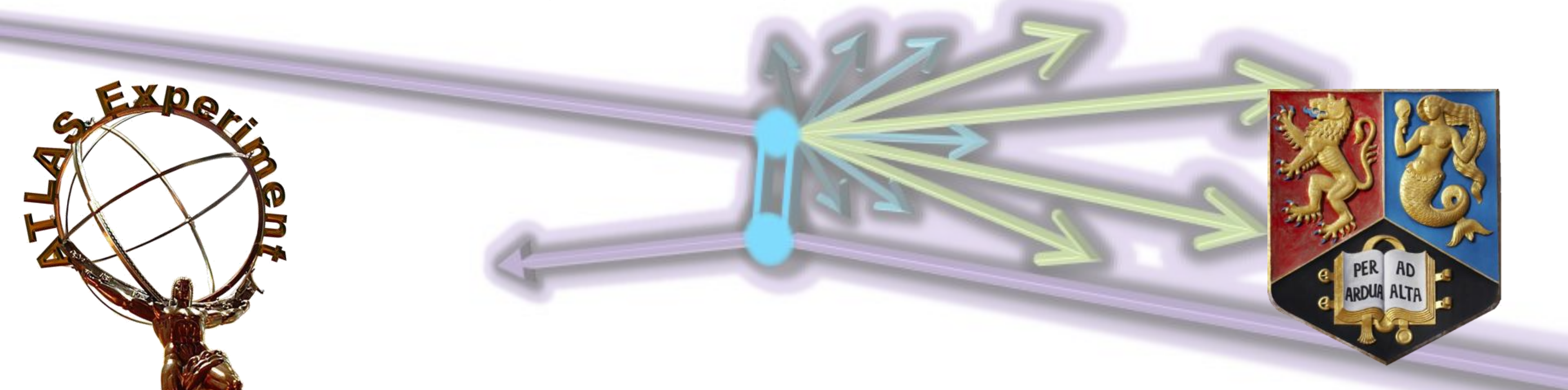
Large rapidity gaps and soft diffraction at ATLAS

Birmingham HEP Seminar

7th March 2012

Tim Martin - University of Birmingham



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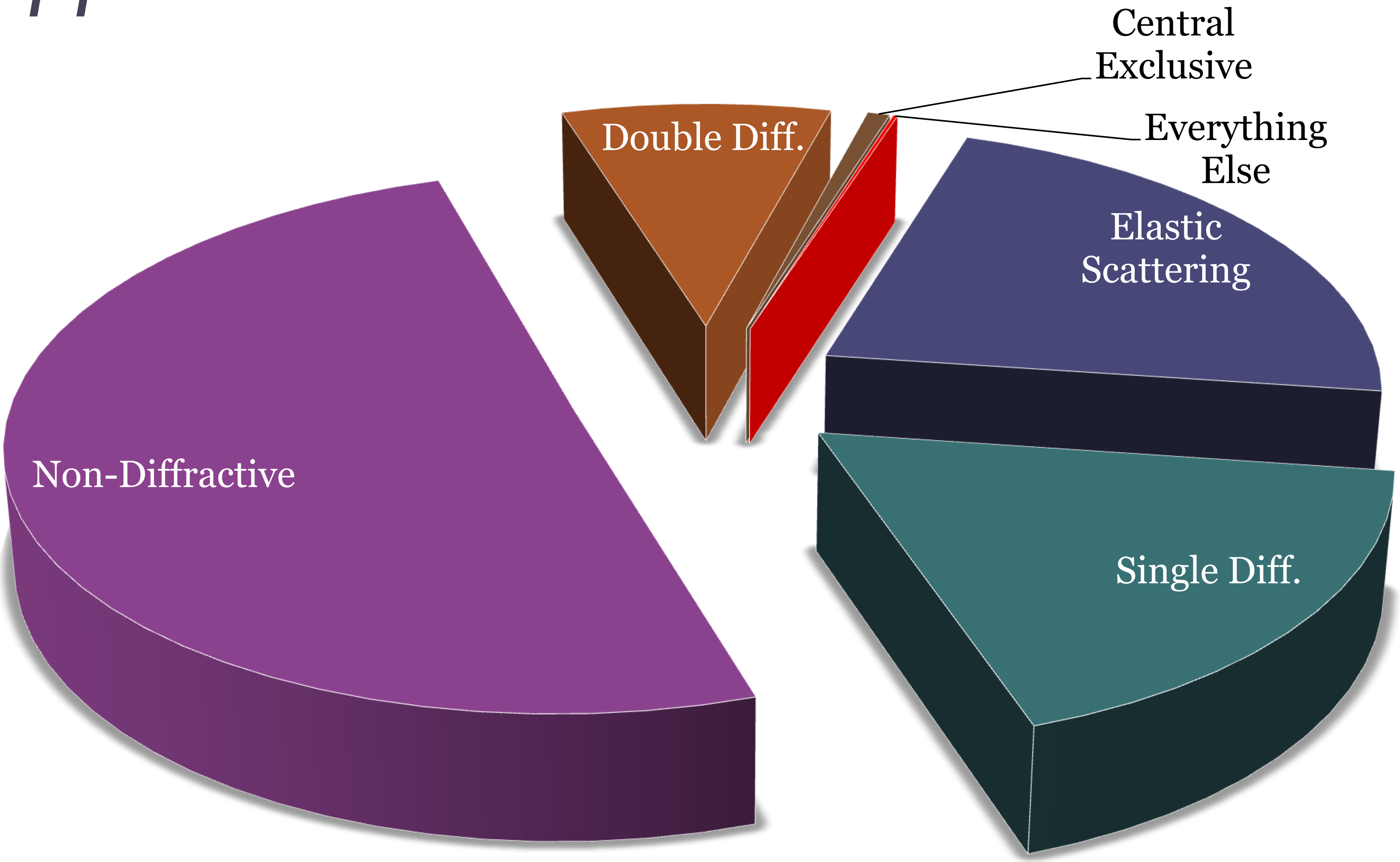
Overview

- Modeling Inelastic Diffraction
- Diffractive Events in ATLAS
- Large Rapidity Gaps
- Interpreting the Data

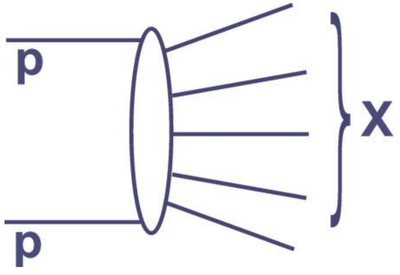
pp Cross Section

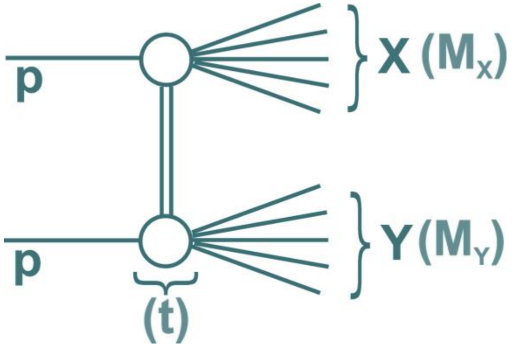


Soft QCD – Inelastic Processes

Non Diffractive Events

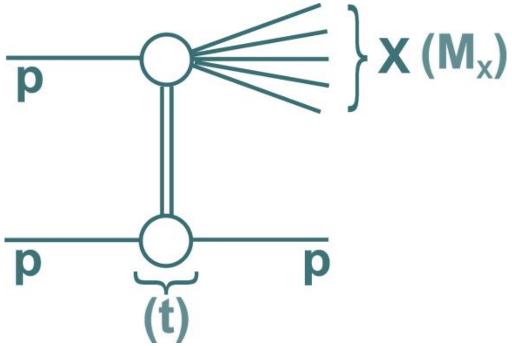
Coloured exchange.
High multiplicity final states peaking at central rapidity.
Soft P_T spectrum.
Largest cross section at LHC.

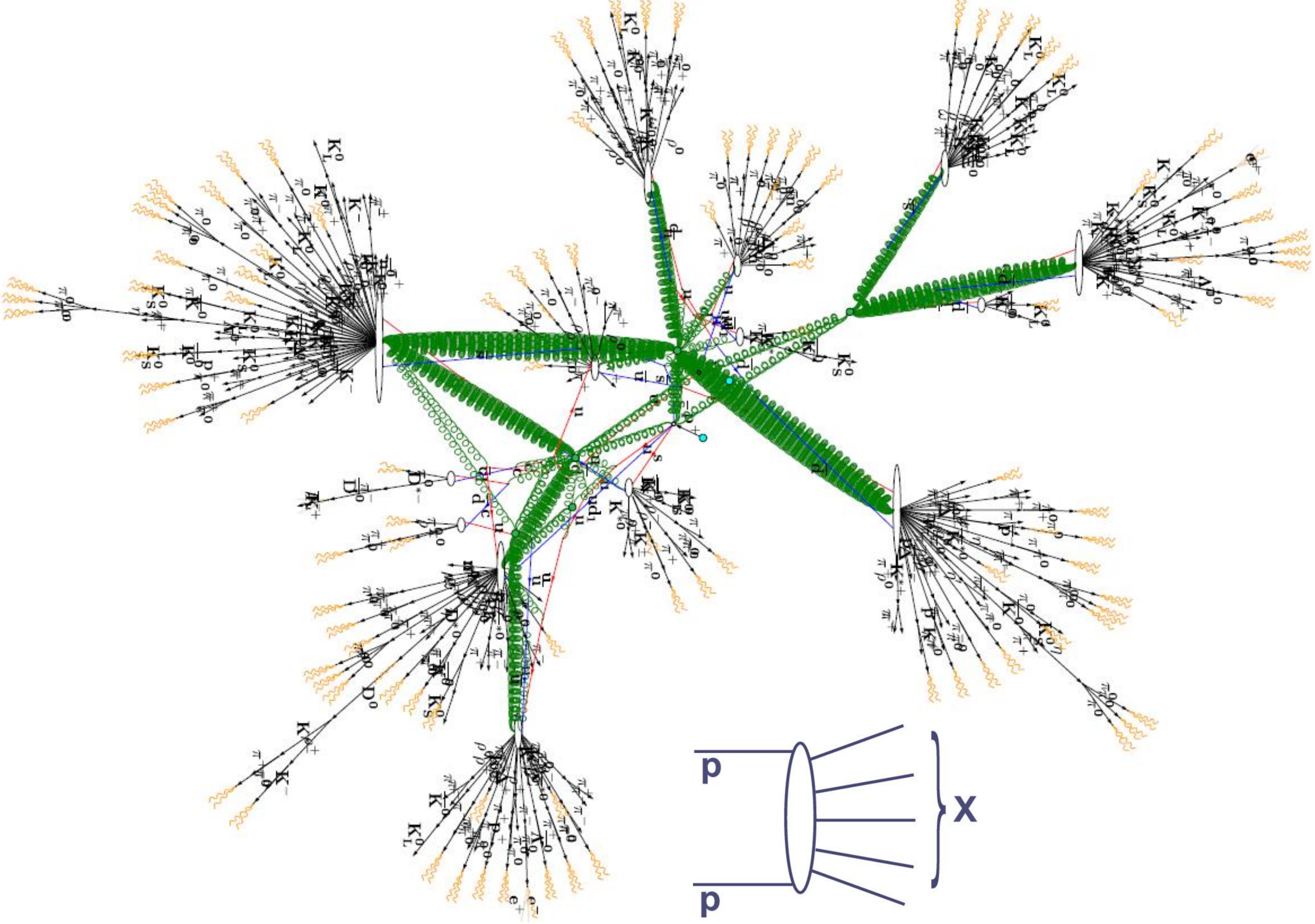


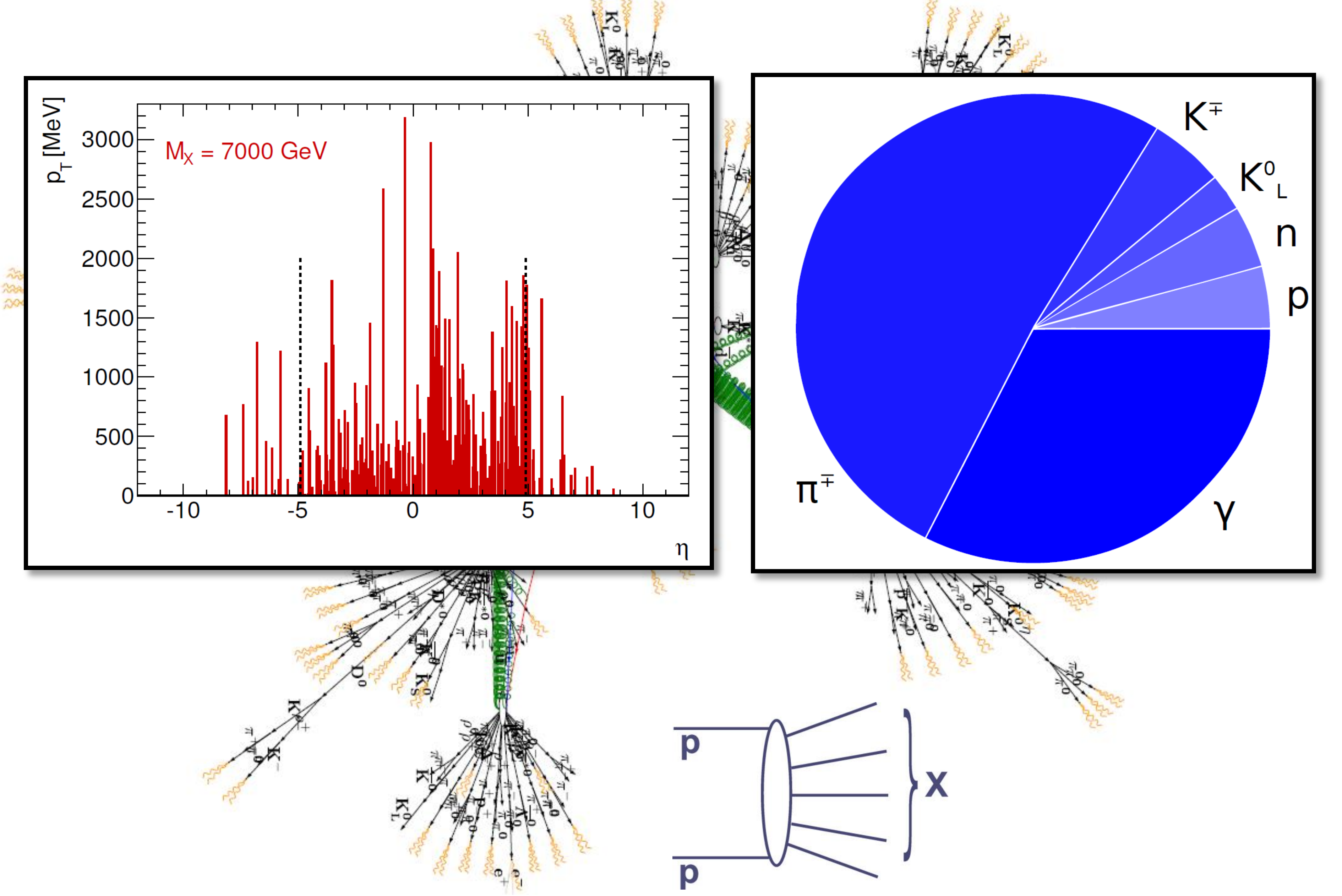


Diffractive Events

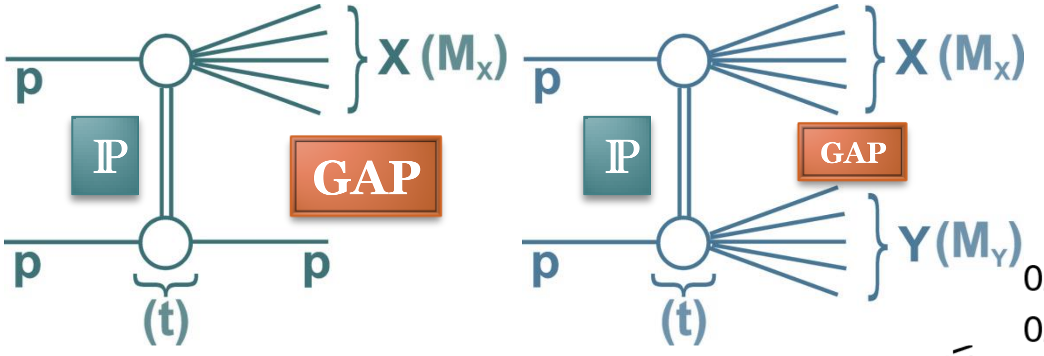
Colour singlet exchange.
Can be **Single** or **Double** proton **dissociation**.
Diffractive mass can be anything from **$p+\pi^0$** up large systems with **hundreds of GeV** invariant mass.
Soft P_T spectrum.
Large forward energy flow.
Less activity in the inner detector.




p
p
X


p_T [MeV]
3000
2500
2000
1500
1000
500
0
M_X = 7000 GeV
-10
-5
0
5
10
η
$K^{\mp}$
K^0_L
n
p
$\pi^{\mp}$
γ
p
p
X

LHC Diffraction

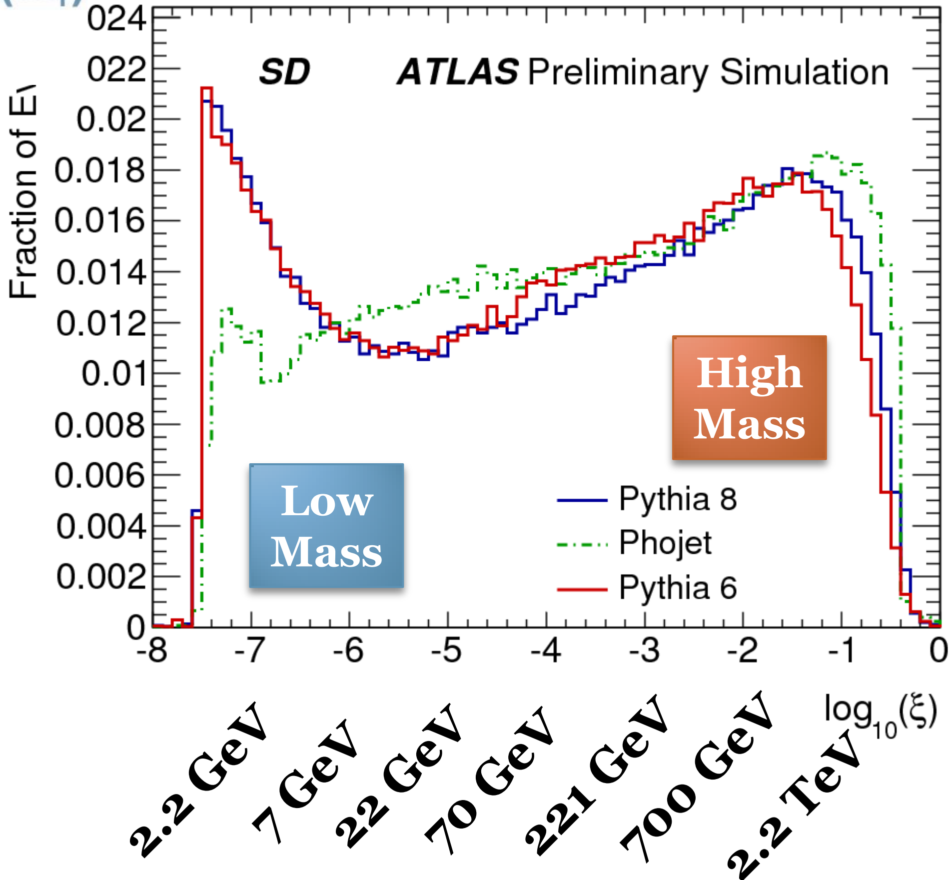


$$\xi_X = \frac{M_X^2}{s}$$

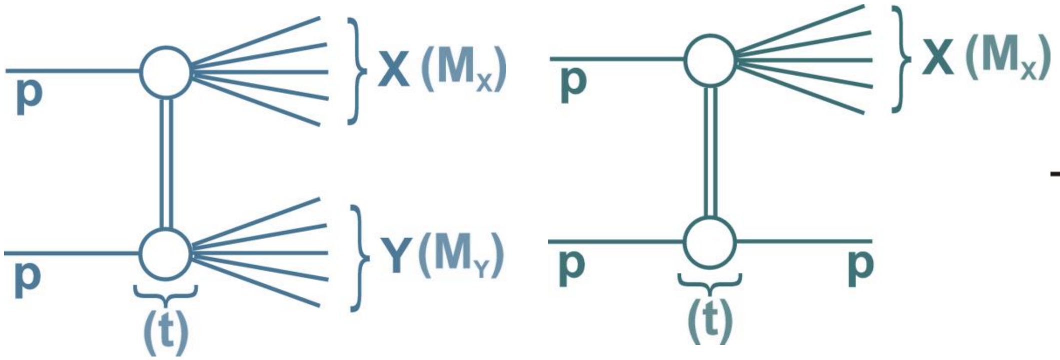
$M_X > M_Y$
(By Construction)

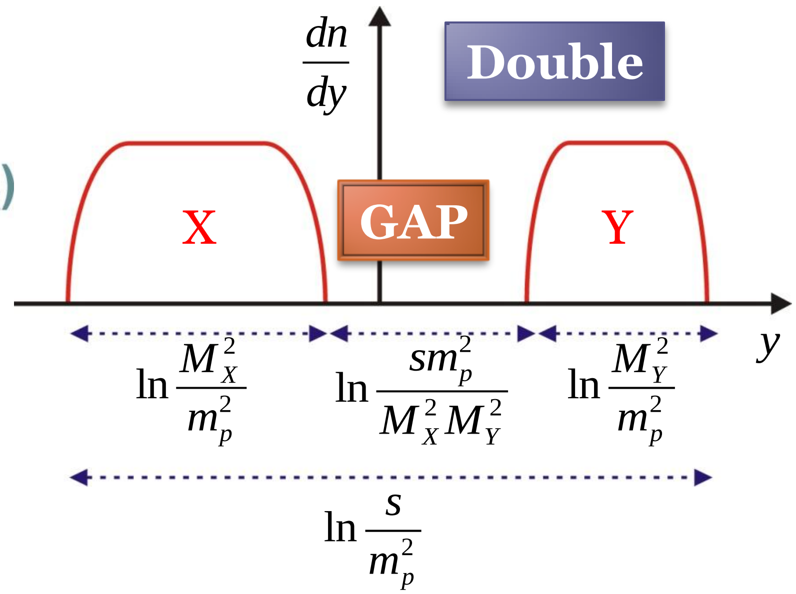
$f_D = \sigma_{Diffractive}/\sigma_{Inelastic}$

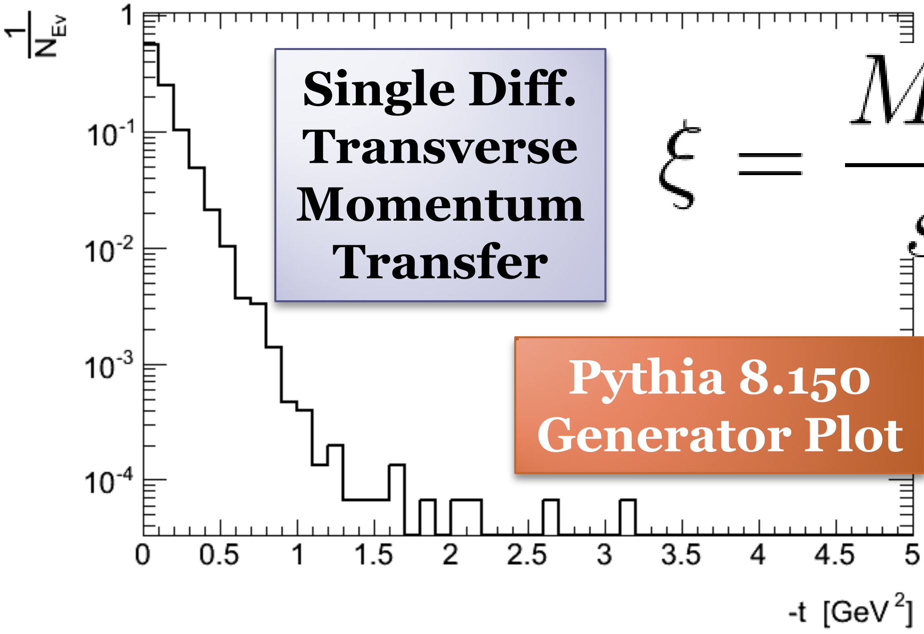
- **f_D = 25-30%** of the **total inelastic cross section ($\xi_X > 5\text{x}10^{-6}$)** is measured to be **inelastic diffractive.**
- **Cross section approximately constant in log(ξ_X)**.
- **Lack of colour flow** results in a **rapidity gap** between the **two dissociated systems** (Double Diff.) or the **dissociated system and the intact proton** (Single Diff.) **devoid of soft QCD radiation**.
- **The size of the rapidity gap** is related to the **invariant mass of the dissociated system(s)**.



LHC Diffraction



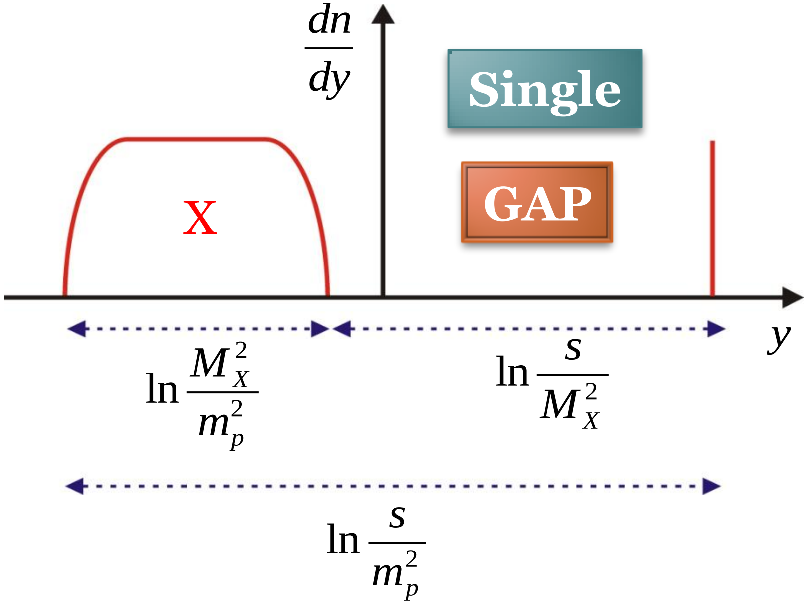


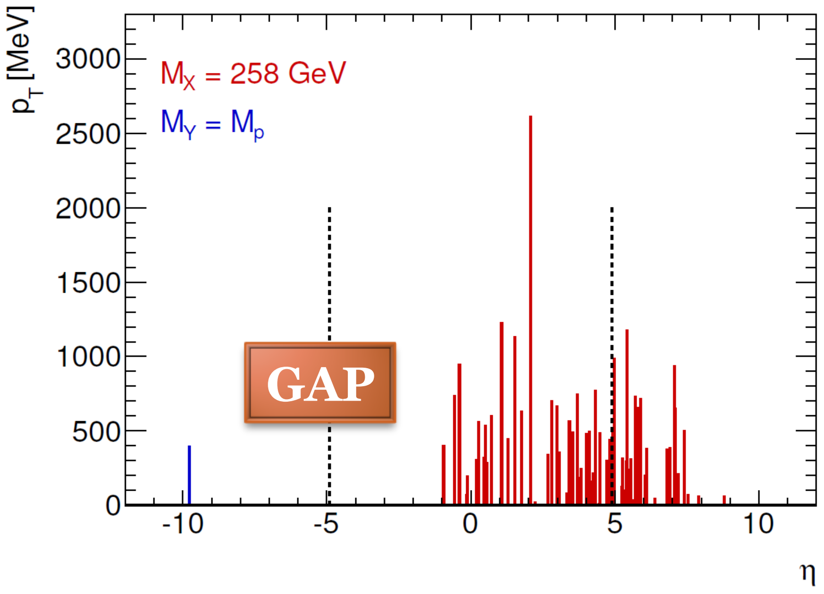


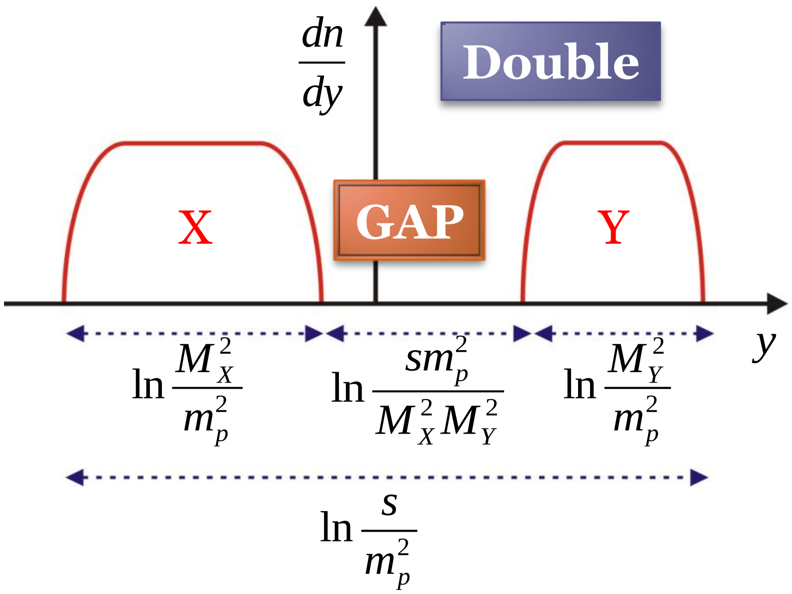
Single Diff. Transverse Momentum Transfer

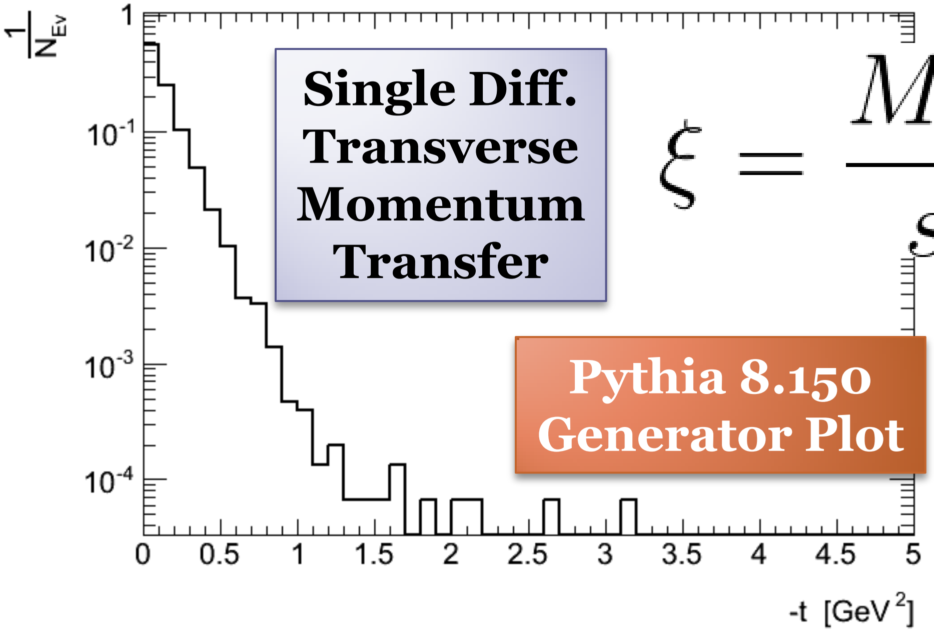
Pythia 8.150 Generator Plot

$$\xi = \frac{M_X^2}{s}$$





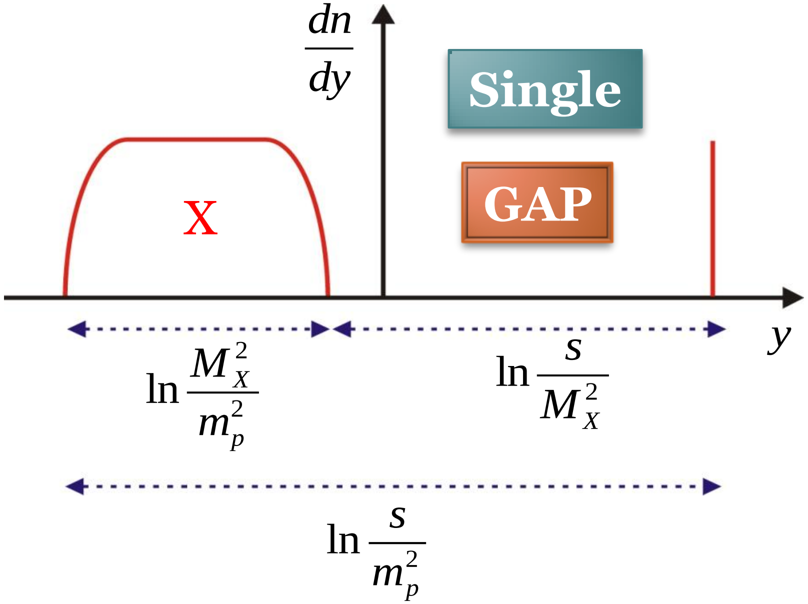




Single Diff. Transverse Momentum Transfer

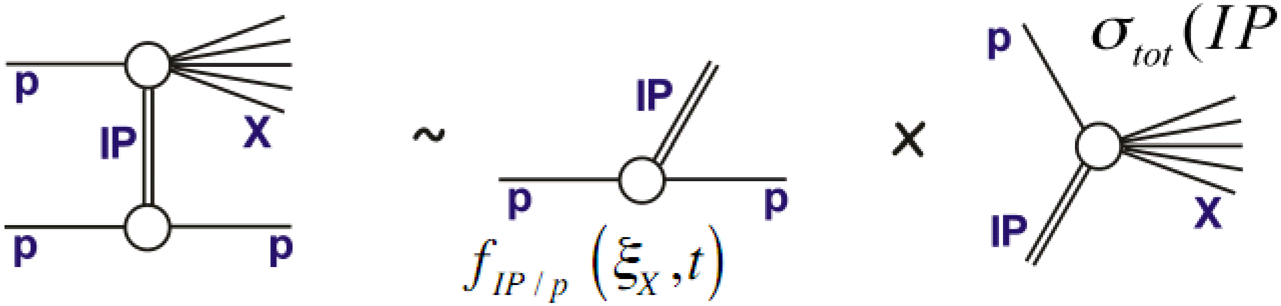
$$\xi = \frac{M_X^2}{s}$$

Pythia 8.150 Generator Plot



Diffraction in the MCs

- MC models split the cross section into two parts.
  - A **Pomeron flux (ξ,t)** and **Pomeron-Proton cross-section**.
  - Vastly dominated by **$|t^2| < 2$ GeV** ∴ **non-perturbative QCD**.
    - Instead use **phenomenological models**.

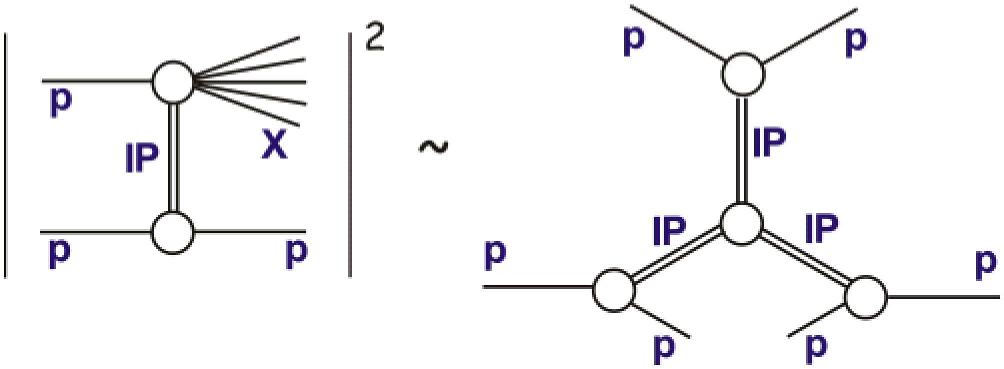


$\sigma_{tot}(IP + p \rightarrow X)$

Optical Theorem

$$\sigma^{AB}_{tot} \sim \frac{1}{s} \mathcal{I}m(T^{AB}_{el})_{t=0}$$

- Utilising the **Optical Theorem** to relate **σ_{Total}(IP +p)** to **elastic IP +p**



$$\frac{d\sigma}{d\xi dt} \propto \left(\frac{1}{\xi_X}\right)^{2\alpha(t)-\alpha(0)} e^{bt}$$

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

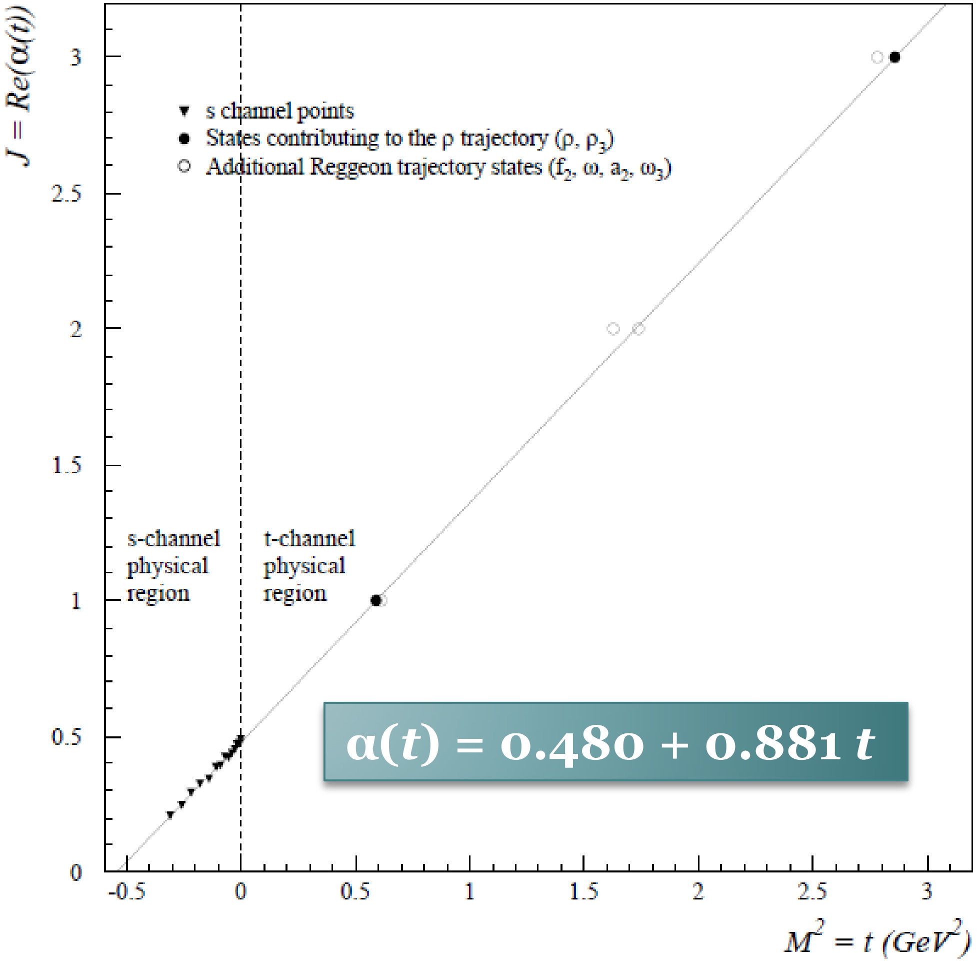
$$\frac{d\sigma}{d\xi_X} \propto \frac{1}{\xi_X}$$

$S >> M_X >> t$

What is the Pomeron?

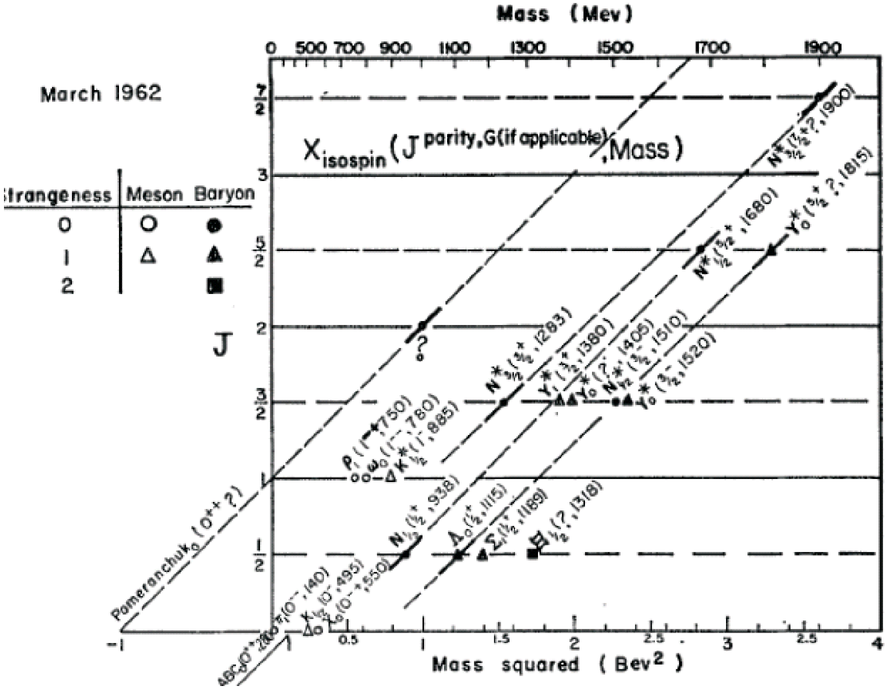
- It is a **Reggeon trajectory**.
- It could be a **glue-ball**.

Chew-Frautschi Plots

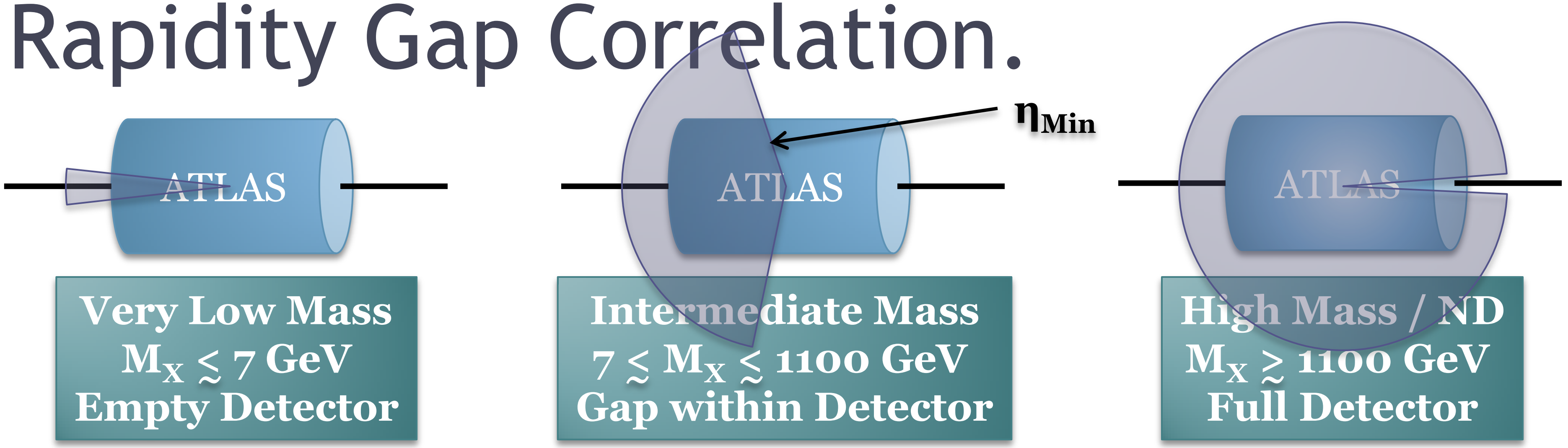


$\alpha(t) = 0.480 + 0.881\, t$

Early (wrong) guess at the Pomeron trajectory.



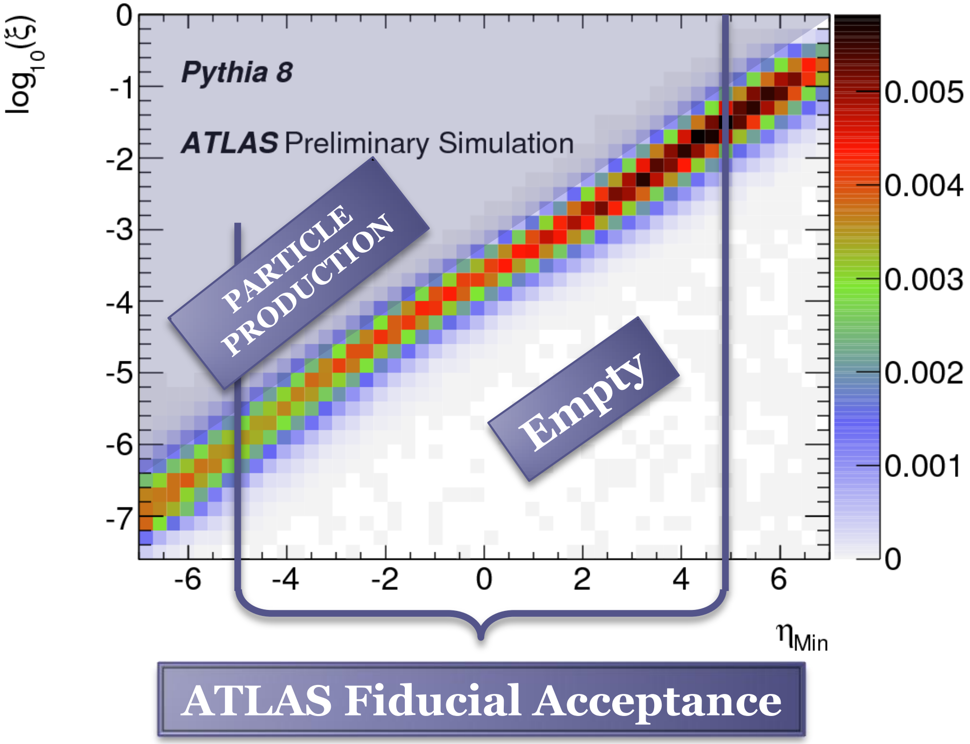
Rapidity Gap Correlation.



Very Low Mass
$M_X \lesssim 7$ GeV
Empty Detector

Intermediate Mass
$7 \lesssim M_X \lesssim 1100$ GeV
Gap within Detector

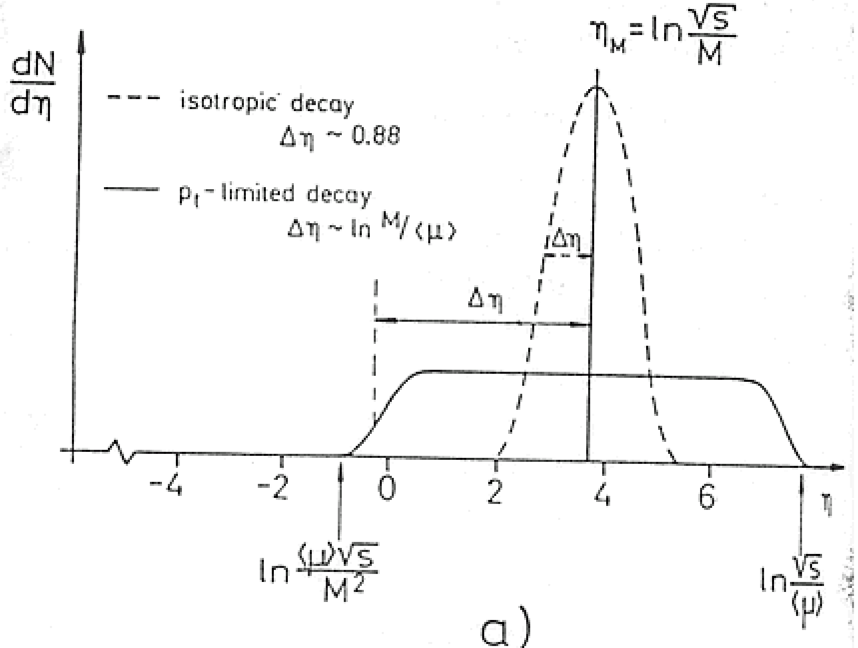
High Mass / ND
$M_X \gtrsim 1100$ GeV
Full Detector

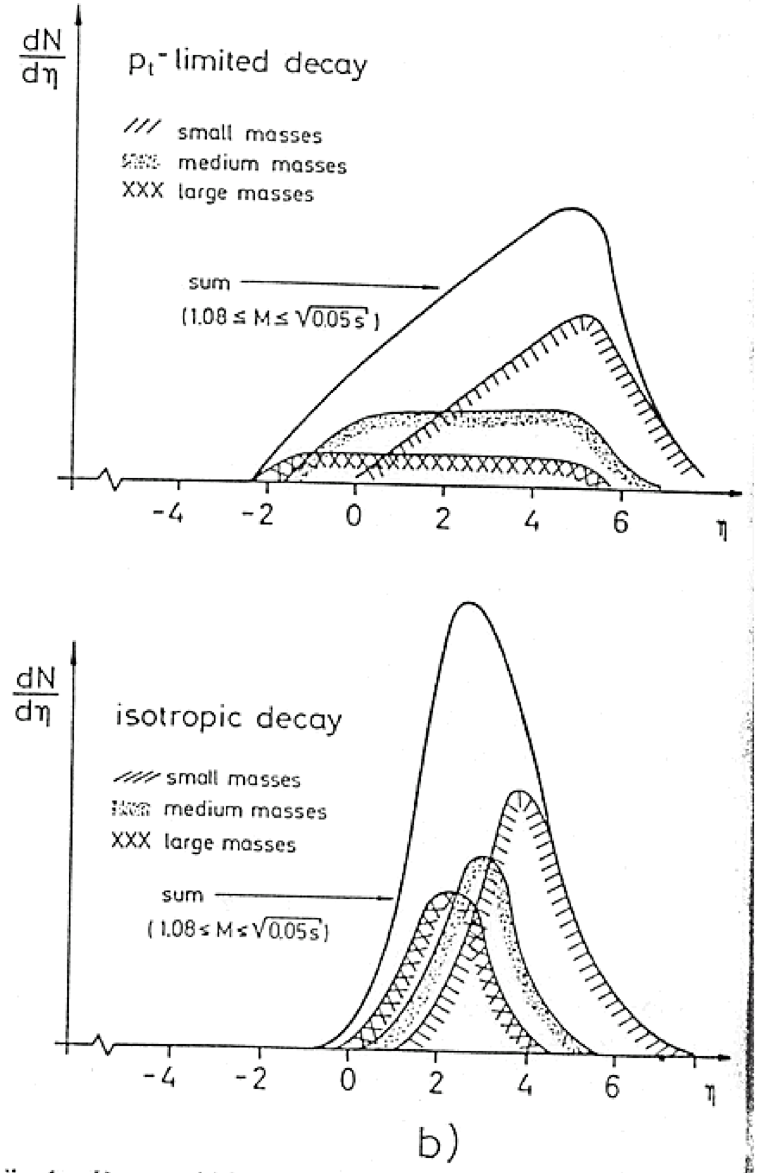


- **Rapidity interval** of **final state** **kinematically linked** to size of **diffractive mass**.
- **Linear relation** between **η of edge of diffractive system** and **ln(M_X)**, smeared out slightly by **hadronisation effects**.

Rapidity Gap Correlation

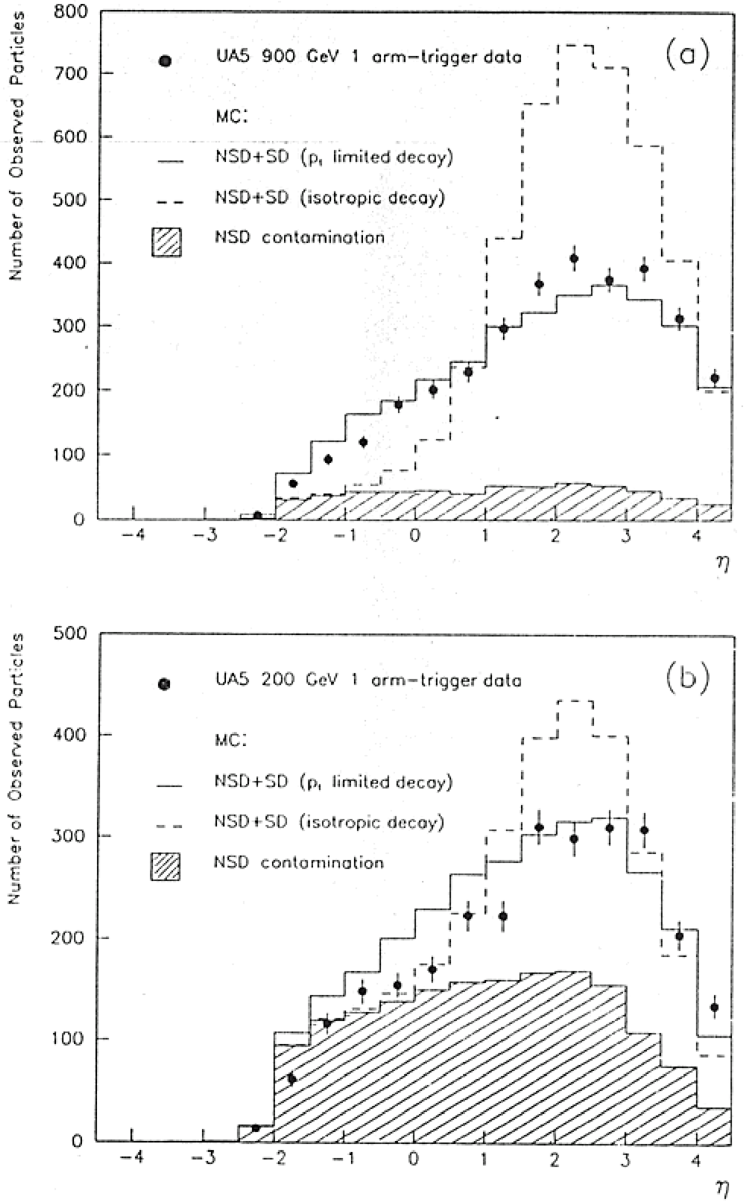
- Historically, rapidity gaps were exploited by **UA5** in **1986** at **√s = 200 and 900 GeV**.
- Investigated the **characteristic rapidity distributions** observed in high energy diffraction.
- Does the diffractive mass **decay homogeneously in its boosted system** or does the width **grow with mass?**





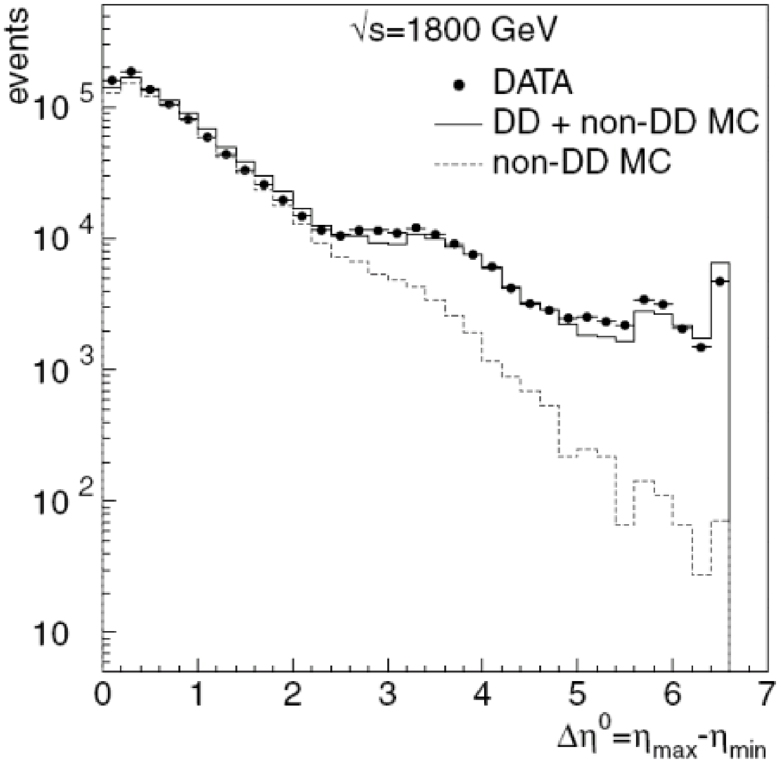
Rapidity Gap Correlation

- **UA5** used a **exclusively single sided scintillator trigger**.
- By looking for **large rapidity gaps** they **excluded the isotropic `fireball' decay model** and **measured the single diffractive cross section**.
- **NSD** or **non-single-diffractive** refers to a **combination of non-diffractive and double diffractive events**.

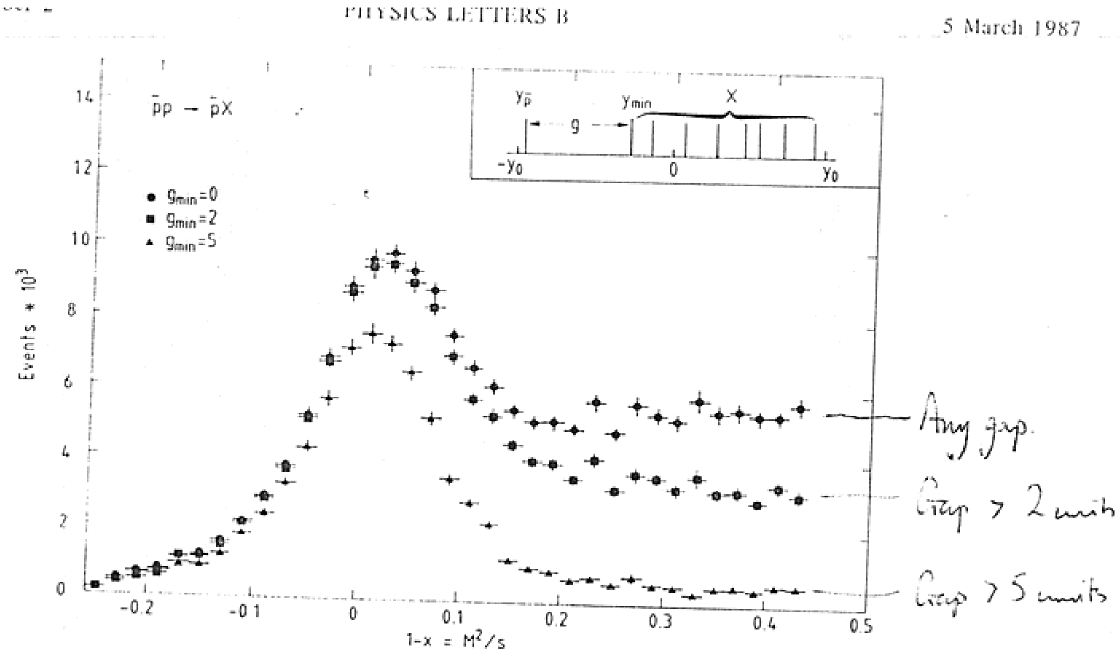


Rapidity Gap Correlation.

Double diffractive dissociation at CDF in 2001 using gaps which span central rapidity.

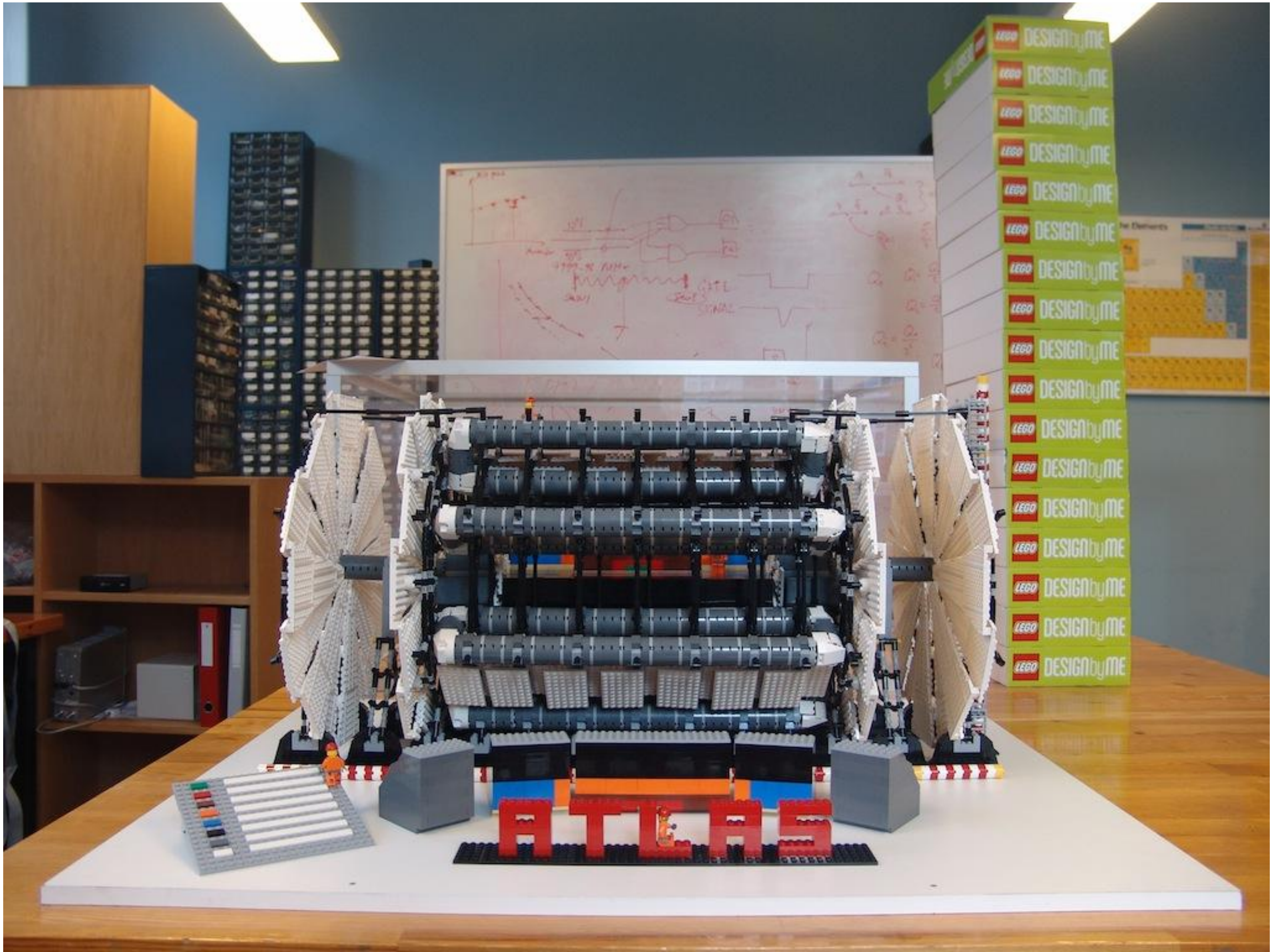


Historically used for cross section evaluation

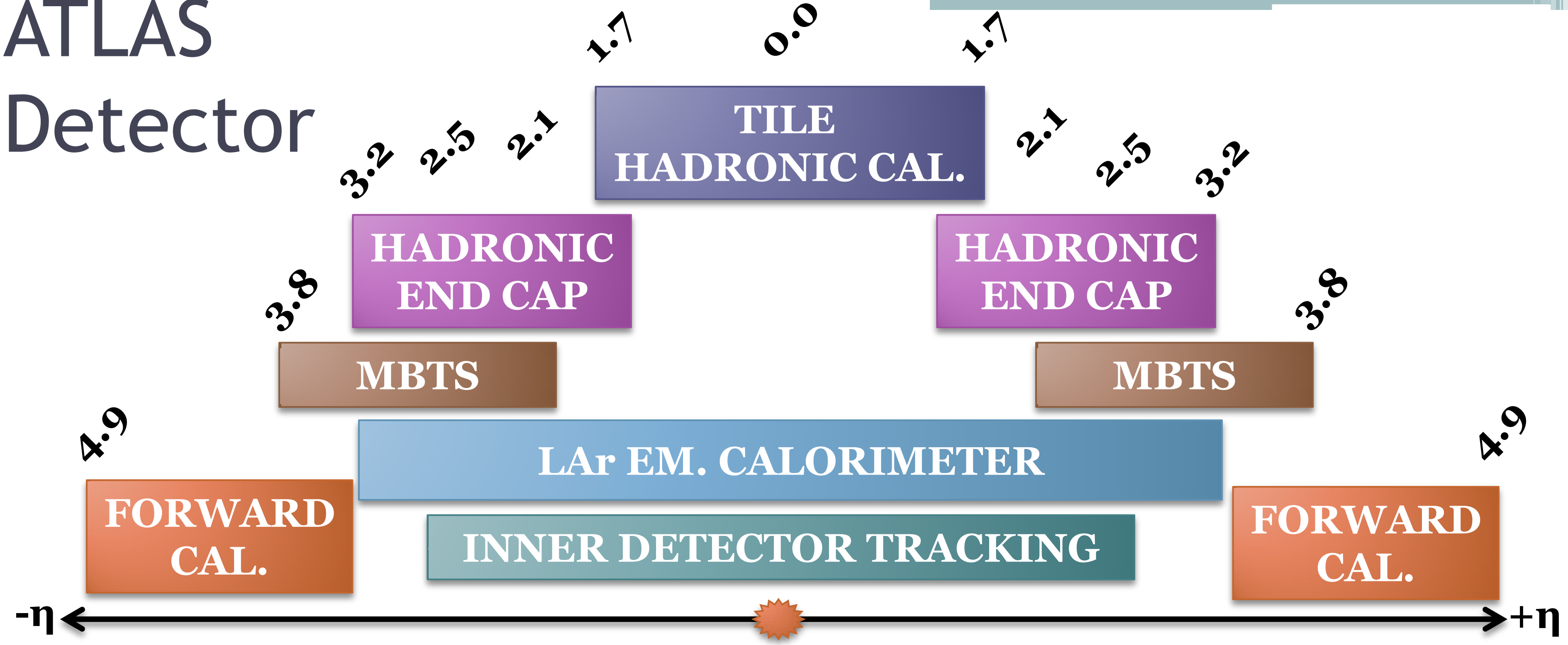


Cross sections for diffractive dissociation from rapidity gaps in UA4

ATLAS Detector



ATLAS Detector



1.7 0.0 1.7

3.2 2.5 2.1 2.1 2.5 3.2

3.8 3.8

4.9 4.9

TILE HADRONIC CAL.

HADRONIC END CAP **HADRONIC END CAP**

MBTS **MBTS**

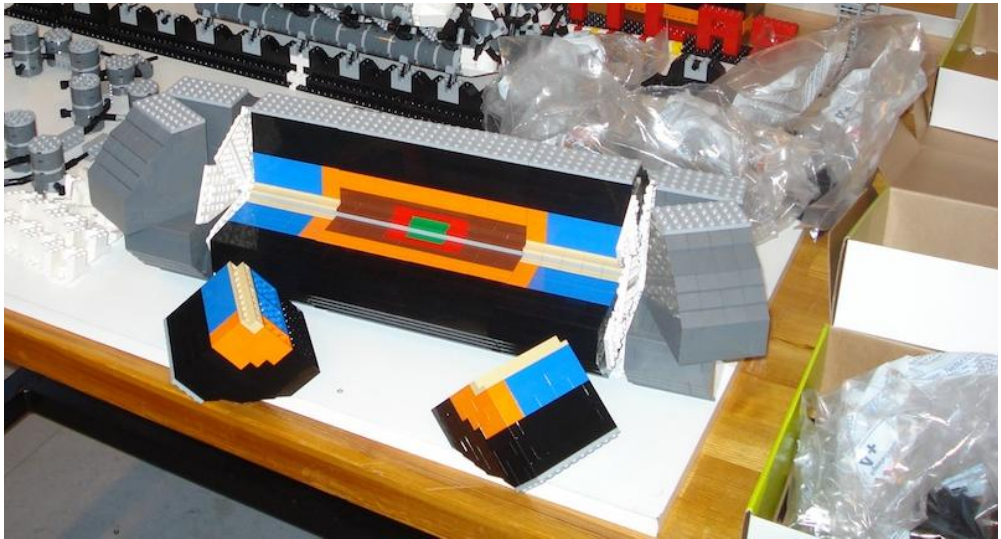
LAr EM. CALORIMETER

FORWARD CAL. **INNER DETECTOR TRACKING** **FORWARD CAL.**

-η +η

We utilise the full tracking and calorimetric range of the detector.

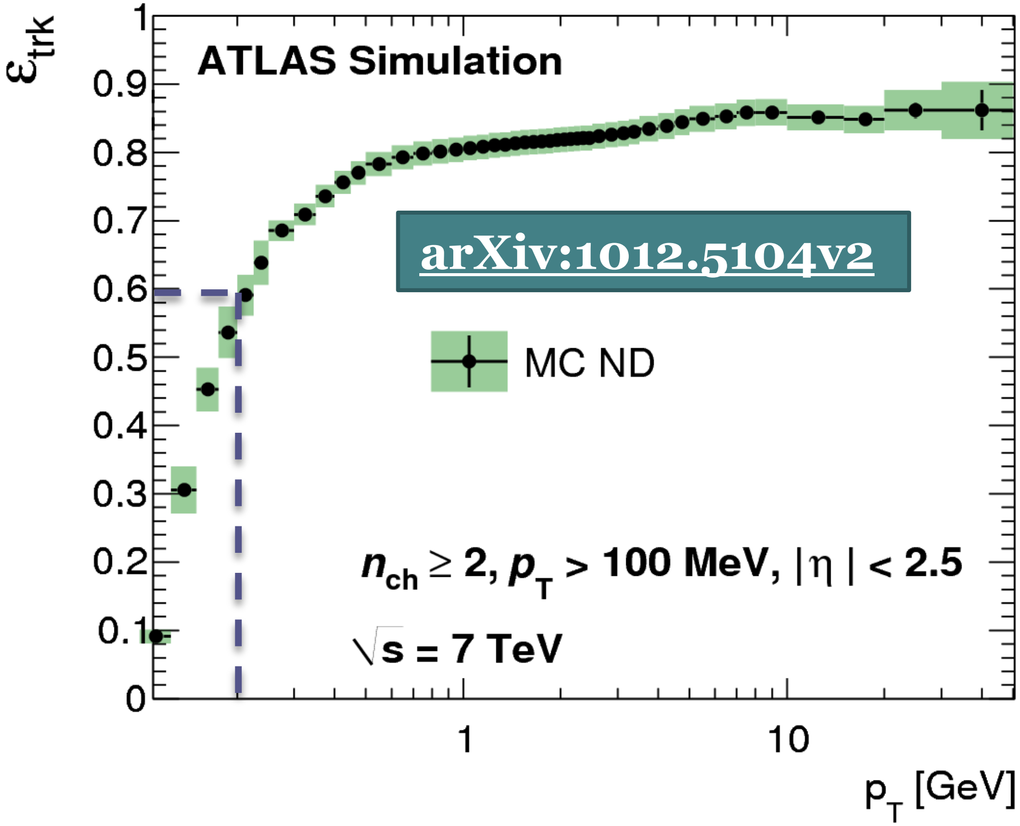
We want to set our thresholds *as low as the detector will allow us.*



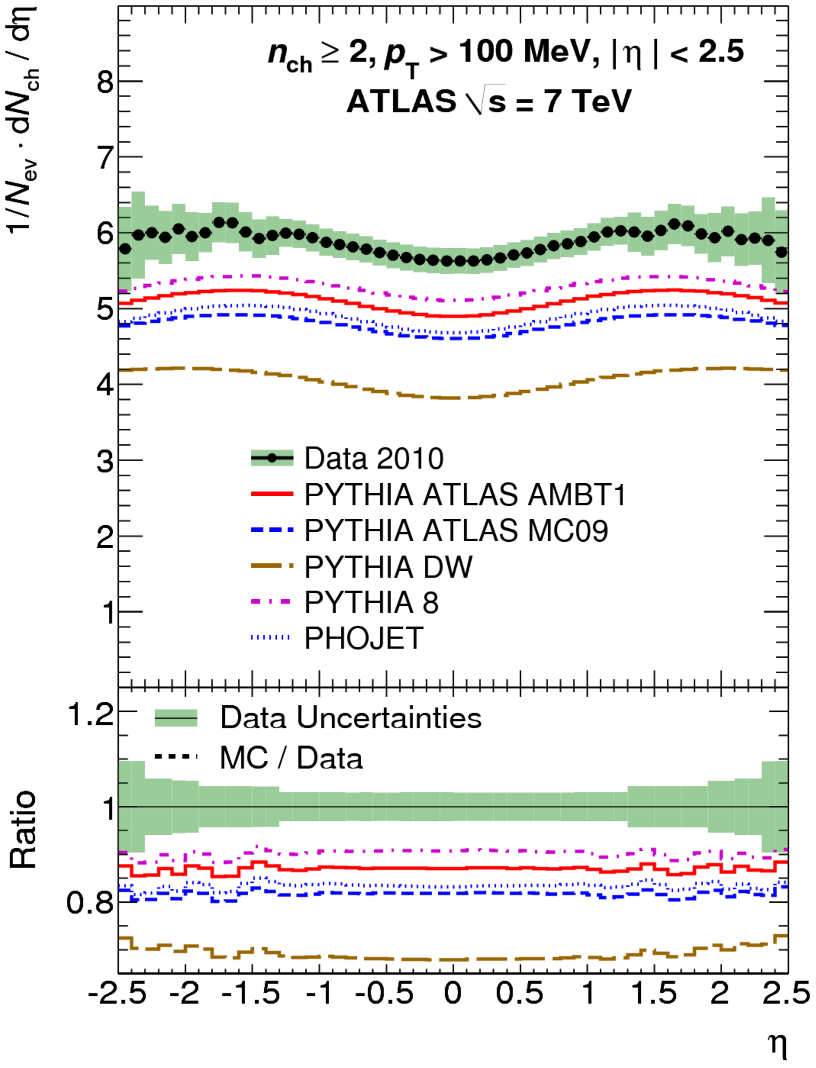
Inner Detector

We have plenty of experience with low-p_T, minimum bias tracking in ATLAS.

Apply standard cuts but *no vertex req.*

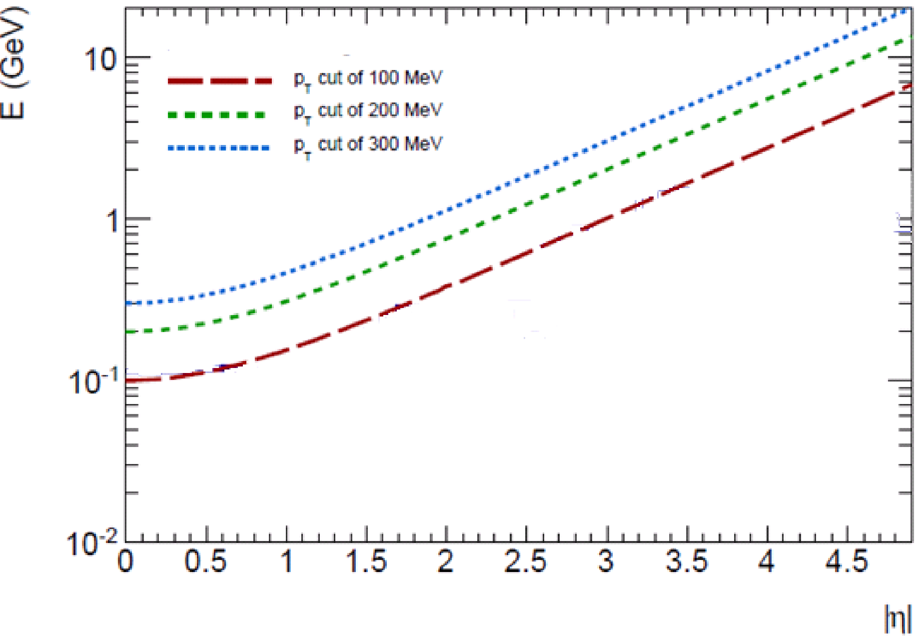


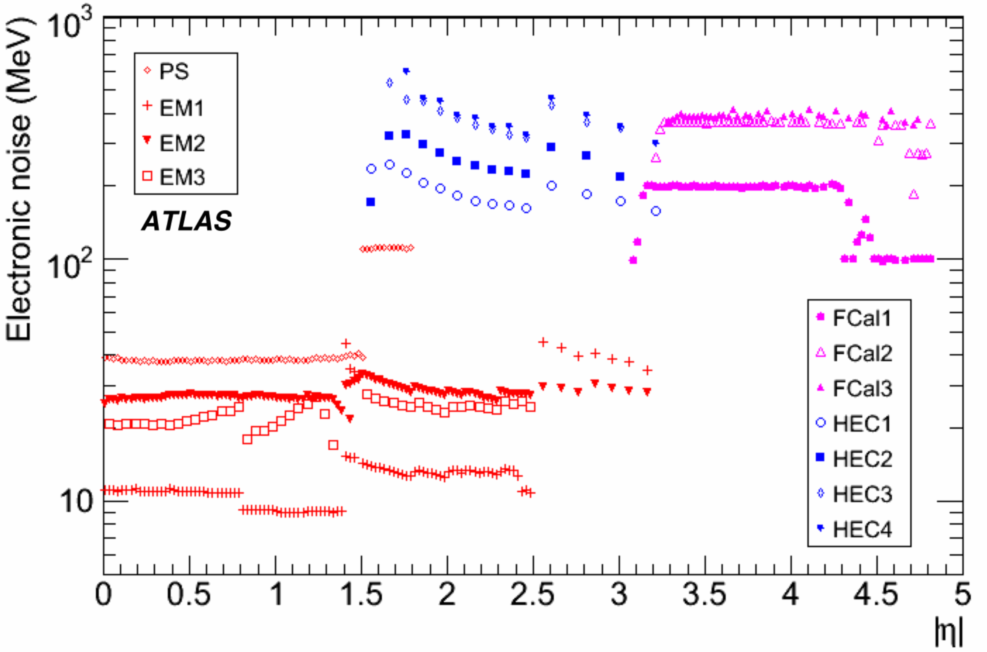
arXiv:1012.5104v2



Calorimeters

- In the calorimeters **electronic noise is the primary concern**.
- We use the **standard ATLAS Topological clustering of cells**. The seed cell is required to have an **energy significance $\sigma = E/\sigma_{Noise} > 4$**.
- Statistically, we **expect 6 topological clusters per event from noise fluctuations alone**.
  - **187,616 cells multiplied by P(σ 4 -> ∞) ~= 6**
- Just **one noise cluster can kill a gap**, additional **noise suppression is employed**.





Calorimeters

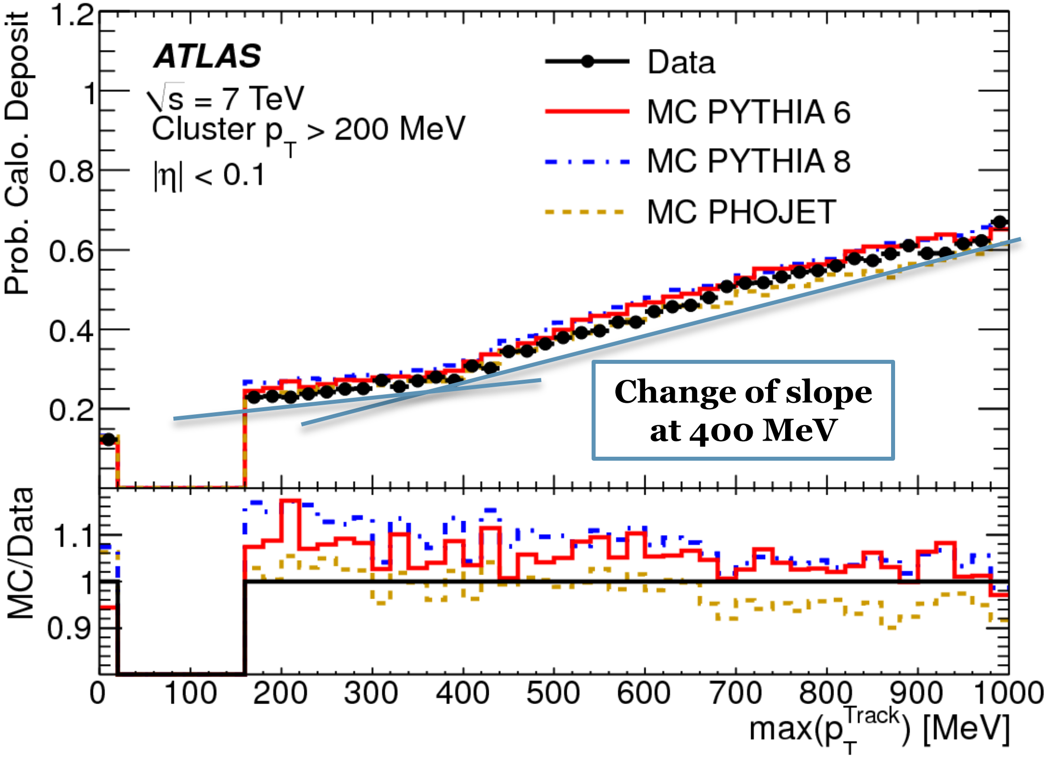
- We apply a **statistical noise cut** to the **leading cell** in the cluster which comes from **the LAr systems** (the hadronic Tile calorimeter's noise is a **double Gaussian**).
- We set P_{noise} within a **0.1 η** slice to be **$1.4\text{x}10^{-4}$**
- **N** is the **number of cells** in the slice.
- The threshold $S_{th}(\eta)$ varies from **5.8σ at η = 0** to **4.8σ at η = 4.9**

$$P_{\text{noise}}/N = \frac{1}{\sqrt{2\pi}}\int_{S_{th}}^{\infty} e^{-s^2/2}\,ds$$

This control distribution shows the probability of a cluster with p_T > 200 MeV which passes the noise cut as a function of the hardest track.

All at mid rapidity (|η| < 0.1)

For hardest track p_T < 400 MeV, this is directly probing neutral particle detection as all these tracks are swept out in the B field.



Change of slope at 400 MeV

Data Set

7 minutes shorter than The Lord of the Rings: The Return of the King

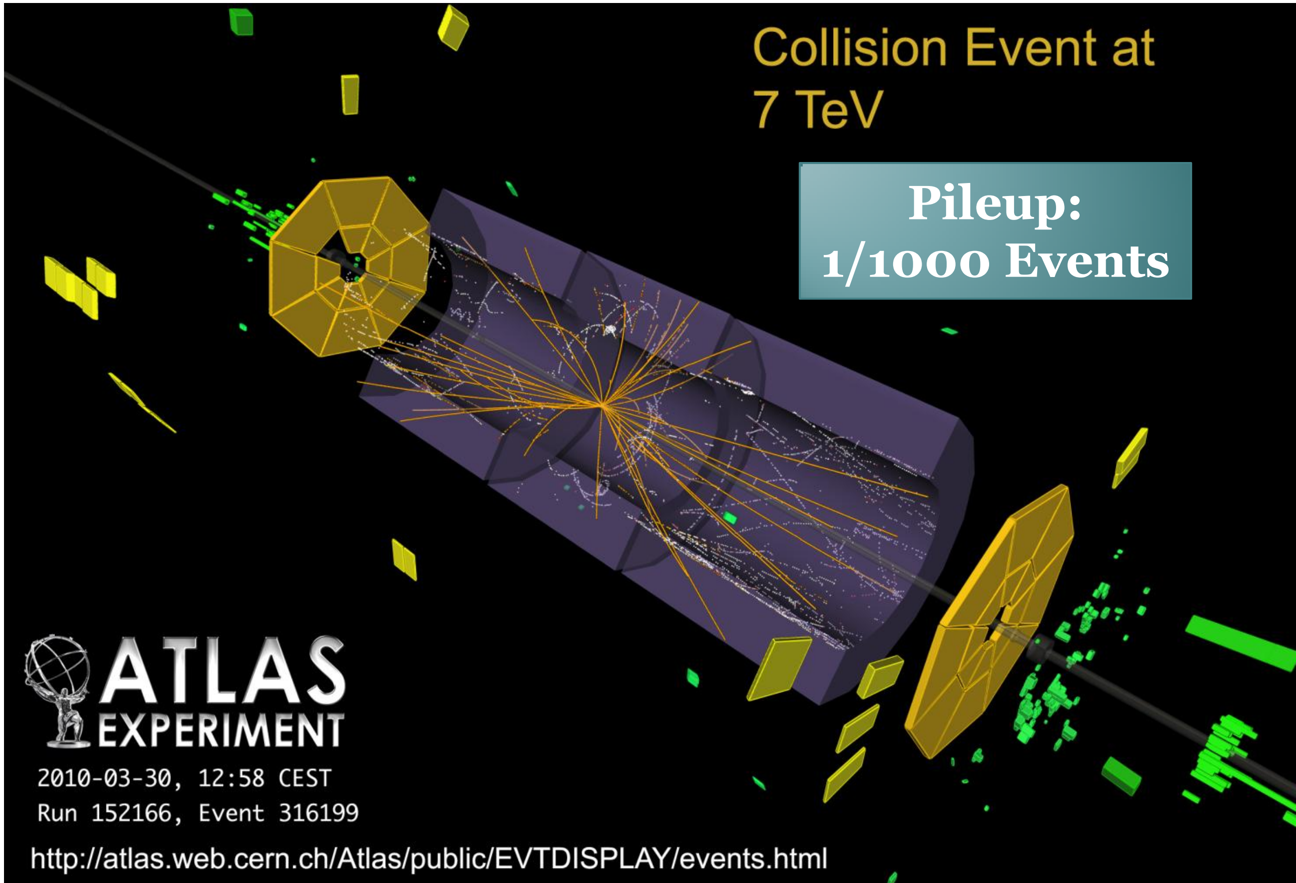
- Utilising the **first stable beam physics run at 7 TeV centre of mass**.
- Data taking started at **13:24** and finished at **16:38** on **30th March 2010**.
- In that time **ATLAS accumulated 422,776 minimum bias events**.
- This corresponds to **7.1 μb^{-1}** at peak instantaneous luminosity **1.1×10^{27} $cm^{-2}s^{-1}$**.

We use fully simulated MC samples roughly three times larger

Pythia 8
Nominal MC

Pythia 6
Different modelling of the final state.

Phojet
Different dynamical diffraction model.



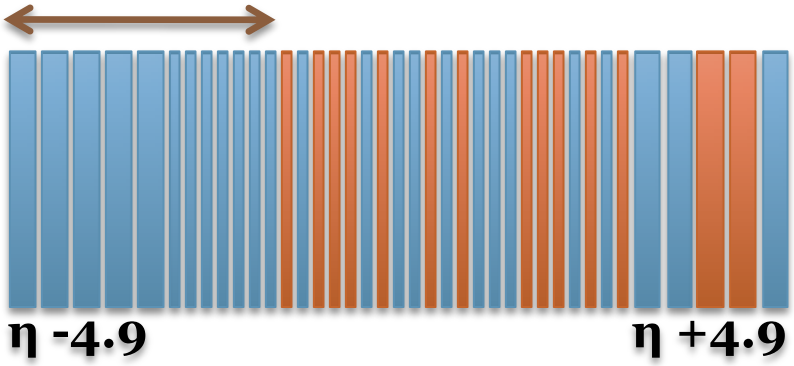
2010-03-30, 12:58 CEST
Run 152166, Event 316199

http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

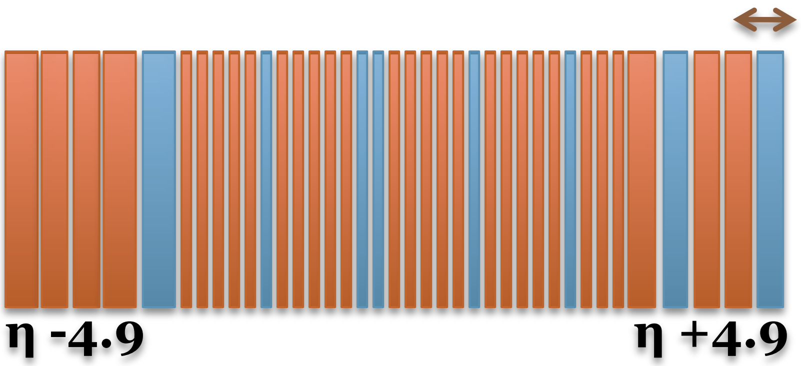
Pileup:
1/1000 Events

Gap Finding Algorithm

- The detector is binned in η.
- **Detector Level Bin** contains particle(s) if one or more **noise suppressed calorimeter clusters** above **E_T *cut*** **AND/OR** one or more **tracks** are reconstructed above **p_T *cut***. (E_T=p_T) .
- **Generator Level Bin** contains particle(s) if it contains one or more **stable** ($c\tau$ > 10 mm) **generator** particles **> p_T *cut***.
- **$\Delta\eta^F$ = Largest region of pseudo-rapidity from detector edge containing no particles with p_T > *cut***.
- For **each event**, we **calculate $\Delta\eta^F$ at p_T cut = 200, 400, 600 & 800 MeV.**
- **Main Physics result** is the at the lowest cut**, 200 MeV**.

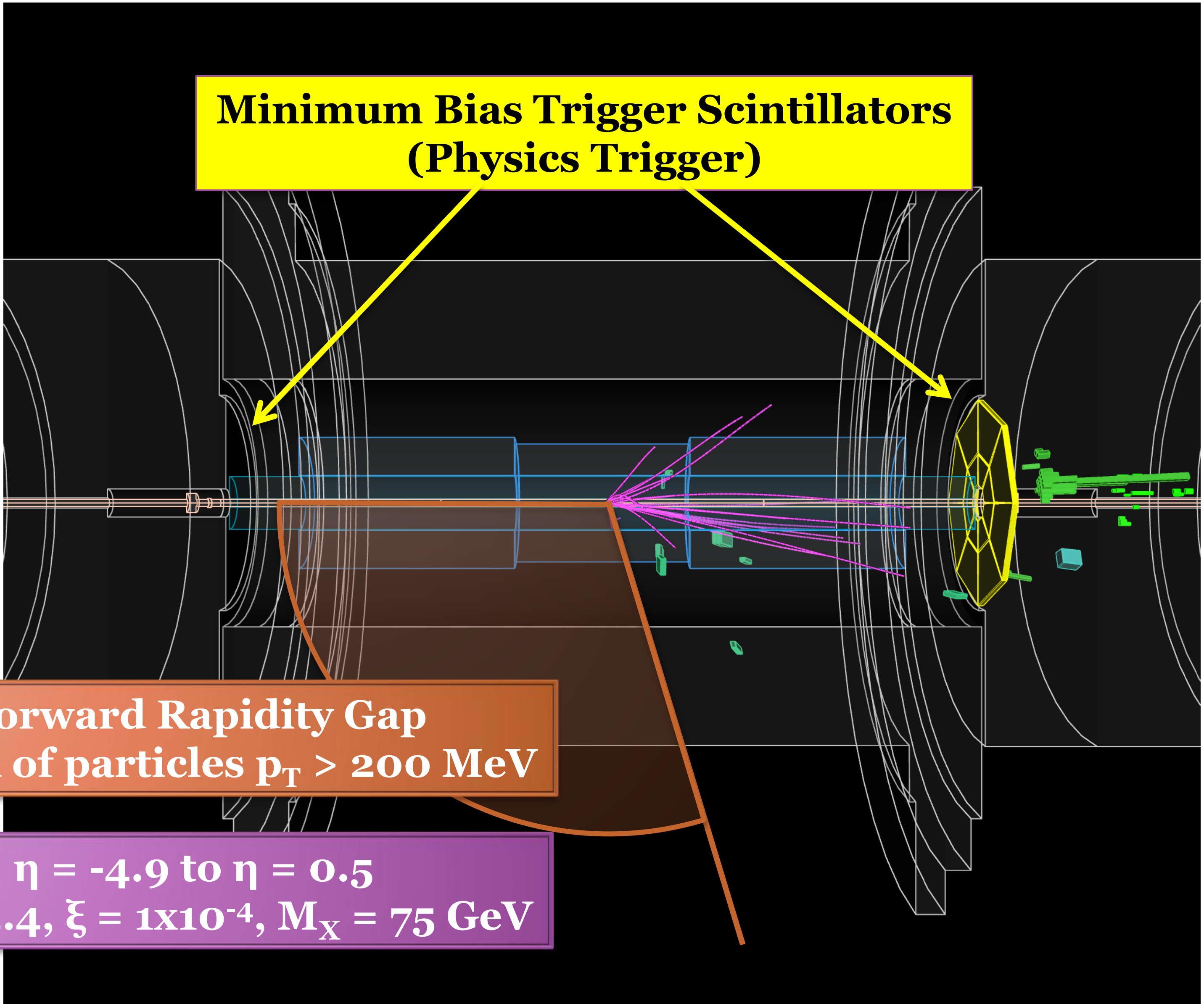


E.G Intermediate Diffractive Mass
$\Delta\eta^F$ = 3.4, ξ = 9x10^{-4}, M_X = 210 GeV



E.G Non Diffractive
$\Delta\eta^F$ = 0.4

Example of Inclusive Gap Algorithm



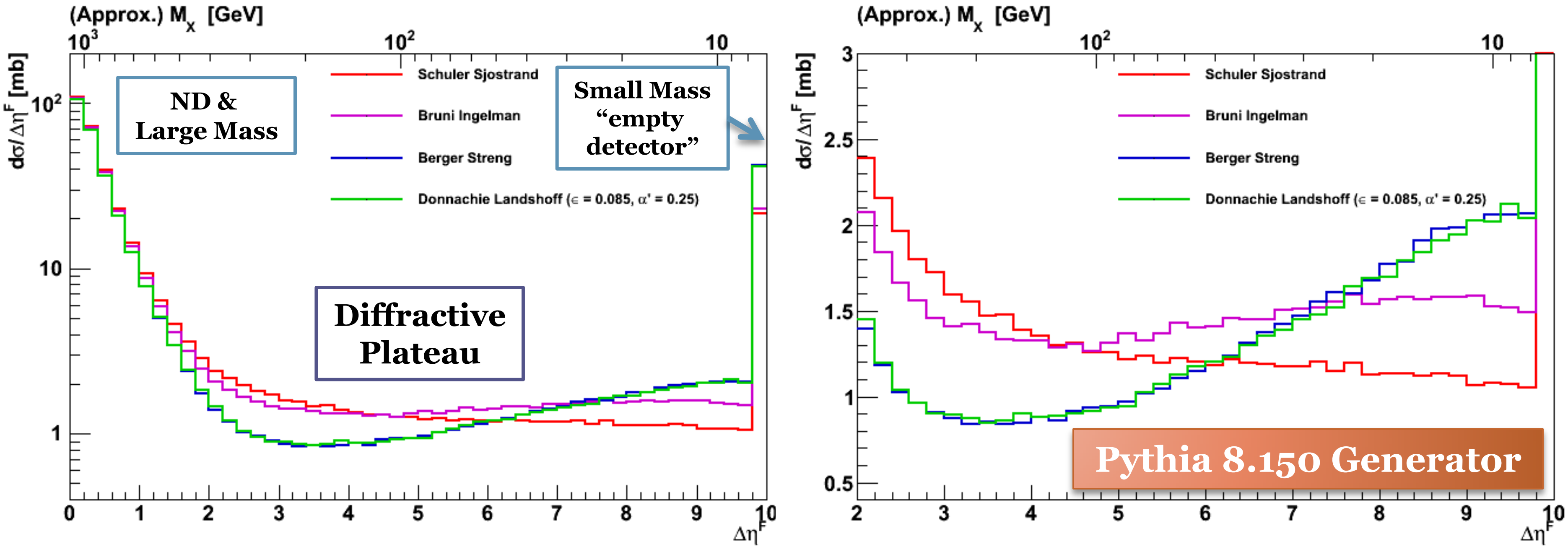
Minimum Bias Trigger Scintillators (Physics Trigger)

Forward Rapidity Gap
Devoid of particles $p_T > 200$ MeV

$\eta = -4.9$ to $\eta = 0.5$
$\Delta\eta^F = 5.4$, $\xi = 1\text{x}10^{-4}$, $M_X = 75$ GeV

Generator Distributions – ℙ Flux

- Plotted are fully inclusive generator level distribution.
- **Schuler & Sjöstrand** (***Default***) - **Critical Pomeron**, **~dm^2/m^2 mass spectrum**, **mass** dependent ***t*** slope with **separate slope for double difffaction** and **low mass resonance enhancement.**
- **Bruni & Ingelman** – **Critical Pomeron**, **~dm^2/m^2 mass spectrum**, **sum of two exponentials** for ***t*** slope.
- **Berger et al. & Streng** – **Super Critical Pomeron** (Intercept>1), **mass** dependent ***t*** slope.
- **Donnachie & Landshoff** - **Super Critical Pomeron**, **power law *t*** distribution.

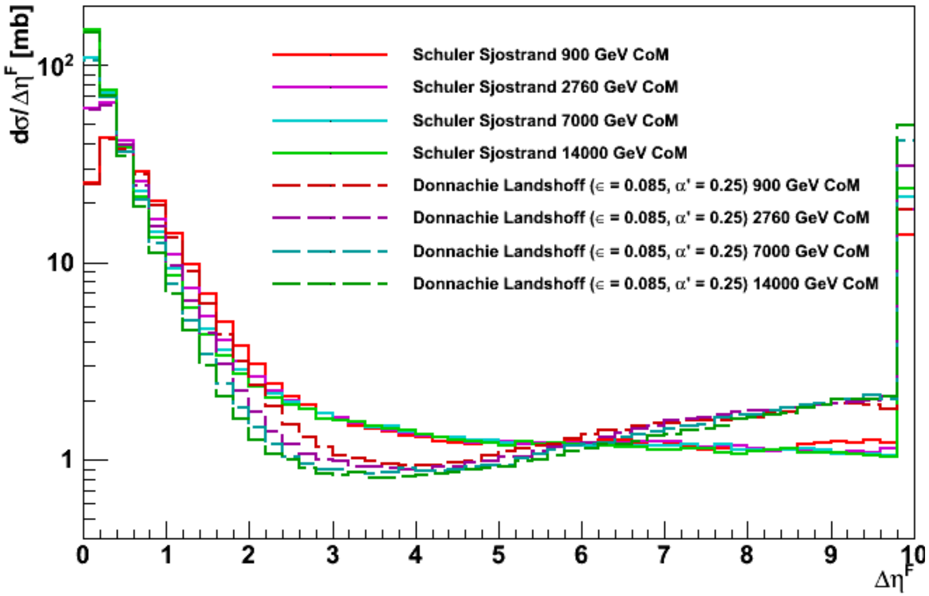


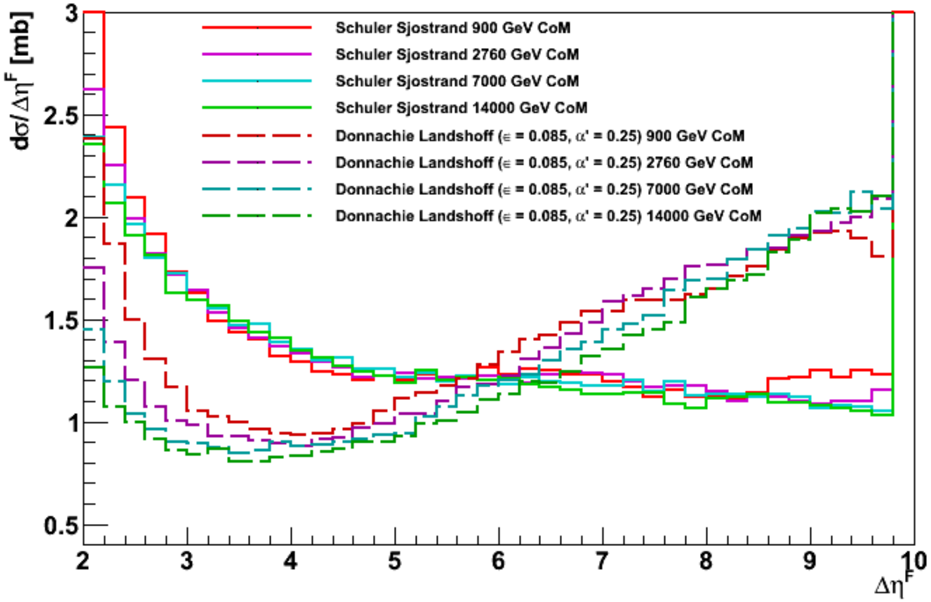
Pythia 8.150 Generator

Generator Distributions - CoM

- Different **centre of mass energies**.
- **Cross section** in **diffractive plateau constant as a** function of **CoM for critical Pomeron**.
- Small variations predicted for **supercritical Pomeron trajectory**.
- **Larger gap size turn over** for **lower energies**.

Pythia 8.150 Generator



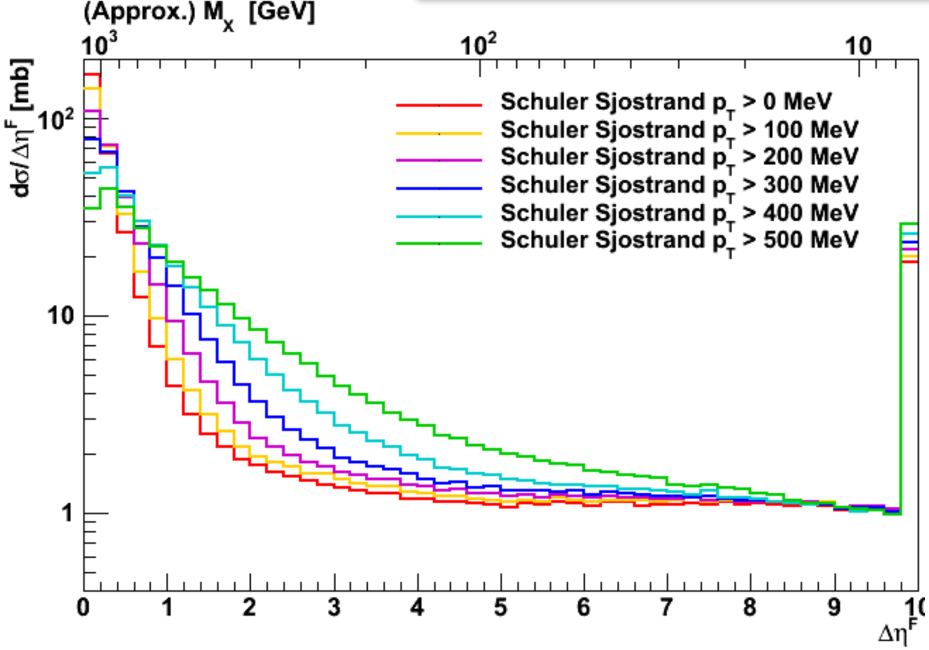


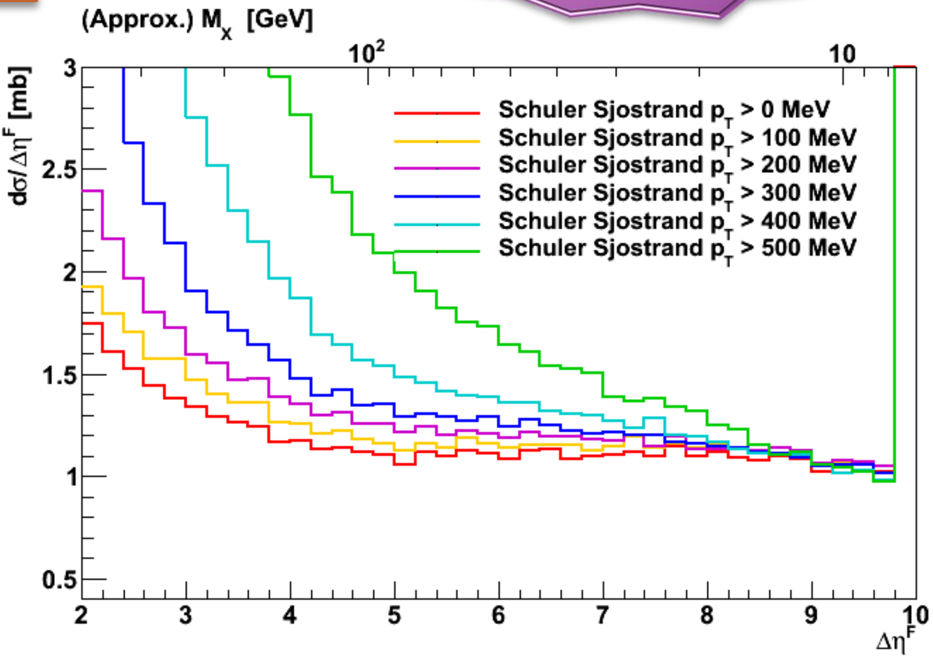
Generator Distributions – p_T Cut

- **Cross section** for **different generator** level gap size definitions.
- Only **stable ($c\tau > 10$mm) particles above cut** are used to calculate gap.
- Larger cuts **enhance** gap sizes in **Non Diffractive events**.
- Cuts can be **replicated** at the **detector** level (**for $p^T > 200$ MeV**).
- Gives **handle** on **hadronisation effects**.

Investigated Later

Pythia 8.150 Generator

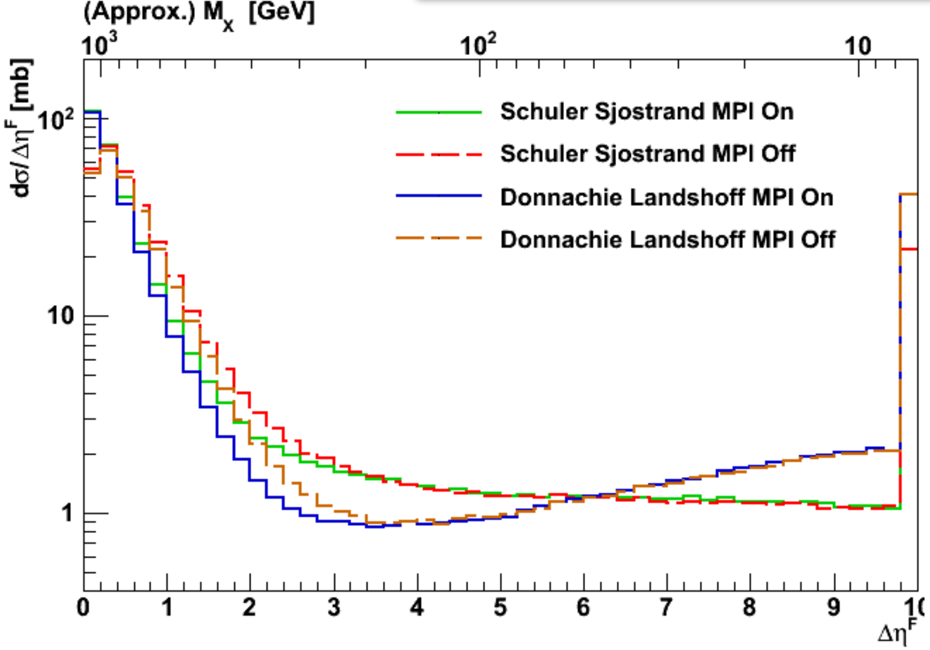


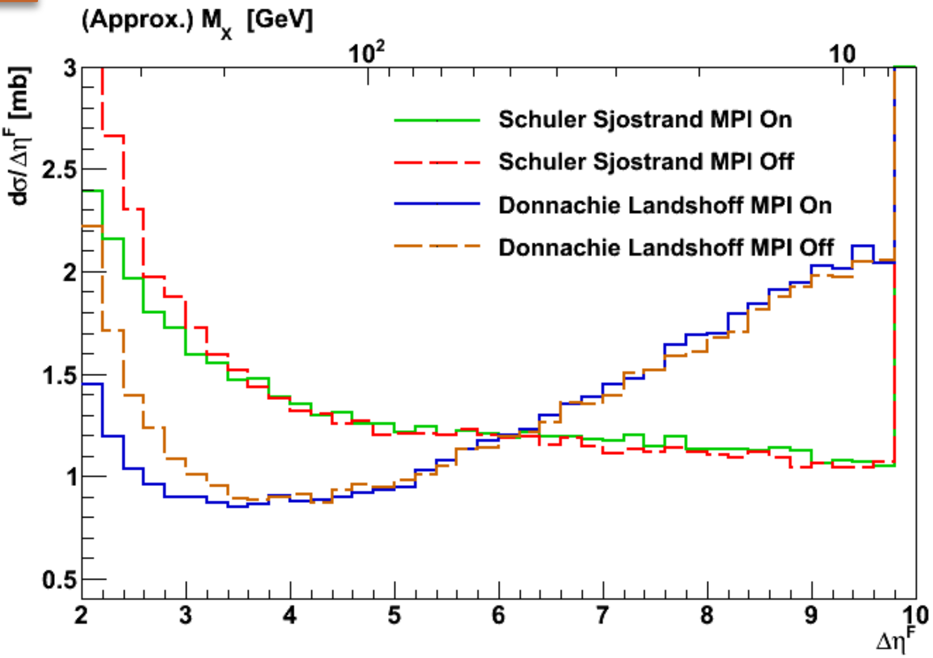


Generator Distributions - MPI

- Effect of switching **Multi Parton Interactions off**.
- **Later turn over of** distribution at **Δη gap size of 0.2**.
- **Enhancement** of gap size in **exponential fall**.
- **Little effect in diffractive plateau**, diffractive interactions tend to be **highly periphery**.

Pythia 8.150 Generator

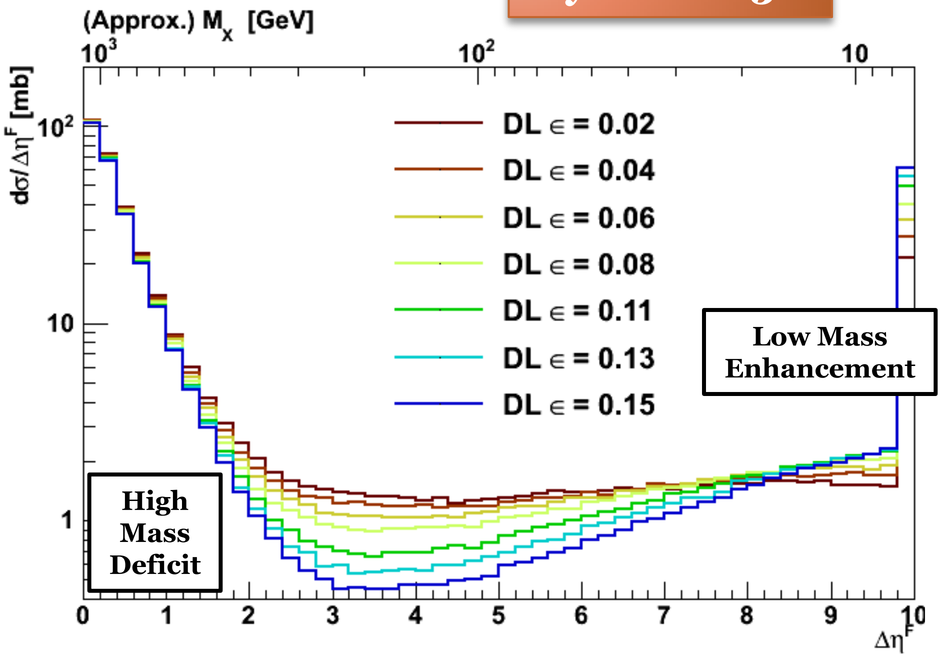




Generator Distributions - ℙ Intercept

- **Donnachie & Landshoff** parameterisation.
- Regge Trajectory: **$\alpha(t) = 1 + \varepsilon + \alpha' t$**
- Gap finding is **insensitive to the *t* slope**, but is **sensitive to the Pomeron intercept**.
- **Large supercritical Pomeron enhances low mass spectrum**.

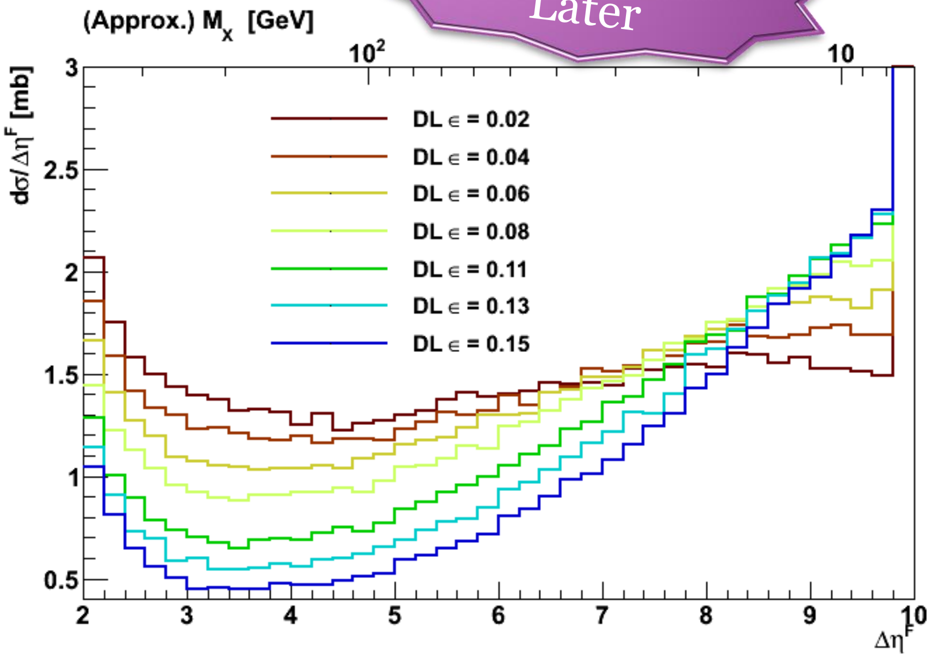
Pythia 8.150



Low Mass Enhancement

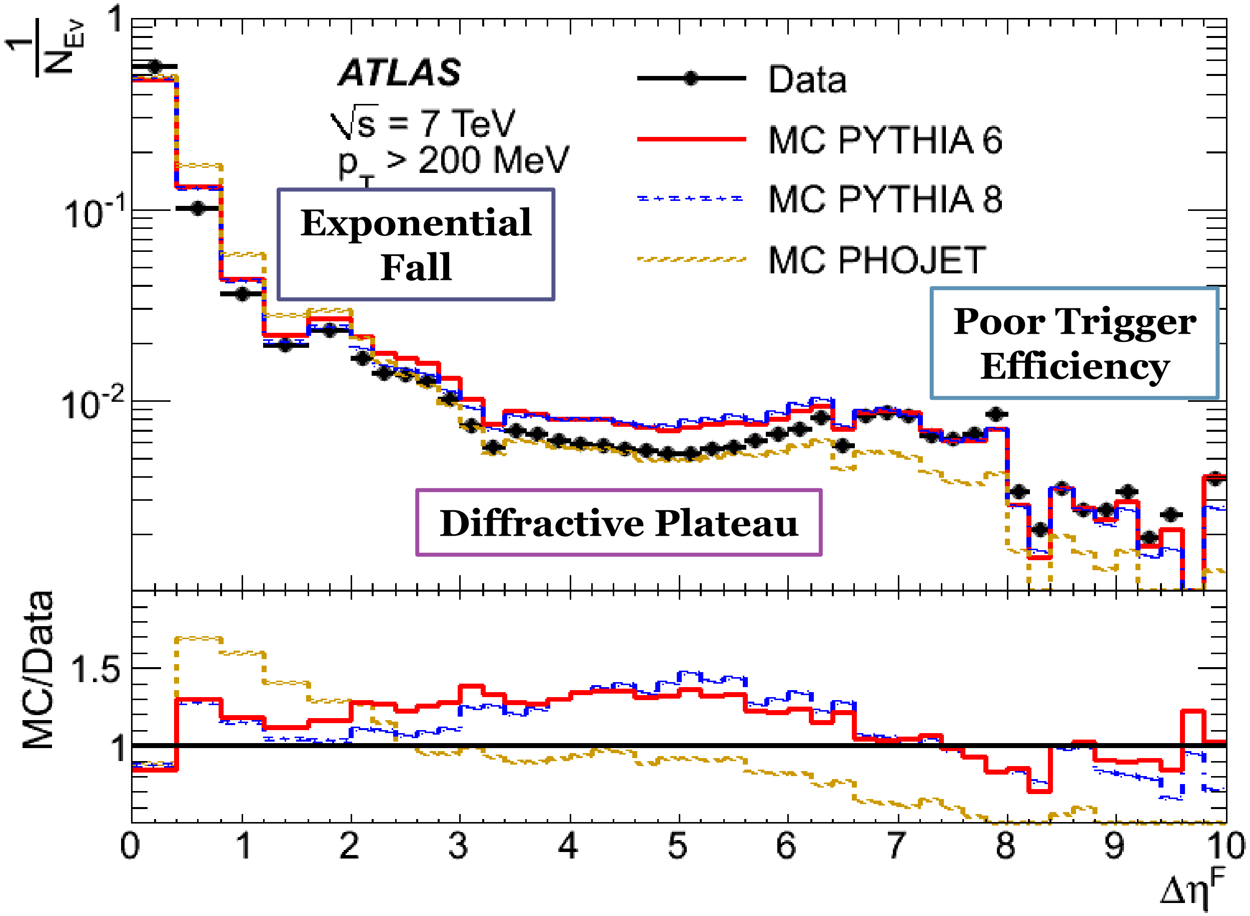
High Mass Deficit

Investigated Later



Detector Distribution

- Trigger requirement **as loose as possible**. Online we **required one hit in the MBTS**, offline we **required two hits with MC thresholds matched to the efficiency observed in data**.
- We only use unfolded data up to a **forward gap size of $\Delta\eta^F = 8$.**
- **Raw $\Delta\eta^F$ plot for data and MC at the detector level**, **including trigger requirement on MC and data**.
- **Event normalised**.



Exponential Fall

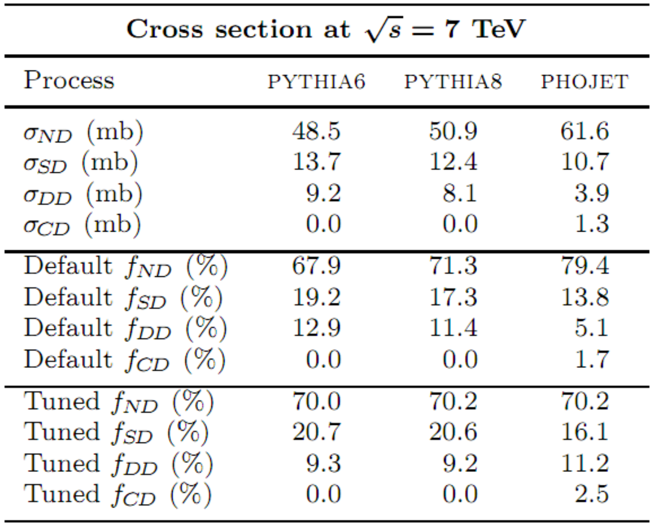
Poor Trigger Efficiency

Diffractive Plateau

Correction Method

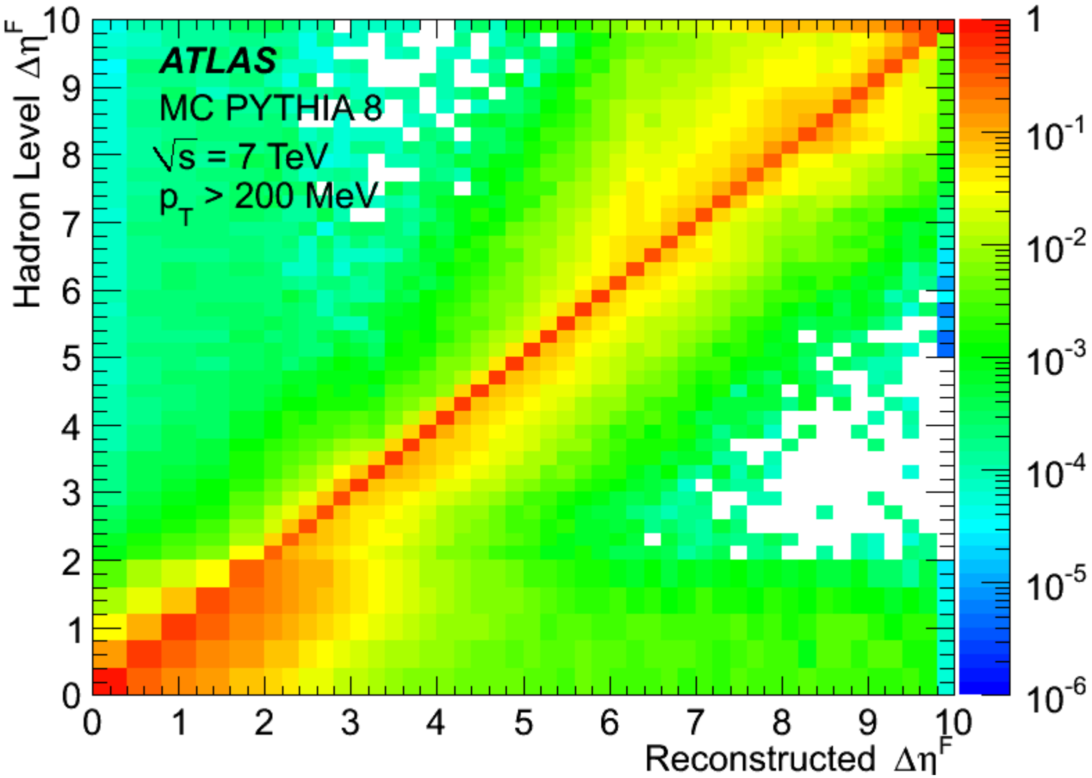
- The Raw gap size distribution is **unfolded** to remove **detector effects**.
- First we tune the **ratios in the MCs from Tevatron data**.
- Data is corrected for **trigger inefficiency** at large gap size.
- We use a single application of **D'Agostini's Bayesian unfolding** method technique to remove detector effects.
- **Thanks Ben** – big help here!

Tuned from Tevatron; ratios of cross sections don't very much with CoM in Regge.



Cross section at $\sqrt{s} = 7$ TeV

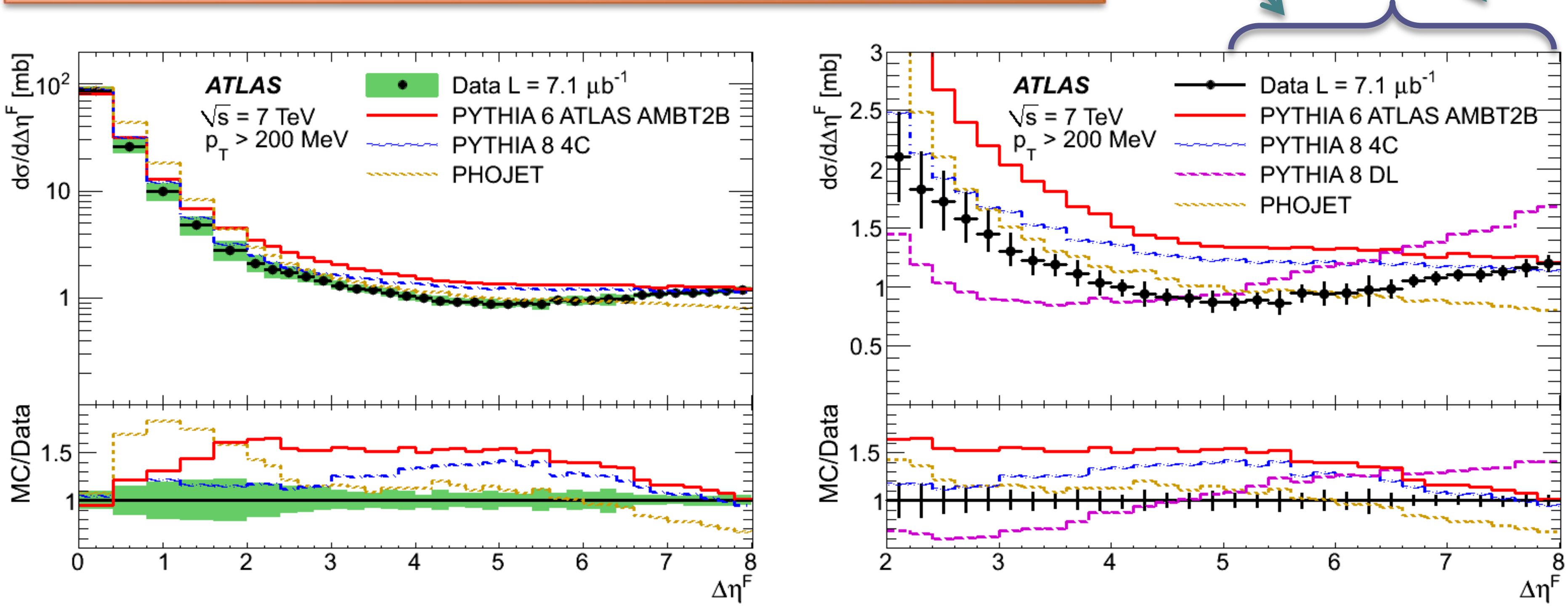
Process	PYTHIA6	PYTHIA8	PHOJET
σ_{ND} (mb)	48.5	50.9	61.6
σ_{SD} (mb)	13.7	12.4	10.7
σ_{DD} (mb)	9.2	8.1	3.9
σ_{CD} (mb)	0.0	0.0	1.3
Default f_{ND} (%)	67.9	71.3	79.4
Default f_{SD} (%)	19.2	17.3	13.8
Default f_{DD} (%)	12.9	11.4	5.1
Default f_{CD} (%)	0.0	0.0	1.7
Tuned f_{ND} (%)	70.0	70.2	70.2
Tuned f_{SD} (%)	20.7	20.6	16.1
Tuned f_{DD} (%)	9.3	9.2	11.2
Tuned f_{CD} (%)	0.0	0.0	2.5



Corrected $\Delta\eta^F$ Distribution

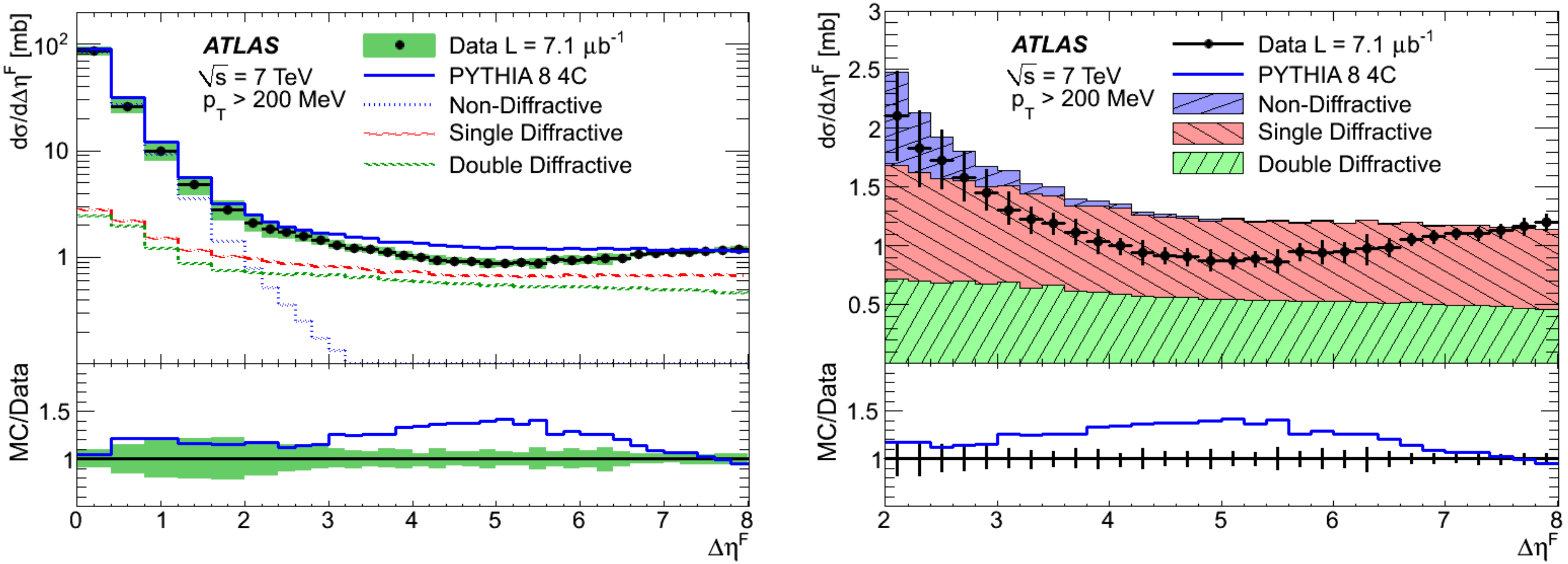
- **MC normalised** to **Default ND, DD and SD Cross section up to $\Delta\eta^F = 8$.**
- **Integrated cross section** in diffractive plateau:
  - **$5 < \Delta\eta^F < 8$** *(Approx:* $-5.1 < \log_{10}(\xi_X) < -3.1$) = **3.05 ± 0.23 mb**
  - **~4% of σ_{Inelas} (From TOTEM)**

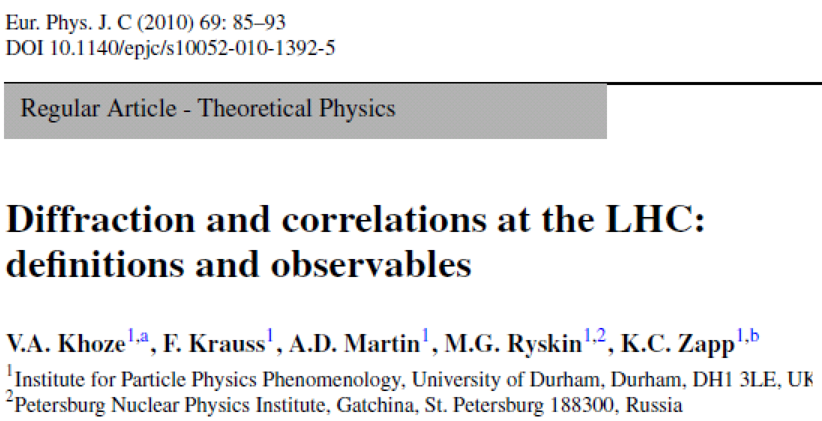
Primary Sources of Uncertainty:
Unfolding with Py6 [Final State] & Pho [Dynamics]
Energy scale systematic from π->γγ & Test Beam



$\Delta\eta^F$ Vs. Pythia 8

- **Pythia 8** split into **sub-components**.
- **Non-Diffractive contribution dominant** up to gap **size of 2, negligible for gaps larger than 3**.
- **Shape OK**, **overestimation of cross section in diffractive plateau**.
- Overestimation is **smaller than Pythi6** due to **author tune 4C** on **ATLAS data.**
- **Large Double Diffraction contribution**.





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THE EUROPEAN
PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Diffraction and correlations at the LHC: definitions and observables

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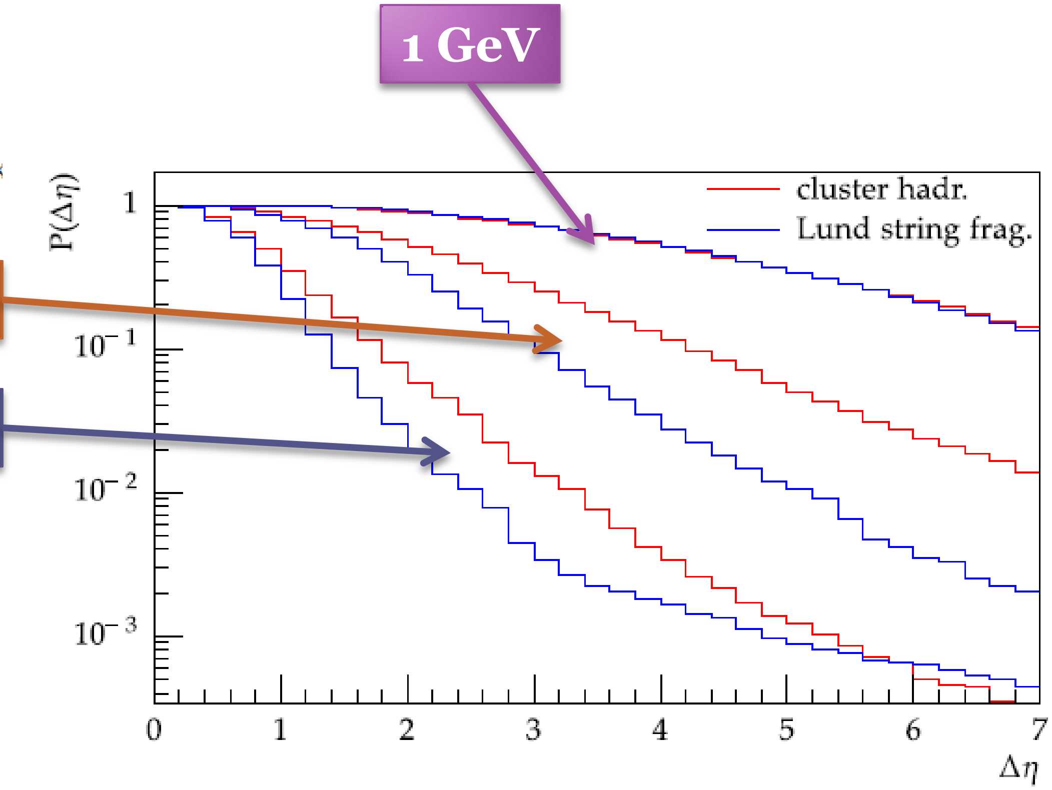
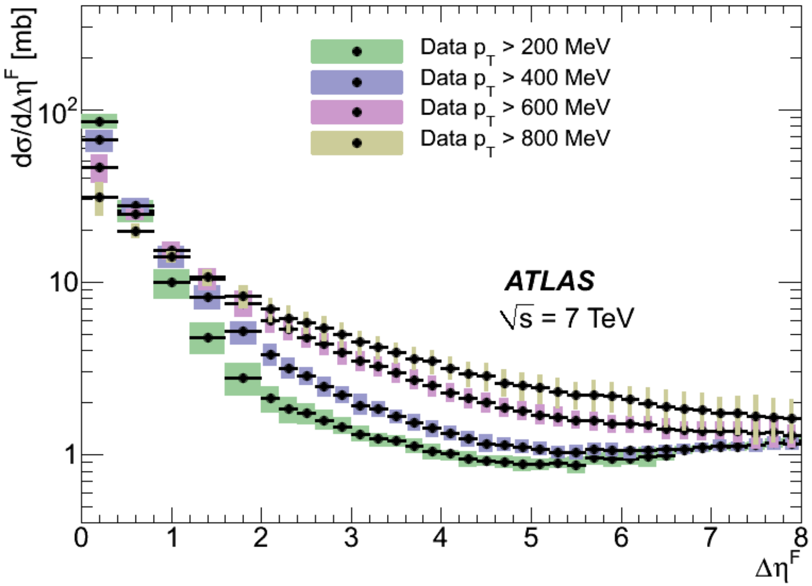
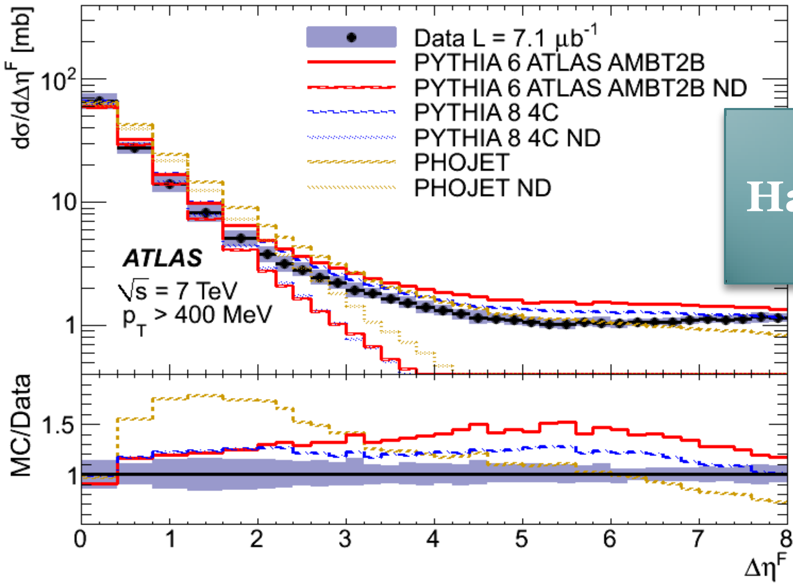


Fig. 4 Probability for finding a rapidity gap (definition 'all') larger than $\Delta\eta$ in an inclusive QCD event for different threshold $p_\perp$. From top to bottom the thresholds are $p_{\perp,\text{cut}} = 1.0, 0.5, 0.1$ GeV. Note that the lines for cluster and string hadronisation lie on top of each other for $p_{\perp,\text{cut}} = 1.0$ GeV. No trigger condition was required, $\sqrt{s} = 7$ TeV

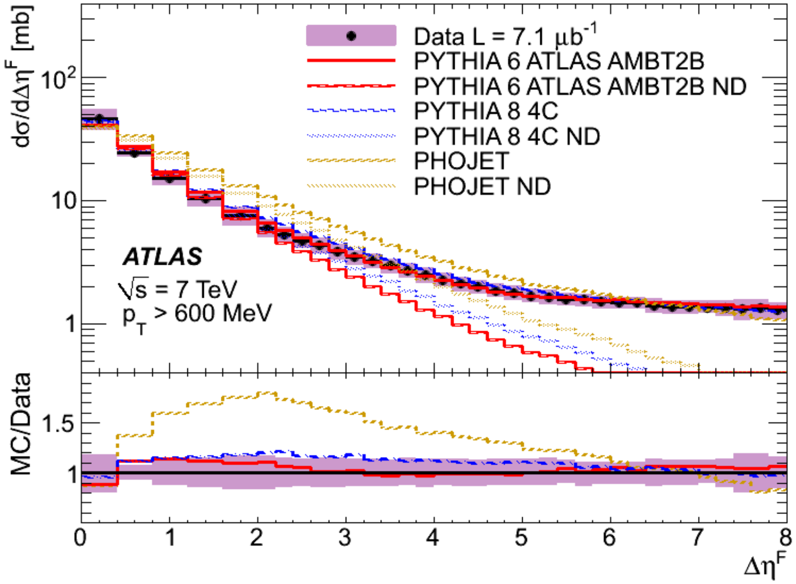
- Motivated by work from **Durham**, we **also investigate the gap spectrum as a function of the p_T cut placed on particles.**

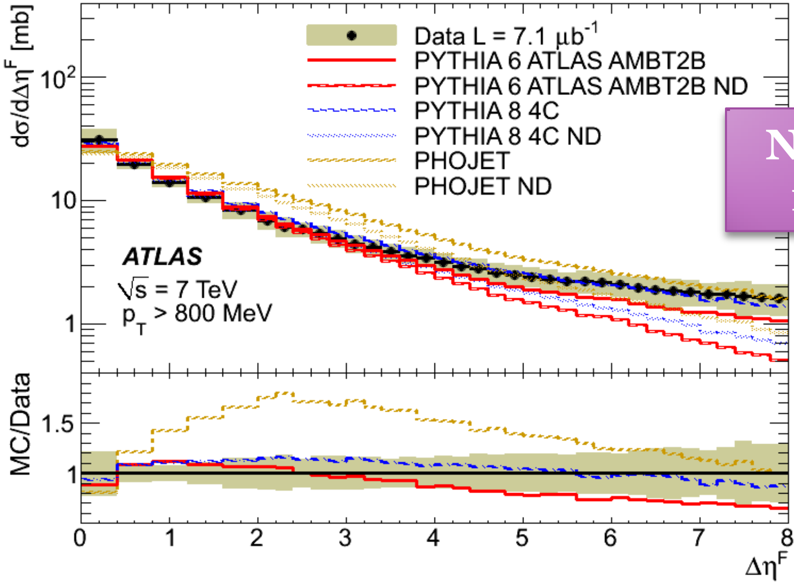
$\Delta\eta^F$ at Different p_T Cut





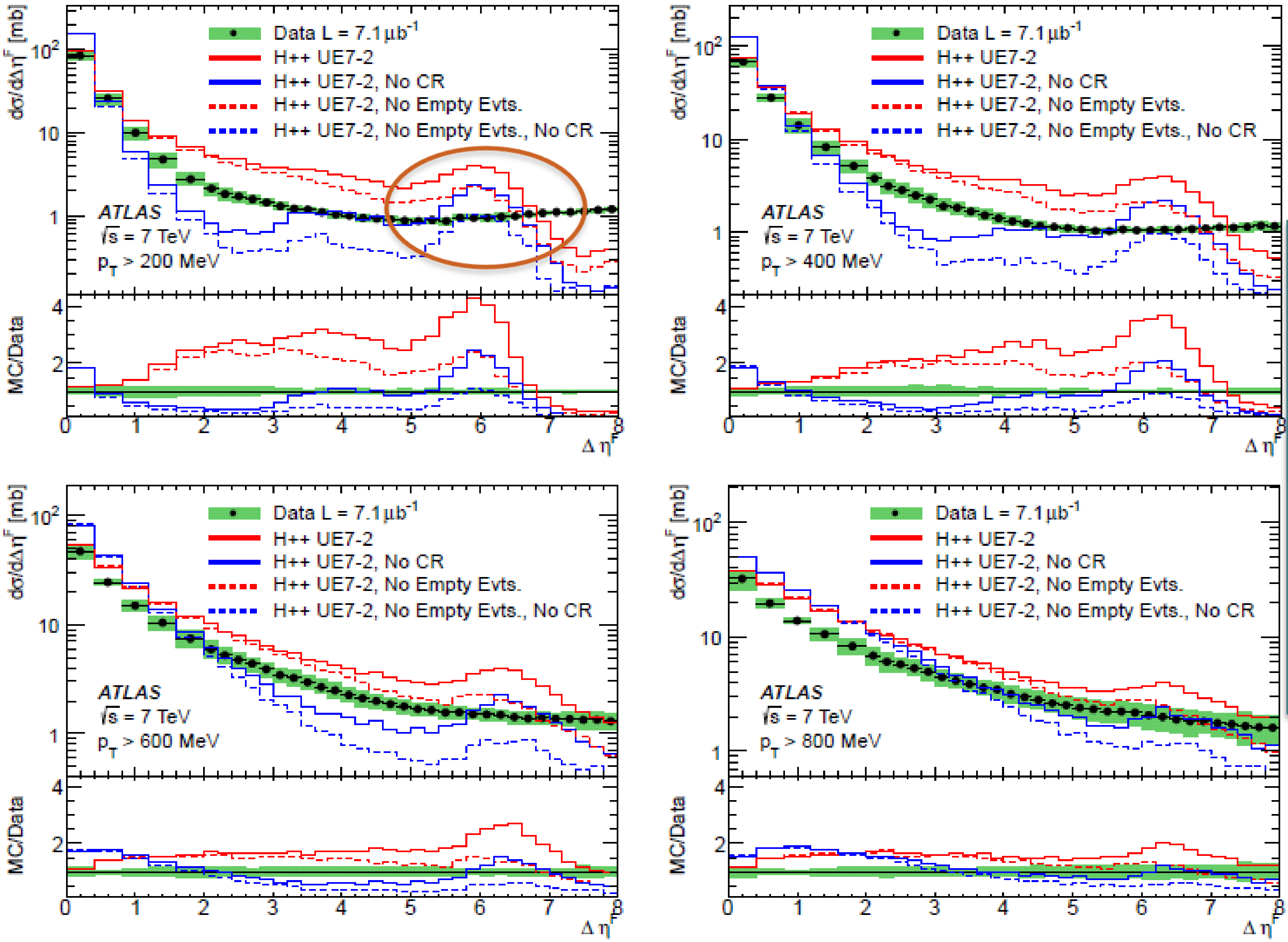
Constrain Hadronisation Models





Never before measured.

H++ at Different p_T Cut

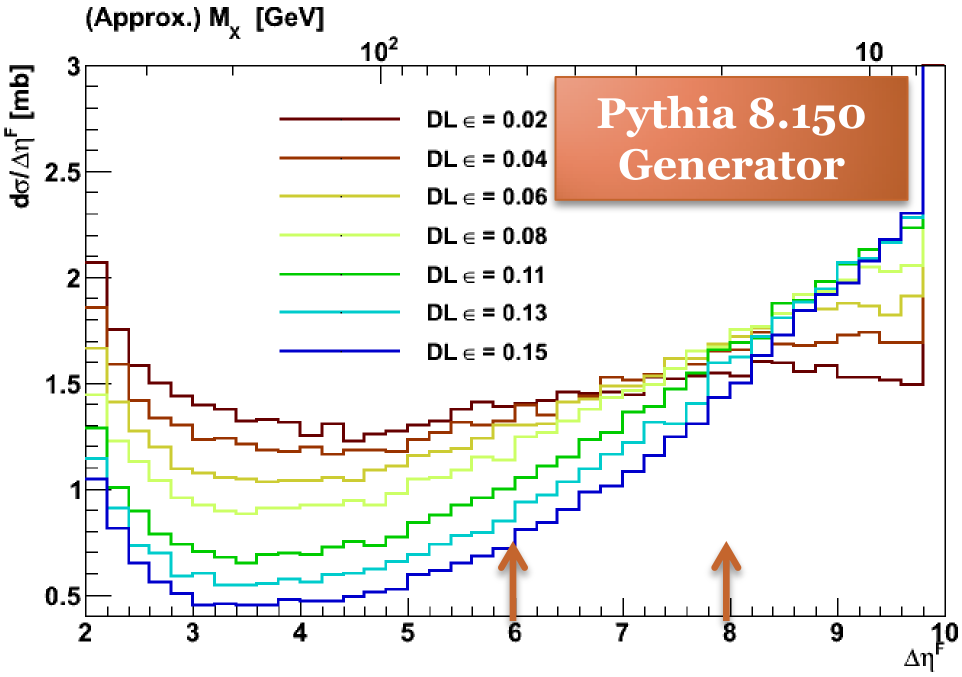


Explicitly Only Non Diffractive! But large gaps produced? Challenge for H++ authors!

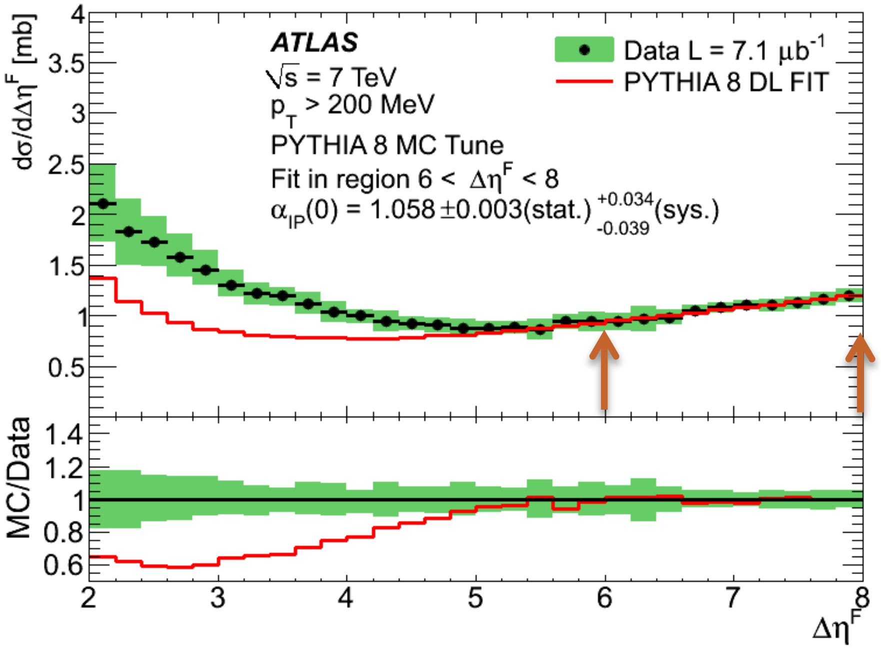
Best Fit to Data

$55 > M_X$ (GeV) > 20

- We **fit to our data in the region $6 < \Delta\eta^F < 8$** to tune **the Pomeron intercept Pythia 8** using the **Donnachie and Landshoff** (and Berger-Streng) **Pomeron** flux. **Insensitive to the non-diffractive** modelling.
- Each **correlated systematic is fitted separately** and the resultant uncertainty is **symmetrised.**
- Default : **$\alpha_{IP}(0) = 1.085$**
- Tuned: **$\alpha_{IP}(0) = 1.058 \text{ +- } 0.003 \text{ (stat.) } ^{+0.034}_{-0.039} \text{ (sys.)}$**

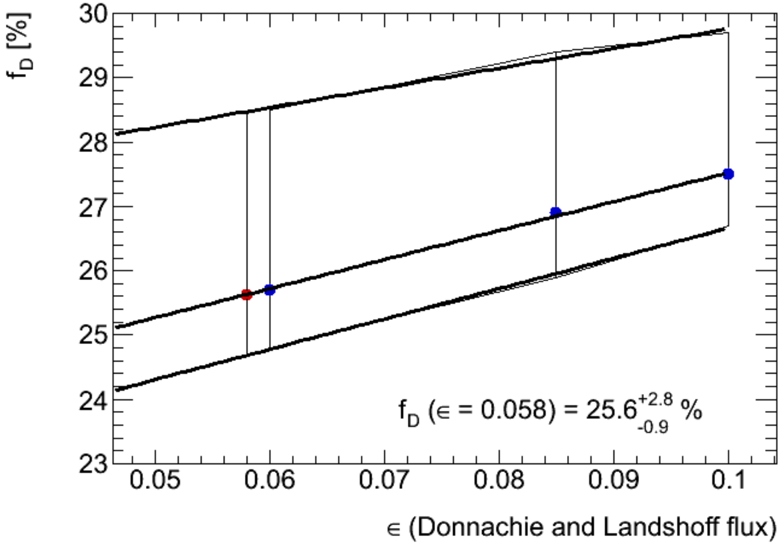


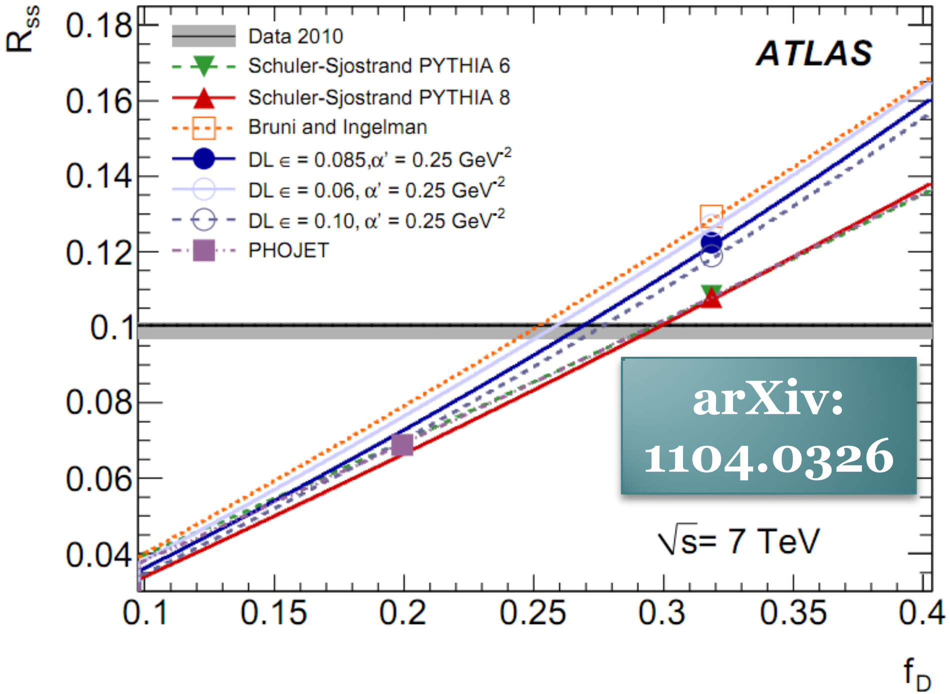
Pythia 8.150 Generator



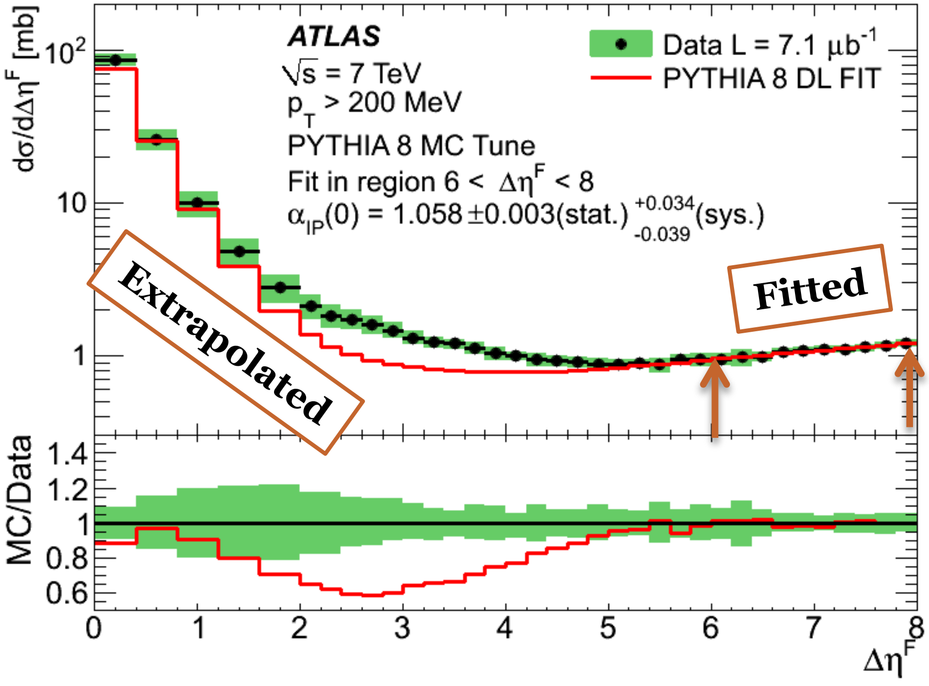
Best Fit to Data

- R_{SS} = Fraction of **exclusive single-sided** events measured in the **MBTS**.
- We take α_{IP} and the **normalisation** from the **fit region**.
- We take f_D from the inelastic cross section paper and we can then have Pythia **predict** the whole spectrum.





arXiv: 1104.0326

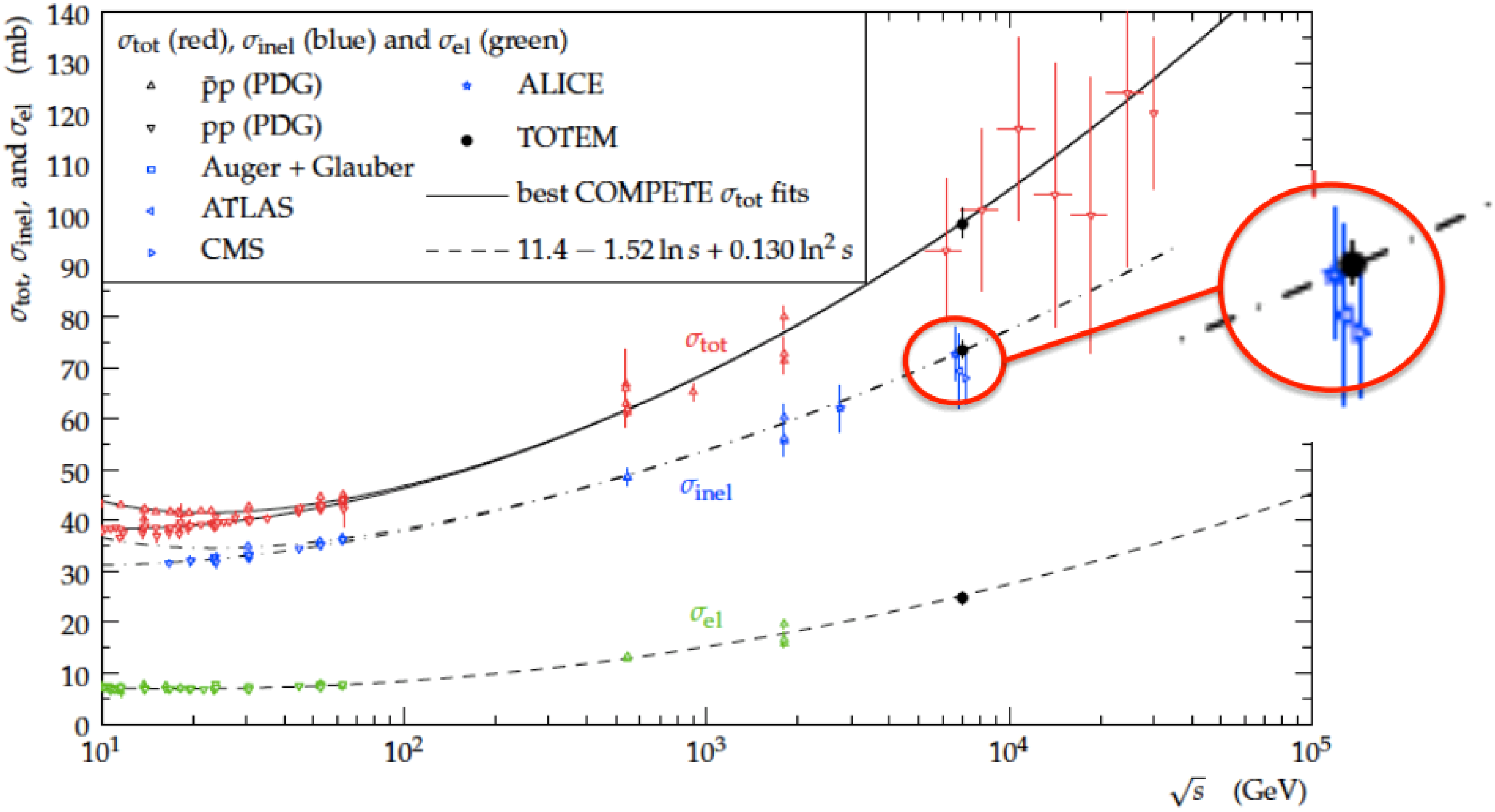


Extrapolated

Fitted

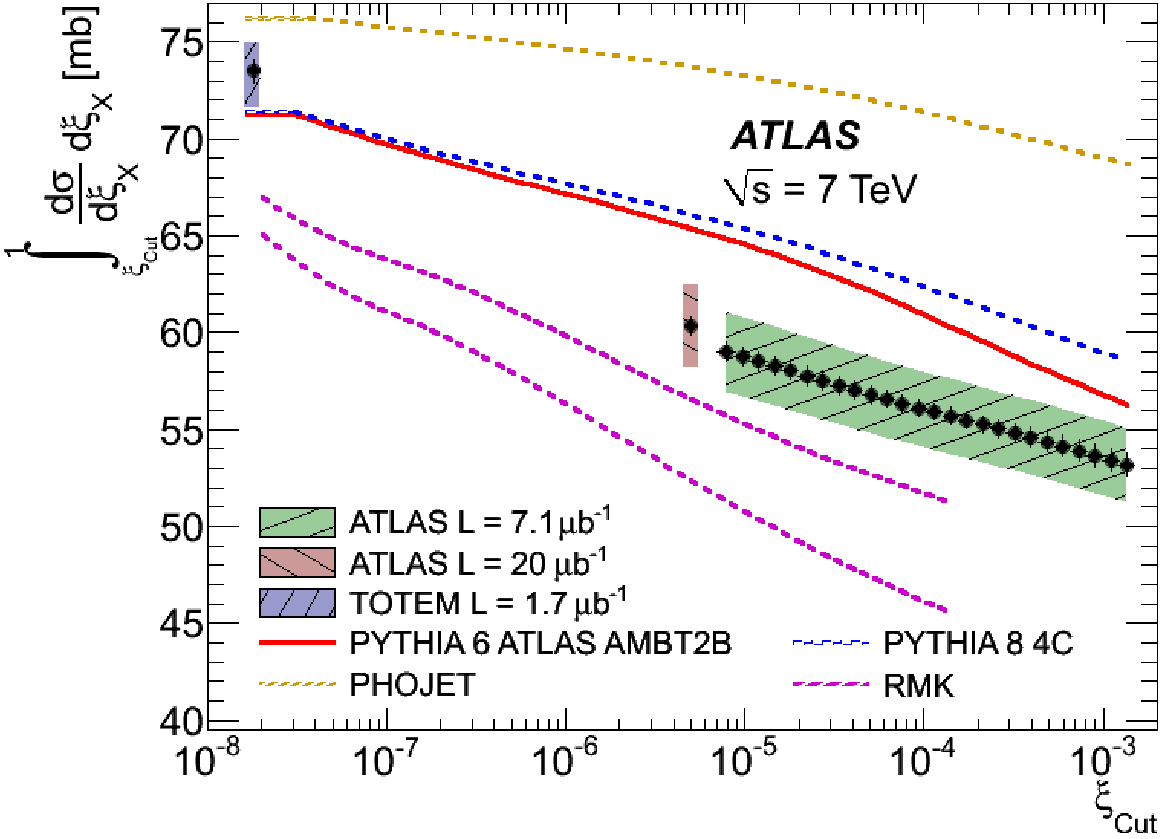
Statement on $\sigma_{\text{Inelastic}}$

- Both **ATLAS** and **CMS** measure **smaller values** for the **total inelastic cross section** than **TOTEM** (which utilises the **optical theorem** on σ_{Elastic}).
- Uncertainty is **dominated by extrapolation to low ξ** which is outside of the **detector acceptance**.



Integration of $\sigma_{\text{Inelastic}}$

- We measure the **total inelastic cross section which produces particles in the main ATALS detector**. Can **integrate** up to a cut point.
- We apply all **correlated systematics symmetrically**.
- Additional **correction** from $\Delta\eta^F$ to ξ derived from **MC**, at most **1.3±0.6%**
- **Luminosity error** dominates.
- Comparison with published **ATALS** paper good to **0.8%**, this is the measured **run-to-run lumi** error.
- Also included, **TOTEM**.
- And **Durham RMK** prediction.



Integration of c

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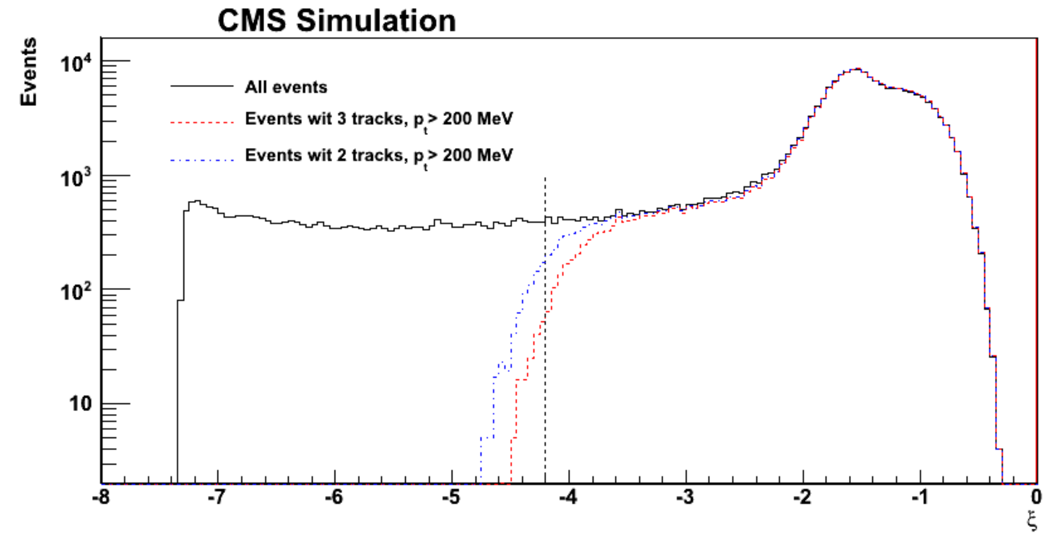
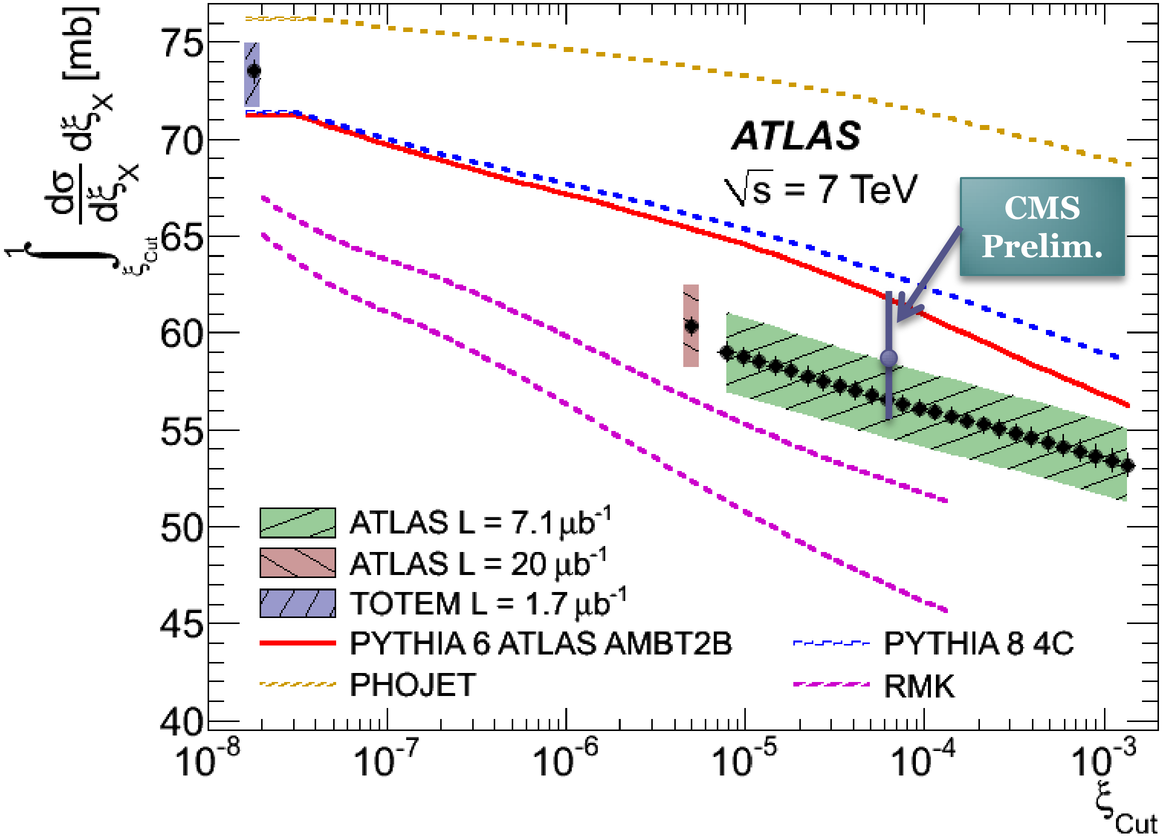
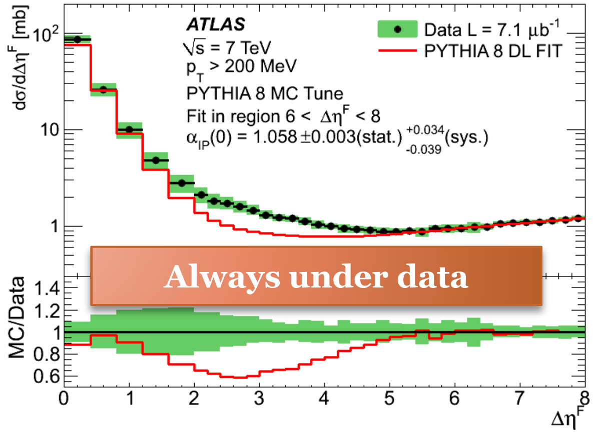




CMS Prelim.

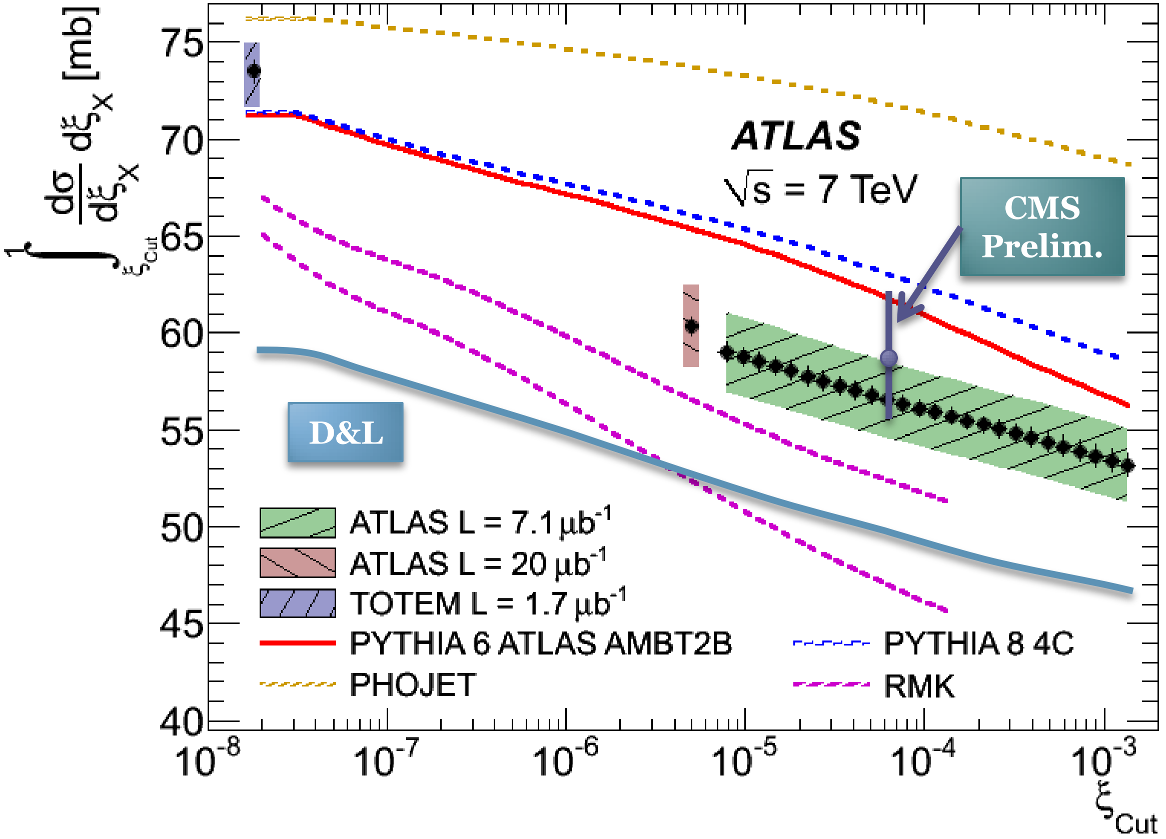
Integration of $\sigma_{\text{Inelastic}}$

- What about the **Donnachie & Landshoff flux?**
- D&L Line generated using **Pythia 8.150**
- **$\alpha(t) = 1.058 + 0.25\,t$**



Always under data

Result is **too low**, but that's understandable. The **normalisation** only came from **an extrapolation** of the fit in a very **limited phase space**.



CMS Prelim.

D&L

Integration of $\sigma_{Inelastic}$

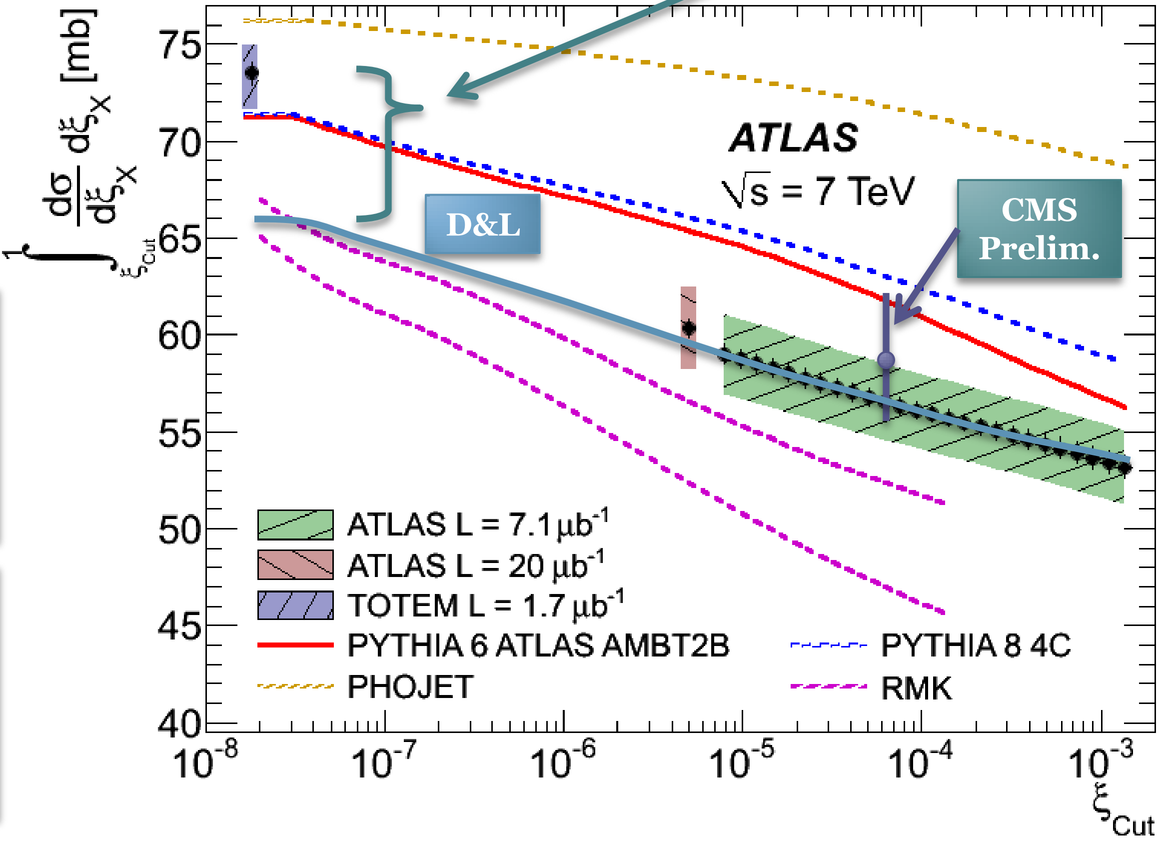
- What about the **Donnachie & Landshoff flux?**
- D&L Line generated using **Pythia 8.150**
- **$\alpha(t) = 1.058 + 0.25\,t$**

Tension of ~7 mb of low mass diffractive cross section.

Can **introduce more non-diffraction** to be in **agreement with the integrated ATLAS data.**

For **tuning purposes**, this is the **most appropriate** as it follows the **distributions observed in ATLAS.**

There is an **unresolved tension** however which the **current models can not describe**



Conclusion

- **Rapidity gaps** in **ATLAS minimum bias data** are a **sensitive probe** to the **dynamics of diffractive proton dissociation at low |t|.**

- **The data can be used to investigate and tune the current triple-Pomeron based MC models**.

- **Data corrected to a range of p_T cuts allow for the tuning of particle production by hadronisation models**.

- **Integration of the gap spectrum** allows for the **inelastic cross section to be measured down to an arbitrary cut off in ξ**. This allows **direct comparisons with other experiments** which have different geometric acceptance and highlights the **difference between the inelastic cross section measured in ATLAS with the total inelastic cross section as measured by TOTEM**.