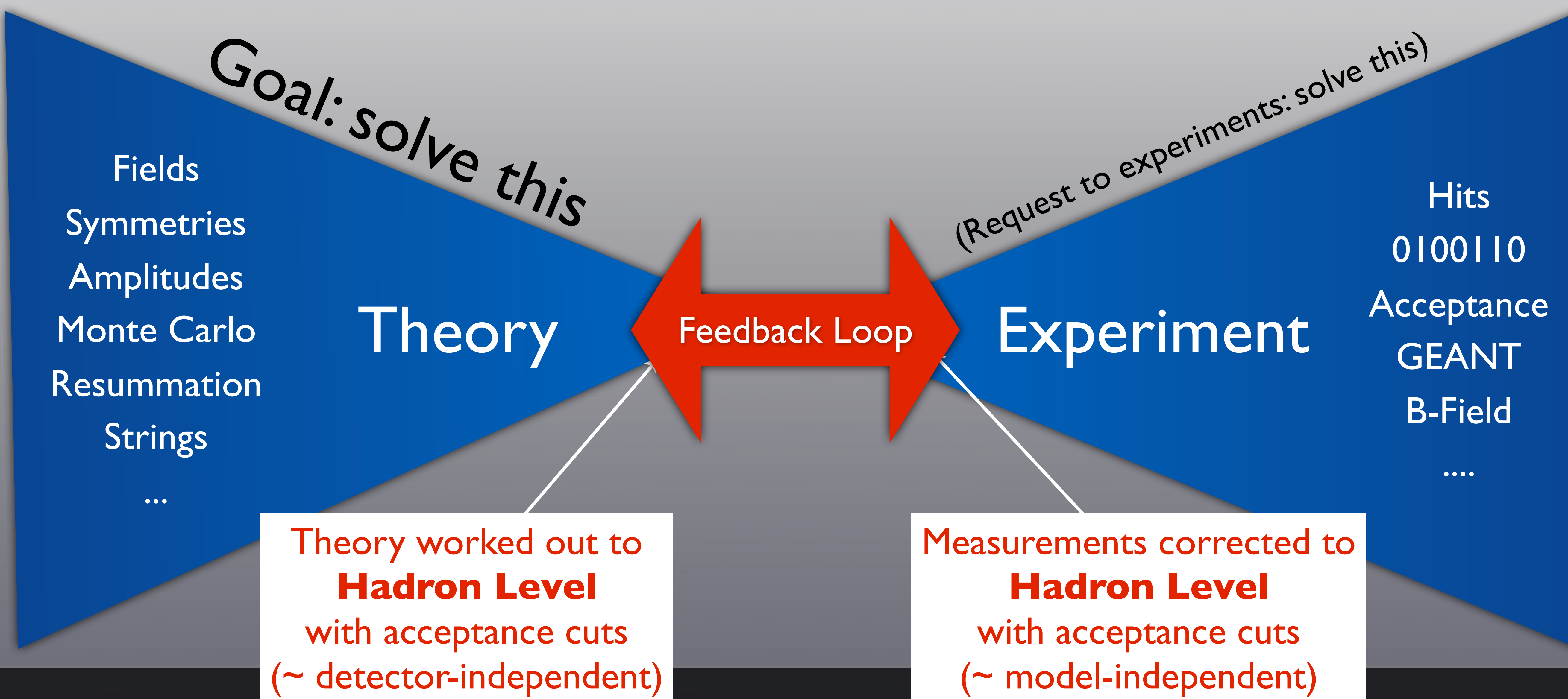
New Developments in Parton Showers

P. Skands (CERN)

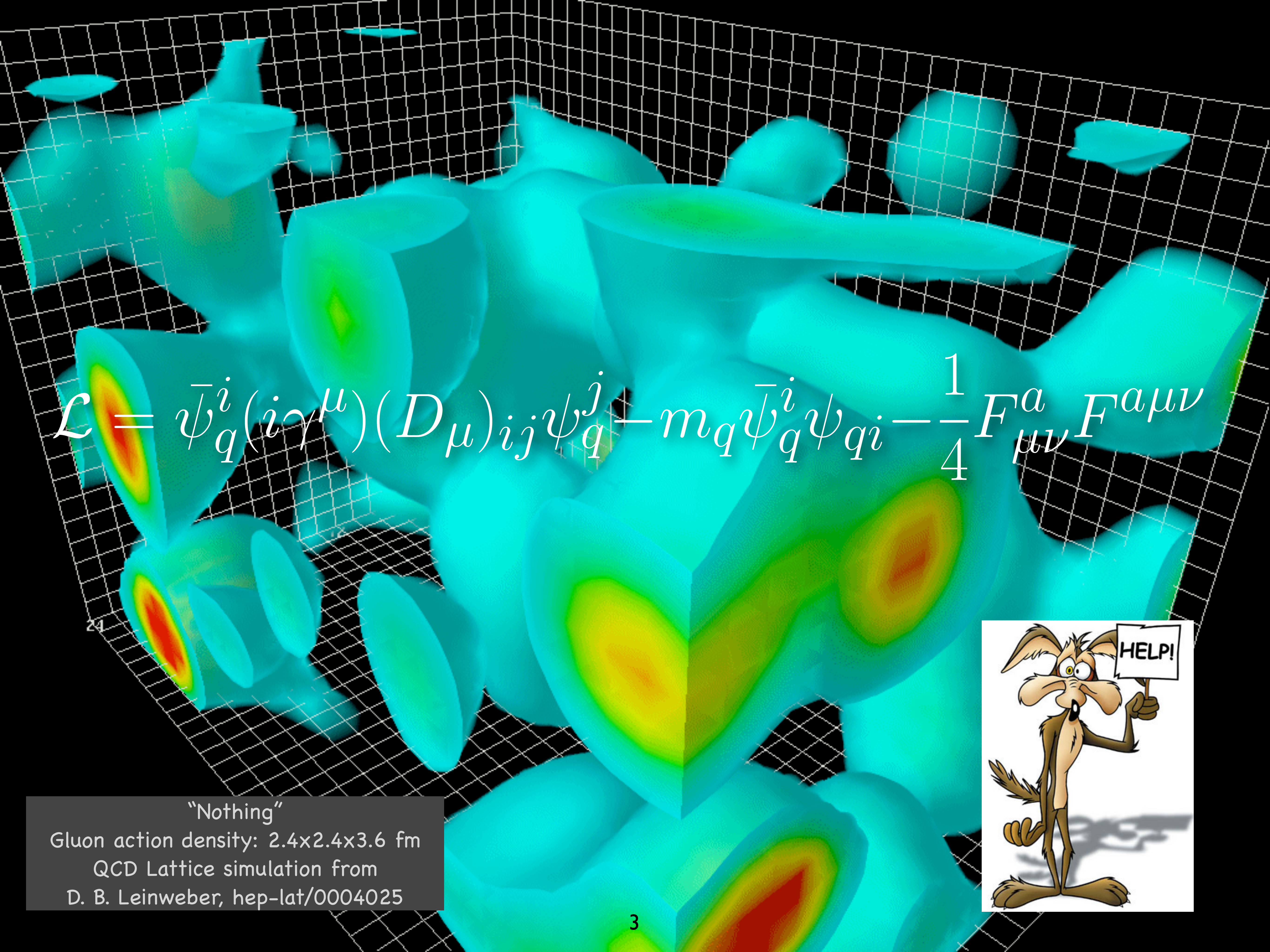


Work in collaboration with W. Giele, D. Kosower,
A. Larkoski, J. Lopez-Villarejo (sector showers, helicity-dependence),
A. Gehrmann-de-Ridder, M. Ritzmann (mass effects, initial-state radiation),
E. Laenen, L. Hartgring (one-loop corrections)

THEORY

$$\mathcal{L} = \bar{\psi}^i_q (i\gamma^\mu)(D_\mu)_{ij}\psi^j_q - m_q \bar{\psi}^i_q \psi_{qi} - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu}$$

+ quark masses and value of α_s

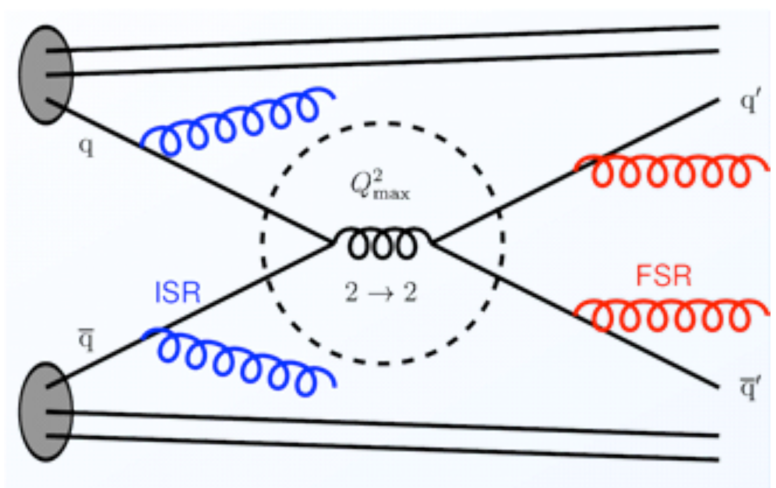


$$\mathcal{L} = \bar{\psi}^i_q (i\gamma^\mu)(D_\mu)_{ij}\psi^j_q - m_q \bar{\psi}^i_q \psi_{qi} - \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu}$$

"Nothing"
Gluon action density: 2.4x2.4x3.6 fm
QCD Lattice simulation from
D. B. Leinweber, hep-lat/0004025

Perturbation Theory

Monte Carlo Generators



Calculate Everything ≈ solve QCD → requires compromise!

Improve Born-level perturbation theory, by including the 'most significant' corrections
→ complete events → any observable you want

1. Parton Showers ↔ *1. Soft/Collinear Logarithms*

2. Matching ↔ *2. Finite Terms, "K"-factors*

3. Hadronisation ↔ *3. Power Corrections (more if not IR safe)*

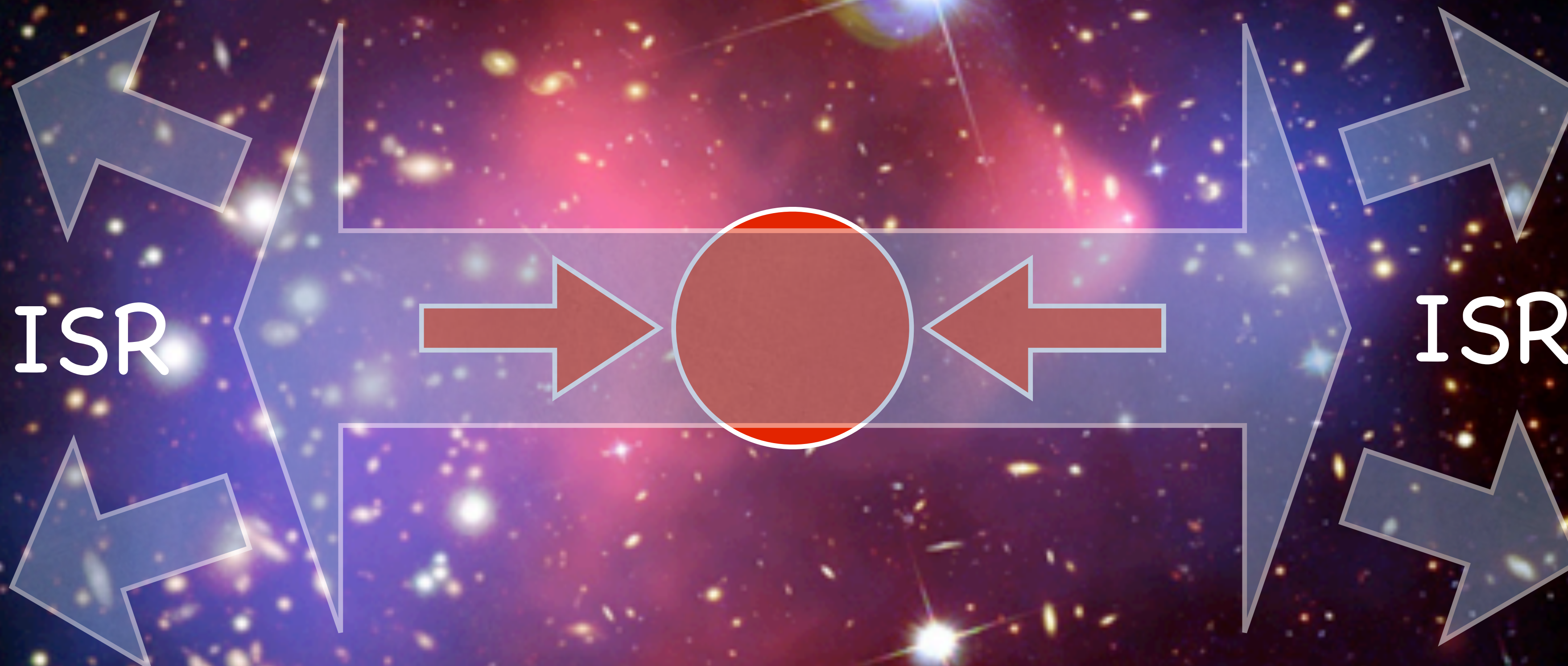
4. The Underlying Event ↔ *4. ?*

(roughly)

(+ many other ingredients: resonance decays, beam remnants, Bose-Einstein, …)

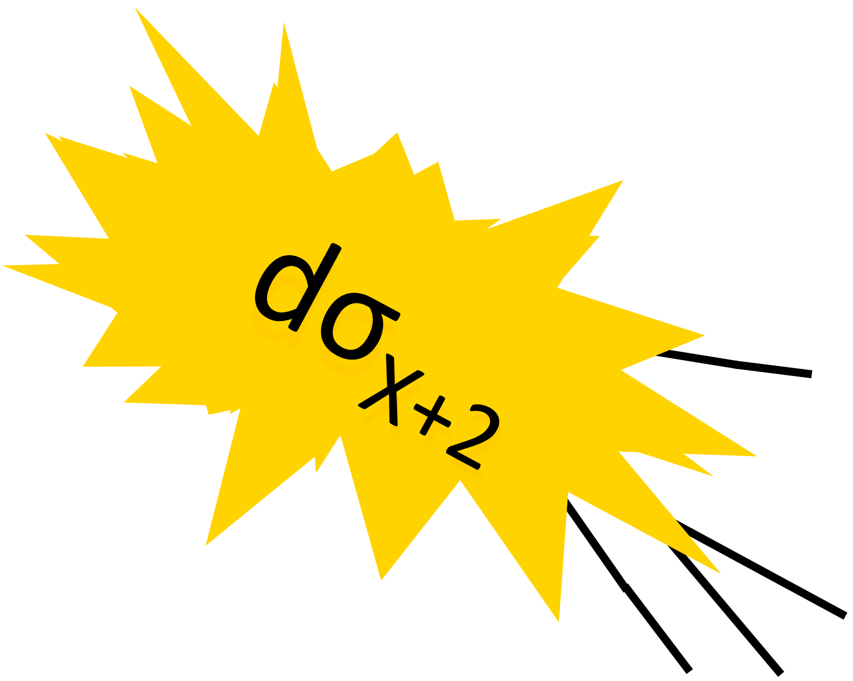
Bremsstrahlung

Charges Stopped

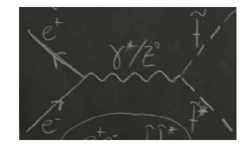


The harder they stop, the harder the fluctations that continue to become strahlung

Bremsstrahlung



$$\mathrm{d}\sigma_X = \ldots$$



$$\mathrm{d}\sigma_{X+1} \sim 2g^2 \mathrm{d}\sigma_X \frac{\mathrm{d}s_{a1}}{s_{a1}} \frac{\mathrm{d}s_{1b}}{s_{1b}}$$

$$\mathrm{d}\sigma_{X+2} \sim 2g^2 \mathrm{d}\sigma_{X+1} \frac{\mathrm{d}s_{a2}}{s_{a2}} \frac{\mathrm{d}s_{2b}}{s_{2b}}$$

$$\mathrm{d}\sigma_{X+3} \sim 2g^2 \mathrm{d}\sigma_{X+2} \frac{\mathrm{d}s_{a3}}{s_{a3}} \frac{\mathrm{d}s_{3b}}{s_{3b}}$$

This gives an approximation to infinite-order tree-level cross sections (here "DLA")

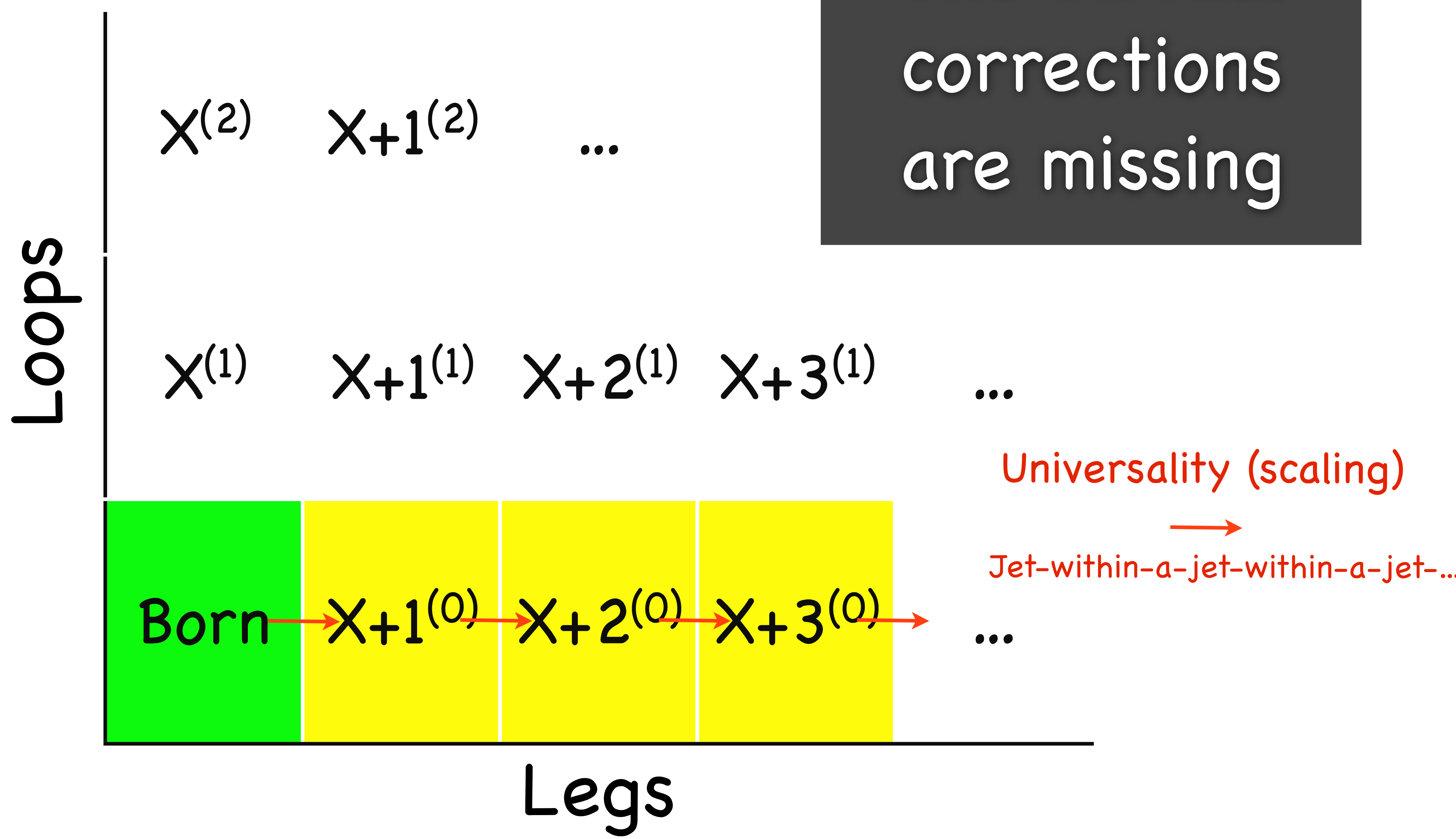
But something is not right …

Total cross section would be infinite …

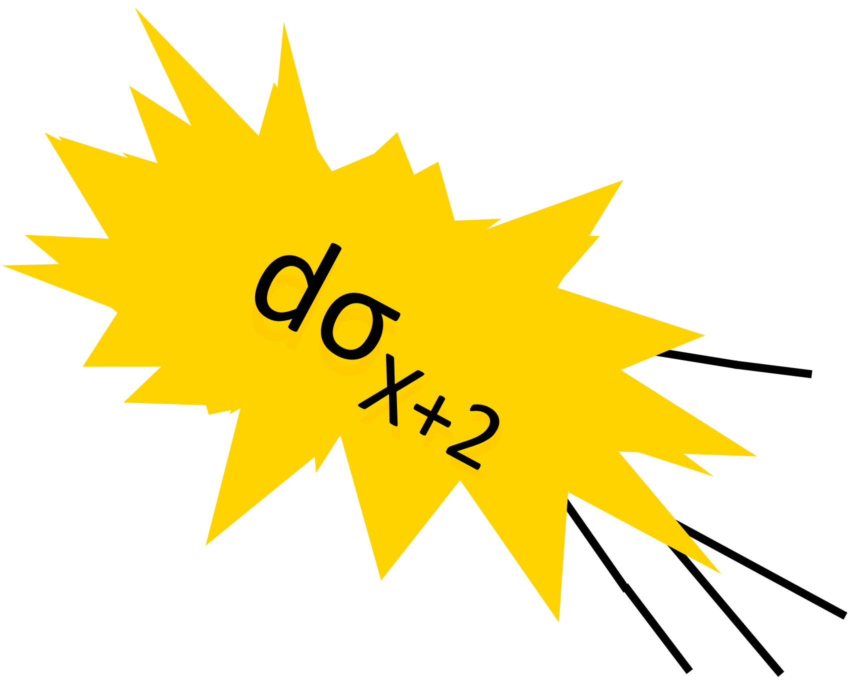
Loops and Legs

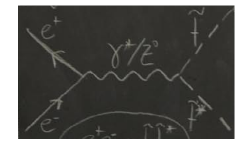
Summation

The Virtual corrections are missing



Resummation



$d\sigma_X = \ldots$ 

$$d\sigma_{X+1} \sim 2g^2 d\sigma_X \frac{ds_{a1}}{s_{a1}} \frac{ds_{1b}}{s_{1b}}$$

$$d\sigma_{X+2} \sim 2g^2 d\sigma_{X+1} \frac{ds_{a2}}{s_{a2}} \frac{ds_{2b}}{s_{2b}}$$

$$d\sigma_{X+3} \sim 2g^2 d\sigma_{X+2} \frac{ds_{a3}}{s_{a3}} \frac{ds_{3b}}{s_{3b}}$$

Unitarity

KLN:

$$\text{Virt} = -\ \text{Int(Tree)} + \text{F}$$

In LL showers : neglect F

Imposed by Event *evolution*:

When (X) branches to (X+1):
Gain one (X+1). Loose one (X).

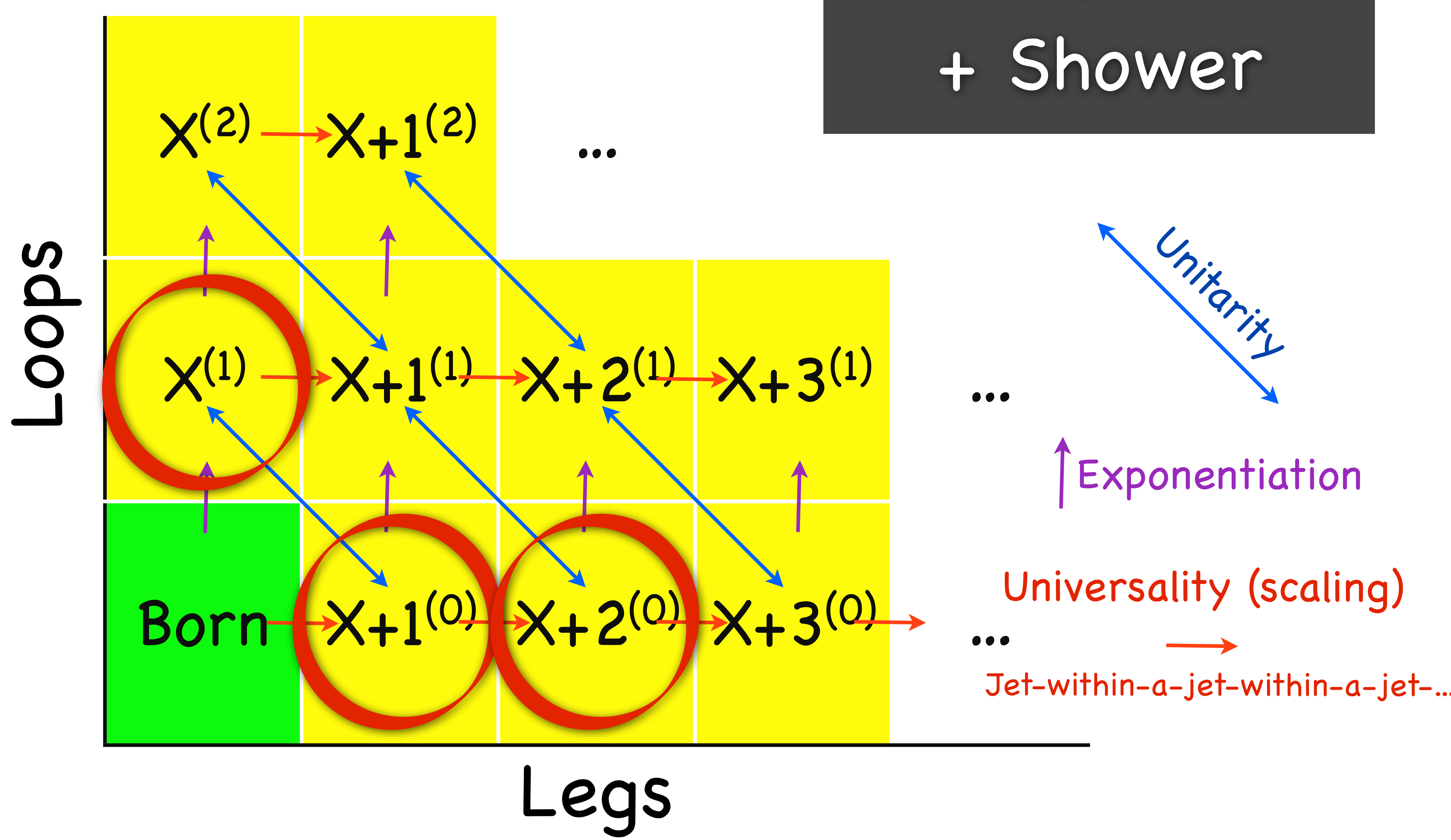
$\sigma_{X+1}(Q) = \sigma_{X;incl} - \sigma_{X;excl}(Q)$

→ includes both real and virtual corrections (in LL approx)

Bootstrapped pQCD

Resummation

Born
+ Shower



Matching

- ► 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

The Matching Game

- Shower off X already contains LL part of all $X+n$

$$d\sigma_{X+1} \sim 2g^2 d\sigma_X \frac{ds_{a1}}{s_{a1}} \frac{ds_{1b}}{s_{1b}}$$

- Adding back full ME for $X+n$ would be overkill

Solution 1: "Additive" (most widespread)

Seymour (Herwig), CPC 90 (1995) 95
CKKW (Sherpa), JHEP 0111 (2001) 063
Lönnblad (Ariadne), JHEP 0205 (2002) 046
Frixione-Webber (MC@NLO), JHEP 0206 (2002) 029
+ many more recent ...

Add event samples, with modified weights

$$w_X = |M_X|^2 \qquad + \text{Shower}$$

$$w_{X+1} = |M_{X+1}|^2 - \text{Shower}\{w_X\} \qquad + \text{Shower}$$

$$w_{X+n} = |M_{X+n}|^2 - \text{Shower}\{w_X, w_{X+1}, \ldots, w_{X+n-1}\} \qquad + \text{Shower}$$

Only CKKW and MLM

HERWIG: for X+1 @ LO (Shower = 0 in dead zone of angular-ordered shower)

MC@NLO: for X+1 @ LO and X @ NLO (note: correction can be negative)

CKKW & MLM : for all X+n @ LO (force Shower = 0 above "matching scale" and add ME there)
SHERPA (CKKW), ALPGEN (MLM + HW/PY), MADGRAPH (MLM + HW/PY), PYTHIA8 (CKKW-L from LHE files), …

The Matching Game

- Shower off X already contains LL part of all X+n

$$d\sigma_{X+1} \sim 2g^2 d\sigma_X \frac{ds_{a1}}{s_{a1}} \frac{ds_{1b}}{s_{1b}}$$

- Adding back full ME for X+n would be overkill

Solution 2: "Multiplicative"

Bengtsson-Sjöstrand (Pythia), PLB 185 (1987) 435 + more
Bauer-Tackmann-Thaler (GenEva), JHEP 0812 (2008) 011
Giele-Kosower-Skands (Vincia), PRD84 (2011) 054003

One event sample

$w_X = |M_X|^2$ + *Shower*

Make a "course correction" to the shower at each order

$R_{X+1} = |M_{X+1}|^2 / Shower\{w_X\}$ + *Shower*

$R_{X+n} = |M_{X+n}|^2 / Shower\{w_{X+n-1}\}$ + *Shower* **Only VINCIA**

PYTHIA: for X+1 @ LO (for color-singlet production and ~ all SM and BSM decay processes)

POWHEG: for X+1 @ LO and X @ NLO (note: positive weights) → POWHEG Box, HERWIG++, ...

VINCIA: for all X+n @ LO and X @ NLO (only worked out for decay processes so far)

Markov pQCD

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

PYTHIA trick

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

Unitarity of Shower

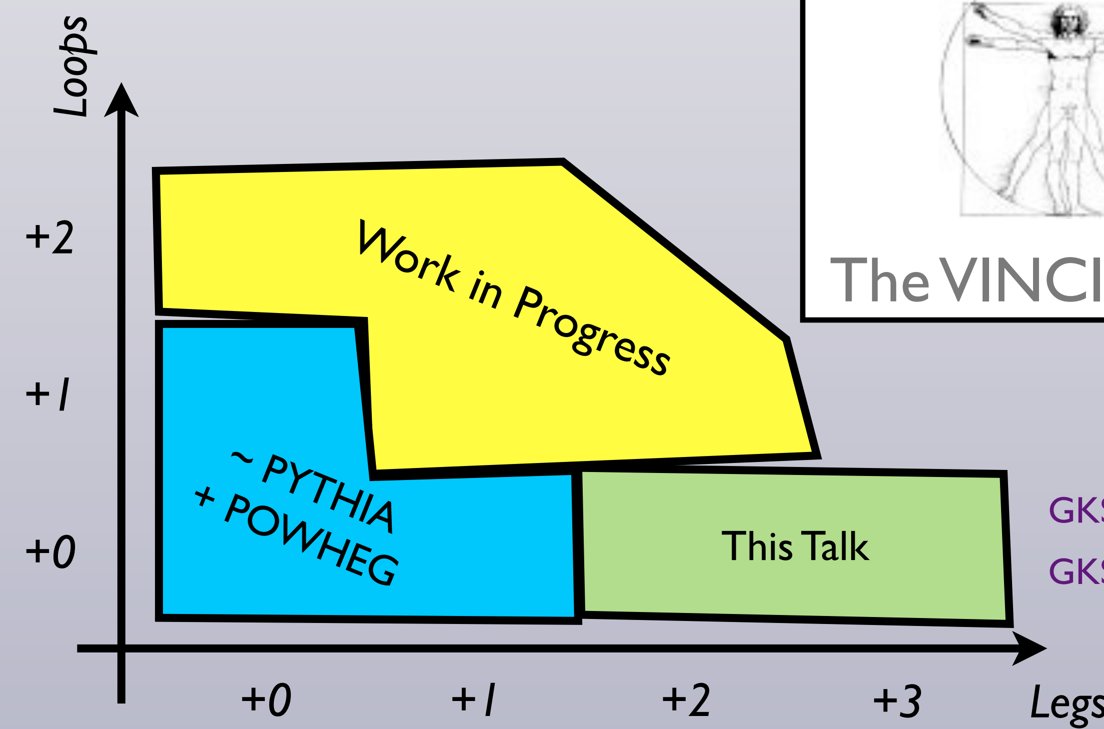
$$\mathrm{Virtual} = -\int \mathrm{Real}$$

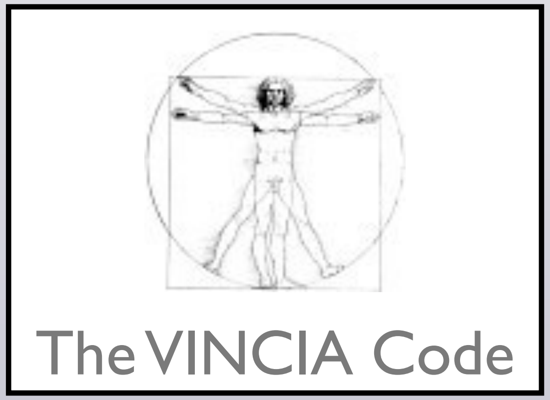
Correct to Matrix Element

$$|M_F|^2 \to |M_F|^2 + 2\mathrm{Re}[M_F^1 M_F^0] + \int \mathrm{Real}$$

POWHEG trick

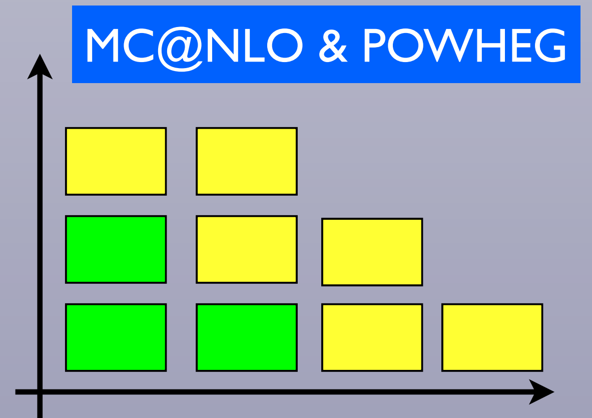
Repeat





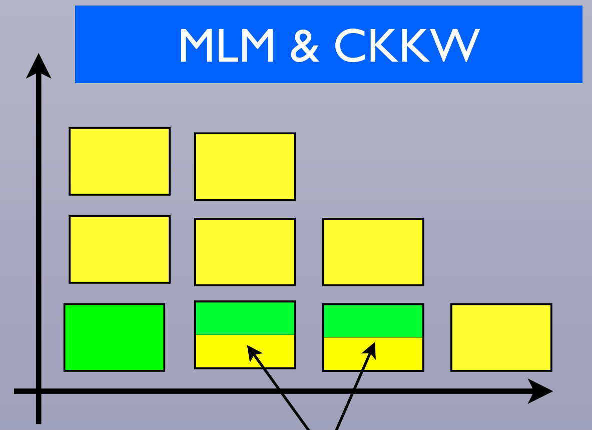
GKS, PRD78(2008)014026

GKS, PRD84(2011)054003



LO for 1st emission

LL for 2nd emission and beyond



"Matching Scale"

→ hierarchies not matched

The Denominator

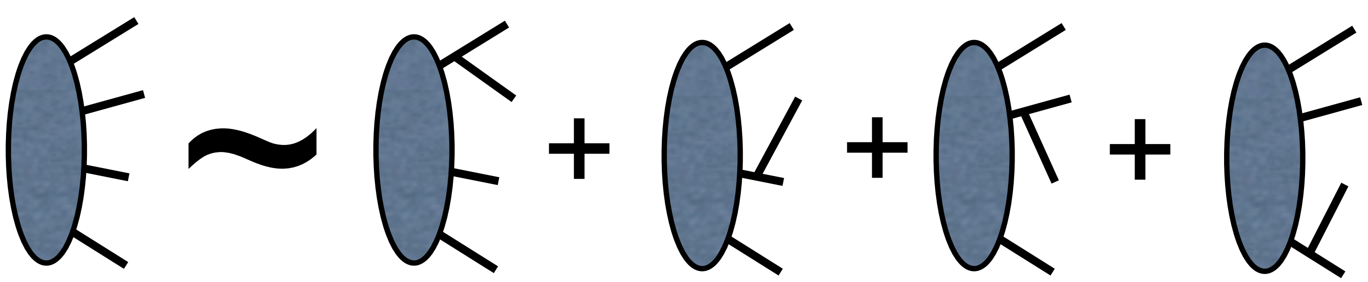
$$a_i \rightarrow \frac{|M_{F+1}|^2}{\sum a_i |M_F|^2}$$

In a traditional parton shower, you would face the following problem:

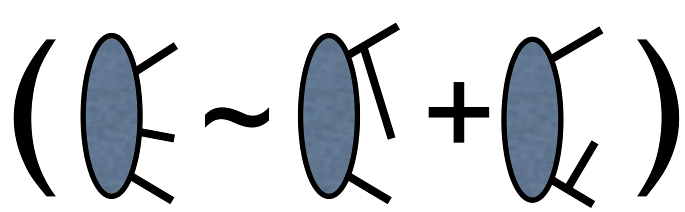
Existing parton showers are *not* really Markov Chains

Further evolution (restart scale) depends on which branching happened last
→ proliferation of terms

Number of histories contributing to n[th] branching ∝ $\mathbf{2^n n!}$



j = 2
→ 4 terms



j = 1
→ 2 terms

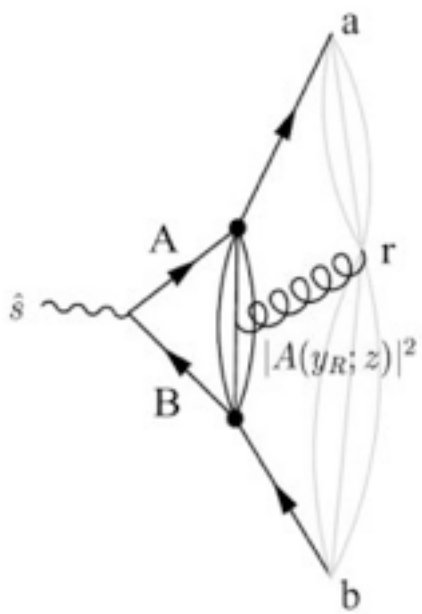
Parton- (or Catani-Seymour) Shower:
After 2 branchings: 8 terms
After 3 branchings: 48 terms
After 4 branchings: 384 terms

(+ parton showers have complicated and/or frame-dependent phase-space mappings, especially at the multi-parton level)

Matched Markovian Antenna Showers

Antenna showers: one term per parton *pair* $2^n n! \rightarrow n!$

Giele, Kosower, Skands, PRD 84 (2011) 054003



(+ generic Lorentz-invariant and on-shell phase-space factorization)

+ Change "shower restart" to Markov criterion:

Given an *n*-parton configuration, "ordering" scale is

$$Q_{ord} = min(Q_{E1}, Q_{E2}, \ldots, Q_{En})$$

Unique restart scale, independently of how it was produced

+ Matching: n! → n

Given an *n*-parton configuration, its phase space weight is:

$|M_n|^2$ *: Unique weight, independently of how it was produced*

Matched Markovian Antenna Shower:
After 2 branchings: 2 terms
After 3 branchings: 3 terms
After 4 branchings: 4 terms

Parton- (or Catani-Seymour) Shower:
After 2 branchings: 8 terms
After 3 branchings: 48 terms
After 4 branchings: 384 terms

+ **Sector** antennae *Larkosi, Peskin,Phys.Rev. D81 (2010) 054010*

→ 1 term at *any* order *Lopez-Villarejo, Skands, JHEP 1111 (2011) 150*

Approximations

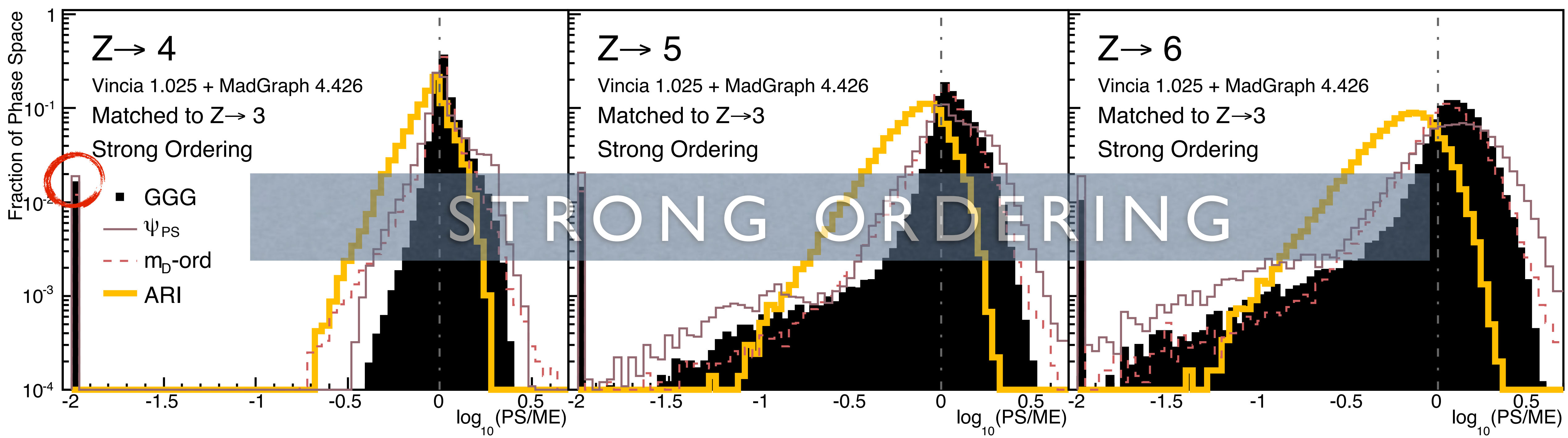
Q: How well do showers do?

Exp: Compare to data. Difficult to interpret; all-orders cocktail including hadronization, tuning, uncertainties, etc

Th: Compare products of splitting functions to full tree-level matrix elements

Plot distribution of **$\mathbf{Log_{10}(PS/ME)}$**

(second order) (third order) (fourth order)



Dead Zone: 1-2% of phase space have no strongly ordered paths leading there*

*fine from strict LL point of view: those points correspond to "unordered" non-log-enhanced configurations

2→4

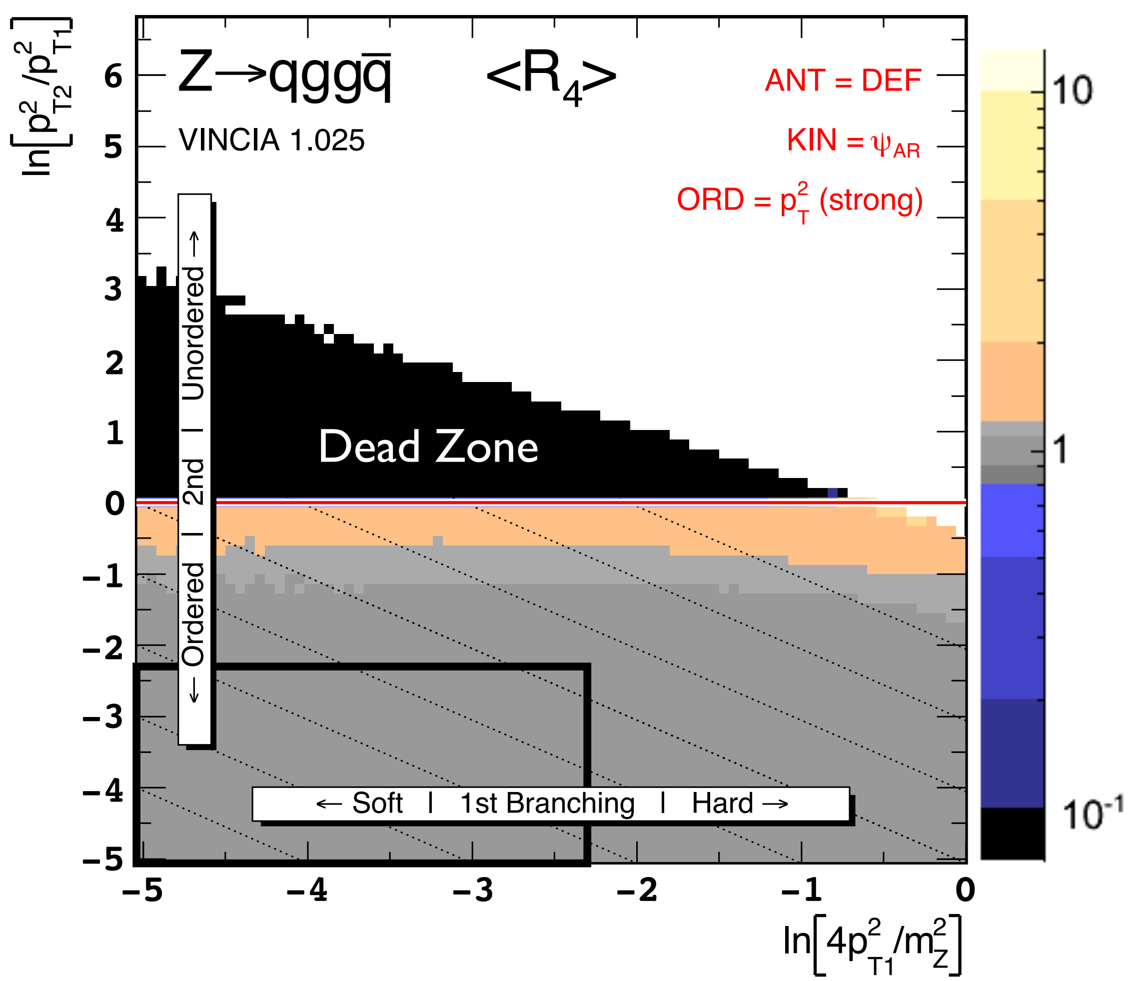
Generate Branchings *without* imposing strong ordering

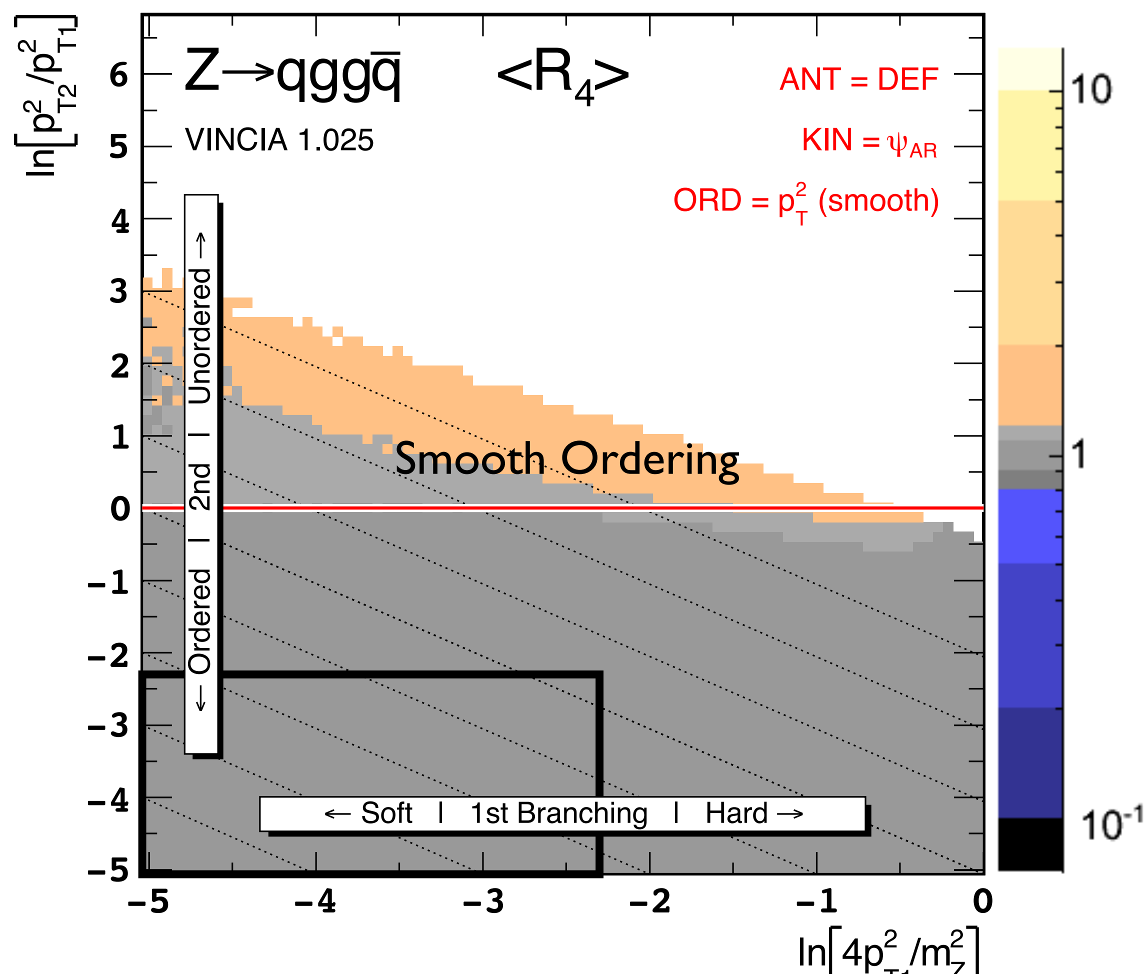
At each step, each dipole allowed to fill its entire phase space

Overcounting removed by matching

+ smooth ordering beyond matched multiplicities

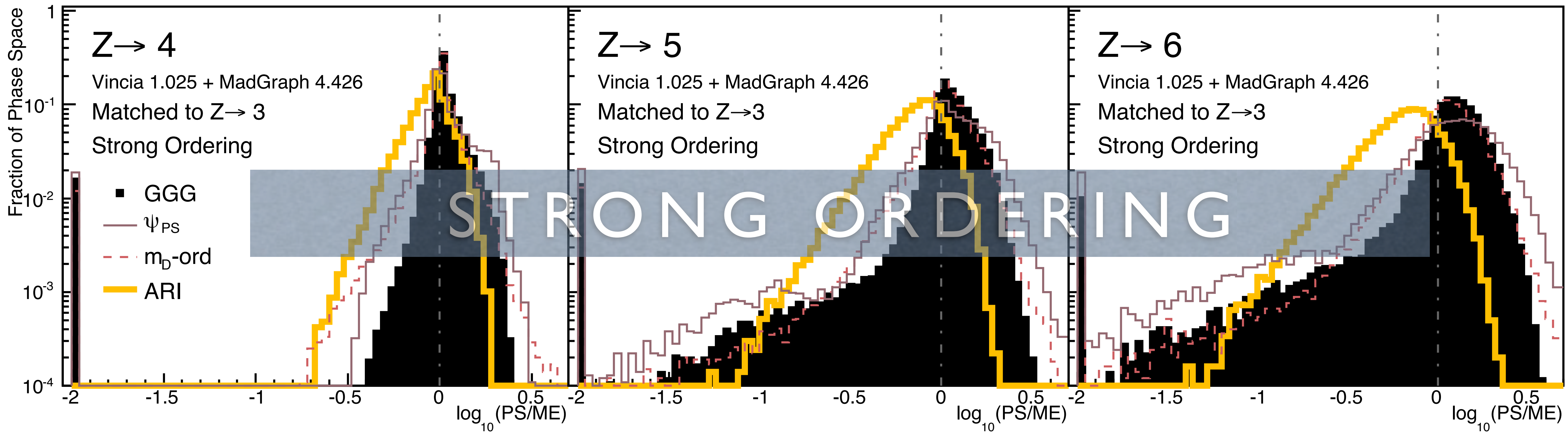
$$\frac{\hat{p}_\perp^2}{\hat{p}_\perp^2 + p_\perp^2} P_{\rm LL} \qquad \begin{array}{ll} \hat{p}_\perp^2 & \text{last branching} \\ p_\perp^2 & \text{current branching} \end{array}$$



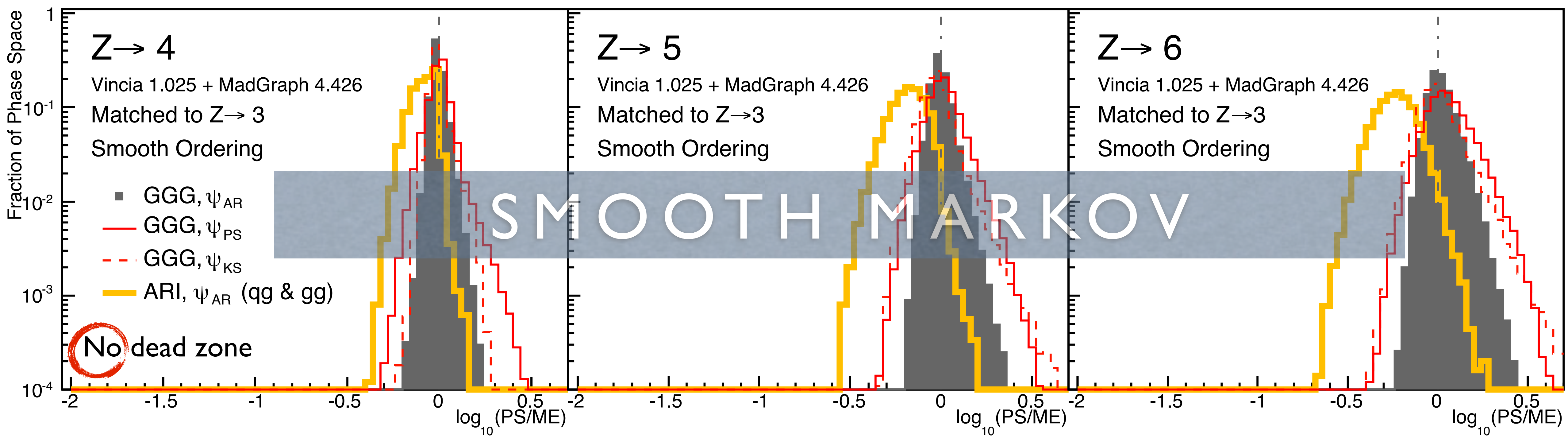


→ Better Approximations

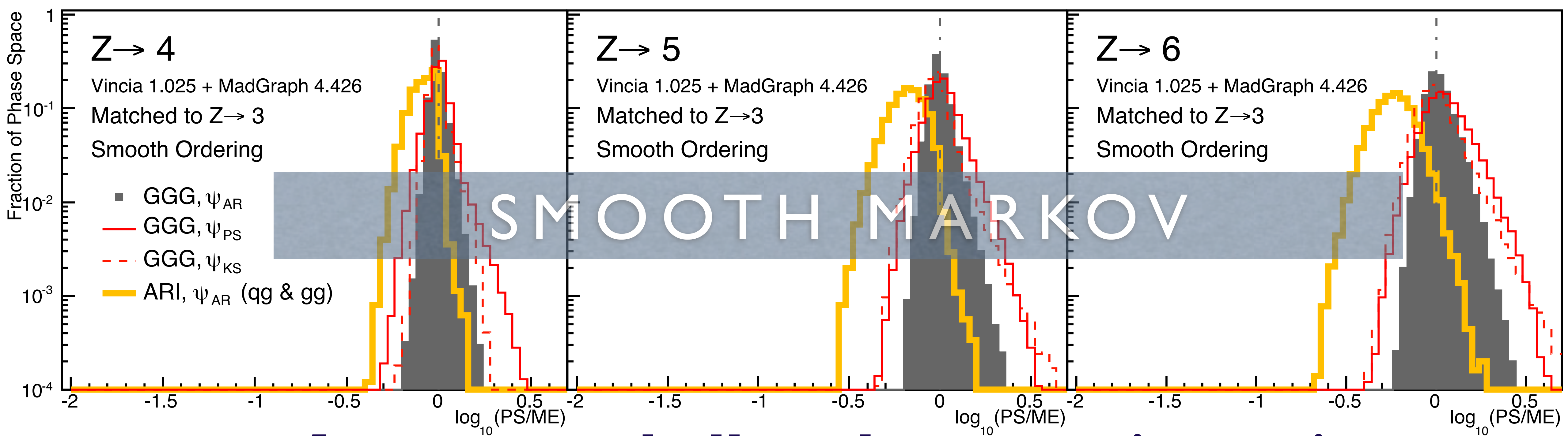
Distribution of **$\log_{10}(PS_{LO}/ME_{LO})$** (inverse ~ matching coefficient)



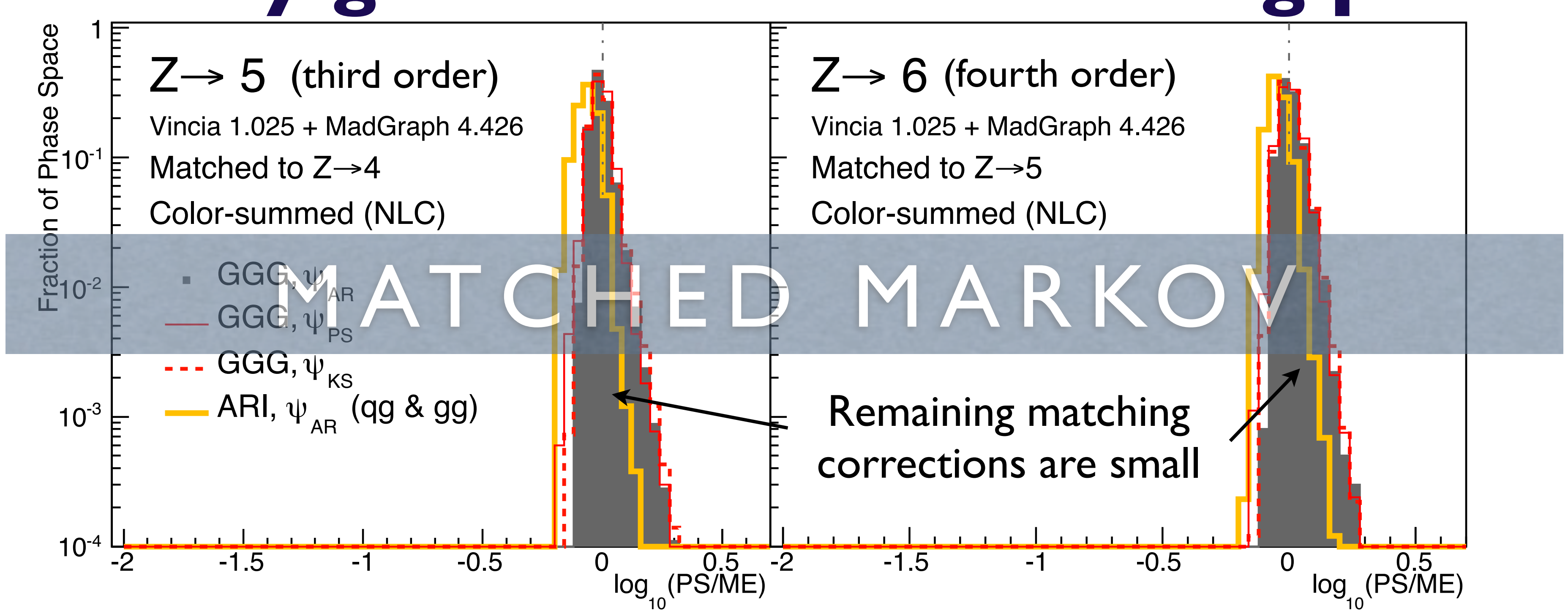
Leading Order, Leading Color, Flat phase-space scan, over **all of phase space** (no matching scale)



+ Matching (+ full colour)



→ A very good all-orders starting point



SPEED : milliseconds / Event

MS/EVENT		Matched through:			
Monte Carlo	Strategy	$Z\to3$	$Z\to4$	$Z\to5$	$Z\to6$
Pythia 8 *Initialization time ~ 0*	TS	0.22	$Z\to qq$ *(q=udscb)* + shower. Matched and unweighted. Hadronization off *gfortran/g++ with gcc v.4.4 -O2 on single 3.06 GHz processor with 4GB memory*		
Vincia *(sector, Q_{match} = 5 GeV)* *Initialization time ~ 0*	GKS	0.26	0.50	1.40	6.70
Sherpa *(Q_{match} = 5 GeV)* *Initialization time =*	CKKW (expect similar scaling for MLM)	5.15* 1.5 minutes	53.00* 7 minutes	220.00* 22 minutes	400.00* 2.2 hours

Generator Versions: Pythia 6.425 *(Perugia 2011 tune)*, Pythia 8.150, Sherpa 1.3.0, Vincia 1.026 *(without uncertainty bands, NLL/NLC=OFF)*

Efficient Matching with Sector Showers
J. Lopez-Villarejo & PS : JHEP 1111 (2011) 150


Uncertainties

Uncertainty Variations

A result is only as good as its uncertainty

Normal procedure:

Run MC 2N+1 times (for central + N up/down variations)

Takes 2N+1 times as long

+ uncorrelated statistical fluctuations

Automate and do everything in one run

VINCIA: all events have weight = 1

Compute *unitary* alternative weights on the fly

→ sets of alternative weights representing variations (all with <w>=1)

Same events, so only have to be hadronized/detector-simulated ONCE!

MC with Automatic Uncertainty Bands

Uncertainties

For each branching, recompute weight for:

- Different renormalization scales
- Different antenna functions
- Different ordering criteria
- Different subleading-color treatments

	Weight
Nominal	1
Variation	$P_2 = \frac{\alpha_{s2} a_2}{\alpha_{s1} a_1} P_1$

+ Matching

Differences explicitly matched out

(Up to matched orders)

(Can in principle also include variations of matching scheme…)

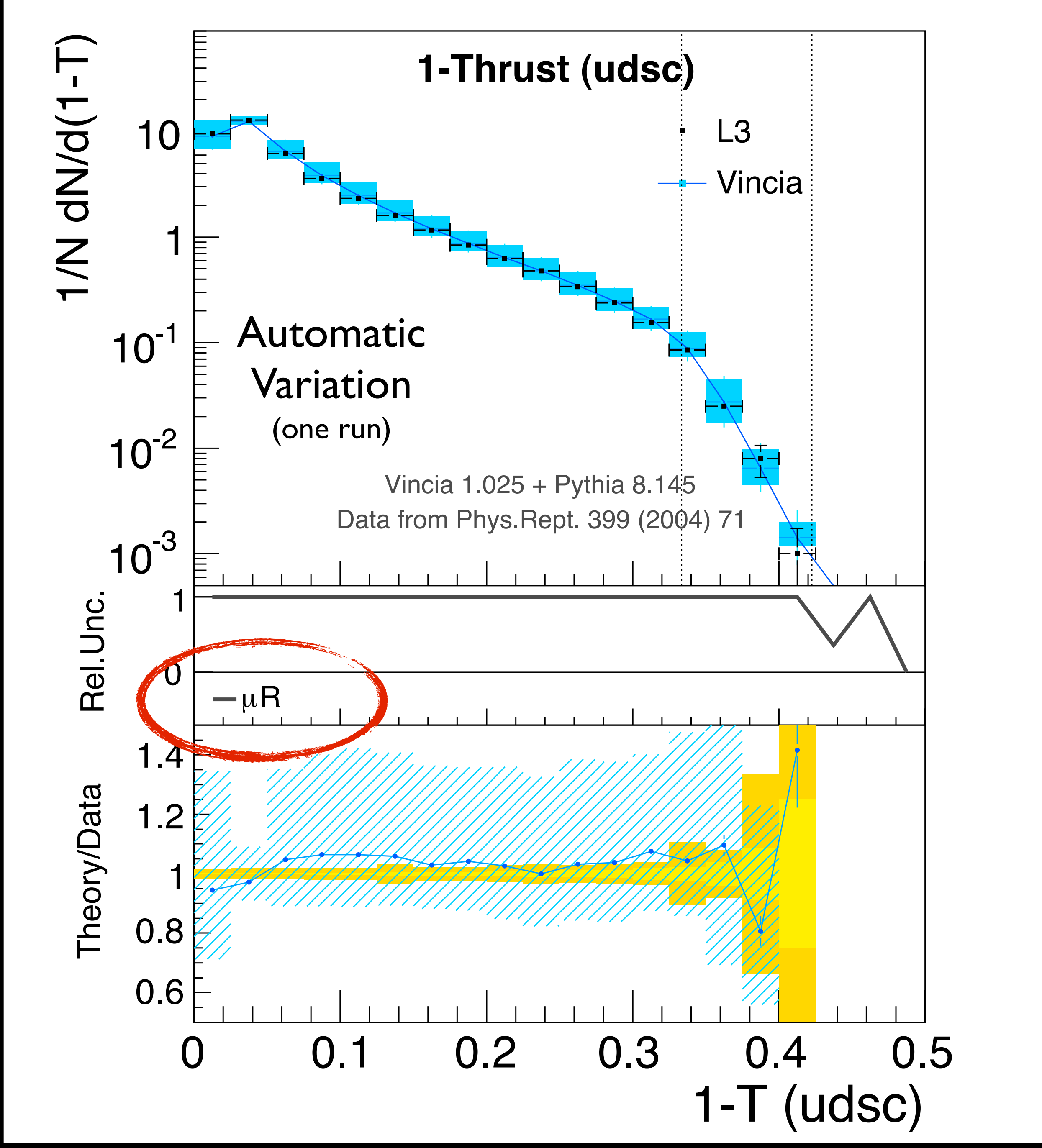
+ Unitarity

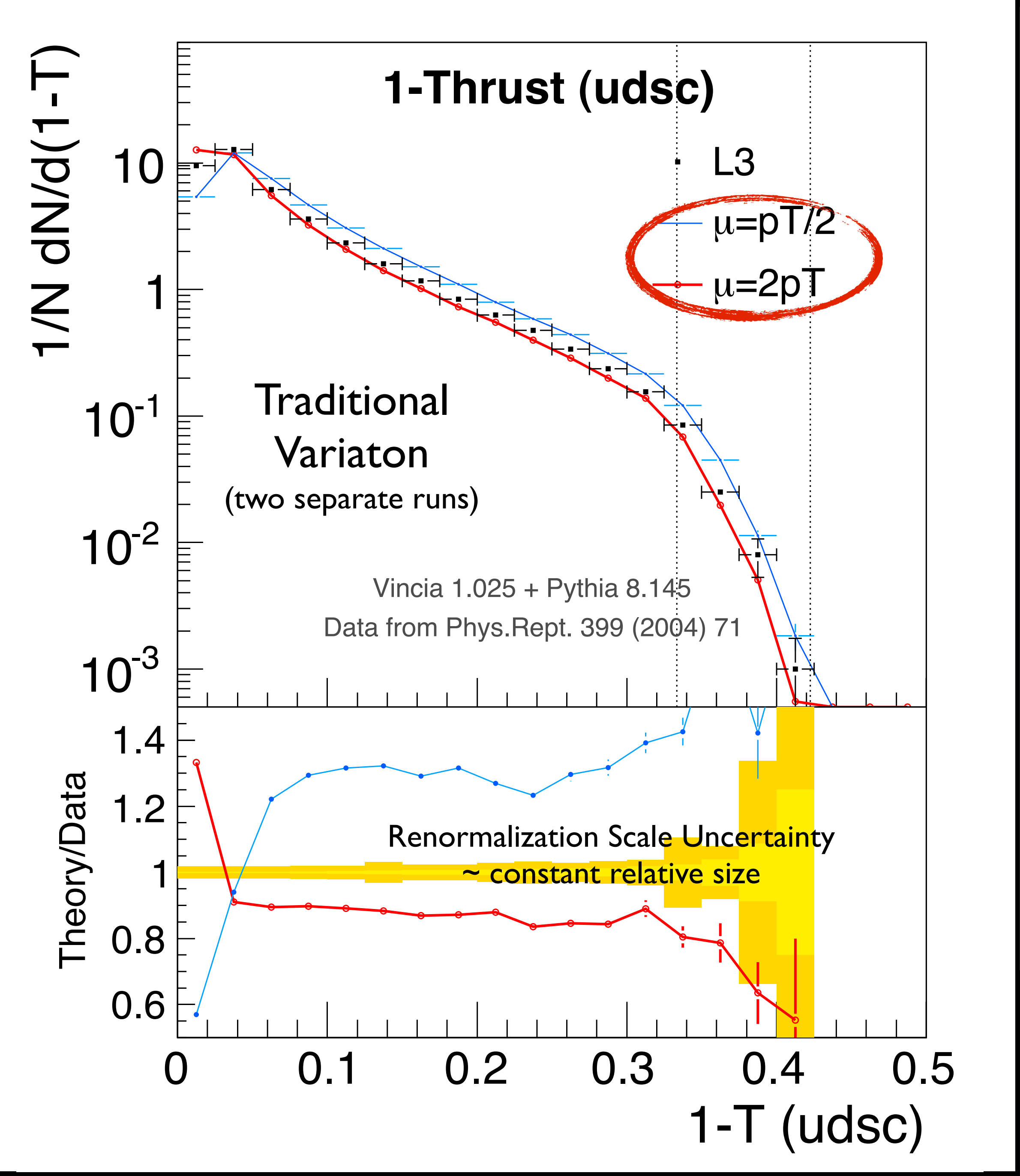
For each *failed* branching:

$$P_{2;\mathrm{no}} = 1 - P_2 = 1 - \frac{\alpha_{s2} a_2}{\alpha_{s1} a_1} P_1$$

Automatic Uncertainties

Vincia:uncertaintyBands = on

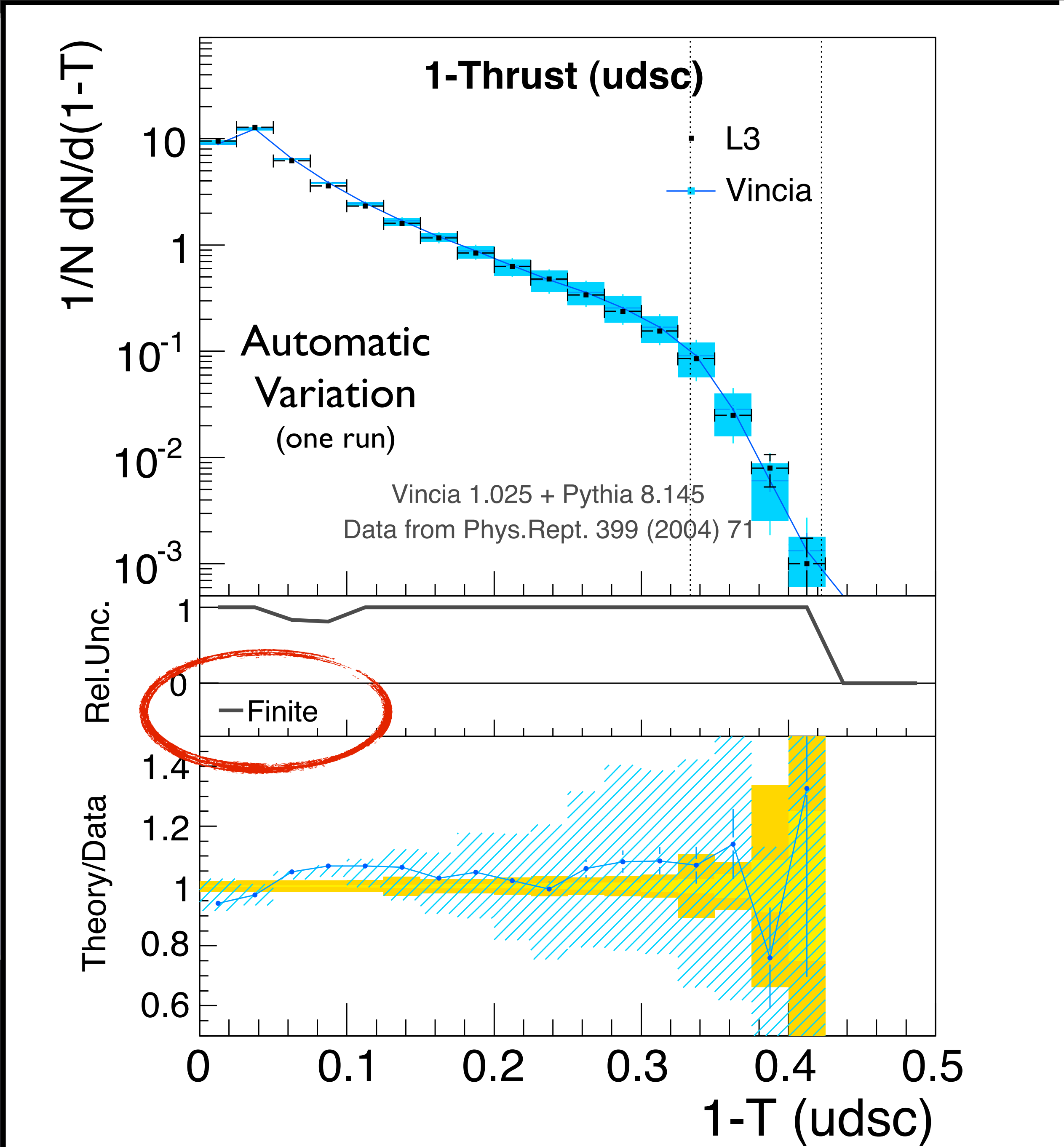


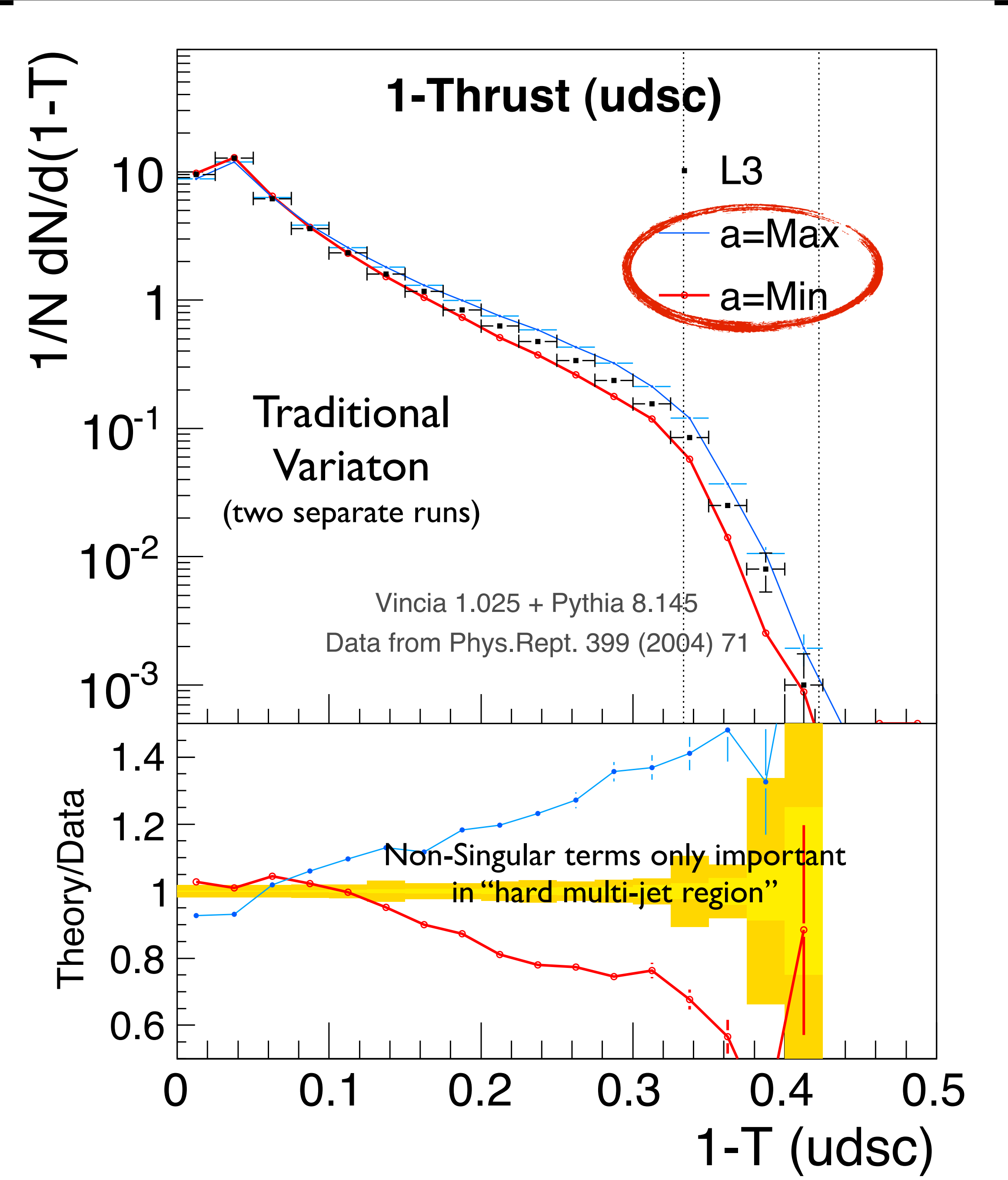


Variation of renormalization scale (no matching)

Automatic Uncertainties

Vincia:uncertaintyBands = on

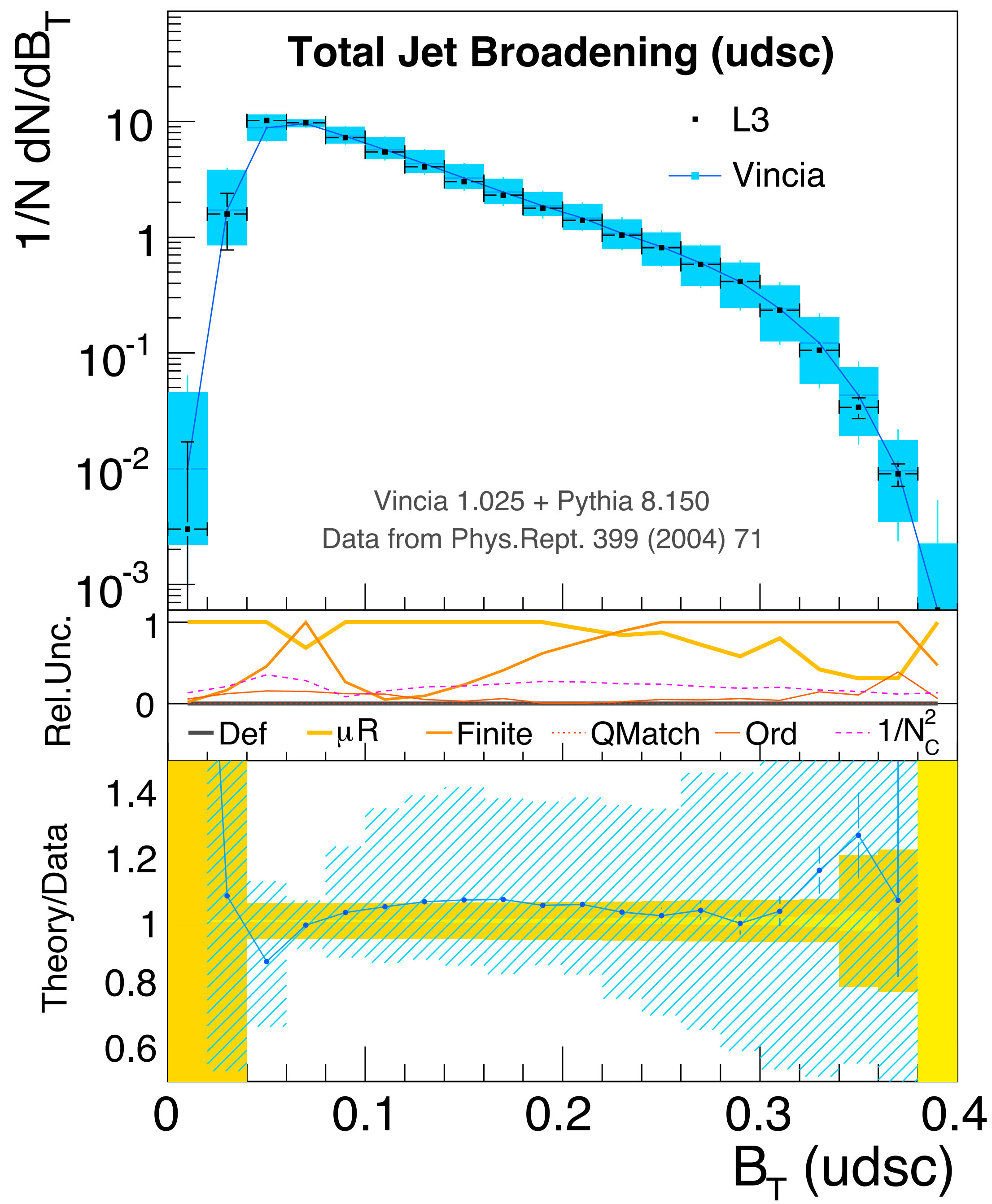




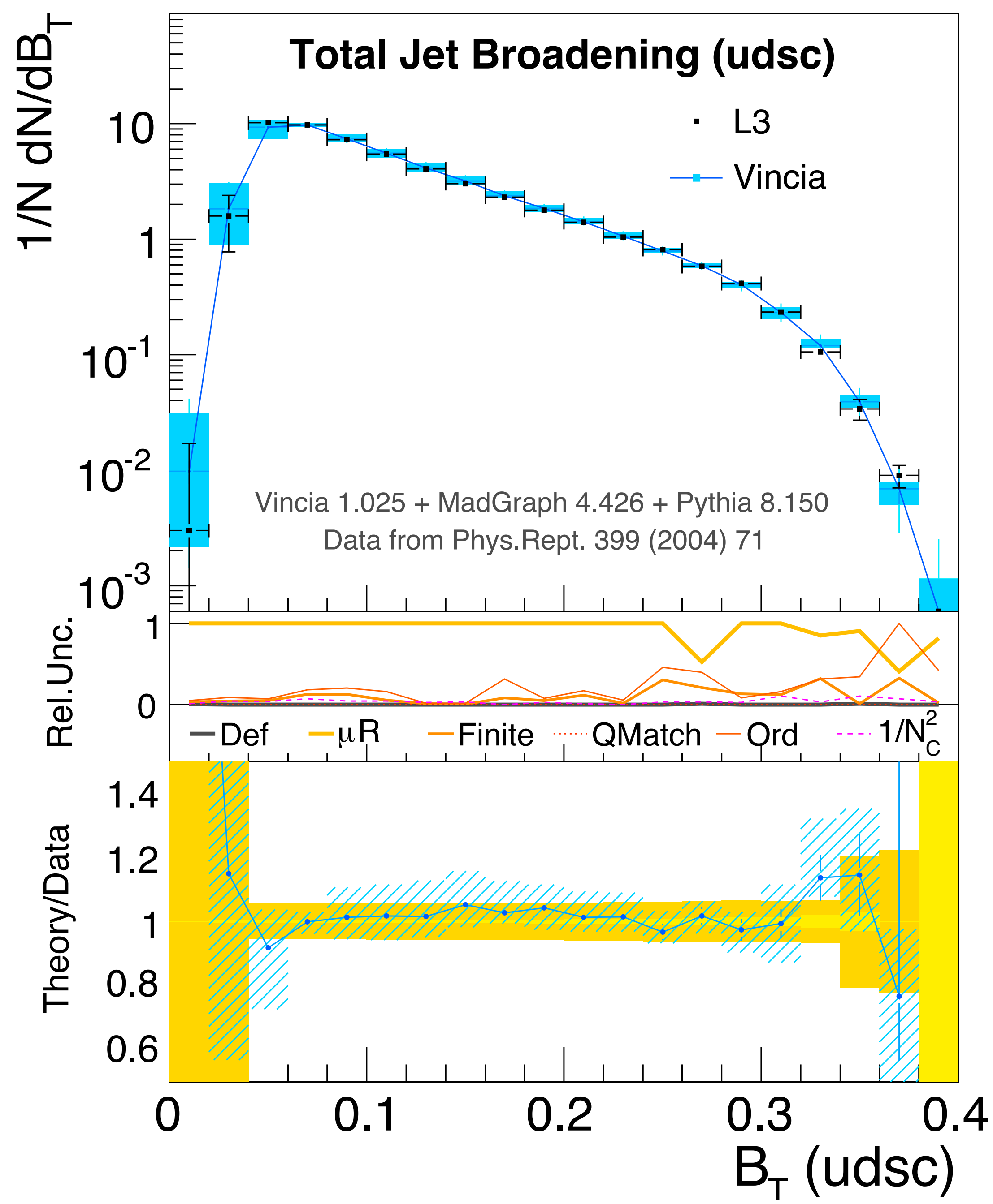
Variation of "finite terms" (no matching)

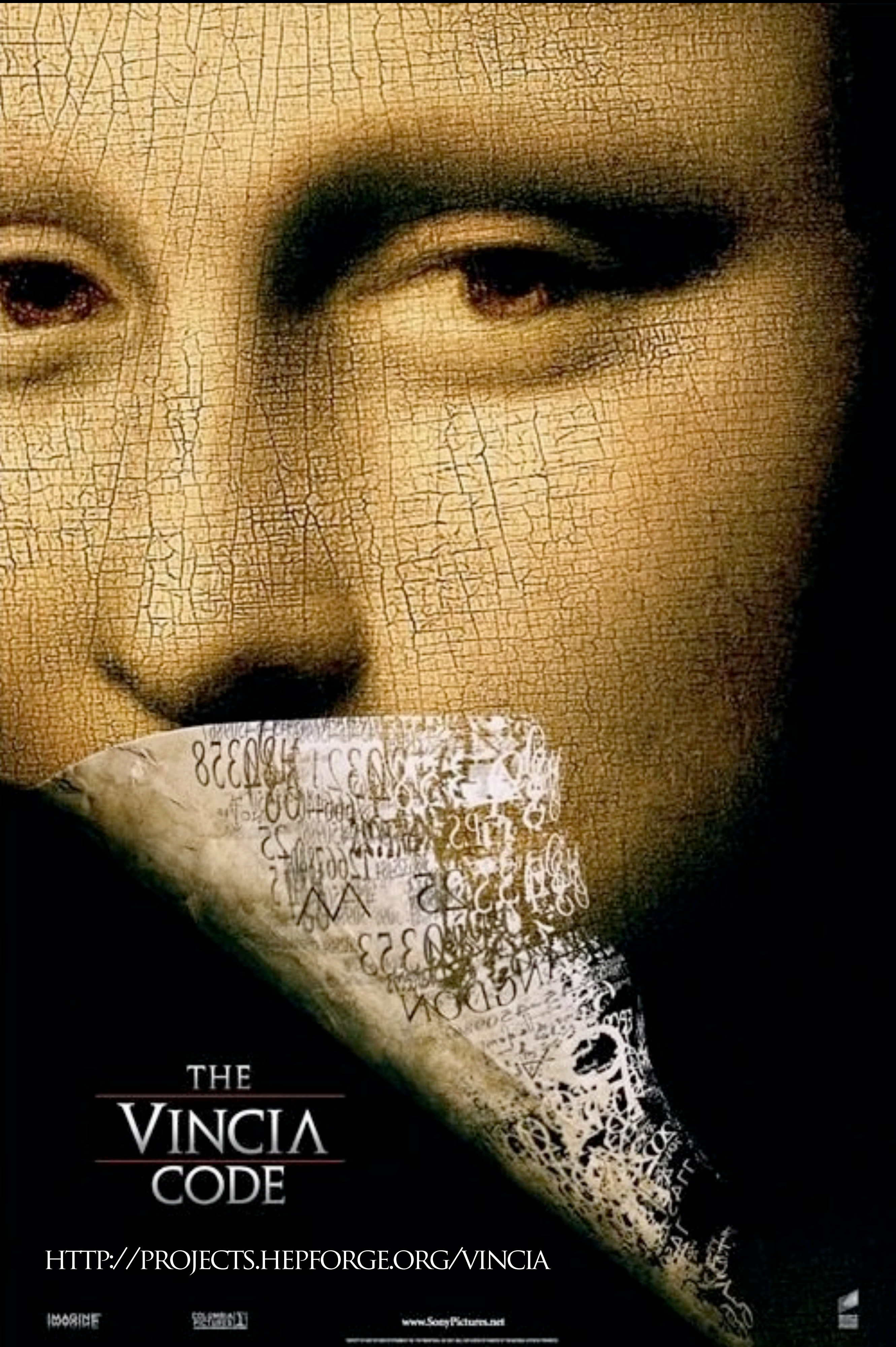
Putting it Together

VinciaMatching:order = 0



VinciaMatching:order = 3





VINCIA Status

Next steps

Multi-leg one-loop matching
(with L. Hartgring & E. Laenen, NIKHEF)

Helicity-dependent Showers
(with A. Larkoski, SLAC, & J. Lopez-Villarejo, CERN)

→ Initial-State Showers
(with W. Giele, D. Kosower, S. Mrenna, M. Ritzmann)

Conclusions

- **QCD Phenomenology** is witnessing a rapid evolution: LO & NLO matching, better showers, tuning, interfaces ...
  - Driven by demand for high precision in complex LHC environment with huge phase space
- BSM Physics
  - Generally relies on chains of tools (MC4BSM)
  - Sufficient to reach O(10%) accuracy, with hard work, though must be careful with scale hierarchies, width effects, decay distributions, …
  - Next machine is a long way off → must strive to build capacity for yet higher precision, to get max from LHC data.
- Ultimate limit set by solutions to pQCD (getting better) and then the **really** hard stuff
  - Like Hadronization, Underlying Event, Diffraction, … (& BSM equivalents?)
  - For which fundamentally new ideas may be needed

For more, see the *MCnet* Review: General-purpose event generators for LHC physics : arXiv:1101.2599

Backup Slides

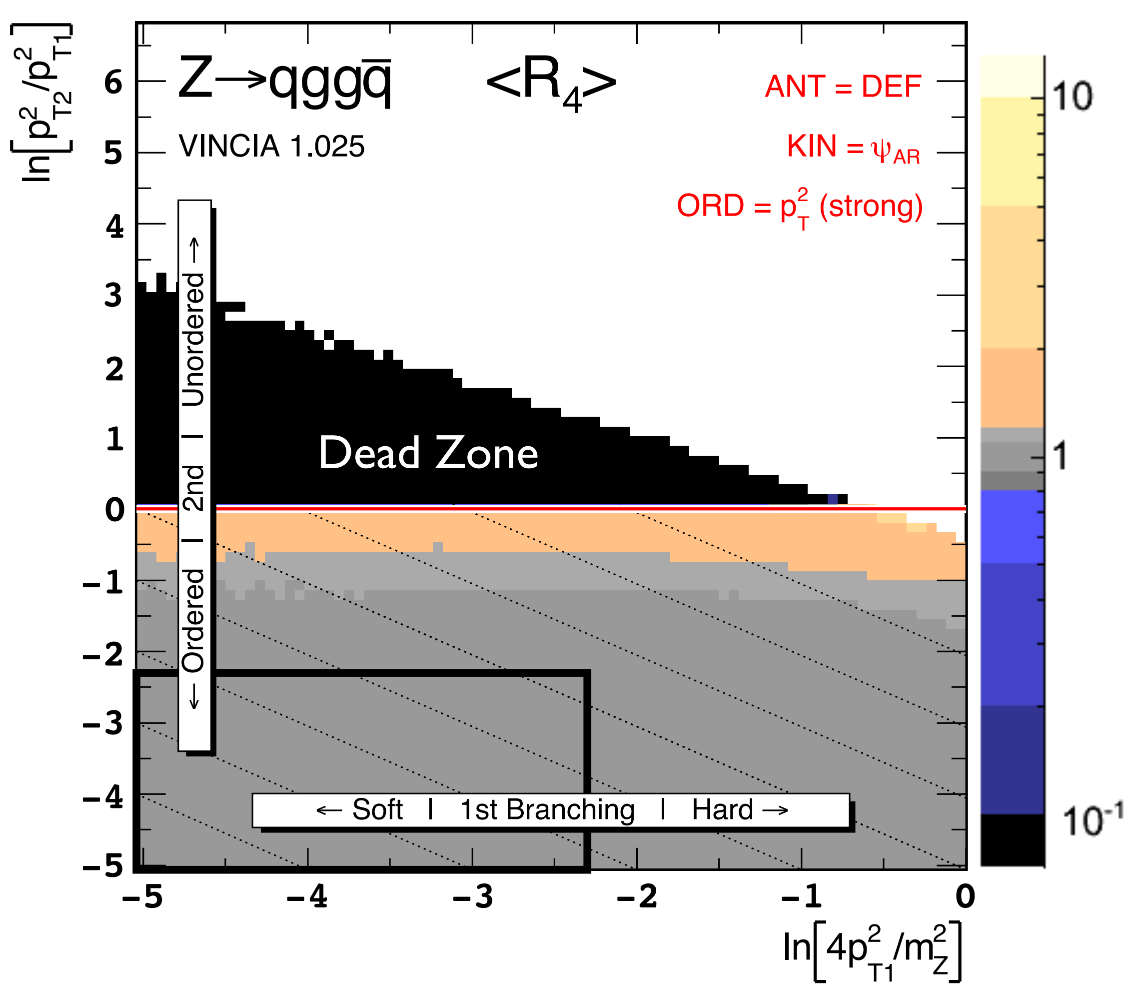
Simple Solution

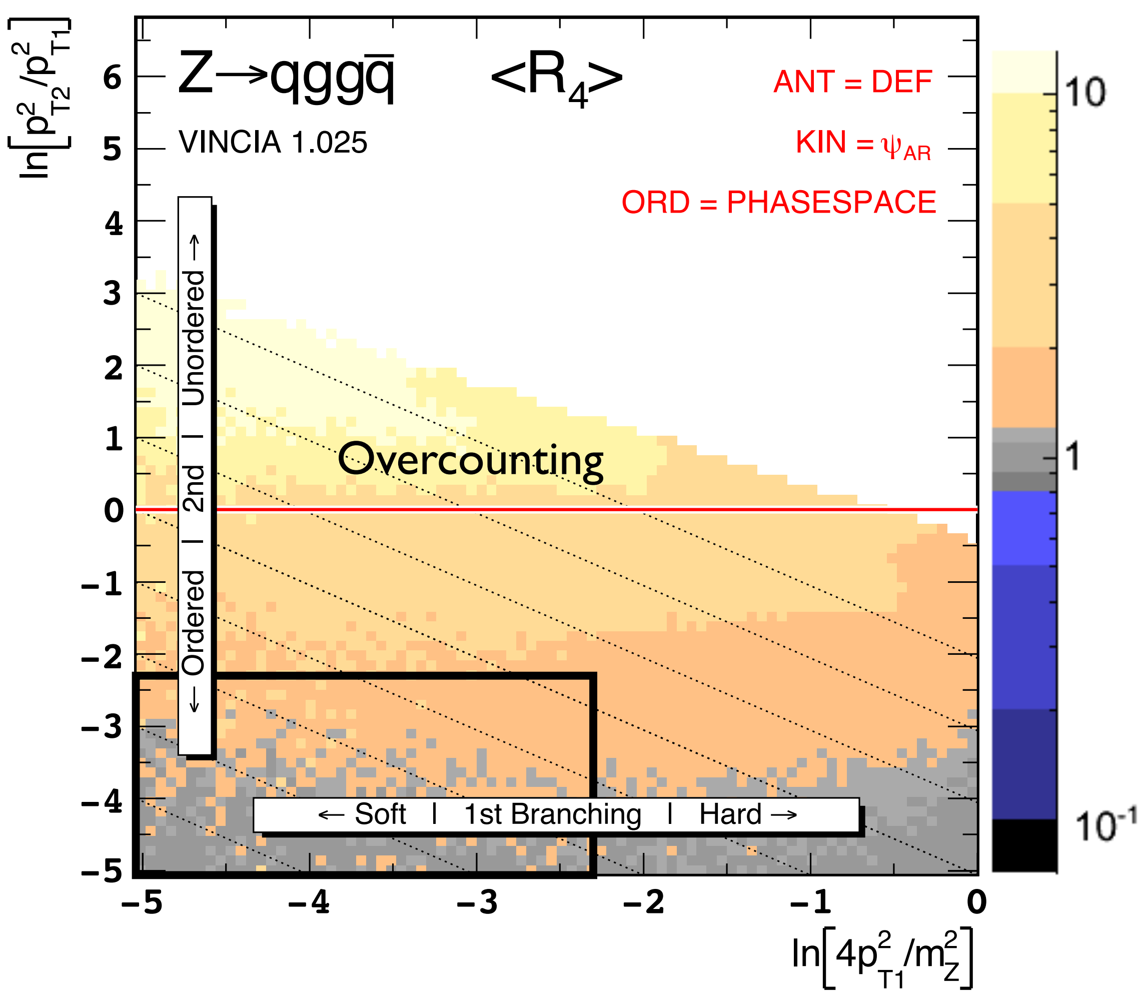
Generate Trials *without* imposing strong ordering

At each step, each dipole allowed to fill its entire phase space

Overcounting removed by matching

(revert to strong ordering beyond matched multiplicities)



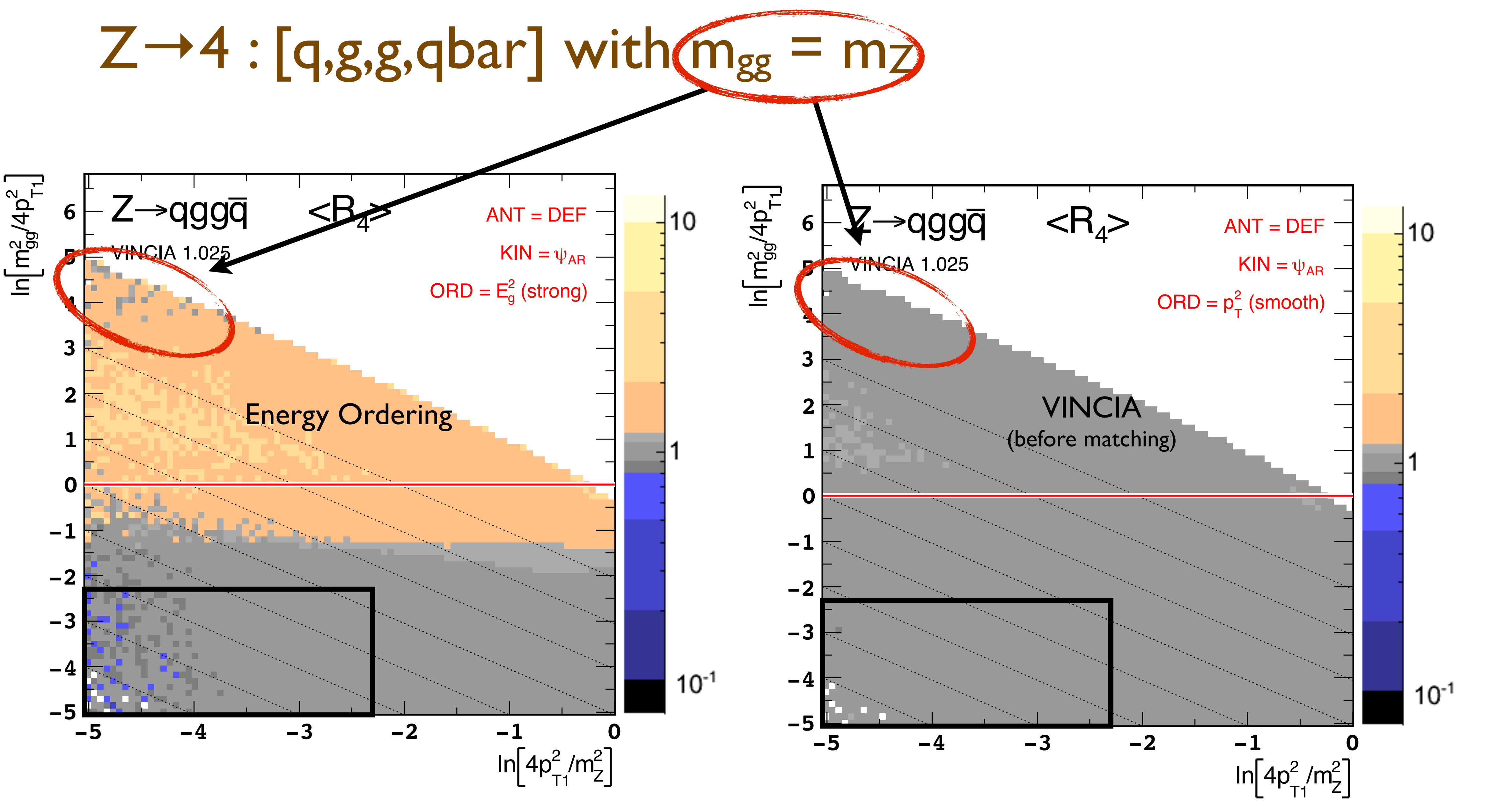


(Subleading Singularities)

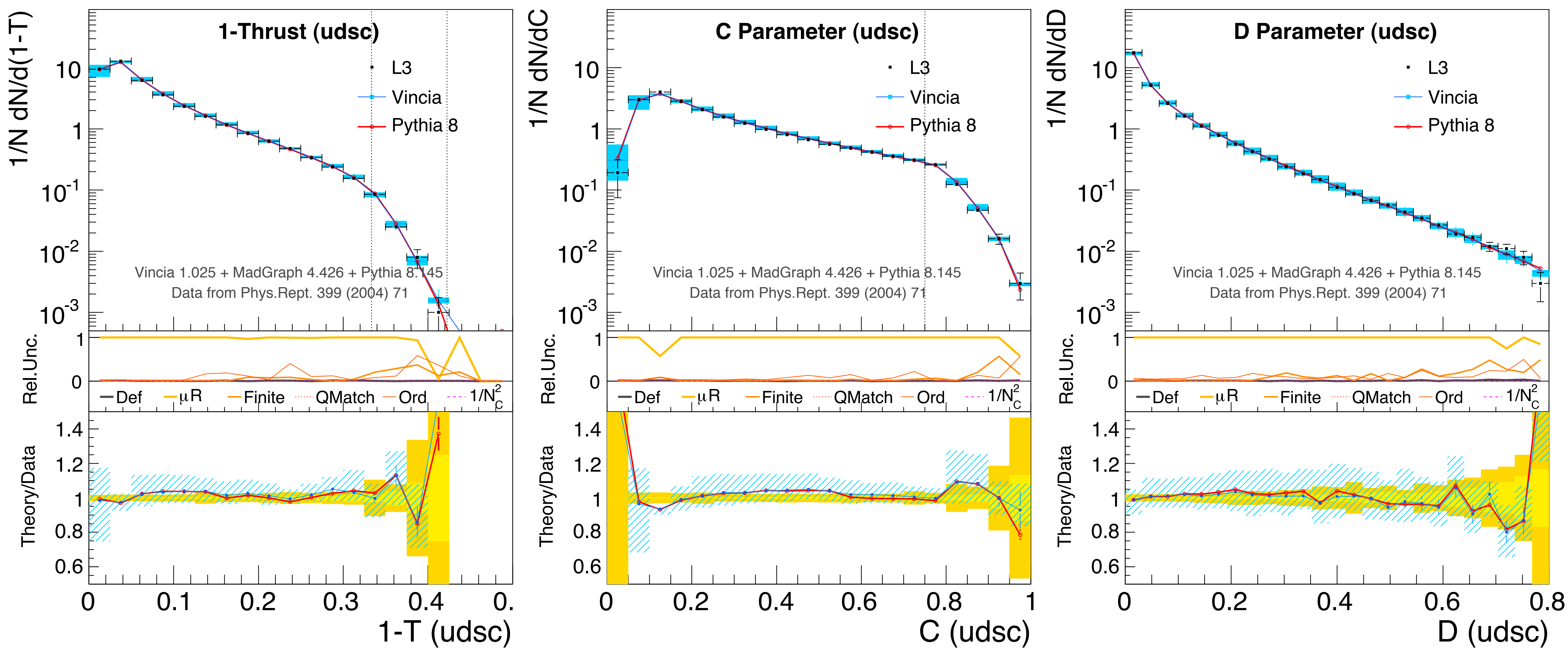
Isolate double-collinear region:

$\alpha_s^2 \ln^2$

$Z \to 4$: [q,g,g,qbar] with $m_{gg} = m_Z$



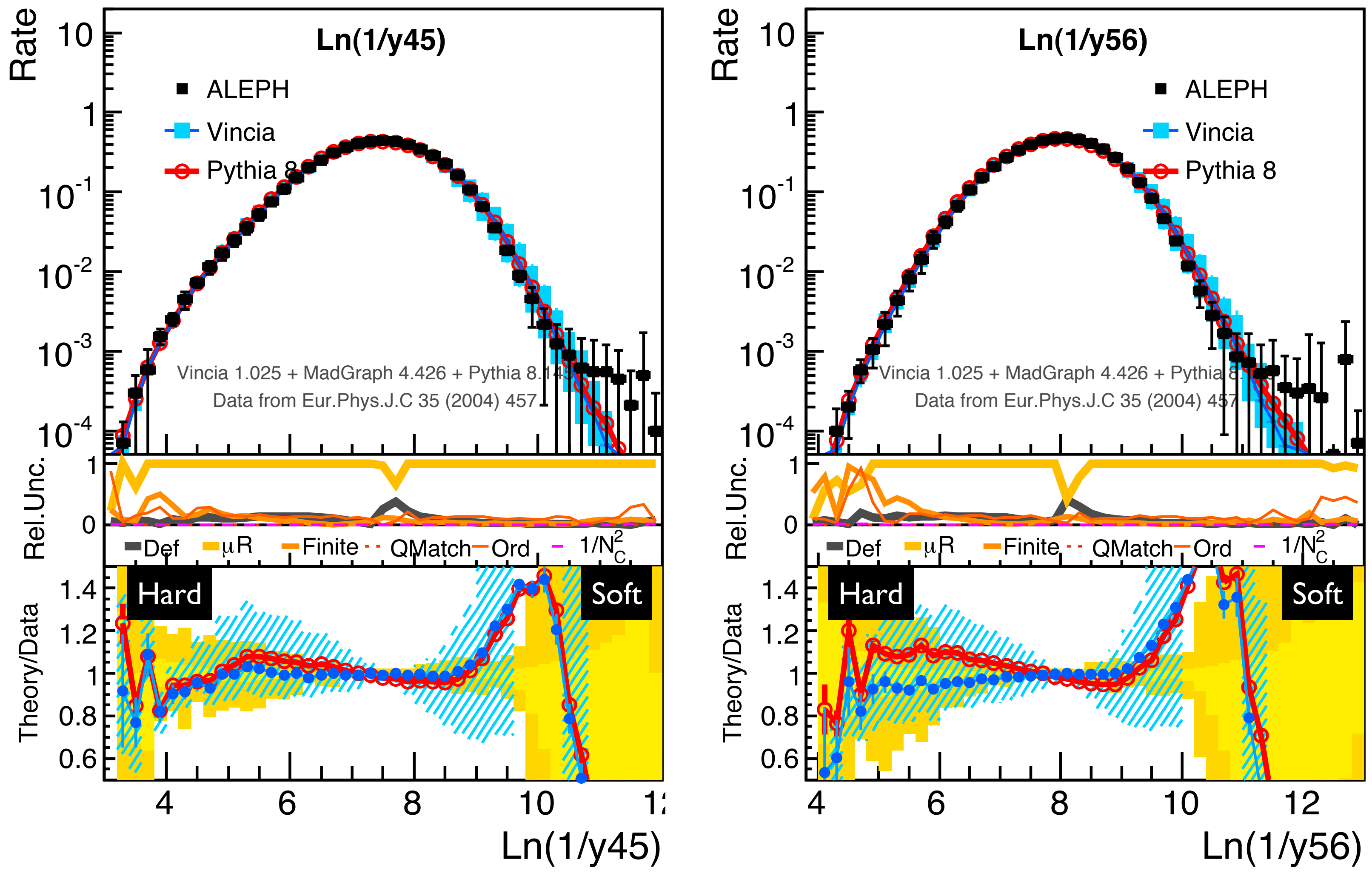
LEP event shapes



PYTHIA 8 already doing a very good job

VINCIA adds uncertainty bands + can look at more exclusive observables?

Multijet resolution scales



y_{45} = scale at which 5th jet becomes resolved ~ "scale of 5th jet"

4-Jet Angles

4-jet angles

Sensitive to polarization effects

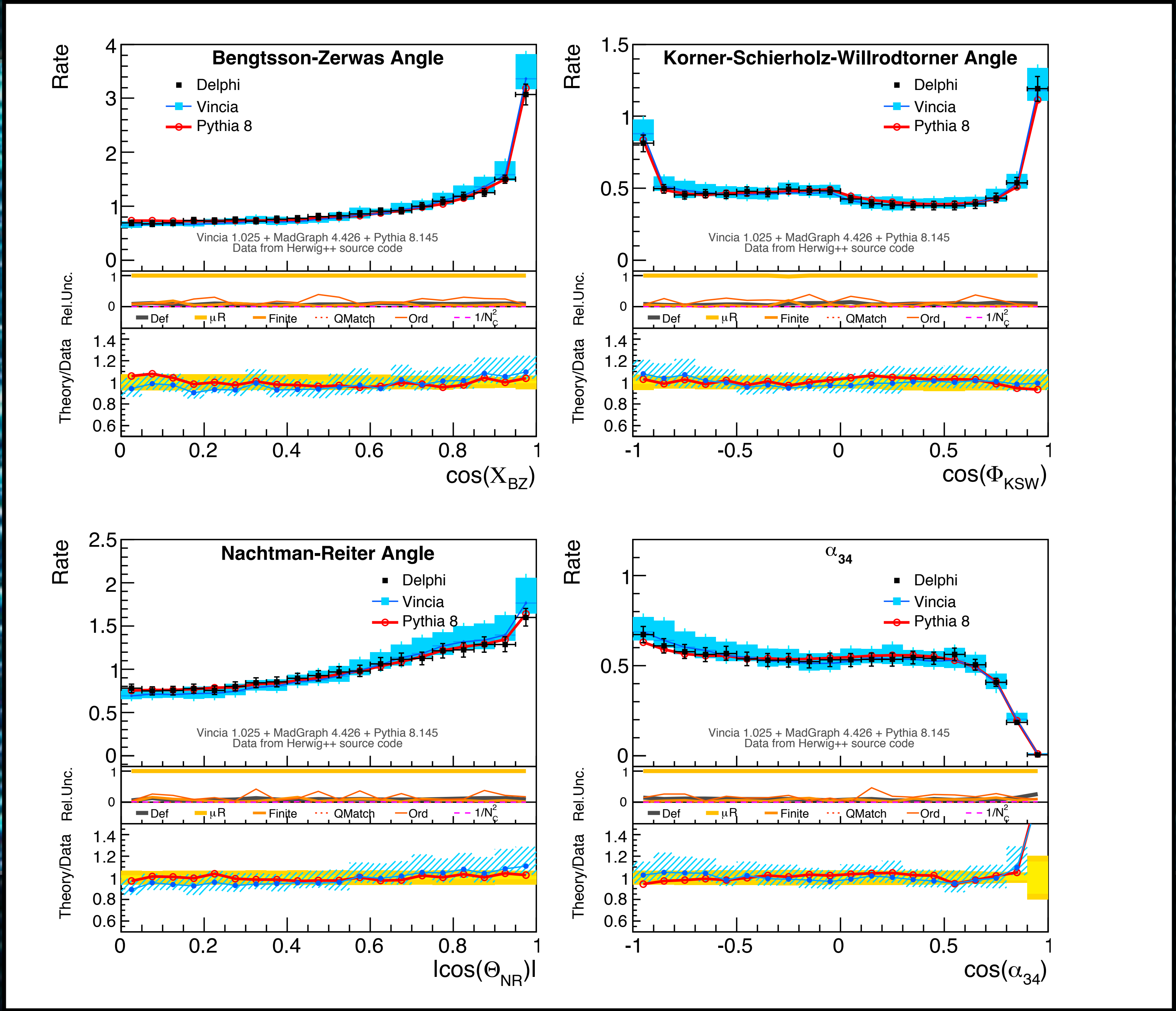
Good News

VINCIA is doing reliably well

Non-trivial verification that shower+matching is working, etc.

Higher-order matching needed?

PYTHIA 8 already doing a very good job on these observables



Interesting to look at more exclusive observables, but which ones?