# **Pythia News & Plans** (+ Tuning Recommendations)

Peter Skands (Monash University) & Leif Gellersen (Lund University)

**New Updated Comprehensive Reference (2022):**

A COMPREHENSIVE GUIDE TO THE PHYSICS AND USAGE OF PYTHIA 8.3 https://arxiv.org/abs/2203.11601

Authors: Christian Bierlich, Smita Chakraborty, Nishita Desai, Leif Gellersen, Ilkka Helenius, Philip Ilten, Leif Lönnblad, Stephen Mrenna, Stefan Prestel, Christian T. Preuss, Torbjörn Sjöstrand, Peter Skands, Marius Utheim, and Rob Verheyen. SciPost Physics Codebases 8 (2022).

**~ 315 pages**

### Pythia 8

**2008**

- Moved from F77 to C++
- (Complete rewrite from scratch.)
- *Since 8.135:* no use of static member methods

### → 8.3

**2019**

- Moved to C++11
- VINCIA and DIRE shower models integrated into standard distribution
- Monash tune as default

### current → 8.309

**Feb 2023**

- aMC@NLO-Delta Matching
- PowhegHooks for all three shower models
- Bug fix for 2nd-order $\alpha_s$
- *Since 8.307:* PythiaParallel

### upcoming 8.310

**Jul/Aug 2023**

- LHAPDF6 Multi-threading
- RecoilToTop hook moved to standard distribution
- New model for onium production (via showers)

### 8.31x 8.4? 9?

**Future …**

- Many active projects.
- Only ~ 12 authors (mainly TH, a few EXP)
- Main focus (& funding): physics
- No current plans for major code restructuring.

## Are shower variations appropriate to use in conjunction with heavy-flavour fragmentation?

(Since the appropriate value of $r_b$ or $r_c$ varies with $\alpha_s$, these variations might break agreement with LEP tuning)

## Quick answer is yes

But the second point is more subtle.

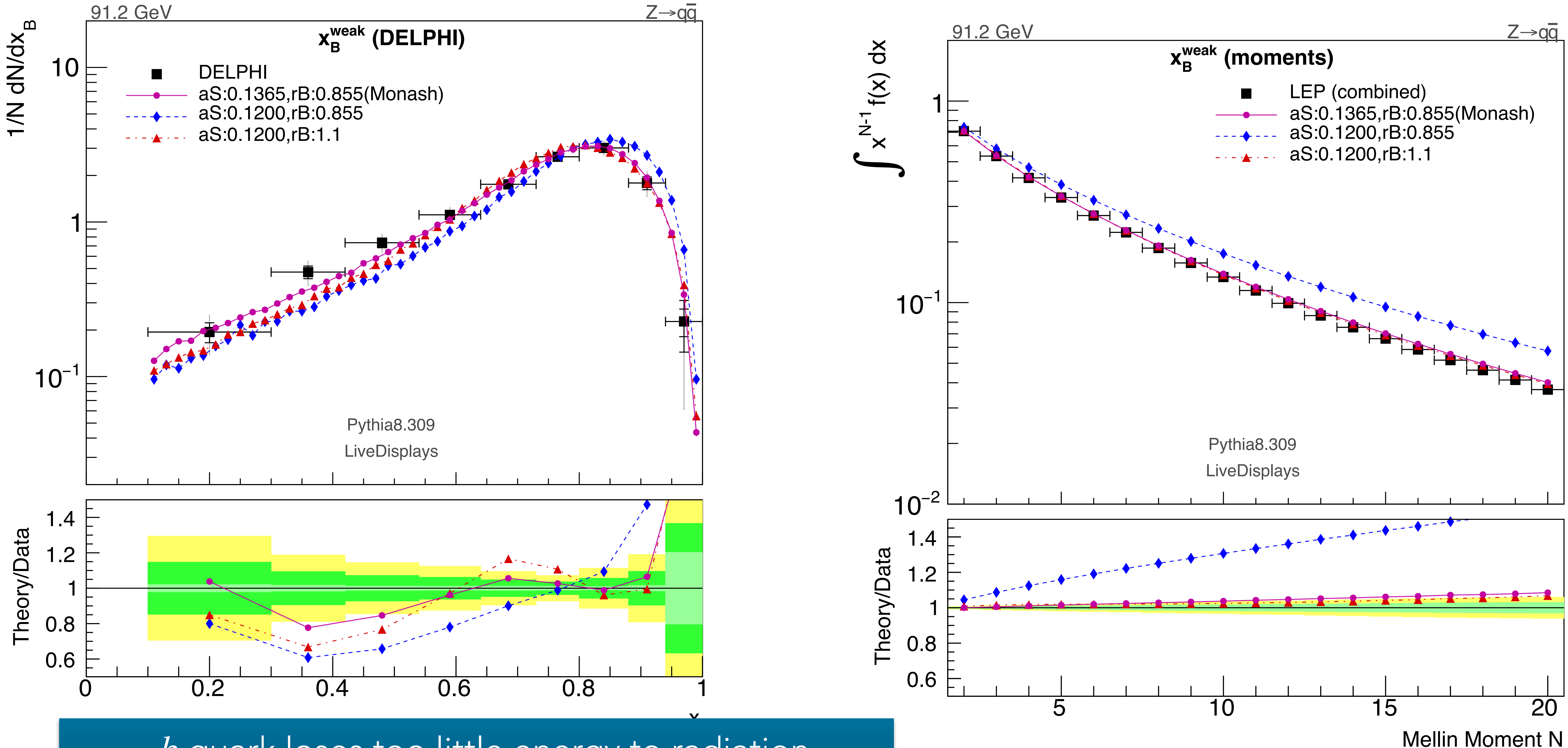
## Parameter hierarchies

**Tuning:** the higher up the chain you change something, the more it will affect the large-scale event structure ➜ Start at the top, and work your way down.

- $\alpha_s$ is a perturbative parameter → affects jet rates, IR safe observables, …
- $r_b$ is a non-perturbative parameter (just like aLund, bLund, sigmaPT, …)

Ideally, should not attempt to determine a non-perturbative parameter if the perturbative ones are not appropriate.

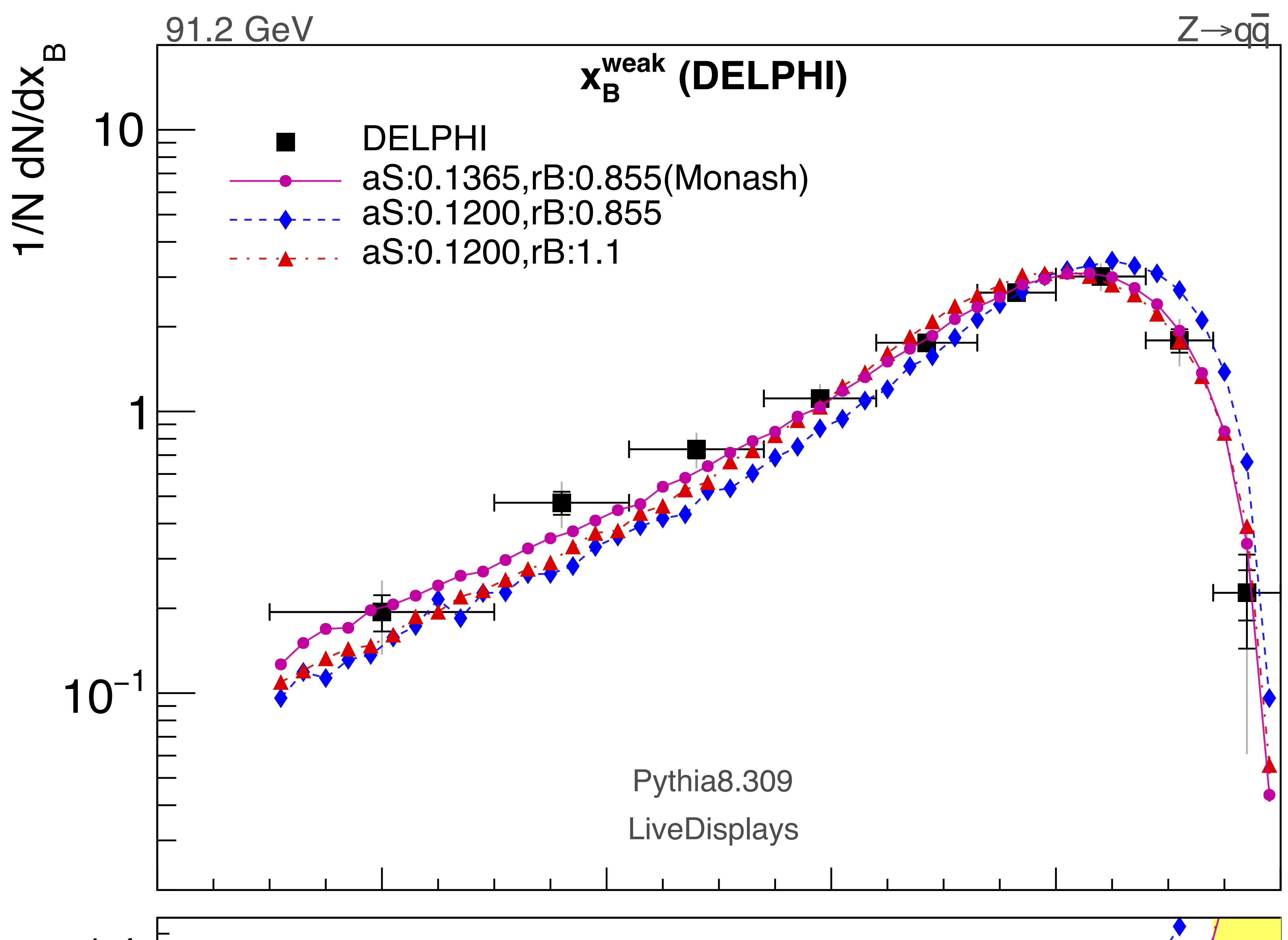
## Changing $r_b$ to "compensate" for change in $\alpha_s(M_Z)$?

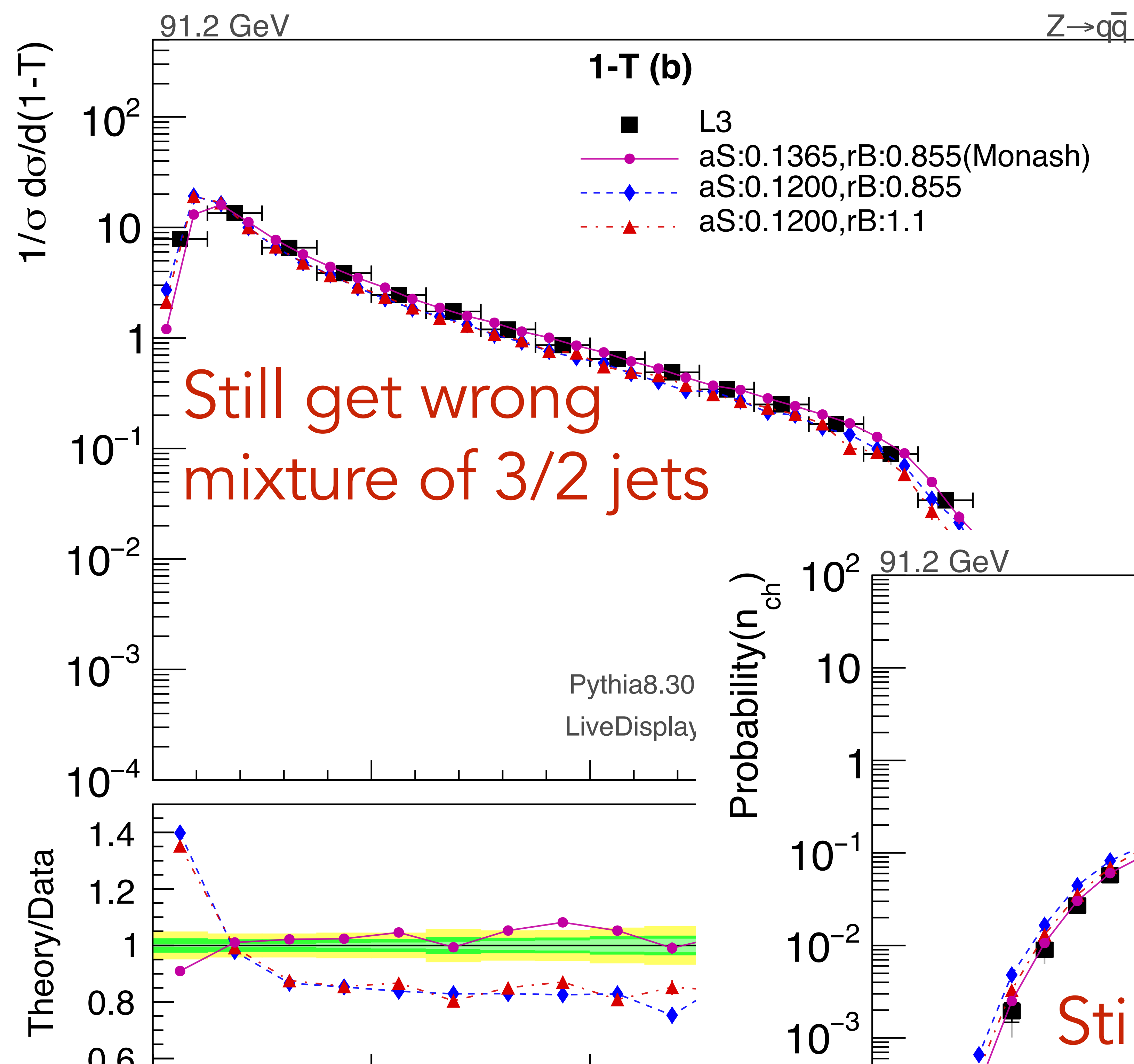


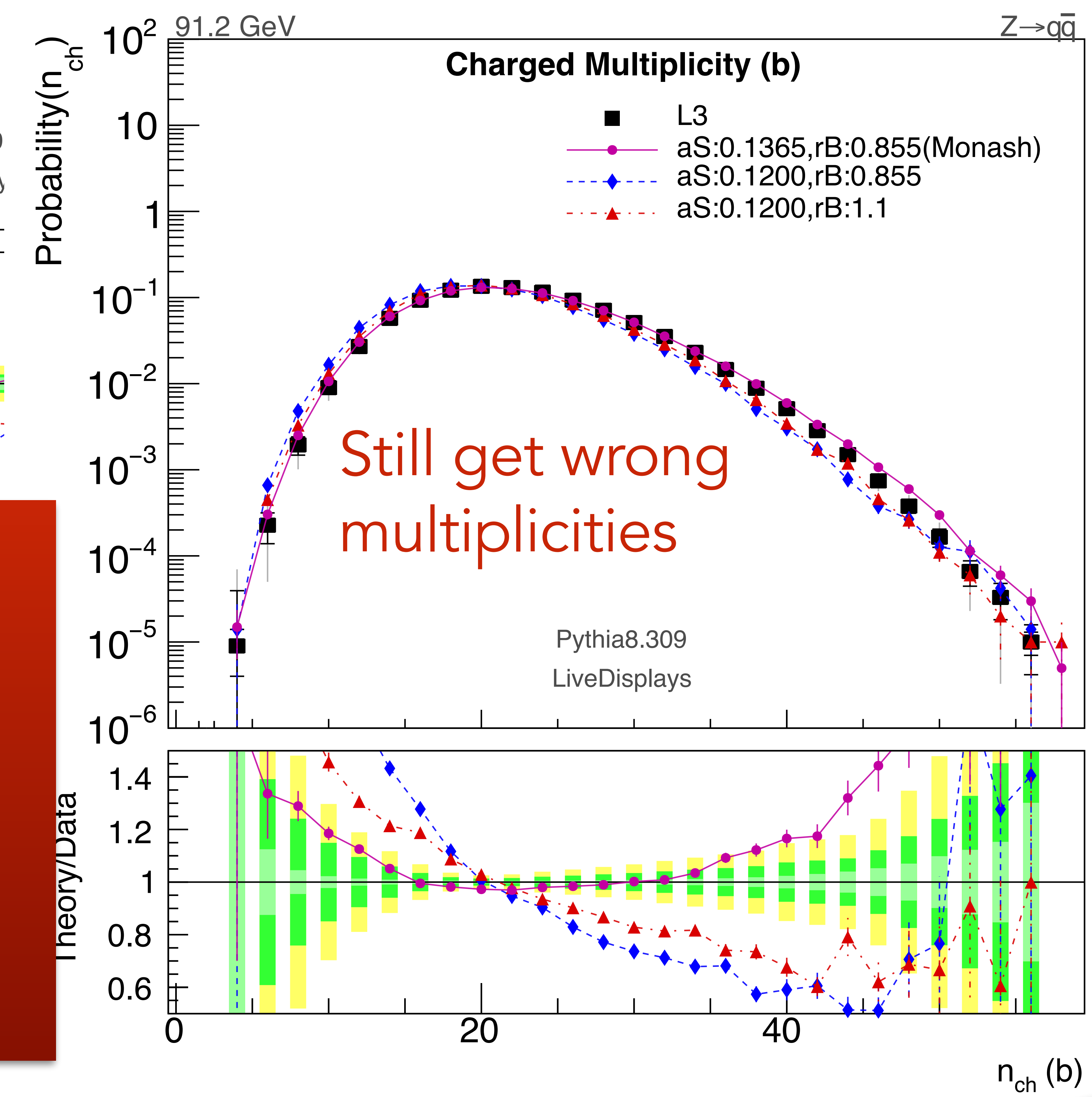

*b* quark loses too little energy to radiation
Increasing $r_b$ forces it to lose more to hadronisation.

Looks like a good idea?

# What happens to other distributions?




What does it mean to get "right" B spectrum if all other event properties are still "wrong" ?

My recommendation: Determine uncertainty on $r_b$ from central tune (crucial to do this with **correct** 3/2 jet ratio, etc).

Then do shower variations for that fixed (central) value of $r_b$

And do $r_b$ variations for fixed (central) shower parameters.

More advanced (correlated) setup would require more thought.

# Parameter Hierarchies Example: Summary

## 3-jet events have a smaller $\langle x_B \rangle$ than 2-jet events

So if you don't get the relative mixture of 2- to 3-jet events right, then you would be in unsafe territory trying to fit **lower-scale** non-perturbative parameters to an inclusive measurement of $\langle x_B \rangle$.

## What can you do?

Use the value for the shower $\alpha_s$ that gets the "right" 3/2 jet ratio at LEP

*Or:* use multi-leg NLO merging (~ NNLO matching)

*Or:* use reweighting to measured 3-jet distributions?

*Or:* use $\langle x_B \rangle$ in an **exclusive 2-jet sample** that does not depend on the relative 2-to-3-jet ratio.

*Or:* say you ***want*** to keep the B hadron energy fraction constant. (My feeling is this overcompensates.)

Similar comments for many other tuning parameters, eg aLund, bLund, sigmaPT, …

# Feedback on Questions from ATLAS

**Are there plans for producing a Monash-level tune for VINCIA showers?**

Is this an area where collaboration between ATLAS and PYTHIA developers would be useful?

**Quick answer is yes:** (partly done already; more work needed for LHC)

`PartonShowers:model = 2` (VINCIA) already automatically switches to a dedicated set of VINCIA default hadronisation parameters

(eg different values for aLund, bLund, etc) ➜ similar level of agreement at LEP as Monash.

Substantial changes across recent versions; full-fledged pp retune not done yet.

➜ UE modelling not as good as Monash & not cross checked at 13 TeV (yet).

Only ~3 people work on VINCIA [PZS, C T Preuss & L Gellersen, all with other big projects];

**Very interested** in feedback, validations, suggestions, from ATLAS!

**Recent effort started in Pythia to produce new default tunes** (Lead: S. Mrenna)

LO *and* NLO level tunes (with new generation of PDFs) + uncertainties

Including both the SimpleShower and VINCIA showers.

Timescale ~ 1 year (?)

# VINCIA Default Tune

| Name | VINCIA Default | Monash |
|---|---|---|
| BeamRemnants:primordialKThard | 0.400 | 1.800 |
| BeamRemnants:primordialKTsoft | 0.250 | 0.900 |
| ColourReconnection:range | 1.750 | 1.800 |
| MultipartonInteractions:alphaSorder | 2 | 1 |
| MultipartonInteractions:alphaSvalue | 0.119 | 0.130 |
| MultipartonInteractions:ecmPow | 0.210 | 0.215 |
| MultipartonInteractions:expPow | 1.750 | 1.850 |
| MultipartonInteractions:pT0Ref | 2.240 | 2.280 |
| SigmaProcess:alphaSorder | 2 | 1 |
| SigmaProcess:alphaSvalue | 0.119 | 0.130 |
| StringFlav:etaPrimeSup | 0.100 | 0.120 |
| StringFlav:etaSup | 0.500 | 0.600 |
| StringFlav:mesonCvector | 1.300 | 0.880 → 1.5 |
| StringFlav:mesonSvector | 0.530 | 0.550 |
| StringFlav:mesonUDvector | 0.420 | 0.500 |
| StringFlav:popcornSmeson | 0.750 | 0.500 |
| StringFlav:popcornSpair | 0.750 | 0.900 |
| StringFlav:probQQ1toQQ0 | 0.025 | 0.028 |
| StringFlav:probQQtoQ | 0.077 | 0.081 |
| StringFlav:probSQtoQQ | 1.000 | 0.915 |
| StringFlav:probStoUD | 0.205 | 0.217 |
| StringPT:sigma | 0.305 | 0.335 |
| StringZ:aExtraDiquark | 0.900 | 0.970 |
| StringZ:aLund | 0.450 | 0.680 |
| StringZ:bLund | 0.800 | 0.980 |
| StringZ:rFactB | 0.850 | 0.855 |
| StringZ:rFactC | 1.150 | 1.320 → 1.5 |
| TimeShower:interleaveResDec | on | off |

**Main Reference:**

Sector Showers for Hadron Collisions

Helen Brooks, Christian T. Preuss, PZS

JHEP 07 (2020) 032

**Dedicated study of VBF with Powheg matching and sector-CKKWL merging:**

A Study of QCD Radiation in VBF Higgs Production with Vincia and Pythia

Stefan Höche Stephen Mrenna, Shay Payne, Christian T. Preuss, PZS

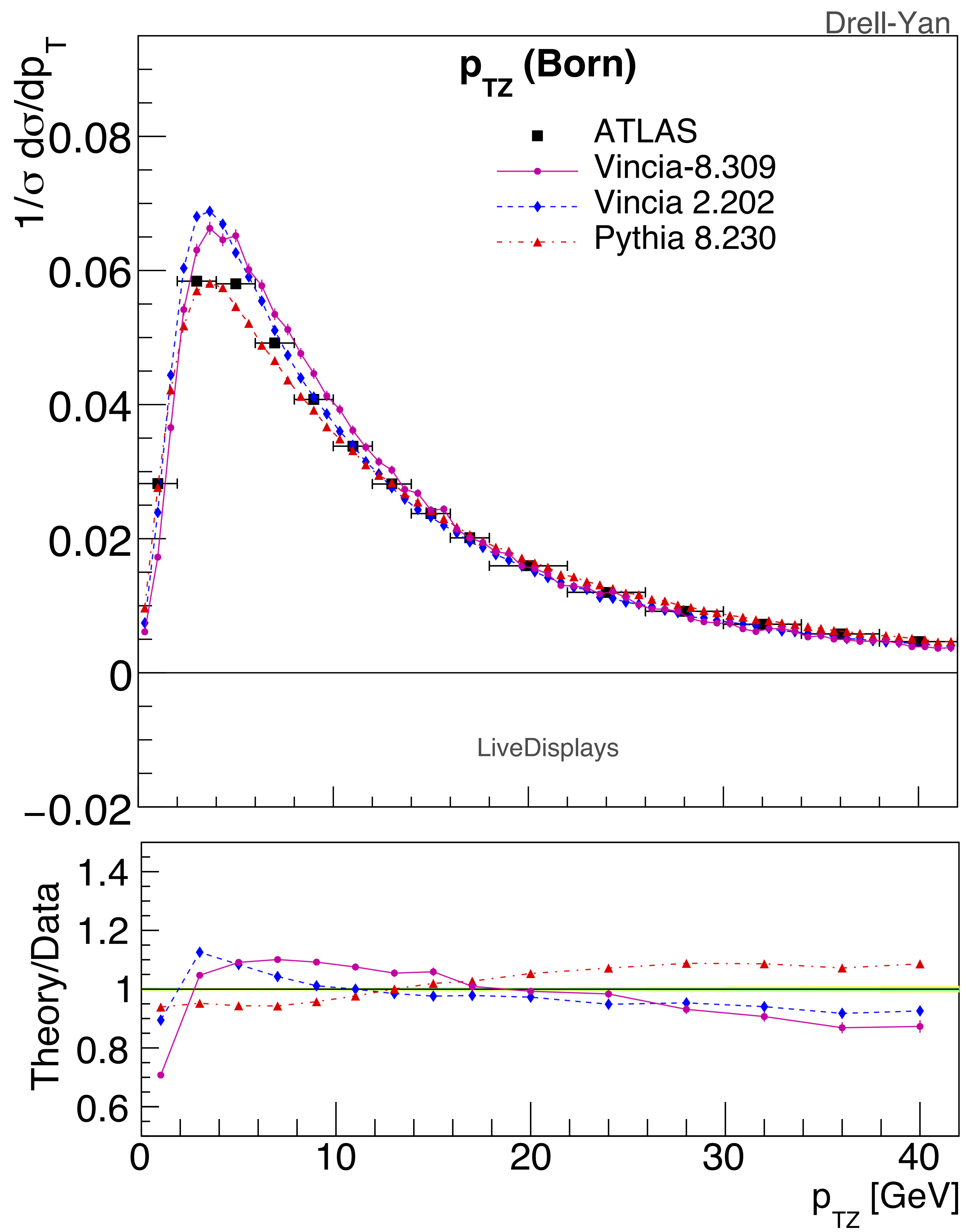
SciPost Phys. 12 (2022) 1, 010

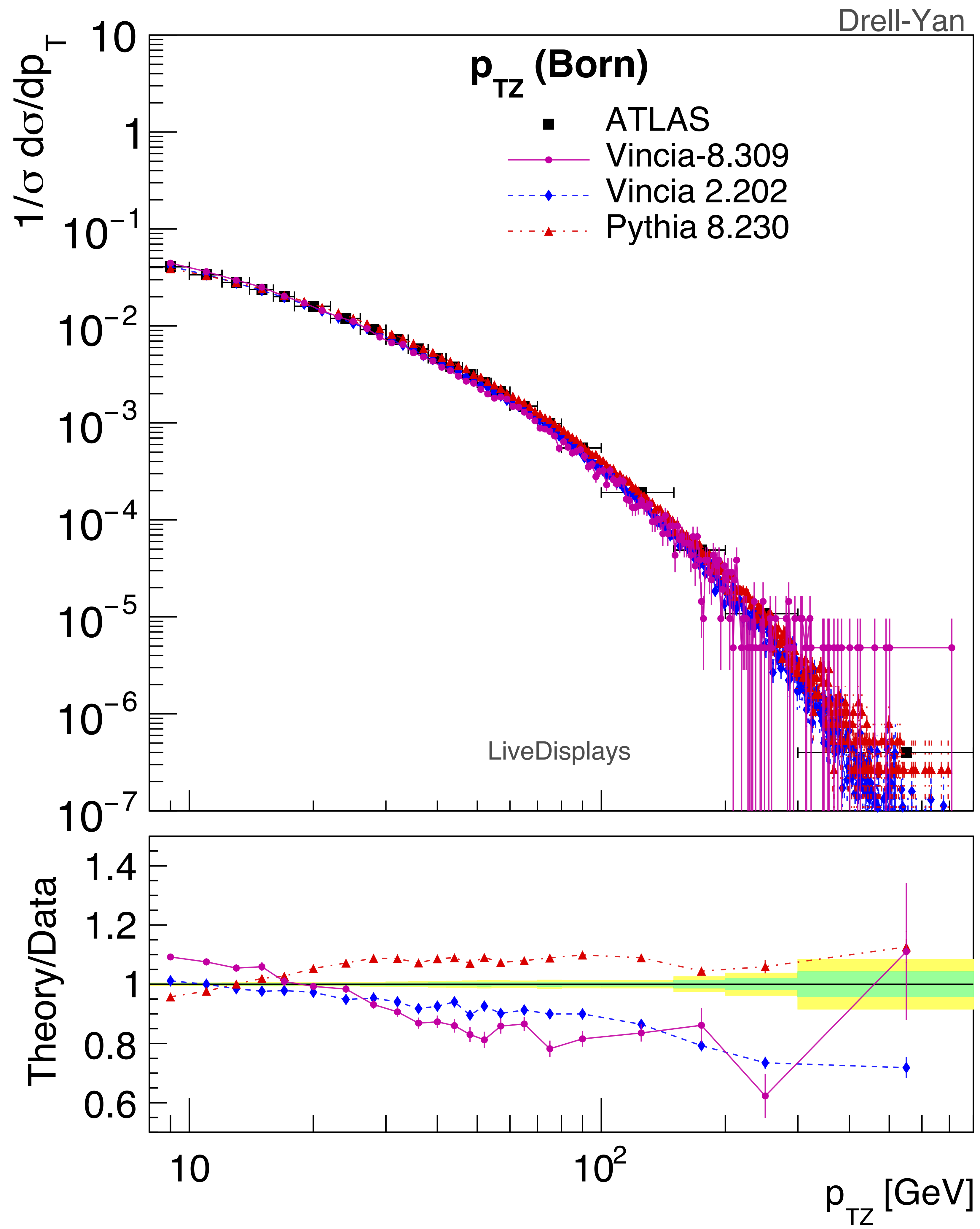
**Also:**

- Multipole QED shower
  - (+ plans to apply to hadron decays)
- Interleaved Resonance Decays
  - (+ plans to apply to hadron decays)
- Full-fledged EW shower
- Several research projects underway
  - LO matrix-element corrections
  - NLO matrix-element corrections
  - NNLO matching

# Vincia Default Tune

## ISR: Drell-Yan pT spectrum



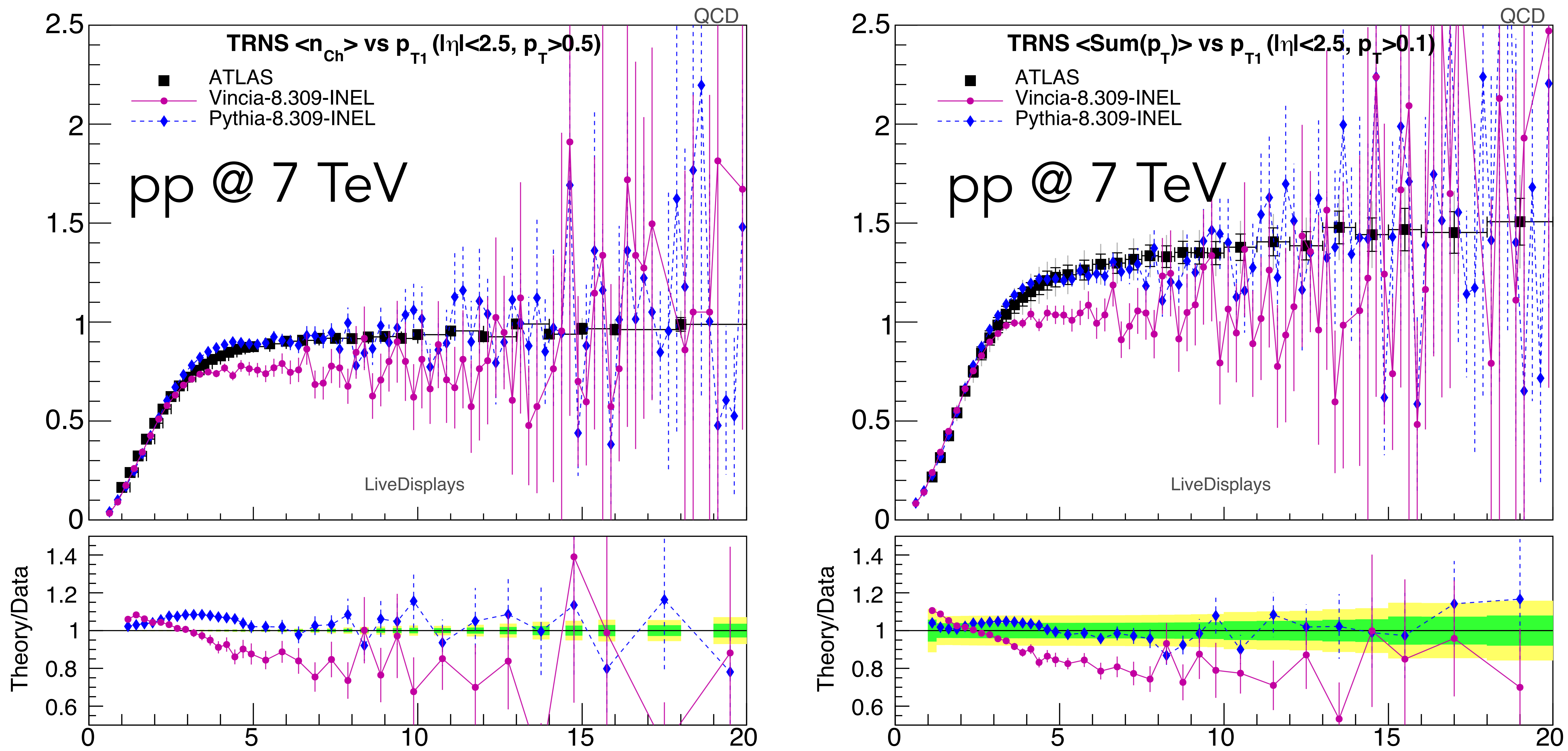

Note:

| | | |
|---|---|---|
| BeamRemnants:primordialKThard | 0.400 | 1.800 |
| BeamRemnants:primordialKTsoft | 0.250 | 0.900 |

Note: expect LO matrix-element corrections for many processes ~ soon

## Multi-parton interactions: UE at 7 TeV

(Sorry, I did not manage to generate much statistics ahead of talk but wanted to show you with current version, 8.309)




Note: will probably be updated (and faster) with new QCD CR in upcoming versions

# Feedback on Questions from ATLAS

## Great if we could have a way to dump out "effective standalone" Pythia configs from the ATLAS interface

As is the case for Herwig and Sherpa.

Requires more standardising of the Pythia executable?

It differs from the other gens in not having one main steering binary

## The quick answer is yes (but only partly)

You can dump all changed settings

**bool Settings::writeFile(string toFile, bool writeAll = false)**
**bool Settings::writeFile(ostream& os = cout, bool writeAll = false)**
write current settings to a file or to an `ostream`.
`argument` **toFile, os** : file or stream on which settings are written.
`argument` **writeAll** (`default = off`) : normally only settings that have been changed are written, but if true then all settings are output.
**Note:** the method returns false if it fails.

**bool Settings::writeFileXML(ostream& os = cout)**
write out the information stored in xmldoc to be used later to initialize Settings through an input stream.

So far no equivalent for ParticleData (but not hard to implement?)

And of course you still need main program + any UserHooks (+ ext libraries) etc you link.

# Feedback on Questions from ATLAS

## Could we get a summary of what has happened in the API?

That might allow us to simplify/standardise our interface code, especially around all the special cases that are coded in there. Some interest in having an "ATLAS example" executable that does "the ATLAS things", but is that the wrong framing? The executable idea is fine, but we really want to have all our current treatments callable from the Pythia library, so both the standalone executable and the interface just consist of very minimal calling of API routines. Then it is easy to synchronise. Otherwise the "Athena ATLAS" and "Pythia ATLAS" modes will not be synced and will drift apart.

## **Sounds** (to me) **mostly like an ATLAS internal discussion / internal consistency?**

No plans from our side to make significant changes to the Pythia "API"

Question: is there something you cannot achieve with current structure?

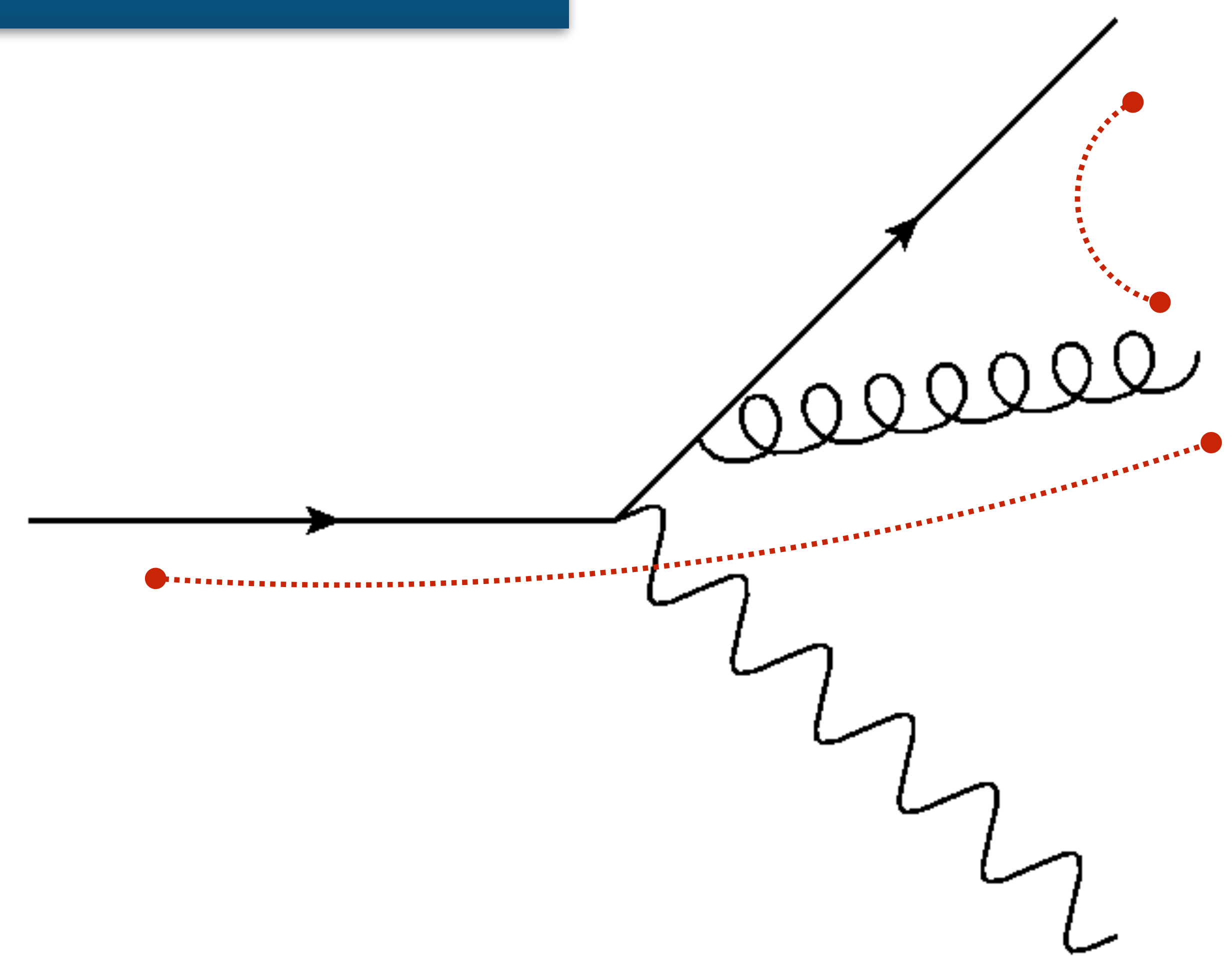
# **RecoilToTop:** Coherence in Top Decay: 2nd emission

## Second (and subsequent) emissions in top decay

Not controlled by PowHeg, nor by Pythia's MECs.

Not as important as 1st em. Still highly significant if goal is per-mille precision on $m_t$

**VINCIA RF**



$tg$ RF antenna:

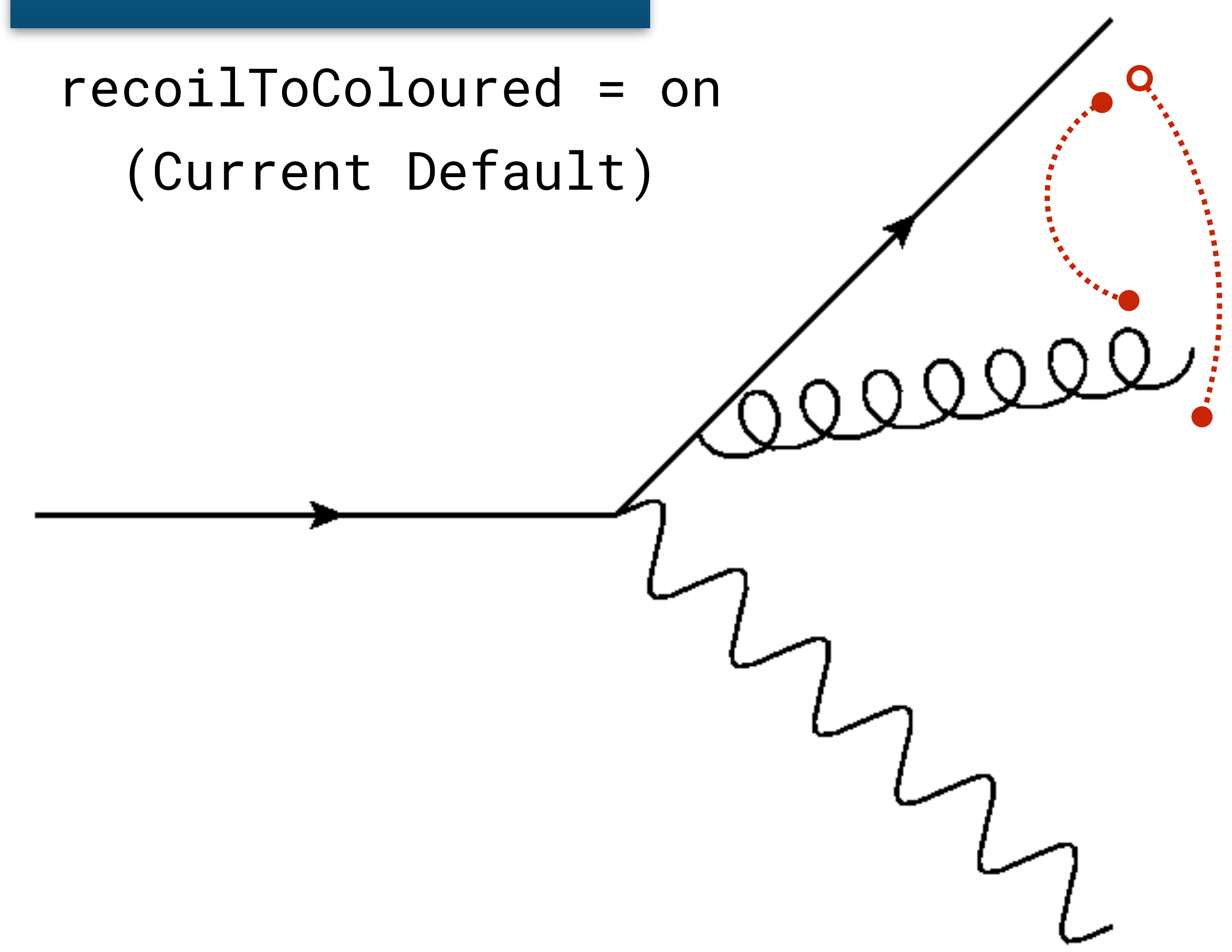
Phase space & recoils set by:

$t - g = b + W$

Collective recoil

**PYTHIA**

`recoilToColoured = on`
`(Current Default)`



$g - t$ dipole treated as $g - b$:

Phase space & recoils set by $b$

Affects $b$ fragmentation

## PYTHIA allows different coherence/recoil options in top decays

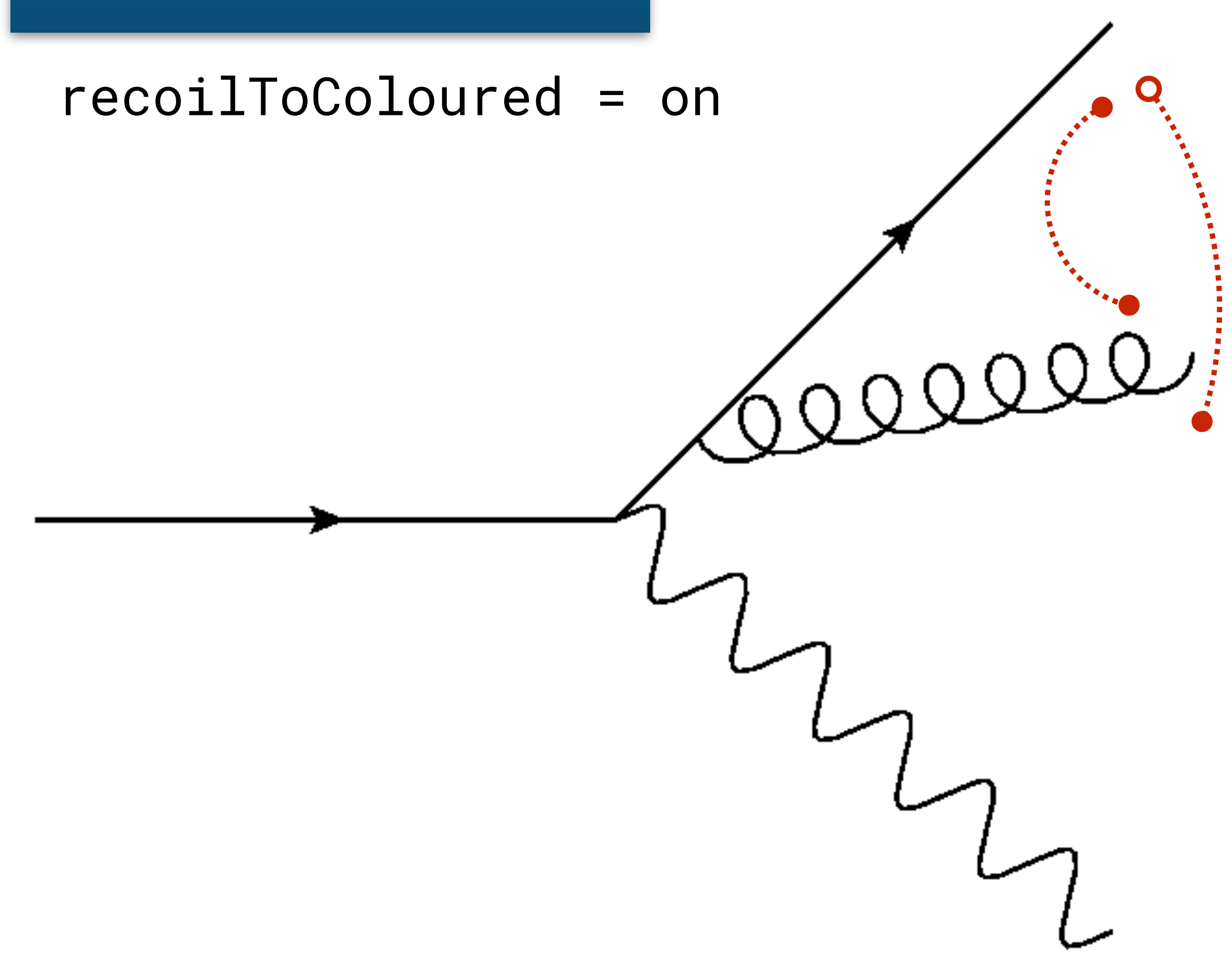
Recently made a dedicated UserHook "recoilToTop" (for use with recToCol = off) → 8.310 in code!

Theoretically the "least bad" option (in absence of Vincia-style RF antennae).

Needs validations & feedback.

**PYTHIA**

`recoilToColoured = on`



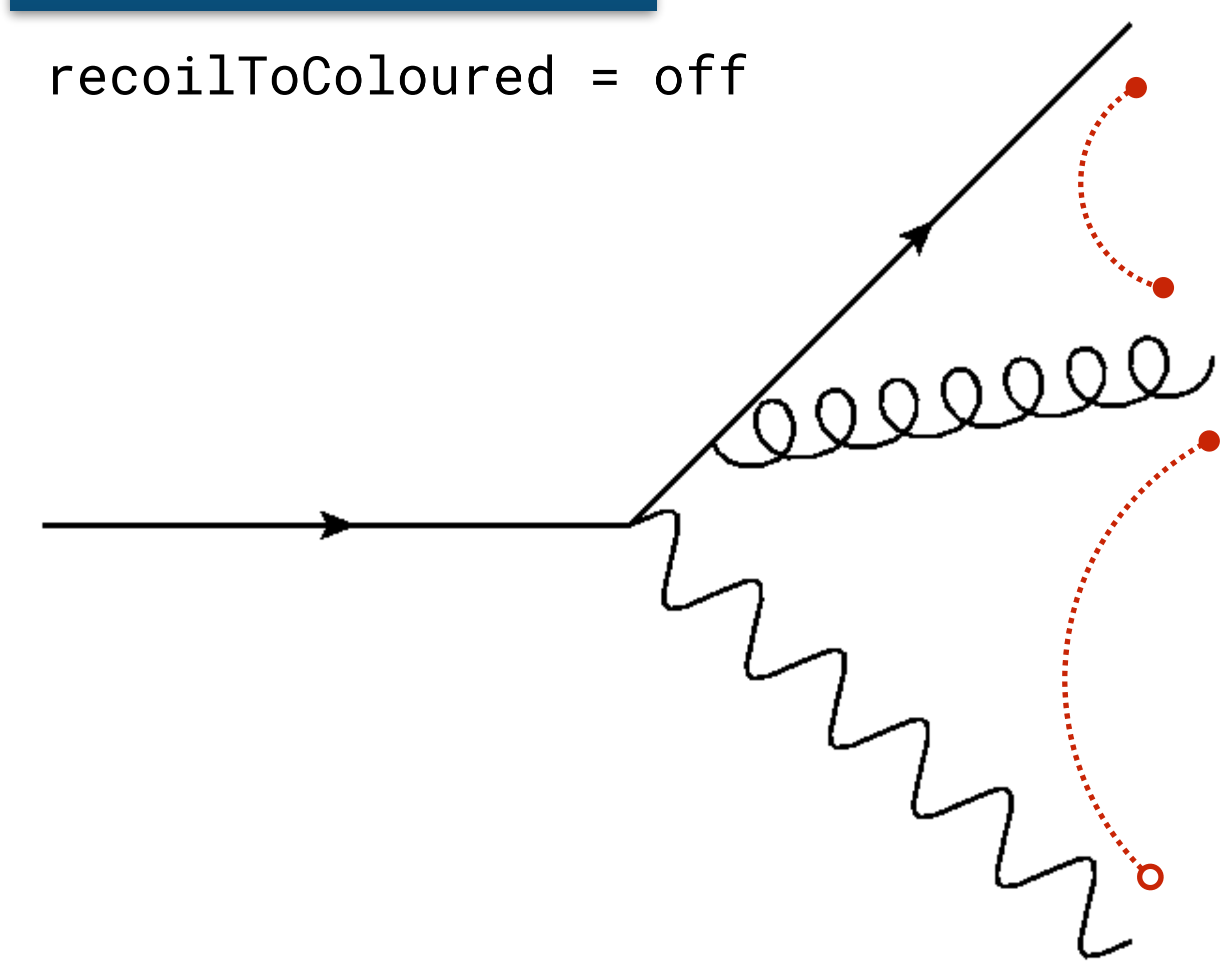
$g-t$ dipole treated as $g-b$:

Phase space & recoils set by $b$

Affects $b$ fragmentation

**PYTHIA**

`recoilToColoured = off`



$g-t$ dipole treated as $g-W$:

Phase space & recoils set by $W$

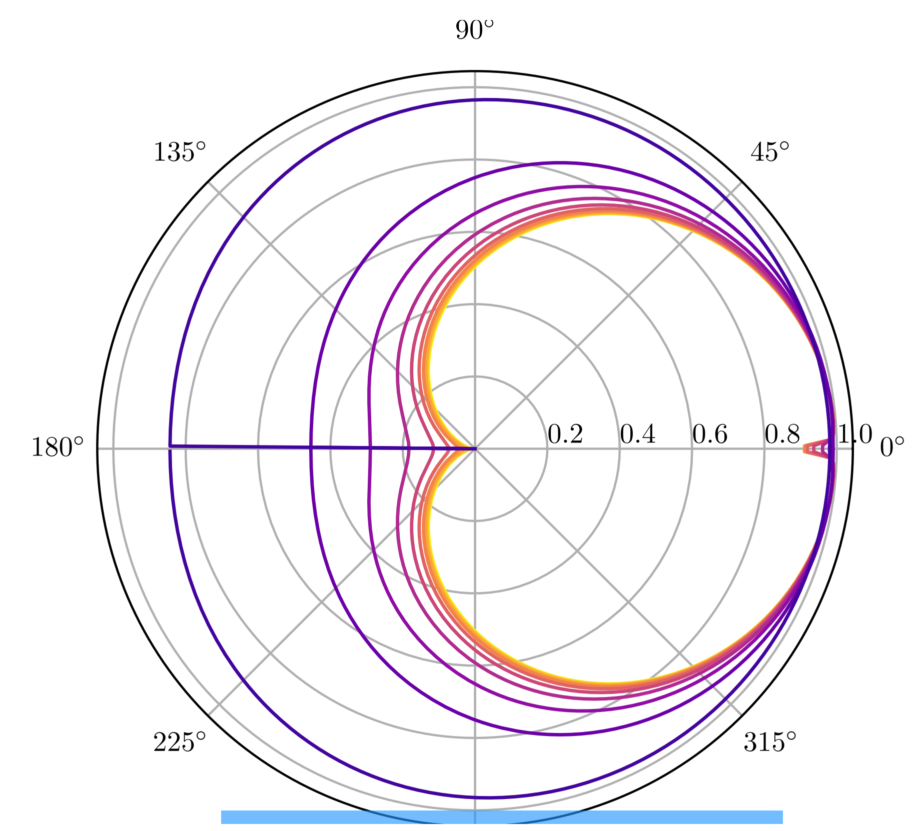
b fragmentation more "normal"?

**recoilToTop UserHook**

Suppresses radiation in W hemisphere

$\otimes$ Correction factor

~




**NEW** in 8.310: ~~`TimeShower:recoilToColoured`~~ → `TimeShower:recoilStrategyRF`

# Feedback on Questions from ATLAS

## What do the MECorrections actually do

Are they also applicable for processes with offshell contributions like bb4l?

There are three different options given in the manual:

TimeShower:MEafterFirst,

TimeShower:MEcorrections,

TimeShower:MEextended.

Could you explain a bit what they do?

## Matrix-Element Corrections

### Modify parton shower

Bengtsson, Sjöstrand, PLB 185 (1987) 435

Use splitting kernels ∝ full matrix element for 1st emission:

$$\text{Parton Shower } \frac{P(z)}{Q^2} \to \frac{P'(z)}{Q^2} = \frac{P(z)}{Q^2} \underbrace{\frac{|M_{n+1}|^2}{\sum_i P_i(z)/Q_i^2 |M_n|^2}}_{\text{MEC}}$$

(suppressing $\alpha_s$ and Jacobian factors)

Process-dependent MEC → P′ different for each process

### Done in PYTHIA for all SM decays and many BSM ones

Norrbin, Sjöstrand, NPB 603 (2001) 297

Based on systematic classification of spin/colour structures

(Also used to account for mass effects, and for a few simple hard processes like Drell-Yan.)

### Difficult to generalise beyond one emission

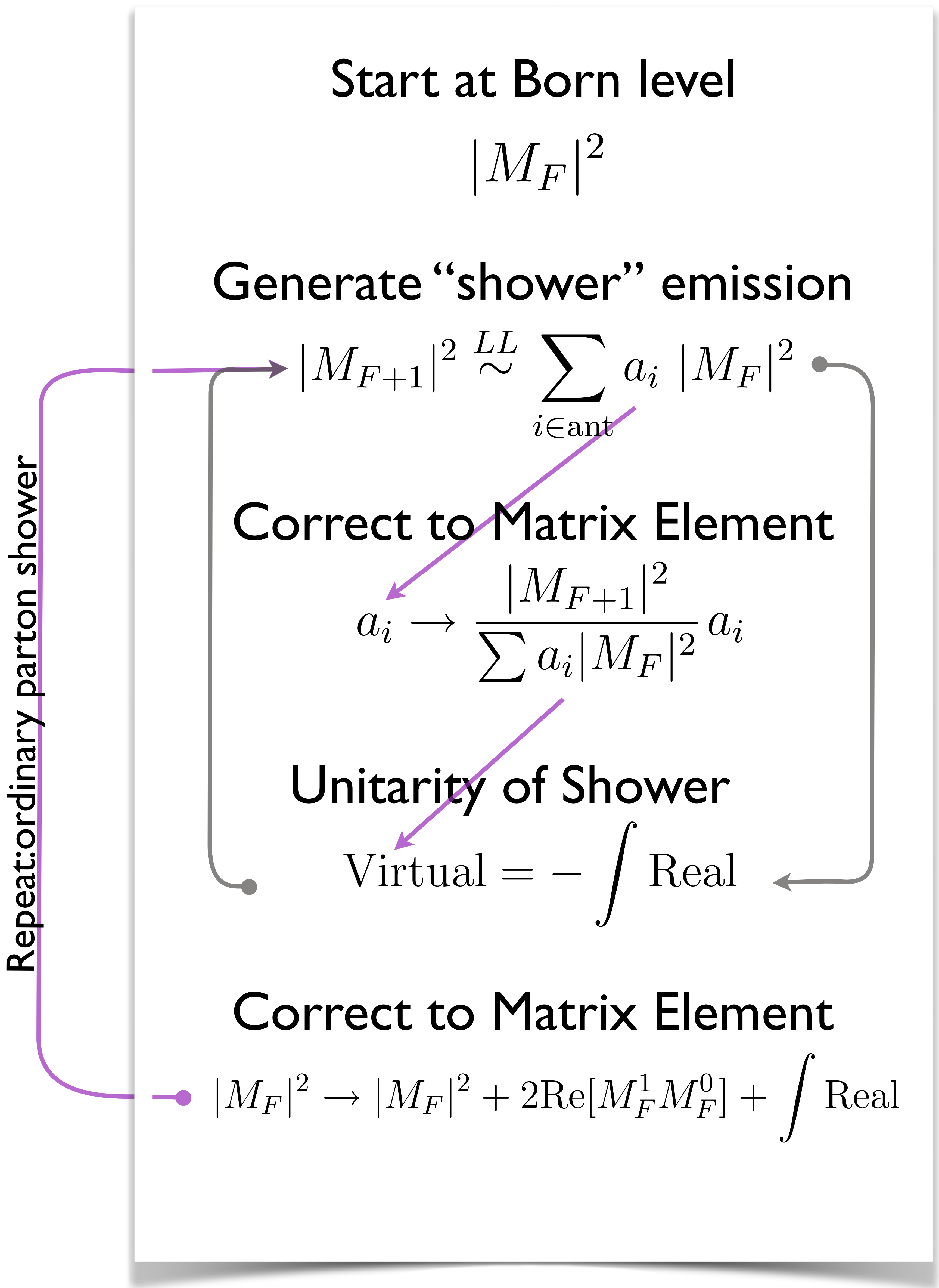
Parton-shower expansions complicated & can have “dead zones”

Achieved in VINCIA (by devising showers that have simple expansions)

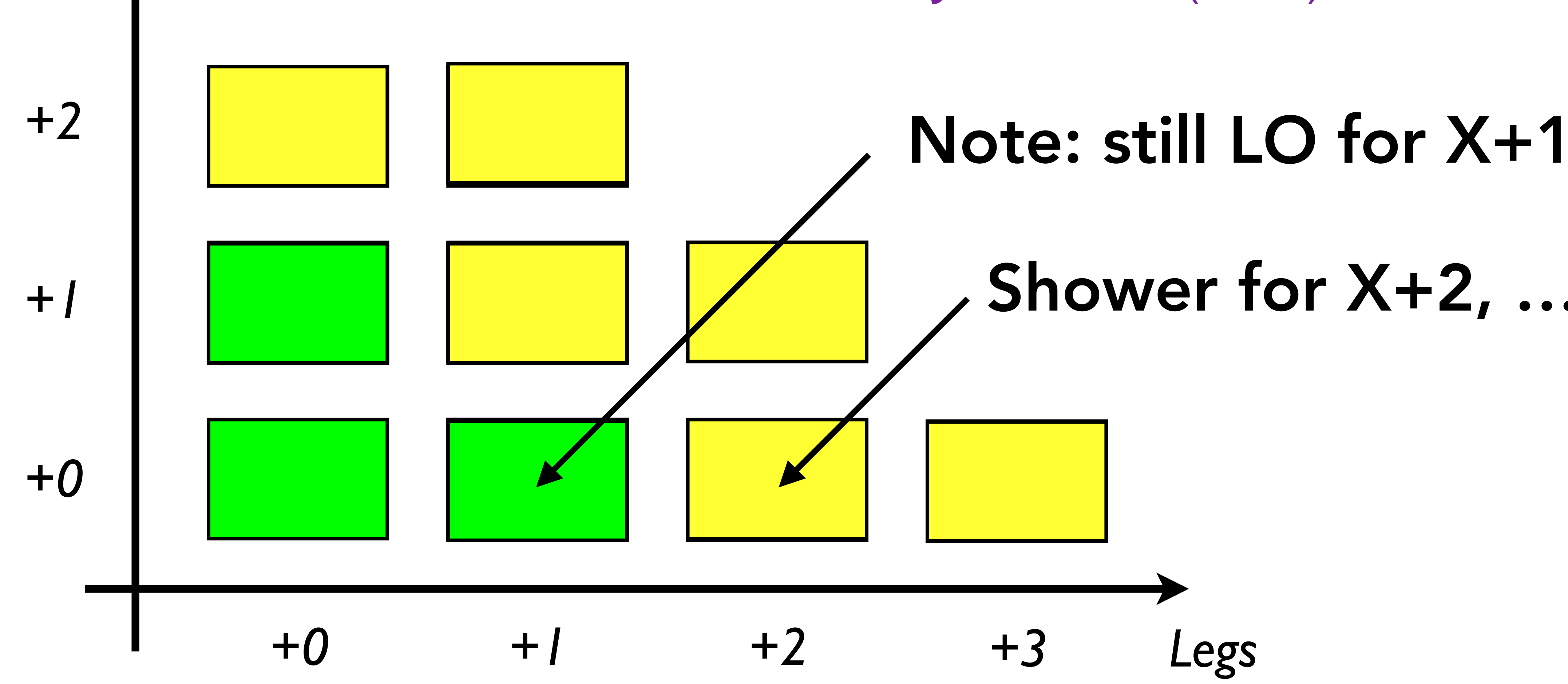
Giele, Kosower, Skands, PRD 84 (2011) 054003
Fischer et al, arXiv:1605.06142

# (MECs with Loops: POWHEG)

Acronym stands for: **Po**sitive **W**eight **H**ardest **E**mission **G**enerator.




Nason, JHEP 0411 (2004) 040
Frixione, Nason, Oleari JHEP 0711 (2007) 070
+ POWHEG Box JHEP 1006 (2010) 043




**PowHeg is widely applied/available, can be used with PYTHIA, HERWIG, SHERPA**

**Subtlety 1: Connecting with parton shower**

*Truncated Showers & Vetoed Showers*

**Subtlety 2: Avoiding (over)exponentiation of hard radiation**

Controlled by *"hFact" parameter (POWHEG)*

# MECs: Pythia Parameters

`flag` **TimeShower:MEcorrections** (`default = on`)
Use of matrix element corrections where available; on/off = true/false.

`flag` **TimeShower:MEextended** (`default = on`)
Use matrix element corrections also for $1 \to n$ and $2 \to n$ processes where no matrix elements are encoded, by an attempt to match on to one of the $1 \to 2$ processes that are implemented.

This should at least provide relevant **mass dampening** for massive radiators and recoilers.

Only has a meaning if `MEcorrections` above is switched on.

`flag` **TimeShower:MEafterFirst** (`default = on`)
Use of matrix element corrections also after the first emission, **for dipole ends of the same system that did not yet radiate**.

Only has a meaning if `MEcorrections` above is switched on.

# Pythia — Other Recent Activity and Plans

## Perturbative Accuracy

**VINCIA:** NNLO matching, iterated ME corrections, $2 \rightarrow 4$ branchings, 2nd-order kernels, recoil strategies, …

**PanScales** showers ↔ Pythia 8 (PZS to spend 1-year sabbatical at Oxford from August onwards)

## Hadronisation and Tuning

Colour Reconnections & String Junctions (QCD CR model being revisited, Dipole Swing)

Strangeness (Close-Packing & Rope hadronization)

QED corrections in hadron decays (esp B hadrons, viz PHOTOS)

B decays (with EVTGEN, Monash-Warwick Alliance)

Forward proton spectra NA61/Shine

Automated Shower **and Hadronisation** Uncertainties

## Heavy-Ion Physics, Collectivity, Cosmic Rays, Low-Energy Scattering

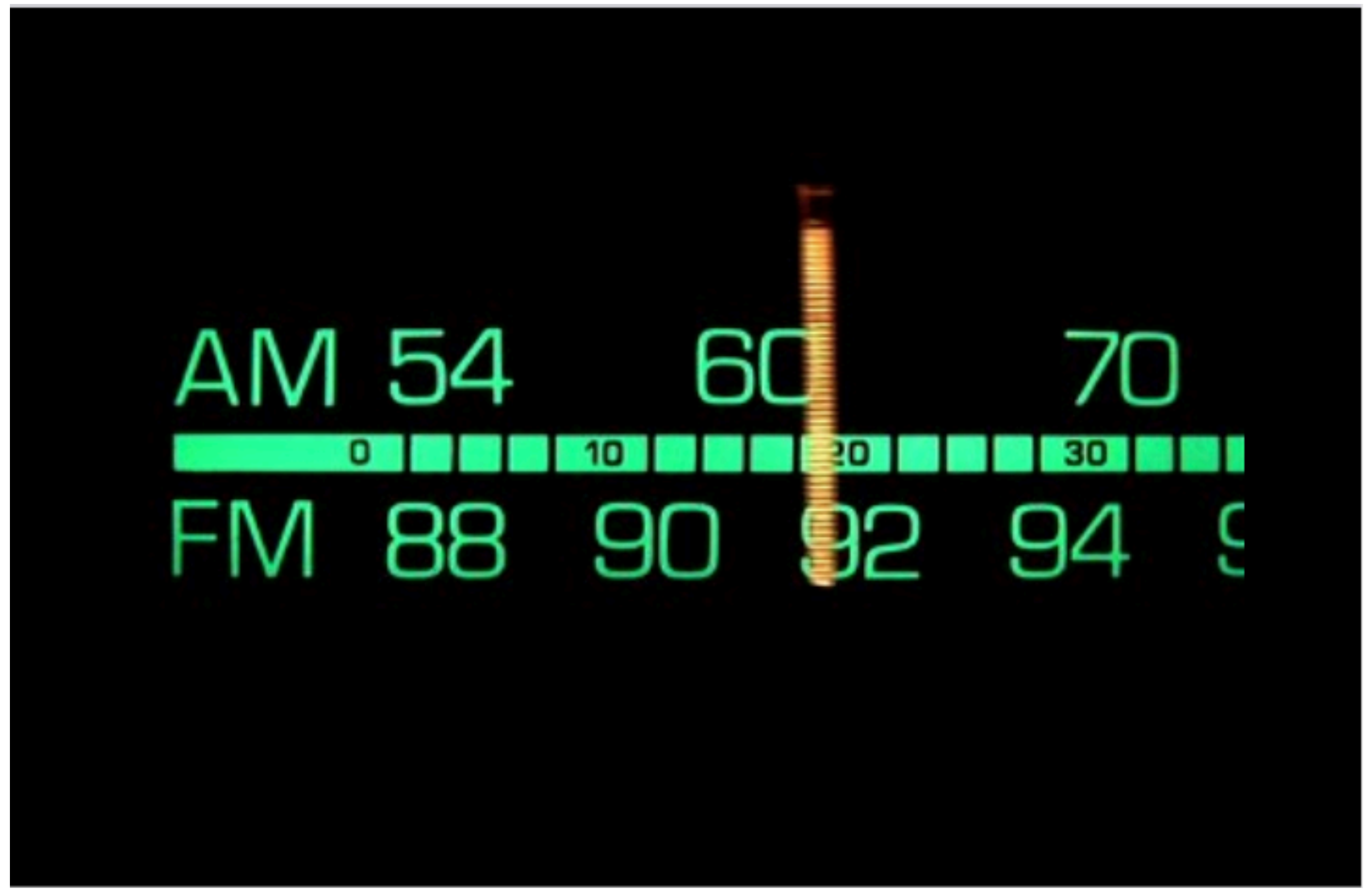
Angantyr / Gleipnir: Pythia-based modelling of Heavy-Ion collisions **without medium**

Hadronic Rescattering and Low-Energy Cross Sections

EIC and Neutrino-Ion?

Cosmic-Ray Air Showers (variable beams & energies)

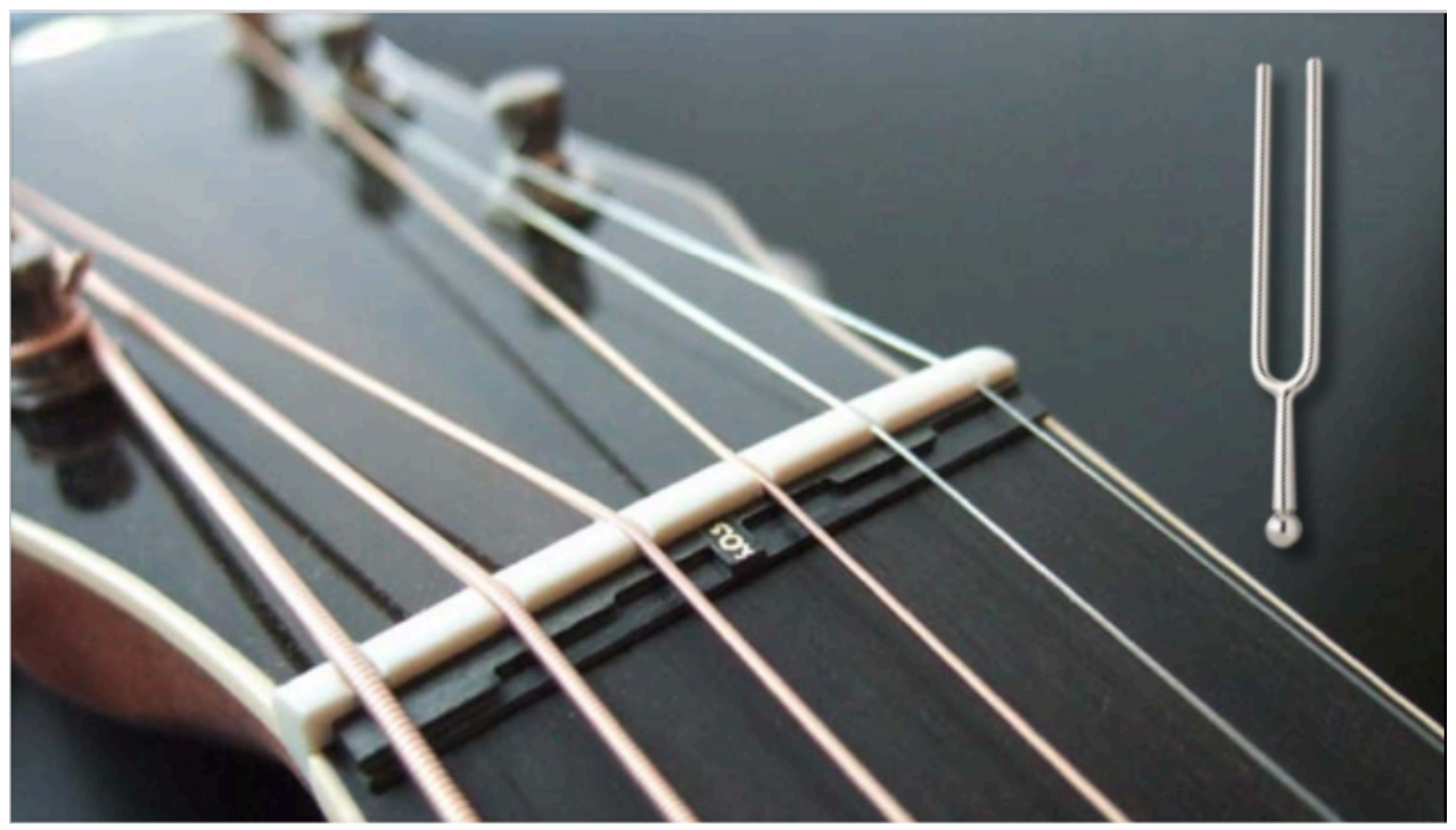
# **Tuning**: Some general comments. What do you want it to be?




## Sensible

A set of physically sensible central parameter values, with good universality.

What does "physically sensible" and "good universality" really mean?
Understanding MC models: hierarchies, universalities, and sensitivities.



## Sophisticated

High-precision & specialised parameter sets, with reliable uncertainties

Tuning in the context of $N^nLO$ matching & precision applications.
Theory uncertainties. Rigorous scientific analyses of parameter spaces.

## Best Fit

A pure optimisation problem. The **best fit** you can get. Ask questions later.

Risky? Overfitting, oversimplification, GIGO, black-box syndrome, tunnel vision, loss of insight & scientific rigour, Tyranny of Carlo,…

# Reliable Uncertainties and Preventing Overfitting

**Monash Tune:** 5% flat sanity-limit Theory Uncertainty to prevent overfitting

Can this be improved on? Using better theory uncertainty estimates? & sensitivities?

Would like TH uncertainties to get to ~ $\chi^2_{\rm red}$ ~ 1. Not well-defined across multiple distributions with unknown correlations.

(Monash Tune was done by eye, so this was simply a matter of judgement.)

Use Pythia to map correlations between observables and incorporate in tuning?

**Professor's eigentunes may be prone to artifacts of overtuning**

E.g., **well-measured peak will dominate**, with arbitrarily tiny uncertainties, at price of not spanning range in tails/asymptotics. Unclear interplay with genuine theory uncertainties.

See eg arXiv:1812.07424 for examples (and slightly more elaborate way to address issue but still fundamentally based on the flat 5% sanity limit)

**There is still a need to develop reliable well-motivated uncertainty variations**

Beyond "eigentunes" (Perugia had simple ones, Monash had none)

Ideally also propose ***method*** for how to obtain them, and justify or improve on the 5% approach.

## Data Preservation: HEPDATA

Online database of experimental measurement results

Please make sure all 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

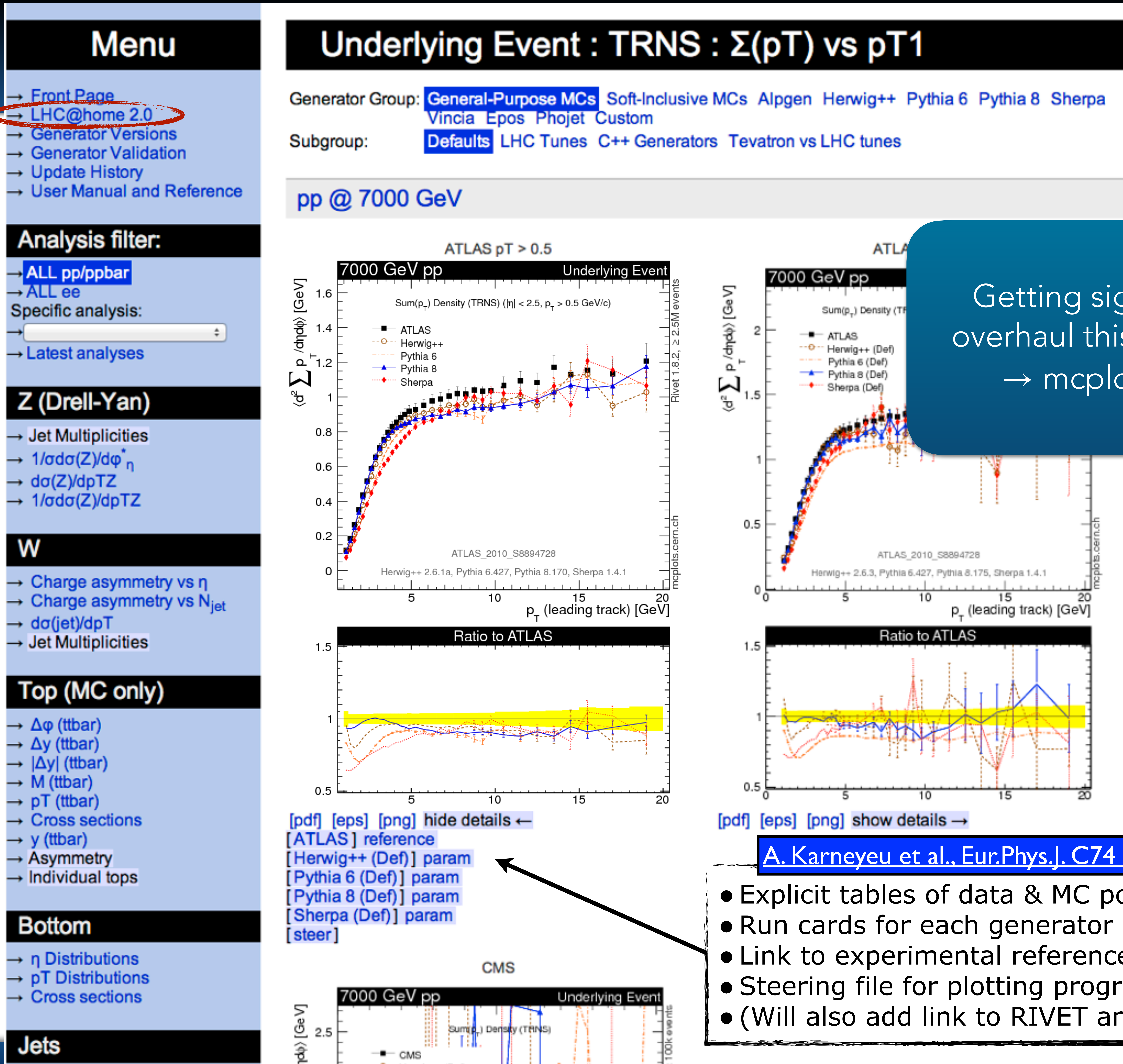
Online plots made from Rivet analyses

Want to help? **Connect to LHC@home project Test4Theory**

## Reproducible tuning: PROFESSOR, AUTOTUNES, APPRENTICE (& more?)

Automated tuning (& more)

mcplots.cern.ch




Getting significant overhaul this summer → mcplots 2.0

[A. Karneyeu et al., Eur.Phys.J. C74 (2014) 1]

- 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)

# Join us at LHC@home Test4Theory

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.


Started in 2010, as the first volunteer cloud in the world to use Virtual Machines

# Future Plans

# Extra Slides

# Parameters (in PYTHIA): **FSR pQCD Parameters**

Matching

## Additional Matrix Elements included?

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

$\alpha_s(m_Z)$

## The value of the strong coupling

In PYTHIA, you set an effective value for $\alpha_s(m_Z^2)$ ⇔ choice of $k$ in $\alpha_s(kp_\perp^2)$

$\alpha_s$ Running

## Renormalization Scheme and Scale for $\alpha_s$

1- vs 2-loop running, MSbar / CMW scheme, choice of $k$ in $\alpha_s(kp_\perp^2)$, cf

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, …

Hadron energy fractions

## Fragmentation Function

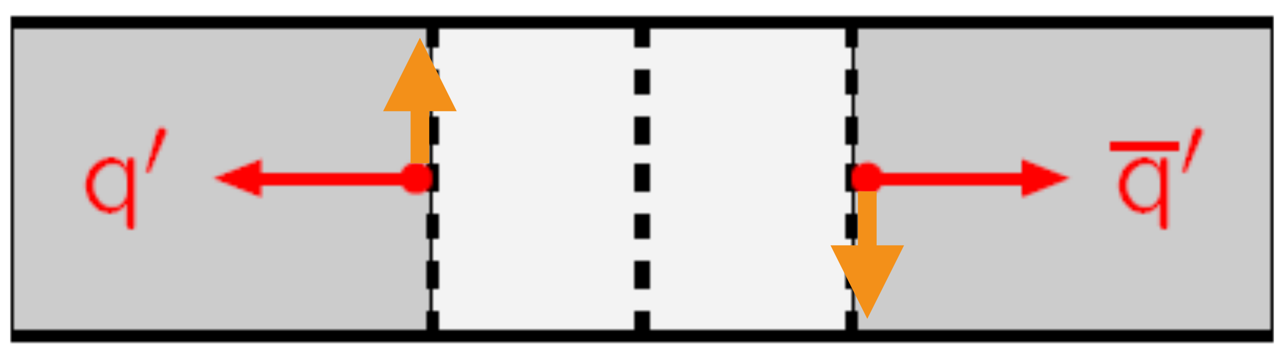

The "Lund $a$ and $b$ parameters" (and $\Delta a_{\mathrm{diquark}}$ for baryons)

Or use $a$ and $\langle z \rangle$ instead (less correlated) A. Jueid et al., *JCAP* 05 (2019) 007

$p_T$ in string breaks

## Scale of string-breaking process

Shower cutoff and $\langle p_\perp \rangle$ in string breaks




Meson Multiplets

## Mesons

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

Baryon Multiplets

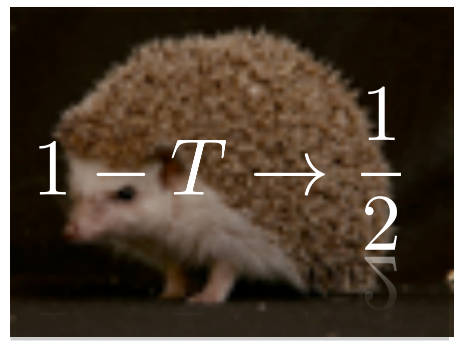
## Baryons

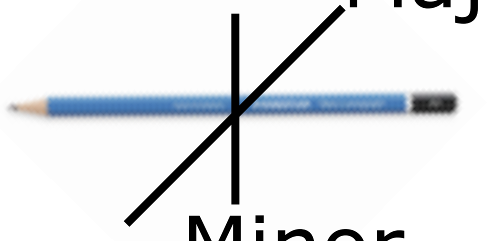
**Baryon-to-meson** ratios, **Spin-3/2 vs Spin-1/2**, "popcorn", colour reconnections (junctions), … ?

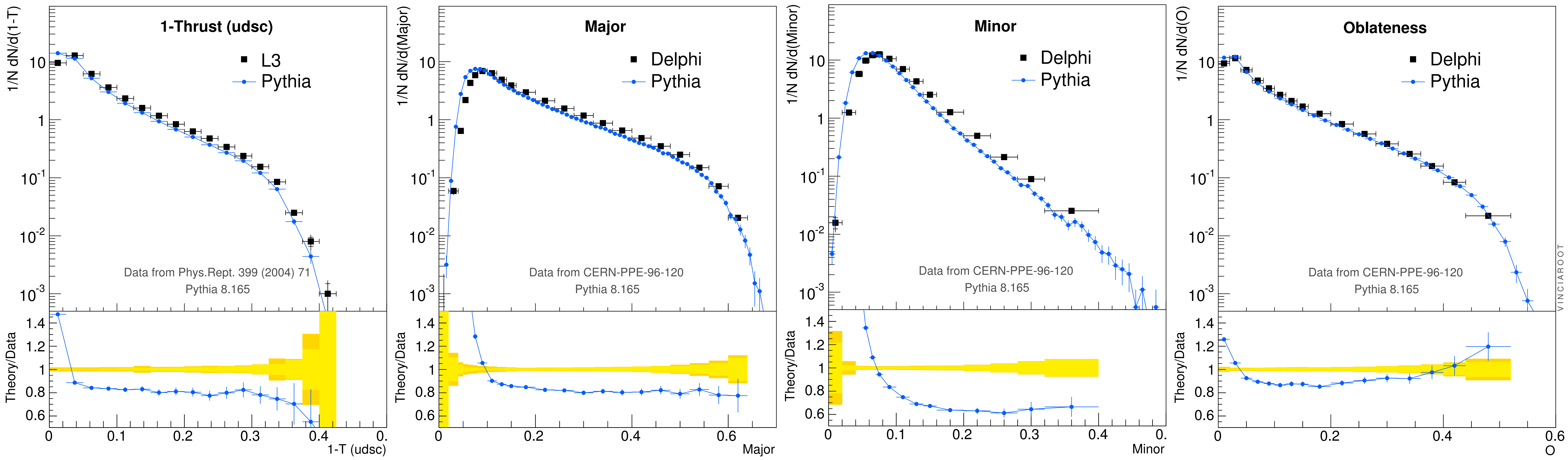
## PYTHIA 8 (hadronization on) vs LEP: Thrust

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

$1 - T \to 0$




Using effective $\alpha_s(M_Z) = 0.12$

# PYTHIA 8 (hadronization on) vs LEP: Thrust

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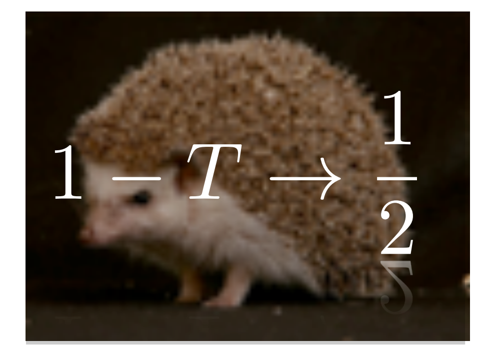
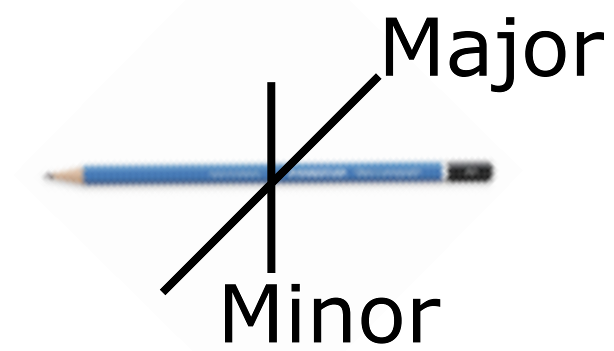
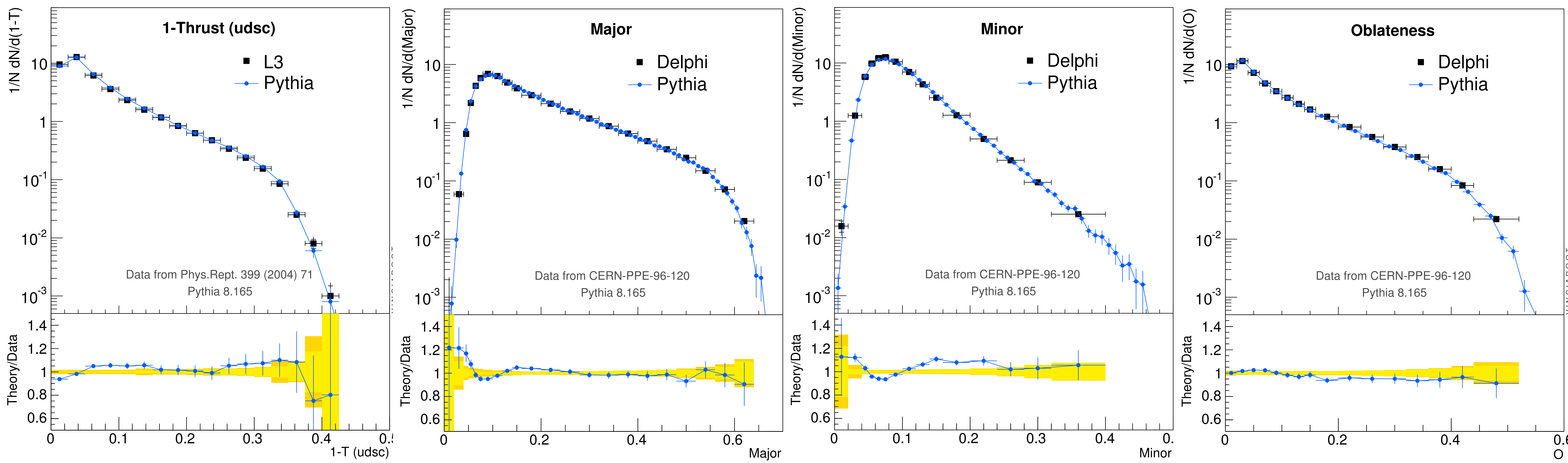
$1 - T \to 0$




Using effective $\alpha_s(M_Z) = 0.14$

# Wait … is this Crazy?

**Best result**

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

$\neq$ World Average ~ 0.118

**Effective value of $\alpha_s$ depends on the order and scheme**

Baseline MC ≈ Leading Order + LL resummation

Other leading-Order extractions of $\alpha_s \approx 0.13 - 0.14$

Effective scheme interpreted as “CMW” → 0.13 Catani, Marchesini, Webber, *Nucl.Phys.B* 349 (1991) 635-654

2-loop running → 0.127; NNLO Matching → 0.12 Hartgring, Laenen, PZS, *JHEP 10 (2013) 127* ; see also backup slides

**Not so crazy** (but does rely on “magic” mathematical accident in Z decay)

Let parameters vary to a level consistent with the (limited) formal accuracy.

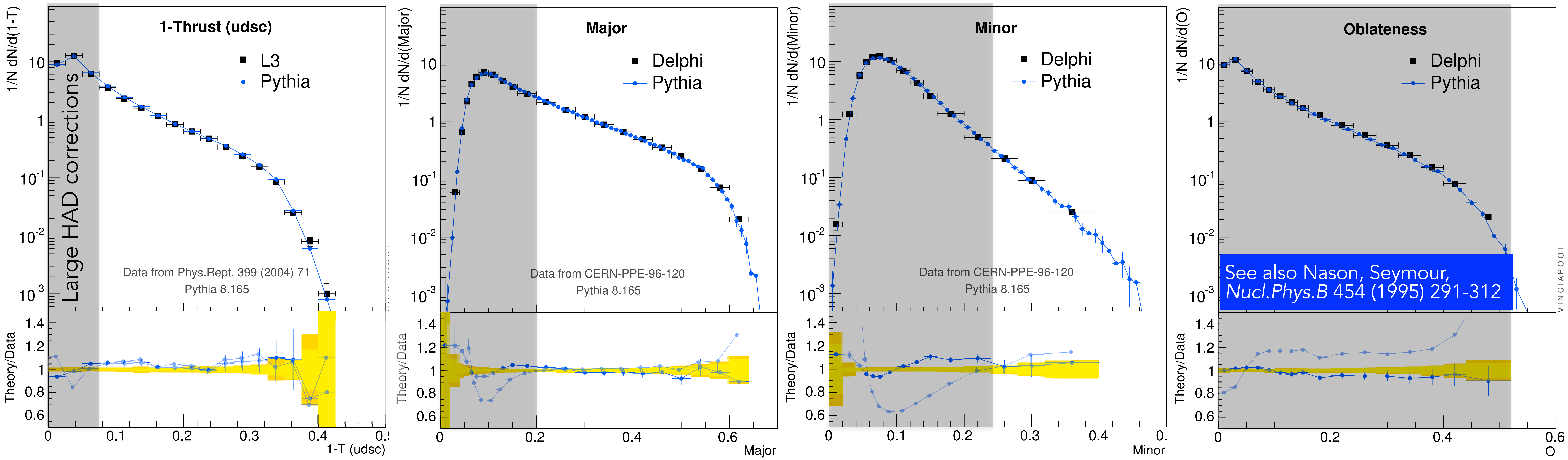
Sanity check = consistency with other determinations at a similar formal order, within the uncertainty at that order (including a CMW-like scheme redefinition to go to ‘MC scheme’)

To improve systematically → Merging at NLO

# PYTHIA 8 (hadronization on) **Vs** (hadronization off)

Important point: These observables are **IR safe ➜ minimal hadronisation corrections**

Big differences in **how** sensitive each of these are to hadronisation & over what **range**

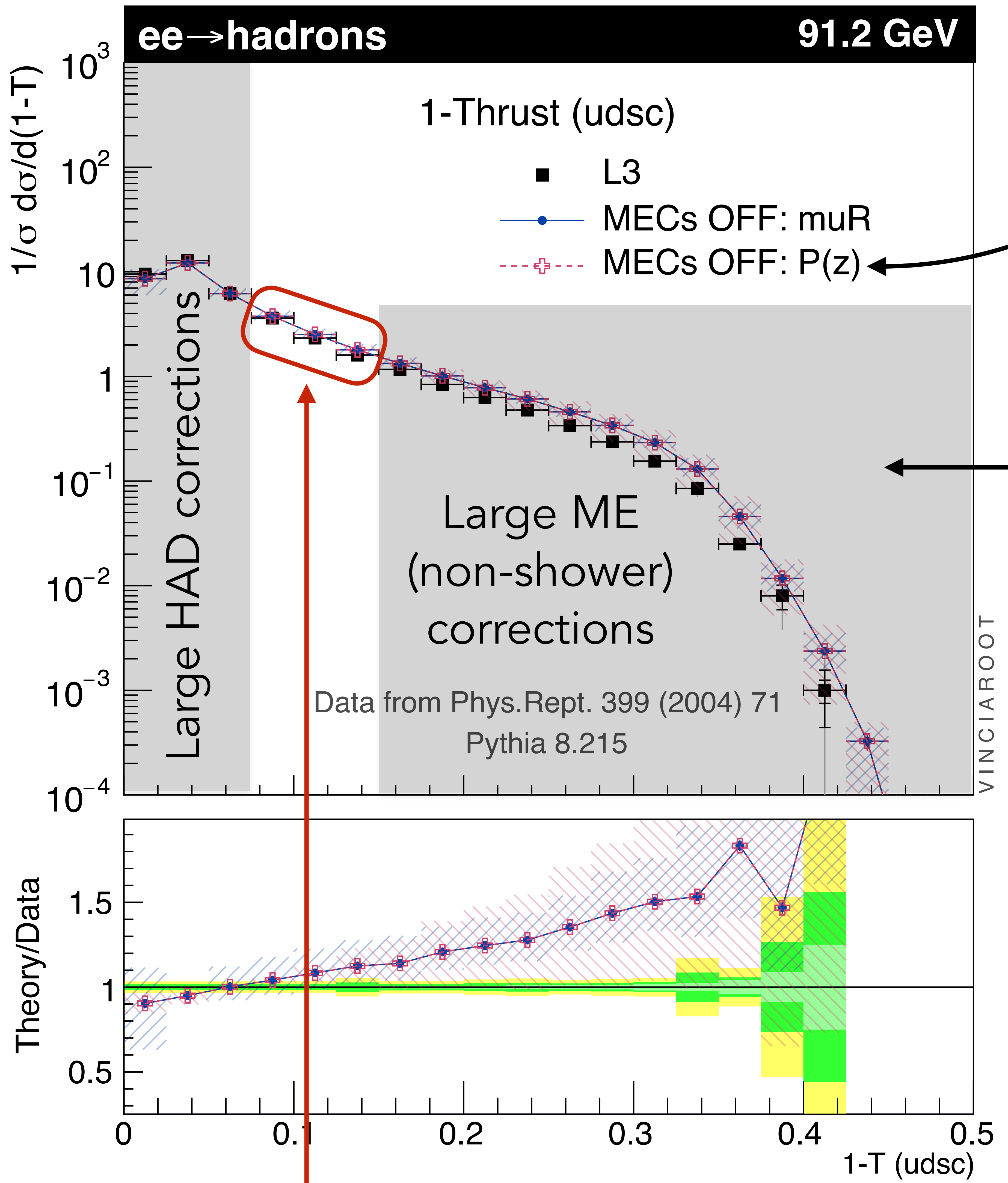



Large sensitivities to "lower" phenomena break the divide-and-conquer simplification.

Another **important** point: **peaks** of distributions are all where **HAD sensitivity is highest**!

# … and **sensitivity** to **fixed-order** corrections

(Adding nuisance terms $\Delta P(z) \propto Q^2$ to the splitting kernels beyond shower accuracy)

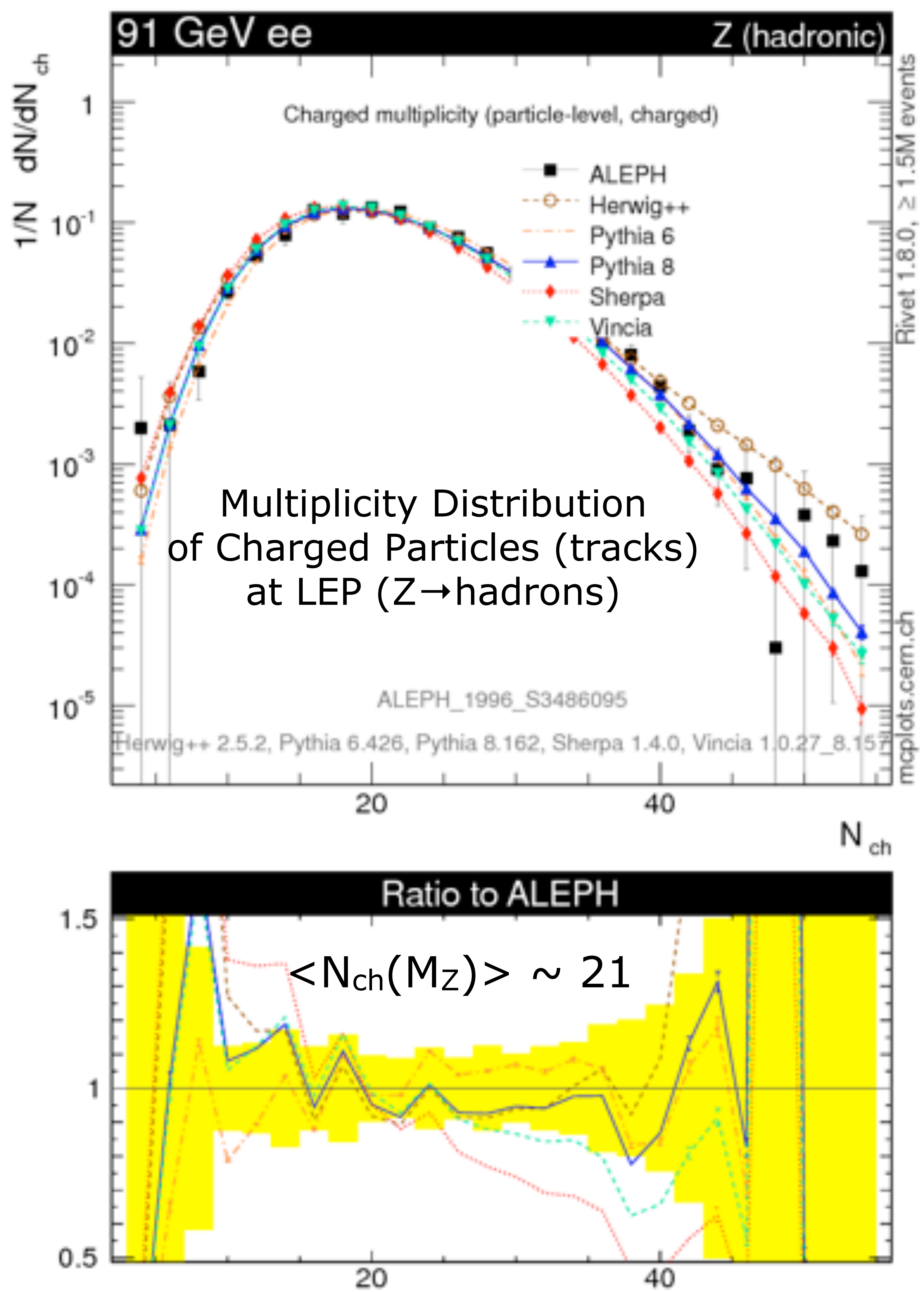


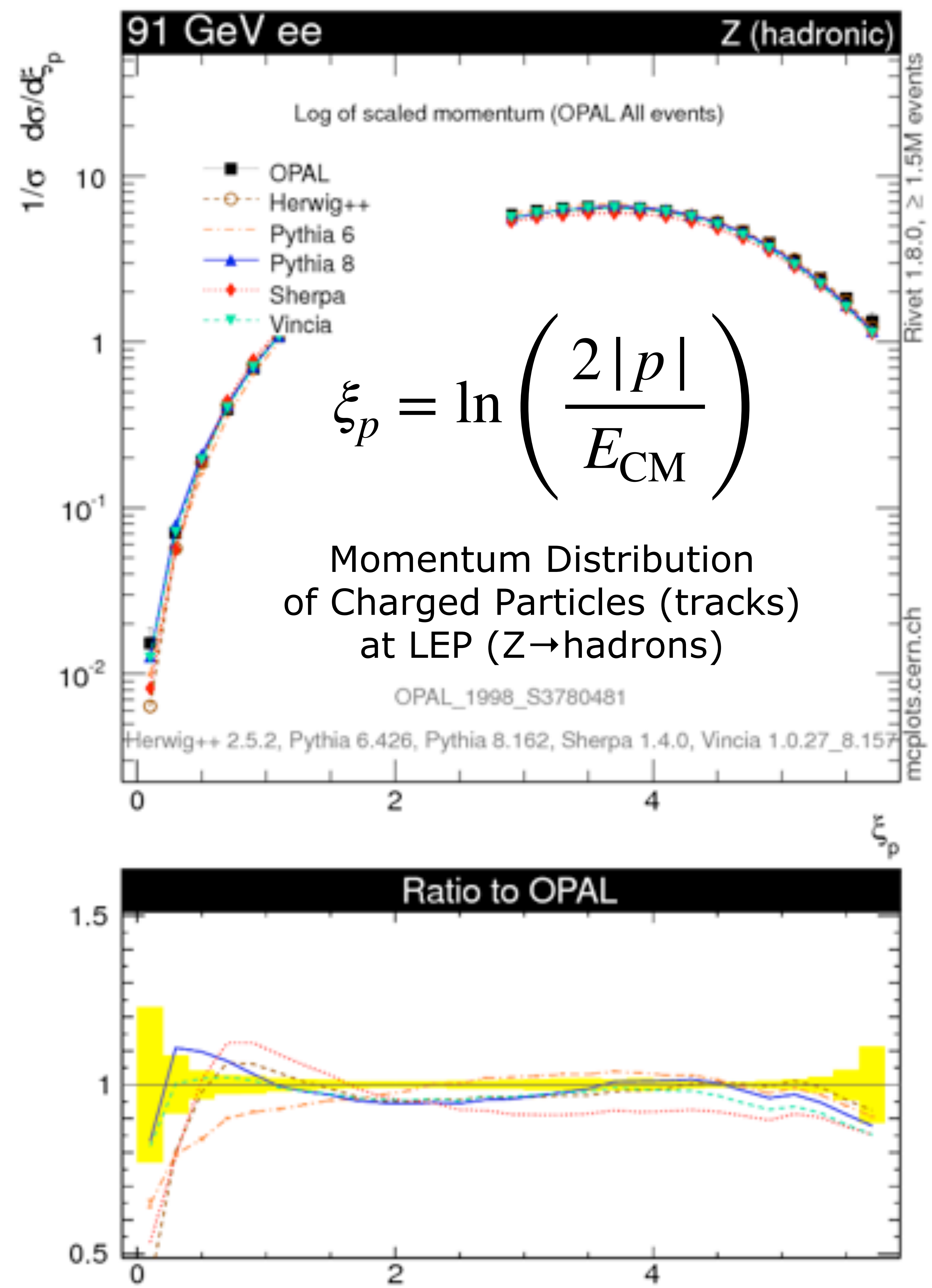

These points are quite sensitive to MECs / Matching / Merging.

➜ we should ensure we do MECs / matching / merging if we want to use them (or something equivalent to that.)

These points are relatively insensitive to **both** hadronization **and** matching/merging

Now use infrared **sensitive** observables - sensitive to hadronization + first few bins of previous (IR safe) ones



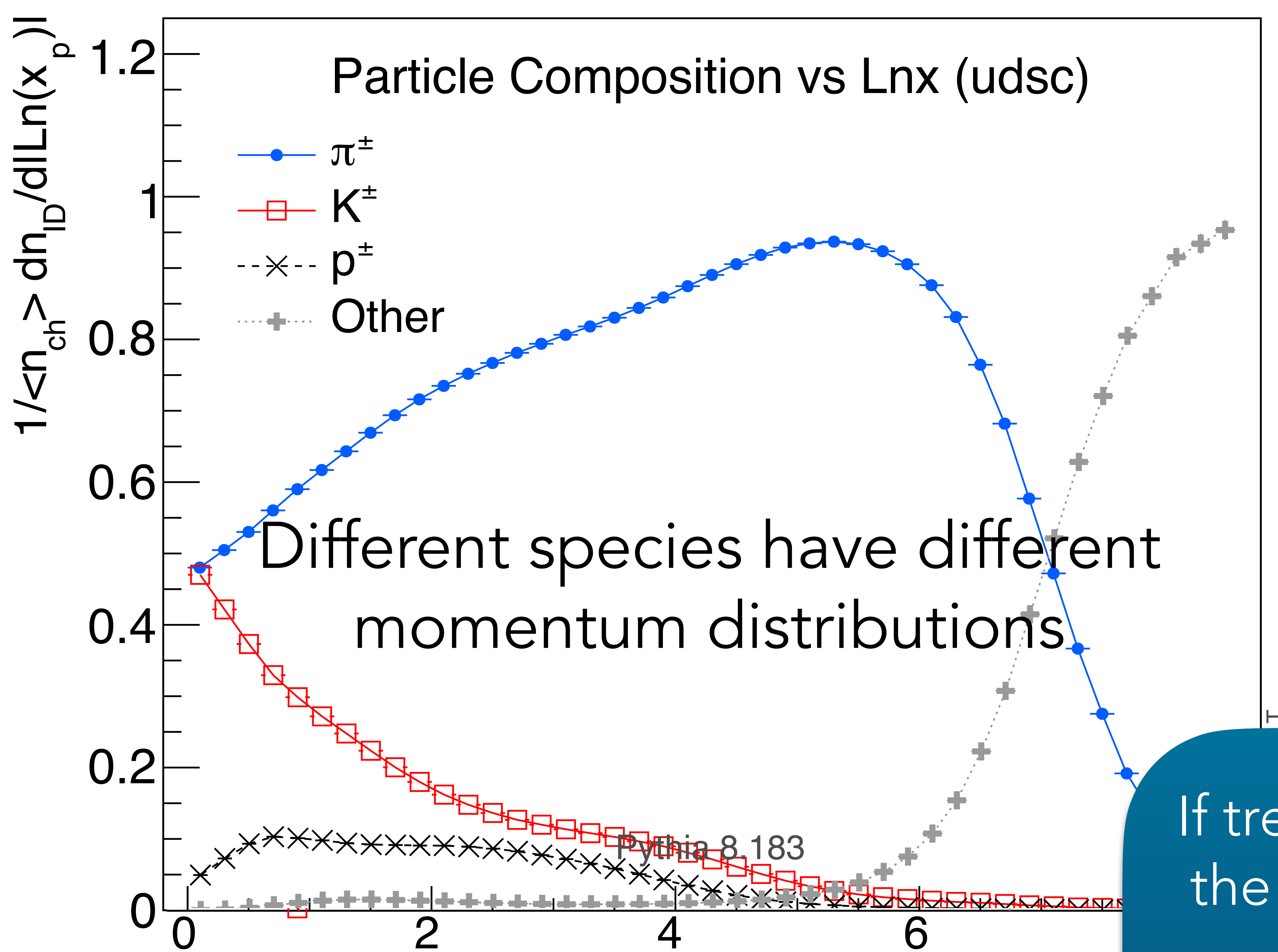




→ Tutorial

# Fragmentation Tuning

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

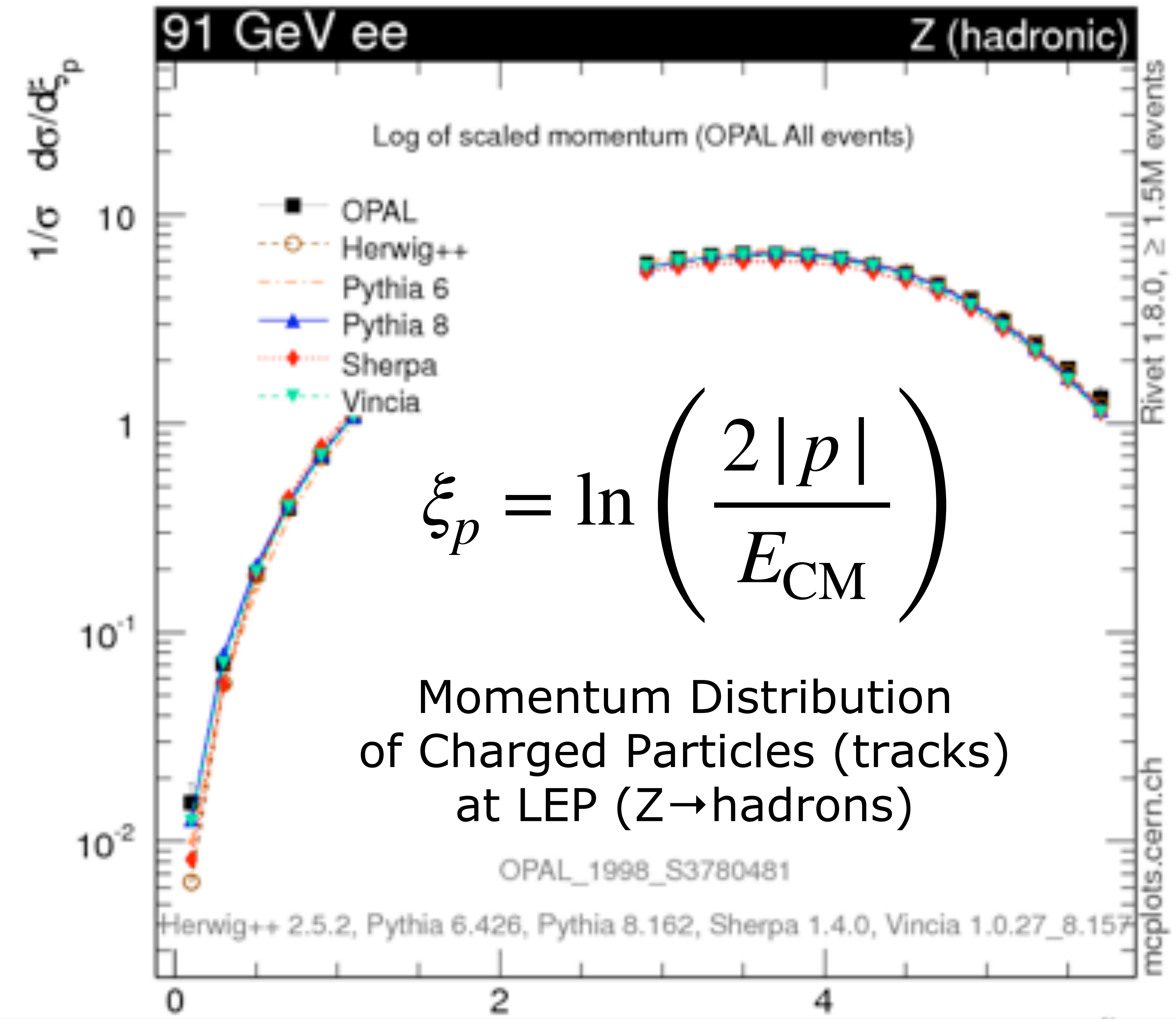
Know what **physics** goes in




Different species have different momentum distributions

+ effects of feed-down!

(e.g., $\rho \to \pi\pi$, $K^* \to K\pi$, $\eta \to \pi\pi\pi$,




$$\xi_p = \ln\left(\frac{2|p|}{E_{CM}}\right)$$

Momentum Distribution of Charged Particles (tracks) at LEP (Z→hadrons)

If treated like a black box, we could tune the shape of the momentum spectrum solely by modifying eg the relative amounts of strangeness! Bad idea?

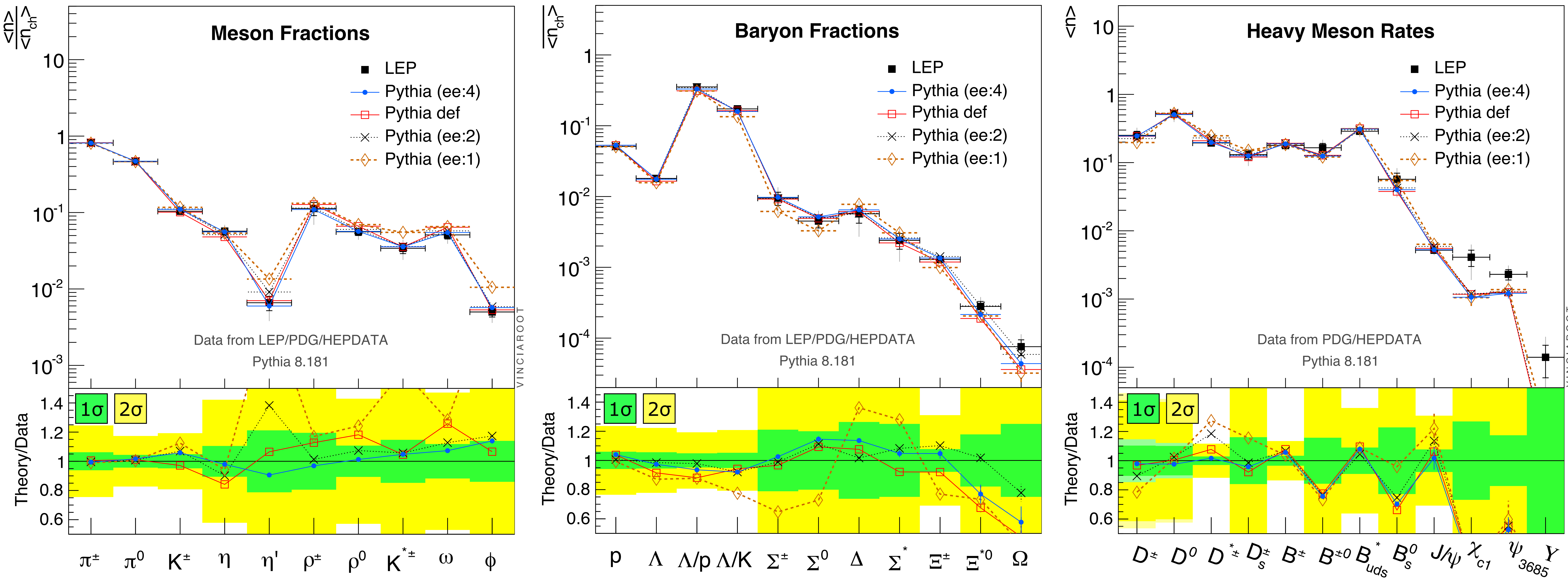
Will get back to that

Need **direct sensitivity to parameters**

# Identified Particles

Plenty of observables have **direct** sensitivity to strangeness (& other PID) fractions

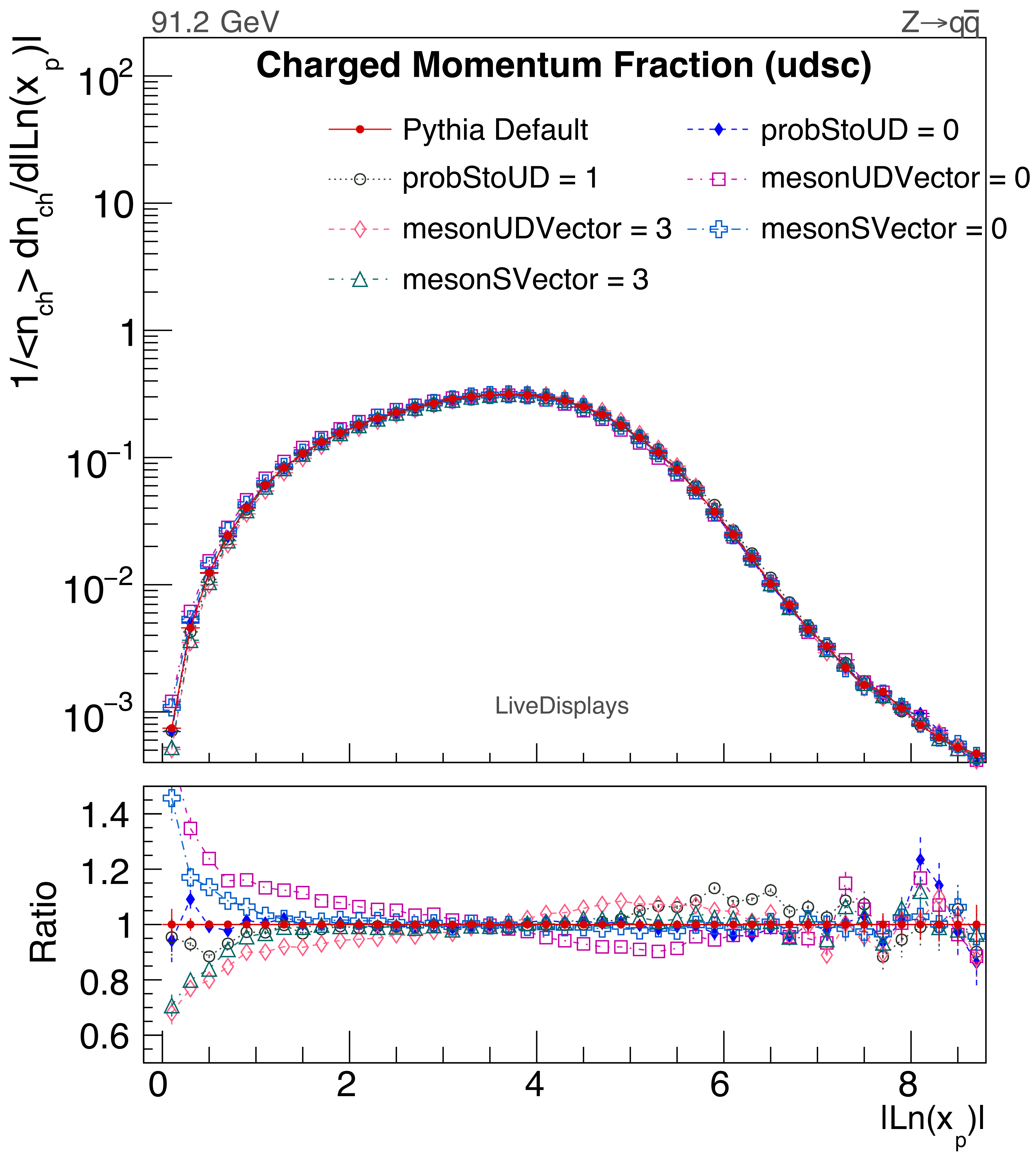
## V/P, B/M, $B_{3/2}/B_{1/2}$, strange/unstrange, Heavy, …

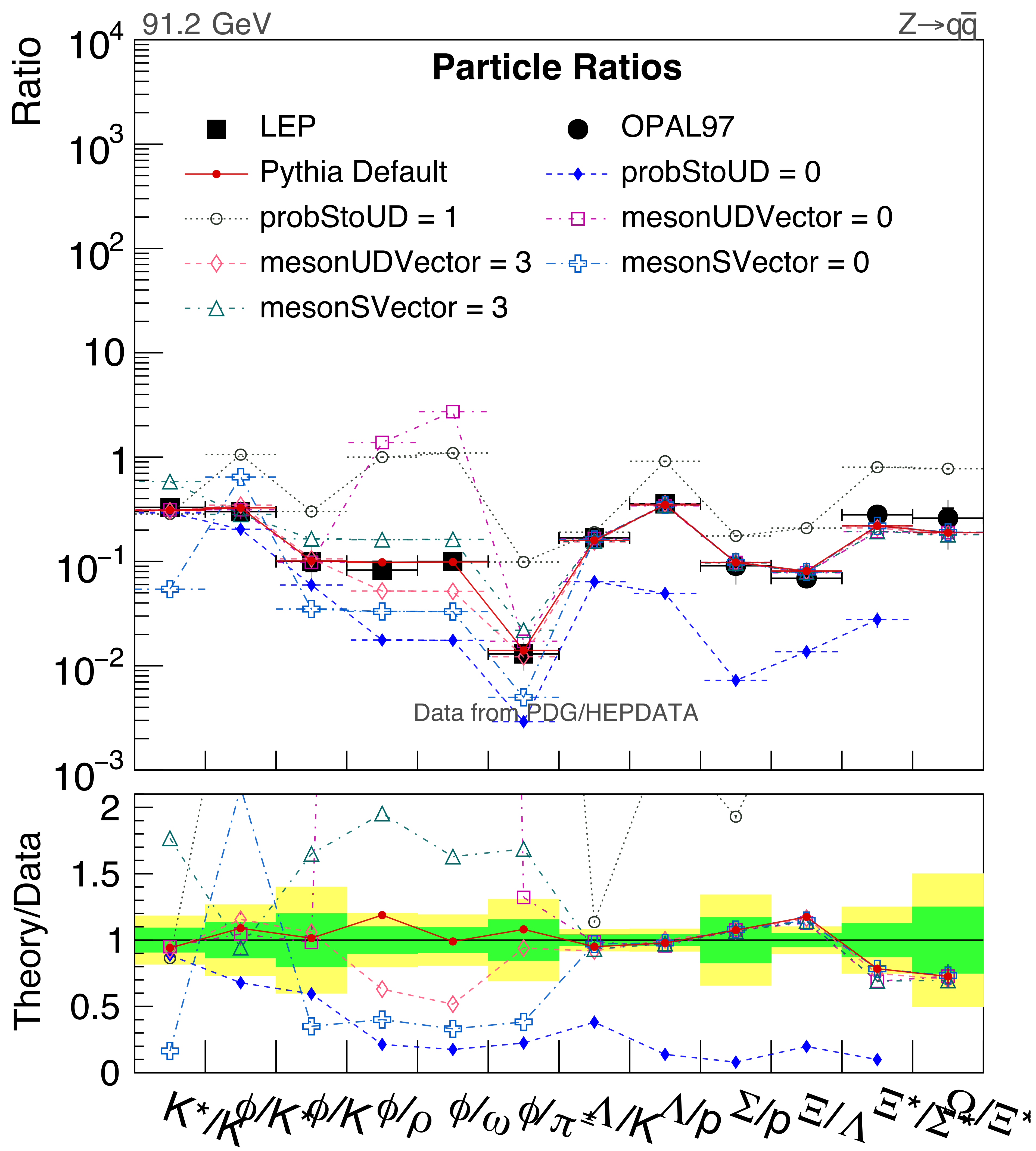



Could be completely mistuned if looking **only** at inclusive charged $\ln(x)$ spectrum

**Point:** include observables with **direct** sensitivity to each parameter you include.

# GIGO




**Large** changes in strangeness or vector/pseudoscalar ratios **do** modify the momentum spectrum

At the cost of totally destroying agreement with observables that are **directly sensitive** to those parameters

# Parameters (in PYTHIA): **Initial-State Radiaton**

**+ PDF Choice**

Matching & Merging

## Additional Matrix Elements included?

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

Size of Phase Space

## Starting scale

Relation between $Q_{PS}$ and $Q_F$ (Vetoed showers? Suppressed? cf matching)

Coherence

## Initial-Final interference

I-F colour-flow interference effects (eg VBF & Tevatron $t\bar{t}$ asym) & interleaving

$\alpha_s$

## Value and running of the strong coupling

Governs overall amount of radiation (cf FSR)

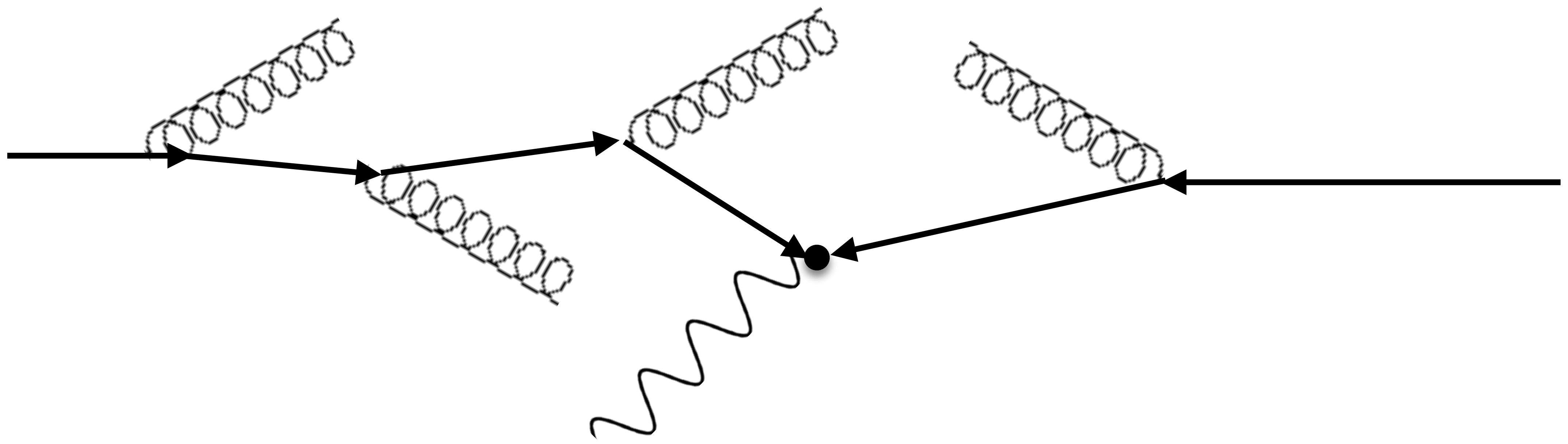
"Primordial kT"

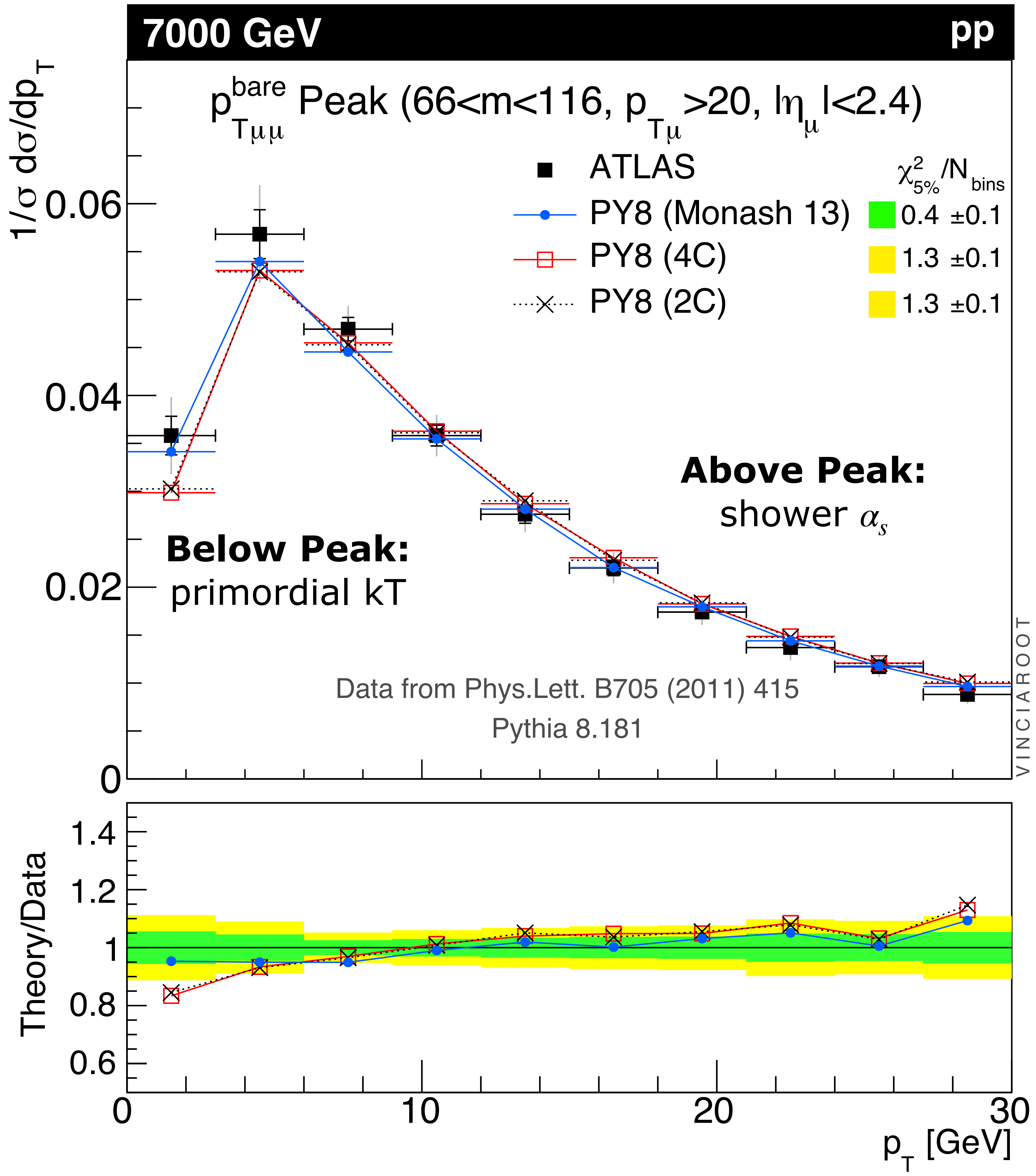
## A small additional amount of "unresolved" kT

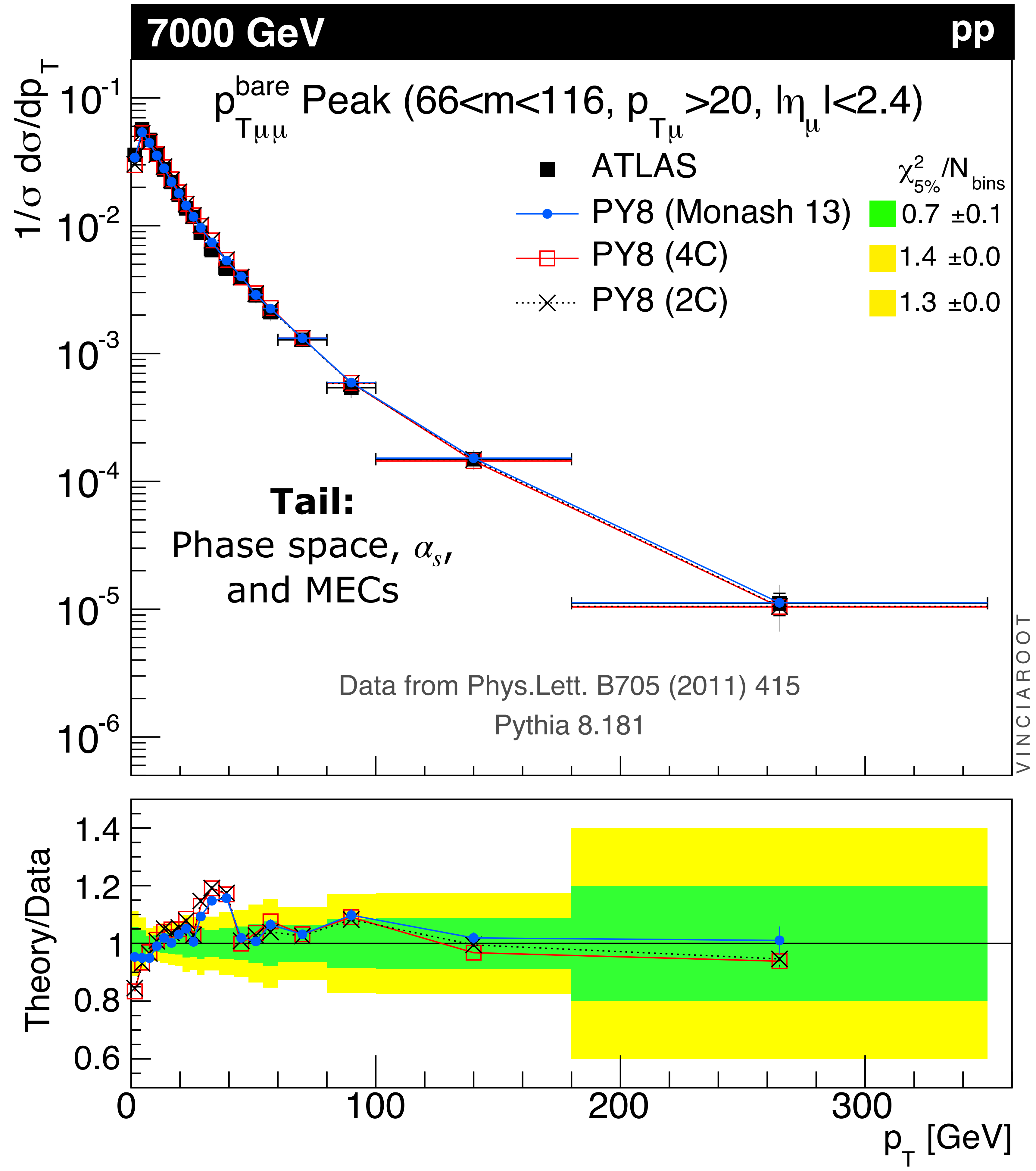
Fermi motion + unresolved ISR emissions + low-x effects?

# ISR + Primordial kT

Drell-Yan pT distribution

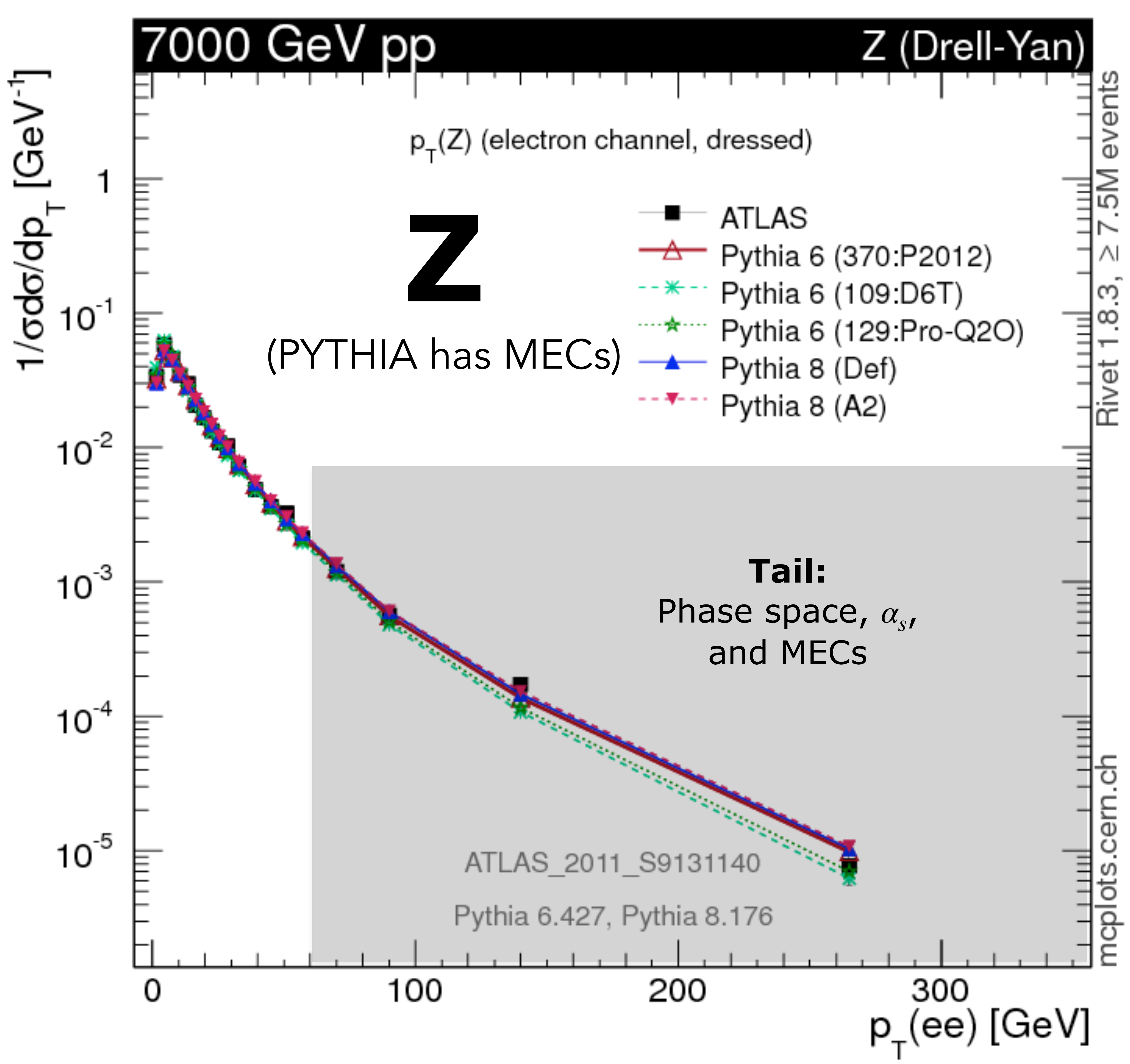




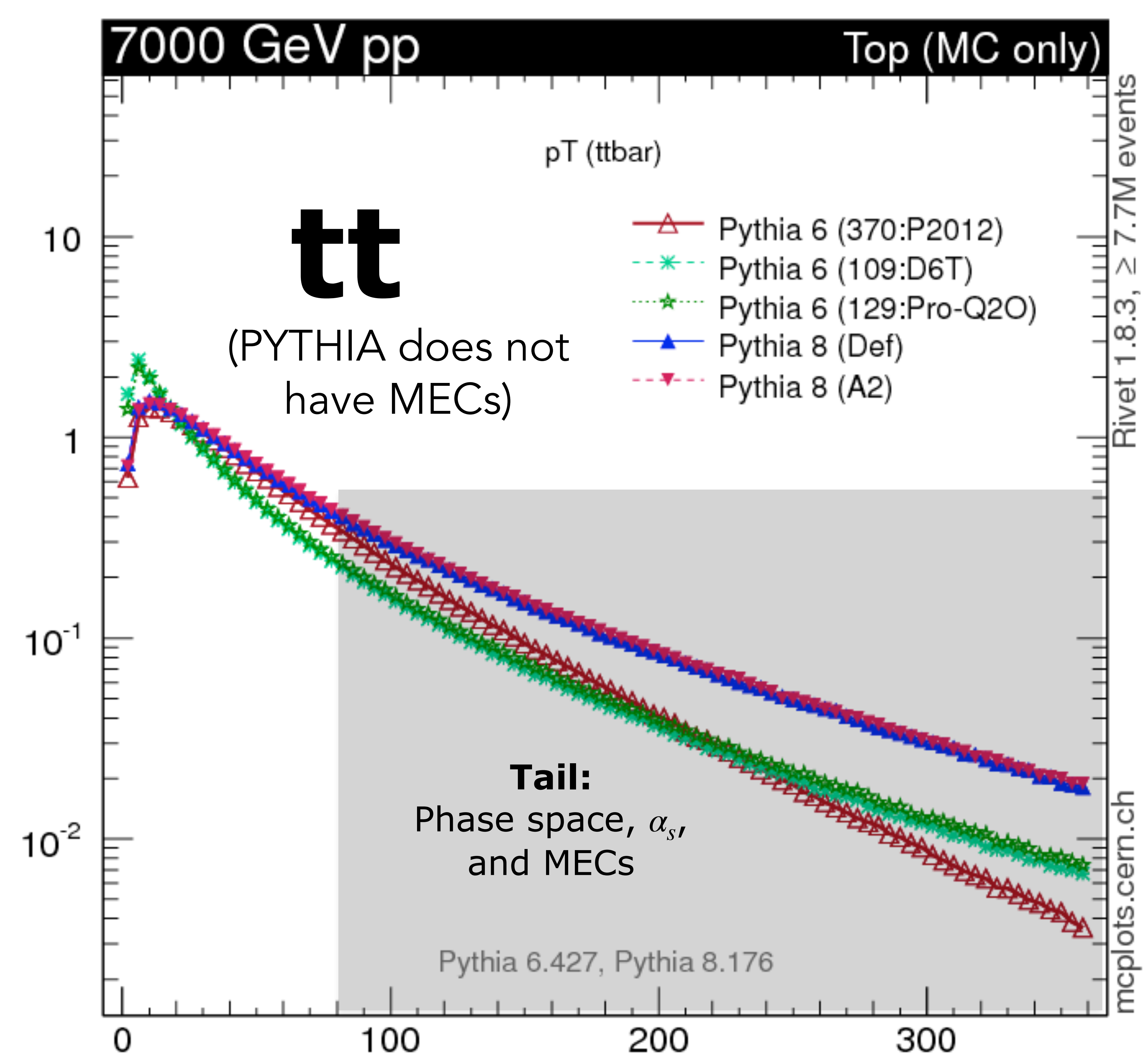




Note: Q.M. requires physical observable!

# Beware Process Dependence!




These points are quite sensitive to MECs / Matching / Merging.




➜ we should ensure we do MECs / matching / merging if we want to use them (or something equivalent to that.)

Number of MPI

**Infrared Regularization scale $p_{\perp 0}$ for the QCD 2→2 (Rutherford) scatterings used for multiple parton interactions → size of overall activity**

Note: strongly correlated with choice of PDF set! (low-x gluon)

Pedestal Rise

**Proton transverse mass distribution → difference between central** (more active) **vs peripheral** (less active) **collisions**

Strings per Interaction

**Color correlations between multiple-parton-interaction systems (aka colour *reconnections* — relative to LC)**

→ shorter or longer strings → less or more hadrons per interaction

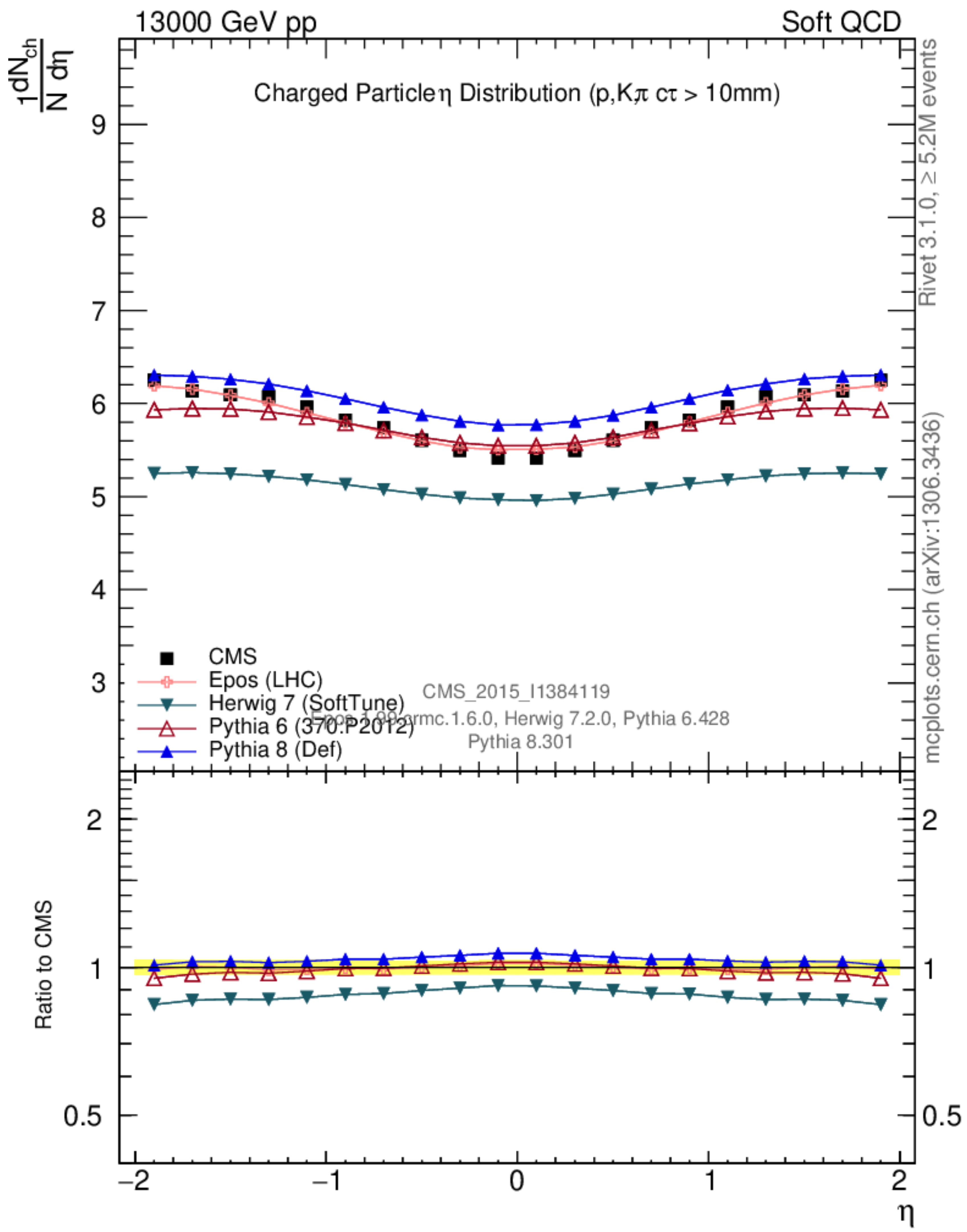
$\sqrt{s}$ scaling

**Evolution of UE, $\langle \mathrm{d}N/\mathrm{d}\eta \rangle$, … with collider CM energy**

Cast as energy evolution of $p_{T0}$ parameter.

# **Bad Example:** Why dN/dη is useless (by itself)

$\langle dN_{ch}/d\eta \rangle$ often used as main constraint on models of minimum-bias physics




But look here:

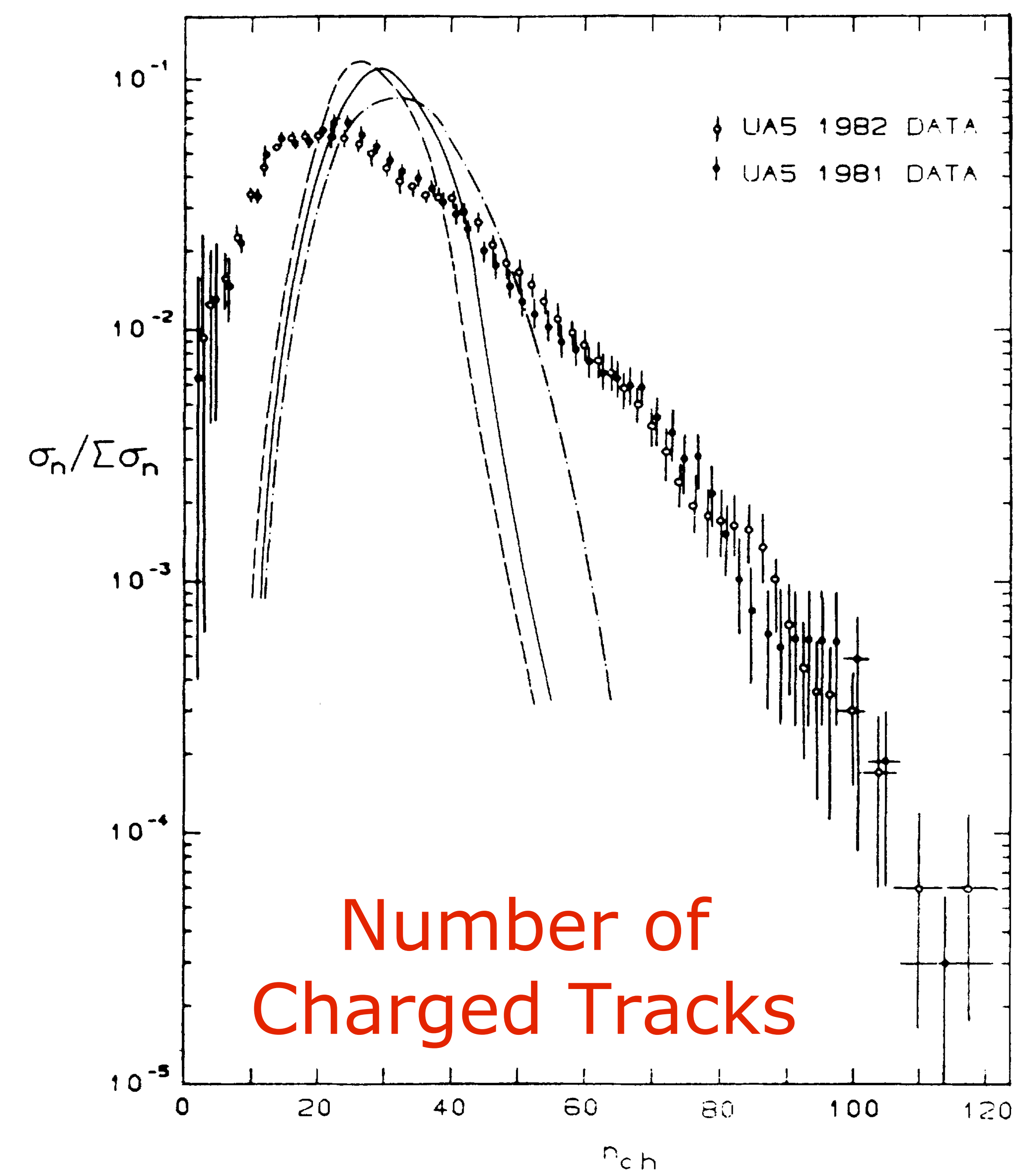



FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low $p_T$ only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

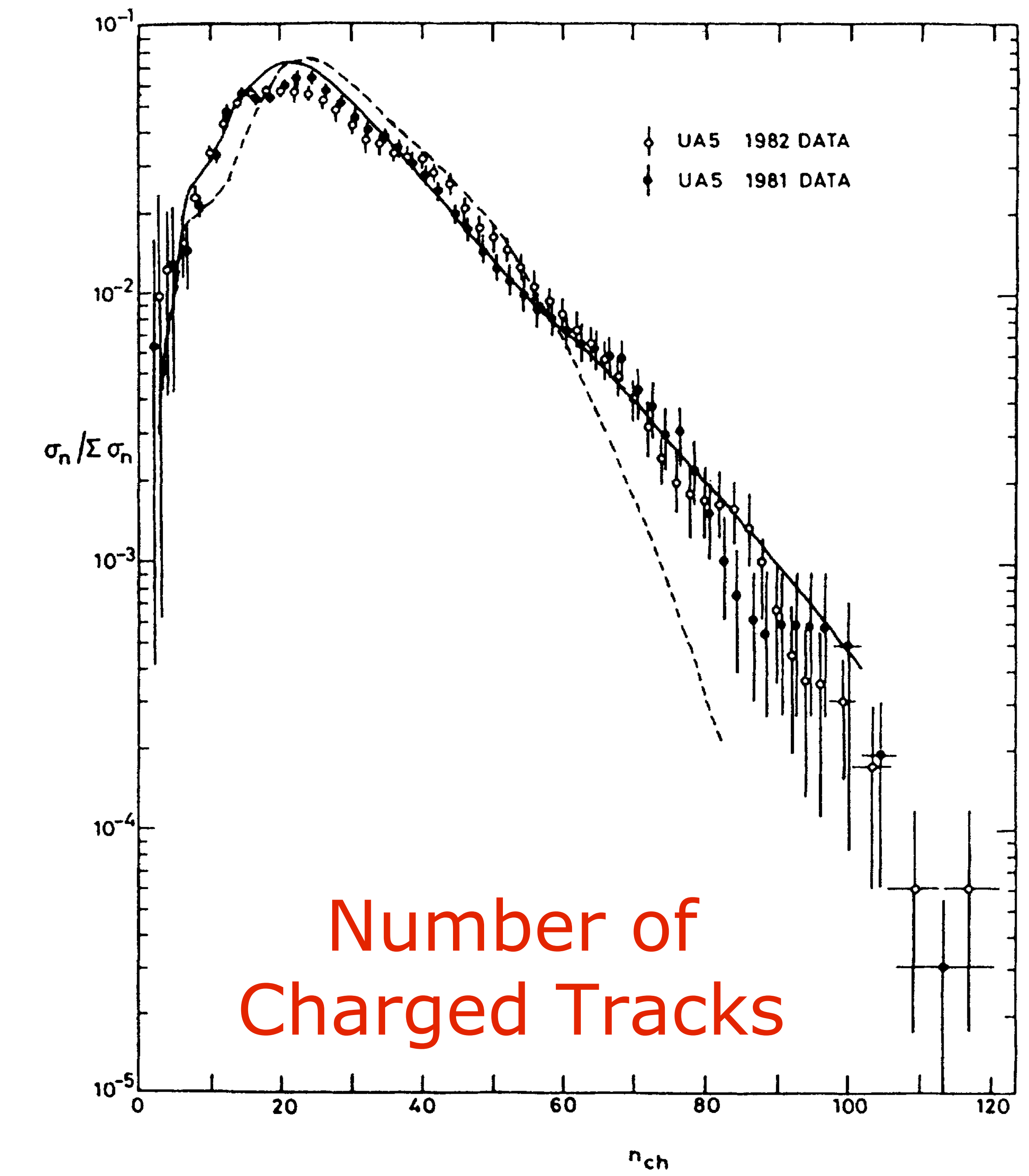
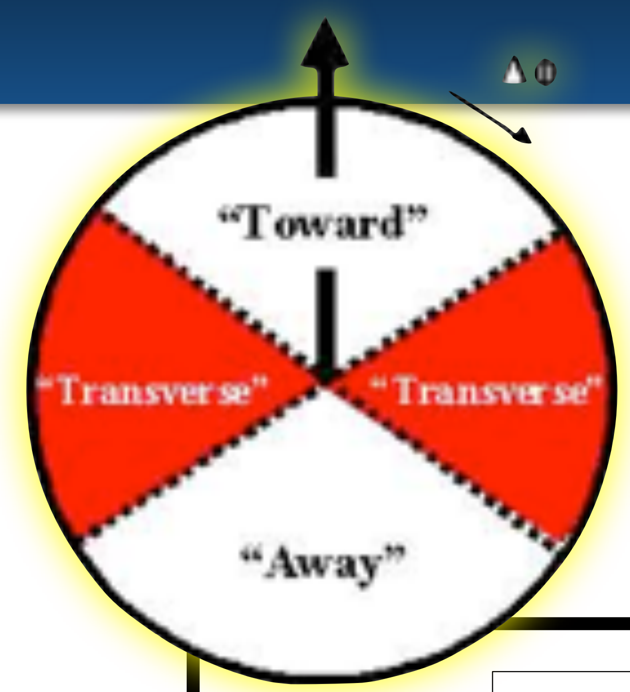


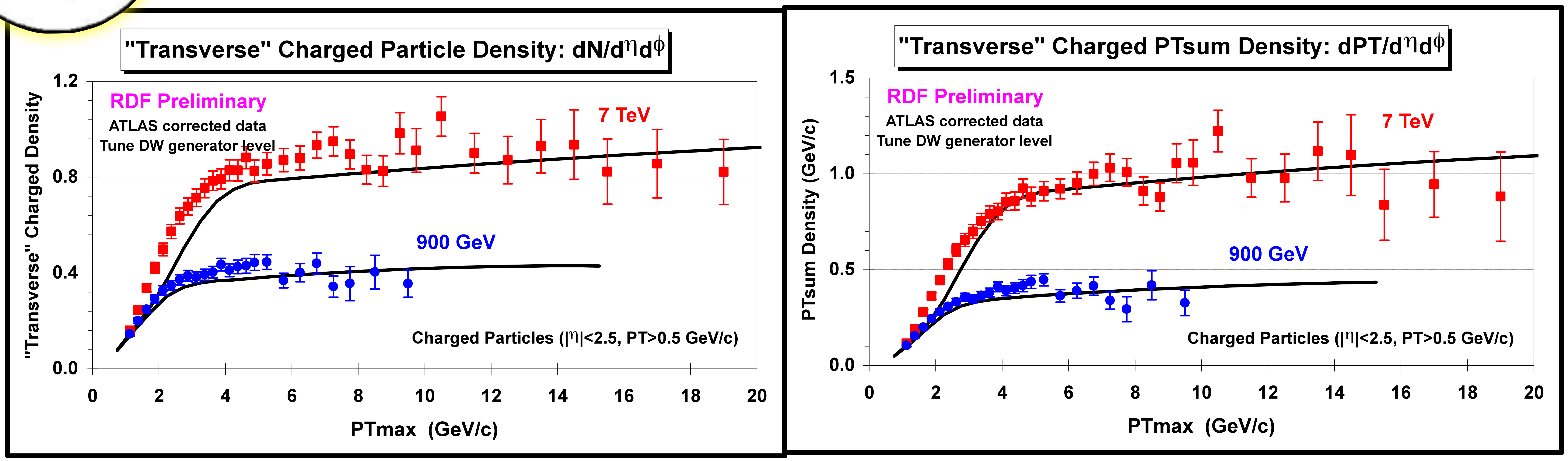

FIG. 12. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs multiple-interaction model with variable impact parameter: solid line, double-Gaussian matter distribution; dashed line, with fix impact parameter [i.e., $\tilde{O}_0(b)$].

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

Can get right $\langle N_{ch} \rangle$ with completely wrong models. (Need a few more moments at least.)




## UE - LHC from 900 to 7000 GeV - ATLAS




As you trigger on progressively higher $p_T$, the entire event increases …

… until you reach a plateau ("max-bias") also called the "jet pedestal" effect

**Interpreted as impact-parameter effect**

Qualitatively reproduced by MPI models

Relative size of this plateau / min-bias depends on pT0, PDF, *and* b-profile

# (More Specialised Parameters)

## Hadron decay tables

Branching fractions and decay modelling

## Collective Effects (in pp)

Colour Reconnections (& effects on precision measurements like $m_{top}$)

Strangeness Enhancements (eg close-packing, ropes, …)

Flow-like effects (eg close-packing, string shoving, …)

## Forward Physics

Beam-Remnant Handling

Diffractive Modelling (incl hard diffraction, Pomeron substructure)

Total and Elastic Cross-section parametrisatons

…