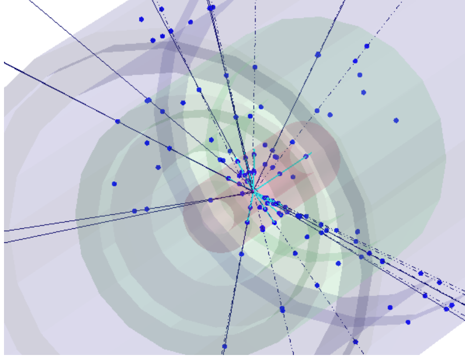

Charged-Particle Multiplicity in Proton-Proton Collisions at Collider Energies

arXiv:0912.0023 - J. Phys. G **37** (2010) 083001

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Hadron-Hadron and Cosmic-Rays
Collisions at multi-TeV Energies

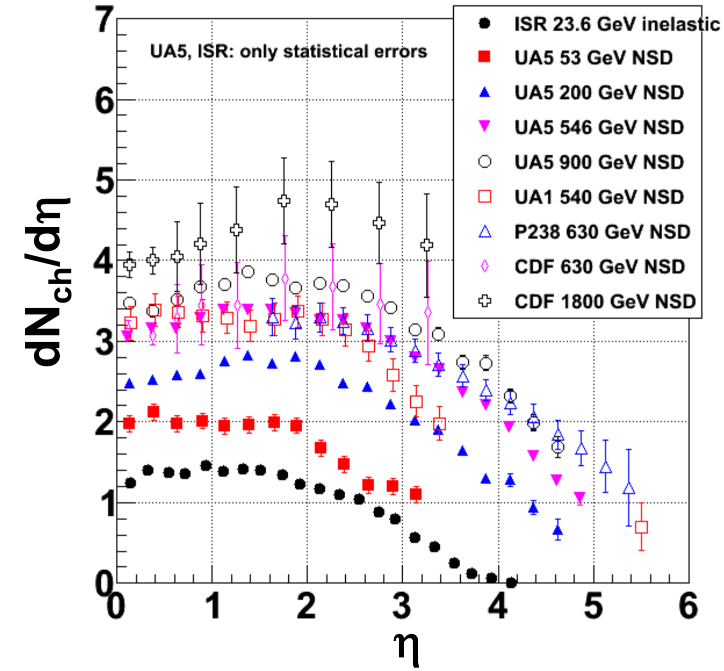
Trento, 29.11. – 3.12.2010

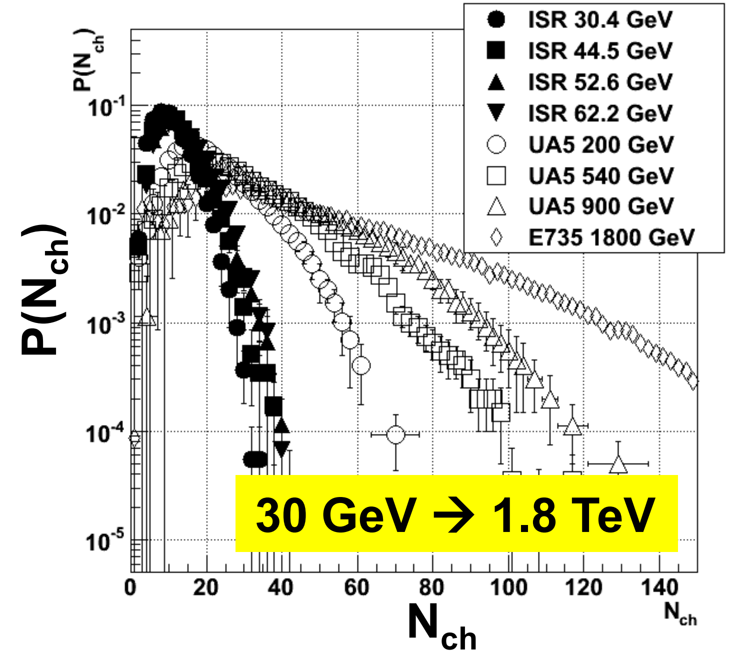
Content

- The topical review "Charged-Particle Multiplicity in Proton-Proton Collisions" aims at given an introduction to the field of multiplicity measurements
- Basic theoretical concepts and their applicability to data
- Overview of the experimental results (from colliders)
  - Critical assessment of correction method
  - Open questions
- Similarity between pp and e^+e^- collisions
- Predictions for the LHC energy regime
  - Today these predictions will be confronted with the early LHC results
- Overview of LHC results

Charged-Particle Multiplicity

- Simple observable in collisions of hadrons
  - Soft physics
  - No pQCD
- 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
- Independent particle emission → Poisson distribution
  - Any departure indicates correlations





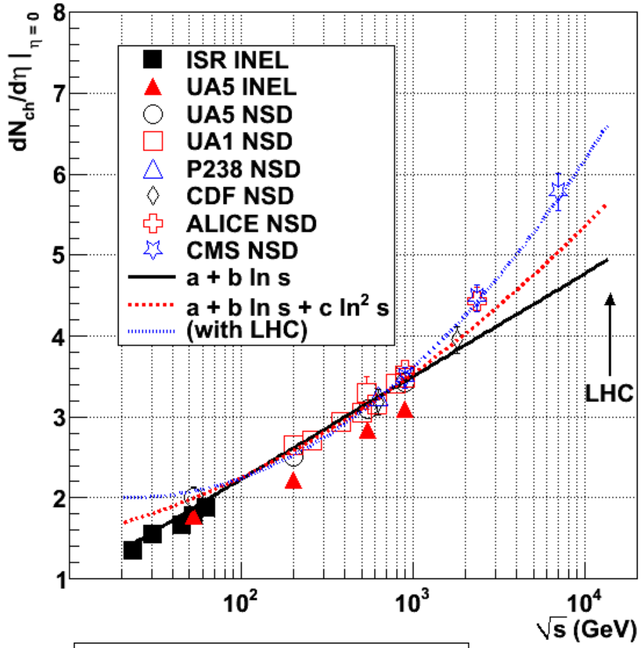
Data Sample

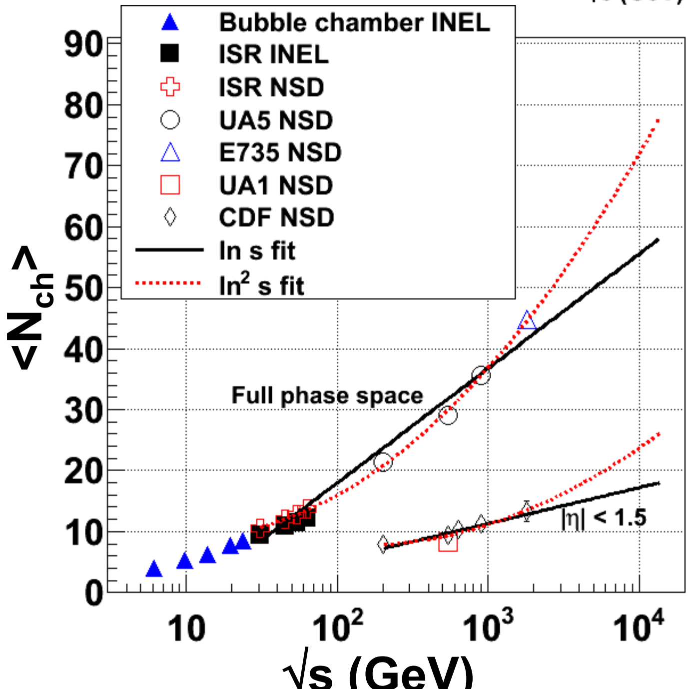
- The review gives an overview of available data from 23.6 – 1800 GeV
- Detector description
- Event sample
- Assessment of correction procedure including critical remarks if needed

Experiment	Ref.	Energy	$dN_{ch}/d\eta$	Mult.
SFM	[8]	30.4, 44.5, 52.6, 62.2 GeV (INEL, NSD)		X
Streamer Chambers Detector	[11]	23.6, 30.8, 45.2, 53.2, 62.8 GeV (INEL)	X	X
UA1	[73]	200, 500, 900 GeV (NSD)		X
	[74]	540 GeV (NSD)	X	
UA5	[75]	53 GeV (INEL)	X	X
	[76]	53, 200, 546, 900 GeV (INEL, NSD)	X	
	[77]	546 GeV (INEL, NSD)	X	X
	[78]	540 GeV (NSD)		X
	[33]	540 GeV (NSD)		X
	[34]	200, 900 GeV (NSD)		X
	[13]	200, 900 GeV (NSD)		X
P238	[79]	630 GeV (NSD)	X	
CDF	[80]	0.63, 1.8 TeV (NSD)	X	
	[14]	1.8 TeV (NSD)		X
E735	[49]	0.3, 0.5, 1.0, 1.8 TeV (NSD)		X
	[81]	0.3, 0.5, 1.0, 1.8 TeV (NSD)		X
	[82]	1.8 TeV (NSD)		X

Data Sample (2)

- $dN_{ch}/d\eta_{\,|\,\eta\,=\,0}$ and $\langle N_{ch} \rangle$ as function of √s
- Fit with ln and ln² term
  - LHC data points change fit results significantly (increases χ^2 by a factor 2)
    - Slope increase at LHC energies
- Full phase space results probably not measurable at LHC without significant extrapolations





Feynman Scaling

- Phenomenological arguments about the exchange of quantur 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

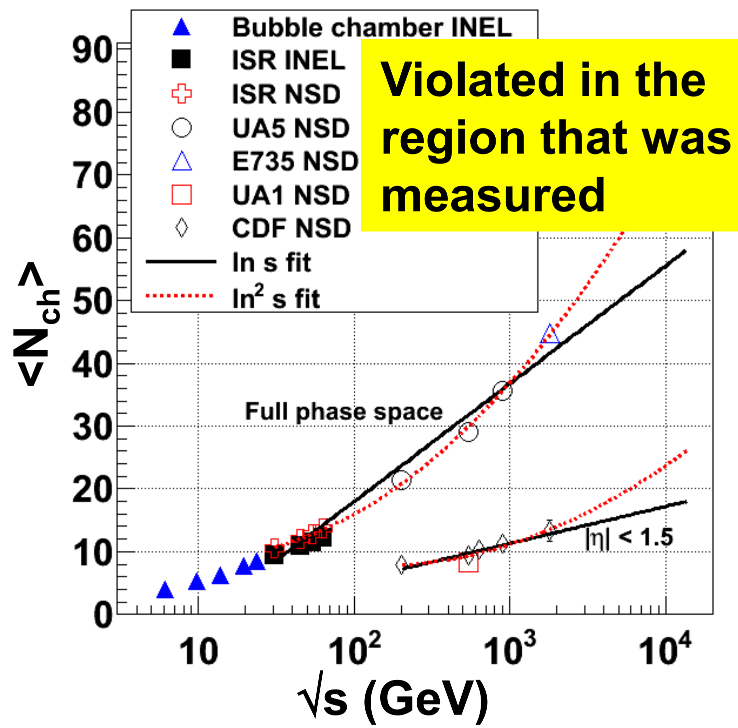
→$dN_{ch}/d\eta$ approx. constant

VERY HIGH-ENERGY COLLISIONS OF HADRONS

Richard P. Feynman
California Institute of Technology, Pasadena, California

(Received 20 October 1969)

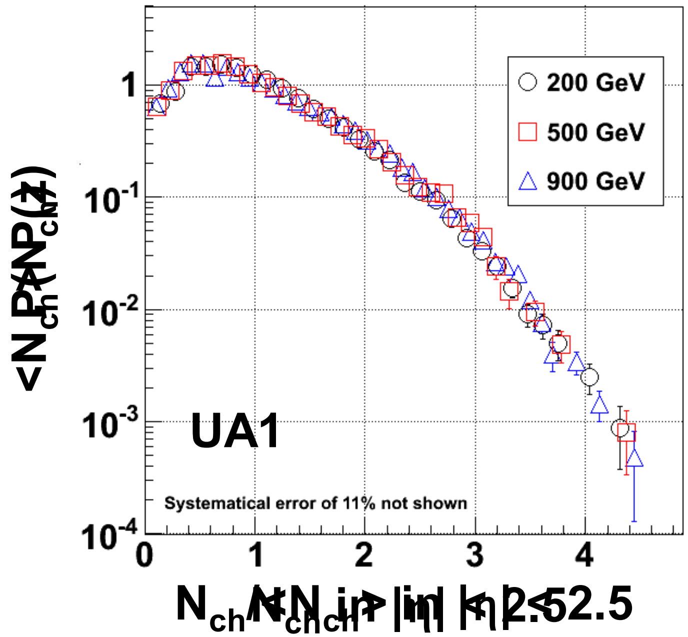
PRL 23 1415 (1969)



Violated in the region that was measured

KNO Scaling

- Koba, Nielsen, Olesen (1972)
- Based on Feynman scaling
- Scaling variable
  $z = N_{ch}/<N_{ch}>$
- Express $P(N_{ch})$ as
  $P(z) * <N_{ch}>$
- 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), $|\eta| < 0.5$ up to 7 TeV (CMS)

Nucl. Phys. B40 317 (1972)

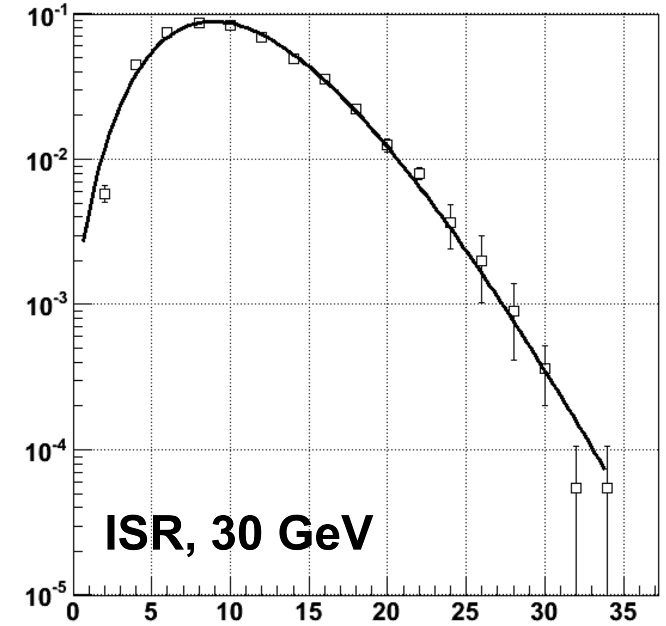
Negative Binomial Distributions

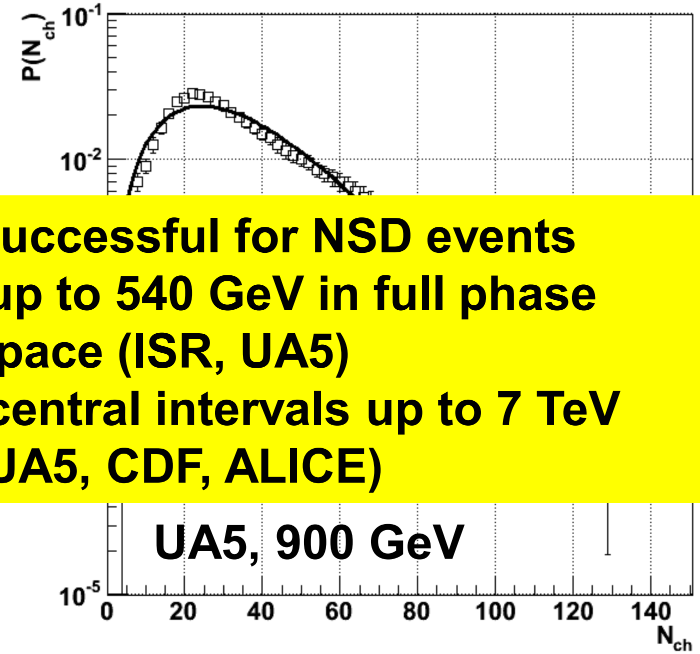
- Bernoulli experiment
  - Probability for n failures and k successes in any order, but the last trial is a success

$$P_{p,k}^{NBD}(n) = \binom{n+k-1}{n}(1-p)^n p^k$$

$$p^{-1} = 1 + \frac{\langle n \rangle}{k}$$

- 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

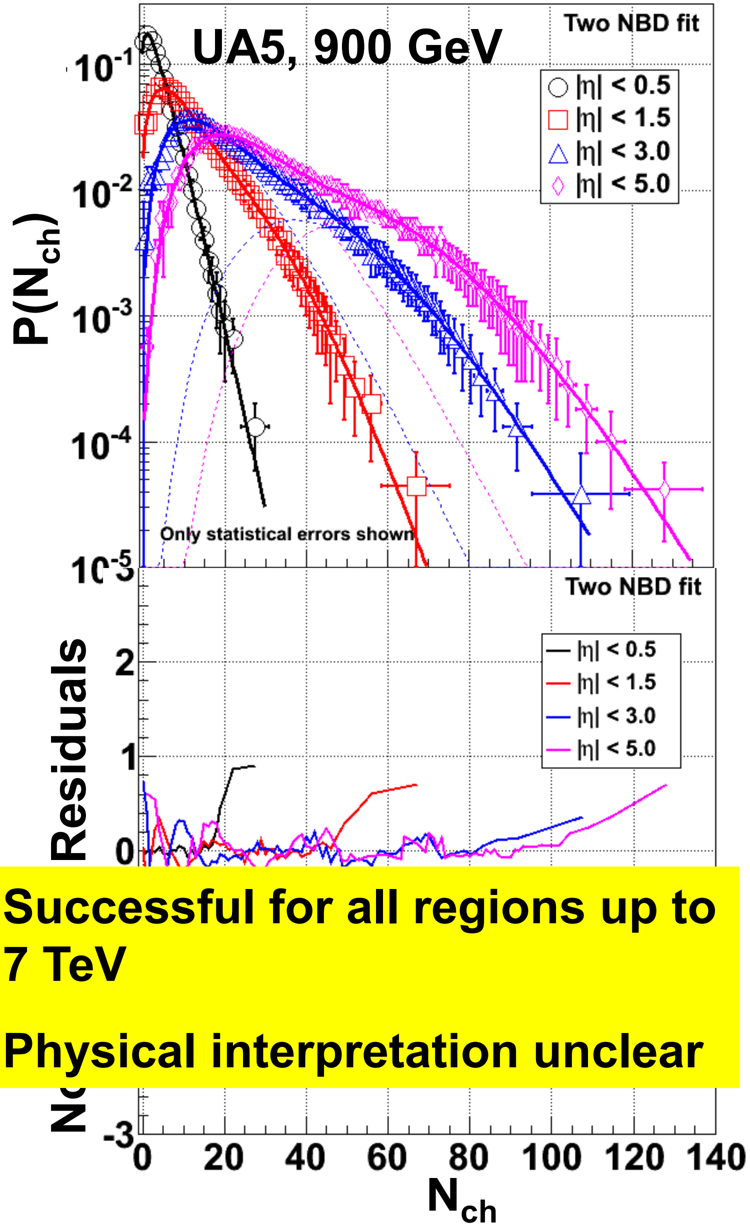




Successful for NSD events
•up to 540 GeV in full phase space (ISR, UA5)
•central intervals up to 7 TeV (UA5, CDF, ALICE)

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))
- IPPI model: MD is superposition of NBDs (each for a definite number of parton-parton scatterings) (Dremin, Phys. Rev. D70 034005 (2004))



Successful for all regions up to 7 TeV

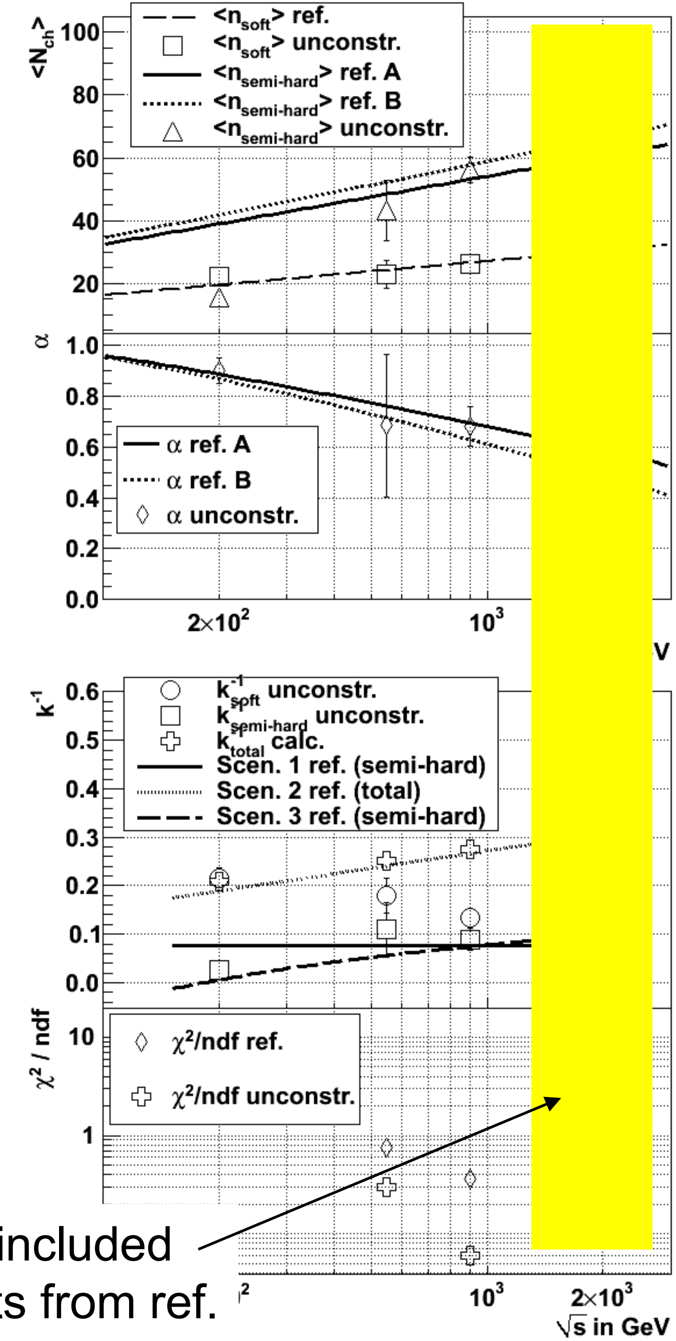
Physical interpretation unclear

Fitting 2 NBDs

- Multiplicity distributions can be fit very well a combination of two NBDs
  - Can one identify trends? → difficult

$$\alpha P^{\mathrm{soft}}_{\langle n\rangle_{soft},k_{soft}}(n)+(1-\alpha)P^{\mathrm{semihard}}_{\langle n\rangle_{semihard},k_{semihard}}(n)$$

- Giovannini et al used a “guided” approach (with data up to 900 GeV)
  - Fit $\langle n\rangle_{soft}$ for $\sqrt{s}$ < 60 GeV with ln
  - $\langle n\rangle_{total}$ for all $\sqrt{s}$ with ln + $\ln^2$
  - $\langle n\rangle_{semihard} \sim 2 \langle n\rangle_{soft}$ (from UA1 minijet analysis)
  - Extract α, fit k_{soft} and $k_{semihard}$
- Unconstrained fits
  - Yield partly different results
  - Large uncertainties
  - Very low χ^2/ndf



not included in fits from ref.

Moments

- Convenient way to study shape as function of √s
  - Moments at all orders contain information from full distribution
  - In practice only lower order moments can be calculated due to uncertainties
- Reduced C-moments
- Normalized factorial F-moments
- D-moments
  - Dispersion $D = D_2$

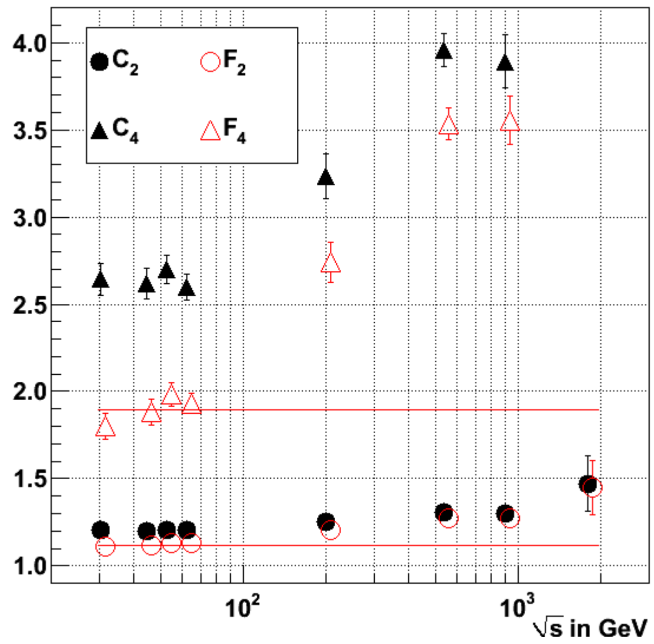
$$C_q = \frac{\langle n^q \rangle}{\langle n \rangle^q}$$

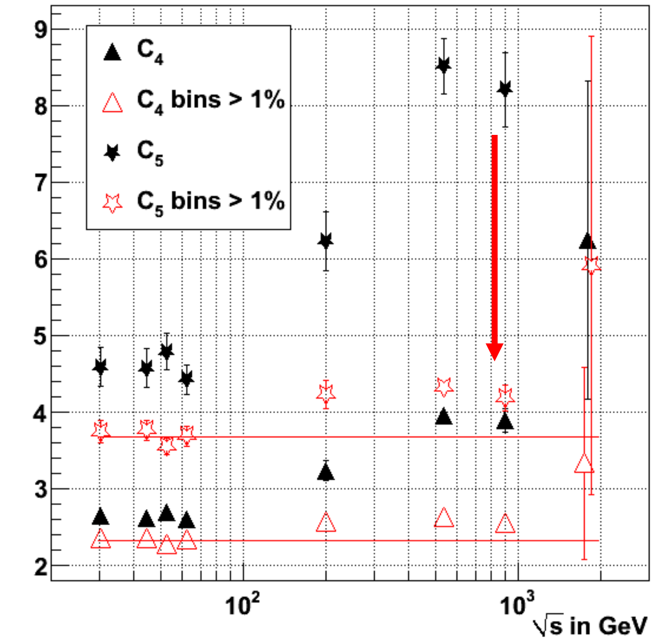
$$F_q = \frac{\langle n(n-1)\ldots(n-q+1) \rangle}{\langle n \rangle^q}$$

$$D_q = \left\langle \left(n - \langle n \rangle\right)^q \right\rangle^{1/q}$$

Moments (2)

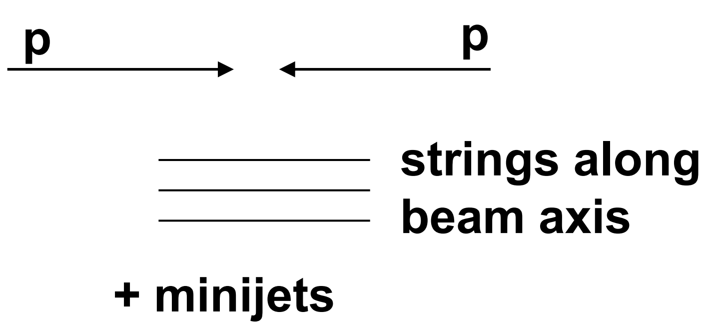
- KNO scaling postulates constant F-moments
  - Often C-moments are analyzed (only an approximation!)
  - However, similar conclusions
- Bins at large multiplicity have large influence (especially on higher moments)
  - Care needed when comparing low and high statistics measurements
  - Uncertainties? → Bin with 0 entry does not contribute

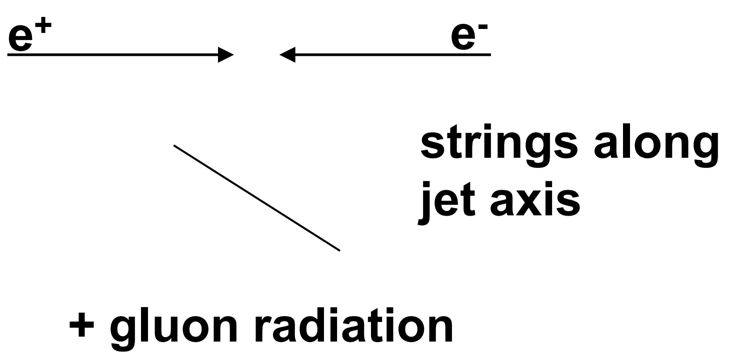




Similarity of e^+e^- and pp collisions

- In pp collisions (without hard scattering) and e^+e^- collisions, particle production results from fragmentation of colour-connected partons
  - pp: along beam axis
  - e^+e^-: along jet axis
- Hard processes different
  - pp: minijet production
  - e^+e^-: gluon radiation
- Phenomenological, but no sound theory arguments for universality of pp and e^+e^-
  → Let‘s try anyway ☺



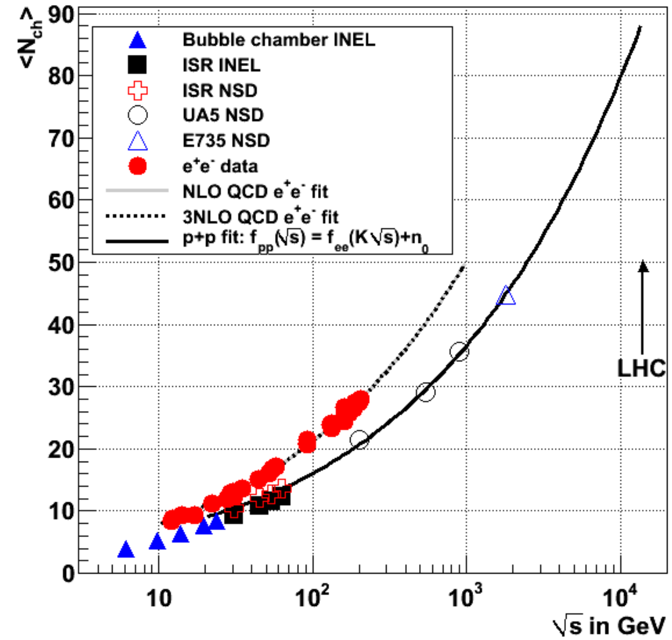


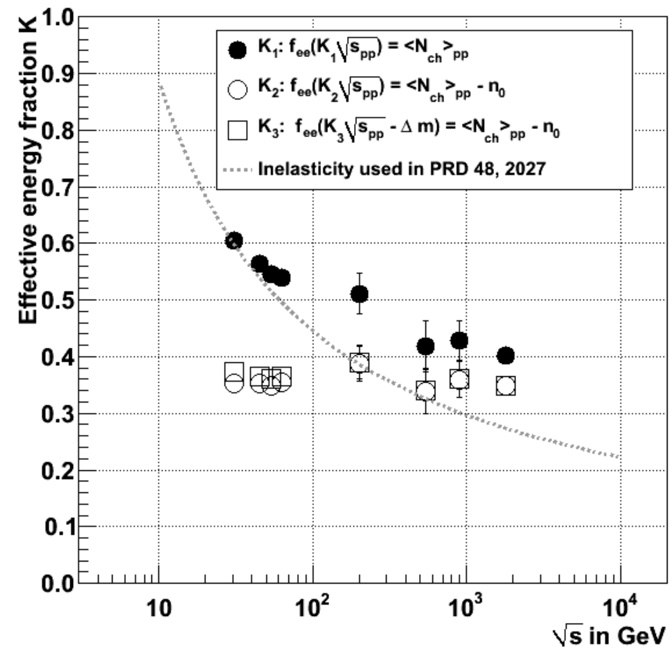
Similarity of e^+e^- and pp collisions (2)

- e^+e^- and pp become similar when pp is plotted at ½√s
- Effective energy $E_{eff} = \sqrt{s} - E_{lead,1} - E_{lead,2}$
- Inelasticity $K = E_{eff}/\sqrt{s}$
- Analytical QCD expression to describe e^+e^-

$$f_{pp}(\sqrt{s}) = f_{ee}(K\sqrt{s}) + n_0$$

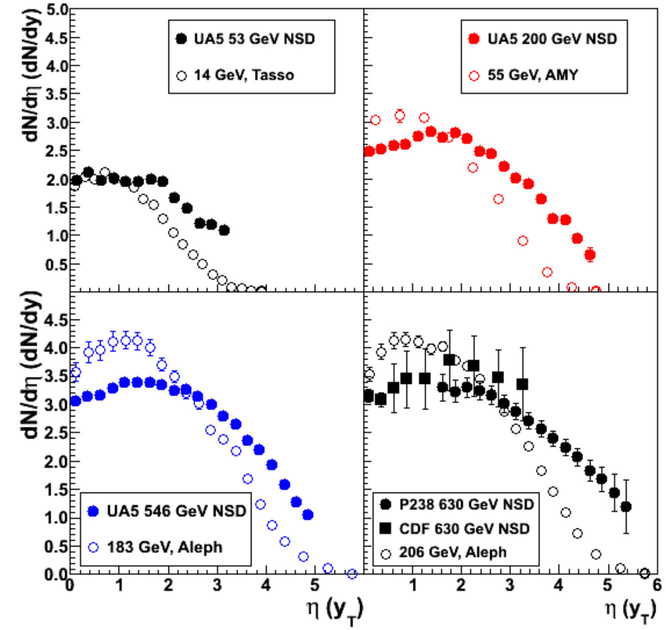
  - n_0 contribution of leading protons
  - Fit yields K = 0.35 and n_0 = 2.2
  - Does K ~ 1/3 mean that only 1 valence quark is part of the collision?
- Calculate K for n_0 = 0, n_0 = 2.2

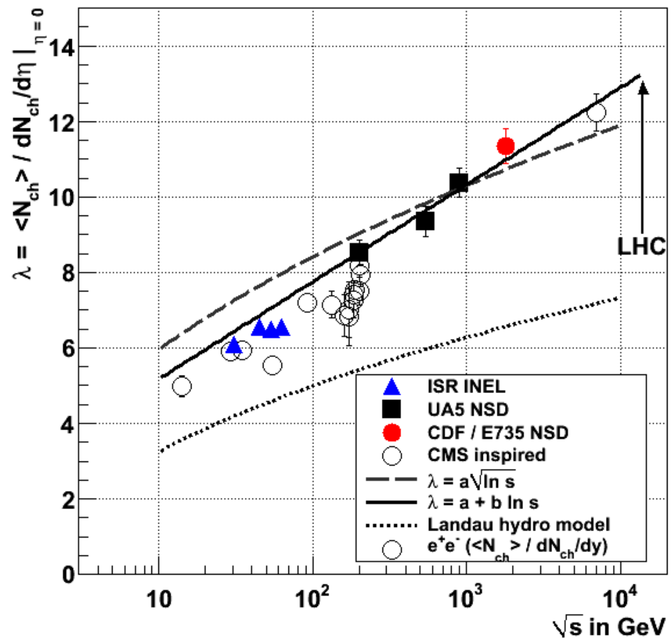




Similarity of e^+e^- and pp collisions (3)

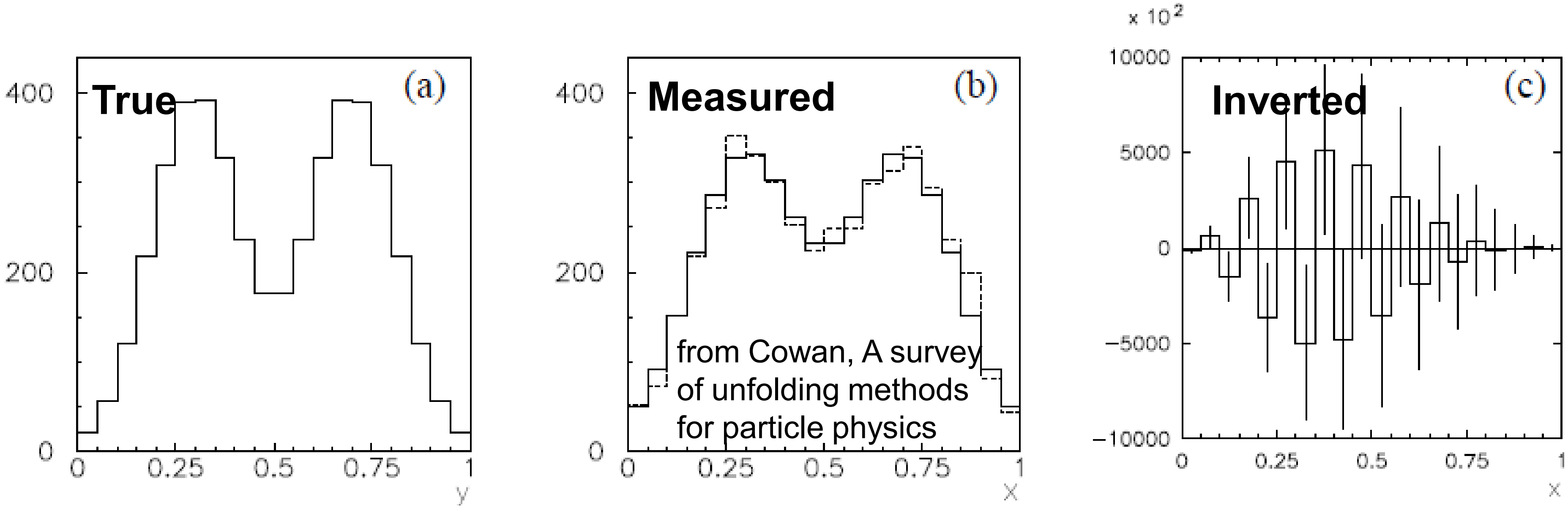
- What about other distributions?
  - Compared at $\sqrt{s_{pp}}$ = 2-3 $\sqrt{s_{ee}}$
  - (Pseudo-)rapidity distributions are different
    - Contribution from beam particle fragmentation?
- Extrapolation
  - Width of distribution
    $\lambda = \langle N_{ch} \rangle / dN_{ch}/d\eta_{\,|\,\eta = 0}$
  - Extrapolated with a+b ln s
  - Together with e^+e^- fit (for total multiplicity extrapolation) yielded 5.5 for 7 TeV
    - CMS measured 5.8 ± 0.23
    - (Obviously) fit can also be done with CMS result (using $\langle N_{ch} \rangle$ from extrapolation)





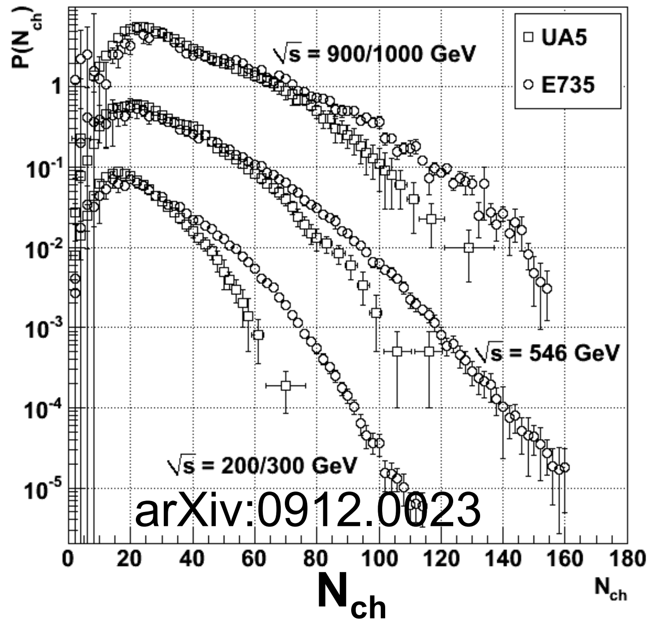
Experimental Challenges

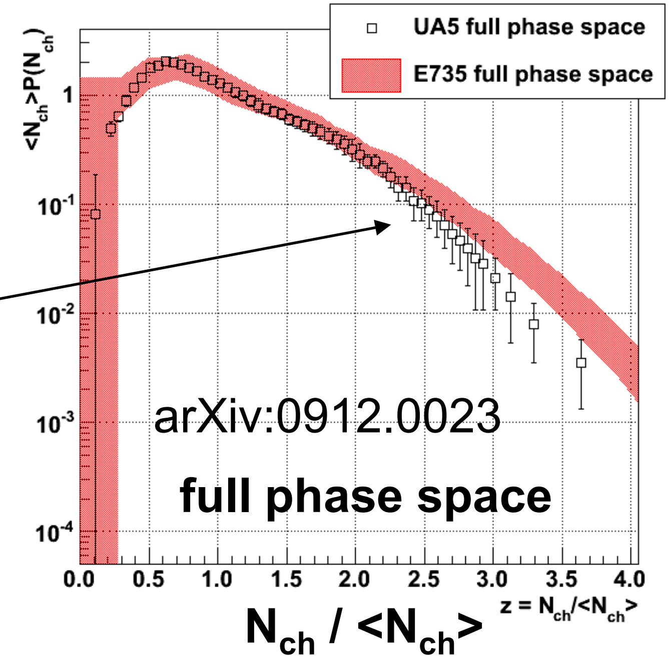
- Multiplicity distributions (usually) need to be unfolded
  - Detector efficiency < 1 → bin migration + steeply falling spectrum
- Unfolding an ill-posed problem
  - Requires regularization
- Slight misestimation of tracking efficiency result in significant uncertainties in the tail of the distribution
  - I.e. 1-2% result in 30-40% at multiplicity 70 (e.g. for 7 TeV in $|\eta| < 1$)

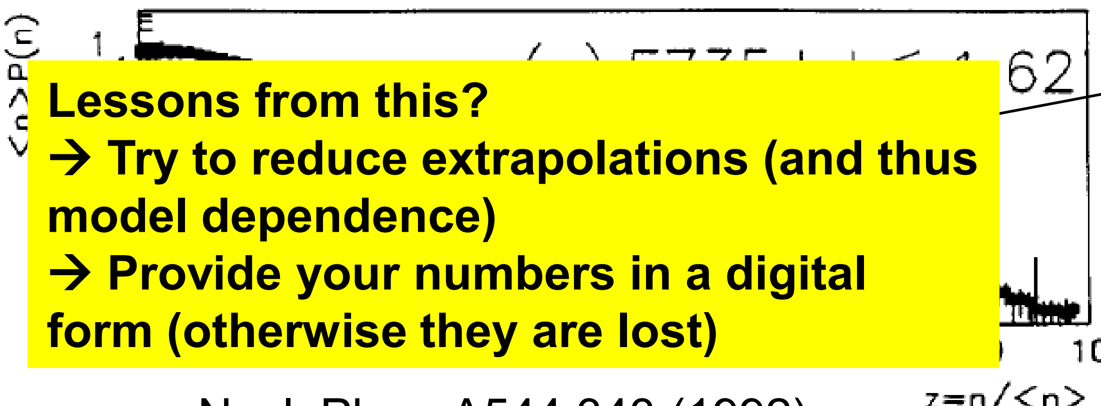


Open Experimental Issues

- Discrepancy of multiplicity distributions of UA5 and E735 in full phase space
  - Extrapolated from |η| < 5 (UA5) and |η| < 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)

$dN_{ch}/d\eta$ in pp (7 TeV)

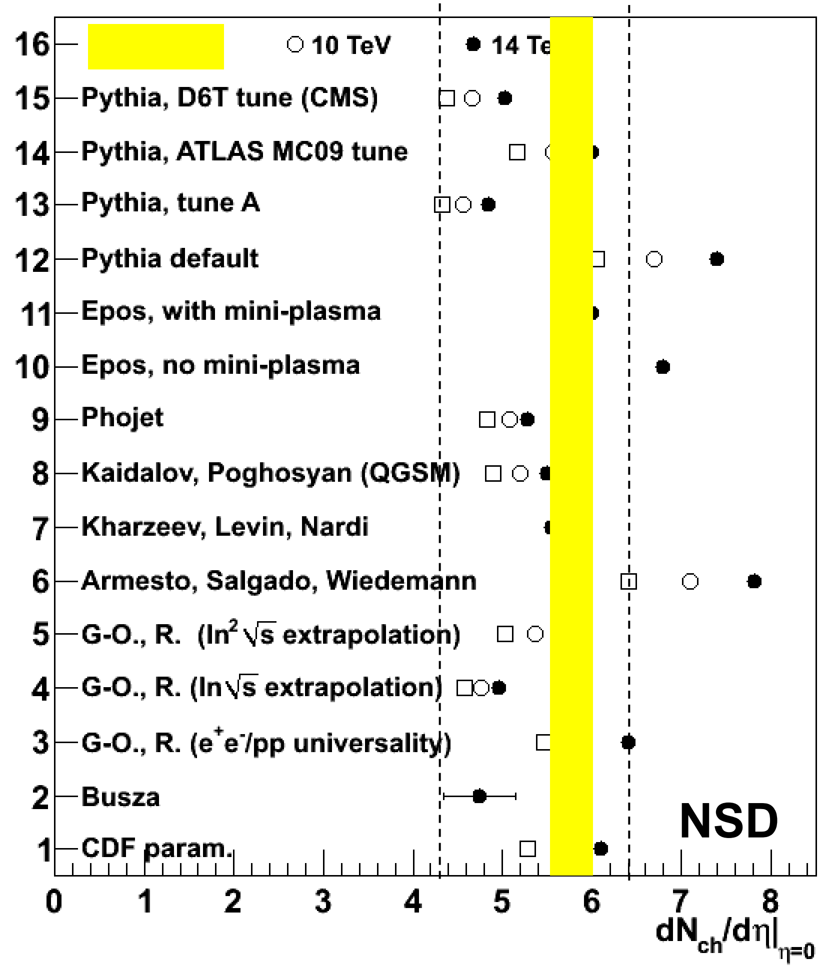
- Extrapolations of trends at lower $\sqrt{s}$
  - Just for average multiplicities
  - For the multiplicity distribution
- Gluon saturation models (Armesto et al, Kharzeev et al)
- Dual Parton Model / Quark-Gluon String Model
- Monte Carlo generators
  - Pythia (pQCD + soft phenomenology) with all its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

too low

too low
too high

too low

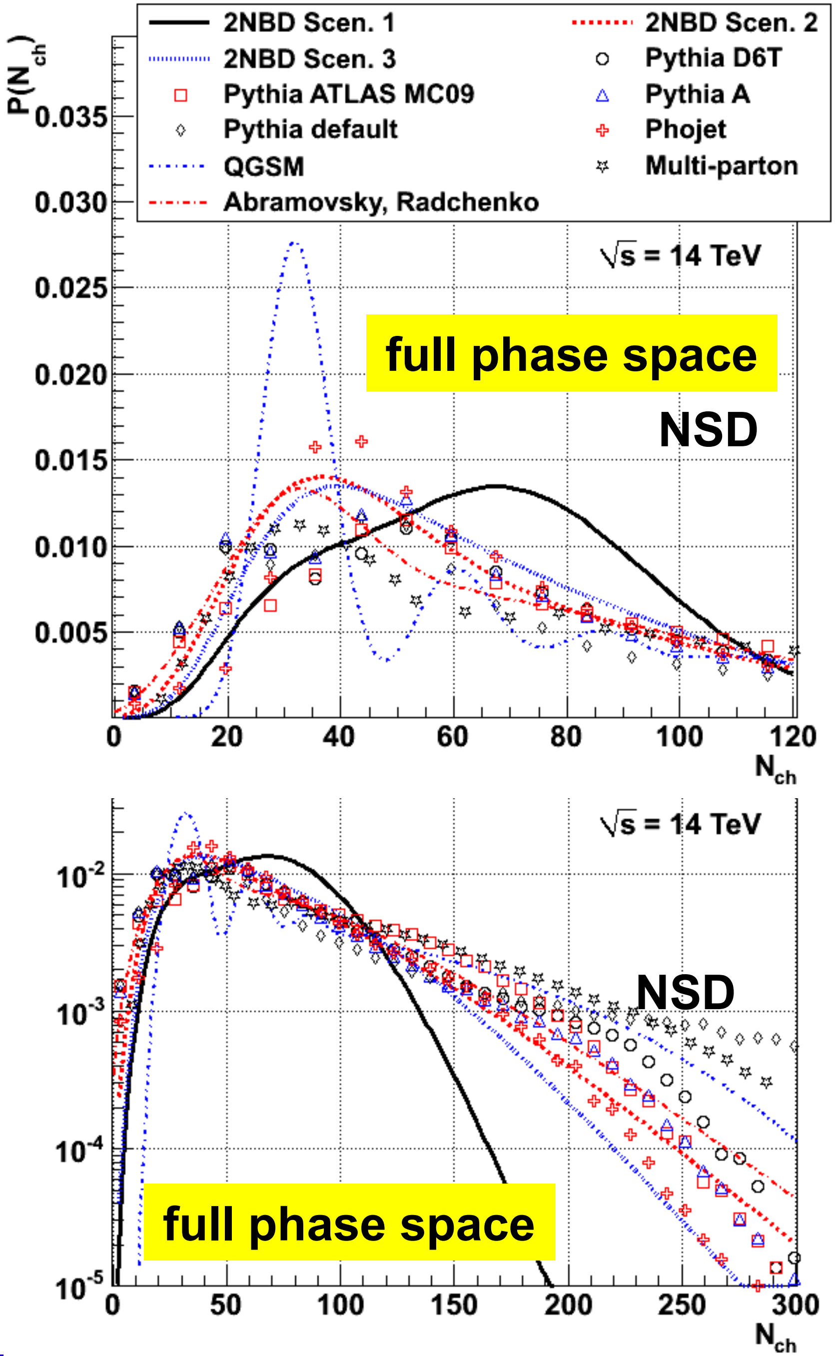
some too low
some ok



$dN_{ch}/d\eta$ value from CMS

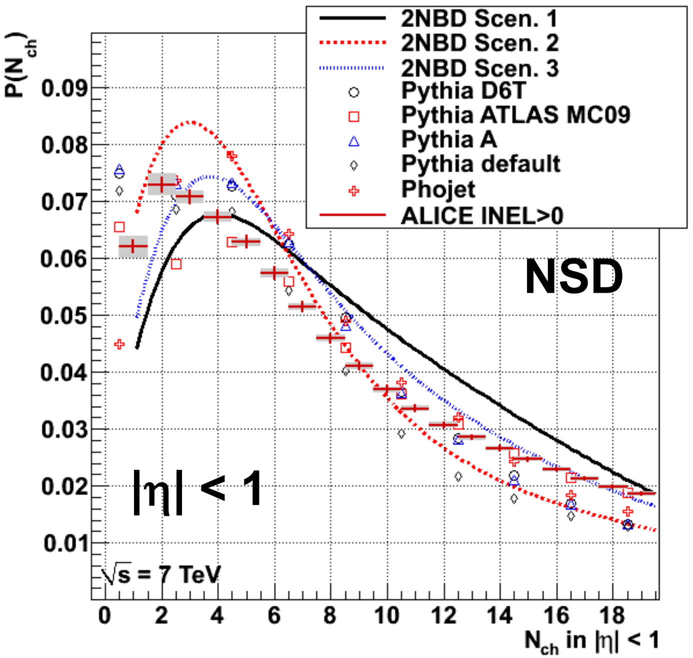
Multiplicity Distributions Predictions

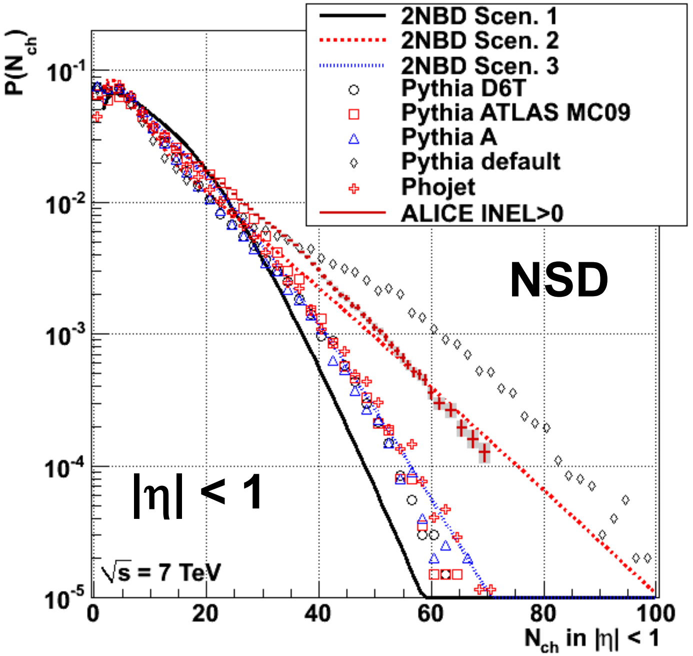
- Most predictions available for 14 TeV
- Multiplicity distributions differ by a factor 2 up to an order of magnitude
- Full phase space not accessible at LHC



Multiplicity Distributions Predictions vs. LHC

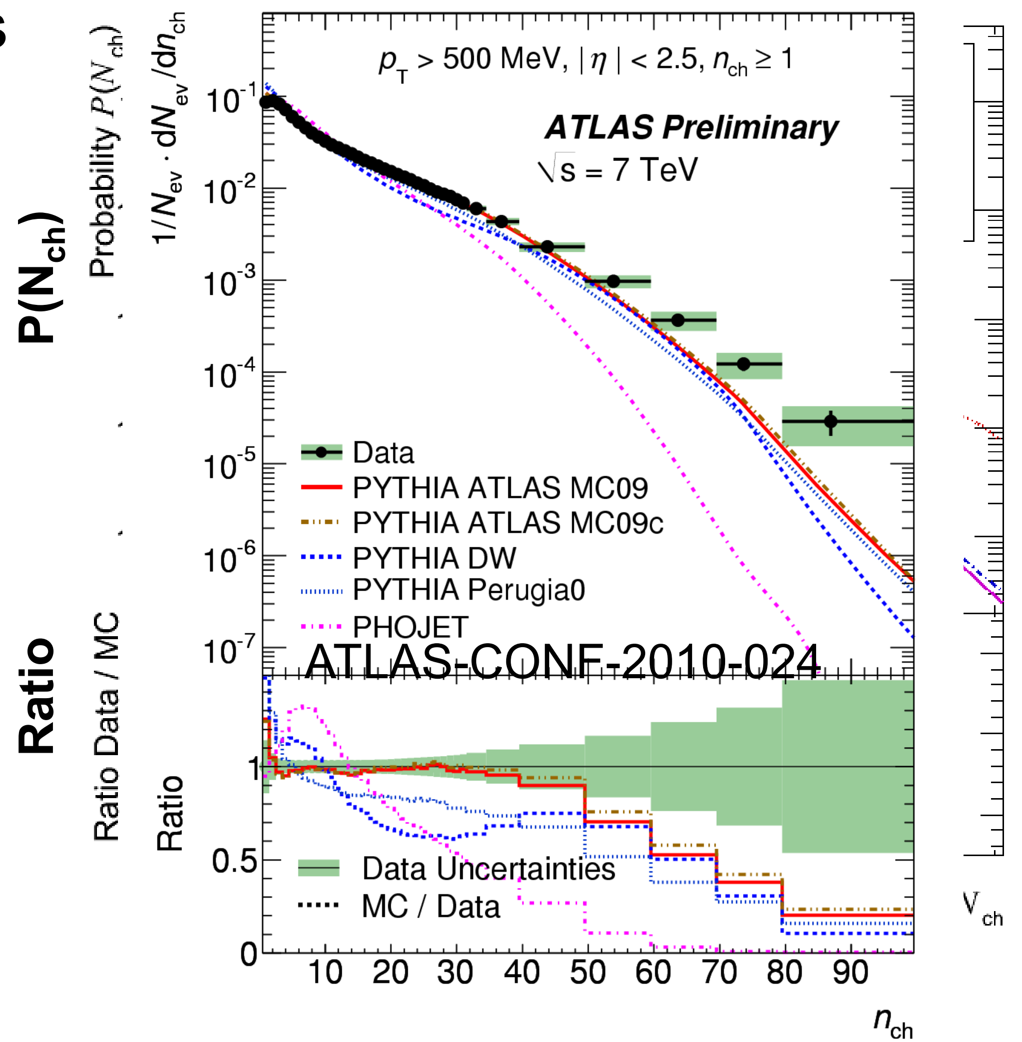
- Limited phase space predictions (|η| < 1) for NSD at 7 TeV
- Overlaid with INEL>0 measurement of ALICE (CMS has a NSD measurement but does not give out the data points before the publication ☹)
  - Scaling arbitrary and with an uncertainty of at least 20%





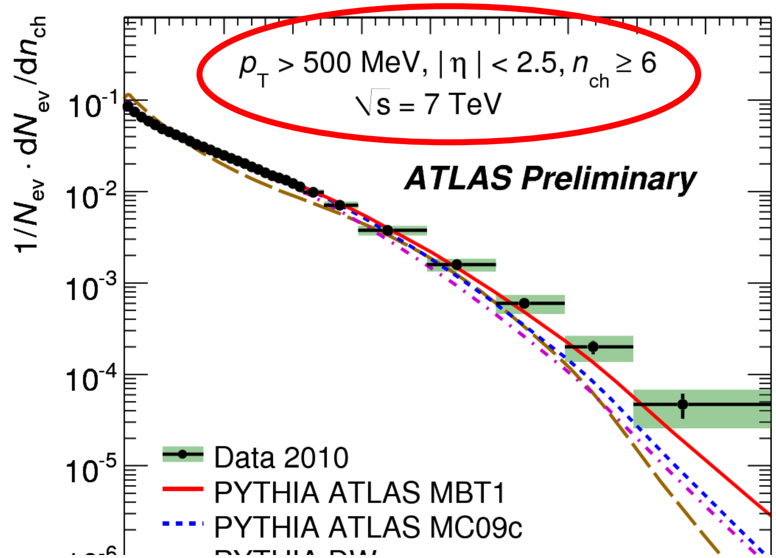
Multiplicity Distributions Predictions vs LHC (2)

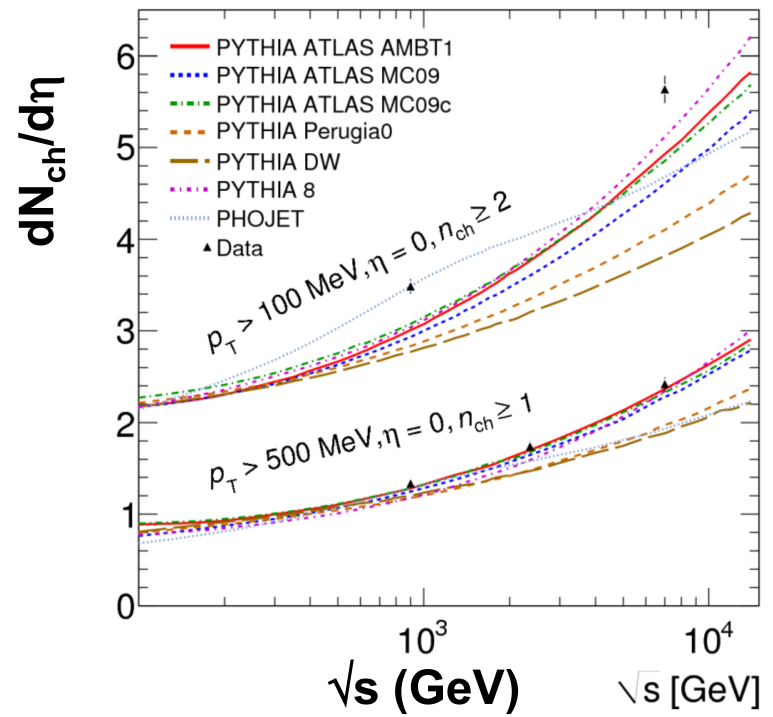
- LHC results in η-intervals up to 2.5
  - No p_T cut (ALICE, CMS)
  - p_T > 500 MeV/c (ATLAS)
  - INEL > 0 (ATLAS, ALICE)
  - NSD (CMS)
- Much wider tail than expected by MCs
- Better agreement for p_T > 500 MeV/c



MC Tuning

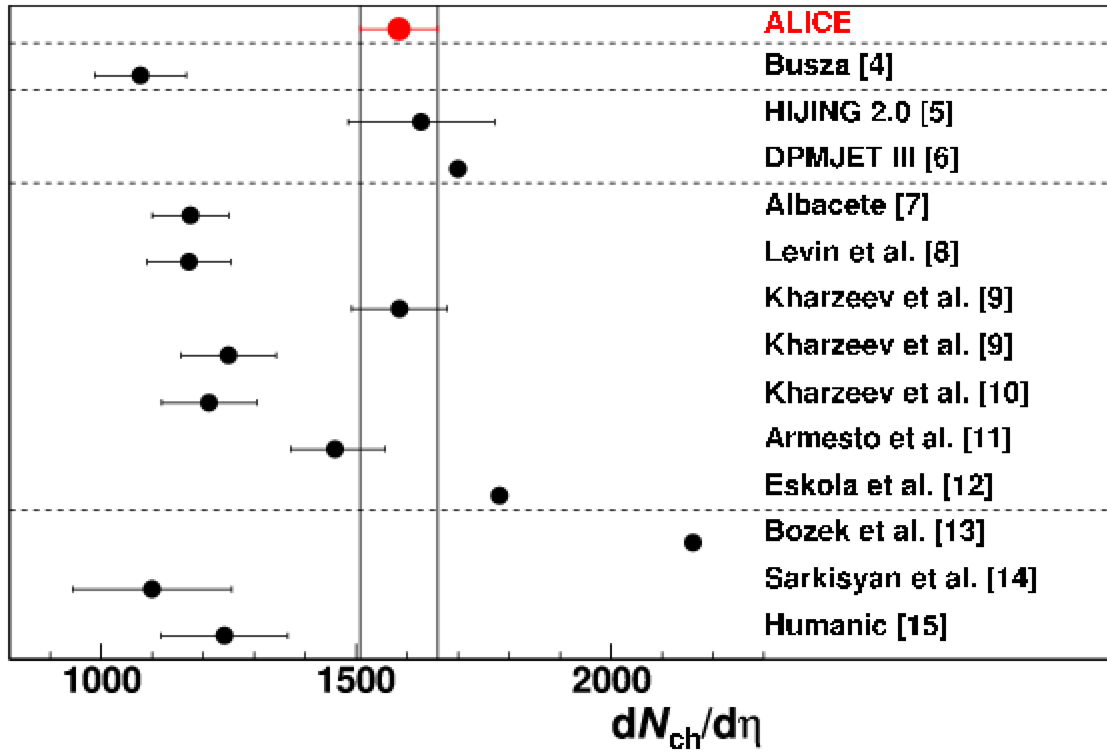
- ATLAS (ATLAS-CONF-2010-031) and CMS (Rick Field, HCP2010) already presented some updated Pythia6 tunes
  - Both essentially change the parameters governing multiple parton interactions
    - $p_{T,min}$ and its energy evolution
    - Proton matter distribution
- Improves consistency with data in considered region
  - Low p_T region + diffractive region difficult





$dN_{ch}/d\eta$ in Pb+Pb (2.76 TeV)

- Empirical extrapolatio] **too low**
- pQCD-inspired MCs
  - HIJING t o 7 TeV pp, n nching [5] **quite good**
  - DPM ET [6]
- Saturation
  - Initial der] **some too low some ok**
  - Hydr ynamic saturation l state phase of scatte d partons [12] **a bit too high**
- Hydrodyna models **too low too high**
- Hadro attering [15]



arXiv:1011.3916

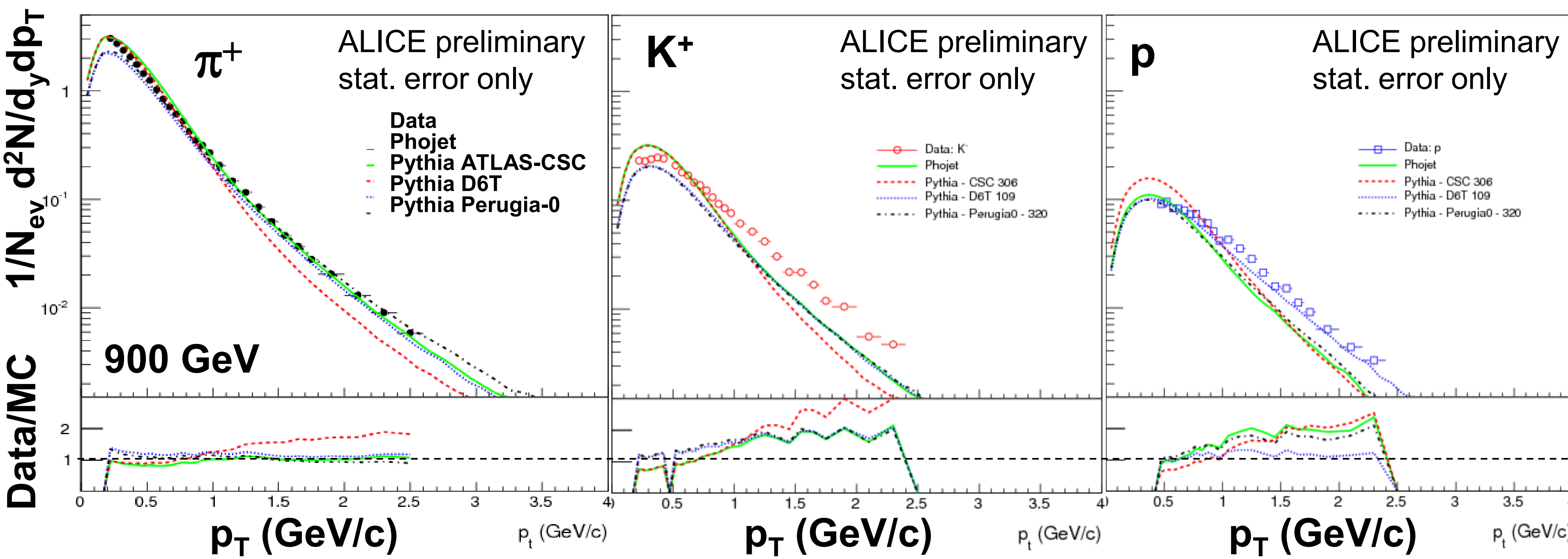
LHC Data References on Multiplicity

- ALICE
  - Eur. Phys. J. C 68 (2010) 345, 7 TeV, INEL>0
  - Eur. Phys. J. C 68 (2010) 89, 0.9 and 2.36 TeV, NSD, INEL
  - arXiv: 1011.3916, 2.76 TeV Pb+Pb
- ATLAS
  - ATLAS-CONF-2010-024, 7 TeV, pT > 0.5 GeV/c, INEL>0
  - ATLAS-CONF-2010-031, 0.9 and 7 TeV, INEL>5 (“diffractive enhanced”)
  - ATLAS-CONF-2010-046, 0.9 and 7 TeV, pT > 0.1 GeV/c, INEL>1
  - ATLAS-CONF-2010-047, 2.36 TeV, pT > 0.5 GeV/c, INEL>0
- CMS
  - CMS-PAS-QCD-10-004, 0.9, 2.36, 7 TeV, NSD

Hadron Yields

Will be published soon…

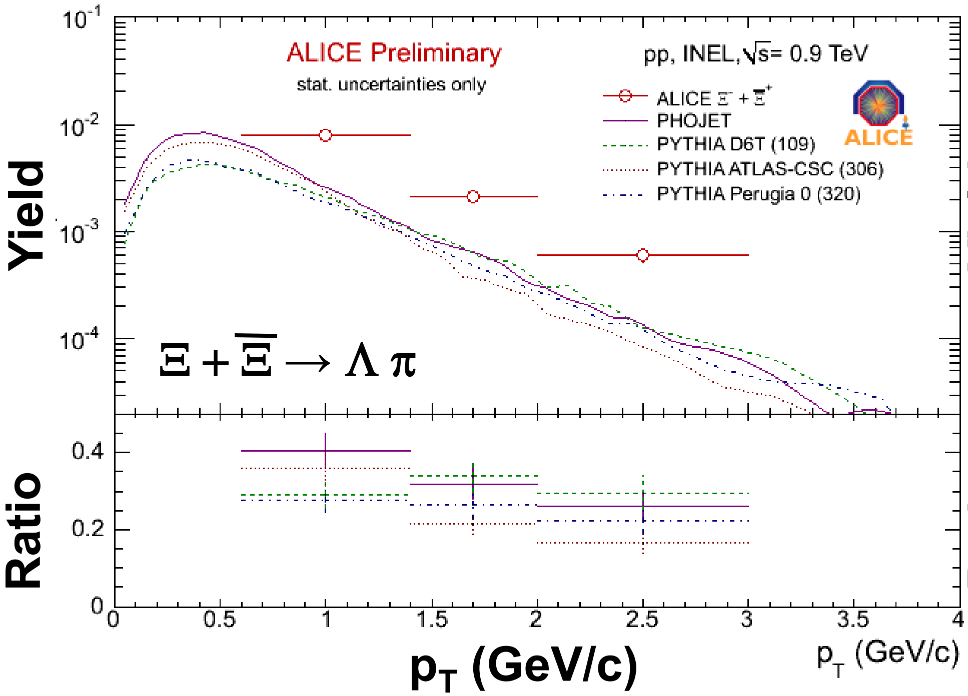
- Yields of π, K, p as function of p_T (here for pos. particles, similar for neg.)
- Pions reasonably described by Phojet, Pythia D6T, Perugia-0
- Kaon yield underestimated above p_T of 1 GeV/c
- Proton yield underestimated except by Pythia D6T

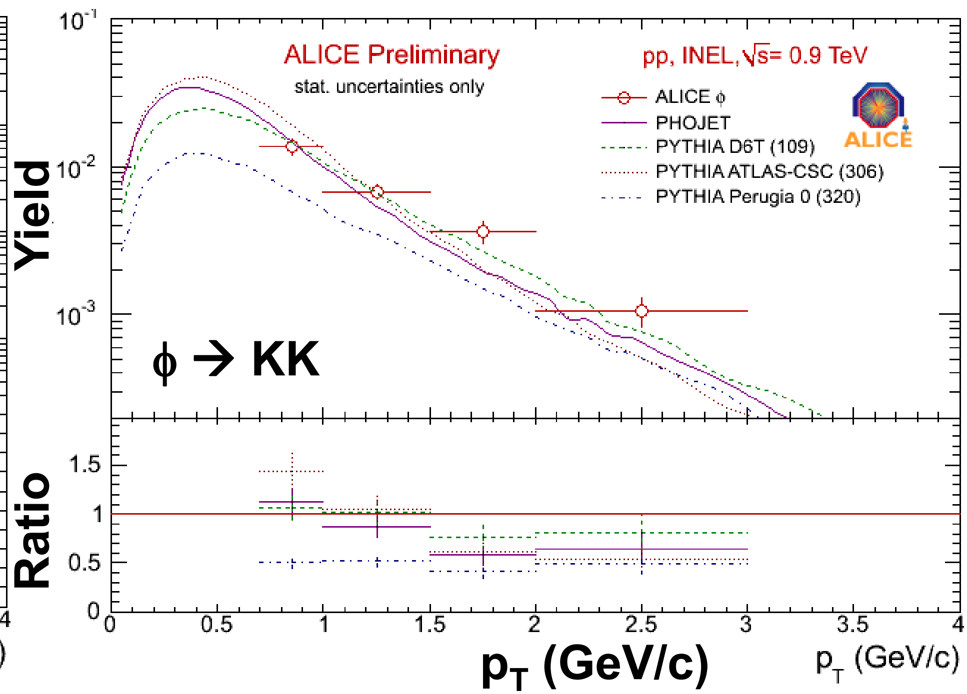


Strange Particle Yields

Will be published soon…

- Yields of K_0^S, Λ, Ξ as function of p_T
- Pythia 6 (D6T, ATLAS-CSC, Perugia-0) and Phojet underestimate overall yields
- Larger discrepancy with increasing particle mass, strangeness and p_T
- But the ϕ is ~ ok within uncertainties





Summary

- Charged-particle multiplicity is
  - a simple observable in collisions of hadrons
  - an important ingredient for the understanding of multi-particle production
  - very sensitive to multiple-parton interactions
- Models have difficulties describing especially the multiplicity distribution
- Steeper than expected increase of the average multiplicity observed at LHC

Phenomenological models Scorecard		
	Full phase space	**$\lvert\eta\rvert < 0.5$**
Feynman scaling	**not fulfilled > 30 GeV**	
KNO	**<= 60 GeV**	**Still valid at LHC**
NBD	**<= 540 GeV**	**Still valid at LHC**
2NBD	**Still valid at LHC**	