Tuning

means different things to different people

The Tyranny of Carlo

J. D. Bjorken

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But it often happens that the physics simulations provided by the the MC generators carry the authority of data itself. They look like data and feel like data, and if one is not careful they are accepted as if they were data. All Monte Carlo codes come with a GIGO (garbage in, garbage out) warning label. But the GIGO warning label is just as easy for a physicist to ignore as that little message on a packet of cigarettes is for a chain smoker to ignore. I see nowadays experimental papers that claim agreement with QCD (translation: someone's simulation labeled QCD) and/or disagreement with an alternative piece of physics (translation: an unrealistic simulation), without much evidence of the inputs into those simulations."

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Account for parameters + pertinent cross-checks and validations
Do serious effort to estimate uncertainties, by salient MC variations

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

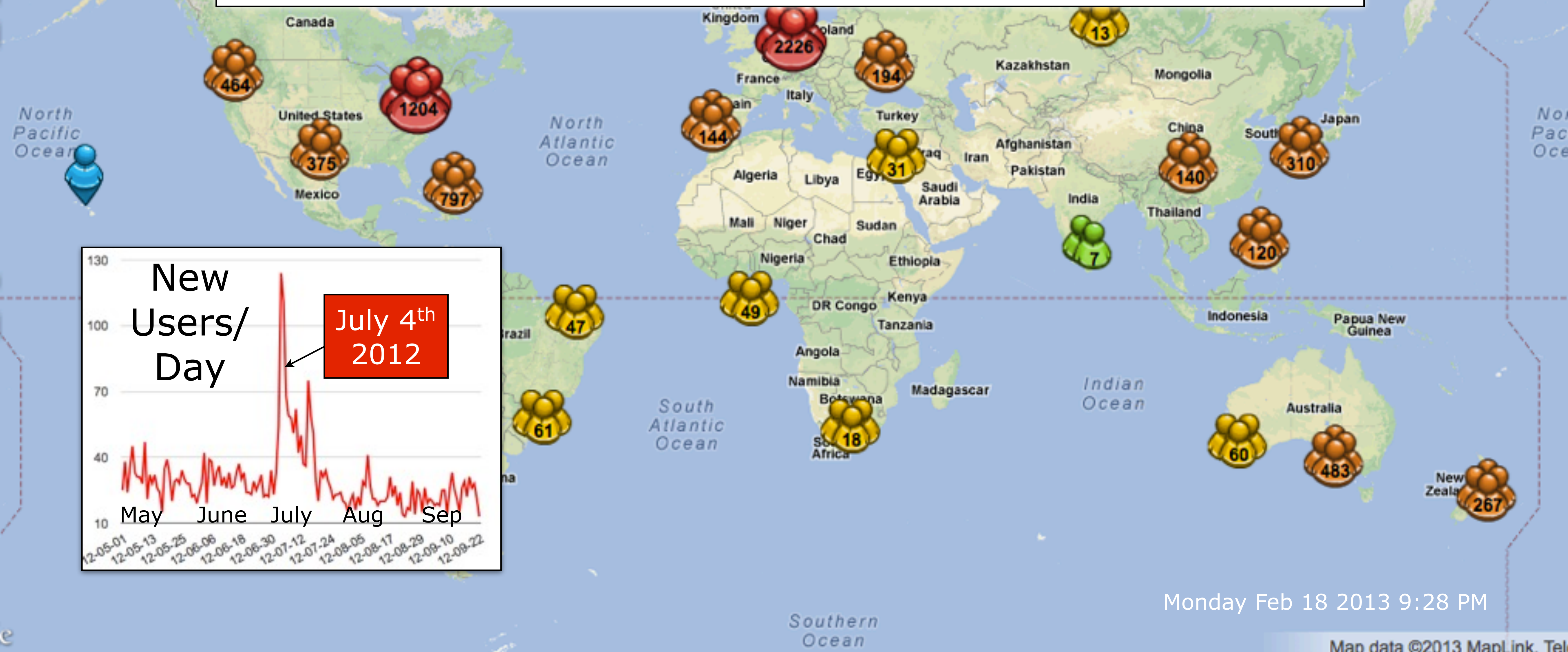
Automated tuning (& more)

(Test4Theory)

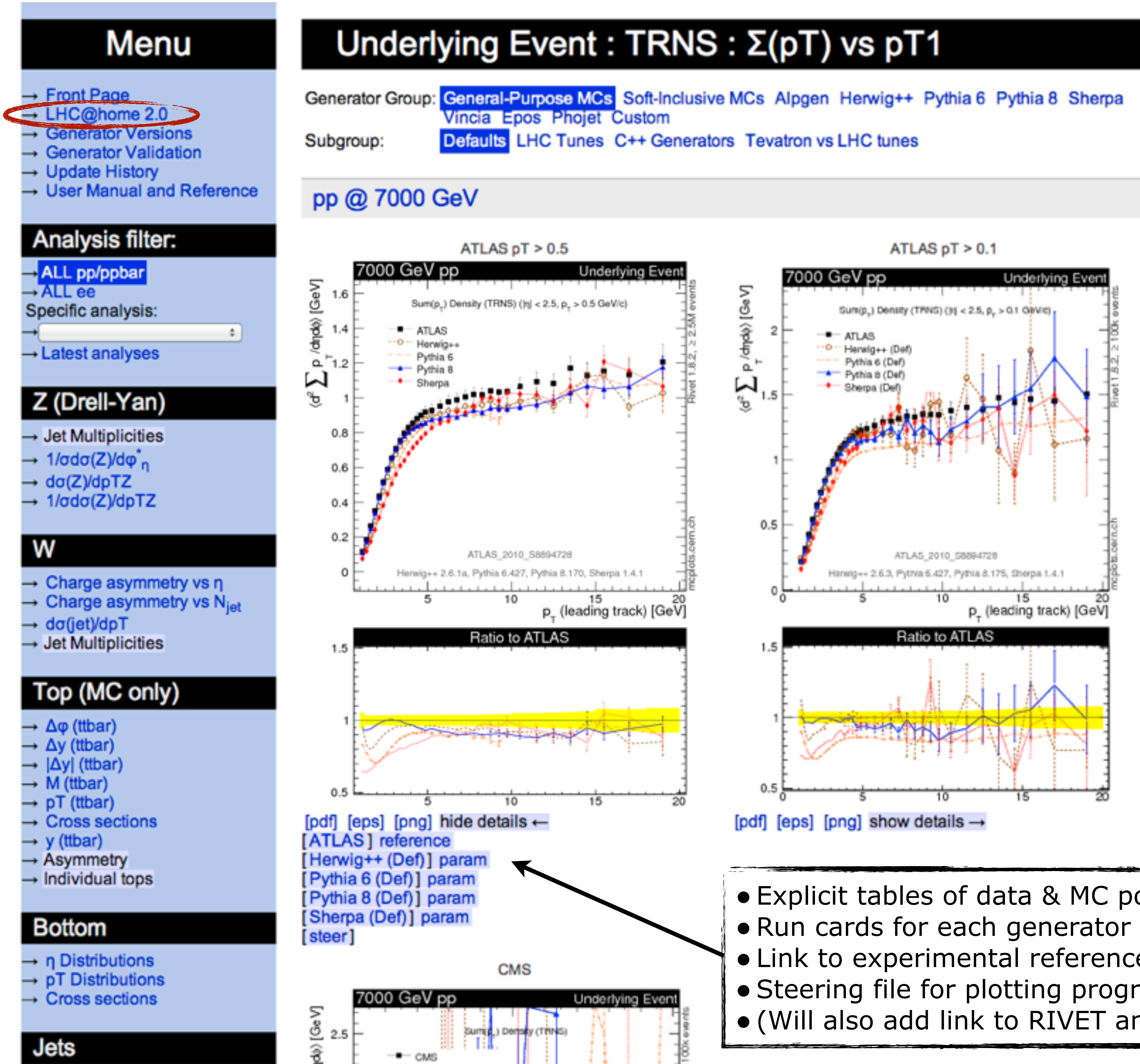
LHC@home 2.0 Test4Theory volunteers' machines seen during the past 24 hours (7011 machines overall)

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



- 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)

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

Additional Matrix Elements included?

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

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, …

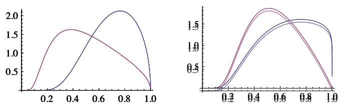
String Tuning

Main String Parameters

Longitudinal FF = f(z)

Lund Symmetric Fragmentation Function

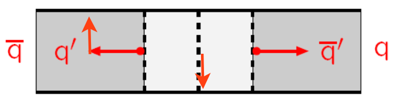
The a and b parameters



pT in string breaks

Scale of string breaking process

IR cutoff and $\langle p_T \rangle$ in string breaks



Meson Multiplets

Mesons

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

Baryon Multiplets

Baryons

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

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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"Primordial kT"

A small additional amount of "unresolved" kT

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

Min-Bias & Underlying Event

Main IR Parameters

Number of MPI

Pedestal Rise

Strings per
Interaction

Min-Bias & Underlying Event

Main IR Parameters

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

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Strings per Interaction

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

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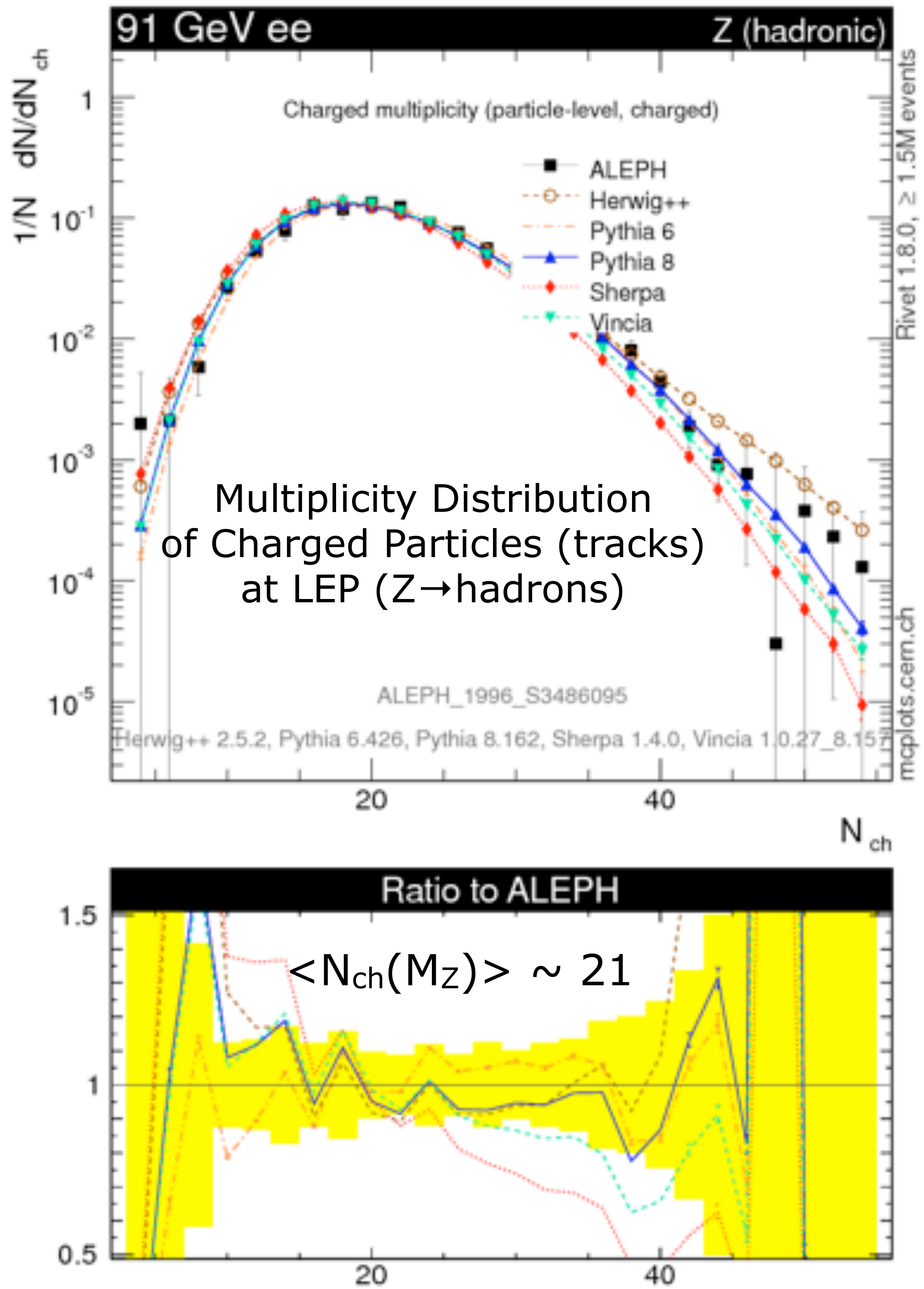
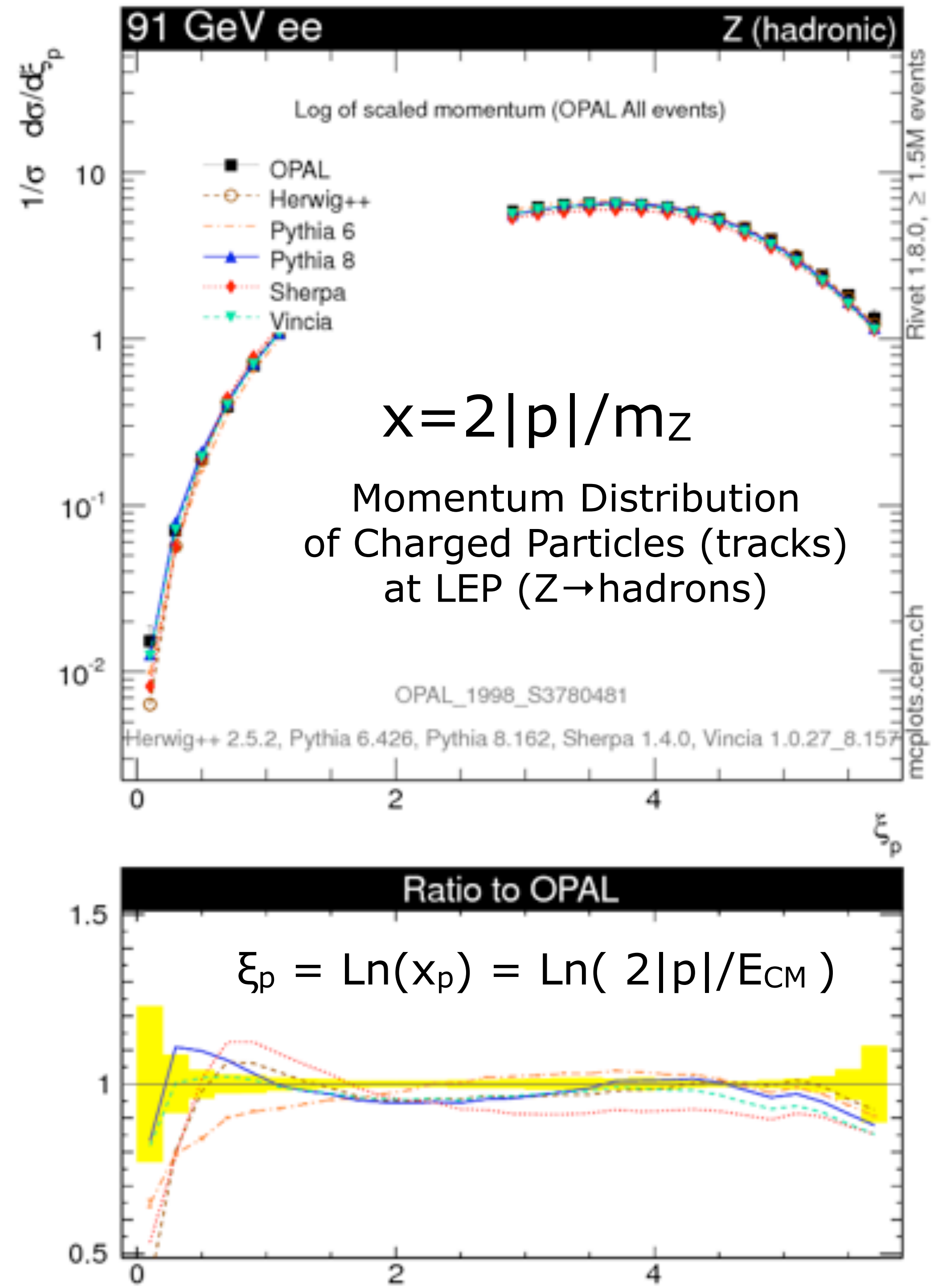
Fragmentation Tuning

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





Fragmentation Tuning

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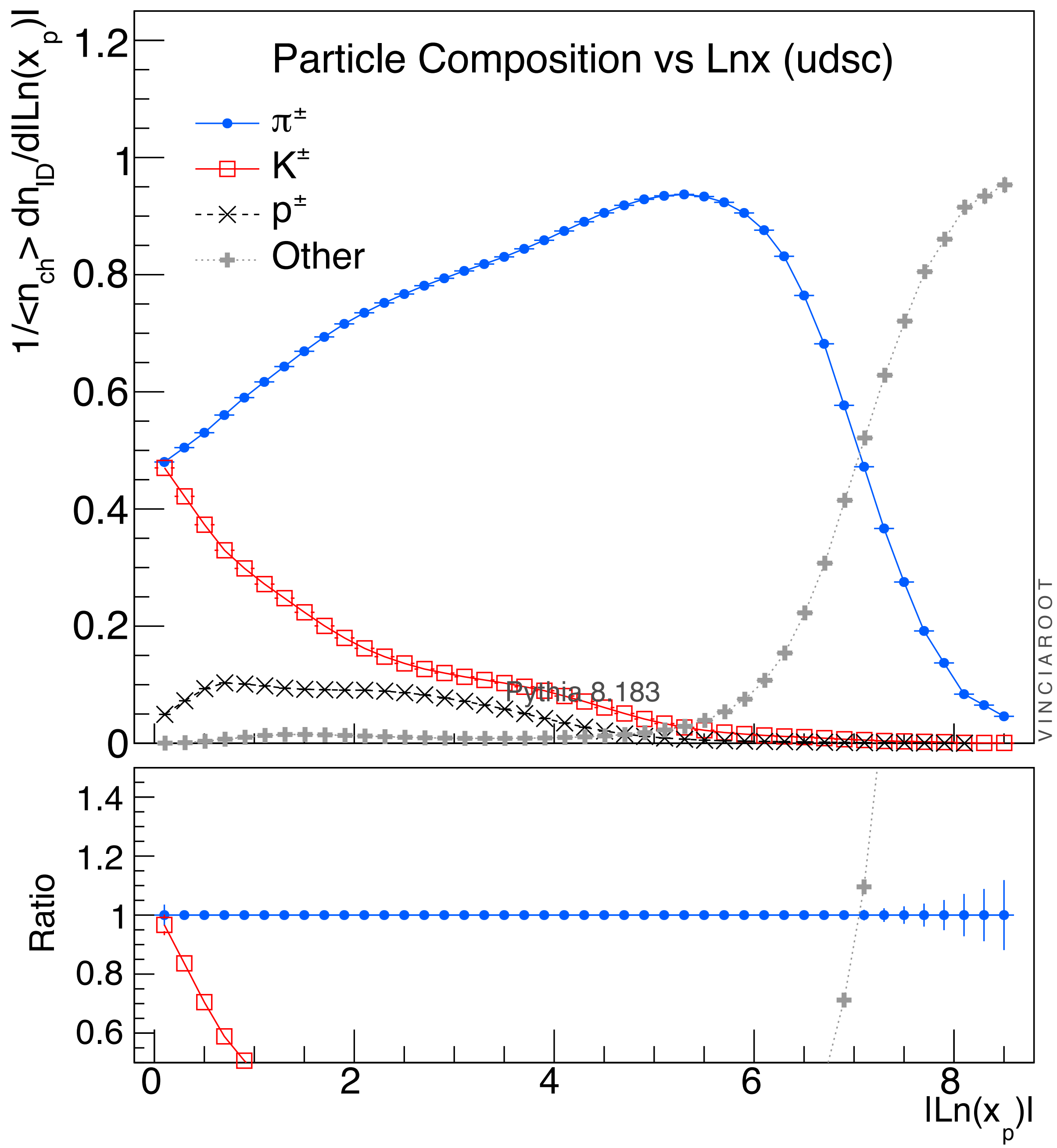
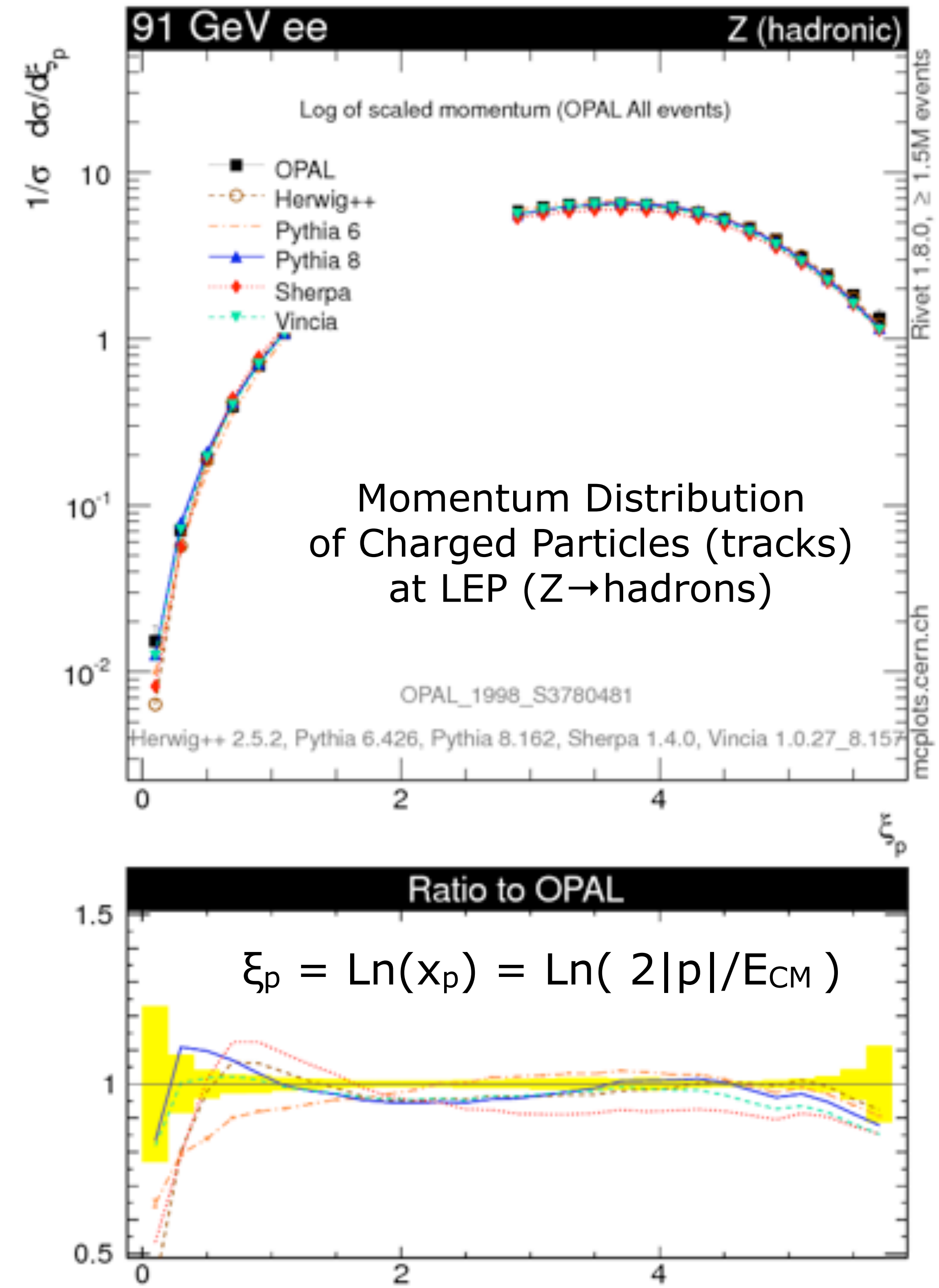
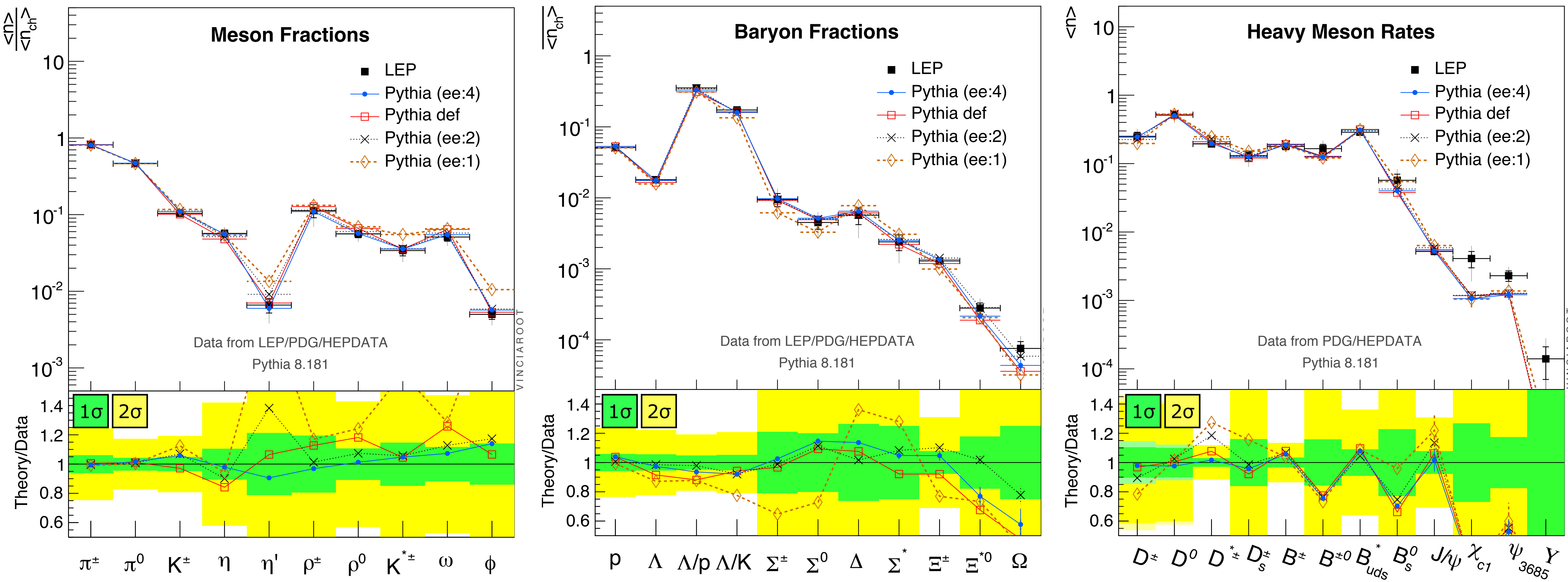
Know what **physics** goes in





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

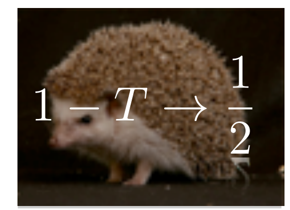
Can variations within uncertainties explain differences? Or not?

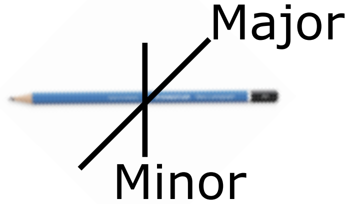
Need IR Corrections?

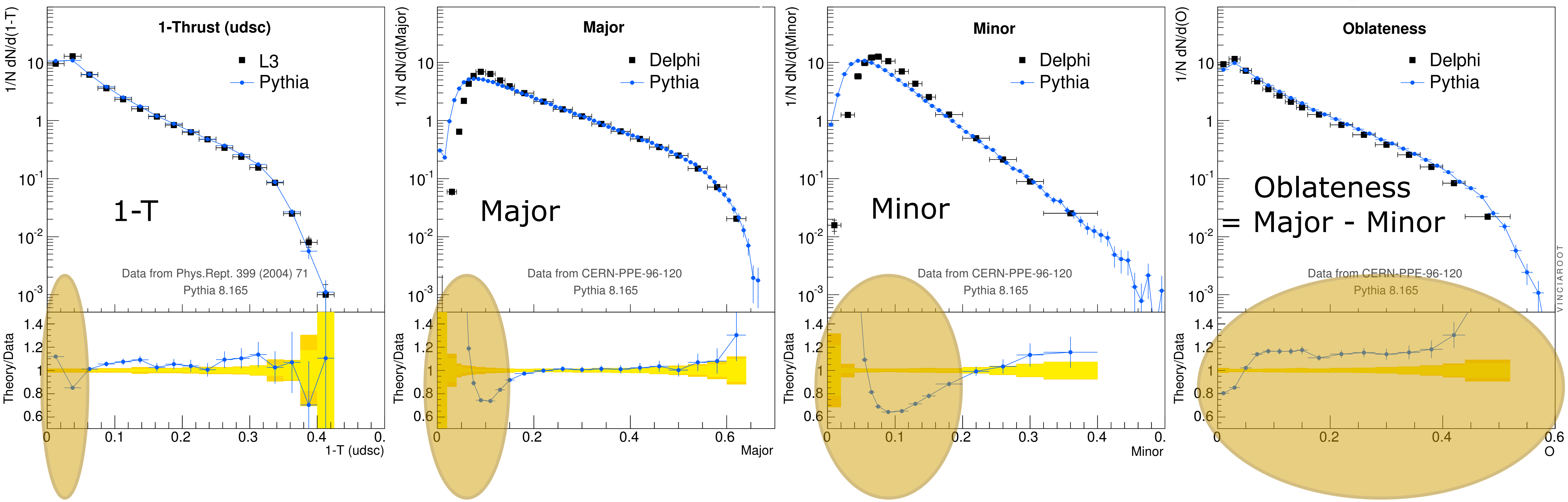
PYTHIA 8 (hadronization off) vs LEP: Thrust

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

$$1 - T \to 0$$







Significant Discrepancies (>10%)

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

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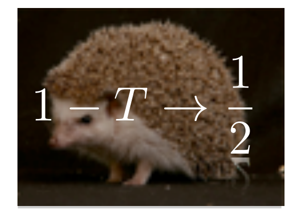

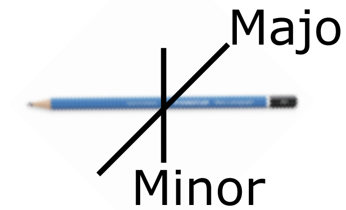

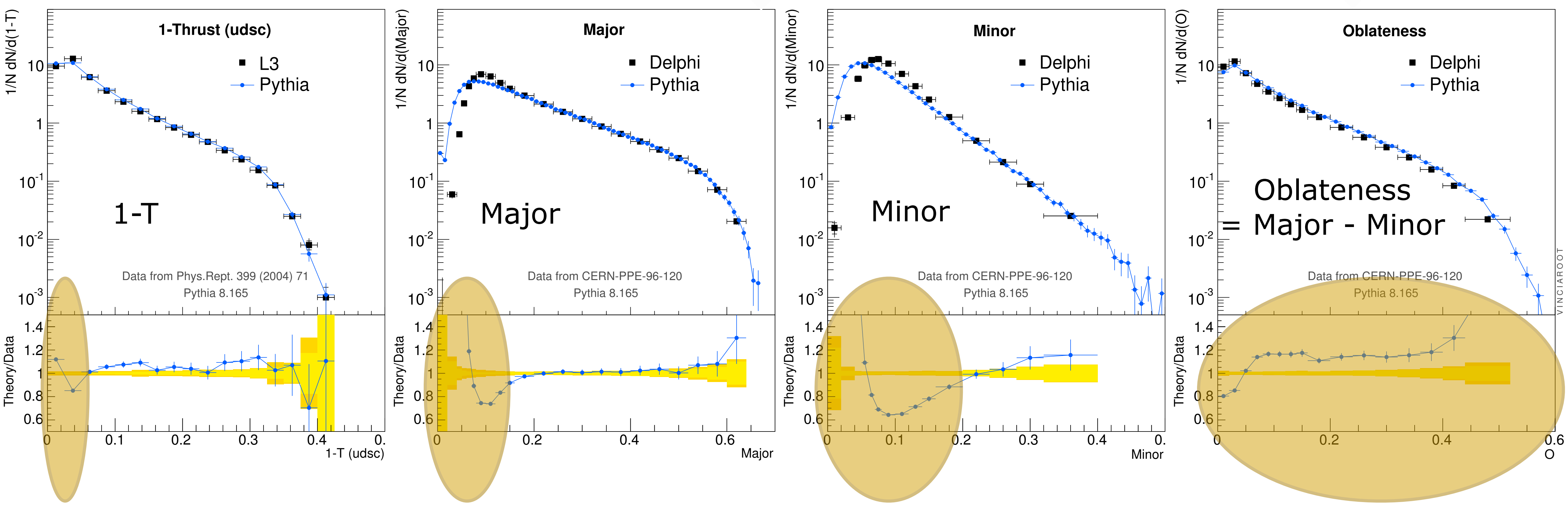

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+ cross checks: different eCM energies (HAD and FSR scale differently)

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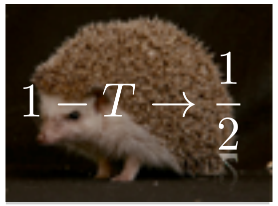

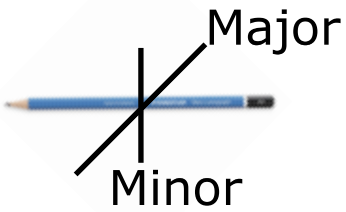

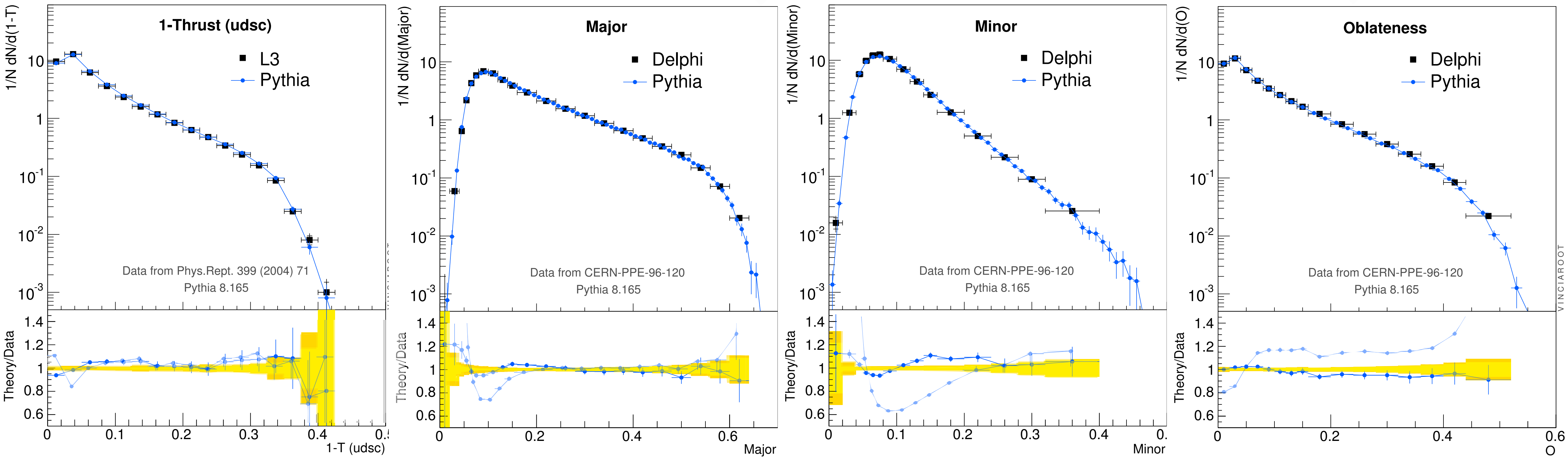

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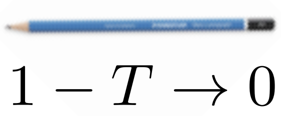

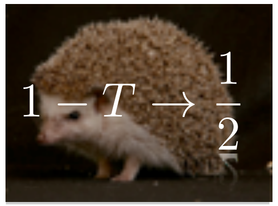

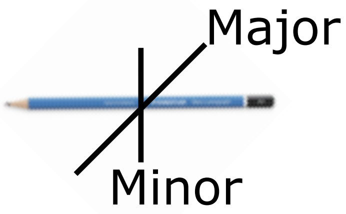

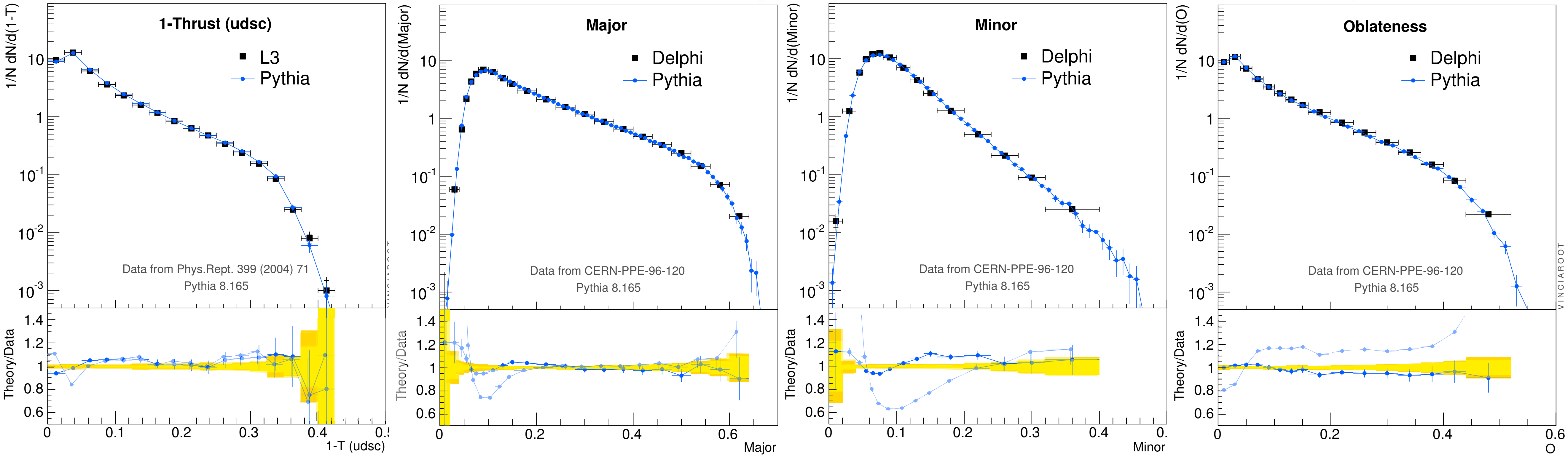

Note: Value of Strong coupling is
$\alpha_s(M_Z) = 0.14$

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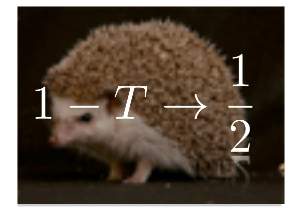
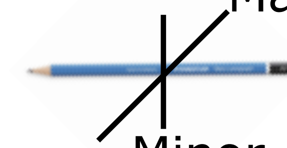
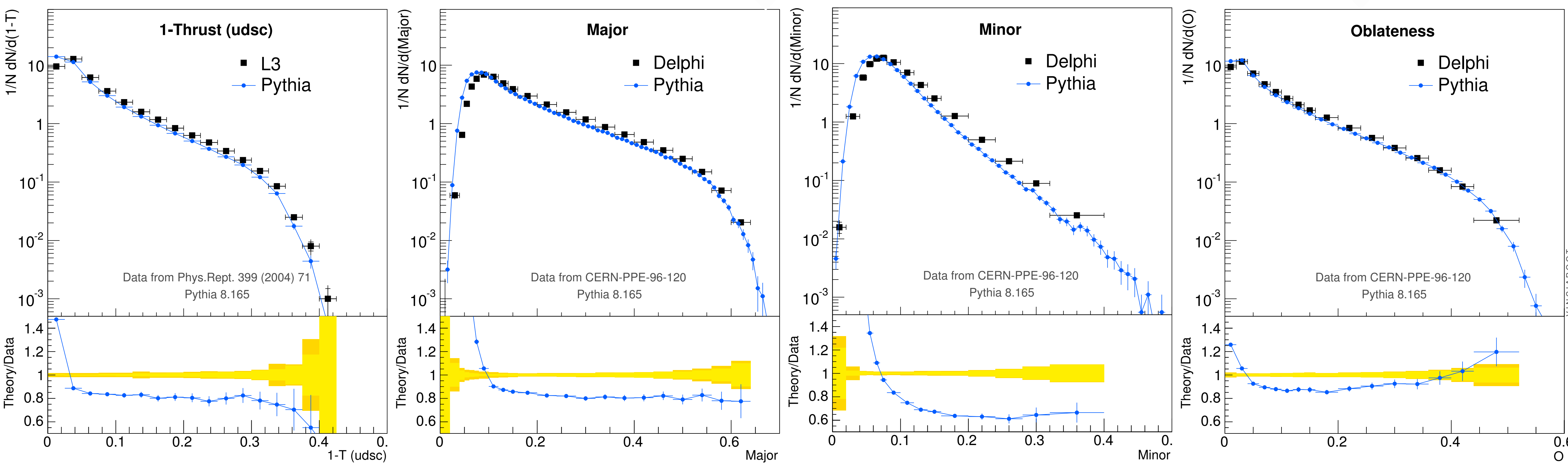


$1 - T \to \frac{1}{2}$





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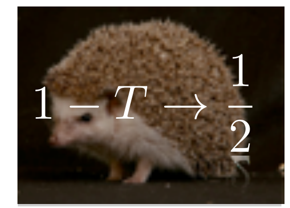

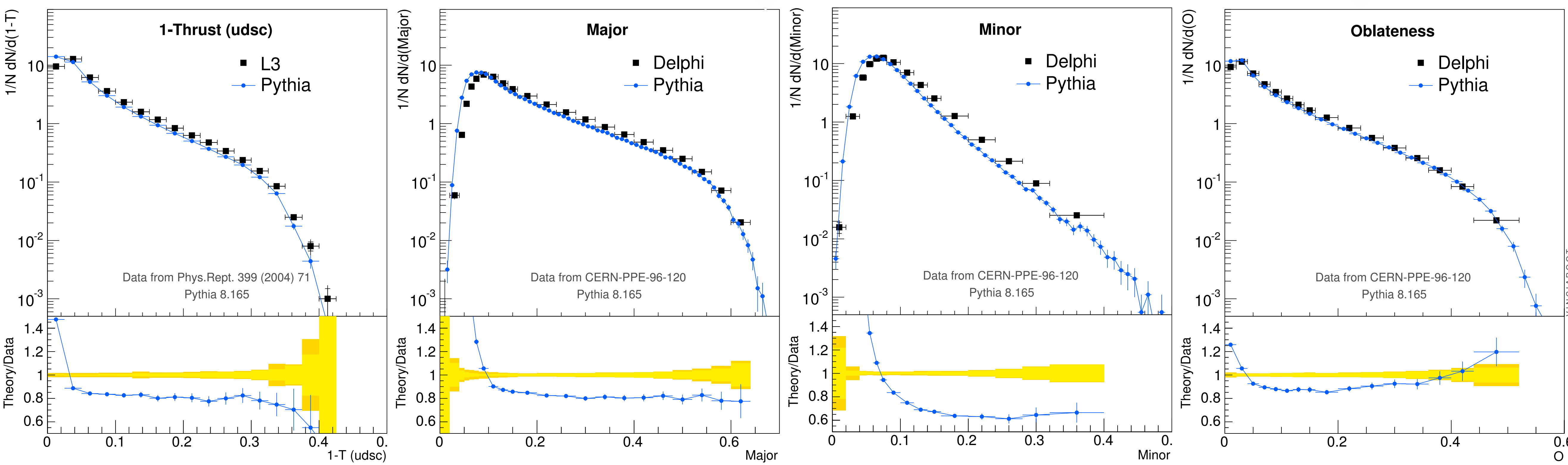

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$\neq$ World Average = 0.1176 ± 0.0020

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Value of α_s depends on the order and scheme

- MC ≈ Leading Order + LL resummation
- Other leading-Order 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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Improve → Matching at LO and NLO

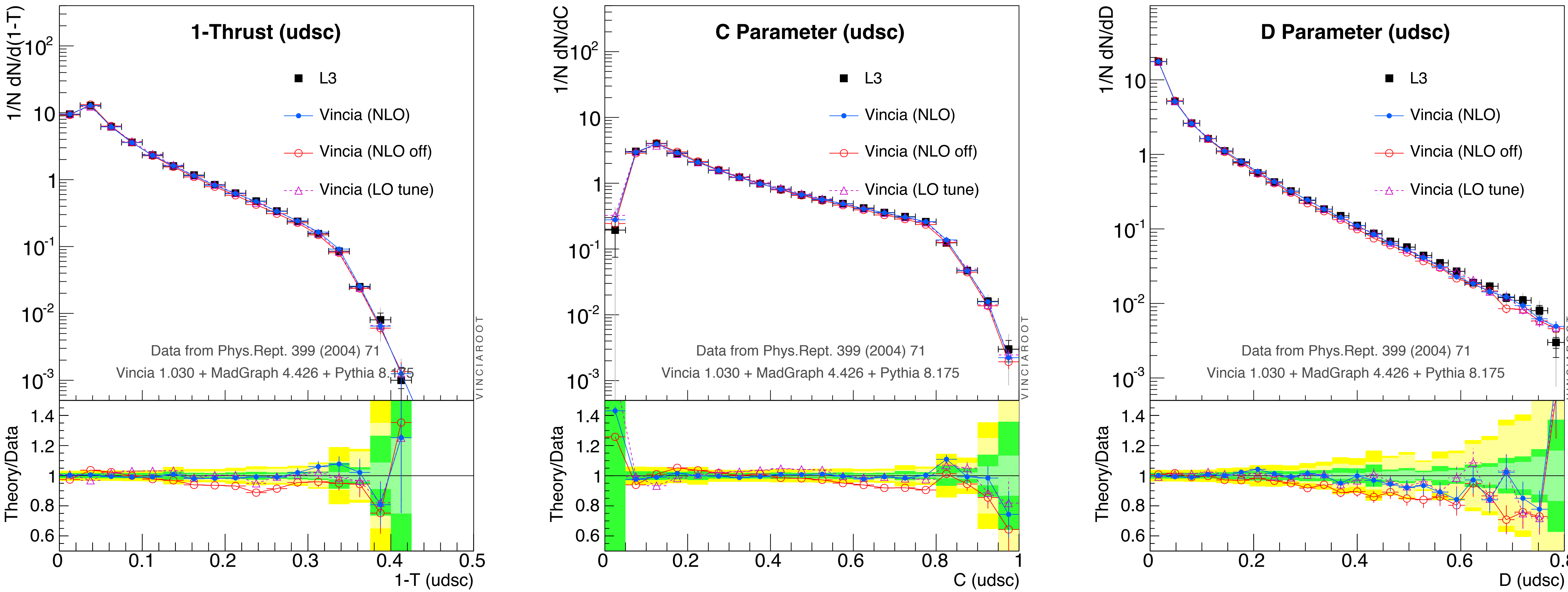
Sneak Preview:
Multijet NLO Corrections with VINCIA

Hartgring, Laenen, Skands, arXiv:1303.4974

First LEP tune with NLO 3-jet corrections

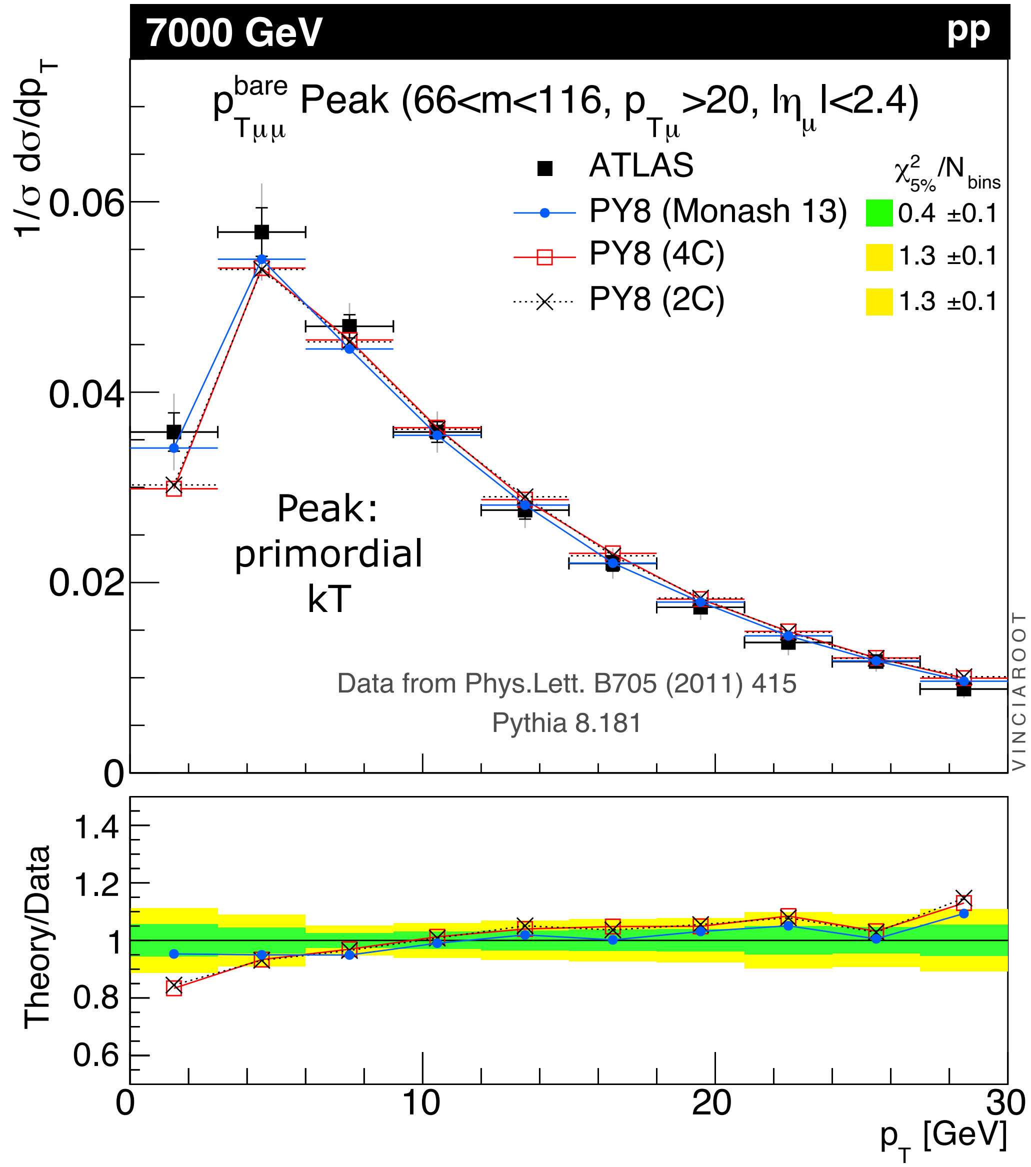
LO tune: $\alpha_s(M_Z) = 0.139$ (1-loop running, MSbar)

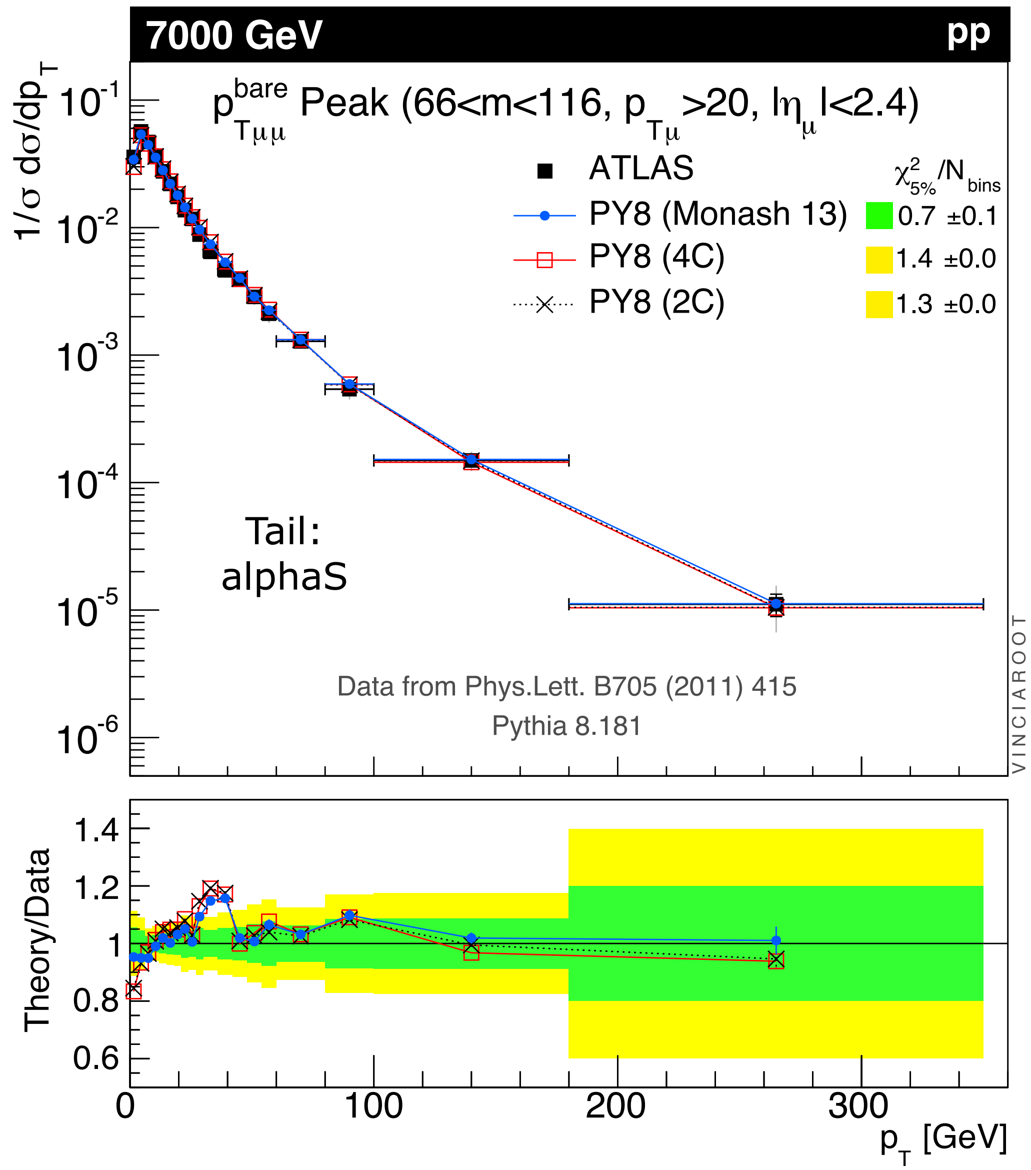
NLO tune: $\alpha_s(M_Z) = 0.122$ (2-loop running, CMW)



ISR + Primordial kT

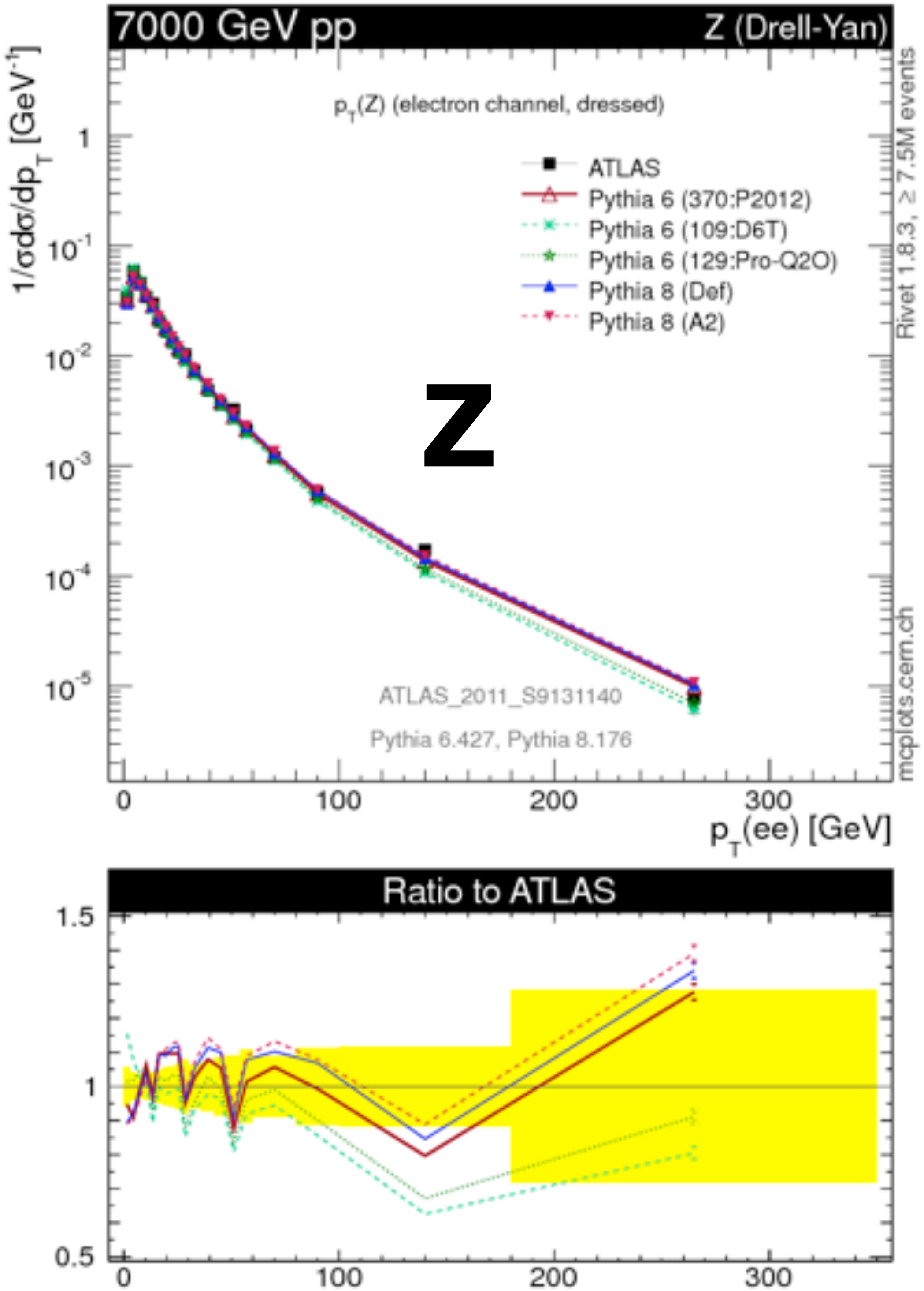
Drell-Yan pT distribution





Note: Q.M. requires physical observable!

Beware Process Dependence!



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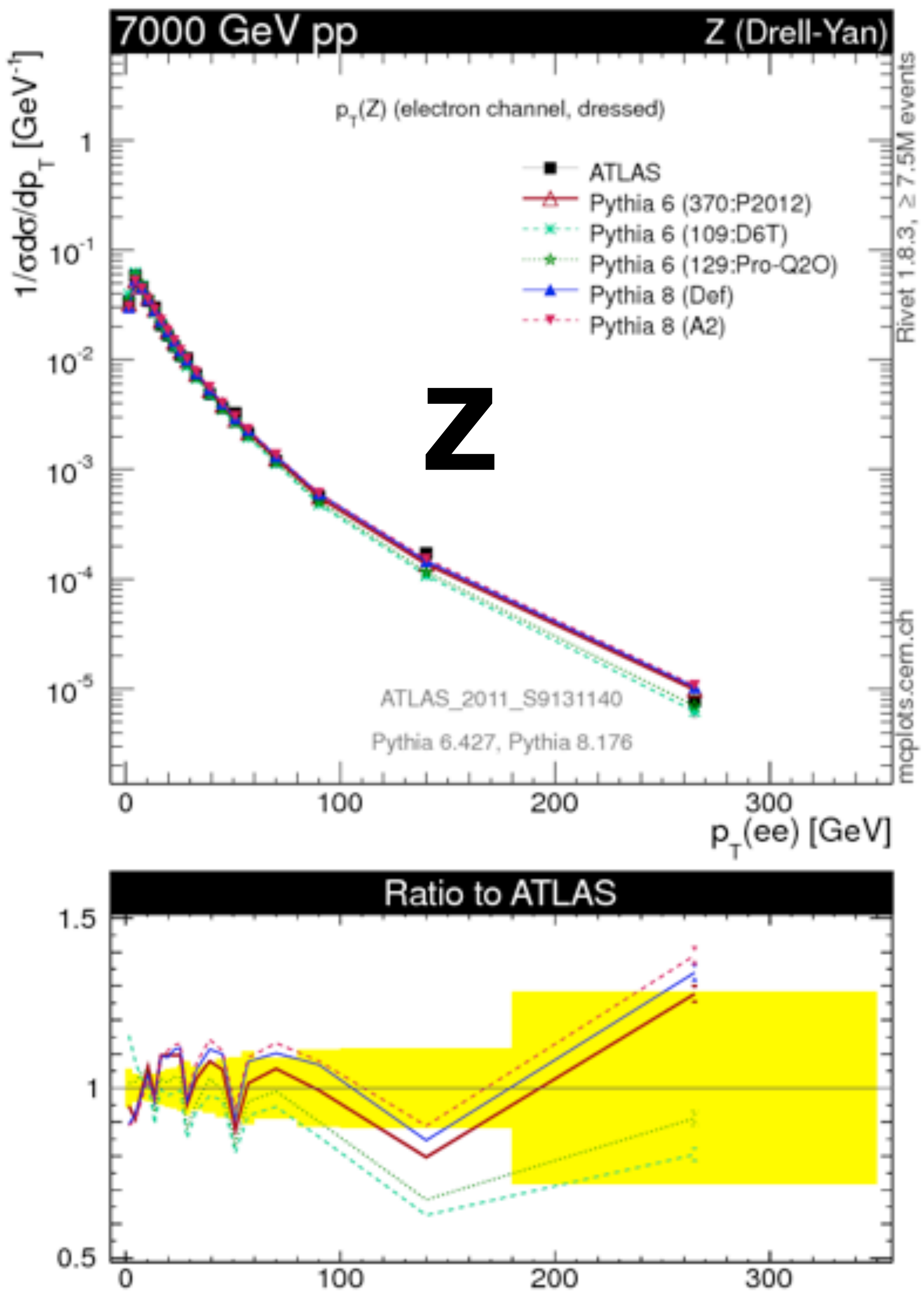
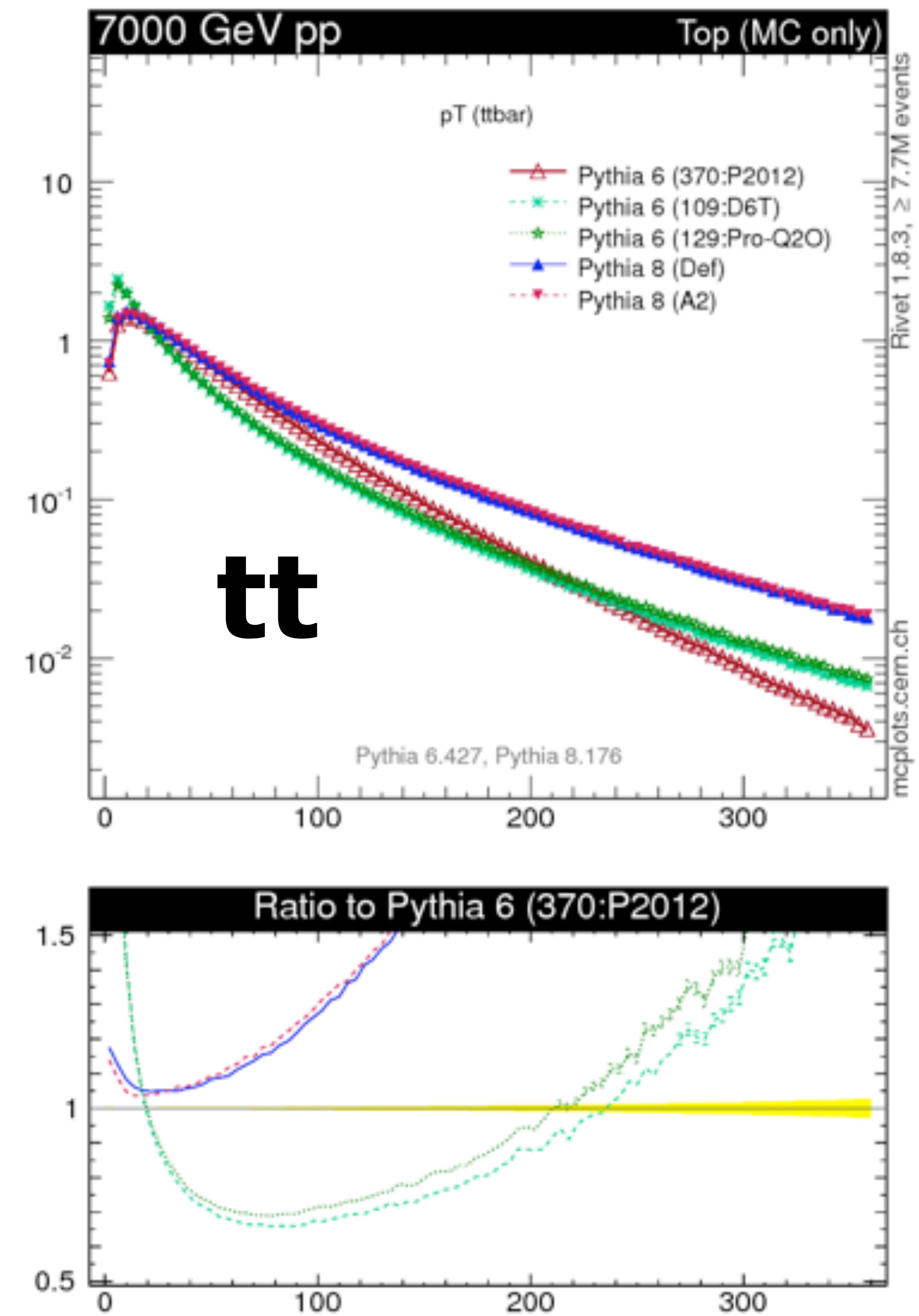




MPI and Beam Remnants

Determine

- p_{T0} : IR regularization scale for MPI
- Impact-parameter distribution (b-shape),
- Colour-reconnection strength ($\sim N_{hadrons}$/string)

We use:

- $P(N_{ch})$
- pT
- $\langle pT \rangle(N_{ch})$
- $dN_{ch}/d\eta$ (~ constant in y, except in forward region)
- UE (including $dN_{ch}/d\Delta\varphi$)

Why dN/dη is useless (by itself)

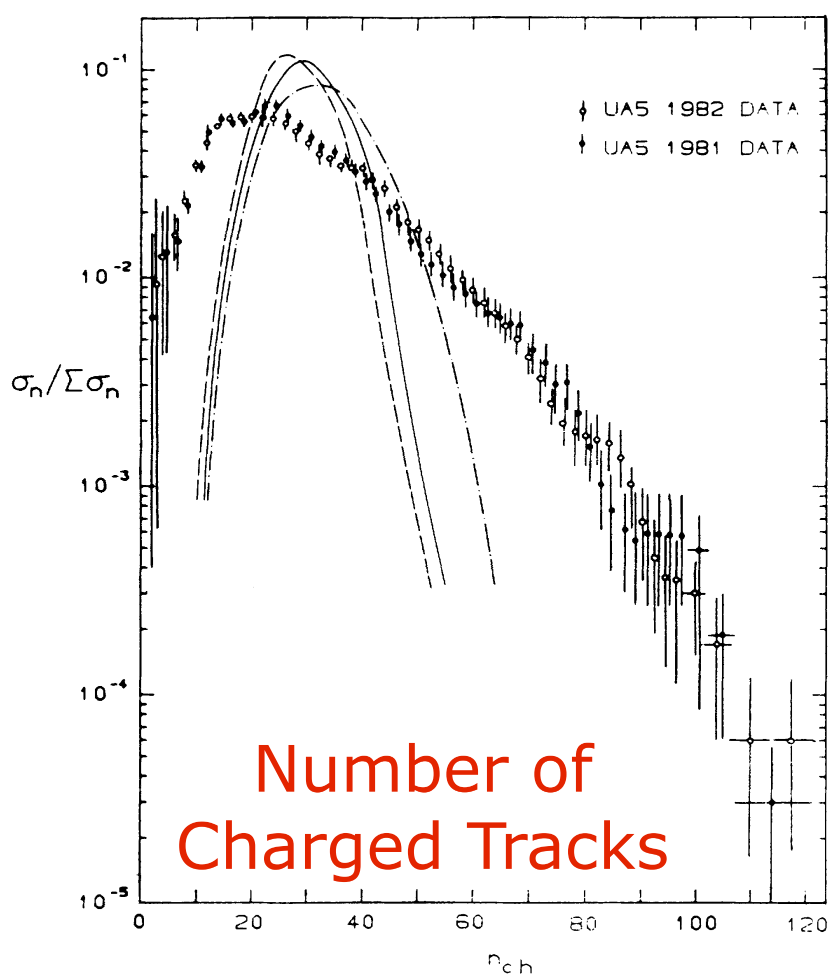


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

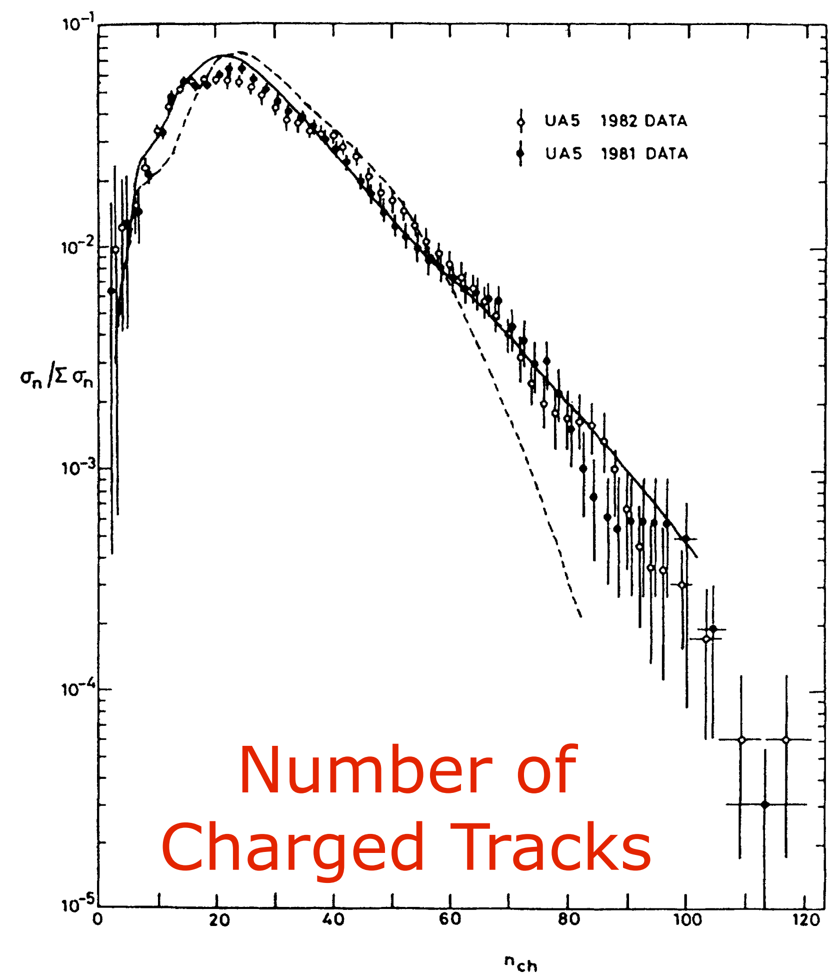
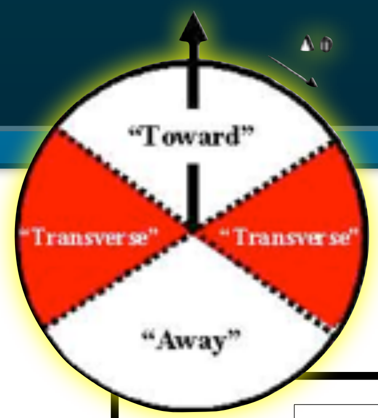


FIG. 12. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs multiple-interaction model with variable impact parameter: solid line, double-Gaussian matter distribution; dashed line, with fix impact parameter [i.e., $\tilde{O}_0(b)$].

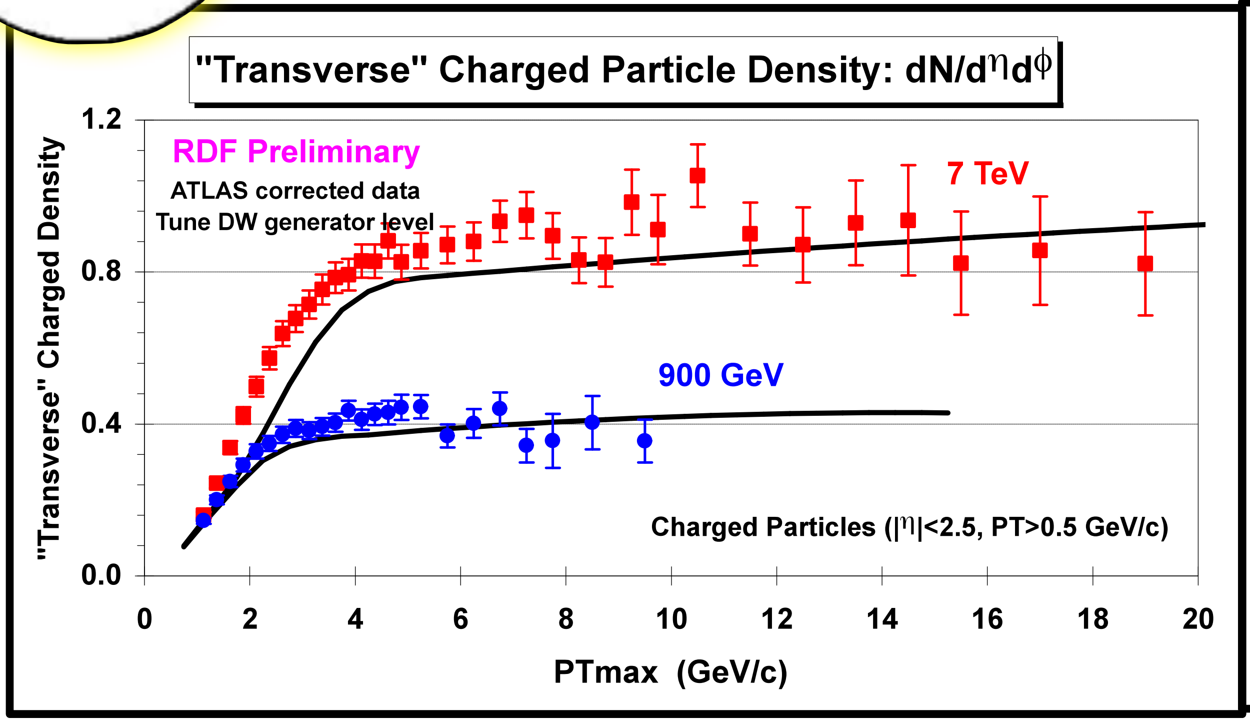
Sjöstrand & v. Zijl, Phys.Rev.D36(1987)2019

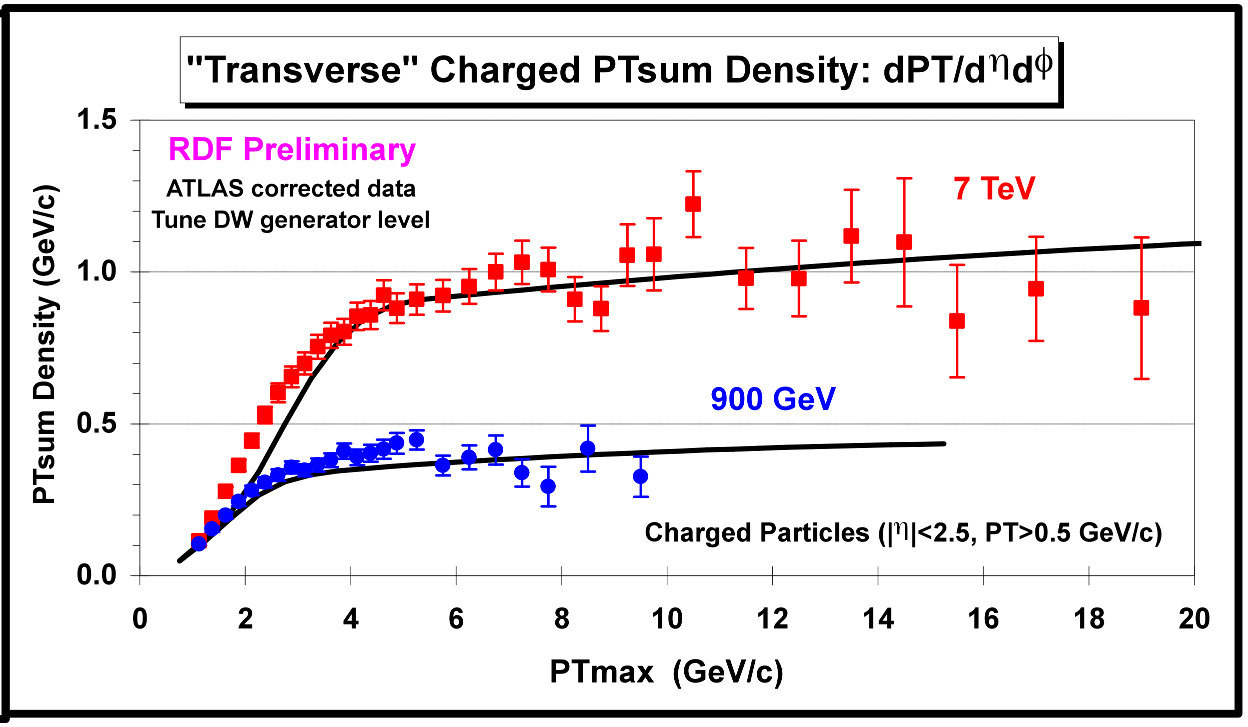
Can get <N> right with completely wrong models. Need RMS at least.

Underlying Event



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")

Interpreted as impact-parameter effect

Qualitatively reproduced by MPI models

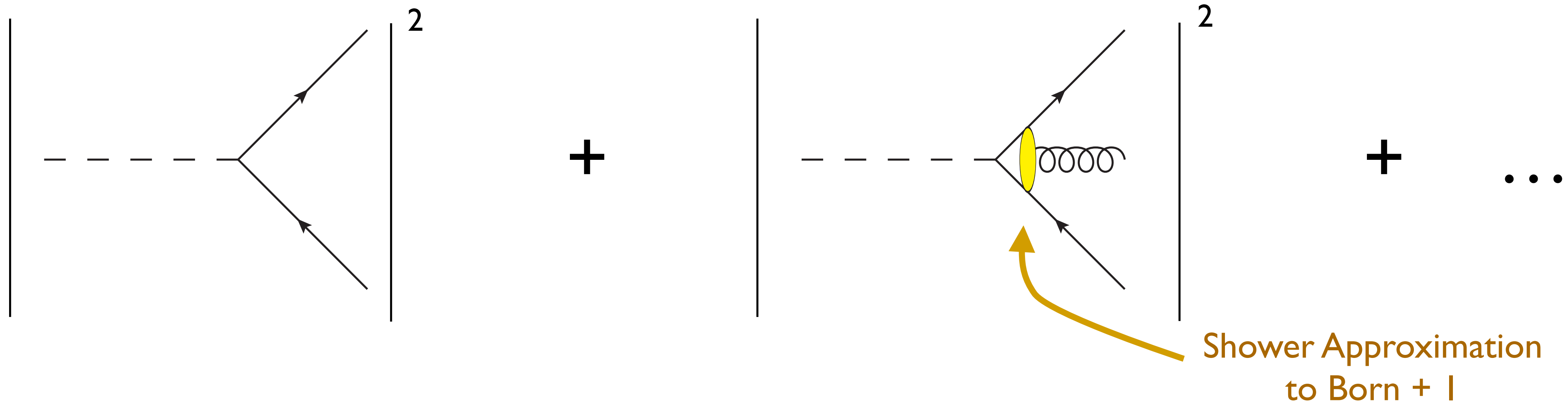
Relative size of this plateau / min-bias depends on pT0 *and* b-profile

Matching

Image Credits: istockphoto

Example: $H^0 \to b\bar{b}$

Born + Shower



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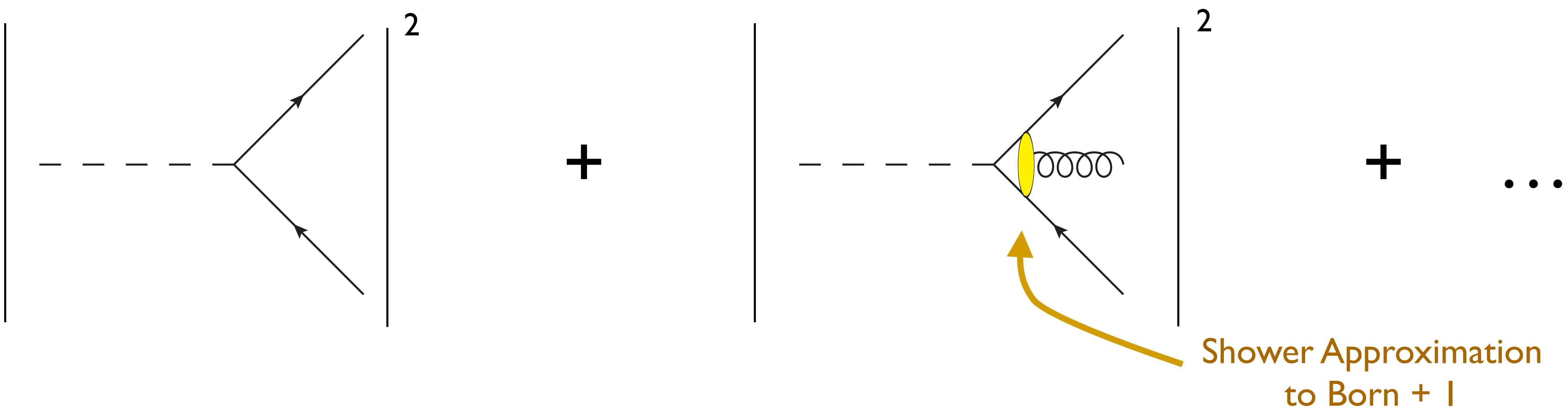
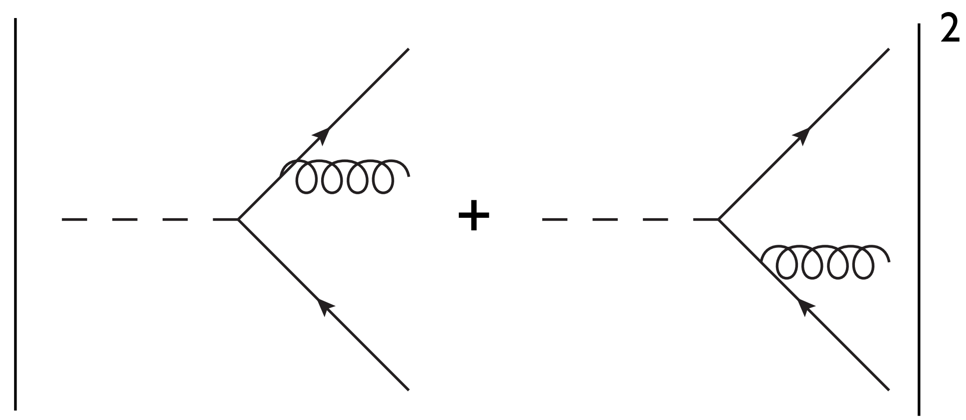


Born + 1 @ LO



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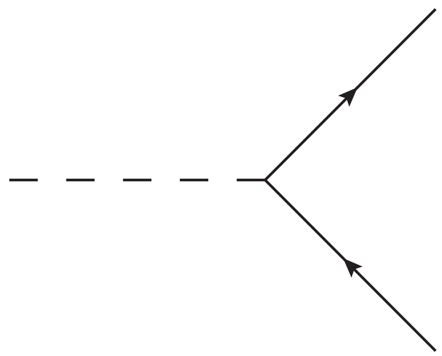
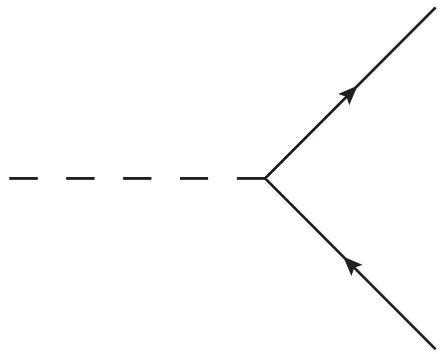


$$\left|\;\cdots\;\right|^2 \left(1 + g_s^2\, 2C_F \left[\frac{2 s_{ik}}{s_{ij} s_{jk}} + \frac{1}{s_{IK}} \left(\frac{s_{ij}}{s_{jk}} + \frac{s_{jk}}{s_{ij}} \right) \right] + \ldots \right)$$

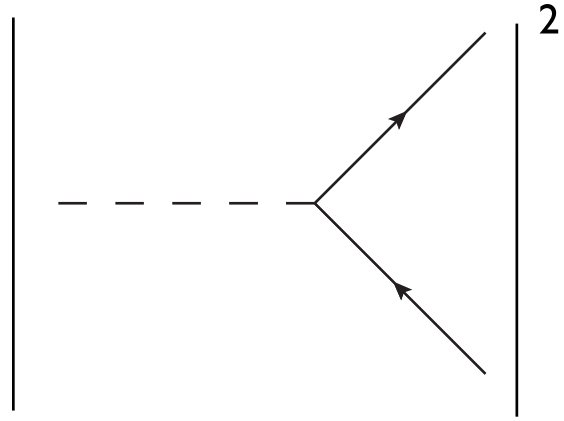
Born + 1 @ LO



$$\left|\;\cdots\;\right|^2 \left(g_s^2\, 2C_F \left[\frac{2 s_{ik}}{s_{ij} s_{jk}} + \frac{1}{s_{IK}} \left(\frac{s_{ij}}{s_{jk}} + \frac{s_{jk}}{s_{ij}} + 2 \right) \right] \right)$$

Example: $H^0 \to b\bar{b}$

Born + Shower



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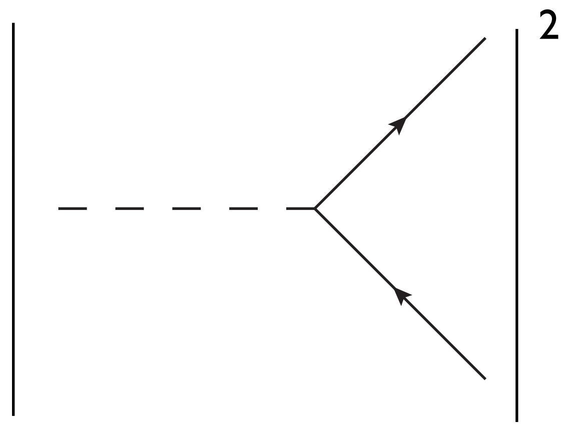
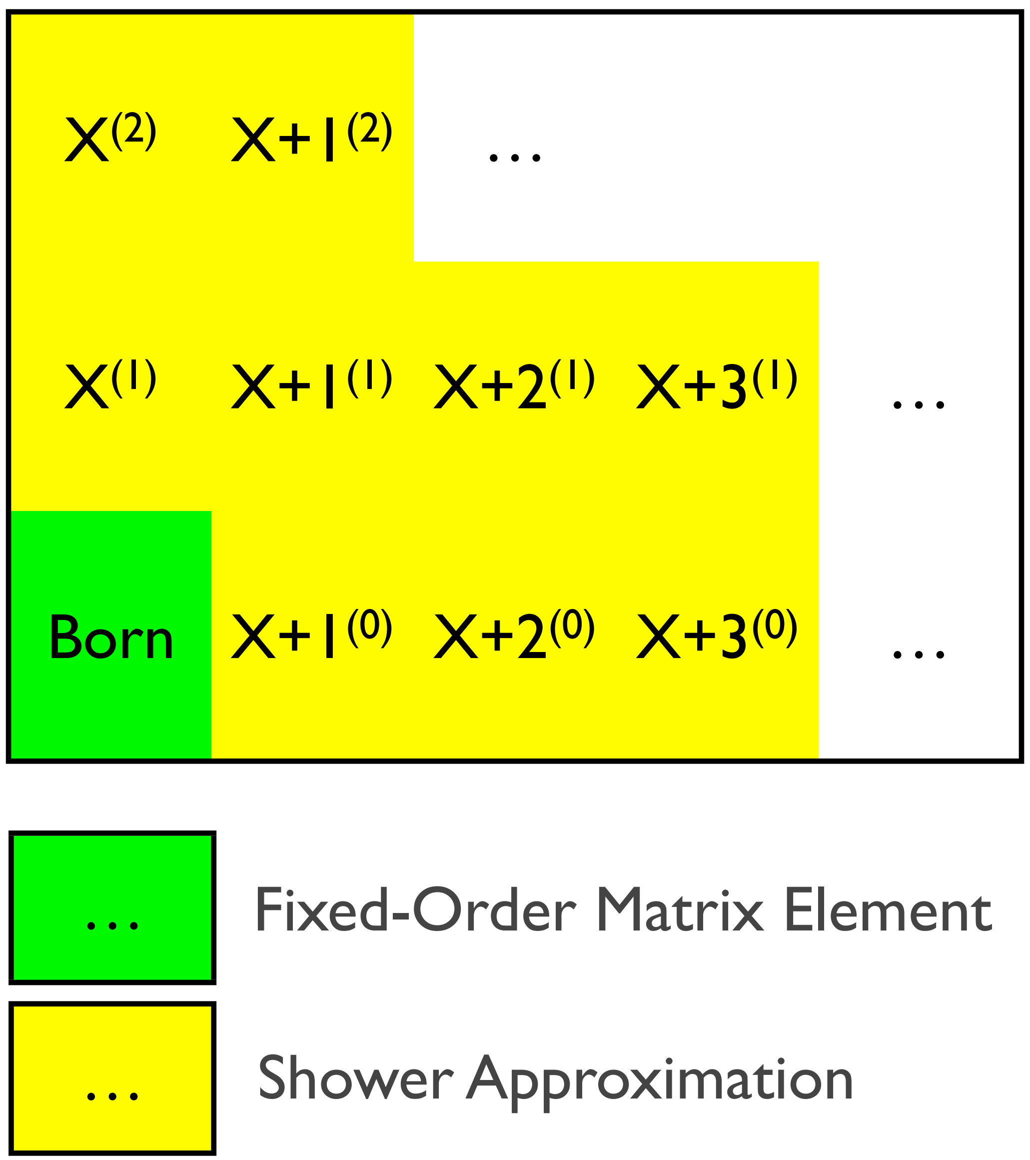


$$\left|\ \cdots\ \right|^2 \left(g_s^2\, 2C_F \left[\frac{2s_{ik}}{s_{ij}s_{jk}} + \frac{1}{s_{IK}} \left(\frac{s_{ij}}{s_{jk}} + \frac{s_{jk}}{s_{ij}} + 2 \right) \right] \right)$$

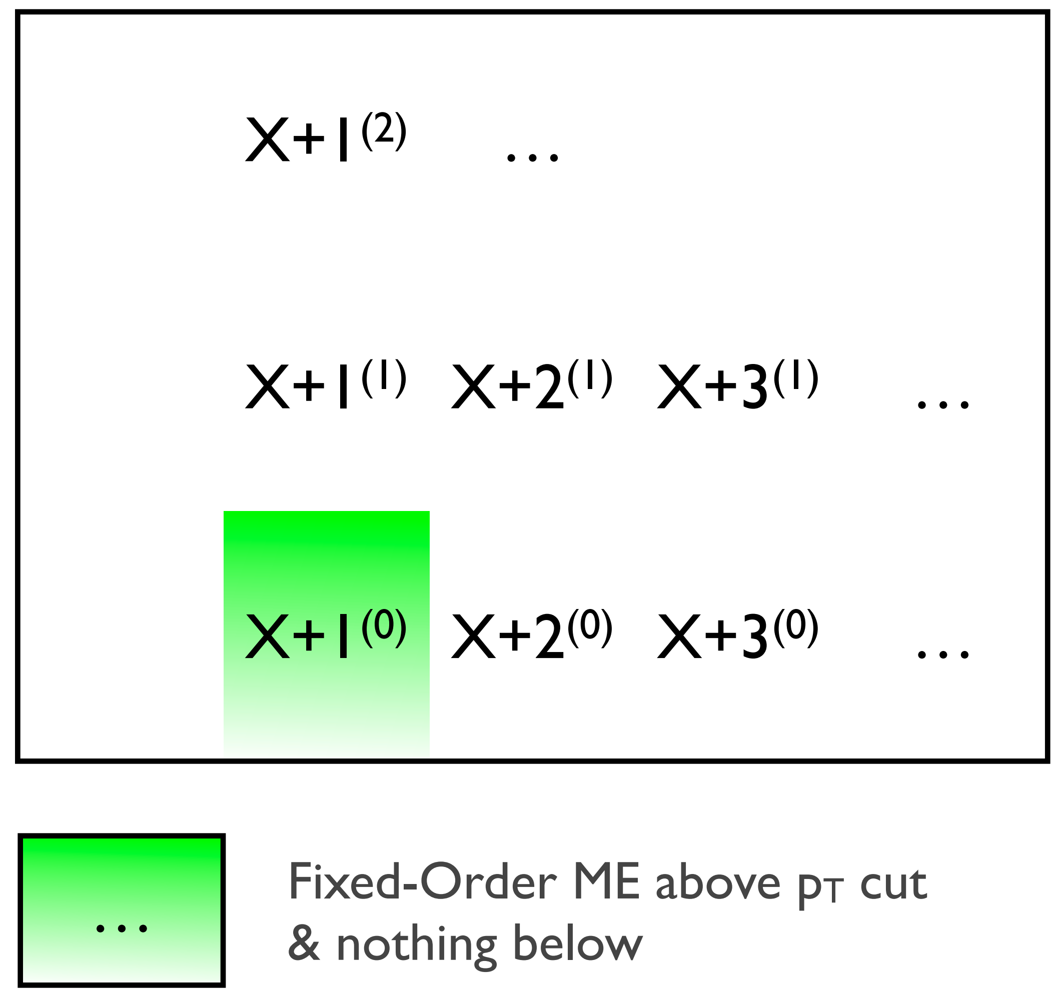
Total Overkill to add these two. All I really need is just that **+2** …

Adding Calculations

Born × Shower
(see lecture 3)



X+1 @ LO
(with p_T cutoff, see lecture 2)



Adding Calculations

Born × Shower

(see lecture 3)

$X^{(2)}$	$X+1^{(2)}$	…		
$X^{(1)}$	$X+1^{(1)}$	$X+2^{(1)}$	$X+3^{(1)}$	…
Born	$X+1^{(0)}$	$X+2^{(0)}$	$X+3^{(0)}$	…

- … Fixed-Order Matrix Element
- … Shower Approximation

X+1 @ LO × Shower

(with p_T cutoff, see lecture 2)

	$X+1^{(2)}$	…		
	$X+1^{(1)}$	$X+2^{(1)}$	$X+3^{(1)}$	…
	$X+1^{(0)}$	$X+2^{(0)}$	$X+3^{(0)}$	…

- … Fixed-Order ME above p_T cut & nothing below
- … Shower approximation above p_T cut & nothing below

→ Double Counting

Born × Shower + (X+1) × shower

Double Counting of terms present in both expansions

$X^{(2)}$	$X+1^{(2)}$	…		
$X^{(1)}$	$X+1^{(1)}$	$X+2^{(1)}$	$X+3^{(1)}$	…
Born	$X+1^{(0)}$	$X+2^{(0)}$	$X+3^{(0)}$	…

Worse than useless

- … Fixed-Order Matrix Element
- … Shower Approximation
- … Double counting above p_T cut & shower approximation below

Interpretation

- A (Complete Idiot's) Solution – Combine
  1. $[X]_{ME}$ + showering
  2. $[X + 1\ \text{jet}]_{ME}$ + showering
  3. …

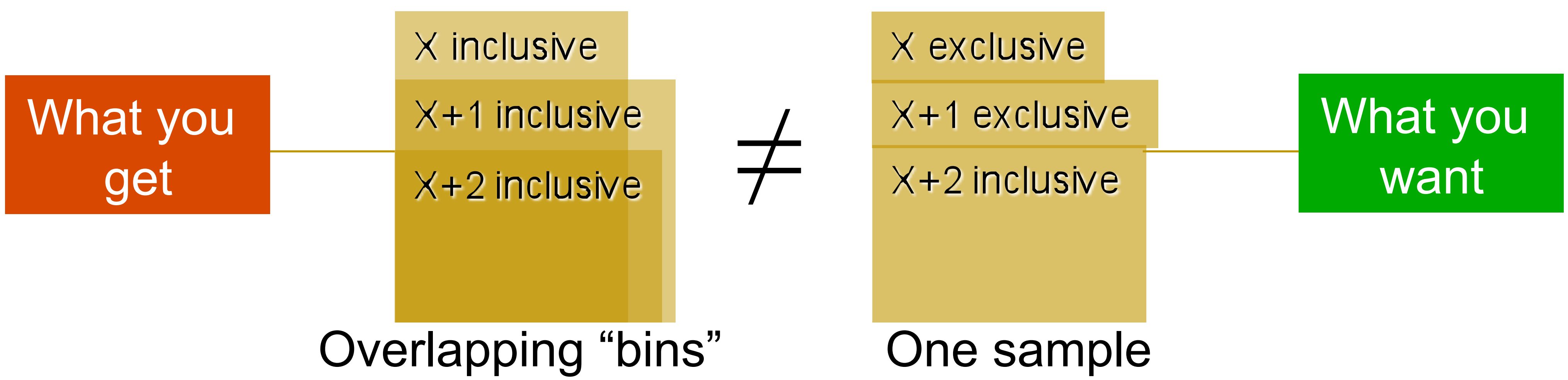
Run generator for X (+ shower)

Run generator for X+1 (+ shower)

Run generator for … (+ shower)

Combine everything into one sample

- Doesn't work
  - [X] + shower is inclusive
  - [X+1] + shower is also inclusive

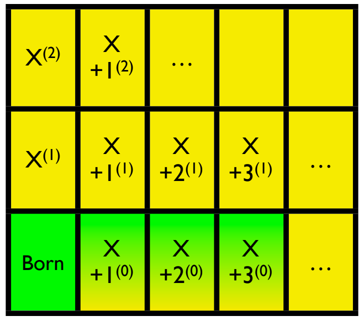


Cures

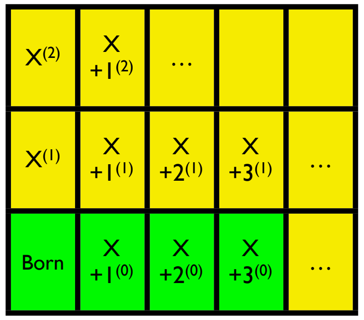
Cures

Tree-Level Matrix Elements

PHASE-SPACE SLICING *(a.k.a. CKKW, MLM, …)*



UNITARITY *(a.k.a. multiplication, PYTHIA, VINCIA, …)*



Cures

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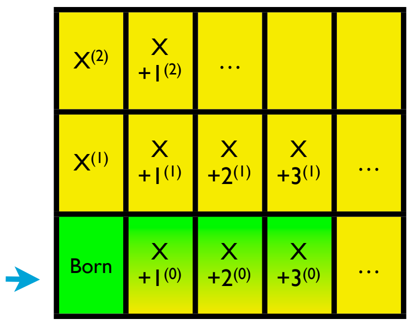

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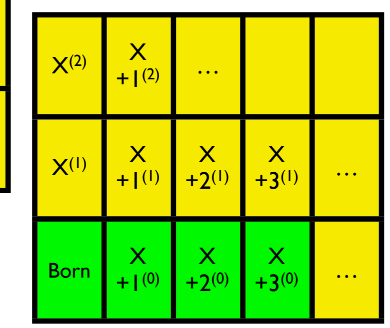
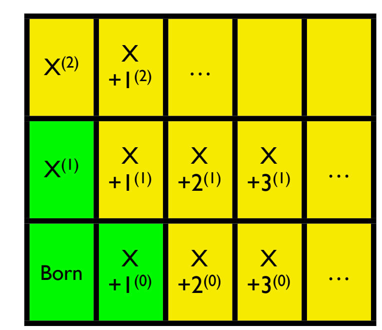


NLO Matrix Elements

SUBTRACTION *(a.k.a. MC@NLO)*

UNITARITY + SUBTRACTION *(a.k.a. POWHEG, VINCIA)*



Cures

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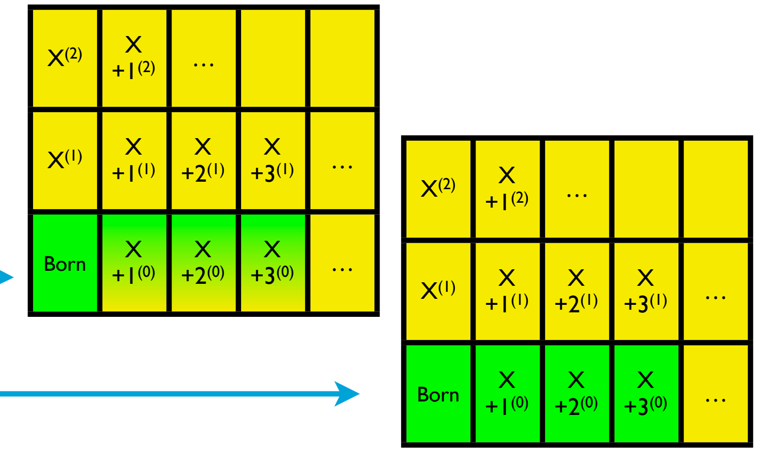

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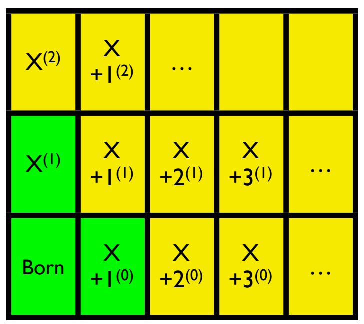
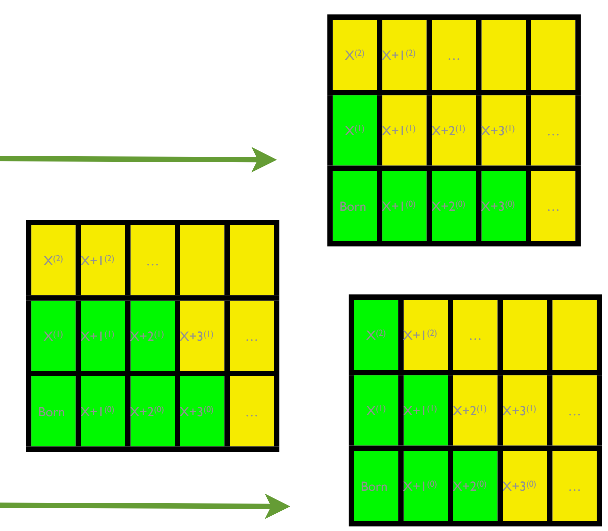


+ WORK IN PROGRESS …

NLO + multileg tree-level matrix elements

NLO multileg matching

Matching at NNLO



Cures

Tree-Level Matrix Elements

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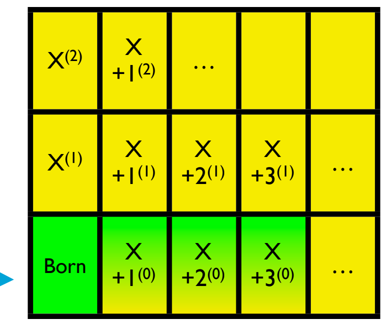

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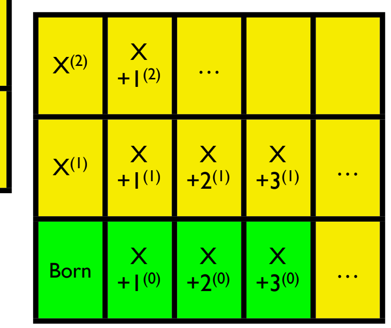

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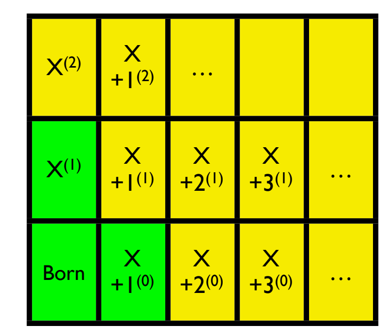

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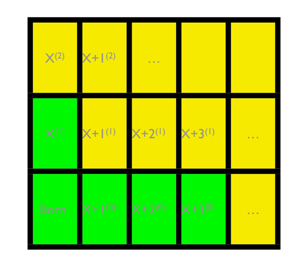
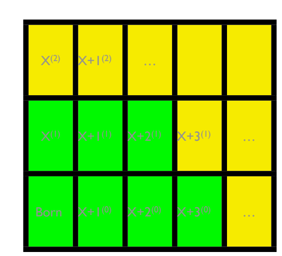
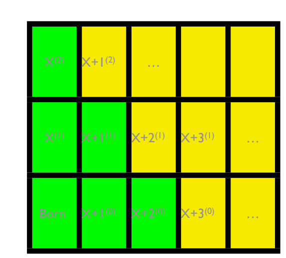


NLO multileg matching



Matching at NNLO



Matching 1: Slicing

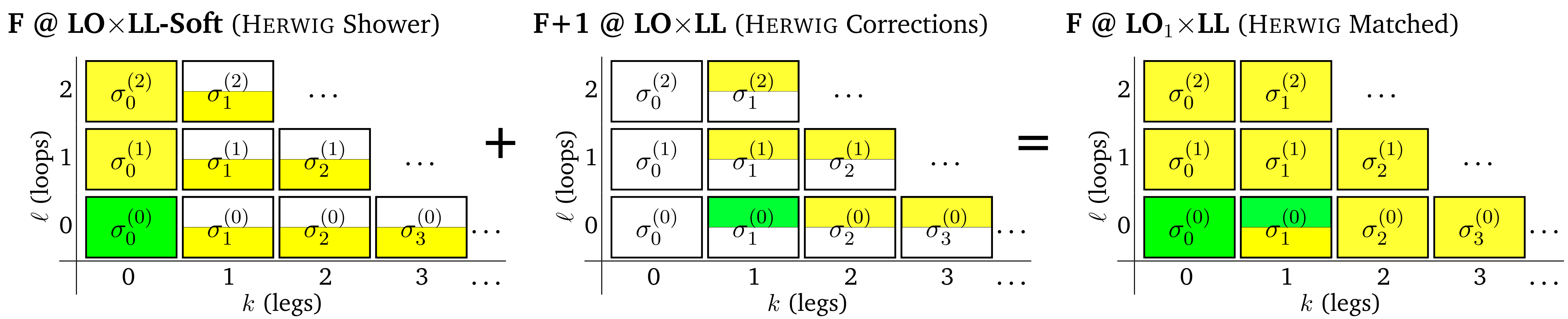
Examples: MLM, CKKW, CKKW-L

Matching 1: Slicing

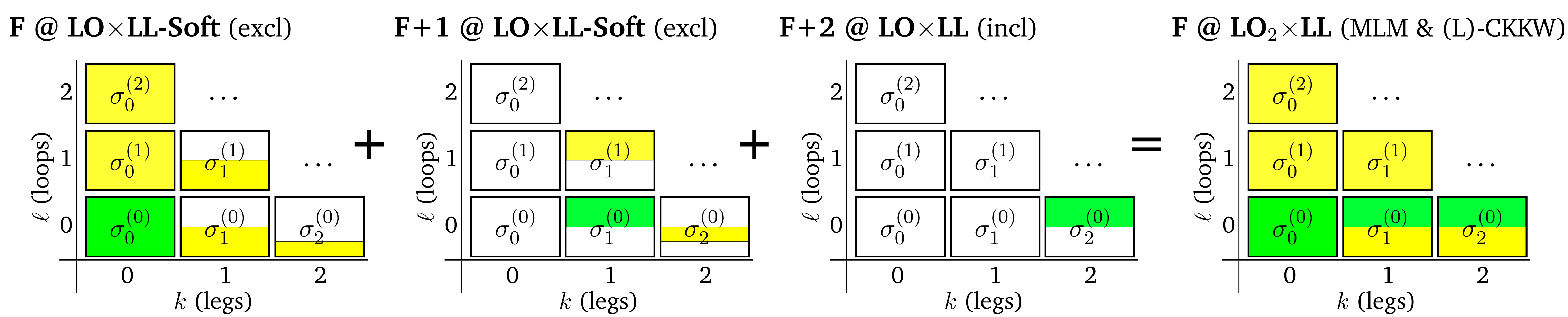
Examples: MLM, CKKW, CKKW-L

First emission: "the HERWIG correction"

Use the fact that the angular-ordered HERWIG parton shower has a "dead zone" for hard wide-angle radiation (Seymour, 1995)



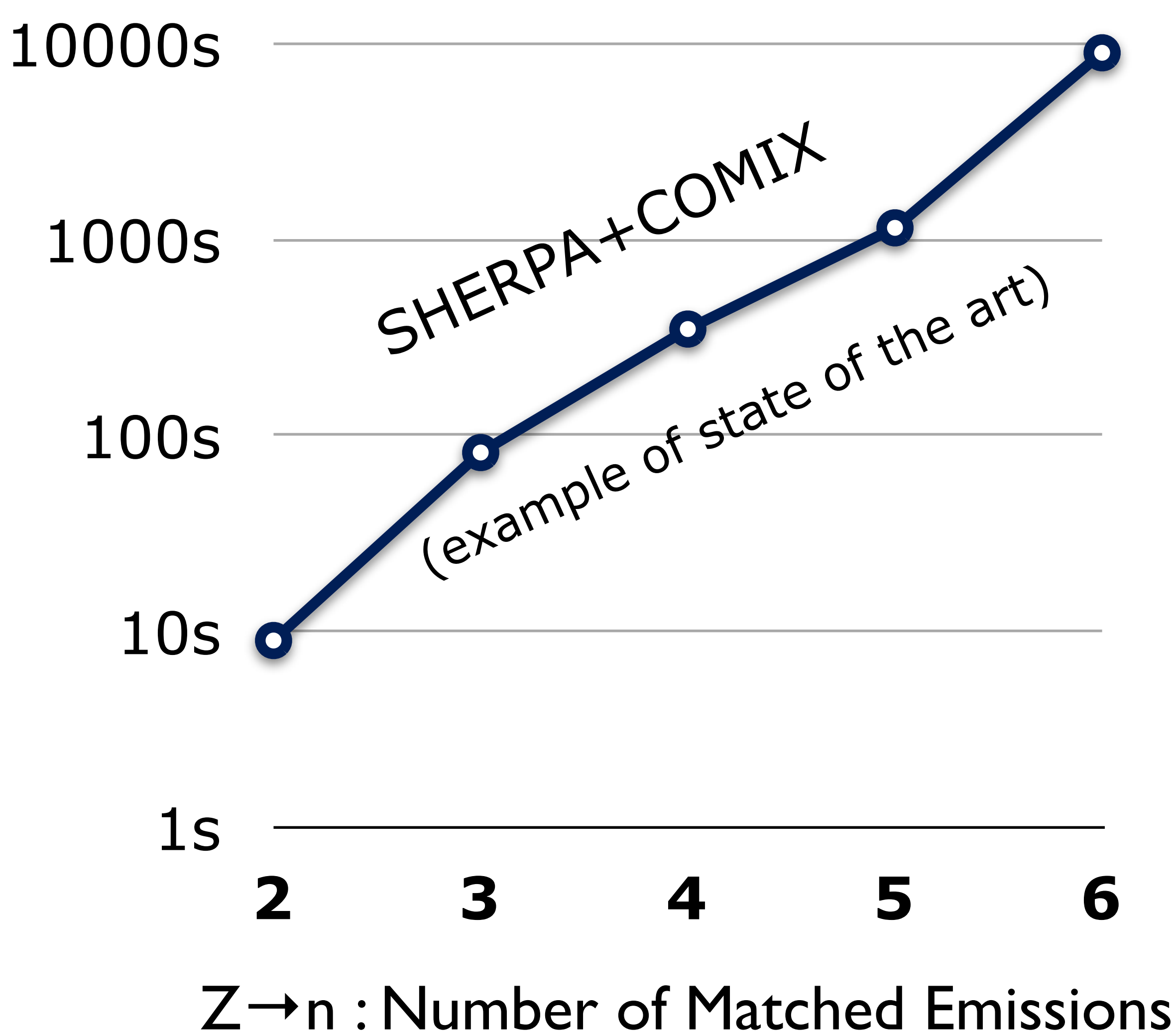
Many emissions: the MLM & CKKW-L prescriptions



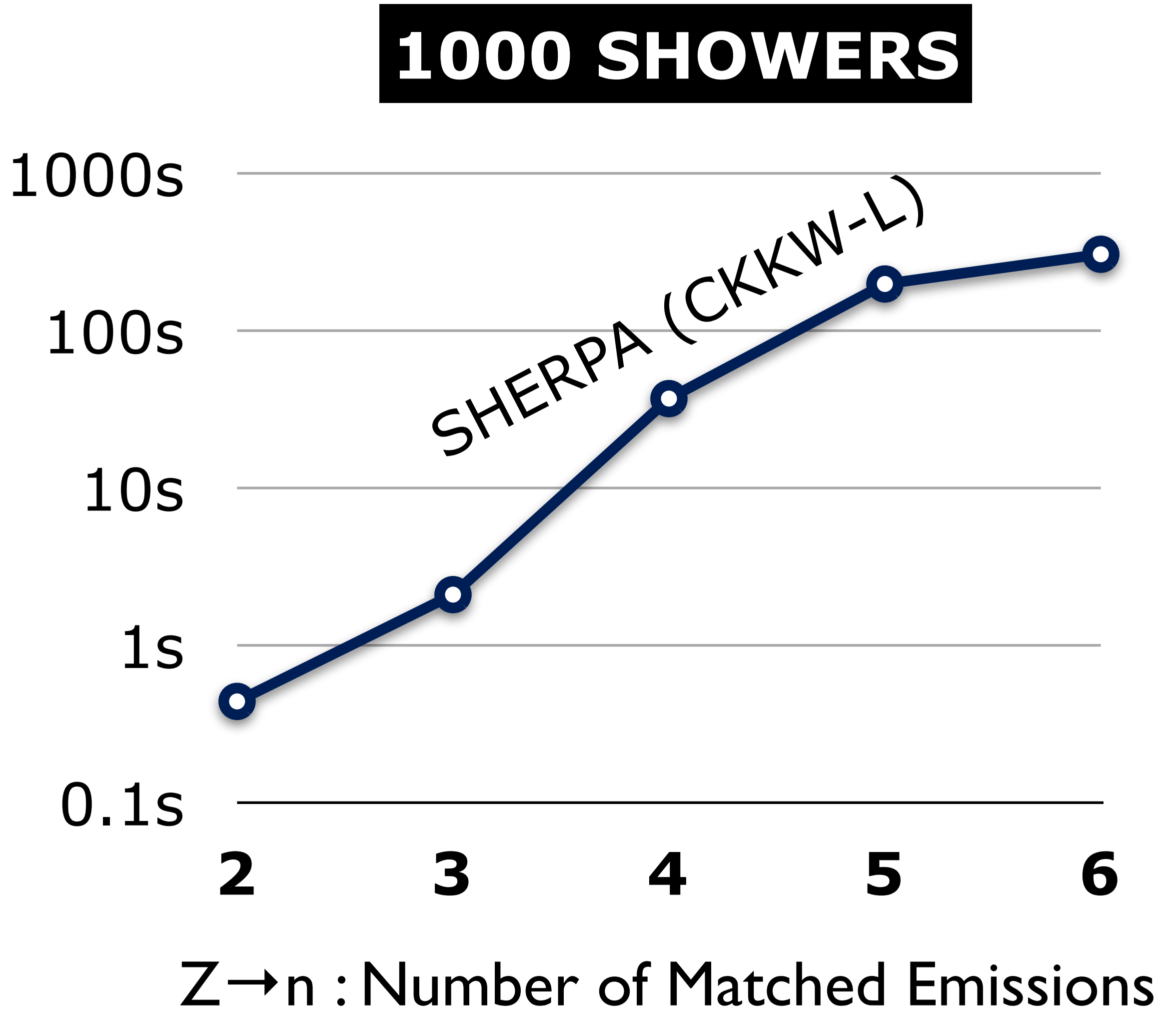
(CKKW & Lönnblad, 2001) (Mangano, 2002) (+many more recent; see Alwall et al., EPJC53(2008)473)

Slicing: The Cost

1. Initialization time
(to pre-compute cross sections and warm up phase-space grids)



2. Time to generate 1000 events
(Z → partons, fully showered & matched. No hadronization.)



Z→udscb ; Hadronization OFF ; ISR OFF ; udsc MASSLESS ; b MASSIVE ; E_{CM} = 91.2 GeV ; Q_{match} = 5 GeV
SHERPA 1.4.0 (+COMIX) ; PYTHIA 8.1.65 ; VINCIA 1.0.29 (+MADGRAPH 4.4.26) ;
gcc/gfortran v 4.7.1 -O2 ; single 3.06 GHz core (4GB RAM)

Classic Example

W + Jets

Number of jets in pp→W+X at the LHC

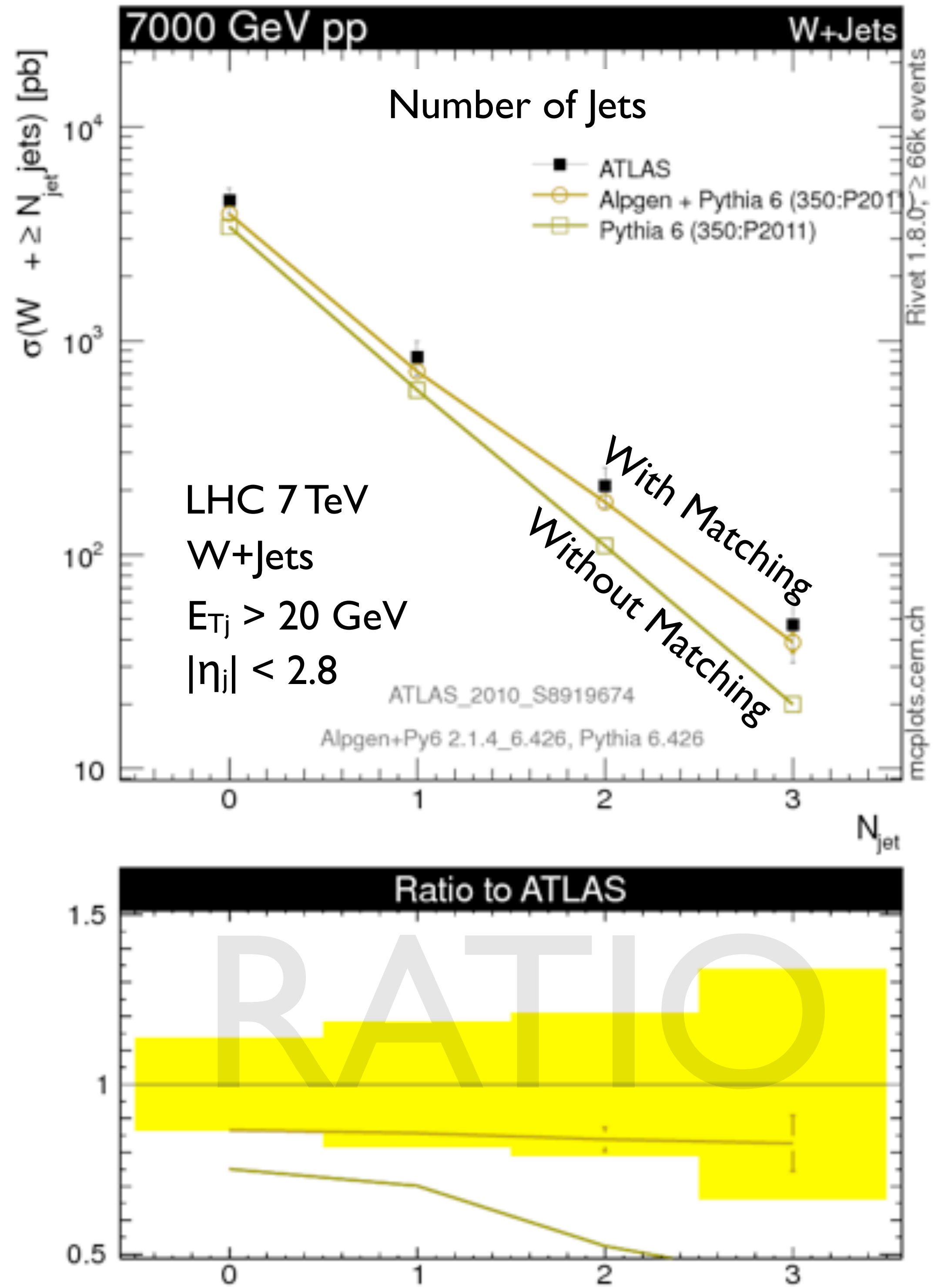
From 0 (W inclusive) to W+3 jets

PYTHIA includes matching up to W+1 jet + shower

With ALPGEN, also the LO matrix elements for 2 and 3 jets are included

But Normalization still only LO

mcplots.cern.ch



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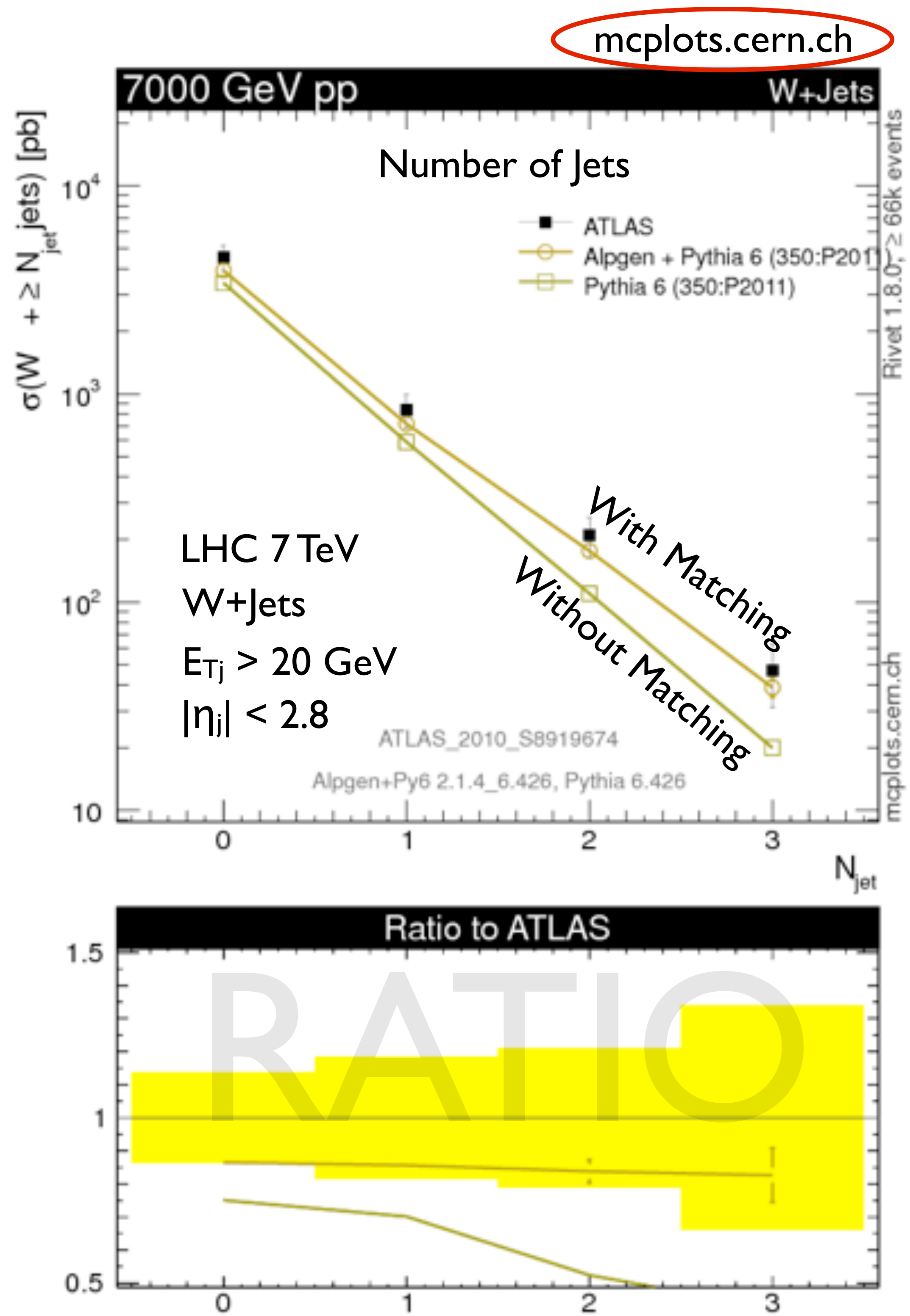


Slicing: Some Subtleties

Choice of slicing scale (=matching scale)

Fixed order must still be reliable when regulated with this scale

→ matching scale should never be chosen more than ~ one order of magnitude below hard scale.

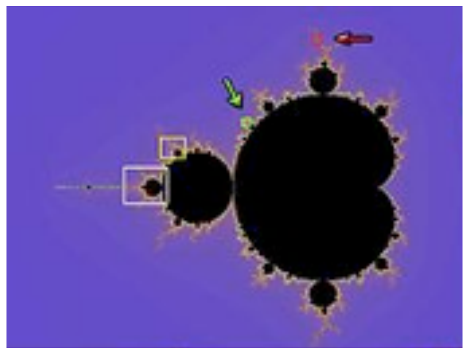
Precision still "only" Leading Order

Choice of Renormalization Scale

We already saw this can be very important (and tricky) in multi-scale problems.

Caution advised (see also supplementary slides & lecture notes)

Choice of Matching Scale

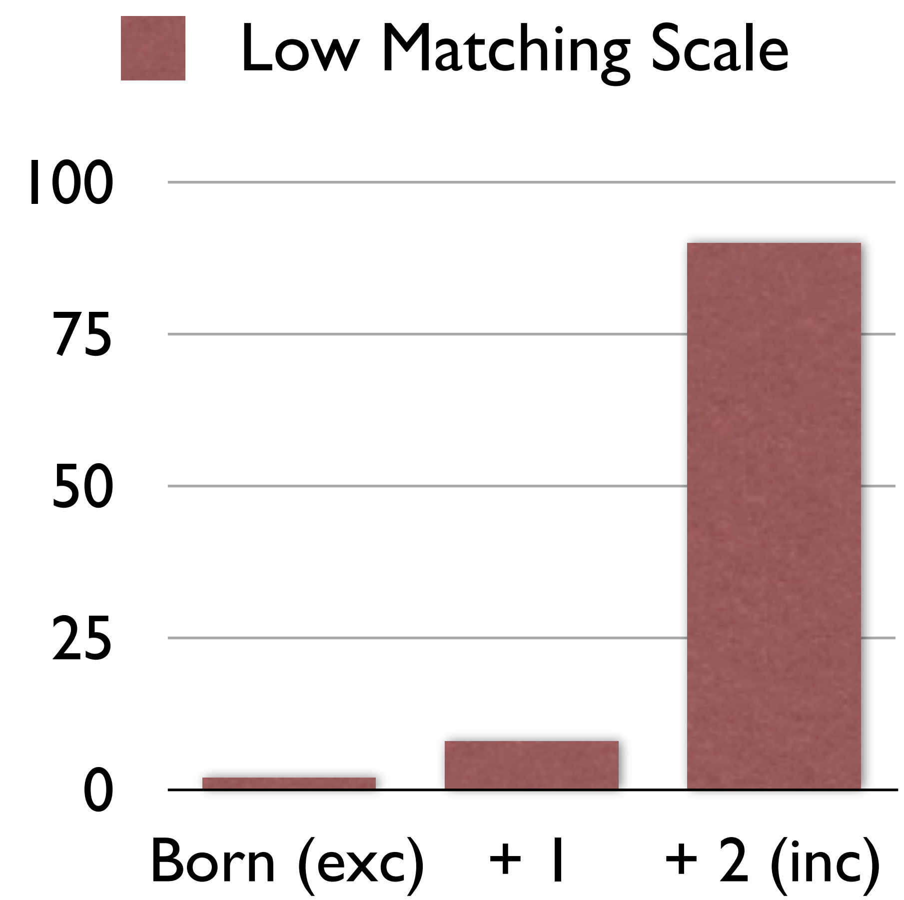


Reminder: in perturbative region, QCD is approximately ***scale invariant***

→ A scale of 20 GeV for a W boson becomes 40 GeV for something weighing $2M_W$, etc … (+ adjust for C_A/C_F if g-initiated)

→ The matching scale should be written as a **ratio** (Bjorken scaling)

Using a too low matching scale → everything just becomes highest ME

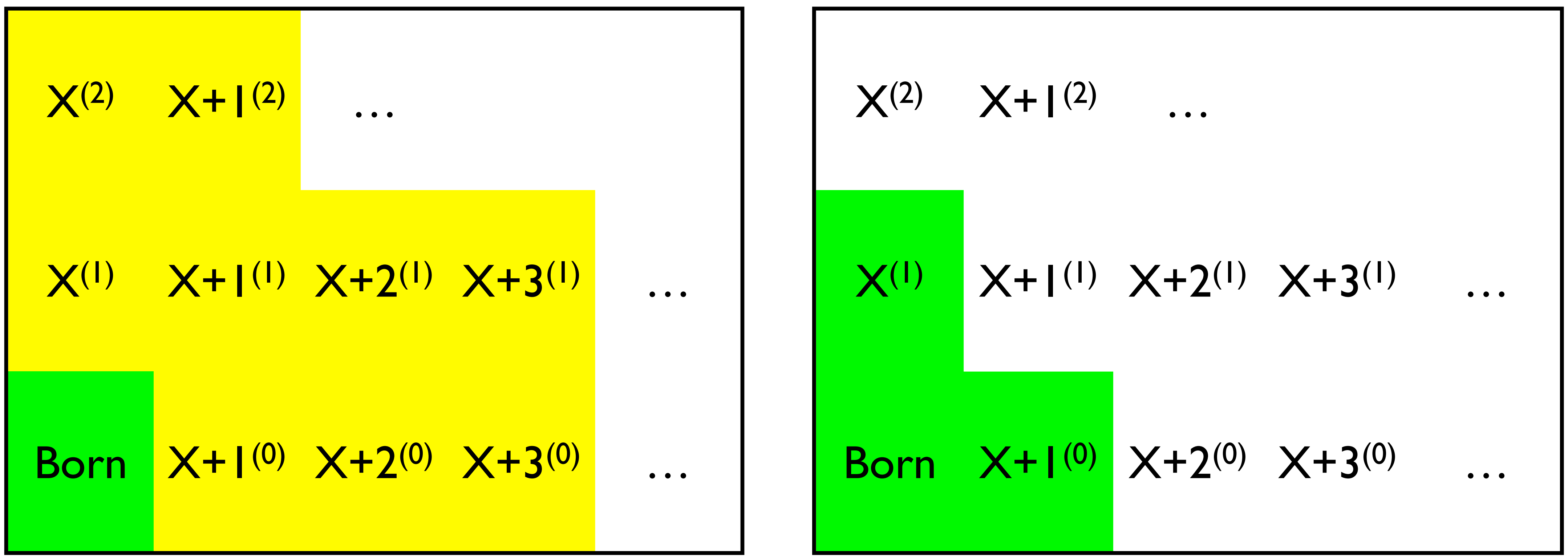


Caveat emptor: showers generally do not include helicity correlations

Matching 2: Subtraction

Examples: MC@NLO, aMC@NLO

LO × Shower   NLO



[green box: …] Fixed-Order Matrix Element

[yellow box: …] Shower Approximation

Matching 2: Subtraction

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LO × Shower

$X^{(2)}$	$X+1^{(2)}$	…		
$X^{(1)}$	$X+1^{(1)}$	$X+2^{(1)}$	$X+3^{(1)}$	…
Born	$X+1^{(0)}$	$X+2^{(0)}$	$X+3^{(0)}$	…

… Fixed-Order Matrix Element

… Shower Approximation

NLO - Shower$_{NLO}$

$X^{(2)}$	$X+1^{(2)}$	…		
$X^{(1)}$	$X+1^{(1)}$	$X+2^{(1)}$	$X+3^{(1)}$	…
Born	$X+1^{(0)}$	$X+2^{(0)}$	$X+3^{(0)}$	…

Expand shower approximation to NLO analytically, then subtract:

… Fixed-Order ME minus Shower Approximation (NOTE: can be < 0!)

Matching 2: Subtraction

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$X^{(2)}$	$X+1^{(2)}$	…		
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… Fixed-Order Matrix Element

… Shower Approximation

(NLO - Shower$_{\text{NLO}}$) × Shower

$X^{(1)}$	$X^{(1)}$	…		
$X^{(1)}$	$X^{(1)}$	$X^{(1)}$	$X^{(1)}$	…
Born	$X+1^{(0)}$	$X^{(1)}$	$X^{(1)}$	…

… Fixed-Order ME minus Shower Approximation (NOTE: can be < 0!)

… Subleading corrections generated by shower off subtracted ME

Matching 2: Subtraction

Examples: MC@NLO, aMC@NLO

Combine → MC@NLO

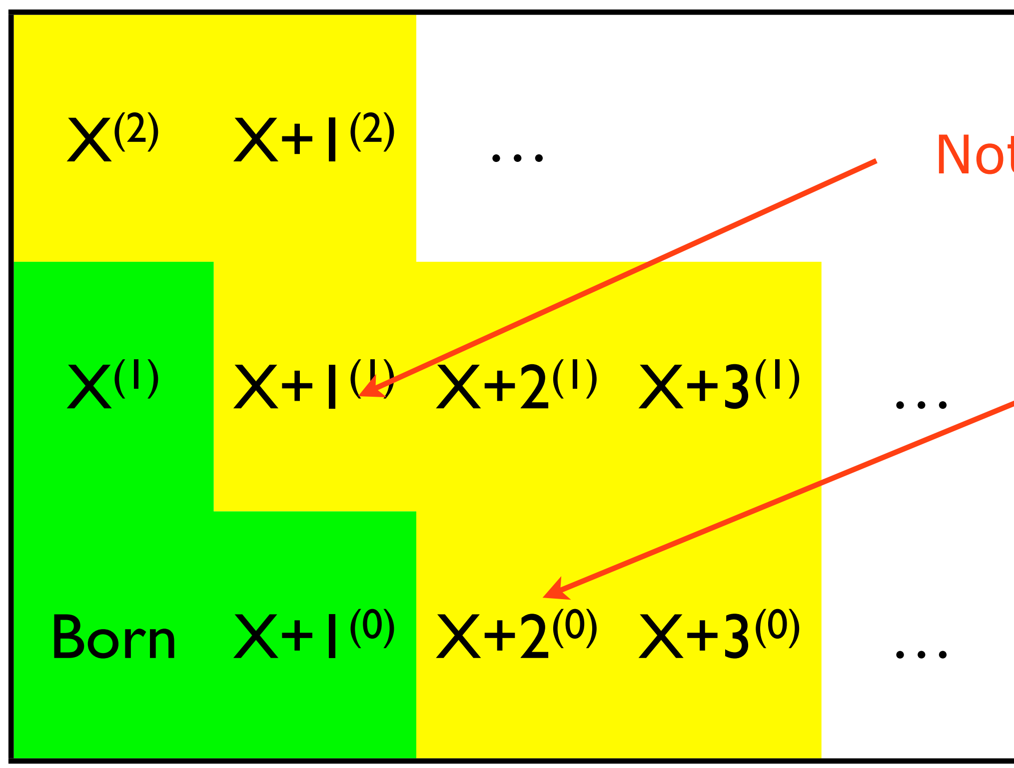
Frixione, Webber, JHEP 0206 (2002) 029

Consistent NLO + parton shower (though correction events can have w<0)

Recently, has been almost fully automated in aMC@NLO

Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli, JHEP 1202 (2012) 048

NLO: for X inclusive
LO for X+1
LL: for everything else



Note 1: NOT NLO for X+1

Note 2: Multijet tree-level matching still superior for X+2

NB: w < 0 are a problem because they kill efficiency:
Extreme example: 1000 positive-weight - 999 negative-weight events → statistical precision of 1 event, for 2000 generated (for comparison, normal MC@NLO has ~ 10% neg-weights)

Matching 3: ME Corrections

Double counting, IR divergences, multiscale logs

Matching 3: ME Corrections

Standard Paradigm:

Have ME for X, X+1,..., X+n;

Want to combine and add showers → "The Soft Stuff"

Double counting, IR divergences, multiscale logs

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Works pretty well at low multiplicities

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Efficiency problems: slowdown from need to compute and generate phase space from $d\sigma_{X+n}$, and from unweighting (efficiency also reduced by negative weights, if present)

Scale hierarchies: smaller single-scale phase-space region

Powers of alphaS pile up

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Better Starting Point: a QCD fractal?

(shameless VINCIA promo)

(plug-in to PYTHIA 8 for ME-improved final-state showers, uses helicity matrix elements from MadGraph)

LO: Giele, Kosower, Skands, PRD84(2011)054003

NLO: Hartgring, Laenen, Skands, arXiv:1303.4974

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(plug-in to PYTHIA 8 for ME-improved final-state showers, uses helicity matrix elements from MadGraph)

Interleaved Paradigm:

Have shower; want to improve it using ME for X, X+1, …, X+n.

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Interleaved Paradigm:

Have shower; want to improve it using ME for X, X+1, …, X+n.

Interpret all-orders shower structure as a trial distribution

Quasi-scale-invariant: intrinsically multi-scale (resums logs)

Unitary: automatically unweighted (& IR divergences → multiplicities)

More precise expressions imprinted via veto algorithm: ME corrections at LO, NLO, … → soft *and* hard corrections

No additional phase-space generator or σ_{X+n} calculations → **fast**

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Automated Theory Uncertainties

For each event: vector of output weights (central value = 1)

+ Uncertainty variations. Faster than N separate samples; only one sample to analyse, pass through detector simulations, etc.

LO: Giele, Kosower, Skands, PRD84(2011)054003

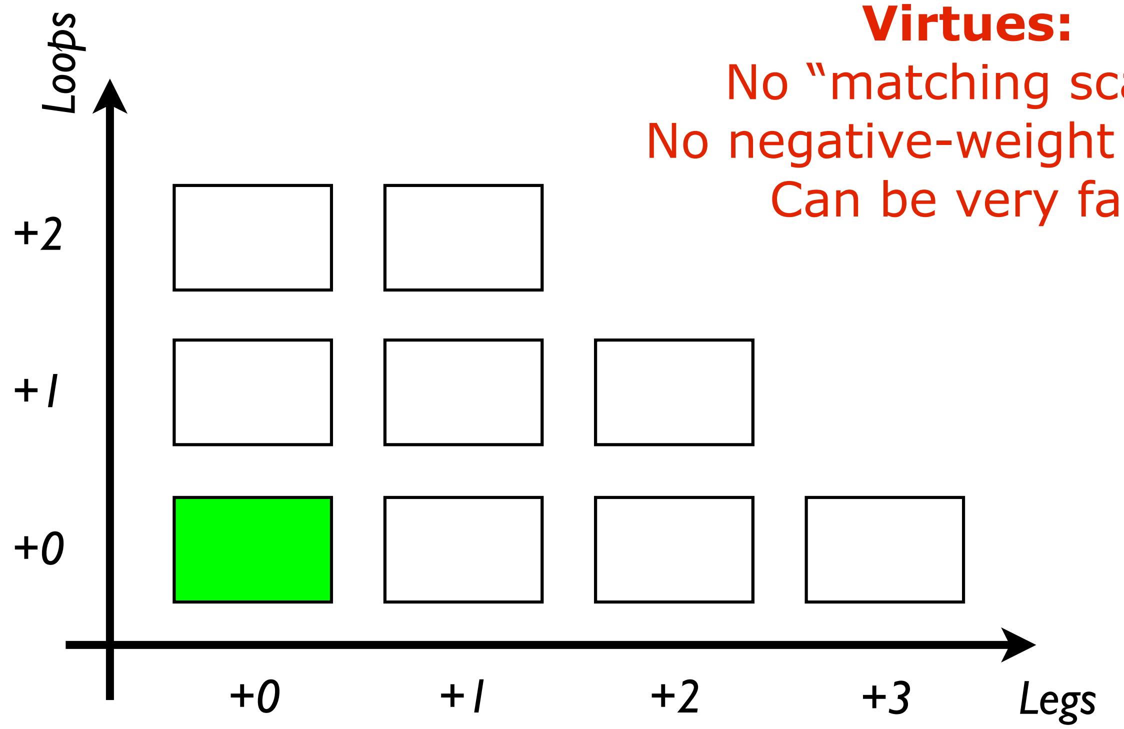
NLO: Hartgring, Laenen, Skands, arXiv:1303.4974

Matching 3: ME Corrections

Examples: PYTHIA, POWHEG, VINCIA

Start at Born level

$$|M_F|^2$$



Virtues:

No “matching scale”

No negative-weight events

Can be very fast

Illustrations from: PS, TASI Lectures, arXiv:1207.2389

Matching 3: ME Corrections

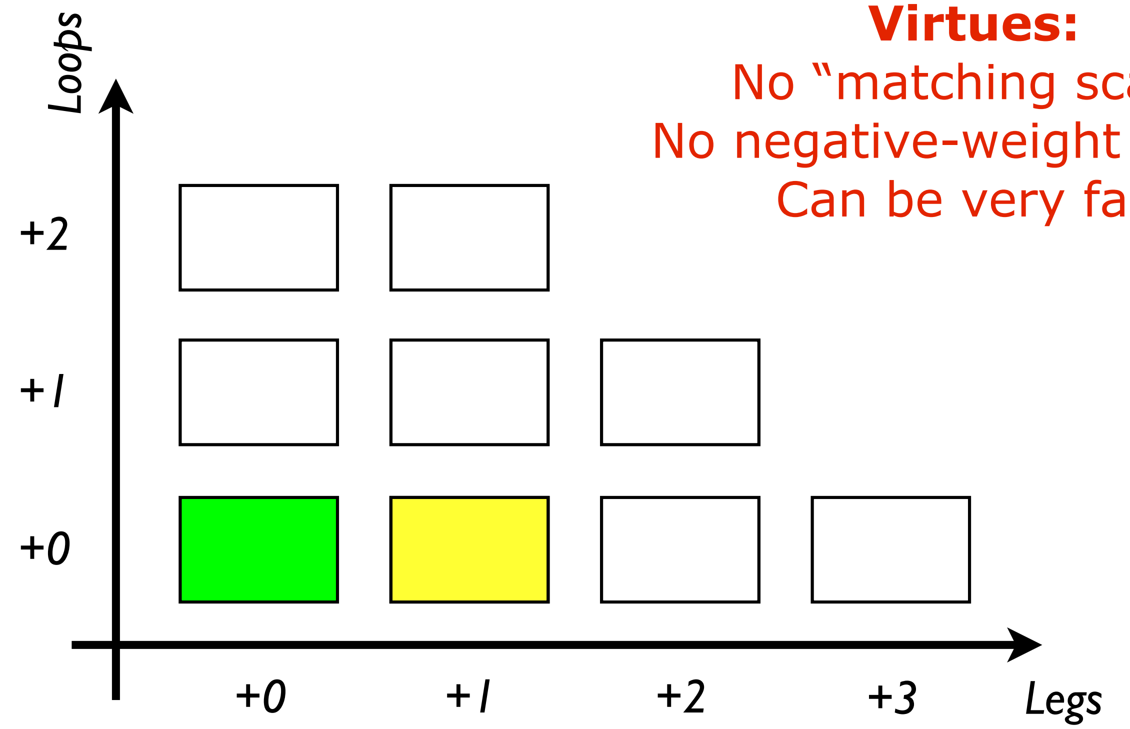
Examples: PYTHIA, POWHEG, VINCIA

Start at Born level

$$|M_F|^2$$

Generate "shower" emission

$$|M_{F+1}|^2 \stackrel{LL}{\sim} \sum_{i\in\mathrm{ant}} a_i \, |M_F|^2$$



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Matching 3: ME Corrections

Examples: PYTHIA, POWHEG, VINCIA

Start at Born level

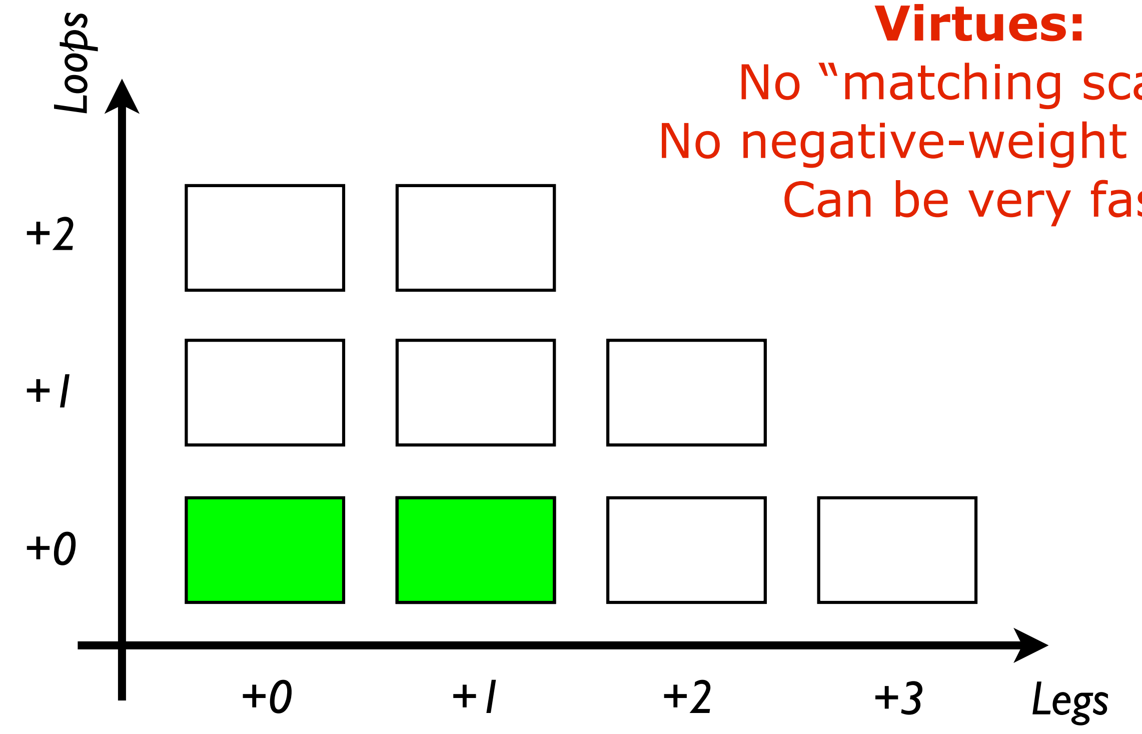
$$|M_F|^2$$

Generate "shower" emission

$$|M_{F+1}|^2 \overset{LL}{\sim} \sum_{i\in \mathrm{ant}} a_i \, |M_F|^2$$

Correct to Matrix Element

$$a_i \to \frac{|M_{F+1}|^2}{\sum a_i |M_F|^2} a_i$$



Virtues:
No "matching scale"
No negative-weight events
Can be very fast

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Unitarity of Shower

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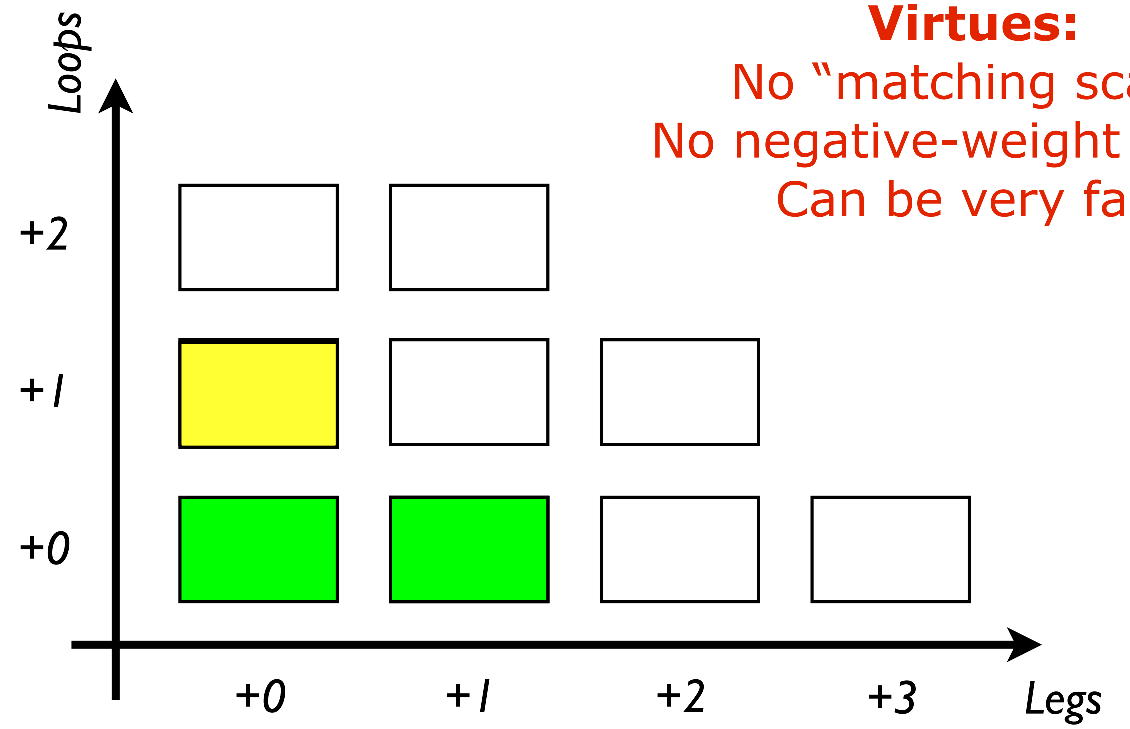

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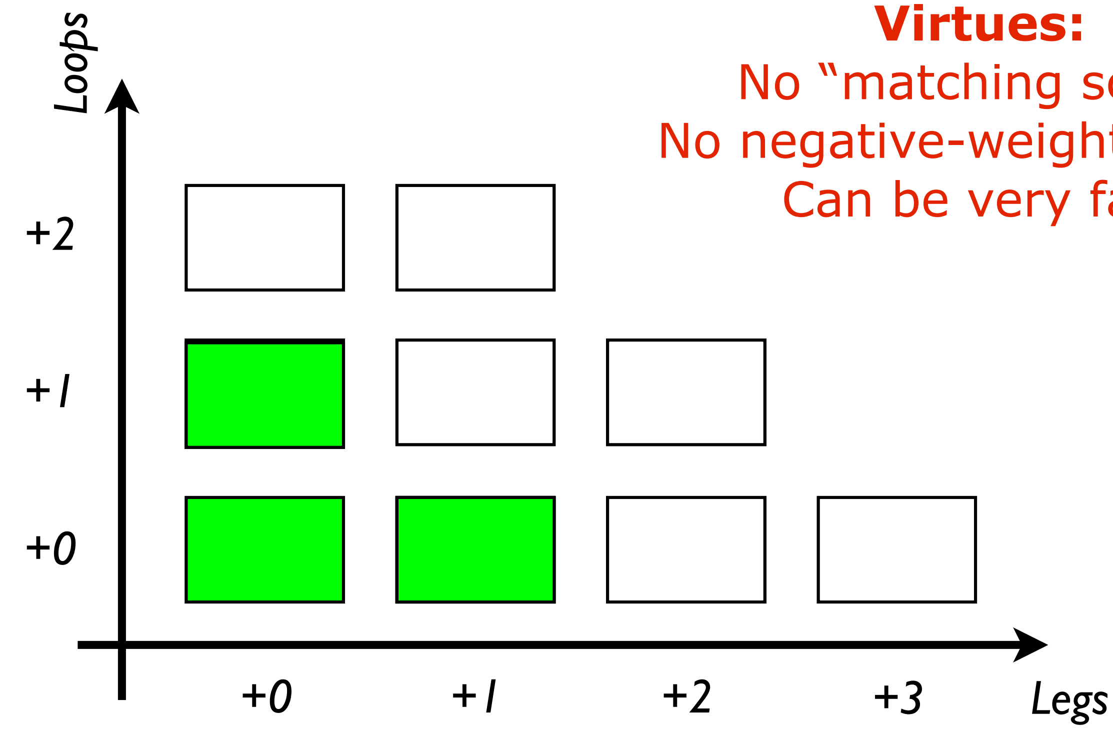

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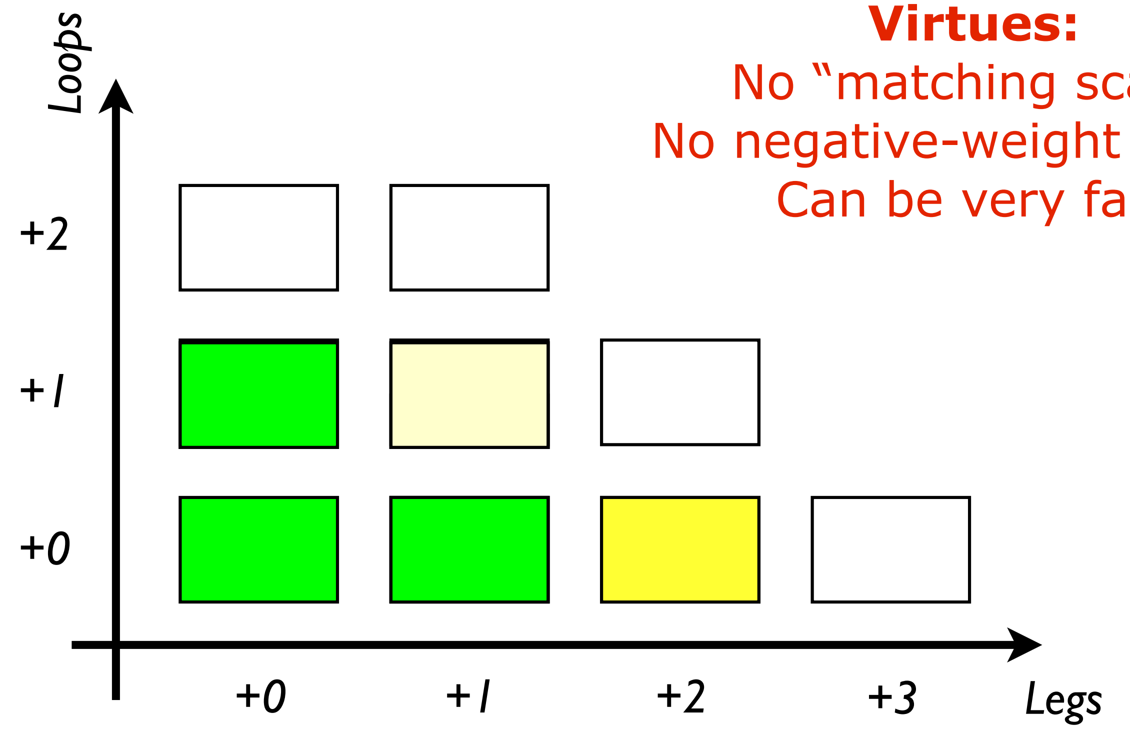

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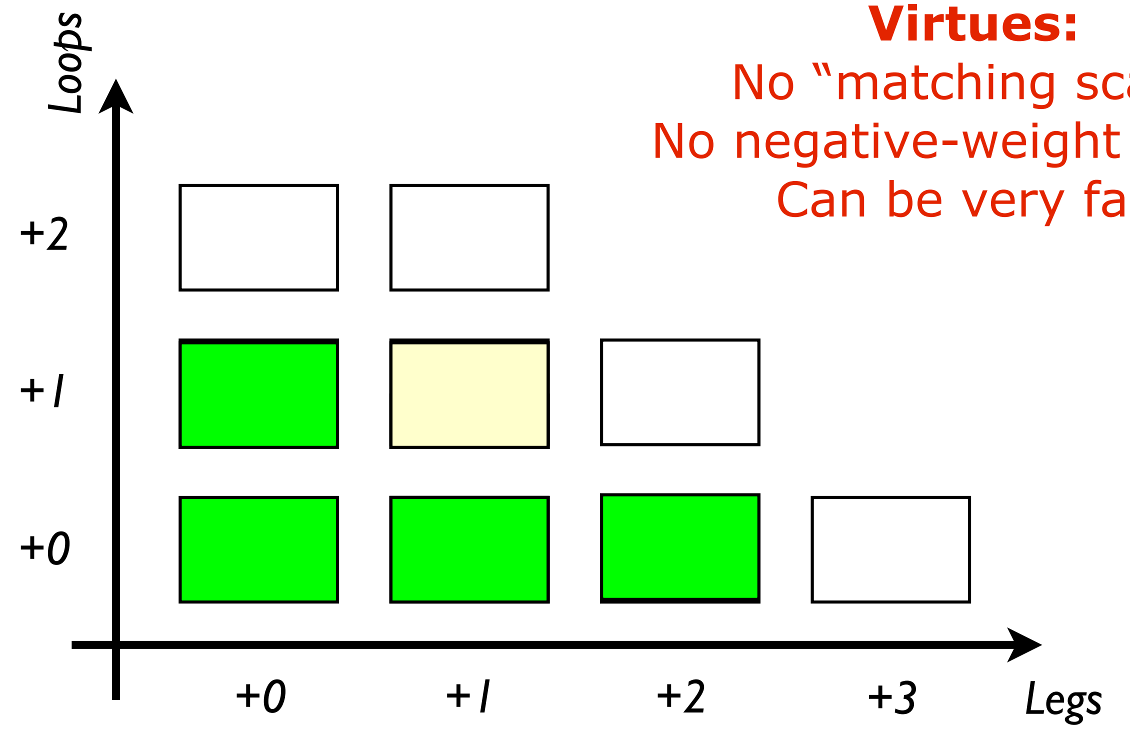

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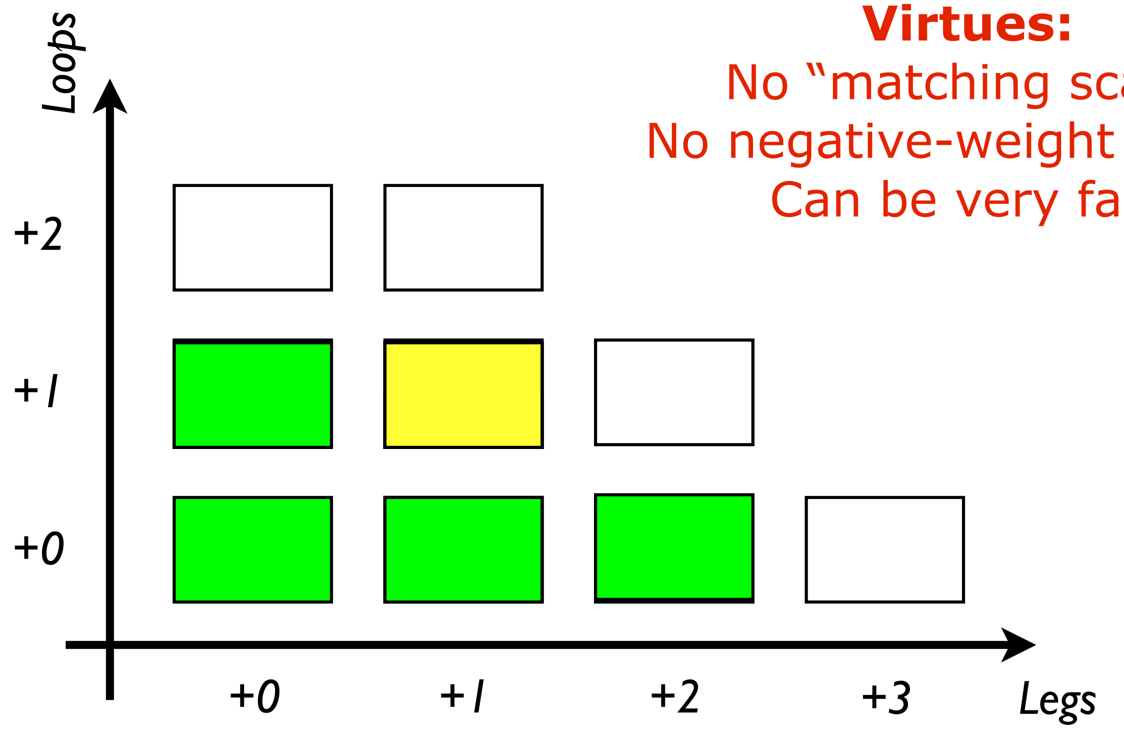

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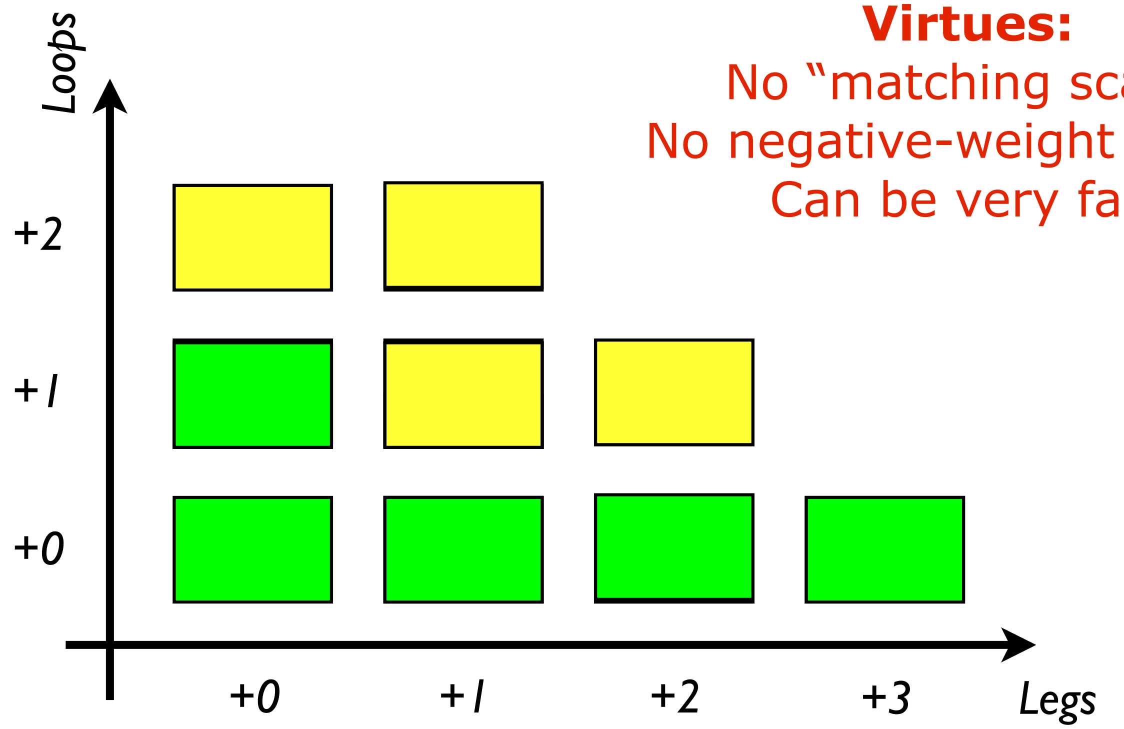

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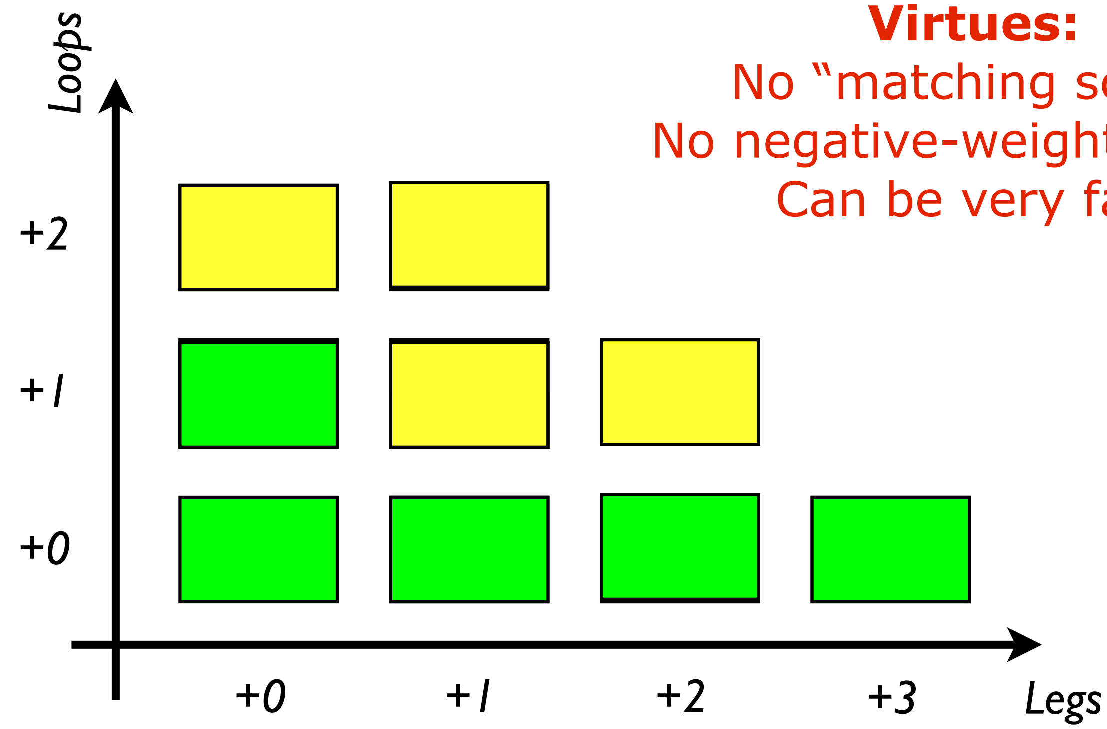

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PYTHIA: LO_1 corrections to most SM and BSM decay processes, and for pp → Z/W/H (Sjöstrand 1987)

POWHEG (& POWHEG BOX): LO_1 + NLO_0 corrections for generic processes (Frixione, Nason, Oleari, 2007)

Multileg NLO:

VINCIA: $LO_{1,2,3,4}$ + $NLO_{0,1}$ (shower plugin to PYTHIA 8; formalism for pp soon to appear) (see previous slide)

MiNLO-merged POWHEG: $LO_{1,2}$ + $NLO_{0,1}$ for pp → Z/W/H

UNLOPS: for generic processes (in PYTHIA 8, based on POWHEG input) (Lönnblad & Prestel, 2013)

Matching 3: ME Corrections

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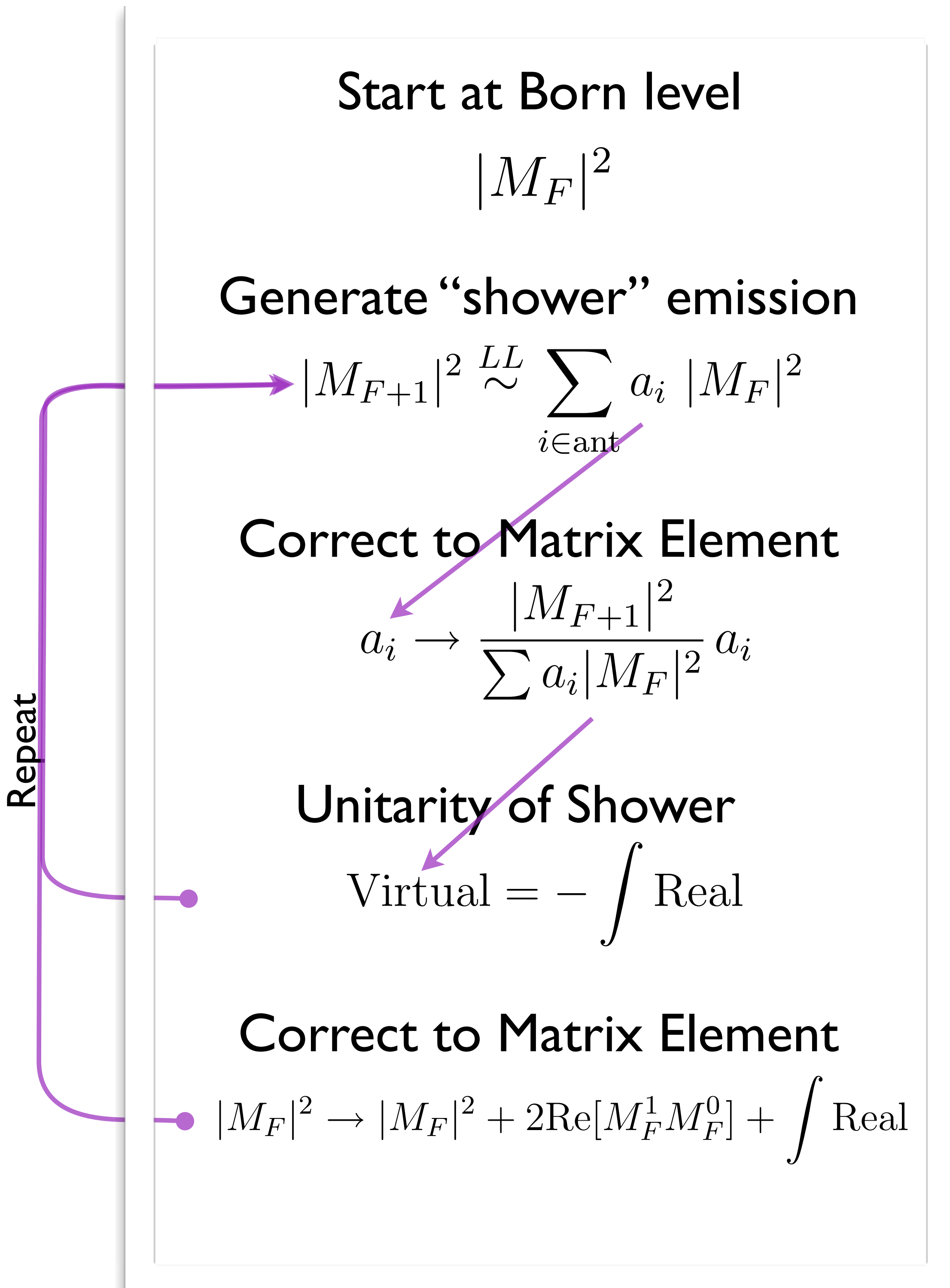

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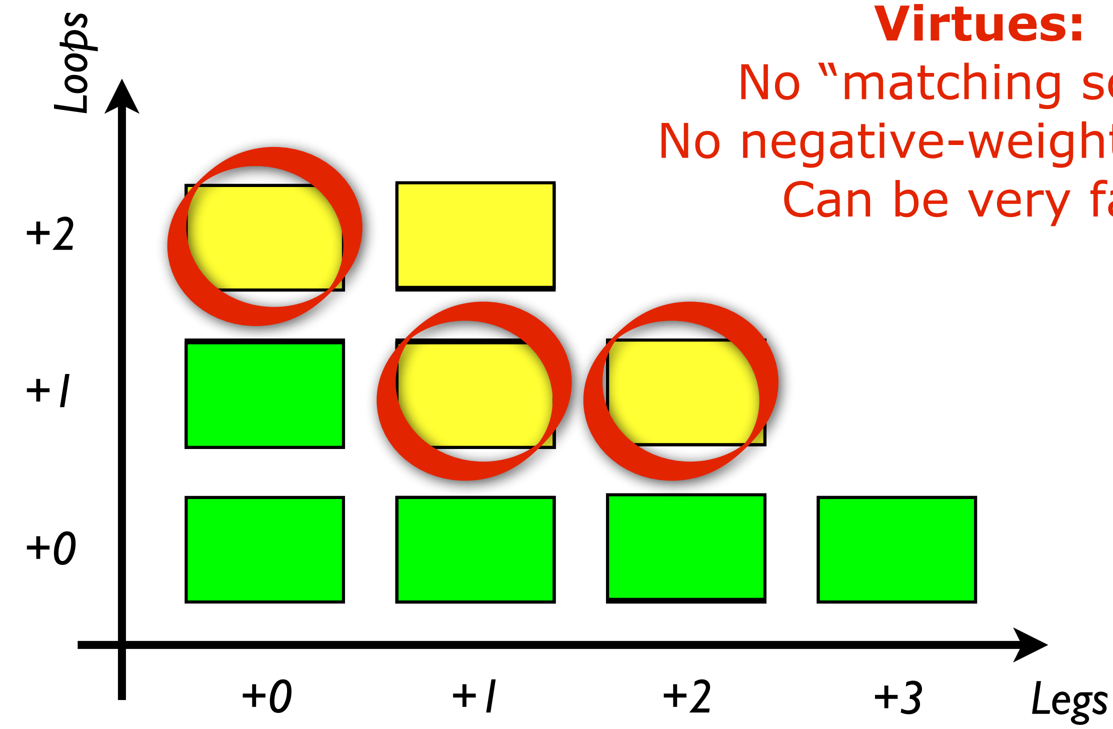

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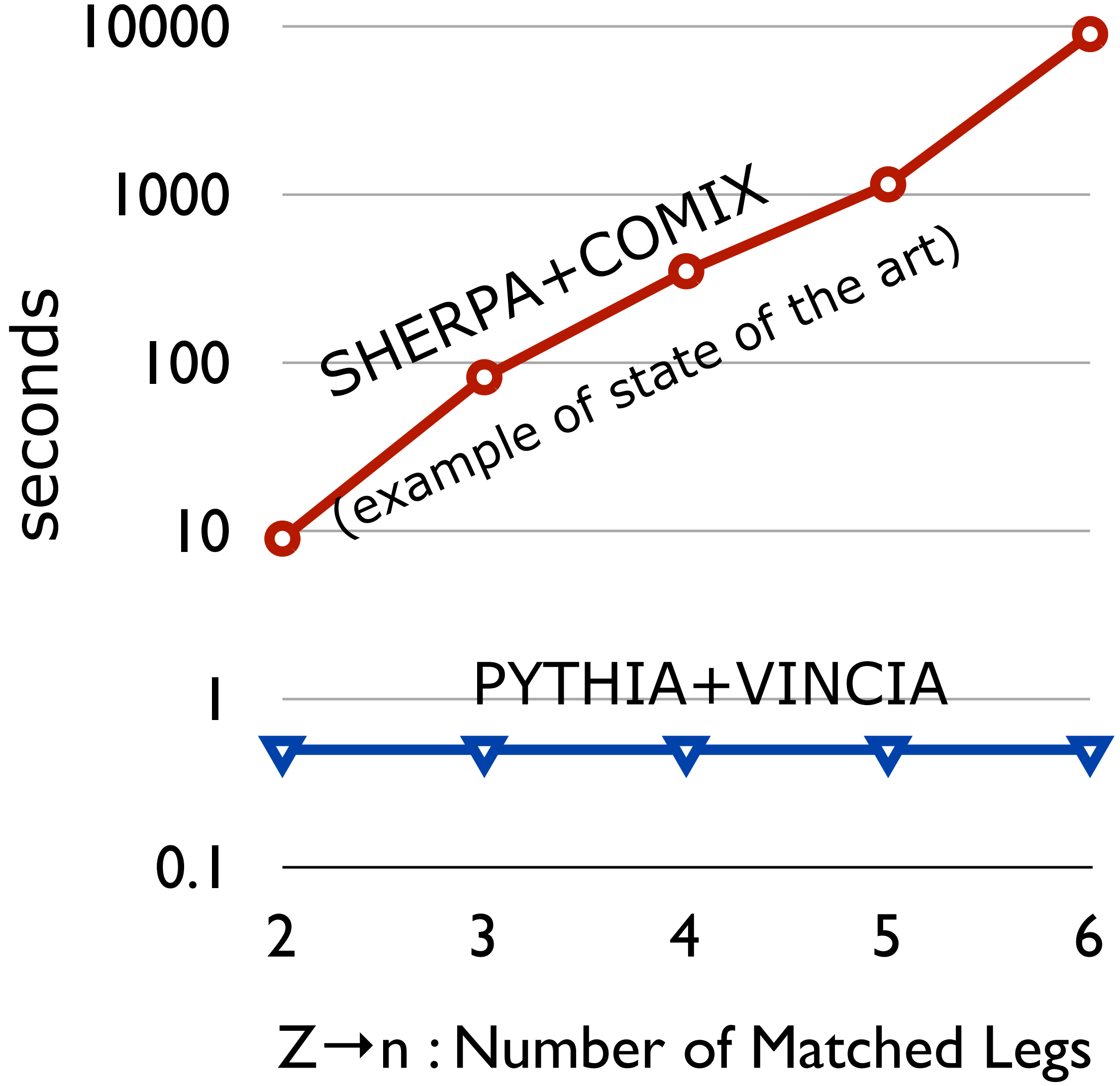
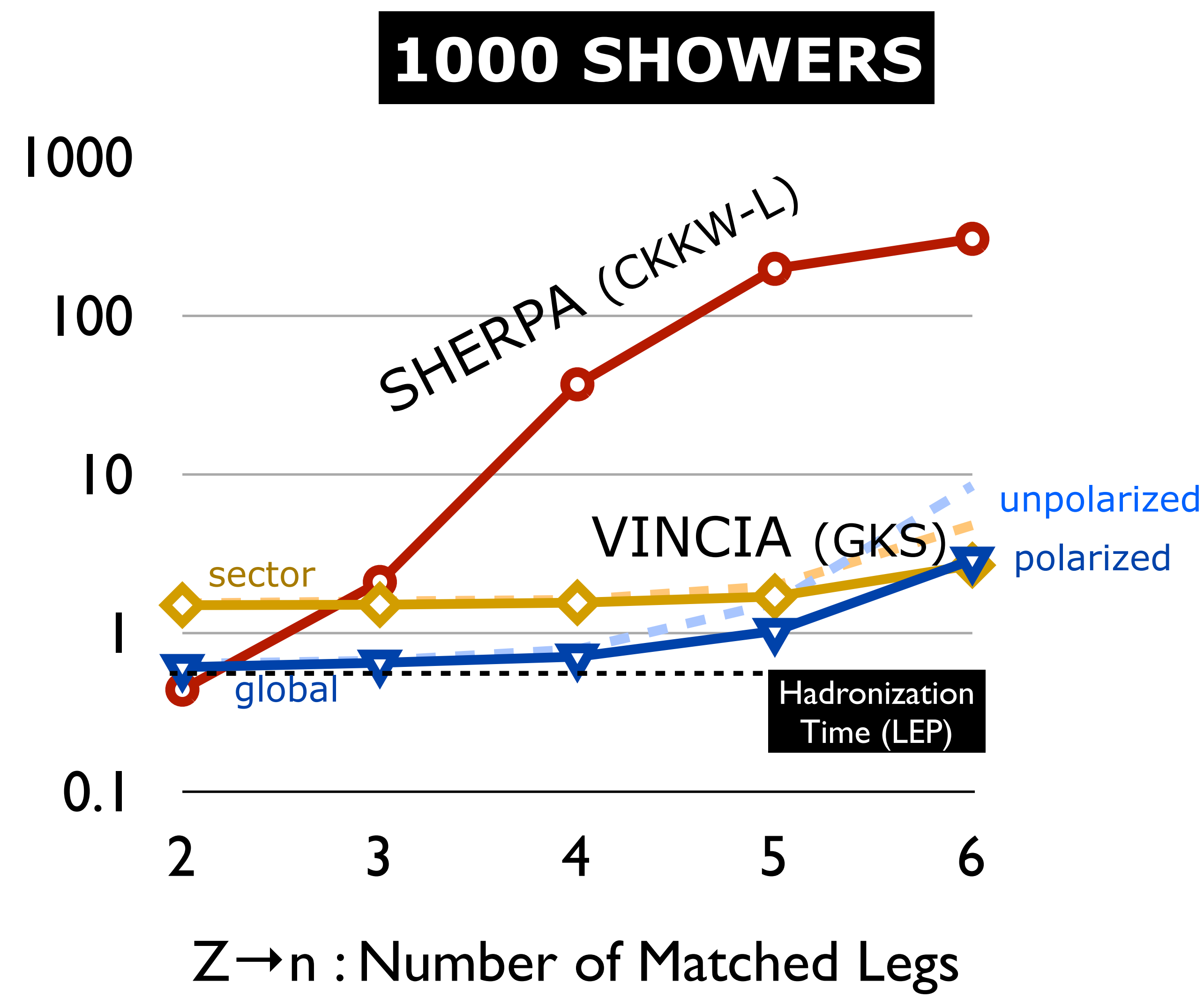
Speed

Larkoski, Lopez-Villarejo, Skands, PRD 87 (2013) 054033

1. Initialization time
(to pre-compute cross sections and warm up phase-space grids)



2. Time to generate 1000 events
(Z → partons, fully showered & matched. No hadronization.)



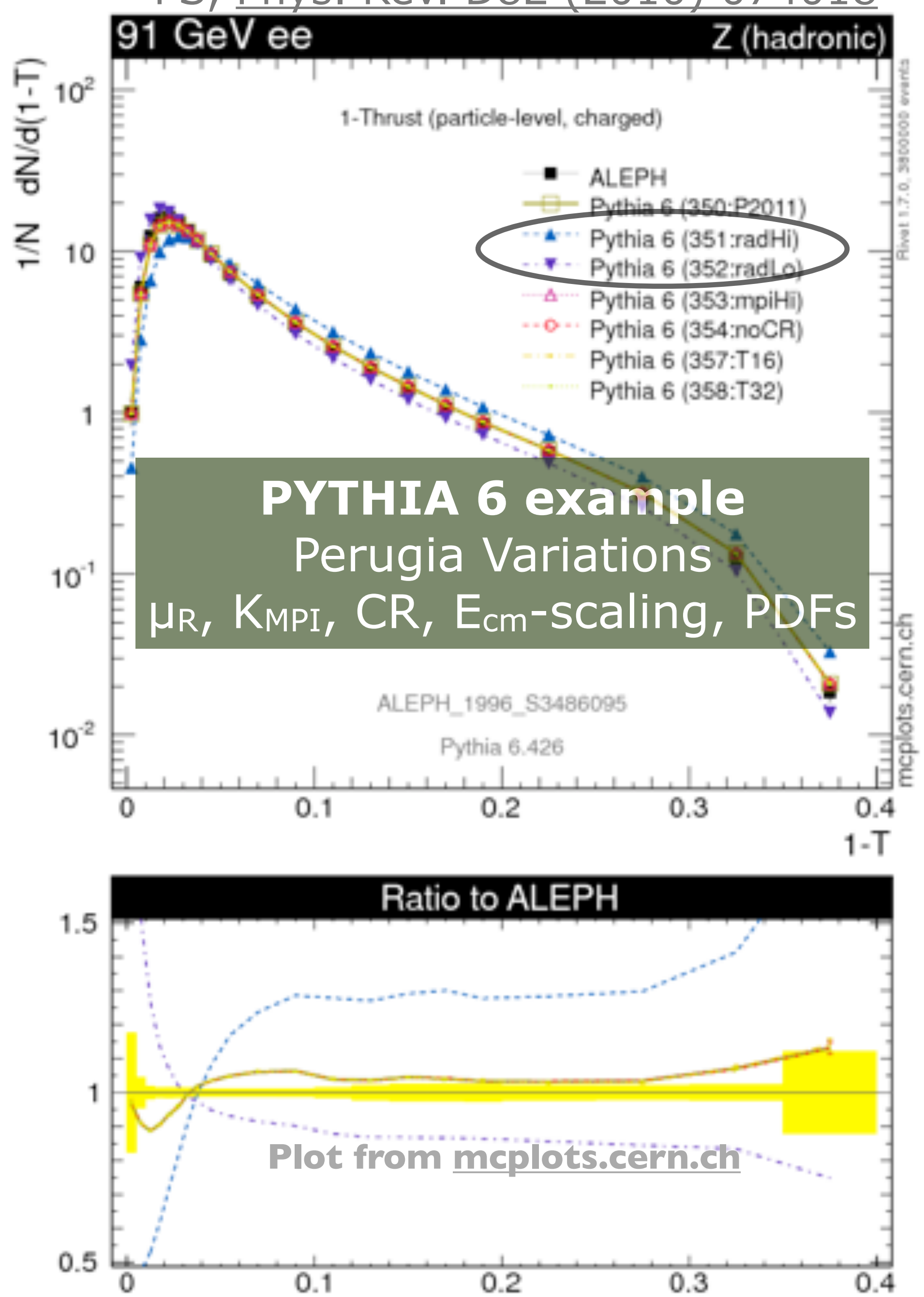
Z→udscb ; Hadronization OFF ; ISR OFF ; udsc MASSLESS ; b MASSIVE ; E_{CM} = 91.2 GeV ; Q_{match} = 5 GeV
SHERPA 1.4.0 (+COMIX) ; PYTHIA 8.1.65 ; VINCIA 1.0.29 + MADGRAPH 4.4.26 ;
gcc/gfortran v 4.7.1 -O2 ; single 3.06 GHz core (4GB RAM)

Uncertainty Estimates

a) Authors provide specific "tune variations"

Run once for each variation→ envelope

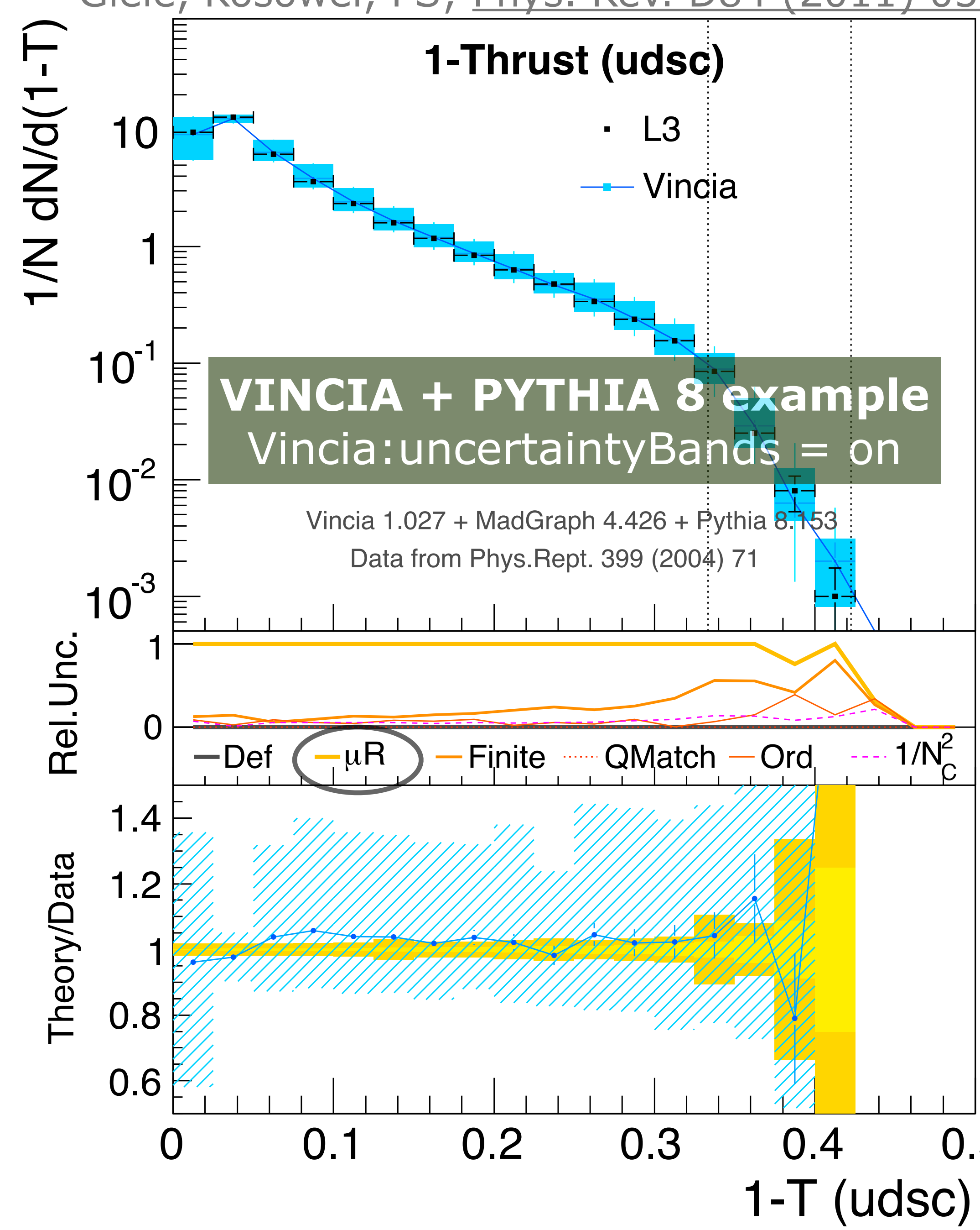
PS, Phys. Rev. D82 (2010) 074018



b) **One** shower run

\+ unitarity-based uncertainties → envelope

Giele, Kosower, PS; Phys. Rev. D84 (2011) 054003



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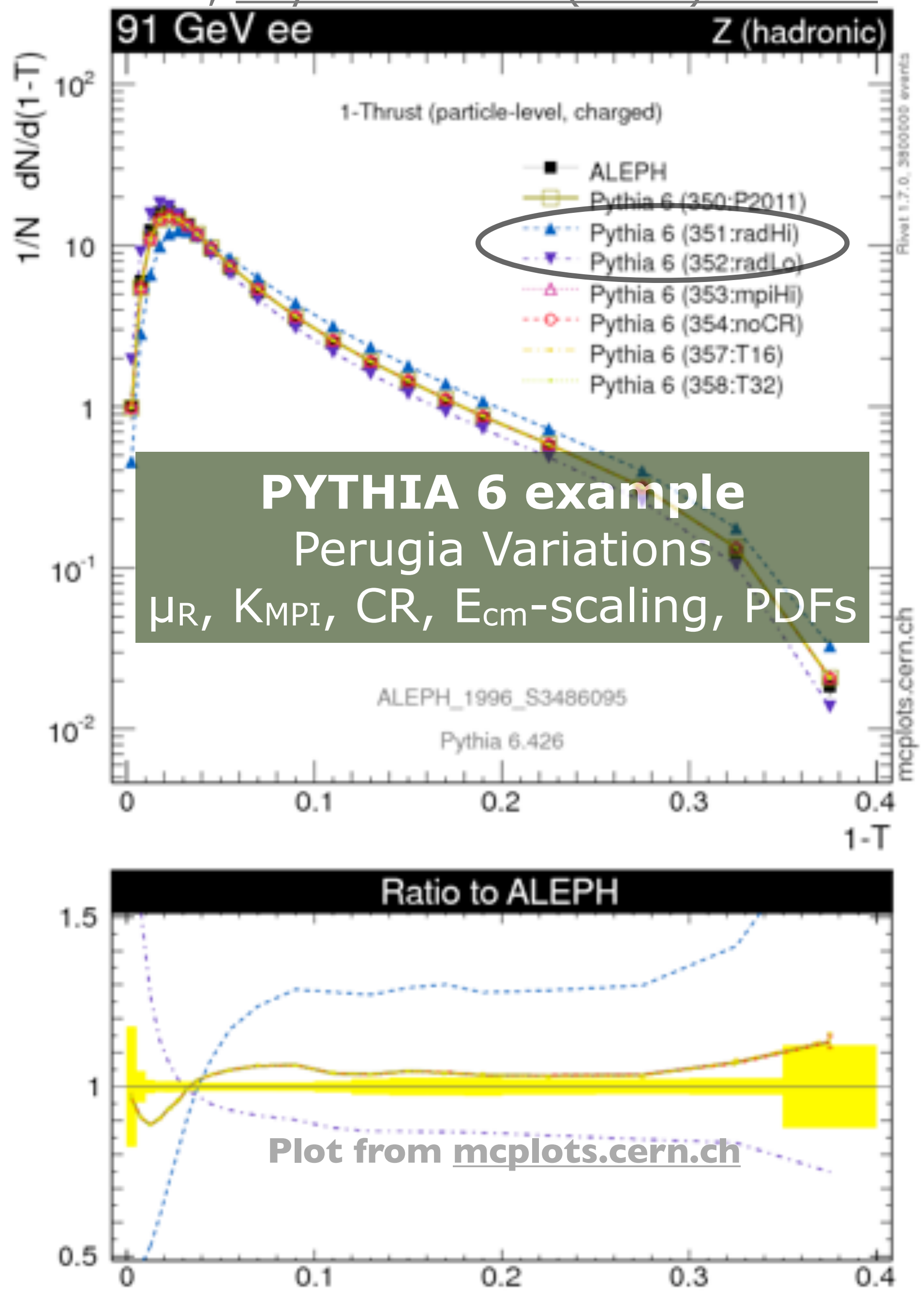

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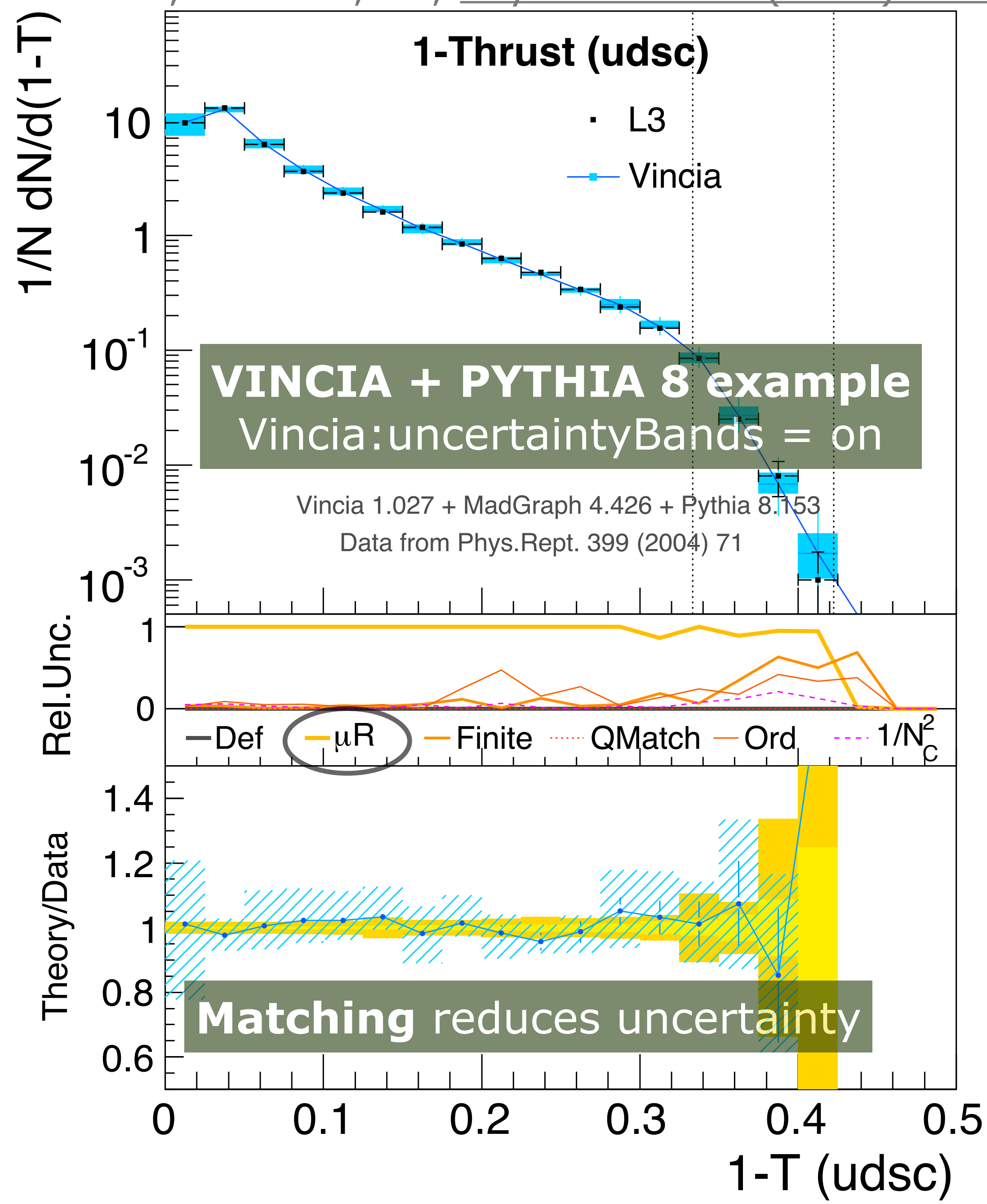


Summary

QCD phenomenology is witnessing a rapid evolution:

Driven by demand of **high precision** for LHC environment

Exploring physics: infinite-order structure of quantum field theory. Universalities vs process-dependence.

Emergent QCD phenomena: **Jets, Strings, Hadrons**

Non-perturbative QCD is still hard

Lund string model remains best bet, but ~ 30 years old

Lots of input from LHC

“Solving the LHC” is both interesting and rewarding

New ideas evolving on both perturbative and non-perturbative sides → many opportunities for theory-experiment interplay

Key to high precision → max information about the Terascale

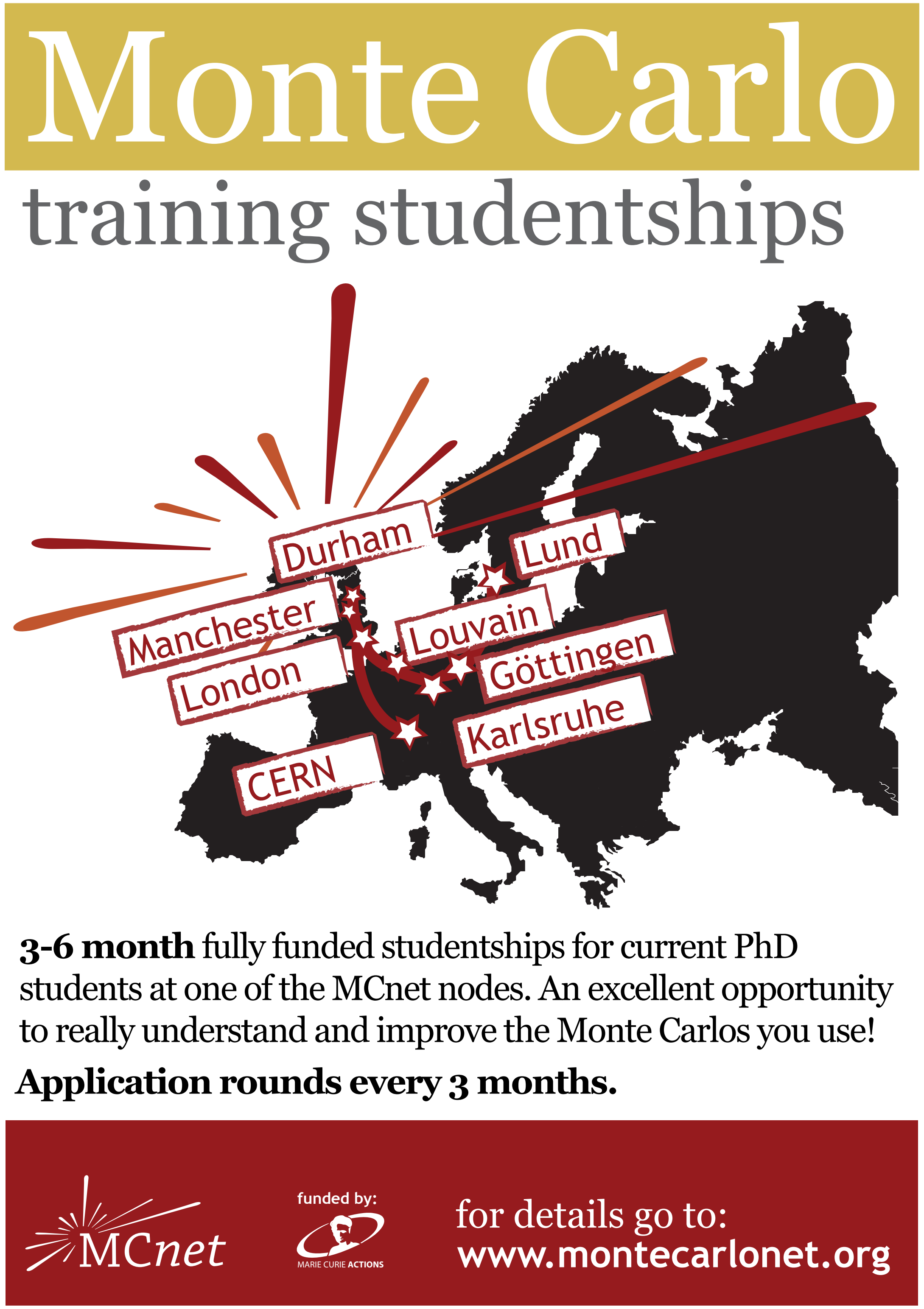
MCnet Studentships

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

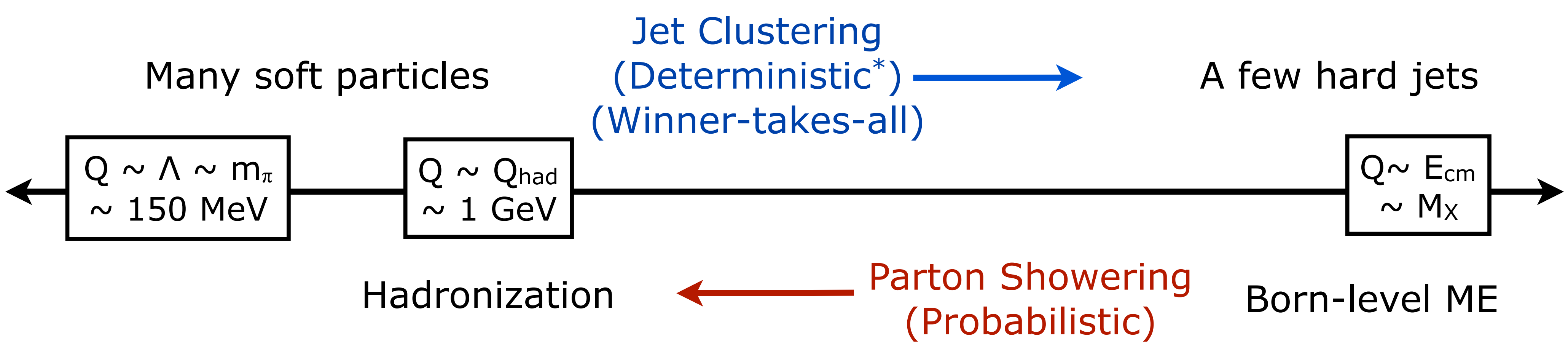
Establishing a new group in **Melbourne**
- Working on **PYTHIA** & **VINCIA**
  - **NLO** Event Generators
    - Precision LHC **phenomenology & soft physics**
      - Support LHC **experiments**, **astro-particle** community, and **future** accelerators
        - Outreach and Citizen Science

Oct 2014
→ Monash University
Melbourne, Australia

Jets vs **Parton Showers**

Jet clustering algorithms

Map event from low E-resolution scale (i.e., with many partons/hadrons, most of which are soft) to a higher E-resolution scale (with fewer, hard, IR-safe, jets)



Parton shower algorithms

Map a few hard partons to many softer ones

Probabilistic → closer to nature.
Not uniquely invertible by any jet algorithm*

(* See "Qjets" for a probabilistic jet algorithm, arXiv:1201.1914)
(* See "Sector Showers" for a deterministic shower, arXiv:1109.3608)