Proton-lead measurements using the ATLAS detector

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Introduction

- Original motivation for p+Pb collisions:
  - to calibrate Pb+Pb measurements,
  - to understand initial state effects,
  - to study nuclear PDFs,
  - …
- ATLAS results in “soft sector”:
  - Charged particle spectra and multiplicities, R_{pPb}
  - Glauber-Gribov analysis for centrality
  - Ridge and flow
- ATLAS results in “hard sector”:
  - Charged particle spectra at high-pt
  - Z-boson production
  - Jet production

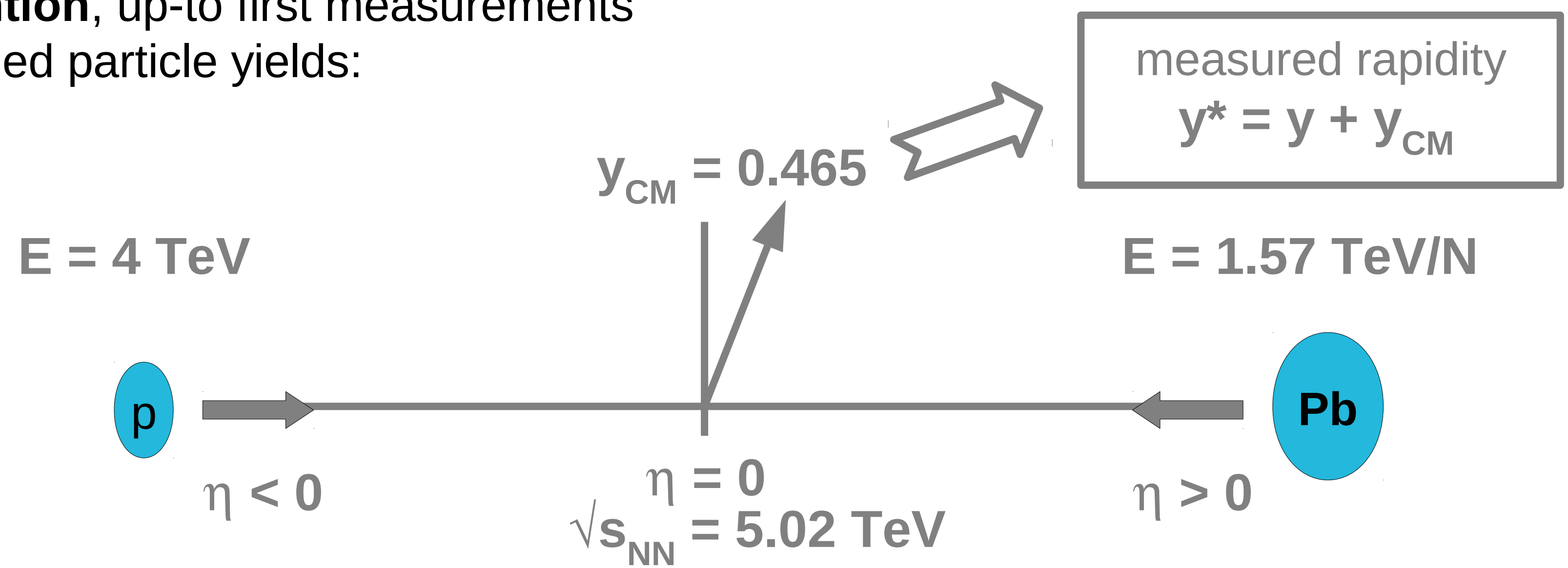
… quite a lot of unexpected seen!

Input data, rapidity convention

- 1 μb^{-1} of **5.02 TeV p+Pb** Minimum Bias events collected during September 2012
  30 nb^{-1} of 5.02 TeV p+Pb, with various triggers in February 2013
- 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

$\left.\right\}$ Interpolation of pp data to get 5.02 TeV reference

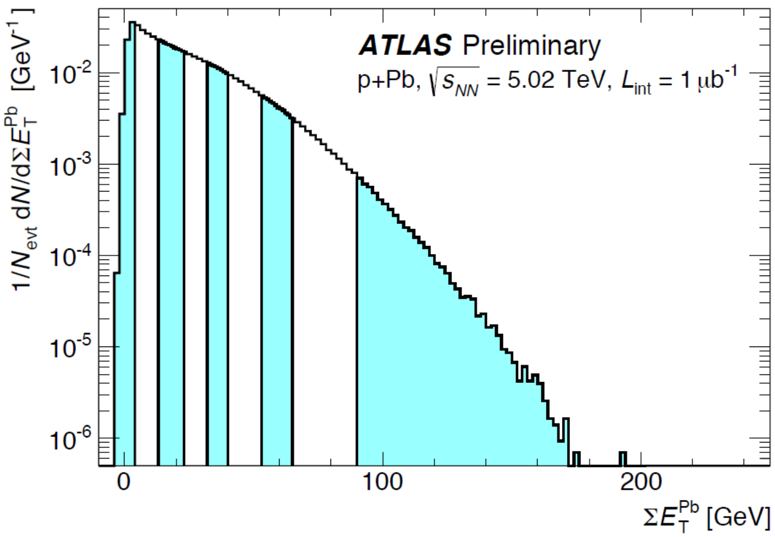
Convention, up-to first measurements of charged particle yields:



Soft physics

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

- Centrality determined using ΣE_T in Pb-going forward calorimeters (η < -3.2)



- $\langle T_{Pb} \rangle$ determined using Glauber and Glauber+Gribov model
  - Glauber:
    - fixed σ_{NN} (σ_{NN}= 70 ± 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 ± 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 $\langle N_{part} \rangle = \langle T_{Pb} \rangle * \sigma_{NN} + 1$

Initial measurements of charged particle R_{pPb}

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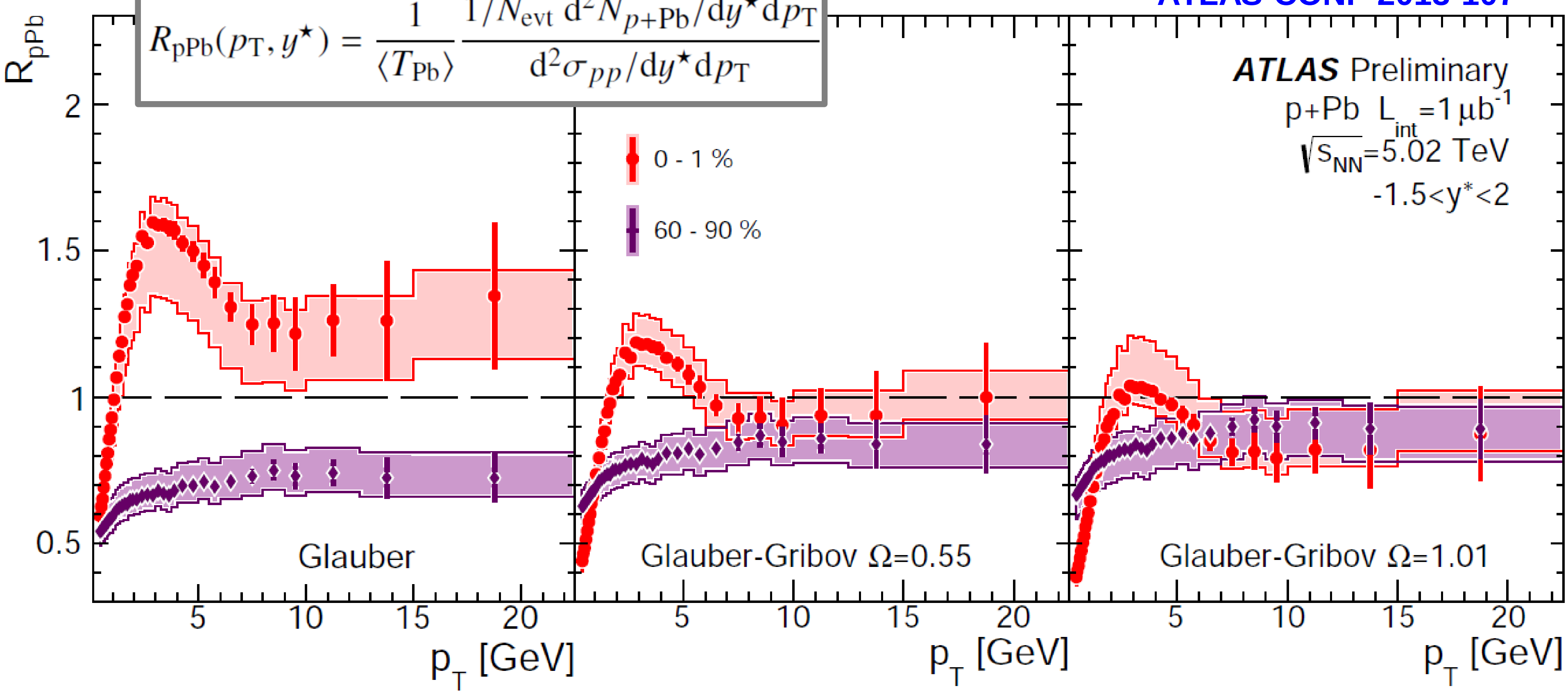
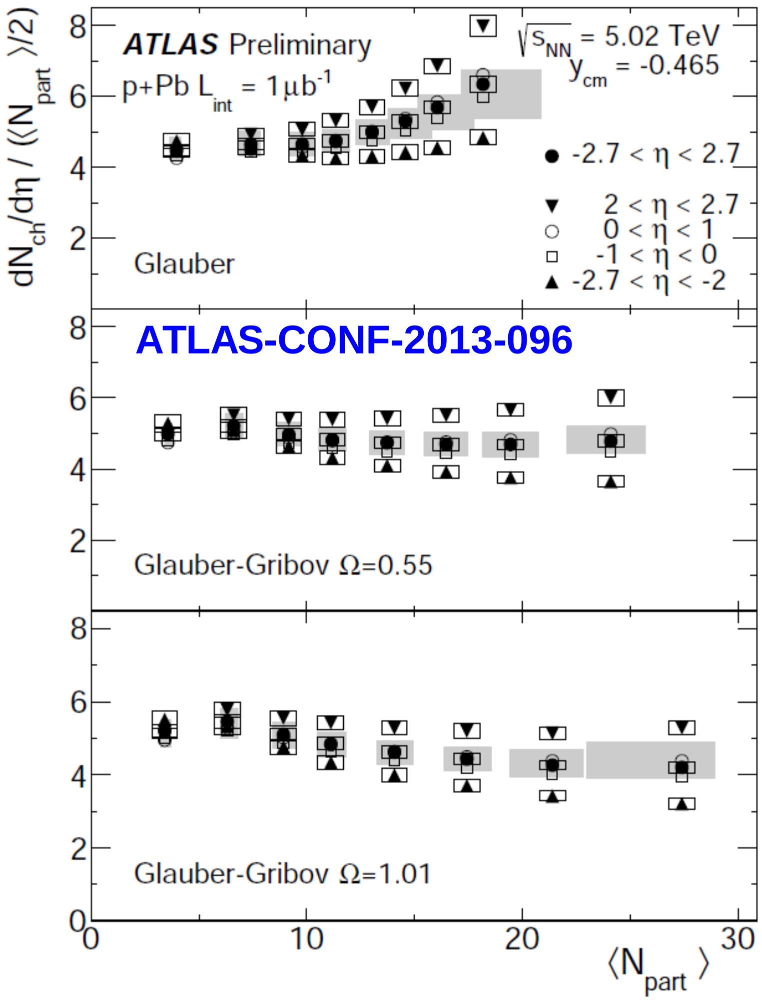
$$R_{\mathrm{pPb}}(p_{\mathrm{T}}, y^{\star}) = \frac{1}{\langle T_{\mathrm{Pb}} \rangle} \frac{1/N_{\mathrm{evt}}\, \mathrm{d}^2 N_{p+\mathrm{Pb}}/\mathrm{d}y^{\star}\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}^2\sigma_{pp}/\mathrm{d}y^{\star}\mathrm{d}p_{\mathrm{T}}}$$



- 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**, but ratio of Cronin region to plateau stays similar

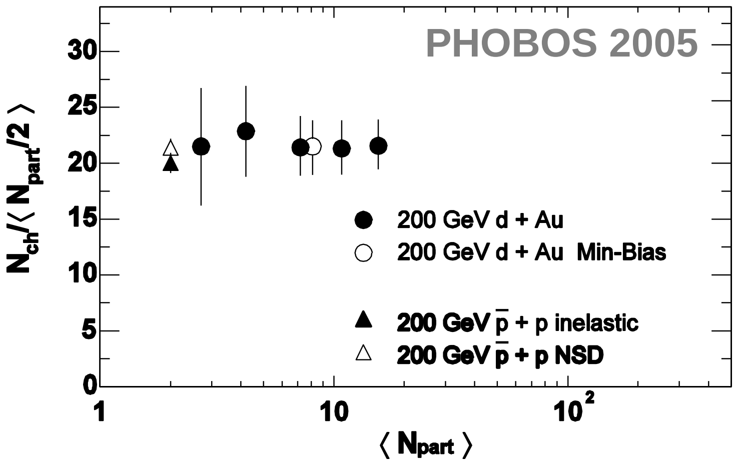
Charged particle multiplicity



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

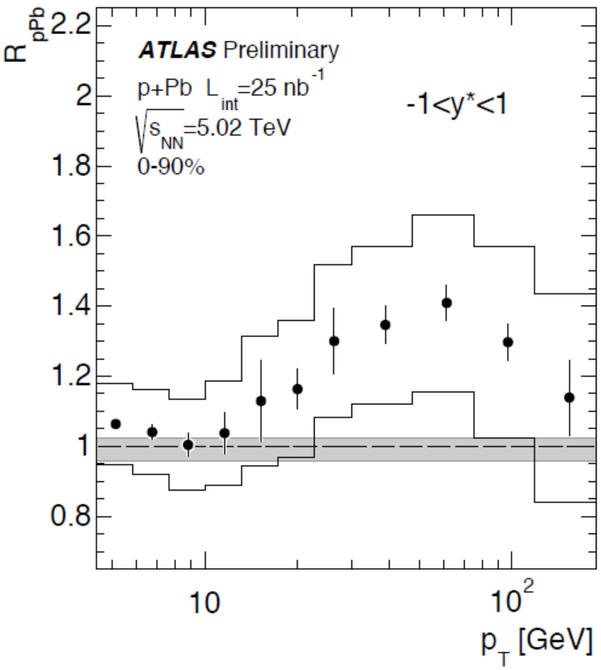
- Glauber case: strong increase with ⟨N_{part}⟩
- Glauber+Gribov: only weak N_{part} dependence

… N_{part} scaling observed previously

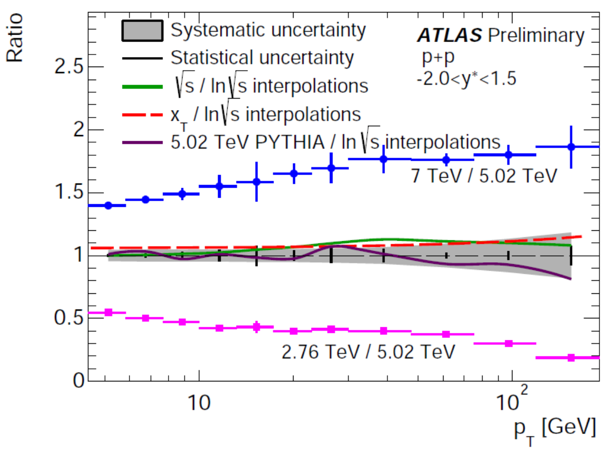


–> Clear need for understanding of **fluctuating nature of nucleon-nucleon collisions** and **geometry of initial state**

Charged particle R_{pPb} II.



- Ratio of 0-90% p+Pb spectra to interpolated pp cross-section
- Three different interpolation methods of 2.76 TeV and 7 TeV cross-sections used to obtain the reference
- Seems to be confirming CMS observation of large **enhancement at high-pt**



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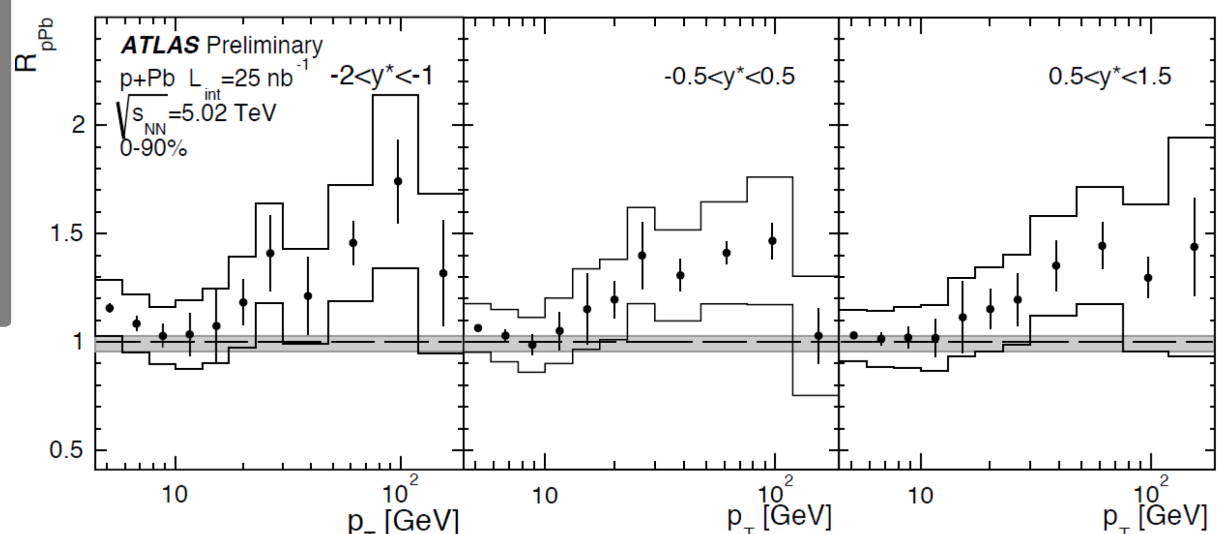
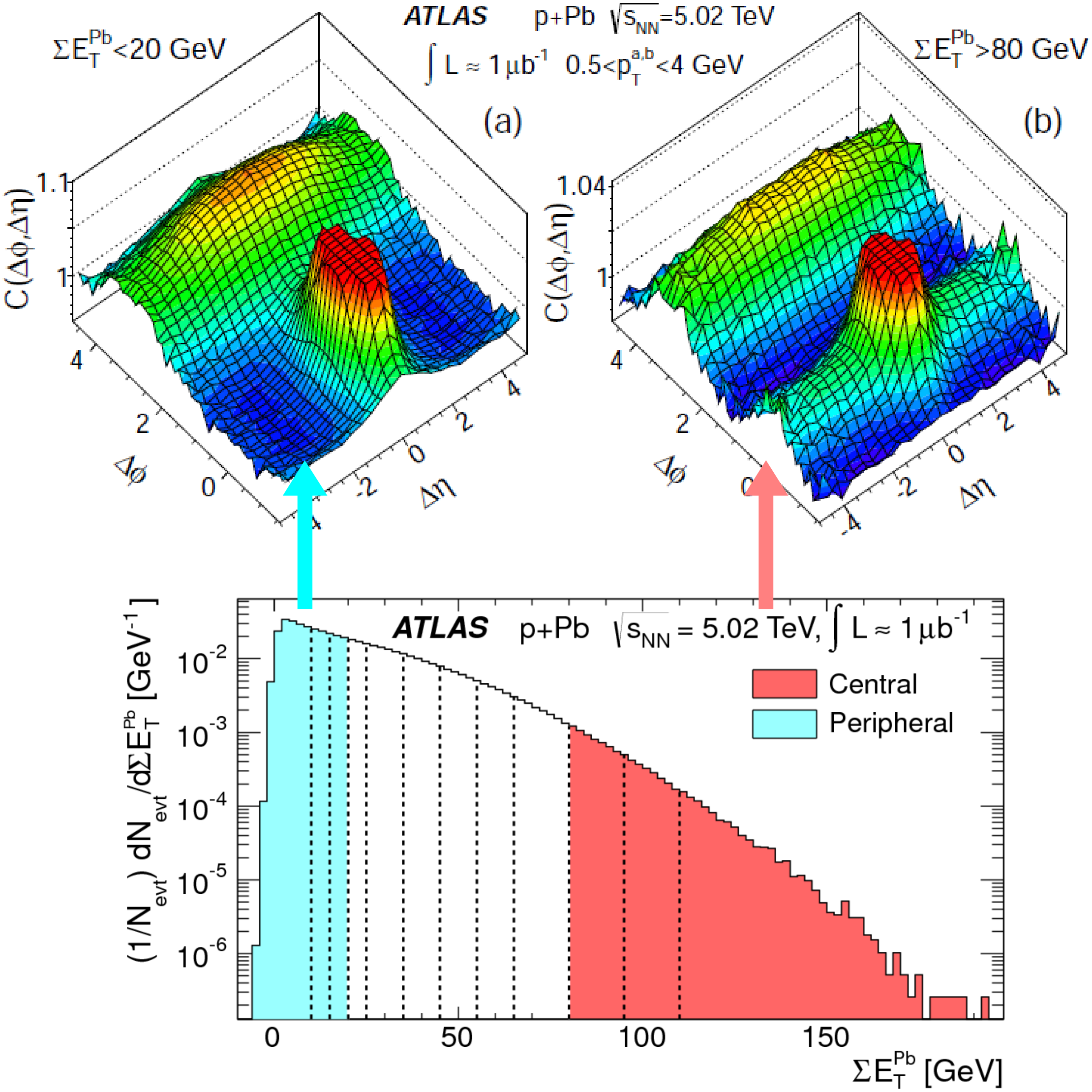
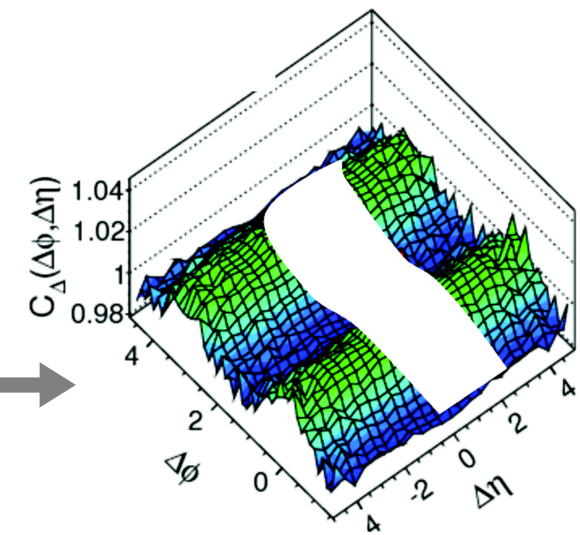


Collectivity in p+Pb (“Ridge”)





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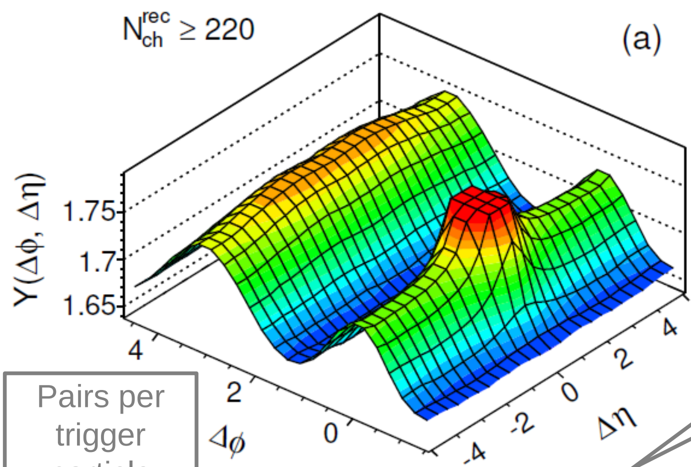
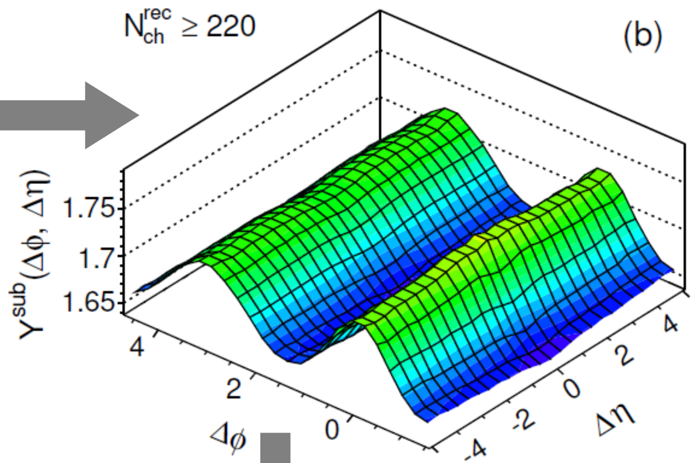
PLB 725 (2013) 60-78
ATLAS-CONF-2014-021

- Discovery of double ridge structure in **high multiplicity** p+Pb events
- Influence of the away-side jet estimated from **low multiplicity** events

Ridge, more details – per-trigger yield



Subtracting the near side short range and away side recoil correlations



Pairs per trigger particle

Normalization

Signal

$$Y(\Delta\phi,\Delta\eta) = \frac{\int B(\Delta\phi,\Delta\eta)d\Delta\phi d\Delta\eta}{\pi\eta_\Delta^{\max}}\left(\frac{S(\Delta\phi,\Delta\eta)}{B(\Delta\phi,\Delta\eta)}\right)$$

Background from mixed events

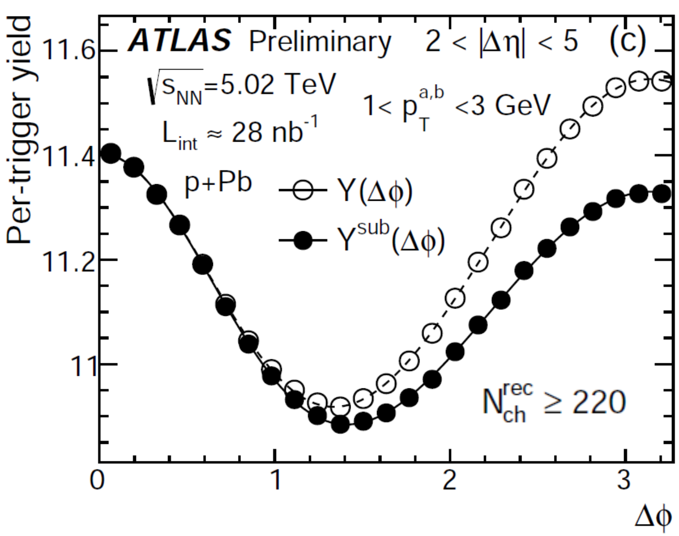
$$Y^{\rm sub}(\Delta\phi,\Delta\eta) = Y(\Delta\phi,\Delta\eta) - \alpha Y^{\rm corr}_{\rm peri}(\Delta\phi,\Delta\eta)$$

$$\alpha = \frac{Y^{\rm N-Peak}}{Y^{\rm N-Peak}_{\rm peri}}$$

Scales the near-side correlation to the yield in a given centrality class

$$Y^{\rm corr}(\Delta\phi,\Delta\eta) = \frac{\int B(\Delta\phi,\Delta\eta)d\Delta\phi d\Delta\eta}{\pi\eta_\Delta^{\max}}\left(\frac{S(\Delta\phi,\Delta\eta)}{B(\Delta\phi,\Delta\eta)} - b_{\rm ZYAM}\right)$$

Subtracting pedestal from uncorrelated pairs

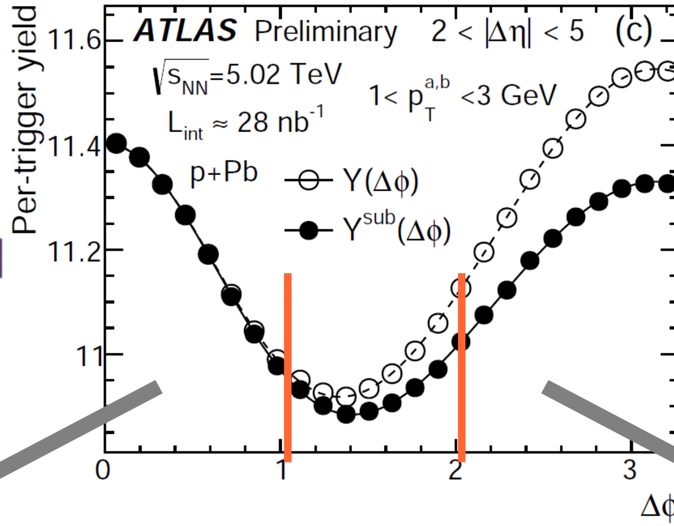


Integrating over $\Delta\eta$

Ridge – integrated per-trigger yield

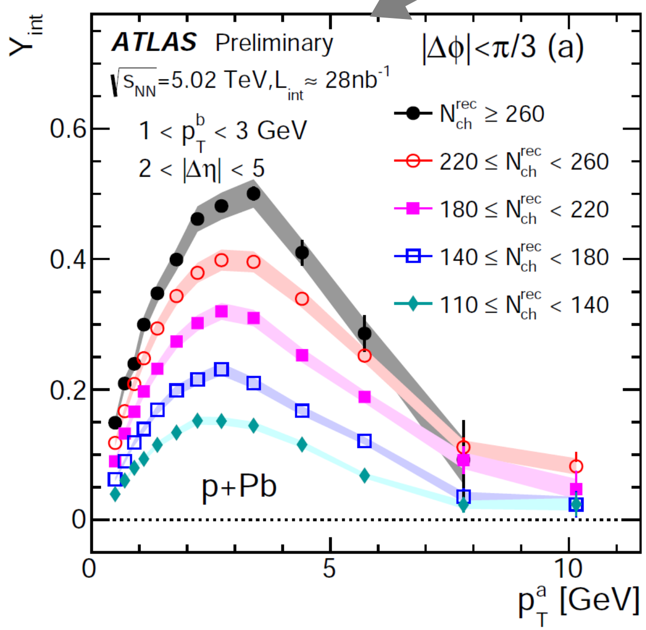
$$Y_{\mathrm{int}} = \int_0^{\pi/3} Y^{\mathrm{corr}}(\Delta\phi)\ \mathrm{d}|\Delta\phi|$$

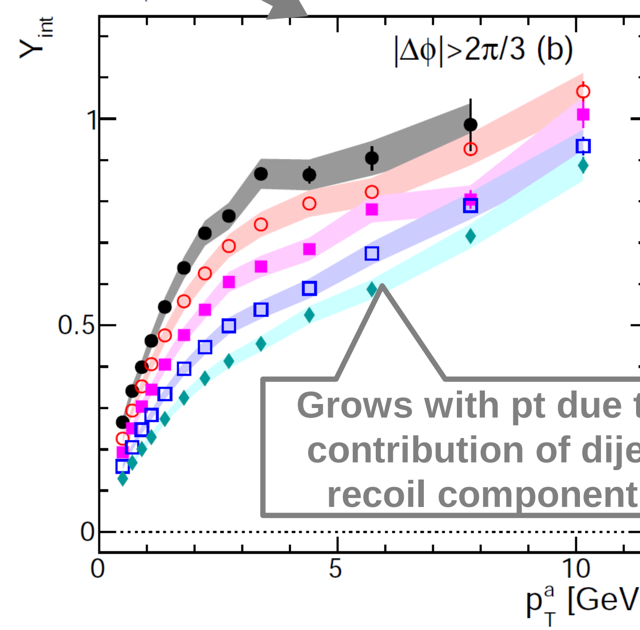
Near-side integrated yield



$$Y_{\mathrm{int}} = \int_{2\pi/3}^{\pi} Y^{\mathrm{corr}}(\Delta\phi)\ \mathrm{d}|\Delta\phi|$$

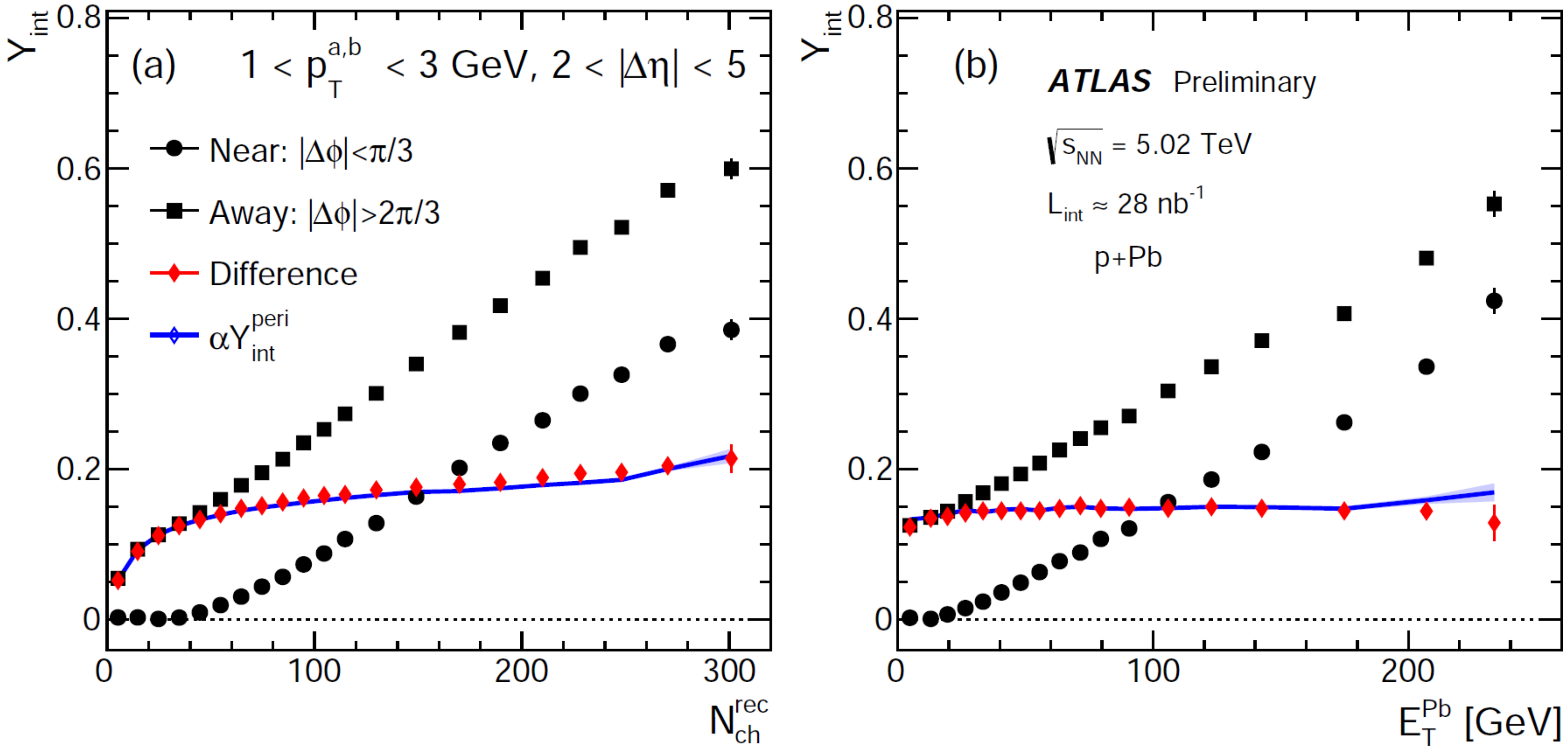
Away-side integrated yield





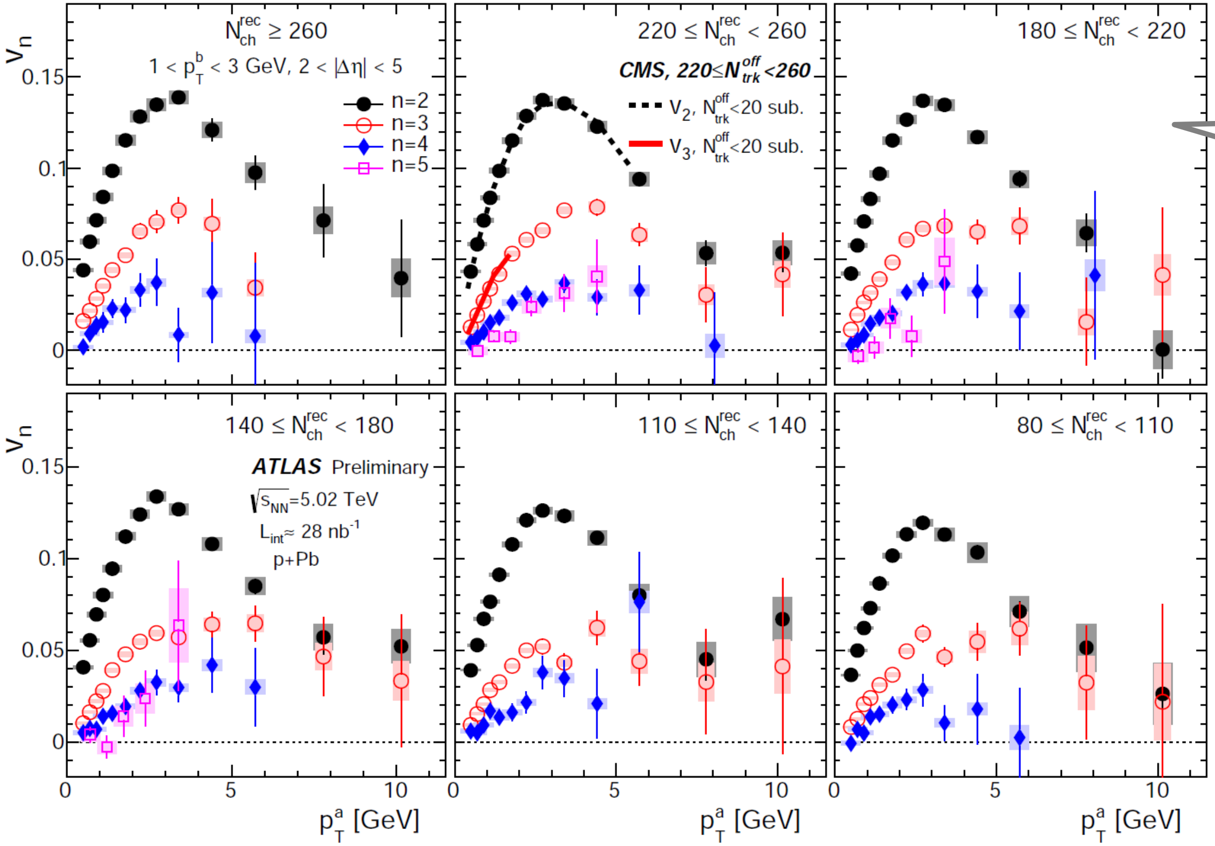
Grows with pt due to contribution of dijet recoil component

Ridge – difference of integrated per trigger yields



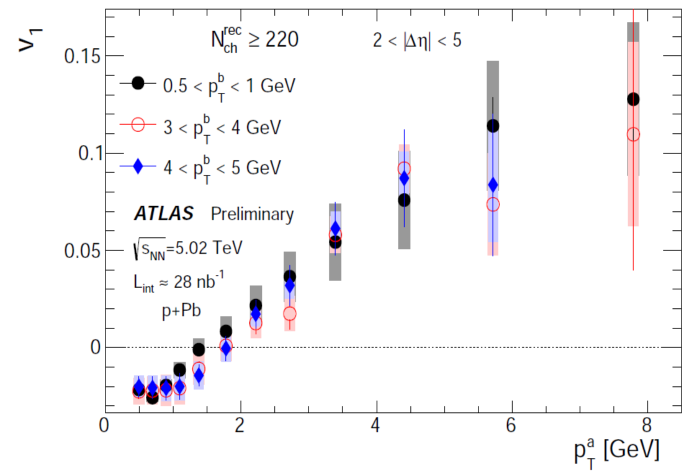
- Difference between near-side and away-side integrated per trigger yields evaluated as a function of **two centrality measures**: number of charged particles, total FCal Et.
- Difference of yields compared with the estimated recoil contribution in the away side.
- Slow variation of the difference with centrality –> a presence of component of the **same magnitude** in the near side and away side

Flow



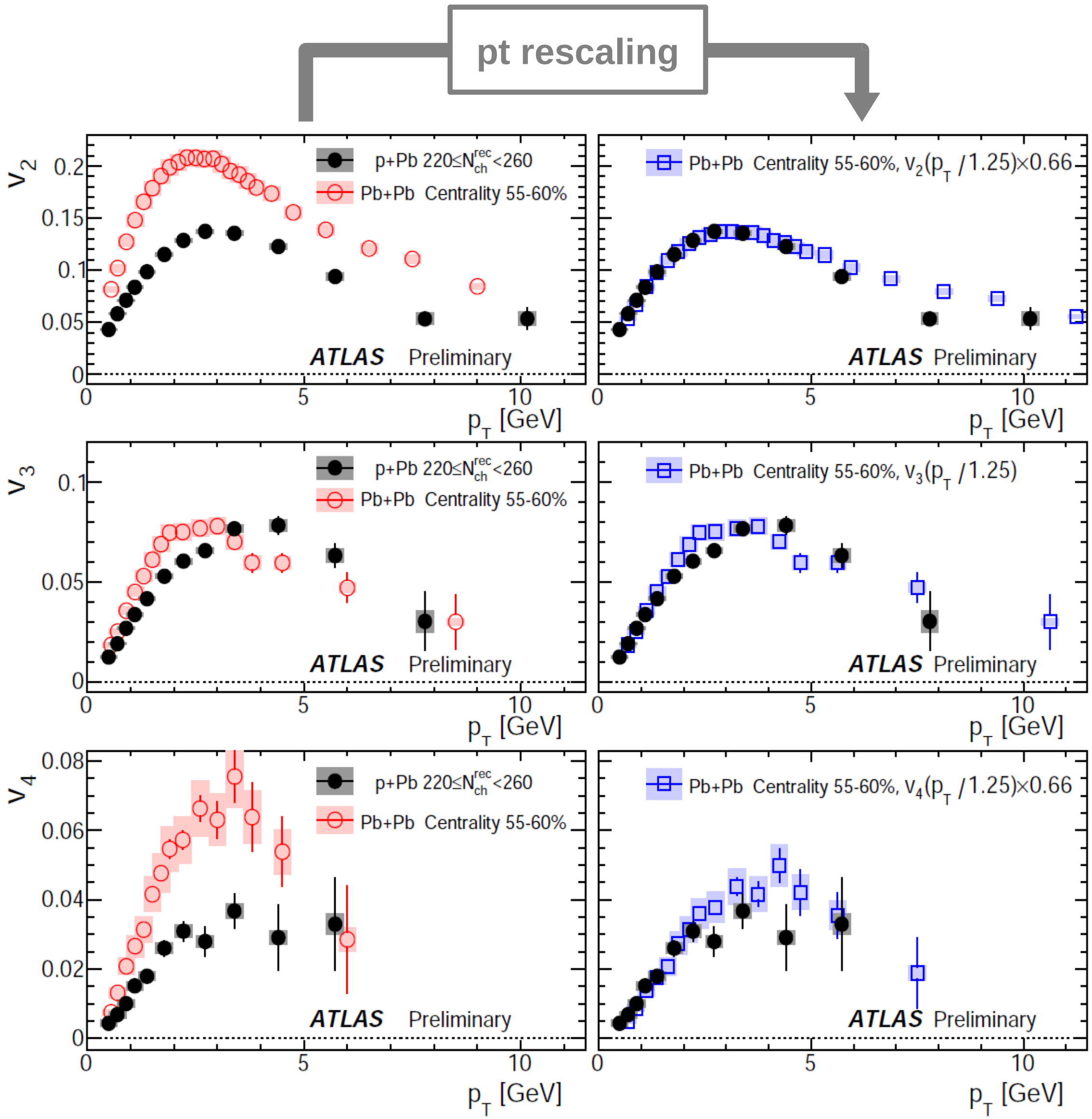
v_2-v_5 vs pt

v_1 vs pt



- Fourier coefficients v_1-v_5 extracted using two particle correlation method.
- Significant v_1-v_5 observed with similar trends as observed in heavy ion collisions.
- Excellent agreement of v_2 and v_3 with results from the CMS Collaboration.

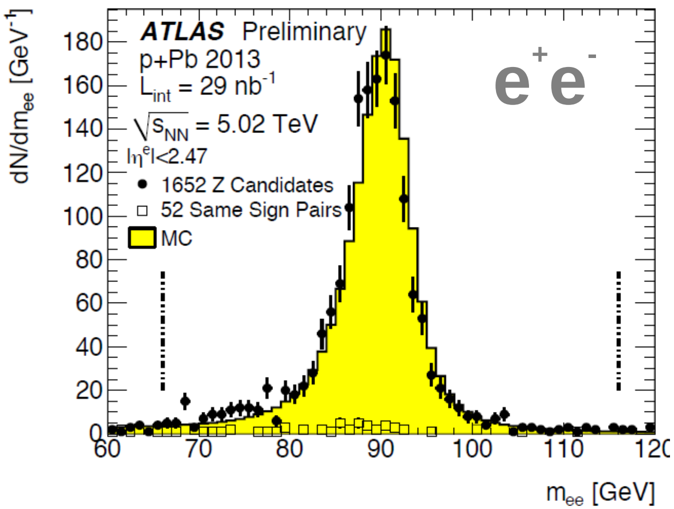
Flow in p+Pb vs flow in Pb+Pb

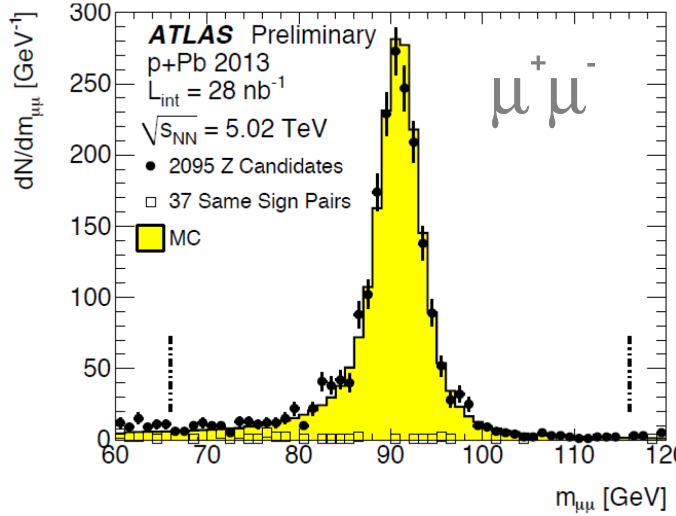


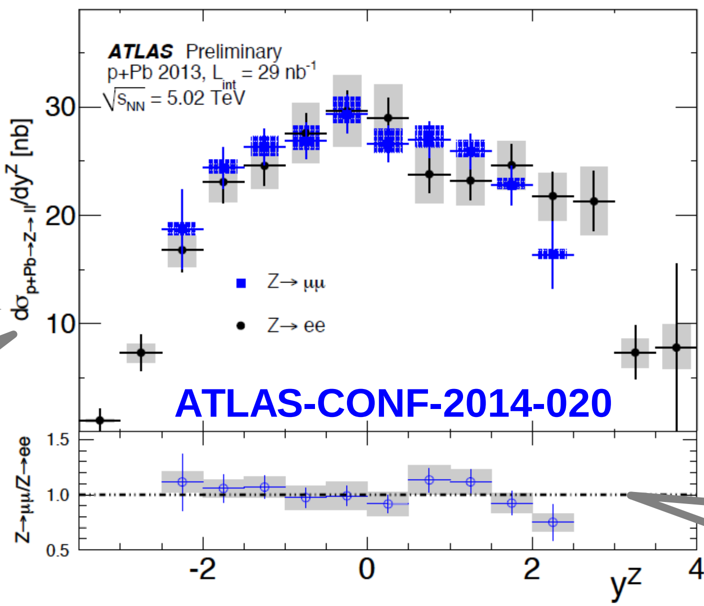
- Basar+Teaney: p+Pb should be **rescaled** to account for a difference between mean pt in p+Pb and Pb+Pb.
- After rescaling same shapes observed => long-range ridge correlations in high-multiplicity p+Pb and peripheral Pb+Pb driven by **similar dynamics**.

Hard physics

Z-boson cross-section



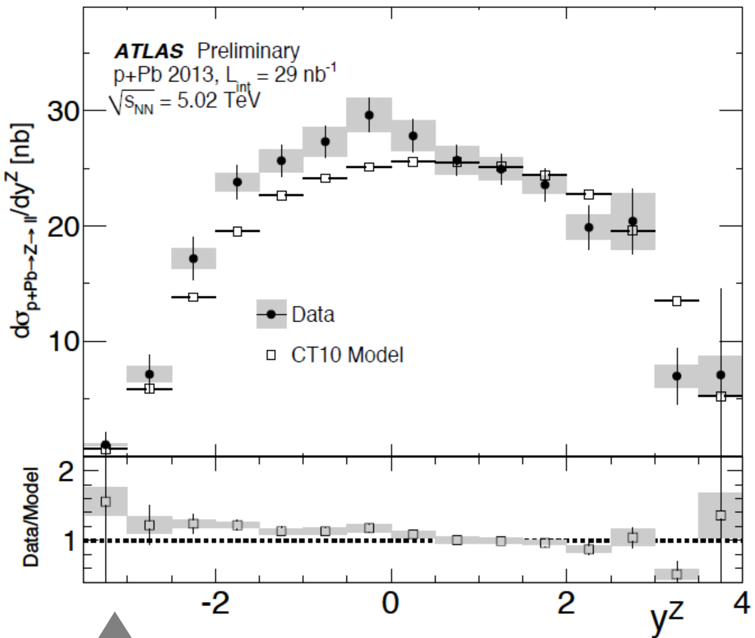




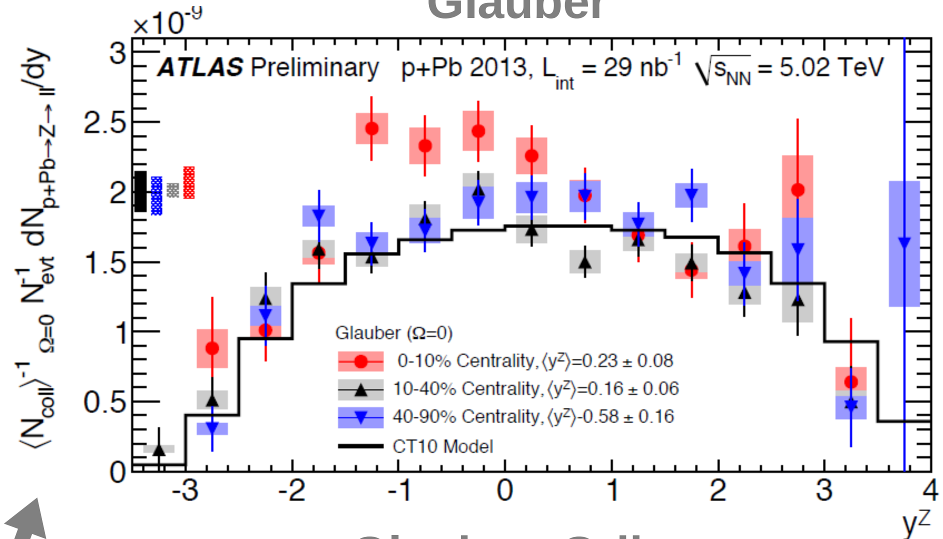
Cross-section, inclusive in centrality

Agreement between the two channels

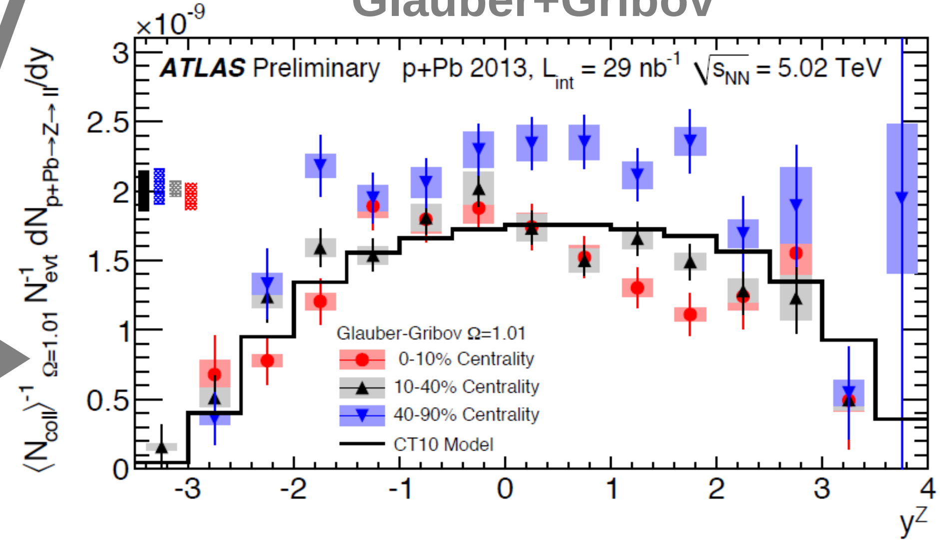
Z-boson cross-section and yields



Glauber

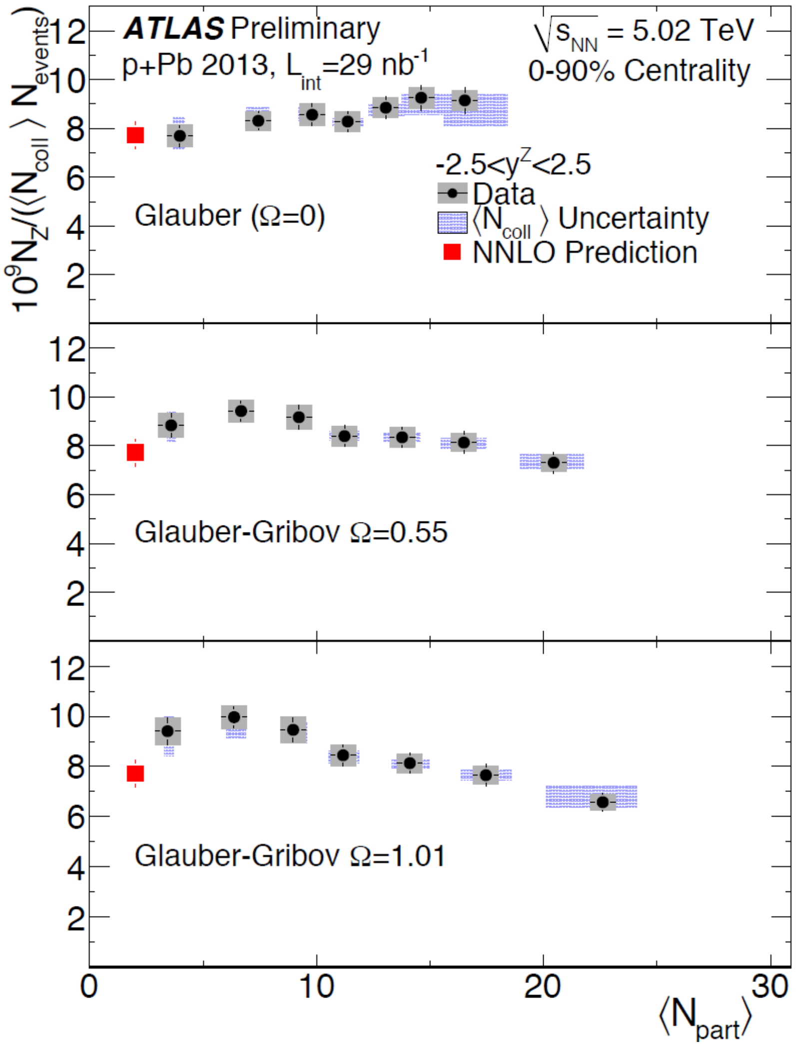


Glauber+Gribov

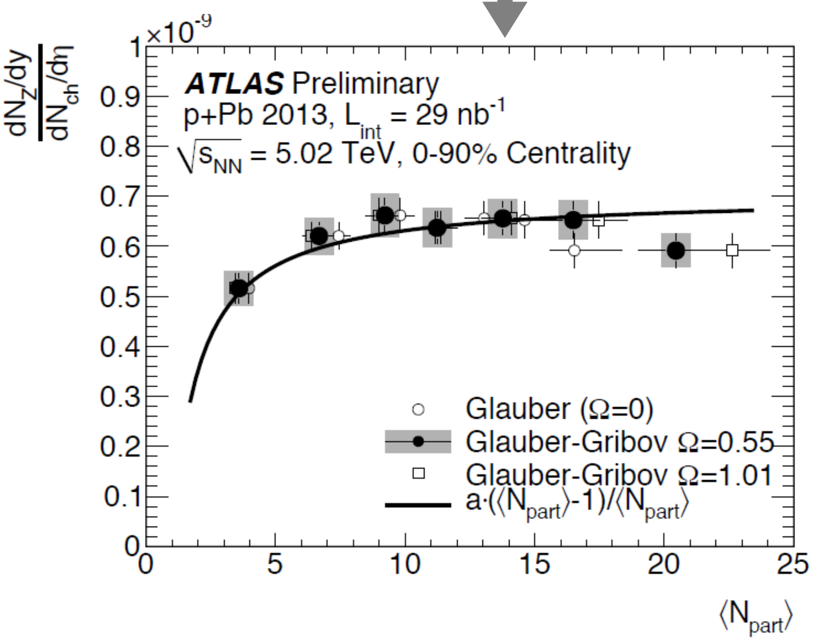


- Cross-section inclusive in flavor, **shape differs from MC** prediction
- **Centrality dependence of yields**, similar shape for different N_{coll} models, but magnitude strongly depends on the choice of the model

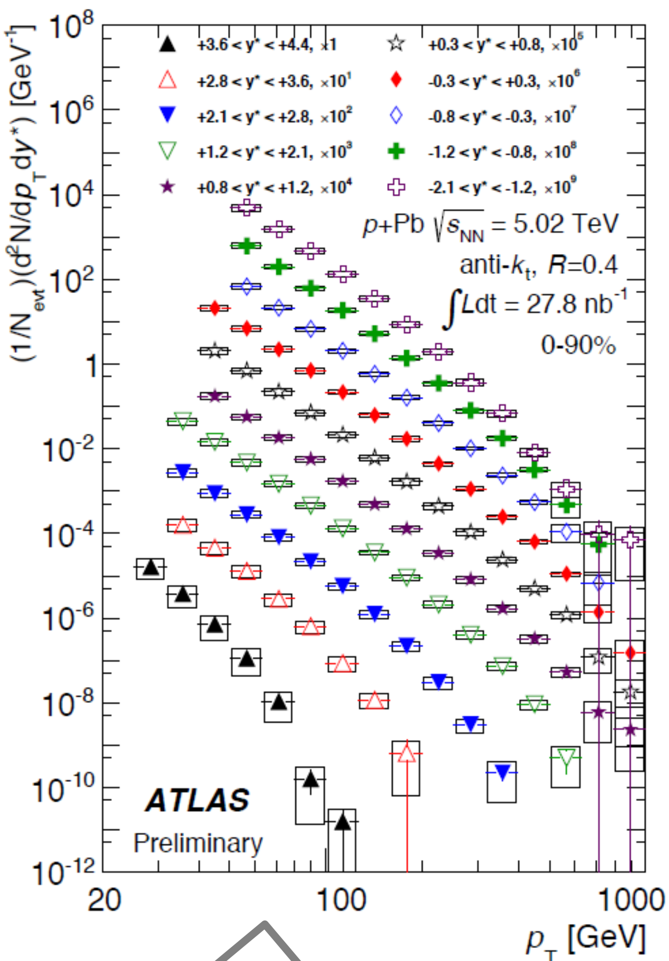
Z-boson production vs N_{part}



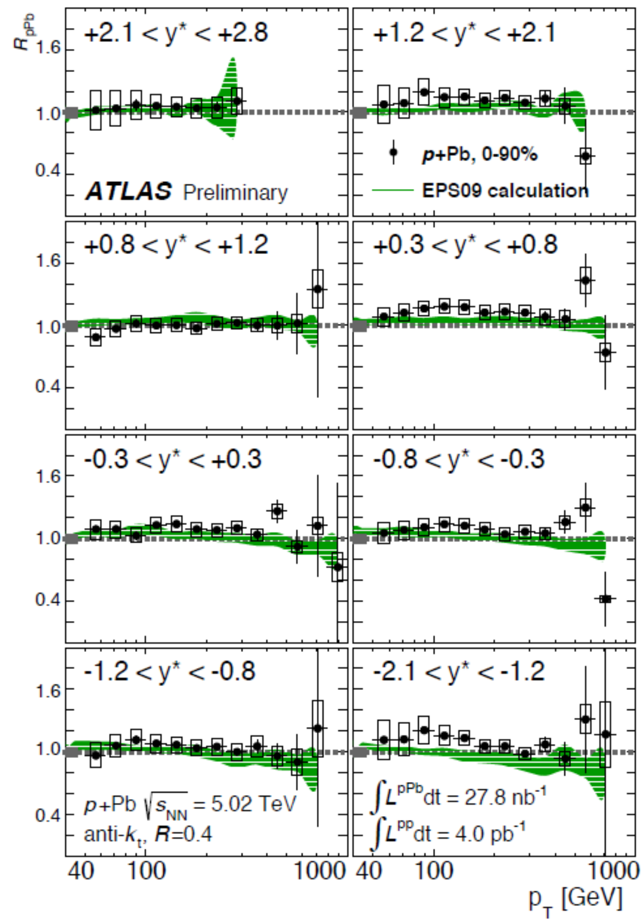
- Z-yield as a function of N_{part}, decrease seen for Glauber-Gribov with Ω=1.01
- Ratio of Z-yield and charged particle yields consistent with $a(N_{part}-1)/N_{part}$ as expected



Jet yields and R_{pPb}



0-90% jet yields



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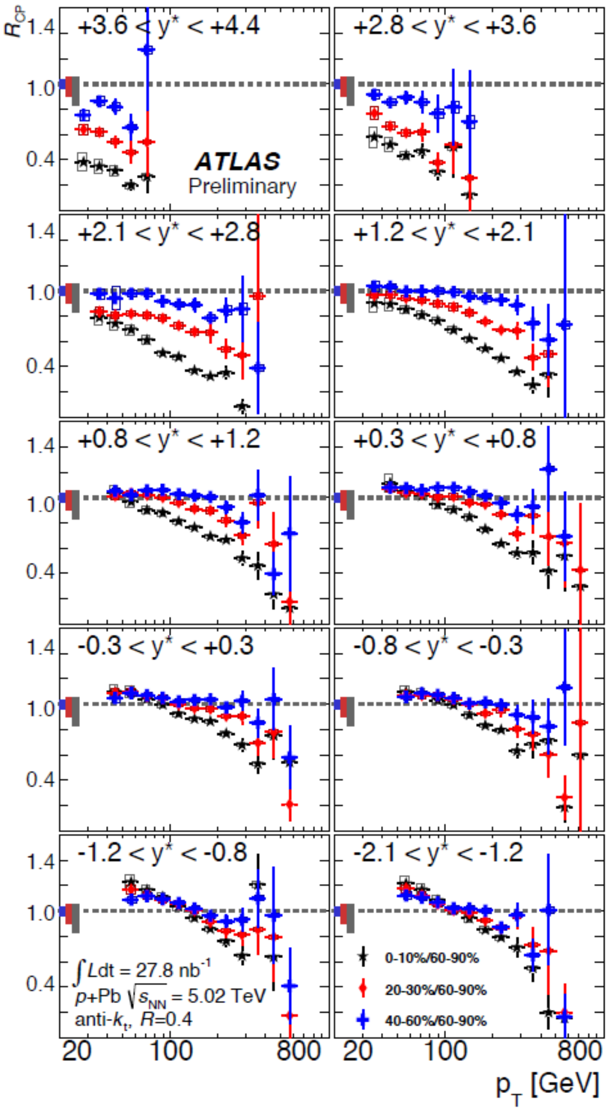
- 0-90% R_{pPb} compared to NLO with EPS09 nPDFs
- R_{pPb} does not differ much from unity if measured inclusively in centrality, **but** ...

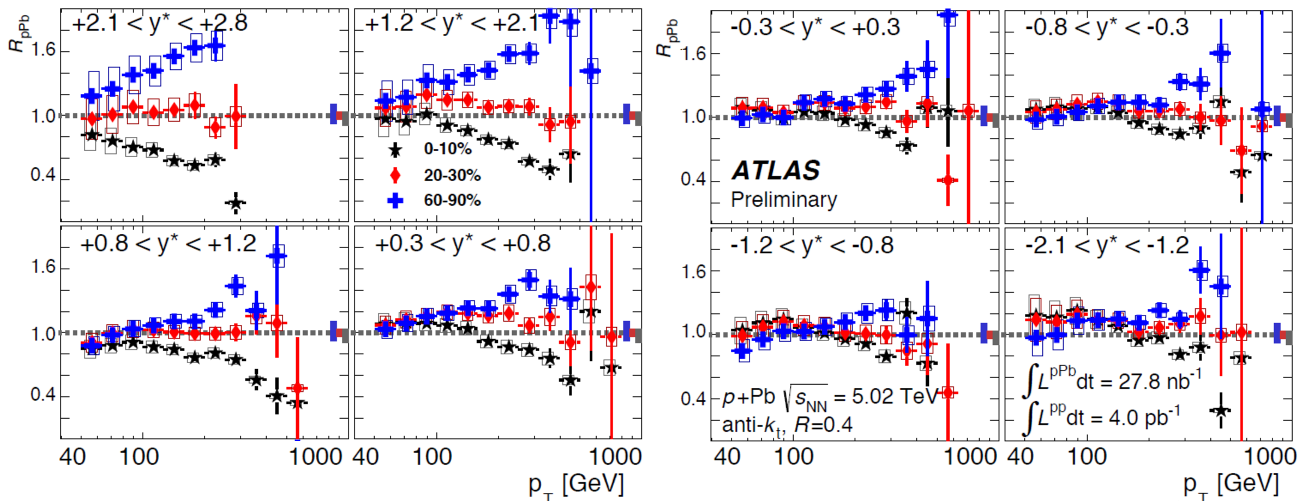
$$R_{pPb} \equiv \frac{1}{T_{pA}} \frac{(1/N_{evt})\ d^2N_{jet}/dp_T dy^*}{d^2\sigma^{pp}_{jet}/dp_T dy^*}$$

Jet R_{pPb} and R_{CP}



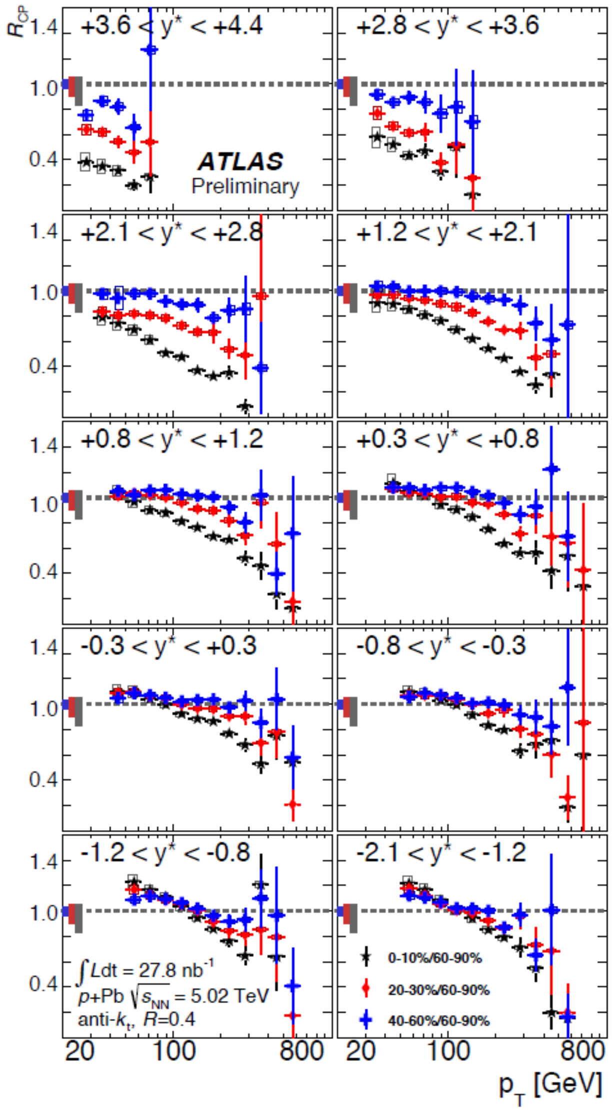
R_{CP}

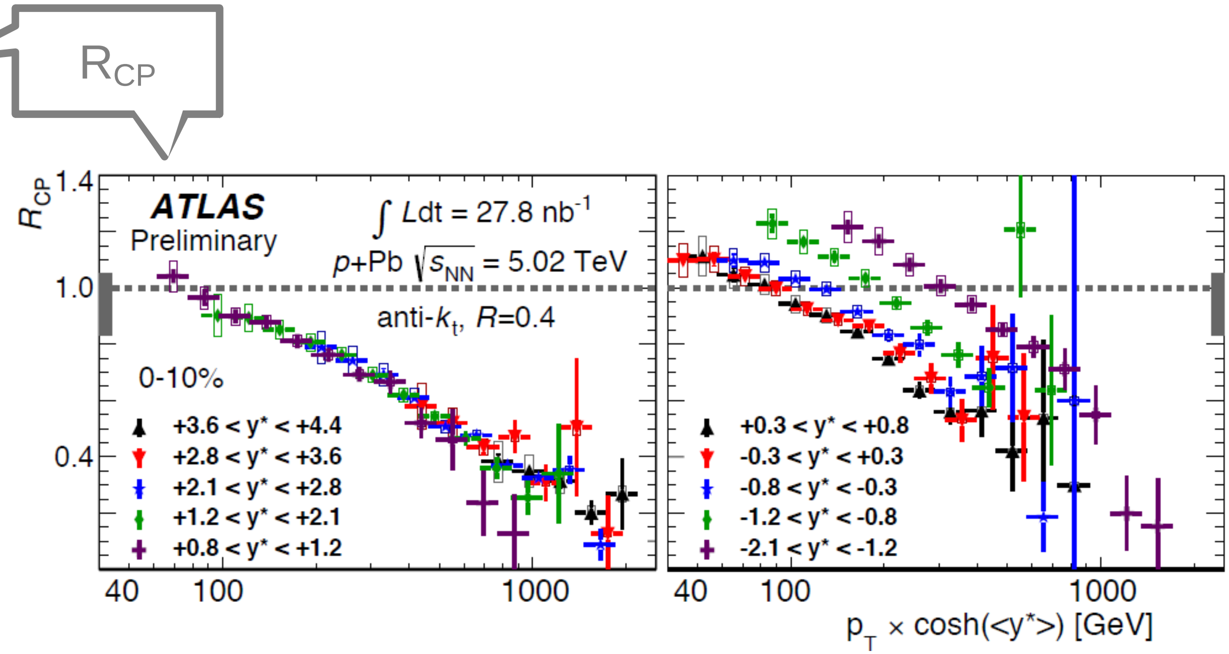
R_{pPb}



- **R_{CP} strongly varies with centrality** exhibiting decrease with increasing pt in all three centrality bins.
- If R_{pPb} is unity and R_{CP} decreases then there must be **enhancement in peripheral collisions** wrt to pp. Indeed, this is observed.
- The use of Glauber-Gribov only amplifies these effects.

Jet R_{CP}





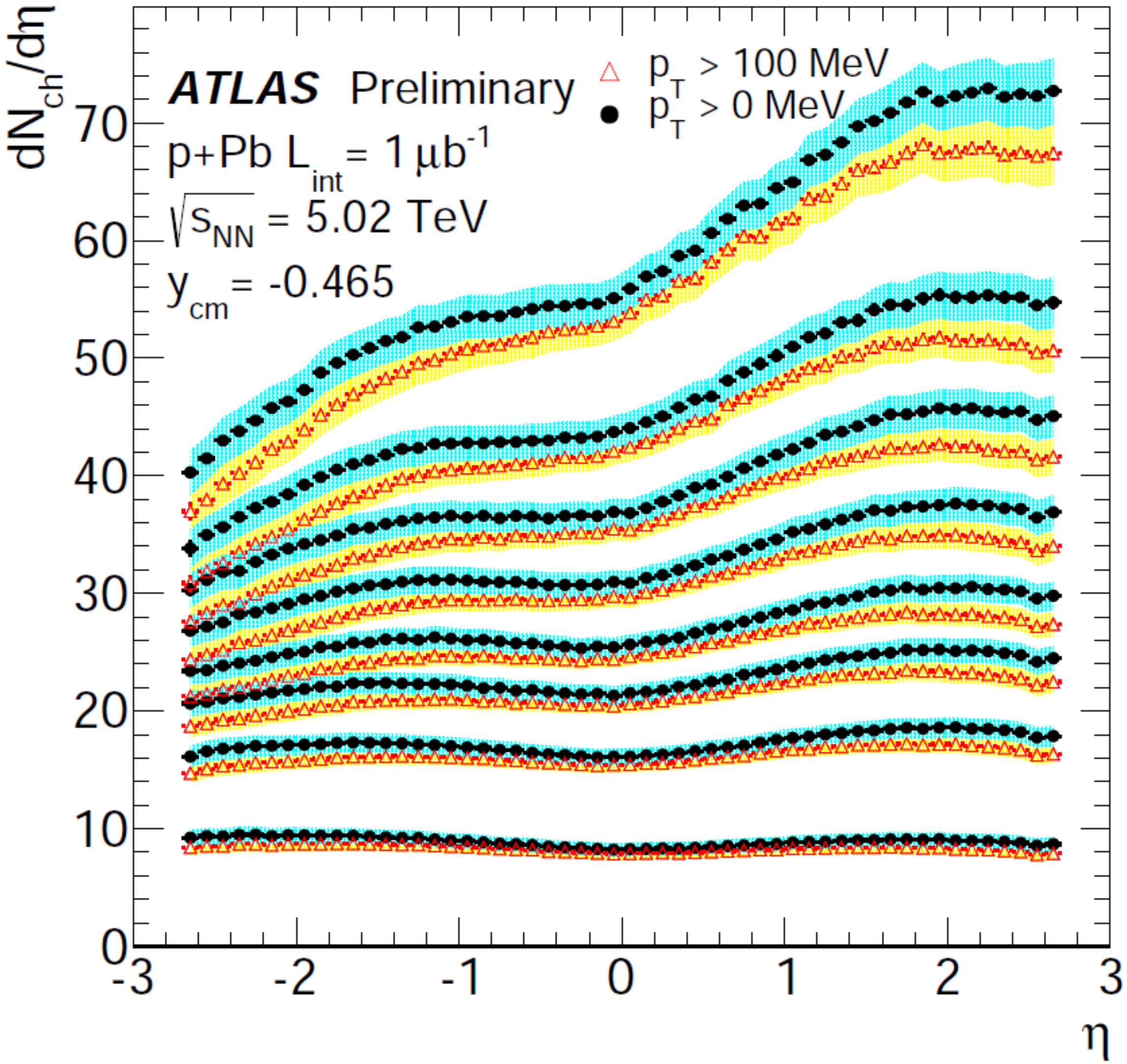
- **R_{CP} scales with E~p = pt·cosh(y) in the forward (p-going) direction**
  - production driven by x_p?
  - strong impact parameter dependence of number of partons available for hard scattering?
  - strong hard-soft correlations?

Conclusions –
– or summary of surprises? ☺

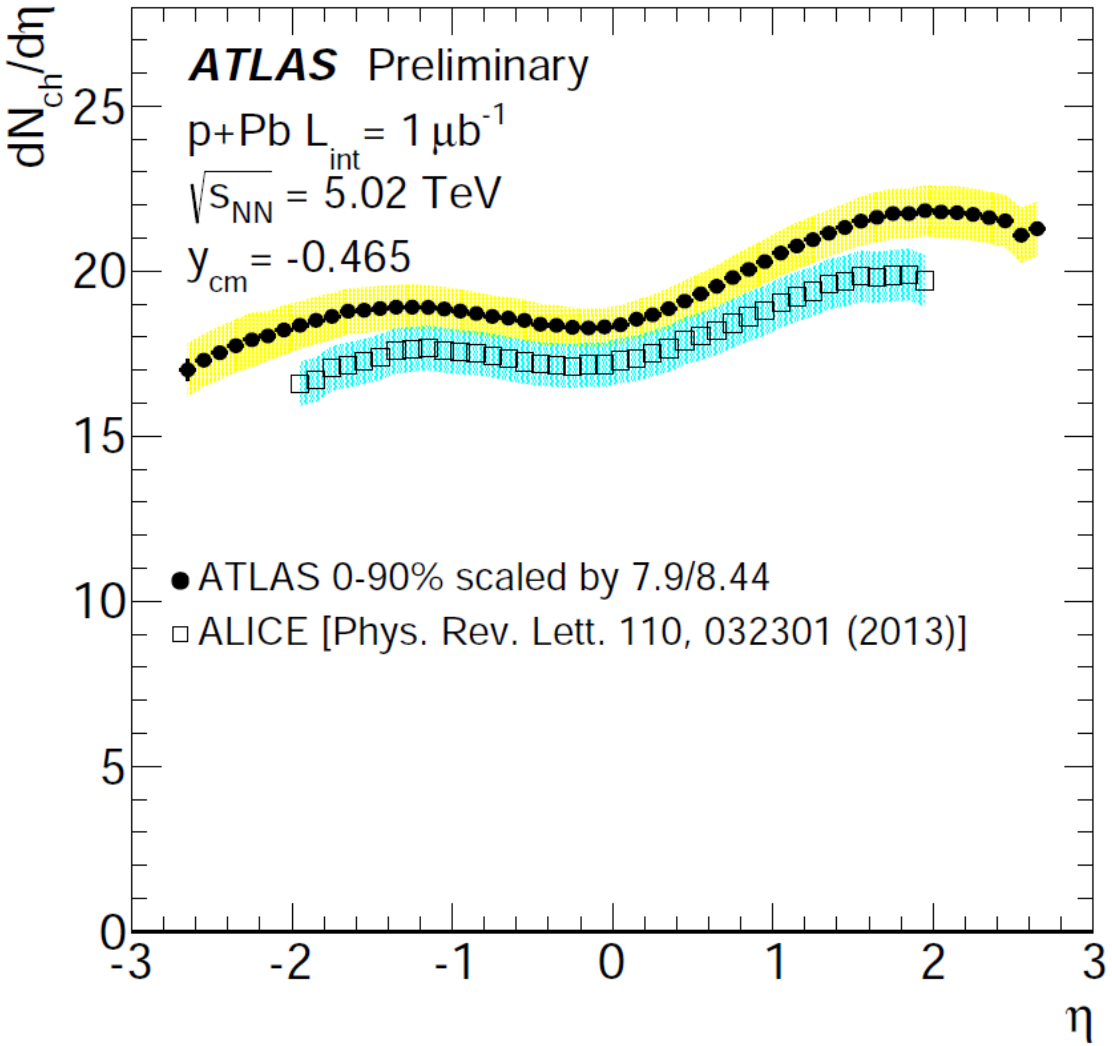
- Charged particle production: magnitude of Cronin peak and trends in the N_{part}-scaling of multiplicities depend on the choice of the centrality model.
- Charge particle R_{pPb}: large enhancement at high-pt.
- Ridge: significant $v_1 - v_5$, similar to those in heavy ion collisions.
- Ridge: long range eta correlations and flow in “central” p+Pb collisions likely driven by the same dynamics as the flow in peripheral Pb+Pb collisions.
- Z-boson: 0-90% cross-section does not fully agree with MC, the production is centrality dependent.
- Z-bosons / charged particles ~ $(N_{part}-1)/N_{part}$.
- Jet production: R_{CP} and R_{pPb} strongly vary with centrality.
- Jet production: R_{CP} scales with the total jet energy in p-going rapidity region.

Backup slides

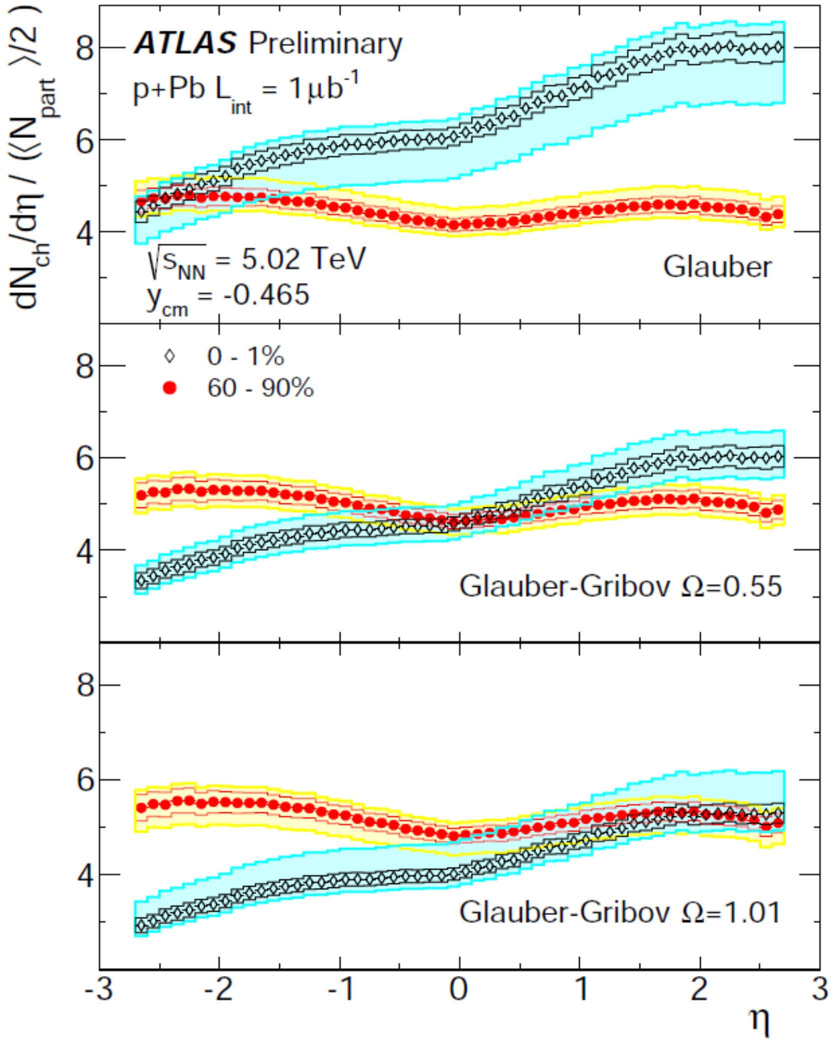
Multiplicity, extrapolation to 0 MeV



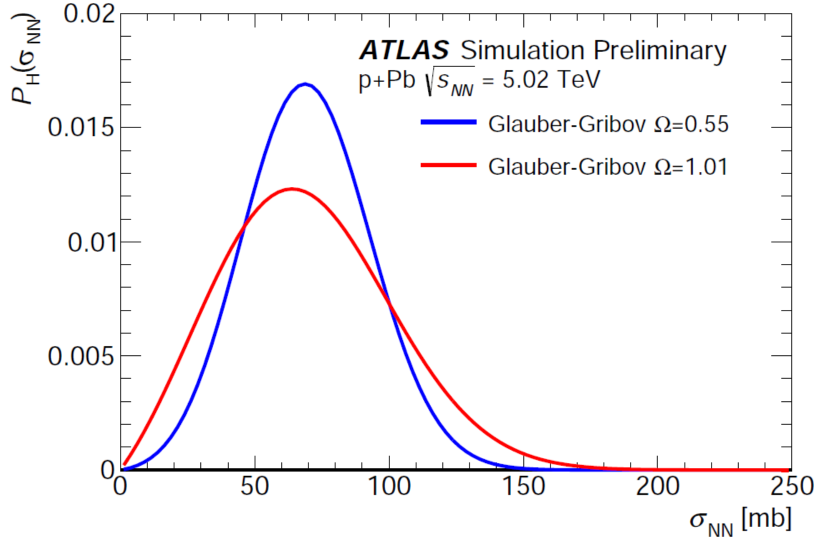
Multiplicity compared to ALICE

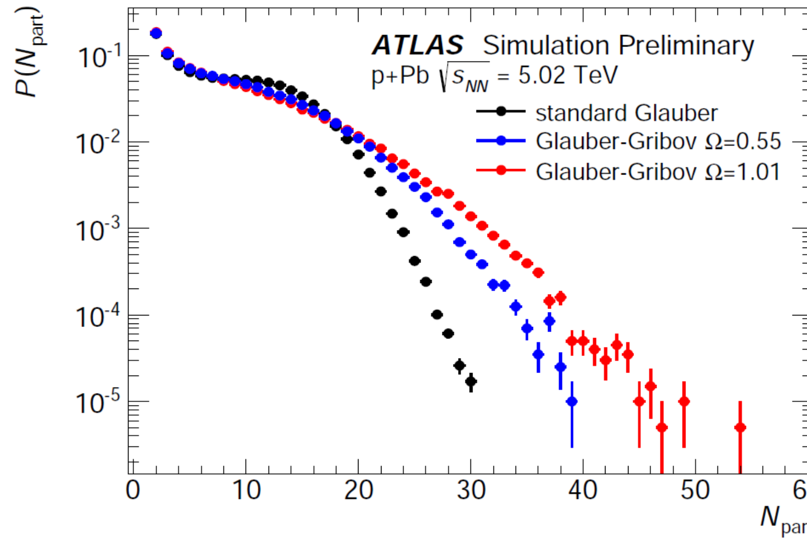


Multiplicity for different models



Glauber-Gribov analysis





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

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

… 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

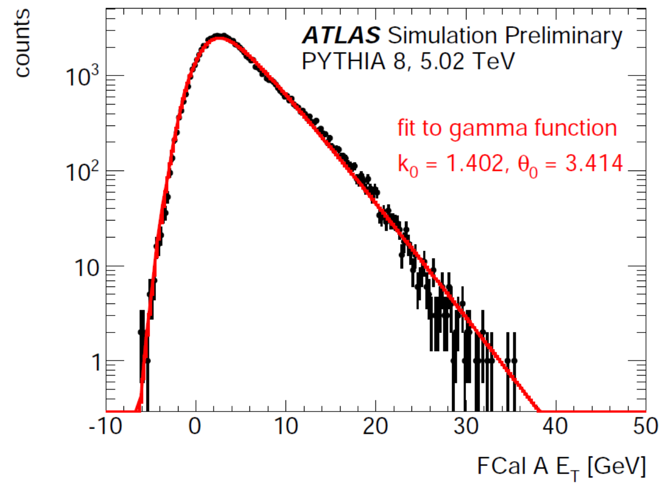
- For fixed N_{part}, ΣE_T^{Pb} ~ N_{part}-fold convolution of ΣE_T^{pp}
- ΣE_T^{pp} ~ gamma function:

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

=> 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

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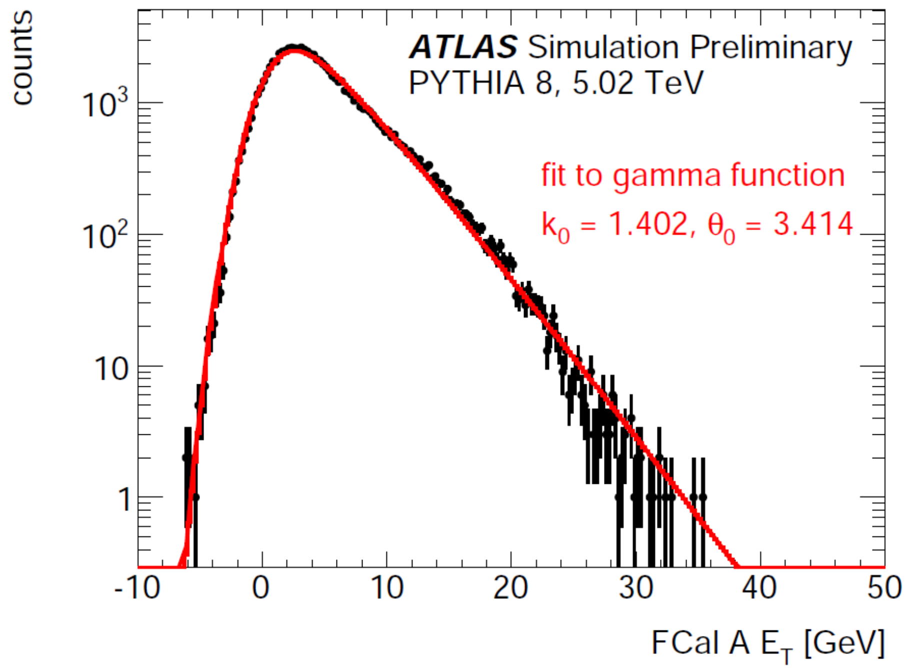

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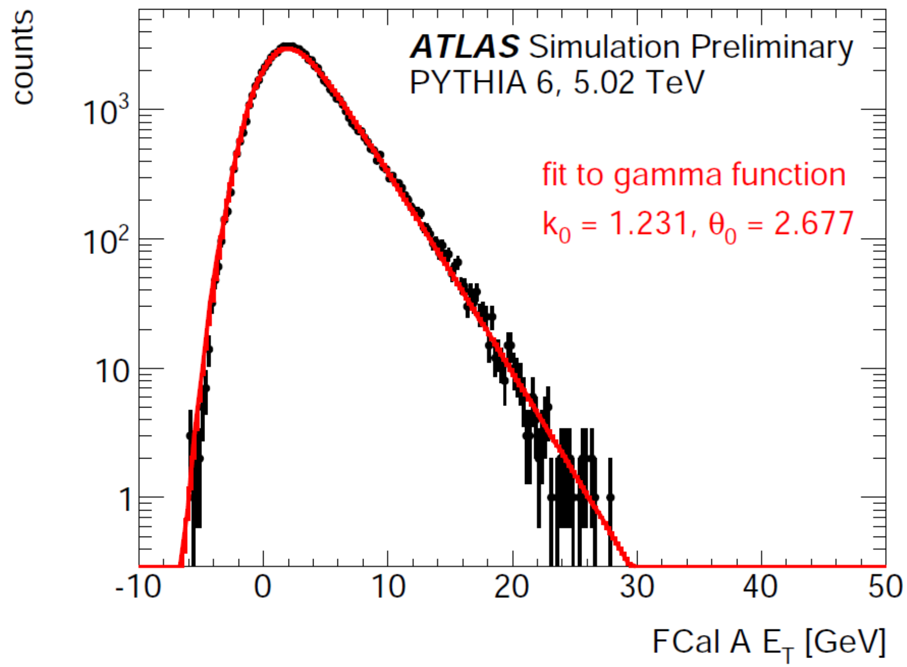
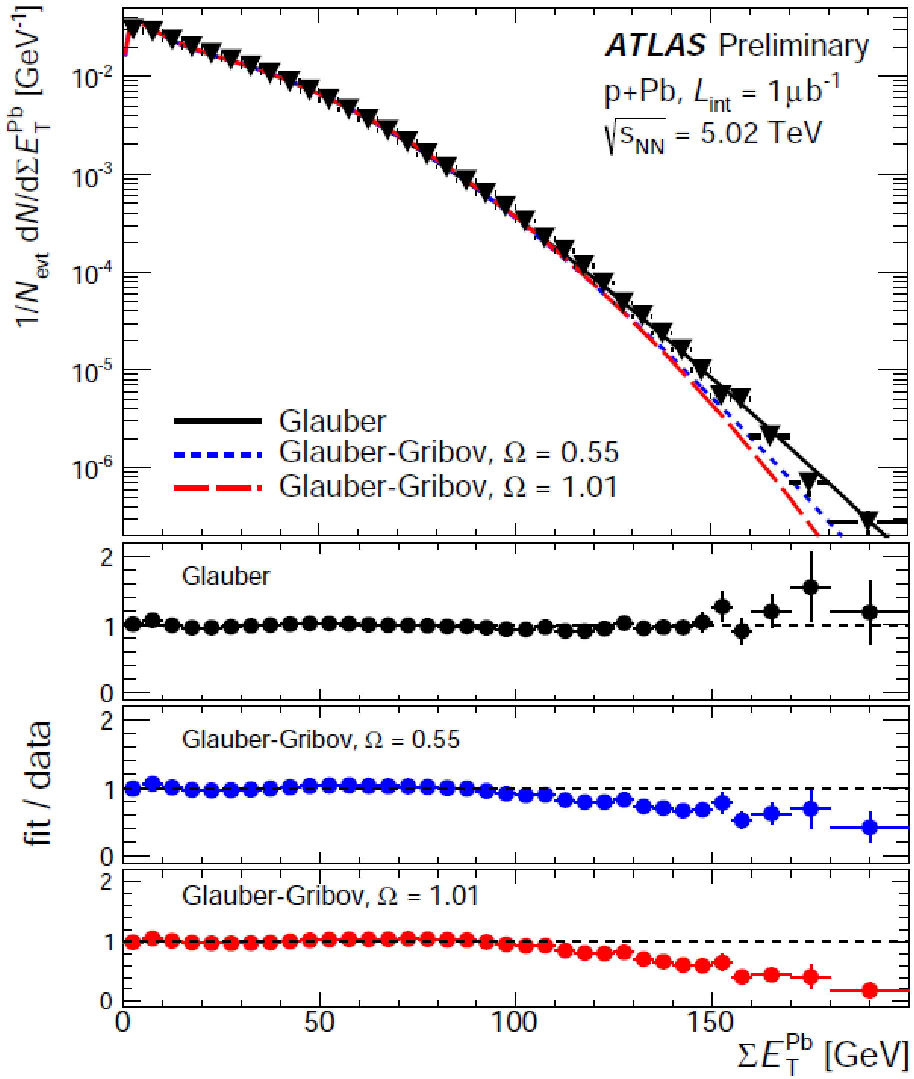
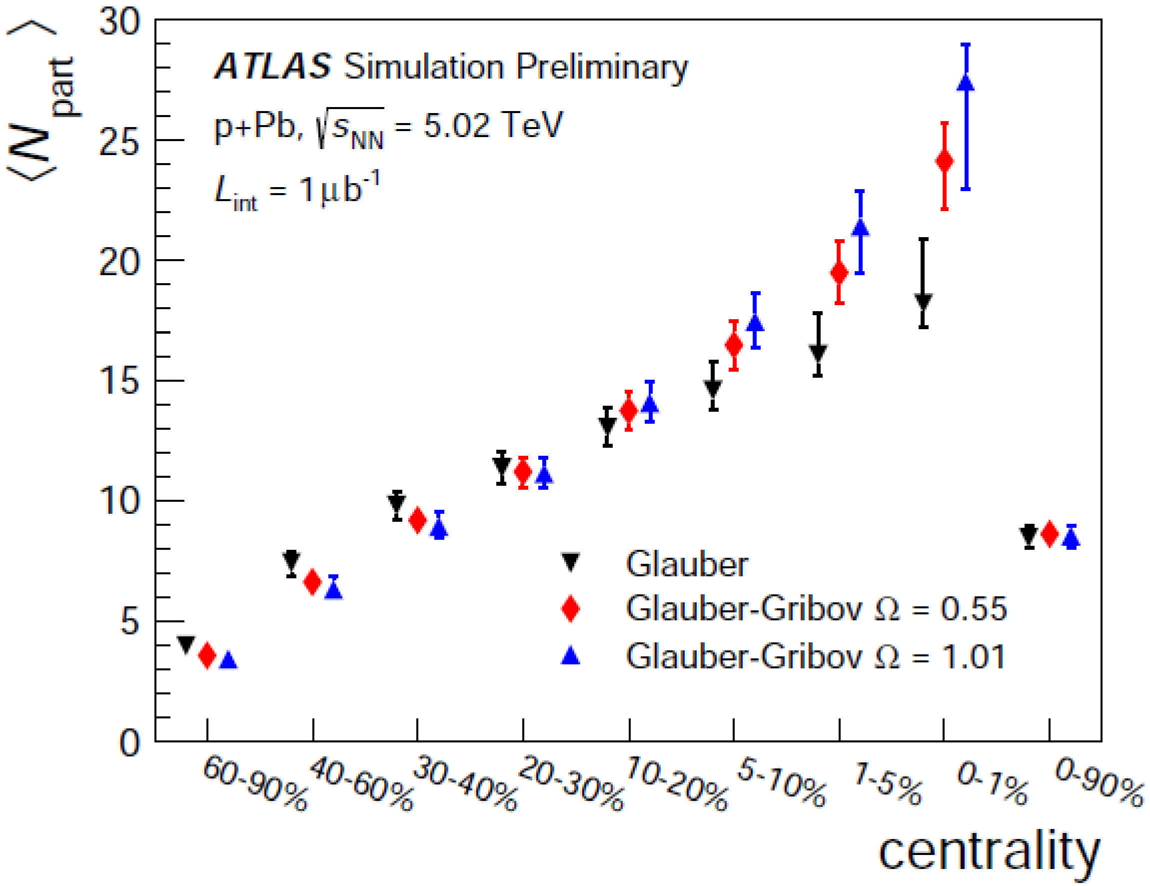


Matching to the FCal sum Et



Glauber-Gribov analysis



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

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

Centrality	Glauber	Glauber-Gribov	
		$\Omega = 0.55$	$\Omega = 1.01$
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	
		$\Omega = 0.55$	$\Omega = 1.01$
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 for charged particle spectra

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

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

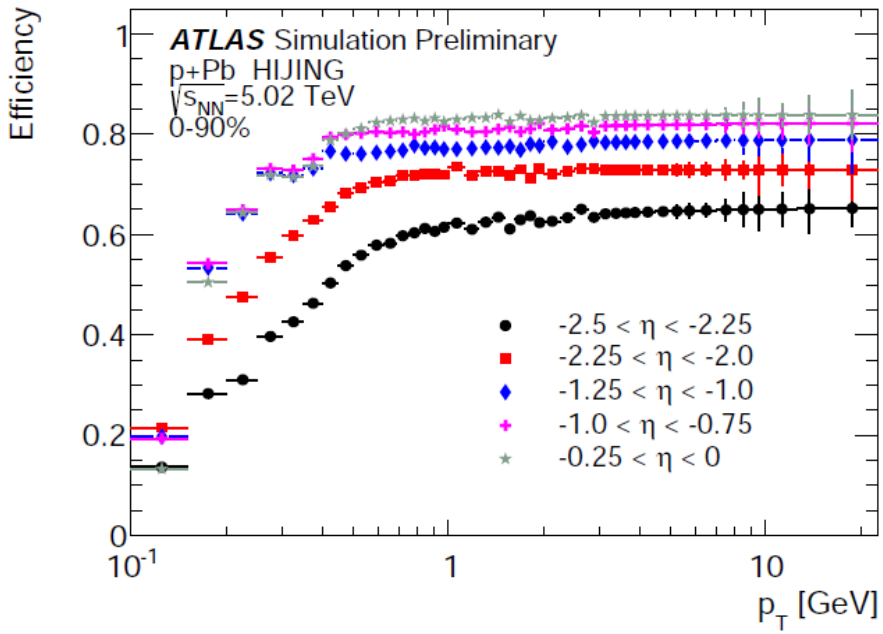
$\epsilon_{\mathrm{trk}}(p_{\mathrm{T}},y^{\star}_{\pi})$ … tracking efficiency

$\mathcal{P}(p_{\mathrm{T}},y^{\star}_{\pi})$ … 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 $\eta \rightarrow y^*_\pi$ (no particle ID)

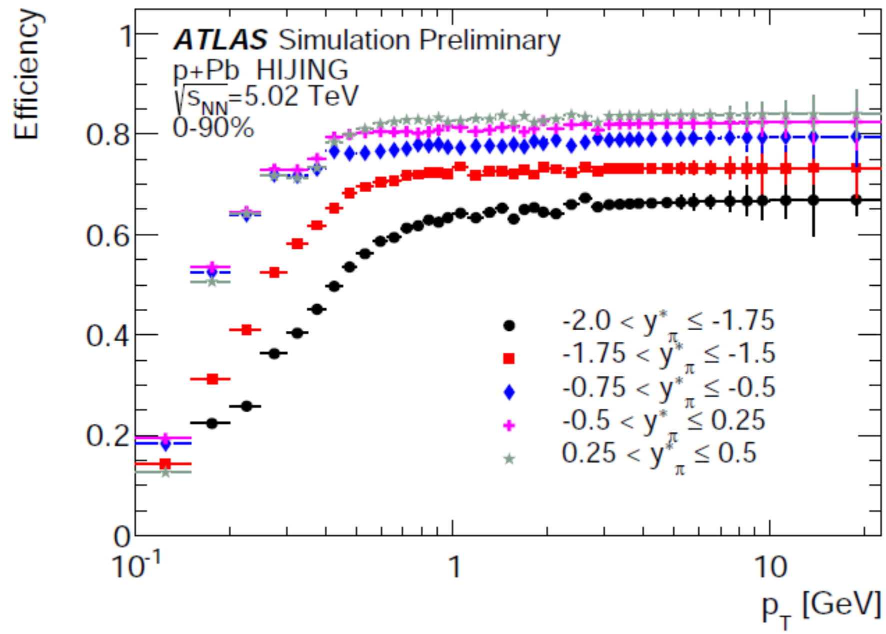
Tracking efficiency

... in η



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

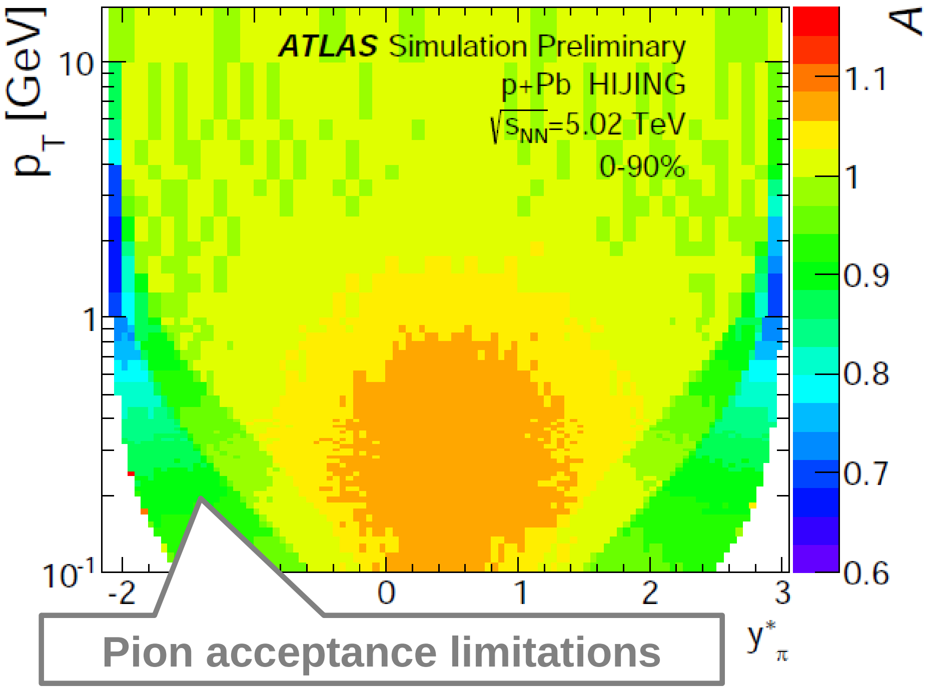
... in y*

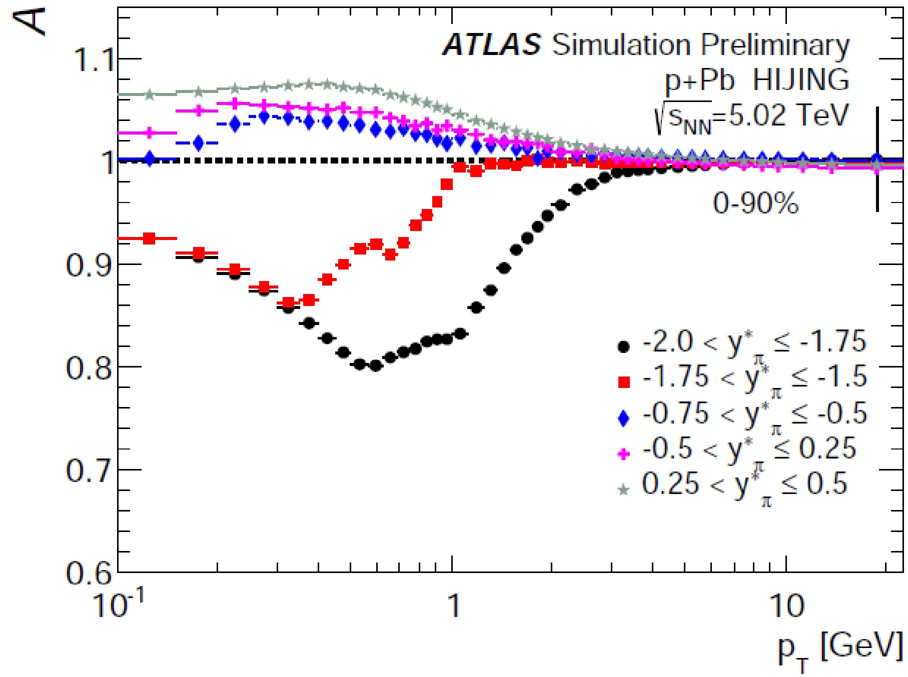


$$\epsilon_{\mathrm{trk}}(p_{\mathrm{T}}, y^\star_\pi) = \frac{N^{Rec}_{Primary}(p_{\mathrm{T}}^{Rec}, y^\star_\pi)}{N^{Gen}(p_{\mathrm{T}}^{Gen}, y^\star_\pi)}$$

"Mass correction"

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



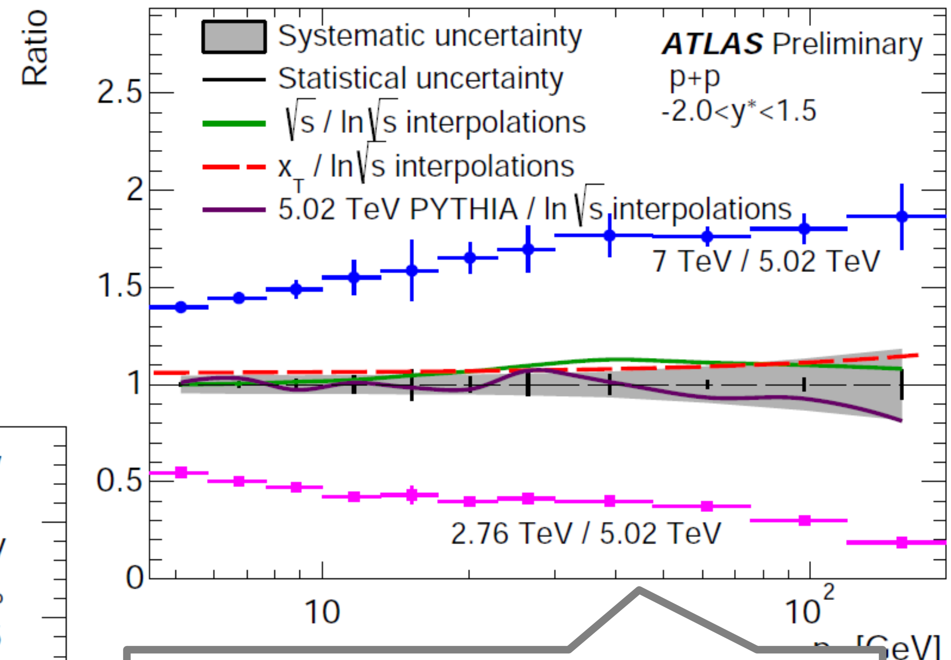


Correction done using HIJING. Difference between realistic particle composition and pp enters estimates of systematic uncertainties based on measurements of particle composition in p+Pb by CMS and ALICE.

Uncertainties for the multiplicity measurement

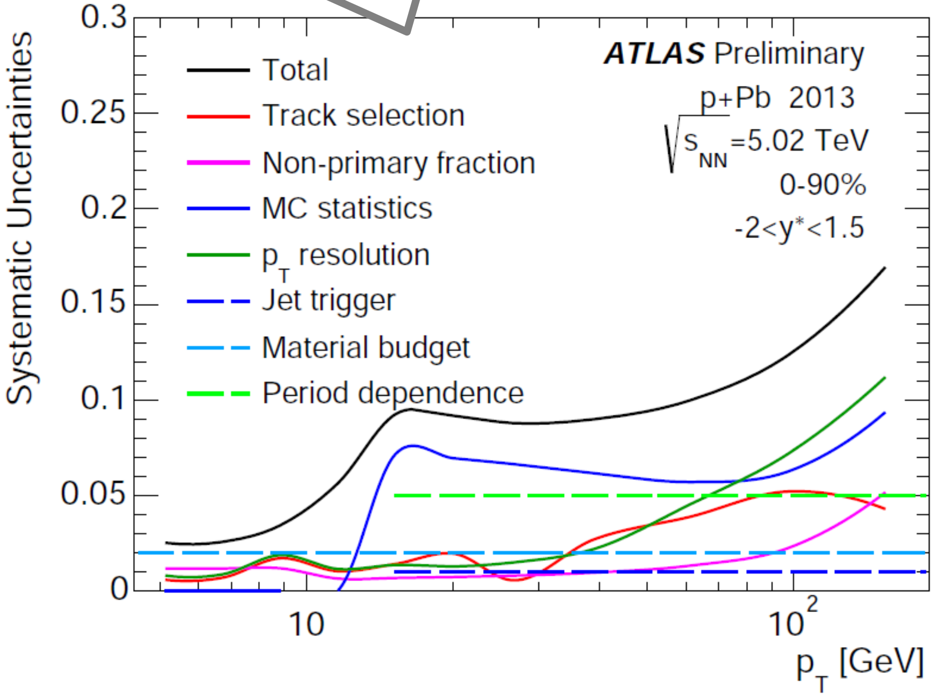
Source	Uncertainty 60-90% barrel	Uncertainty 60-90% endcap	Uncertainty 0-1% barrel	Uncertainty 0-1% endcup
MC detector description	1.7%		1.7%	
Extra material	1%	2%	1%	2%
Tracklet selection	0.5%	1.5%	0.5%	1.5%
p_{T} re-weighting	0.5%	0.5%	0.5%	3.0%
Extrapolation to p_{T}=0	1%	2.5%	1%	2%
Particle composition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

Uncertainties for the charged particle RpPb at high-pt



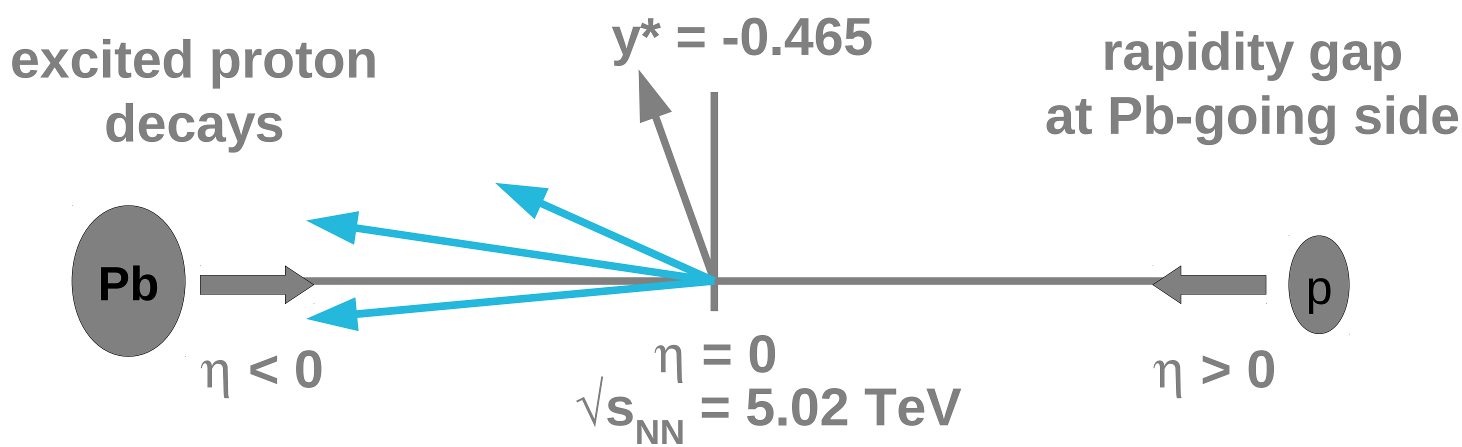
Uncertainties on the interpolation; Total uncertainty on 2.76 TeV spectra (gray band) used for the interpolated results

Uncertainty on the tracking

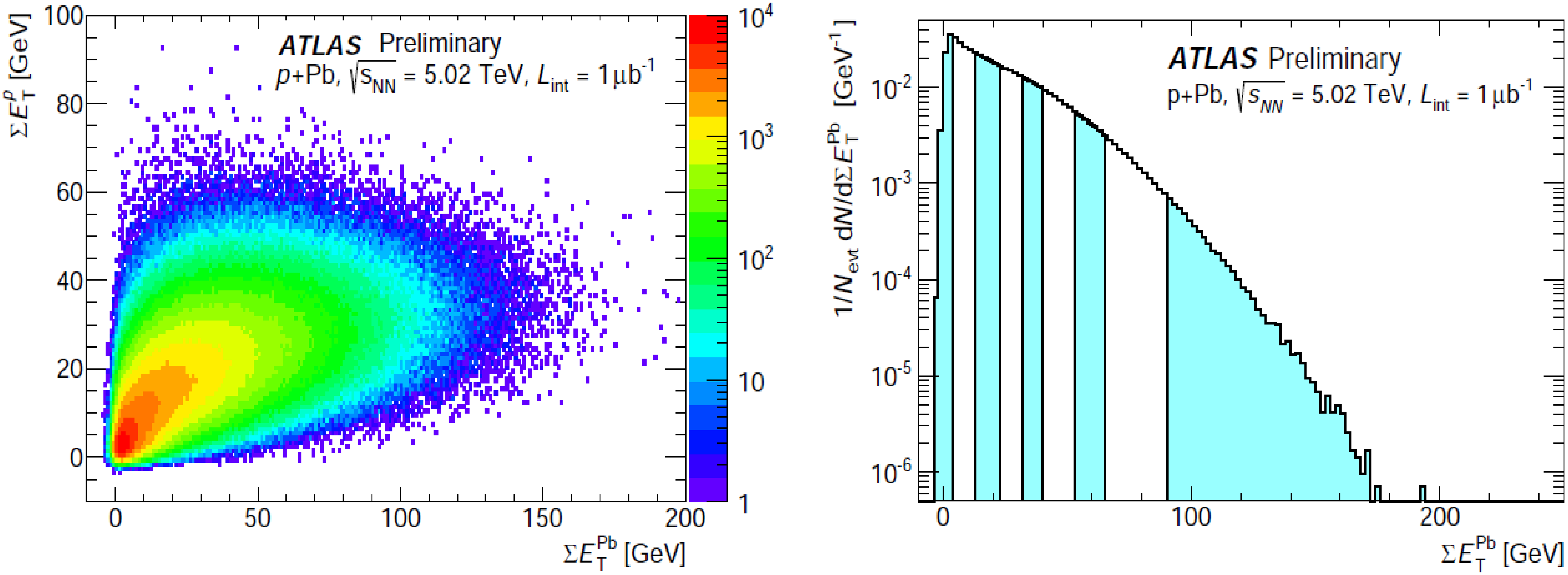


Rapidity gap analysis

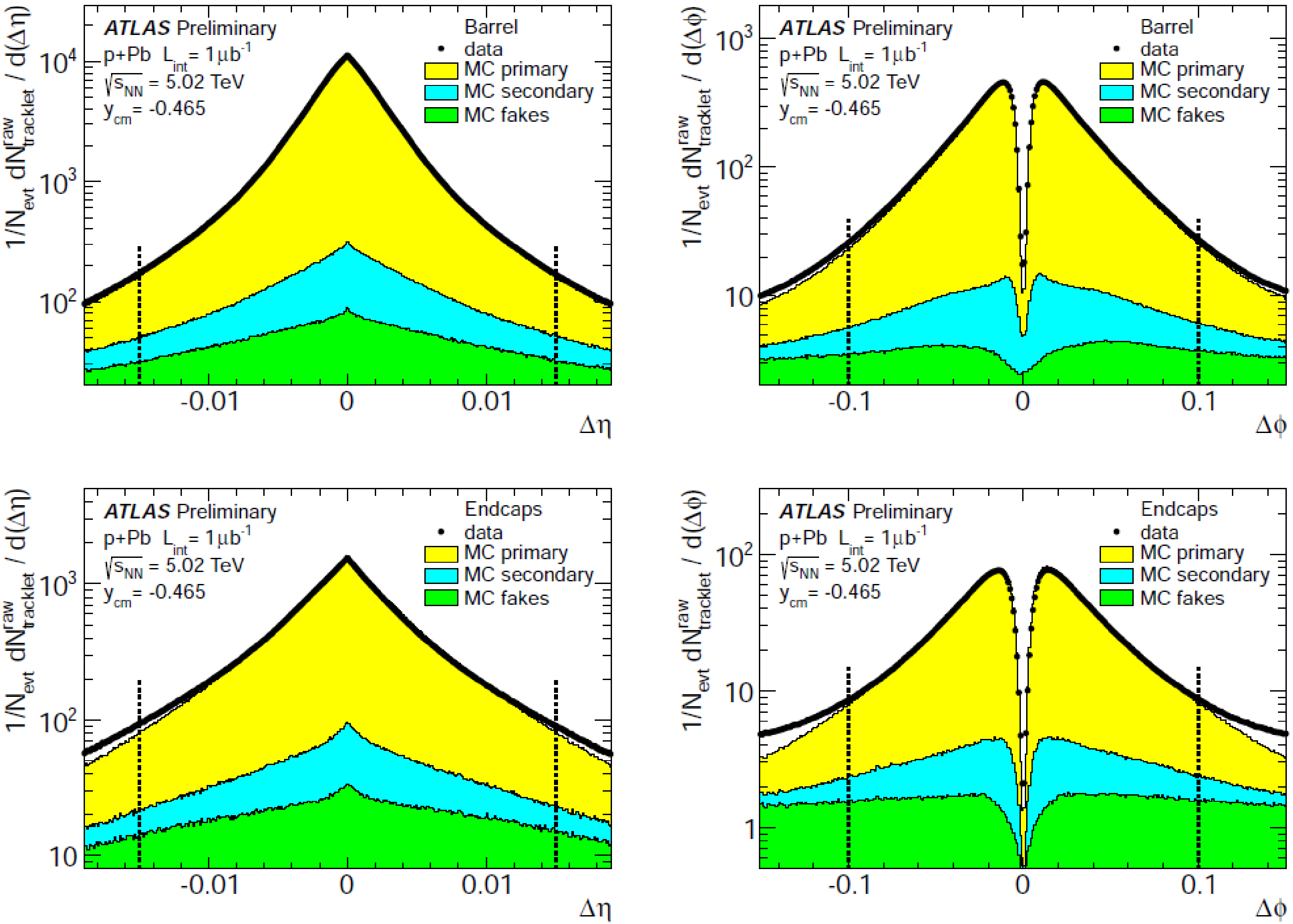
- Diffractive and electromagentic excitations of proton rejected:
  - rapidity gap analysis (similar to EPJ C72 (2012) 1926)
  - rapidity interval starting from $\eta_{\text{Pb-edge}} = 4.9$ divided into clusters in $\Delta\eta = 0.2$
  - occupied cluster = cluster with $p_T > 200$ MeV
  - events with $\Delta\eta_{gap} = |\eta_{\text{Pb-edge}} - \eta_{cluster}| > 2$ rejected



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



Extracting flow

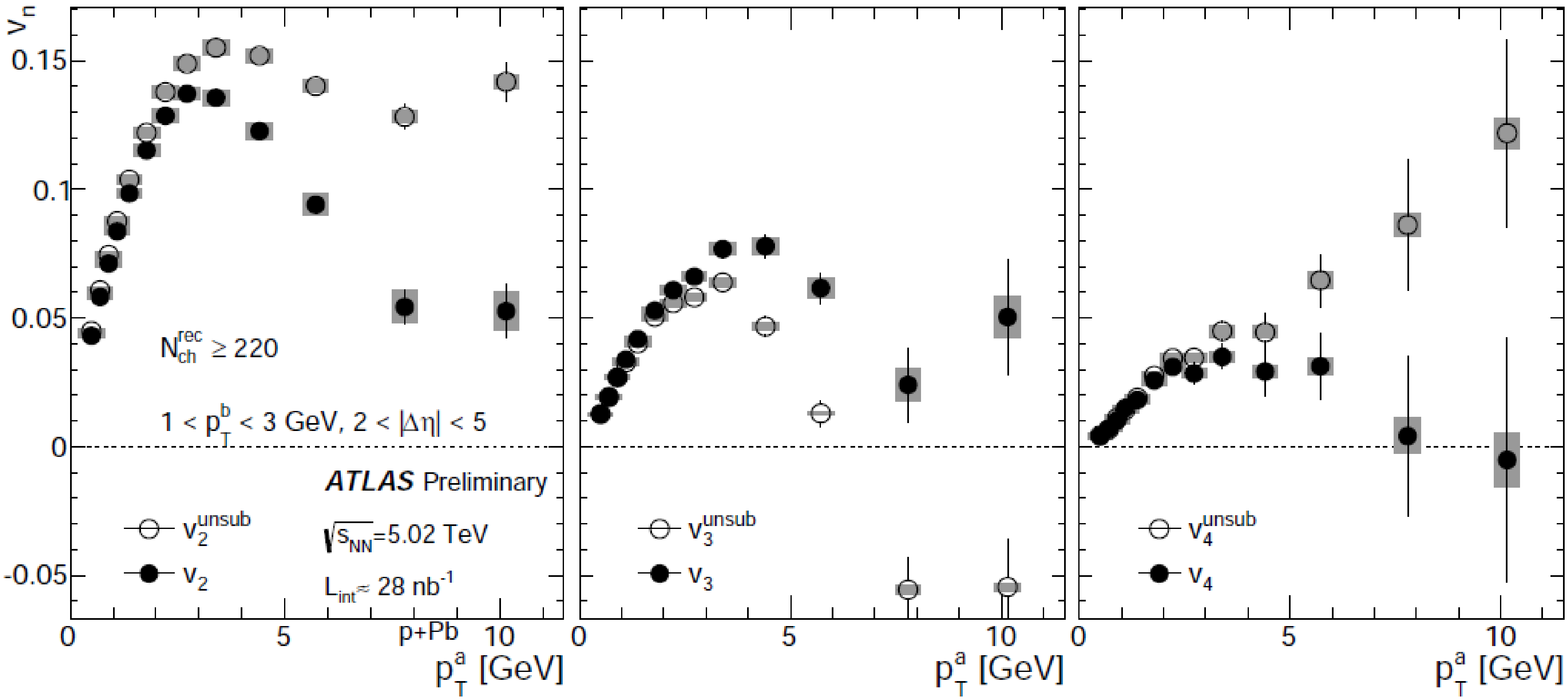
$$Y^{\mathrm{sub}}(\Delta\phi) = \frac{\int Y^{\mathrm{sub}}(\Delta\phi)d\Delta\phi}{\pi}\left(1 + \sum_n 2v_{n,n}\cos(n\Delta\phi)\right)$$

$$v_{n,n} = \frac{\sum_{m=1}^{N}\cos(n\Delta\phi_m)Y^{\mathrm{sub}}(\Delta\phi_m)}{\sum_{m=1}^{N}Y^{\mathrm{sub}}(\Delta\phi_m)}$$

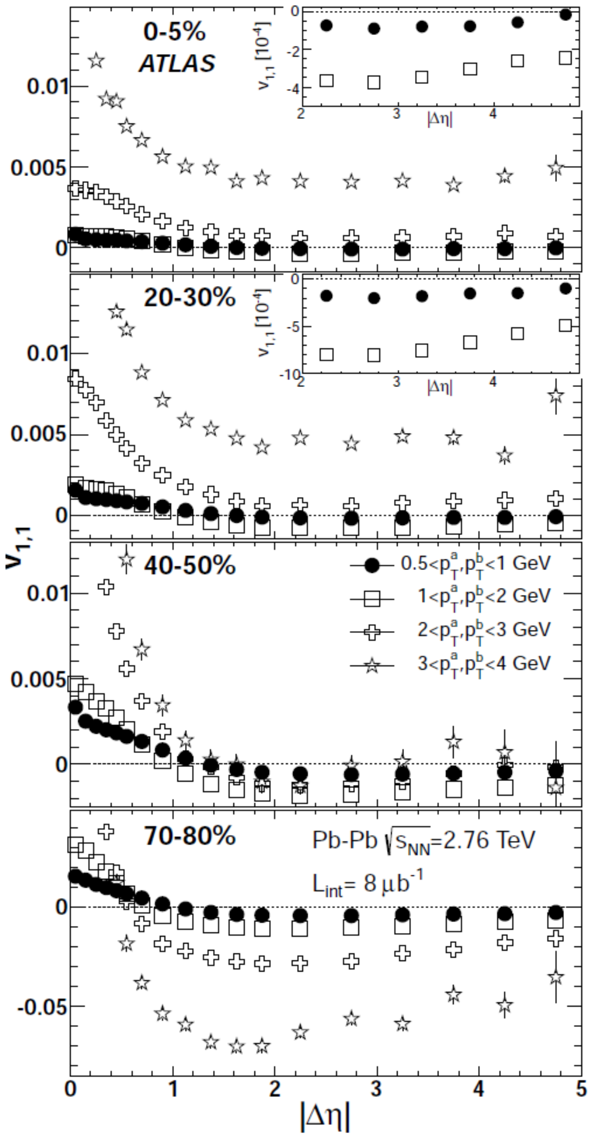
$$v_{n,n}(p_{\mathrm{T}}^{\mathrm{a}}, p_{\mathrm{T}}^{\mathrm{b}}) = v_n(p_{\mathrm{T}}^{\mathrm{a}})v_n(p_{\mathrm{T}}^{\mathrm{b}})$$

$$v_n(p_{\mathrm{T}}) = v_{n,n}(p_{\mathrm{T}}, p_{\mathrm{T}}^{\mathrm{ref}})/\sqrt{v_{n,n}(p_{\mathrm{T}}^{\mathrm{ref}}, p_{\mathrm{T}}^{\mathrm{ref}})}$$

Unsubtracted v_n values



v_1



Negative recoil + positive dipolar flow