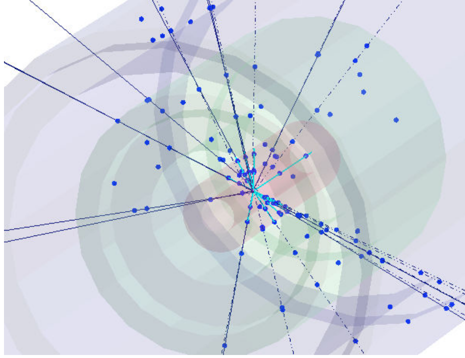


Charged-Particle Multiplicity at LHC Energies

Jan Fiete Grosse-Oetringhaus, CERN/PH
for the ALICE collaboration

CERN PH Seminar
22nd March 2010

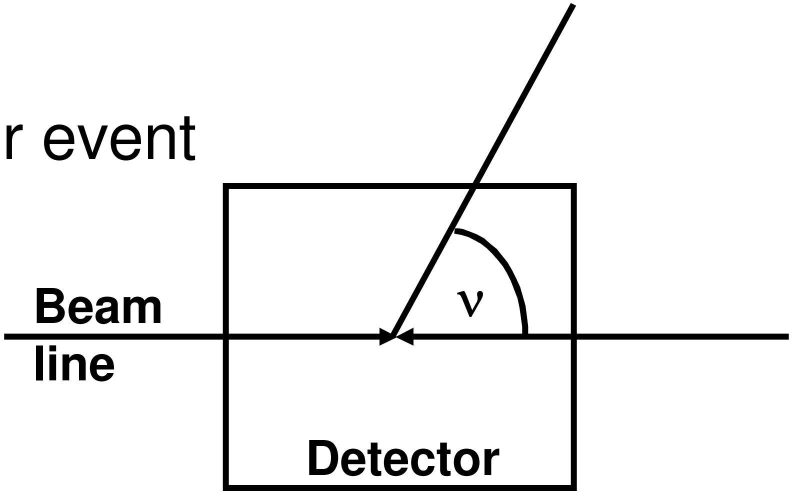
Charged-Particle Multiplicity

- Previous measurements at hadron colliders, theoretical models and predictions for LHC
- Pseudorapidity density and multiplicity distribution measurement procedure with ALICE
  - Detector status and data taking
  - Analysis procedure
  - Systematic uncertainties
- Data sample and MC validation
- Results

Definitions

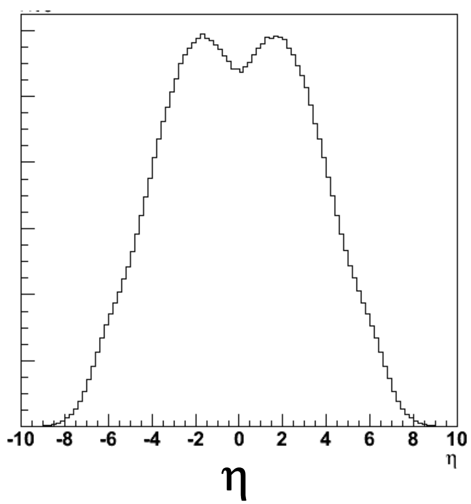
- Primary charged particles N_{ch} per event
- Number of events N_{ev}
- Pseudorapidity

$$\eta = \frac{1}{2} \ln \frac{p + p_L}{p - p_L} = -\ln \tan \frac{\upsilon}{2}$$



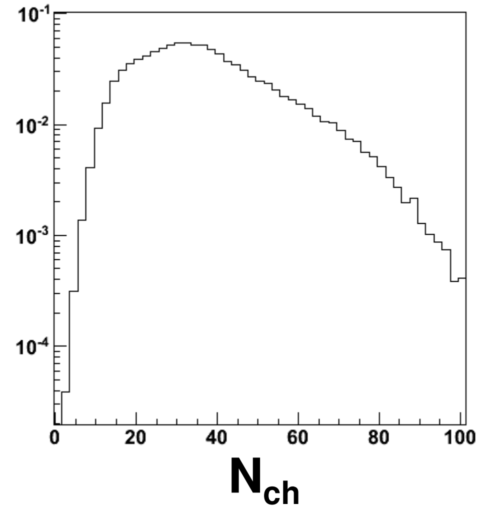
- Pseudorapidity density

$$\frac{dN_{ch}}{d\eta}$$



- Multiplicity distribution

$$P(N_{ch}) = \frac{1}{N_{ev}} \frac{dN_{ev}}{dN_{ch}}$$



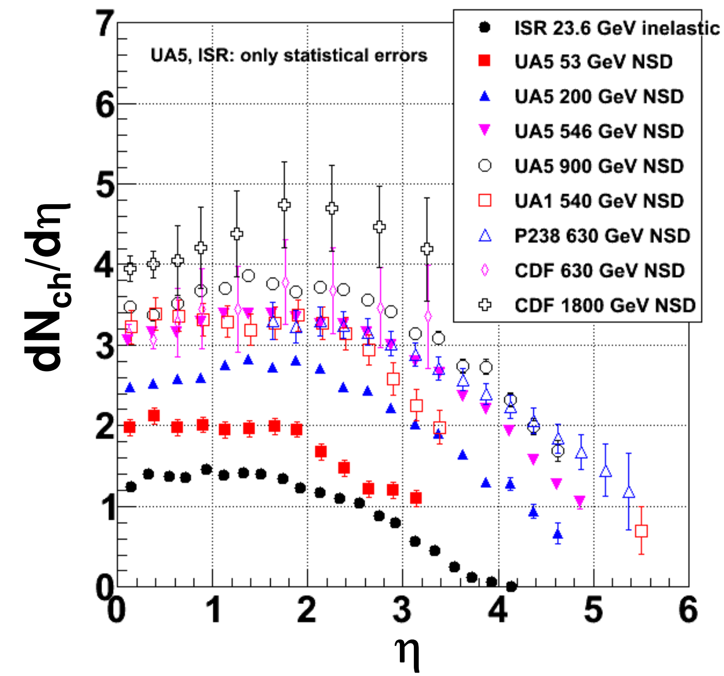
Part 1

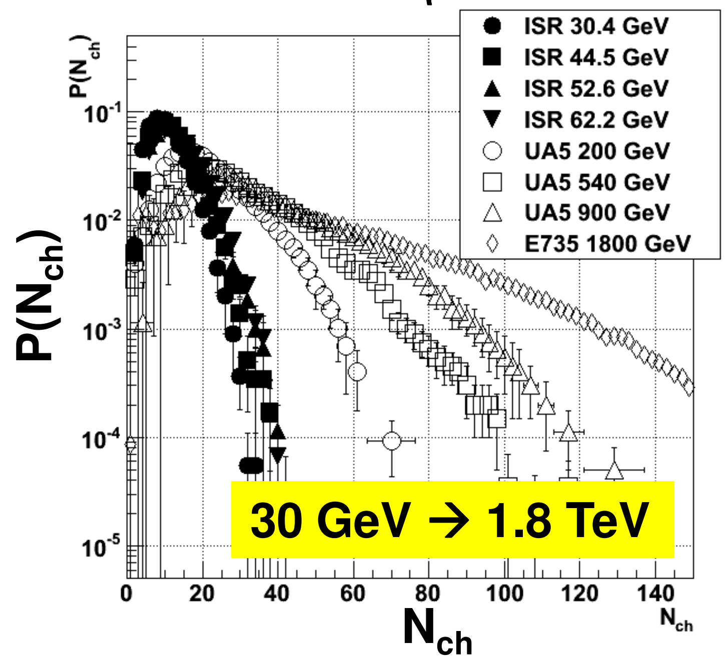
Previous measurements at hadron colliders, theoretical models and predictions for LHC

Charged-Particle Multiplicity

- Simple observable in collisions of hadrons
- Important ingredient for the understanding of multi-particle production
  - LHC is in an energy realm where multiple parton interactions are in the bulk of the events
- Constrain, reject and improve models

Review article (K. Reygers, JFGO)
Charged-Particle Multiplicity in Proton–Proton Collisions
arXiv:0912.0023
submitted to Journal of Physics G





Feynman Scaling

- Phenomenological arguments about the exchange of quantum numbers
- Feynman-x: $x = 2p_z/\sqrt{s}$
- Feynman scaling function $f(p_T, x)$ independent of cms energy (for large energies)

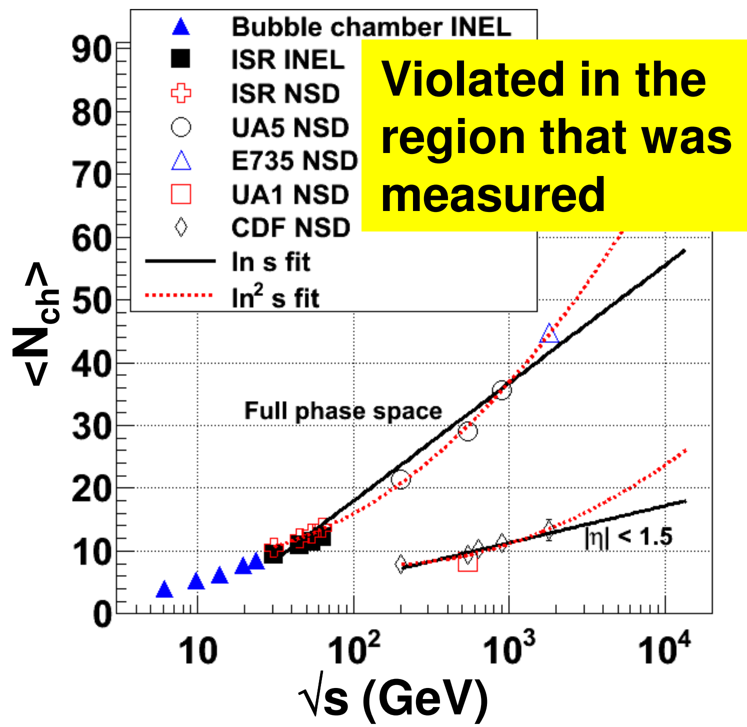
→ Average N_{ch} increases with ln s

→ $dN_{ch}/d\eta$ approx. constant

VERY HIGH-ENERGY COLLISIONS OF HADRONS

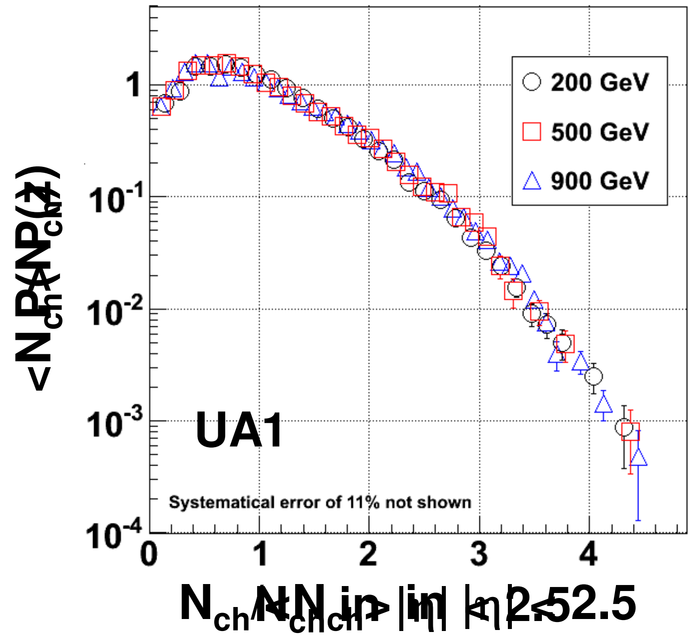
Richard P. Feynman
California Institute of Technology, Pasadena, California
(Received 20 October 1969)

PRL 23 1415 (1969)



KNO Scaling

- Koba, Nielsen, Olesen (1972)
- Based on Feynman scaling
- Scaling variable
  $z = N_{ch}/\langle N_{ch}\rangle$
- Express $P(N_{ch})$ as
  $P(z) * \langle N_{ch}\rangle$
- Multiplicity distributions measured at different energies fall onto universal curve

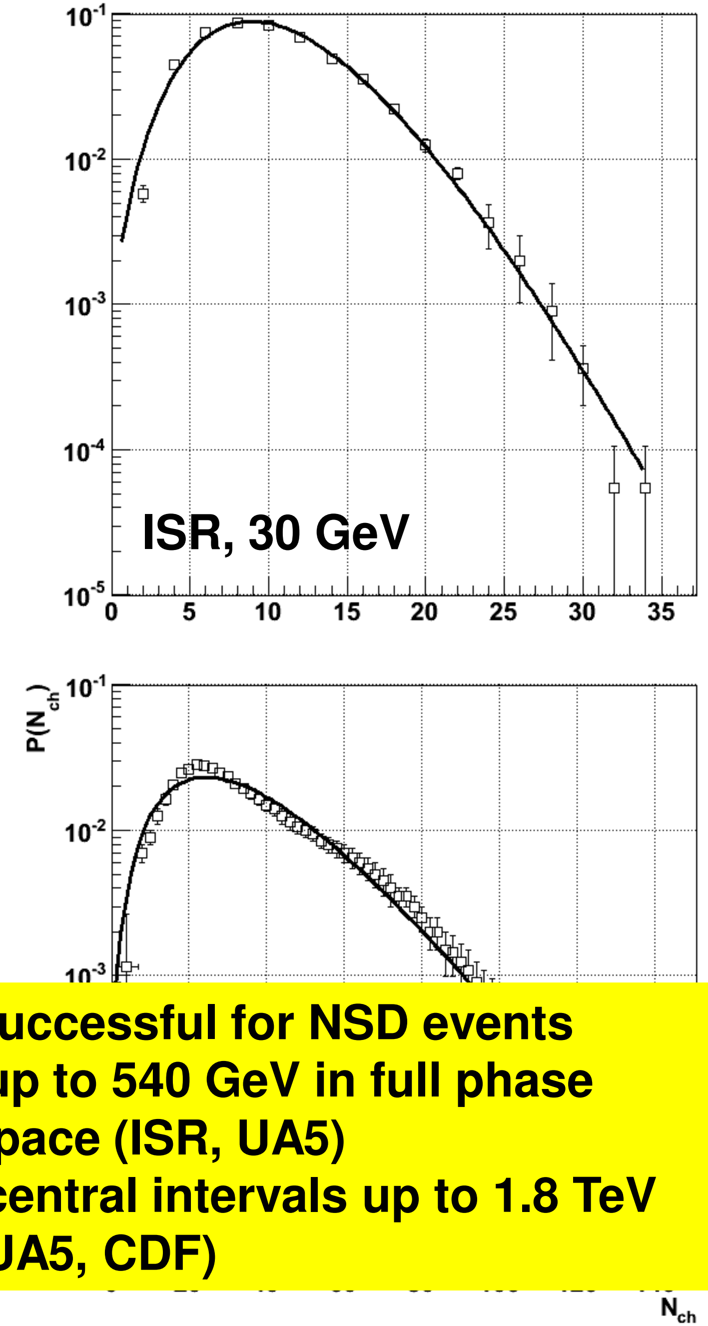


Successful for NSD events
•up to 60 GeV for full phase space (ISR)
•up to 900 GeV in central region (UA1, UA5)
•remains only valid in $|\eta| < 1$ for soft events at 1.8 TeV (CDF)

Nucl. Phys. B40 317 (1972)

Negative Binomial Distributions

- Bernoulli experiment
  - Probability for n failures and k success in any order, but the last trial is a success
- Physical interpretation
  - Cascade production (clan model, Giovannini, Z. Phys. C30 391 (1986))
    - Ancestor particle are produced independently (Poisson)
    - Existing particle can produce additional one with some probability p



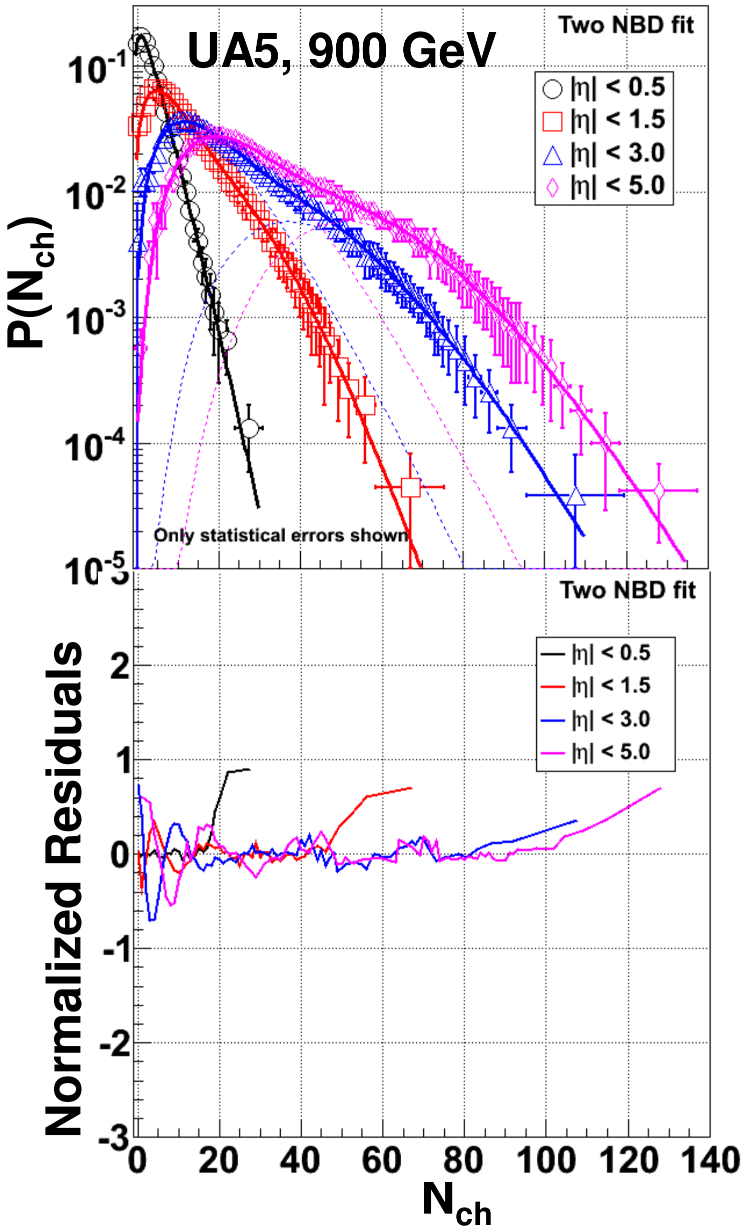
Successful for NSD events
•up to 540 GeV in full phase space (ISR, UA5)
•central intervals up to 1.8 TeV (UA5, CDF)

Two Component Approaches

- Combination of 2 NBDs representing soft and semihard part of the collision (with and without minijets) (Giovannini, PRD59 094020 (1999))
  - Two classes of events, not two production mechanisms in the *same* event
- Other data-driven approach identifies several KNO components (Alexopoulos, Phys. Lett. B435 453 (1998))

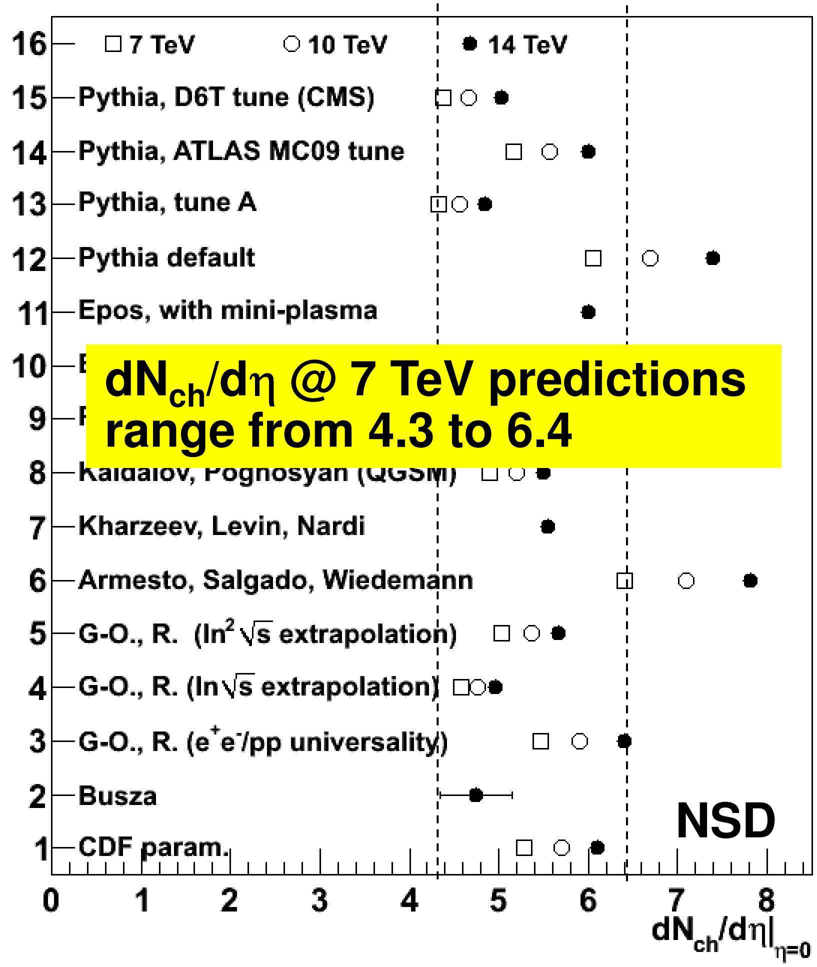
Successful for all regions up to 1.8 TeV

Physical interpretation unclear



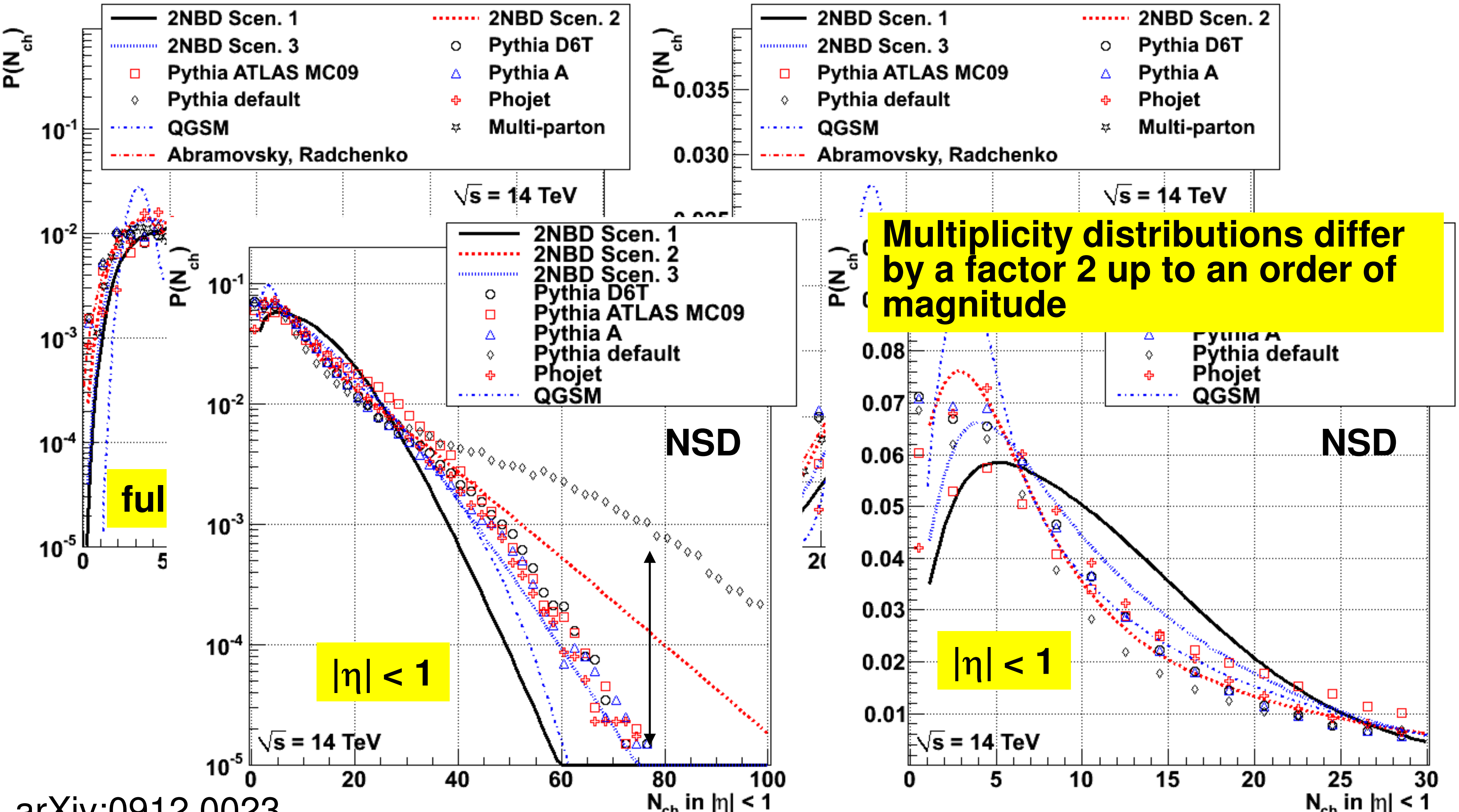
Predictions for LHC Energies

- Extrapolations of trends at lower √s
  - Just for average multiplicities
  - For the multiplicity distribution
- Gluon saturation models (Armesto et al, Kharzeev et al)
- Dual Parton Model / Quark-Gluon String Model
- Monte Carlo generators
  - Pythia (pQCD + soft phenomenology) with all its tunes
  - Phojet (based on DPM/QGSM)
  - Epos (allows mini-plasma in p+p)



arXiv:0912.0023

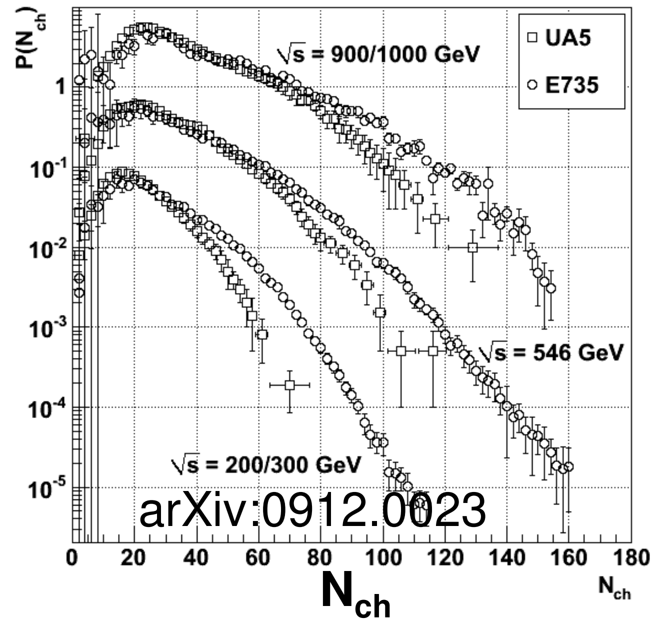
Predictions for √s = 14 TeV

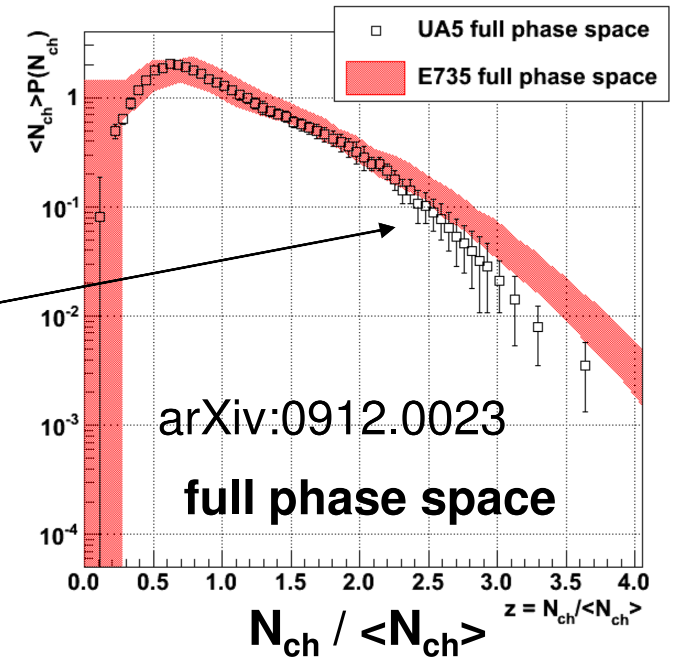


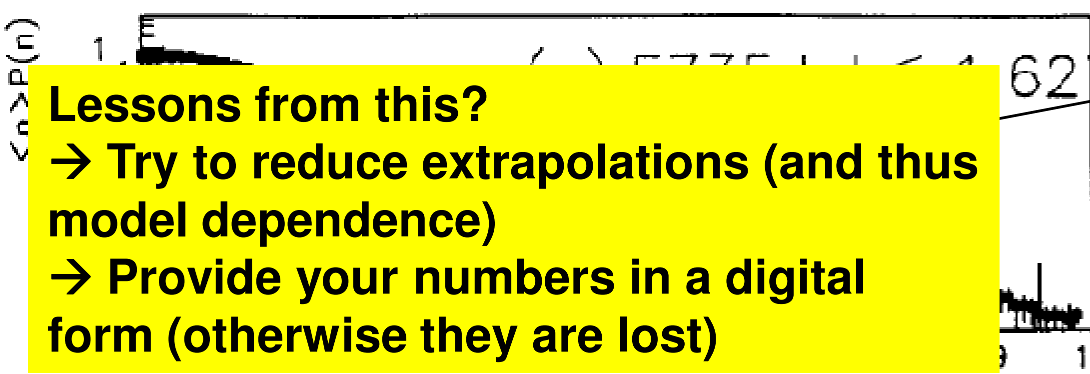
arXiv:0912.0023

Open Experimental Issues

- Discrepancy of multiplicity distributions of UA5 and E735 in full phase space
  - Extrapolated from $|\eta| < 5$ (UA5) and $|\eta| < 3.25$ (E735)
- Restricted phase space?
  - Data points not in electronic format
  - Go to the publication: plot quality?







Lessons from this?
→ Try to reduce extrapolations (and thus model dependence)
→ Provide your numbers in a digital form (otherwise they are lost)

Nucl. Phys. A544 343 (1992)

Part 2

Pseudorapidity density and multiplicity distribution measurement procedure with ALICE

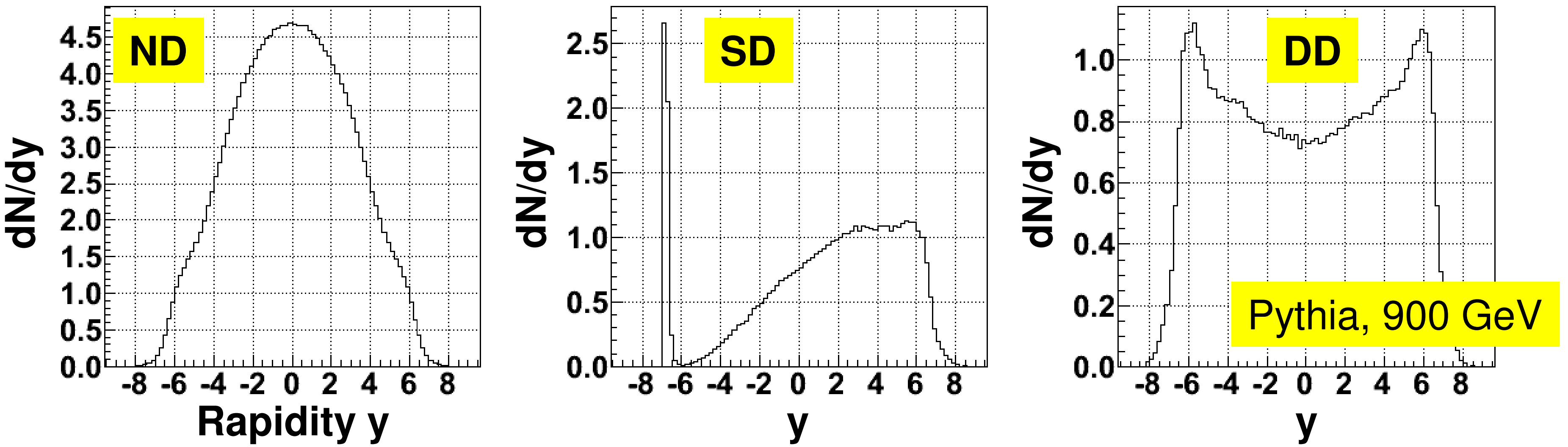
Proton-Proton Cross-section

$$\sigma_{total} = \sigma_{elastic} + \underbrace{\sigma_{non-diffractive} + \sigma_{single-diffractive} + \sigma_{double-diffractive}}_{\text{inelastic, ALICE trigger}}$$

$\sigma_{elastic}$: **insensitive**

inelastic, ALICE trigger

- Many experiments triggered on and published non single-diffractive events (NSD=ND+DD)
- ALICE measures inelastic (INEL) and NSD



Treatment of Diffractive Interactions
Single Diffraction

- Use MC generator for corrections per process type (ND, DD, SD)
- Combine using measured weights
- Replay measurement conditions
  - $M^2/s < 0.05$ for UA5 measurement
  - Weight SD such that replayed fraction matches measurement
  - Experiments have corrected for non-SD contribution in their measurements

SD, 900 GeV	Pythia	Phojet
MC fraction	22.3%	19.1%
Replay	18.9%	15.2%
Measurement*	(15.3 ± 2.3)%	

*UA5: Z. Phys. C33, 175, (1986) derived from ratio of SD/NSD

Measurement for 1.8 TeV
E710, Phys. Lett. B301, 313 (1993)
Other cut on SD: $2 < M^2 < 0.05s$

Can be used for 2.36 TeV (ratios SD/INEL, DD/INEL fairly constant as function of cms)

Treatment of Diffractive Interactions Double Diffraction

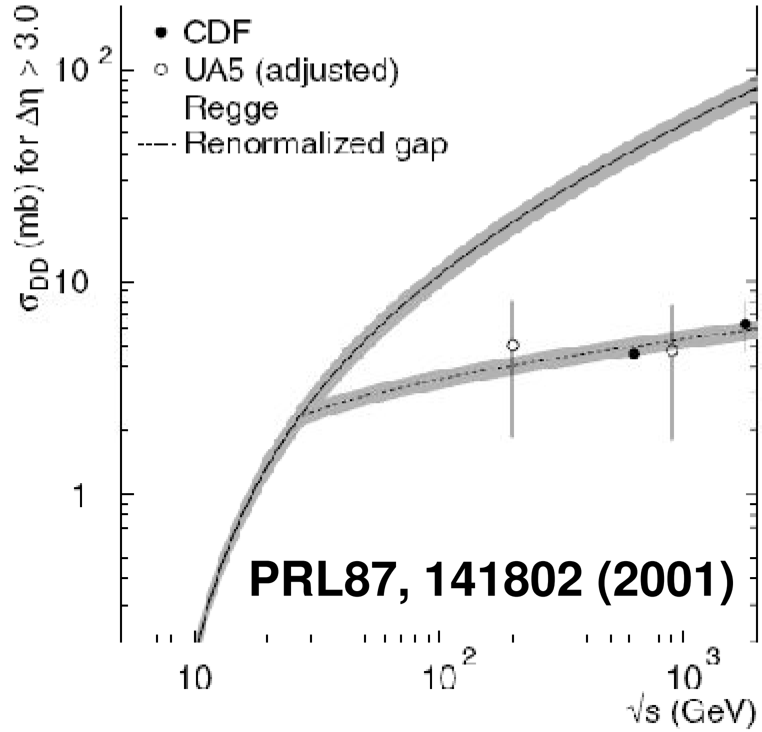
- UA5 (Z. Phys. C33, 175, (1986))
  - Centered gap $|\eta| < 1 .. 3$
  - Somehow corrected for efficiency to find certain gap sizes
  - Hadron-level definition for DD not evident from the paper
- CDF (PRL87, 141802 (2001))
  - Measures with a gap of 3 η-units (including $\eta = 0$)

DD, 900 GeV	**Pythia**	**Phojet**
MC	**12.3%**	**6.4%**
Measurement	**(8 ± 5)%**	

DD, 1.8 TeV	**Pythia**	**Phojet**
MC	**12.6%**	**5.8%**
Replay $\Delta\eta^0 > 3$	**6.6%**	**2.2%**
Measurement	**(7.5 ± 2.2)%**	

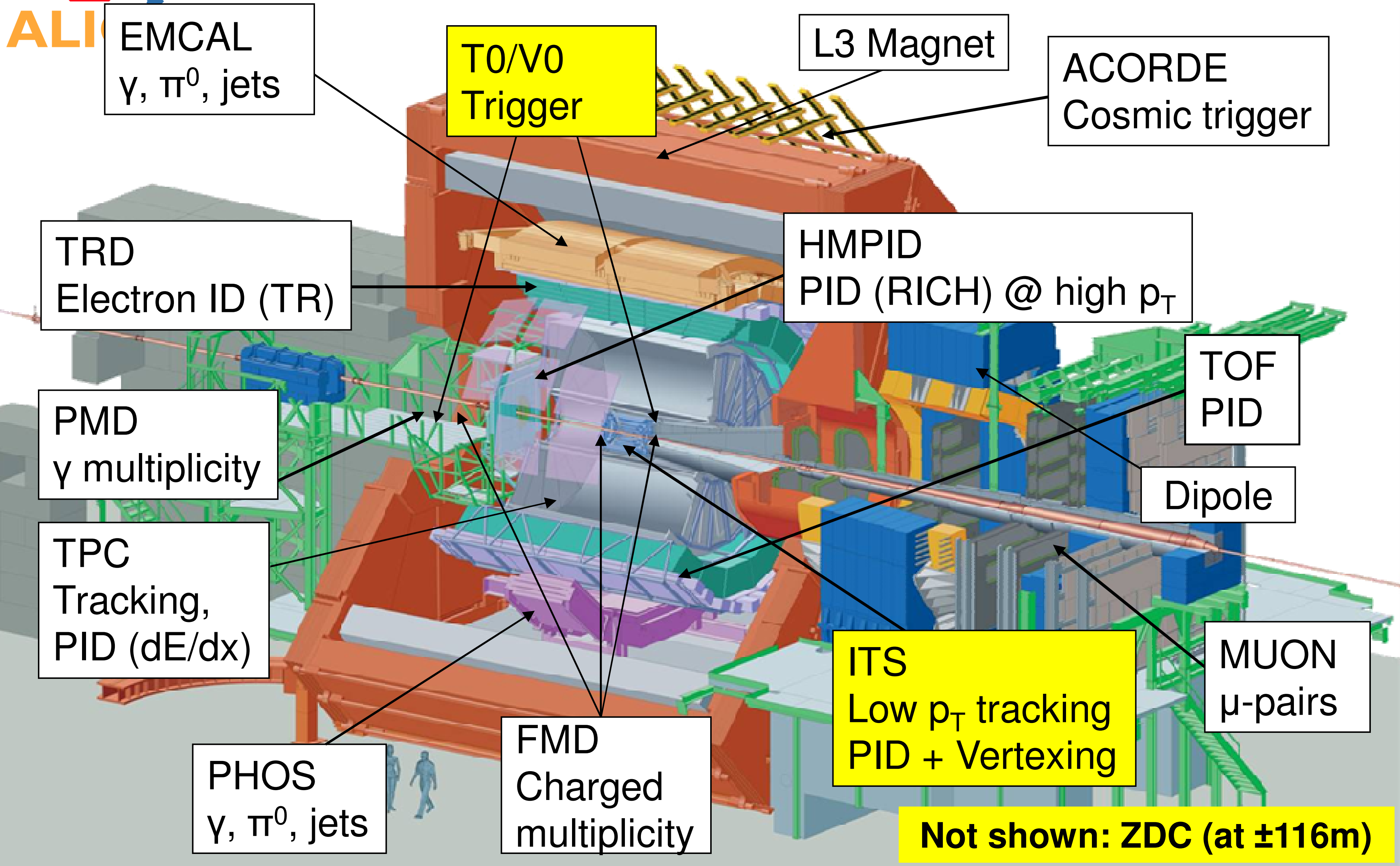
Treatment of Diffractive Interactions - DD (2)

- CDF scales their and UA5 result to floating gap of 3 η-units (“$\Delta\eta > 3$”)
- Consistent measurements
- Replay works for Pythia, but not for Phojet
- Treatment of DD remains ambiguous

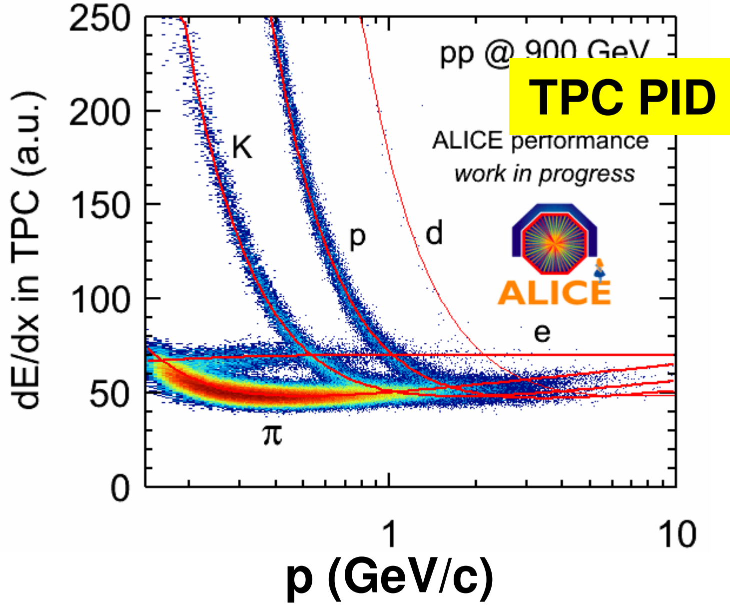


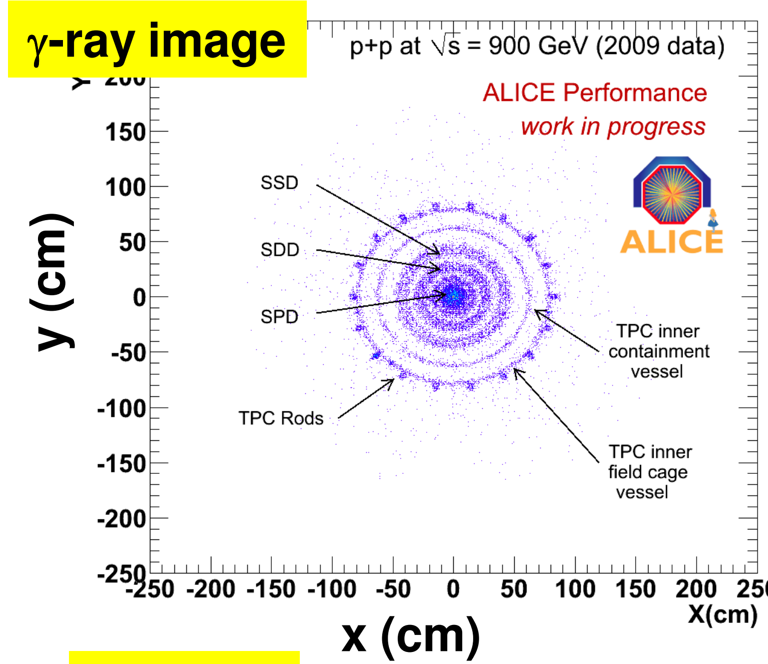
		Pythia	Phojet
900 GeV	**MC**	**12.3%**	**6.4%**
	Replay $\Delta\eta > 3$	**10.6%**	**3.6%**
	UA5 scaled	**(9.5 ± 6)%**	
1.8 TeV	**MC**	**12.6%**	**5.8%**
	Replay $\Delta\eta > 3$	**10.3%**	**3.5%**
	CDF scaled	**(10.7 ± 3.1)%**	

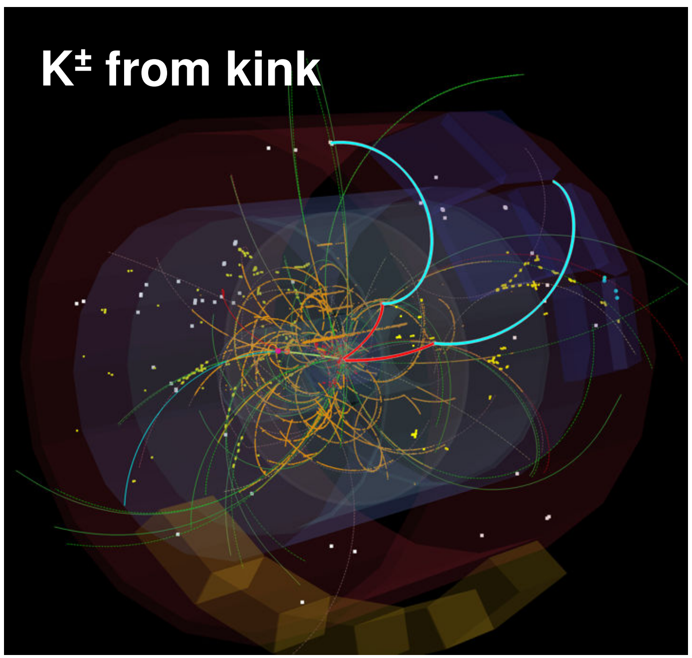
A Large Ion Collider Experiment

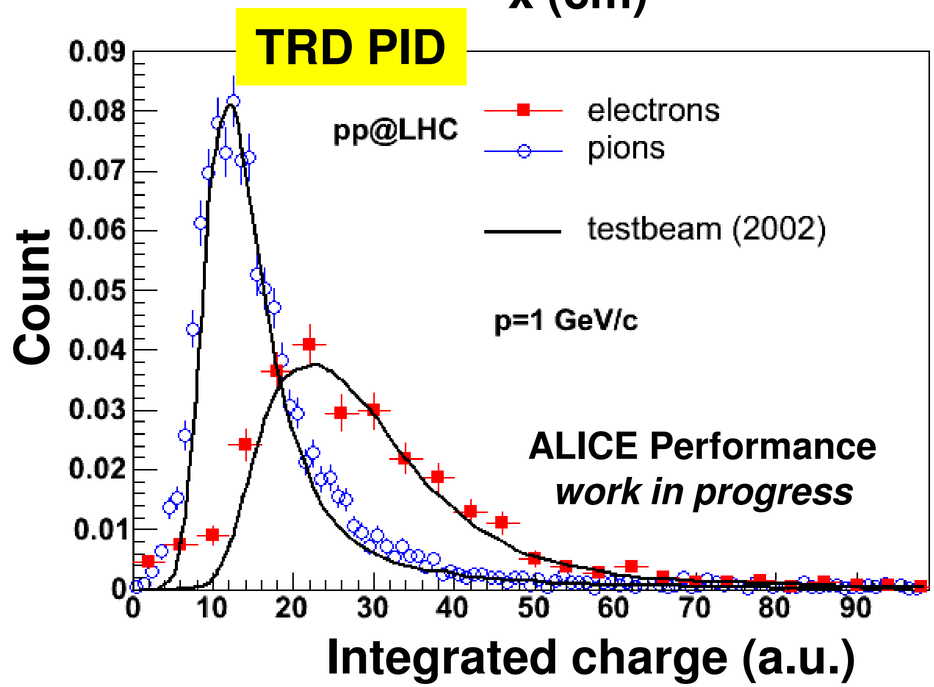


P E R F O R M A N C E





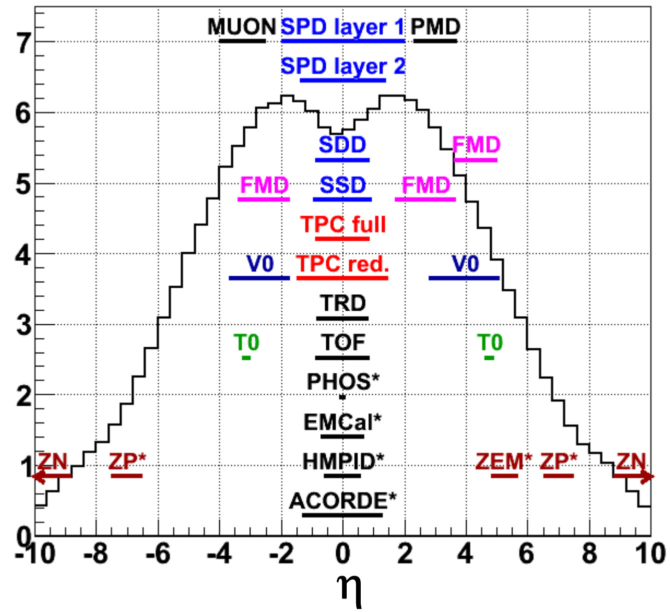


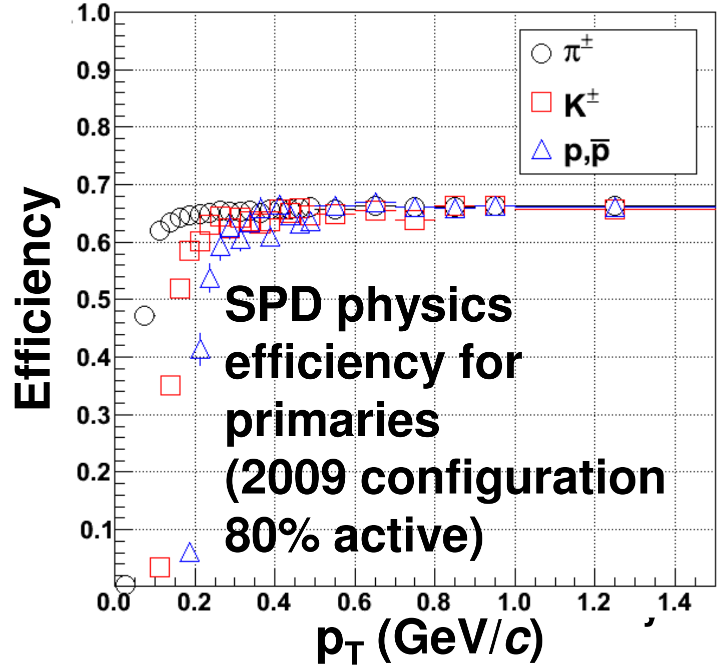


Detectors

- V0 scintillator array
  - Trigger
  - $2.8 < \eta < 5.1$ and $-1.7 < \eta < -3.7$
- Silicon Pixel Detector (SPD)
  - Two innermost layers of the Inner Tracking System (ITS)
  - Radii of 3.9/7.6 cm ($|\eta| < 2.0/1.4$)
  - Trigger & Tracking
  - $|\eta| < 1.4$
  - $p_T > 50$ MeV/c
  - 9.8 M channels
  - Tracklet: 2 points + vertex

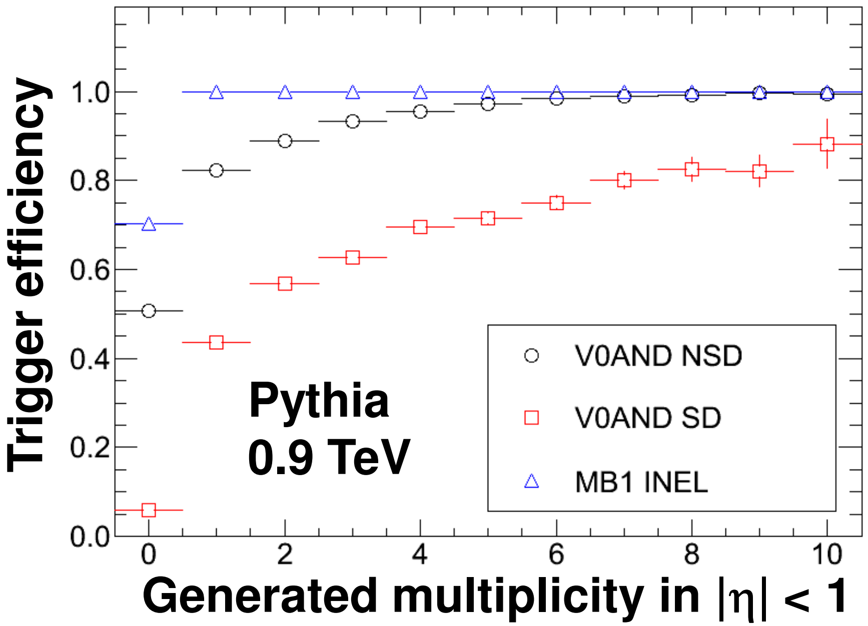
Detector Acceptance





Trigger for MB Physics

- ALICE measures MB properties for INEL and NSD events
- Inclusive trigger ("MB1") for INEL: central pixel hit (SPD) or forward scintillator (V0)
  - One particle in 8 η units
  - (Trigger-)sensitive to 95-97% of the inelastic x-section
- Two-arm trigger ("V0AND") for NSD
  - Both forward scintillators
  - One particle in $2.8 < \eta < 5.1$ and one in $-1.7 < \eta < -3.7$



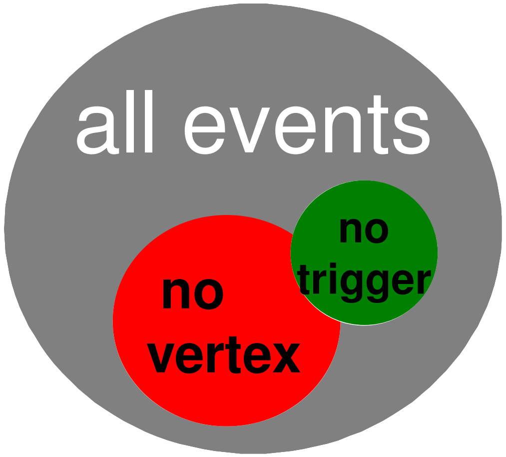
Efficiency in %		ND	DD	SD
Pythia	MB1	100	92	77
	V0AND	98	49	29
Phojet	MB1	100	98	86
	V0AND	98	66	34

900 GeV

$dN_{ch}/d\eta$ Measurement

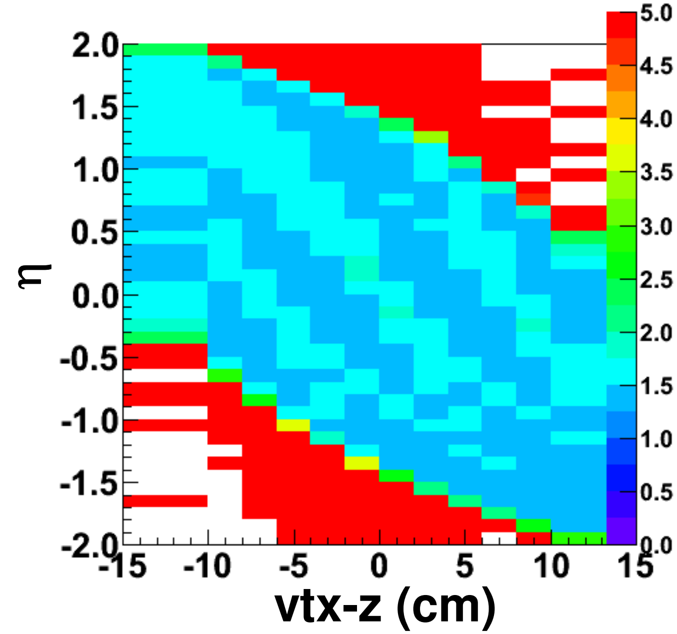
- Basically $\frac{dN_{ch}}{d\eta} = \frac{\text{Tracks}}{\text{Events}}$ if the detector was perfect
- But… there is
  - Detector acceptance, tracking efficiency
  - Decay, conversions, stopping, etc.
  - Vertex reconstruction efficiency/bias, trigger efficiency/bias
  - Low momentum cut-off
- Three corrections needed
  - Track-to-particle correction
  - Vertex reconstruction correction
  - Trigger bias correction

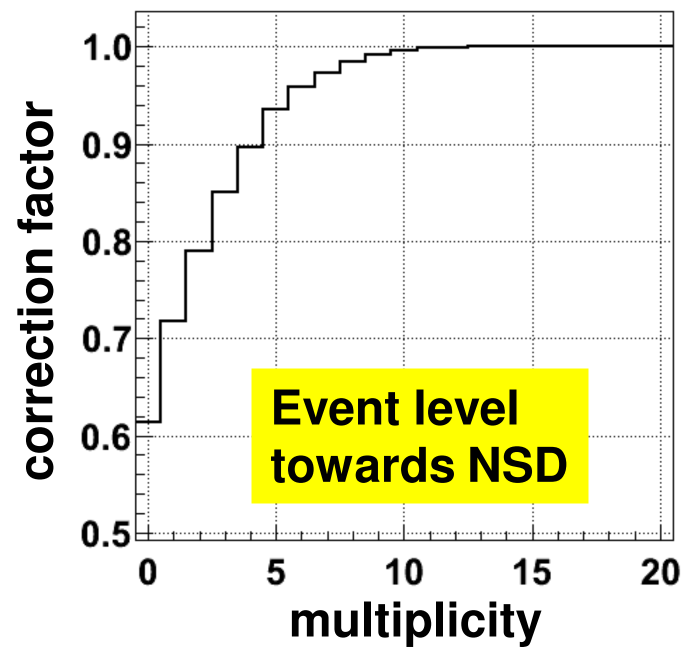
Primary particles = charged particles produced in the collision and their decay products excluding weak decays from strange particles



Corrections

- Track-to-particle correction
  - Acceptance of the SPD clearly visible
  - Function of η, z-position of event vertex (vtx-z)
- Trigger-bias correction
  - Corrects towards
    - Inelastic events
    - NSD events
  - Event and track level
  - Function of multiplicity, vtx-z





<u>Average correction factors</u>
Tracking: 1.53
Events (INEL): 1.05
Events (NSD): 1.02 [+8.3% (NSD) – 6.8% (SD)]
Subtraction of SD tracks for NSD: 3%

Normalization

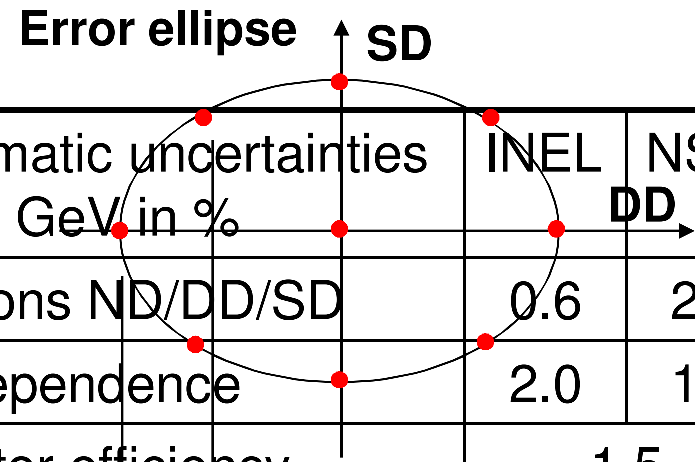
- Triggered events without vertex $N_{trig,novtx}$ used in the normalization $N(z) = N_{vtx}(z) + N_{trig,novtx}(z)$
- Triggered events without vertex are – well – *without* vertex position
- Have to be put "in the right place" (at the right vertex)
  - $N_{trig, novtx}$ are distributed like the vertex distribution from data: $\alpha(z)$
  - The vertex distribution is biased (~ 1%) due to the vertex requirement, this effect is corrected for: F(z)

$$N_{trig,novtx}(z) = N_{trig,novtx} \times \alpha(z) \times F(z) \times \tilde{C}_{trig}(z)$$

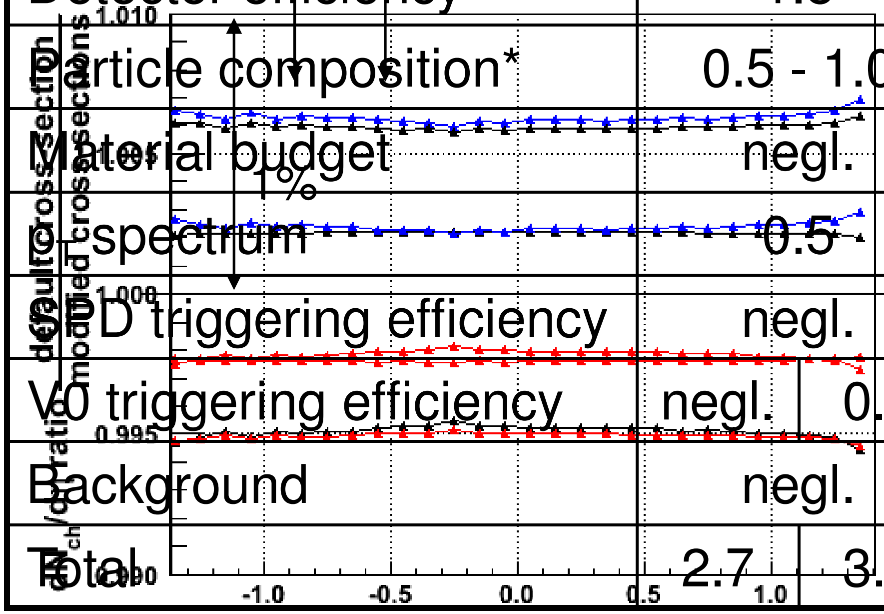
- $N_{trig,novtx}$ contains beam-induced background and noise
  - Assessed from control triggers (discussed later)
  - At 2.36 TeV no control triggers
    - Use 0 bin from MC → larger systematic uncertainty

Systematic Uncertainties

- Influence of systematic effects on result evaluated
- E.g. fractions ND/DD/SD
  - Change SD/DD by measurement error
  - E.g. SD (15.3 ± 2.3)% (scaled as discussed before)
- Larger uncertainty for NSD than for INEL



Systematic uncertainties at 900 GeV in %	INEL	NSD
Fractions ND/DD/SD	0.6	2.8
MC dependence	2.0	1.0
Detector efficiency	1.5	
Particle composition*	0.5 - 1.0	
Material budget	negl.	
p_T spectrum	0.5	
SPD triggering efficiency	negl.	
V0 triggering efficiency	negl.	0.5
Background	negl.	
Total	2.7	3.4

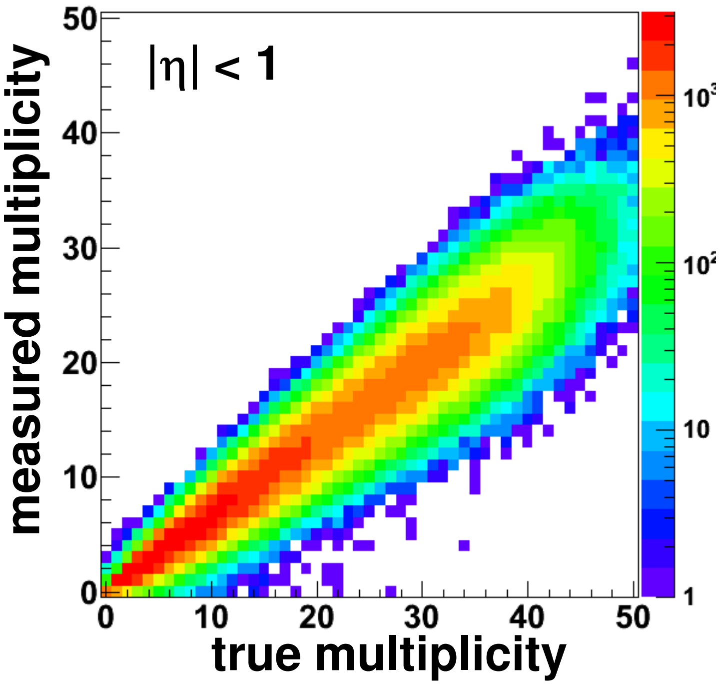


* η-dependence

Multiplicity Distribution

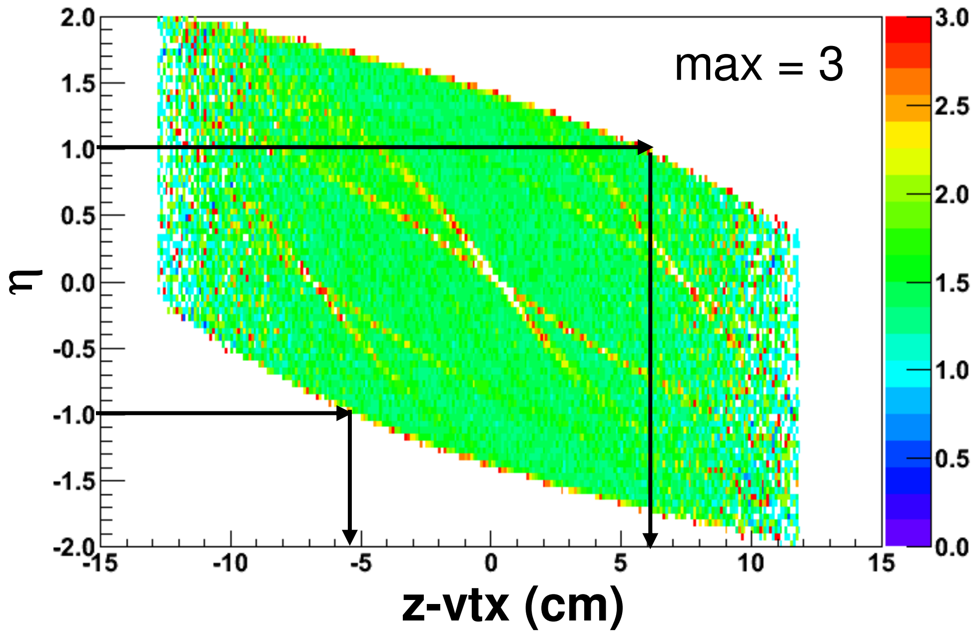
$$P(N_{ch}) = \frac{\text{Events with multiplicity } N_{ch}}{\text{All events}}$$

- Efficiency, acceptance
  - Resolution vs. bin size → bin flow
  - Correction by unfolding
- Detector response $M = RT$
  - Probability that a collision with the true multiplicity ***t*** is measured as an event with the multiplicity ***m***
- Vertex reconstruction, trigger bias correction
  - Like for $dN_{ch}/d\eta$, but in unfolded variables (true multiplicity) because it is applied after unfolding



Multiplicity Distribution (2)

- For the multiplicity distribution all considered events have to have full acceptance in η
- For each η-region a different acceptance
  - Reduces statistics
  - Not centered around 0 due to small shift of the ITS vs. the nominal interaction point
- Use number of triggered events without vertex to estimate vertex efficiency in “0 bin” from data



$\|\eta\|$ <	z (cm)	Fraction 0.9 TeV
0.5	-10 … 10	99%
1.0	-5.6 … 6.1	84%
1.3	-1.9 ... 2.4	53%
1.4	-0.3 … 0.8	11%

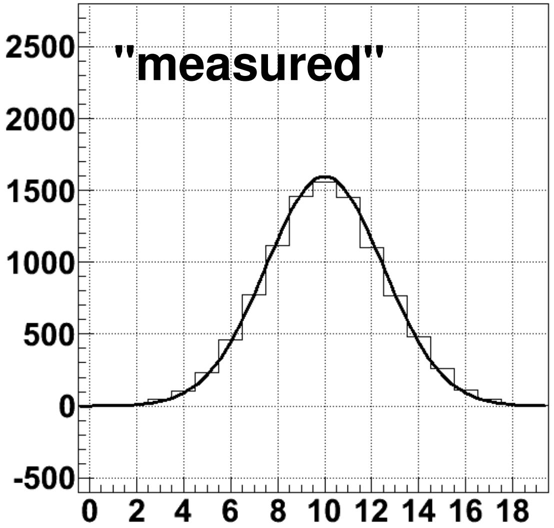
Challenges with Unfolding

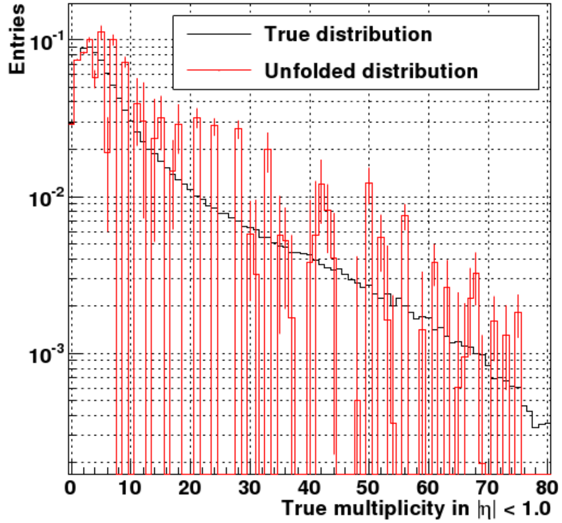
- Example with a simple quadratic response matrix R
- True distribution (Gaussian is assumed) converted to measured distribution using R
- 10,000 measurements generated
- R is inverted and used to infer the 'true' distribution
  → large statistical fluctuations

$$\begin{pmatrix} 0.75 & 0.25 & 0 & \cdots \\ 0.25 & 0.50 & 0.25 & \\ 0 & 0.25 & 0.50 & \\ \vdots & & & \ddots \end{pmatrix}$$

$$T = R^{-1} M$$

V. Blobel, Yellow report, 1984





Unfolding using χ^2-Minimization

$$\chi^2(U) = \sum_m \left(\frac{M_m - \sum_t R_{mt} U_t}{e_m} \right)^2 + \beta R(U)$$

- One free parameters per bin for unfolded spectrum U_t
- Regularization
  - Prefer constant locally
  - Prefer linear function locally
- Weight parameter β needs to be tuned
  - χ^2/ndf not larger than 1
  - Keep bias low

Regularizations

$$R(U) = \sum_t (a_t)^2$$

$$a_t = \frac{U_t'}{\sqrt{U_t}} = \frac{U_t - U_{t-1}}{\sqrt{U_t}}$$

$$a_t = \frac{U_t''}{\sqrt{U_t}} = \frac{U_{t-1} + 2U_t - U_{t+1}}{\sqrt{U_t}}$$

V. Blobel, Yellow report, 1984

Unfolding using Bayesian Method

Bayesian method (based on Bayes' theorem)

(e.g. Nucl.Instrum.Meth.A362:487-498,1995)

$$\tilde{R}_{tm} = \frac{R_{mt} P_t}{\sum_{t'} R_{mt'} P_{t'}}$$

$$U_t = \sum_m \tilde{R}_{tm} M_m$$

$$\hat{U}_t = (1-\alpha) U_t + \frac{\alpha}{3}(U_{t-1} + U_t + U_{t+1}) \quad \text{(optional)}$$

R_{mt}	**Response matrix**
$\tilde{R}_{tm}$	**Smearing matrix**
P_t	**Prior distribution (guess)**
M_m	**Measured distribution**
U_t	**Unfolded distribution**
α	**Weight parameter**

Limited number of iterations provides implicit regularization (V. Blobel, hep-ex/0208022)

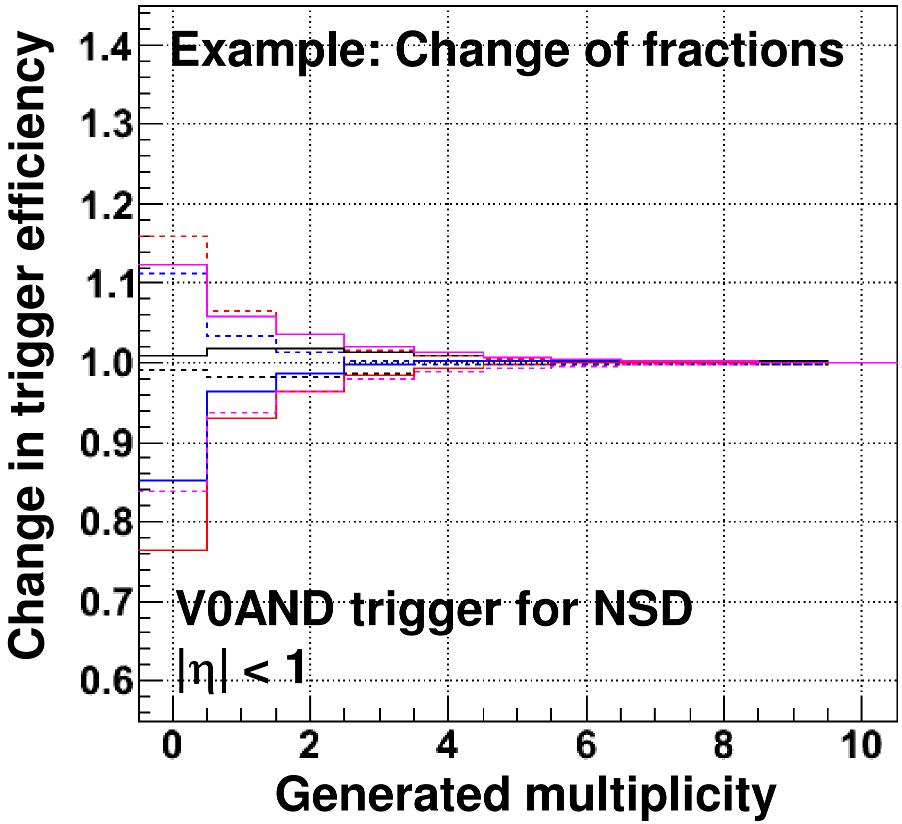
Iterative method:

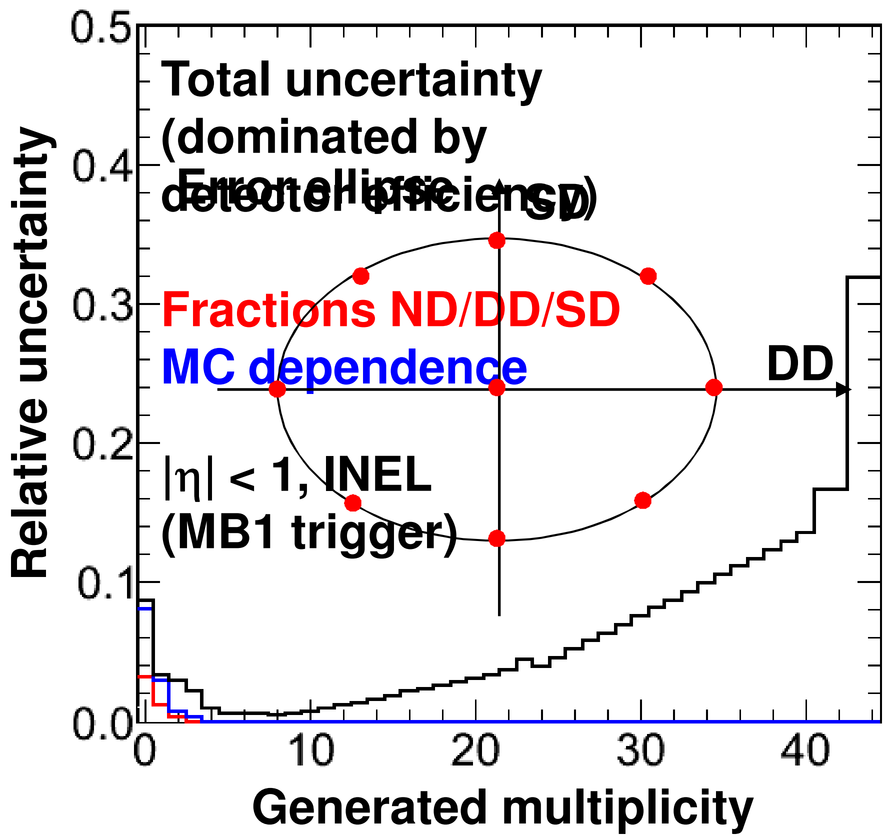
1. **Choose prior distribution P_t**
2. **Calculate** $\tilde{R}_{tm}, U_t, \hat{U}_t$
3. **Replace P_t by** $\hat{U}_t$**; go to 2.**

Systematic Uncertainties

- The influence of the systematic effect on the unfolded result is studied
- Uncertainty as function of multiplicity
- Fractions ND/DD/SD and MC dependence effects only trigger efficiency and vertex reconstruction correction
- Detector efficiency evaluated by changing the response matrix (higher / lower efficiency)
  - Uncertainty on the p_T spectrum and particle composition is effectively an uncertainty on the total efficiency
  - Overlaid by usual fluctuations from the unfolding
    - Fit with a smooth function
- Different V0 selections to assess effect of trigger

Systematic Uncertainties





Only effect in low-multiplicity region
Large effect in 0 bin

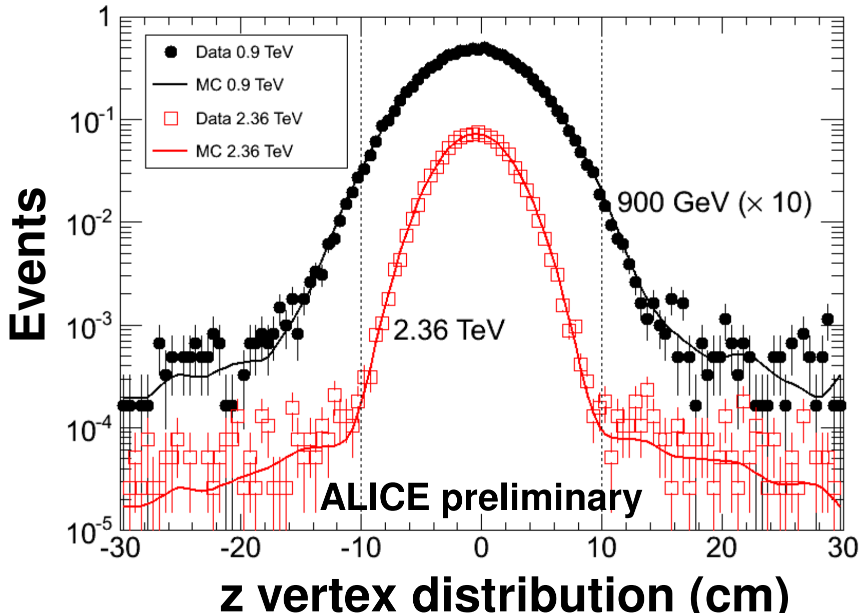
Detector efficiency dominates at large multiplicities

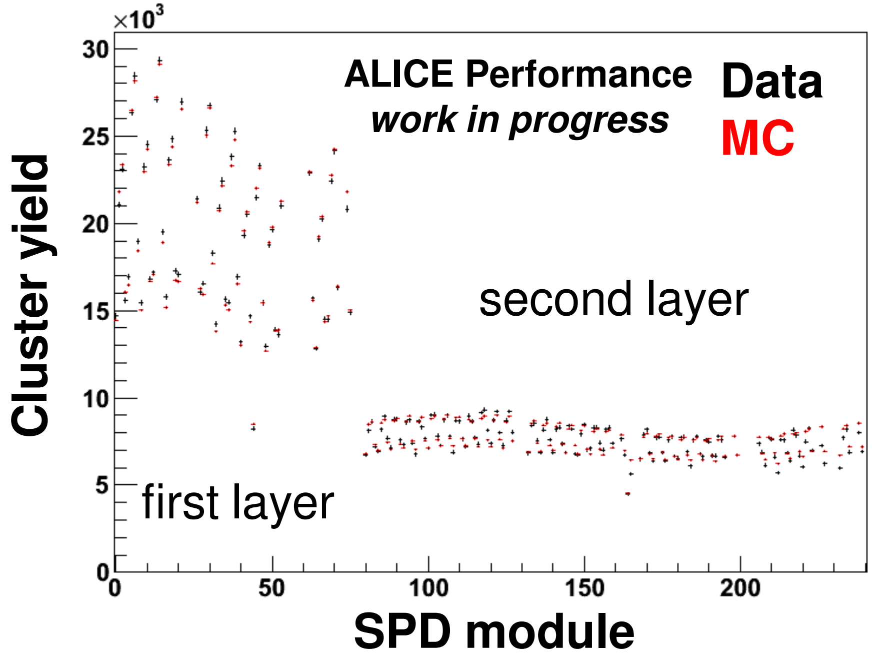
Part 3

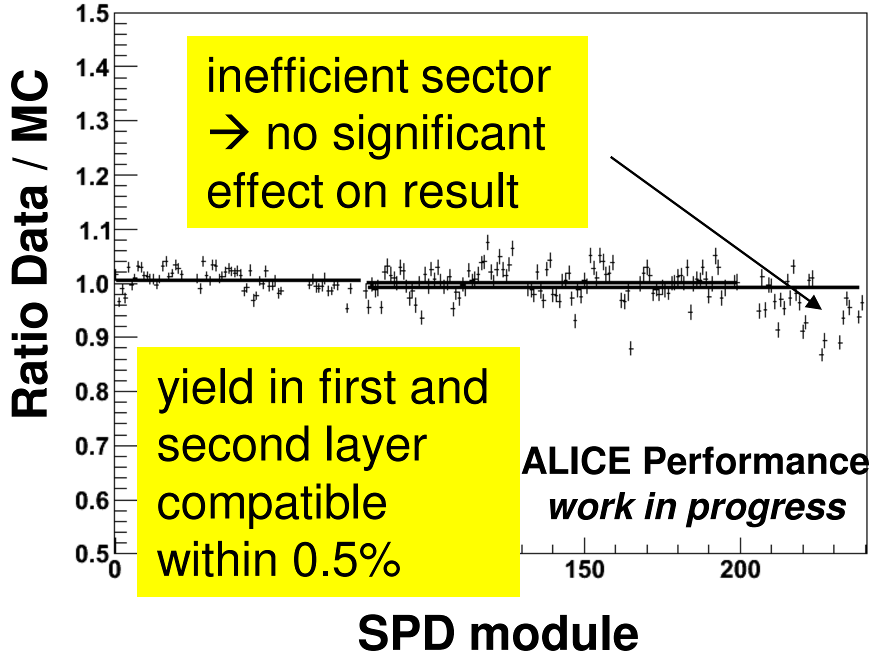
Data sample and MC validation

Data Sample

- Analysis based on
  - 900 GeV: 186k collision events out of ~430k total
  - 2.36 TeV: 41k collision events
- MC adapted to mean vertex position and spread

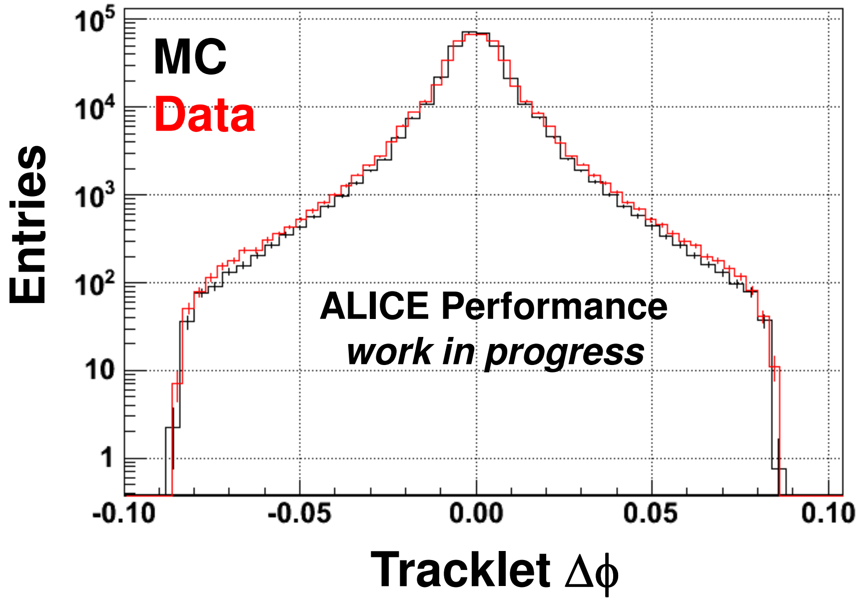


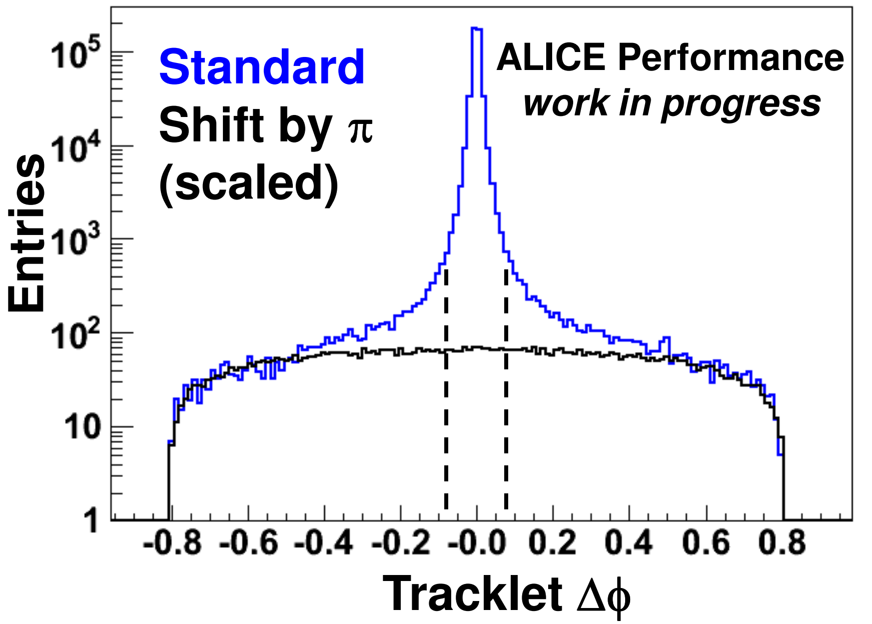




Data Sample (2)

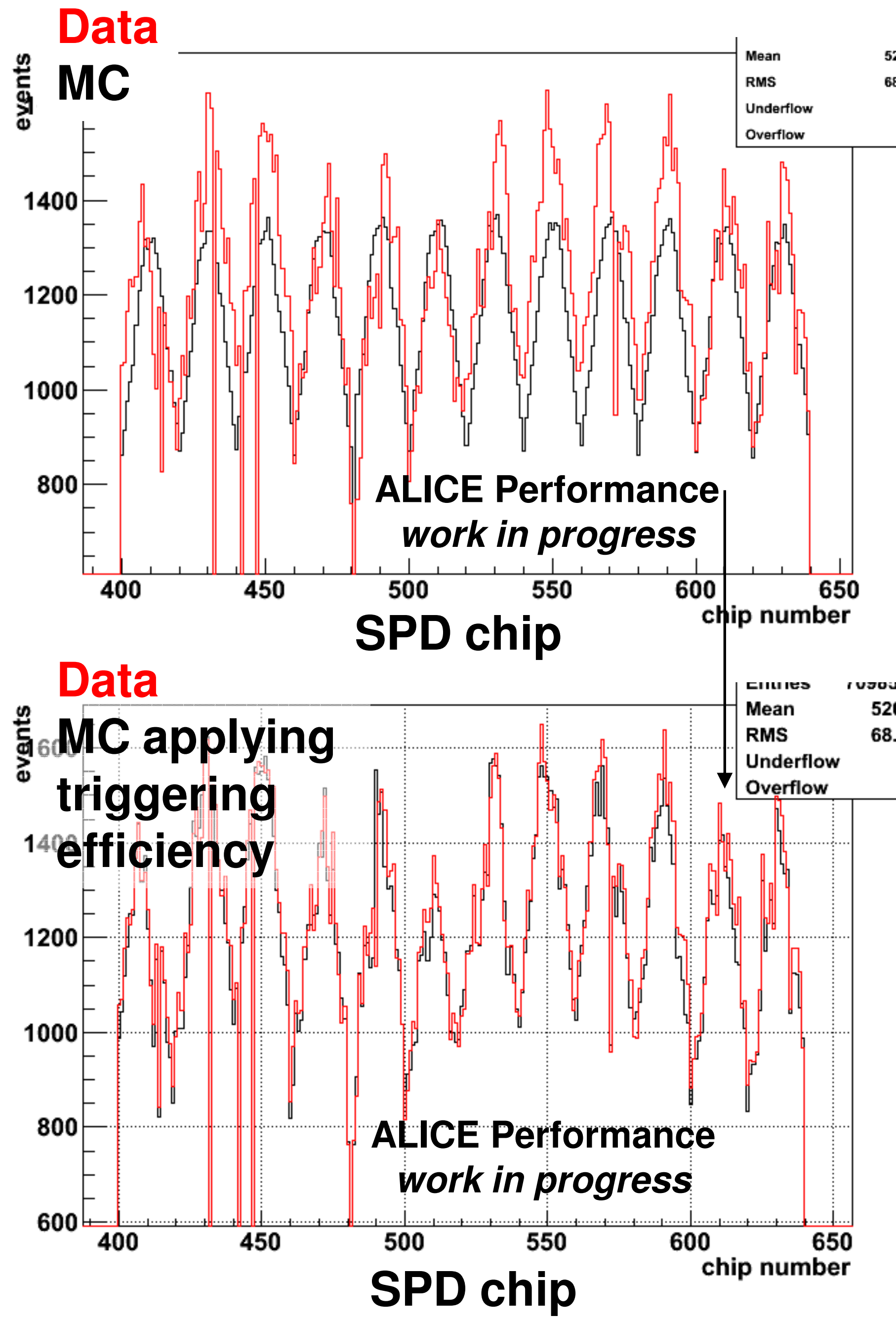
- Tracklet finding quality parameter match between MC and data
- Combinatorial background assessed
  - Side-band technique
  - Shift of clusters in outer layer by π
    - Needs scaling factor
  - Combinatorial background amounts to 0.2 – 0.4%





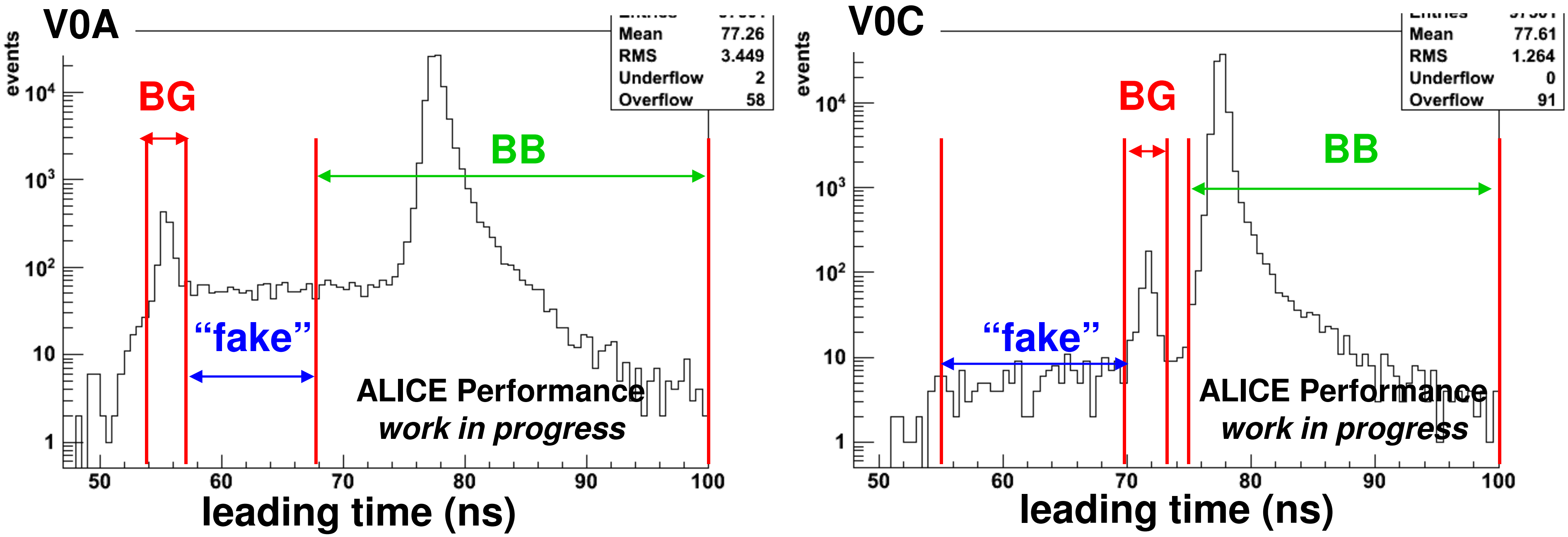
SPD Triggering Efficiency

- SPD triggering efficiency evaluated with data
  - Fired triggered chips over chips that have clusters
  - Using V0 triggered data sample (unbiased)
- Applied in MC
  - Essentially no influence on the trigger efficiency (MB1)



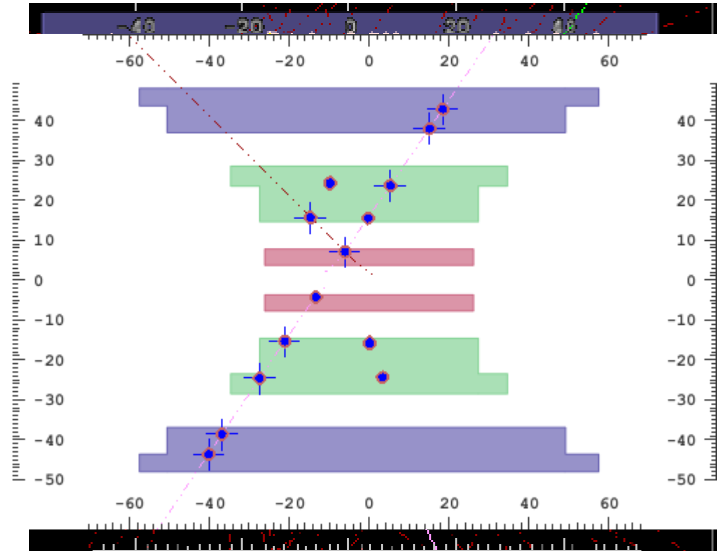
V0 Trigger

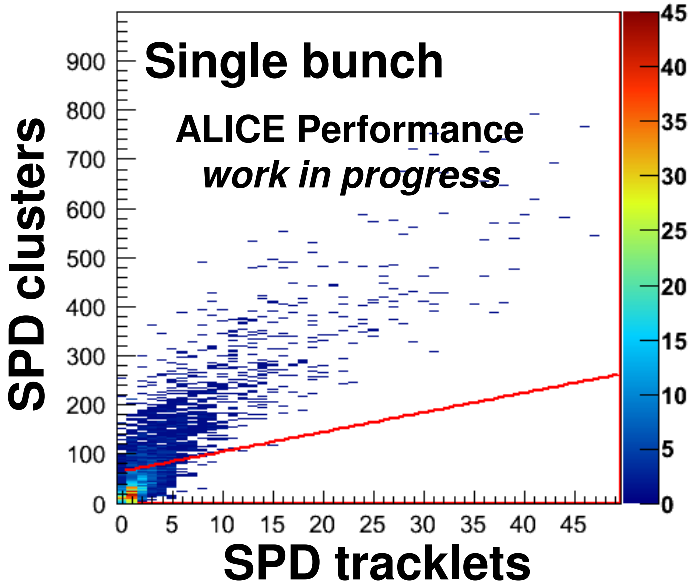
- MC has been adapted to reproduce the spectra found with data
- Same time windows for beam-beam (BB) and beam-gas (BG) applied to data and MC
- Estimation of fake rate from data



Background Identification

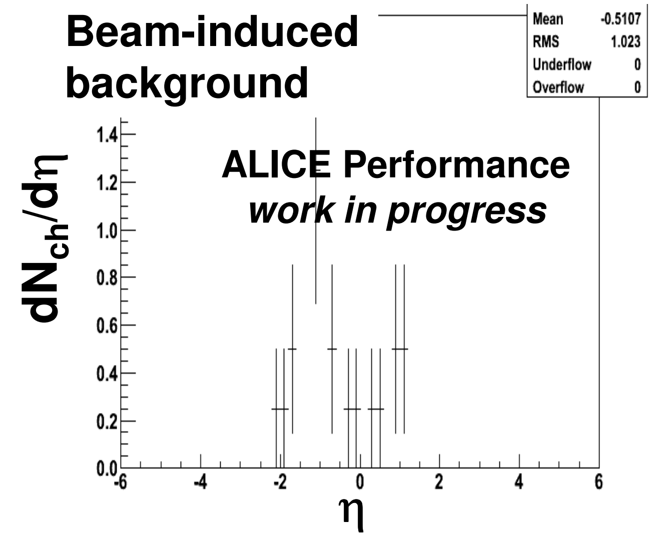
- Beam “splashes”
  - Lots of clusters caused by particles traversing the detector in direction of the beam line
  - Identified by
    - Correlation of number of tracklets with number of clusters
    - V0 information
- Cosmics
  - Rate that causes valid vertex 10^{-2} Hz
    - In coincidence with passing beam ~10^{-6} Hz

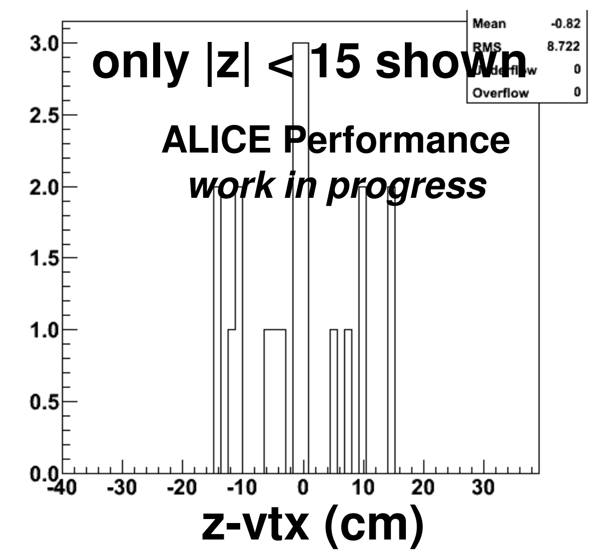




Background @ 900 GeV

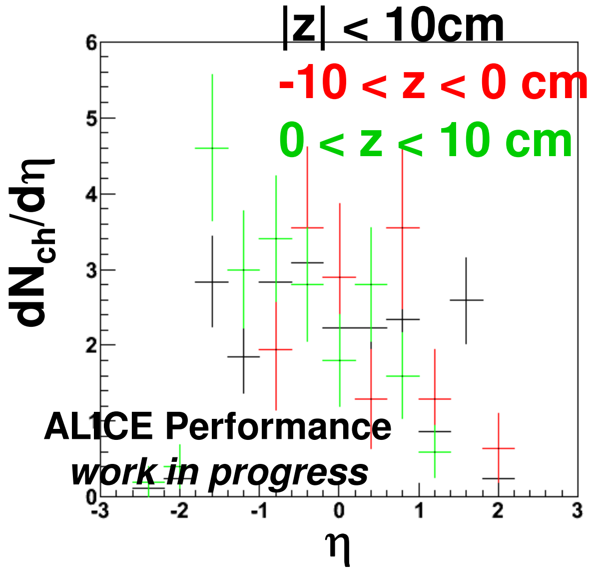
- Relative to accepted events in bunch crossing trigger
  - About 2.1% each in single bunch triggers
  - About 1.2% in “empty” trigger (= noise)
  - 0.02% have a vertex and tracks
  - The remaining go into the 0 bin, which can be subtracted with the control triggers
  - Bunch intensities taken into account
- Background with activity is negligible

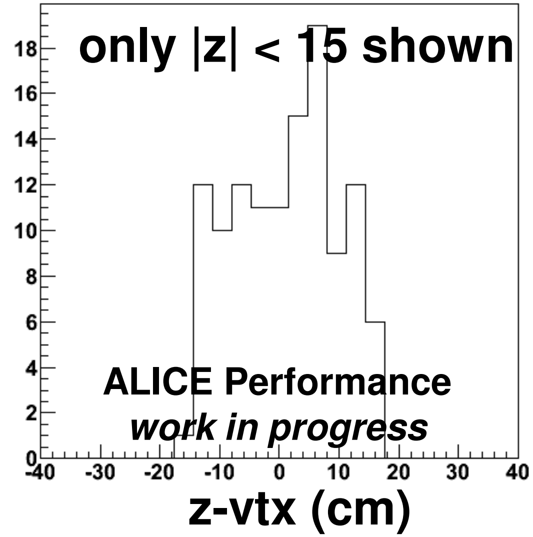




Background @ 2.36 TeV

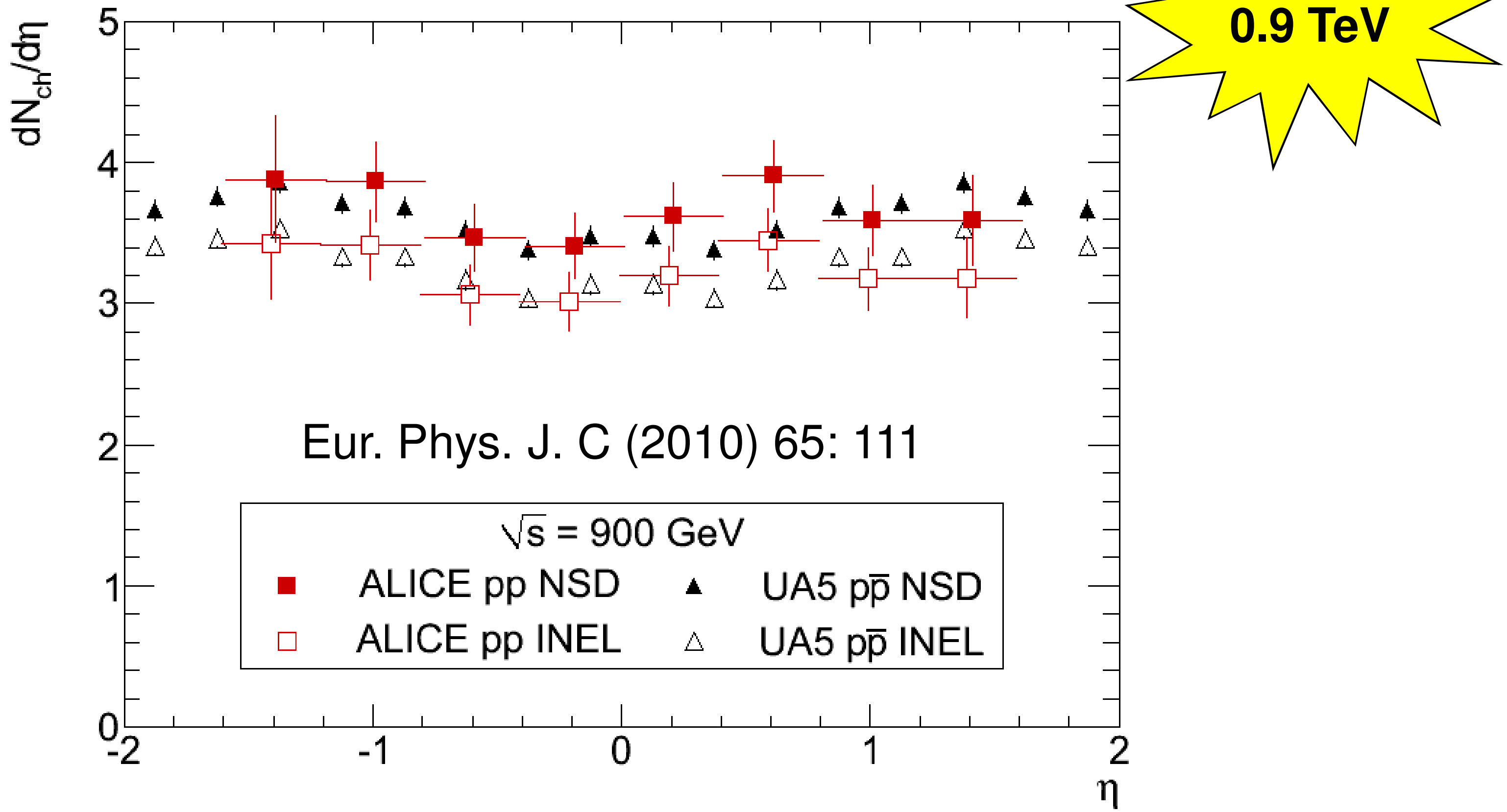
- No control triggers for this data sample
- Assess background by replaying the 2.36 TeV trigger conditions on the 900 GeV sample
- Look at those events which are flagged as background by the V0
  - 0.9% events w.r.t to all triggered
  - 23% of those are found by the background identification
  - Of the remainder, 10% have tracklets, the rest goes into the 0 bin (which is not used at 2.36 TeV)





Part 4

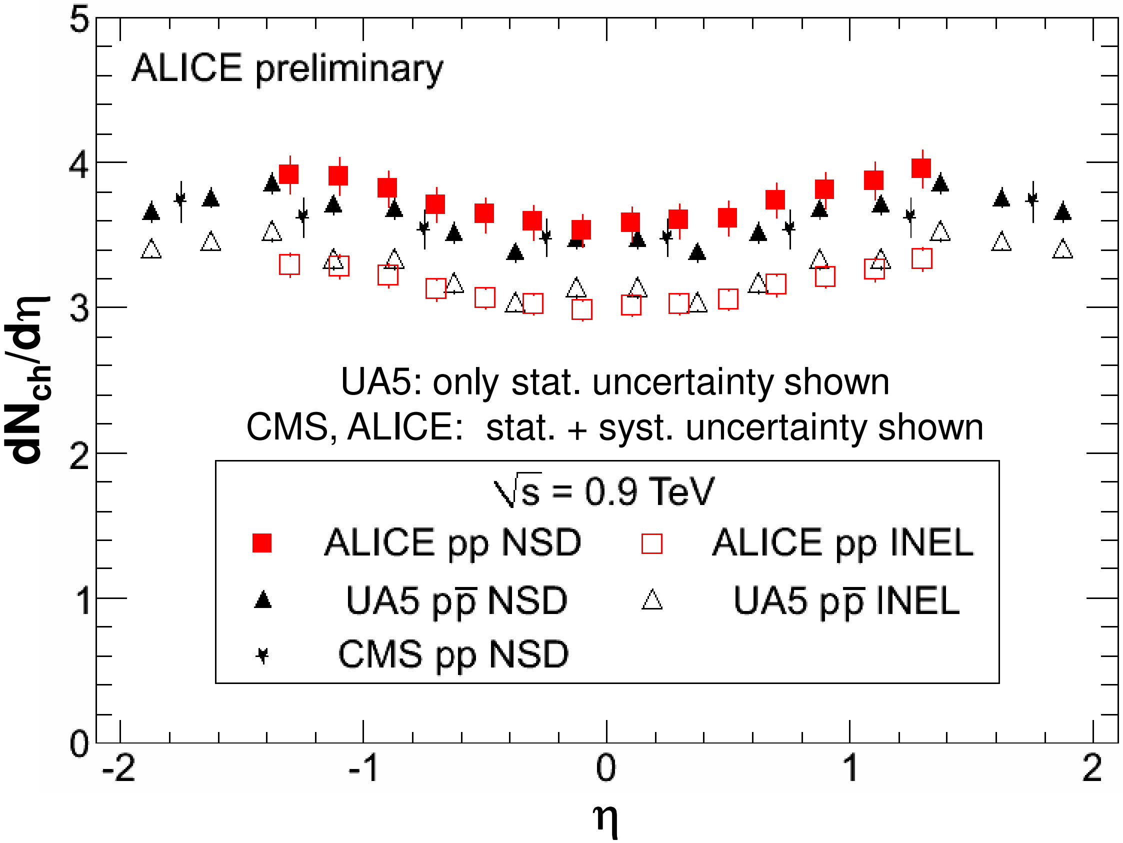
Results



I will not comment much about this distribution today, except…

that it is based on 284 events
and has 1056 authors

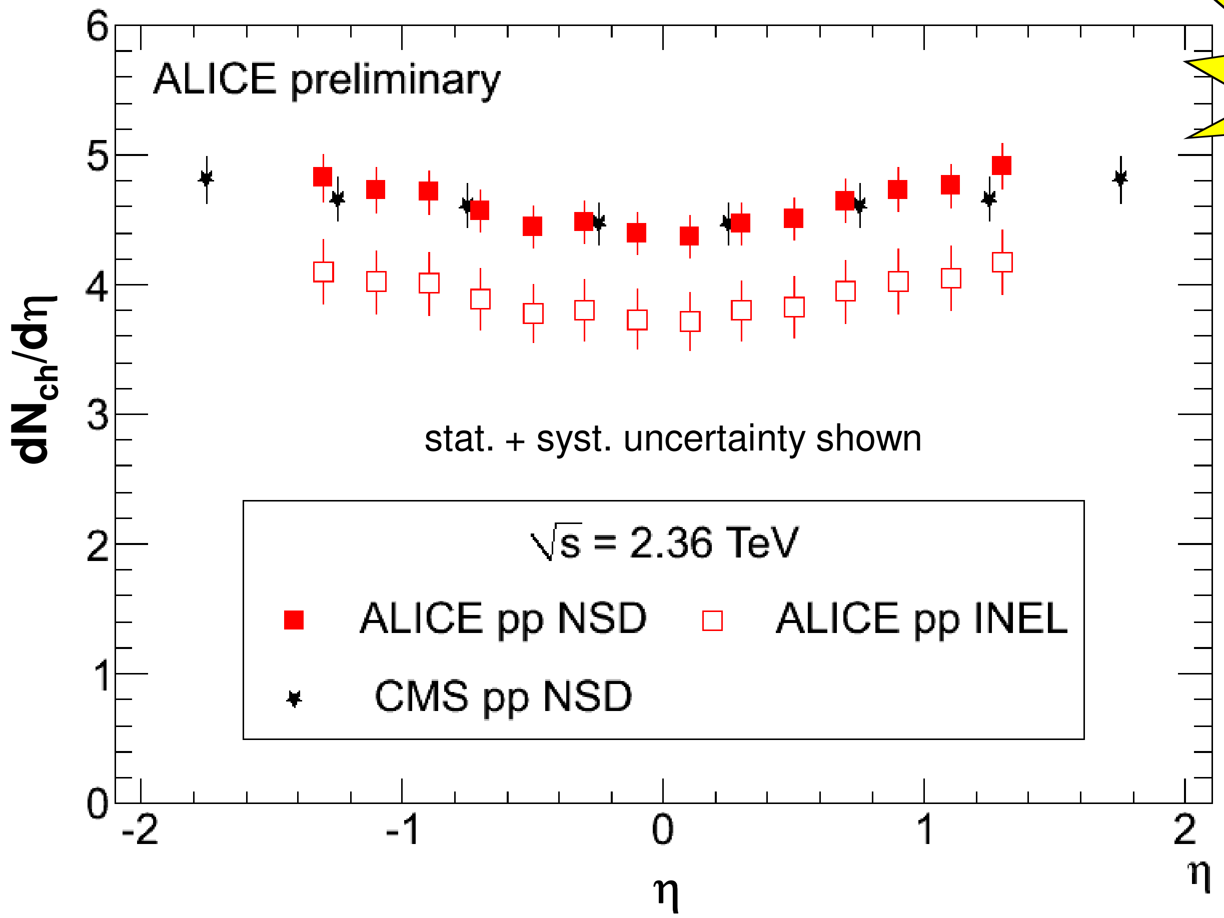
ALICE



0.9 TeV

CMS does not include charged leptons → ~1.5 % difference

$dN_{ch}/d\eta$ in $\|\eta\| < 0.5$	INEL	NSD
ALICE preliminary	**3.02 ± 0.01 ± 0.07**	**3.58 ± 0.01 ± 0.11**
ALICE EPJ C (2010) 65: 111	**3.10 ± 0.13 ± 0.22**	**3.51 ± 0.15 ± 0.25**
UA5 Z. Phys. C33 1 (1986)	**3.09 ± 0.05 ± ?**	**3.43 ± 0.05 ± ?**
UA5 Z. Phys. C43 357 (1989)		**3.61 ± 0.04 ± 0.12**
CMS JHEP 02 (2010) 041		**3.48 ± 0.02 ± 0.13**

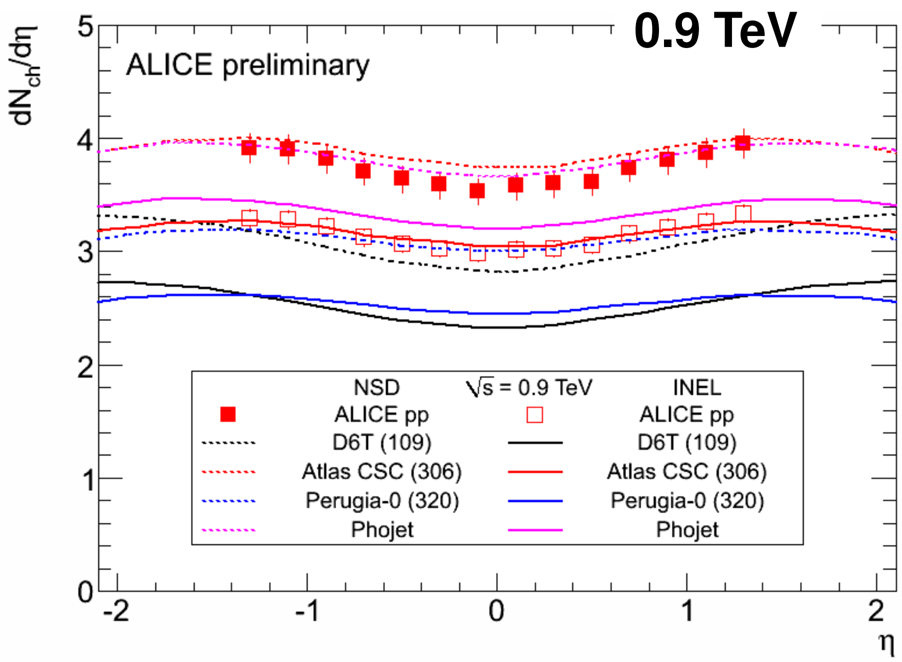


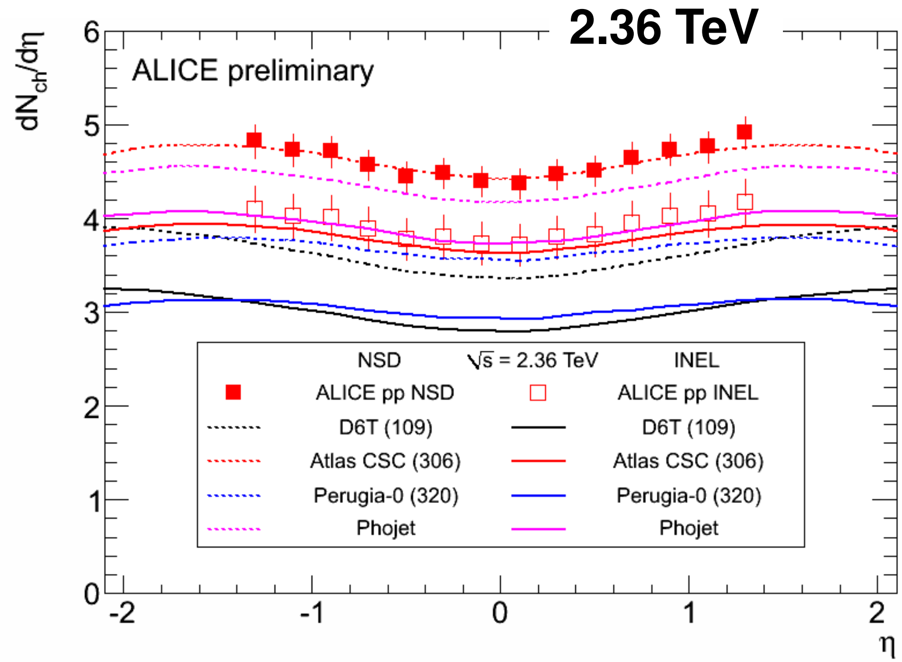
2.36 TeV

CMS does not include charged leptons → ~1.5 % difference

$dN_{ch}/d\eta$ in $\|\eta\| < 0.5$	INEL	NSD
ALICE preliminary	**3.77 ± 0.01 ± 0.23**	**4.44 ± 0.01 ± 0.16**
CMS JHEP 02 (2010) 041		**4.47 ± 0.04 ± 0.16**

Comparison to Monte Carlo



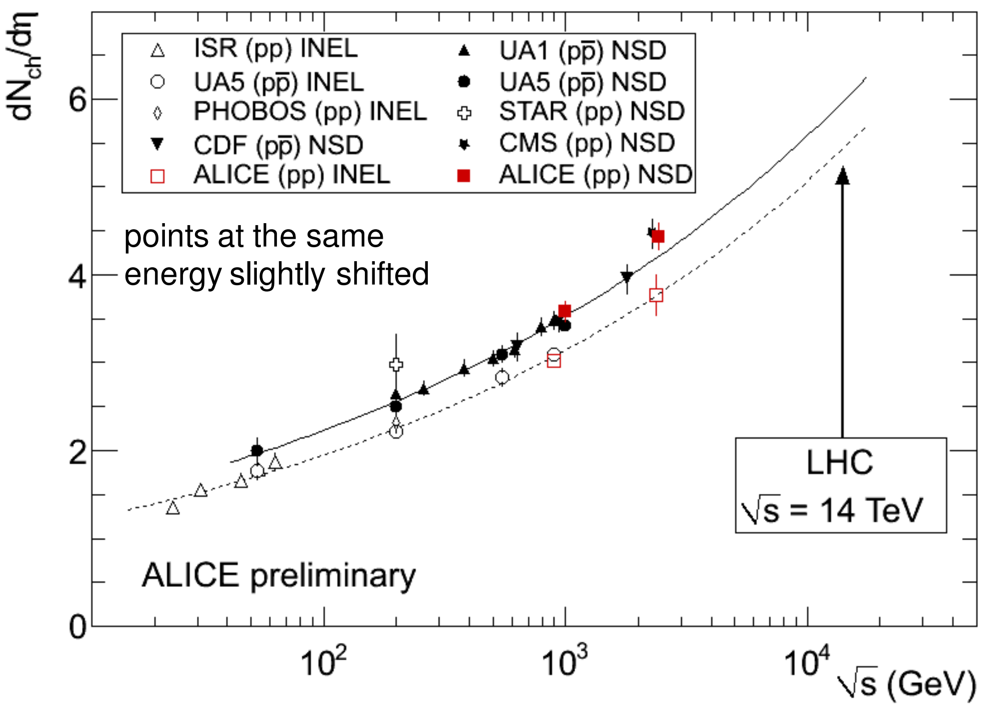


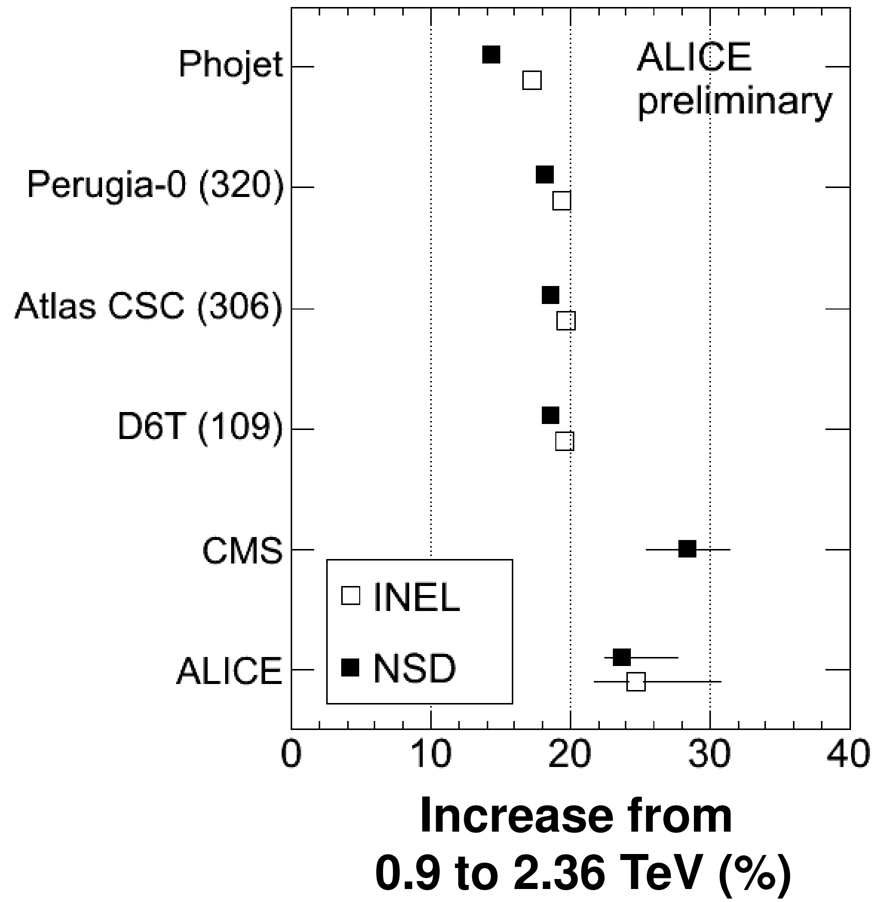
- **Pythia D6T and Perugia-0 match neither INEL nor NSD at both energies**
- **Pythia Atlas CSC and Phojet reasonably close with some deviations**

D6T/Atlas: Pythia 6.4.14 - Perugia-0: Pythia 6.4.21 - Phojet 1.12 with Pythia 6.2.14

$dN_{ch}/d\eta$ vs. $\sqrt{s}$

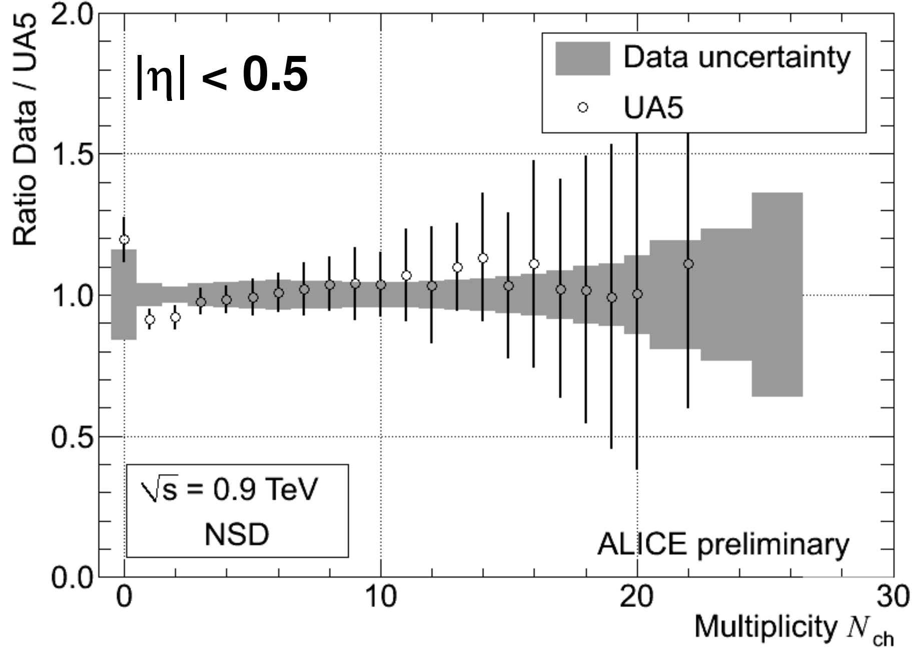
- Larger increase from 0.9 to 2.36 TeV at mid-rapidity as in MC generators

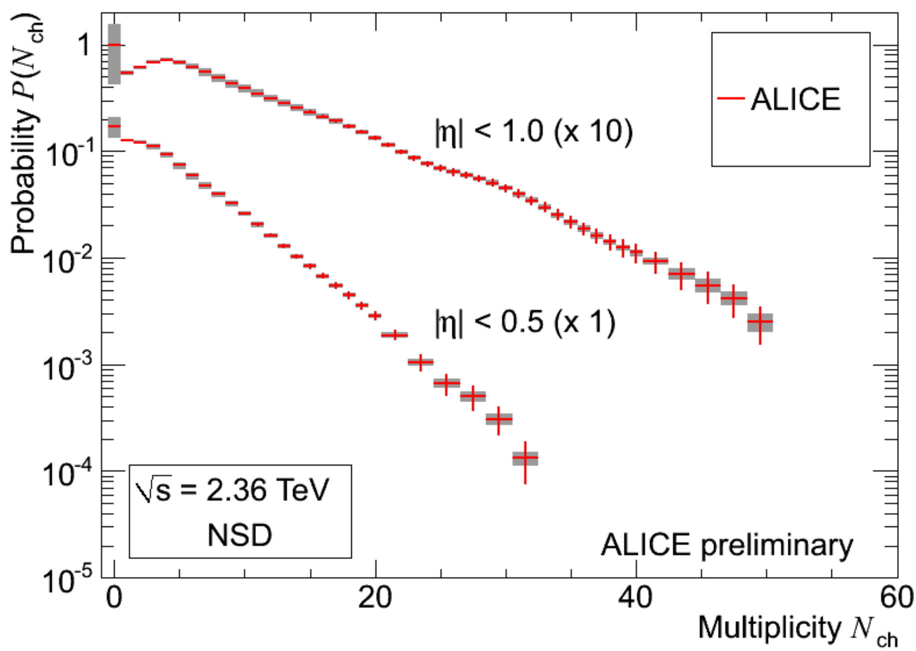




Multiplicity Distributions

- Distributions in limited η-regions
- The average multiplicity of the distribution reproduces the $dN_{ch}/d\eta$ measurement within 1%
- Consistent with UA5

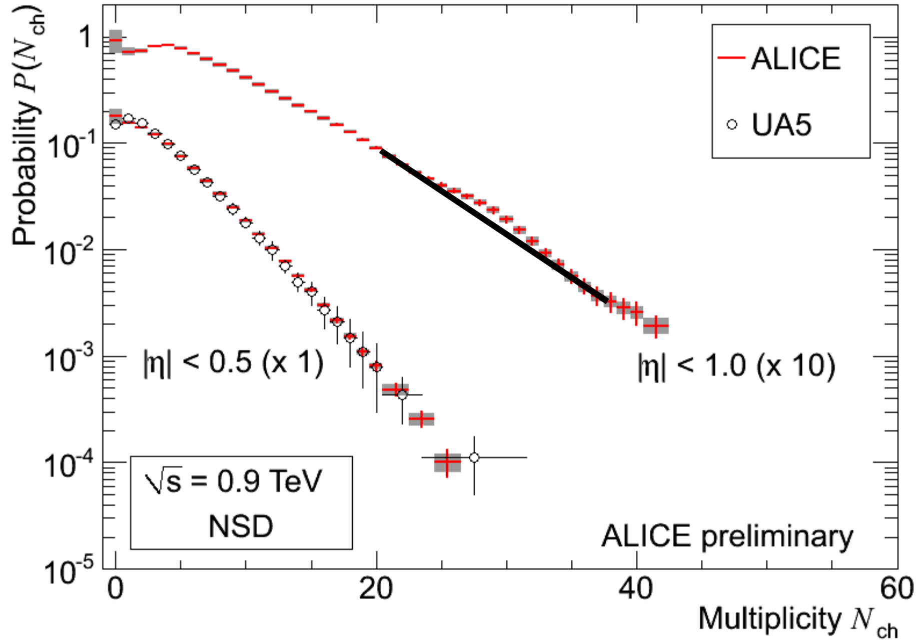


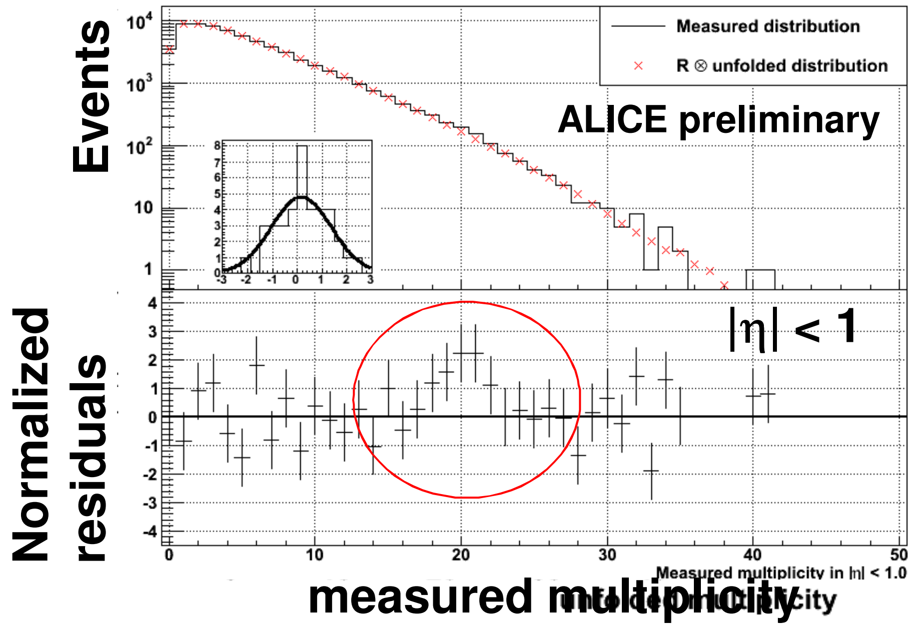


UA5: ZP C43,357

A structure?

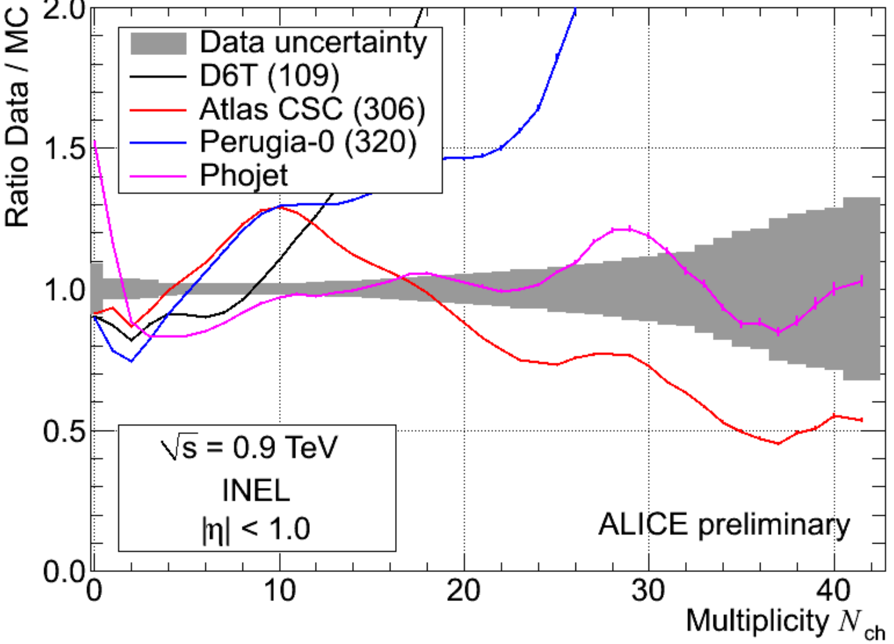
- Independent of
  - Regularization scheme
  - Unfolding method
  - Data sample
- Unfolded distribution changed to exponential
  - Residuals show structure
  - Slope change already in raw data
- But… errors in unfolded spectrum correlated
  - Moving all points by 2σ → structure disappears
  - Might just be a fluctuation

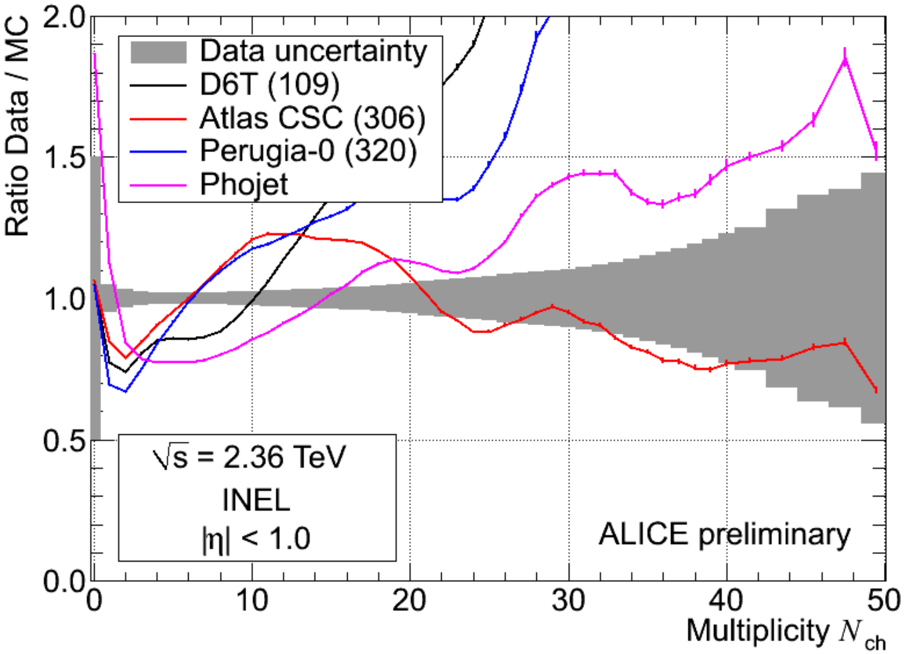




Comparison to Monte Carlo

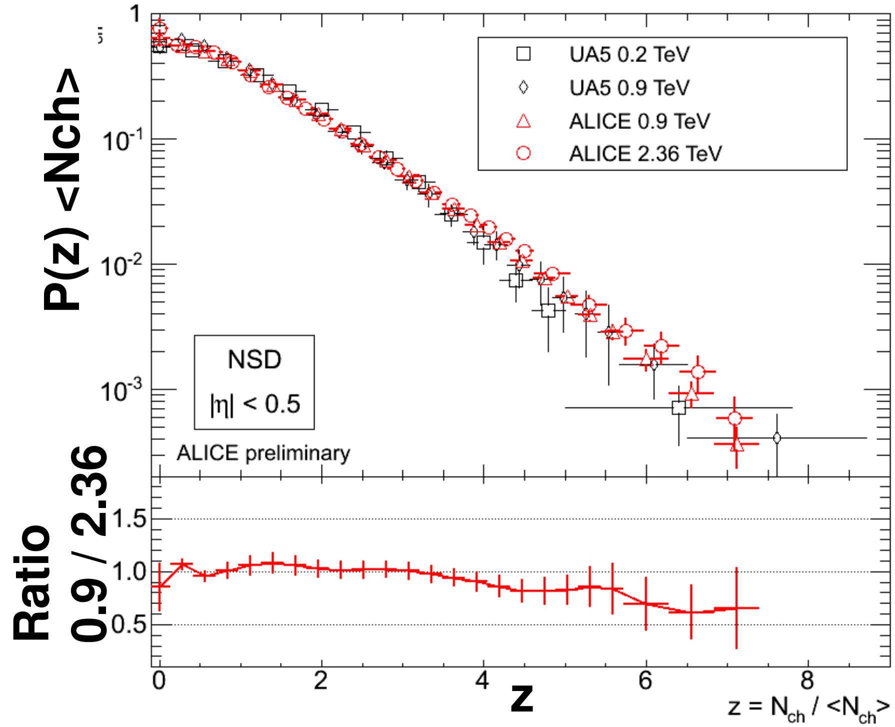
- Phojet provides a good description at 900 GeV, but fails at 2.36 TeV
- Distribution at 2.36 TeV closer to Pythia with Atlas CSC tune
  - Qualitatively same conclusions for NSD
- MC generators do not describe the energy dependence of the tail of the distribution correctly

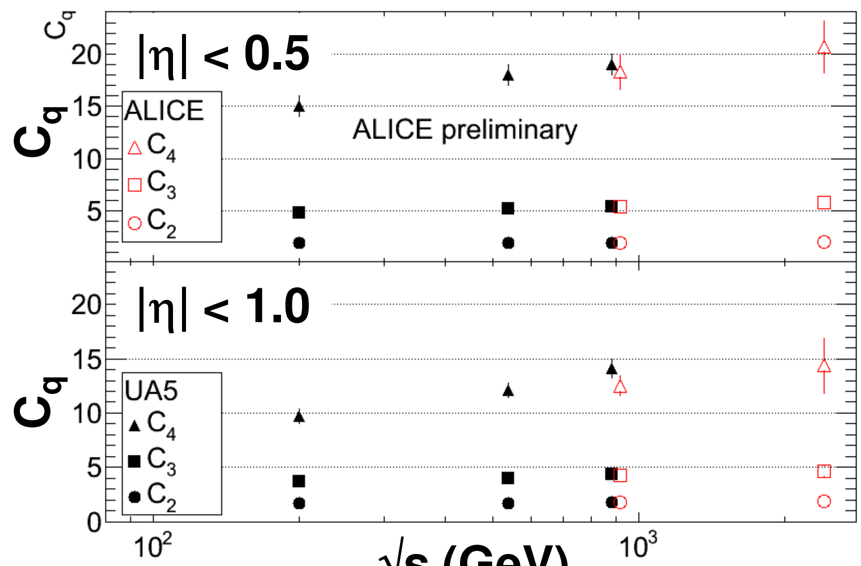




KNO Scaling

- KNO scaling violation in restricted phase space
  - Scaling variable $z = N_{ch}/\langle N_{ch}\rangle$
  - Very sensitive to average multiplicity
    - $dN_{ch}/d\eta$ in $|\eta| < 0.5$ used
    - Consistent with $\langle N_{ch}\rangle$ from distribution
  - KNO scaling fulfilled until z ~ 4
  - For z > 4 trend visible, not significant
- Reduced moments $C_q = \langle n^q\rangle/\langle n\rangle^q$
  - KNO scaling requires constant moments as function of $\sqrt{s}$
  - Slight increase, not significant

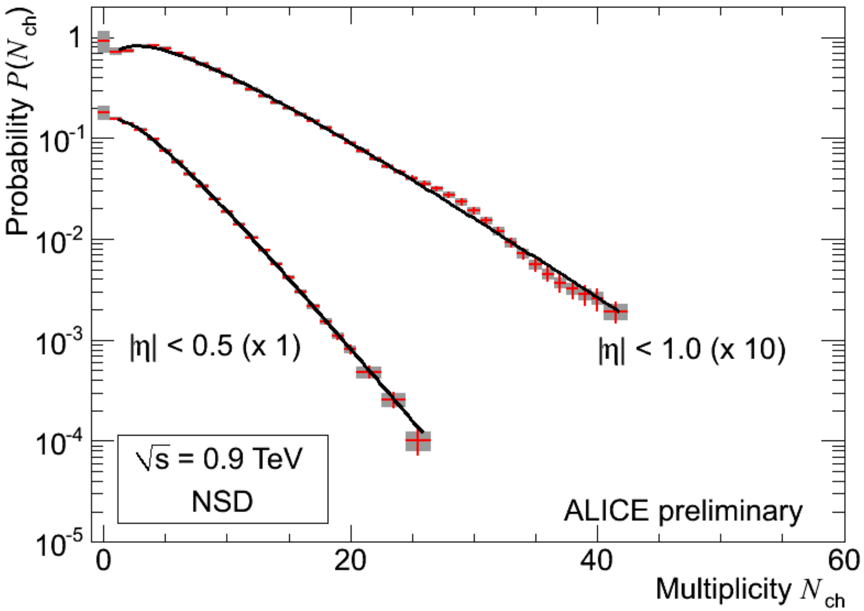


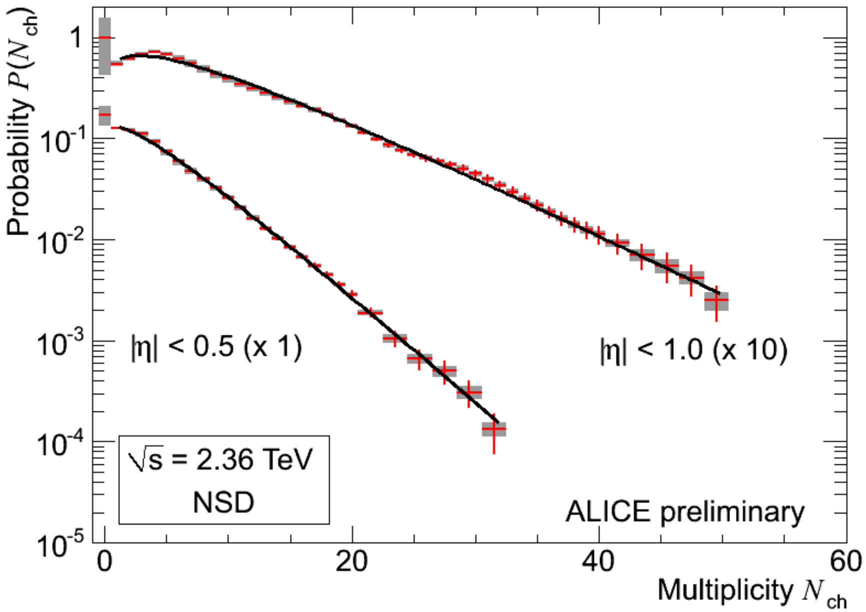


UA5: ZP C43,357

Negative Binomial Distributions

- Fits with one NBD work well at both energies in limited η-regions
  - X^2/ndf between 0.2 and 0.9 (not taking into account correlations between the errors, yet)
- Fit with two NBDs have slightly lower X^2/ndf





References

- The ALICE collaboration, First proton-proton collisions at the LHC as observed with the ALICE detector: measurement of the charged particle pseudorapidity density at sqrt(s) = 900 GeV
  - The European Physical Journal C: Volume 65, Issue 1 (2010), Page 111
  - http://dx.doi.org/10.1140/epjc/s10052-009-1227-4
- JFGO, K. Reygers, Invited review on charged-Particle Multiplicity in Proton-Proton Collisions
  - submitted to Journal of Physics G
  - http://arxiv.org/abs/0912.0023v2
- JFGO, Measurement of the Charged-Particle Multiplicity in Proton-Proton Collisions with the ALICE Detector
  - CERN-THESIS-2009-033
  - http://cdsweb.cern.ch/record/1175646

Summary

- The pseudorapidity density and multiplicity distributions at 0.9 and 2.36 TeV have been presented
  - Consistent with UA5 and CMS
- MC generators do not describe the energy-dependence of the average multiplicity as well as the tail of the distributions correctly
  - Significantly larger increase of the multiplicity measured
- KNO scaling in $|\eta| < 0.5$ and 1.0 remains valid
- Negative binomial distributions reproduce the shape at 0.9 and 2.36 TeV

Thanks for help with preparing this talk to Michele Floris, Andreas Morsch, Sparsh Navin, Maria Nicassio, Martin Poghosyan

Thank you for your attention!