STUDIES OF THE UNDERLYING EVENT AND PARTICLE PRODUCTION WITH THE ATLAS DETECTOR.

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on behalf of the ATLAS Collaboration

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HELMHOLTZ ASSOCIATION

ATLAS EXPERIMENT

DESY

Introduction

ATLAS has measured particle production and the underlying event

- using various different hard processes
- at several centre-of-mass energies

Too much to discuss in full, so I will show only most recent results:

13 TeV! Detector-level underlying event distributions	ATL-PHYS-PUB-2015-019
Underlying event in jet events	EPJC 74 (2014) 2965
Underlying event in inclusive Z-boson production	EPJC 74 (2014) 3195
Dijet production with large rapidity gaps	accepted by PLB
Exclusive dilepton production	PLB 749 (2015) 242-61
Transverse polarisation of Λ and $\bar{\Lambda}$ hyperons	PRD 91 (2015) 032004

Underlying event

What is the underlying event?

Any hadronic activity not associated with hard scattering process

- Unavoidable background to collision events
- Non-perturbative effects dominate $\rightarrow$ not well-predicted

Typically modelled with

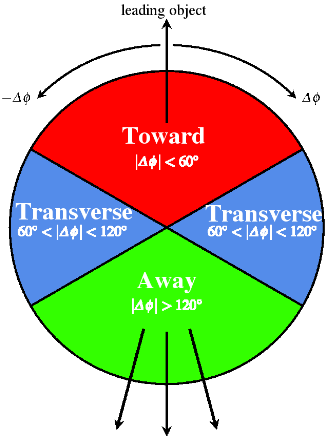
- Multiple parton interactions
- Initial/final-state radiation
- Colour reconnection with beam remnants

Impossible to unambiguously assign particles to hard scatter or UE

- Measurements must not be dependent on details of model used

Underlying event topology

- Identify a "hard scatter" using a reference object (eg. jet/Z/track)
- Define azimuthal regions with respect to this leading object



- Toward and transverse regions most sensitive to the underlying event
- High p_{T} recoil important in away region $\rightarrow$ perturbative QCD
- Transverse region can be further divided into trans-max and trans-min depending on the amount of activity

Underlying event observables

Reconstruct kinematics: calorimeter deposits and charged tracks

Densities and averages

- Average p_{T} of charged particles: $\langle p_{\mathrm{T}} \rangle$
- Number density of charged particles: $N_{ch}/\delta\eta\delta\phi$
- p_{T} density of charged particles: $\sum p_{\mathrm{T}}/\delta\eta\delta\phi$
- E_{T} density of all particles: $\sum E_{\mathrm{T}}/\delta\eta\delta\phi$

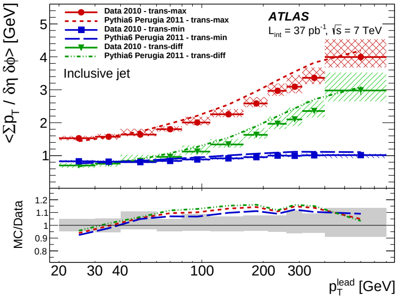
Particle spectra

- Charged particle p_{T} spectrum
- Charged particle multiplicity spectrum

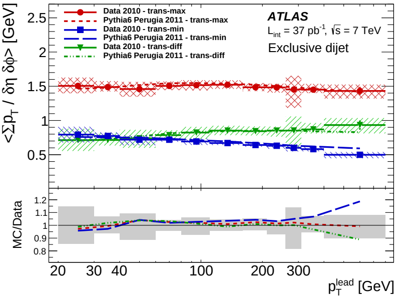
Underlying event in 7 TeV jet events

EPJC 74 (2014) 2965

≥ 1 jet



Exactly 2 jets



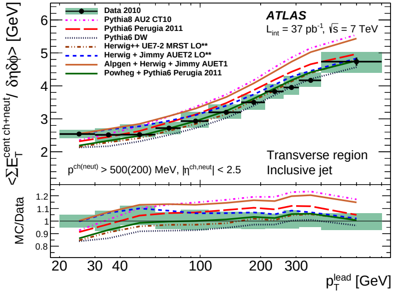
- Trans-min flat (at hard enough scales) $\rightarrow$ treat UE activity as constant
- Increasing activity for trans-max $\rightarrow$ pQCD
- Colour connection to jet?

- Both trans-max and trans-min regions flat in p_T
- Veto on extra hard activity lessens sensitivity to pQCD

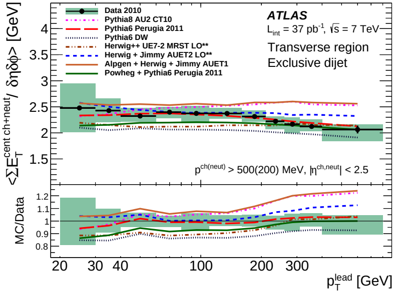
Underlying event in 7 TeV jet events

EPJC 74 (2014) 2965

Inclusive jet selection



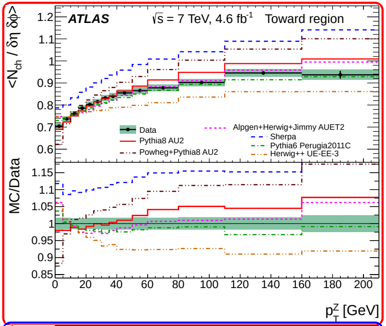
Exclusive dijet selection

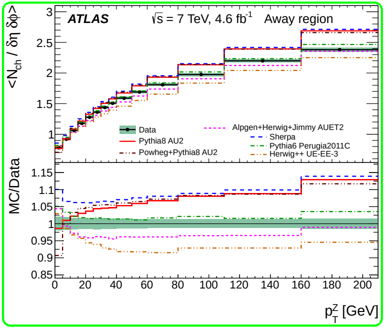


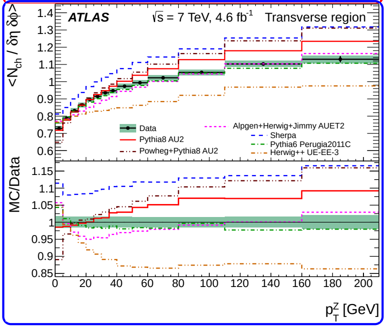
- Similar distributions for $\sum E_T$ from calorimeter clusters
- Compare to different Monte Carlo models and tunes
- Best agreement given by PYTHIA 6 with Perugia 2011 tune

Underlying event in 7 TeV Drell-Yan events

EPJC 74 (2014) 3195



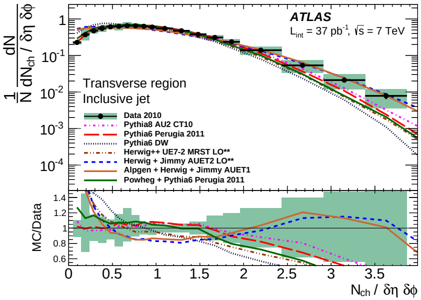




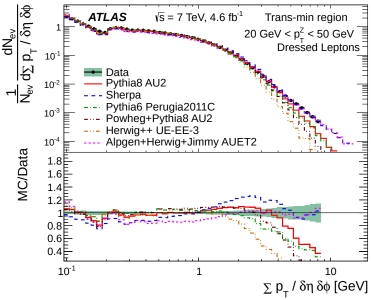
- Measurement of toward UE!
- Tune non-perturbative models with low p_{T} region
- Away region dominated by *Z*+j
- Toward and transverse regions sensitive to higher N_{jets}

Particle p_T and multiplicity

EPJC 74 (2014) 3195



Jet selection



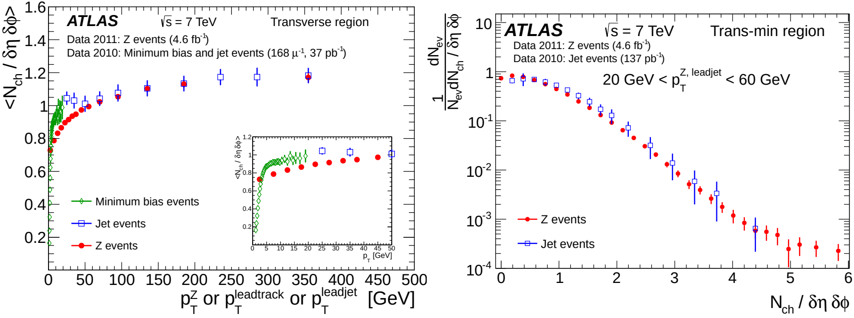
Z-boson selection

- Double differential charged particle multiplicity and p_T spectra
- Provide further discrimination between Monte Carlo models
- Current models do not describe these observables well

Universality of MPI model

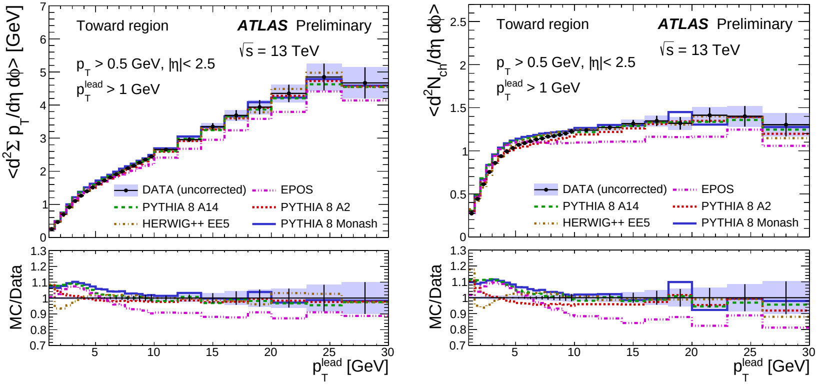
EPJC 74 (2014) 3195

- Compare UE measurements with different hard scatters
- Qualitative test of MPI universality in different hard processes



- Good agreement between jet and *Z*-boson measurements
  $\rightarrow$ especially for trans-min (most sensitive to MPI)
- How well does the MPI model extrapolate to higher energies?...

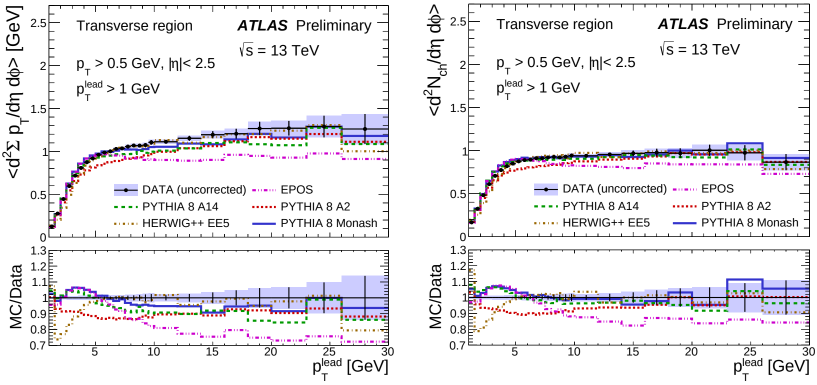
Leading track underlying event at 13 TeV



- Detector-level only (preliminary result)
- Good agreement with data in toward region

Leading track underlying event at 13 TeV

ATL-PHYS-PUB-2015-019

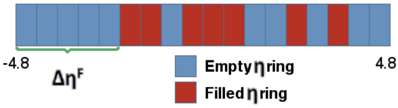


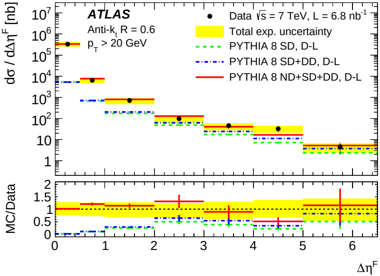
- Greater discriminating power in transverse region
- Still only minor discrepancies from the data
  $\rightarrow$ MPI energy extrapolation working well

Particle Production

Dijet production with rapidity gaps

arXiv:1511.00502



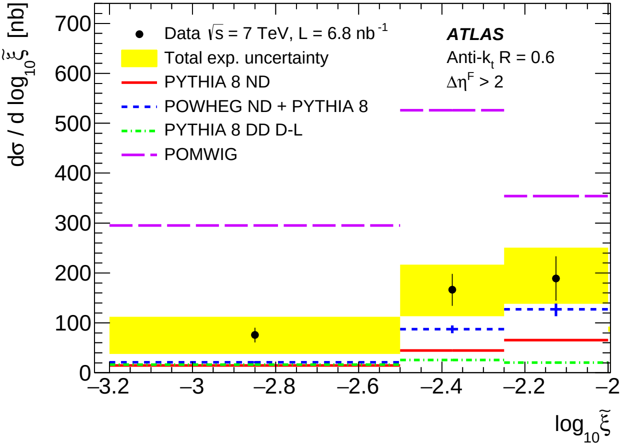


- Use tracks and calorimeter deposits to identify activity
- Rapidity gap is largest empty η span from detector edge

- Decomposition into diffractive components
- Non-negligible contribution from **ND** even at large $\Delta\eta^F$

Cross sections as a function of diffractive mass

arXiv:1511.00502



- Consider $\xi = M_X^2/s$
- In region $\Delta\eta^F > 2$

- ND contribution from PYTHIA or POWHEG+PYTHIA 8 not enough
- PYTHIA 8 DD contribution also falls short of the data
- POMWIG SD-only overshoots $\rightarrow$ need gap survival factor

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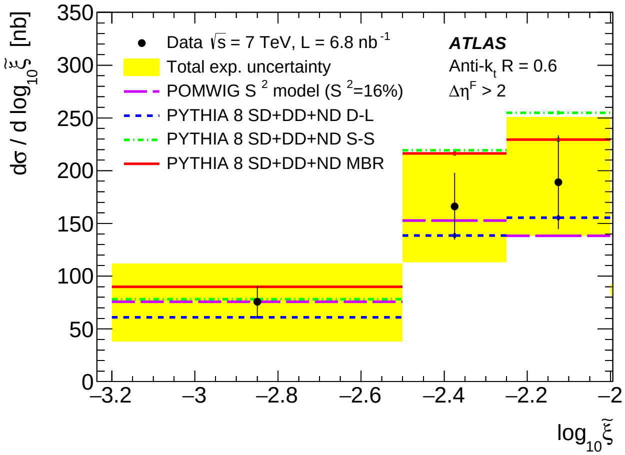
Scaling by gap survival probability

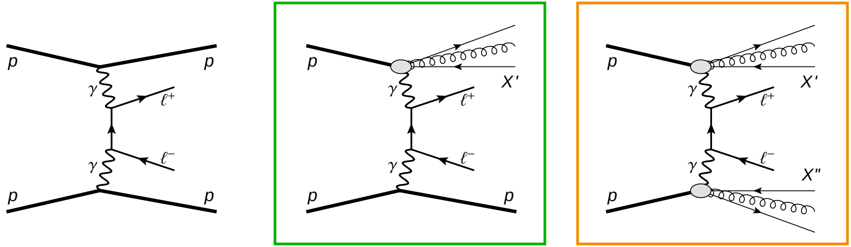
arXiv:1511.00502

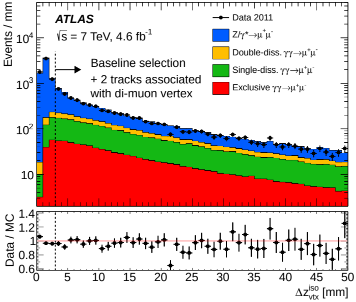


- Scale **POMWIG** to lowest $\log \xi$ bin $\rightarrow S^2 = 16\%$
- PYTHIA 8 for three different Pomeron flux choices
  $\rightarrow$ compatible without needing gap survival factor

Exclusive $\gamma\gamma \rightarrow ll$ production

PLB 749 (2015) 242-61

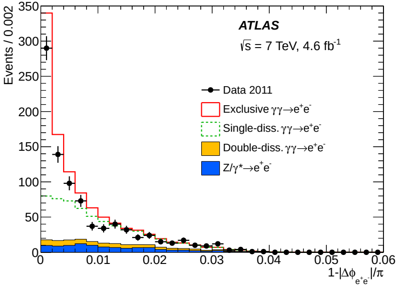




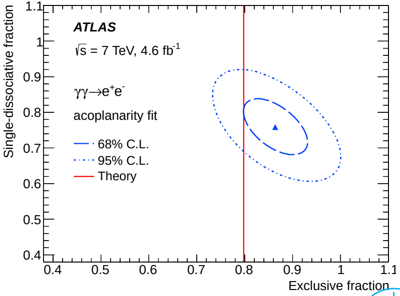
- Large **backgrounds** dominate
- Complex selection to extract **signal**
- Irreducible **SD** and **DD** contributions important

Extracting single-diffractive fraction

PLB 749 (2015) 242-61

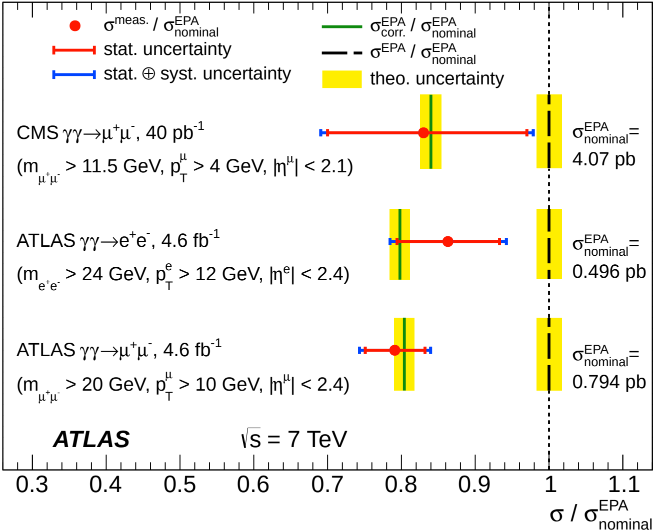


- Agreement with **world average**
- For e^+e^- and $\mu^+\mu^-$ channels



- Fit **acoplanarity** distributions
- Subtract **DD** and **Drell-Yan** backgrounds
- Template fit allows extraction of **SD fraction**

Equivalent Photon Approximation



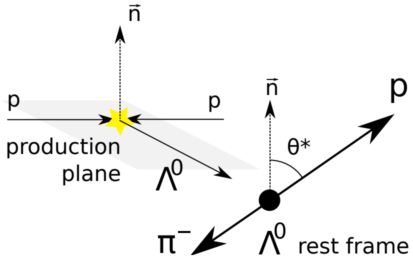
› Corrected for interactions between elastically scattered protons

Transverse polarization of Λ and $\bar{\Lambda}$ hyperons

PRD 91 (2015) 032004

- Λ hyperon: spin ½ particle
- Polarisation, *P*, defined as:

$$P = \frac{N_{+1/2} - N_{-1/2}}{N_{+1/2} + N_{-1/2}}$$



$\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$ decays

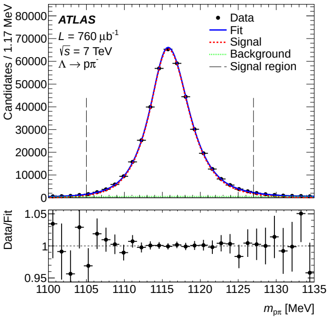
- Angular distribution given by: $w(\cos\theta^*) = \frac{1}{2}(1 + \alpha P \cos\theta^*)$
- $\alpha = 0.642 \pm 0.013$ (parity-violating decay asymmetry) is well-known

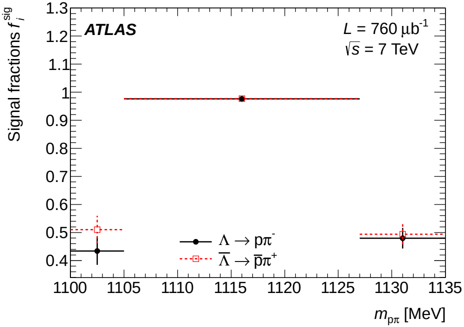
No theoretical model exists!

- polarization measured normal to production plane:
- as function of p_T and $x_F = p_z/p_{beam}$
- in region $x_F < 0.0025$

Signal extraction

- Kinematic cuts to reduce background
- Signal from long-lived two-prong decays



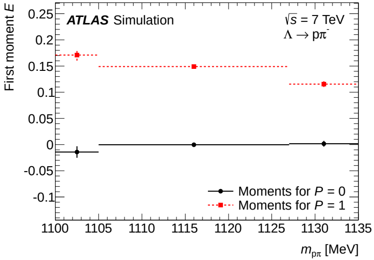


- Divide invariant mass range into signal region and sidebands
- Multi-parameter fit to Λ candidate distribution
  $\rightarrow$ allows extraction of signal fractions, f_i^{sig} in each region

Polarisation of background contribution

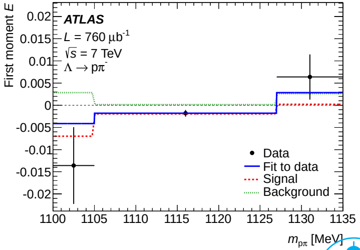
PRD 91 (2015) 032004

- Expectation value (first moment) of decay angle linear in *P*

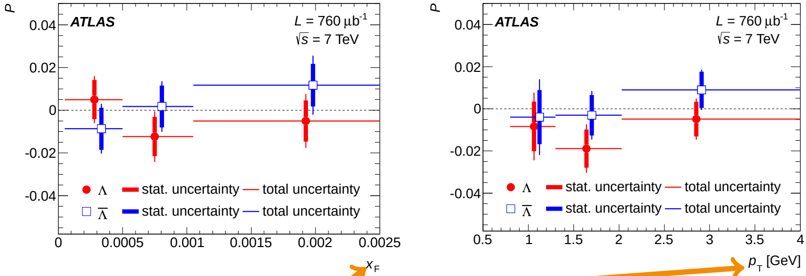


- Use $P = 0, 1$ templates
- Assume polarisation of background events [E_{bkg}] independent of mass

- Calculate moments separately in the signal region and sidebands
- Signal fractions already known
- Simultaneously fit signal and sidebands to extract E_{bkg} and *P*



Extracted polarisations

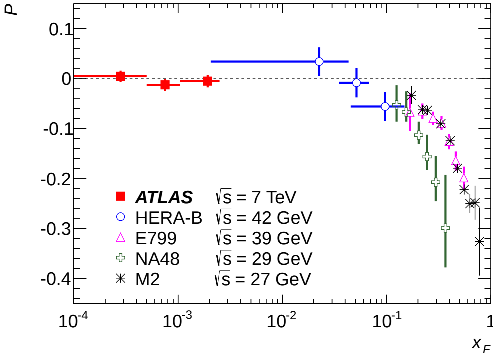


- Measurement binned in x_F and p_{T}
- Polarization $< 2\%$ in all bins
- Consistent with zero in full fiducial phase space

$$P(\Lambda) = -0.010 \pm 0.005(stat) \pm 0.004(syst)$$
$$P(\bar{\Lambda}) = 0.002 \pm 0.006(stat) \pm 0.004(syst)$$

Comparison to previous results

PRD 91 (2015) 032004



- ATLAS tests different kinematic phase space $\rightarrow$ direct comparison of results non-trivial
- No theoretically motivated prediction, only empirical models

Propose introduction of energy dependence

- about half the Λ produced in ATLAS come from decays
- dilutes polarisation $\rightarrow$ smaller than extrapolation

Conclusions

Underlying Event

- NEW measurements of underlying event [first Run II results]
- Large variety of multiplicity and energy density distributions
- MC models tuned to previous LHC data working well
  $\rightarrow$ particularly MPI energy extrapolation

Particle Production

- Complex measurements extracting small signals
- Measurements provided in well-defined fiducial regions for easy comparison with theory
- Many more Run II results on the way

Backup

Method of moments

Reconstructed decay angle distribution

$$w(t) \propto \epsilon(t)\,[(1+\alpha P t)] \otimes R(t', t)$$

where t' and t are true and reconstructed decay angles ($\cos\theta^*$), $\epsilon(t)$ is the efficiency function and $R(t', t)$ the resolution function

Method of moments

- The expectation value (first moment) of $w(t)$ is linear in P:

$$E(w|P=p) \equiv E(p) = C_0 + C_1 p = E(0) + [E(1) - E(0)]p$$

- $E(0)$ and $E(1)$ estimated from MC with polarisation set to 0 and 1

$$E_i^{exp}(P, E_{bkg}) = f_i^{sig}\left[E_i^{MC}(0) + \left[E_i^{MC}(1) - E_i^{MC}(0)\right]P\right] + (1 - f_i^{sig})E_{bkg}$$

Λ polarisation parametrisation

- Many possible parametrisations
- B. Lundberg [PRD 40 (1989) 3557] is a popular choice
- Assumes energy independence and neglects detector effects

$$P = \left(-0.268 x_F - 0.338 x_F^3\right) \times \left(1 - e^{-4.5 {p_\mathrm{T}}^2}\right)$$

- **ATLAS**: $\langle p_\mathrm{T} \rangle \sim$ 1.8 – 2.1 GeV and $\sqrt{s} = 7\,\mathrm{TeV}$
- **HERA-B and E799**: $\langle p_\mathrm{T} \rangle \sim$ 0.67 – 2.2 GeV and $\sqrt{s} \sim 40\,\mathrm{GeV}$