Charged particle production in p+Pb collisions with the ATLAS detector

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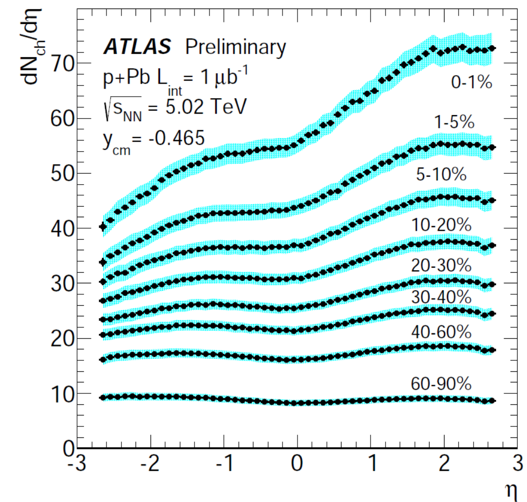
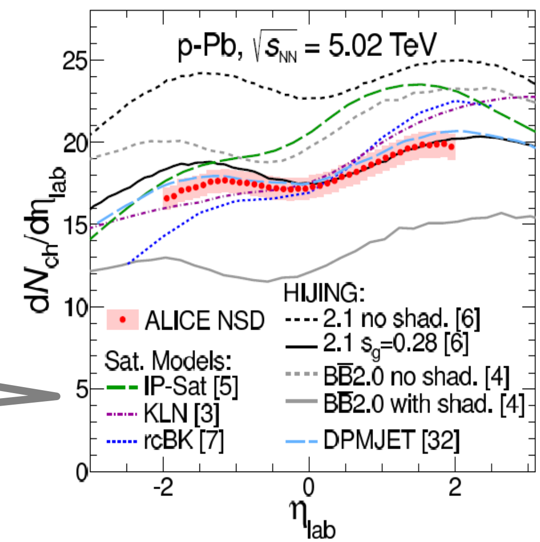
Physics motivation

- Deviations from simple geometrical expectations due to
  - Shadowing (suppression of yields at small p_T)
    - modifications of nuclear PDFs
    - parton saturation at low-x (CGC)
  - Cronin effect (enhancement at intermediate p_T)
    - k_T broadening due to multiple scattering
  - Possible energy loss in “cold nuclear matter”

- Baseline to understand the role of the nuclear environment in modifying hard scattering rates.



clear discriminative power



Observables

- Charged particle R_{pPb}

$$R_{\mathrm{pPb}}(p_{\mathrm{T}}, y) = \frac{1}{\langle T_{\mathrm{Pb}} \rangle} \frac{1/N_{\mathrm{evt}}\, \mathrm{d}^2 \mathrm{N}_{p+\mathrm{Pb}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}^2\sigma_{pp}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}}$$

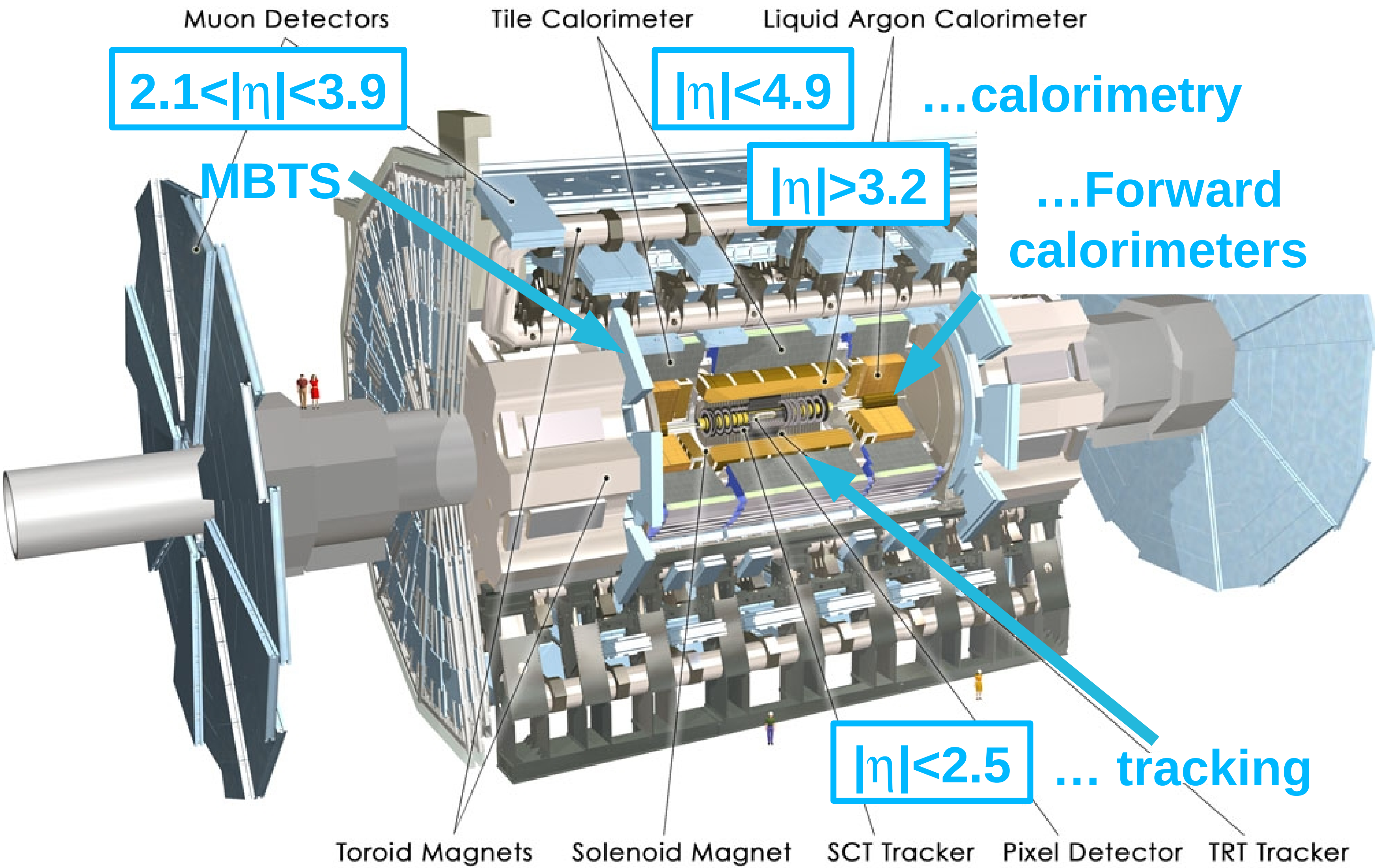
- Charged particle R_{CP}

$$R_{\mathrm{CP}}(p_{\mathrm{T}}, \eta) = \frac{\langle T_{\mathrm{Pb,P}} \rangle}{\langle T_{\mathrm{Pb,C}} \rangle} \frac{(1/N_{\mathrm{evt,C}})\mathrm{d}^2 N_{p+\mathrm{Pb,C}}/\mathrm{d}\eta\mathrm{d}p_{\mathrm{T}}}{(1/N_{\mathrm{evt,P}})\mathrm{d}^2 N_{p+\mathrm{Pb,P}}/\mathrm{d}\eta\mathrm{d}p_{\mathrm{T}}}$$

- Charged particle pseudorapidity distributions

$dN_{ch}/d\eta$ $\quad\quad$ $(dN_{ch}/d\eta|_{cent.}) / (dN_{ch}/d\eta|_{60\text{-}90\%})$

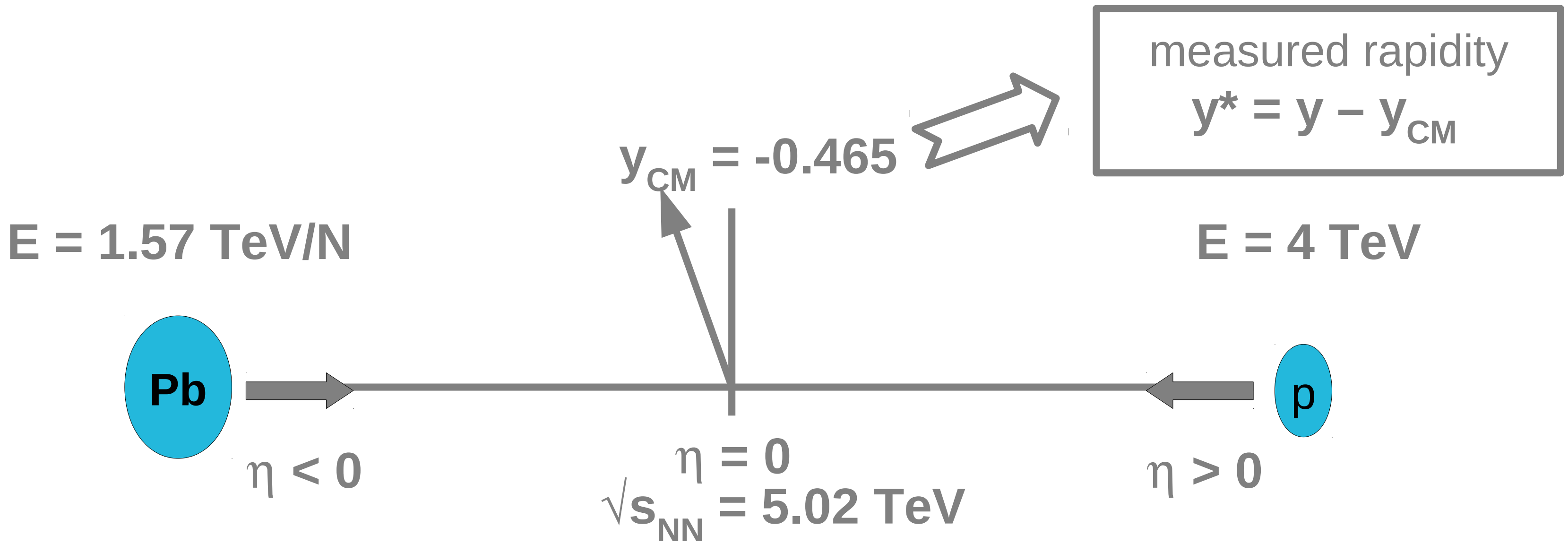
ATLAS Detector



Input data

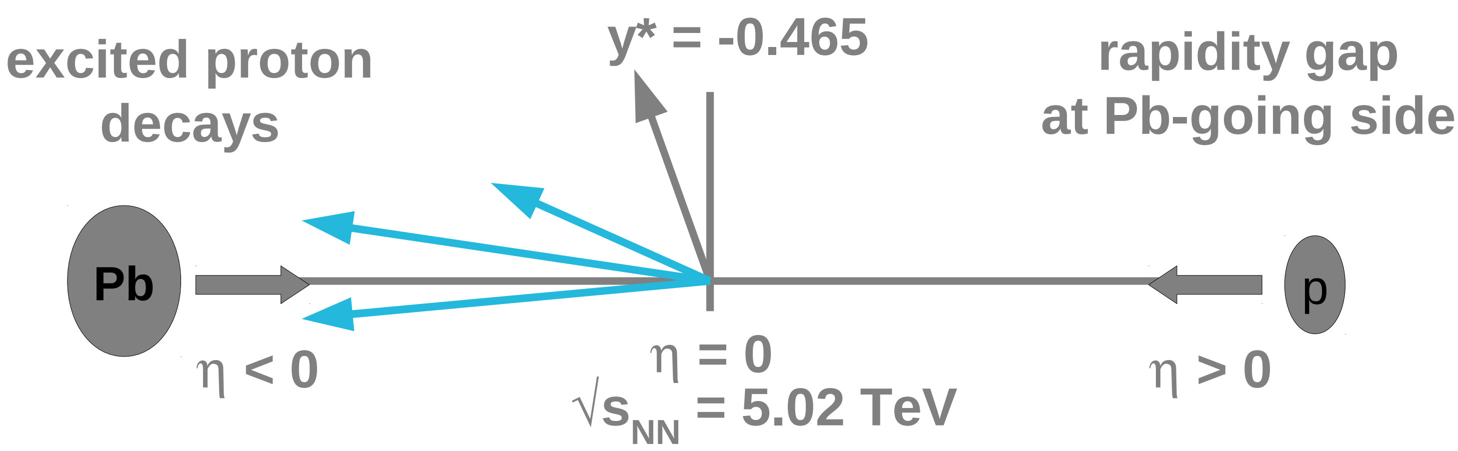
- 1 μb^{-1} of **5.02 TeV p+Pb** Minimum Bias events (~ 2.1 x 10^6 events after cleaning) collected during September 2012
- 188 μb^{-1} **7 TeV pp** Minimum Bias events collected during April 2010
- 202 nb^{-1} **2.76 TeV pp** Minimum Bias events collected during March 2011

Interpolation of pp data to get 5.02 TeV reference



Event selection

- Events selected using the Minimum Bias Trigger Scintilators (MBTS).
- Pile-up of ~10^{-3} reduced 10^{-4} by rejecting events with two or more good vertices.
- Diffractive and electromagentic excitations of proton rejected:
  - rapidity gap analysis (similar to EPJ C72 (2012) 1926)
  - rapidity interval starting from $\eta_{Pb\text{-}edge}$ = 4.9 divided into clusters in $\Delta\eta$ = 0.2
  - occupied cluster = cluster with p_T > 200 MeV
  - events with $\Delta\eta_{gap} = |\eta_{Pb\text{-}edge} - \eta_{cluster}| > 2$ rejected
- Total 2.1 M events = 98% ± 2% of inelastic events.



Centrality and $\langle T_{Pb} \rangle$

- Centrality determination
  - Total transverse energy in Pb-going using forward calorimeters (eta < -3.2)
  - Eight centrality bins: 0-1%, 1-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-60%, 60-90%.

- $\langle T_{Pb} \rangle$ determined using Glauber and Glauber+Gribov model
  - Glauber:
    - fixed σ_{NN} (σ_{NN}= 70 $\pm$ 5 mb)
    - ☹ incoming proton is off-shell between successive interactions!
  - Glauber+Gribov model:
    - allows for event-by-event fluctuations in σ_{NN} , $\langle \sigma_{NN} \rangle$ = 70 $\pm$ 5 mb
    - fluctuations quantified using parameter Ω
    - two choices for Ω (Ω=0.55, Ω=1.01) based on extraction from experimental data (see PLB 633 (2006) 245 and PLB 722 (2013) 347)
  - Glauber and Glauber+Gribov model can reproduce the measured centrality distribution => determination of $\langle T_{Pb} \rangle$ or $\langle N_{part} \rangle = \langle T_{Pb} \rangle * \sigma_{NN} + 1$

Example of $\langle T_{Pb} \rangle$

$\langle T_{Pb} \rangle$ [b^{-1}]

Centrality	Glauber	Glauber-Gribov $\Omega = 0.55$	Glauber-Gribov $\Omega = 1.01$
60-90%	$42.3^{+2.8}_{-4}$ $\left(^{+7\%}_{-10\%}\right)$	$36.6^{+2.7}_{-2.2}$ $\left(^{+7\%}_{-6\%}\right)$	$34.4^{+4}_{-2.1}$ $\left(^{+11\%}_{-6\%}\right)$
0-1%	245^{+37}_{-7} $\left(^{+15\%}_{-2.7\%}\right)$	330^{+15}_{-23} $\left(^{+5\%}_{-7\%}\right)$	377^{+12}_{-60} $\left(^{+3.2\%}_{-16\%}\right)$
0-90%	$106.3^{+4}_{-2.7}$ $\left(^{+4\%}_{-2.5\%}\right)$	$107.3^{+4}_{-2.6}$ $\left(^{+4\%}_{-2.4\%}\right)$	$108.5^{+4}_{-2.4}$ $\left(^{+4\%}_{-2.2\%}\right)$

$$\frac{\langle T_{Pb} \rangle_{cent}}{\langle T_{Pb} \rangle_{60\text{-}90}}$$

Centrality	Glauber	Glauber-Gribov $\Omega = 0.55$	Glauber-Gribov $\Omega = 1.01$
40-60% / 60-90%	$2.16^{+0.09}_{-0.06}$ $\left(^{+4\%}_{-3\%}\right)$	$2.19^{+0.04}_{-0.06}$ $\left(^{+2.6\%}_{-2.7\%}\right)$	$2.21^{+0.05}_{-0.06}$ $\left(^{+2.4\%}_{-2.8\%}\right)$
0-1% / 60-90%	$5.80^{+1.3}_{-0.33}$ $\left(^{+23\%}_{-6\%}\right)$	$9.0^{+0.5}_{-1.1}$ $\left(^{+6\%}_{-12\%}\right)$	$11.0^{+0.6}_{-2.6}$ $\left(^{+5\%}_{-23\%}\right)$

Uncertainties:

- central collisions: model + pp cross-section
- peripheral collisions: model + pp cross-section + event selection

Corrections

$$\frac{1}{2\pi p_{\mathrm{T}}}\frac{dN_{\mathrm{ch}}}{dp_{\mathrm{T}}d\eta} = \frac{1}{2\pi p_{\mathrm{T}} N_{\mathrm{evt}}\Delta\eta}\frac{N_{ch}(p_{\mathrm{T}},\eta)}{\Delta p_{\mathrm{T}}}\boxed{\frac{\mathcal{P}(p_{\mathrm{T}},\eta)}{\epsilon_{trk}(p_{\mathrm{T}},\eta)}}$$

$$\frac{1}{2\pi p_{\mathrm{T}}}\frac{dN_{\mathrm{ch}}}{dp_{\mathrm{T}}dy^{\star}} = \frac{1}{2\pi p_{\mathrm{T}} N_{\mathrm{evt}}\Delta y^{\star}_{\pi}}\frac{N_{ch}(p_{\mathrm{T}},y^{\star}_{\pi})}{\Delta p_{\mathrm{T}}}\boxed{\frac{\mathcal{P}(p_{\mathrm{T}},y^{\star}_{\pi})\mathcal{A}(p_{\mathrm{T}},y^{\star}_{\pi})}{\epsilon_{trk}(p_{\mathrm{T}},y^{\star}_{\pi})}}$$

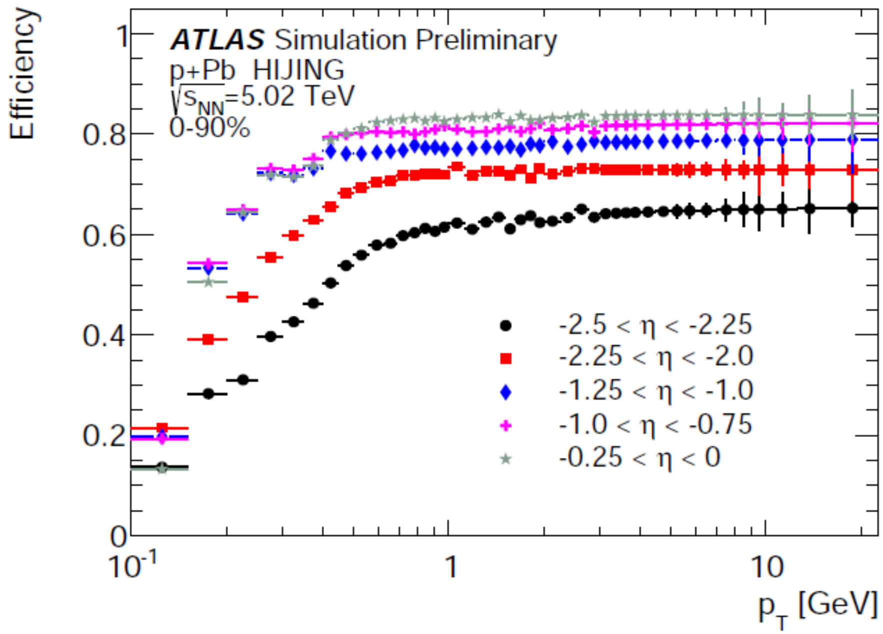
$\epsilon_{\mathrm{trk}}(p_{\mathrm{T}},y^{\star}_{\pi})$ … tracking efficiency

$\mathcal{P}(p_{\mathrm{T}},y^{\star}_{\pi})$ … purity (to remove fakes and residual secondary tracks)

$\mathcal{A}(p_{\mathrm{T}},y^{\star}_{\pi})$ … to correct $N(y^*_{\pi})$ to $N(y^*)$ since $\eta \to y^*_{\pi}$ (no particle ID)

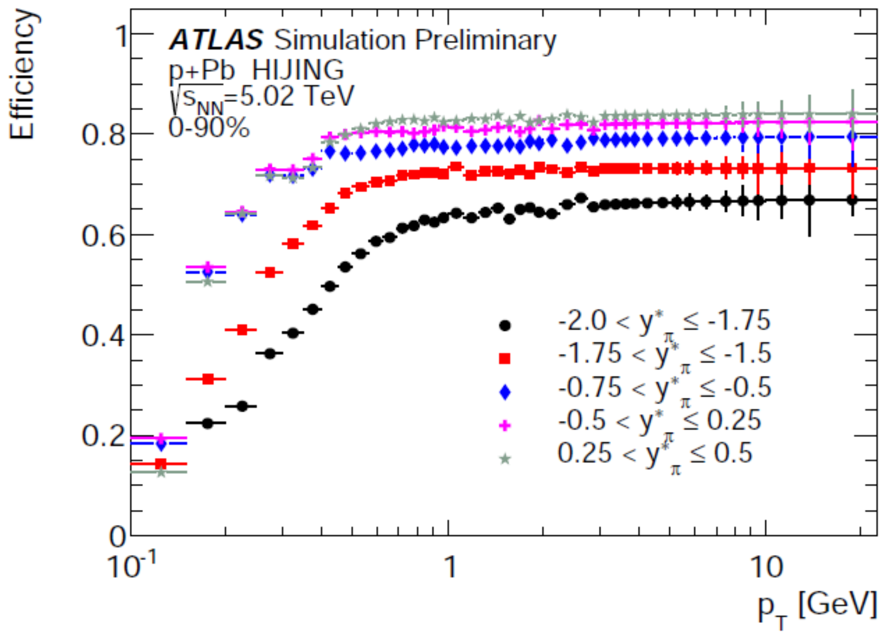
Tracking efficiency

... in η



$$\epsilon_{\rm trk}(p_{\rm T},\eta) = \frac{N^{Rec}_{Primary}(p^{Rec}_{\rm T},\eta)}{N^{Gen}(p^{Gen}_{\rm T},\eta)}$$

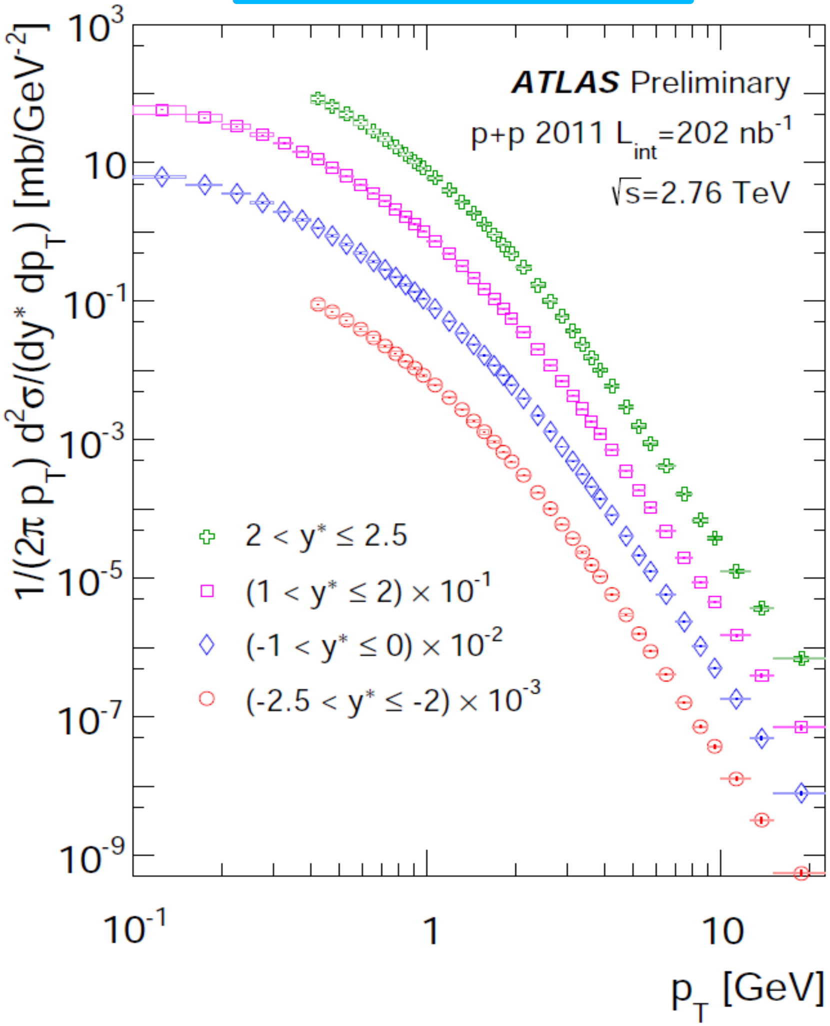
... in y*



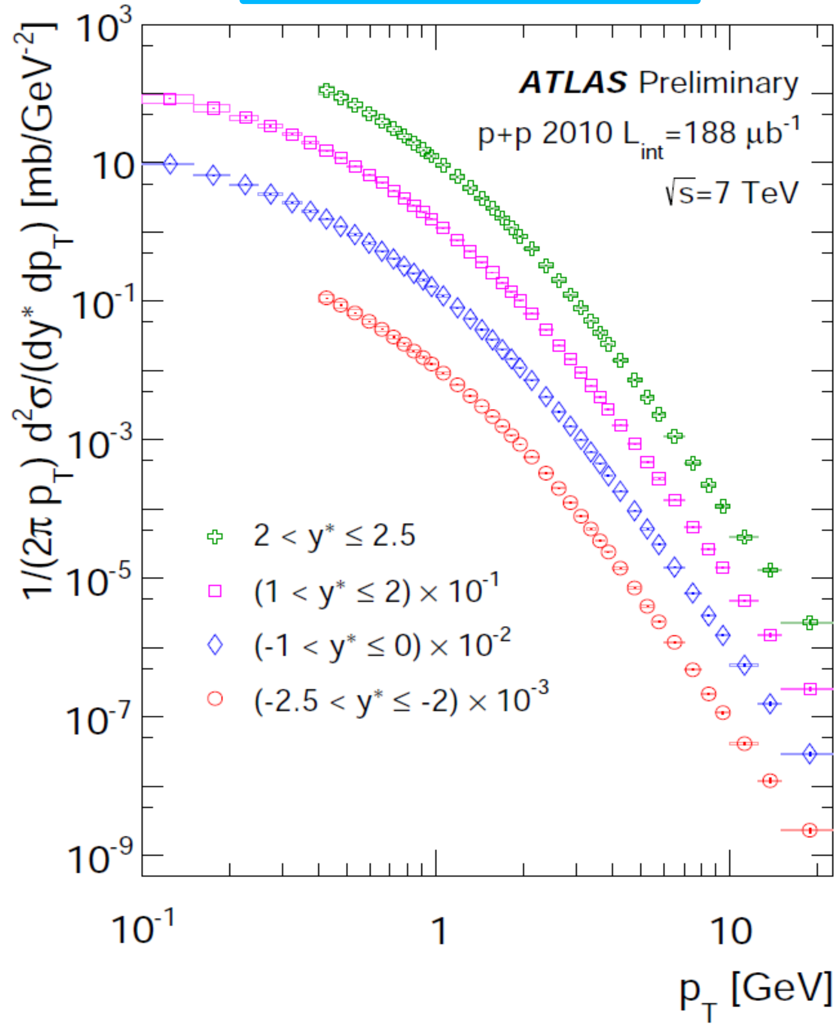
$$\epsilon_{\rm trk}(p_{\rm T},y^\star_\pi) = \frac{N^{Rec}_{Primary}(p^{Rec}_{\rm T},y^\star_\pi)}{N^{Gen}(p^{Gen}_{\rm T},y^\star_\pi)}$$

Reference spectra from pp collisions

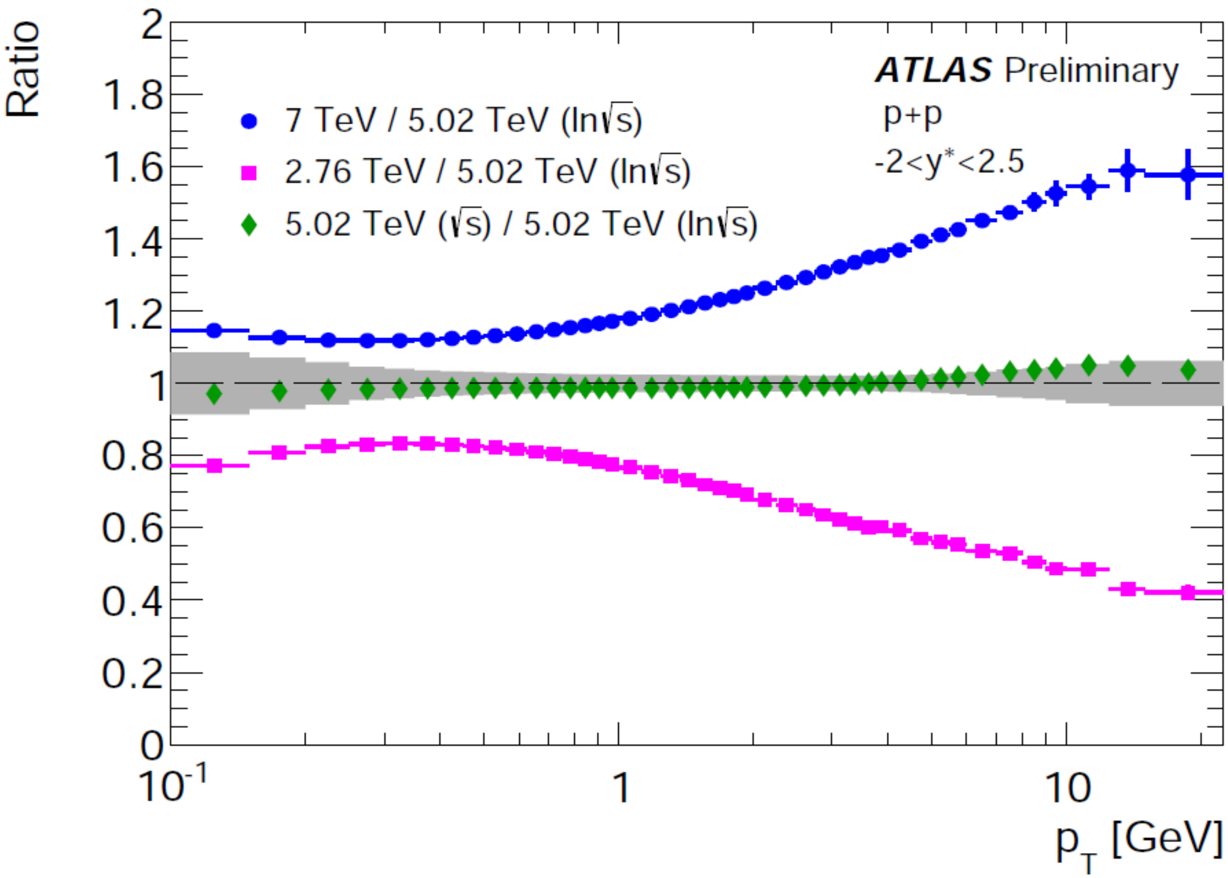
pp@2.76 TeV



pp@7 TeV



Reference spectra from pp collisions



measured @ 7 TeV / interpolated

interpolated using ln(√s) / interpolated using √s

measured @ 2.76 / interpolated

… pp reference at √s = 5.02 TeV does not exists => existing pp measurements at 7 TeV and 2.76 TeV interpolated using linear and logarithmic dependence on √s

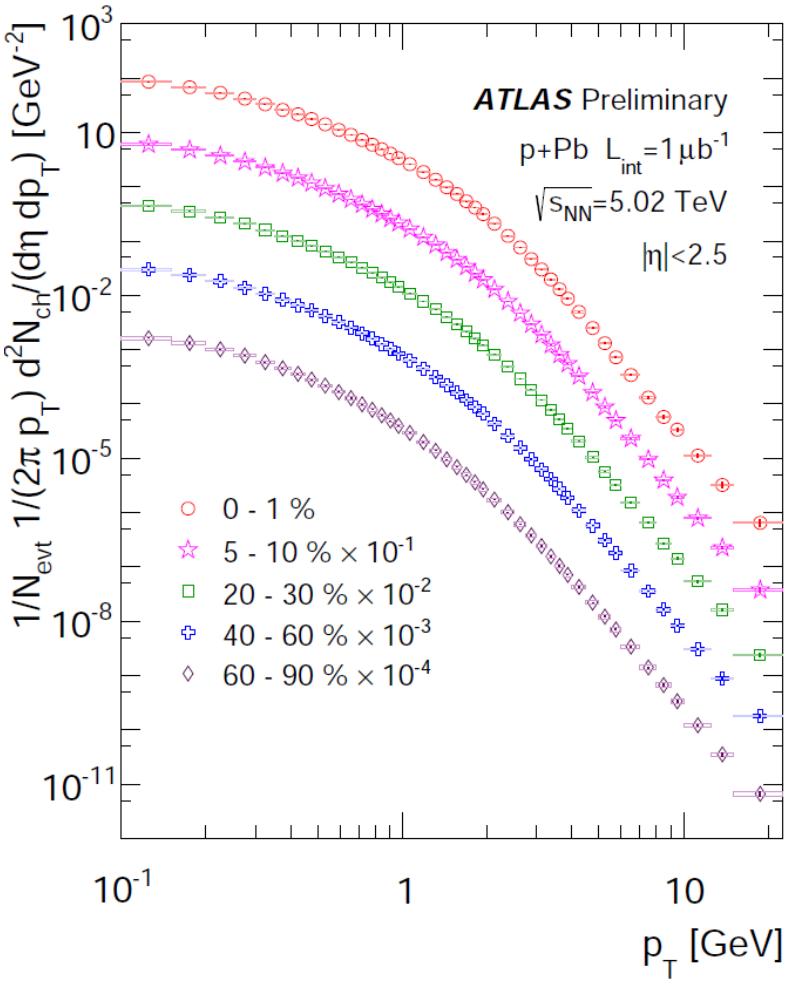
Systematic uncertainties for R_{pPb} and R_{CP} measurement

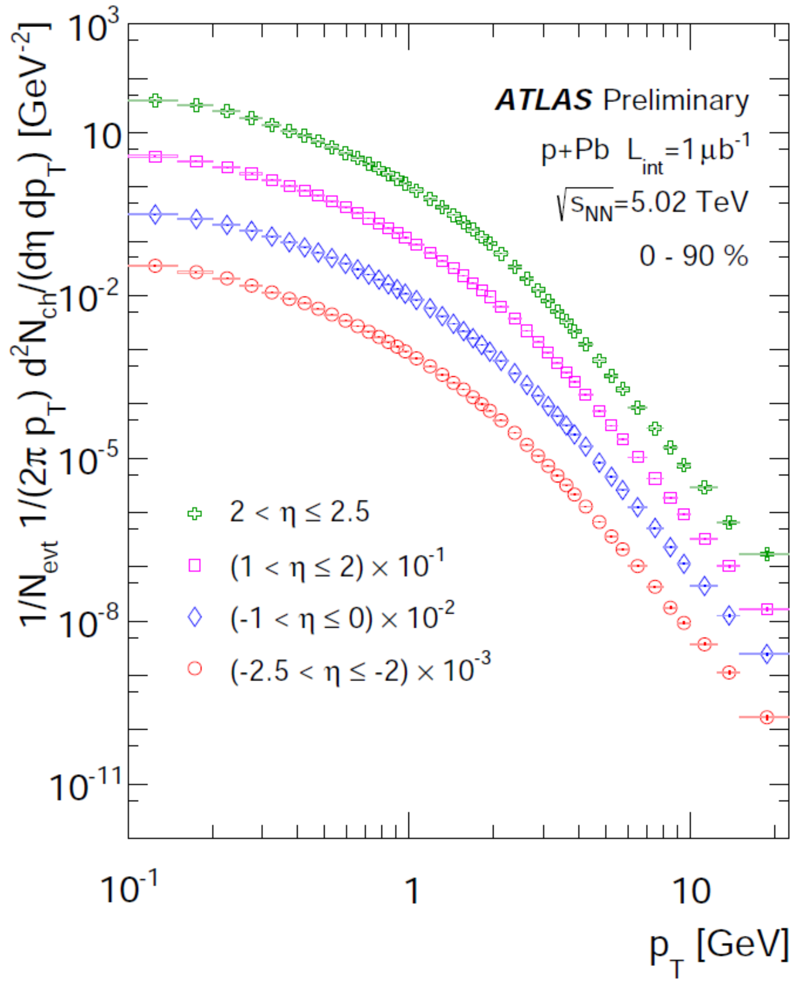
Uncertainty	p+Pb	pp
Track selection	1%	1%
Particle composition	1-6%	2%
Material budget	1-7%	
p_T reweighting	1%	
Rapidity transformation	0-8%	
Centrality selection	1-6%	n/a
Trigger Efficiency	n/a	0.5%
Luminosity	n/a	2.7% (2%)
$\sqrt{s}$ interpolation	n/a	3-9%
Vertex reconstruction	n/a	1%

+

Uncertainties on $\langle T_{Pb} \rangle$

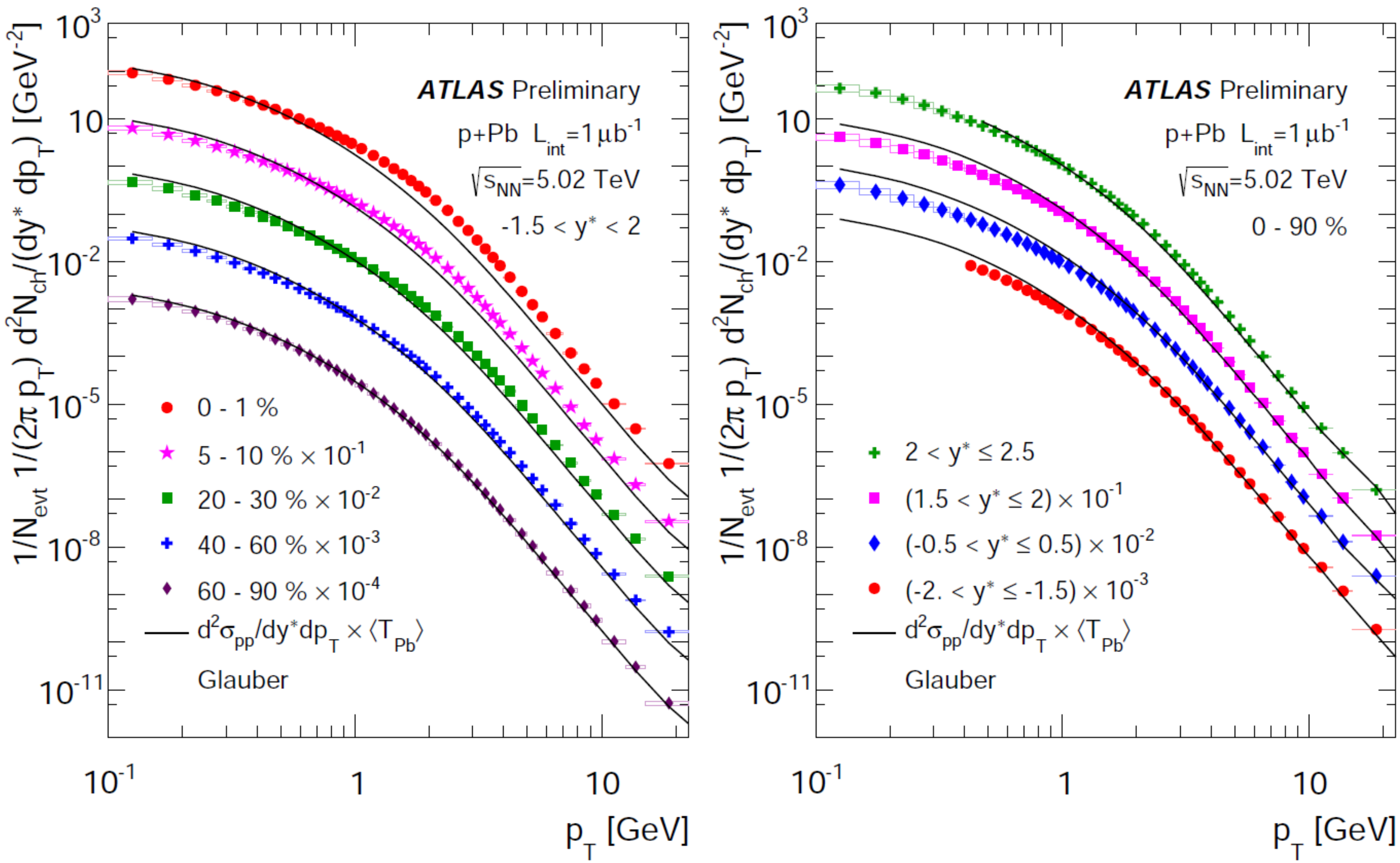
Spectra in η





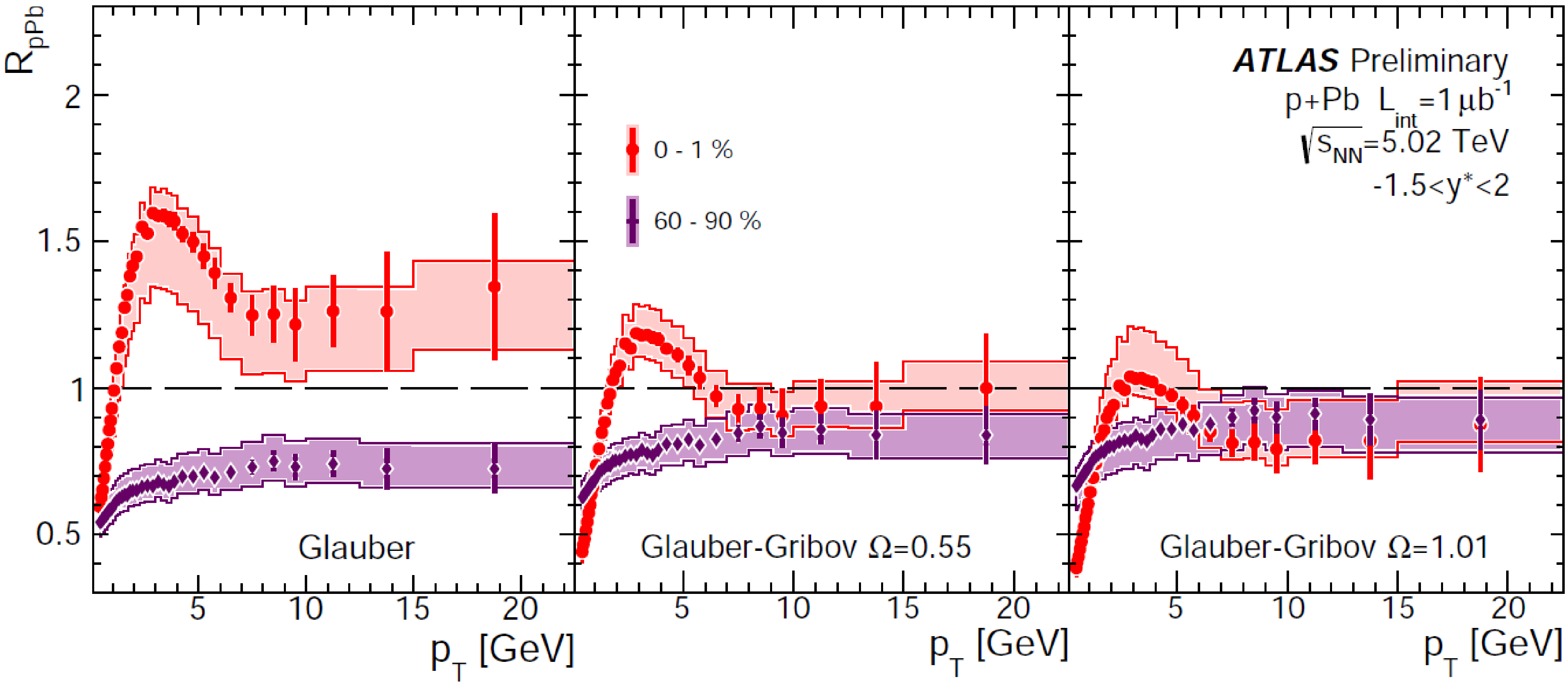
Measured spectra: left inclusive in pseudorapidity, right inclusive in centrality.

Spectra in y*



Measured spectra: left inclusive in rapidity, right inclusive in centrality.
Full line $\langle T_{Pb} \rangle$ scale pp cross-section.

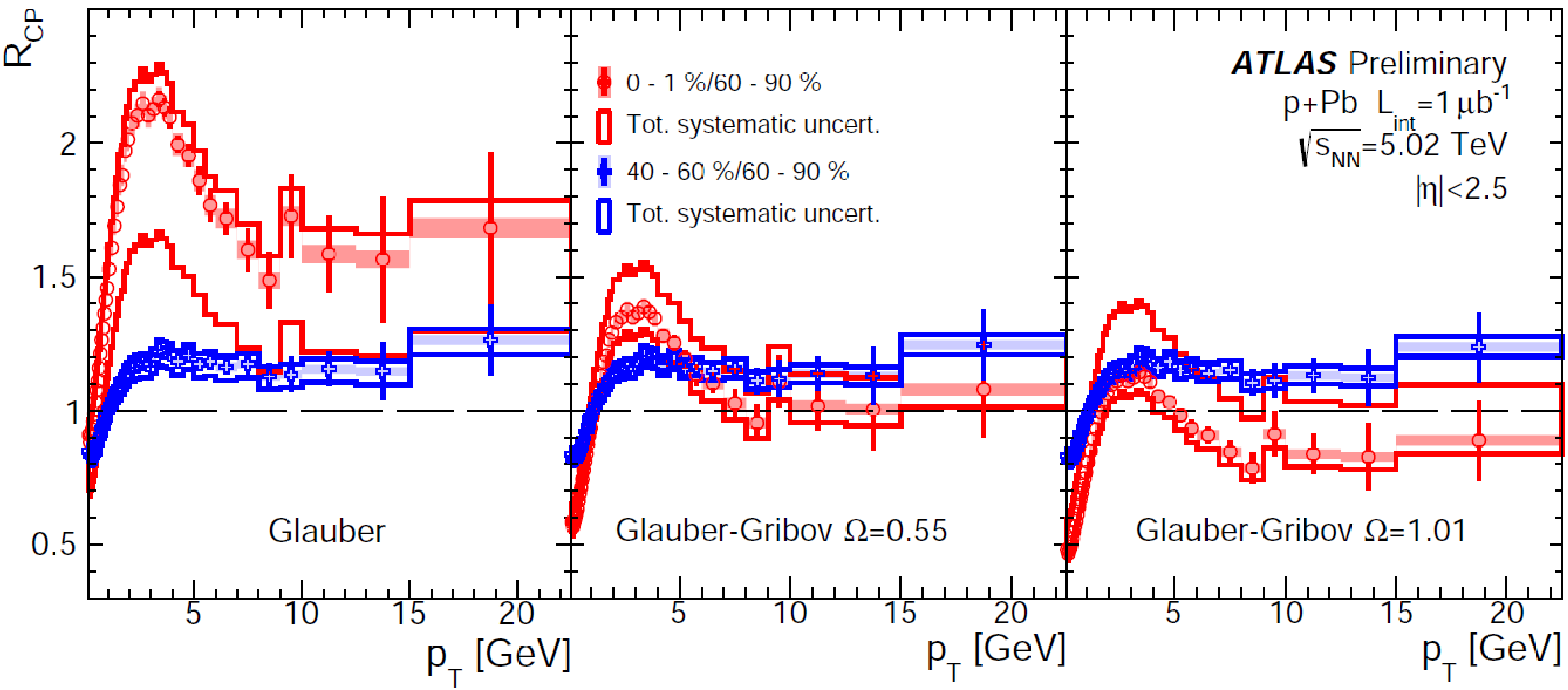
R_{pPb}



- Increase between 0.1-2 GeV, decrease up to ~8 GeV, flattening above 8 GeV.
- Three different geometrical models used to extract $\langle T_{Pb} \rangle$

  –> very different magnitude x ratio of Cronin region to plateau stays similar

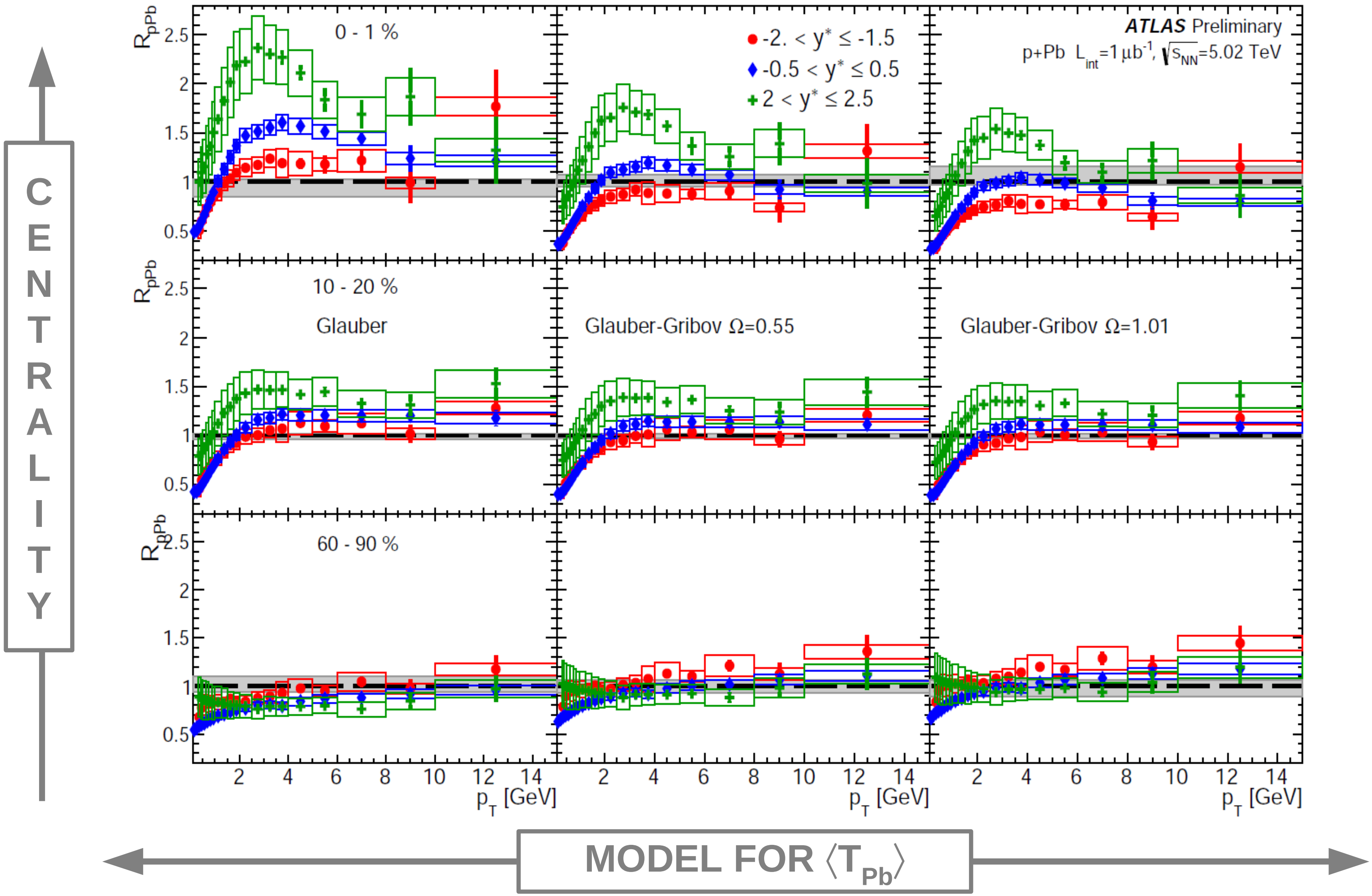
R_{CP}



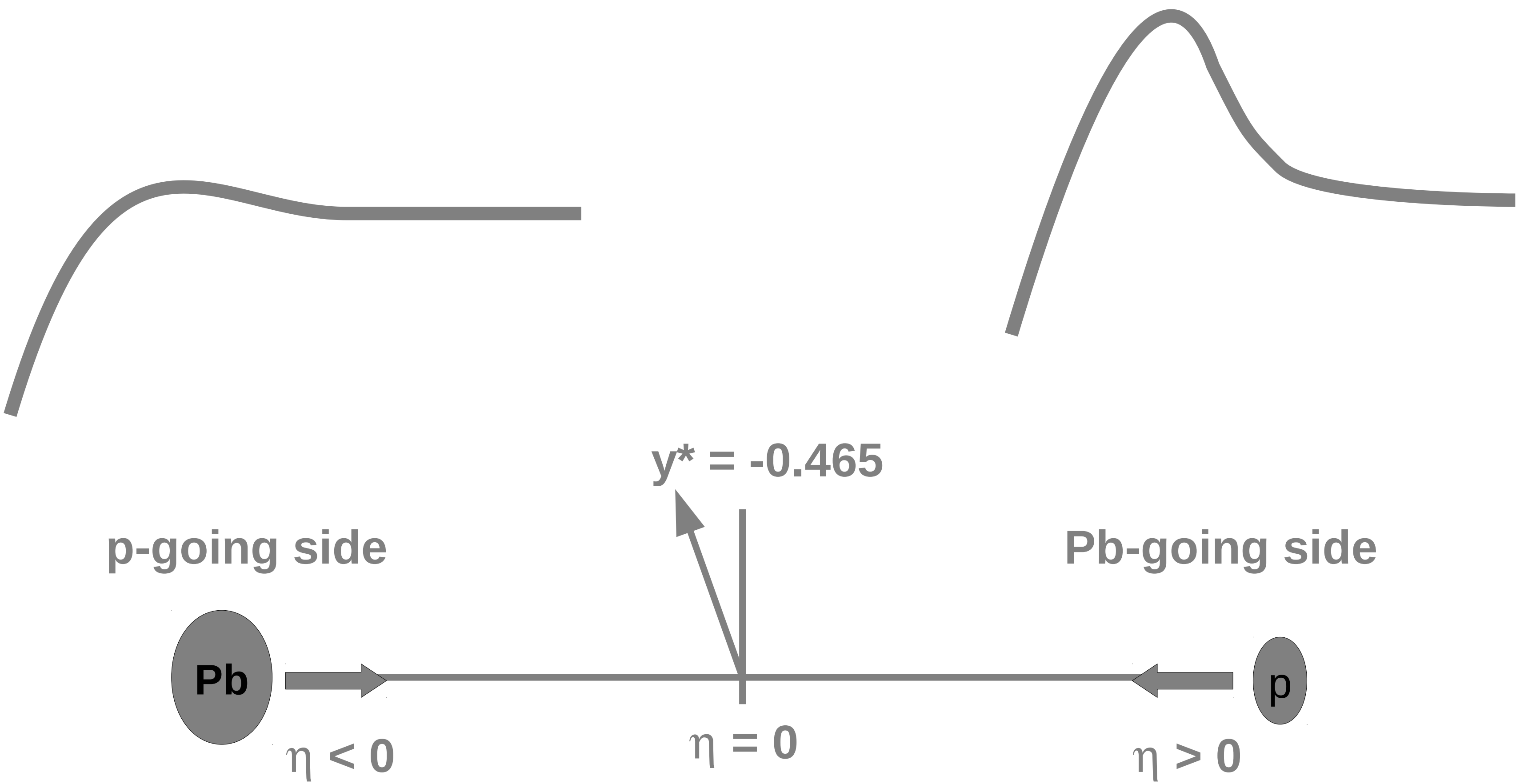
Systematics without δ(⟨T_{Pb}⟩)

All systematics

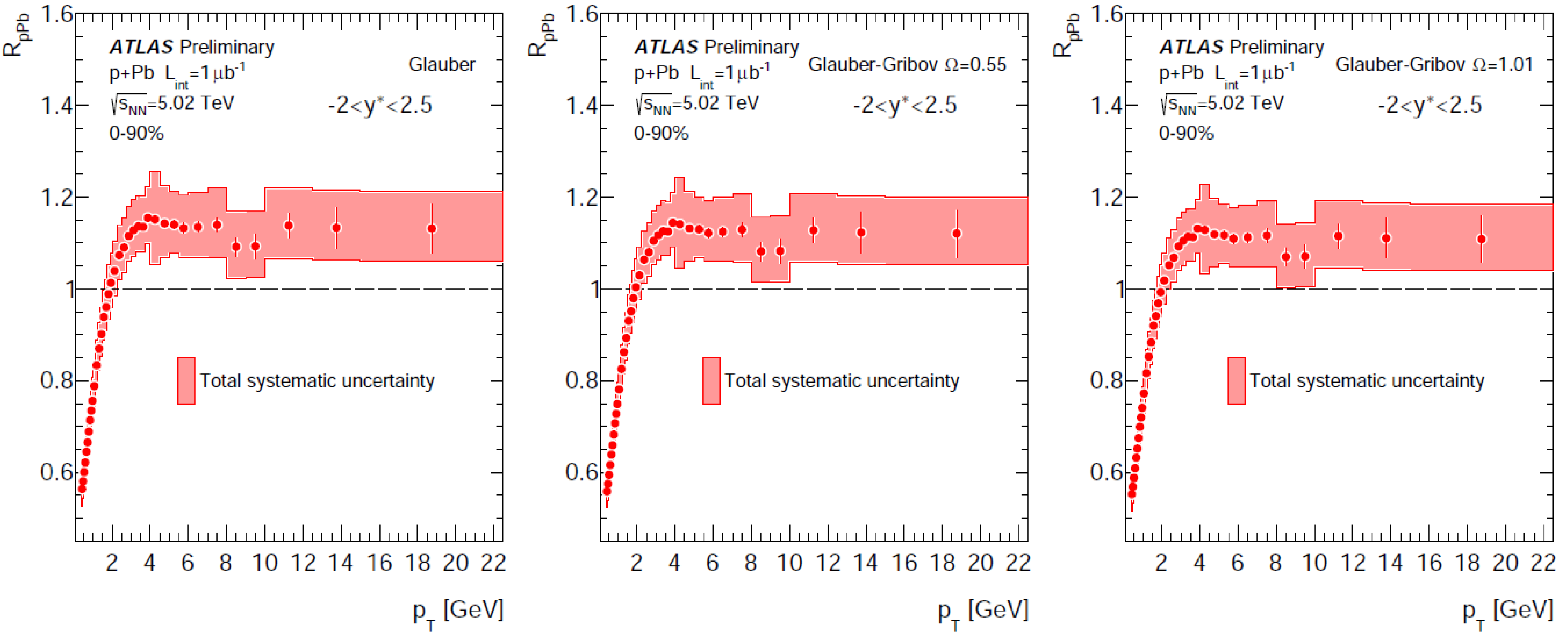
R_{pPb} more differentially



R_{pPb} more differentially

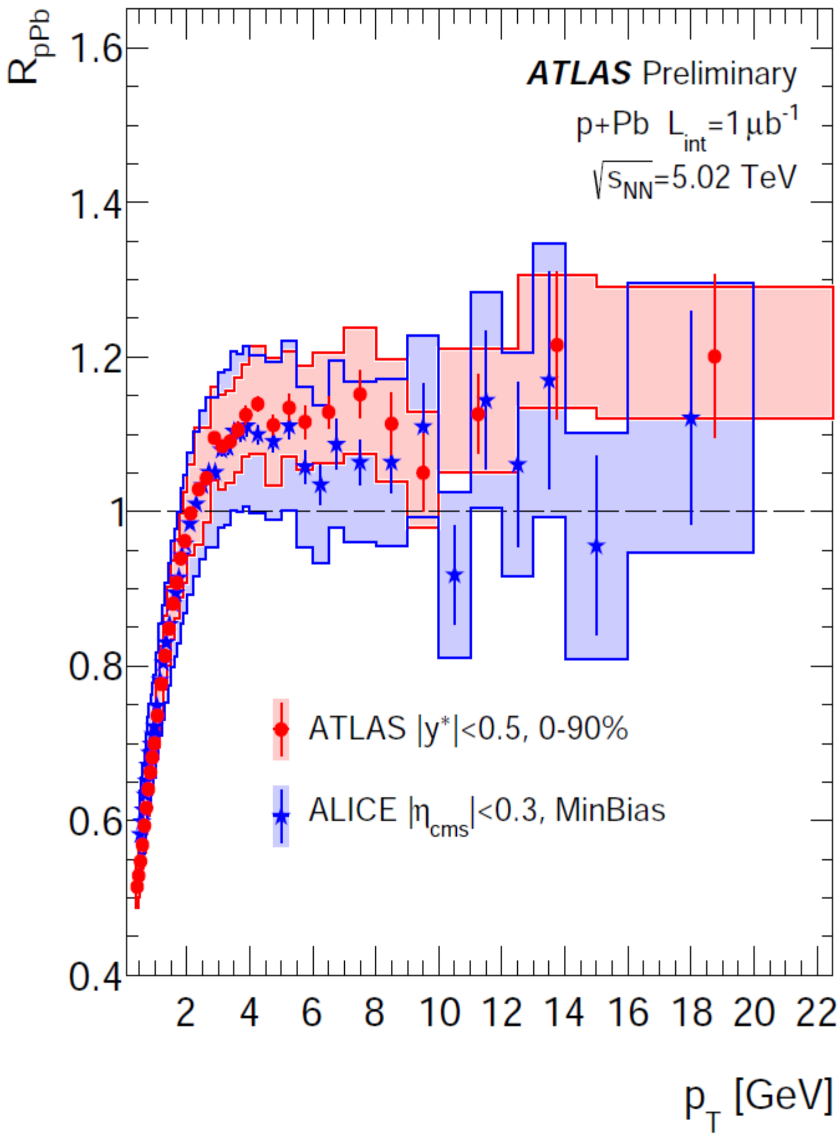


Inclusive R_{pPb}



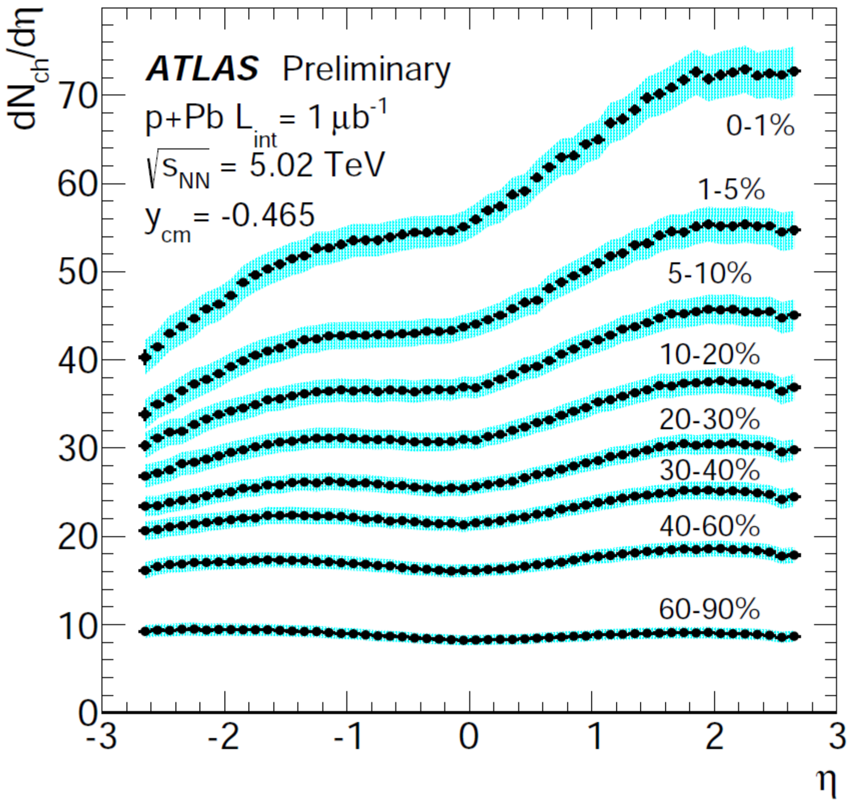
… Good agreement among R_{pPb} obtained using different models when evaluated inclusively in centrality.

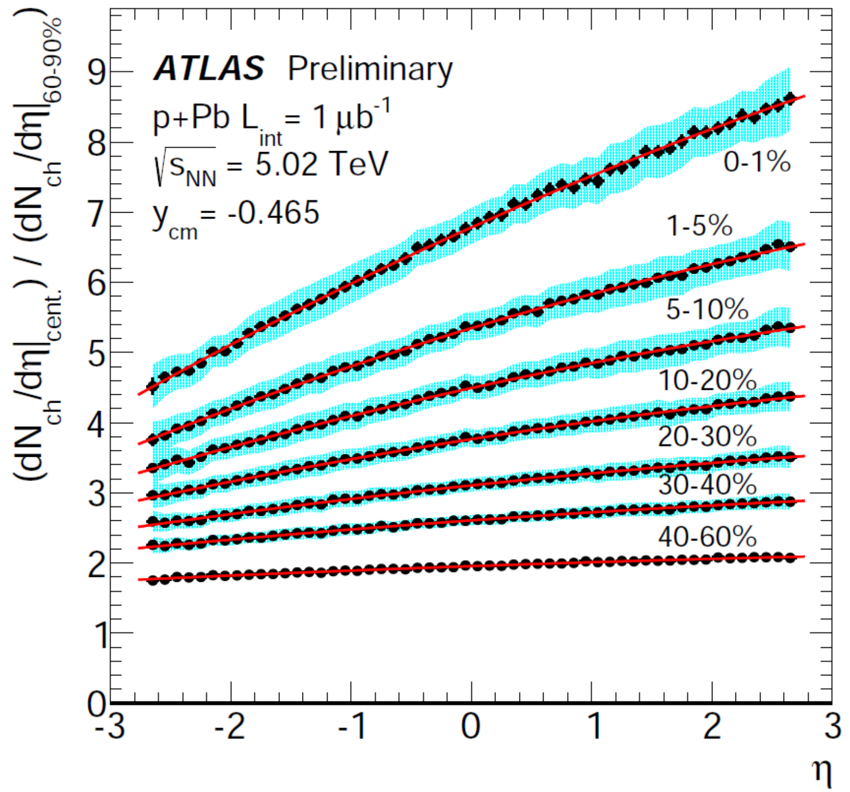
Inclusive R_{pPb}



… Good agreement of R_{pPb} with ALICE.

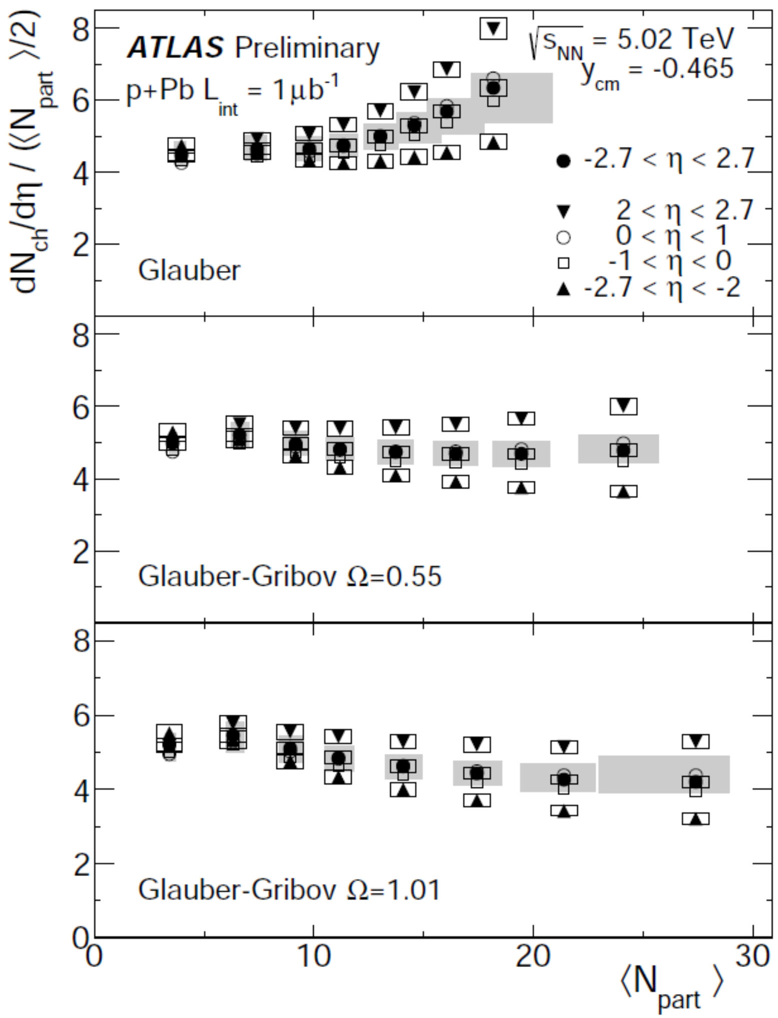
Charged particle multiplicity





Multiplicities as a function of pseudorapidity (left) and their central to peripheral ratio along with the fit by second order polynomial (right).

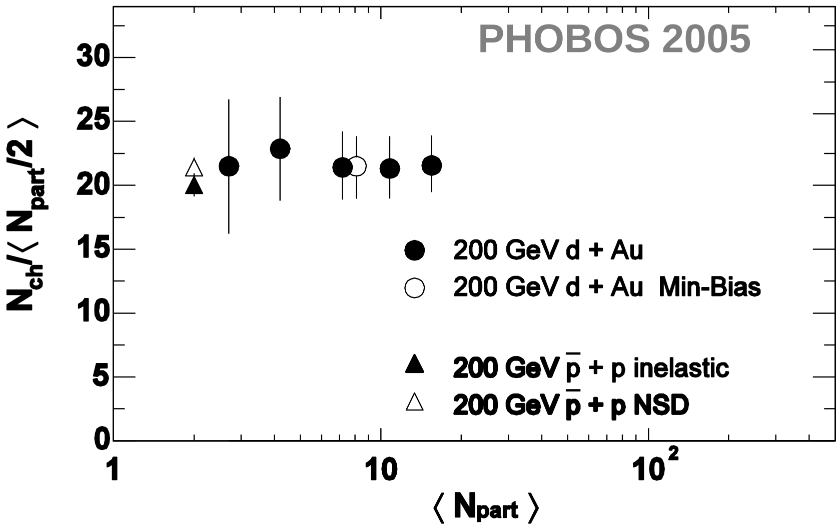
Charged particle multiplicity



Charged particle multiplicity per participant pair … sensitivity to the choice of the model to extract ⟨N_{part}⟩:

- Glauber case: strong increase with centrality
- Glauber+Gribov: only weak centrality dependence

… N_{part} scaling observed previously



Summary and conclusions

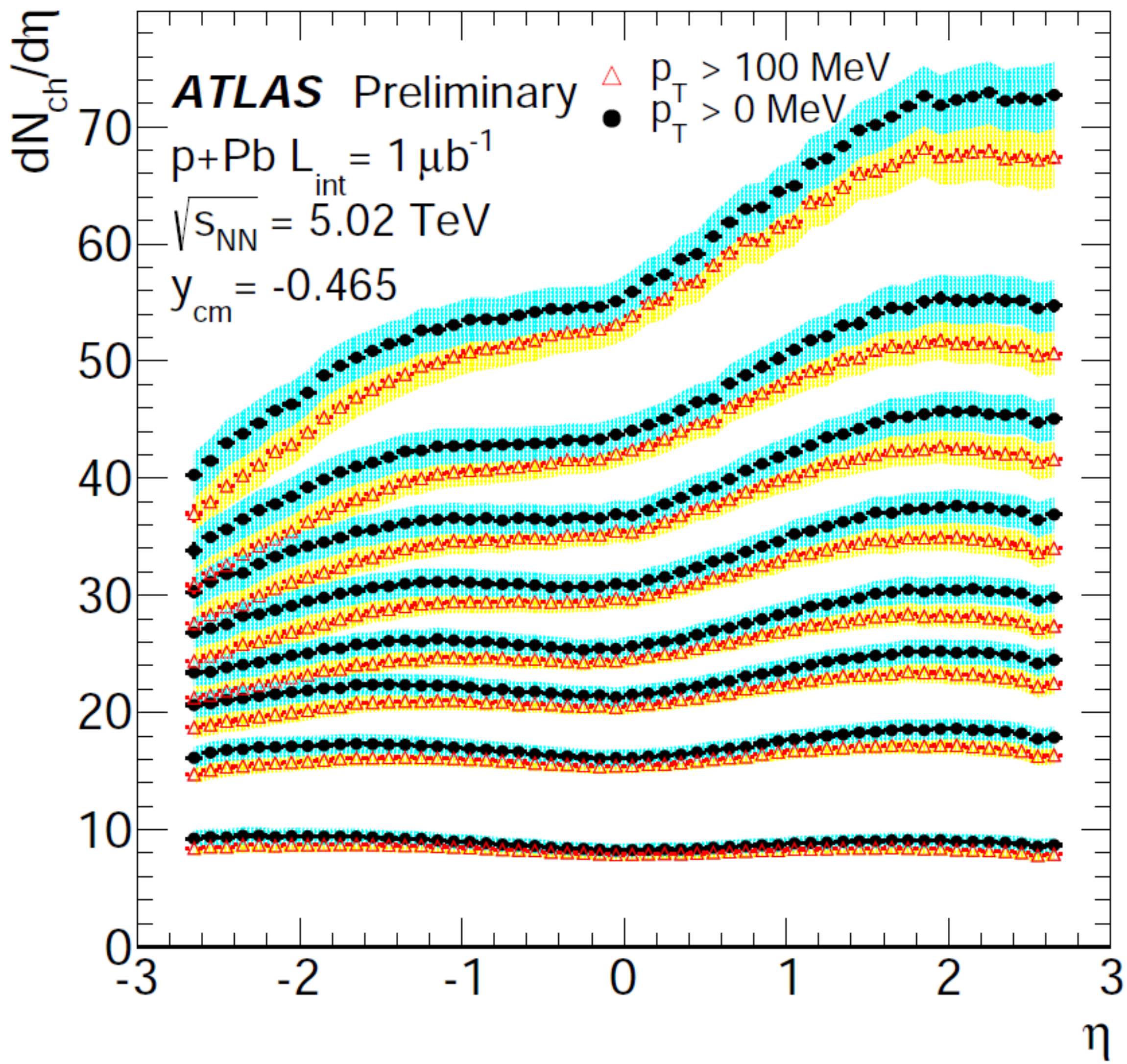
- Nuclear modification factors in p+Pb collisions
  - measured for p_T = 0.1– 22 GeV, η = -2.5 –2.5, y* = -2– 2.5
  - trends: increase between 0.1–2 GeV, decrease up to 8 GeV, then plateau
  - magnitude of the peak (at ~3 GeV) increases with centrality and from p-going to Pb-going direction
  - magnitude of the peak strongly depends on the choice of geometric model
- Charged particle multiplicity in p+Pb collisions
  - measured for $|\eta|<2.7$
  - almost symmetric shape in peripheral –> highly asymmetric shape in central
  - central to peripheral ratio linear with a slope strongly dependent on centrality
  - multiplicity per participant pair strongly depends on the geometric model
- These data should provide an input for:
  - understanding the modifications of gluon distributions in the Pb-target
  - discrimination among different saturation scenarios
  - understanding the fluctuating nature of nucleon-nucleon collisions and geometry of the initial state

Summary and conclusions

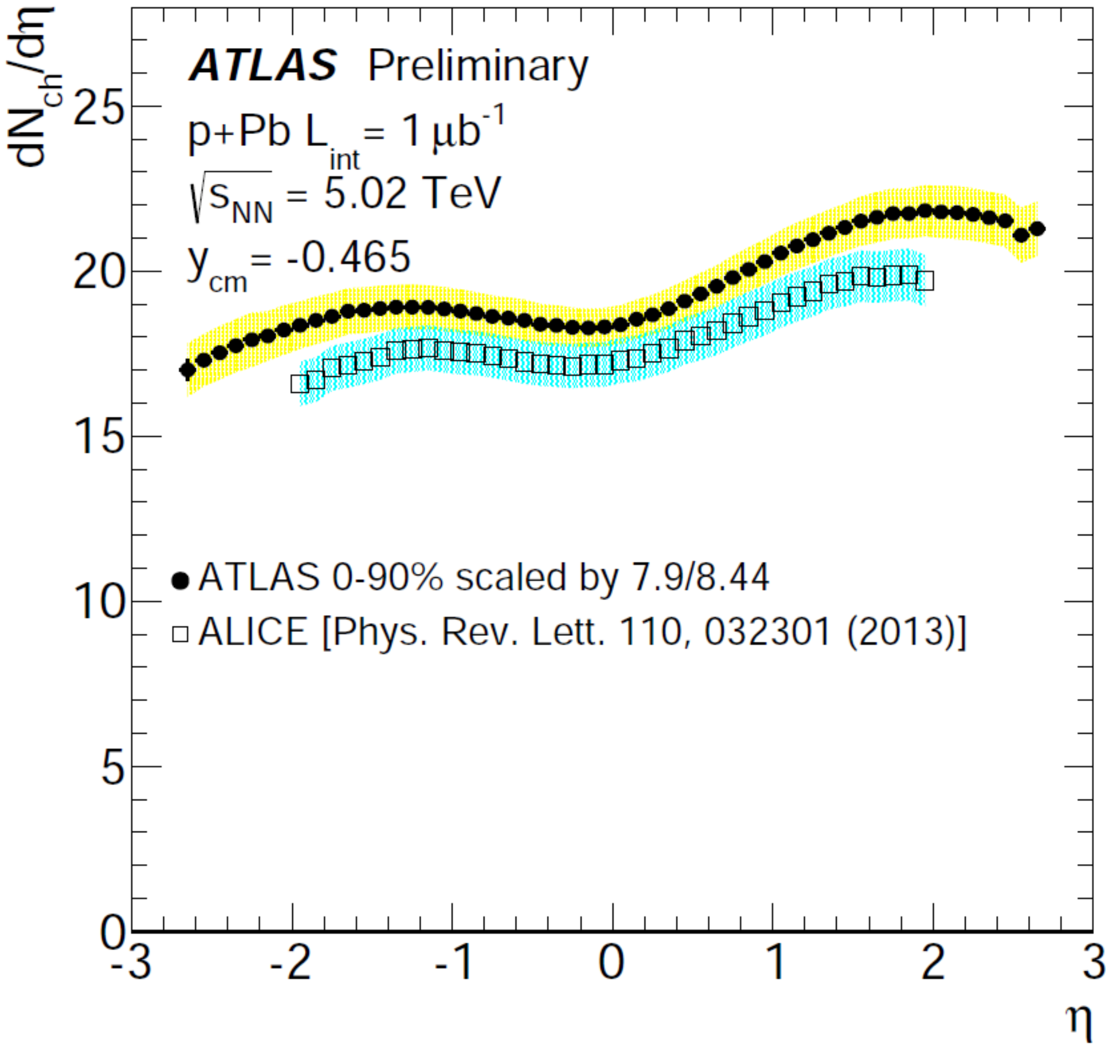
- Details can be found in:
  - ATLAS-CONF-2013-107
  - ATLAS-CONF-2013-096

Backup

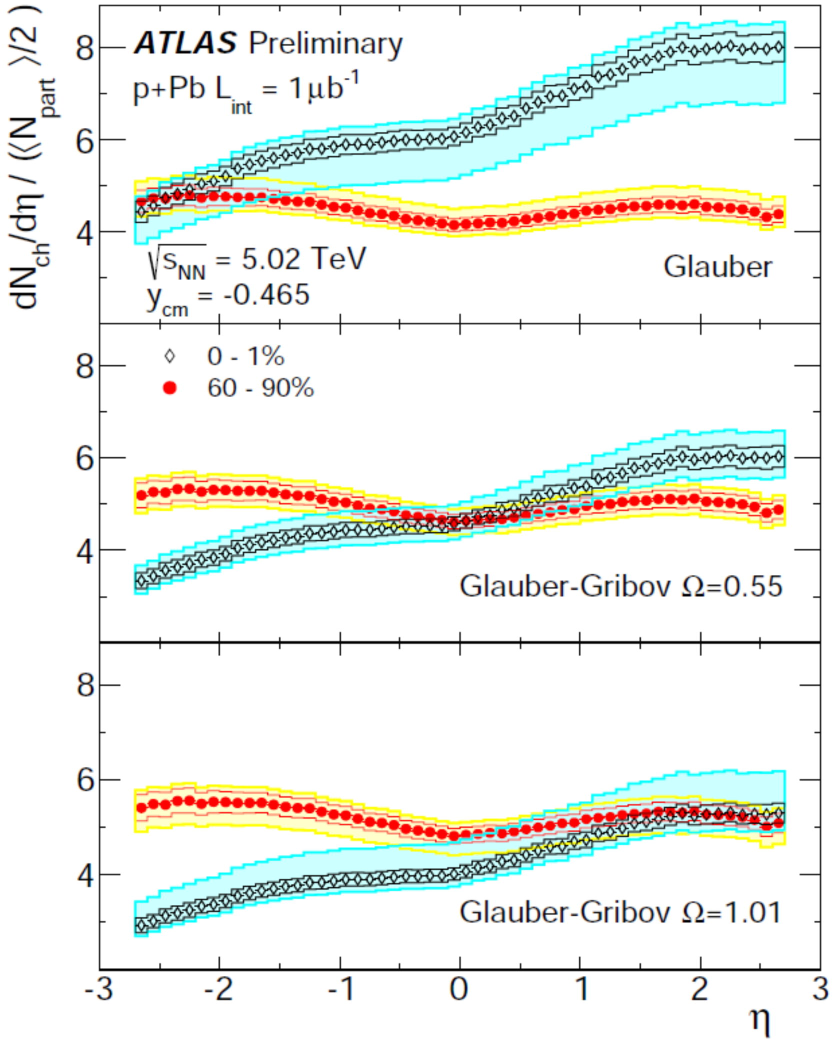
Multiplicity, extrapolation to 0 MeV



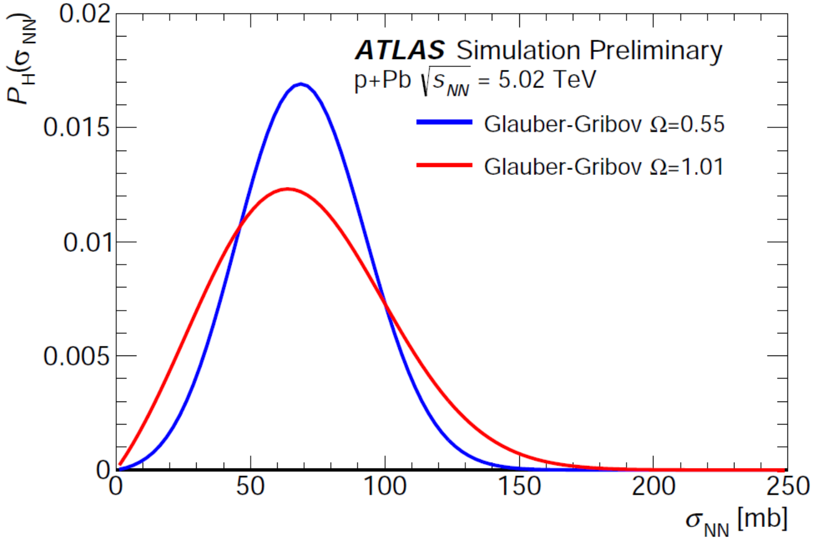
Multiplicity compared to ALICE

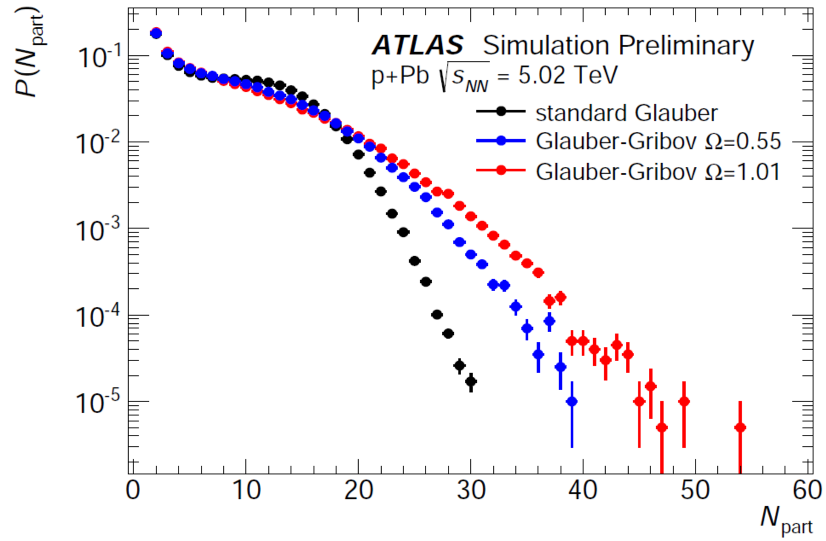


Multiplicity for different models



Glauber-Gribov analysis





$$P_h(\sigma_{\rm tot}) = \rho \frac{\sigma_{\rm tot}}{\sigma_{\rm tot}+\sigma_0} \exp\left\{-\frac{(\sigma_{\rm tot}/\sigma_0 - 1)^2}{\Omega^2}\right\}$$

$$P_H(\sigma_{\rm NN}) = \frac{1}{\lambda} P(\sigma_{\rm NN}/\lambda) \qquad \sigma_{\rm NN} = \lambda \sigma_{\rm tot}$$

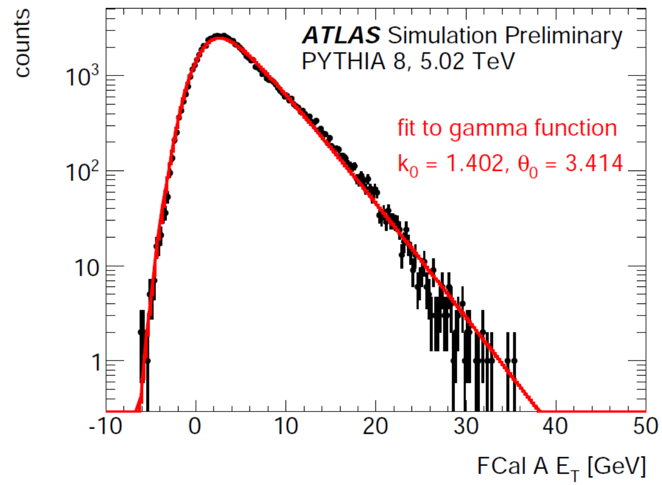
… constant inelastic cross section

- Estimates of Ω based on data at 1.8, 9, and 14 TeV –> interpolation to 5 TeV => Ω=0.55, corresponding σ_0 = 78.6 mb
- New results from diffractive analysis from LHC => Ω=1.01, σ_0 = 72.5 mb
- For each choice of Ω and σ_0 , λ chosen to produce σ_{NN} = 70 mb.

Glauber-Gribov analysis

- For fixed N_{part}, ΣE_T^{Pb} ~ N_{part}-fold convolution of ΣE_T^{pp}
- ΣE_T^{pp} ~ gamma function:

$$\mathrm{gamma}(x;k,\theta) = \frac{1}{\Gamma(k)}\frac{1}{\theta}\left(\frac{x}{\theta}\right)^{k-1} e^{-x/\theta}$$



=> can fit the measured ΣE_T^{Pb} x unsatisfactory result

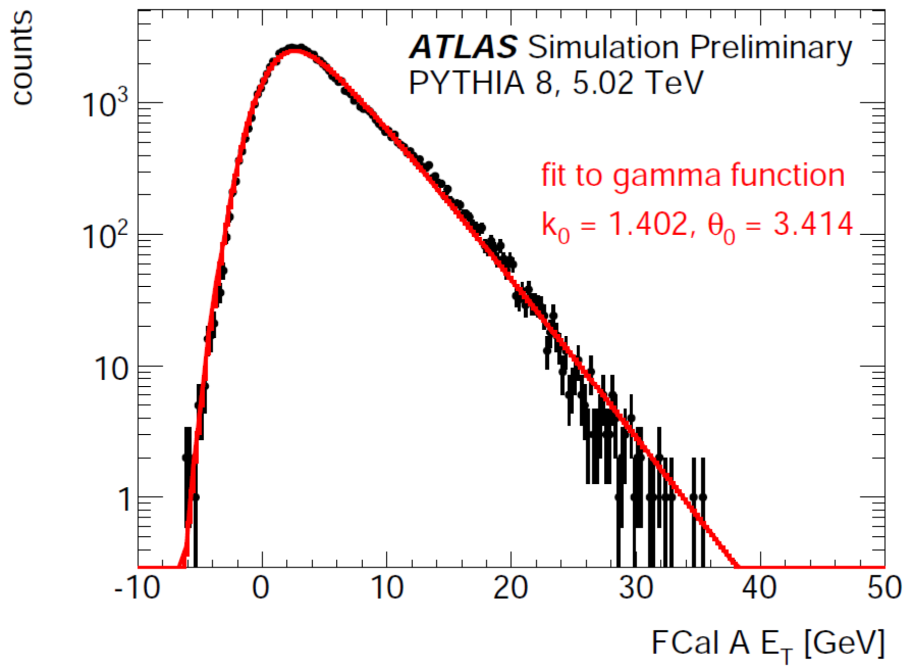
=> generalized WN-model:

$$k\left(N_{\mathrm{part}}\right) = k_0 + k_1\left(N_{\mathrm{part}} - 2\right),$$
$$\theta\left(N_{\mathrm{part}}\right) = \theta_0 + \theta_1 \log\left(N_{\mathrm{part}} - 1\right)$$

… e.g. allows for possible variation in effective acceptance of FCal due to Npart-dependent backward shift

Glauber-Gribov analysis

PYTHIA 8



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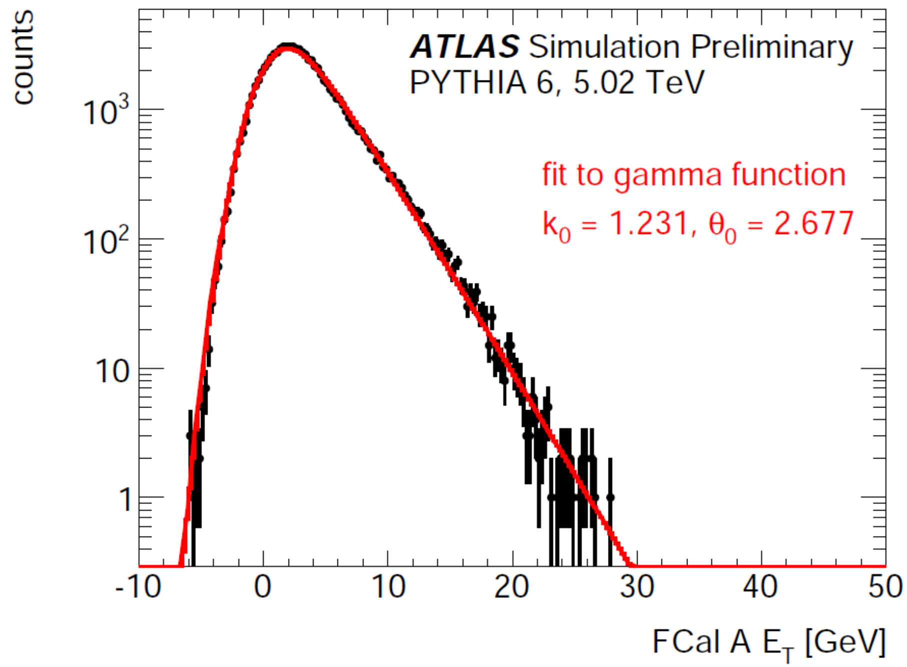
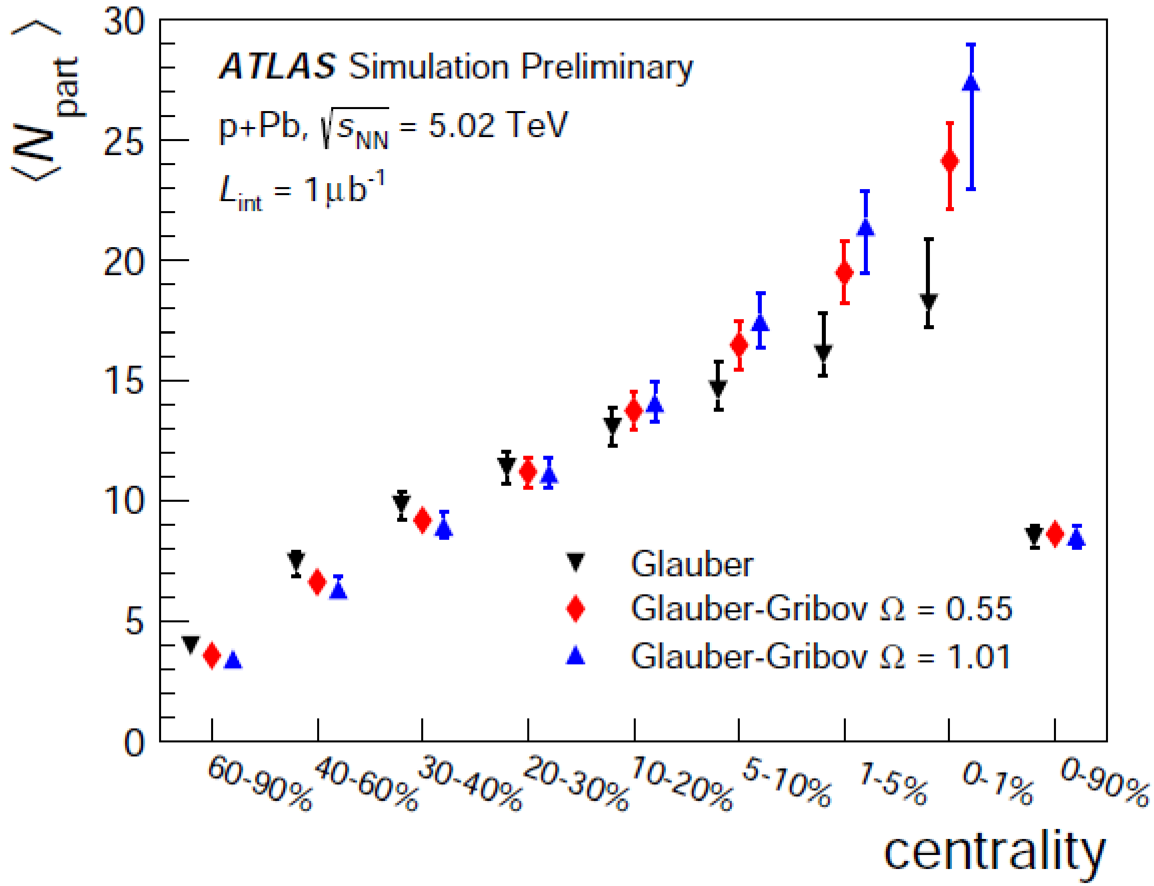
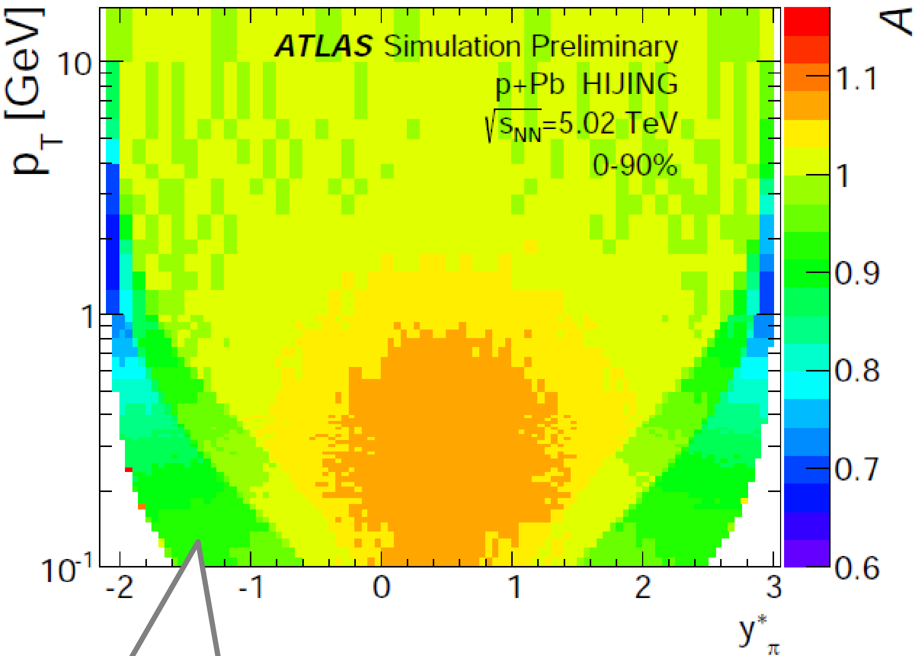
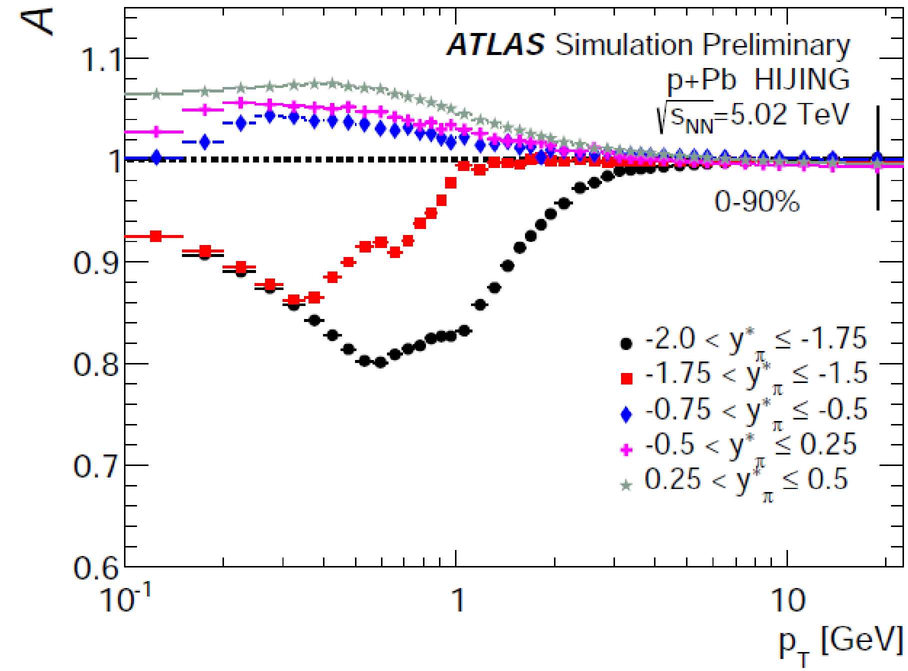


Glauber-Gribov analysis



"Mass correction"





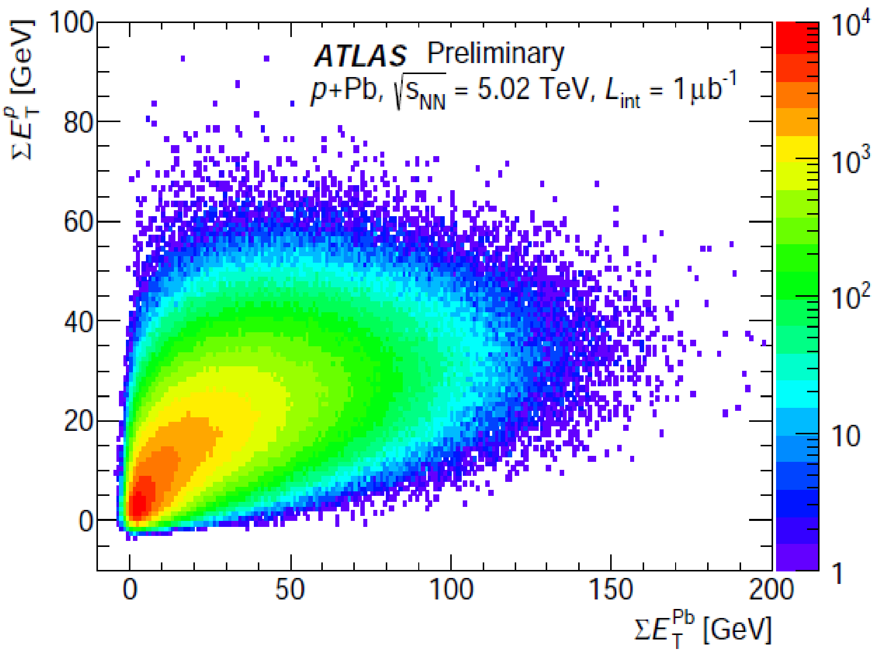
Pion acceptance limitations

$$\mathcal{A}(p_{\mathrm{T}}, y^{\star}_{\pi}) = \left.\frac{N_{Gen}(m, p_{\mathrm{T}}, y^{\star})}{N_{Gen}(m_{\pi}, p_{\mathrm{T}}, y^{\star}_{\pi})}\right|_{y^{\star}=y^{\star}_{\pi}}$$

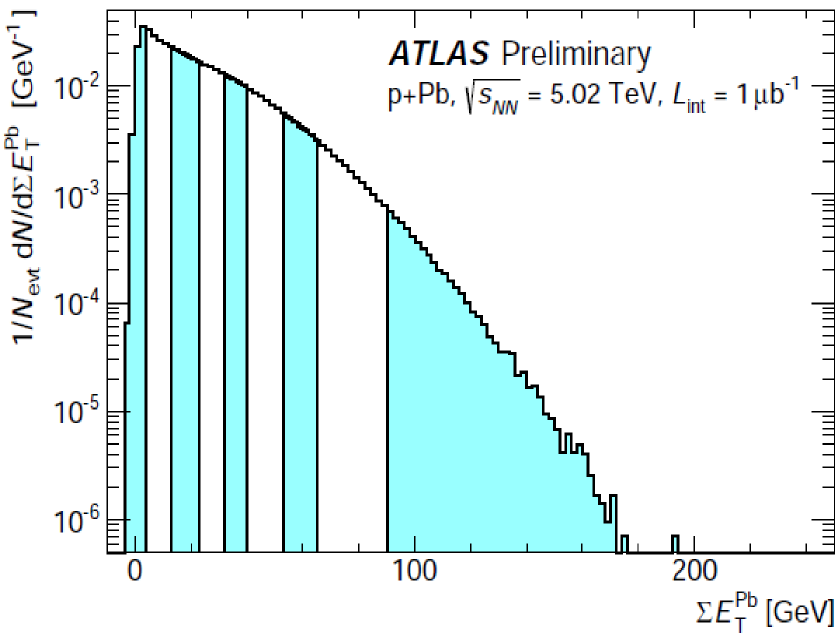
Uncertainties for the multiplicity measurement

Source	Uncertainty 60-90% barrel	Uncertainty 60-90% endcap	Uncertainty 0-1% barrel	Uncertainty 0-1% endcup
MC detector description	1.7%		1.7%	
Extra material	1%	2%	1%	2%
Tracklet selection	0.5%	1.5%	0.5%	1.5%
p_{T} re-weighting	0.5%	0.5%	0.5%	3.0%
Extrapolation to p_{T}=0	1%	2.5%	1%	2%
Particle composition	1%		1%	
Analysis method	1.5%	2.0%	1.5%	2.5%
Event selection	5.0%	6.0%	0.5%	0.5%

Centrality



ATLAS Preliminary
p+Pb, $\sqrt{s_{NN}}$ = 5.02 TeV, L_{int} = 1 μb^{-1}
ΣE_T^p [GeV]
ΣE_T^{Pb} [GeV]



ATLAS Preliminary
p+Pb, $\sqrt{s_{NN}}$ = 5.02 TeV, L_{int} = 1 μb^{-1}
$1/N_{evt}\, dN/d\Sigma E_T^{Pb}$ [GeV^{-1}]
ΣE_T^{Pb} [GeV]

Two methods for tracklet reconstruction