An Overview of Diffractive Photon+Jet Production at the ATLAS Detector

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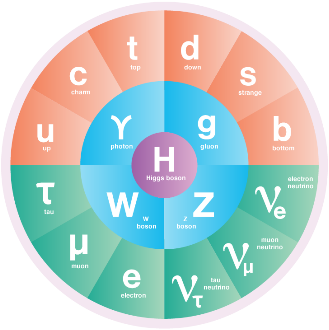
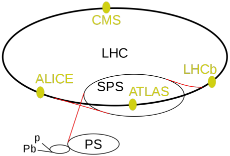
Introduction: The Standard Model

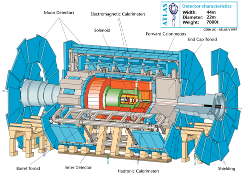
- The Standard Model (SM) of particle physics is the most successful theory to date in describing the fundamental particles and their interactions.
- Needs to be tested as strictly as possible to be verified or find avenues to new physics.
- For this purpose the most powerful particle accelerator in the world, the Large Hadron Collider LHC, was built.



Introduction: LHC and the ATLAS detector

- The Large Hadron Collider (LHC) is a particle accelerator that can accelerate proton beams to up to 7 TeV.
- The experiments are built in the interaction points, where the beams cross.

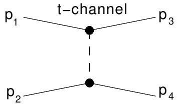




- The ATLAS detector has a multilayered structure, with each layer focusing in measuring different physical properties.
- Its one of the two multipurpose detectors at the LHC.

History: How to Describe Analytic Properties of Particle Scattering?

- Concept of Tullio Regge (1959):



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  - in QM the bound states for a spherically symmetric potential fall into families with increasing angular momentum and energy,
  - these bound states appear as poles of the partial wave amplitude with a given integer angular momentum,
  - idea: continue these amplitudes to complex values of angular momentum,
  - for 'well behaved' potentials (like the Yukawa one) the poles lie on a straight line, called the Regge trajectory:
    $\alpha_R(t) = \alpha_R(0) + \alpha'_R(0) \cdot t$, where
    $\alpha_R(0)$ is called the intercept
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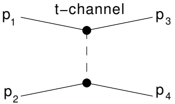

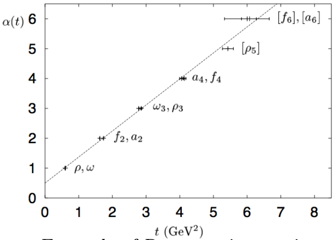

Example of Regge trajectory in the
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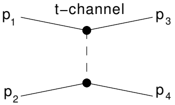
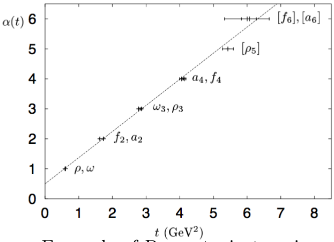
- All known resonances lie on trajectories with an intercept smaller than 1 $\rightarrow$ the total cross section should decrease with increasing collision energy.





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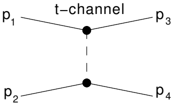
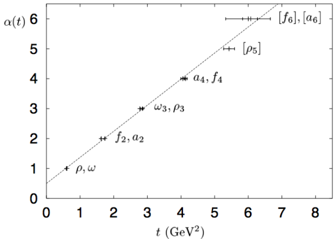
- Which was the case at low energies





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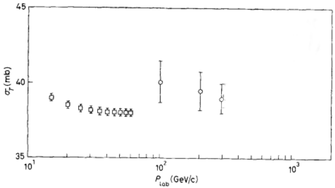

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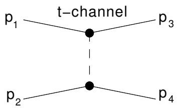
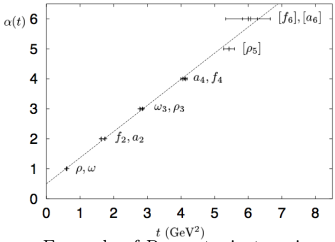
- All known resonances lie on trajectories with an intercept smaller than 1 → the total cross section should decrease with increasing collision energy.
- Which was the case at low energies , but clearly not true at higher ones.





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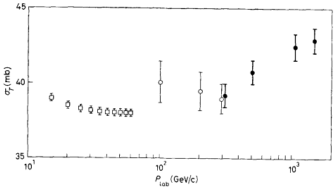


Regge Theory and Pomeron Concept

Regge theory studies the analytical properties of scattering. By expanding the partial wave equation to imaginary angular momentum is possible to build (Regge) trajectories which contain all bound states. For the case of Yukawa potential.

$$\alpha_R(t) = \alpha_R(0) + \alpha'_R(0)t$$

- The Reggeon object, which is what is exchanged, is a mixture of all the resonances in the trajectory. It predicts a descending cross-section with increase of centre-of-mass energy.
- Pomeron trajectory is introduced, which produces a cross-section that increases logarithmically with energy.

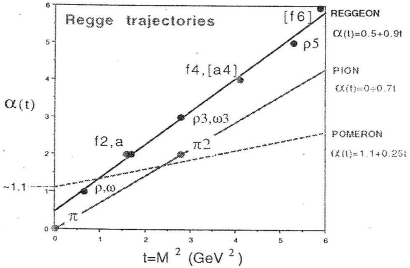
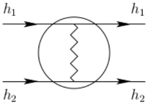


Figure: Selected Regge trajectories. On the dashed line Pomeron trajectory, with $\alpha(0) \sim 1.1$. Extracted from [3]

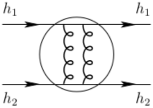
Diffraction at the LHC

- Diffraction in high energy physics is referred to as events governed by the mechanism of colourless exchange of vacuum quantum numbers:
  - photon in case of electromagnetic and
  - Pomeron for strong interactions.
- The Pomeron trajectory does not hold any known resonance:
  - its actual structure is as yet unknown,
  - the simplest possibility being a two-gluon glueball (+h.o. contributions).



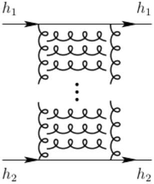
"Regge Pomeron"

→



two-gluon glueball

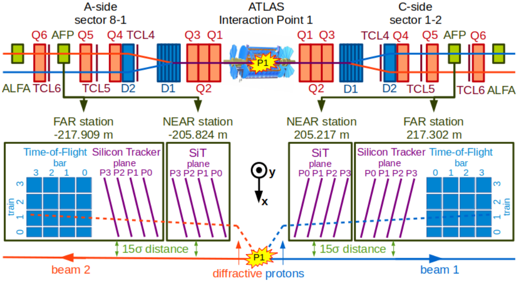
→

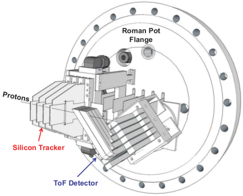


h.o. corrections → internal structure

- Main signatures are the presence of a large rapidity gap devoid of particles, that can be destroyed by further interactions, and protons scattered at very small angles (μrad)
- Generally soft, low transverse momentum p_T transfer, makes them intractable by perturbation methods. Need for effective theories.

Measuring forwards protons: The AFP, Atlas Forwards Proton detector





- Silicon Tracker (SiT): A set of four planes in each Roman Pot (RP) station.
  - 50 x 250 μm pixel size.
  - Planes tilted 14° to improve resolution.
  - Resolution: $\sigma_x = 6\mu m$, $\sigma_y = 30\mu m$.
- Time-of-flight (ToF): Designed to measure the primary vertex z-coordinate.
  - Installed only in the FAR stations.
  - Composed of a 4 x 4 matrix of quartz bars, L-shaped and rotated 48° with respect to the LHC beam.

Measurement Principle: SiT

The proton trajectory depends on:

- The energy loss on the interaction $\xi = 1 - \frac{E_{proton}}{E_{beam}}$.
- The transverse momentum p_T at Interaction Point 1 (IP1).

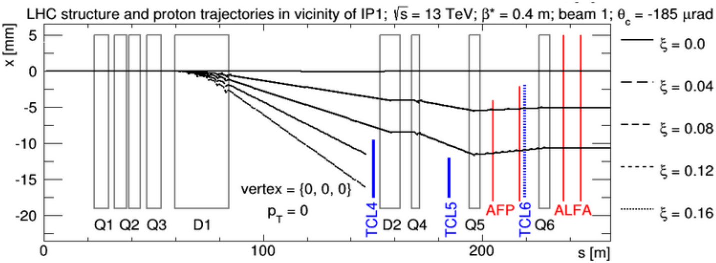
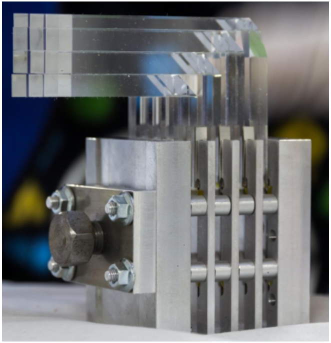


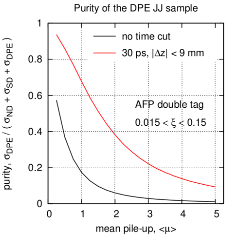
Figure: AFP measures displacement, which is related to mass of the central system.

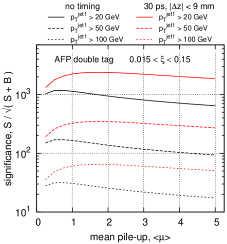
Acceptance of the detector limited by collimator apertures and beam-detector distance.

Backgrounds and Time of Flight detector

- Cross sections are expected to be low, while production of single diffraction protons is around 10% of the total → High probability coincidental fake double tag events.
- Need to operate at regimes with low number of interaction per bunch crossing (low μ) → Need longer times to accumulate enough events.
- ToF times the arrival of the protons, which allows to reconstruct the longitudinal position of the event. Comparing with information of the central detectors permits to reject background events.

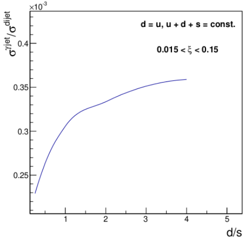


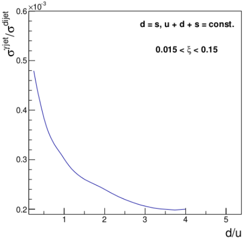




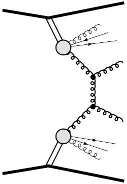
Double Pomeron Exchange Photon+Jet Production

- Analogically to the proton internal structure, Pomeron might be a quite complicated object:
  - gluonic structure can be probed by looking at properties of events coming from gluon-gluon interactions, e.g. studies of Double Pomeron Exchange Jet Production (top diagram),
  - quark structure can be studied using processes like DPE γ+jet (see middle diagram) or DPE W production (bottom diag.).
- DPE γ+jet production signature:
  - both protons exchange a Pomeron, remaining intact,
  - one Pomeron emits a gluon and takes a quark from the other, generating a photon and a jet,
  - intact protons might be later destroyed by further soft interactions; this is modelled by a gap survival probability, which is expected to be of about 0.03 for DPE processes at the LHC energies.
- Quark composition can be studied by measuring the ratio of DPE γ + jet to DPE JJ:

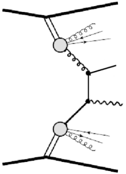




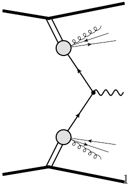
DPE JJ



DPE γ+J

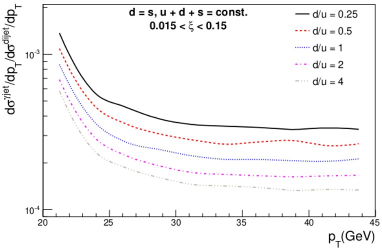


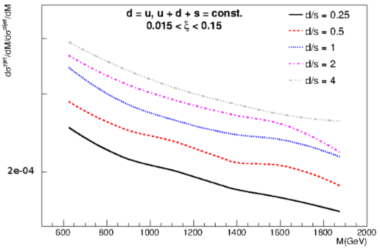
DPE W

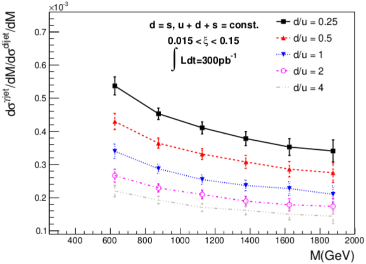


Pomeron Quark Content: Observables

- Top left: ratio of DPE γ+jet to DPE JJ as a function of p_T. Color lines represent various assumption of d/u ratio in the Pomeron.
- Bottom: distribution of diffractive mass $M = \sqrt{\xi_1 \xi_2 s}$. $\xi_{1,2}$ denotes energy lost by protons for various assumption of d/s (left) and d/u (right) ratio in the Pomeron.







Datasets for SD and DPE γ+jet

Run 2 (tables taken from SD JJ analysis):

Table 5.1: An overview of 2017 low-μ runs with integrated luminosity from LBs passing the GRL requirements separate for protons on the ATLAS A and C sides.

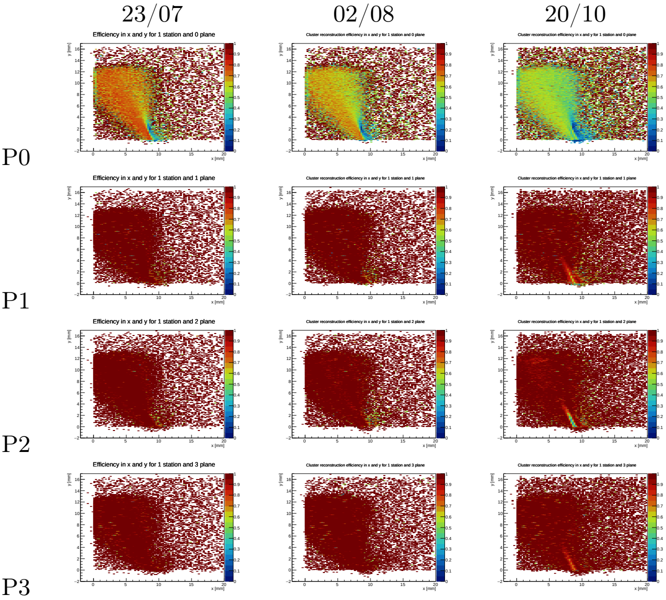
ATLAS Run Number	LHC Fill	Pile-up μ	Int. Luminosity [nb^{-1}] for protons on side A	Int. Luminosity [nb^{-1}] for protons on side C
331020	6019	~1.0	56.866	510.841
336505	6238	~0.04	44.751	60.2411
341294	6404	~2.0	709.542	709.542
341312	6405	~2.0	18245.492	18234.639
341419	6411	~2.0	31636.072	31593.050
341534	6413	~2.0	47663.701	52680.387
341615	6349	~2.0	31772.631	31772.631
341649	6417	~2.0	6543.940	6449.680
		~1.0	3325.167	3325.167

Sample	Consecutive Cut					
	Side	All	1 Vertex	GRL	2 Jets	1 Proton
SD MC	A	239499	136390	136390	4825	2061
	C					2654
331020	A	1952990	357983	35404	23810	4447
	C			321605	217344	86869
336505	A	41908	30857	22712	8536	658
	C			30784	11602	4262
341294	A	116385	7124	6977	4651	1122
	C			6977	4651	1214
341312	A	940071	70859	70717	47080	3111
	C			70710	47076	19056
341419	A	1649173	123268	123124	81825	5436
	C			123003	81745	32564
341534	A	2864217	246297	212460	143152	10453
	C			244662	164771	63254
341615	A	1650721	130234	130114	86375	6217
	C			130114	86375	34642
341649	A	236404	44633	39653	26460	2011
$\mu \sim 1.0$	C			39653	26460	10533
341649	A	354020	27503	26387	17611	1315
$\mu \sim 2.0$	C			26124	17439	6943

Run 3:

- $\mu \sim 1$:
  - 455818 $\approx$ 230 nb^{-1},
- $\mu \sim 0.2$:
  - 455818 $\approx$ 35 nb^{-1},
- $\mu \sim 0.05$:
  - 428770 $\approx$ 34 nb^{-1},
  - 455818 $\approx$ 20 nb^{-1},
  - 455838 $\approx$ 43 nb^{-1},
- $\mu \sim 0.02$ (higher ξ_{min}):
  - 435229 $\approx$ 155 nb^{-1},
  - 435333 $\approx$ 15 nb^{-1},
- $\mu \sim 0.005$:
  - 427929 $\approx$ 0.46 nb^{-1},
- $\mu \sim 0.005$ (low-B):
  - 460348 $\approx$ 1.75 nb^{-1}.

A NEAR, Cluster Reco. Efficiency (2022)



Summary

- Diffraction in high energy physics, characterized by large rapidity gaps and presence of forward protons, can be studied using data collected by ATLAS Roman Pots.
- Double Pomeron Exchange γ + jet production offers a probe in the quark content of the Pomeron; note that by using ratio to DPE JJ, the impact of gap survival will be effectively cancelled out.
  - cross-section determination,
  - if enough statistics – quark structure of Pomeron.

- Existing Run 3 datasets will be checked for evidence of single diffractive γ+jet events. First task is to measure cross section $\rightarrow$ determine gap survival probability.
- Not enough data to see the evidence of DPE γ+jet in Run 3:
  - pp reference run may be a nice opportunity to make such measurement at $\sqrt{s} = 5.36$ TeV,
  - Run 2, $\sqrt{s} = 13$ TeV, 2017, $\mu \sim 2$ data-sets to be investigated.
  - measurement at $\sqrt{s} = 13.6$ TeV would require a few days of low-μ run.

References

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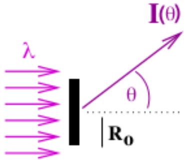
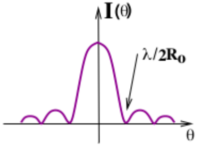
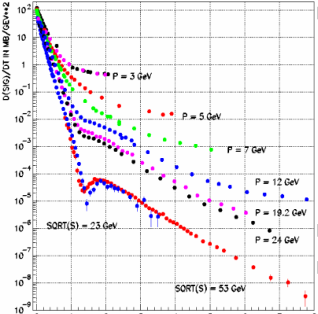
Backup

Digression: Why “Diffraction”?

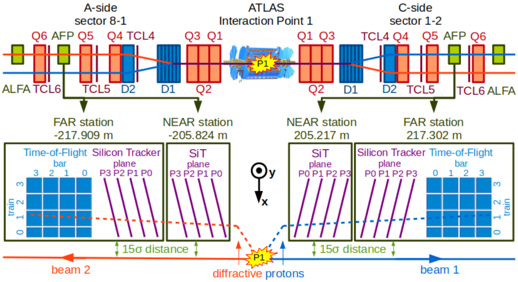


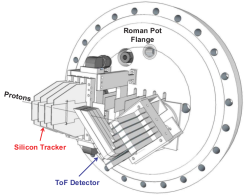




- ‘Diffraction’ in optics:
  - light with wavelength of λ is shining on black disc with radius R_0,
  - distant screen – characteristic ‘diffractive’ pattern:
    - large forward peak for scattering angle $\theta = 0$,
    - series of symmetric minima and maxima, with the first minimum at $\theta_{min} \simeq \pm\lambda/(2R_0)$,
  - intensity as a function of scattering angle:
    $\frac{I(\theta)}{I(\theta=0)} = \frac{[2J_1(x)]^2}{x^2} \simeq 1 - \frac{R_0^2}{4}(k\theta)2$
    - J_1 is the Bessel function of the first order,
    - $x = kR_0 \sin\theta \simeq kR_0\theta$ with $k = 2\pi/\lambda$.
  - diffraction pattern is related to the size of the target and to the wavelength of the light beam.
- Differential cross-section for $pp \to pp$:
  $\frac{\frac{d\sigma}{dt}(t)}{\frac{d\sigma}{dt}(t=0)} \simeq e^{-b|t|} \simeq 1 - b(P\theta)^2$
  - $|t| \simeq (P\theta)^2$ – absolute value of the squared four-momentum transfer,
  - P is the incident proton momentum,
  - θ is the scattering angle,
  - $b = R^2/4$, where R is related to the target size,
- Data: a dip followed by a secondary maximum.
- Similar t distributions observed for other reactions $\to$ diffractive processes.

The ATLAS Forward Proton Detector





- Silicon Tracker (SiT): A set of four planes in each Roman Pot (RP) station.
  - 50 x 250 μm pixel size.
  - Planes tilted 14° to improve resolution.
  - Resolution: $\sigma_x = 6\ \mu m$, $\sigma_y = 30\ \mu m$.
- Time-of-Flight (ToF): Designed to measure the primary vertex z-coordinate.
  - Installed only in the FAR stations.
  - Composed of a 4 x 4 matrix of quartz bars, L-shaped and rotated 48° with respect to the LHC beam.

Measurement Principle: SiT

The proton trajectory depends on:

- The energy loss on the interaction $\xi = 1 - \frac{E_{proton}}{E_{beam}}$.
- The transverse momentum p_T at Interaction Point 1 (IP1).

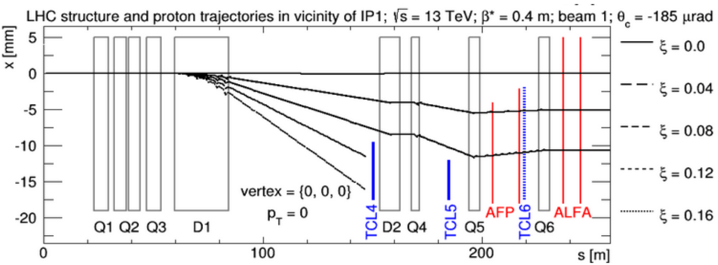


Figure: AFP measures displacement, which is related to mass of the central system.

Acceptance of the detector limited by collimator apertures and beam-detector distance.