Hadronic Modelling in Geant4

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(on behalf of Geant4 Collaboration)

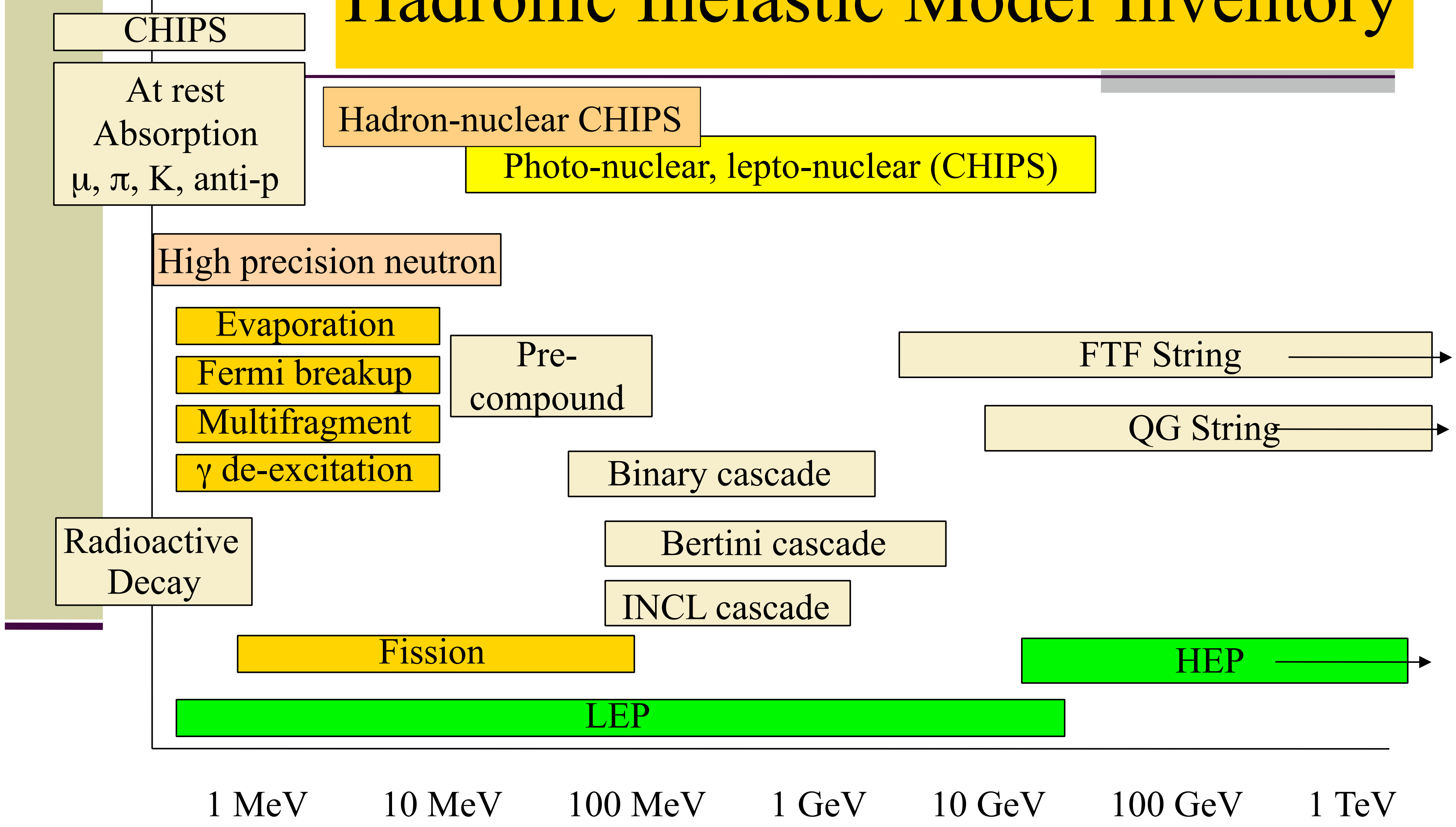
Used many slides from talks of Dennis Wright
at Hadronic Shower Simulation Workshop
FNAL, 6-8 September 2006

Overview

- Key characteristics of modelling
- A tour of key hadronic models
  - String Models E > 5-10 GeV
  - Cascades: ~150 MeV < E < 3-10 GeV
  - CHIPS
  - Pre-compound/Evaporation
- Latest developments, known limitations

- Can models be ‘tuned’ ?

Hadronic Inelastic Model Inventory



Survey of Hadronic Models

- Three broad categories of models:
  - tabulated: based on (large) databases
    - For neutrons (E<20 MeV), photon de-excit.
  - parametrized: key aspects parameterised for speed
    - Parameters determined from fits to data
  - theory-based: based on (theoretical) models
    - Parameters chosen by comparing with thin-target data

‘Theory-based’ models

Phenomenology-based really.

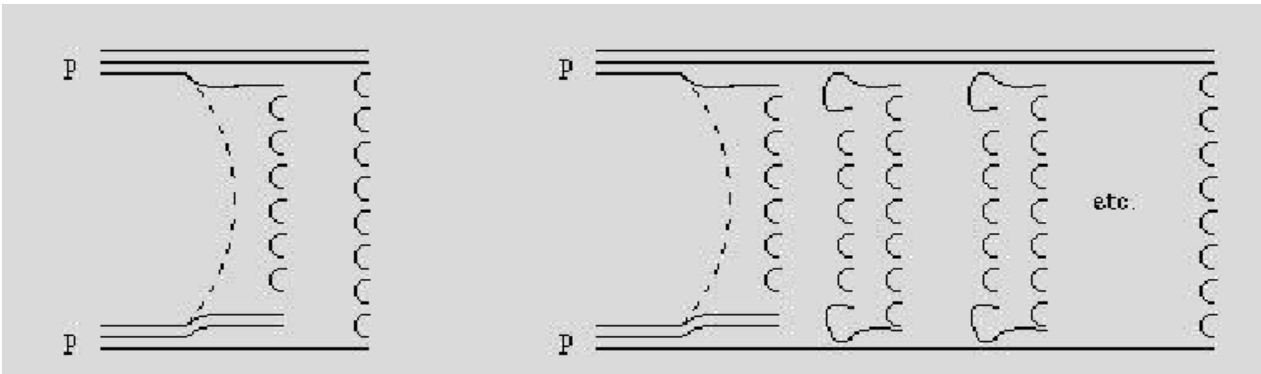
- Evaporation and pre-compound models
  - Use well-established recipes
- Cascade and CHIPS
  - Bertini-like
  - Binary Cascade
  - Chiral Invariant Phase Space
- Quark-Gluon String (QGS) model
  - Alternative FTF model, using Fritiof approach

Quark-Gluon String Model: Applicability

- Incident p, n, π, K
  - $\sim$20 GeV < E < 50 TeV
- Also for high energy γ - nuclear
  - $\sim$ 5 GeV < E < 50 TeV
- Model handles:
  - Selection of collision partners
  - Splitting of nucleons into quarks and diquarks
  - Formation and excitation of quark-gluon string
  - String hadronization

Quark Gluon String Model

- Two or more strings may be stretched between partons within hadrons
  - Strings from cut cylindrical Pomerons
- Parton interaction leads to color coupling of valence quarks
  - sea quarks included too
- Partons connected by quark gluon strings, which hadronize

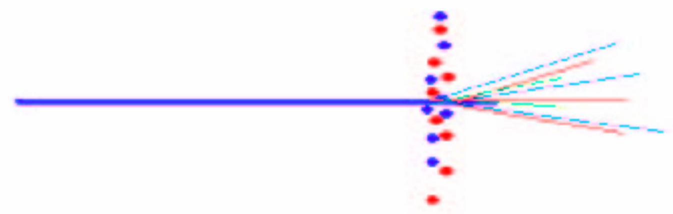


QGS Model
Options for 'back-end'

- Damaged nucleus handed to other Geant4 model
  - nuclear fragmentation and de-excitation
  - re-interaction of products (optional)

- Options for handling damaged nucleus:
  - pre-compound model (QGS/Preco – in QGSP)
  - CHIPS for nuclear fragmentation (QGS/Chips – labelled QGSC in physics lists naming)
  - Binary cascade reinteracts products (QGS/Binary in QGS_BIC)

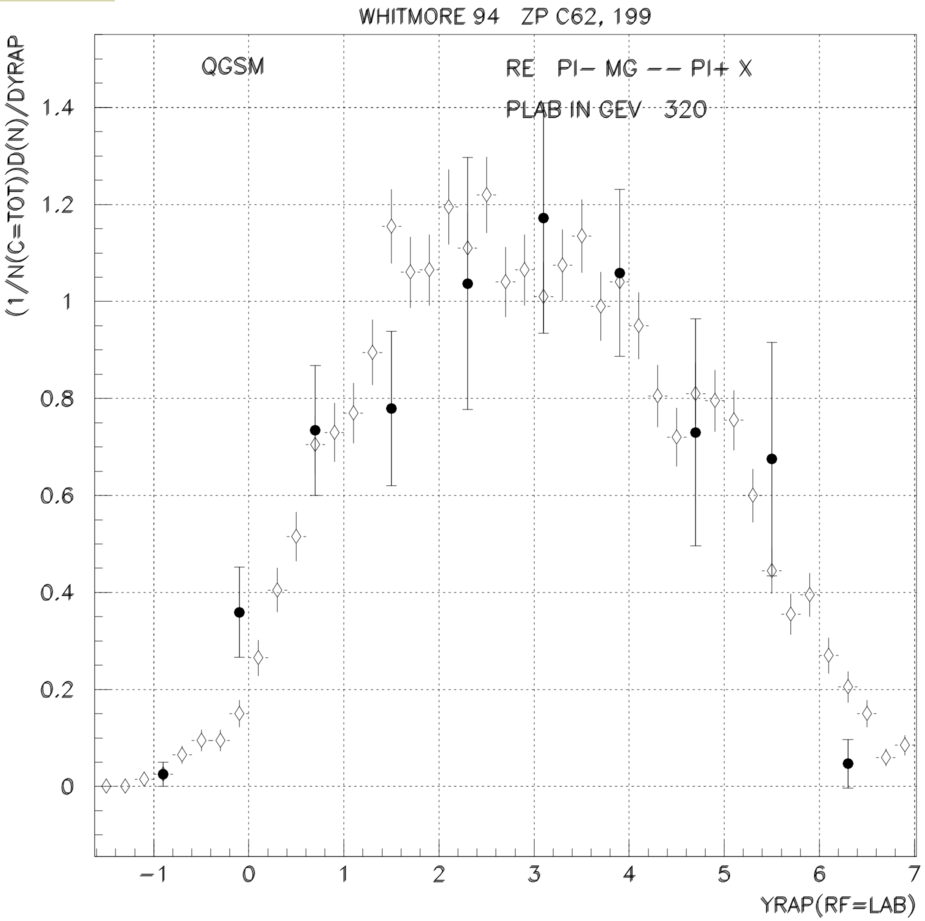
Quark Gluon String Model Algorithm

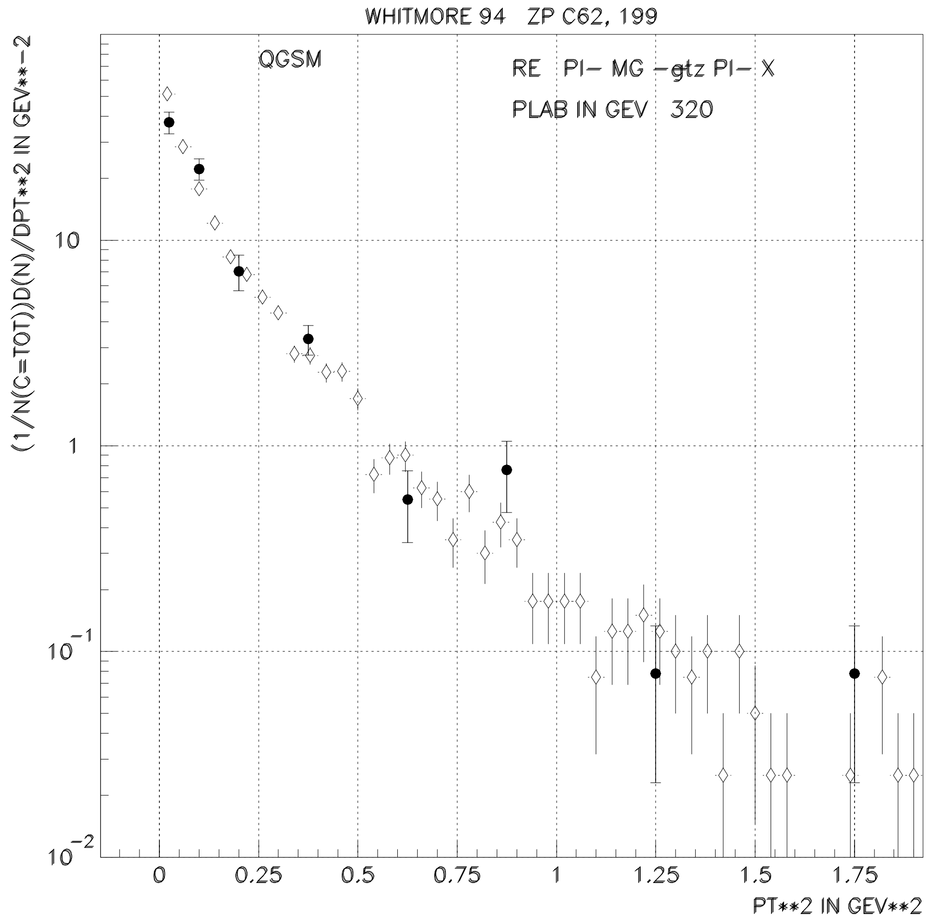


- Build up 3-dimensional model of nucleus
- Large γ-factor collapses nucleus to 2 dimensions
- Calculate impact parameter with all nucleons
- Calculate hadron-nucleon collision probabilities
  - based on quasi-eikonal model, using Gaussian density distributions for hadrons and nucleons
- Sample number of strings exchanged in each collision
- Unitarity cut, string formation and decay

QGSM - Results

π^{-} Mg $\rightarrow$ π^{+} X , P_{lab} 320 GeV/c (Whitmore)

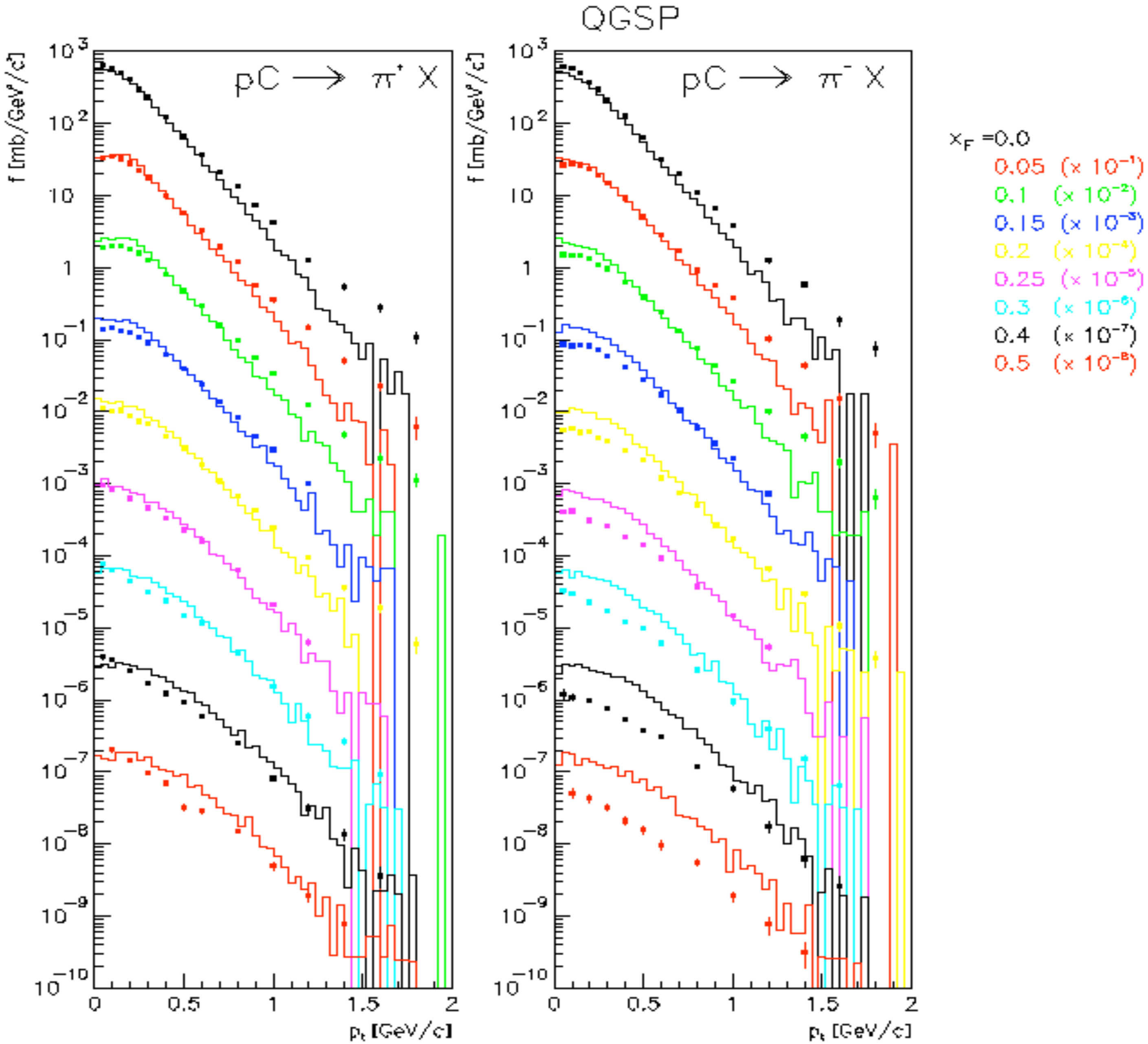




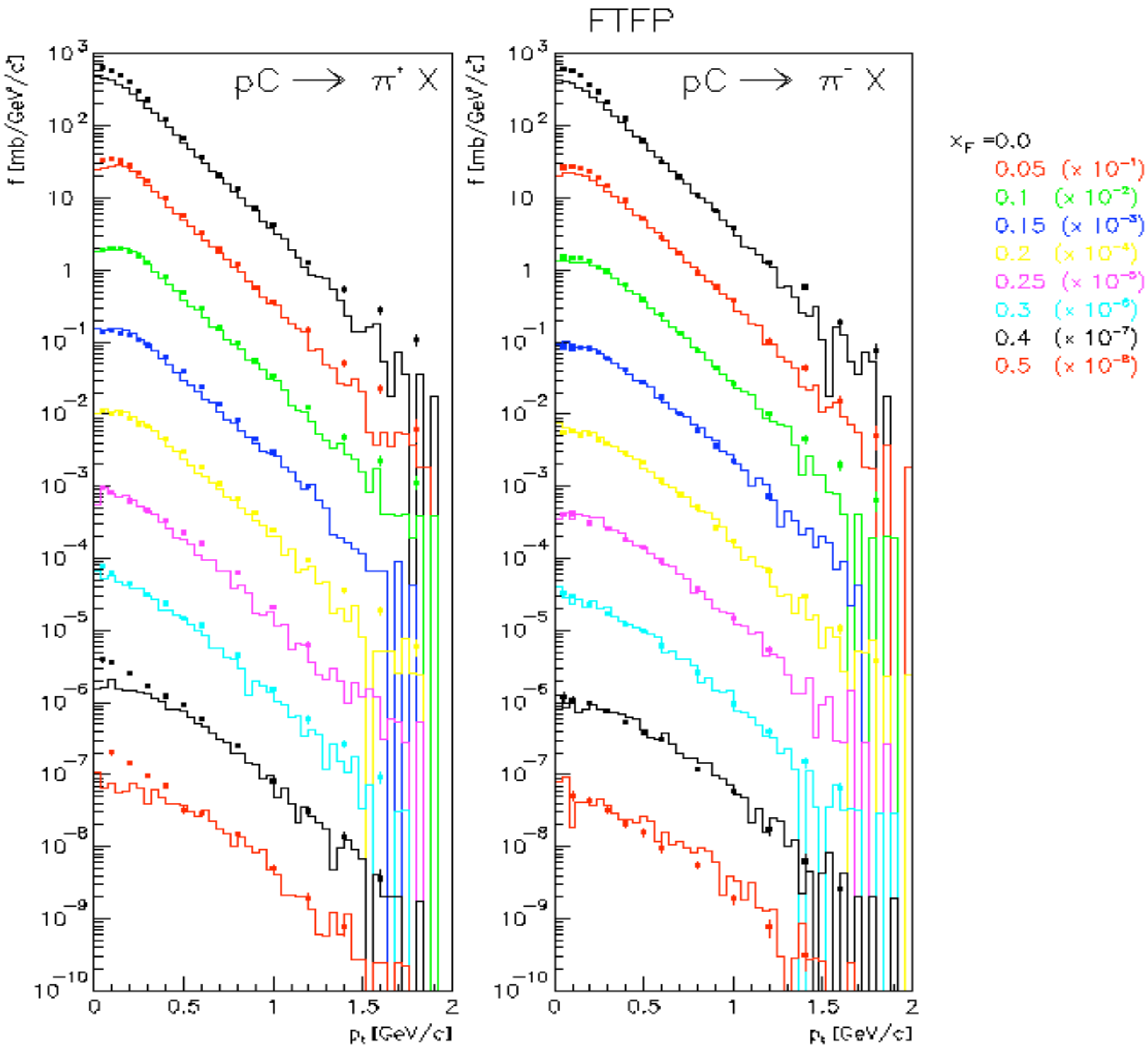
Rapidity $\eta = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$

P_t^2 [GeV^2]

NA49 158 GeV/c (QGSP)

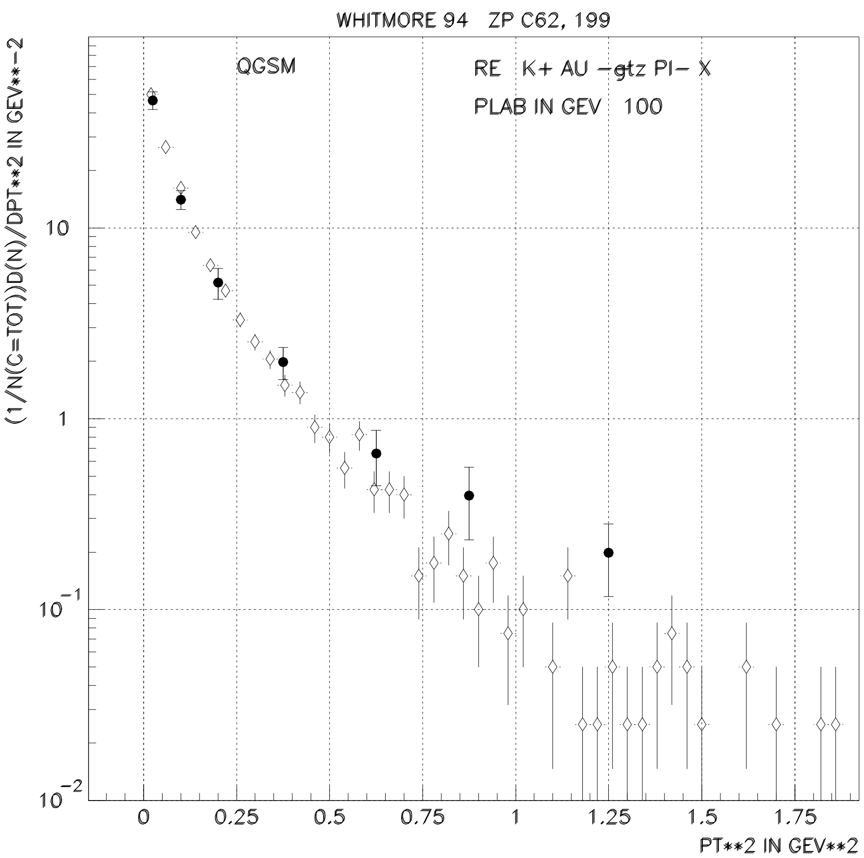


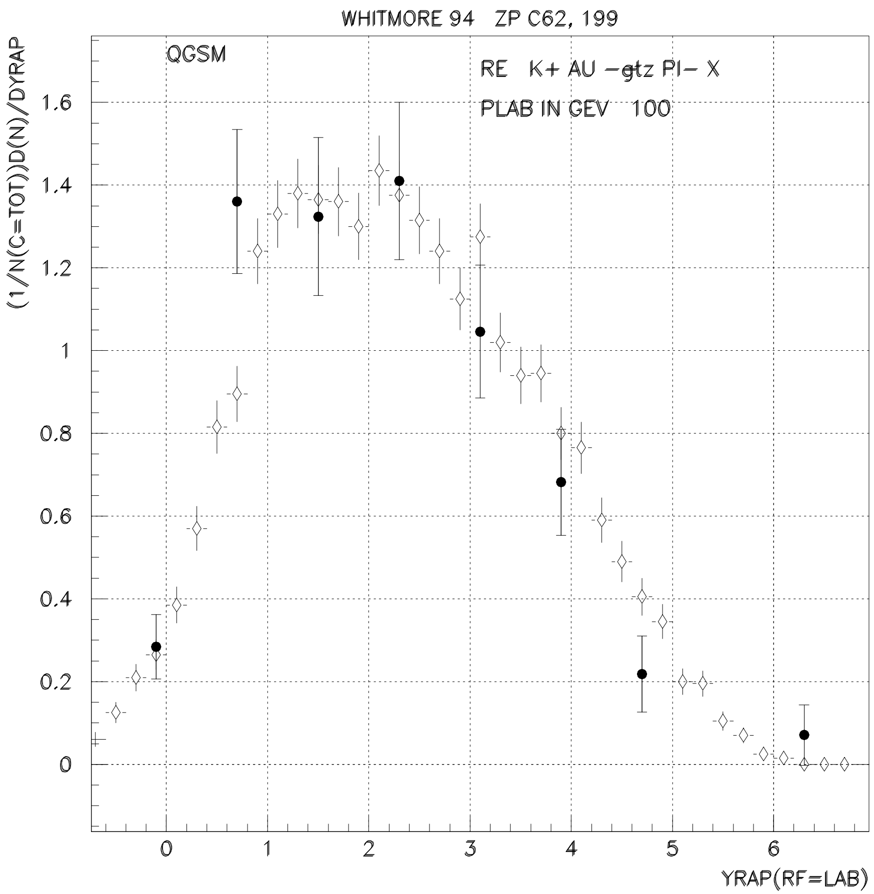
NA49 158 GeV/c (FTFP)



QGS Model Validation

K+ Scattering from Au (π^- inclusive)



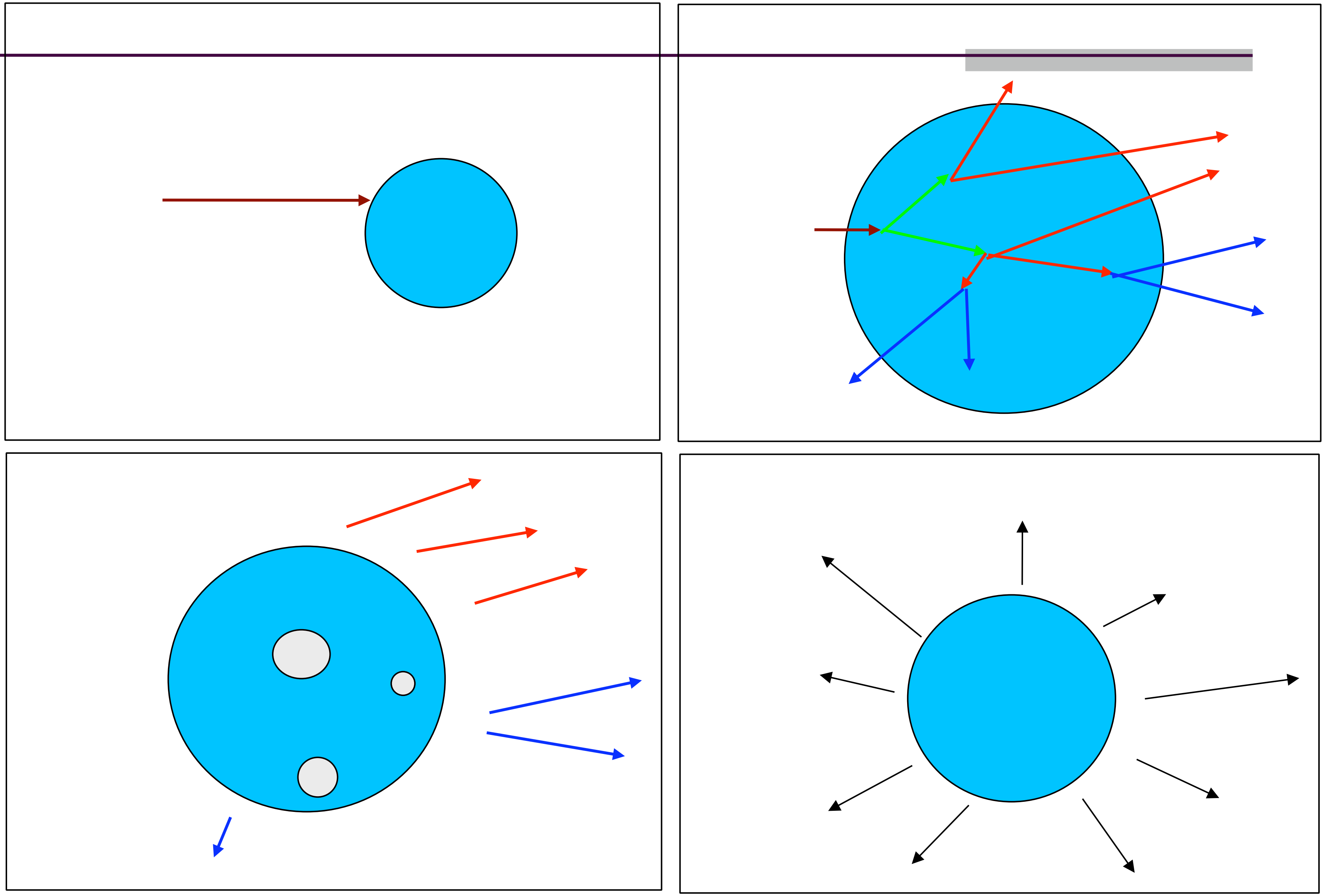


Solid dots: J.J.Whitmore et.al., Z.Phys.C62(1994)199

Description of High Energy Benchmarks

- http:// geant4.fnal.gov/hadronic_validation/validation_plots.htm
- 100 GeV/c (π-,π-X), (π-,π+ X) on Au
  - Whitmore, 1994
  - dN/dy vs y (rapidity)
- 158 GeV/c (p,πX) on C
  - NA49, 2007
  - Double differential cross section vs p_T, x_F
- 250 GeV/c (π+, charged) on Al, Au
  - NA22, 1991
  - Double particle density vs y
- 320 geV/c (π-,π-X), (π-,π+ X) on Au
  - Whitmore, 1994
  - dN/dp_T vs p_T, dN/dy vs y
- 400 GeV/c (p,π+X) on Ta
  - Bayukov, 1980
  - Invariant cross section vs kinetic energy

Cascade Modeling Concept



Applicability of the Bertini Cascade

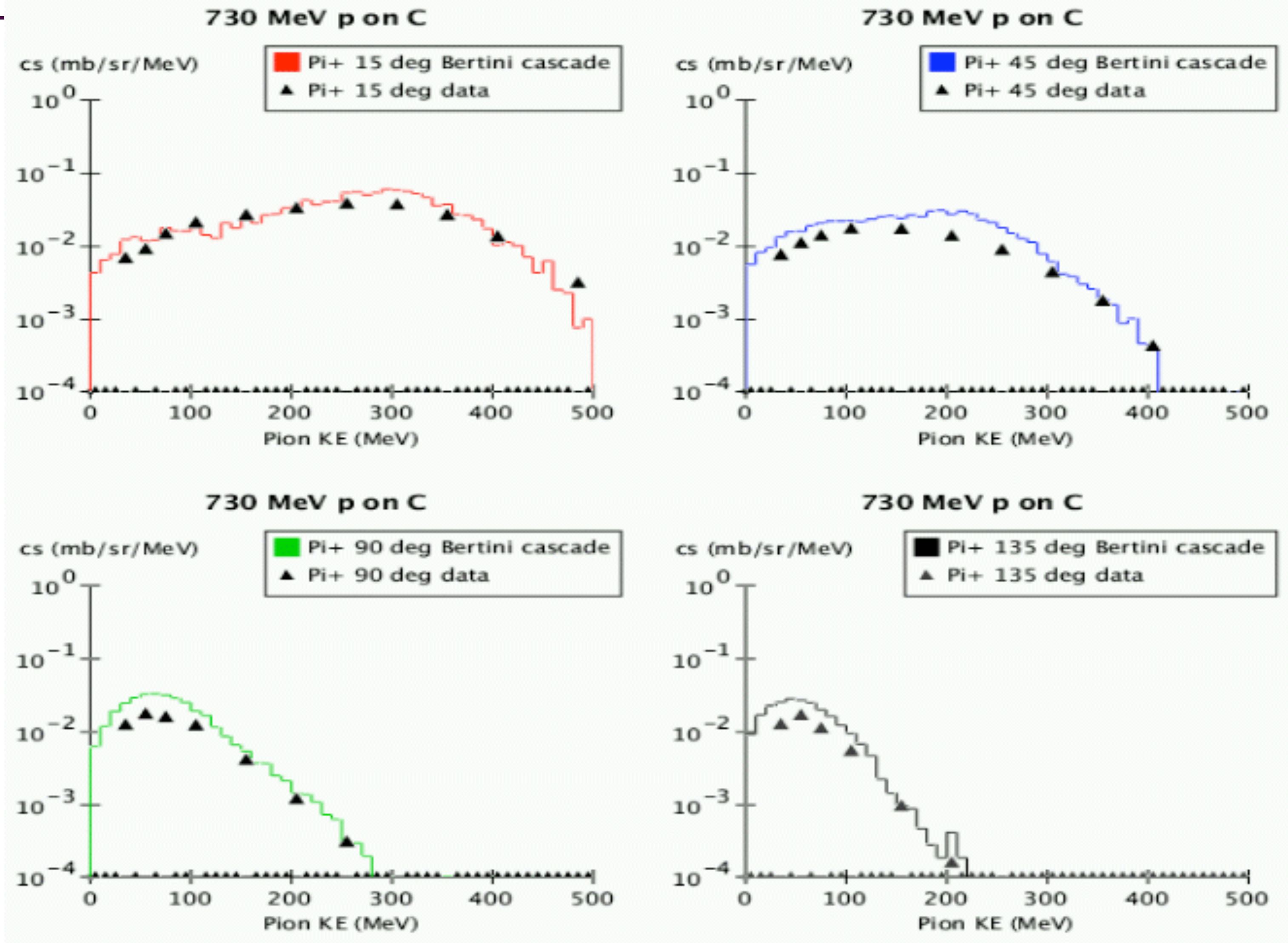
- inelastic scattering of p, n, π, K, Λ, Σ, Ξ
- incident energies: $0 < E < 10$ GeV
  - upper limit determined by lack of partial final state cross sections and the end of the cascade validity region
  - lower limit due to inclusion of internal nuclear de-excitation models
- in principle, can be extended to:
  - anti-baryons
  - ion-ion collisions

Geant4 Bertini Cascade: Origin

- Employs standard INC methods from Bertini (1968)
  - using free particle-particle collisions within cascade
  - step-like nuclear density

- Core code:
  - elementary particle collider: uses free cross sections to generate secondaries
  - cascade in nuclear medium
  - pre-equilibrium and equilibrium decay of residual nucleus
  - nucleus modelled as three concentric spheres of different densities; density constant within sphere

Validation of the Bertini Cascade



Applicability of the Binary Cascade

- Incident p, n
  - 0 < E < ~3 GeV
- light ions
  - 0 < E < ~3 GeV/A
- π
  - 0 < E < ~1.5 GeV

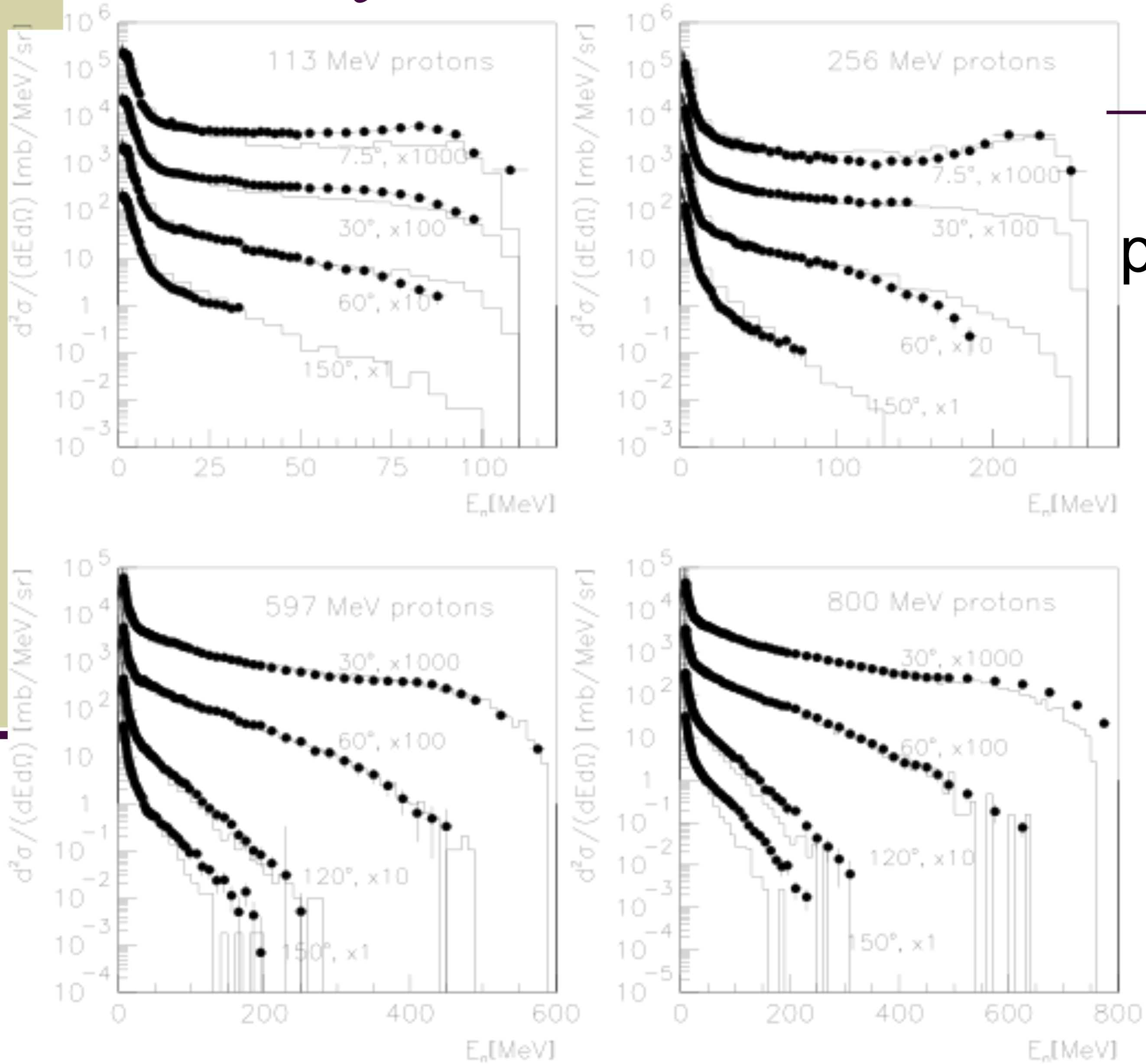
Binary Cascade

- Hybrid between classical cascade and full QMD model
- Detailed model of nucleus
  - nucleons placed in space according to nuclear density
  - nucleon momentum according to Fermi gas model
- Nucleon momentum taken into account when evaluating cross sections, collision probability
- Collective effect of nucleus on participant nucleons described by optical potential
  - numerically integrate equation of motion

Binary Cascade Modelling

- Resonances (to $\Delta 1950$, N^* 2250)
  - Created in NN scattering (t-channel) – use pp data σ
  - may interact or decay
- NN elastic scattering angular distributions
  - from Arndt phase shift analysis of exp. data
- Pauli blocking for final state nucleons
- Pion absorption on pseudo-deuterons
- Coulomb barrier present for charged hadrons
- Stop cascade when <E> below A-dependent cut

Binary Cascade - results

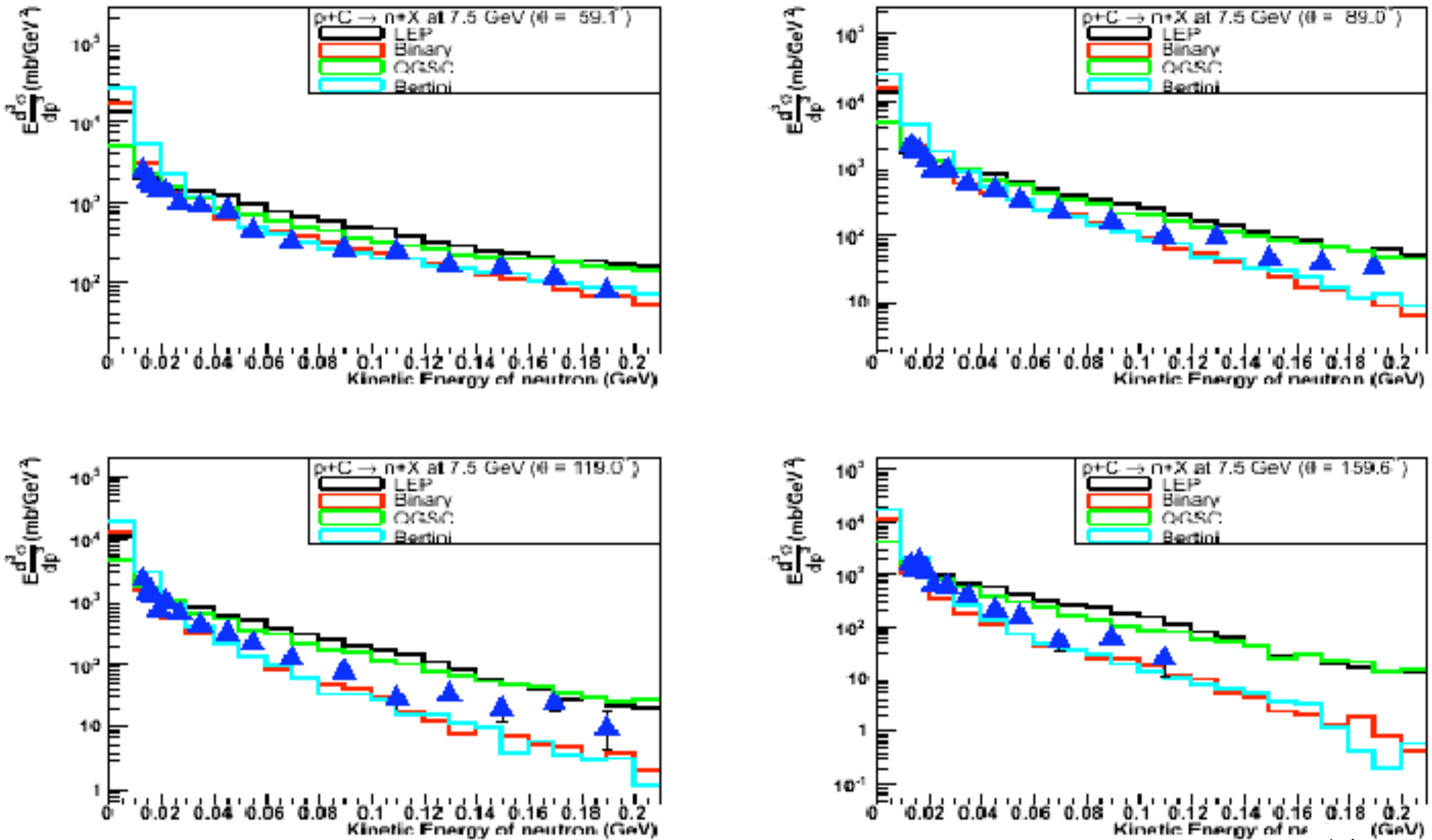


p Pb -> n X

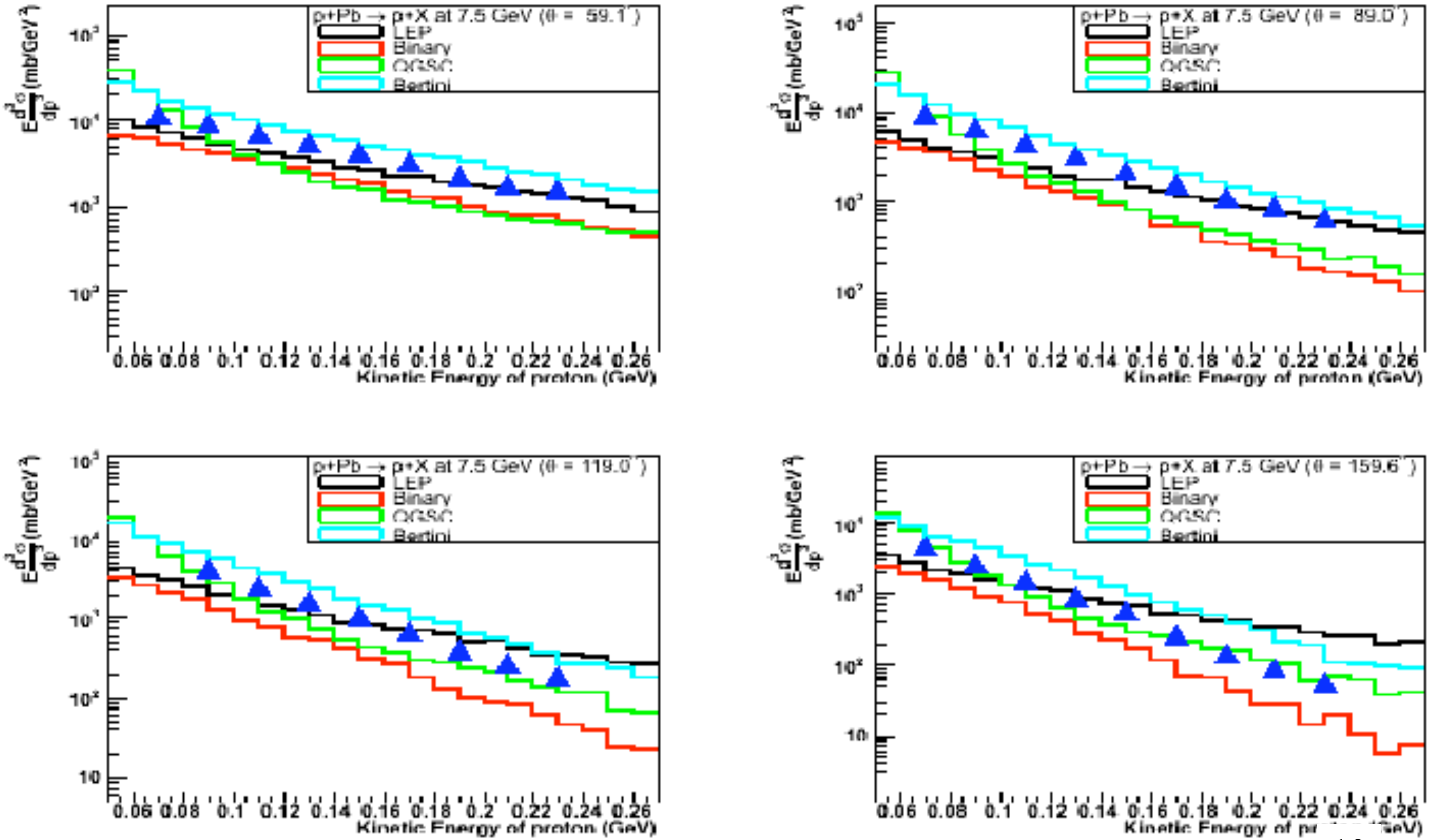
Overview of Medium Energy Benchmarks

- http:// geant4.fnal.gov/hadronic_validation/validation_plots.htm
- 1.4 – 9.0 GeV (p,pX) on Be, C, Cu, Pb, U
  - Bayukov, 1985
  - Invariant cross section vs kinetic energy
- 1.4 – 5.0 GeV (π+,p), (π+,n) on Be, C, Cu, Pb, U
  - Bayukov, 1985
  - Invariant cross section vs kinetic energy
- 14.6 GeV/c (p,π+X), (p,π-X) on Be, Al, Cu, Au
  - Abbot, 1992
  - Invariant cross section vs transverse mass
- 14.6 GeV/c (p,pX) on Cu
  - Abbot, 1992
  - Invariant cross section vs transverse mass

7.5 GeV (p,nX) on C



7.5 GeV (p,pX) on Pb



Chiral Invariant Phase Space (CHIPS)

- Origin: M.V. Kosov (CERN, ITEP)
  - Manual for the CHIPS event generator, KEK internal report 2000-17, Feb. 2001 H/R.
- Use:
  - capture of negatively charged hadrons at rest
  - anti-baryon nuclear interactions
  - gamma- and lepto-nuclear reactions
  - back end (nuclear fragmentation part) of QGSC model

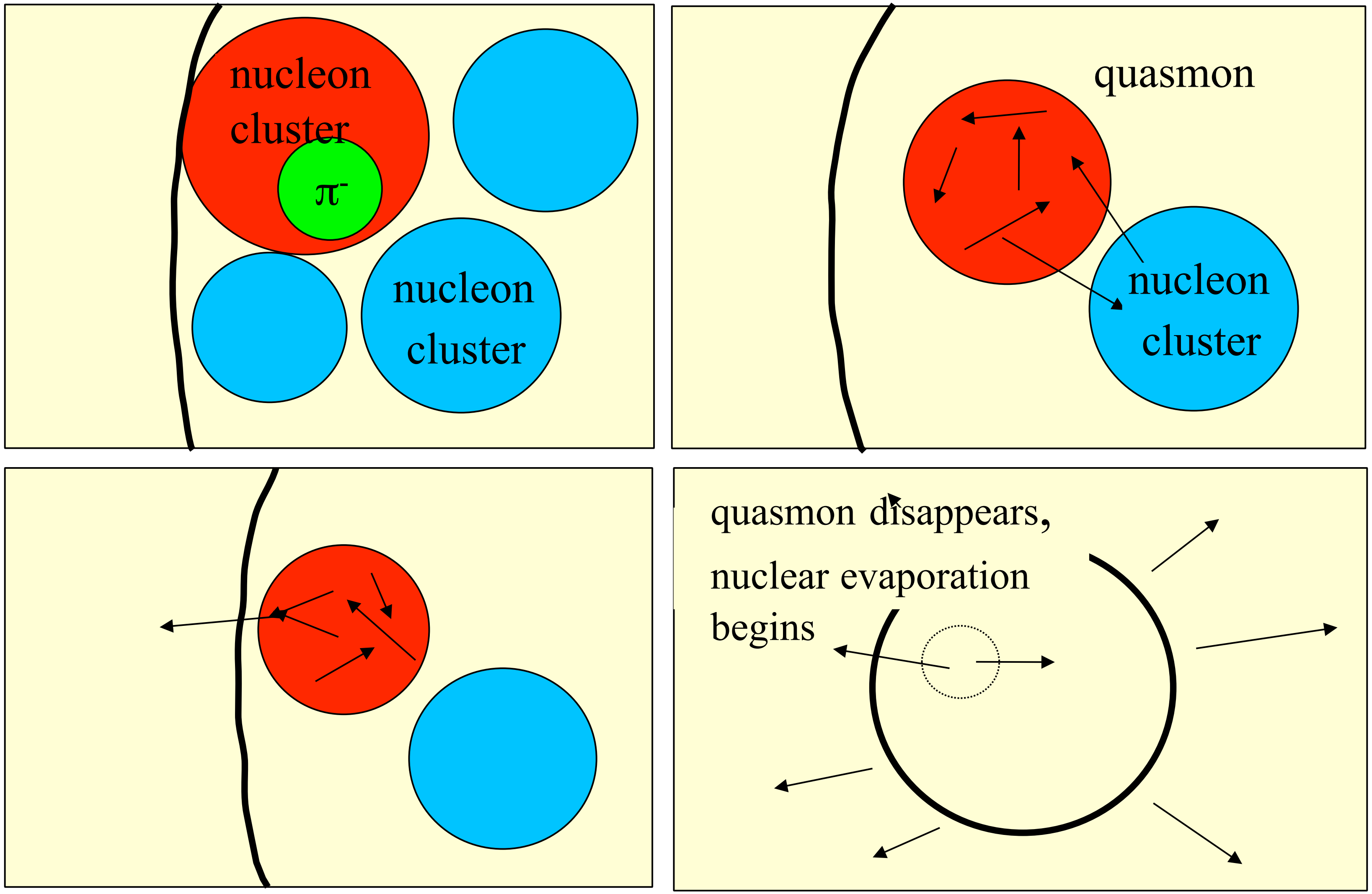
CHIPS Fundamental Concepts

- Quasmon: an ensemble of massless partons uniformly distributed in invariant phase space
  - a 3D bubble of quark-parton plasma
  - can be any excited hadron system or ground state hadron
- Critical temperature T_C : model parameter which relates the quasmon mass to the number of its partons:
  - $M^2_Q = 4n(n-1)T^2_C$ => $M_Q \sim 2nT_C$
  - $T_C = 180 – 200$ MeV
- Quark fusion hadronization: two quark-partons may combine to form an on-mass-shell hadron
- Quark exchange hadronization: quarks from quasmon and neighbouring nucleon may trade places

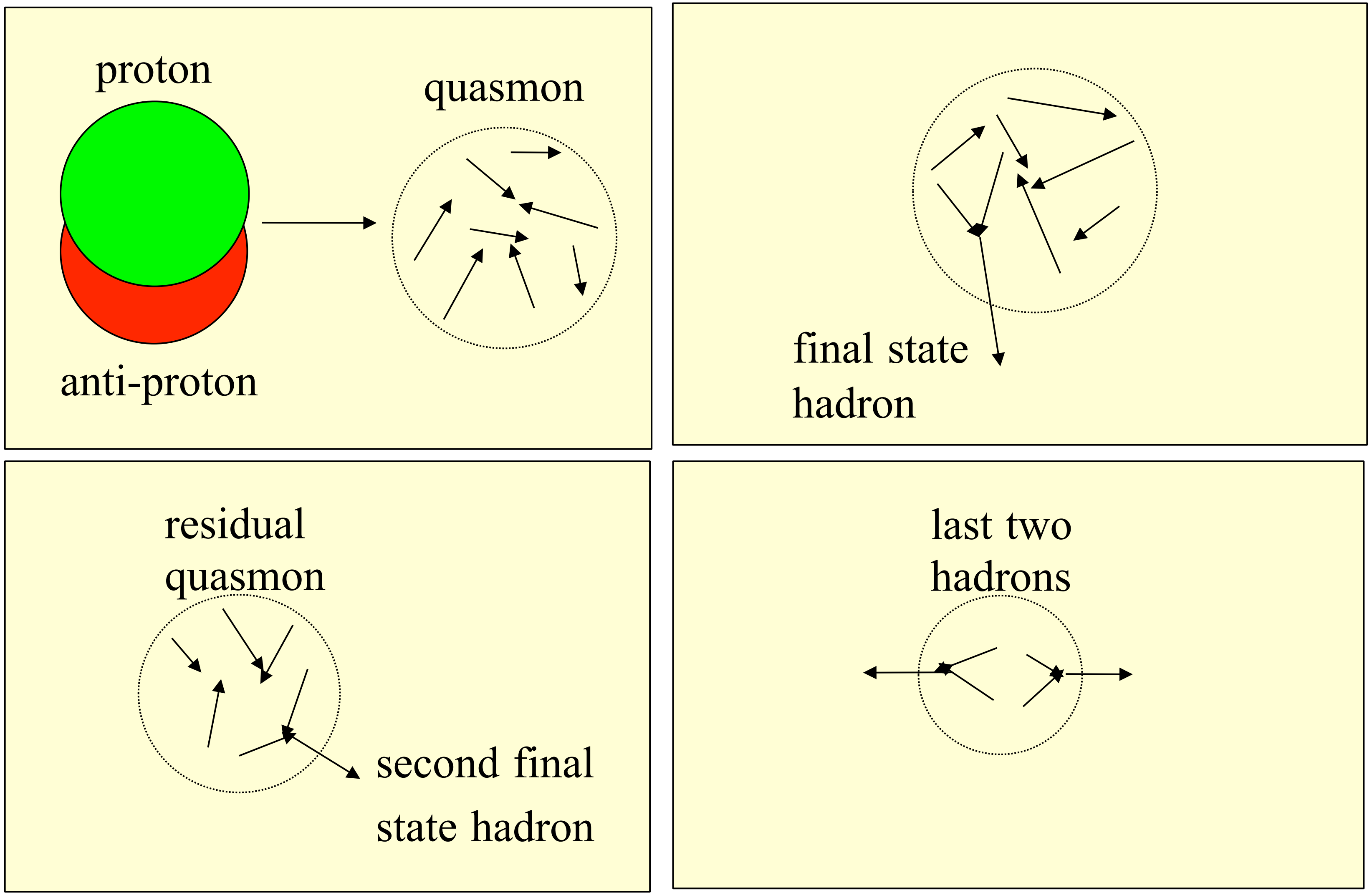
CHIPS Applications

- u,d,s quarks treated symmetrically (all massless)
  - model can produce kaons, but s suppression parameter is needed, η suppression parameter also required
  - real s-quark mass is taken into account by using masses of strange hadrons
- CHIPS is a universal method for fragmentation of excited nuclei (containing quasmons).
- Unique, initial interactions were developed for:
  - interactions at rest such as π^- capture, pbar annihilation
  - gamma- and lepto-nuclear reactions
  - hadron-nuclear interaction in-flight are in progress
- Anti-proton annihilation on p and π^- capture at rest in a nucleus illustrate two CHIPS modelling sequences

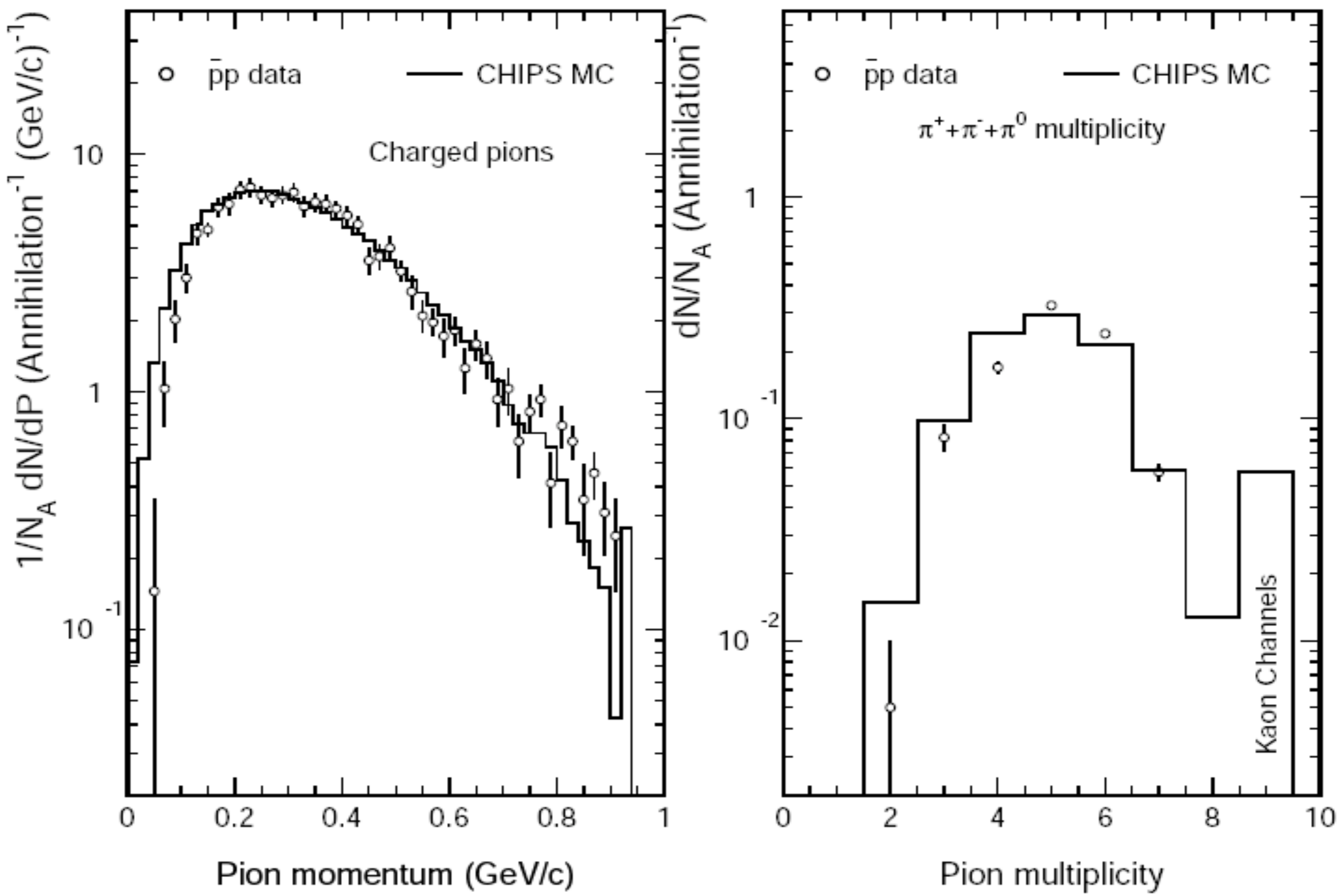
Modeling Sequence for π^- Capture at Rest in a Nucleus



Modeling Sequence for Proton – antiproton Annihilation



Validation of CHIPS for Proton Anti-Proton Annihilation



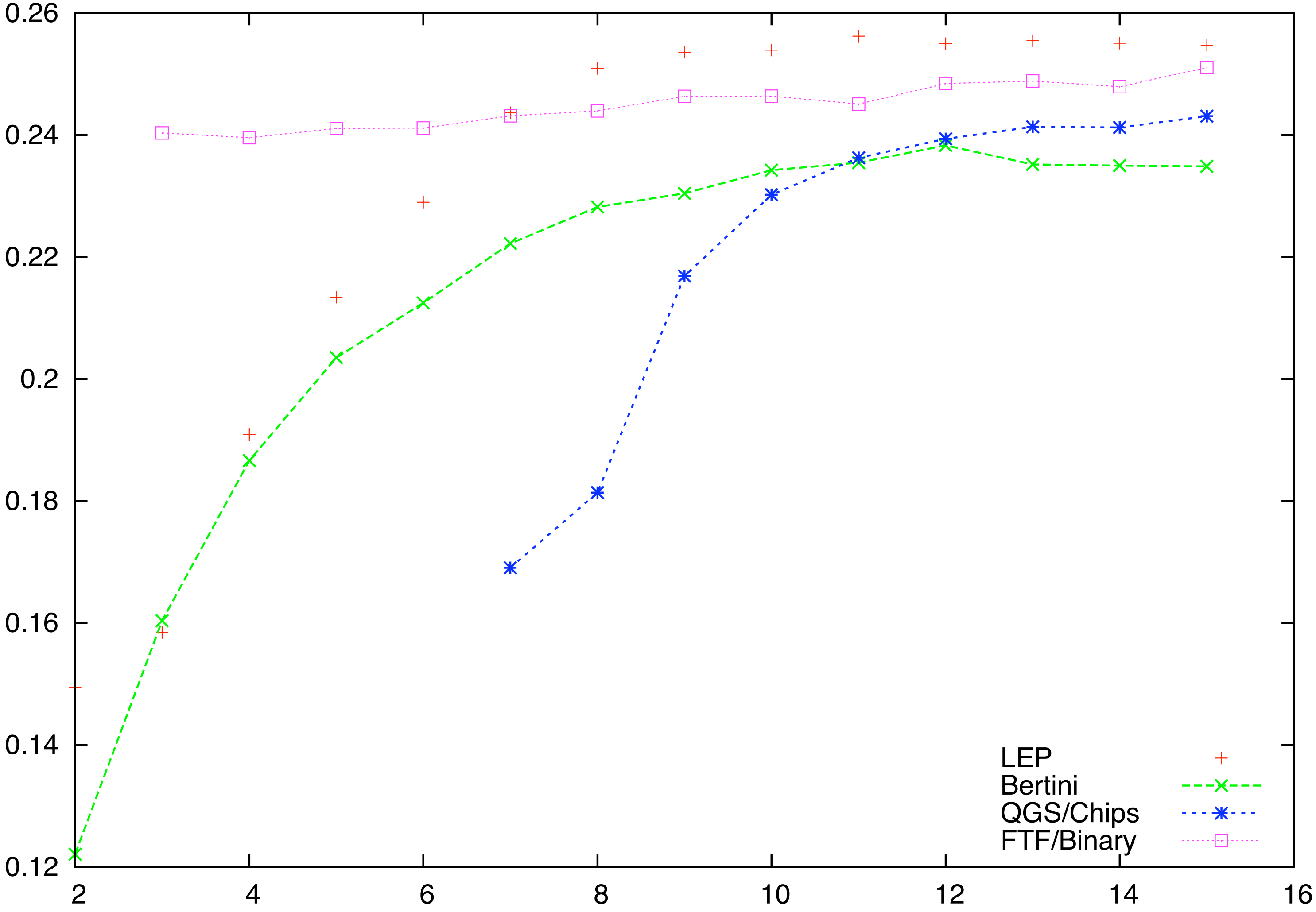
(Personal perspective)

LATEST

Known issues; challenges

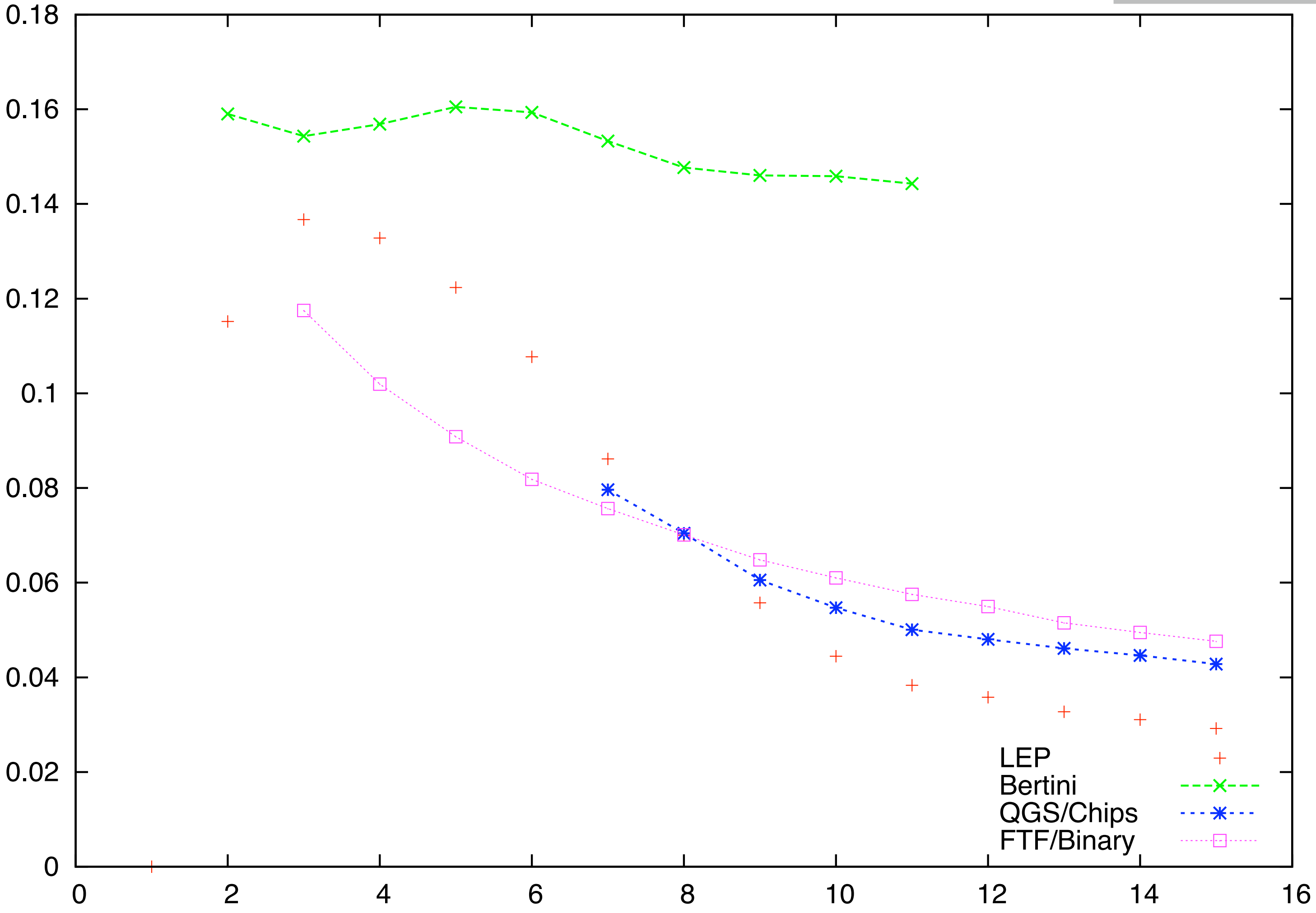
- ‘Discontinuity’ in energy deposition in transition between Bertini and LEP QGSP_BERT
  - Reported by CMS, ATLAS
- Deficiencies of LEP model
  - Conservation laws
  - Spectra
- Gap between ‘applicability’ of cascades and string models (general issue for MCs)
  - Bertini validated up to ~5 GeV
  - Binary limited to ~2.5 GeV (protons), ~1.5 GeV (pions)
  - QGS validated from E > ~ 13/15 GeV
  - FTF potential to fill the gap (under validation 3+ GeV)

π^- on Fe: Energy fraction in π^0



Sum E tot / E_{beam}

π^- on Fe: Energy fraction in protons



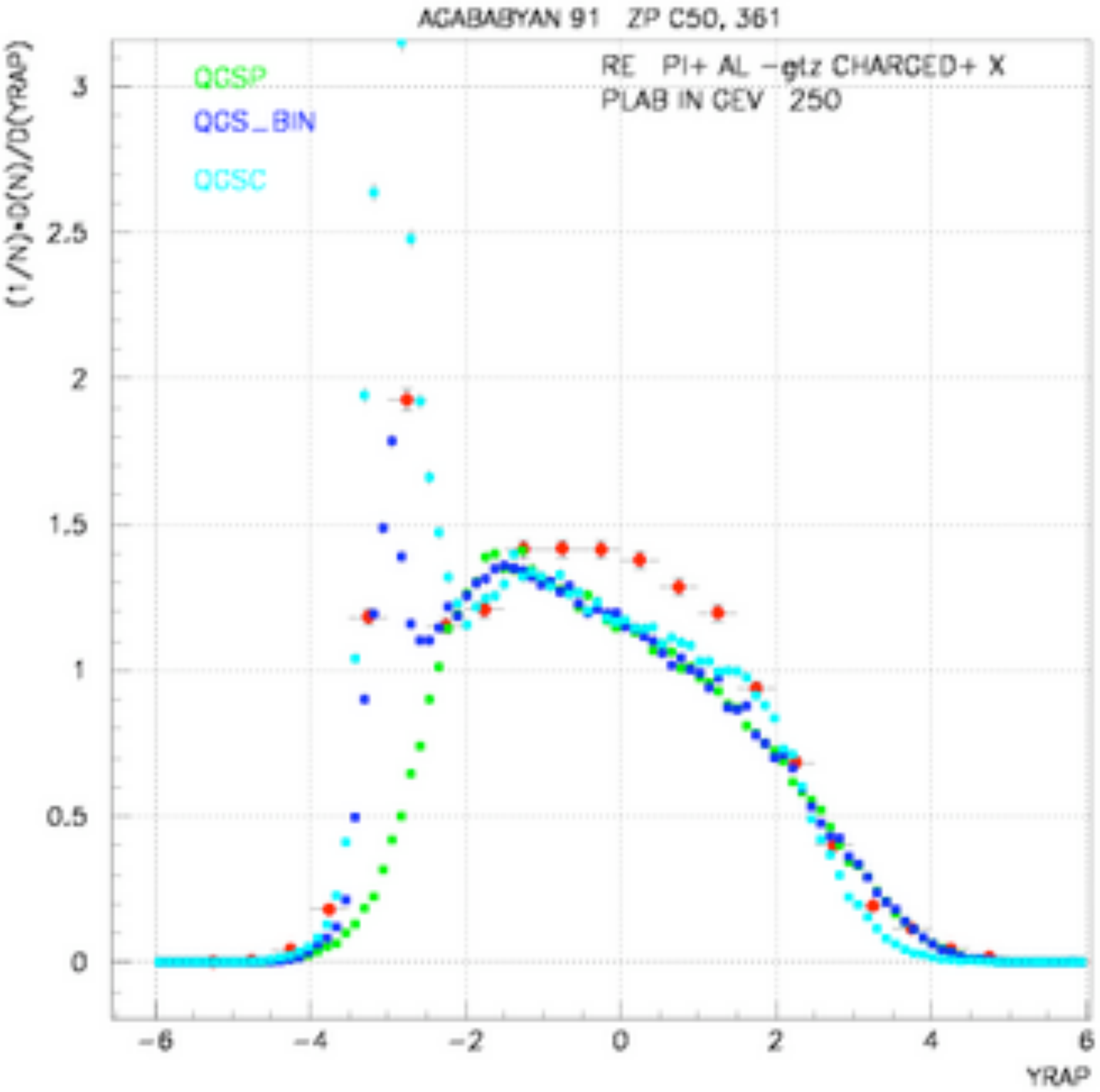
Description of QGSP_BERT

- Elastic n/p from M. Kosov
- Uses BERTini up to about 9.7 GeV for p/n/pi
- Uses LEP for most interactions 9.7<E<18 GeV
  - And for hyperons
- QGS for most interactions E> 18 GeV
  - Links with Precompound for de-Excitation
    - Underestimates target framentation
- Neutron capture from LEP model
  - Significant limitations
    - alternative HP can be used via QGSP_BERT_HP)

Underway

- Expansion of validation
  - Status for 5-20 GeV presented at CHEP 2009
    - Additional comparisons being prepared & sought
  - Future 25-70+ GeV
- Linking of cascade to string model(s)
  - To model re-interaction of low-energy products
- Study of transitions between models
  - Multiplicity, energy moments of products
- Trial physics lists
  - FTF in place of LEP and QGS
  - Others without LEP models

- Effect of reinter-action



Transitions between models

- Transitions in existing physics lists
  - QGSP_BERT: Between Bertini, LEP and QGS/P
    - Bertini E< 9.9; LEP: 9.5<E<25; QGS/Preco: E>12.5
- Studying
  - Energy in π^0, π^+/π^- (total), in p, n, light ions (kinetic)
  - Multiplicities, spectra (to do)
- Future
  - Identifying best criteria for transitioning between models

Potential production physics lists

- Old: LHEP, QGSP
    - QGSP: uses QGS/Preco phased in over interval 12-25 GeV)
  - Alternative: QGSC (CHIPS as de-excitation, QGS 8-25)
- 'Production' at LHC: QGSP_BERT
- Emerging: Featuring FTF in place of LEP and QGS
  - FTF_BERT: transition from BERTinit to FTF at 4-5 GeV
    - QGS not used at all
- New: Linking of cascade to string model(s)
  - To model re-interaction of low-energy products
    - Improve target fragmentation
  - FTF_BIC and QGS_BIC

Development / Trial physics lists

- Others without LEP models
  - QBBC: Binary for p/n, BERTini for pions
- Experimental combinations
  - Chosen guided by the studies of Energy per particle type
  - QGSP_FTFP_BERT
    - replaces LEP in QGSP_BERT; transition BERT/FTF 7-9GeV
  - FTFP_BERT_TRV
    - Changes BERT/FTF transition to 6-8 GeV – not 4-5 FTFP_BERT
  - Not yet searched for ‘ideal’ transition point
- Exposure to new models
  - QGSC_CHIPS
    - Direct use of CHIPS for p (soon n) E < 300 MeV, soon higher

Physics Model: Strengths and Limitations

- Cascades created for 200 MeV – 3 GeV
  - Based on nuclear models, p-p data
  - Strength: Pion creation
  - Do not include ‘formation time’ (yet)
    - needed above ~ 4 GeV to reduce reinteraction and nucleon emission
  - Binary based on resonances
    - creates, transports, interacts, decays them
      - give correlations
      - Resonances are not resolved above ~ 2.5 GeV; for p-incident 1.5 GeV is ‘strict’ limit

Strengths and weaknesses

- INUCL Bertini
  - Based on hadron-nucleus data
    - Extended above 5 GeV (but missing formation time)
    - Production of 6+ secondaries not well measured
  - Not yet able to transport products of high energy collision (reinteraction after QGS or FTF)
- LEP
  - Problems with energy partitioning at E <~ 20 GeV
  - Spectra have several unphysical features
- QGS
  - Assumptions of high energy limit (E > 20-50 GeV)
  - Stretches down to 12-15 GeV, but breaks between 8-10 GeV

Transitions between models

- Choice made for transition points
  - Stretching model on each side if needed
  - Looking at validation, strengths and limitations
  - By trial and error
- QGSP_BERT: started from QGSP (LEP and QGSP)
  - BERT has better behaviour than LEP: push BERT to 9.5-9.9 GeV
  - Trial transition at 5 GeV (QGSP_BERT_TRV) not better (ATLAS studies ca 2007)
  - Transition LEP to QGS (12-25 GeV) unchanged

Known Problems and Improvements (1)

- QGS:
  - gaussian sampling of p_T too simple => incorrect diffraction, not enough π^- suppression in p scattering
  - internal cross sections being improved
- Medium energy (~5 GeV - 20 GeV):
  - too low for QGS, HEP models
  - too high for cascades, LEP models
  - FTF model developed, being improved
    - improved parameterized model will be developed (2010?)
- Cascades:
  - no Coulomb barrier in Bertini

Known Issues and Improvements (2)

- CHIPS:
  - originally designed only as final state generator, not intended for projectile interaction with nucleus
  - neutrino scattering added 2006
  - extension underway for nucleon inelastic scattering
    - Available: protons (E < 300 MeV), shortly neutrons (ditto)
    - Extension to higher energies during next months.

Can G4 models be 'tuned'?

- Can (individual) physics models be tuned with LHC experiment data ?
  - Tuning is constrained by some data
    - tuning of parameters is done against thin-target data
      - where the results of single microscopic interactions is directly comparable.
    - These constraint the model parameters where measured data exists
      - there are regions where comparisons are not possible or have not been undertaken yet.
  - A few parameters are simpler to change:
    - P_t in the QGS model
    - Partial cross sections in Bertini cascade
    - Fragmentation time (FTF)

Model tuning

- G4 model parameters
  - Are not like Event Generator parameters
  - In many cases are constrained by data
    - In others either no data exists or a comparison is pending
- Changing model parameters is complicated
  - Needs collaboration with authors, preparation
    - If it is to be attempted

Other tuning

- The choice of models (choosing physics list)
- The transition points between physics models
  - is a parameter for which there are indications but not yet clear optimal values.
- The choice of cross sections
- The choice of de-excitation model for the high energy interaction.

Varying the Transition points between models

- Example: choices for QGSP_BERT
  - The interval for the transition between the Bertini and LEP model in was chosen as [9.5, 9.9] GeV.
    - A trial to bring this to the region of 5 GeV did not improve physics results.
    - Between these extremes the values for the upper and lower limits of the transition can be seen as tunable parameters.
  - The transition between the LEP model and the QGSP model is currently undertaken between [12, 25] GeV.

Choice of de-excitation

- QGSP: This is chosen as the Pre-Compound model (the P in QGSP).
  - Alternatives include CHIPS (QGSC) and Binary-cascade (QGS_BIC).
  - Seen improvements in
    - the emision of light ions (CHIPS) and
    - Extra low momentum outgoing hadrons (rescater using Binary – ie BIC).
  - Until now, the visible energy has not been shown to be significantly different in setups tested
    - but the number of secondary nucleons and light ions are increased.

Recent Improvements – 2008/9

Improvements in hadronic processes in Release 9.2 (Dec 2008) and its patch 1

Selected from G. Cosmo's talk at March 9th Geant4 Technical Forum meeting

Hadronics: the Improved and New

Improved (9.2, Dec. 2008) :

- Corrections & tuning in **pre-compound** and **de-excitation** code
  - affecting results for low-energy secondaries in Binary cascade
- Revised string fragmentation and tuned parameters in **FTF** model
  - For `Pi+P` and `pion-nucleon` interactions
  - Implemented quasi-elastic hadron-nucleus scattering and formation time
- Enabled/added Coulomb barrier penetration in **Bertini** cascade

New:

- **INCL** cascade and **ABLA** evaporation model officially released
  - Can be used for incident `p, n, d, t, 3He, alpha` and `pions` from `200 MeV` up to `3 GeV`, on nuclei ranging from carbon to uranium
- *Beta* release of *new* quantum molecular dynamics (**QMD**) model
  - For nucleus-nucleus collisions; valid from `50 MeV` to `5 GeV`

Hadronic processes: major fixes

- Bug fix in the final state multiplicity sampling in **Bertini** cascade
  - Fixes observed problem of quasi-elastic peak in energy spectra
- Corrections to the **multi-fragmentation** model to ensure it conforms with the original SMM model (from its authors)
- Improved energy and angular distributions for both scattered neutron and recoil targets in the **hp_neutron** model
- Code review and performance improvements to **Bertini** code
  - Measured ~25% CPU time boost for QGSP_BERT for **`50 GeV pi-`**
- Tuned absorption coefficient in Bertini cascade
  - Changed pion absorption coefficient from 0.2 to 1.0

OTHER / BACKUP

New Features – physics - 2

- Standard Electromagnetic processes
  - Enabled by default Cubic Spline interpolation of **`dedx`** and cross section tables
  - New multiple-scattering process and model
    - **`G4eMultipleScattering`**, specialized for simulation of e+ and e-
    - **`G4WentzelVIModel`** for multiple scattering of muons and hadrons
  - New Bremsstrahlung model, **`G4eBremsstrahlungRelModel`**, including advanced description of LPM effect
  - New utility classes
    - **`G4EmSaturation`** for sampling of Birks saturation; **`G4ElectronIonPair`** based on the ICRU'31 report for sampling electron/ion pairs in sensitive detectors; **`G4EmConfigurator`** for configuration of models in physics lists
  - Initialization of **`SubType`** added for all processes

Major fixes – physics - 1

- Electromagnetic processes
  - Improved implementation of the `G4LogLogInterpolation` class
    - Providing visible CPU improvement in low-energy physics processes
  - More precise multiple scattering model for e- and e+
    - Providing wider shower (about 0.5% measured for the CMS calorimeter)
    - Increase of visible energy in sampling calorimeters (due also to Spline approx)
  - Fixed cases of string comparison when computing transport cross-sections in MSC models, compare masses instead
  - Speedup run-time computations in e-Coulomb scattering model
    - Using pre-computed nuclear form-factors per element
  - Added scintillation with Birk's law and modified sampling of the Cerenkov photon origins

Improved in 2008: De-excitation

- De-excitation reviewed & corrected
  - Many components improved
    - Pre-compound model (JM Quesada)
    - Evaporation (A Howard, JM Q)
    - Multi-fragmentation (donated by SMM authors)

DETAILS OF MODELING (BACKUP SLIDES 1)

QGS MODEL

The Nuclear Model

- Nucleon momenta are sampled assuming Fermi gas model
- Nuclear density
  - harmonic oscillator shape for $A < 17$
  - Woods-Saxon for others
- Sampling is done in a correlated manner:
  - local phase-space densities are constrained by Pauli principle
  - sum of all nucleon momenta must equal zero

Collision Criterion

- In the Regge-Gribov approach, the probability of an inelastic collision with nucleon i can be written as

$$p_i(b_i,s) = (1/c)(1-\exp[-2u(b_i,s)]) = \sum_{n=1}^{\infty} p_{i^{(n)}}(b_i\,,s)$$

- where

$$p_{i^{(n)}}(b_i,s) = (1/c)\exp[-2u(b_i,s)]\frac{[2u(b_i,s)]^n}{n!}$$

is the probability of finding n cut pomerons in the collision

$$u(b_i,s) = \frac{z(s)}{2}\exp(b_i^2/4L(s))$$

is the eikonal amplitude for hadron-nucleon elastic scattering with pomeron exchange

Pomeron Parameters

- The functions z(s) and L(s) contain the pomeron parameters:
  - fitted to N-N, π−N, K-N collision data (elastic, total, single diffraction cross sections)
  - pomeron trajectory: $\alpha_P' = 0.25\ \mathrm{GeV}^{-2}$, $\alpha_P(0) = 1.0808$ for π, K, 0.9808 for N

- Other parameters:
  - energy scale $s_0 = 3.0\ \mathrm{GeV}^2$ for N, $1.5\ \mathrm{GeV}^2$ for π, $2.3\ \mathrm{GeV}^2$ for K
  - Pomeron-hadron vertex parameters also included:
    - coupling: $\gamma_P^N = 6.56\ \mathrm{GeV}^{-2}$
    - radius of interaction: $R^{2N}{}_P = 3.56\ \mathrm{GeV}^{-2}$

Diffractive Dissociation

- Need to sample the probability of diffraction
  - get it from difference of total and inelastic collision probabilities

$$p_{ij}{}_{diff}(b_{ij}, s) = \frac{c-1}{c}\left(p_{ij}{}_{tot}(b_{ij}, s) - p_{ij}(b_{ij}, s)\right)$$

  - where c is the “shower enhancement” coefficient
  - c = 1.4 for nucleons, 1.8 for pions
- Splitting off diffraction probabilities with parameter c follows method of Baker 1976

String Formation

- Cutting the pomeron yields two strings
- String formation is done by parton exchange (Capella 94, Kaidalov 82)
  - for each participating hadron, parton densities are sampled
  - requires quark structure function of hadron
  - parton pairs combined into color singlets
  - sea quarks included with u:d:s = 1: 1: 0.27

Longitudinal String Fragmentation

- String extends between constituents
- Break string by inserting q-qbar pair according to
  - u : d : s : qq = 1 : 1 : 0.27 : 0.1
- At break -> new string + hadron
- Gaussian P_t , $\langle P_t^2 \rangle$ = 0.5 GeV
- Created hadron gets longitudinal momentum from sampling QGSM fragmentation functions
  - Lund functions also available

BERTINI CASCADE

Bertini Cascade Modeling Sequence (1)

- Nuclear entry point sampled over projected area of nucleus
- Incident particle is transported in nuclear medium
  - mean free path from total particle-particle cross sections
  - nucleus modeled as 3 concentric, constant-density shells
  - nucleons have Fermi gas momentum distribution
  - Pauli exclusion invoked
- Projectile interacts with a single nucleon
  - hadron-nucleon interactions based on free cross sections and angular distributions
  - pions can be absorbed on quasi-deuterons

Bertini Cascade Modeling Sequence (2)

- Each secondary from initial interaction is propagated in nuclear potential until it interacts or leaves nucleus
  - can have reflection from density shell boundaries
  - Coulomb barrier applied for emission of positives (2008)
- As cascade collisions occur, exciton states are built up, leading to equilibrated nucleus
  - selection rules for p-h state formation: $\Delta p = 0, +/1,$ $\Delta h = 0, +/-1, \quad \Delta n = 0, +/-2$
- Model uses its own exciton routine based on that of Griffin
  - Kalbach matrix elements used
  - level densities parametrized vs. Z and A

Bertini Cascade Modeling Sequence (3)

- Cascade ends and exciton model takes over when secondary KE drops below 20% of its original value or 7 X nuclear binding energy
- Nuclear evaporation follows for most nuclei
  - emission continues as long as excitation is large enough to remove a neutron or α
  - γ emission below 0.1 MeV
- For light, highly excited nuclei, Fermi breakup
- Fission also possible

BINARY CASCADE

Binary Cascade Modeling (1)

- Nucleon-nucleon scattering (t-channel) resonance excitation cross-sections are derived from p-p scattering using isospin invariance, and the corresponding Clebsch-Gordan coefficients
  - elastic N-N scattering included
- Meson-nucleon inelastic (except true absorption) scattering modelled as s-channel resonance excitation. Breit-Wigner form used for cross section.
- Resonances may interact or decay
  - nominal PDG branching ratios used for resonance decay
  - masses sampled from Breit-Wigner form

Binary Cascade Modeling (2)

- Calculate imaginary part of the R-matrix using free 2-body cross-sections from experimental data and parametrizations
- For resonance re-scattering, the solution of an in-medium BUU equation is used.
  - The Binary Cascade at present takes the following strong resonances into account:
    - The delta resonances with masses 1232, 1600, 1620, 1700, 1900, 1905, 1910, 1920, 1930, and 1950 MeV
    - Excited nucleons with masses 1440, 1520, 1535, 1650, 1675, 1680, 1700, 1710, 1720, 1900, 1990, 2090, 2190, 2220, and 2250 MeV

Binary Cascade Modeling (3)

- Resonances may interact or decay
- Nucleon-nucleon elastic scattering angular distributions taken from Arndt phase shift analysis of experimental data
- Pauli blocking implemented in its classical form
  - finals state nucleons occupy only states above Fermi momentum
- Pion absorption modelled as s-wave absorption on quasi-deuterons
- Coulomb barrier present for charged hadrons

Binary Cascade Modeling (4)

- Cascade stops when mean energy of all scattered particles is below A-dependent cut
  - varies from 18 to 9 MeV
  - if primary below 45 MeV, no cascade, just precompound
- When cascade stops
  - the properties of the residual exciton system and nucleus are evaluated, and
  - passed to a pre-equilibrium decay code for nuclear de-excitation

CHIPS

Modeling Sequence for Proton - antiproton Annihilation (2)

- anti-proton and proton form a quasmon in vacuum
  - no quark exchange with neighboring nucleons
  - $n = M/2T_C$ quark-partons uniformly distributed over phase space with spectrum $dW/kdk \propto (1 - 2k/M)^{n-3}$
- quark fusion occurs
  - calculate probability of two quark-partons in the quasmon to combine to produce effective mass of outgoing hadron:
    - sample k in 3 dimensions
    - second quark momentum q from spectrum of n-1 quarks
    - integrate over vector q with mass shell constraint for outgoing hadron

Modeling Sequence for Proton - antiproton Annihilation (3)

- determine type of final state hadron to be produced
  - probability that hadron of given spin and quark content is produced: $P = (2s_h + 1)\, z^{N-3}\, C_Q$
  - C_Q is the number of ways a hadron h can be made from the choice of quarks in the quasmon
  - z^{N-3} is a kinematic factor from the previous momentum selection
- first hadron is produced, escapes quasmon
- randomly sample residual quasmon mass, based on original mass M and emitted hadron mass

Modeling Sequence for Proton - antiproton Annihilation (4)

- Repeat quark fusion with reduced quasmon mass and quark-parton content
- hadronization process ends when minimum quasmon mass m_{min} is reached
  - m_{min} is determined by quasmon quark content at final step
  - depending on quark content, final quasmon decays to two hadrons or a hadron and a resonance
  - kaon multiplicity regulated by the s-suppression parameter (s/u = 0.1)
  - η/η' suppression regulated by η−suppression parameter (0.3)

Modeling Sequence for π^- Capture at Rest in a Nucleus (2)

- pion captures on a subset or cluster of nucleons
  - resulting quasmon has a large mass, many partons
  - capture probability is proportional to number of clusters in nucleus
  - 3 clusterization parameters determine number of clusters
- both quark exchange and quark fusion occurs
  - only quarks and diquarks can fuse
  - mesons cannot be produced, so quark-anti-quark cannot fuse as in vacuum case (p-pbar)
  - because q-qbar fusion is suppressed, quarks in quasmon exchange with neighboring nucleon or cluster
    - produces correlation of final state hadrons

Modeling Sequence for π^- Capture at Rest in a Nucleus (3)

- some final state hadrons escape nucleus, others are stopped by Coulomb barrier or by over-barrier reflection
- as in vacuum, hadronization continues until quasmon mass reaches lower limit m_{min}
  - in nuclear matter, at this point nuclear evaporation begins
  - if residual nucleus is far from stability, a fast emission of p, n, α is made to avoid short-lived isotopes

RECENT FIXES, IMPROVEMENTS

Hadronics: the Improved and New

Improved:

- Corrections & tuning in **pre-compound** and **de-excitation** code
  - affecting results for low-energy secondaries in Binary cascade
- Revised string fragmentation and tuned parameters in **FTF** model
  - For `Pi+P` and `pion-nucleon` interactions
  - Implemented quasi-elastic hadron-nucleus scattering and formation time
- Enabled/added barrier penetration for the Coulomb barrier in **Bertini** cascade

New:

- **INCL** cascade and **ABLA** evaporation model officially released
  - Can be used for incident `p, n, d, t, 3He, alpha` and `pions` from `200 MeV` up to `3 GeV`, on nuclei ranging from carbon to uranium
- *Beta* release of *new* quantum molecular dynamics (**QMD**) model
  - For nucleus-nucleus collisions; valid from `50 MeV` to `5 GeV`

Hadronic processes: major fixes

- Bug fix in the final state multiplicity sampling in **Bertini** cascade
  - Fixes observed problem of quasi-elastic peak in energy spectra
- Corrections to the **multi-fragmentation** model to ensure it conforms with the original SMM model (from its authors)
- Improved energy and angular distributions for both scattered neutron and recoil targets in the **hp_neutron** model
- Code review and performance improvements to **Bertini** code
  - Measured ~25% CPU time boost for QGSP_BERT for **`50 GeV pi-`**
- Technical
  - Rationalised usage of the nuclear mass tables

Latest Hadronic fixes – 9.2.p01

- Corrected light ion emission in pre-compound/de-excitation
  - Probability of emission in pre-compound
  - Implementation of the emission probability in de_excitation model
  - Added smearing of Coulomb barriers for **`d, t, he3`** and **`alpha`**
- Tuned absorption coefficient in Bertini cascade
  - Changed pion absorption coefficient from 0.2 to 1.0
- Technical
  - Activate proper deletion of processes, models and cross-sections at job closure

FURTHER INFORMATION

String Formation

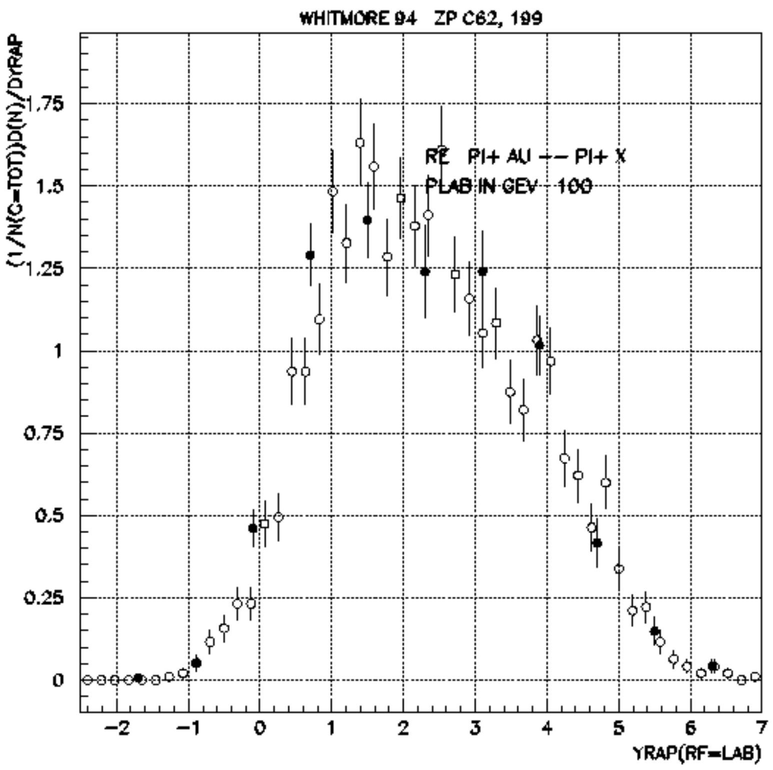
- Cutting the pomeron yields two strings
- String formation is done by parton exchange (Capella 94, Kaidalov 82)
  - for each participating hadron h, parton densities are sampled

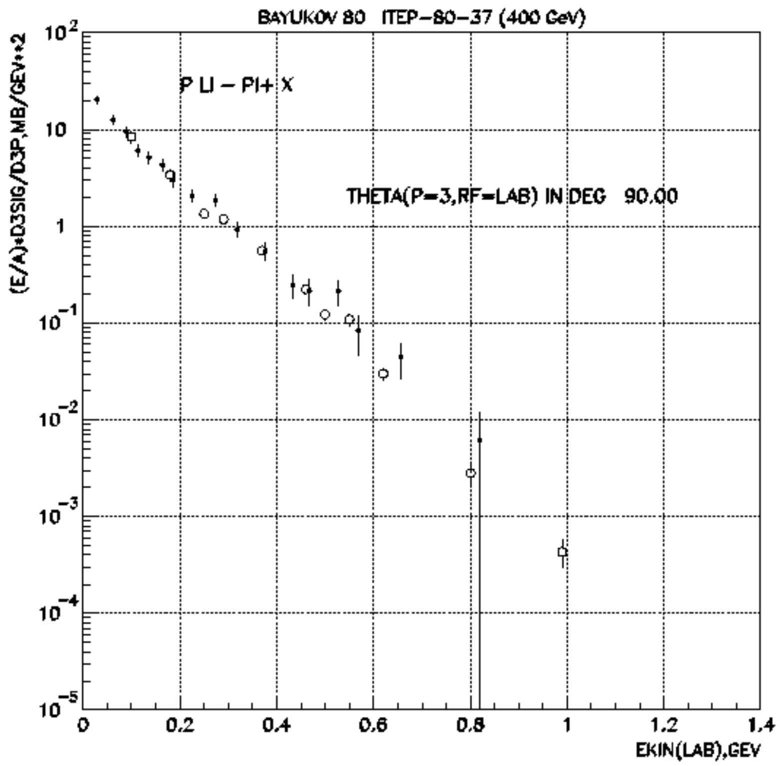
$$f^{h}(x_1, x_2, \ldots, x_{2n-1}, x_{2n}) = f_0 \prod_{i=1}^{2n} u_{p_i}^{h}(x_i)\,\delta(1 - \sum_{i=1}^{2n} x_i)$$

  - parton pairs combined to form color singlets
  - u is quark structure function of hadron h
  - sea quarks included with u:d:s = 1: 1: 0.27

QGS Model

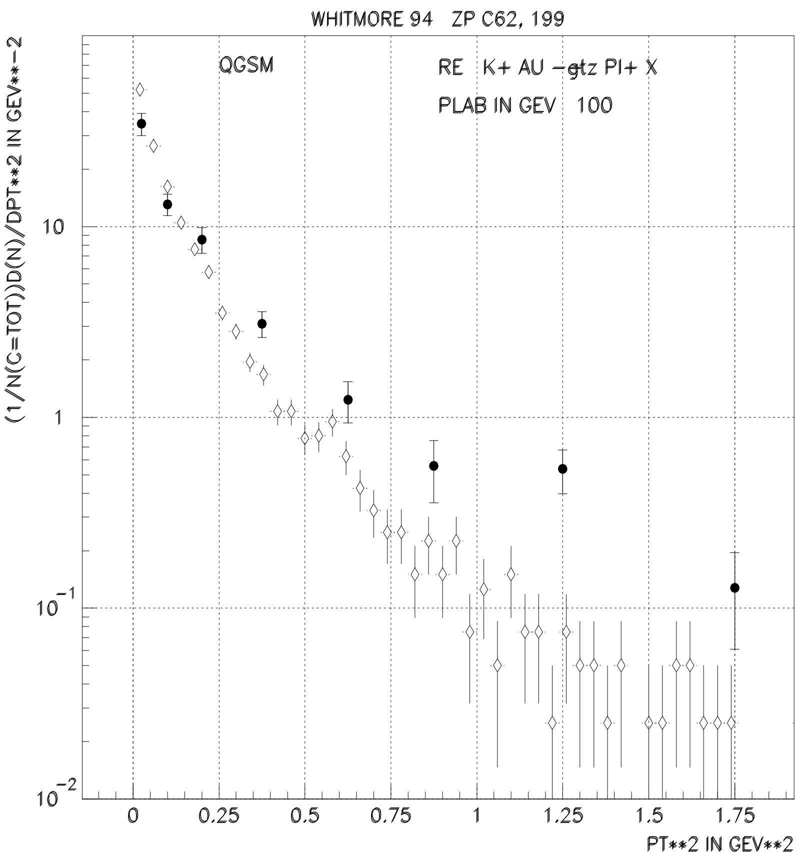
Pion and proton scattering

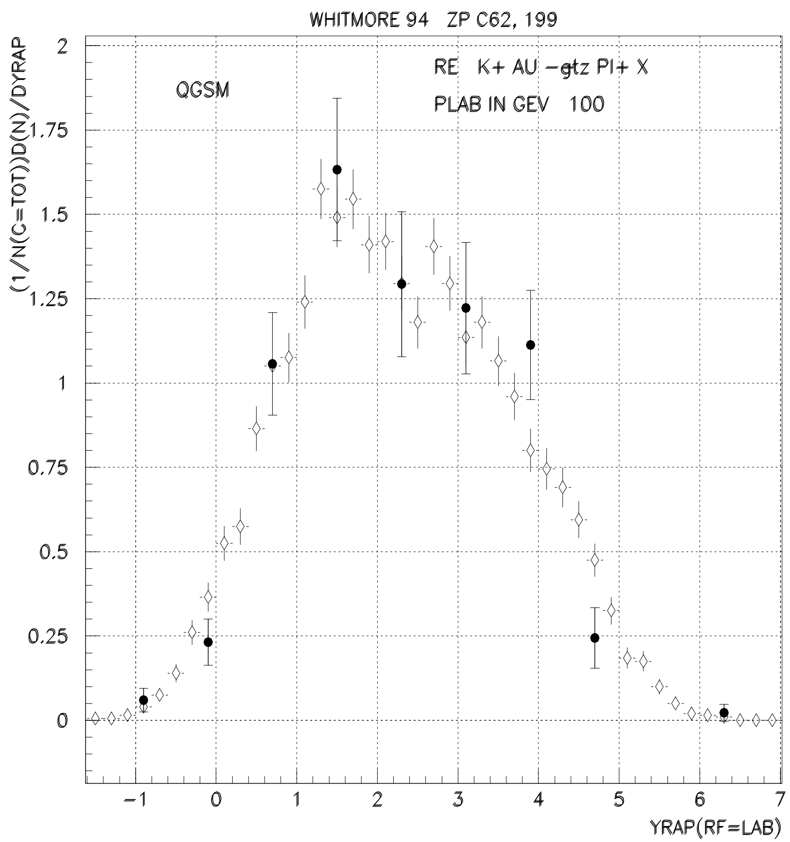




QGS Model

K+ Scattering from Au (π^+ inclusive)

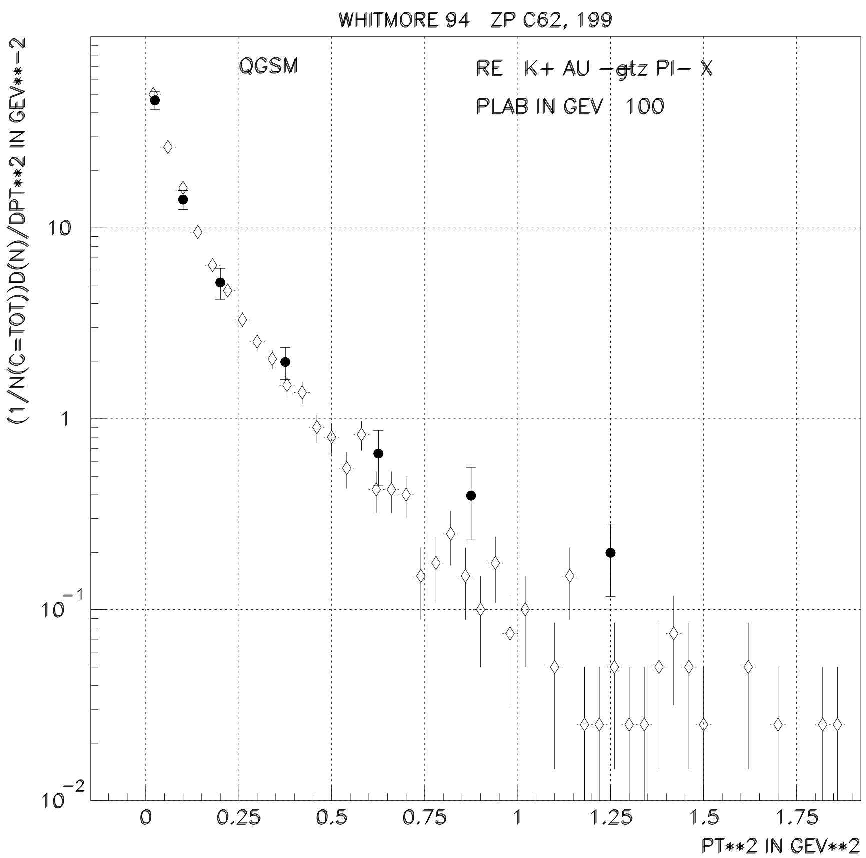


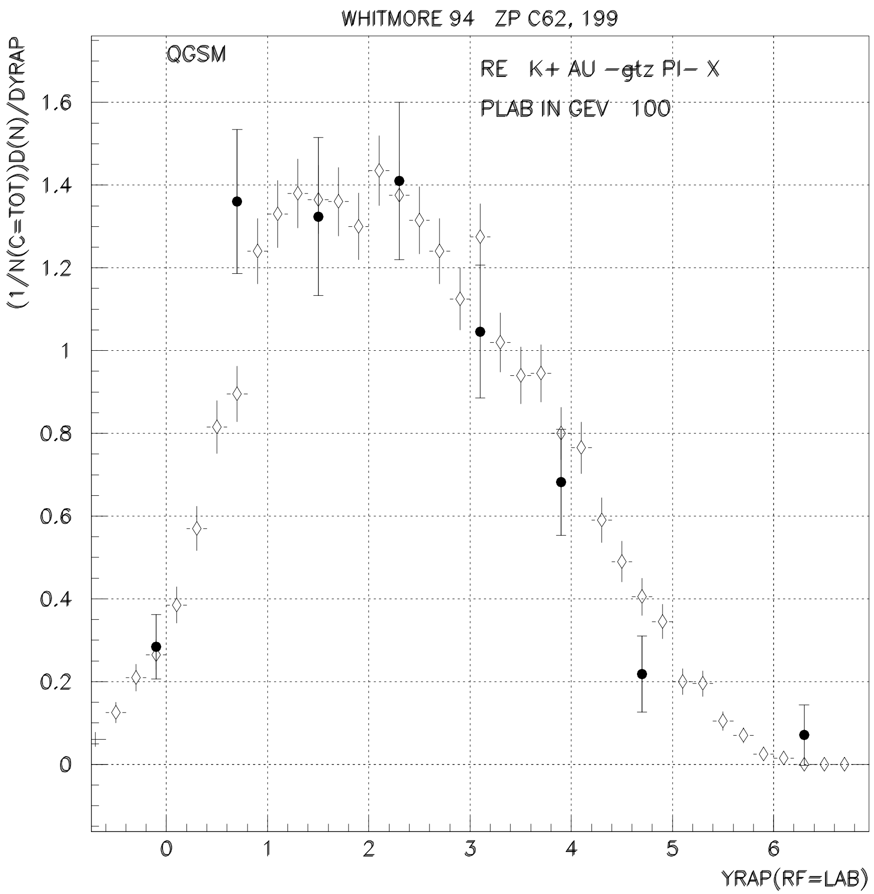


Solid dots: J.J.Whitmore et.al., Z.Phys.C62(1994)199

QGS Model

K+ Scattering from Au (π^- inclusive)





Solid dots: J.J.Whitmore et.al., Z.Phys.C62(1994)199

Chiral Invariant Phase Space (CHIPS)

- Hadron spectra reflect spectra of quark-partons within quasmon
  - 1-D quark exchange:

    $k + M = q + E, \ \ k = p - q \ \ \Rightarrow \ \ k = (E - M + p)/2$
  - 1-D quark fusion:

    $k + q = E, \ \ k - q = p \ \ \Rightarrow \ \ k = (E + p)/2$

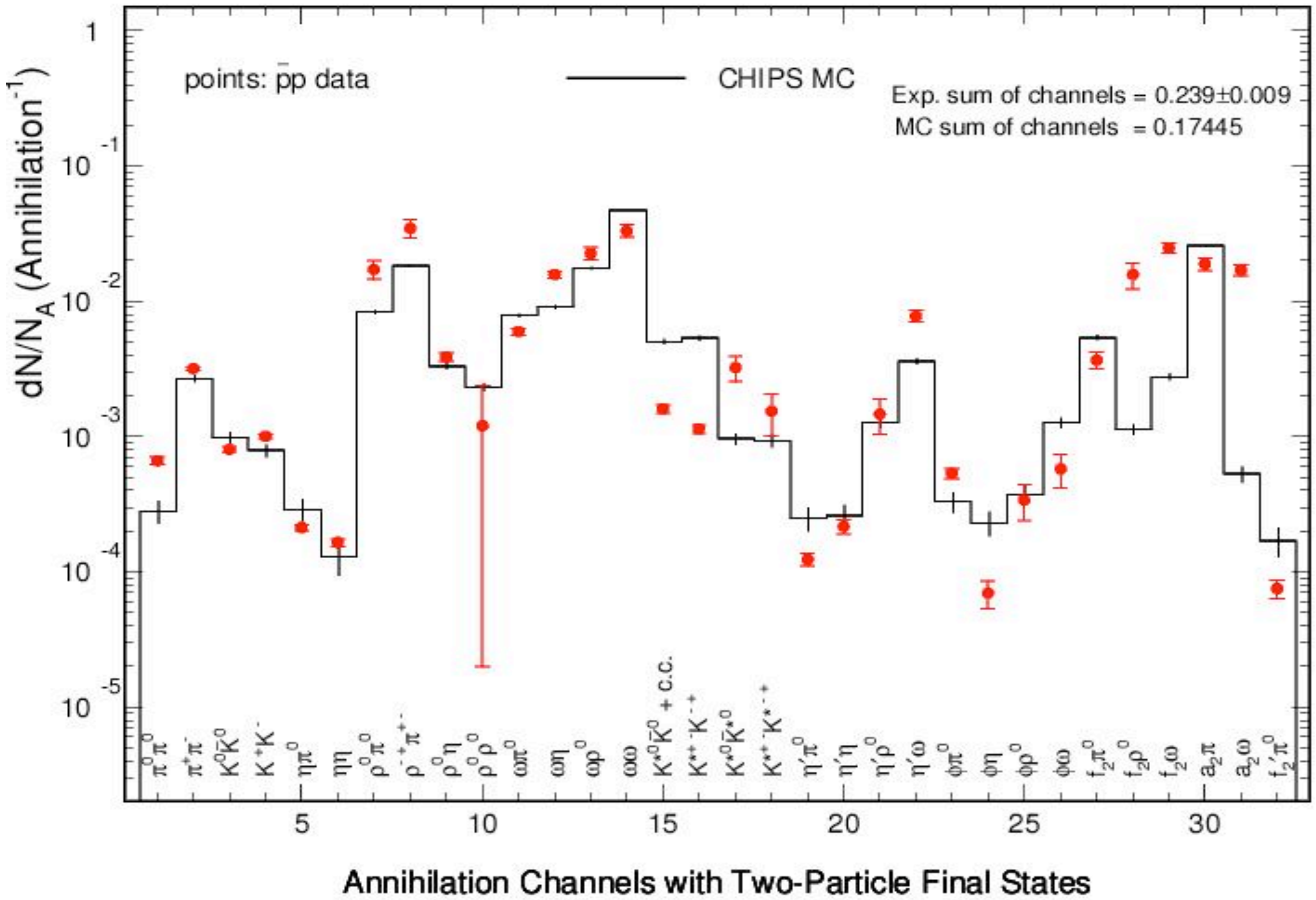
Currently Implemented Mechanisms (1)

- Negative meson captured by nucleon or nucleon cluster:
  - $dE_\pi = m_\pi$, $dE_K = m_K + m_N - m_\Lambda$
- Negative hyperon captured by nucleon or nucleon cluster:
  - $dE_{\Sigma-} = m_{\Sigma-} - m_\Lambda$, $dE_{\Xi-} = m_{\Xi-} + m_N - 2m_\Lambda$, $dE_\Omega = m_\Omega + 2m_N - 3m_\Lambda$
- Nuclear capture of anti-baryon:
  - annihilation happens on nuclear periphery
  - 4π explosion of mesons irradiates residual nucleus
  - secondary mesons interacting with residual nucleus create more quasmons in nuclear matter
  - large excitation: $dE = m_{antibaryon} + m_N$

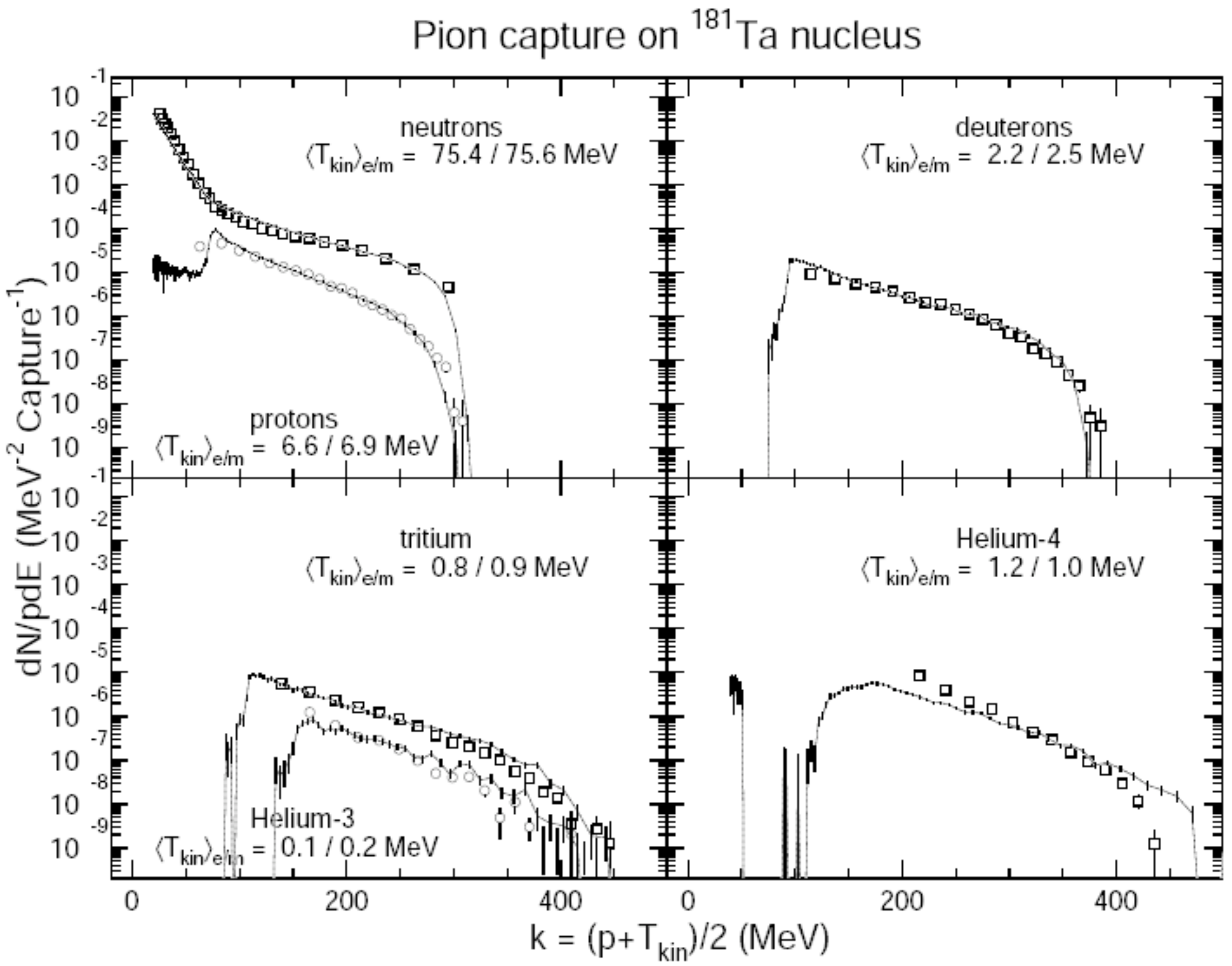
Currently Implemented Mechanisms (2)

- In photo-nuclear reactions γ is absorbed by a quark-parton
  - $dE_\gamma = E_\gamma$
- In back-end of string-hadronization (QGSC model) soft part of string is absorbed:
  - $dE_{QGSC} = 1$ GeV/fm
- lepto-nuclear reactions γ^* , W^* are absorbed by quark-parton:
  - $dE_l = E_{\gamma*}$, $\cos(\theta_k) = (2k/\nu - Q^2)/2kq$, $Q^2 = q^2 - \nu^2$
  - with $k < M/2$, if $q - \nu < m_N$, virtual γ cannot be captured by one nucleon

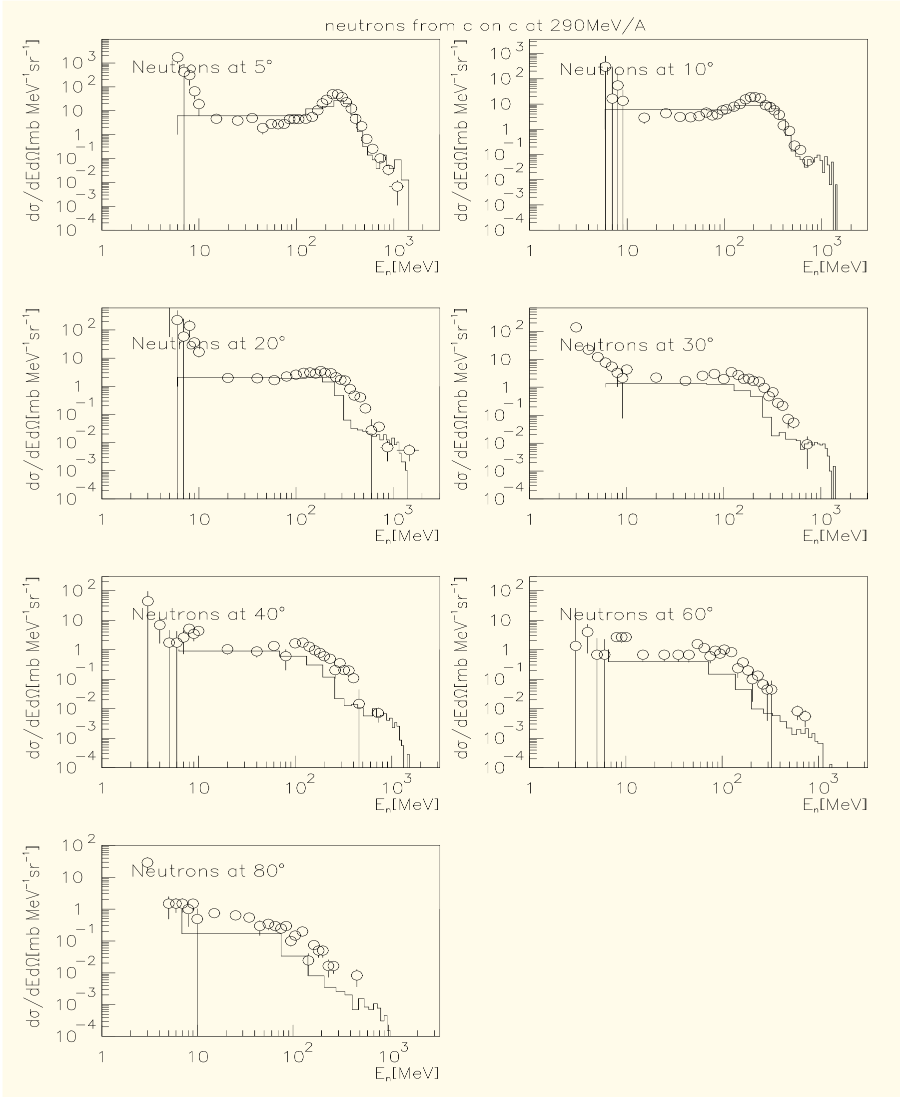
P-pbar Annihilation into Two Body Final States



Validation of CHIPS Model for Pion Capture at Rest on Tantalum



Neutrons from C on C at 290 MeV/c



p+Ta=h+X, 400 GeV, 90^o