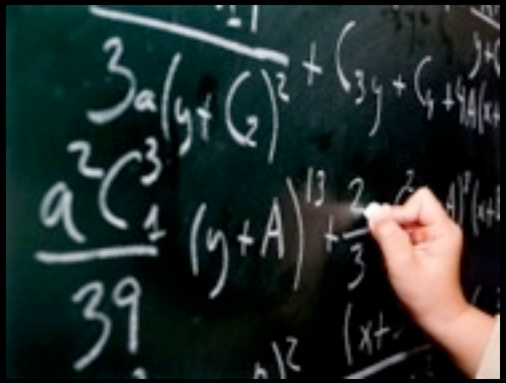
Physics and Generator Tuning

Peter Skands (CERN Theoretical Physics Dept)

CMS Physics Comparisons and Generator Tunes Meeting
October 2013, CERN

What is Tuning?



Theory

Experiment

Adjust this to agree with this

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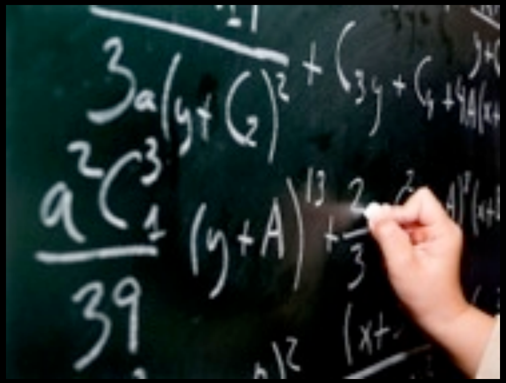


Theory

Experiment

Adjust this to agree with this

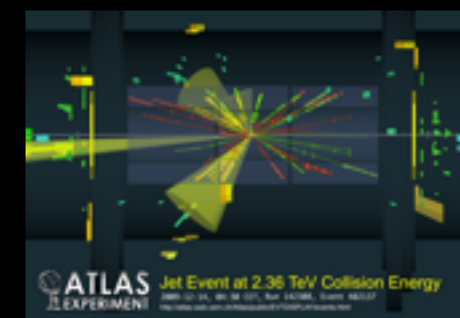
→ Science

In Practice

PYTHIA

VINCIA

…



"Virtual Colliders"
= Simulation Codes

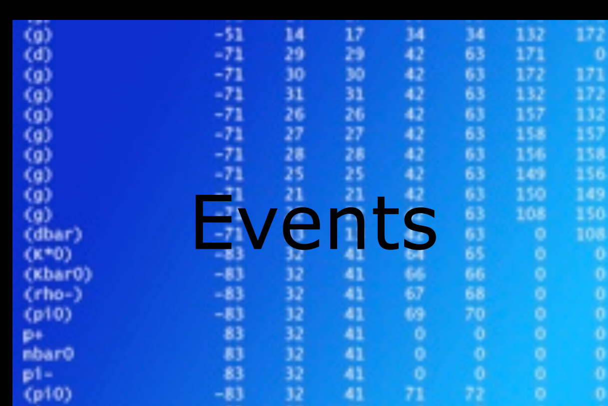
Particle Physics Models,
Simplifications, Algorithms, …

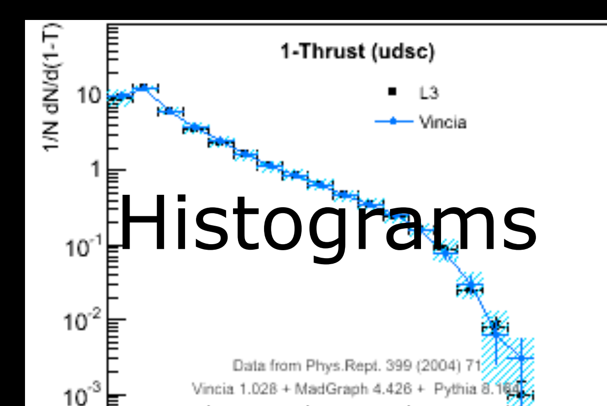
→ Simulated Particle Collisions

Real Universe
→ Experiments & Data

Particle Accelerators, Detectors,
Statistical Analyses, Calibrations

→ Published Measurements





Resources

Data Preservation: HEPDATA

Online database of experimental results

Please make sure published results make it there

Analysis Preservation: RIVET

Large library of encoded analyses + data comparisons

Main analysis & constraint package for event generators

All your analysis are belong to RIVET

Updated validation plots: MCPLOTS.CERN.CH

Online plots made from Rivet analyses

Want to help? Connect to Test4Theory (LHC@home 2.0)

Reproducible tuning: PROFESSOR

Automated tuning (& more)

(Test4Theory)

LHC@home 2.0 Test4Theory volunteers' machines seen during the past 24 hours (7011 machines overall)

The LHC@home 2.0 project Test4Theory allows users to participate in running simulations of high-energy particle physics using their home computers.

The results are submitted to a database which is used as a common resource by both experimental and theoretical scientists working on the Large Hadron Collider at CERN.

mcplots.cern.ch

Menu

- → Front Page
- → LHC@home 2.0
- → Generator Versions
- → Generator Validation
- → Update History
- → User Manual and Reference

Analysis filter:

- → ALL pp/ppbar
- → ALL ee

Specific analysis:

- → Latest analyses

Z (Drell-Yan)

- → Jet Multiplicities
- → $1/\sigma d\sigma(Z)/d\phi^*_\eta$
- → $d\sigma(Z)/dpTZ$
- → $1/\sigma d\sigma(Z)/dpTZ$

W

- → Charge asymmetry vs η
- → Charge asymmetry vs N_{jet}
- → $d\sigma(jet)/dpT$
- → Jet Multiplicities

Top (MC only)

- → $\Delta\phi$ (ttbar)
- → Δy (ttbar)
- → $|\Delta y|$ (ttbar)
- → M (ttbar)
- → pT (ttbar)
- → Cross sections
- → y (ttbar)
- → Asymmetry
- → Individual tops

Bottom

- → η Distributions
- → pT Distributions
- → Cross sections

Jets

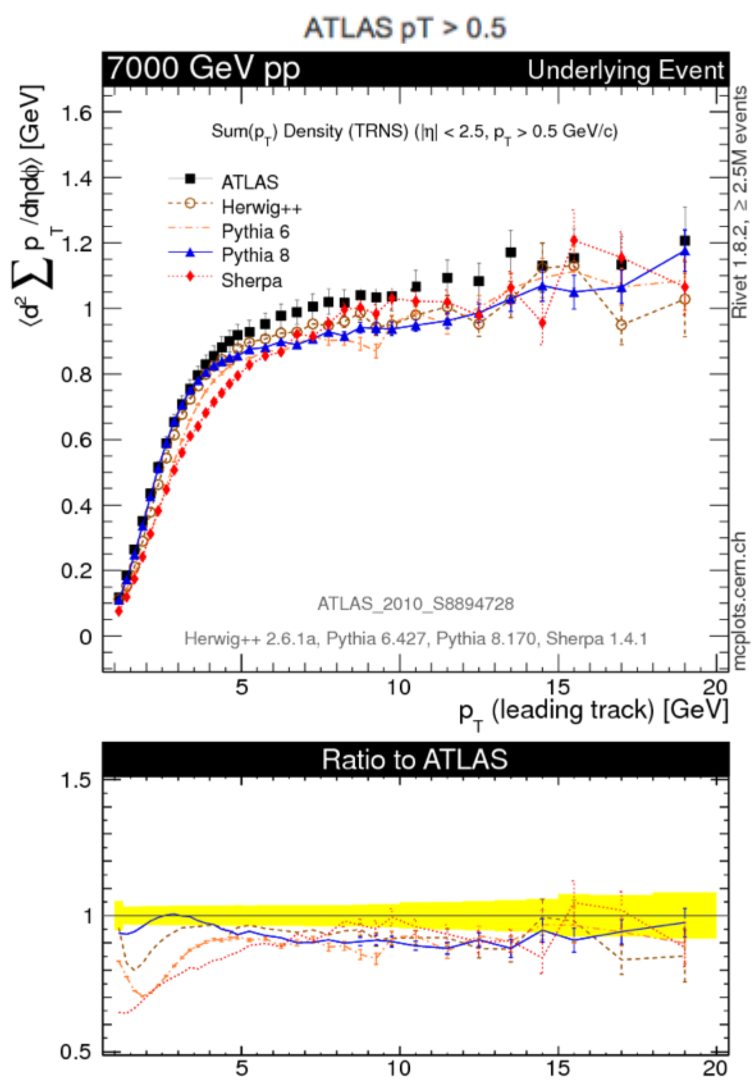
Underlying Event : TRNS : Σ(pT) vs pT1

Generator Group: General-Purpose MCs Soft-Inclusive MCs Alpgen Herwig++ Pythia 6 Pythia 8 Sherpa Vincia Epos Phojet Custom

Subgroup: Defaults LHC Tunes C++ Generators Tevatron vs LHC tunes

pp @ 7000 GeV

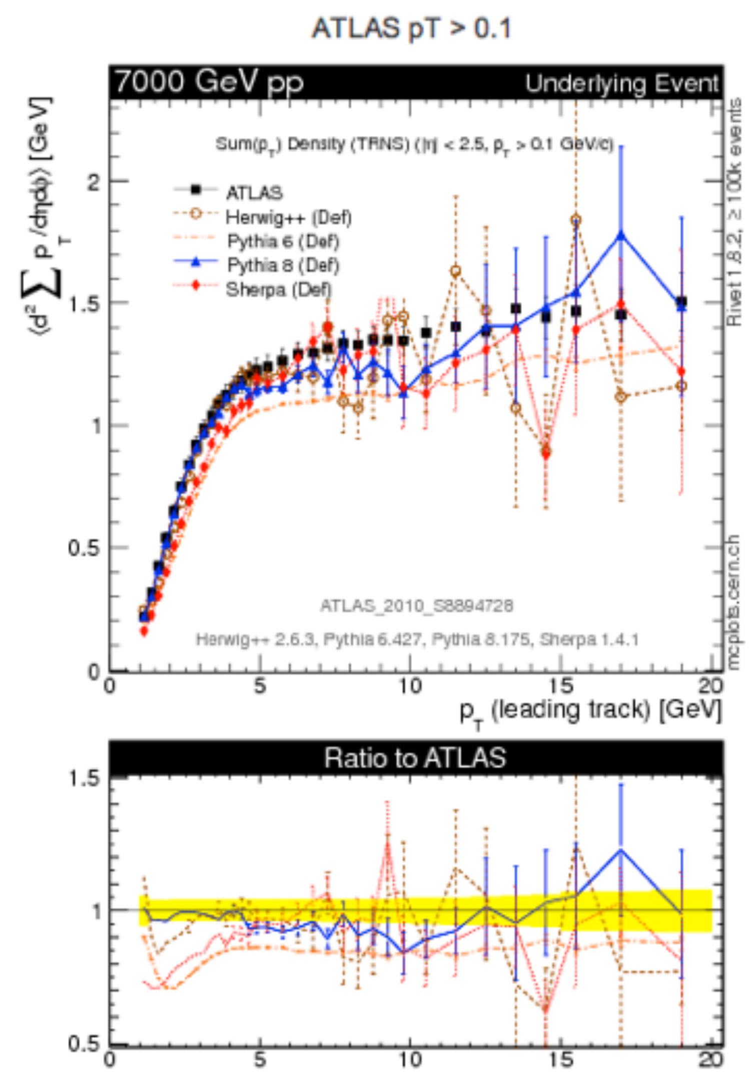
ATLAS pT > 0.5



[pdf] [eps] [png] hide details ←

[ATLAS] reference
[Herwig++ (Def)] param
[Pythia 6 (Def)] param
[Pythia 8 (Def)] param
[Sherpa (Def)] param
[steer]

ATLAS pT > 0.1



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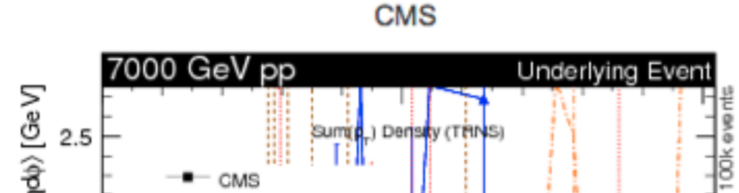
CMS



- Explicit tables of data & MC points
- Run cards for each generator
- Link to experimental reference paper
- Steering file for plotting program
- (Will also add link to RIVET analysis)

Current Methods

Manual Tunes

- Tuning done by hand/eye (few parameters and observables at a time)
- Common sense (and experience) → subjective judgement of importance of each observable, and tails vs averages
- Theoretically motivated uncertainty variations can be included

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Automated Tunes (Professor, Profit?)

Sense and experience encoded as elaborate sets of weights + "sensible" parameter ranges → faster & "easier" than manual

Does not relieve you from critical judgement

Are/were ranges, weights, and observables included indeed "sensible"?
Are tuning interpolations looking stable and convergent?
Are there strong correlations / flat directions?
Do some parameters end up at the end of their physical ranges?

"Data-driven" uncertainty variations do not reflect intrinsic theory uncertainties (cf PDF "errors"!) → Systematic mis-tuning?

Quo Vadis?

*) This is intended as a cultural reference, not a religious one

Not only central tunes

Your experimental (and other user-end) colleagues are relying on you for **serious** uncertainty estimates

Modeling uncertainties are intrinsically non-universal. Including data uncertainties only → lower bound (cf PDFs)

A **serious** uncertainty estimate includes some modeling variation (irrespectively of, and in addition to, what data allows)

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Not only global tunes

Your theoretical (MC author) colleagues are relying on you for stringent tests of the **underlying physics** models, not just 'best fits' (which may obscure "tensions")

Tuning can be done to several complementary data sets.

All give same parameters → universality ok → model ok
Some give different parameters → universality is breaking down → can point to where → feedback to authors → improved models

Example: α_s

Theory: default is factor 2 μ_R variation

→ lots/less of FSR! Use this to define a theory uncertainty associated with α_s (e.g., done in Perugia tunes)

Data-driven (expect smaller?): define variations by ~ 2-sigma consistent with 3-jet observables

Use as cross check on theory uncertainty. How much variation does data actually allow (for the included observables)?

Decide (if you dare) to reduce nominal factor 2, keeping in mind that a larger theory uncertainty is still needed to evaluate uncertainty on extrapolating to other observables/processes.

Bonus! Can re-use the data-driven ones …

Retune string parameters, using the data-driven large/small α_s

→ hadronization variations for use with central α_s

→ can add more systematic "mistunings" to explore uncertainty envelope better

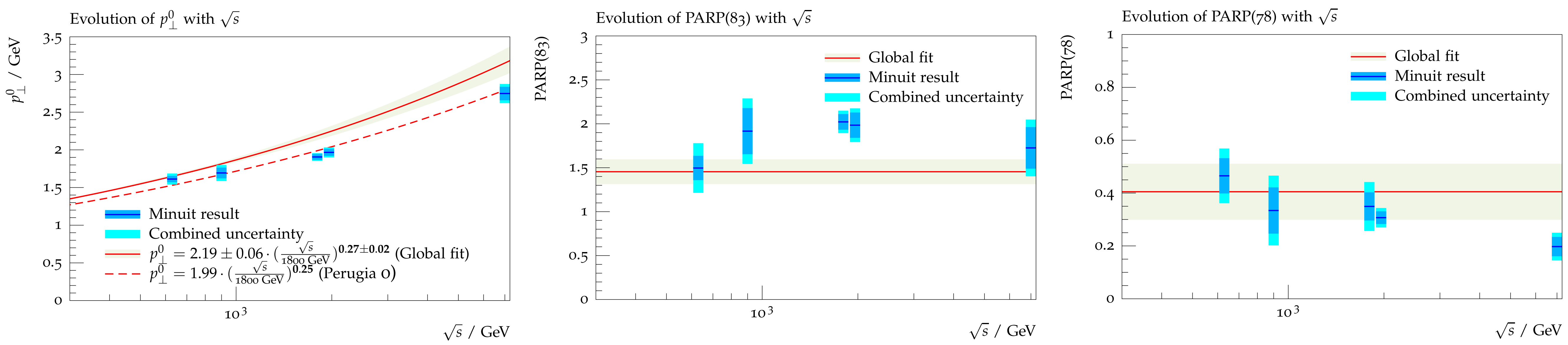
Global Tunes vs Model Tests

Do independent tunes for several complementary "windows" on same physics

- Similar observables at different CM energies
- Similar observables, ee vs pp
- Same collider, different observable ranges
  - E.g., for different pTjet, different Q^2, different cuts, …

Schulz, Skands, arXiv:1103.3649

Example: 3-parameter tuning at 630, 900, 1800, and 7000 GeV



pT0 for MPI | Impact-parameter profile | CR Strength

What is Tuning?

FSR pQCD Parameters

$\alpha_s(m_Z)$

The value of the strong coupling at the Z pole

Governs overall amount of radiation

α_s Running

Renormalization Scheme and Scale for α_s

1- vs 2-loop running, MSbar / CMW scheme, $\mu_R \sim p_T^2$

Matching

Subleading Logs

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At tree level / one-loop level? Using what matching scheme?

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Subleading Logs

Ordering variable, coherence treatment, effective 1→3 (or 2→4), recoil strategy, …

Branching Kinematics (z definitions, local vs global momentum conservation), hard parton starting scales / phase-space cutoffs, masses, non-singular terms, …

Value of Strong Coupling

PYTHIA 8 (hadronization on) vs LEP: Thrust

$$T = \max_{\vec{n}} \left(\frac{\sum_i |\vec{p_i} \cdot \vec{n}|}{\sum_i |\vec{p_i}|} \right)$$

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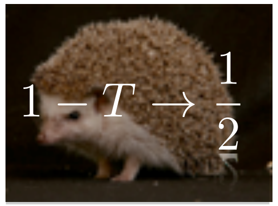

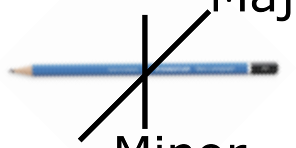

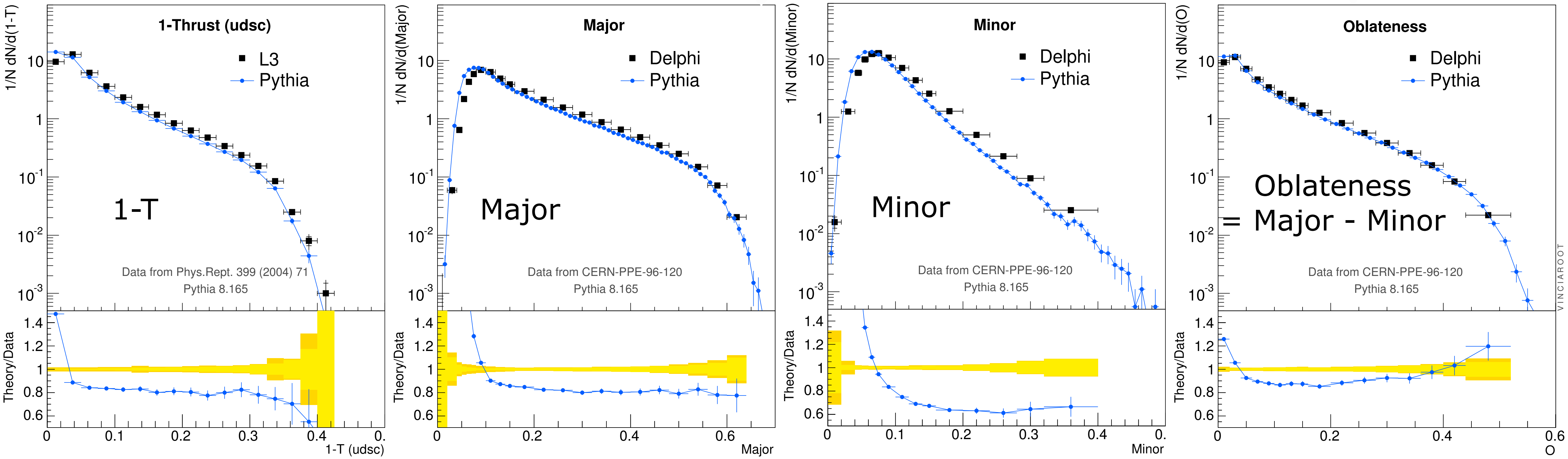

Note: Value of Strong coupling is
$\alpha_s(M_Z) = 0.12$

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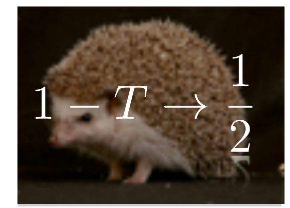

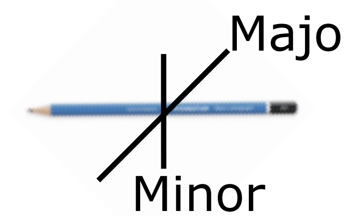

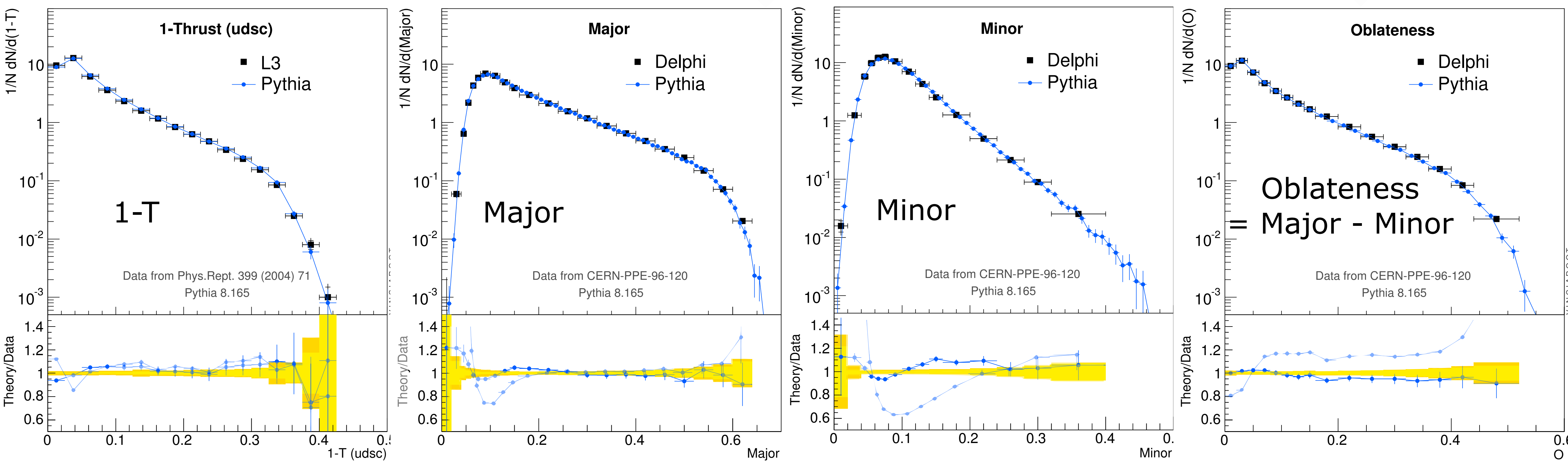

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$\alpha_s(M_Z) = 0.14$

Wait … is this Crazy?

Best tuning result (and default in PYTHIA)

Obtained with $\alpha_s(M_Z) \approx 0.14$

$\neq$ World Average = 0.1176 ± 0.0020

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Value of α_s depends on the order and scheme

MC ≈ Leading Order + LL resummation

Other LO extractions of $\alpha_s \approx 0.13 - 0.14$

Effective scheme interpreted as "CMW" → 0.13;

2-loop running → 0.127; NLO → 0.12 ?

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Tune/measure even pQCD parameters with the actual generator.

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Improve → Matching at LO and NLO

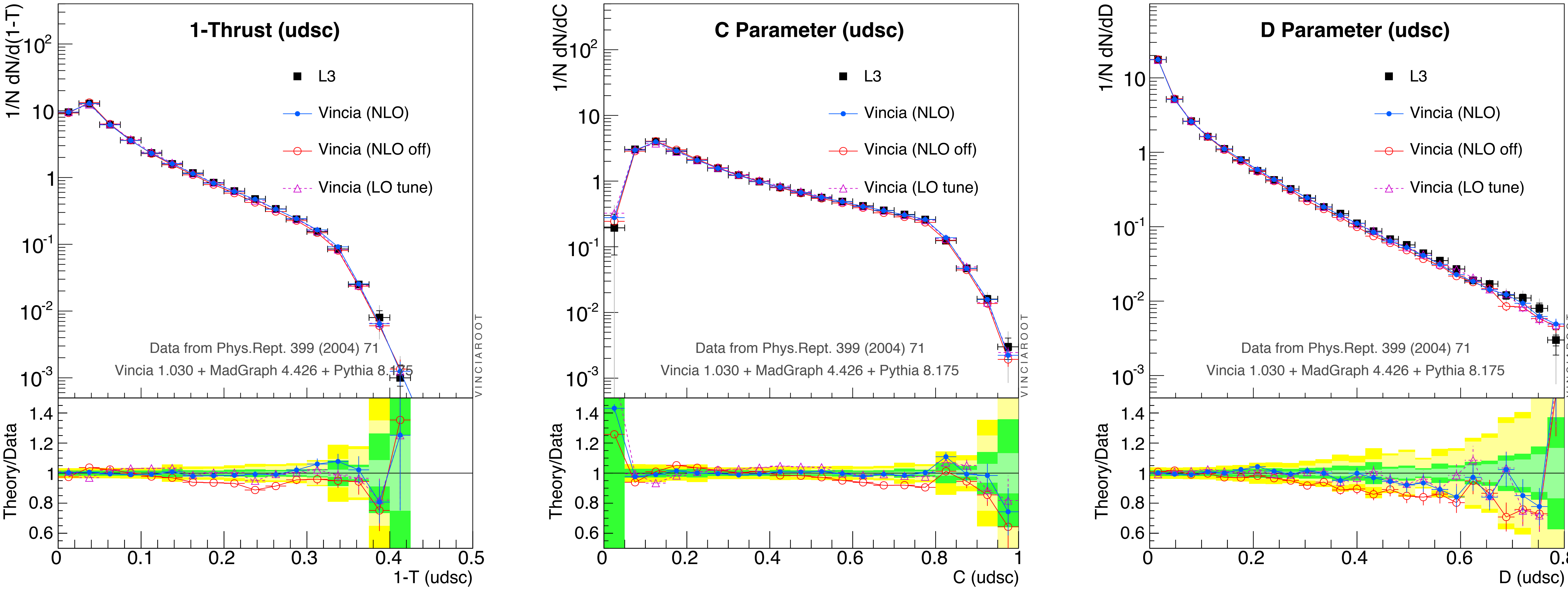
VINCIA: Multijet NLO Corrections

Hartgring, Laenen, Skands, arXiv:1303.4974

First LEP tune with NLO 3-jet corrections

LO tune: $\alpha_s(M_Z) = 0.139$ (1-loop running, MSbar)

NLO tune: $\alpha_s(M_Z) = 0.122$ (2-loop running, CMW)



Sneak Preview:

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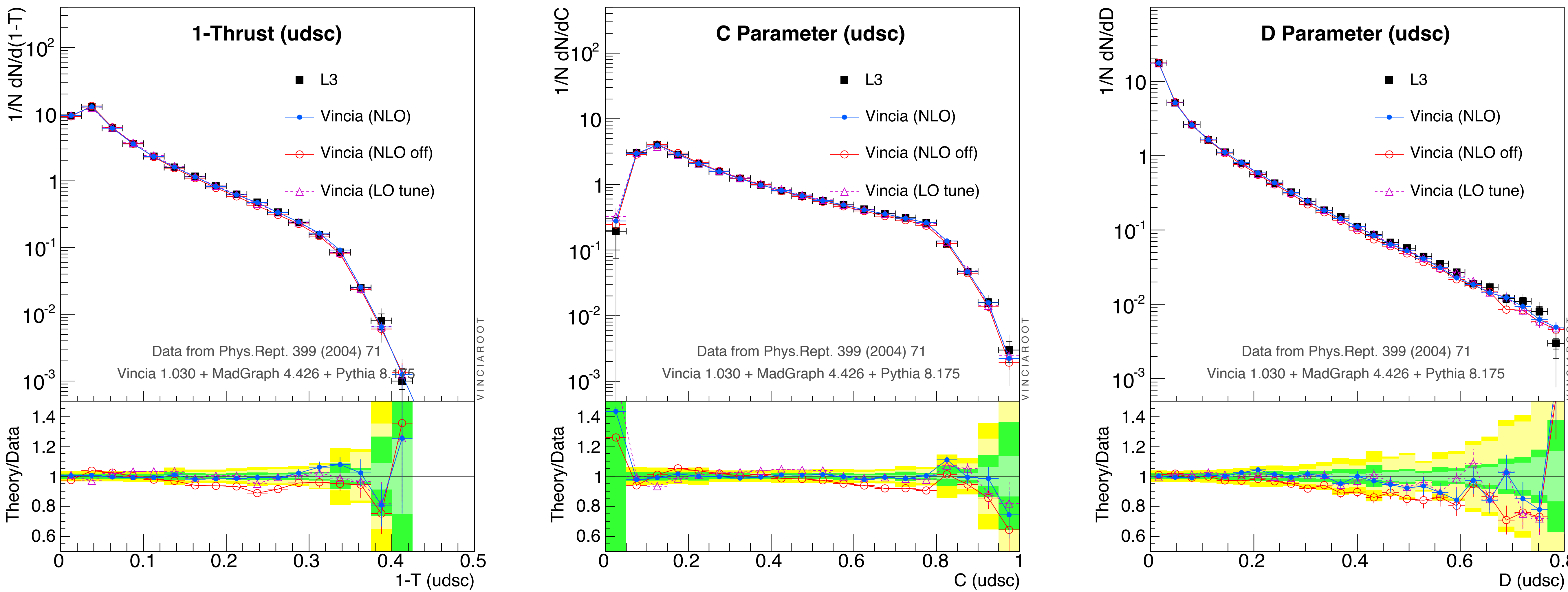


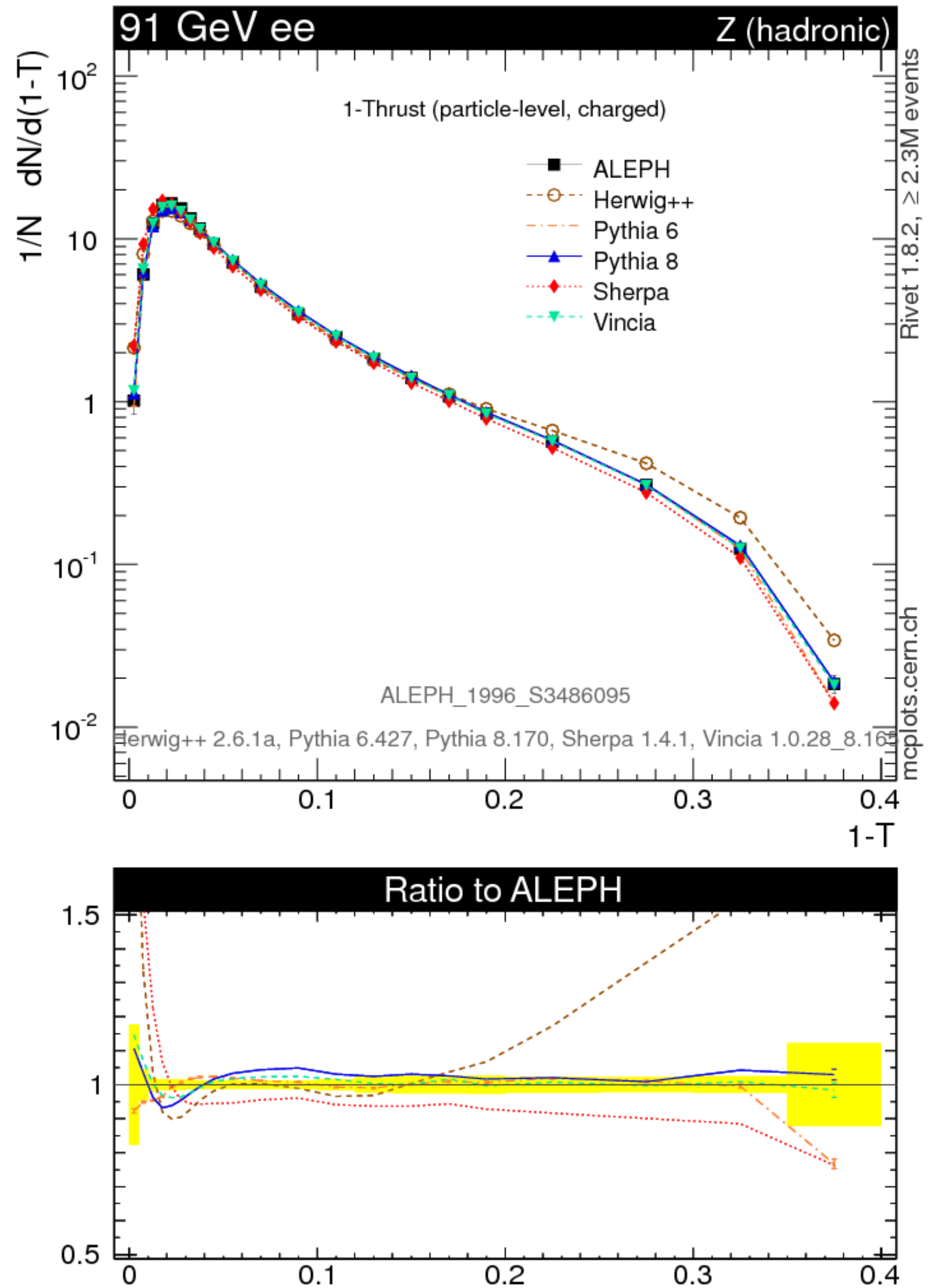
Observable Ranges

Classic example:

Thrust distribution at LEP

Herwig++ (unmatched) generates too many hard 4-jet events

- Can attempt to tune away (if possible)
  - Do not sacrifice agreement in logarithmic region for arm-twisting tuning in hard region
- Or choose to not use problematic region for Herwig++
  - Problematic for universal approach to tuning?
- In any case, must be *aware*, and must make and report a **decision**



String Tuning

Main String Parameters

Longitudinal FF = f(z)

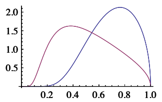
pT in string breaks

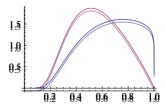
Meson Multiplets

Baryon Multiplets

Lund Symmetric Fragmentation Function

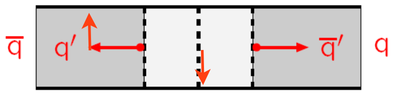
The a and b parameters





Scale of string breaking process

IR cutoff and <p_T> in string breaks



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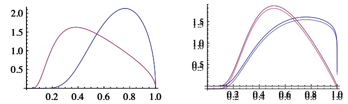

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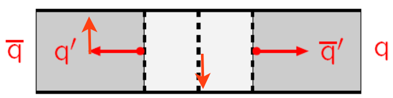

Meson Multiplets

Mesons

Strangeness suppression, Vector/Pseudoscalar, η, η′, …

Baryon Multiplets

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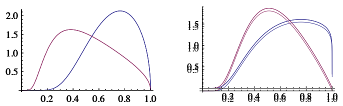

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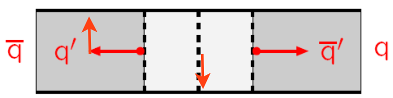

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Diquarks, Decuplet vs Octet, popcorn, junctions, … ?

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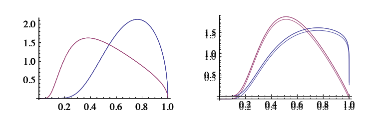

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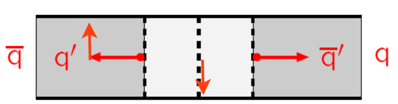

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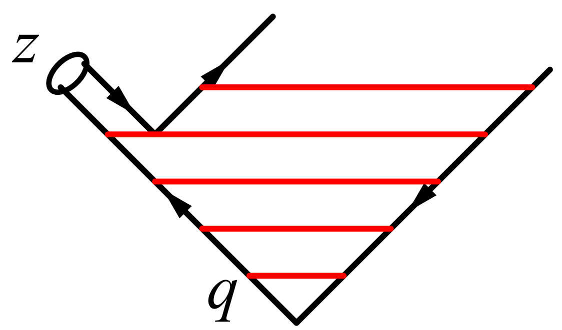
(or equivalent parameters for Cluster Model)

Left-Right Symmetry

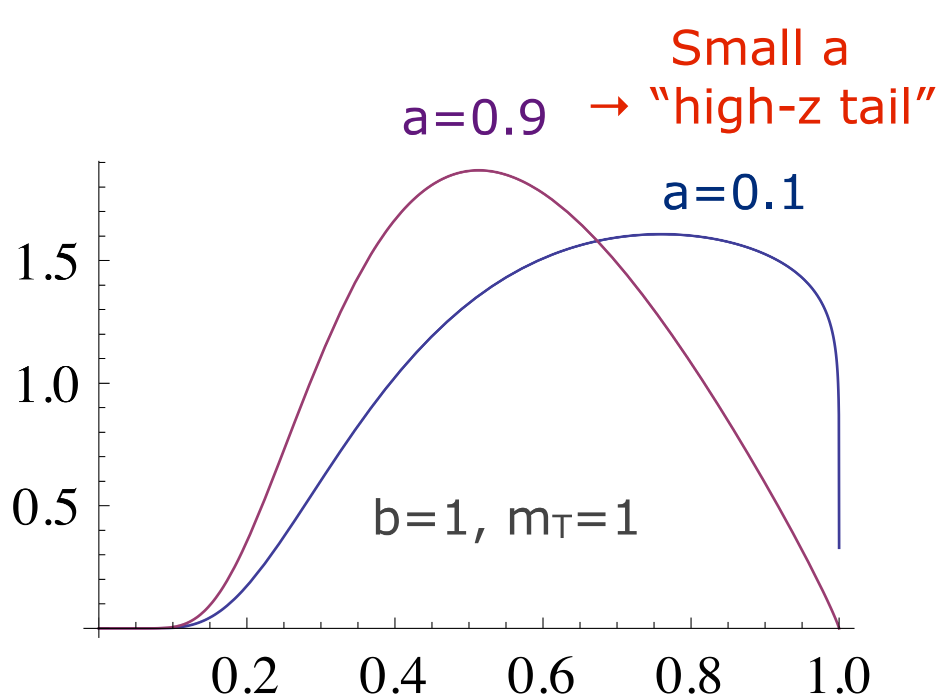
Causality → Left-Right Symmetry

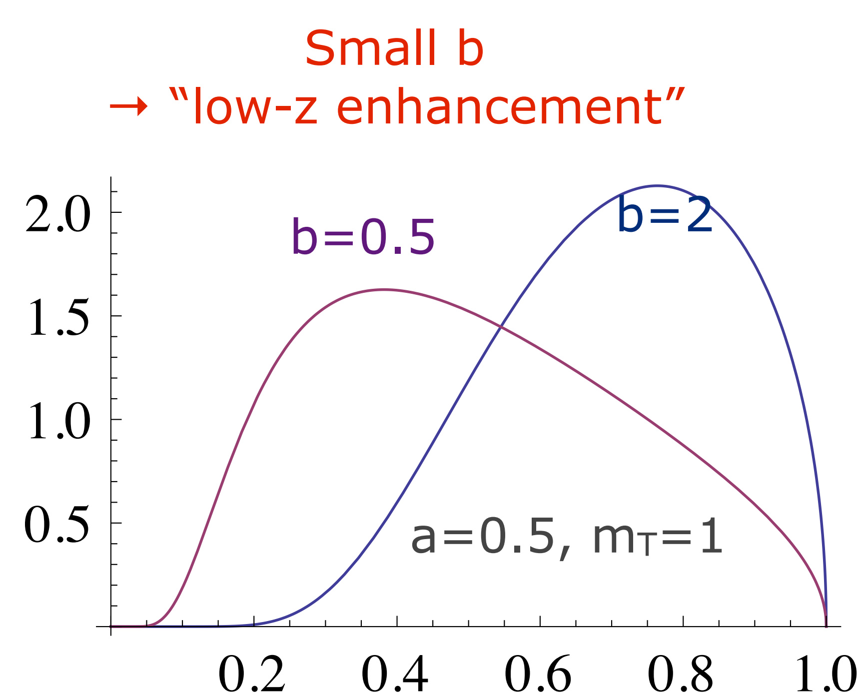
→ Constrains form of fragmentation function!

→ Lund Symmetric Fragmentation Function



$$f(z) \propto \frac{1}{z}(1-z)^a \exp\left(-\frac{b\,(m_h^2 + p_{\perp h}^2)}{z}\right)$$

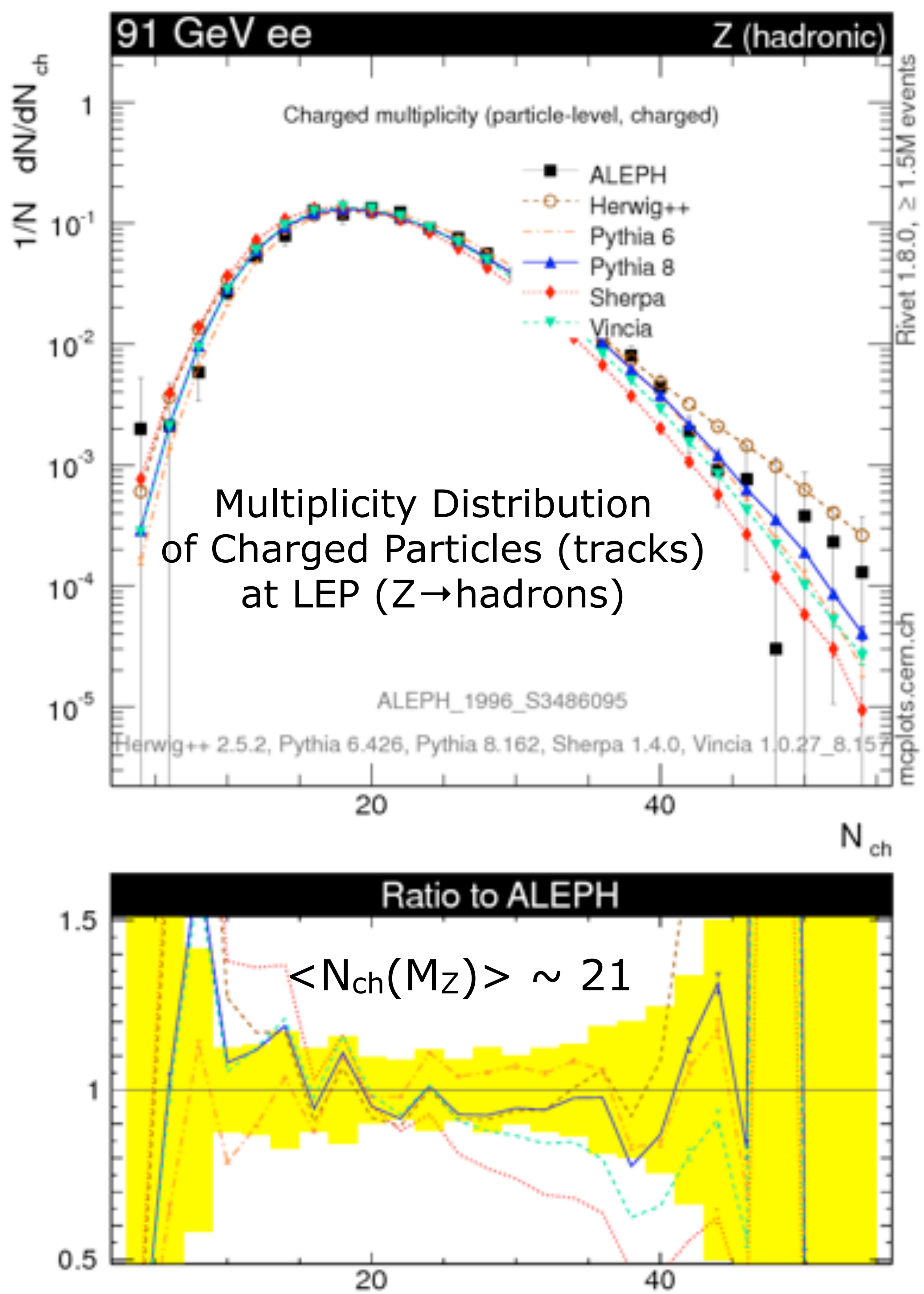


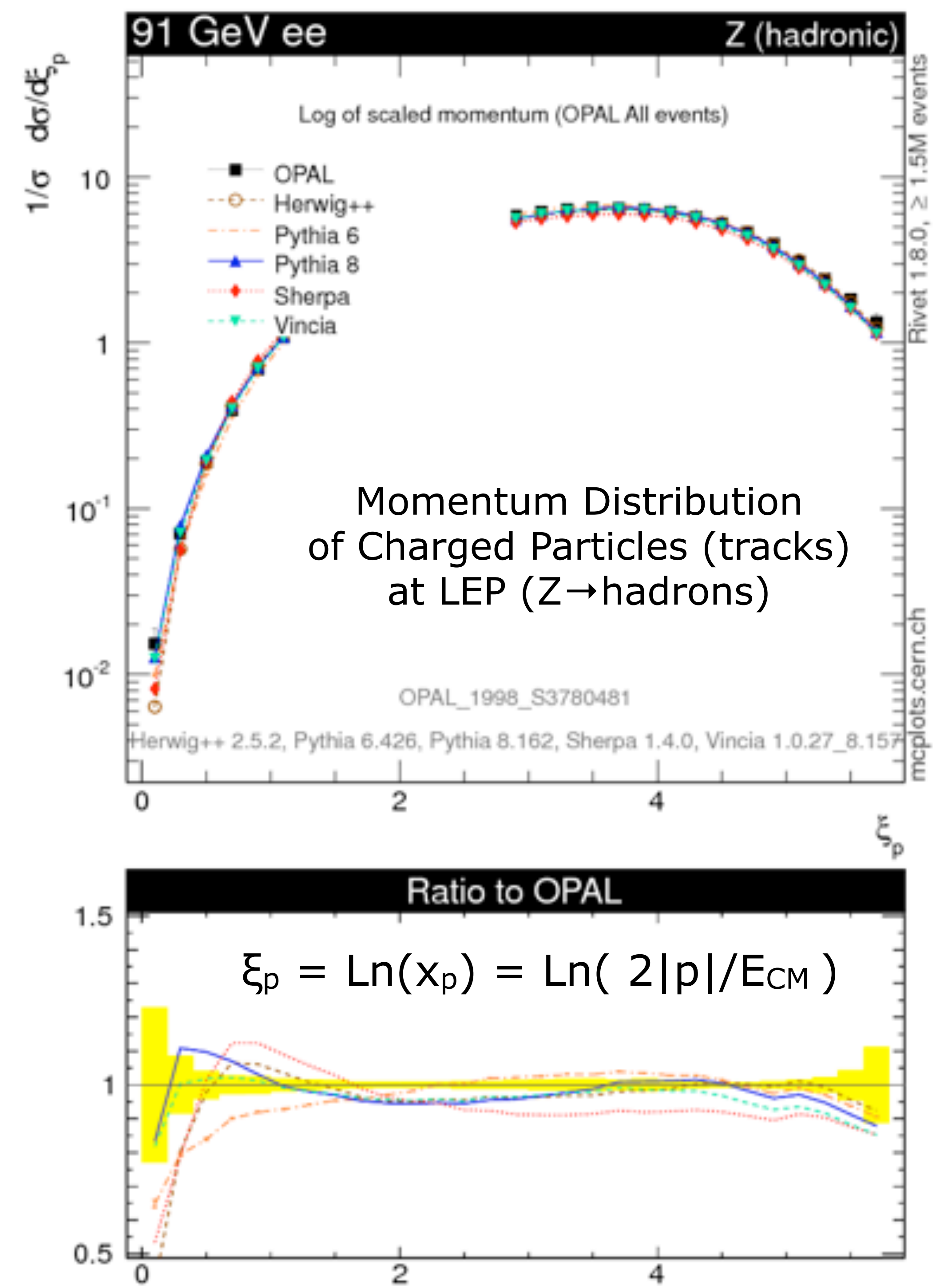


Note: In principle, a can be flavour-dependent. In practice, we only distinguish between baryons and mesons

Hadronization Tuning

Note: use infrared-**unsafe** observables - sensitive to hadronization (example)





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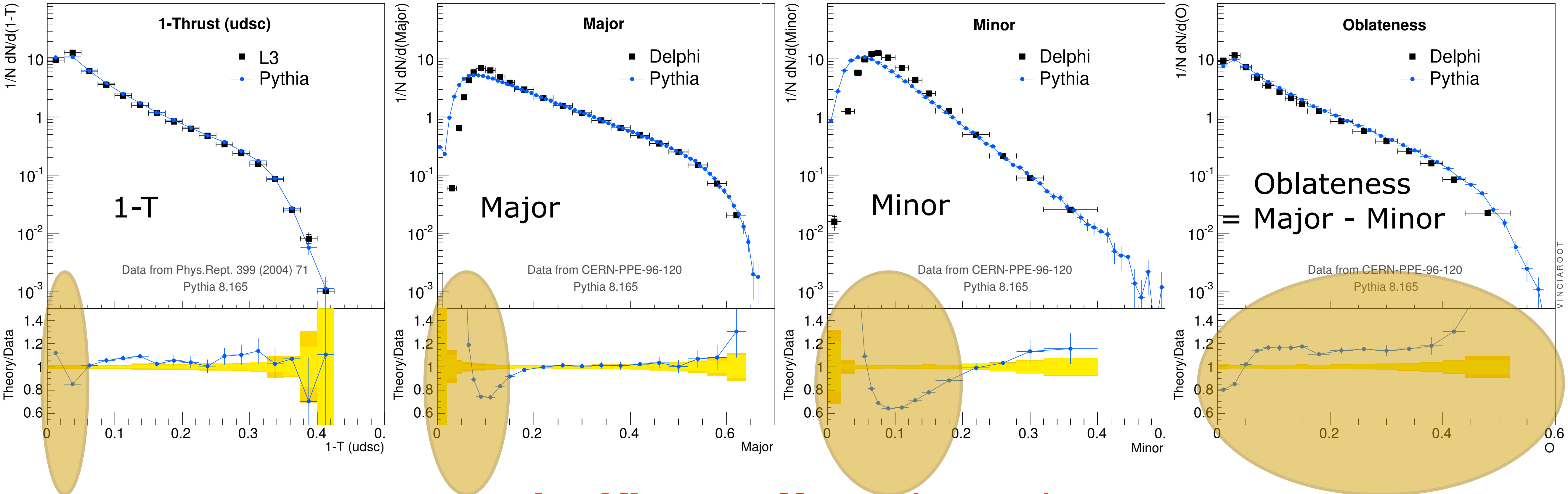

Significant Effects (>10%)

for T < 0.05, Major < 0.15, Minor < 0.2, and for all values of Oblateness

Observable Ranges: Hadronization

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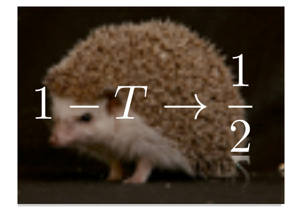

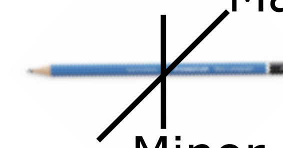

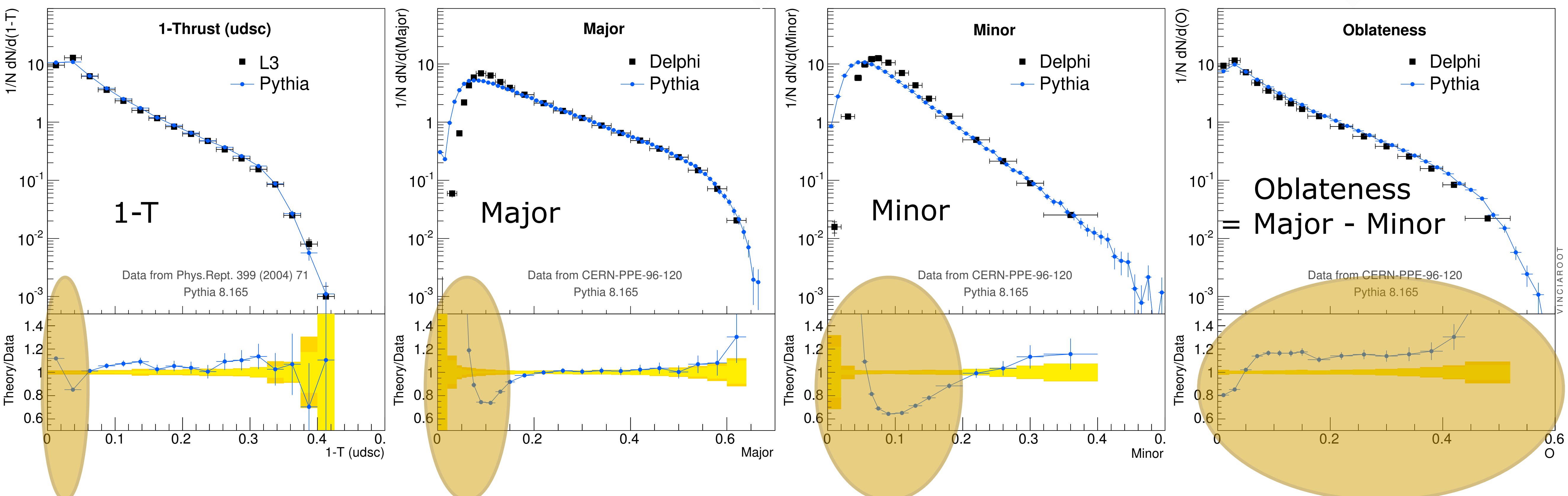

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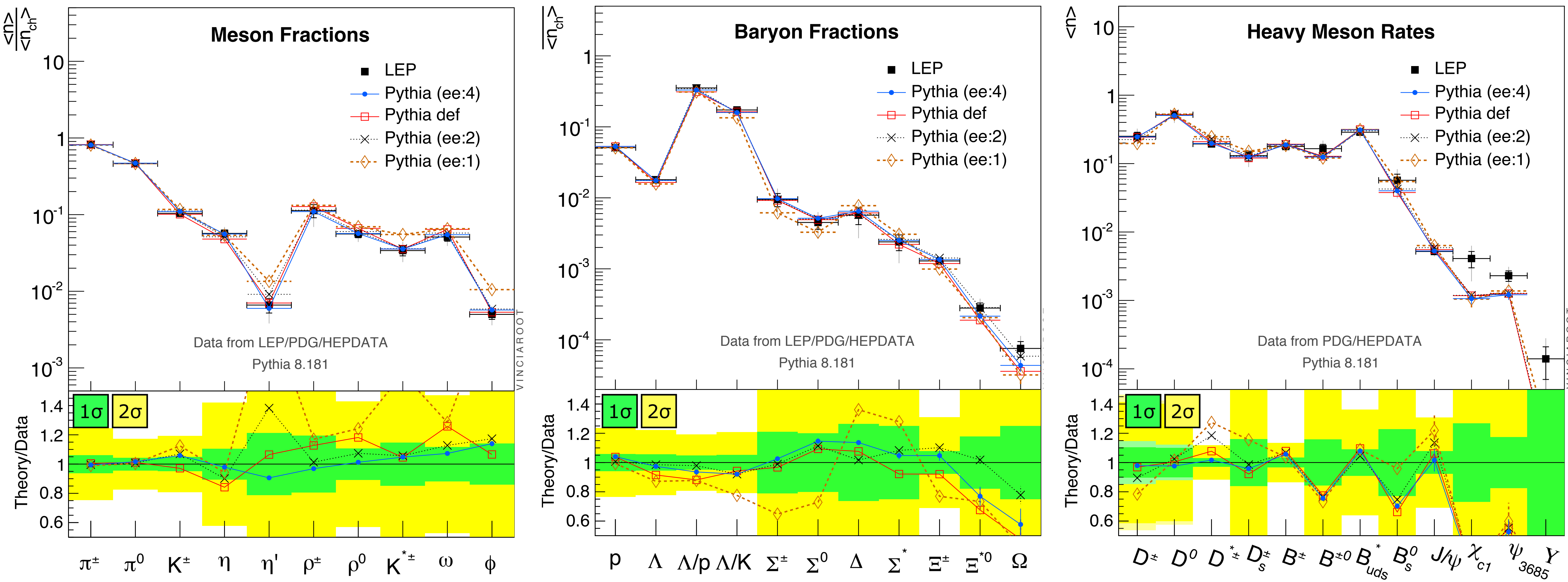
+ cross checks: different eCM energies (HAD and FSR scale differently)

Identified Particles

S_1/S_0, B/M, $B_{3/2}/B_{1/2}$, strange/unstrange, Heavy



Compare with what you see at LHC

Correlate with what you see at LHC

Can variations within uncertainties explain differences? Or not?

Initial-State Radiaton

Main ISR Parameters

α_s

Value and running of the strong coupling

Governs overall amount of radiation (cf FSR)

Size of Phase Space

Starting scale & Initial-Final interference

Relation between Q_{PS} and Q_F (vetoed showers? cf matching)

I-F colour-flow interference effects (cf ttbar asym) & interleaving

Matching

"Primordial kT"

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Additional Matrix Elements included?

At tree level / one-loop level? What matching scheme?

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Matching

Additional Matrix Elements included?

At tree level / one-loop level? What matching scheme?

"Primordial kT"

A small additional amount of "unresolved" kT

Fermi motion + unresolved ISR emissions + low-x effects?

Min-Bias & Underlying Event

Main UE/MB Parameters

Number of MPI

Pedestal Rise

Strings per Interaction

Beam Remnant

Min-Bias & Underlying Event

Main UE/MB Parameters

Number of MPI

Infrared Regularization scale for the QCD 2→2 (Rutherford) scattering used for multiple parton interactions (often called p_{T0}) → overall amount of energy in UE

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Proton transverse mass distribution → difference betwen central (active) vs peripheral (less active) collisions. Affects fluctuations & UE/MB ratios.

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Color correlations between multiple-parton-interaction systems → shorter or longer strings → less or more hadrons per interaction → can allow more or less MPI

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Strings per Interaction

Color correlations between multiple-parton-interaction systems → shorter or longer strings → less or more hadrons per interaction → can allow more or less MPI

Beam Remnant

Beam remnant parameters → forward fragmentation, remnant blowup, baryon transport

Why dN/dη is useless (by itself)

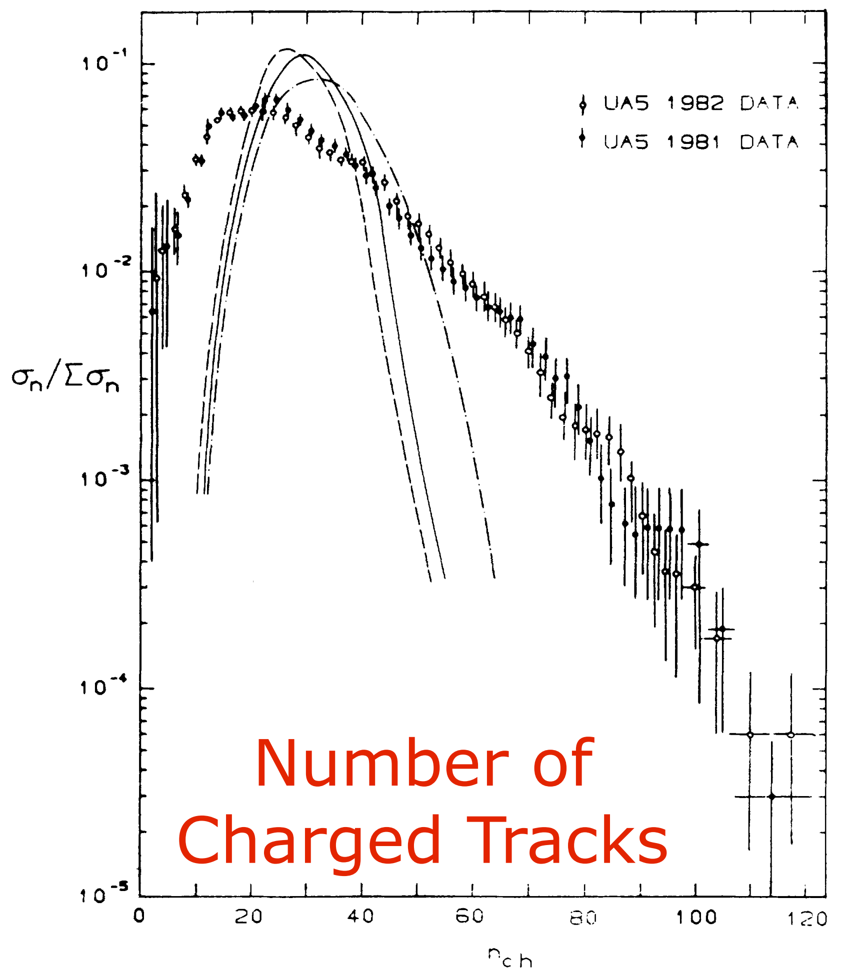


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

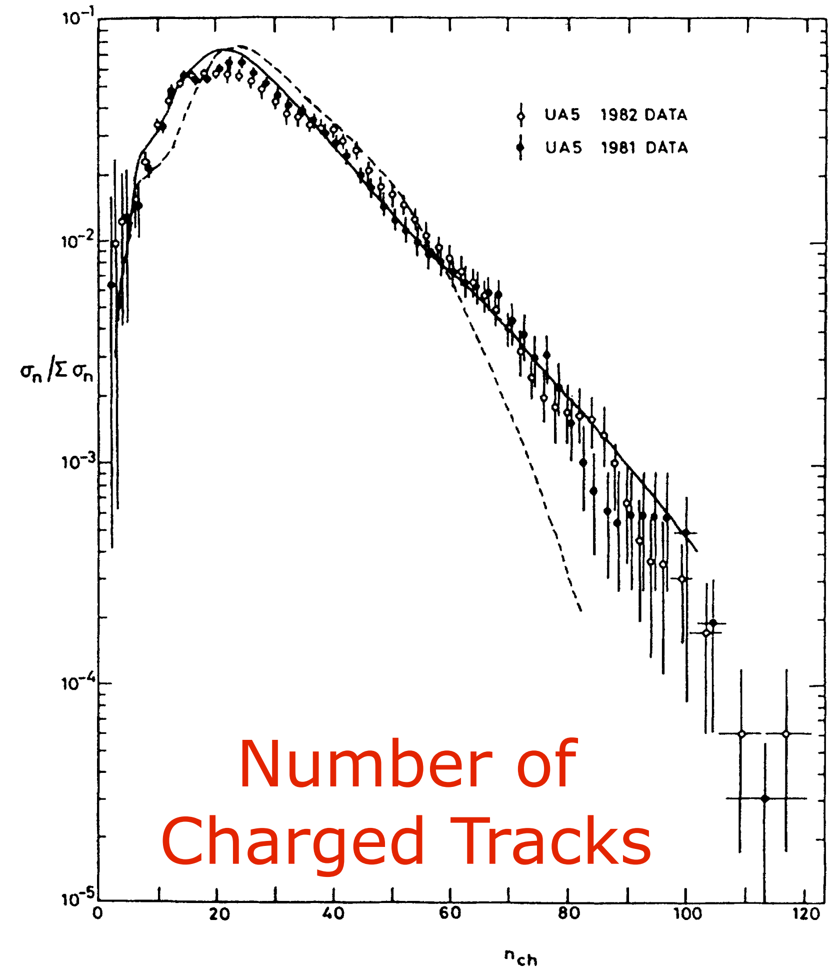


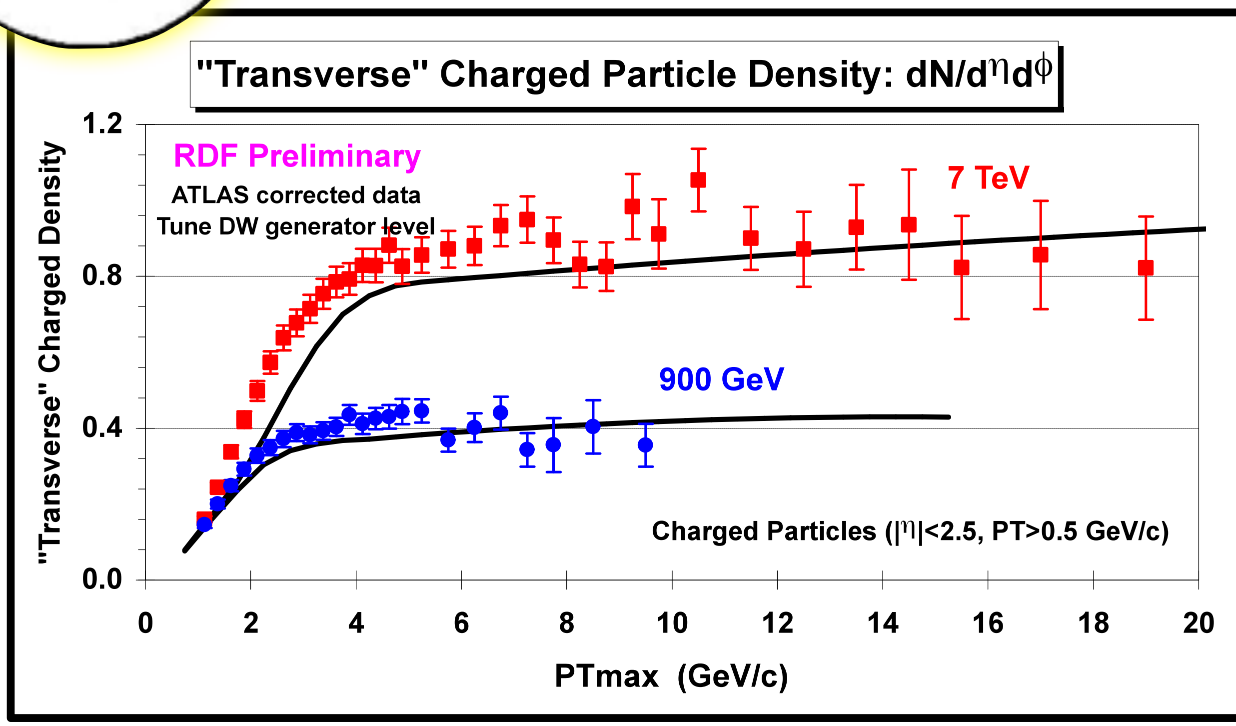
FIG. 12. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs multiple-interaction model with variable impact parameter: solid line, double-Gaussian matter distribution; dashed line, with fix impact parameter [i.e., $\tilde{O}_0(b)$].

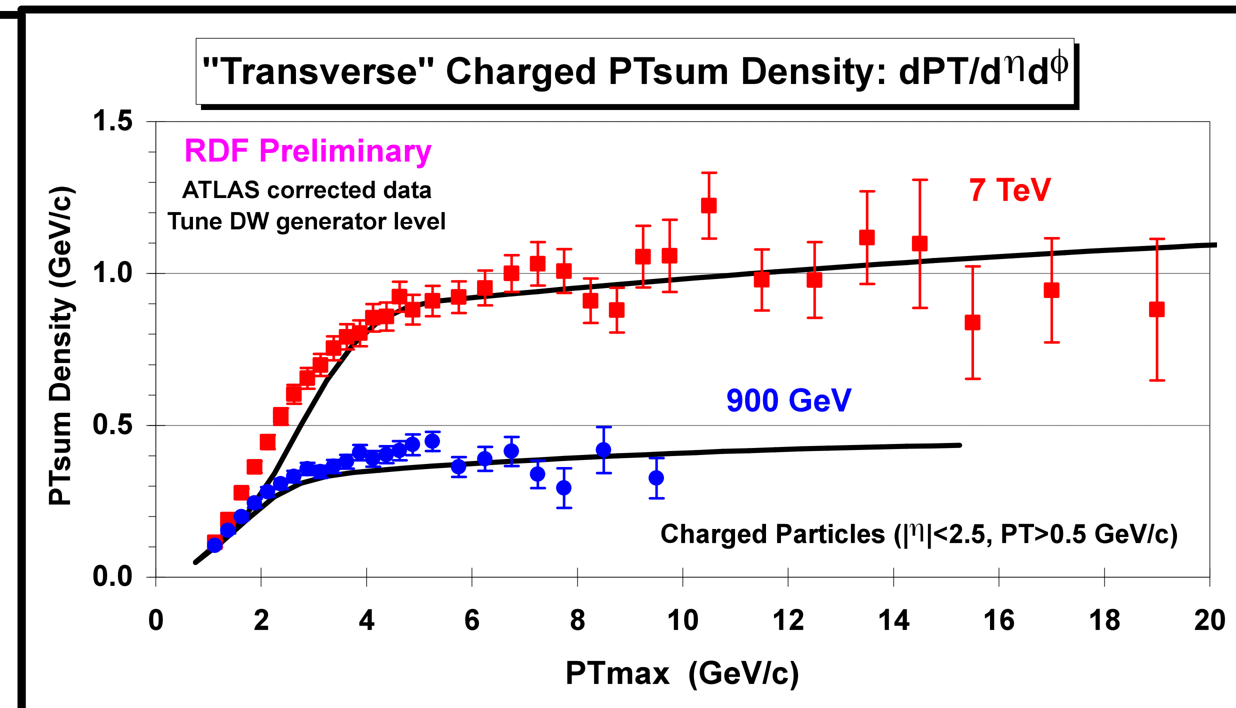
Sjöstrand & v. Zijl, Phys.Rev.D36(1987)2019

Can get <N> right with completely wrong models. Need RMS at least.

Truth is in the eye of the beholder

UE - LHC from 900 to 7000 GeV - ATLAS

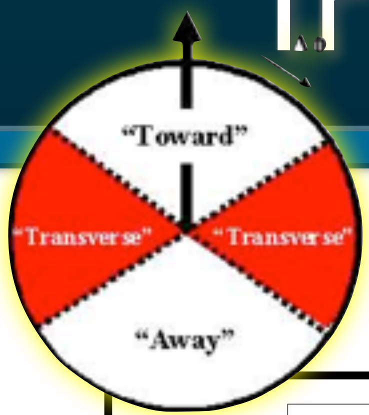




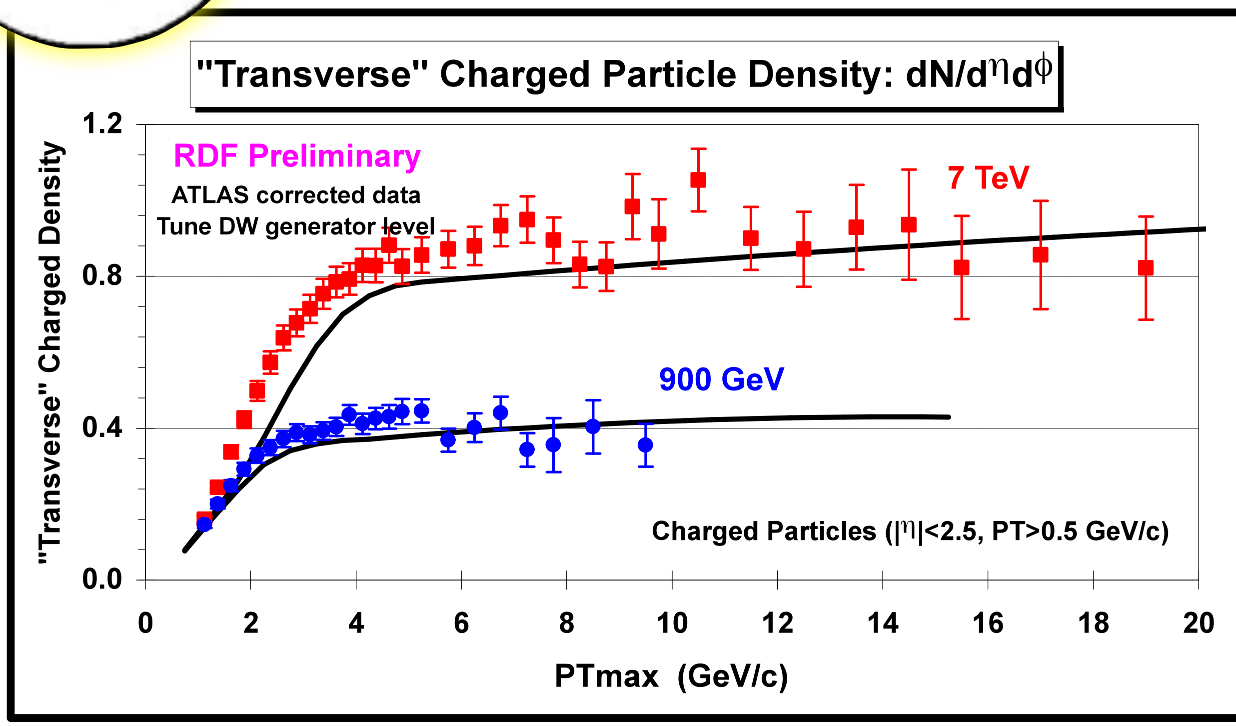
Track Density (TRANS)

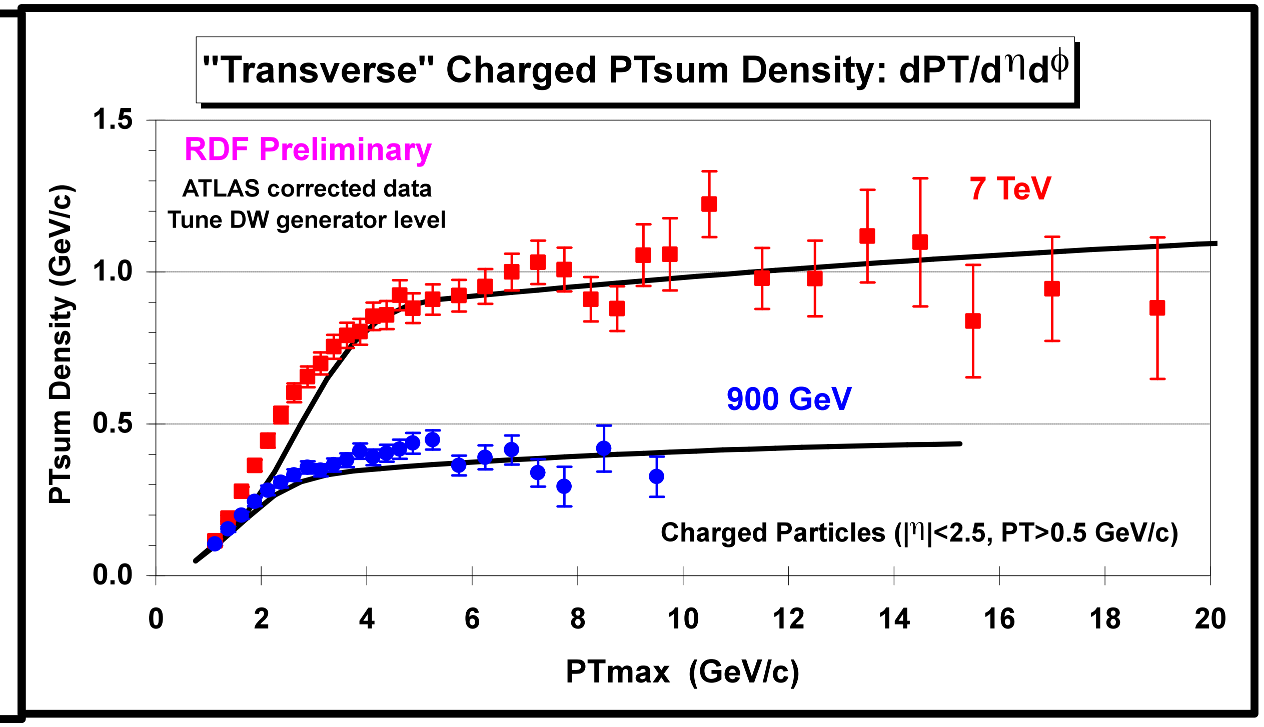
Sum(pT) Density (TRANS)

Truth is in the eye of the beholder



UE - LHC from 900 to 7000 GeV - ATLAS





Track Density (TRANS)

Not Infrared Safe

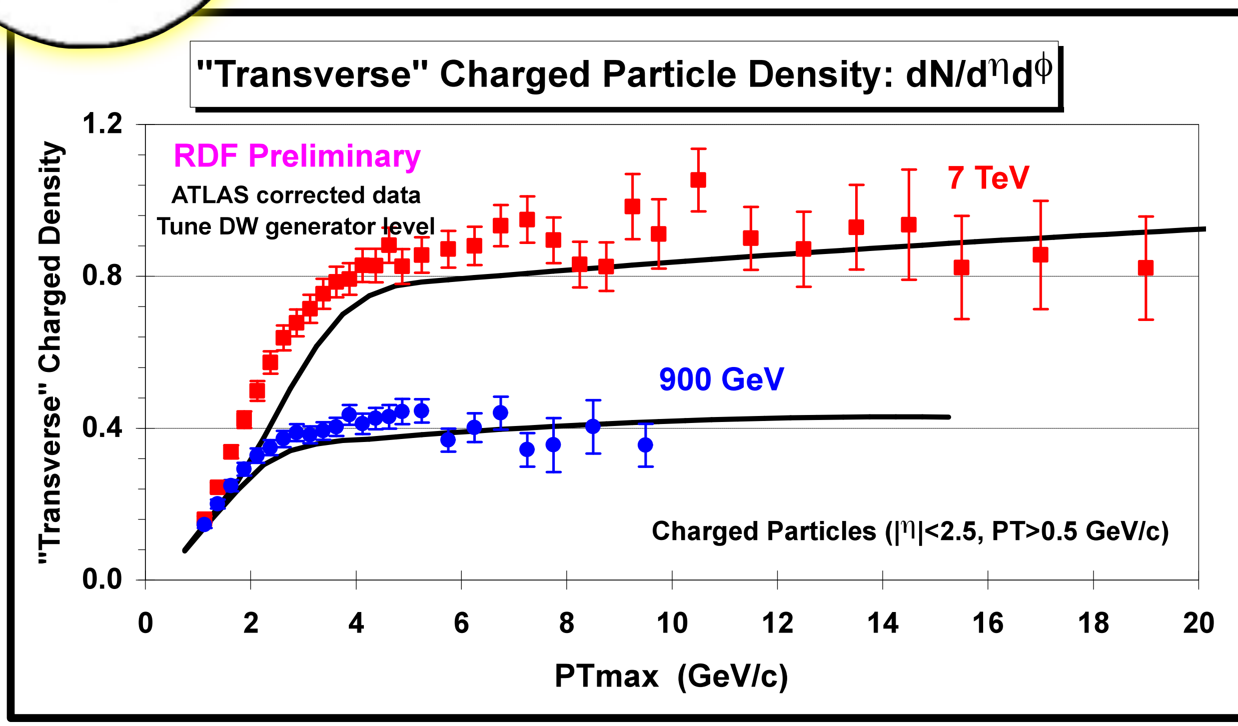
Large Non-factorizable Corrections

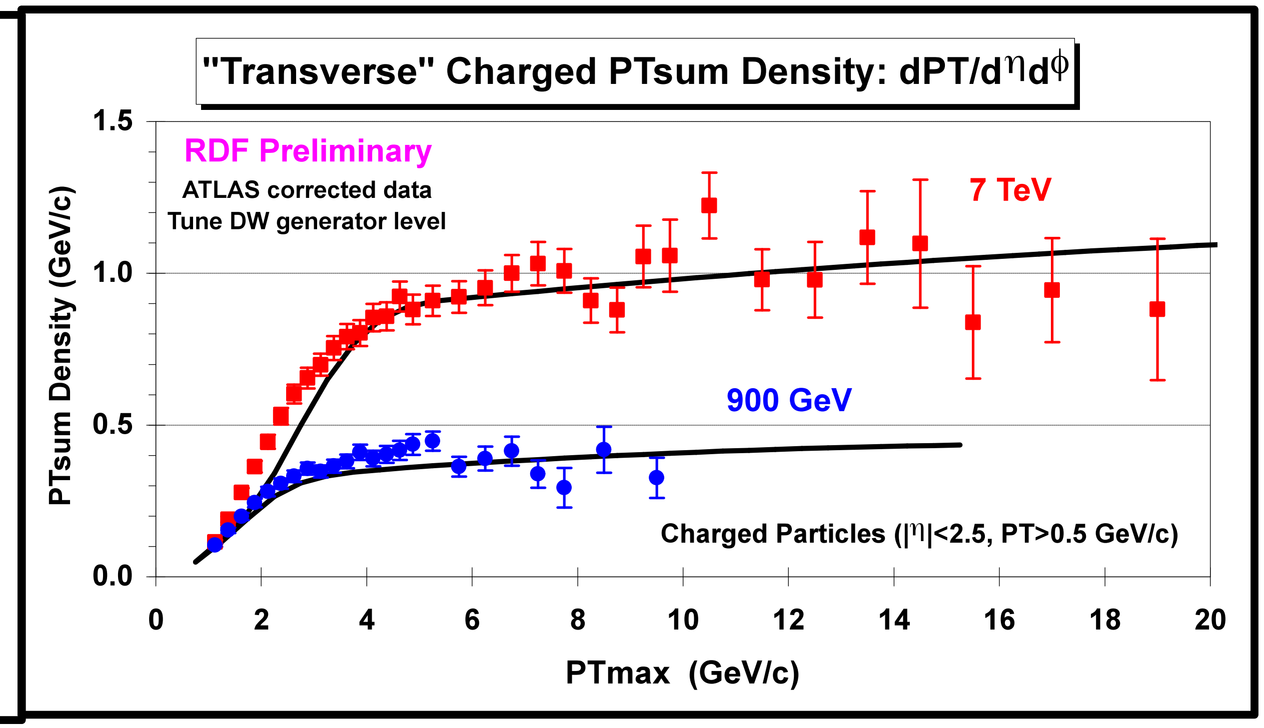
Prediction off by ≈ 10%

Sum(pT) Density (TRANS)

Truth is in the eye of the beholder

UE - LHC from 900 to 7000 GeV - ATLAS





Track Density (TRANS)

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Sum(pT) Density (TRANS)

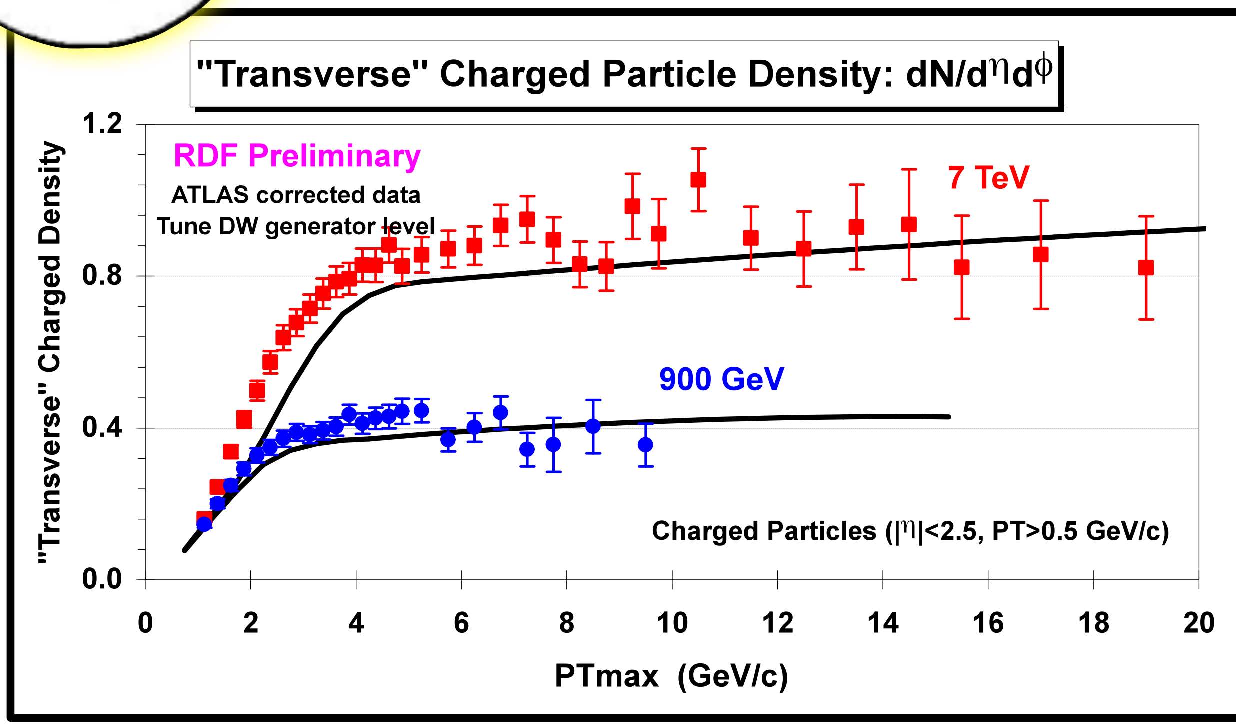
(more) Infrared Safe

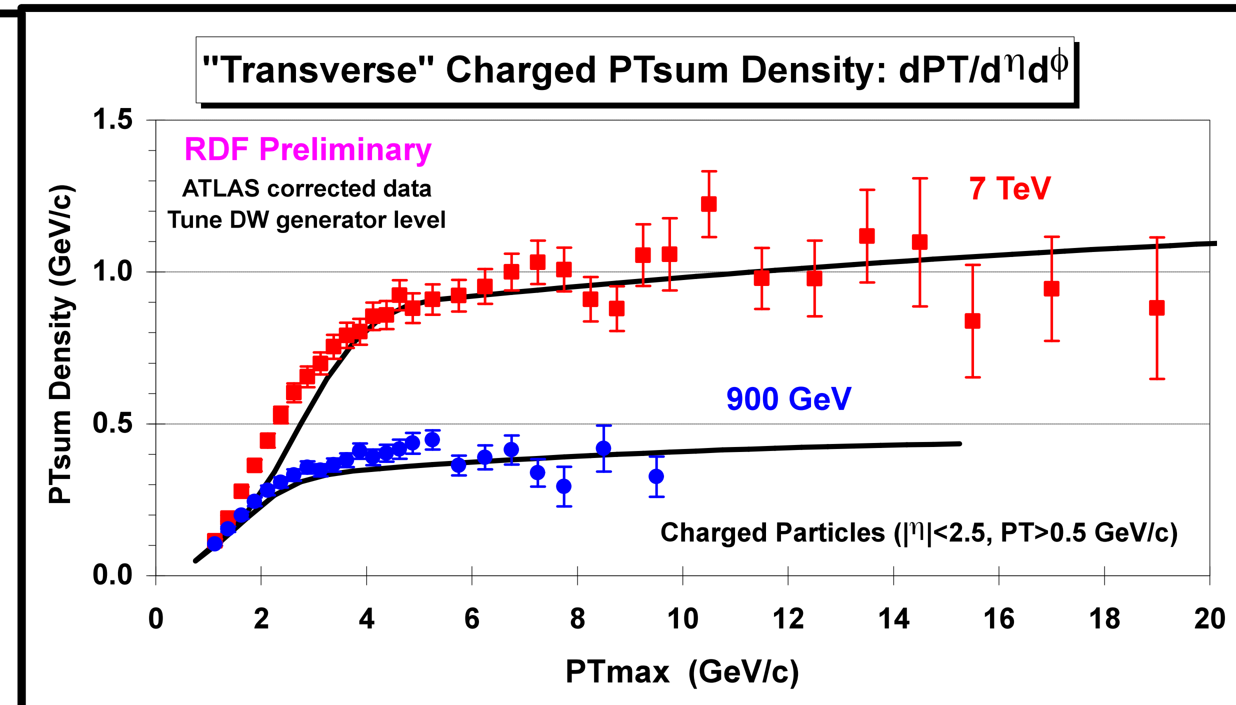
Large Non-factorizable Corrections

Prediction off by < 10%

Truth is in the eye of the beholder

UE - LHC from 900 to 7000 GeV - ATLAS





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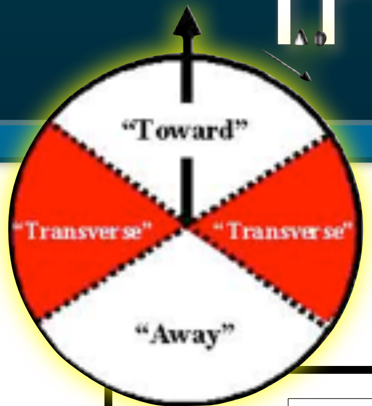
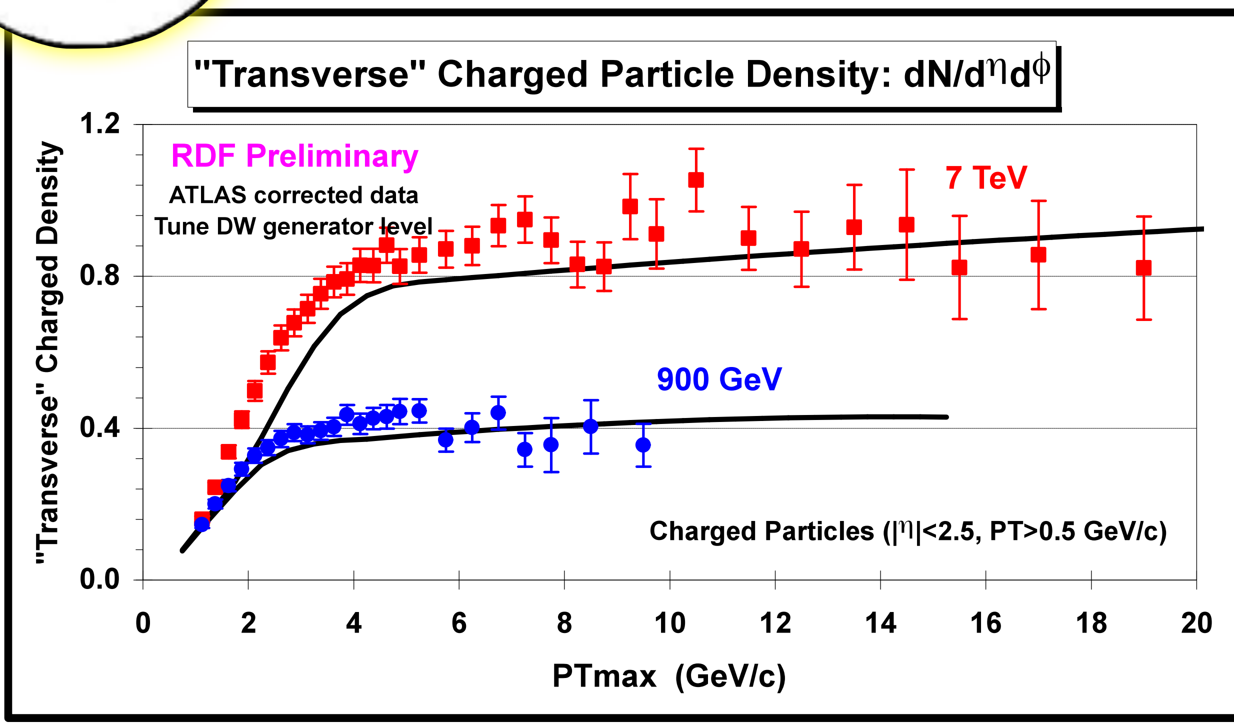
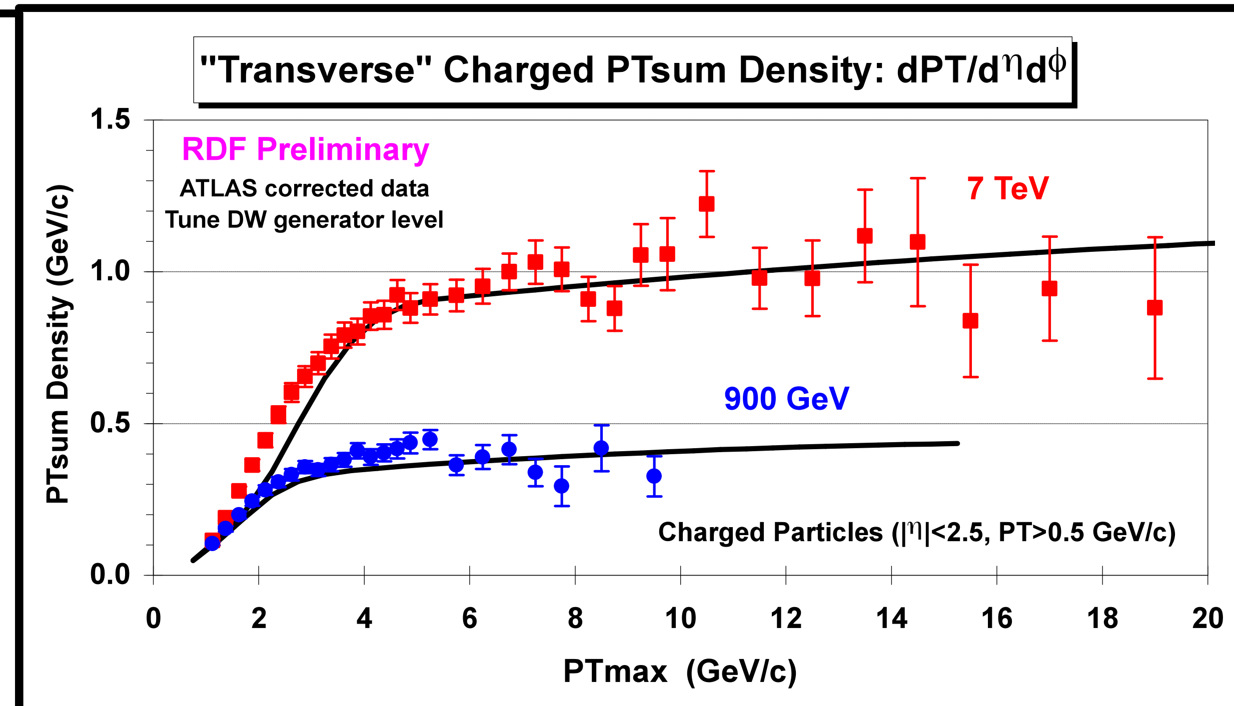
R. Field: “See, I told you!”

Truth is in the eye of the beholder



UE - LHC from 900 to 7000 GeV - ATLAS





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Sum(pT) Density (TRANS)

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R. Field: "See, I told you!" Y. Gehrstein: "they have to fudge it again"

Truth is in the eye of the beholder

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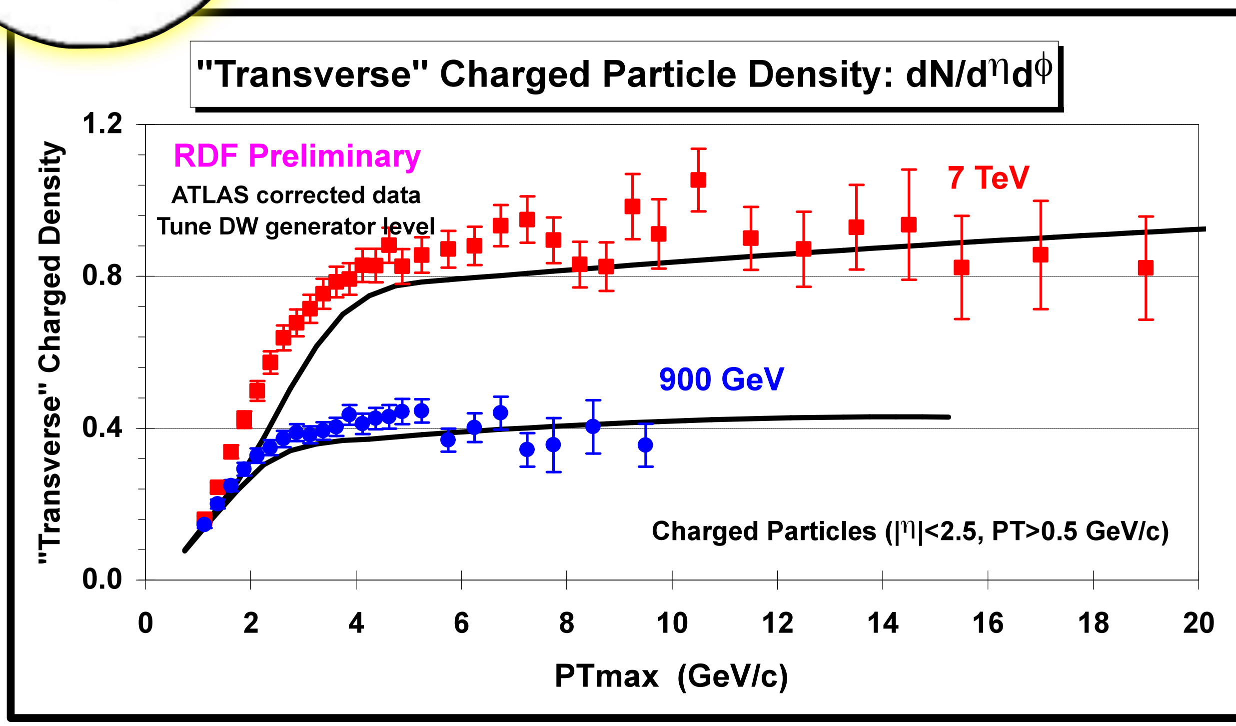
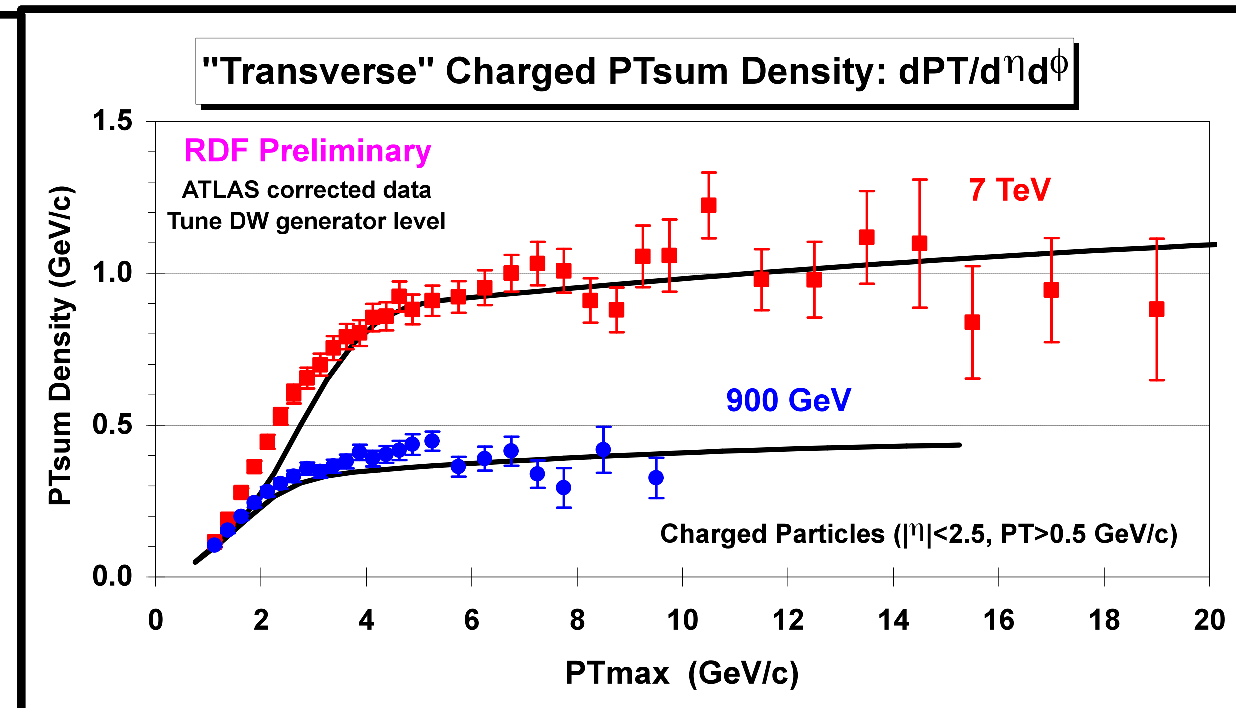


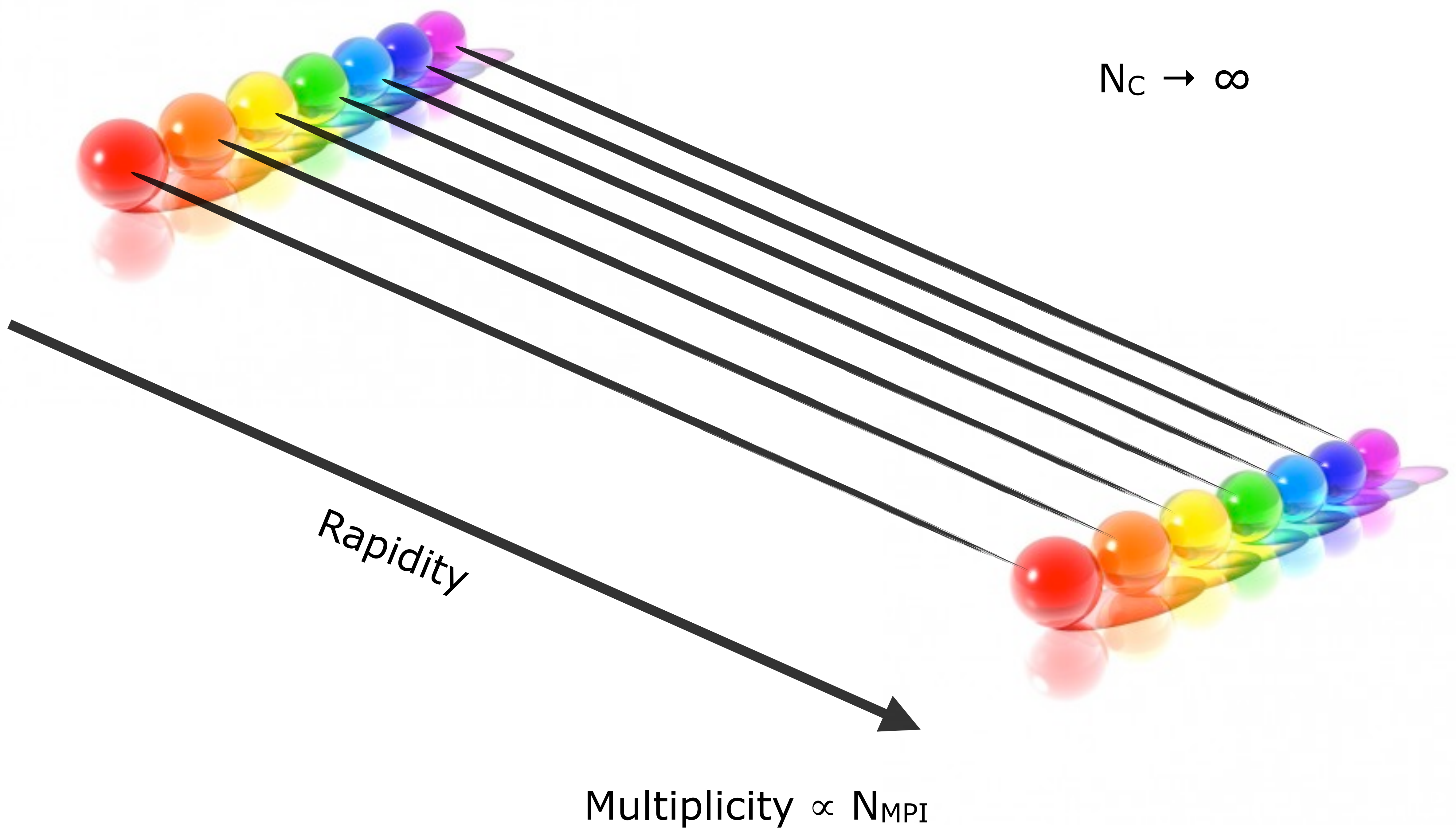


Track Density (TRANS)	Sum(pT) Density (TRANS)
Not Infrared Safe	(more) Infrared Safe
Large Non-factorizable Corrections	Large Non-factorizable Corrections
Prediction off by ≈ 10%	Prediction off by < 10%

Two beholders: R. Field: "See, I told you!" Y. Gehrstein: "they have to fudge it again"

Color Connections

Better theory models needed

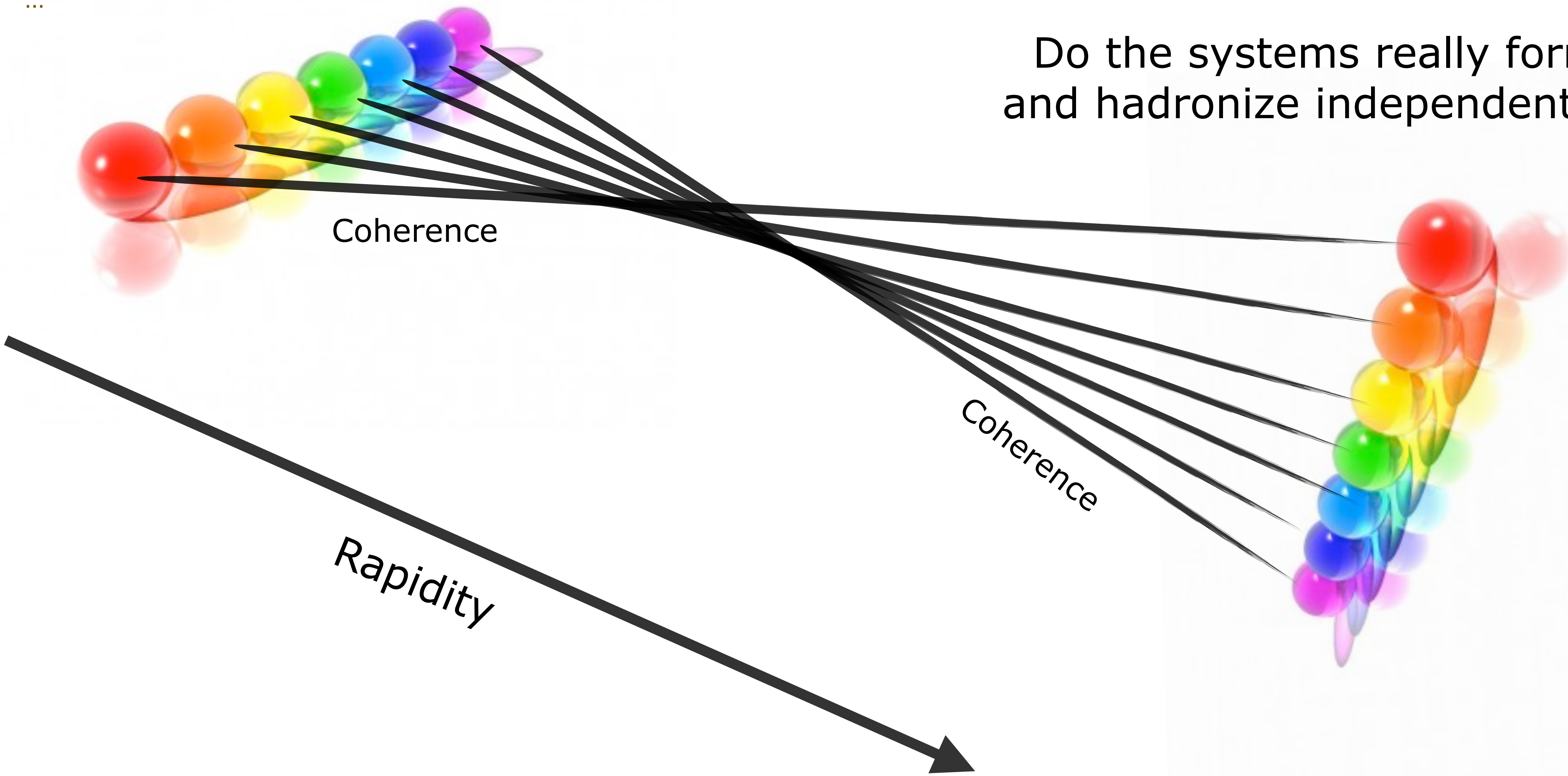


Color Reconnections?

E.g.,
Generalized Area Law (Rathsman: Phys. Lett. B452 (1999) 364)
Color Annealing (P.S., Wicke: Eur. Phys. J. C52 (2007) 133)
…

Better theory models needed

Do the systems really form
and hadronize independently?



$$\text{Multiplicity} \overset{<}{\not\propto} N_{\text{MPI}}$$

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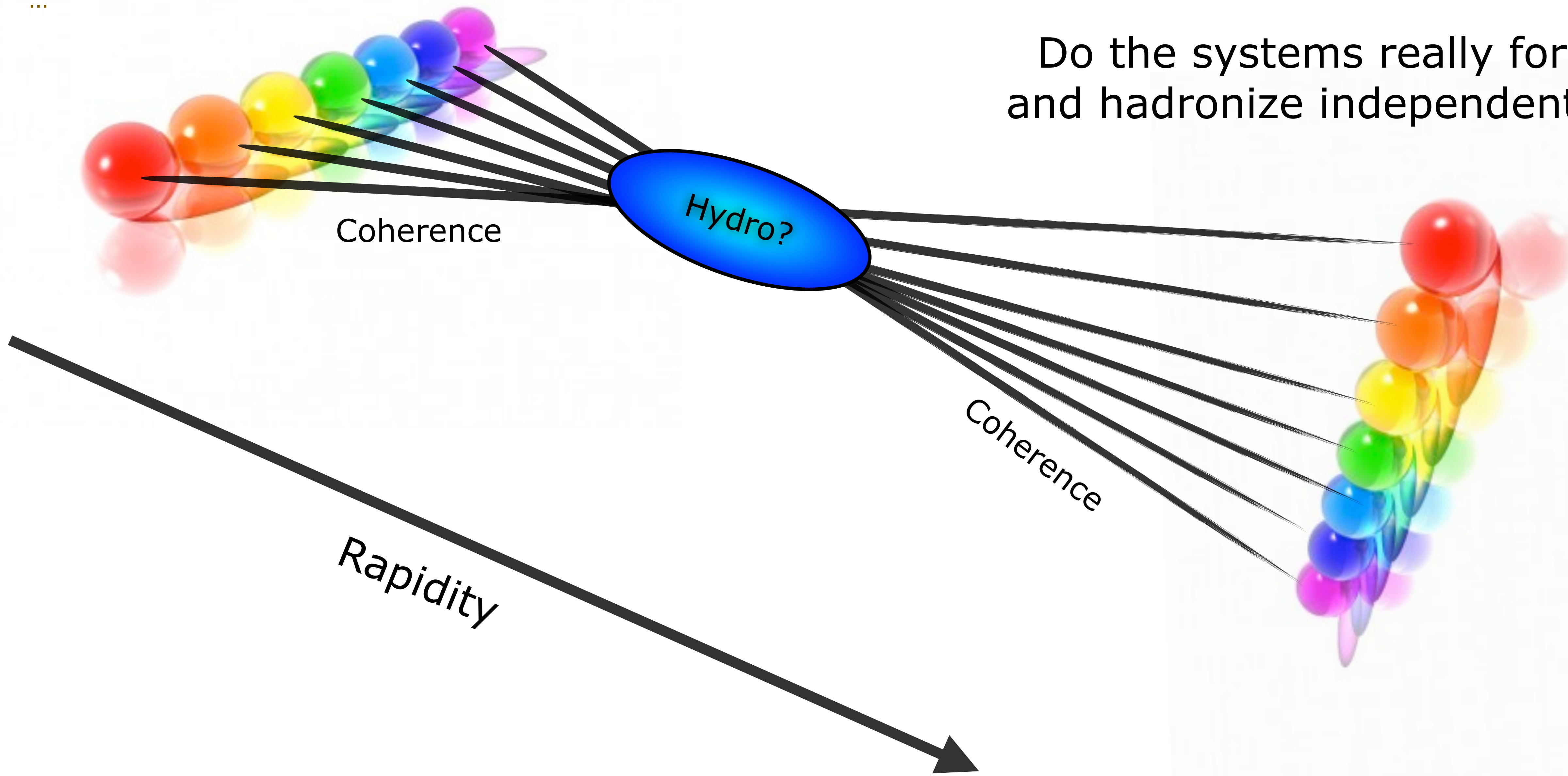


Multiplicity $\overset{<}{\not\propto}$ N_{MPI}

Notes on Diffraction

1. Fragmentation in diffraction

Low mass diffr modeled as fragmenting string (parameters from LEP)

- But LEP starts with FSR → Q_{had} → string-frag = $f(z,Q_{had})$

In diffraction, no equivalent definition of Q_{had}

- Do LEP tunes work for diffraction? At all masses? Depends on Q_{had}? Make direct (in situ) checks!

Observables:

- Nch and x spectra, event shapes (e.g., transverse Thrust), ID-paricle ratios (Baryons, s, c, b)

How high masses can be reached with decent rates? (100k events, 10k, 1k?)

- (and what kind of luminosity conditions are required / prohibitive?)

Outcome: more reliable fragmentation models, tunes for diffraction

2. MPI in diffraction.

Expected to increase multiplicity in diffractive (jet) events

- Pythia 8 incorporates a model, so far largely unconstrained. Main parameter = σ_{Pp}

UE style analyses in diffractive jets (measuring transverse PTsum and Nch, average and rms, wrt diffractive jet pt, etc).

3. Colour reconnections.

How to separate "genuine" diffraction from accidental gaps created by CR?

On Physical Observables
and MC "truth"

N. Bohr:

Only physical observables are quantum mechanically meaningful (it does not make sense to ask which slit the photon went through)

QFT generalization: it does not make sense to ask which quantum path led to the given event

Tevatron example:

Measurement of the pT of the "Z boson" (classified according to "truth" in an MC model.)

Really, observed dimuon system (including some collinear photons)

CMS example:

Measurement of Non-Single Diffractive (NSD) events (in oldest measurements, classified according to MC "truth")

Really, events with large rapidity gap and one surviving proton

Note: please tell us which of the existing min-bias / NSD CMS analyses in Rivet use the old (unphysical) definition (to be compared with MC with SD switched off) and which use the new observable definition (to be compared to all-inelastic MC, since they include an explicit trigger/cut to single out NSD) - currently we don't know, so don't dare use.

Summary

*) This is intended as a cultural reference, not a religious one

Not only central tunes

Your experimental (and other user-end) colleagues are relying on you for **serious** uncertainty estimates

Must includes some modeling variation

Not only global tunes

Your theoretical (MC author) colleagues are relying on you for stringent tests of the **underlying physics** models, not just ‘best fits’ (which may obscure “tensions”)

Tuning & Matching → Matching & Tuning

Step 1 (now): tune first, match later. Study change in χ^2 on tuning distributions after matching. Bad? Or not bad?

Step 2: match first, tune later. (Requires tuning a matched generator, so need fast matching strategies.)

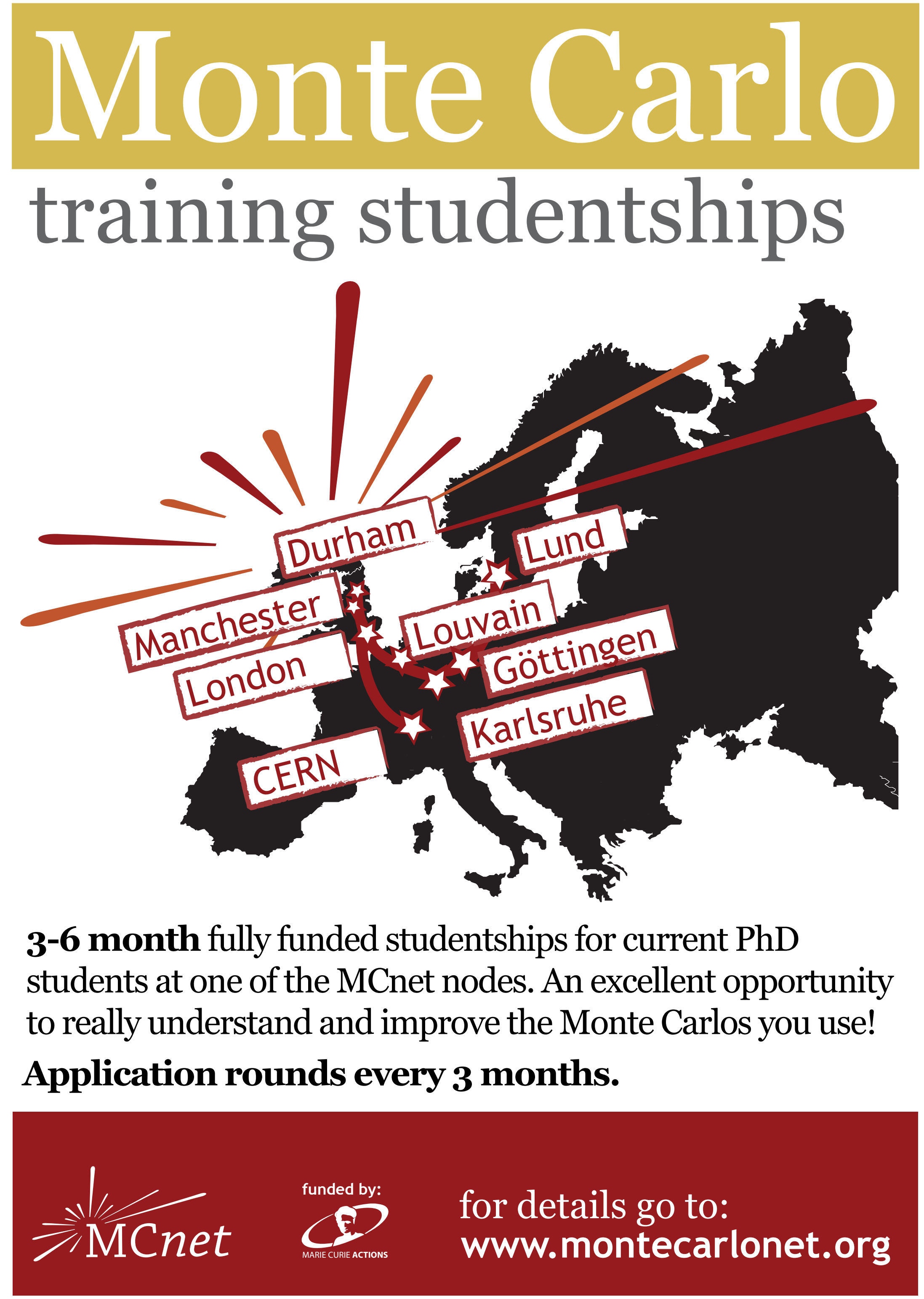
MCnet Studentships

MCnet projects:

- PYTHIA (+ VINCIA)
- HERWIG
- SHERPA
- MadGraph
- Ariadne (+ DIPSY)
- Cedar (Rivet/Professor)

Activities include

- summer schools (2014: Manchester?)
- short-term studentships
- graduate students
- postdocs
- meetings (open/closed)



Come to Australia

p

p

Establishing a new group in **Melbourne**

Working on **PYTHIA** & **VINCIA**

NLO Event Generators

Precision LHC **phenomenology & soft physics**

Support LHC **experiments**, **astro-particle** community, and **future** accelerators

Outreach and Citizen Science

ANCORA · IMPARO

Oct 2014
→ Monash University
Melbourne, Australia