Recent soft and diffractive QCD measurements at the LHC

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QCD@LHC, Durham, 2023

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ATLAS EXPERIMENT

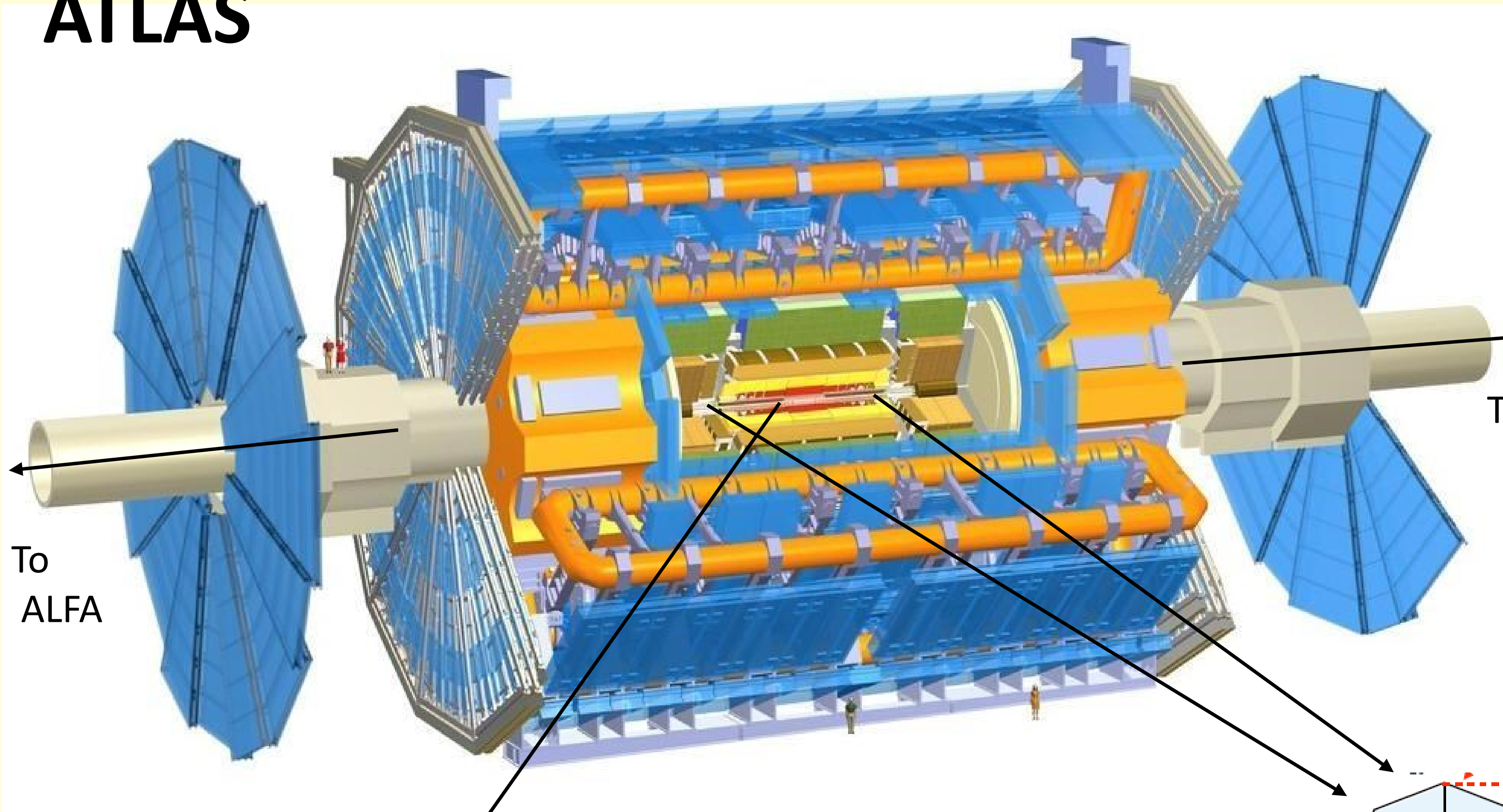
CMS

TOTEM

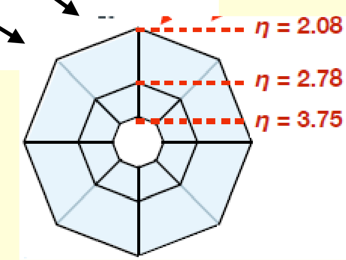
ALICE

LHCb

ATLAS

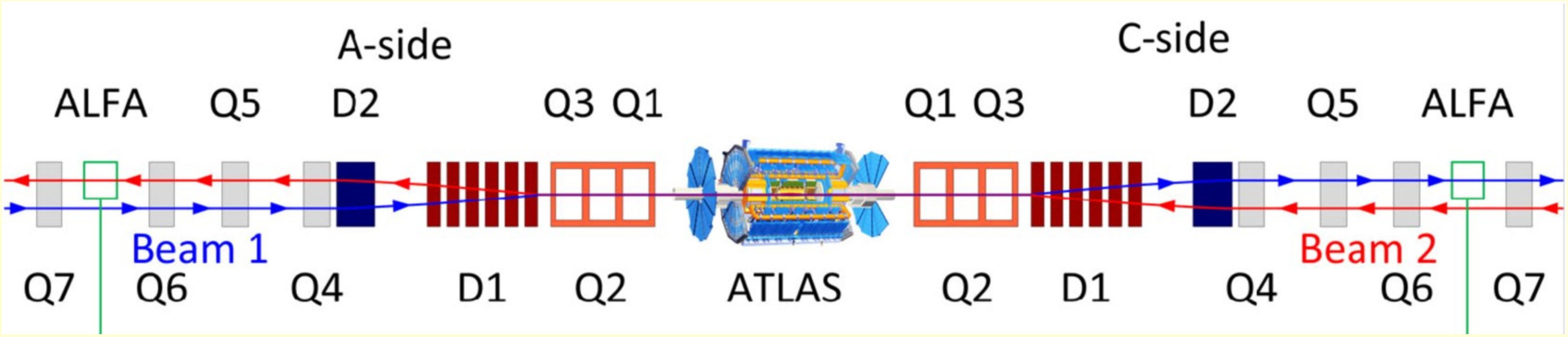


Inner detector
(tracker)



MBTS at z=±3.6m
2.1 < |η< 3.8
(Minimum Bias Trigger Scintillators)

Results using ATLAS ALFA detector system



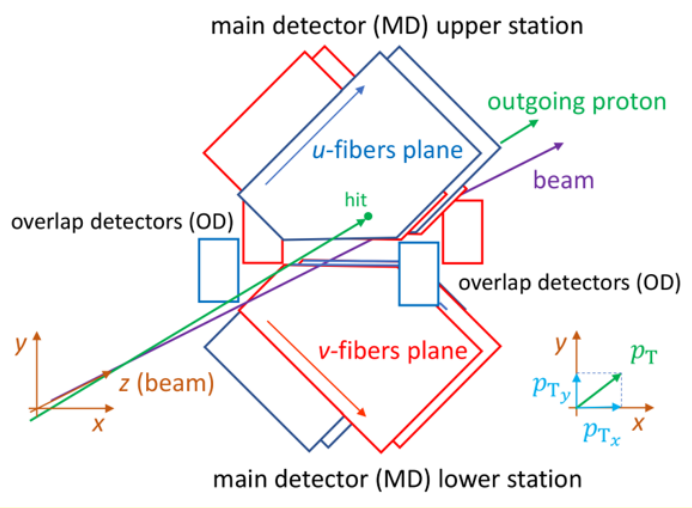
Recent publications

1) Measurement of the total cross section and *ρ*-parameter from elastic scattering in *pp* collisions at √s=13 TeV with the ATLAS detector.
EJPC 83 (2023) 441

7 dedicated runs at β^* = 2500 m, total integrated luminosity =340 μb^{-1}

2) Measurement of exclusive pion pair production in proton–proton collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector.
EJPC 83 (2023) 627

Reconstruction efficiency is measured by a tag-and-probe method (well-measured protons on one side as tags for a proton on the other side.) Typically 83-88%.



An elaborate **alignment method** makes use of the overlap counters OD. "Global tracks" are used, which are back-to-back pairs of tracks, giving alignment accuracy of 5-10 microns.

Systematics: reconstruction efficiency uncertainty is 0.4% - 0.9%, dominated by the evaluation of accidental coincidences and uncertainties in backgrounds, and t-dependent effects.

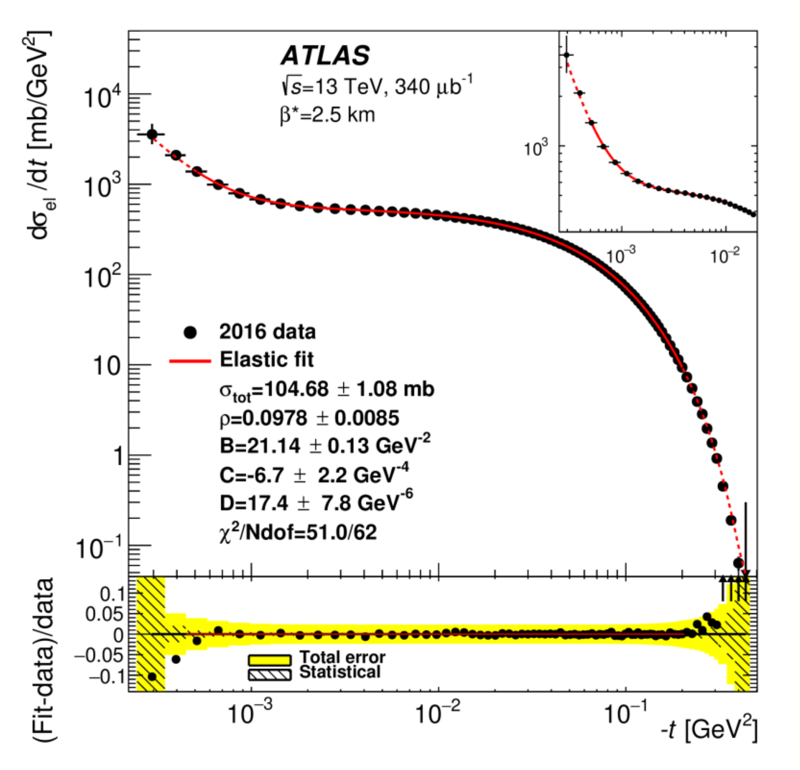
The tracking accuracy is dominated by the global vertical distance uncertainty (after alignment) of +/- 22 microns.

Evaluation of results

$-t = (\theta_x^{\,2} + \theta_y^{\,2})p$ at IP.

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t_i} = \frac{1}{\Delta t_i} \times \frac{\mathcal{M}^{-1}[N_i - B_i]}{A_i \times \epsilon^{\mathrm{reco}} \times \epsilon^{\mathrm{trig}} \times \epsilon^{\mathrm{DAQ}} \times L_{\mathrm{int}}}$$

(*M* corrects for unfolding procedure in *t*)

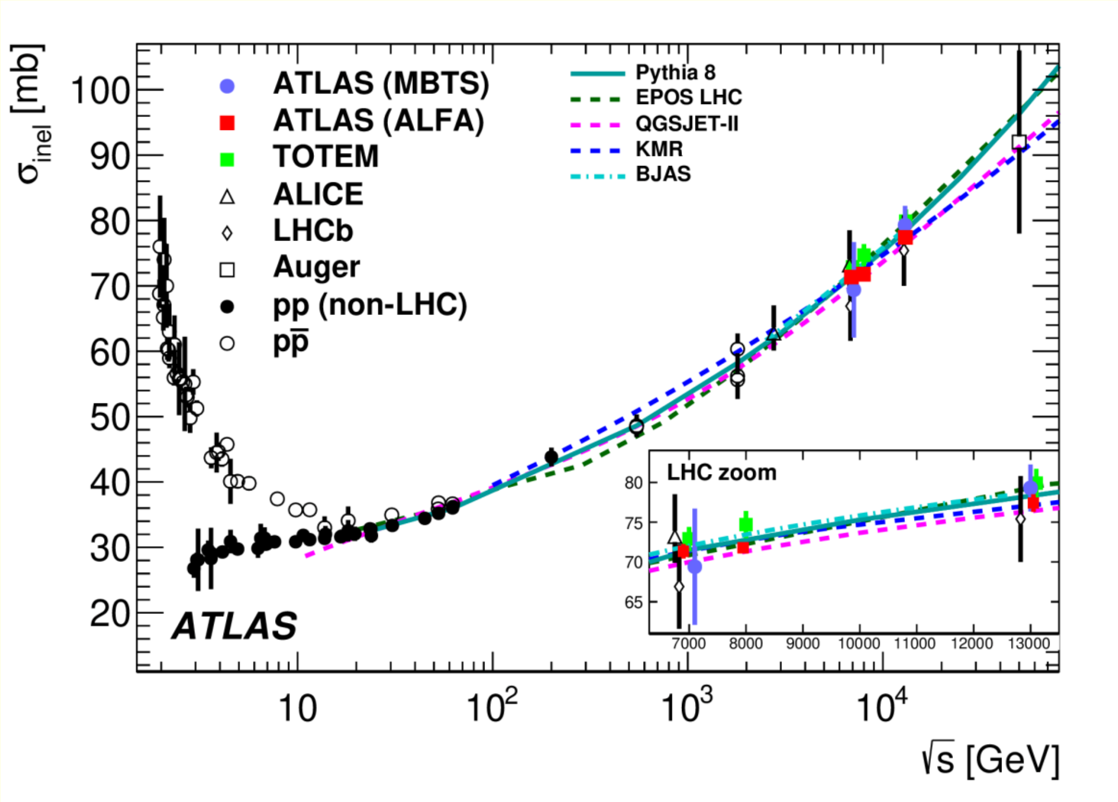


Total elastic and inelastic cross sections

Can perform a (model-dependent) integration of the nuclear part of the elastic cross section over all phase space to get:

$$\sigma_{\rm el}^{\rm extr} = 27.27 \pm 1.10\,({\rm exp.}) \pm 0.30\,({\rm th.})\ {\rm mb.}$$

which can be subtracted off the total measured cross section to give the inelastic xsec.

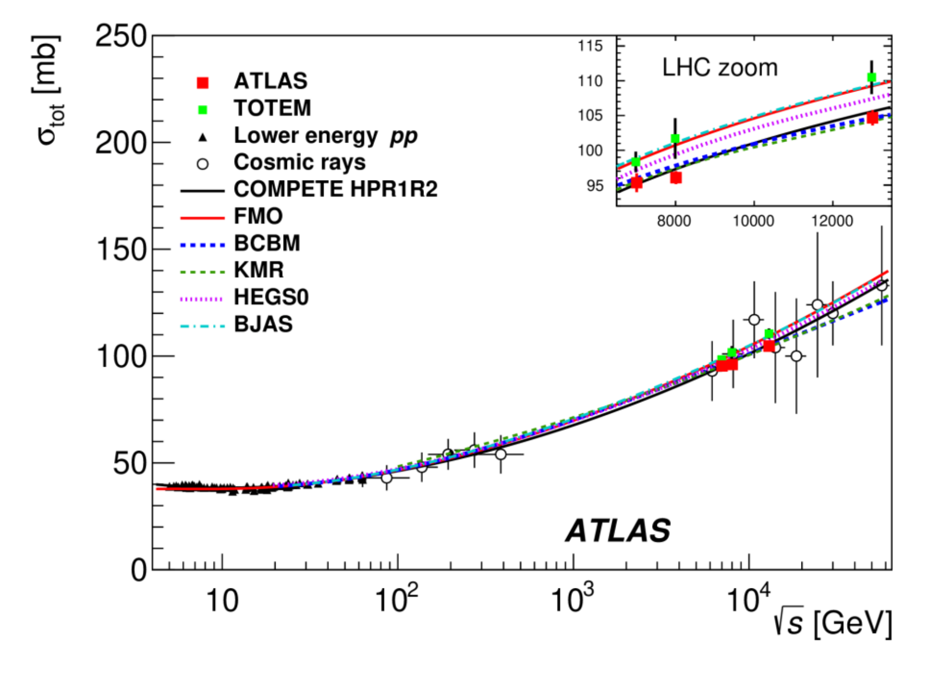


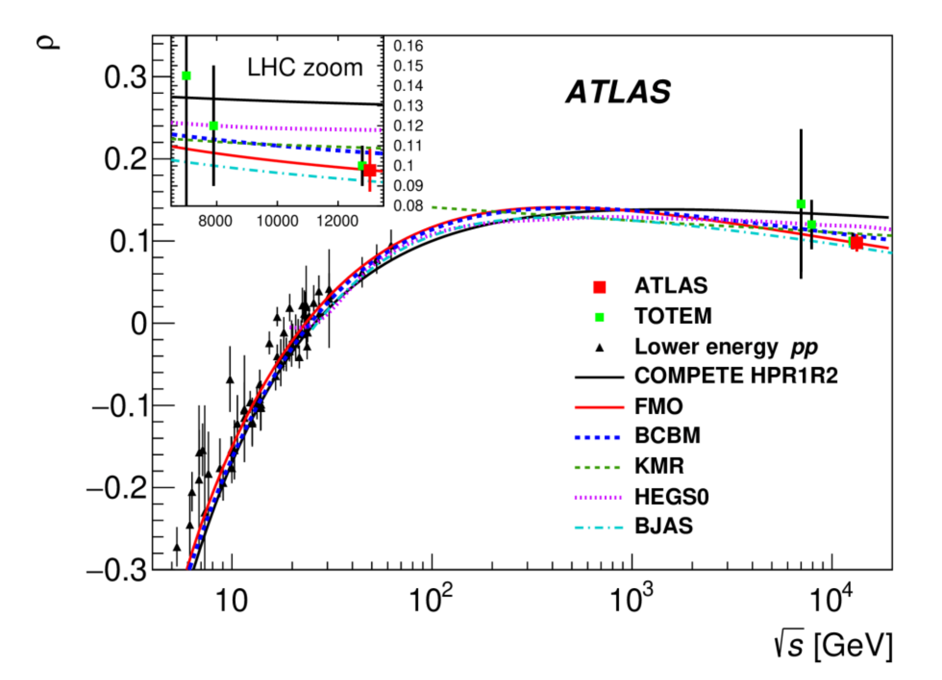
Finally we can get the **total cross section** using the Optical theorem:

$$\sigma_{tot}^2 = \frac{16\pi}{1+\rho^2} \cdot \left.\frac{d\sigma_{el}}{dt}\right|_{t\to 0}$$

where

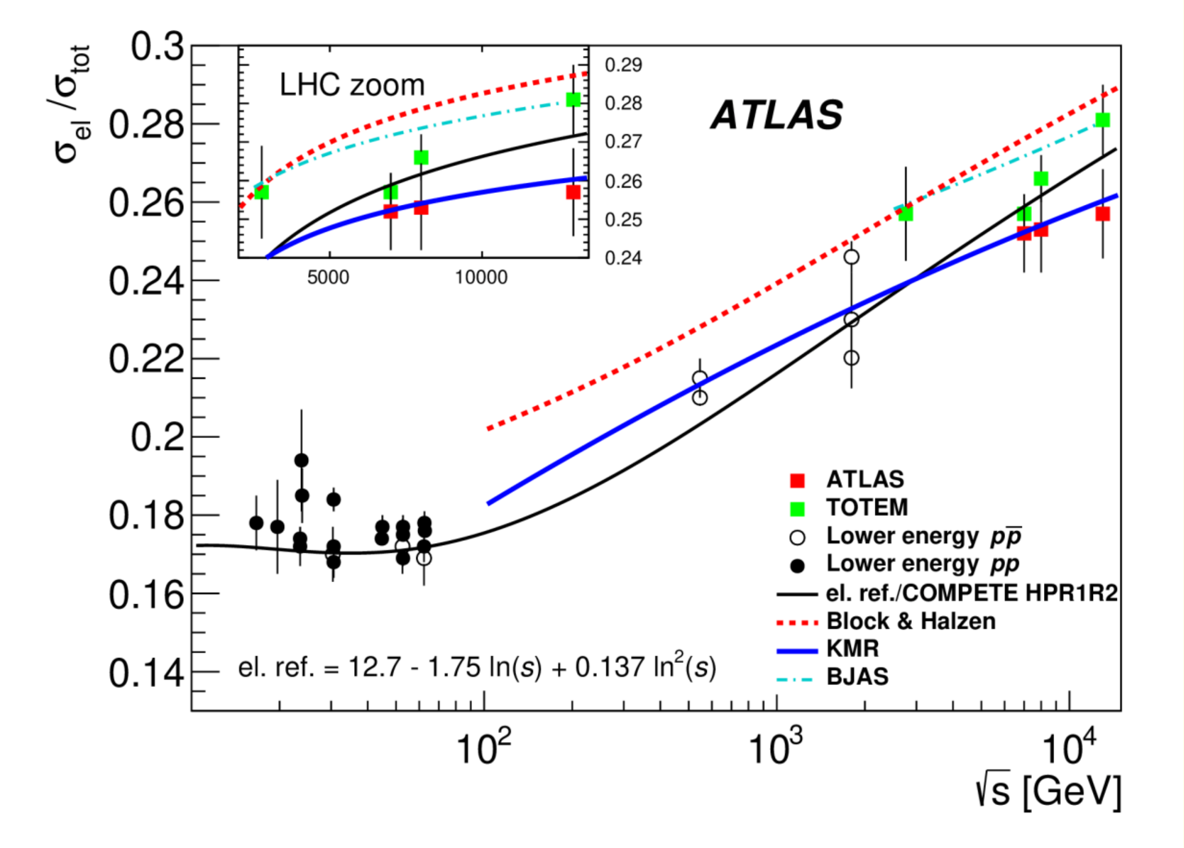
$$\rho = \left.\frac{\mathrm{Re}(f_{el}(t))}{\mathrm{Im}(f_{el}(t))}\right|_{t\to 0}$$





- The widely used model COMPETE is in poor agreement with above (predicts $\rho = 0.13$)
- Model with Odderon tuned to TOTEM is in poor agreement with ATLAS
- ALFA and TOTEM disagree at 2.2 σ level.

Ratio of elastic to total:



Data not in perfect agreement, and the models also differ!

Conclusions from total pp cross section measurements from ATLAS:

- Most precise LHC measurements of σ_{tot} , measured numbers from ATLAS are:

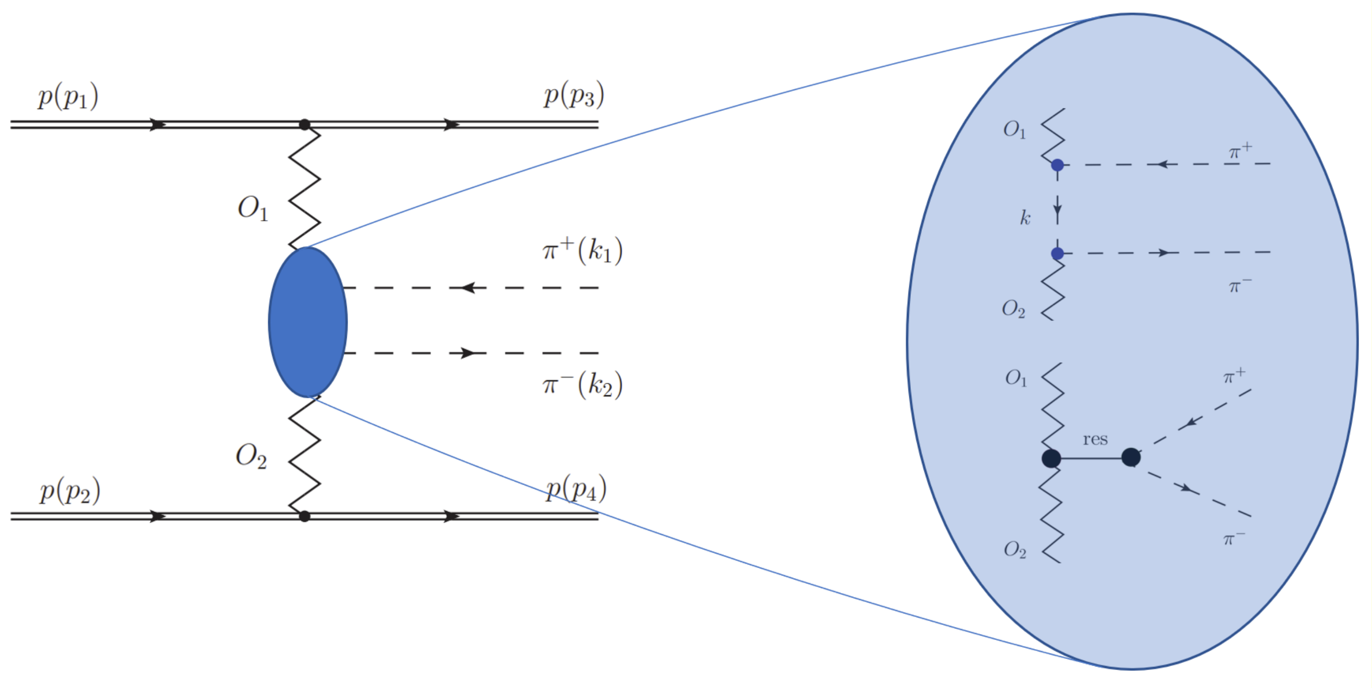
$$
\begin{aligned}
\sigma_{\mathrm{tot}}(pp \to X) &= 104.68 \pm 1.08\,(\mathrm{exp.}) \pm 0.12\,(\mathrm{th.})\ \mathrm{mb}, \\
\rho &= 0.0978 \pm 0.0085\,(\mathrm{exp.}) \pm 0.0064\,(\mathrm{th.}), \\
B &= 21.14 \pm 0.13\ \mathrm{GeV}^{-2}, \\
C &= -6.7 \pm 2.2\ \mathrm{GeV}^{-4}, \\
D &= 17.4 \pm 7.8\ \mathrm{GeV}^{-6}.
\end{aligned}
$$

- ATLAS values of ρ and σ_{tot} are in tension with COMPETE

- σ_{tot} somewhat lower than TOTEM, largely due to normalisation

The exclusive diffractive dipion process at the LHC

ATLAS



We measure this by measuring the two pions in the ATLAS inner detector and both forward protons in the ALFA detectors.
Proton excitation processes are excluded.

First measurement of exclusive process pp → $pp\pi^+\pi^-$

Trigger:

Elastic - ALFA coincidence of detectors in an elastic combination.
Anti-elastic – signal in any ALFA detector, prescaled by 15

In ALFA detectors:

One good quality track on each side

In ATLAS Inner Detector:

Two oppositely charged tracks, taken as pions,
satisfying $|\eta(\pi)| < 2.5$, $p_{\mathrm{T}}(\pi) > 0.1$ GeV, $2m\pi < 2.0$ GeV. (fiducial)

Quality requirements on the pion tracks were imposed.

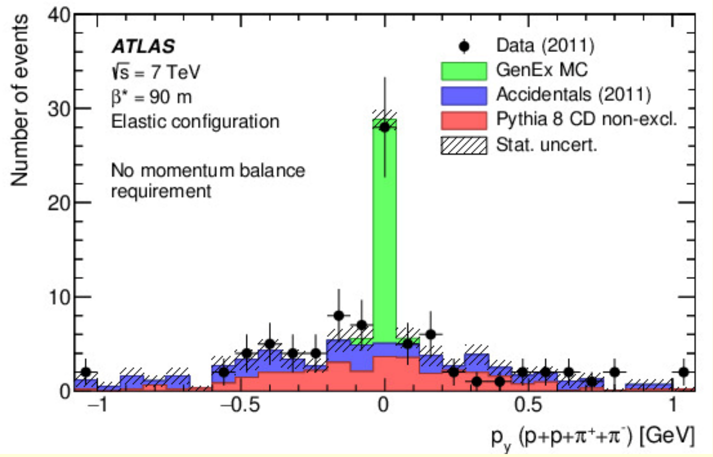
MBTS veto:

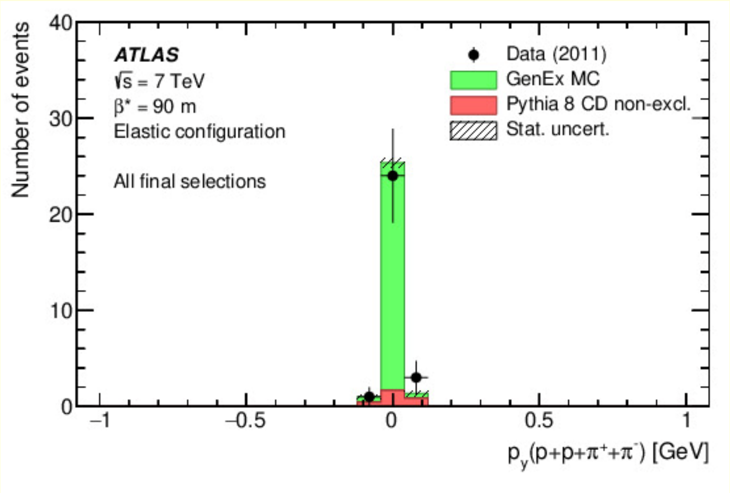
At most one hit, in the combined inner MBTS scintillators, to remove diffractive-dissociative and non-diffractive events.

Overall momentum balance:

$pp\pi^+\pi^-$ momentum balance in x and in y consistent with zero (±3,5σ)

Final results for elastic combination.





Before and after final momentum balance cut.

To note:

- The cuts are *very* effective at removing background.
- A cut on the MBTS counts was essential.
- Low statistics from this short run in 2011 at 7 TeV (4 hours high β^*, $\mu = 0.035$)
- Feasibility of the measurement has been demonstrated.

Results

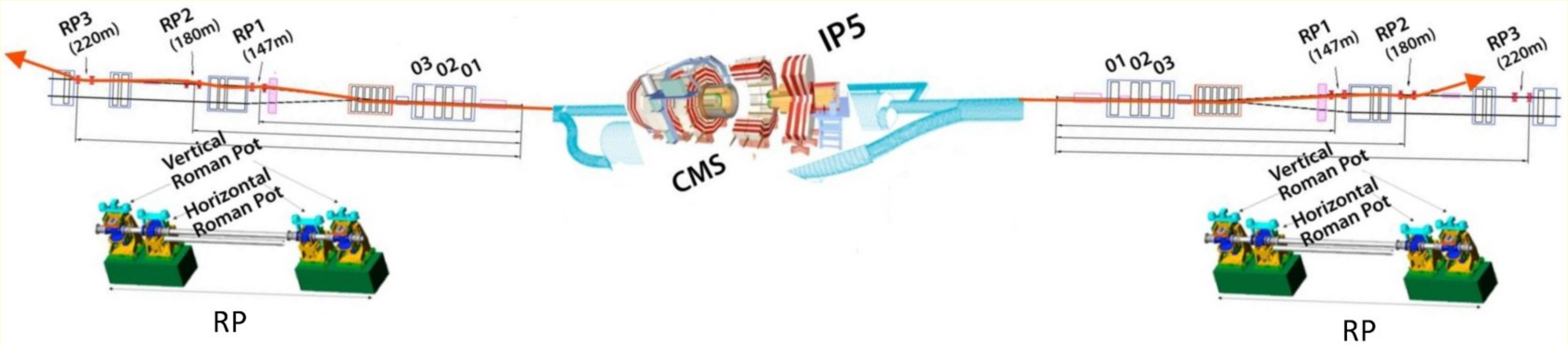
Exclusive $\pi^+\pi^-$ cross-section [μb]	
Elastic configuration	
Measurement	4.8 ± 1.0 (stat) $^{+0.3}_{-0.2}$ (syst) ± 0.1 (lumi) ± 0.1 (model)
GenEx $\times$ 0.22 (absorptive correction)	1.5
Dime	1.6

GENEX: R. A. Kycia et al., *Commun. Comput. Phys.* 24 (2018) 3, 860-884
DIME: (Harland-Lang, Khoze, Ryskin, EPJC 74 (2014) 2848

Comments:

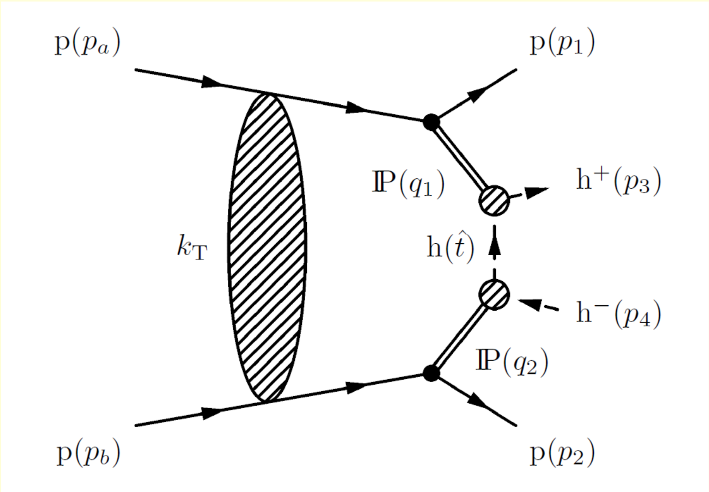
- Absorptive correction included for GENEX as recommended by the author
- First measurements, more to follow soon!
- The MC appears a little low but there are parameters that could be varied.

CMS-TOTEM Exclusive pion pair production in non-resonant region.



(Preliminary results from F. Siklér, EPS-HEP Hamburg.)

CMS-PAS-SMP-21-004, I http://cds.cern.ch/record/2867988



Non-resonant hadron pair production.
Subprocesses include:

- Simple two-pomeron exchange
- Initial pp interaction
- Proton-hadron final state interactions

Modelled in DIME MC.

Data taking and analysis.

- Data from special run at beta* = 90m in 2018
- Use near and far stations at 213m and 220m
- Top and Bottom pots
  - 80M events with pph^+h^- topology
- No other central tracks
- Good central particle identification for p < 1 GeV. Select pi+pi-
- Events selected on the basis of transverse momentum conservation

Events from the $\pi^+\pi^-$ resonance region are not considered here. The principal kinematic ranges studied, for different $\pi^+\pi^-$ mass ranges, are:

- the distribution of the azimuthal angle between the scattered proton momenta, $\mathrm{d}^3\sigma/\mathrm{d}p_{1,\mathrm{T}}\,\mathrm{d}p_{2,\mathrm{T}}\,\mathrm{d}\phi$, if $0.35 < m < 0.65\,\mathrm{GeV}$;
- the distribution of the two-hadron invariant mass at low masses, $\mathrm{d}^3\sigma/\mathrm{d}p_{1,\mathrm{T}}\,\mathrm{d}p_{2,\mathrm{T}}\,\mathrm{d}m$, if $m < 0.7\,\mathrm{GeV}$;
- the distribution of the two-hadron invariant mass at high masses, $\mathrm{d}^3\sigma/\mathrm{d}p_{1,\mathrm{T}}\,\mathrm{d}p_{2,\mathrm{T}}\,\mathrm{d}m$, if $1.8 < m < 2.2\,\mathrm{GeV}$;
- the distribution of the squared four-momentum of the virtual meson, $\mathrm{d}^3\sigma/\mathrm{d}p_{1,\mathrm{T}}\,\mathrm{d}p_{2,\mathrm{T}}\,\mathrm{d}\max(\hat{t},\hat{u})$, if $1.8 < m < 2.2\,\mathrm{GeV}$;

Outgoing protons in the transverse momentum range: $0.2 < p_{1,T}, p_{2,T} < 0.8$ GeV

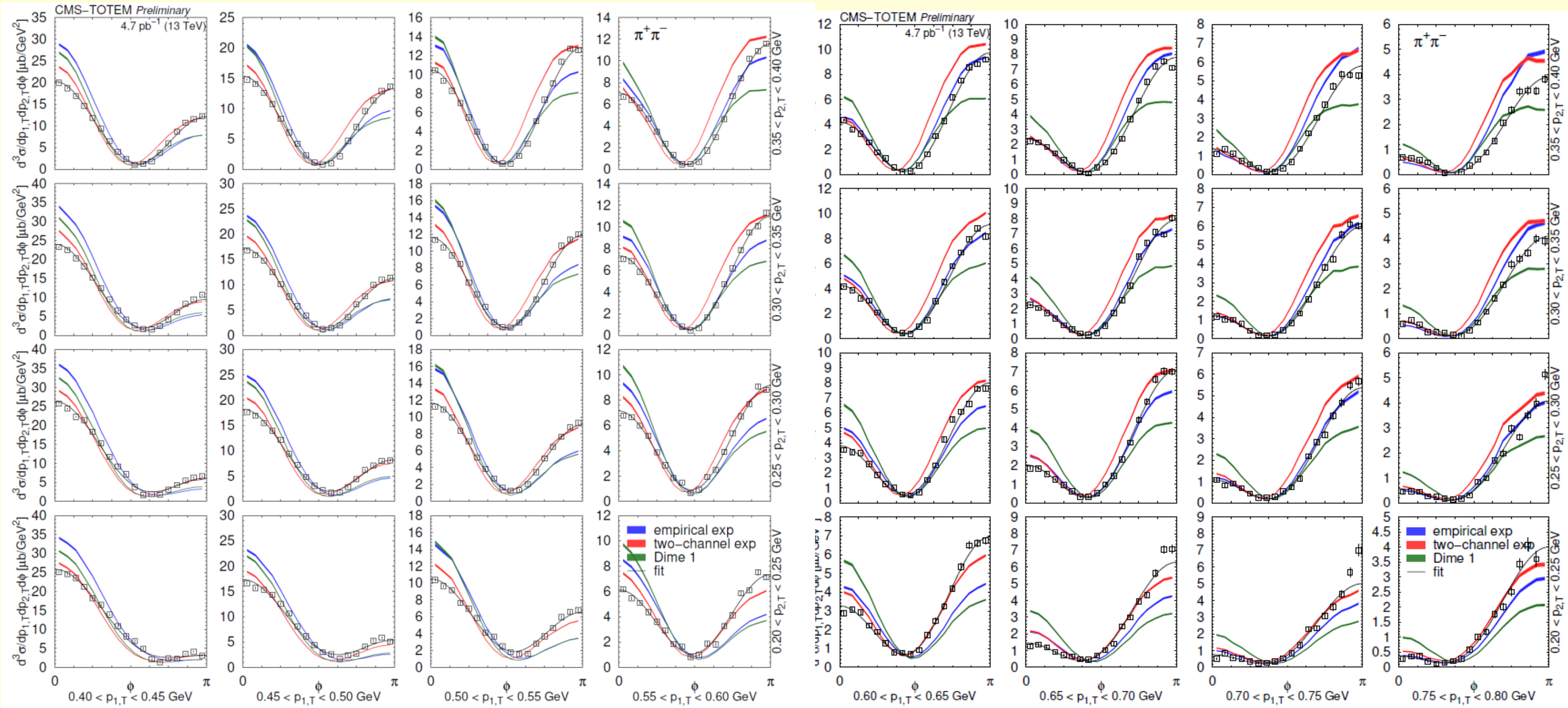
Model tuning.

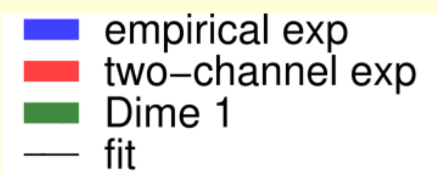
Several models were tuned to the Data. The table indicates the complexity of the situation!

Focus on the pipi mass region 0.35-0.65 GeV to keep clear of resonances.

Parameter	Exponential	Orear-type	Power-law	DIME 1 / 2
empirical model				
a_{ore}[GeV]	—	0.735 ± 0.015	—	
$b_{\text{exp/ore/pow}}$[GeV^{-2} or $^{-1}$]	1.084 ± 0.004	1.782 ± 0.014	1.356 ± 0.001	
$B_{\mathbb{P}}$ [GeV^{-2}]	3.757 ± 0.033	3.934 ± 0.027	4.159 ± 0.019	
χ^2/dof	$9470/5796$	$10059/5795$	$11409/5796$	
one-channel model				
σ_0[mb]	34.99 ± 0.79	27.98 ± 0.40	26.87 ± 0.30	
$\alpha_P - 1$	0.129 ± 0.002	0.127 ± 0.001	0.134 ± 0.001	
α'_P [GeV^{-2}]	0.084 ± 0.005	0.034 ± 0.002	0.037 ± 0.002	
a_{ore}[GeV]	—	0.578 ± 0.022	—	
$b_{\text{exp/ore/pow}}$[GeV^{-2} or $^{-1}$]	0.820 ± 0.011	1.385 ± 0.015	1.222 ± 0.004	
$B_{\mathbb{P}}$ [GeV^{-2}]	2.745 ± 0.046	4.271 ± 0.021	4.072 ± 0.017	
χ^2/dof	$7356/5793$	$7448/5792$	$8339/5793$	
two-channel model				
σ_0[mb]	20.97 ± 0.48	22.89 ± 0.17	23.02 ± 0.23	23 / 33
$\alpha_P - 1$	0.136 ± 0.001	0.129 ± 0.001	0.131 ± 0.001	0.13 / 0.115
α'_P [GeV^{-2}]	0.078 ± 0.001	0.075 ± 0.001	0.071 ± 0.001	0.08 / 0.11
a_{ore}[GeV]	—	0.718 ± 0.012	—	
$b_{\text{exp/ore/pow}}$[GeV^{-2} or $^{-1}$]	0.917 ± 0.007	1.517 ± 0.008	0.931 ± 0.002	0.45
$\Delta\lvert a\rvert^2$	0.070 ± 0.026	-0.058 ± 0.009	0.042 ± 0.011	-0.04 / -0.25
$\Delta\gamma$	0.052 ± 0.042	0.131 ± 0.018	0.273 ± 0.023	0.55 / 0.4
b_1 [GeV^2]	8.438 ± 0.108	8.951 ± 0.041	8.877 ± 0.040	8.5 / 8.0
c_1 [GeV^2]	0.298 ± 0.012	0.278 ± 0.004	0.266 ± 0.006	0.18 / 0.18
d_1	0.472 ± 0.007	0.465 ± 0.002	0.465 ± 0.003	0.45 / 0.63
b_2 [GeV^2]	4.982 ± 0.133	4.222 ± 0.052	4.780 ± 0.060	4.5 / 6.0
c_2 [GeV^2]	0.542 ± 0.015	0.522 ± 0.006	0.615 ± 0.006	0.58 / 0.58
d_2	0.453 ± 0.009	0.452 ± 0.003	0.431 ± 0.004	0.45 / 0.47
χ^2/dof	$5741/5786$	$6415/5785$	$7879/5786$	

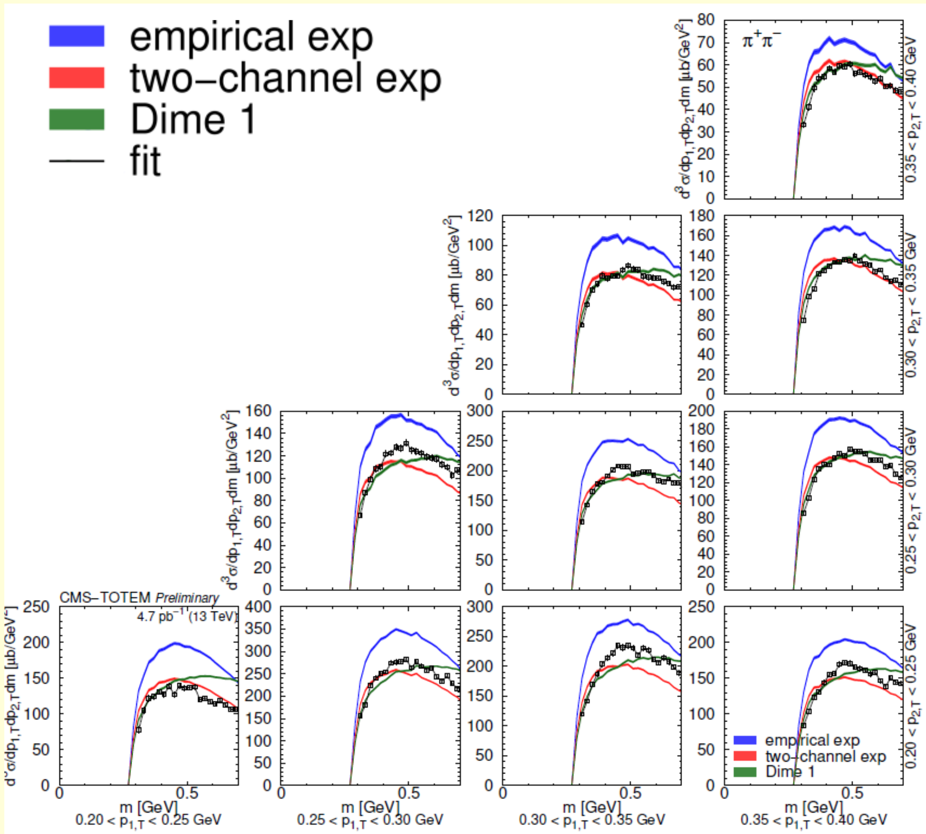
Results (sample): ϕ between *protons* in intervals of $p_{1,T}$ (0.4 – 0.8 GeV) and $p_{2,T}$ (0.2-0.4 GeV)

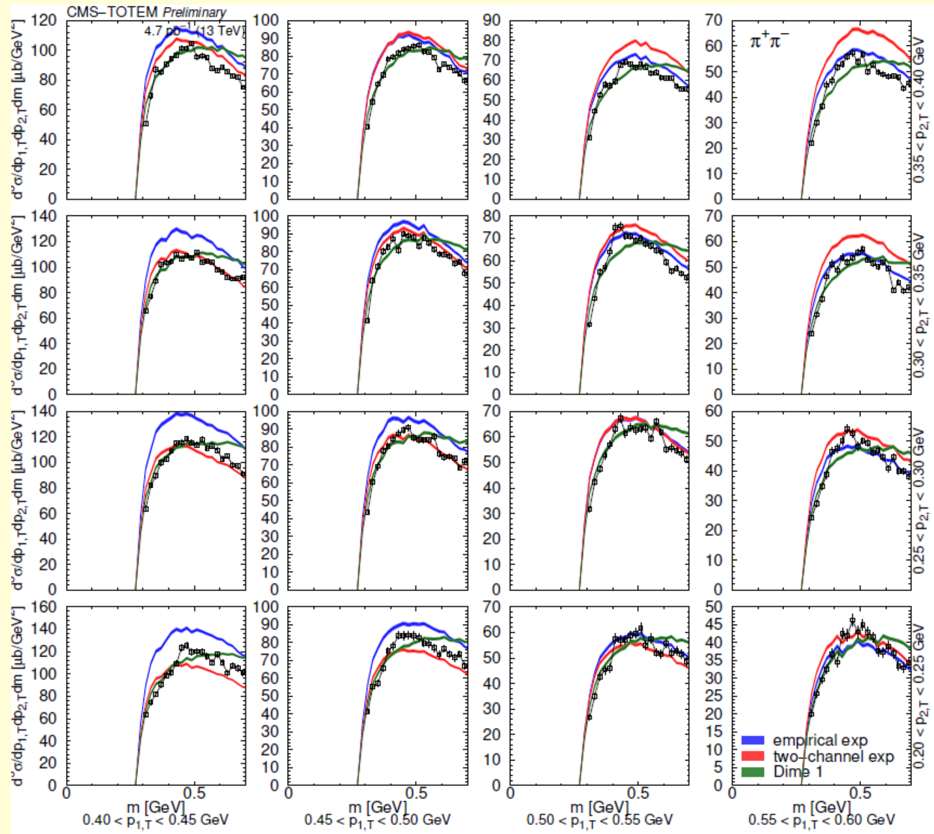




Shape variations – partly of kinematic origin, but considerably model-dependent.

$\pi^+\pi^-$ mass cross section spectra up to 0.7 GeV in similar intervals.





Somewhat similar data shapes, model effects apparent, DIME does well mostly.

Summary

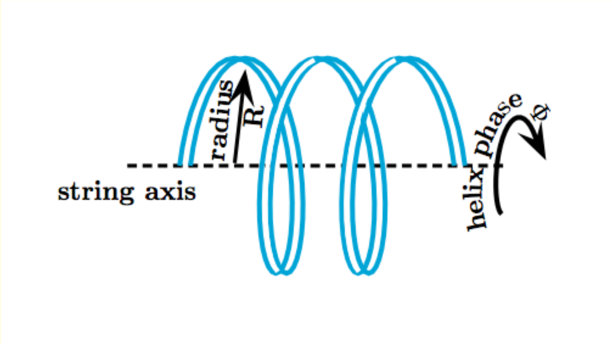
With good sample statistics, the results in the non-resonant region show structures (not just kinematic) that provide good opportunities for tuning and evaluating different models of the diffractive physics. Choice of form factors.

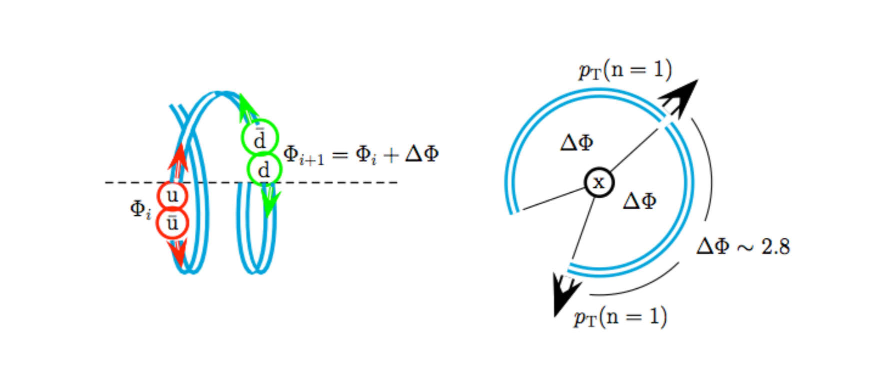
Double Pomeron exchange – a gluon-rich initial state.
Apparently a simple final state, there is so much physics to be coaxed out of the data!

First observation of a parabolic minimum in phi between the outgoing protons.
It is understood as an effect of interference between the bare and rescattered amplitudes.

Study of ordered hadron chains in proton-proton, proton-lead and lead-lead collisions with the ATLAS detector

An alternative to the Lund string model: strings are here seen as helical structures.
ATLAS-CONF-2022-055
Š. Todorova-Nová, Phys. Rev. D **89** (2014) 015002, arXiv: 1309.6761 [hep-ph]





The string fragments into hadrons.
The parameters of the string affect the momentum distribution of the hadrons.
Hadron masses are no longer as given parameters but can arise from the quantised nature imputed to the helical string.

(See talk by G. Navarro at EPS-HEP 2023 conference)

Run 2 data under different conditions are studied.

collision system	$\sqrt{s}$	integrated luminosity	$< \mu >$	number of events
pp	0.9 TeV	53.9 pb^{-1}	0.005	4.4×10^6
pp	5.02 TeV	31.4 nb^{-1}	0.47	8.2×10^6
pp	13 TeV	14.0 nb^{-1}	0.003 - 0.321	65.5×10^6
p+Pb	5.02 TeV	0.27 nb^{-1}	0.0002-0.005	18.7×10^6
Pb+Pb	5.02 TeV	19.3 pb^{-1}	0.002 - 0.003	9.3×10^6

4-momentum difference between two particles:

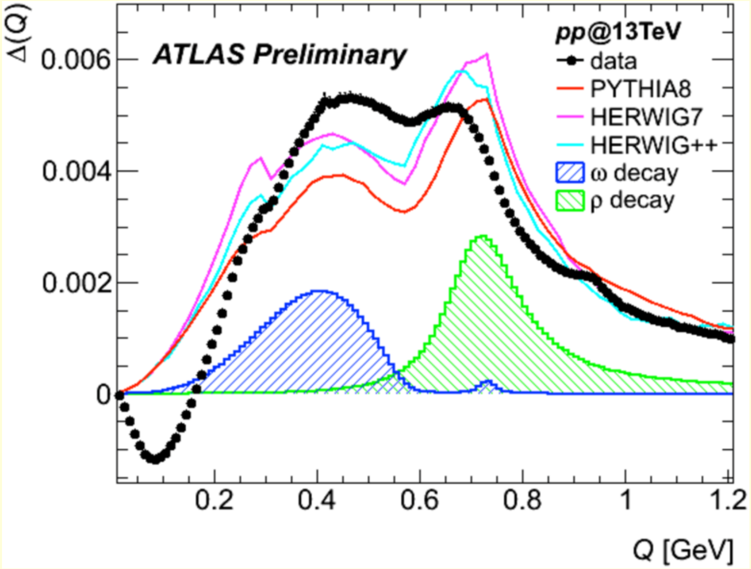
$$Q(p_i, p_j) = \sqrt{-(p_i - p_j)^2}$$

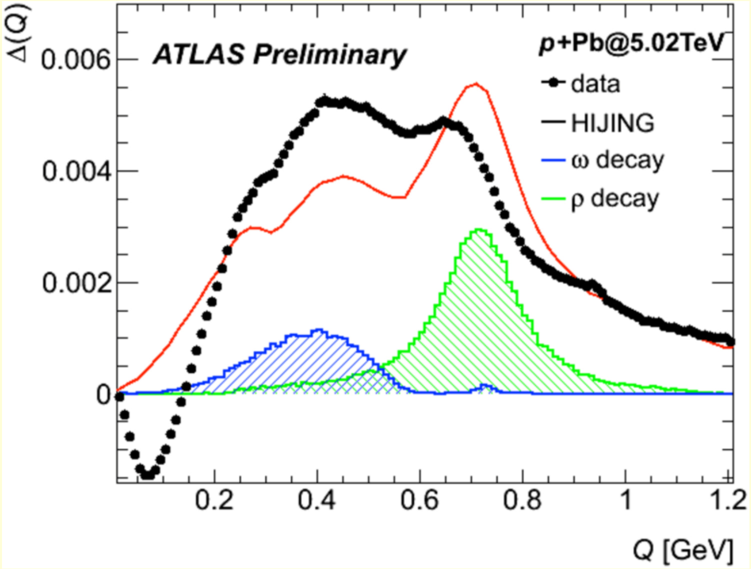
Count numbers of opposite-sign (OS) and like-sign (LS) events, in given Q interval in event sample: $N^{OS}(Q)$ and $N^{LS}(Q)$.

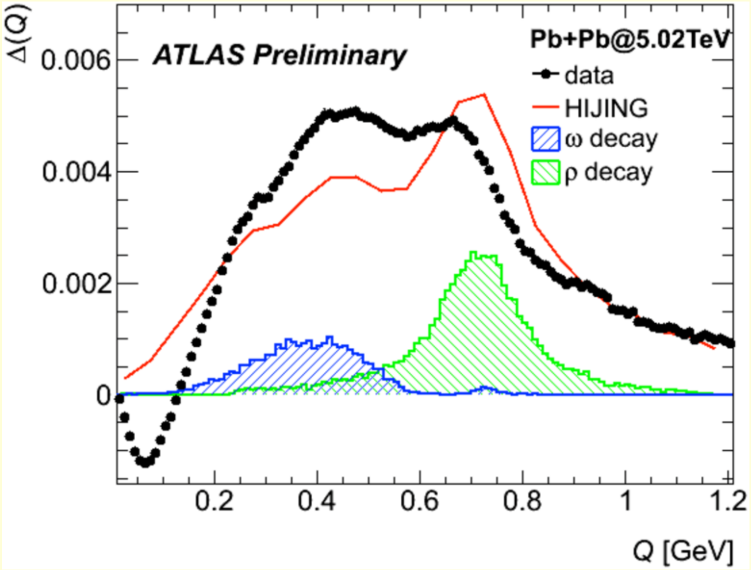
Then define:

$$\Delta(Q) = \frac{1}{N_{ch}} \left[N^{OS}(Q) - N^{LS}(Q) \right]$$

Some results:





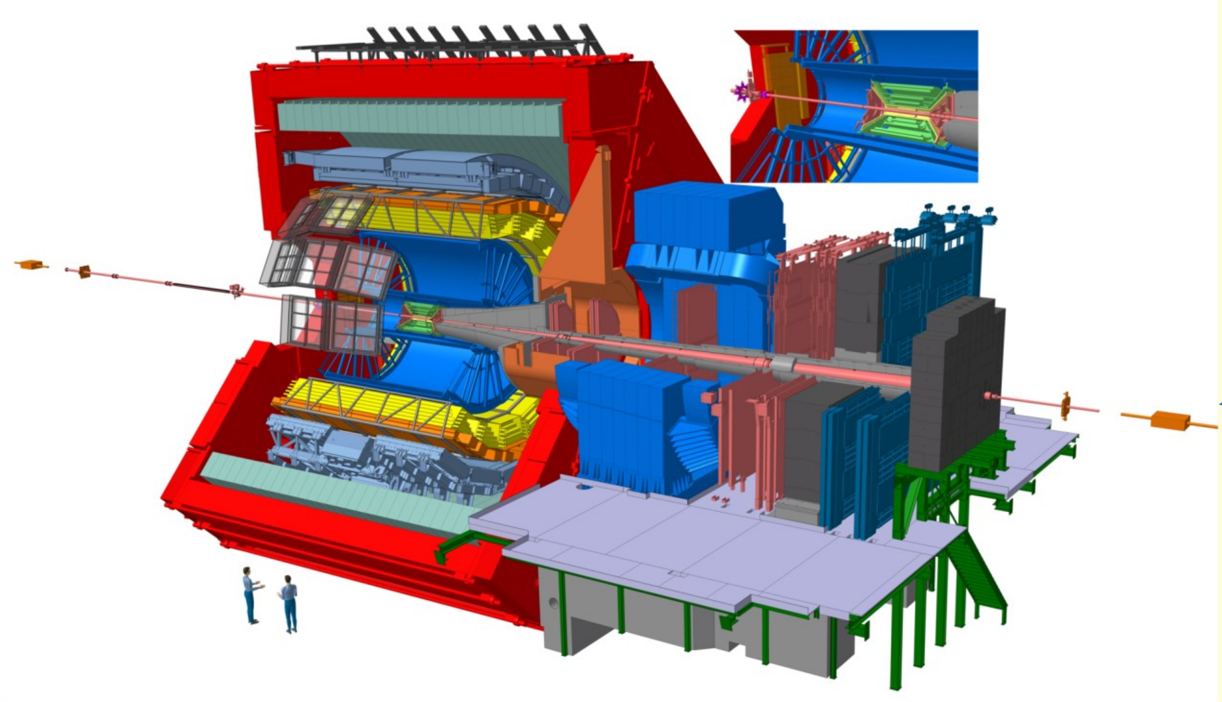


The negative discrepancy at low *Q seen in all three types of collision* indicates an excess of LS neighbouring hadrons. “Correlated hadron chains”.

Could be Bose-Einstein condensates, but it is consistent with predictions of ordered helical chain model.

ALICE: Study of very forward energy and its correlation with particle production at midrapidity in pp and p-Pb collisions at the LHC. JHEP 08 (2022) 086

A wide-ranging study of how energy measured in the ALICE forward detectors is correlated with general properties of the central event.



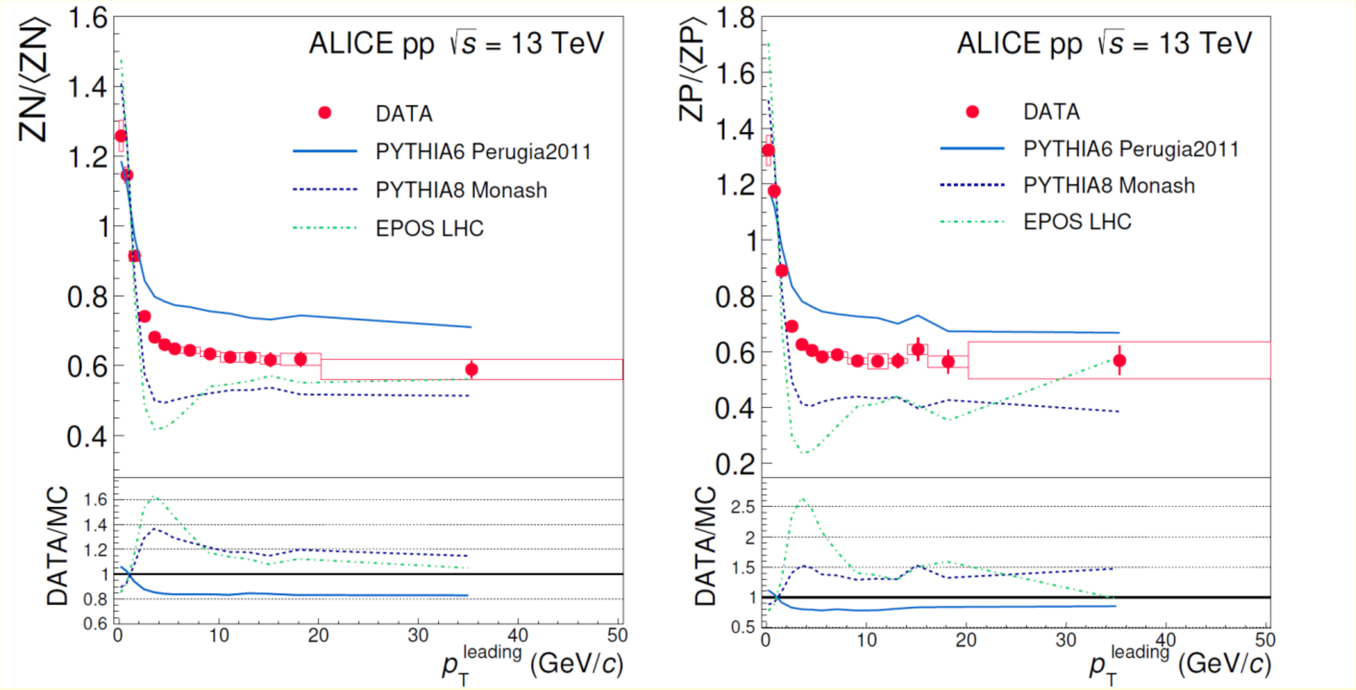
Two "very forward" detectors:
for neutral and charged particle detection:
ZN and ZP.

Data taken in pp and p-Pb collisions with suitable beam optics.

Events with >1 primary vertex (pile-up) were rejected.

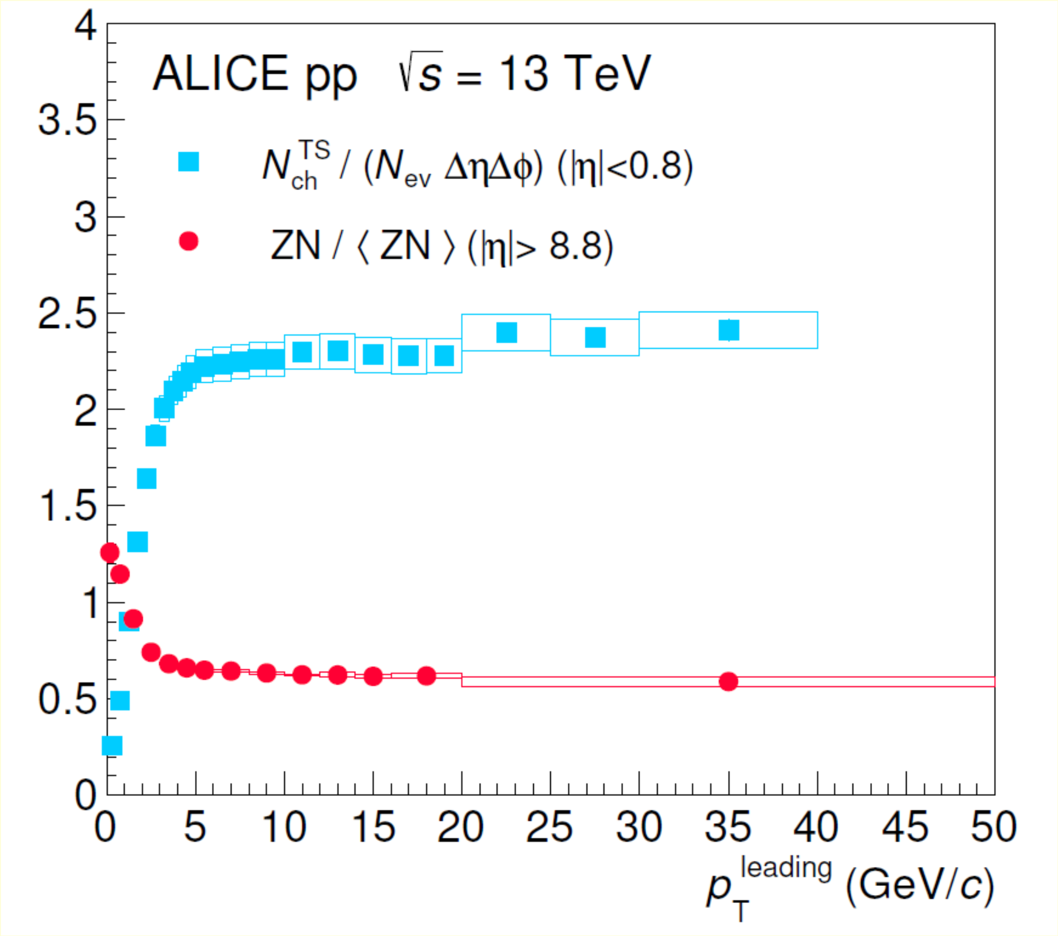
Minimum-bias trigger.

(For more details see talk by Chiara Oppedisano.)



As function of leading p_T in central tracker, normalised neutral and charged (proton) energy is flat over “hard” p_T range but rises at low values. Transition to soft events with more forward energy.

The PYTHIA models are not successful but the Perugia 2011 tune is best.



Red: as before

Blue: Flux of central charged particles in angle range orthogonal to leading particle (no forward requirement). $60^o < \Delta\phi < 120^o$.

Underlyng event less evident with less hard jets.

LHCb:
Measurement of prompt charged-particle production in *pp* collisions at $\sqrt{s}$ =13 TeV
JHEP 01 (2022) 166

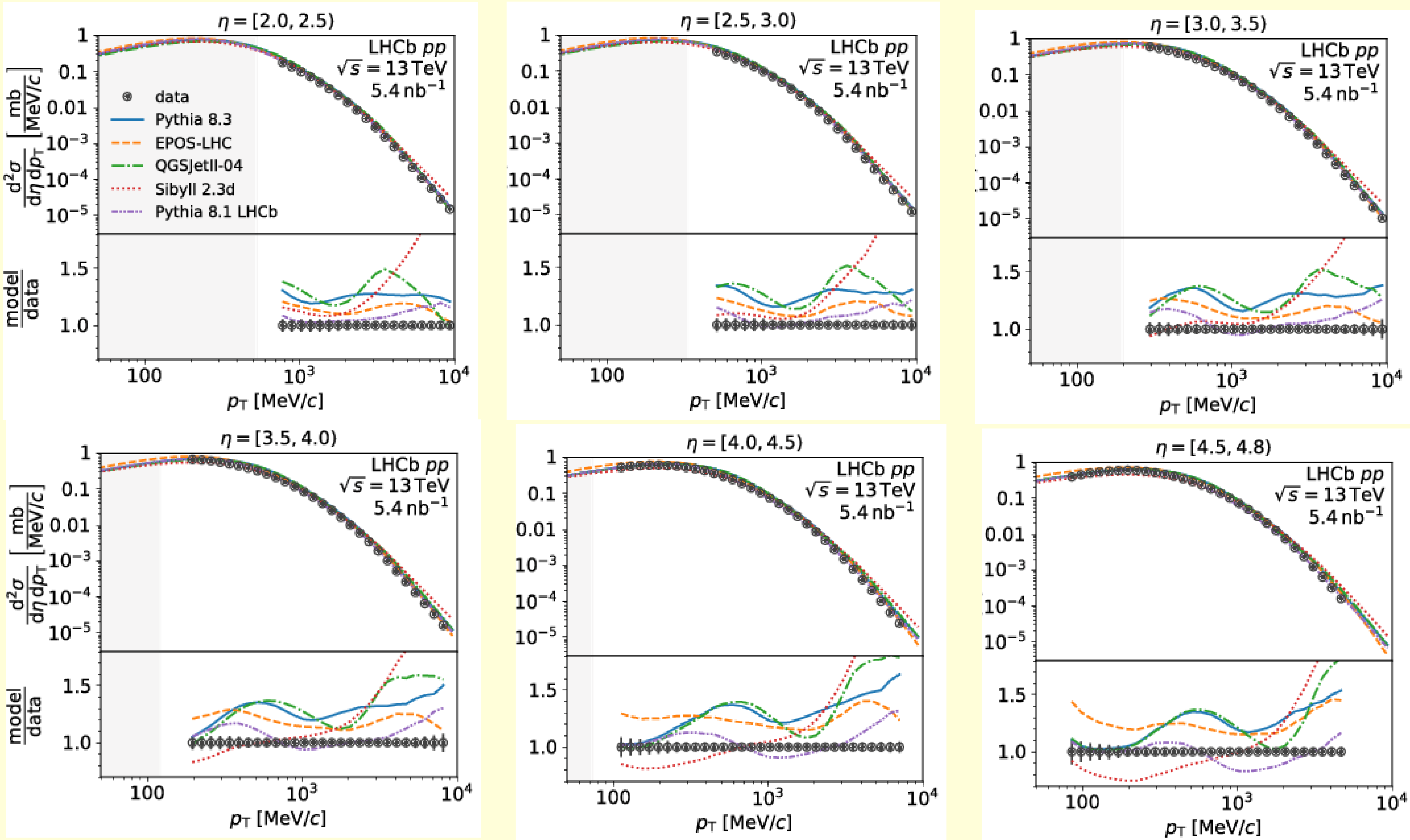
Data taken with an unbiased trigger at $\sqrt{s}$ =13 TeV, integ. lumi = 5.4 nb^{-1}

Differential cross sections for forward charged particles in η range 2.0 – 4.8
Products of decays removed.

Compare to various models.

The precision achieved is essential for tuning underlying-event models
and is good for understanding cosmic air showers.

Results for differential cross sections.



For these cross sections EPOS-LHC seems best.

Overall summary

Diffractive and soft events at the LHC present a rich diversity of physics. Details of the Standard Model still need to be better understood in some areas!