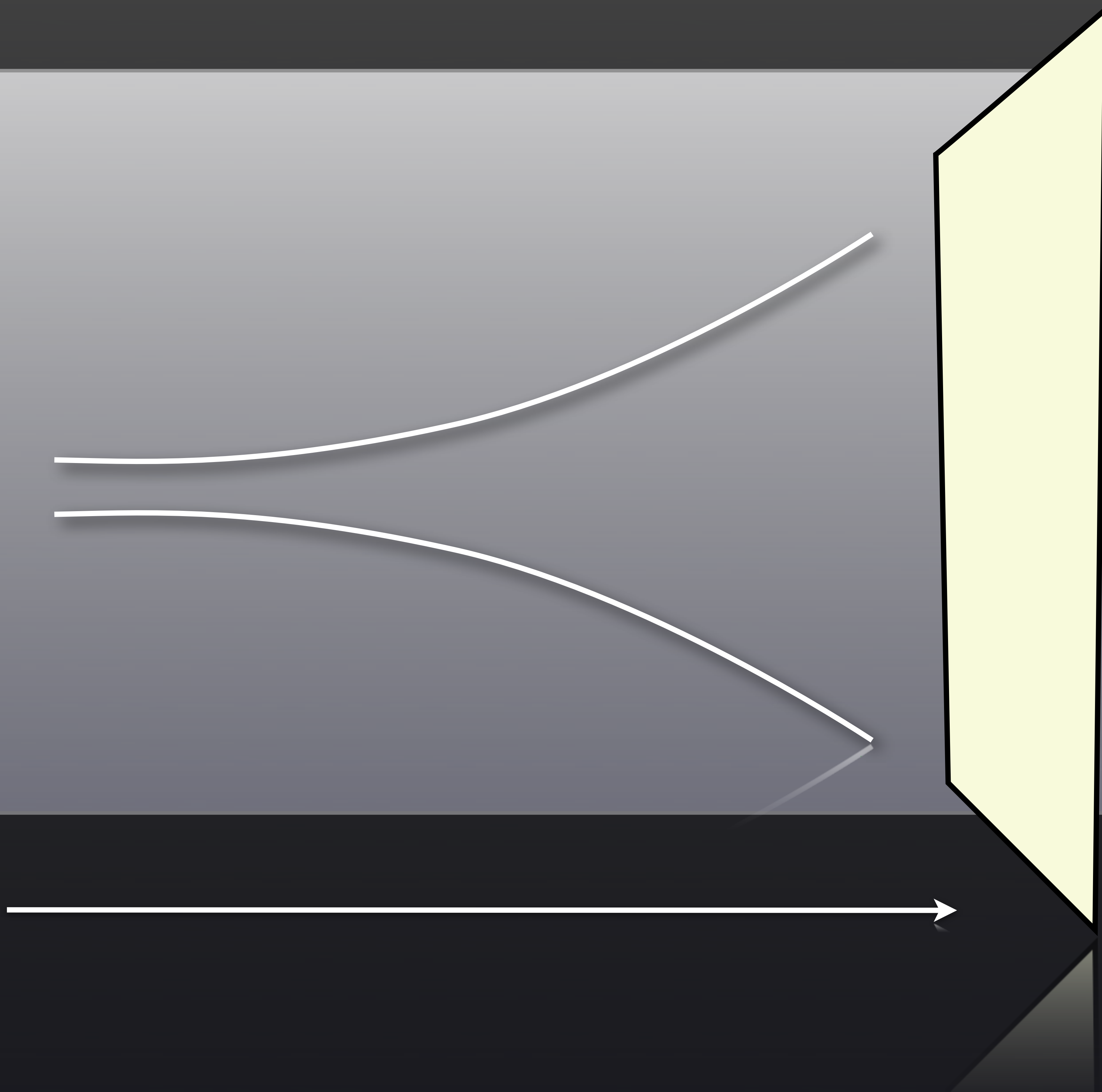
Boost 2011

VINCIA

Peter Skands (CERN)



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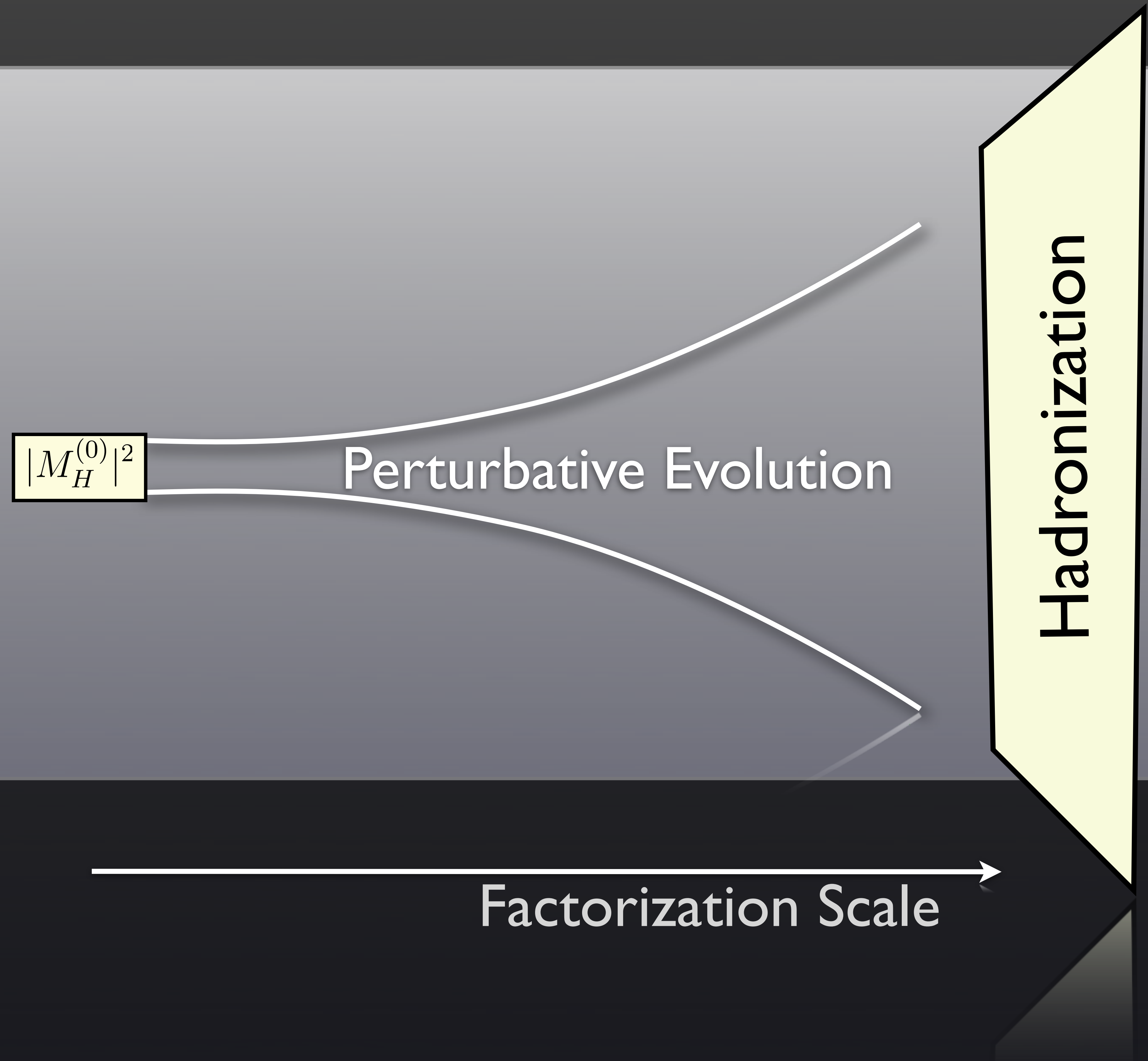

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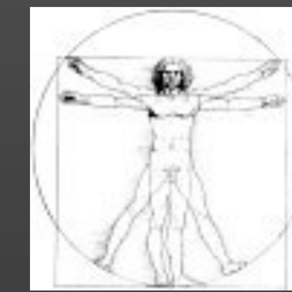

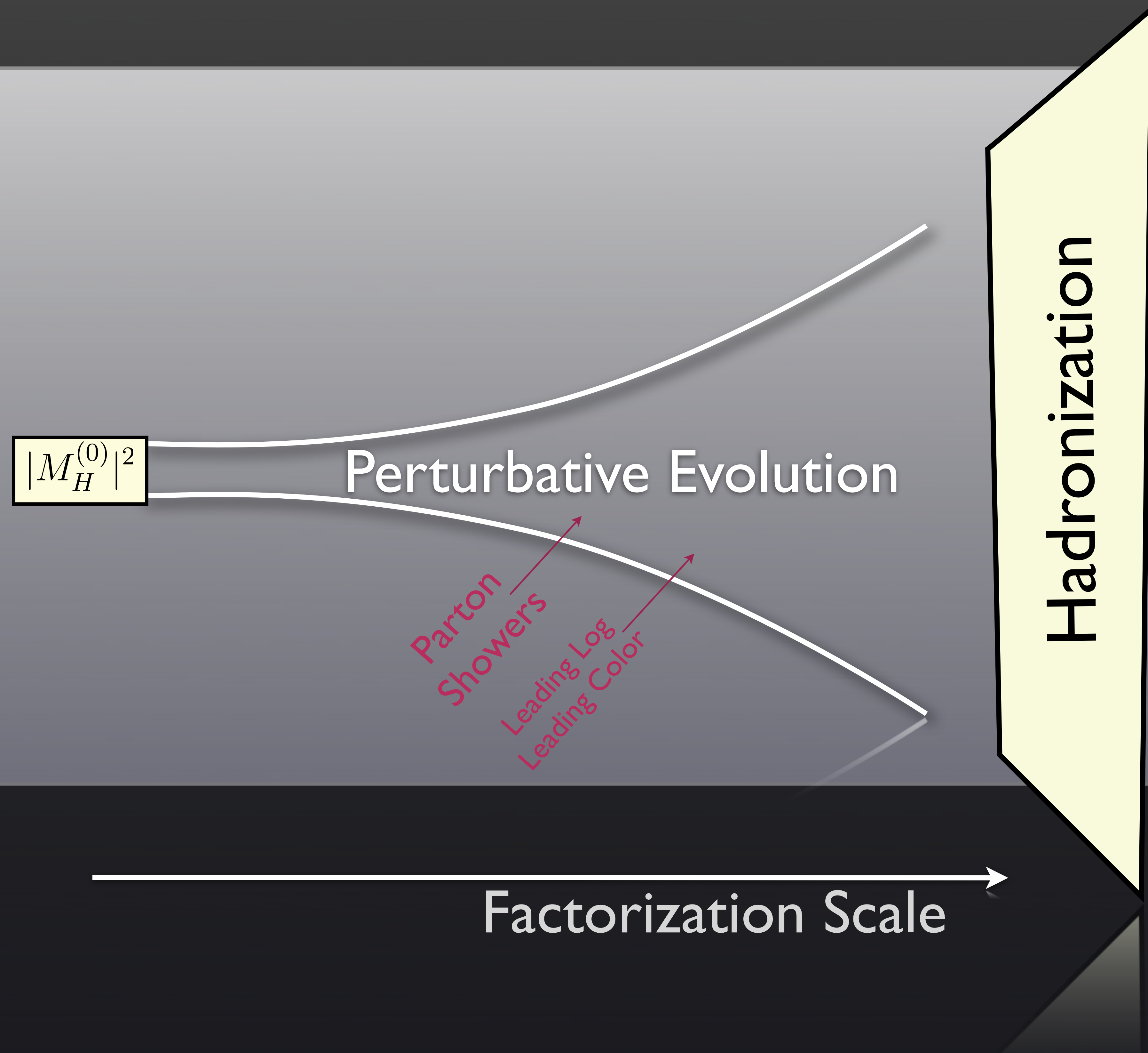

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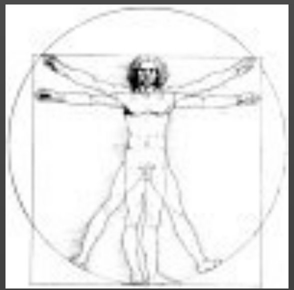

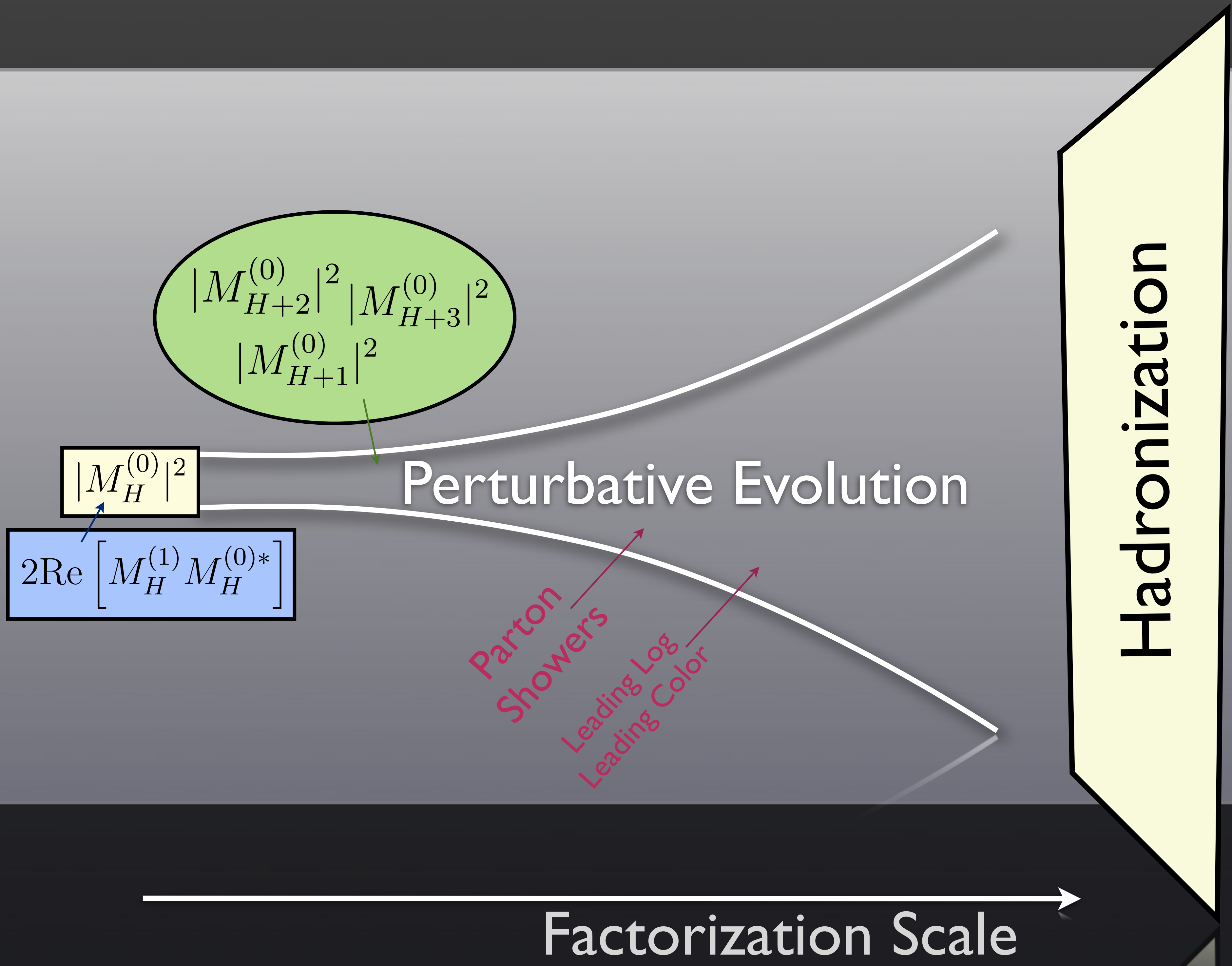

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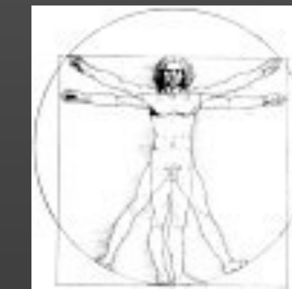

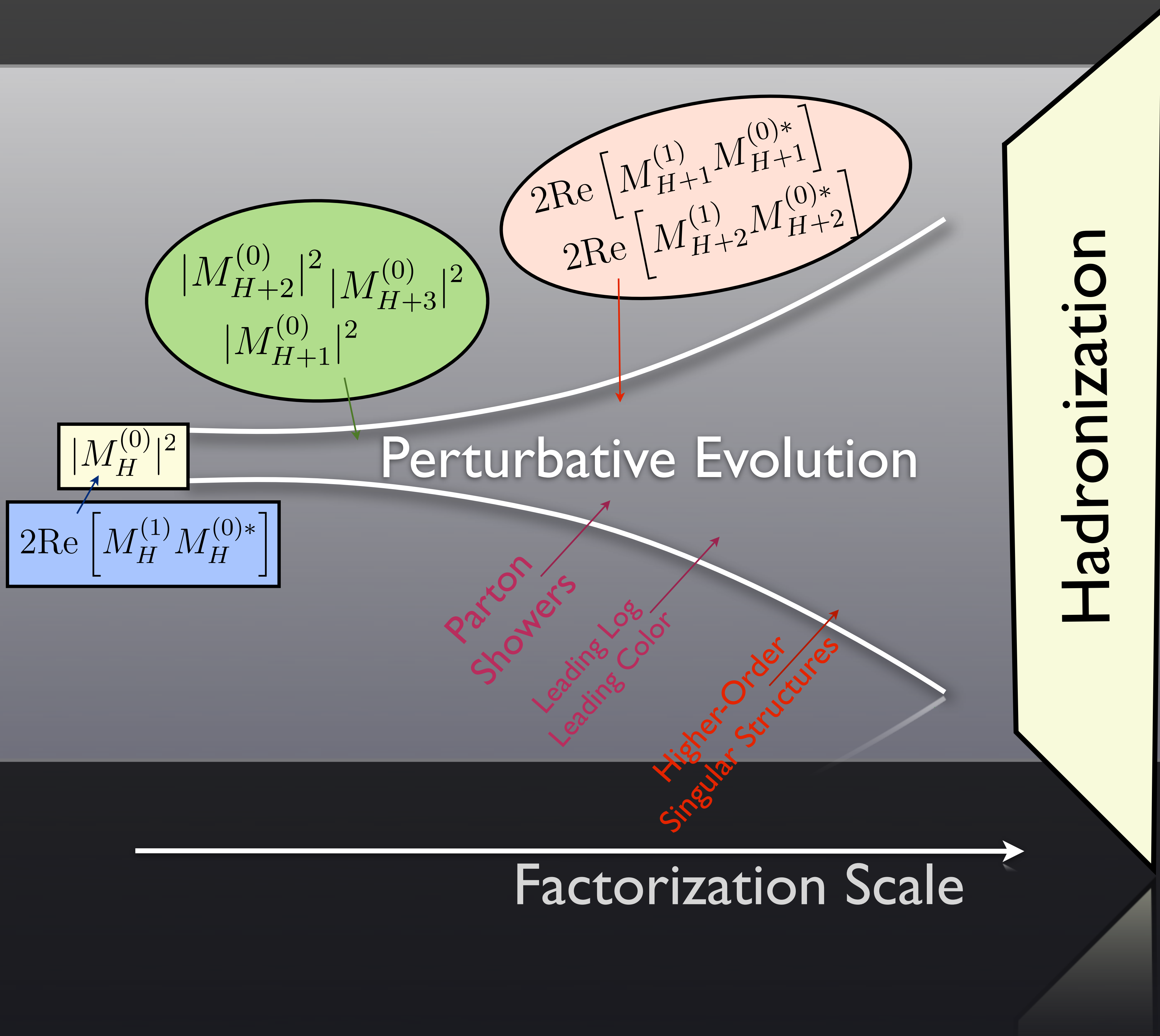

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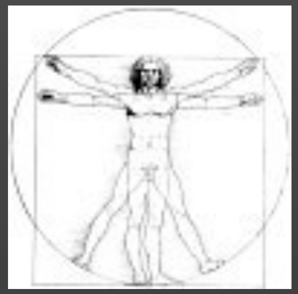
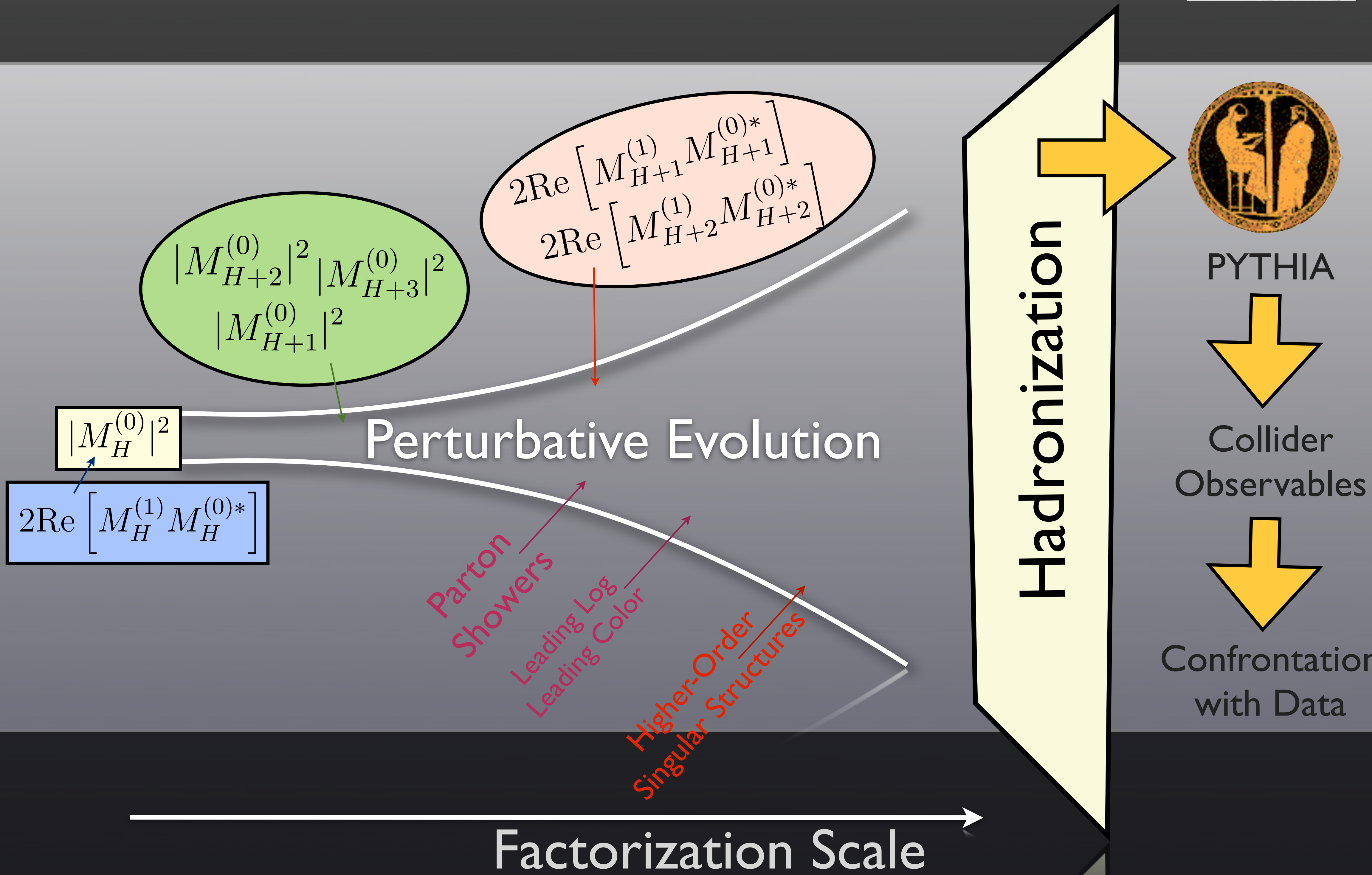




Why?

Jet Substructure

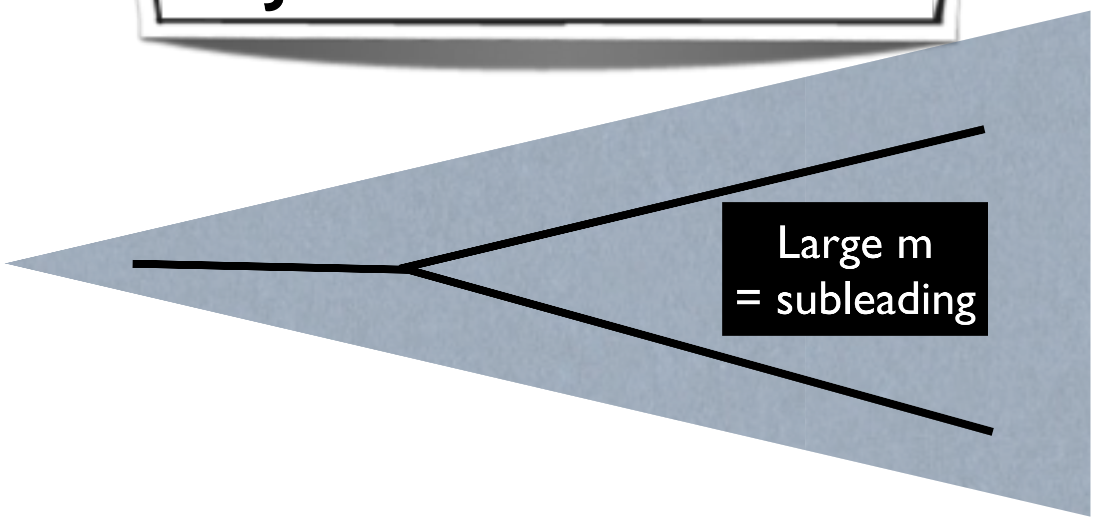
Underlying Event &
Jet Calibration

Hadronization

Structure of QCD

Why?

Jet Substructure



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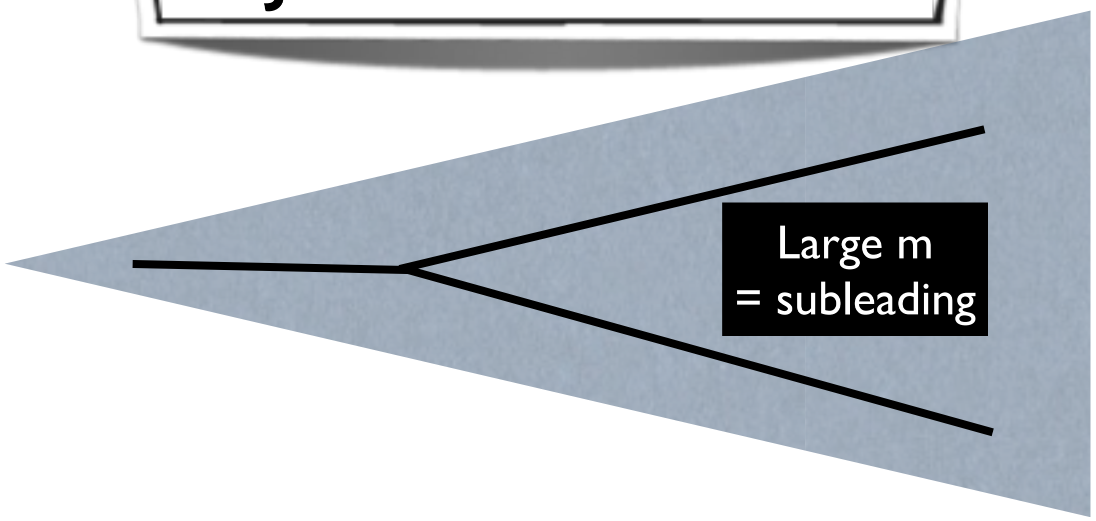

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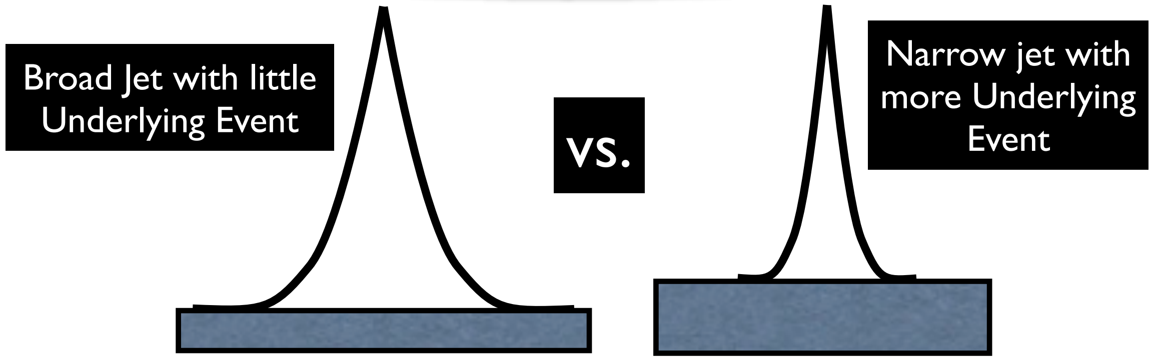

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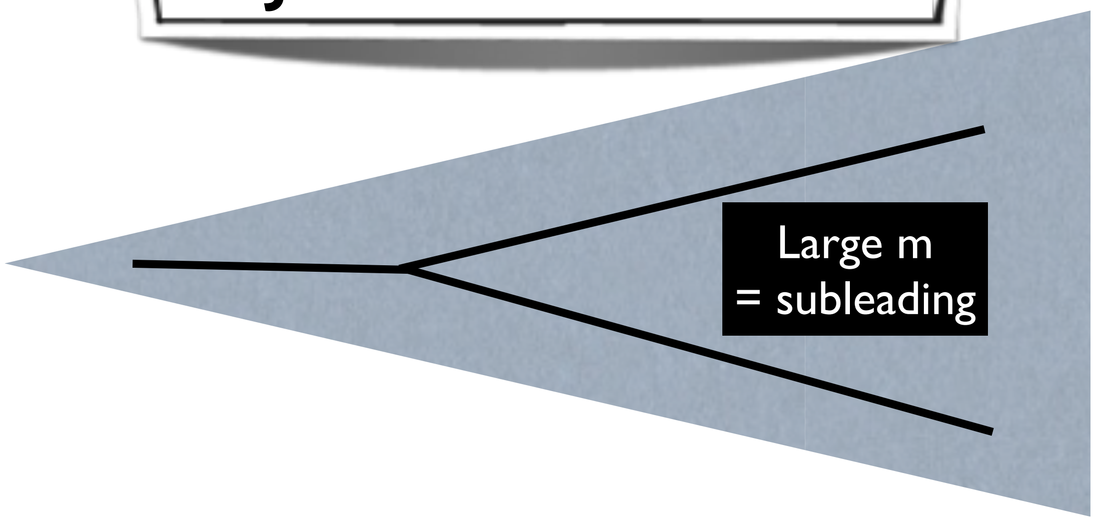

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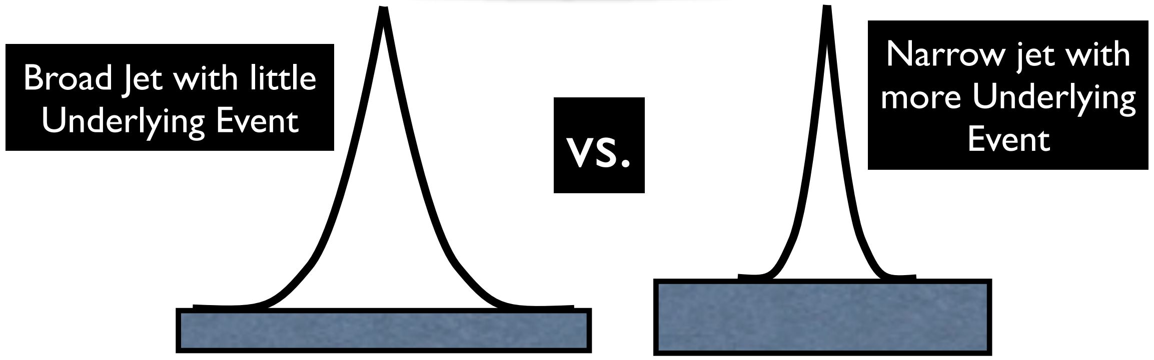

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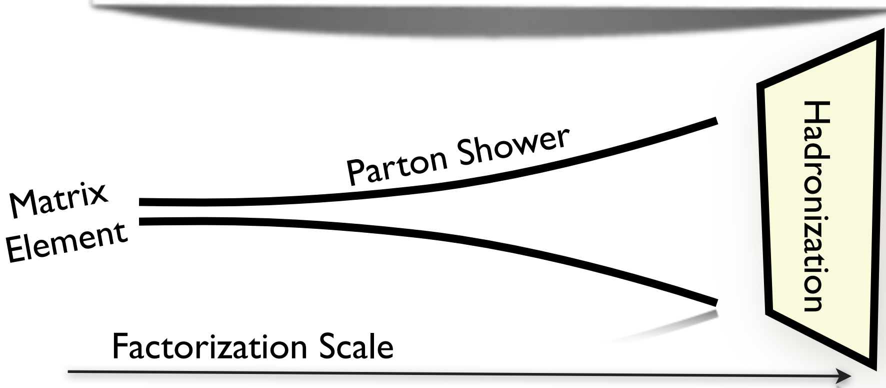

Better control of perturbative part
→ better constraints on non-perturbative part

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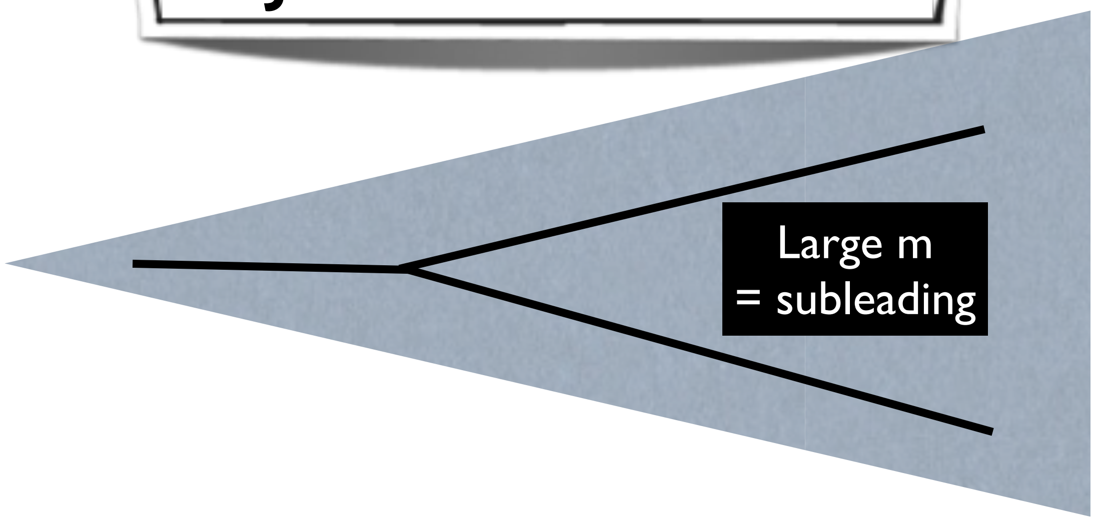

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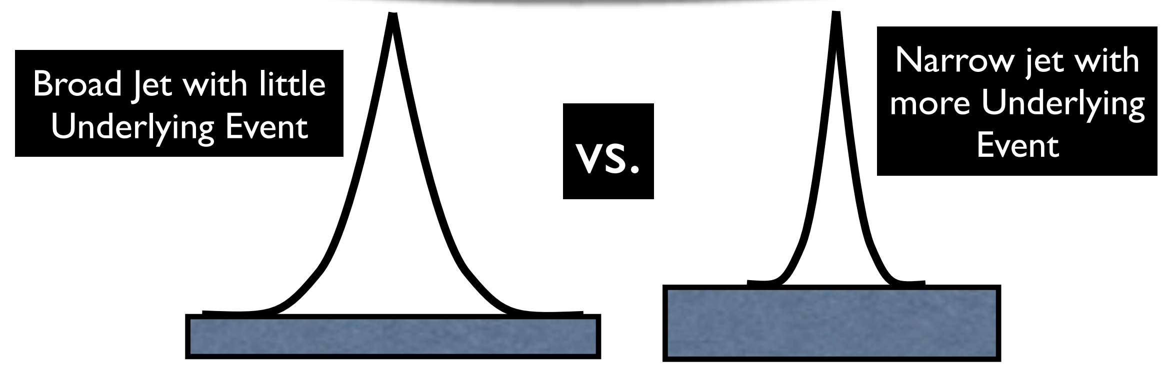

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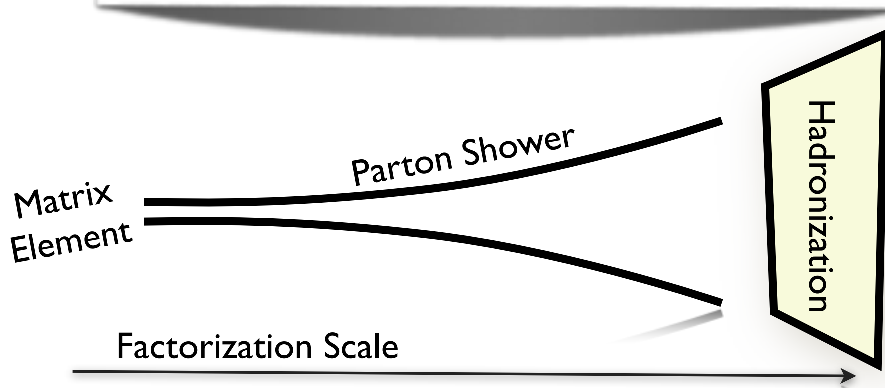

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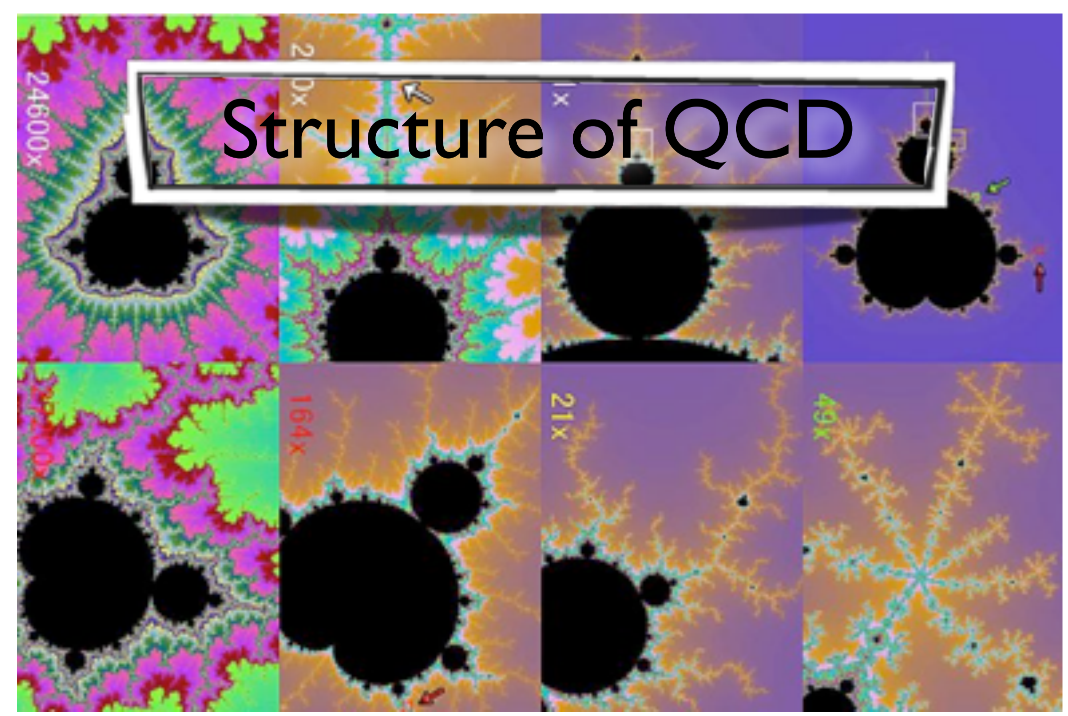

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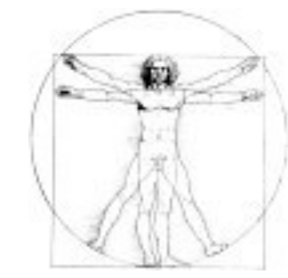

The VINCIA Code

What is it?

Plug-in to PYTHIA 8 (http://projects.hepforge.org/vincia)

What does it do?

"Matched Markov antenna showers"

Improved parton showers

+ Re-interprets tree-level matrix elements as 2→n antenna functions

+ Extends matching to soft region (no "matching scale")

Extensive *(and automated)* uncertainty estimates

Systematic variations of shower functions, evolution variables, μ_R , etc.

→ A vector of output weights for each event (central value = unity = unweighted)

Who is doing it?

GEEKS: Giele, Kosower, Skands + Gehrmann-de-Ridder & Ritzmann *(mass effects)*, Lopez-Villarejo *("sector showers")*, Hartgring & Laenen *(NLO multileg)*

pQCD with Markov Chains

Starting Point: *reformulate perturbative series as Markov Chain*

~ all-orders parton shower with all-orders matrix-element corrections

For Each "Evolution Step" = *increase in parton multiplicity (on-shell)*

Cover **all** of phase space with (large) trial overestimate = "approximate"

Compute the physical evolution probability using ...

E.g., get from MadGraph

$$\text{Matched} = \text{Approximate}\,\frac{\text{Exact}}{\text{Approximate}}$$

→ *Must be able to compute both numerator and denominator*

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Already widely used at first order:

E.g., by PYTHIA for mass and ME corrections,

and by POWHEG for virtual ones

Also similar to GenEva?

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→ **One single unweighted event sample** *(Effectively, n-parton samples use parton shower itself as phase space generator = highly efficient "multi-channel" integration → speed gains expected, + unitarity → unit-weights)*

The Denominator

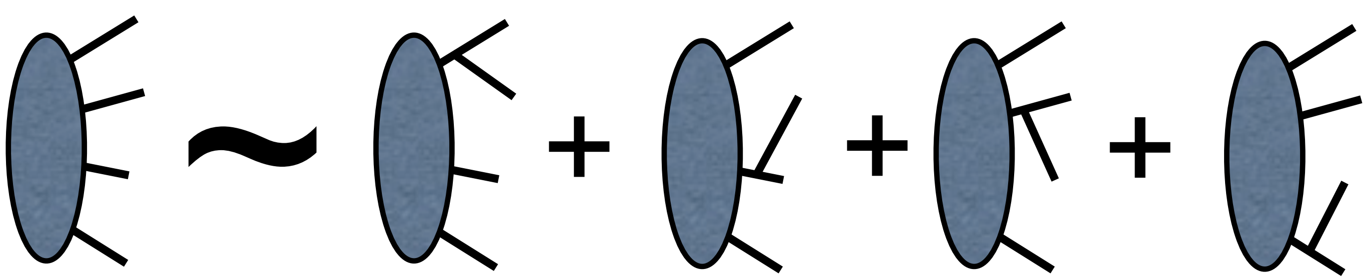
$$\text{Matched} = \text{Approximate}\frac{\text{Exact}}{\text{Approximate}}$$

Number of Histories:

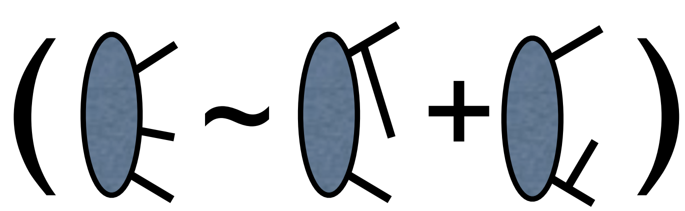
Existing parton showers are *not* really Markov Chains

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

Number of histories contributing to n^{th} branching $\propto$ **$2^n n!$**



j = 2
→ 4 terms



j = 1
→ 2 terms

The Denominator

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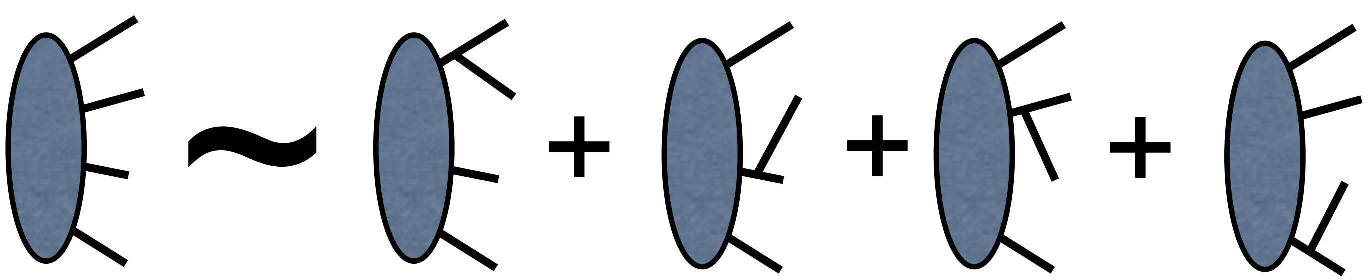

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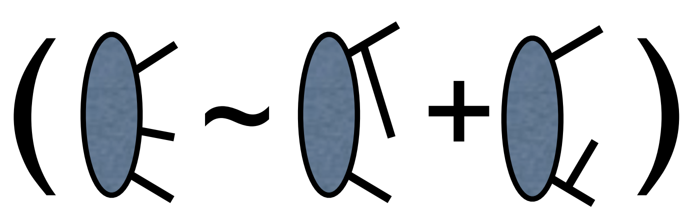


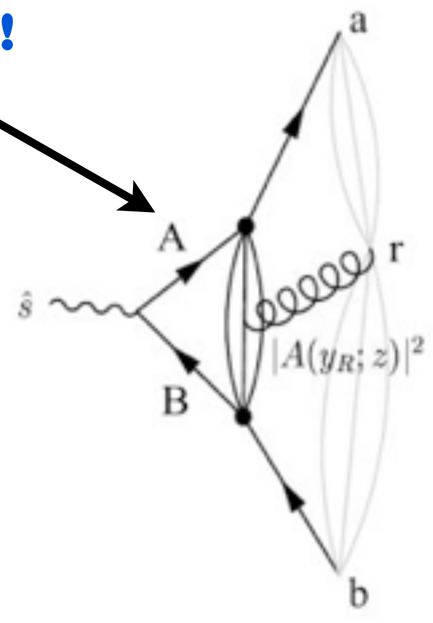
j = 1
→ 2 terms

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

Matched Markovian Antenna Showers

Parton and CS showers: $2^n n!$
One term per parton (two for gluons)

Antenna showers: $2^n n! \to n!$
One term per parton *pair*



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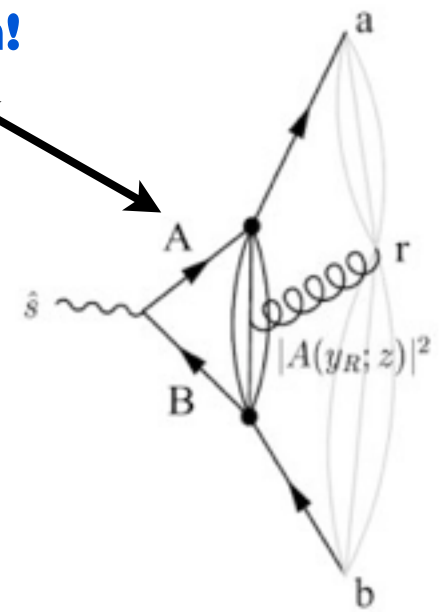

+ Change "shower restart" to Markov criterion:

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: $n! \to n$

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

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

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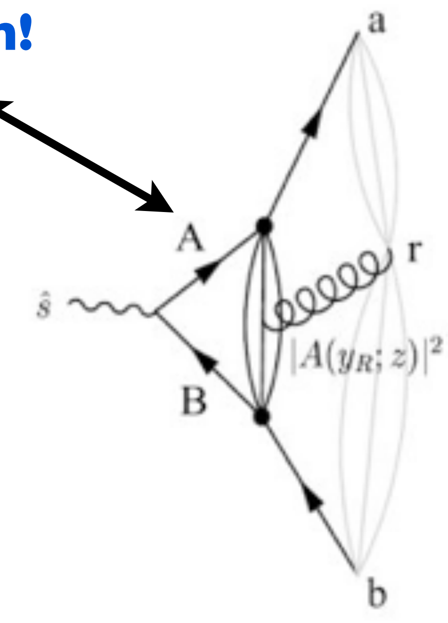

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After 2 branchings: 2 terms
After 3 branchings: 3 terms
After 4 branchings: 4 terms

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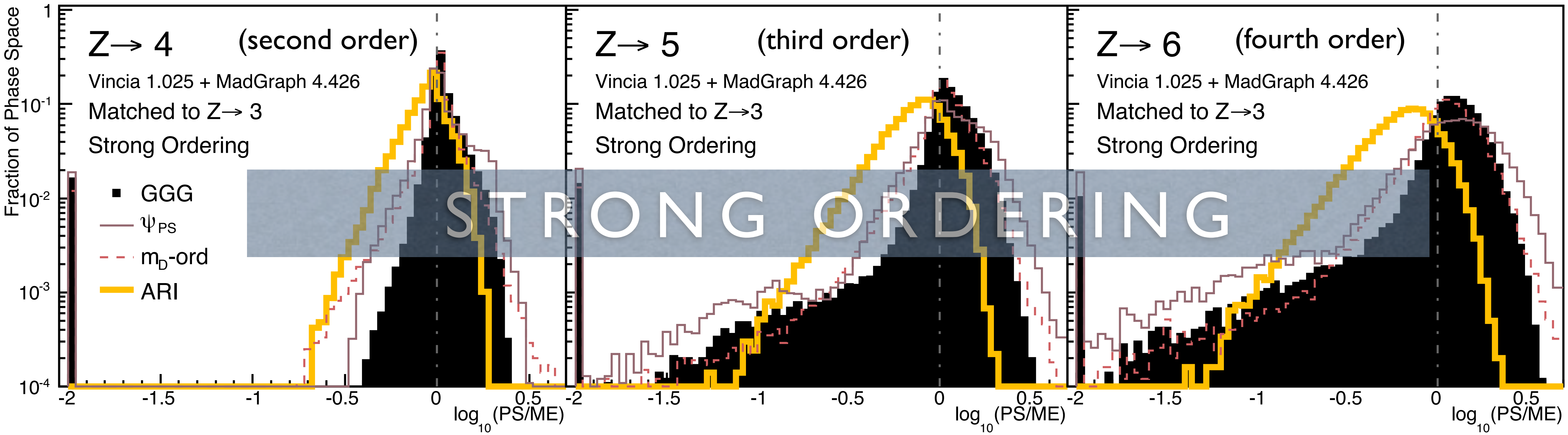
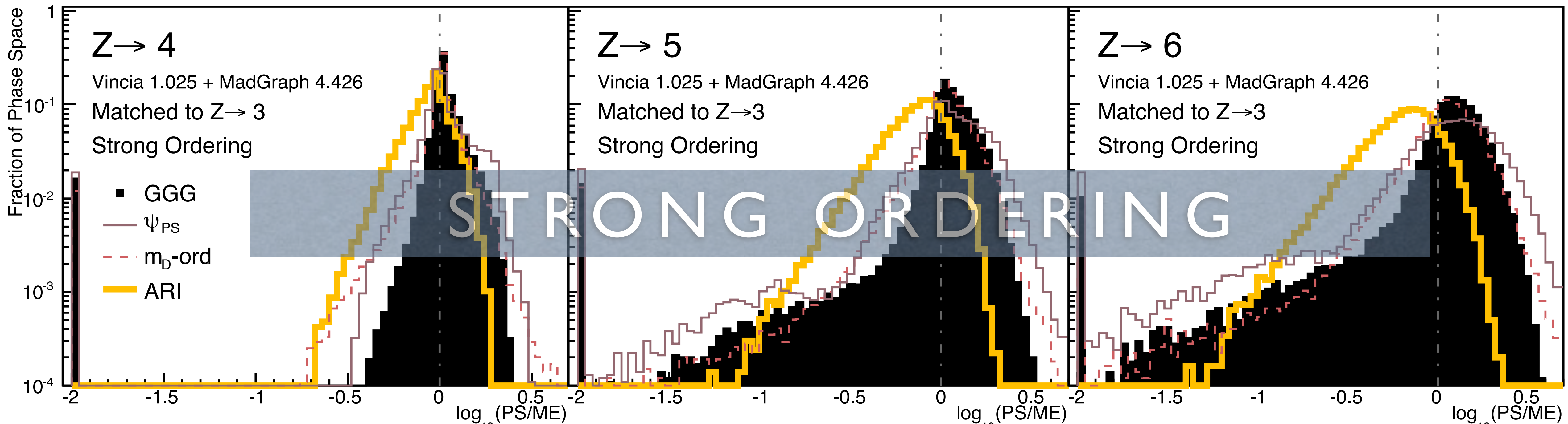
Approximations

Distribution of **$\mathrm{Log}_{10}(\mathrm{PS}_{LO}/\mathrm{ME}_{LO})$** (inverse ~ matching coefficient)

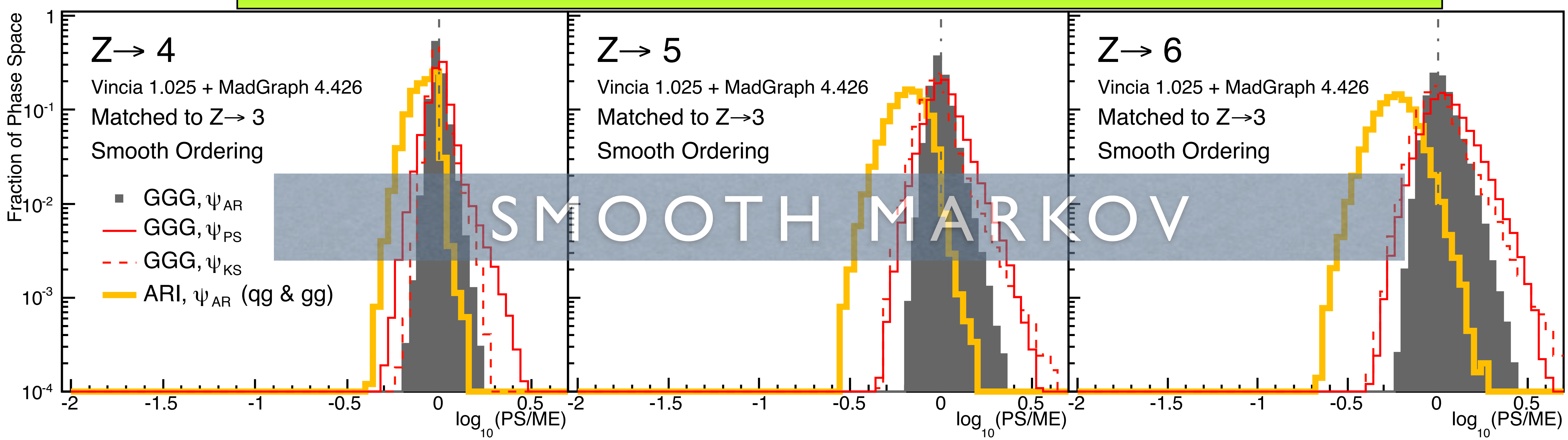


→ Better Approximations

Distribution of **Log10(PSLO/MELO)** (inverse ~ matching coefficient)

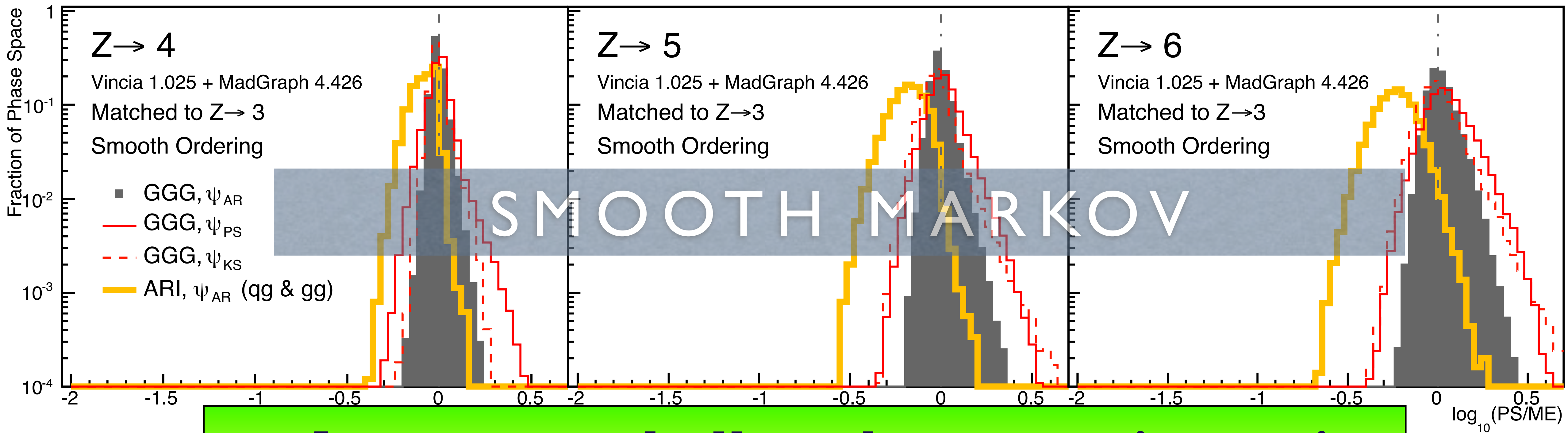


Leading Order, Leading Color, Flat phase-space scan, over **all of phase space** (no matching scale)

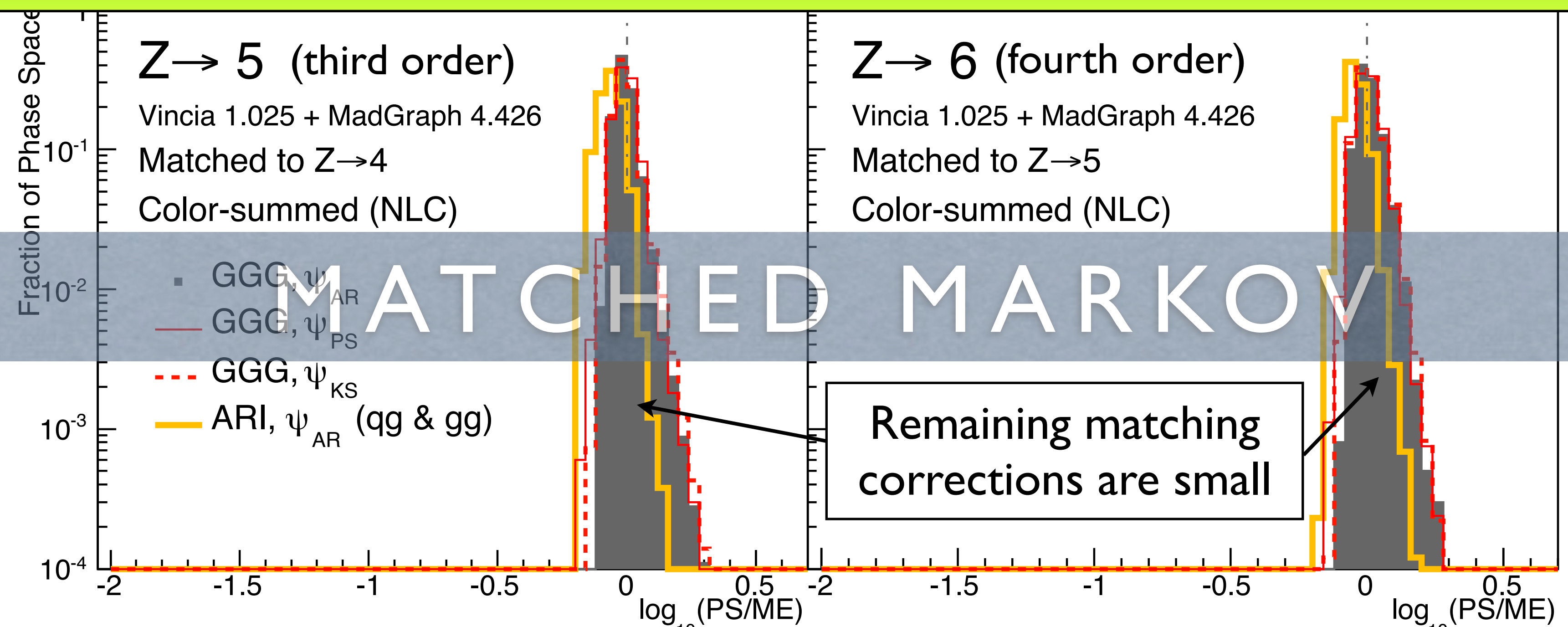


GEEKS (Giele, Kosower, Skands): arXiv:1102.2126

+ Matching (+ full colour)



→ A very good all-orders starting point



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(Speed)

Matched through:	$Z\to 3$	$Z\to 4$	$Z\to 5$	$Z\to 6$
Pythia 6 *(initialization time = zero)*	0.19	ms/event $Z\to qq$ + shower. Matched and unweighted. **Hadronization off** *gfortran/g++ with gcc v.4.4 -O2 on single 3.06 GHz processor with 4GB memory*		
Pythia 8 *(initialization time = zero)*	0.20			
Vincia *(initialization time = zero)*	0.24	0.62	5.60	112.50
Sherpa *(Q_{match} = 5 GeV)* * + *initialization time*	5.15* 90,000 ms	53.00* 420,000 ms	220.00* 1,320,000 ms	400.00* 7,920,000 ms

Generator Versions: Pythia 6.425 *(with Perugia 2011 tune)*, Pythia 8.150, Sherpa 1.3.0 *(*not including initialization)*, Vincia 1.026 *(NLL,NLC, and uncertainties OFF)*

(+ working with J. Lopez-Villarejo at CERN to further increase multi-parton matching speed)


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

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Automate and do everything in one run

VINCIA: all events have weight = 1

GEEKS (Giele, Kosower, Skands): arXiv:1102.2126

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-colour treatments

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

Uncertainties

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+ Unitarity

For each *failed* branching:

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

Uncertainties

For each branching, recompute weight for:

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	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…)

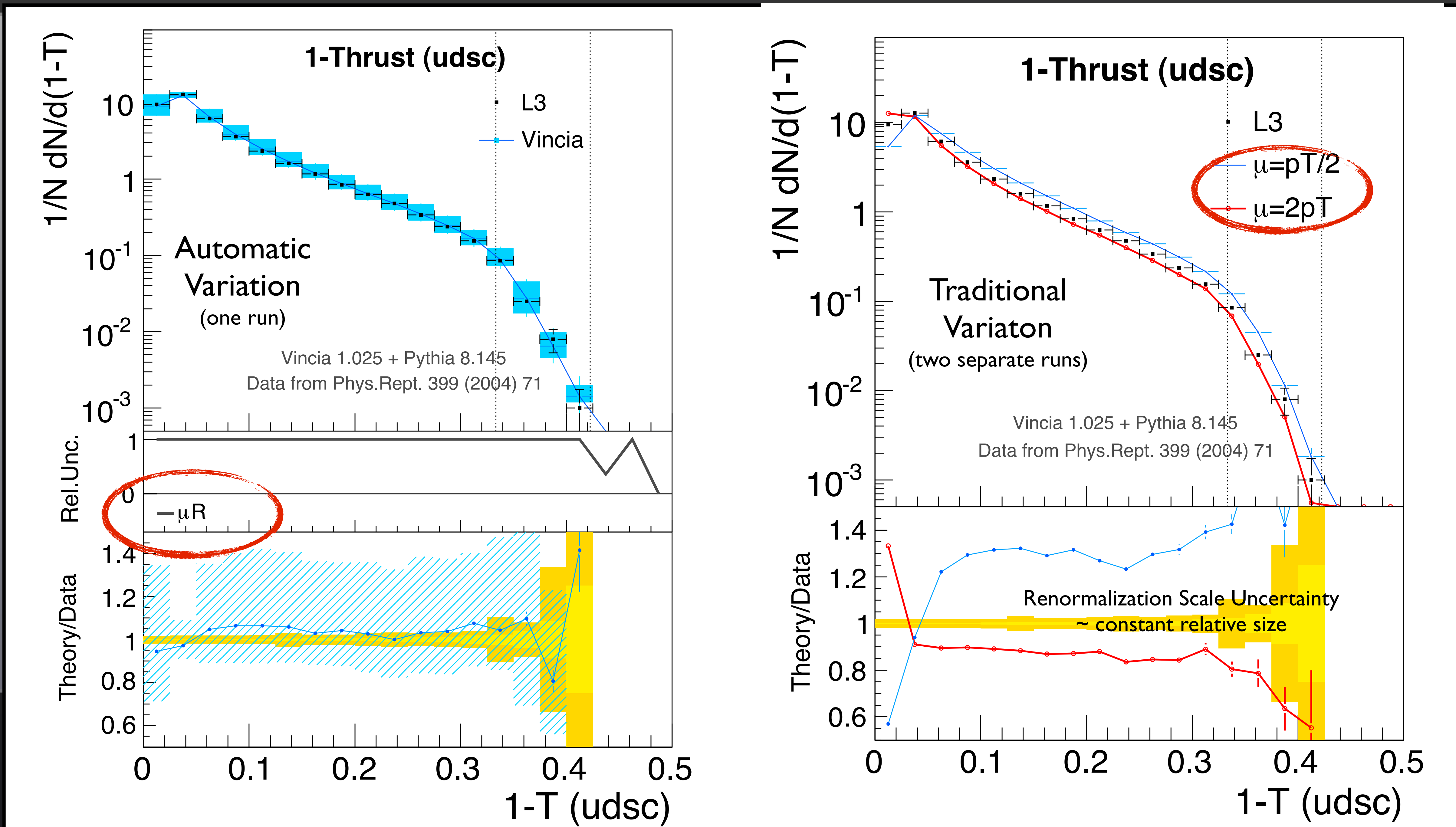
+ Unitarity

For each *failed* branching:

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

Automatic Uncertainties

Vincia:uncertaintyBands = on



Variation of renormalization scale (no matching)

Automatic Uncertainties

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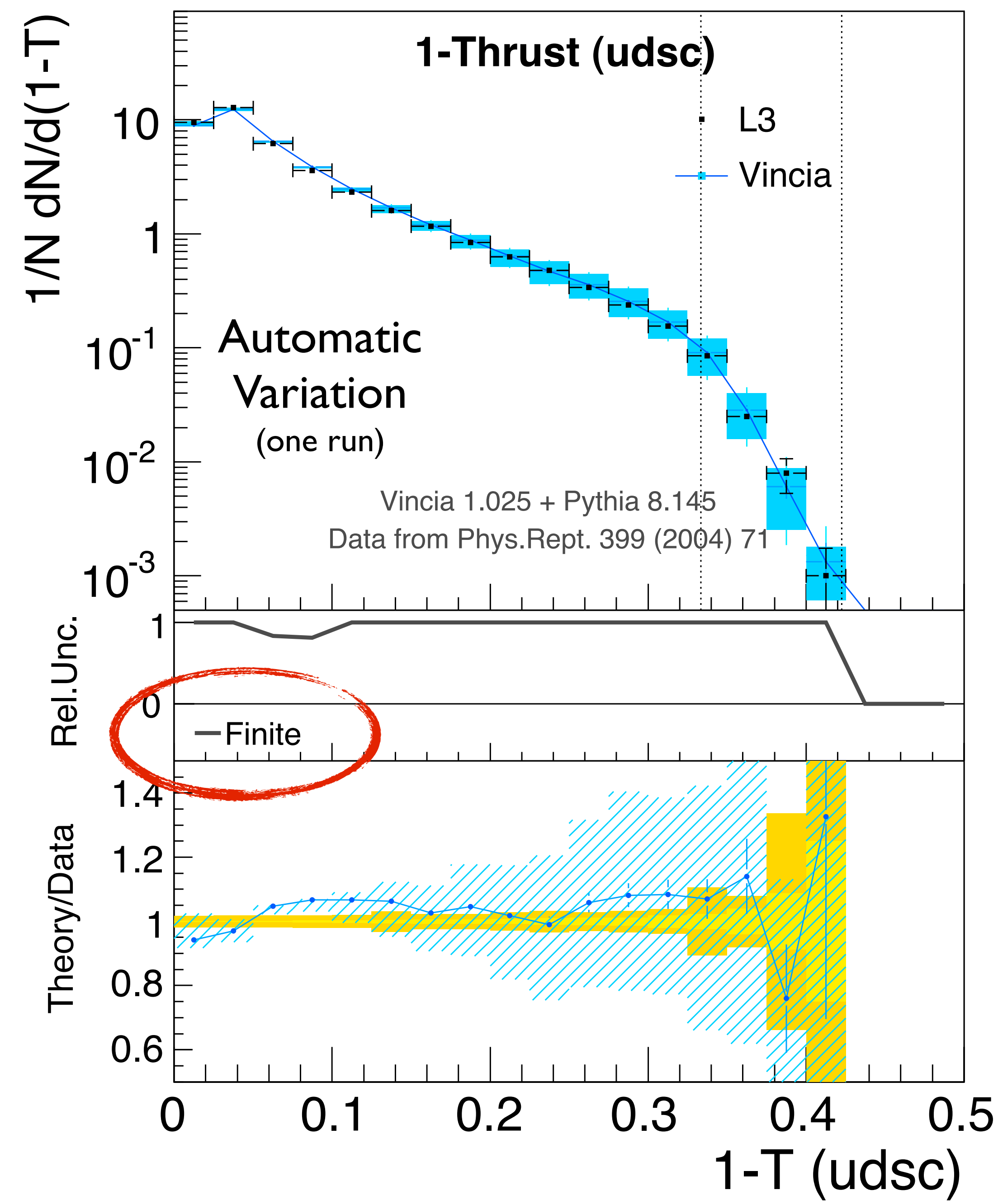
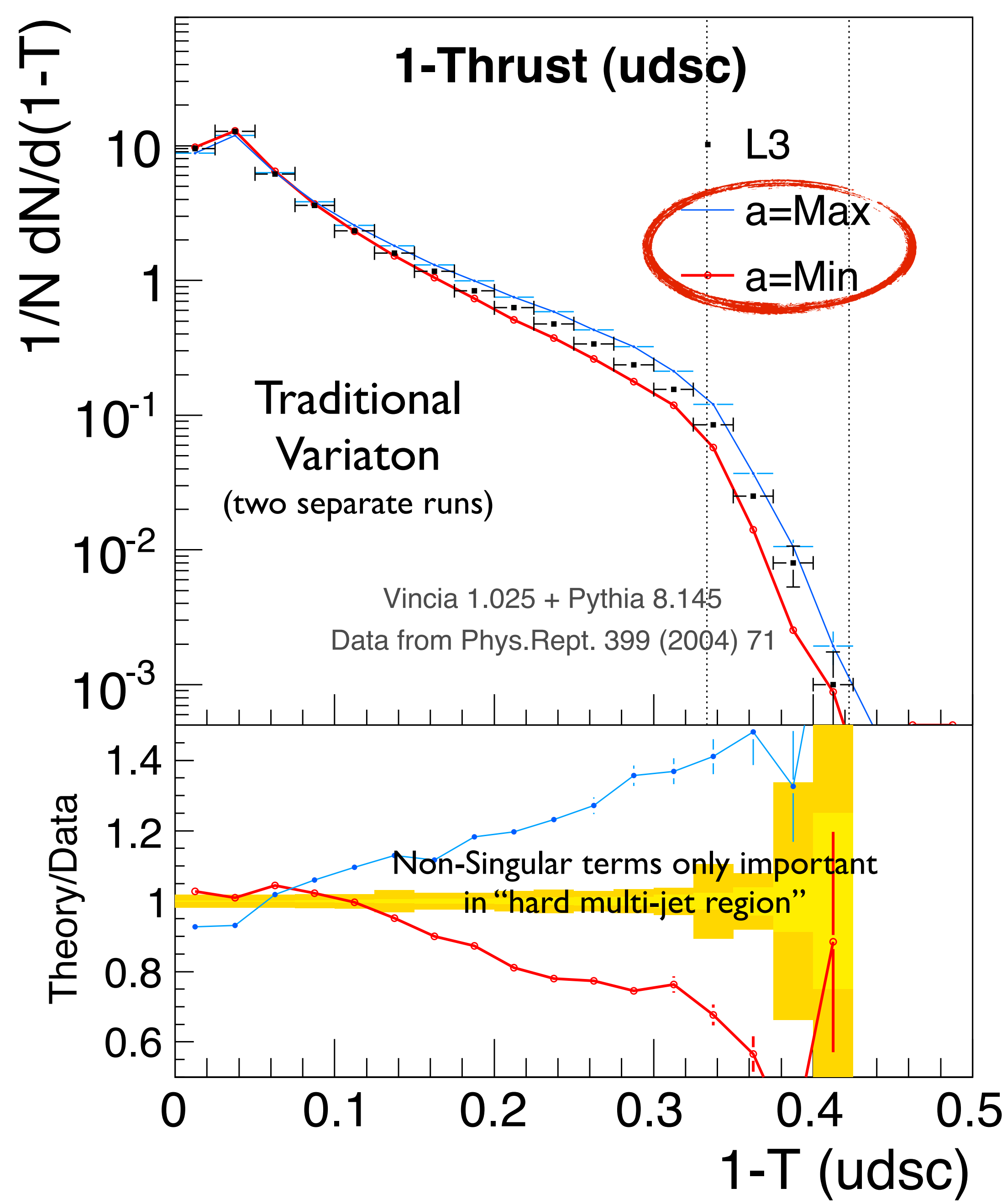
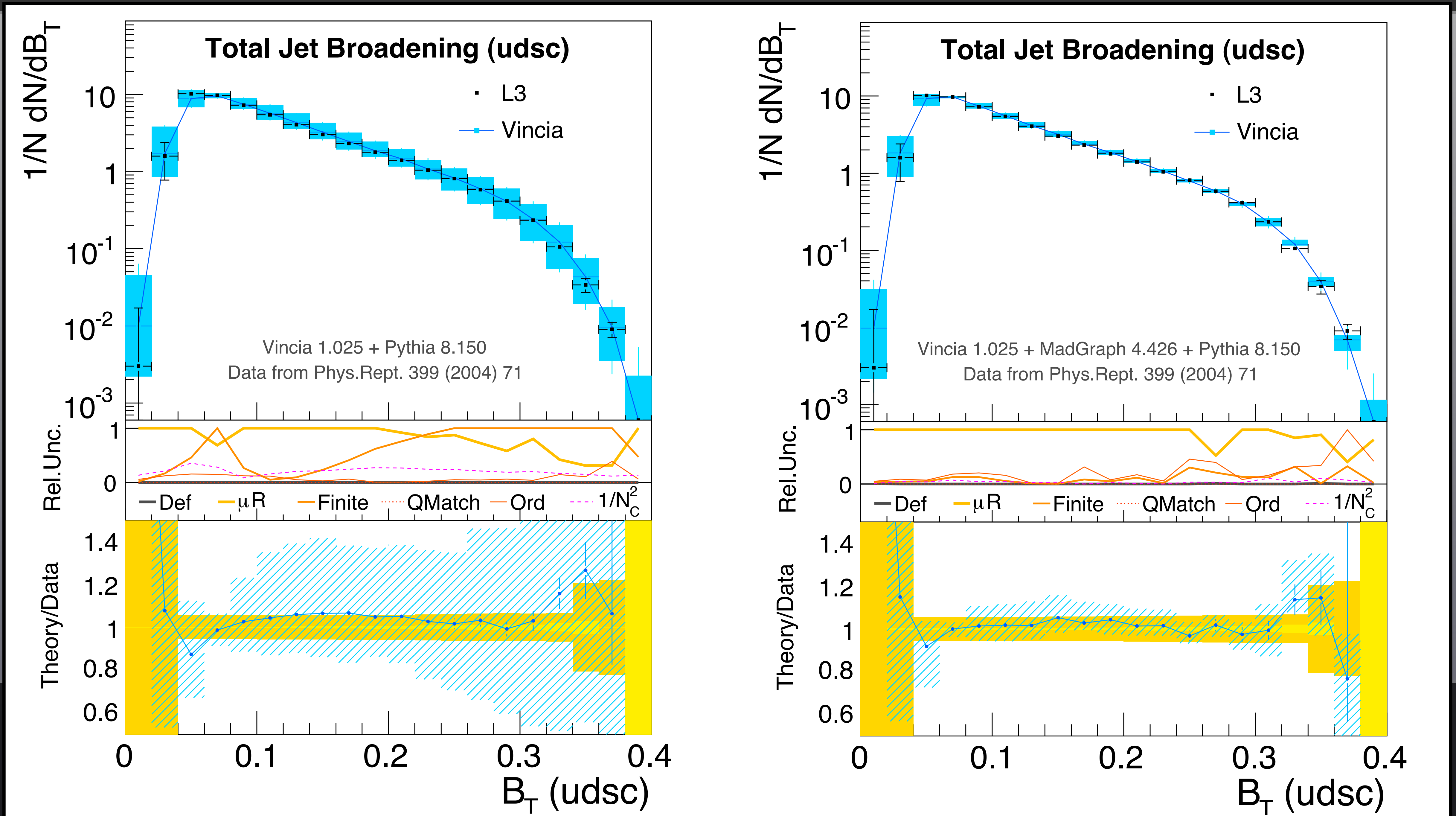


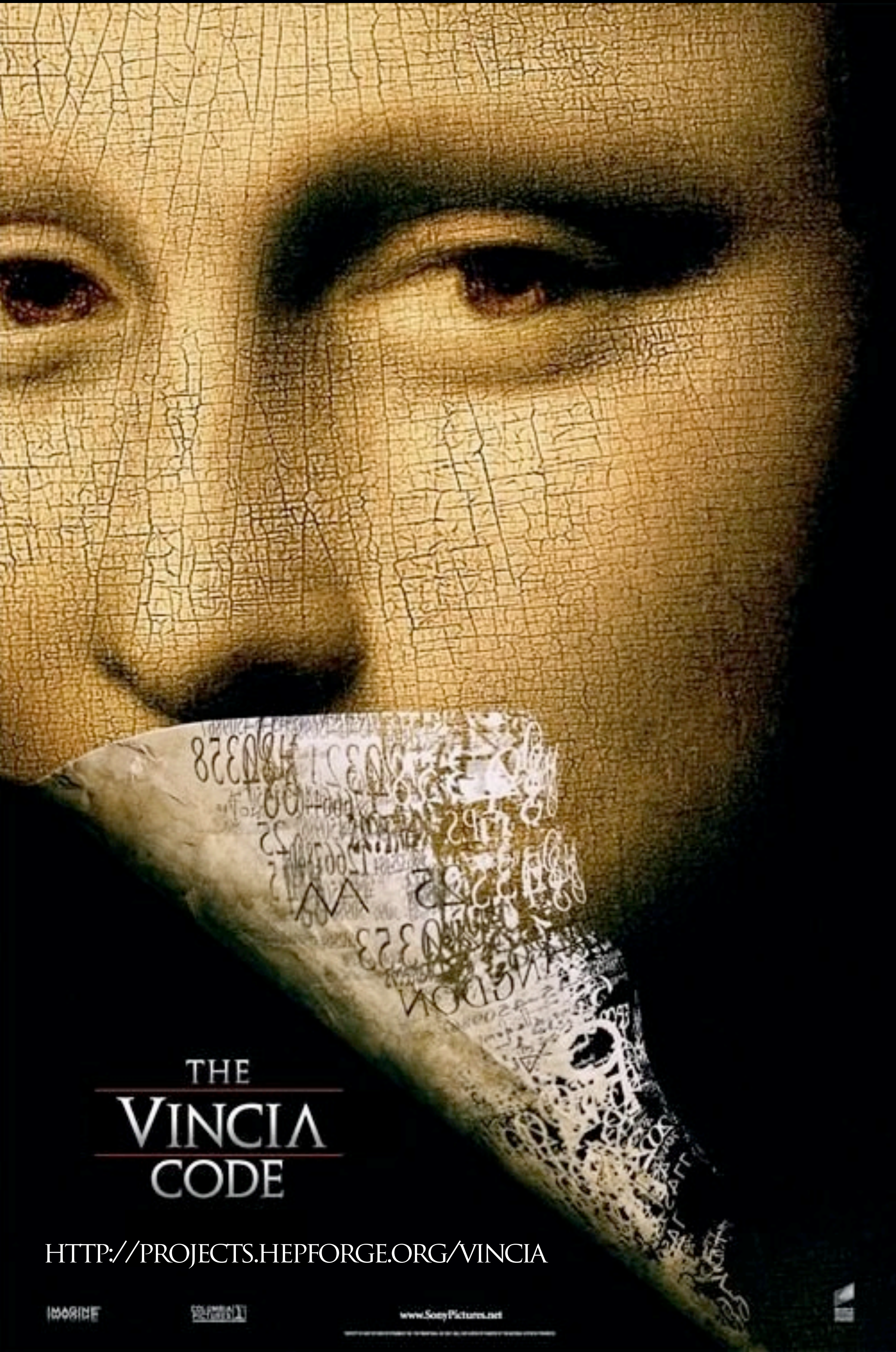


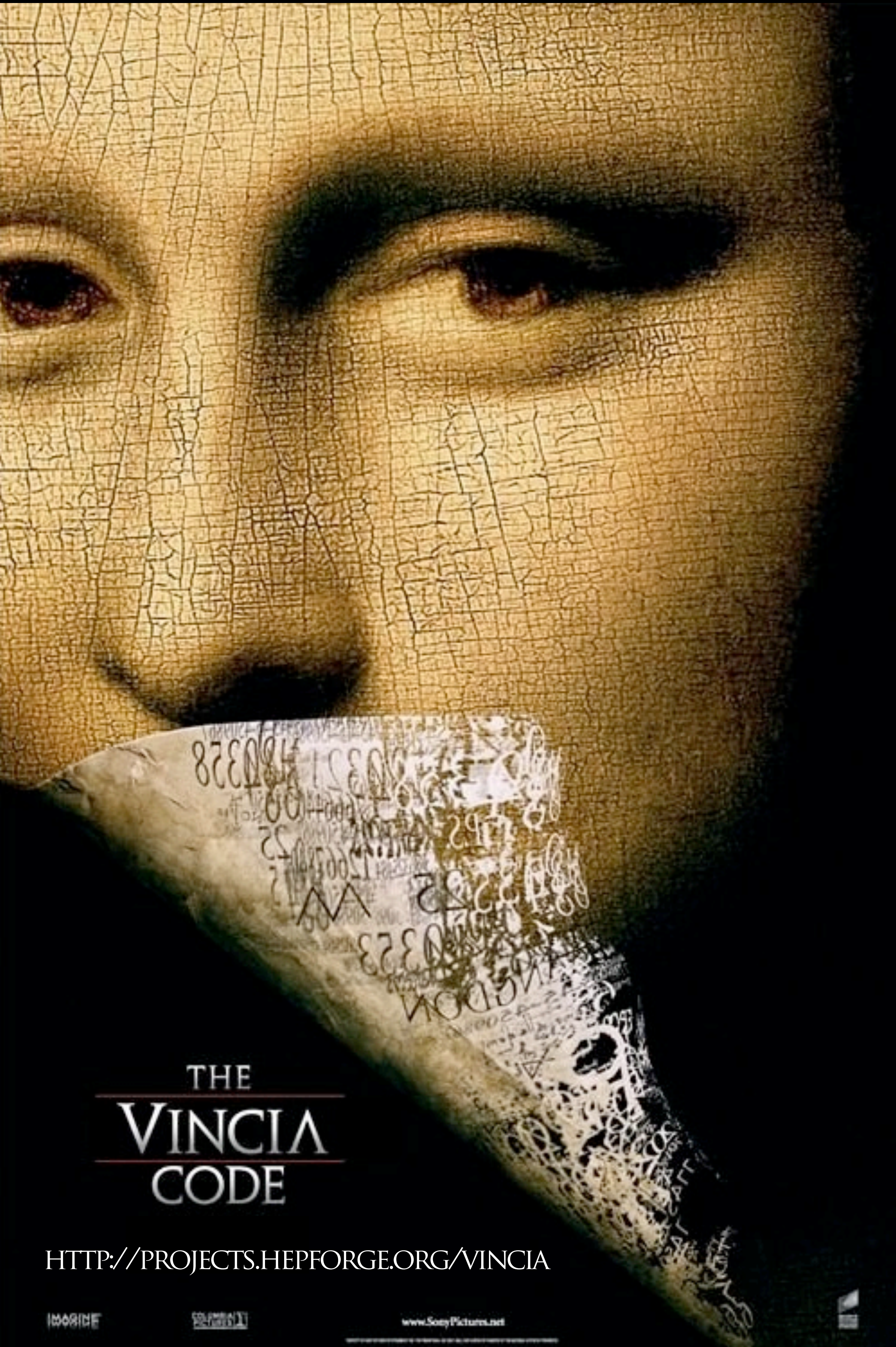
Variation of "finite terms" (no matching)

Putting it Together

VinciaMatching:order = 0 VinciaMatching:order = 3




THE
VINCIA
CODE
HTTP://PROJECTS.HEPFORGE.ORG/VINCIA
www.SonyPictures.net



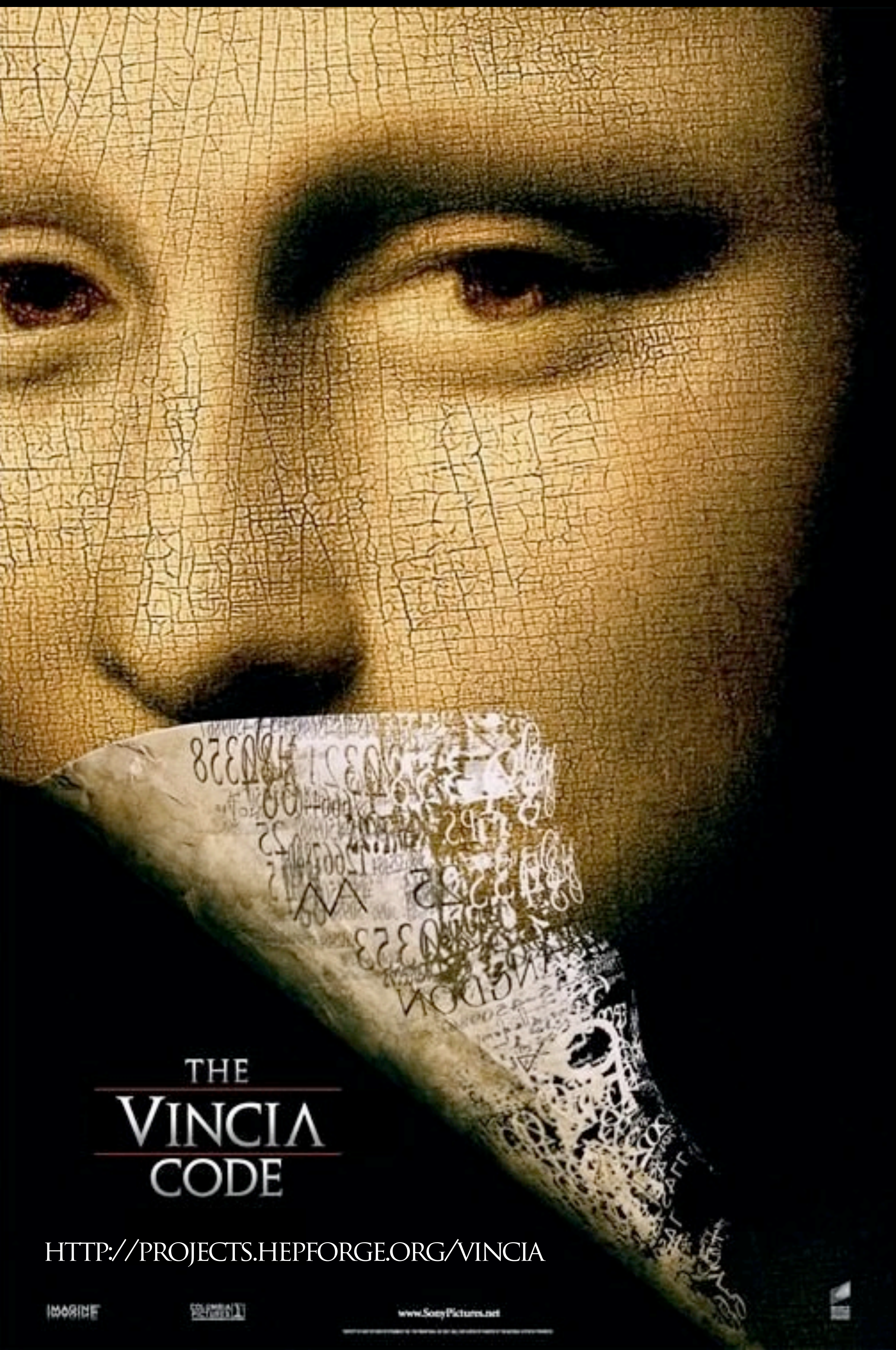
GEEKS (Giele, Kosower, Skands): arXiv:1102.2126

VINCIA Status

- Plug-in to PYTHIA 8
- Stable and reliable for Final-State Jets (e.g., LEP)
  - Automatic matching and uncertainty bands
  - improvements in shower (smooth ordering, NLC, Matching, …)
- Paper on mass effects ~ ready (with A. Gehrmann-de-Ridder & M. Ritzmann)

Next steps

- Multi-leg one-loop matching (with L. Hartgring & E. Laenen, NIKHEF)
- "Sector Showers" (with J. Lopez-Villarejo, CERN)
- → Initial-State Showers (with W. Giele, D. Kosower)



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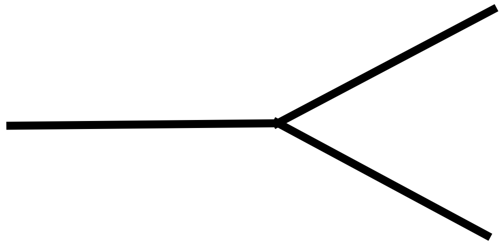
Backup Slides

pQCD as Markov Chain

Start from Born Level:



Born-Level Phase Space

Born-Level Matrix Element

On-Shell Momentum Configuration

$$\left.\frac{\mathrm{d}\sigma_H}{\mathrm{d}\mathcal{O}}\right|_{\mathrm{Born}} = \int \mathrm{d}\Phi_H \; |M_H^{(0)}|^2 \; \delta(\mathcal{O} - \mathcal{O}(\{p\}_H))$$

H = Arbitrary hard process

pQCD as Markov Chain

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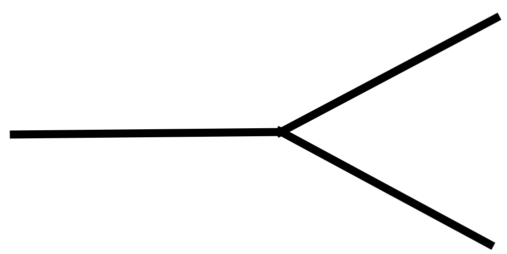

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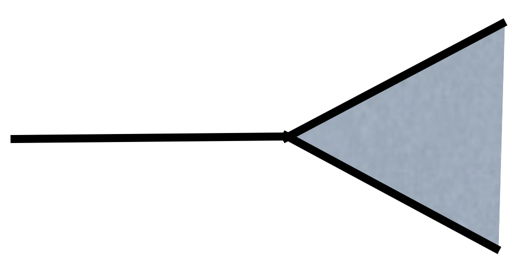
Born-Level Matrix Element
On-Shell Momentum Configuration

$$\left.\frac{\mathrm{d}\sigma_H}{\mathrm{d}\mathcal{O}}\right|_{\mathrm{Born}} = \int \mathrm{d}\Phi_H\ |M_H^{(0)}|^2\ \delta(\mathcal{O} - \mathcal{O}(\{p\}_H))$$

H = Arbitrary hard process

Insert Evolution Operator, *S*:

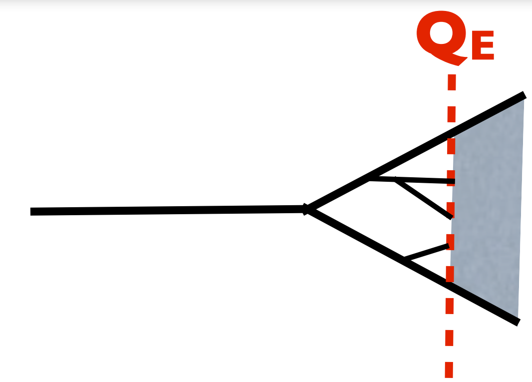


Evolution operator

$$\left.\frac{\mathrm{d}\sigma_H}{\mathrm{d}\mathcal{O}}\right|_{\mathcal{S}} = \int \mathrm{d}\Phi_H\ |M_H^{(0)}|^2\ \mathcal{S}(\{p\}_H, \mathcal{O})$$

Think: starting a shower off an incoming on-shell momentum configuration
Postpone evaluating observable until shower "finished"

The Evolution Operator



Depends on Evolution Scale : Q_E

No-evolution Probability

$$\mathcal{S}(\{p\}_H, s, Q_E^2, \mathcal{O}) = \underbrace{\Delta(\{p\}_H, s, Q_E^2)\, \delta\left(\mathcal{O} - \mathcal{O}(\{p\}_H)\right)}_{H+0 \text{ exclusive above } Q_E}$$

"Corrected" Radiation Functions

Continue Markov Chain off H+1

$$+ \underbrace{\sum_r \int_{Q_E^2}^{s} \frac{\mathrm{d}\Phi_{H+1}^{[r]}}{\mathrm{d}\Phi_H}\, S_r\, \Delta(\{p\}_H, s, Q_{H+1}^2)\, \mathcal{S}(\{p\}_{H+1}, Q_{H+1}^2, Q_E^2, \mathcal{O})}_{H+1 \text{ inclusive above } Q_E}$$

Sum over radiators

Exact Phase Space Factorization

Legend:

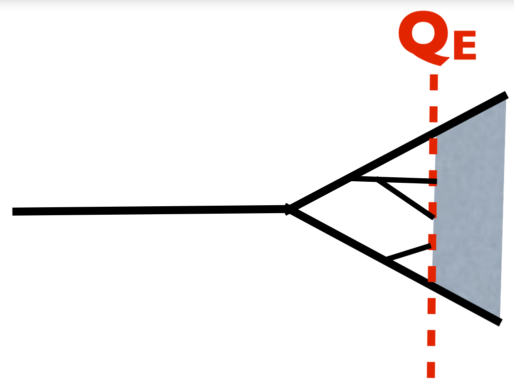
Δ represents *no-evolution* probability (Sudakov): conserves probability = preserves event weights

S_r = Emission probability (partitioned among radiators r)

According to best known approximation to |H+1|² (e.g., ME or LL shower)

The Evolution Operator

Depends on Evolution Scale : Q_E



No-evolution Probability

$$\mathcal{S}(\{p\}_H, s, Q_E^2, \mathcal{O}) = \underbrace{\Delta(\{p\}_H, s, Q_E^2)\, \delta\left(\mathcal{O} - \mathcal{O}(\{p\}_H)\right)}_{H + 0 \text{ exclusive above } Q_E}$$

"Corrected" Radiation Functions

Continue Markov Chain off H+1

$$+ \underbrace{\sum_r \int_{Q_E^2}^{s} \frac{\mathrm{d}\Phi_{H+1}^{[r]}}{\mathrm{d}\Phi_H}\, S_r\, \Delta(\{p\}_H, s, Q_{H+1}^2)\, \mathcal{S}(\{p\}_{H+1}, Q_{H+1}^2, Q_E^2, \mathcal{O})}_{H + 1 \text{ inclusive above } Q_E}$$

Sum over radiators

Exact Phase Space Factorization

Legend:

Δ represents *no-evolution* probability (Sudakov): conserves probability = preserves event weights

S_r = Emission probability (partitioned among radiators r)

According to <u>best known approximation</u> to $|H+1|^2$ (e.g., ME or LL shower)

(Expand S to First Order)

Equivalent to Sjöstrand/POWHEG

"NLO" virtual correction

Sudakov Expansion

$$\mathcal{S}^{(1)}(\{p\}_H, s, Q_E^2, \mathcal{O}) \quad = \quad \left(1 + K_H^{(1)} - \int_{Q_E^2}^{s} \frac{\mathrm{d}\Phi_{H+1}}{\mathrm{d}\Phi_H} \frac{|M_{H+1}^{(0)}|^2}{|M_H^{(0)}|^2}\right) \delta(\mathcal{O} - \mathcal{O}(\{p\}_H))$$

Unitarity

$$+ \int_{Q_E^2}^{s} \frac{\mathrm{d}\Phi_{H+1}}{\mathrm{d}\Phi_H} \frac{|M_{H+1}^{(0)}|^2}{|M_H^{(0)}|^2} \delta(\mathcal{O} - \mathcal{O}(\{p\}_{H+1})) \; .$$

Torbjörn's trick

Virtual Correction (NLO normalization)

$$\underbrace{\frac{2\mathrm{Re}[M_H^{(0)} M_H^{(1)*}]}{|M_H^{(0)}|^2}}_{\frac{a}{\epsilon^2} + \frac{b}{\epsilon} + c + \mathcal{O}(\epsilon)} = K_H^{(1)} - \underbrace{\int_0^s \frac{\mathrm{d}\Phi_{H+1}}{\mathrm{d}\Phi_H} \frac{|M_{H+1}^{(0)}|^2}{|M_H^{(0)}|^2}}_{\frac{a}{\epsilon^2} + \frac{b}{\epsilon} + c' + \mathcal{O}(\epsilon)}$$

$c - c'$

(Expand S to First Order)

Equivalent to Sjöstrand/POWHEG

“NLO” virtual correction

Sudakov Expansion

$$\mathcal{S}^{(1)}(\{p\}_H, s, Q_E^2, \mathcal{O}) \;=\; \left(1 + \boxed{K_H^{(1)}} - \int_{Q_E^2}^{s} \frac{\mathrm{d}\Phi_{H+1}}{\mathrm{d}\Phi_H}\frac{|M_{H+1}^{(0)}|^2}{|M_H^{(0)}|^2}\right)\delta(\mathcal{O}-\mathcal{O}(\{p\}_H))$$

Unitarity

$$+\int_{Q_E^2}^{s} \frac{\mathrm{d}\Phi_{H+1}}{\mathrm{d}\Phi_H}\frac{|M_{H+1}^{(0)}|^2}{|M_H^{(0)}|^2}\delta(\mathcal{O}-\mathcal{O}(\{p\}_{H+1}))\;.$$

Torbjörn’s trick

Virtual Correction (NLO normalization)

$$\underbrace{\frac{2\mathrm{Re}[M_H^{(0)}M_H^{(1)*}]}{|M_H^{(0)}|^2}}_{\frac{a}{\epsilon^2}+\frac{b}{\epsilon}+c+\mathcal{O}(\epsilon)} = \boxed{K_H^{(1)}} - \underbrace{\int_0^{s} \frac{\mathrm{d}\Phi_{H+1}}{\mathrm{d}\Phi_H}\frac{|M_{H+1}^{(0)}|^2}{|M_H^{(0)}|^2}}_{\frac{a}{\epsilon^2}+\frac{b}{\epsilon}+c'+\mathcal{O}(\epsilon)}$$

$c - c'$

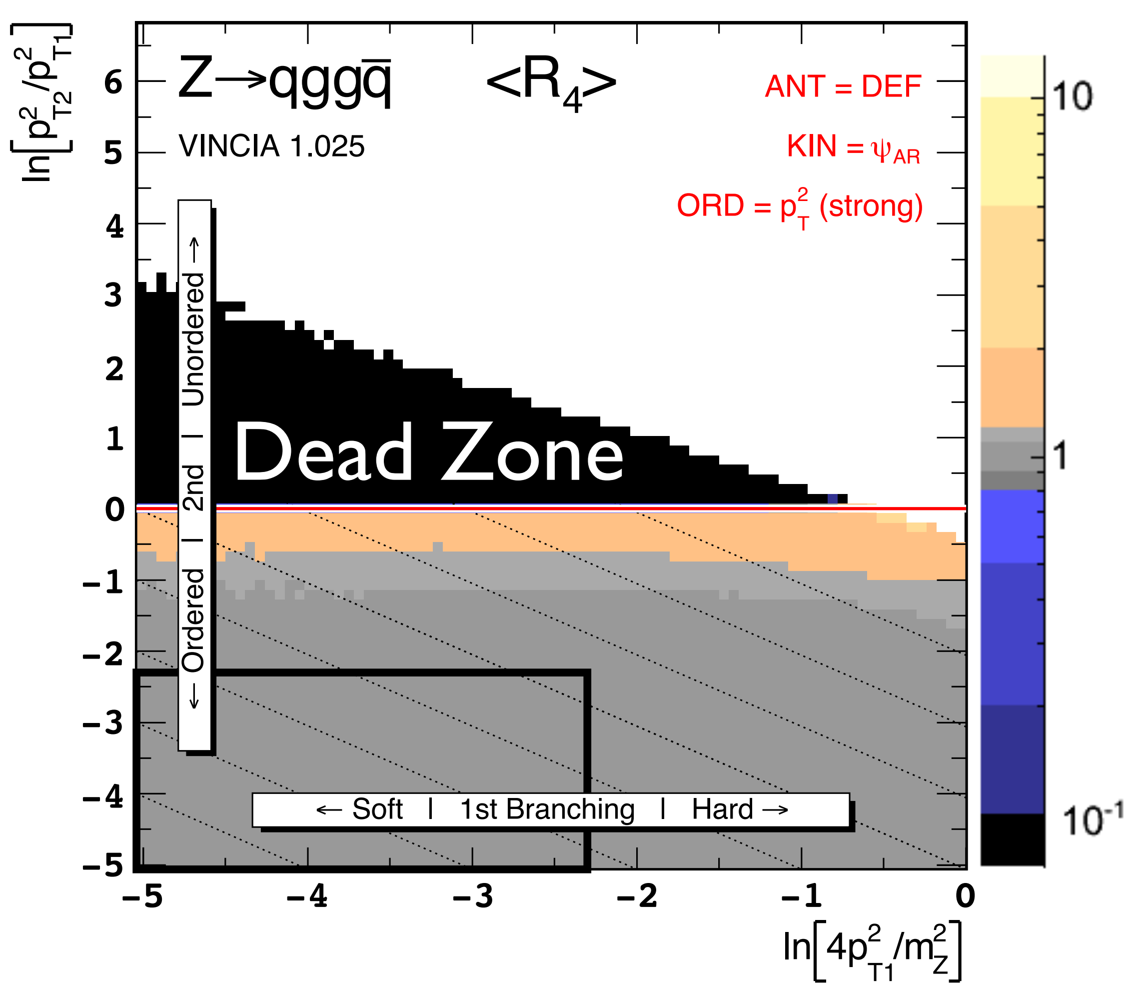
Simple Solution

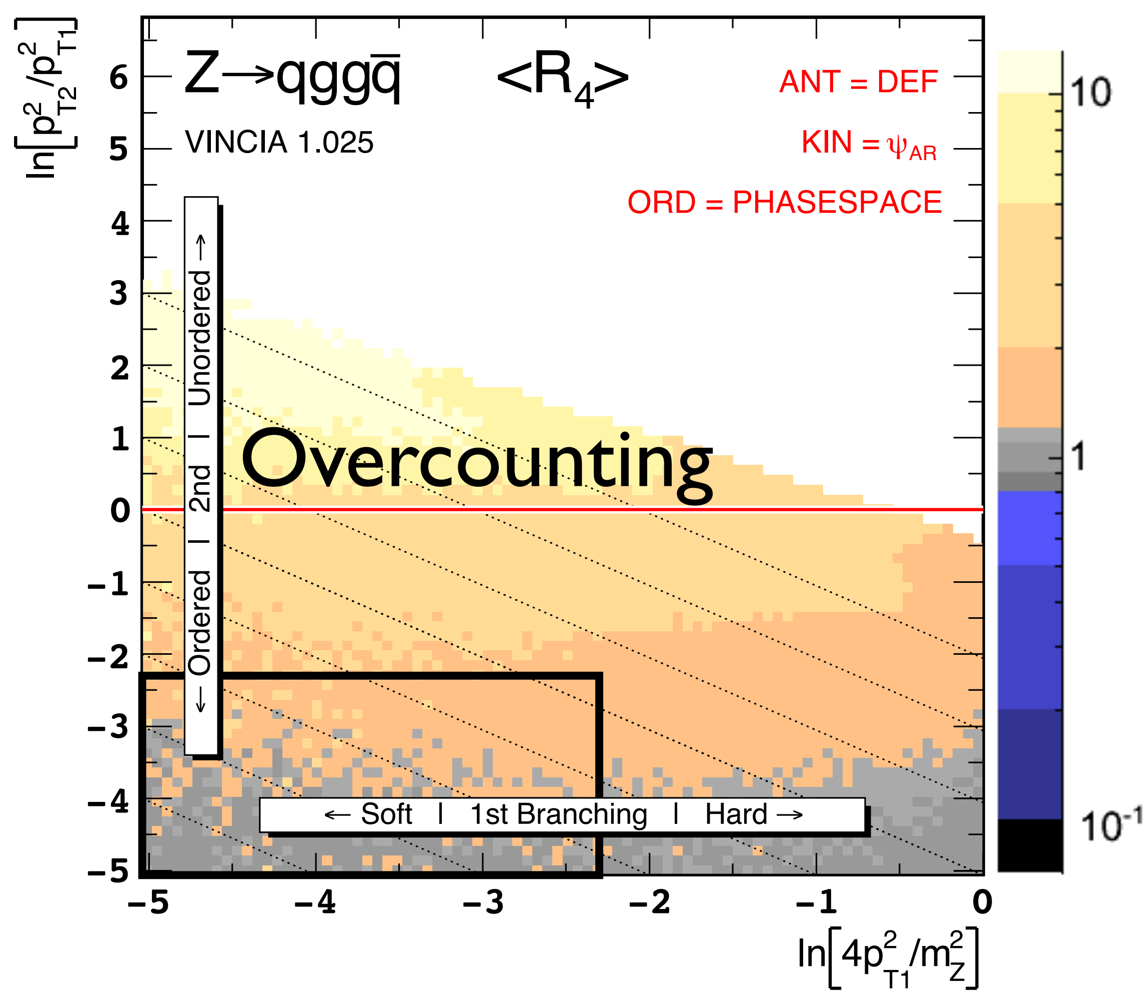
Generate Trials *without* imposing strong ordering

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

Overcounting removed by matching

(revert to strong ordering beyond matched multiplicities)





Better Solution

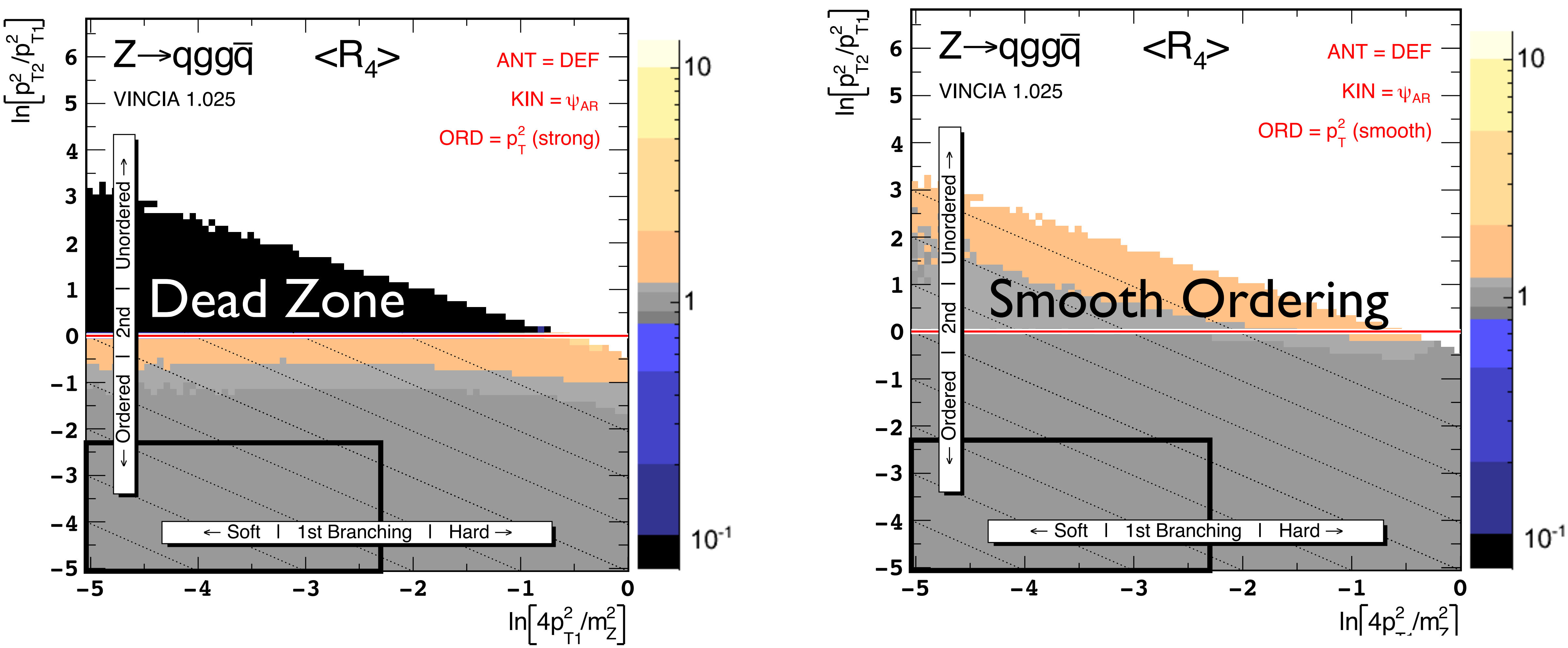
Generate Trials *without* imposing strong ordering

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

Overcounting removed by matching

+ smooth ordering beyond matched multiplicities

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

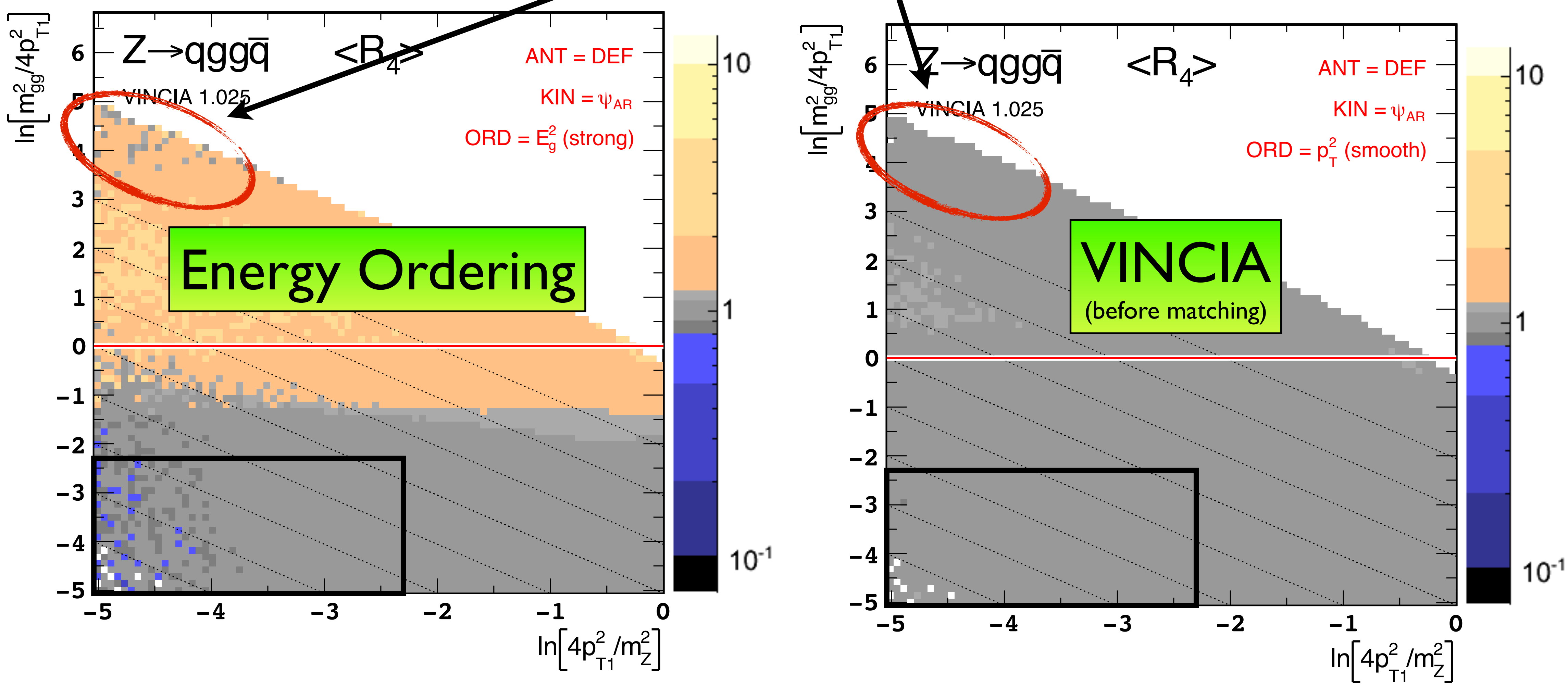


(Subleading Singularities)

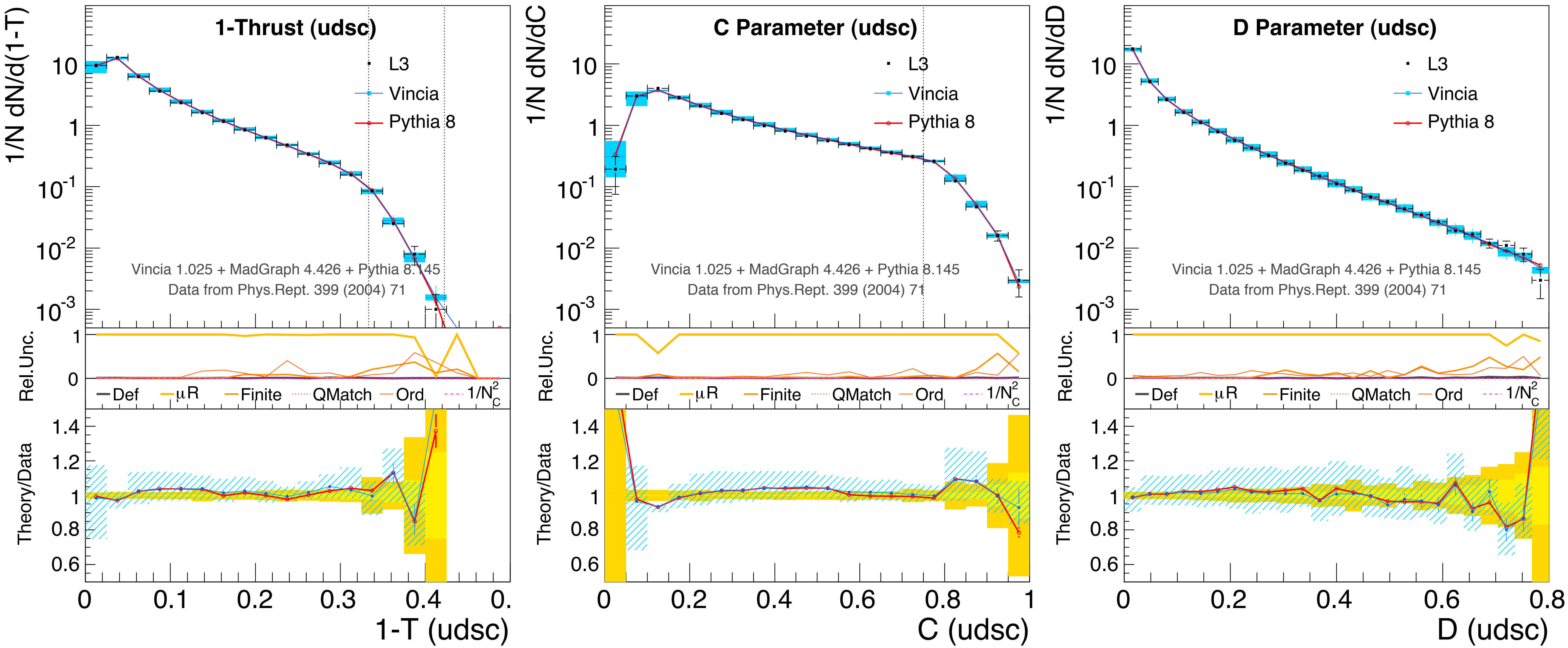
Isolate double-collinear region:

$\alpha_s^2 \ln^2$

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

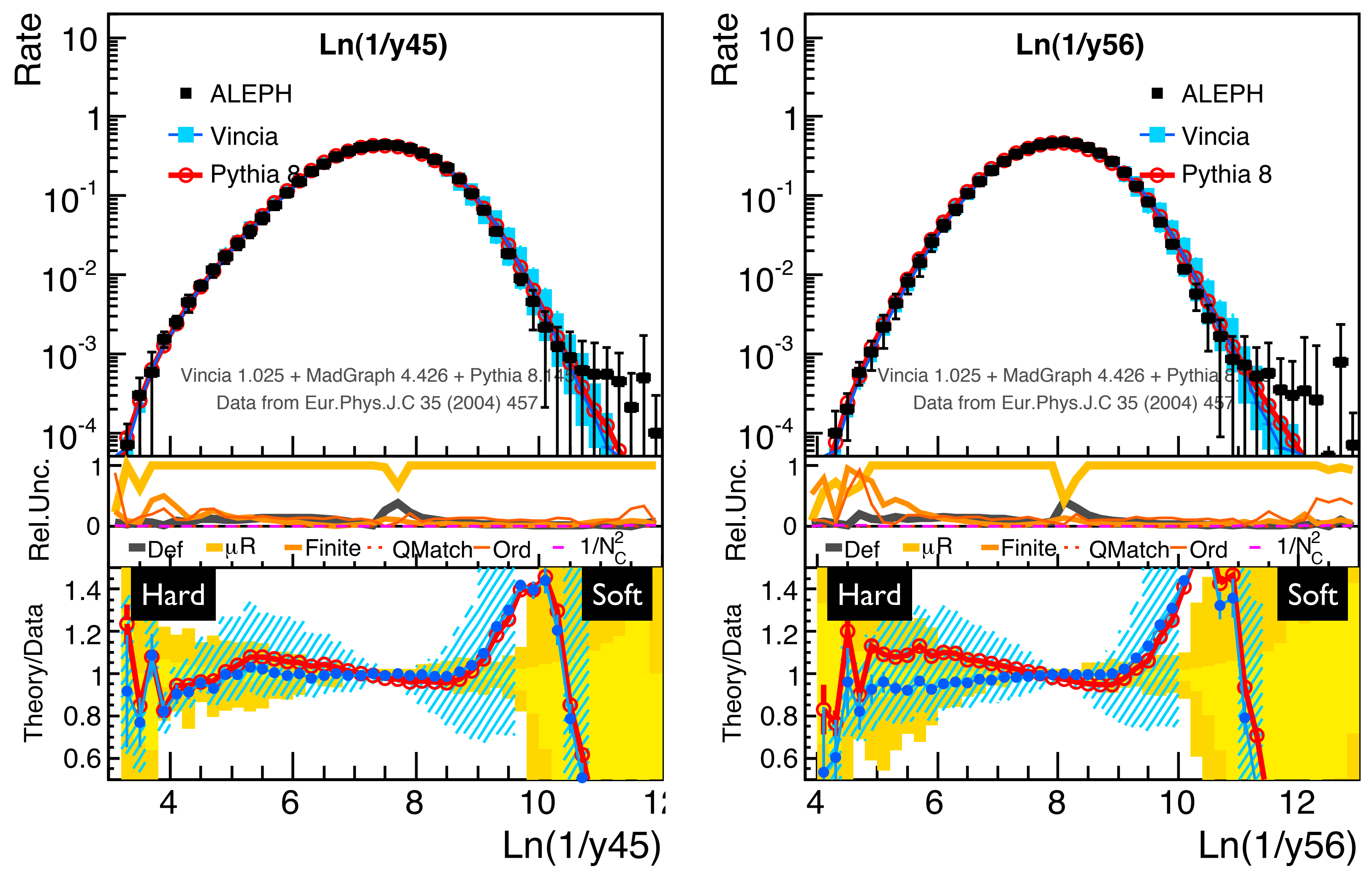


LEP event shapes



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

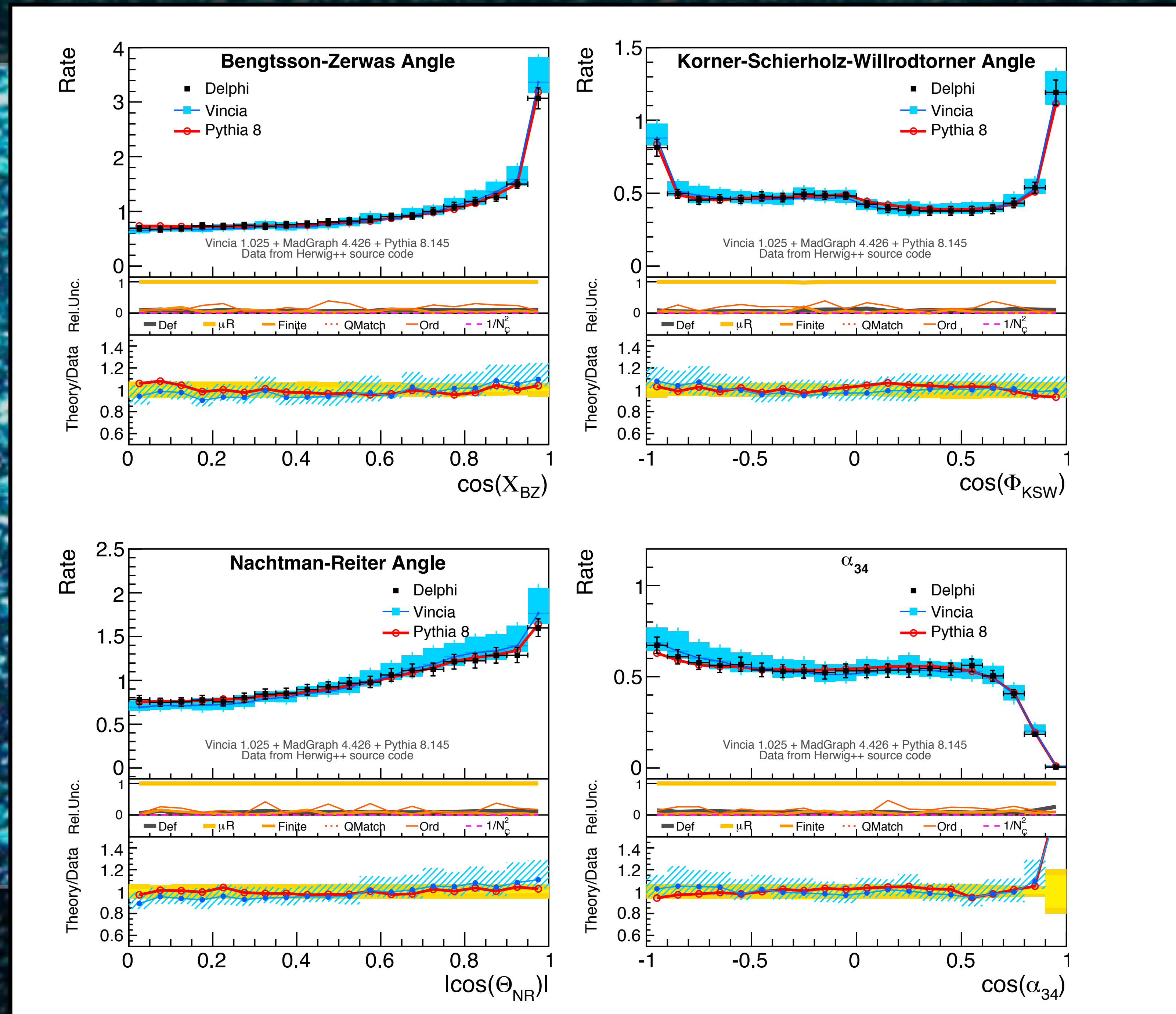
Good News

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?