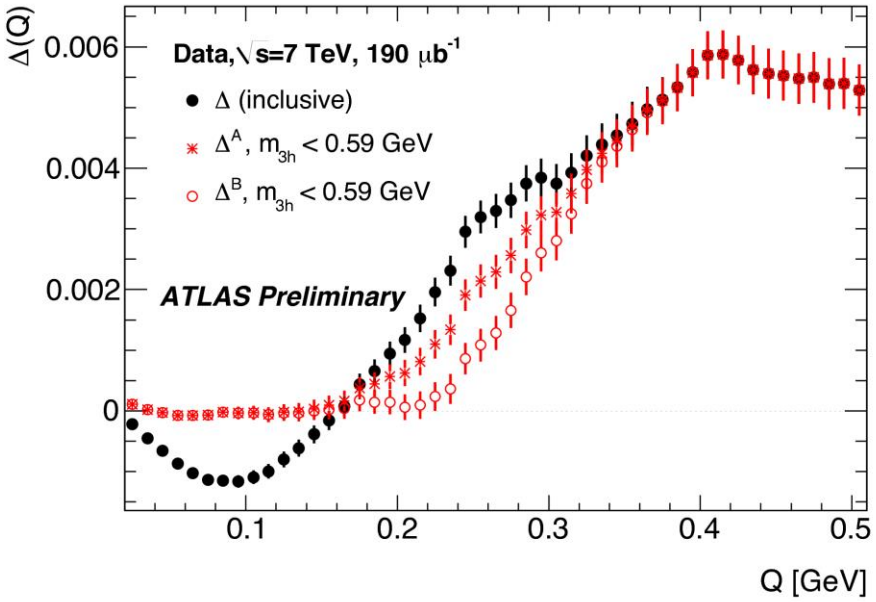


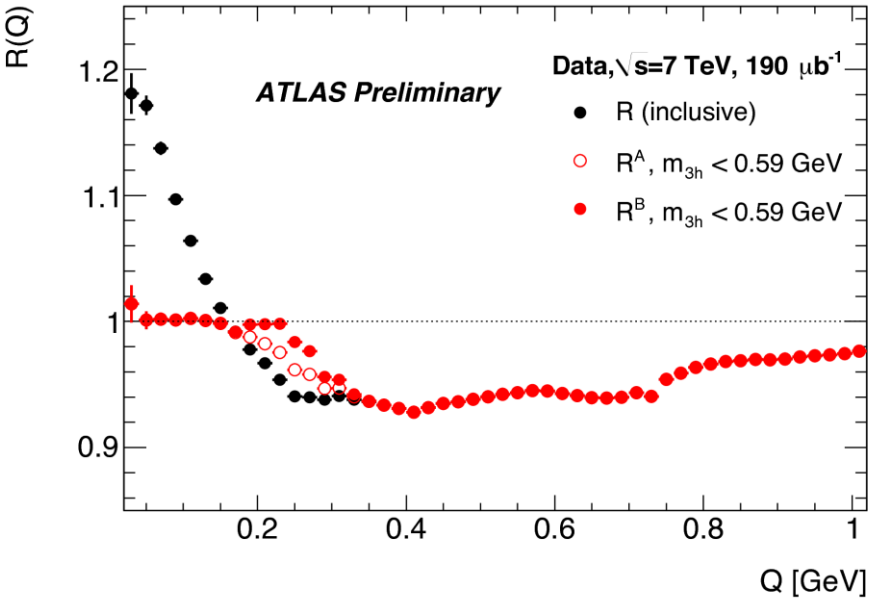




Ordered hadron chains - ratios

Identical data – two different physics interpretations





Quantized Helical sting fragmentation
- causal coherent production
- model predicts momentum thresholds

Bose-Einstein interference
- incoherent probabilistic production