Theory Lessons from the First LHC Runs at O(1 TeV)

Peter Skands (CERN PH-TH)

Disclaimer

- Impossible to cover everything
- *Focus* on important outstanding questions which could be settled by early LHC measurements at 900 and 2360 GeV
- Note that, for most of them, this is our *only* chance to settle these questions
- The answers are crucial to improving our physics models

Monte Carlos and Precision

- A Good Physics Model gives you
  - Reliable calibrations for both signal and background (e.g., jet energy scales)
  - Reliable corrections (e.g., track finding efficiencies)
  - Background estimates with as small uncertainty as possible (fct of both theoretical accuracy and available experimental constraints)
  - Reliable discriminators with maximal sensitivity to New Physics

Count what is Countable

Measure what is Measurable

(and keep working on the beam) *G. Galilei*

Amplitudes
Monte Carlo
Resummation
Strings
...

Theory

Feedback Loop

Experiment

Hits
0100110
GEANT
B-Field
....

Theory worked out to
Hadron Level
with acceptance cuts
(~ detector-independent)

Measurements corrected to
Hadron Level
with acceptance cuts
(~ model-independent)

If not worked out to hadron level: data must be unfolded with *someone else's* hadron-level theory

Unfolding beyond hadron level dilutes precision of raw data (Worst case: data unfolded to ill-defined 'MC Truth' or 'parton level')

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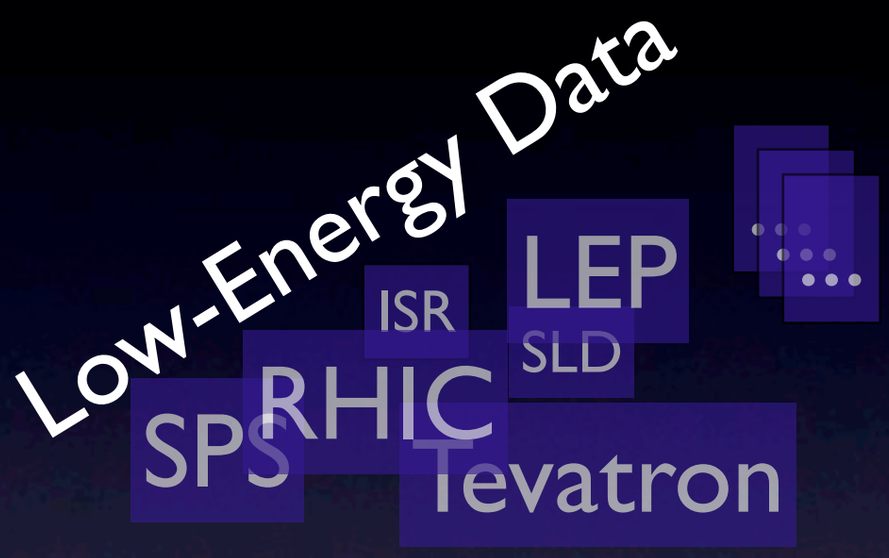
- Which model would you trust more? One that also describes SPS, RHIC, Tevatron, Low-Energy LHC? Or one that doesn't?

Constraining Models



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But wait ... which gaps?

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- One of the most fundamental quantities to measure
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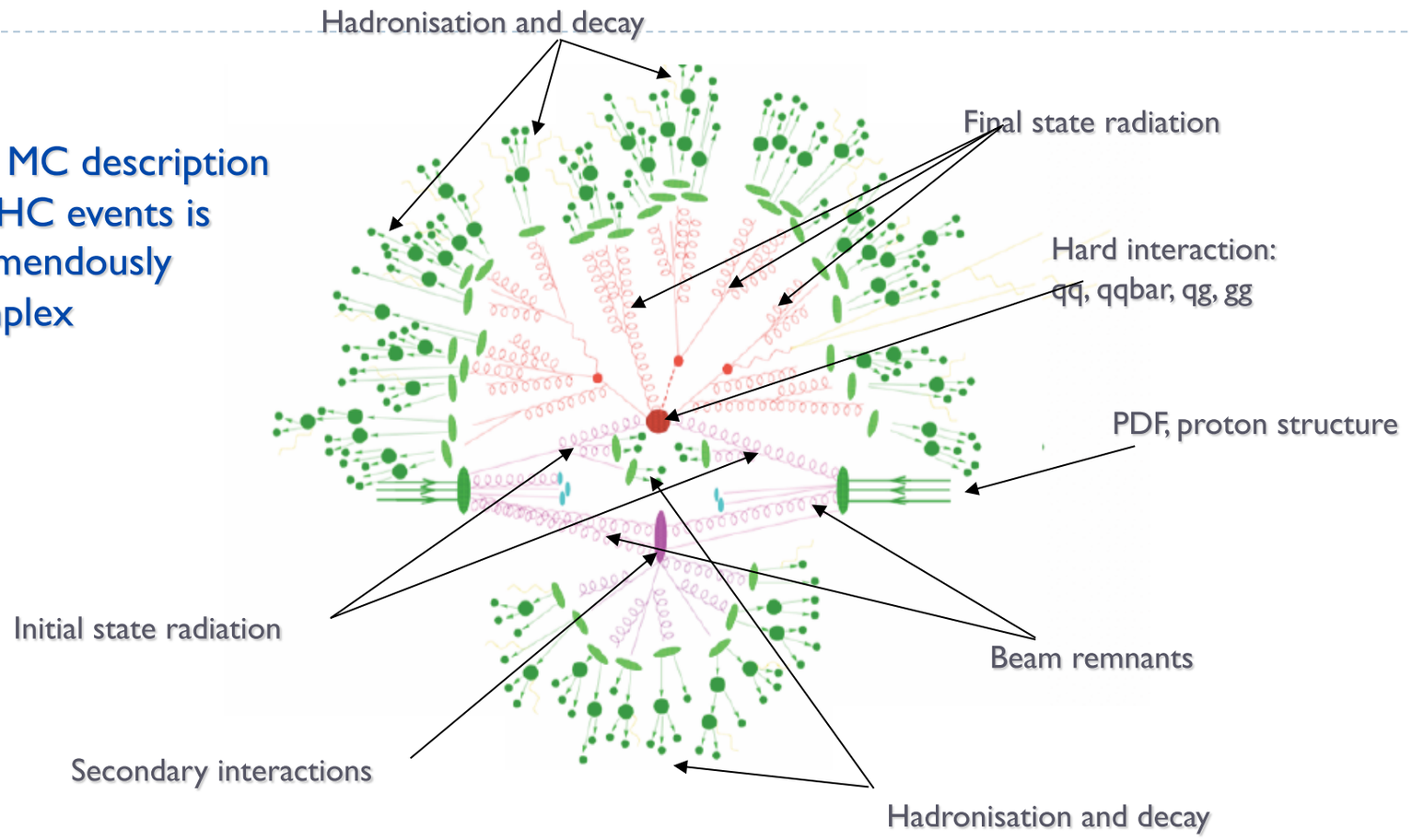
- One of the most fundamental quantities to measure
- But fundamental does not imply easy
- Complications: Corrections for Trigger Bias, Diffraction, Zero Bin, Long-Lived particles, Extrapolations from raw measurement to: hadron-level (with acceptance cuts) and/or to: hadron-level (full phase space), ...

Dissecting Minimum-Bias

Physics requirements: basics

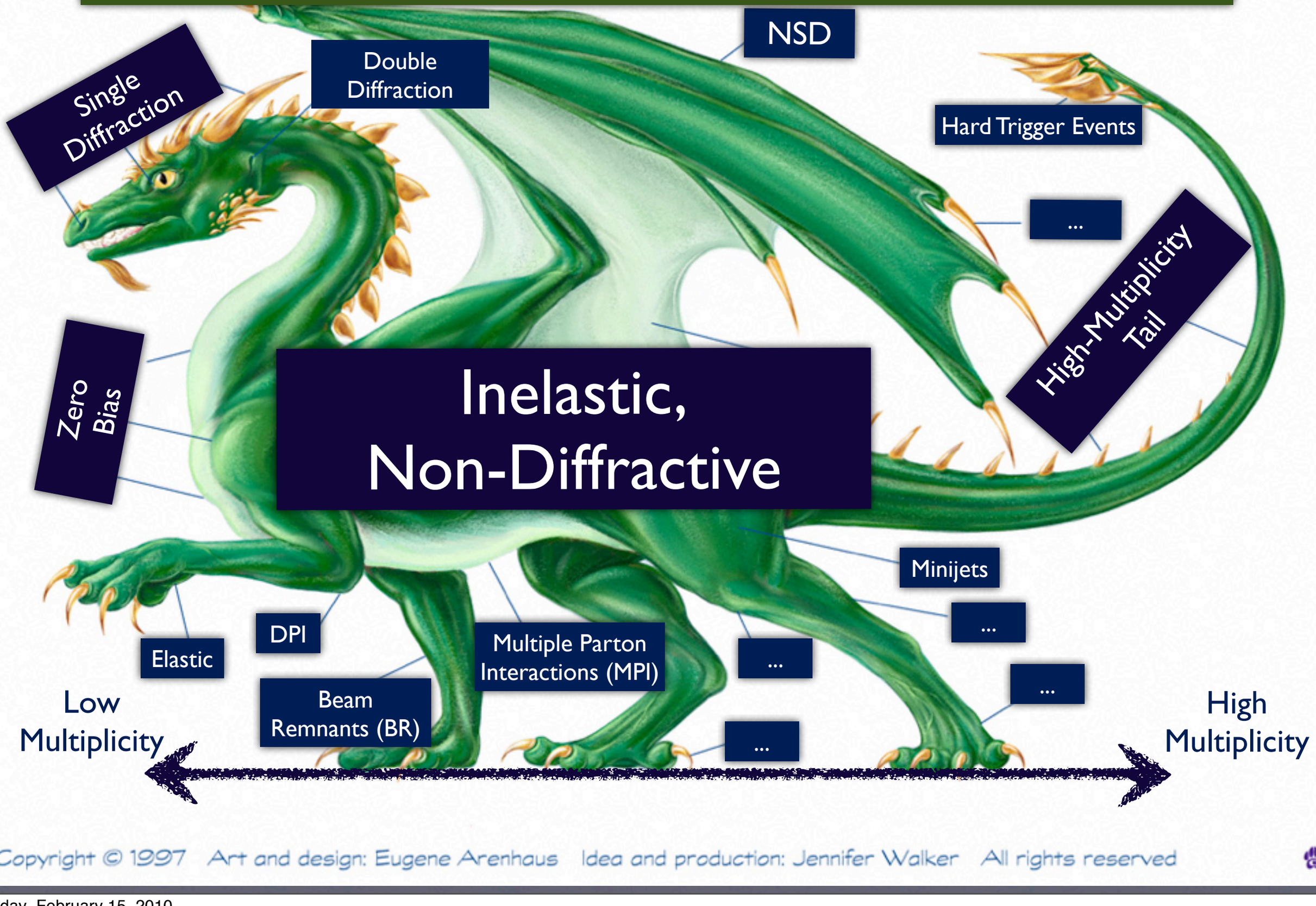
The MC description of LHC events is tremendously complex



This is a schematization to be able to cut down the problem in pieces and model them in a different way. The "pieces" are correlated !

(slide from F. Cossutti (CMS), 7th MCnet Annual Meeting, January 2010)

Dissecting Minimum-Bias



Measured Results

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  - Bubble chambers etc extrapolated to full phase space
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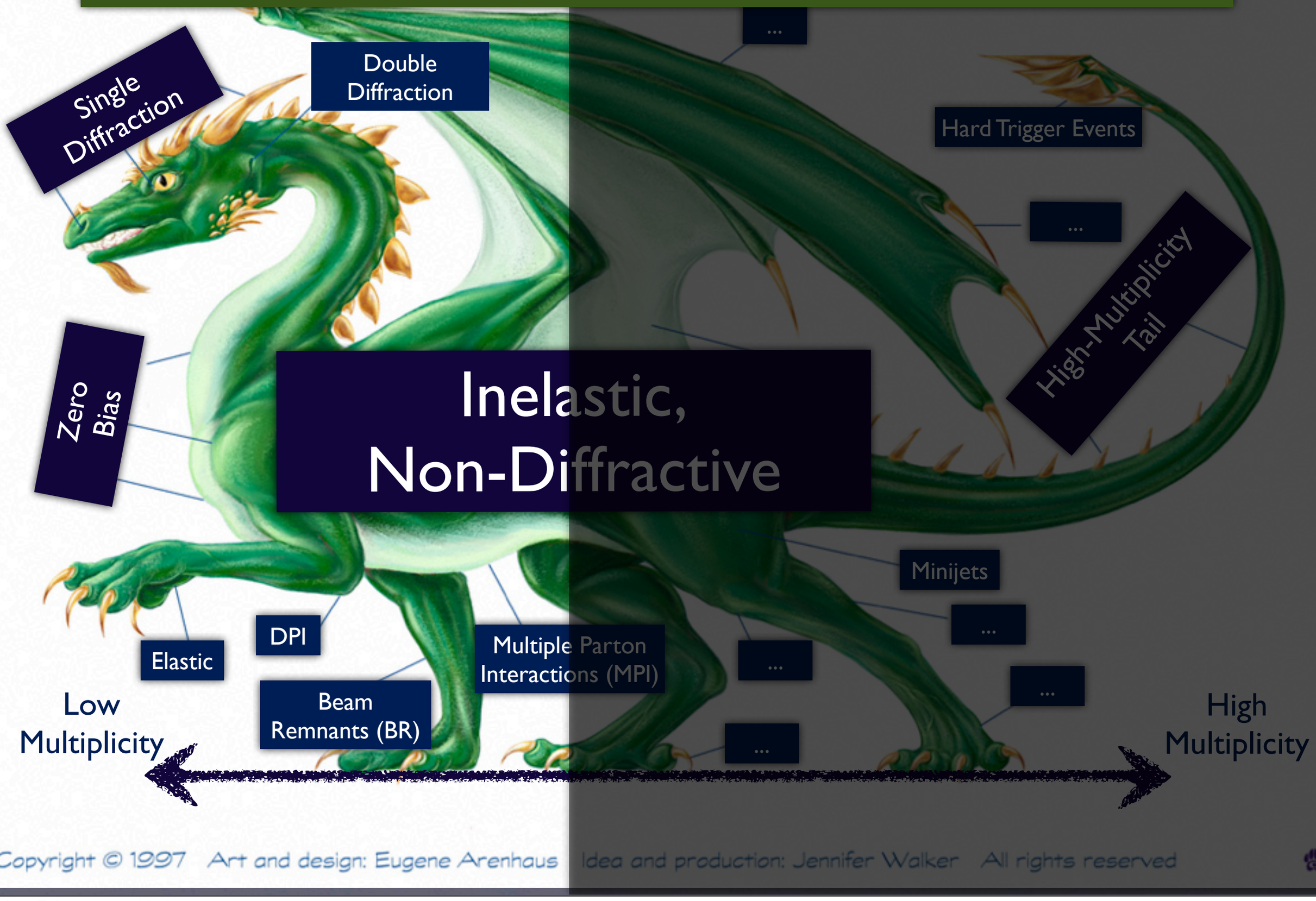
- How to Compare to Theory?
  - Inelastic > 'NSD' > Inelastic Non-Diffractive, ... ?
    - For all: Define event set in terms of hadron-level cuts (model-*inspired, yes,* but model-*dependent, no*)
  - Today's theorists not interested in filling up unmeasured region with some model/fit (especially if it is some other guy's model) - Keep main measured result as close to raw acceptance as possible. Extrapolate *only* to do comparisons (inflates uncertainties)

Issues at Low Multiplicity

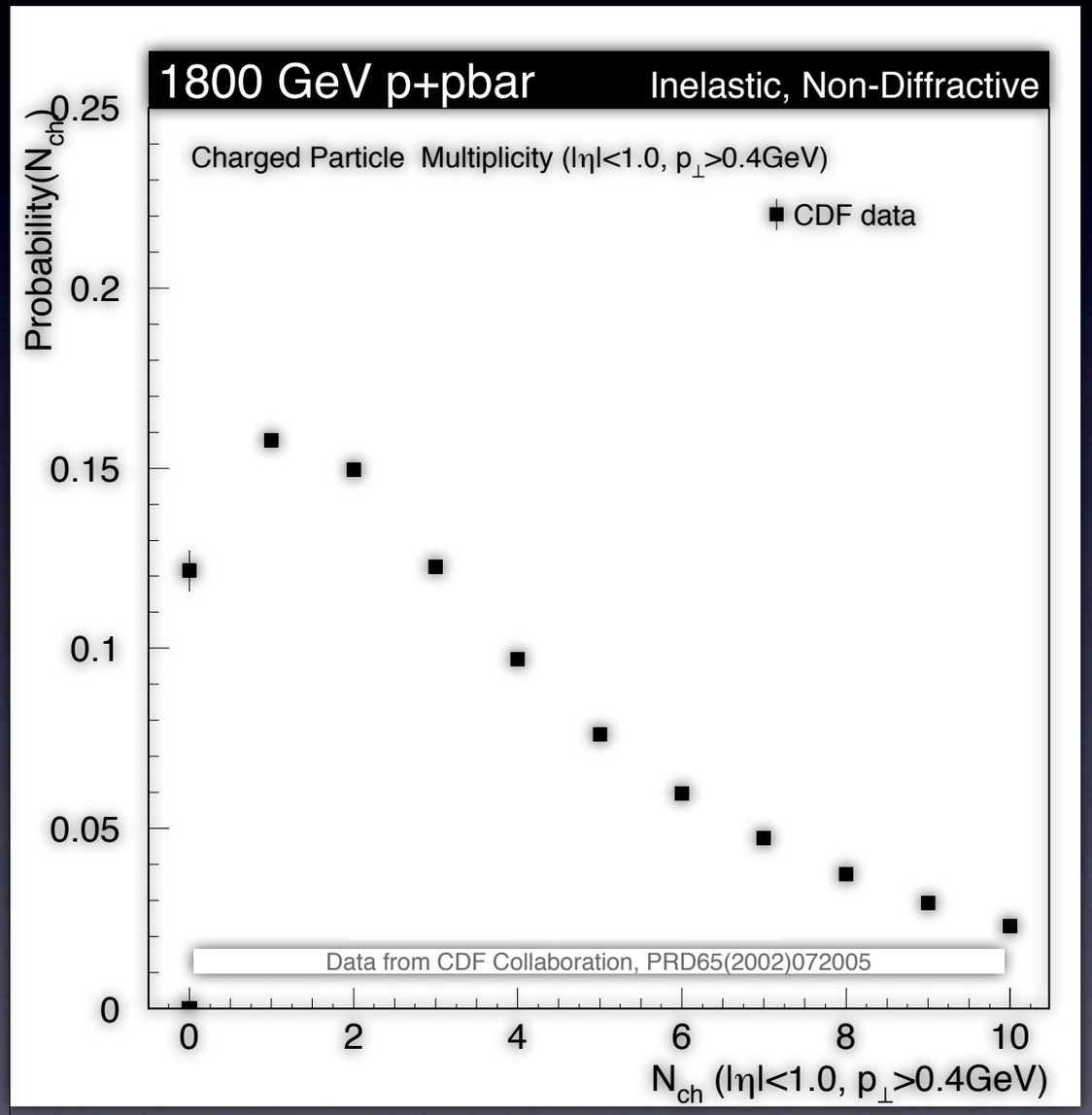


Low Multiplicities: Correcting for Diffraction

- Diffractive processes
  - Large part of total cross section
  - Populate the low-multiplicity bins: lower $\langle N_{ch} \rangle$
  - Characteristic rapidity spectrum with large rapidity gaps: affect $dN_{ch}/d\eta$
  - Impossible to interpret min-bias spectra without knowing precisely how diffraction was treated

Low Multiplicities: Correcting for Diffraction

- CDF Run-I Data
  - Corrected to pT>0.4 GeV instead of full PS: less model dependence
  - First few bins corrected for diffraction (also affects average Nch and dN/deta)



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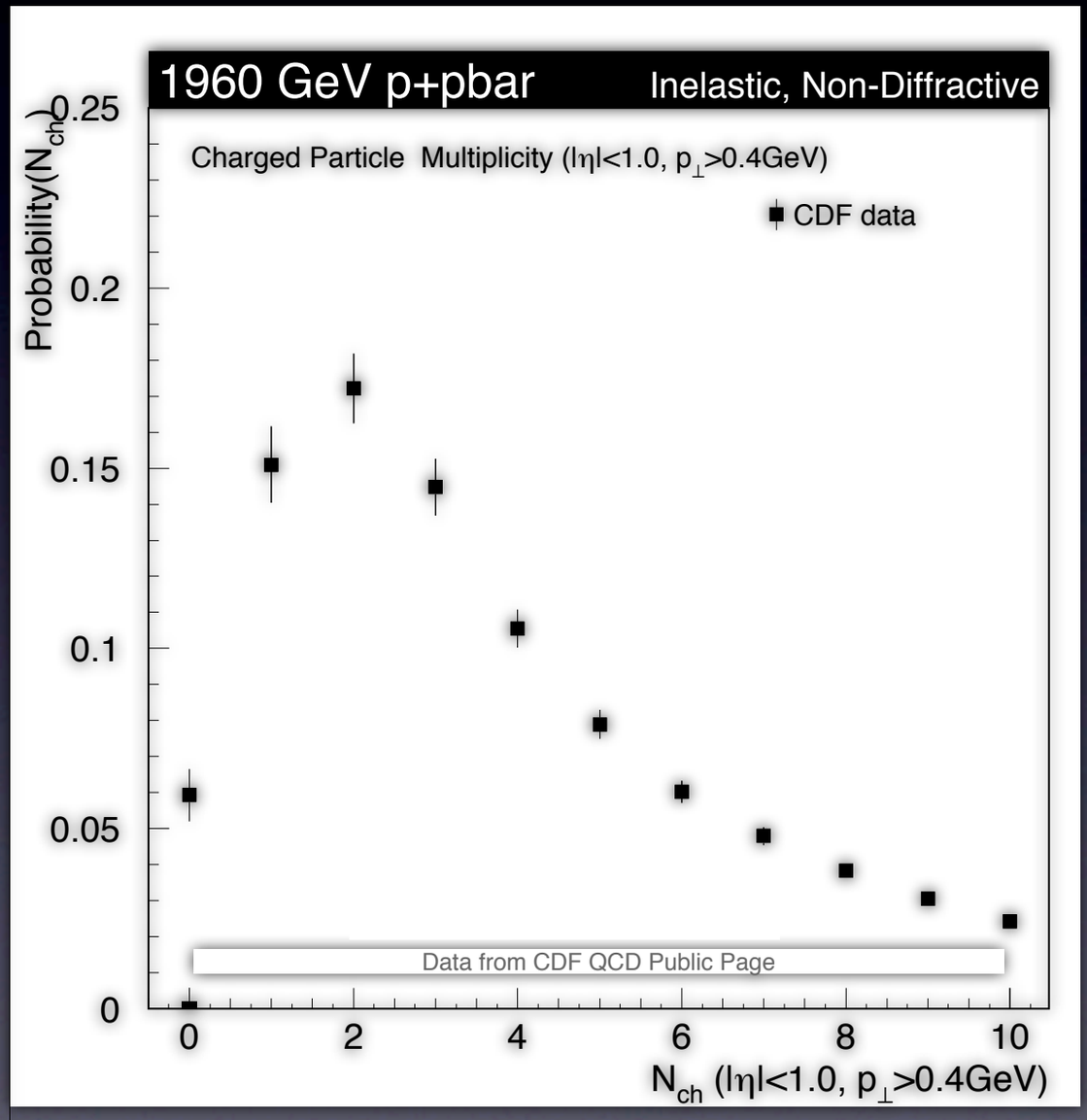

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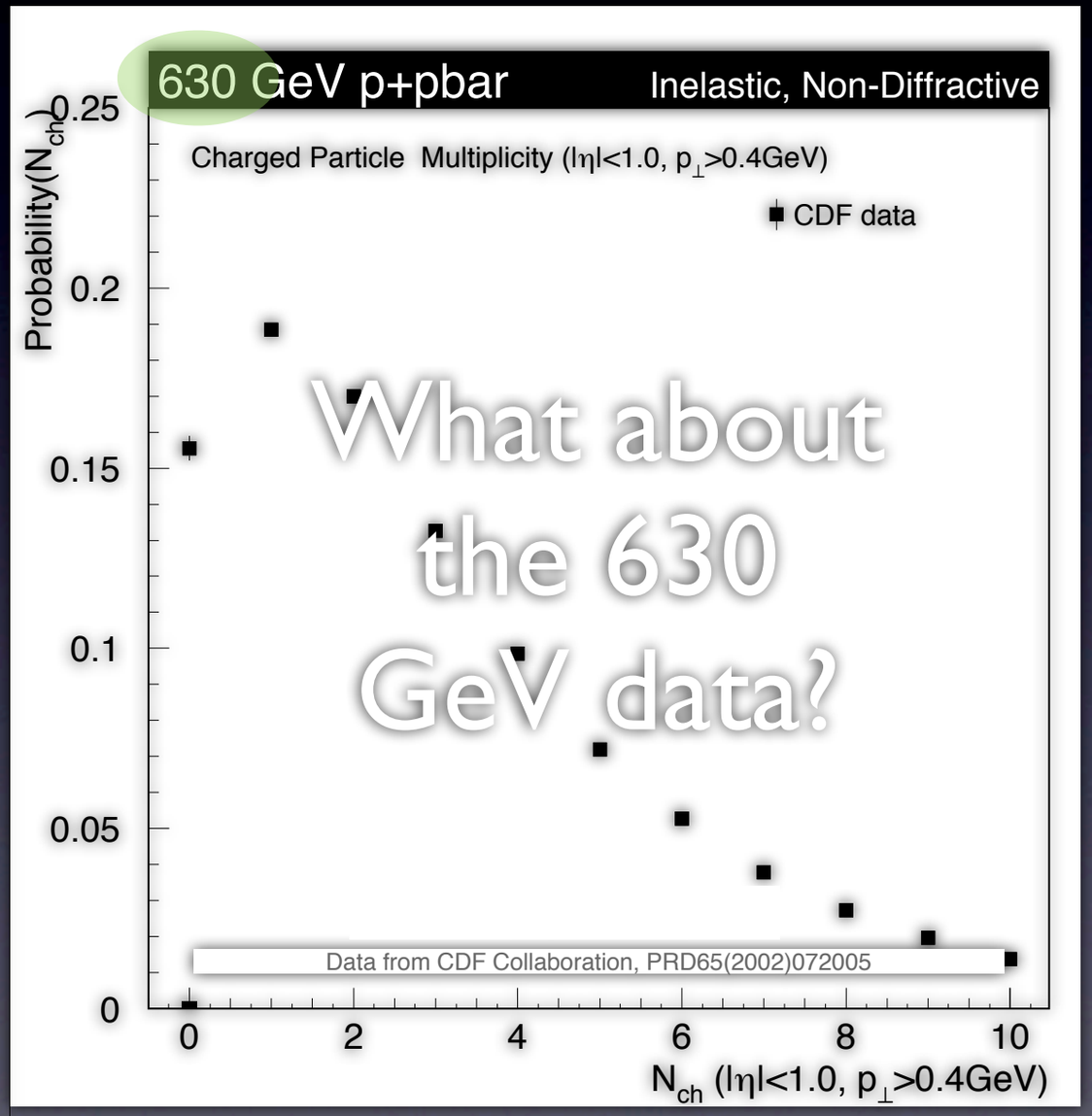

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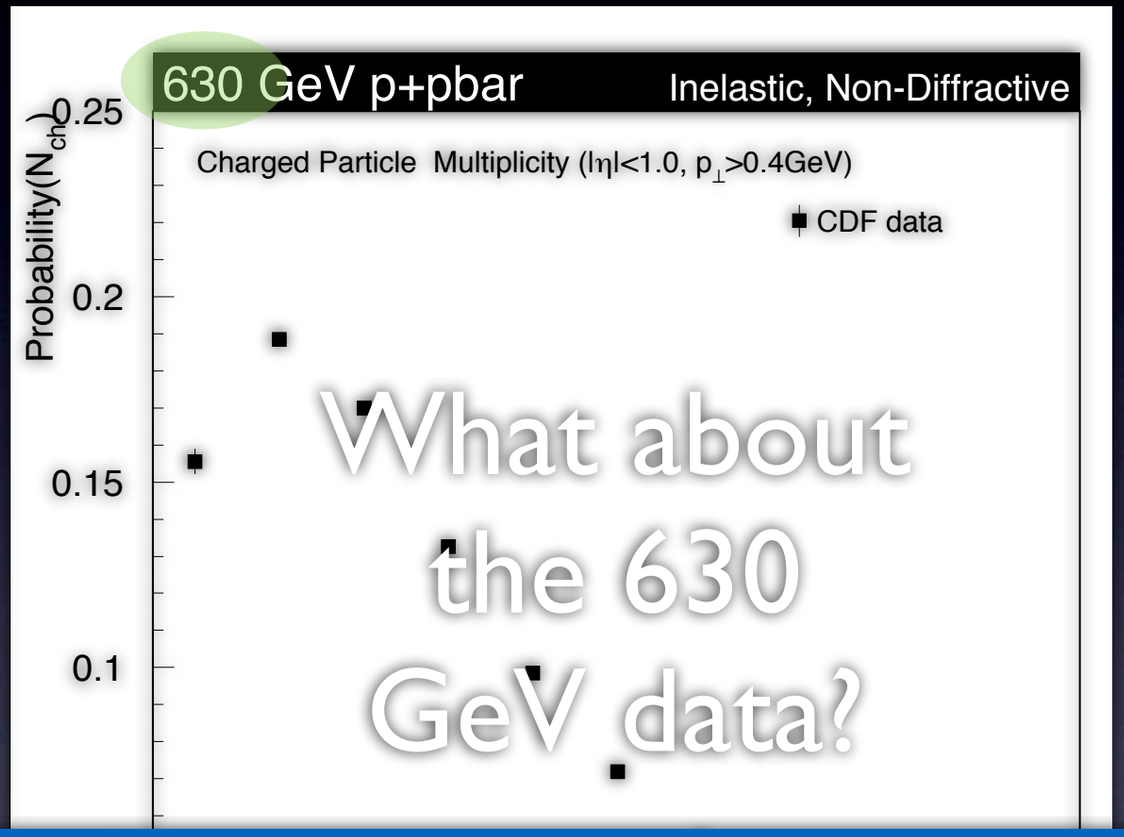
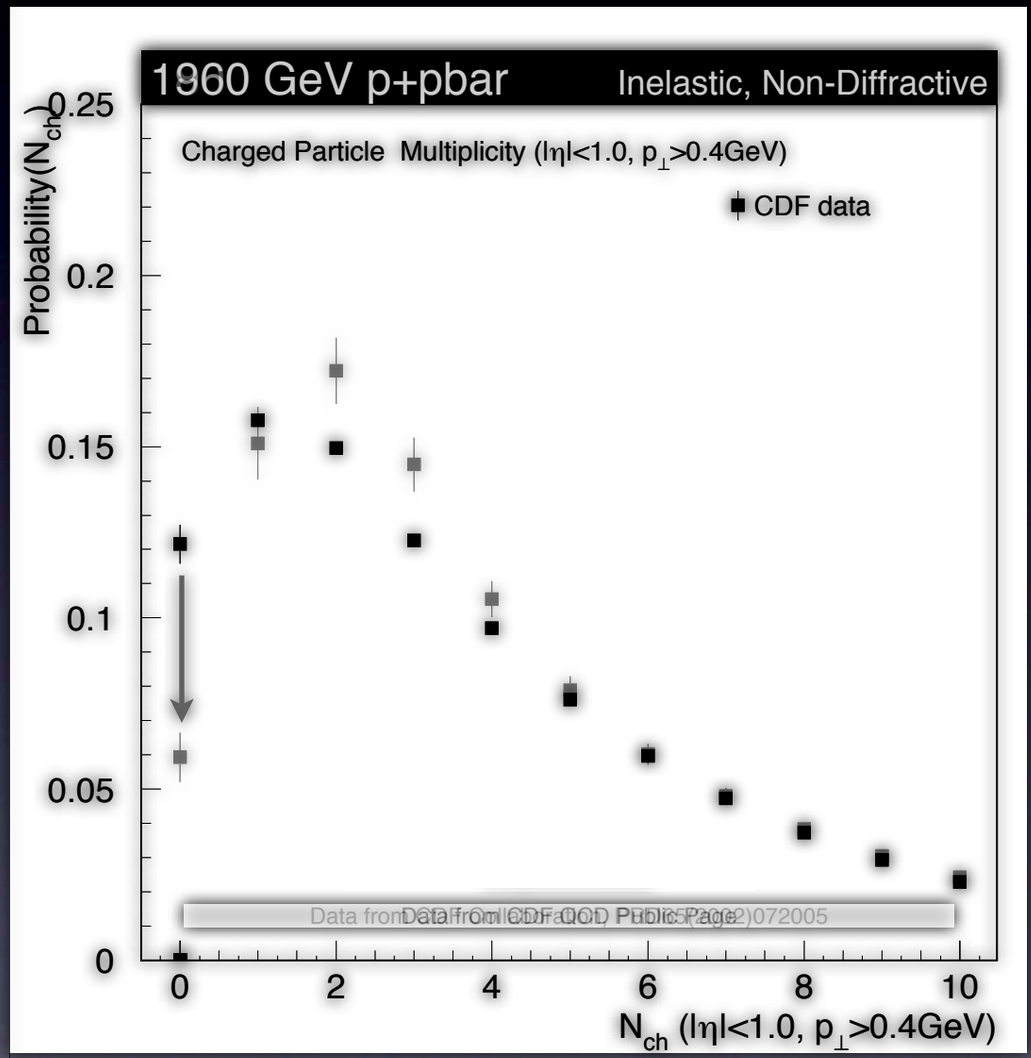


LHC Measurements at 900 and 2360 GeV, with a well-defined, agreed-upon, definition of diffraction can kill this issue

The Zero Bin

- The most problematic is the zero bin: *the event was triggered, but no fiducial tracks*
  - *E.g, was it a diffractive event with no tracks, or an inelastic non-diffractive event, with no tracks? Or … ?*



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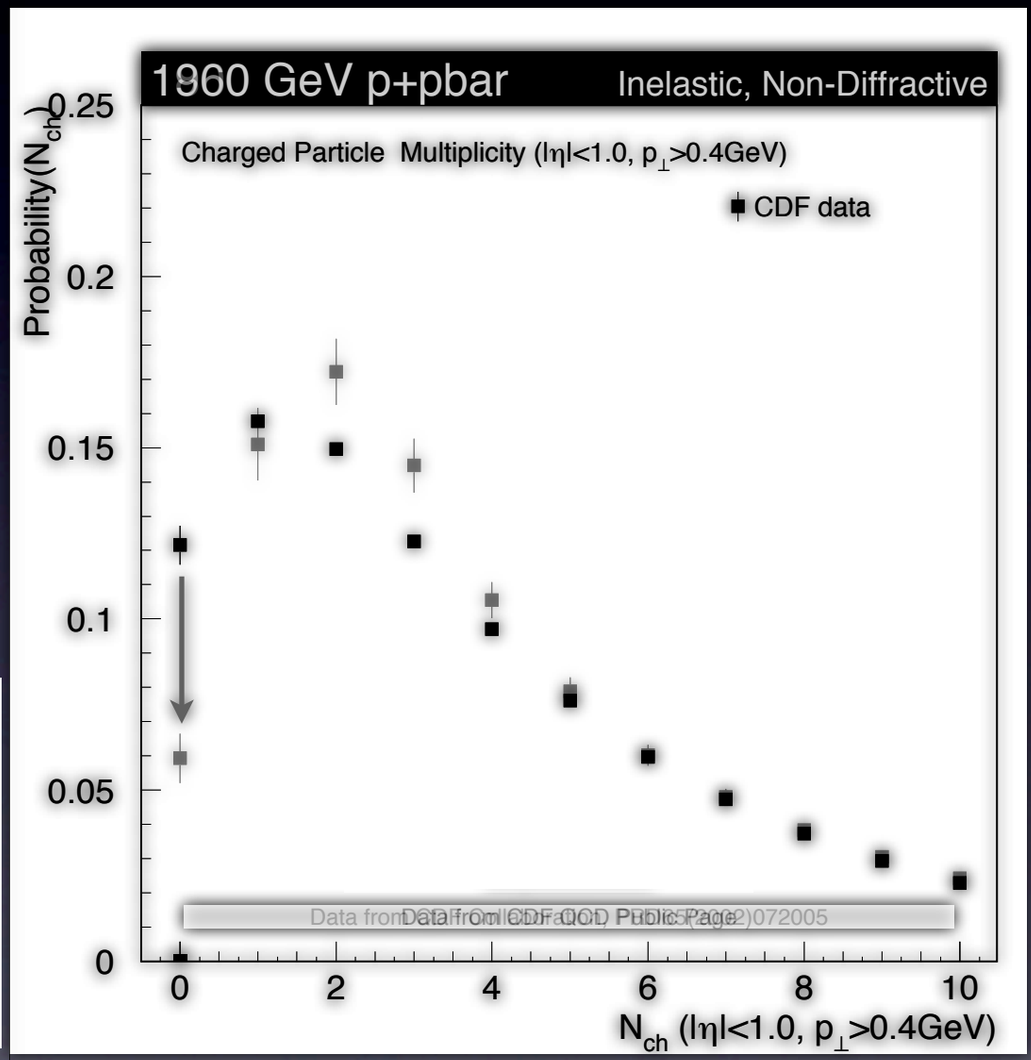

Predictions for Mean Densities of Charged Tracks

	$\frac{\langle N_{\rm ch}\rangle\,\vert_{N_{\rm ch}\geq 0}}{\Delta\eta\Delta\phi}$	$\frac{\langle N_{\rm ch}\rangle\,\vert_{N_{\rm ch}\geq 1}}{\Delta\eta\Delta\phi}$	$\frac{\langle N_{\rm ch}\rangle\,\vert_{N_{\rm ch}\geq 2}}{\Delta\eta\Delta\phi}$	$\frac{\langle N_{\rm ch}\rangle\,\vert_{N_{\rm ch}\geq 3}}{\Delta\eta\Delta\phi}$
LHC 10 TeV	0.40 ± 0.05	0.41 ± 0.05	0.43 ± 0.05	0.46 ± 0.06
LHC 14 TeV	0.44 ± 0.05	0.45 ± 0.06	0.47 ± 0.06	0.51 ± 0.06

PS, Perugia Proceedings, arXiv:0905.3418 [hep-ph]

Redefine the event sample to include at least one fiducial track?

Phase Space Extrapolations

Measure what is Measurable

- A FIT IS NOT A MEASUREMENT (even if it is a very good fit)

The $dN_{\mathrm{ch}}/d\eta$ spectrum was obtained by summing the measured differential yields for $0.1 < p_{\mathrm{T}} < 3.5$ GeV/c and adding the result to the integral of the fit function for $p_{\mathrm{T}} < 0.1$ GeV/c and $p_{\mathrm{T}} > 3.5$ GeV/c. The latter term amounts to 5% of the total.

CMS-QCD-09-010 [arXiv:1002.0621]

Phase Space Extrapolations

Measure what is Measurable

- A FIT IS NOT A MEASUREMENT (even if it is a very good fit)
- Put the burden of extrapolation on the whining theorists instead?
- (Theorists are able to use simple efficiency functions too)

The $dN_{\rm ch}/d\eta$ spectrum was obtained by summing the measured differential yields for $0.1 < p_{\rm T} < 3.5$ GeV/c . *Table X contains* the integral of the fit function for $p_{\rm T} < 0.1$ GeV/c and $p_{\rm T} > 3.5$ GeV/c , i.e., our estimate of the additional correction that would be necessary to compare to an all-phase-space calculation or measurement, with a correspondingly larger uncertainty generated by the errors in Table X.

?

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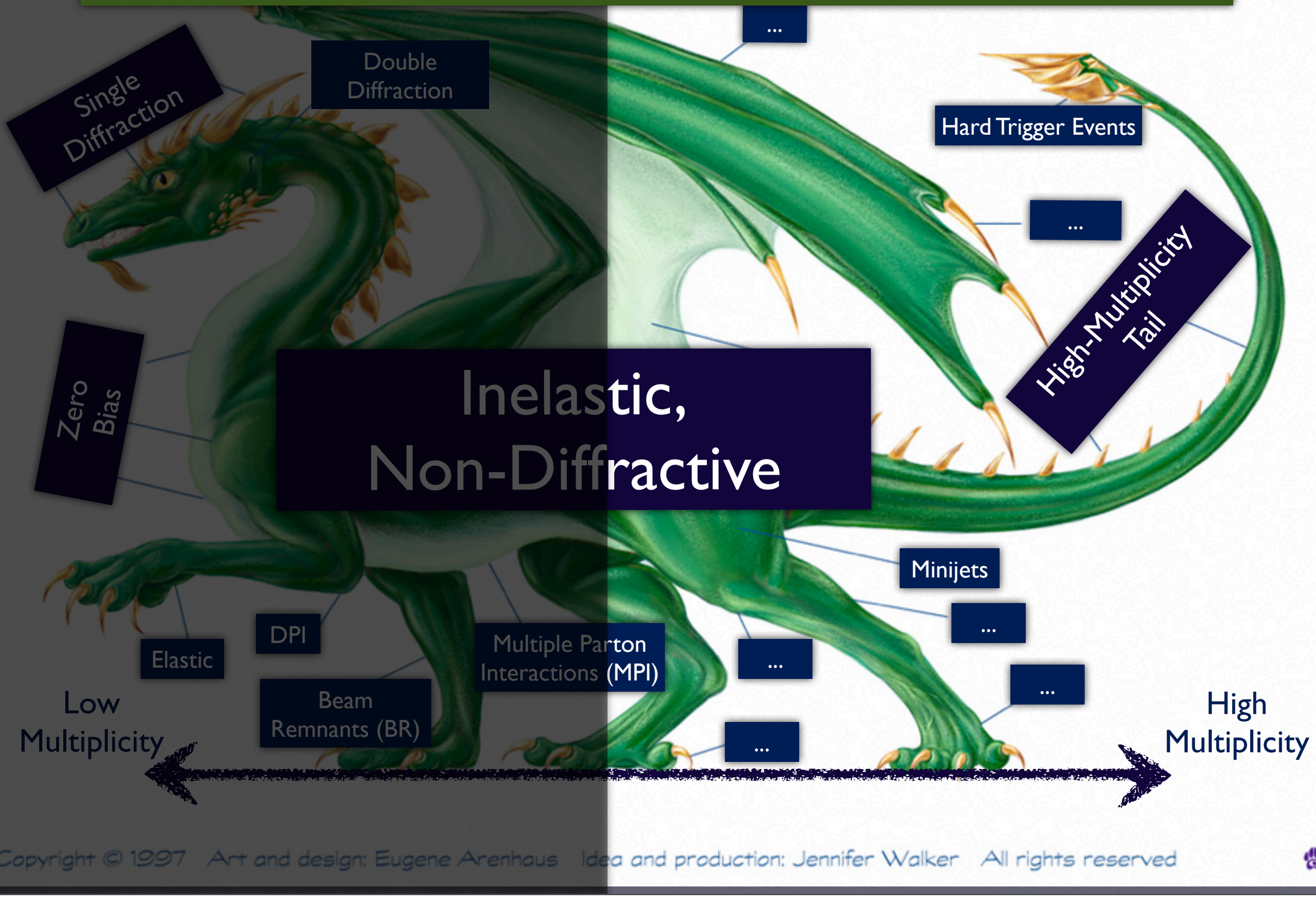
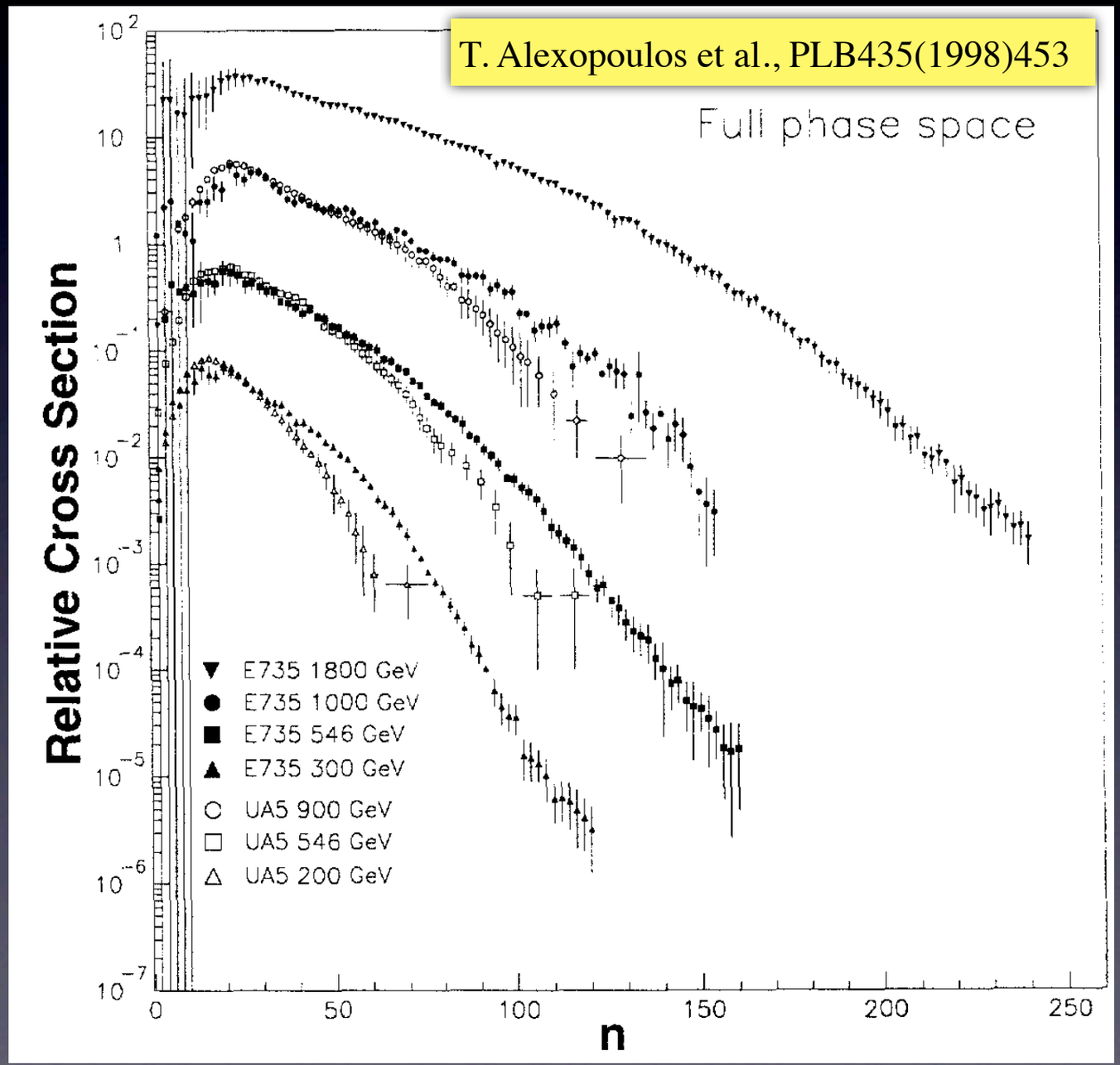


High Multiplicities: An Unresolved Question

- UA5 at 200, 546, and 900 GeV
- E735 at 300, 546, 1000, and 1800 GeV
- Mutually Inconsistent over *Entire Range*



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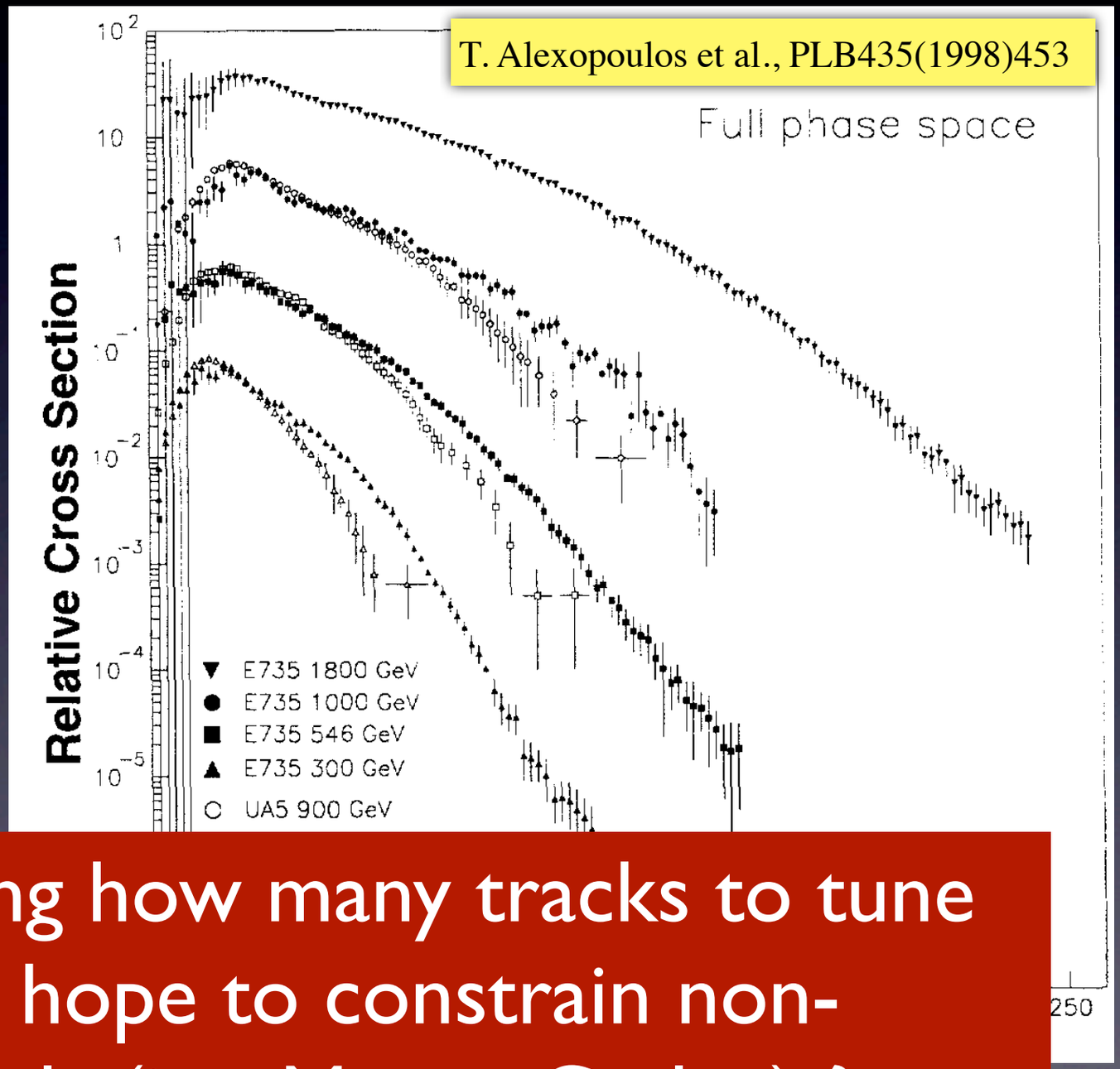

Without even knowing how many tracks to tune to, how could we hope to constrain non-perturbative models (i.e., Monte Carlos) ?

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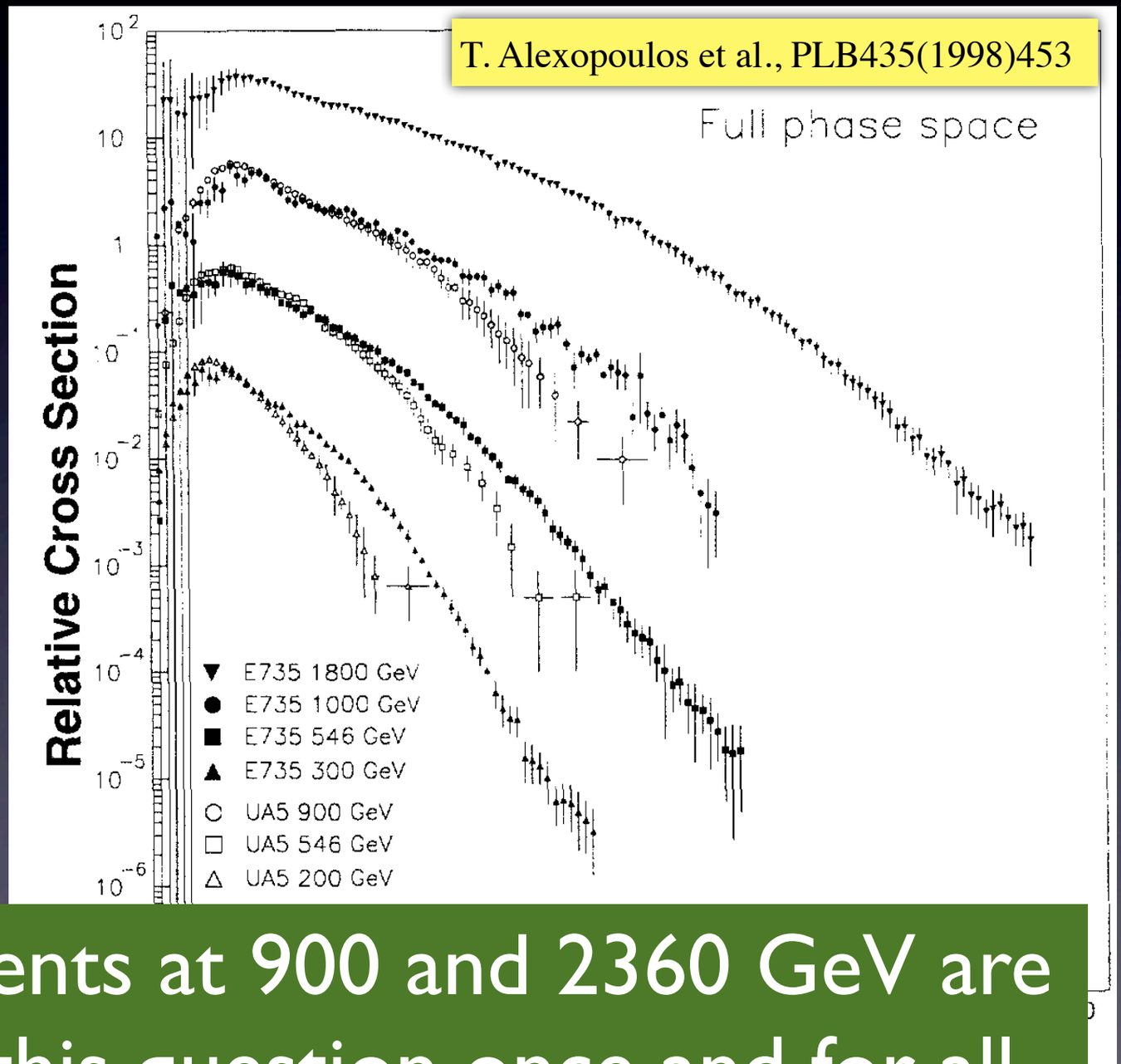

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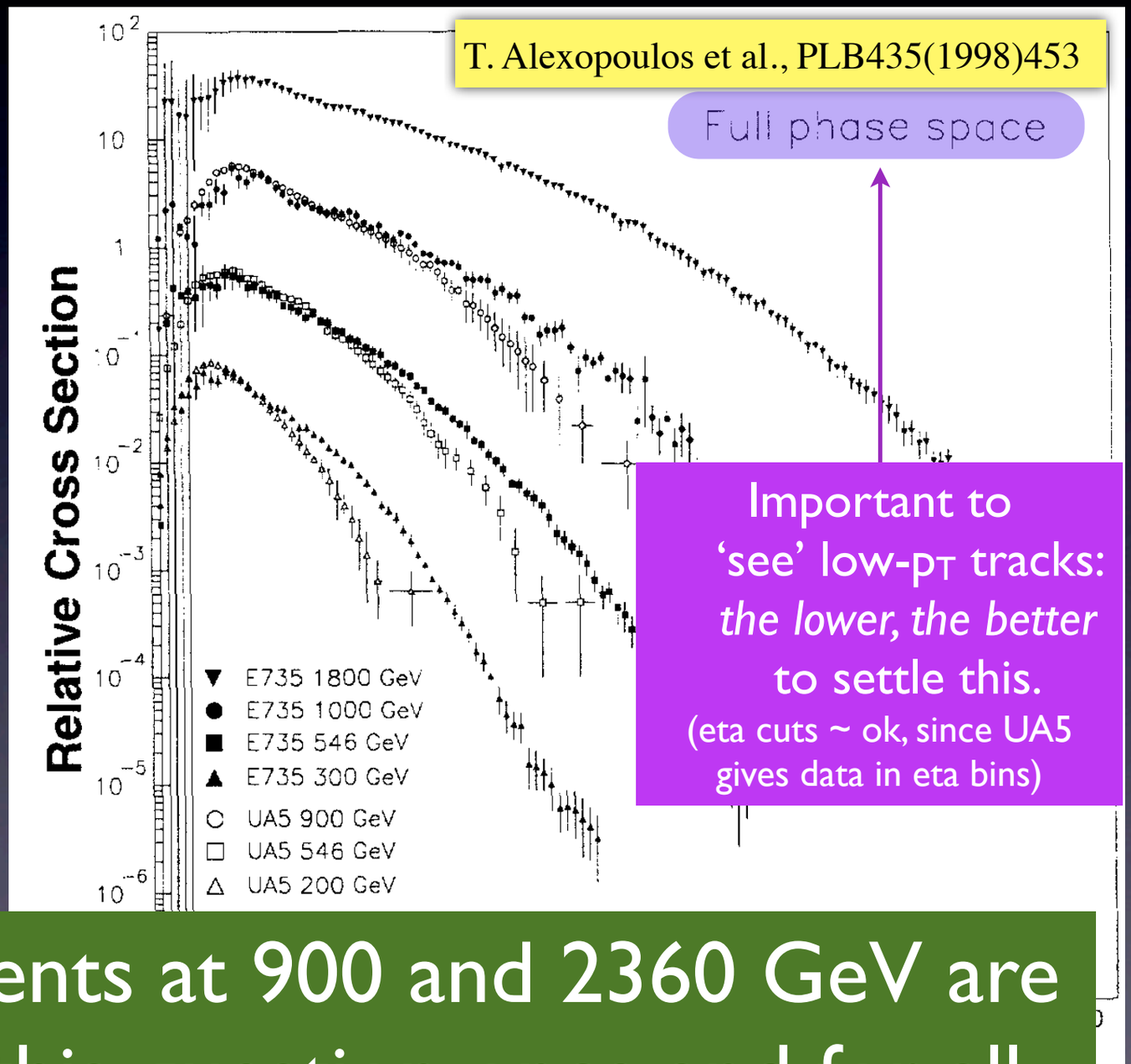

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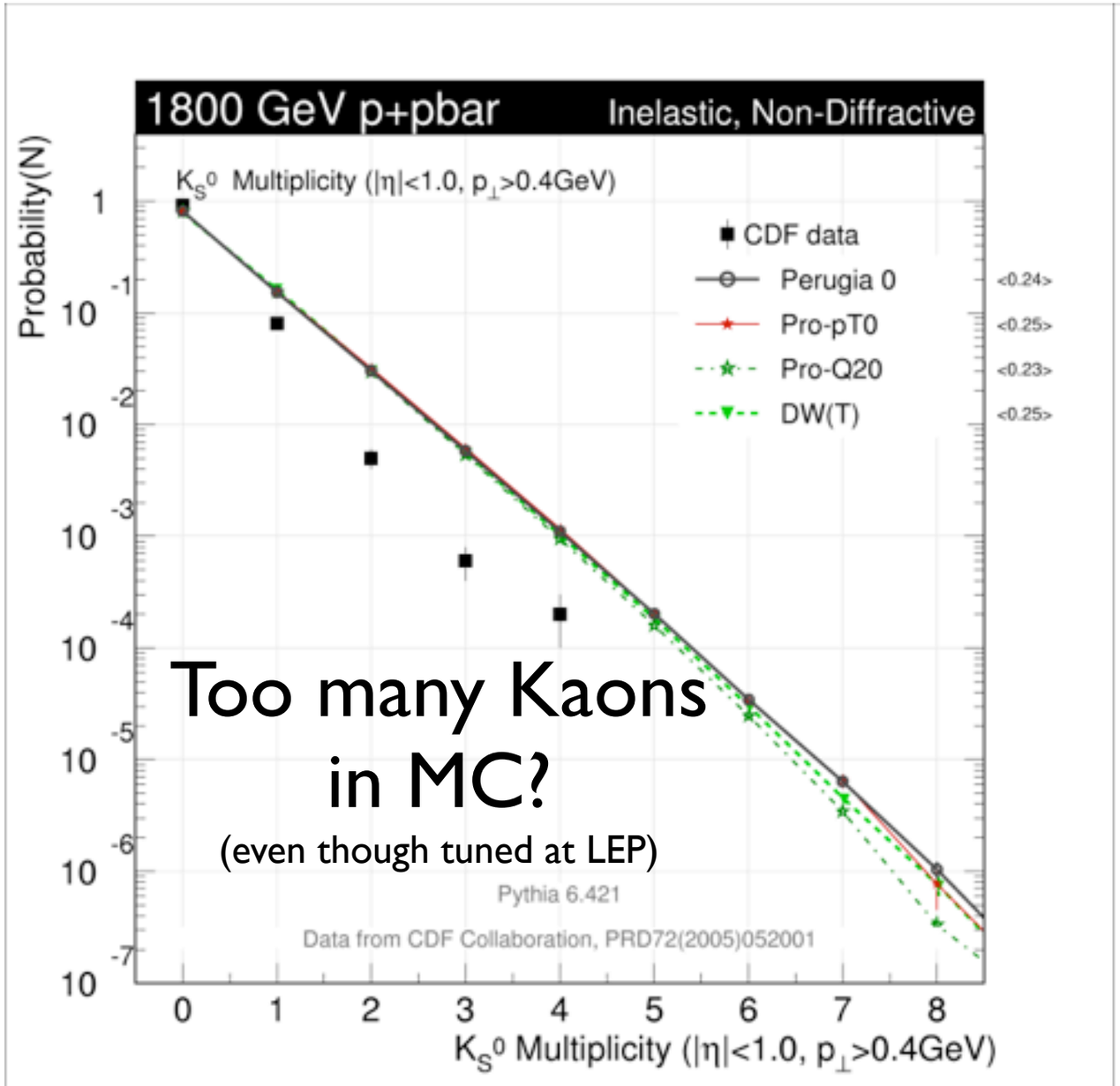
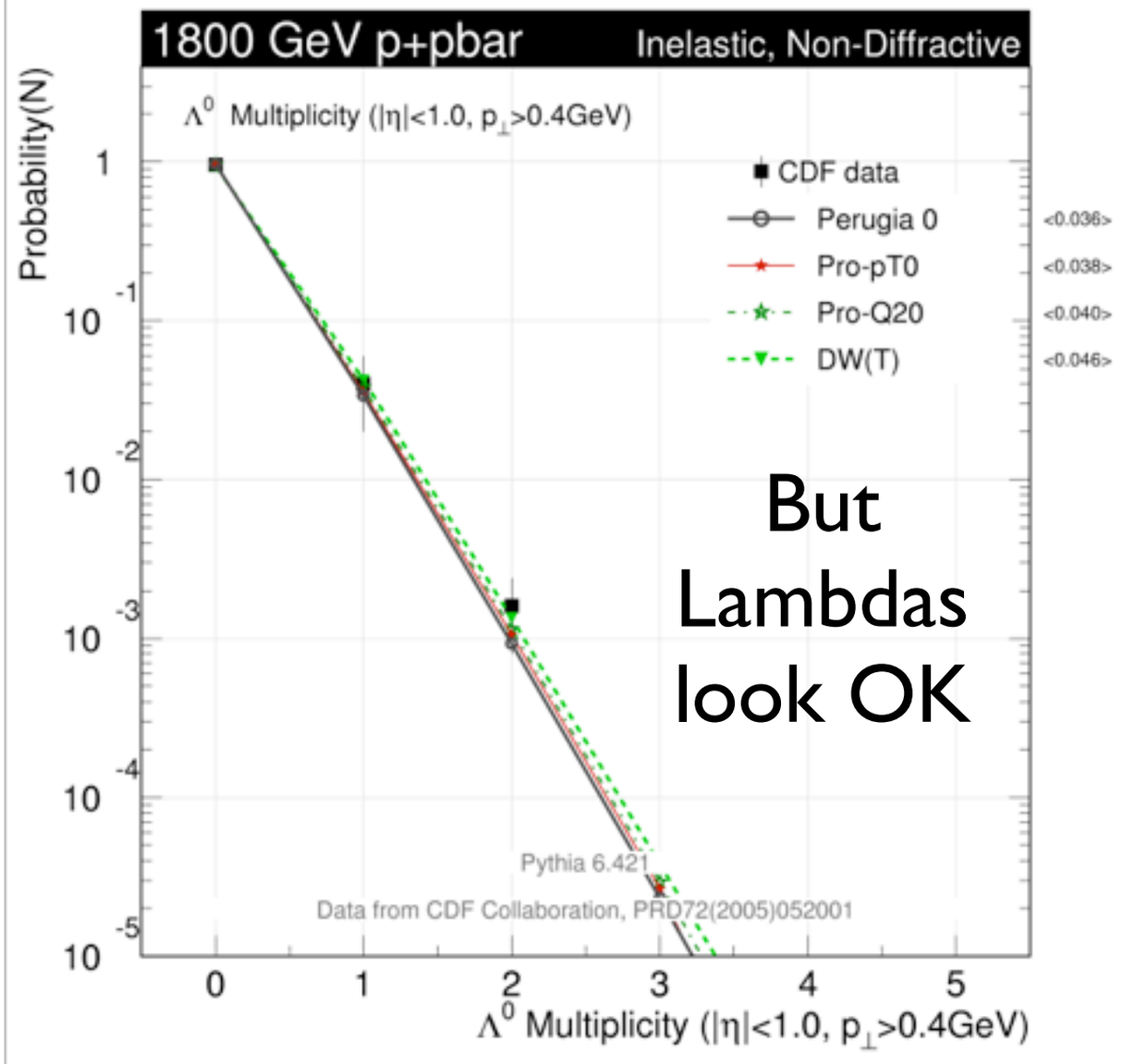
- Check fragmentation *in situ* at hadron colliders
  - *N* and p_T spectra (and *x* spectra normalized to 'jet'/minijet energy?)
    Identified particles highly important to dissect fragmentation

The Kaon Problem





http://home.fnal.gov/~skands/leshouches-plots

PS, fermilab-conf-07-706-t, in arXiv:0803.0678 [hep-ph]

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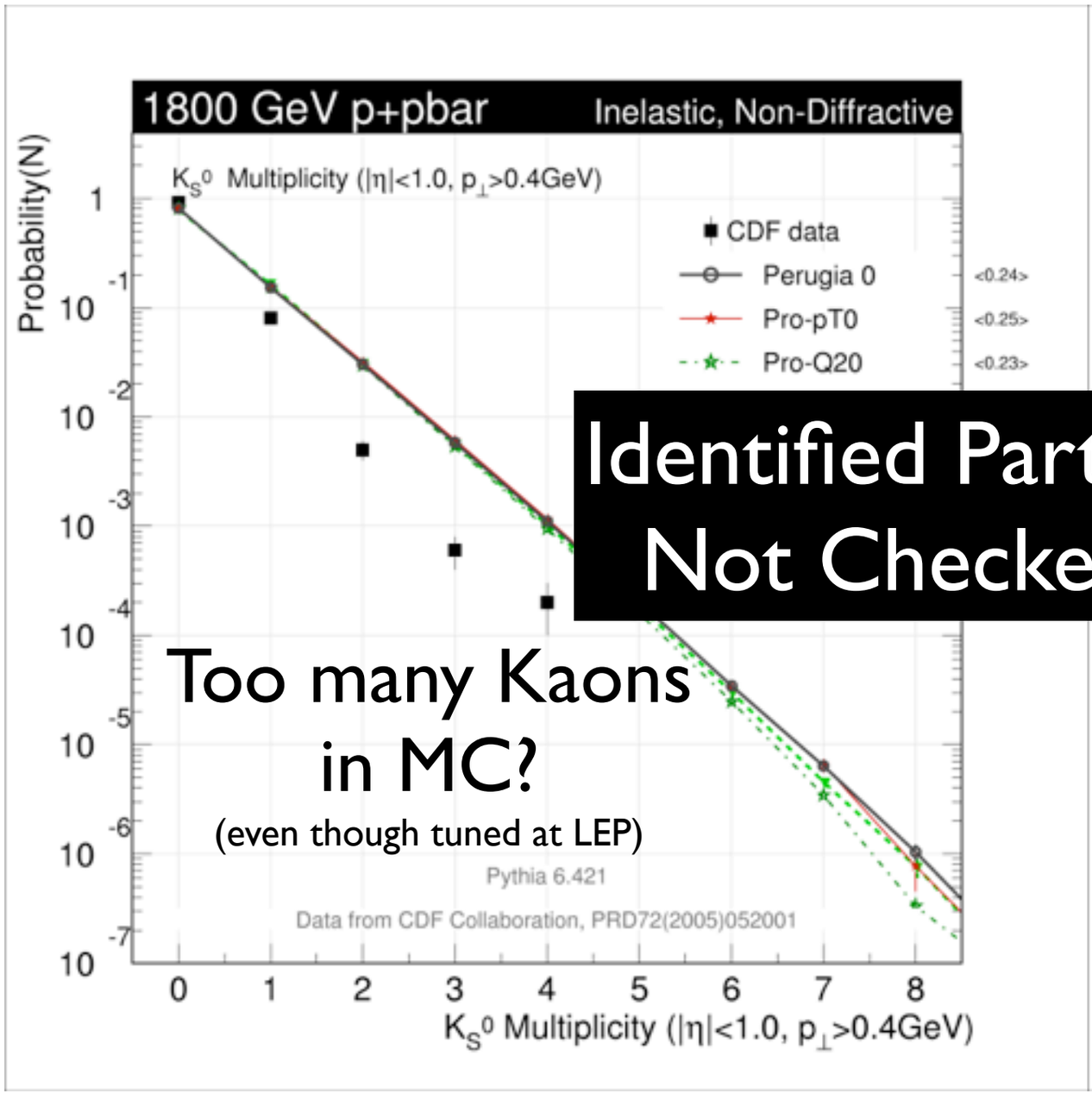
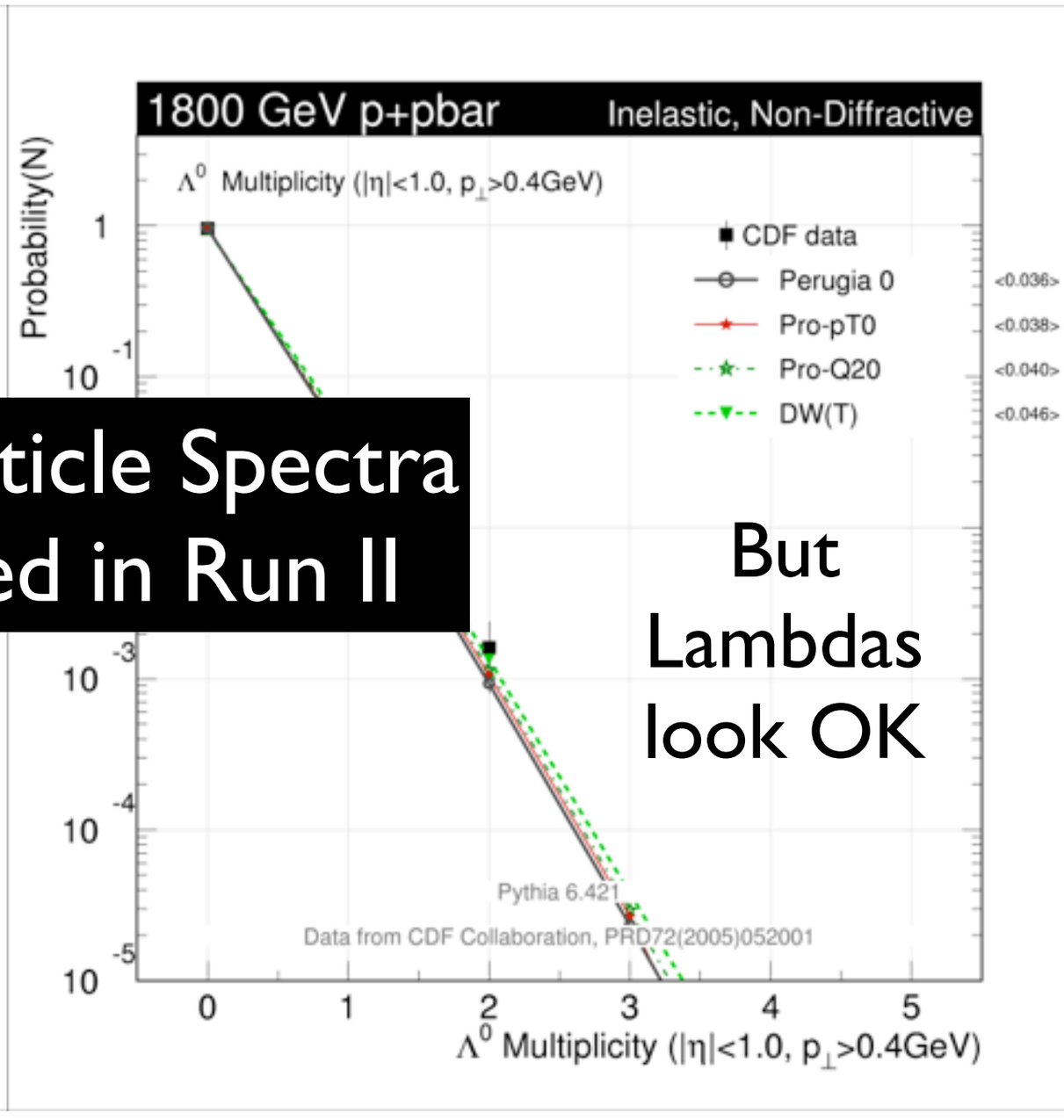


Too many Kaons in MC?

(even though tuned at LEP)



But Lambdas look OK

Identified Particle Spectra Not Checked in Run II

http://home.fnal.gov/~skands/leshouches-plots

PS, fermilab-conf-07-706-t, in arXiv:0803.0678 [hep-ph]

Fragmentation

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  - But pp/ppbar is a very different environment, at the infrared level!

- Check fragmentation *in situ* at hadron colliders
  - *N* and p_T spectra (and *x* spectra normalized to 'jet'/minijet energy?) **Identified particles** highly important to dissect fragmentation
  - (How) do the spectra change with (pseudo-)rapidity? (different dominating production/fragmentation mechanisms as fct of rapidity? E.g., compare LHCb with central?)
  - How do they change with event activity? (cf. heavy-ion ~ central vs peripheral collisions)

Change with Event Activity

- One (important) example: $\langle p_T \rangle (N_{ch})$

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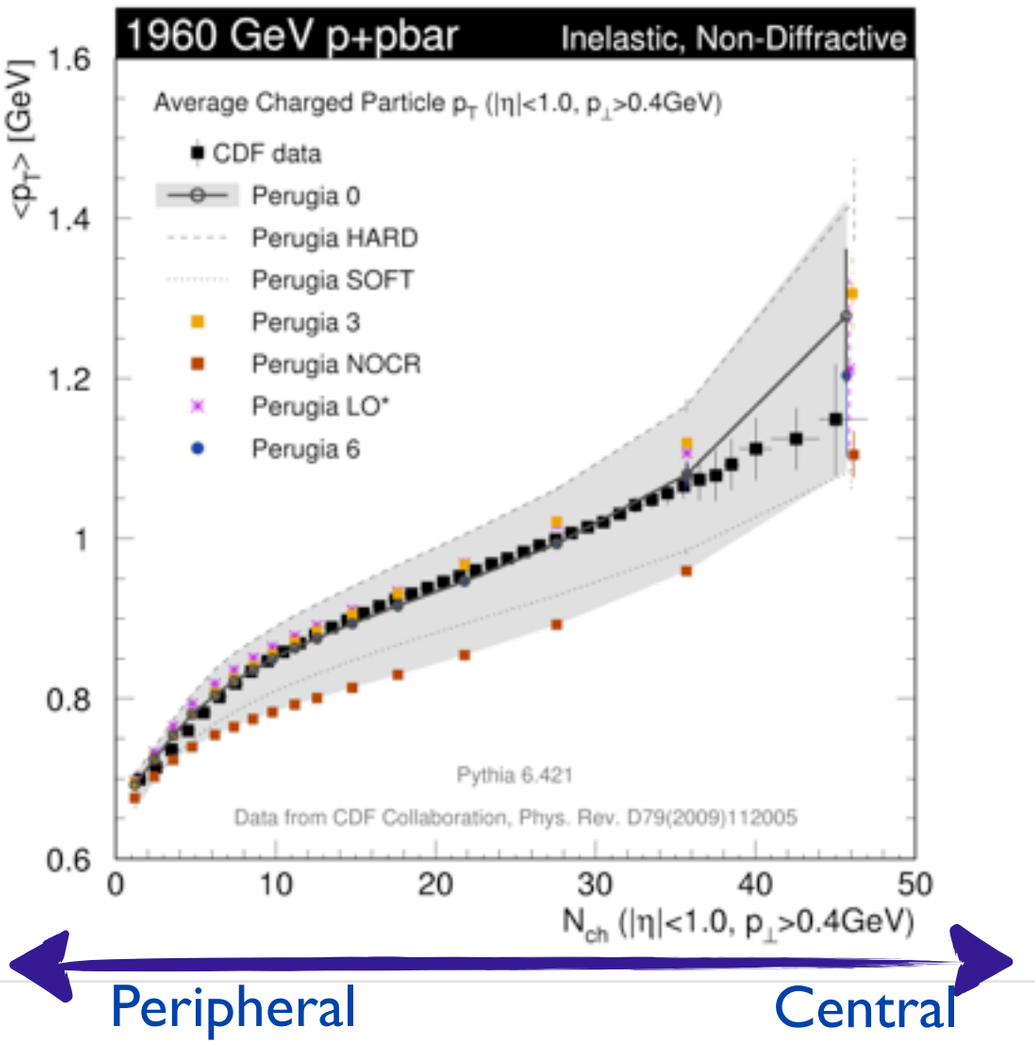

The p_T spectrum becomes harder as we increase N_{ch}.

Important tuning reference (highly non-trivial to describe correctly)

(Color reconnections, string interactions, rescattering, collective flow in pp, ...?)

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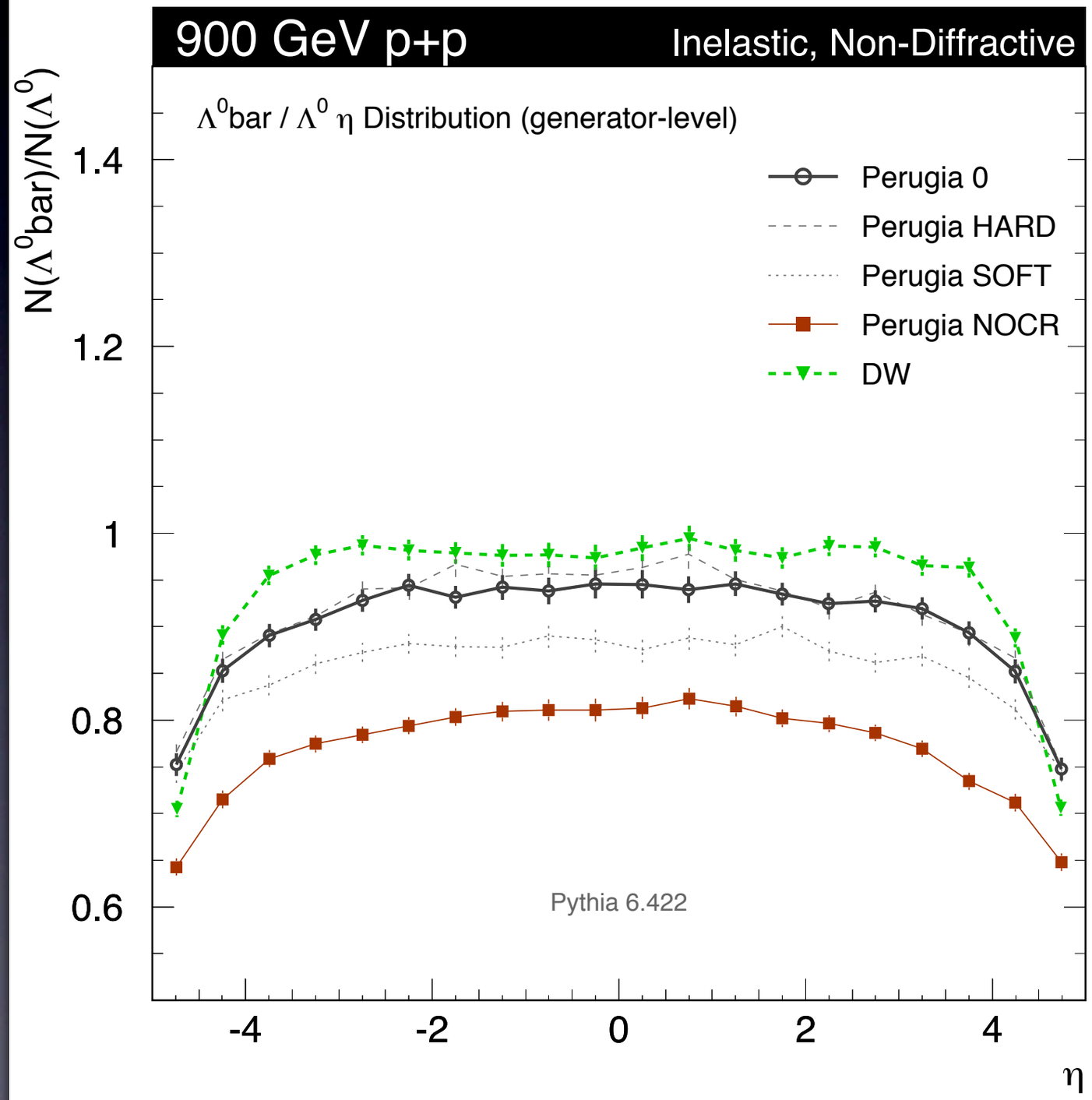
- Check extrapolation to forward region
  - Subir's synergy with Cosmic Ray Fragmentation
  - 'New' Physics: collective effects, multiple scatterings, low-x evolution, BFKL, ..., but central region remains important testing ground

(Additional Observables)

- **Particle-Particle Correlations** probe fragmentation beyond single-particle level. E.g.,:
  - A baryon here, where's the closest antibaryon?
    - + Is the Baryon number of the beam carried into the detector?
  - A Kaon here, where's the closest strange particle?
    - + Multi-Strange particles. Over how big a distance is the strangeness 'neutralized'?
  - Charge correlations. Special case: is the charge of the beam carried into the detector?

Baryon Transport

- Models disagree wildly.
- Don't listen to them
- (Still, can be used to gauge possible size of effect)



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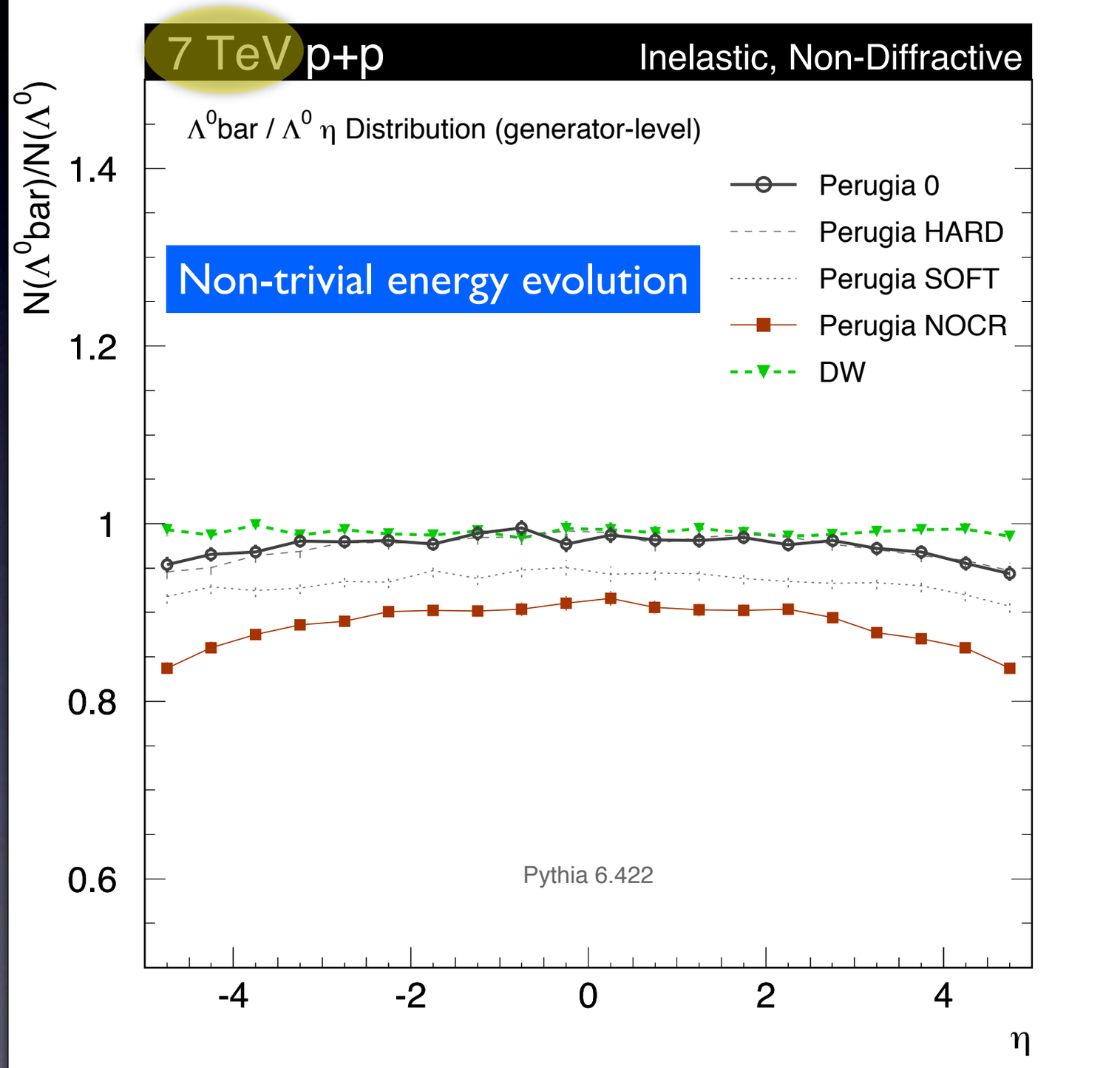

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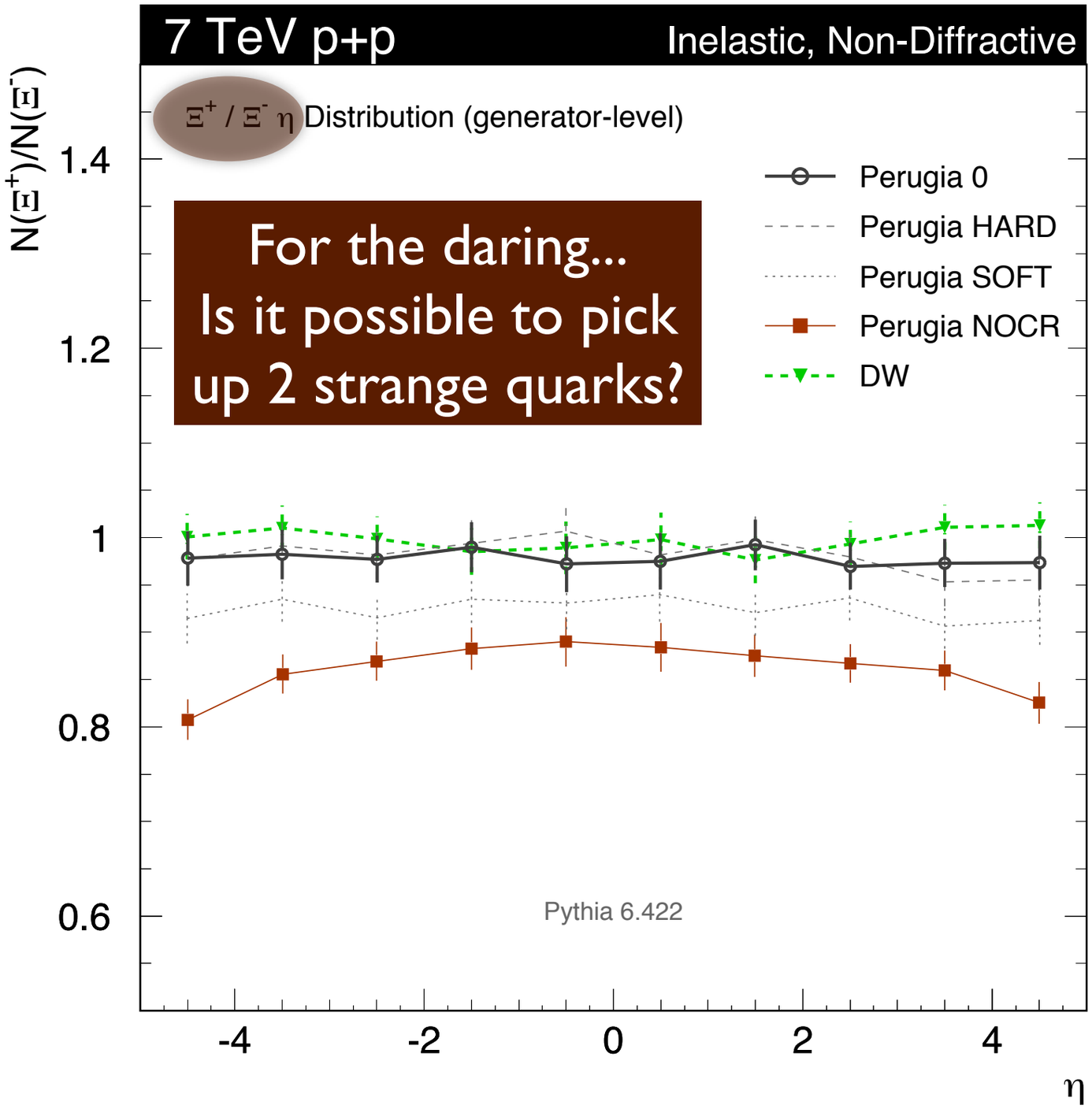

Radiation vs MPI

- What is producing the tracks?
  - Is it **Radiation**? (tends to produce partons close in phase space)
  - Or is it **MPI**? (partons going out in opposite directions)
  - Or is it soft production between the **remnants**?

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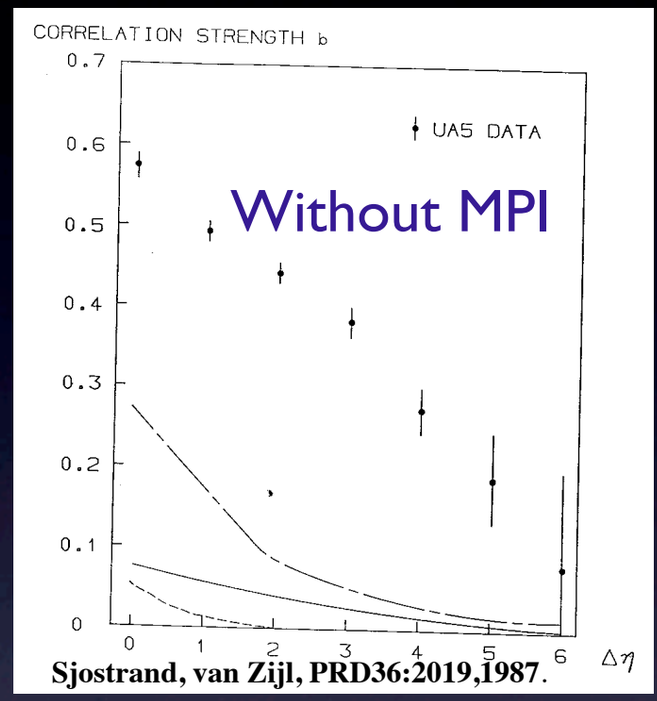
  - E.g., forward-backward correlation, *b*



Sjostrand, van Zijl, PRD36:2019,1987.

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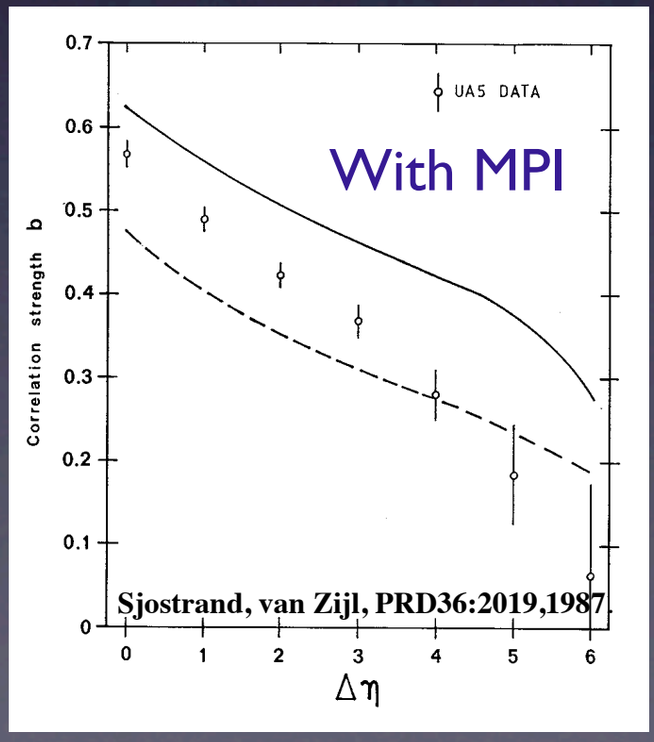

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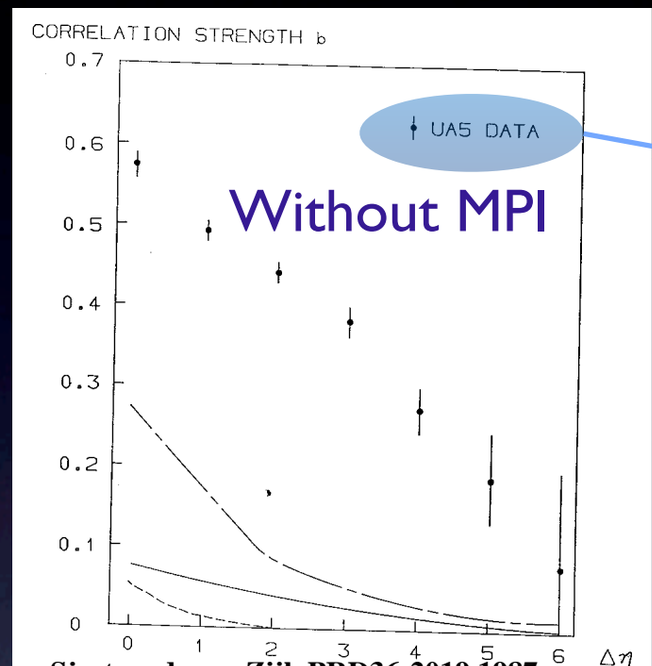

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b Not measured at Tevatron

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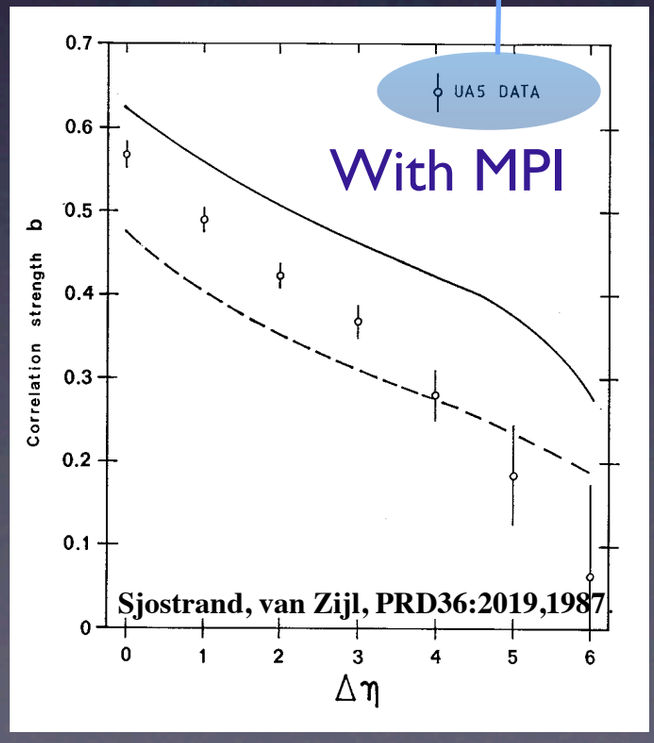

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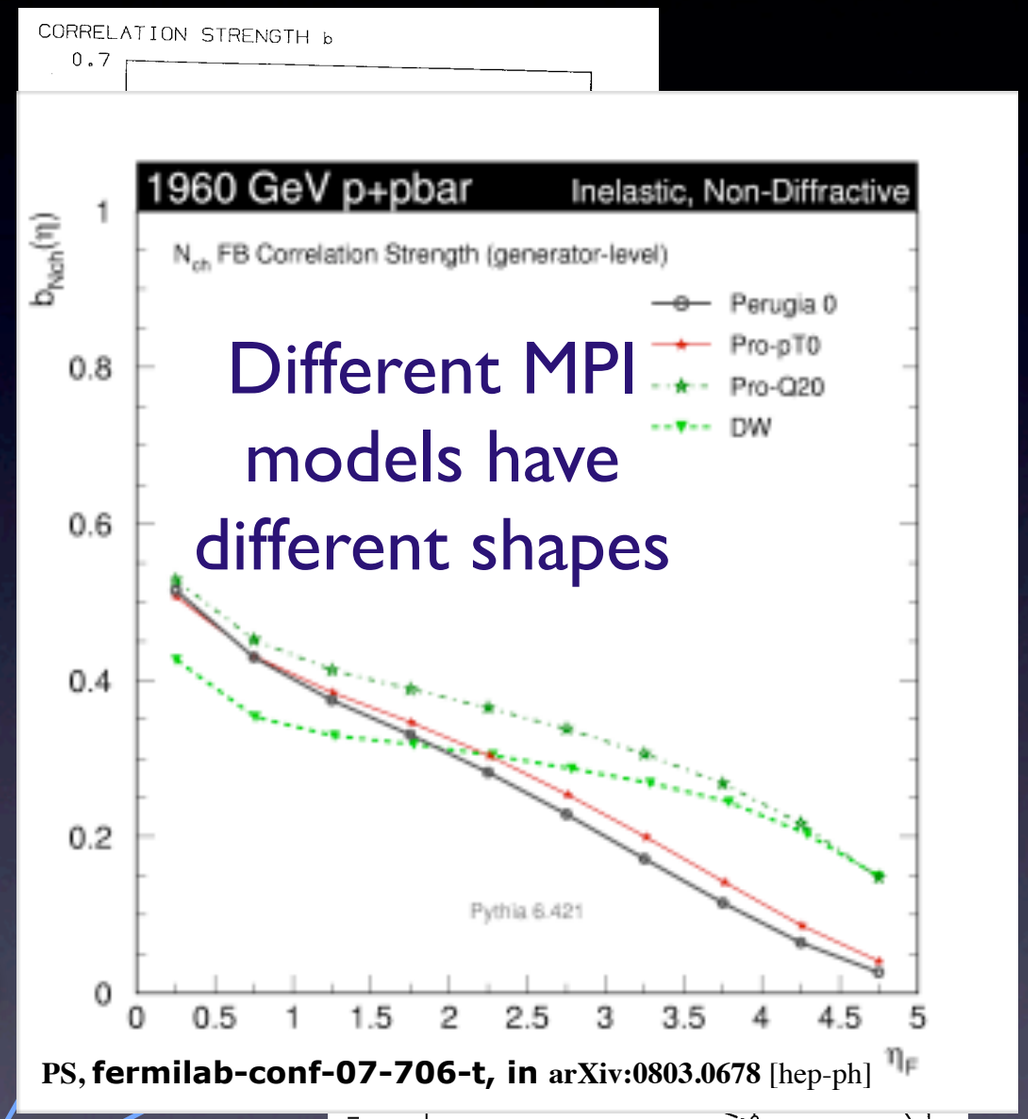

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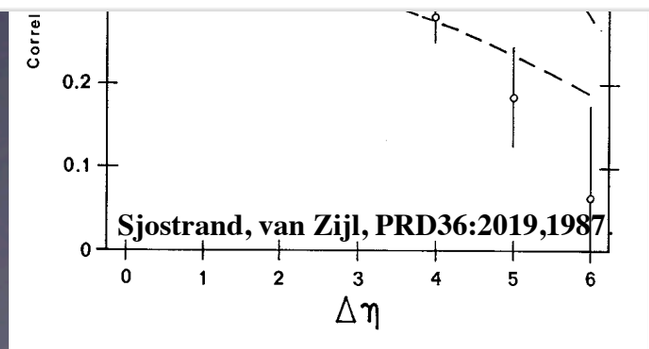
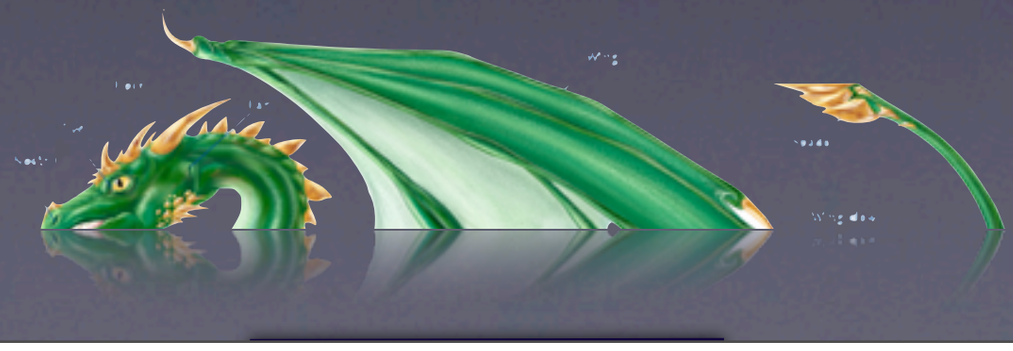


Summary

- The Low-Energy LHC runs offer a unique possibility to settle important business
- These are questions faced by every person (within or outside experiments) trying to constrain ('tune') physics models
- In a broader context, they concern our *knowledge* of nature



A Systematic Dissection

Perturbative Dynamics :
Infrared **safe** observables
"pQCD"

→ Single-Jet Spectra
Jet-Jet distributions
IR safe Energy Flow variables

Non-perturbative dynamics :
Infrared **sensitive** observables
"MB"

→ Single-Particle Spectra
Particle-Particle distributions
Quantum Number Flow variables

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Single-Jet Spectra
Jet-Jet distributions
IR safe Energy Flow variables

"UE"

IR-sensitive vs IR-safe observables
(e.g., <Nch> vs pTjet)

Non-perturbative dynamics :
Infrared **sensitive** observables

"MB"

Single-Particle Spectra
Particle-Particle distributions
Quantum Number Flow variables