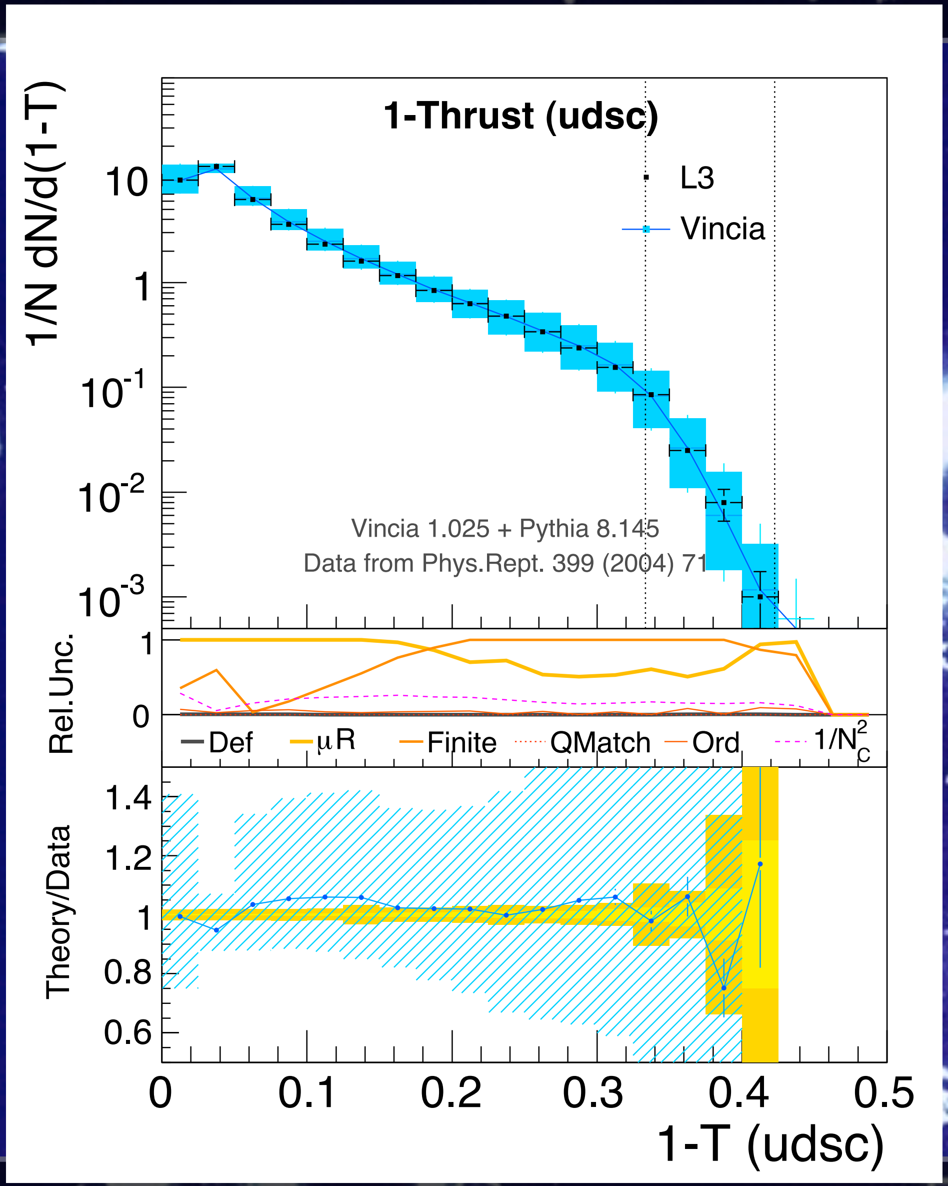
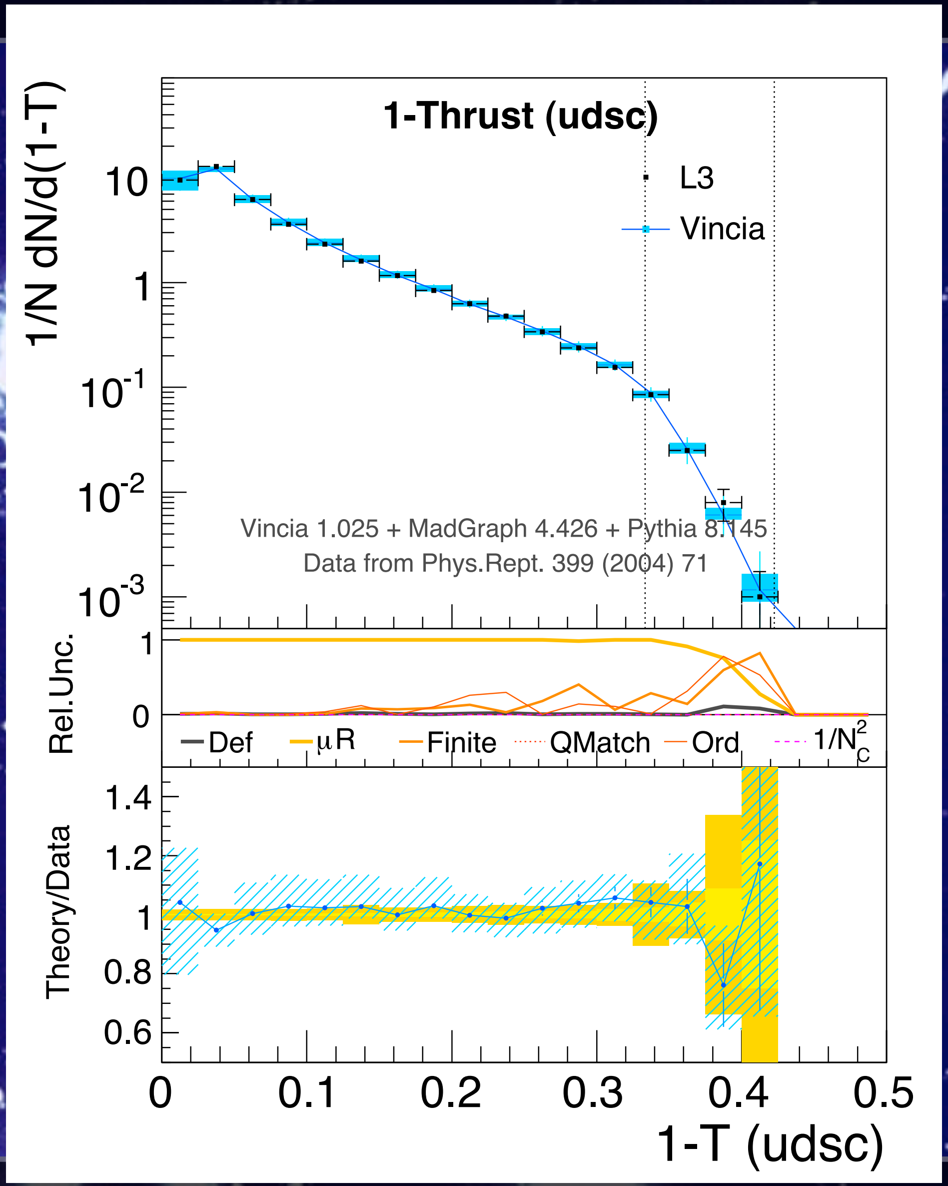
Higher-Order Corrections to Timelike Jets

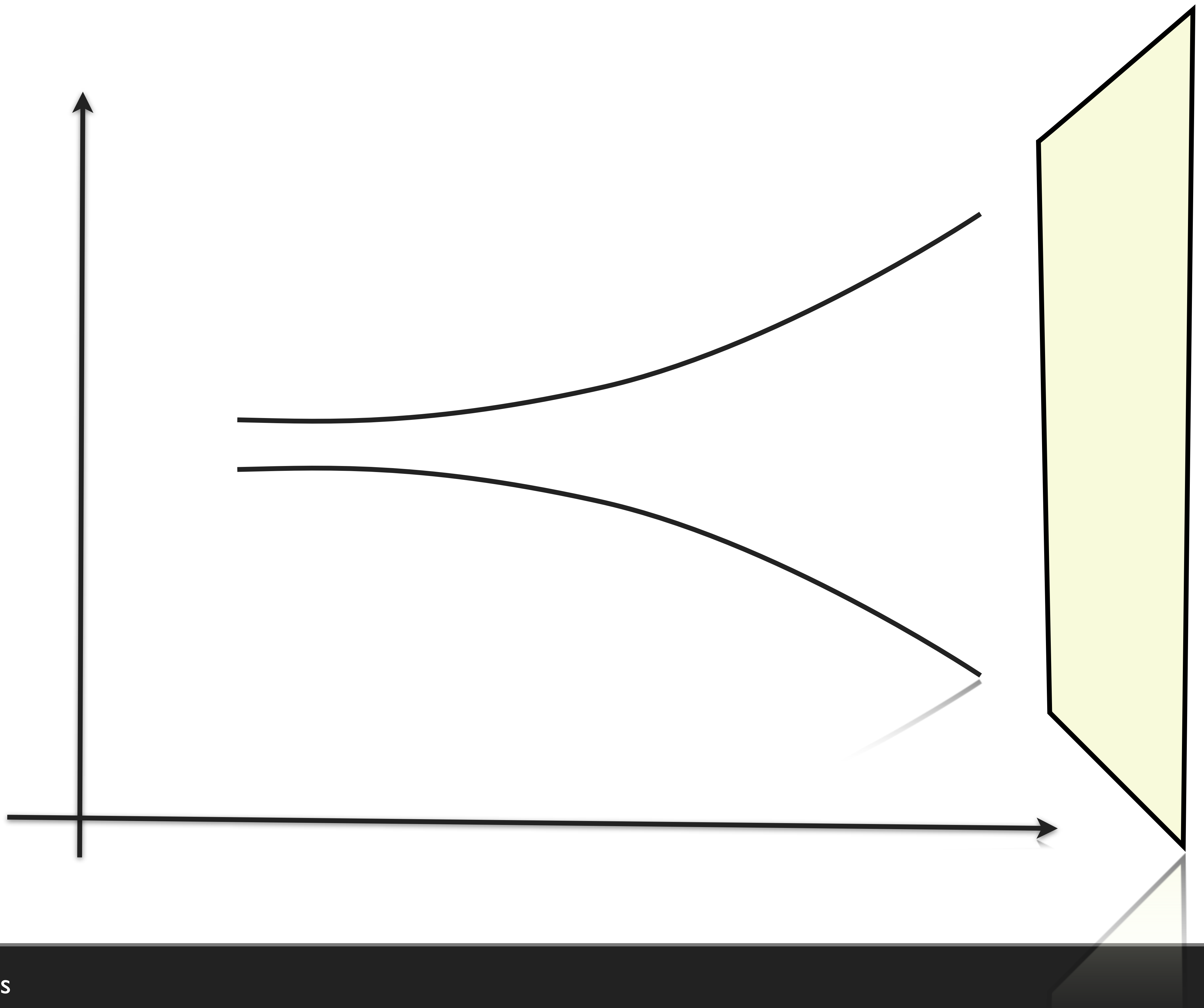




Peter Skands (CERN)

Physics Seminar, THEP, Lund, December 2010

Higher-Order Corrections...



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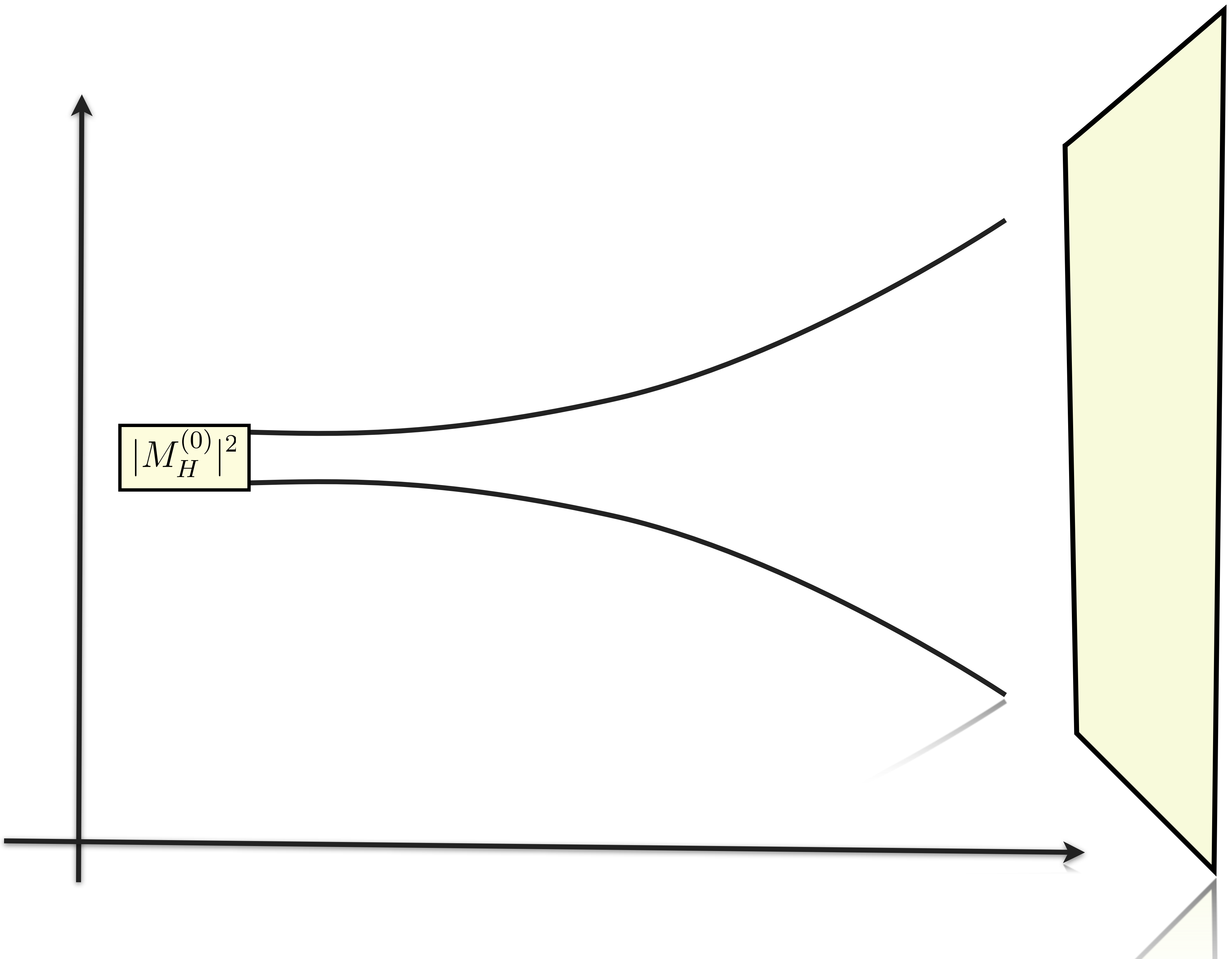

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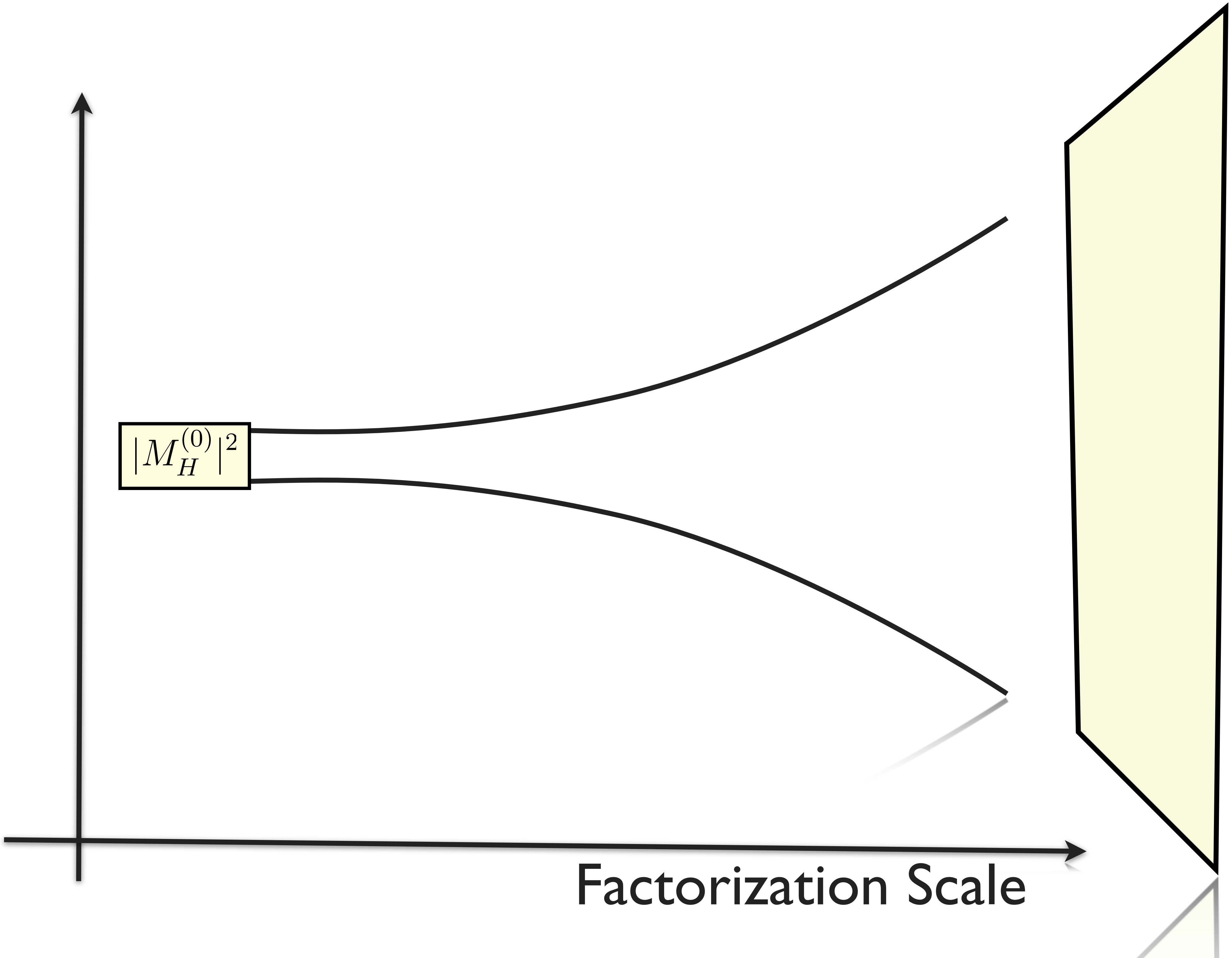

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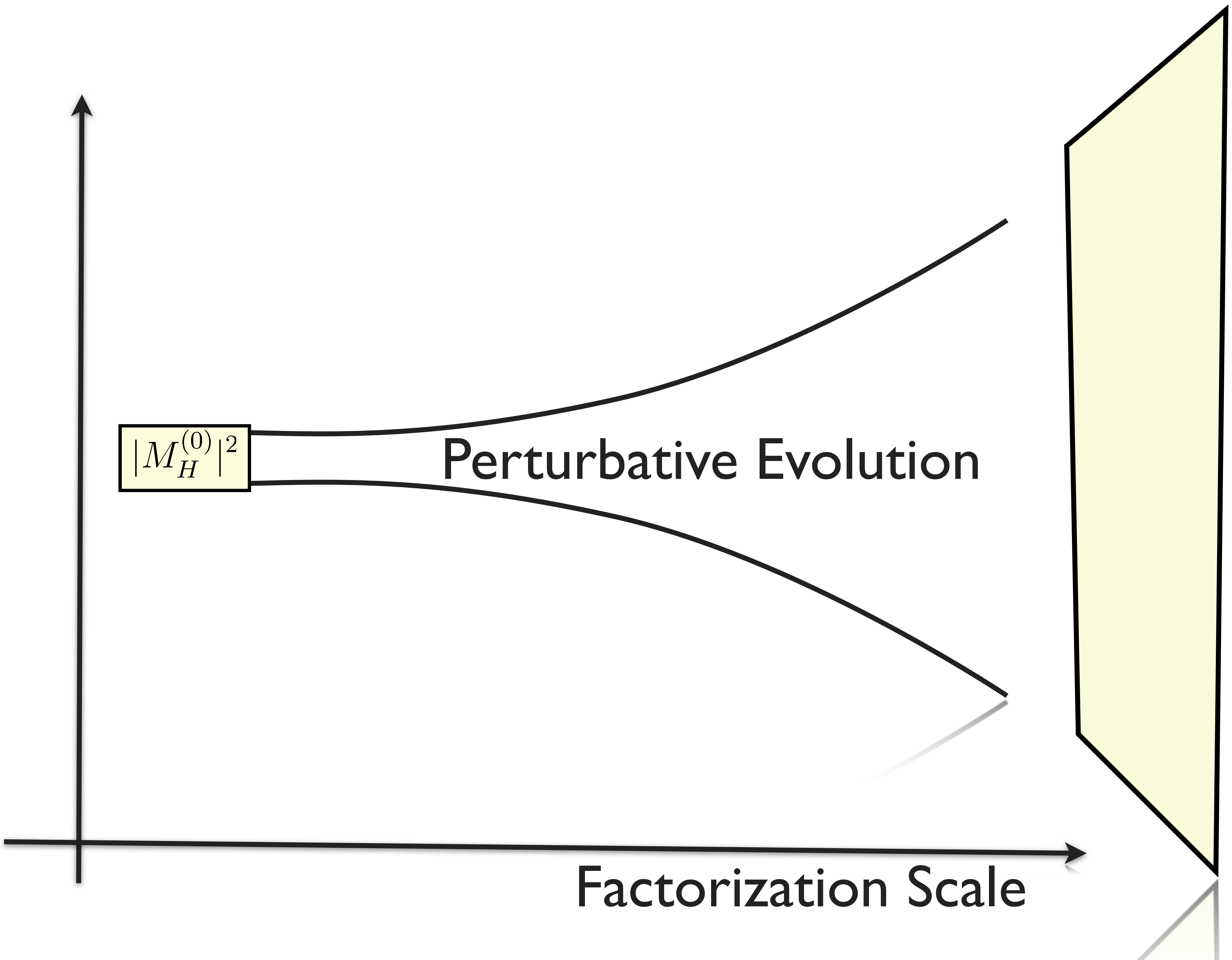

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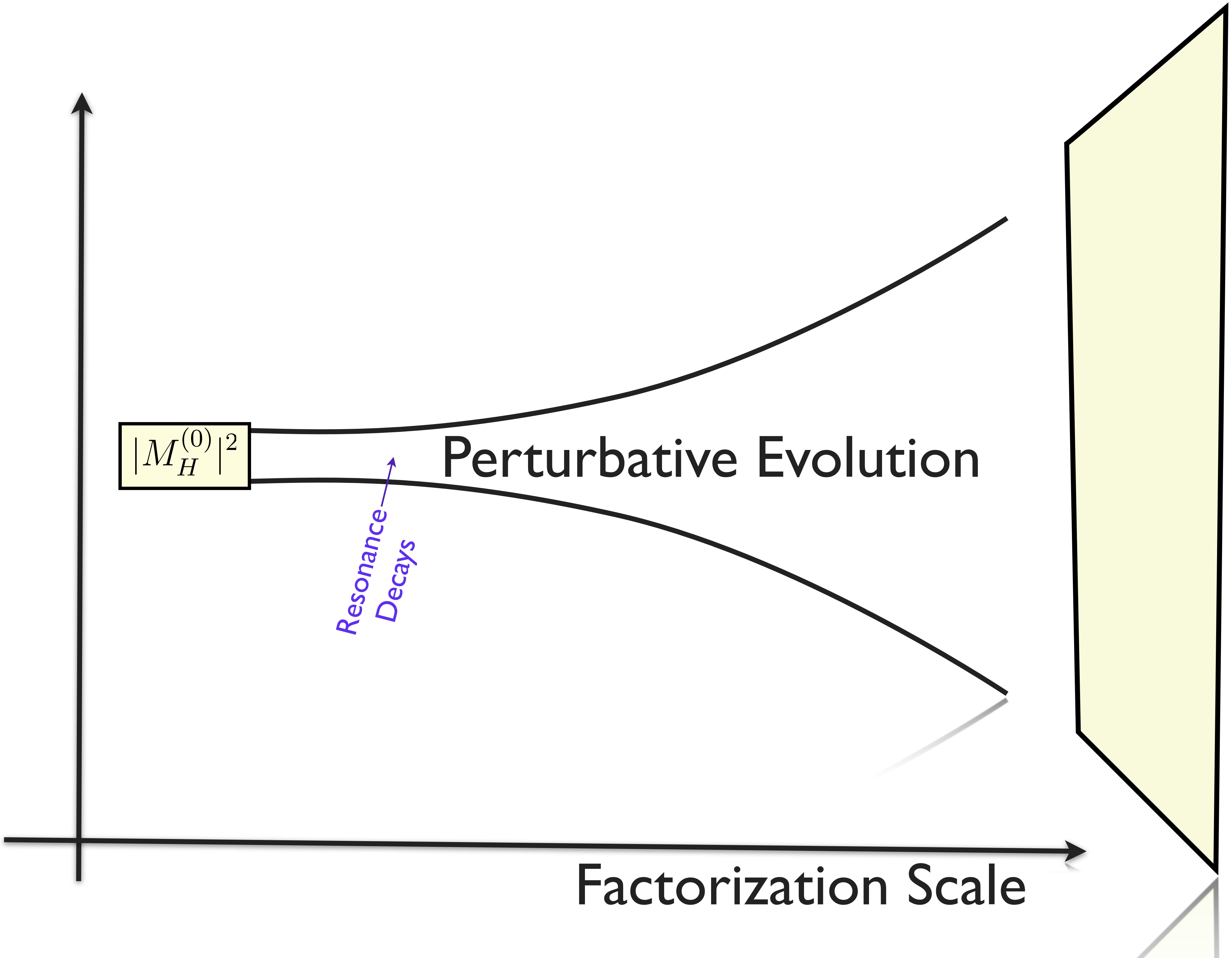

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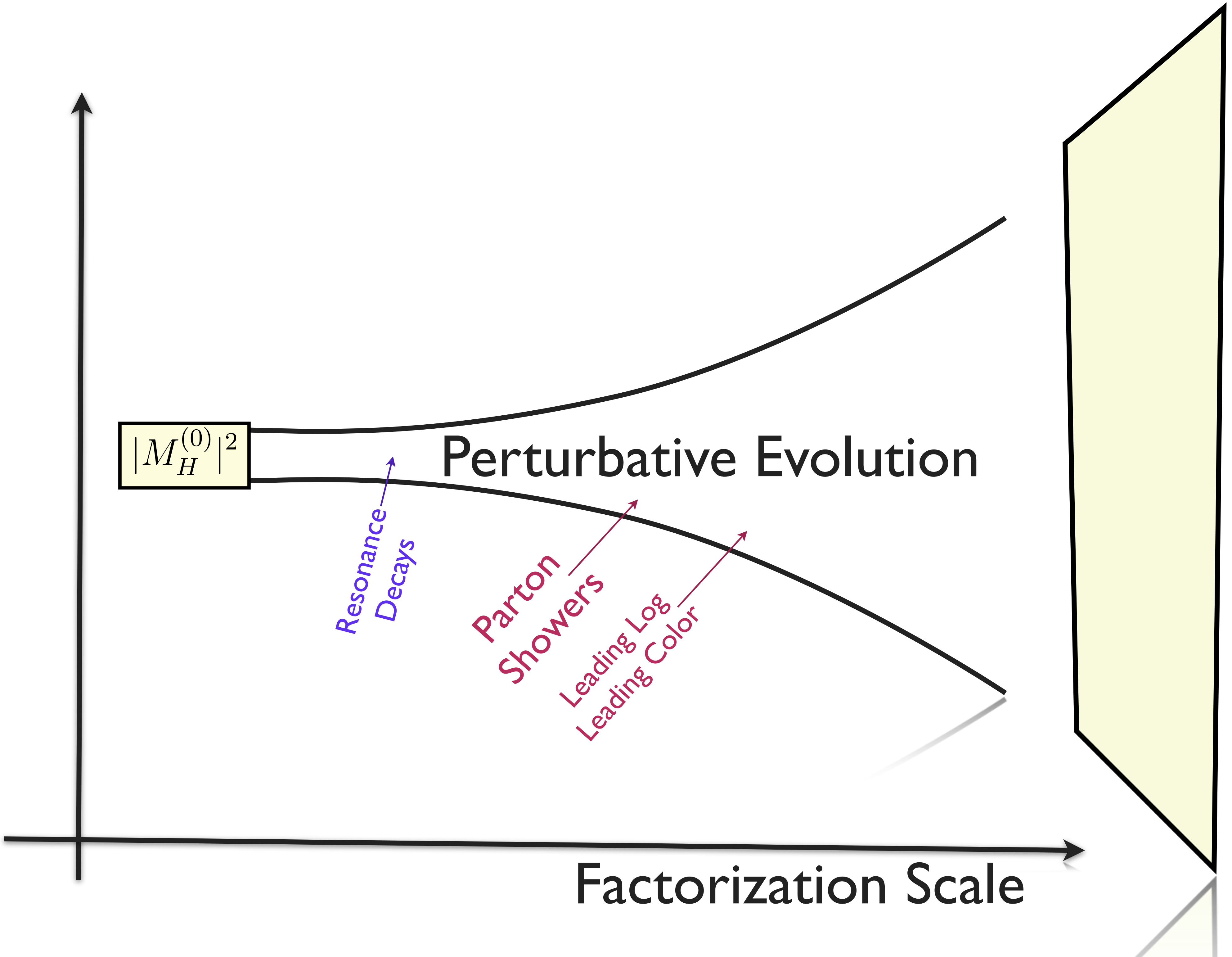

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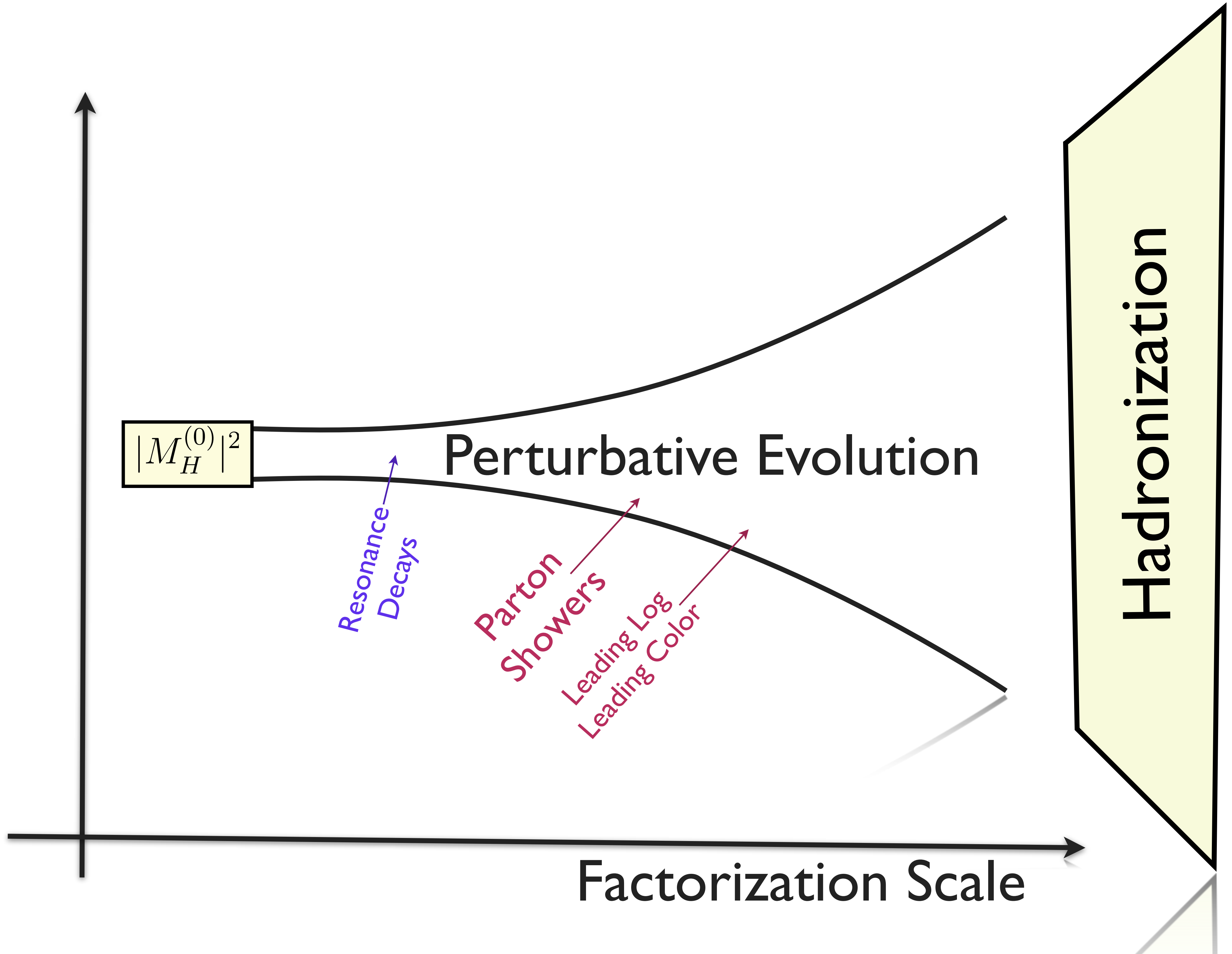

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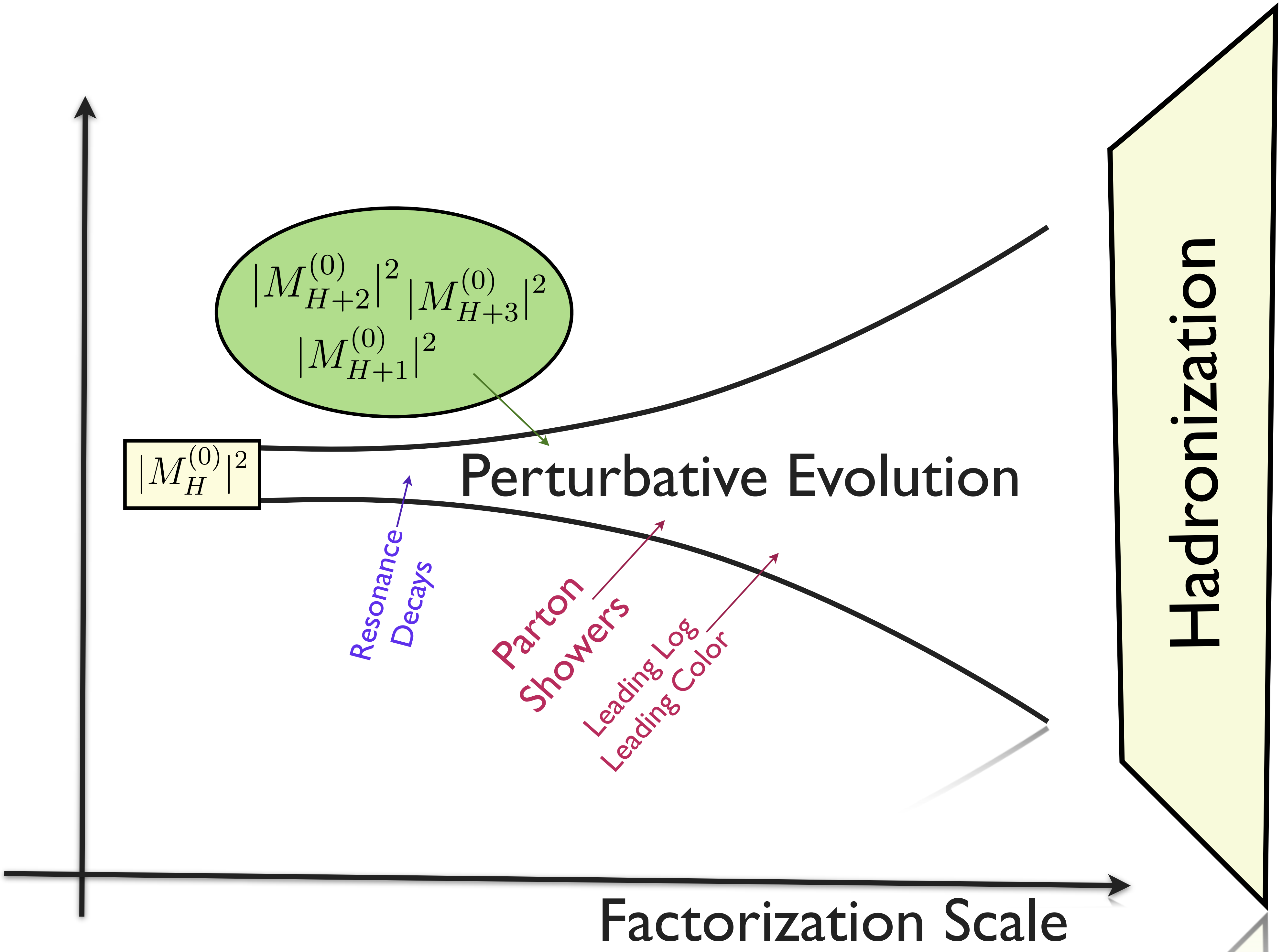

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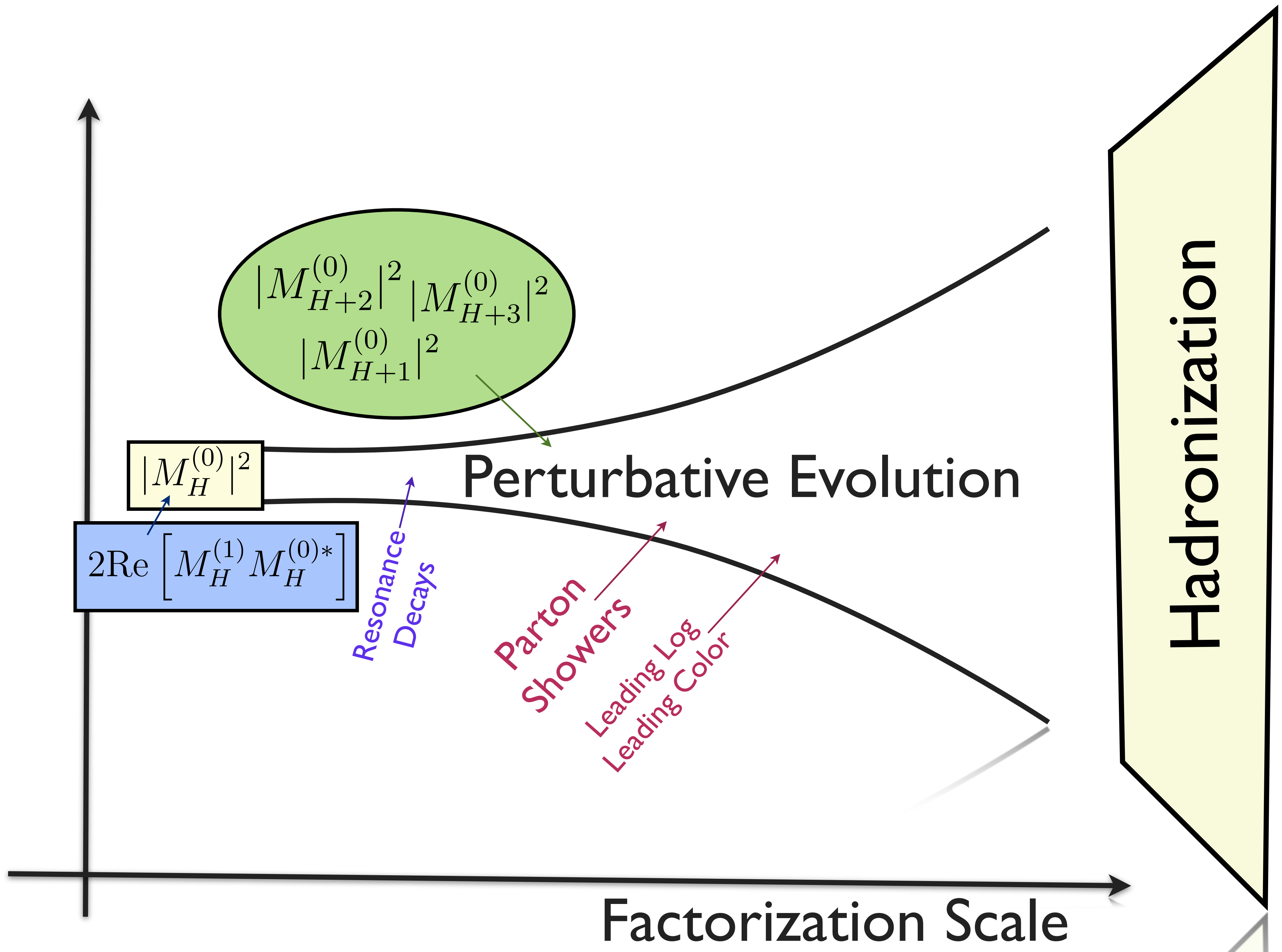

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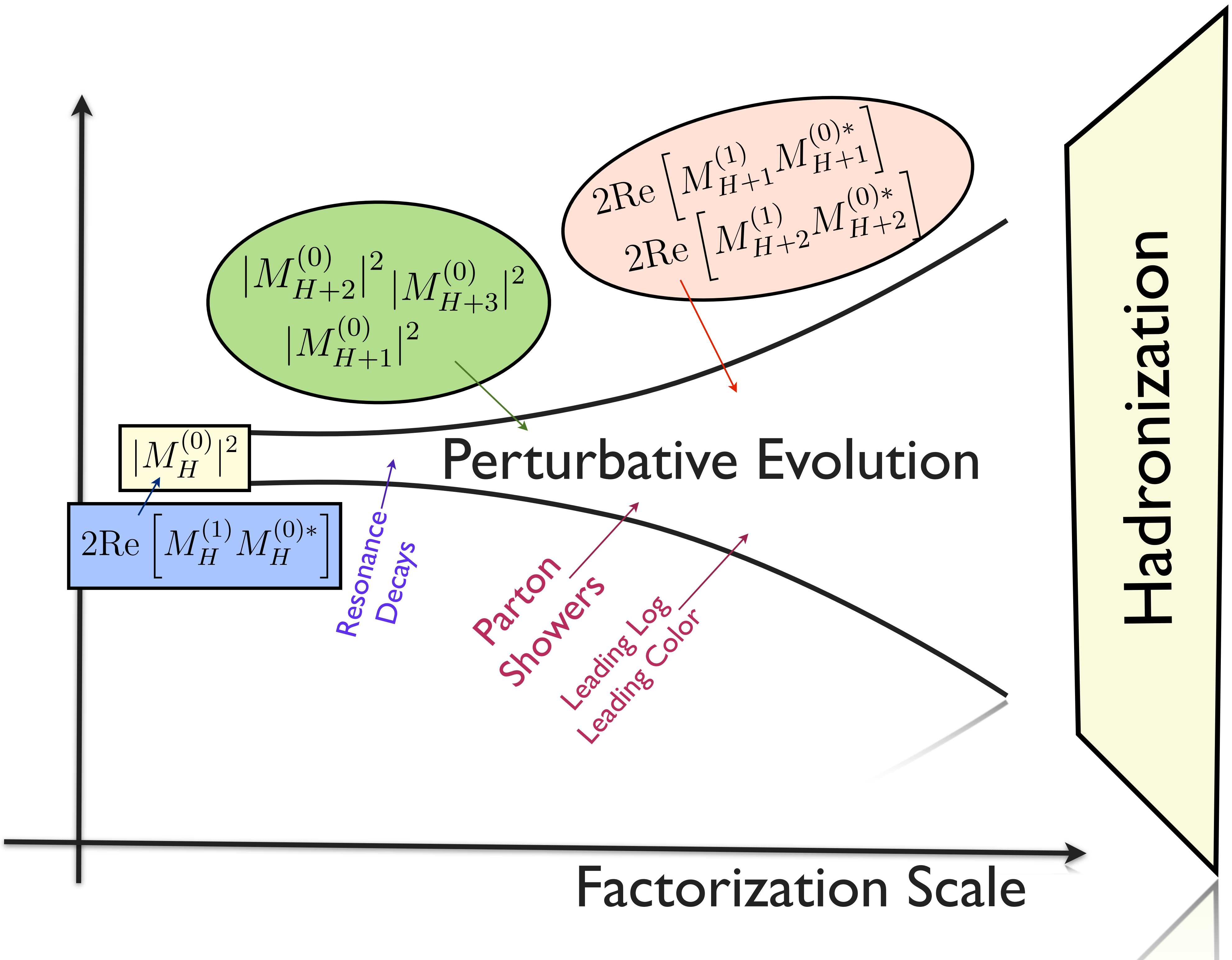

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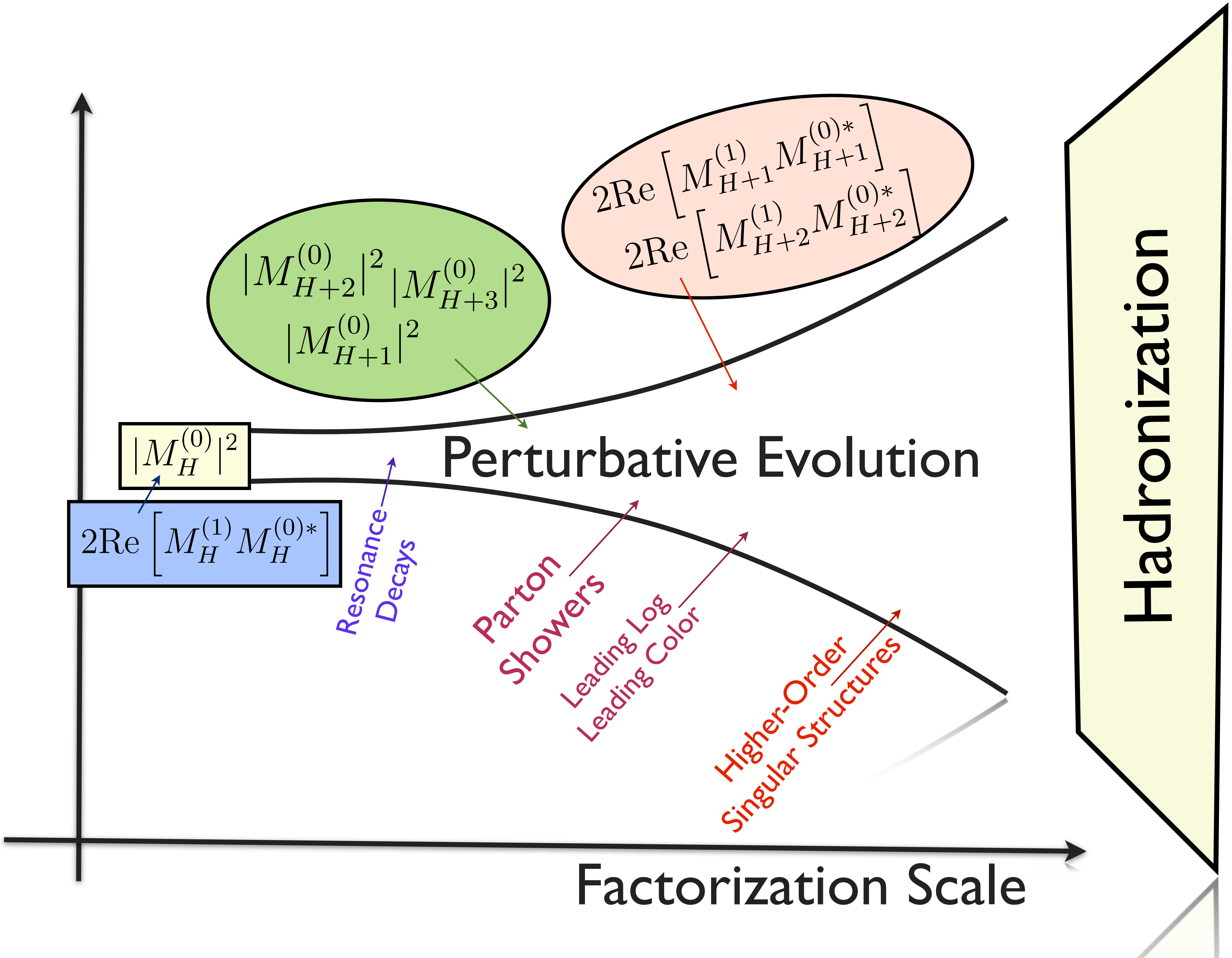

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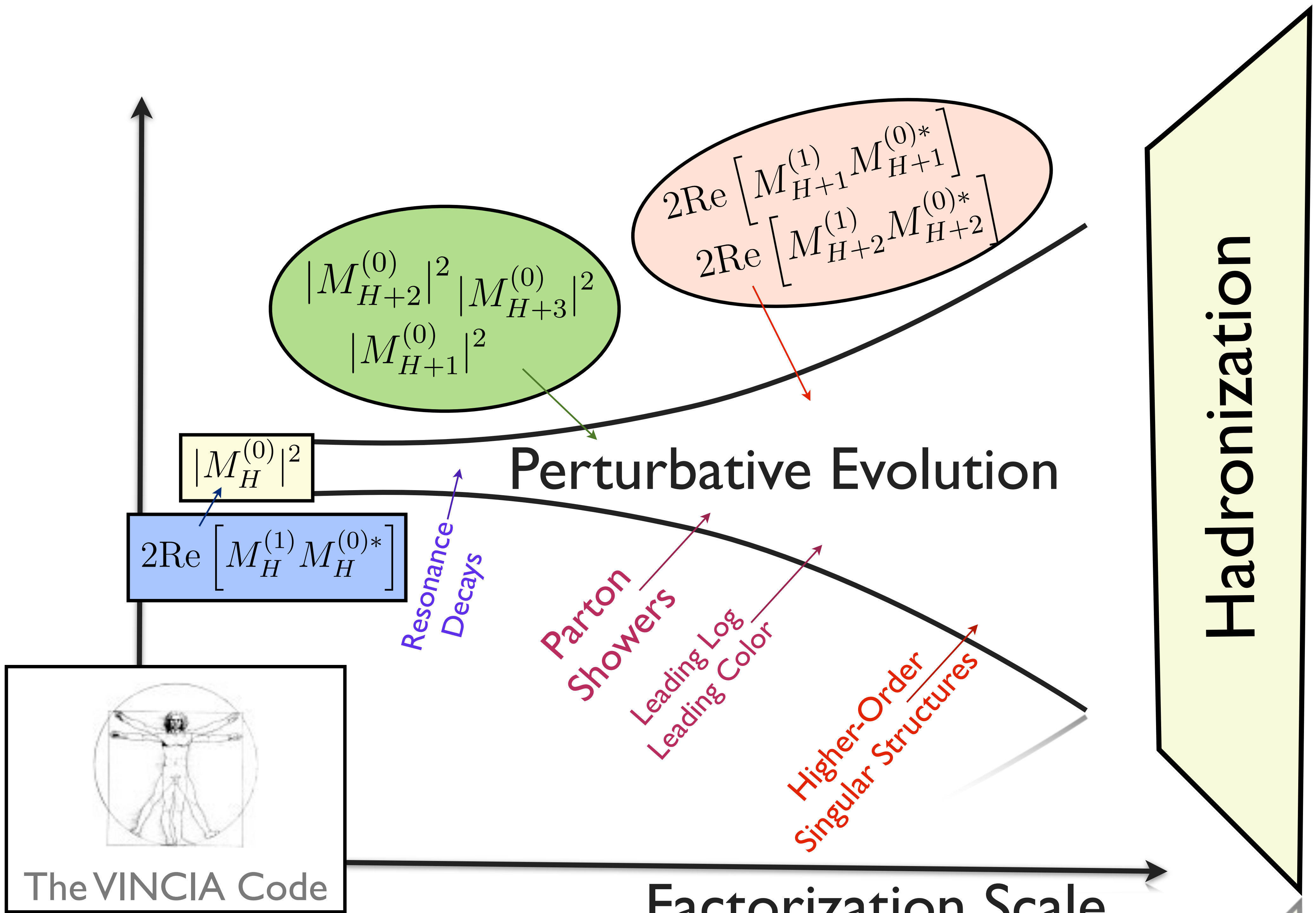

Giele, Kosower, PS
Gehrmann-de-Ridder, Ritzmann, PS

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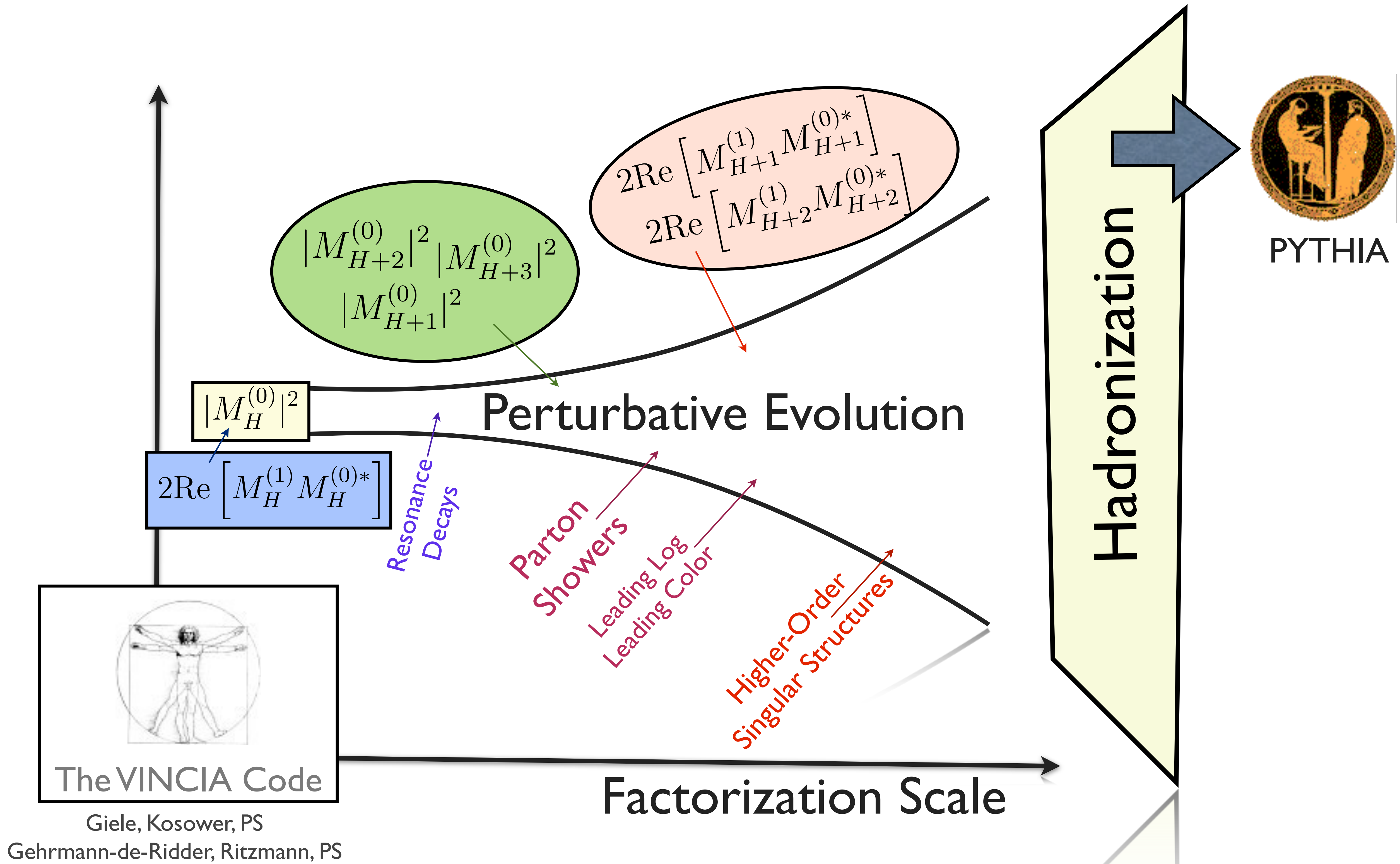

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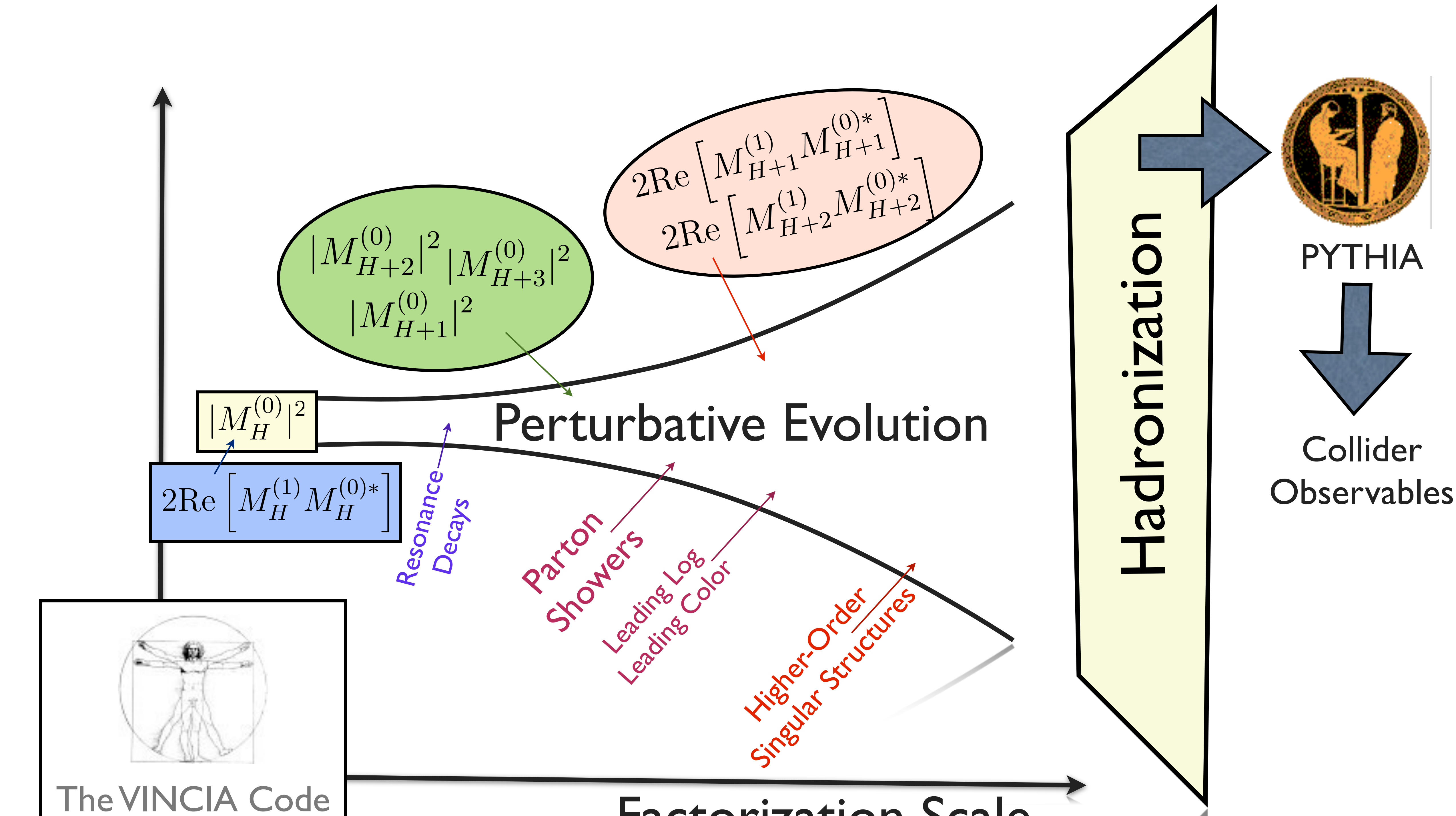

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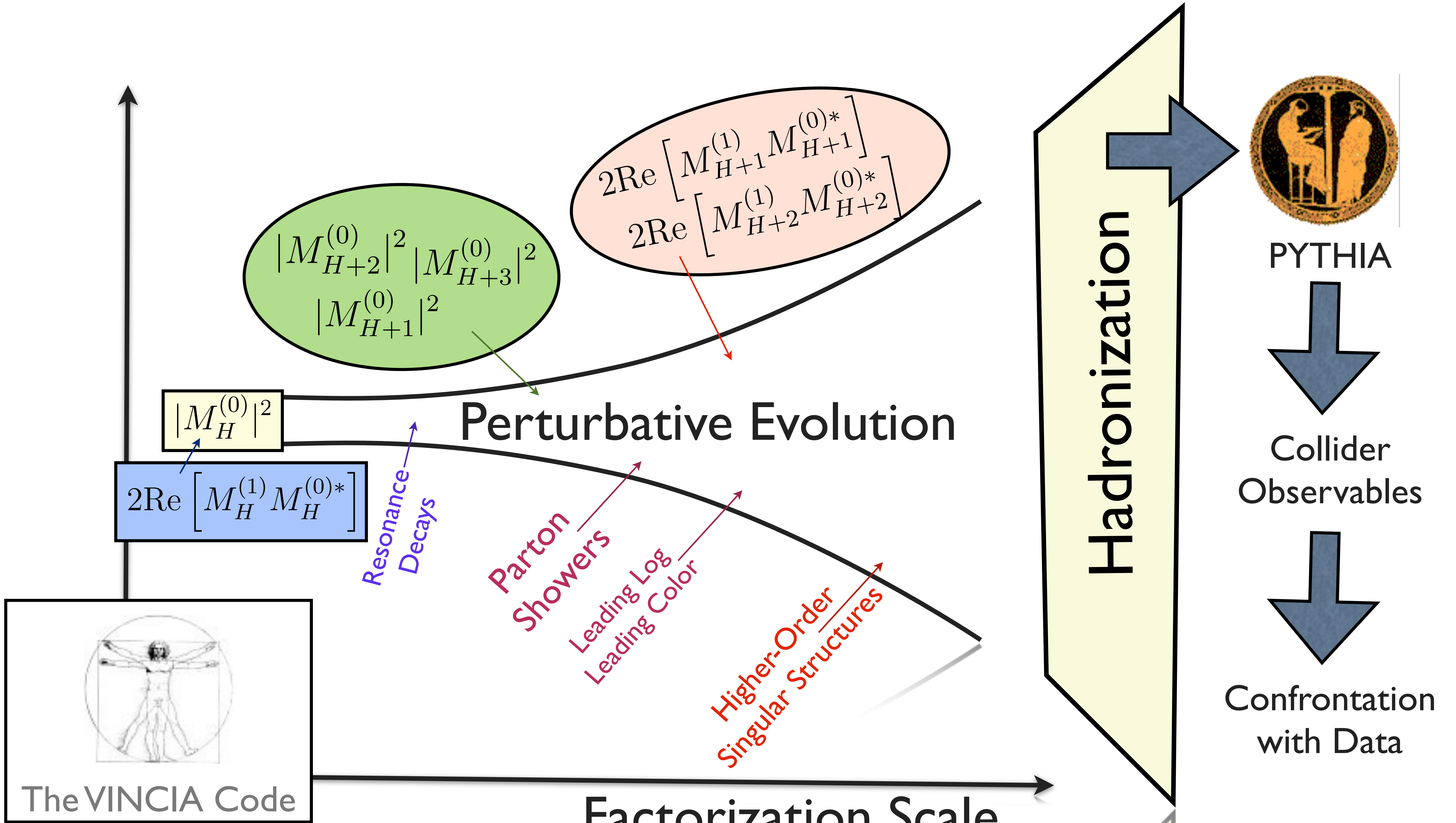

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... to Timelike Jets

Jet Substructure

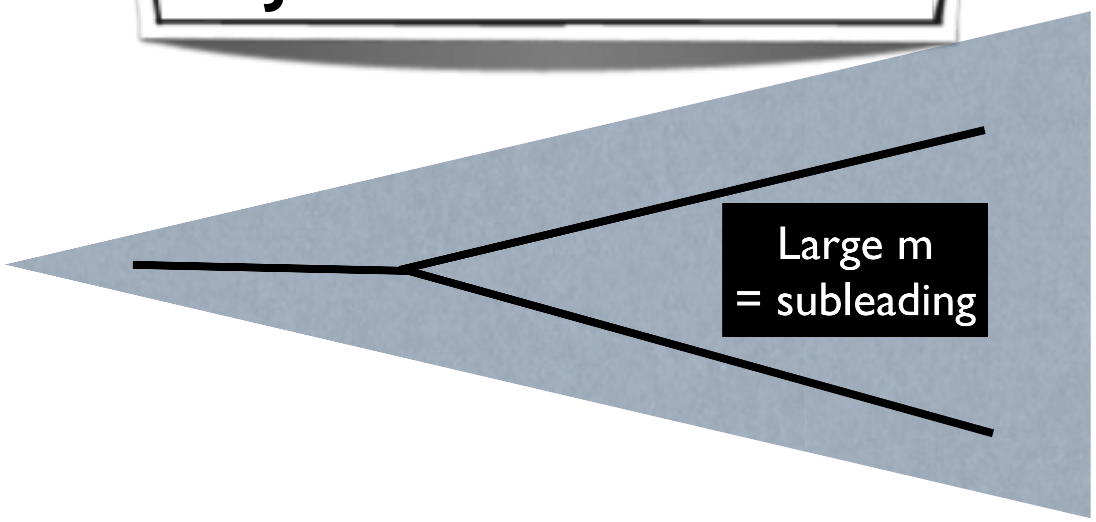
Underlying Event & Jet Calibration

Hadronization

Structure of QCD

... to Timelike Jets

Jet Substructure



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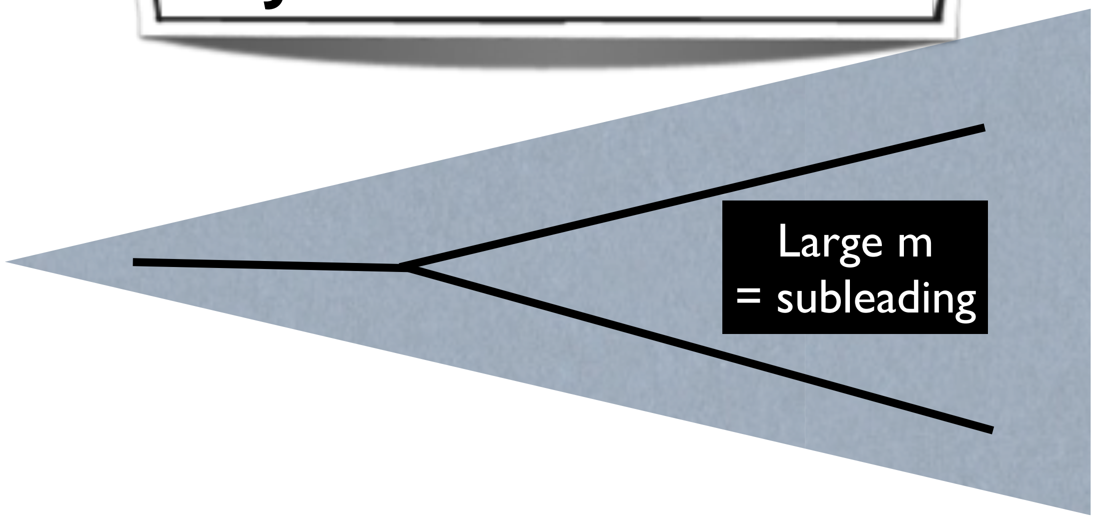

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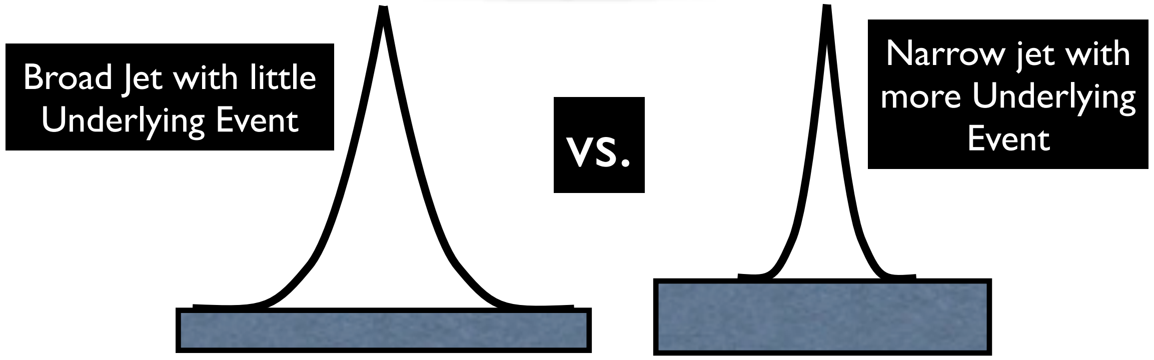

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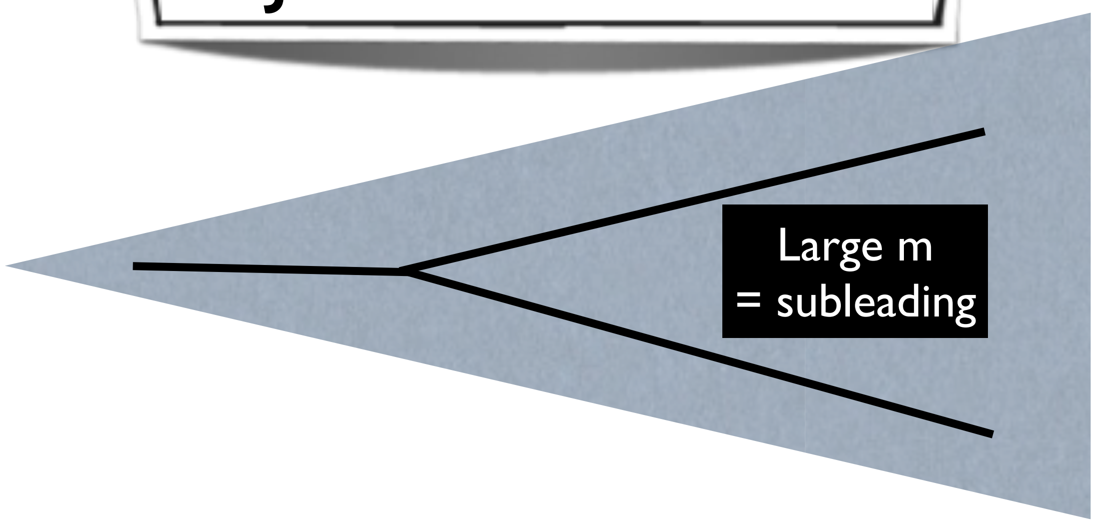

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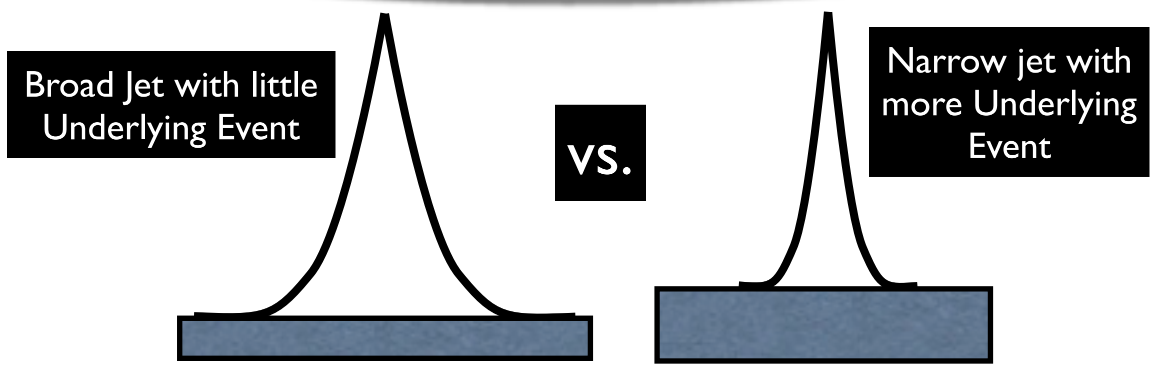

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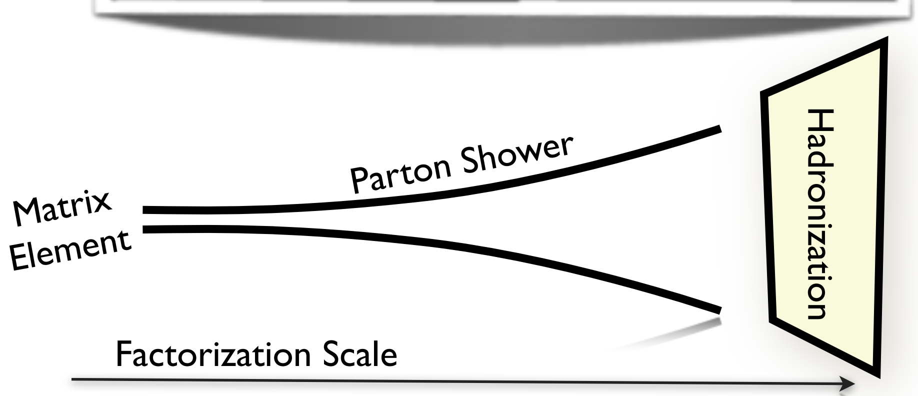

Better control of perturbative part
→ better constraints on non-perturbative part

Structure of QCD

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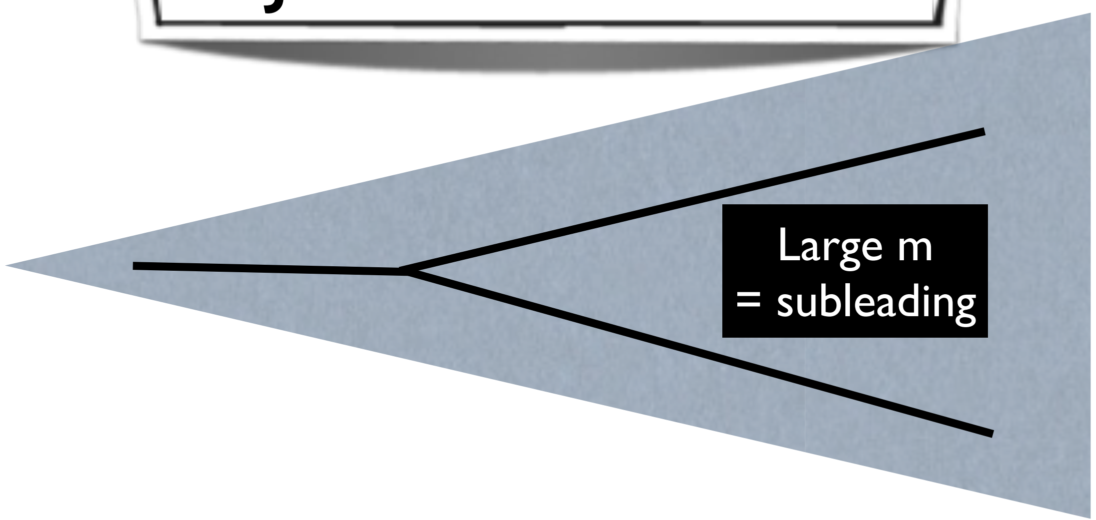

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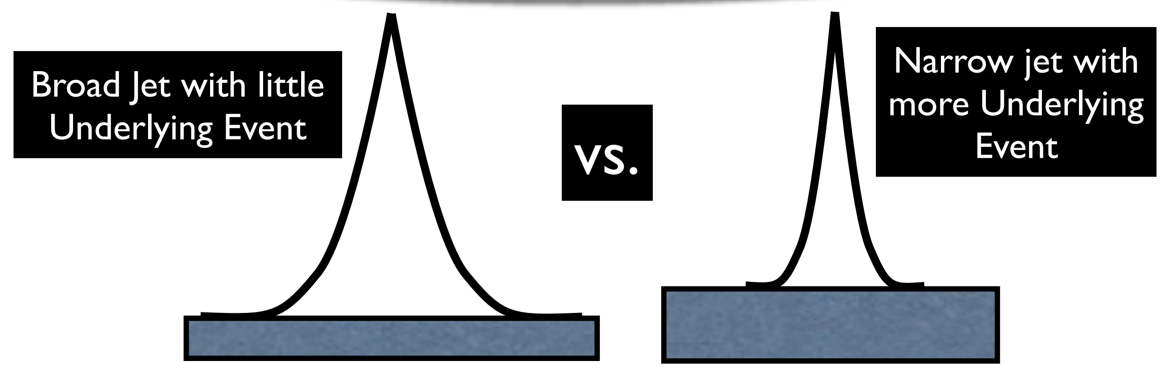

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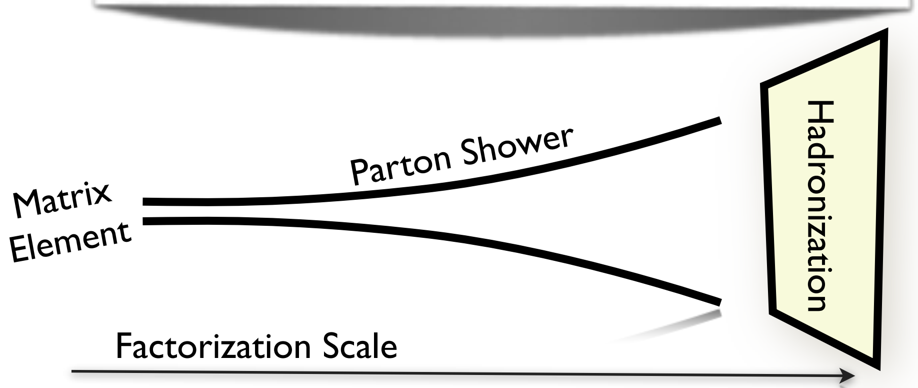

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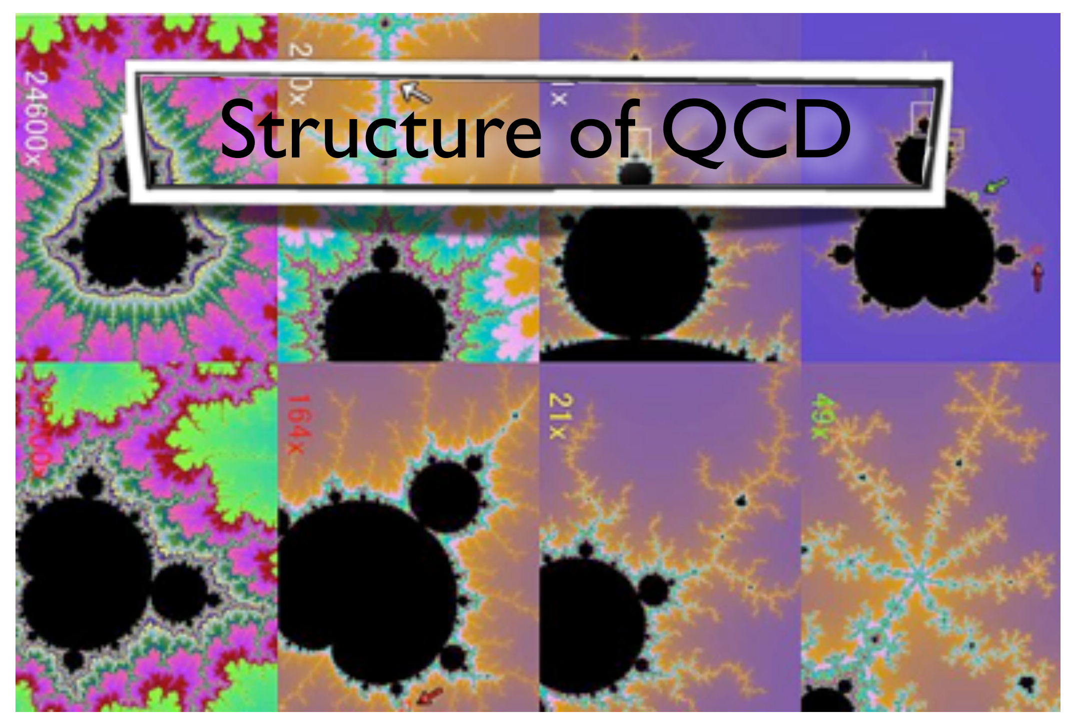

How do we make the predictions?

Archaic period
(750-550 BC)

“The reply from Apollo would be channelled through priestesses, known as Pythia, who would be seated on a tripod over a chasm that expelled mystic vapours.”

J. Collier (1891)

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2000 AD

mystic vapours → random numbers

Delphi (in Greece) → Lund (in Monaco)

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This talk is about Monte Carlo Event Generators

pQCD with Markov Chains

Starting Point:

Reformulate perturbative series as Markov Chain

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

<u>Aim:</u> see how well we can approximate this

For Each "Evolution Step":

Cover all of phase space with (large) trial overestimate

Compute the physical evolution probability using ...

NLO or LO matrix element ratios *(where available)*

else NLL or LL universal splitting functions *(antenna functions)*

P(accept) = Physical / Trial

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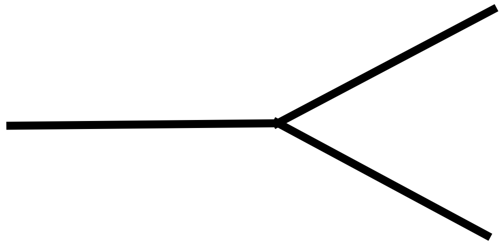
Already widely used at first order:

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

and by POWHEG for virtual ones

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

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

pQCD as Markov Chain

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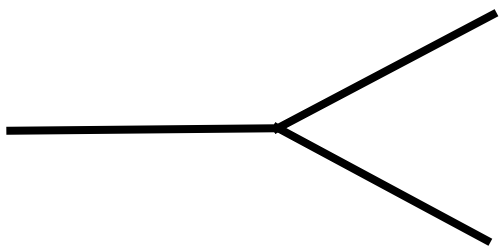

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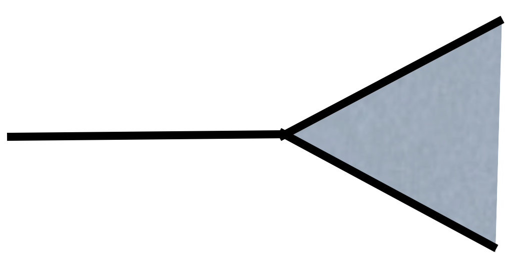
Insert Evolution Operator, *S*:



Evolution operator

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

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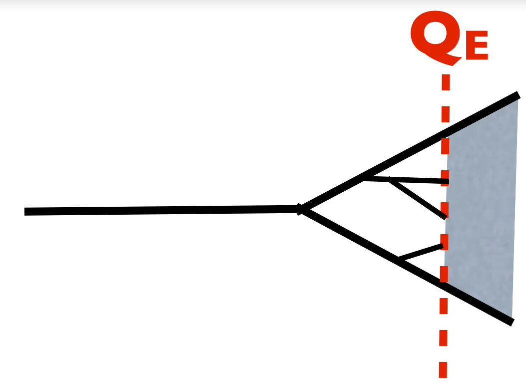
Depends on Evolution Scale : Q_E



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:

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)

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

Equivalent to Sjöstrand/POWHEG

"NLO" virtual correction

Sudakov Expansion

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

Unitarity

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

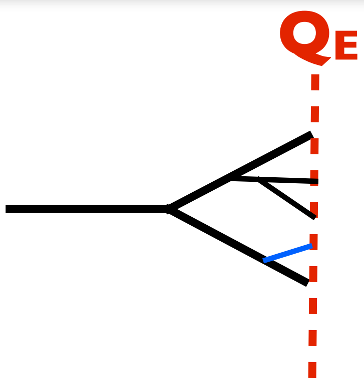
Torbjörn's trick

Virtual Correction (NLO normalization)

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

$c - c'$

Higher Orders



Unitary matching philosophy:

Generate Trial Evolution Step with approximate (e.g., LL) weight

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

Reweight evolution step probability by "best available" approximation (e.g., Matrix Element) divided by trial approximation

→ Must be able to compute both numerator and denominator

Higher Orders

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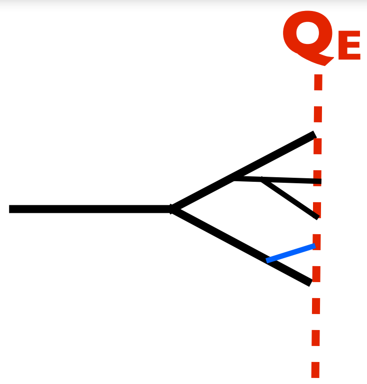

Generate Trial Evolution Step with approximate (e.g., LL) weight

E.g., get from MadGraph

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→ Must be able to compute both numerator and denominator

The Denominator

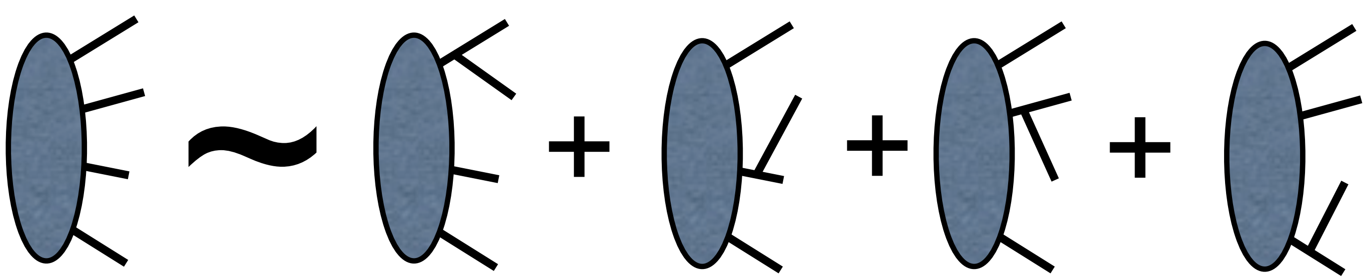
$$\text{Matched} = \text{Approximate}\,\frac{\text{Exact}}{\text{Approximate}}$$

Number of Histories:

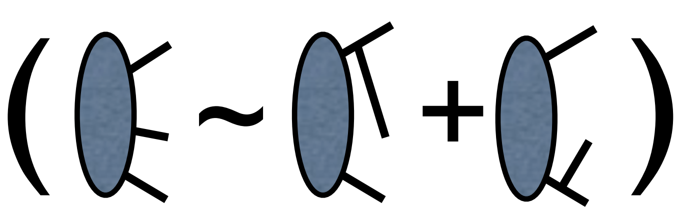
Existing parton showers are *not* Markov Chains

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



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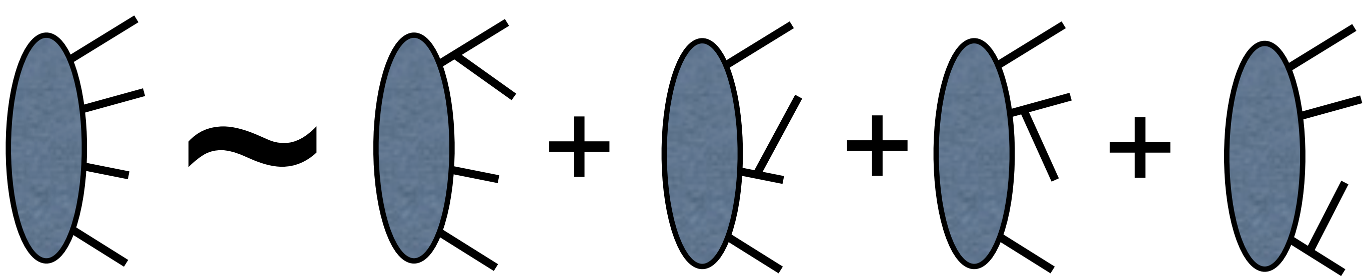

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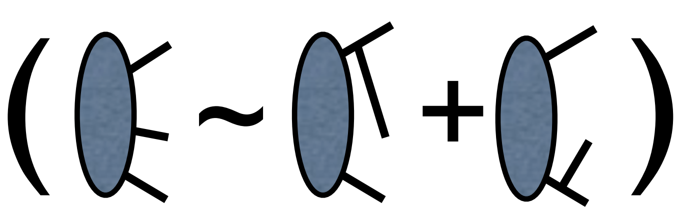

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Parton / Catani-Seymour Shower:
After 2 branchings: 8 terms
After 3 branchings: 48 terms
After 4 branchings: 384 terms

Antenna Showers

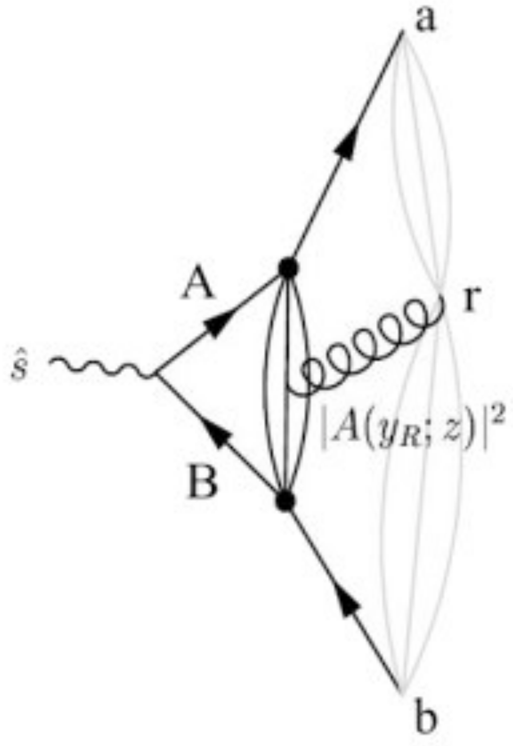
Parton and CS showers

One term per parton (two for gluons)

Antenna showers

One term per parton *pair*

$2^n n! \rightarrow n!$



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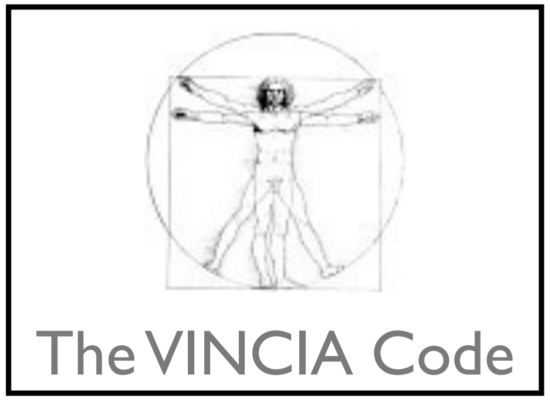

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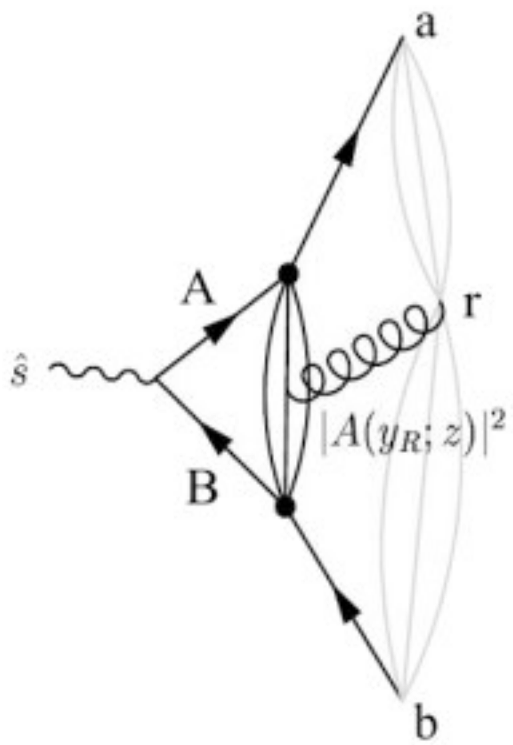

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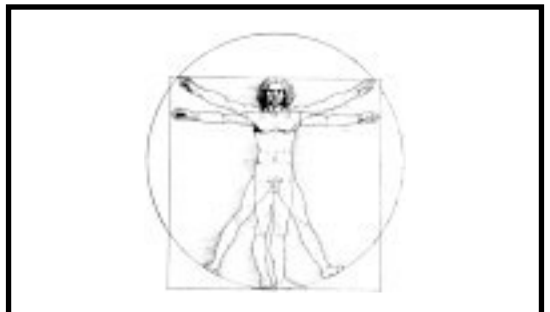

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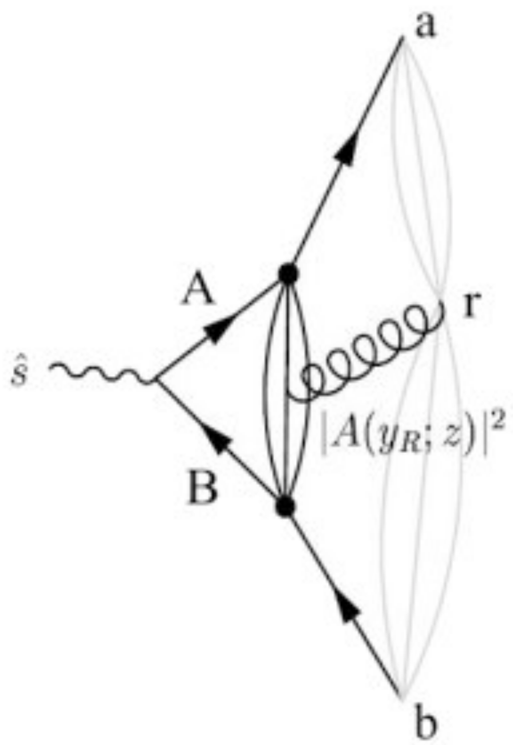


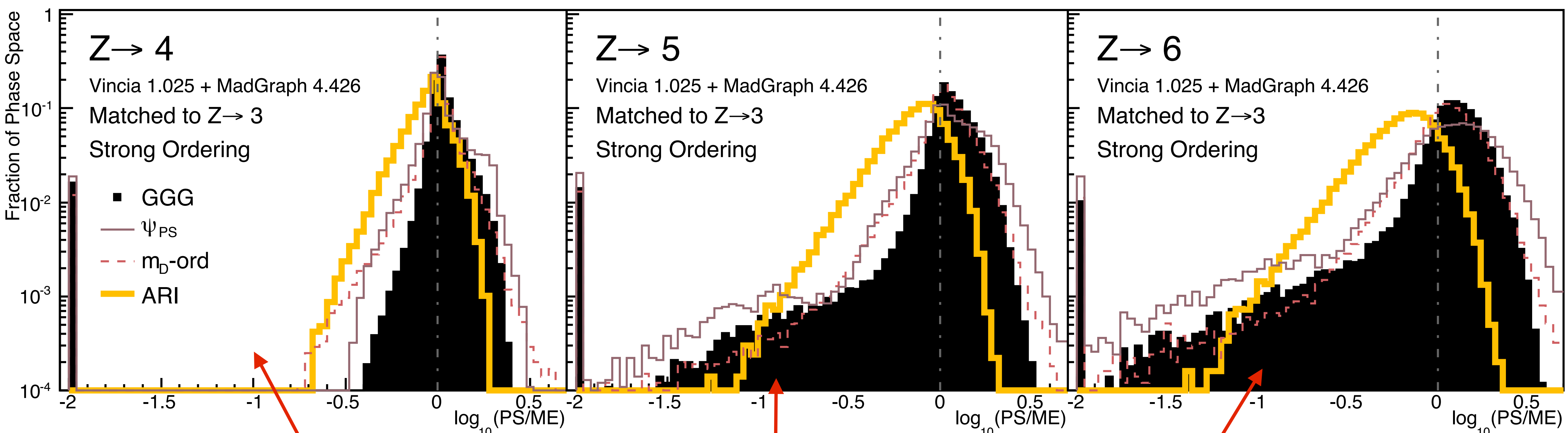
Antenna Shower:
After 2 branchings: 2 terms
After 3 branchings: 6 terms
After 4 branchings: 24 terms

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

Approximation

Compare shower expansion to “exact” ME

Flat phase-space scan, Leading Order, Leading Color



Antenna Shower:
After 2 branchings: 2 terms
After 3 branchings: 6 terms
After 4 branchings: 24 terms

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

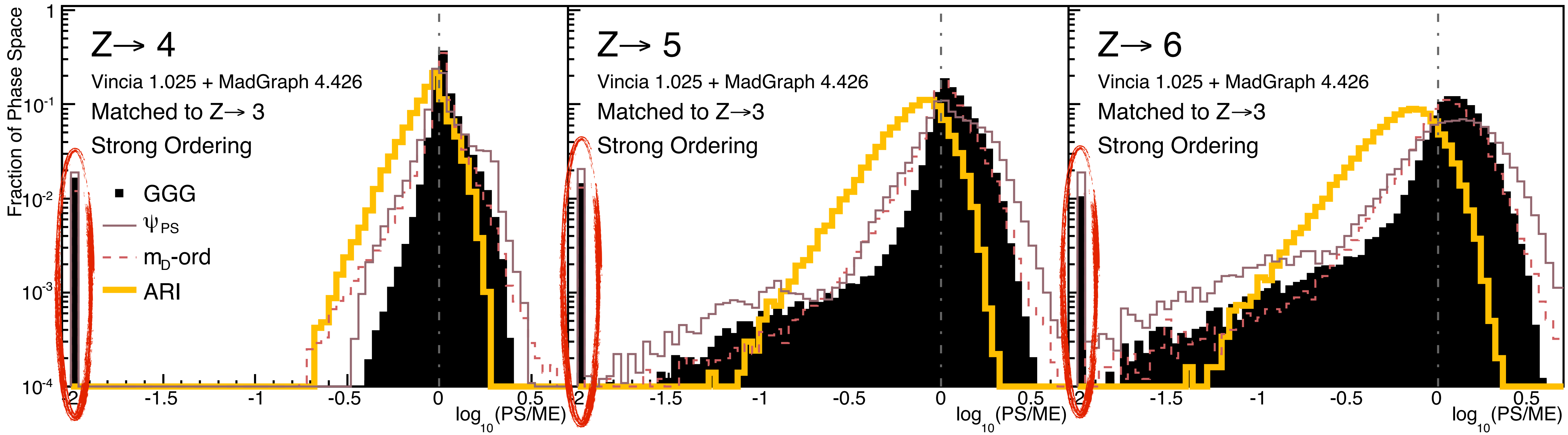
Matrix Elements from MadGraph

Dead Zones!

Also studied by Andersson, Sjögren, Gustafson, Nucl.Phys. B380 (1992) 391-407

Strong ordering → dead zones

Phase space points that cannot be reached by *any* orderd history



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

Dead points → cannot apply reweighting

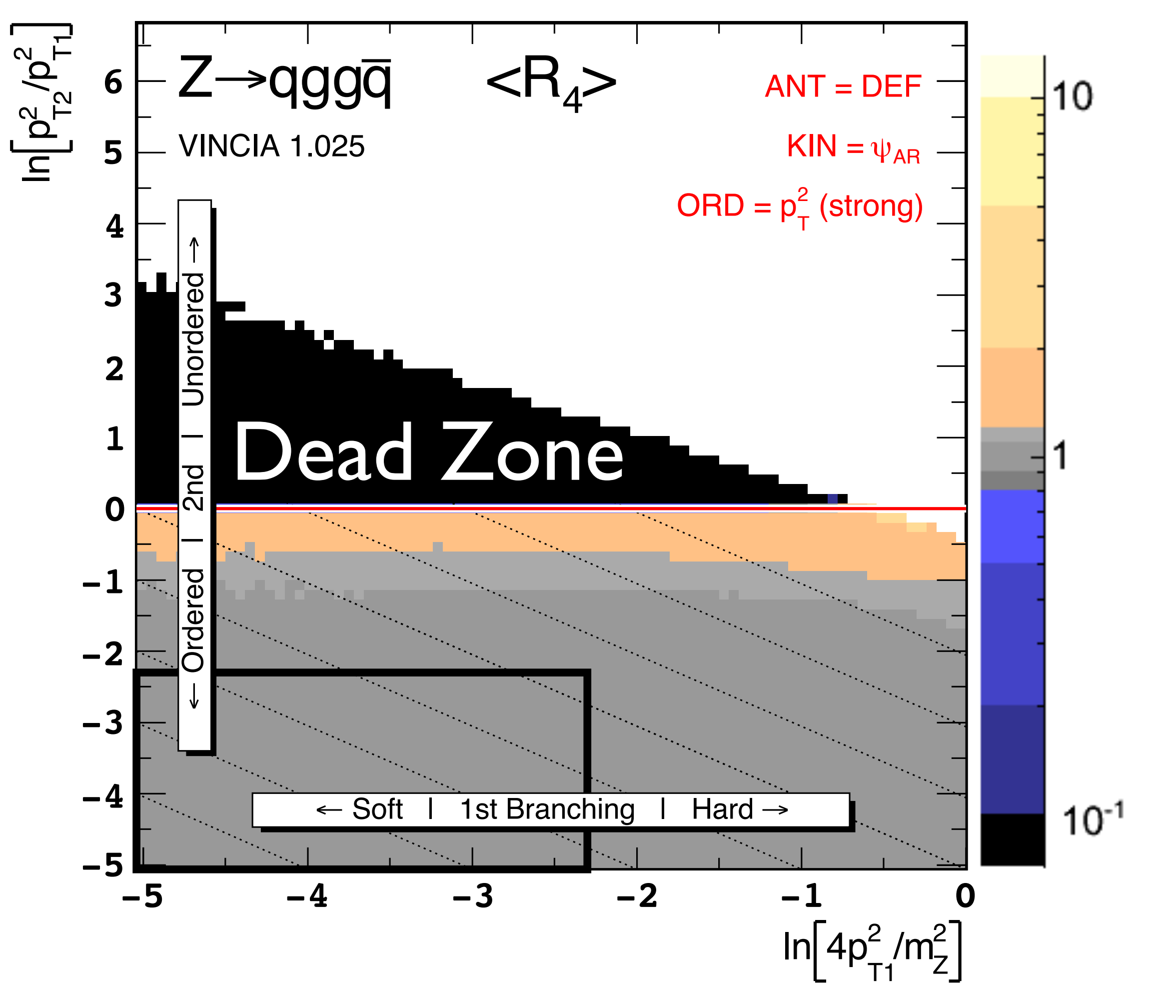
Simple Solution

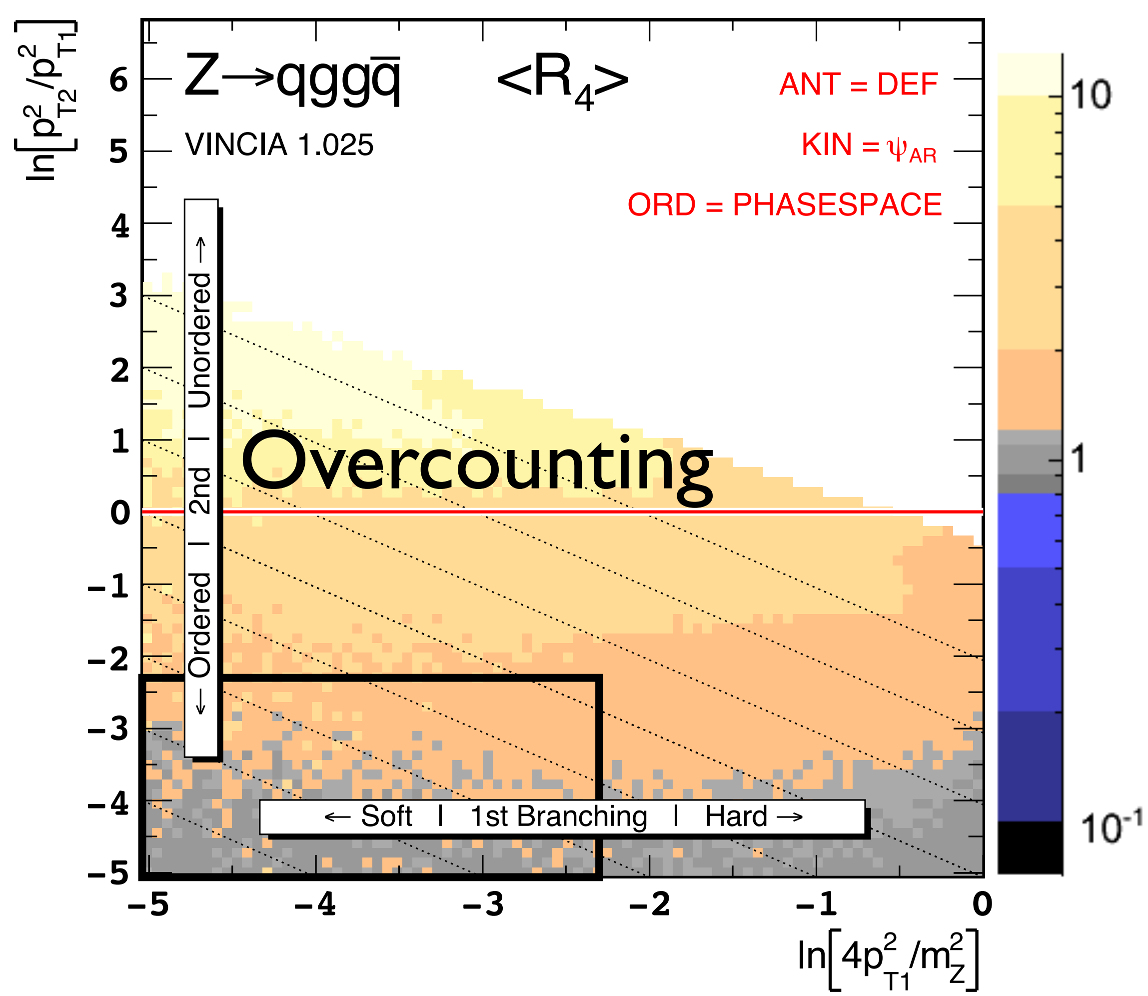
Generate Trials *without* imposing strong ordering

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

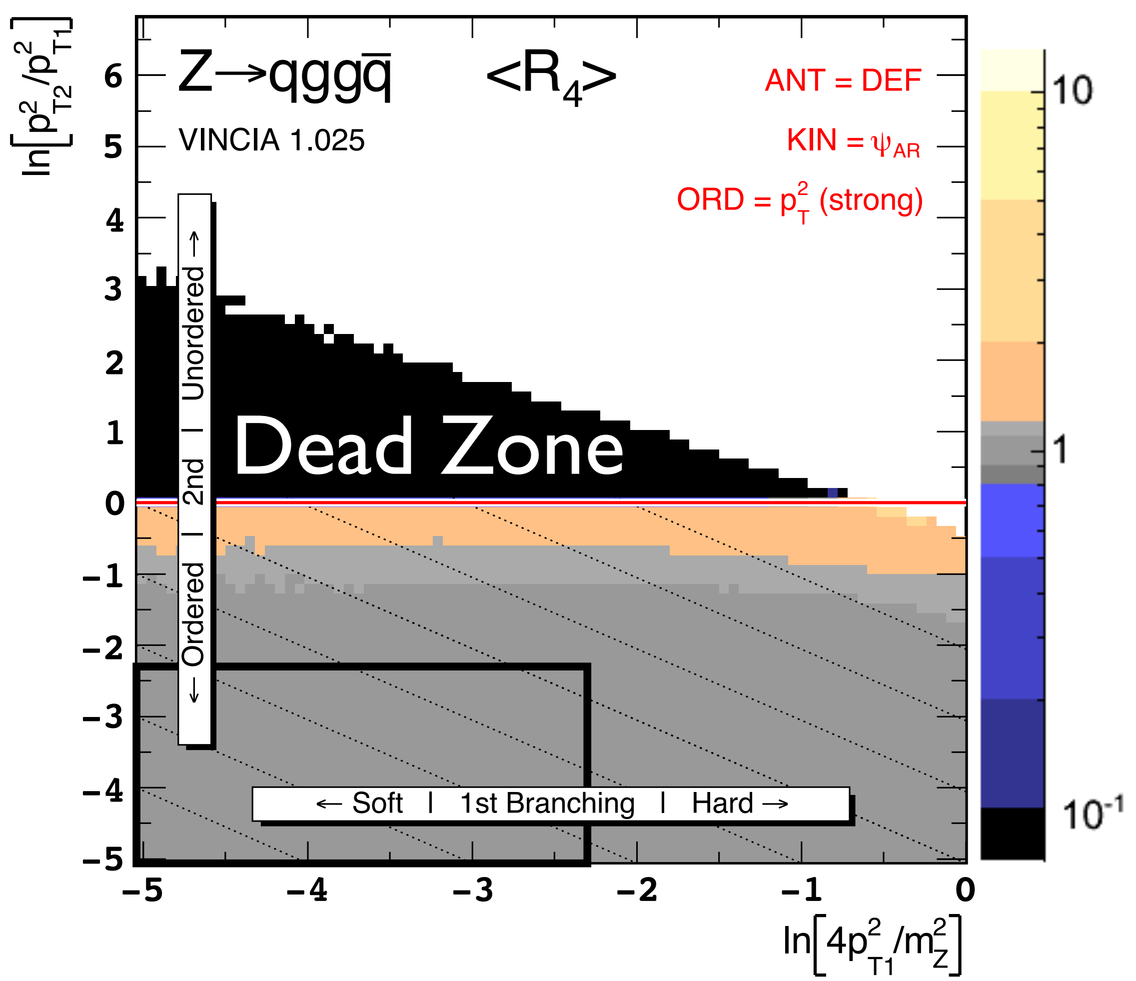
Generate Trials *without* imposing strong ordering

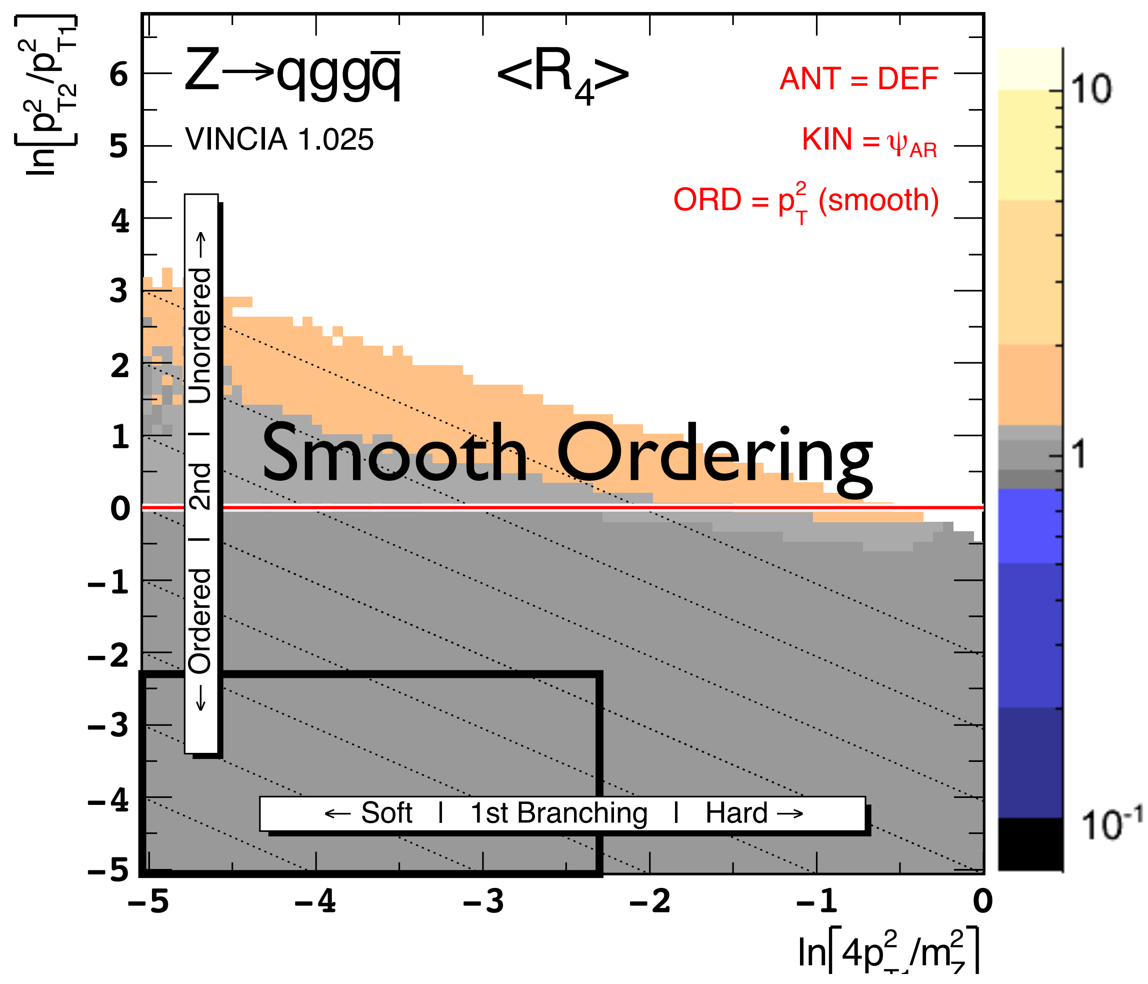
At each step, each dipole allowed to fill its entire phase space

Overcounting removed by matching

+ smooth ordering beyond matched multiplicities

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



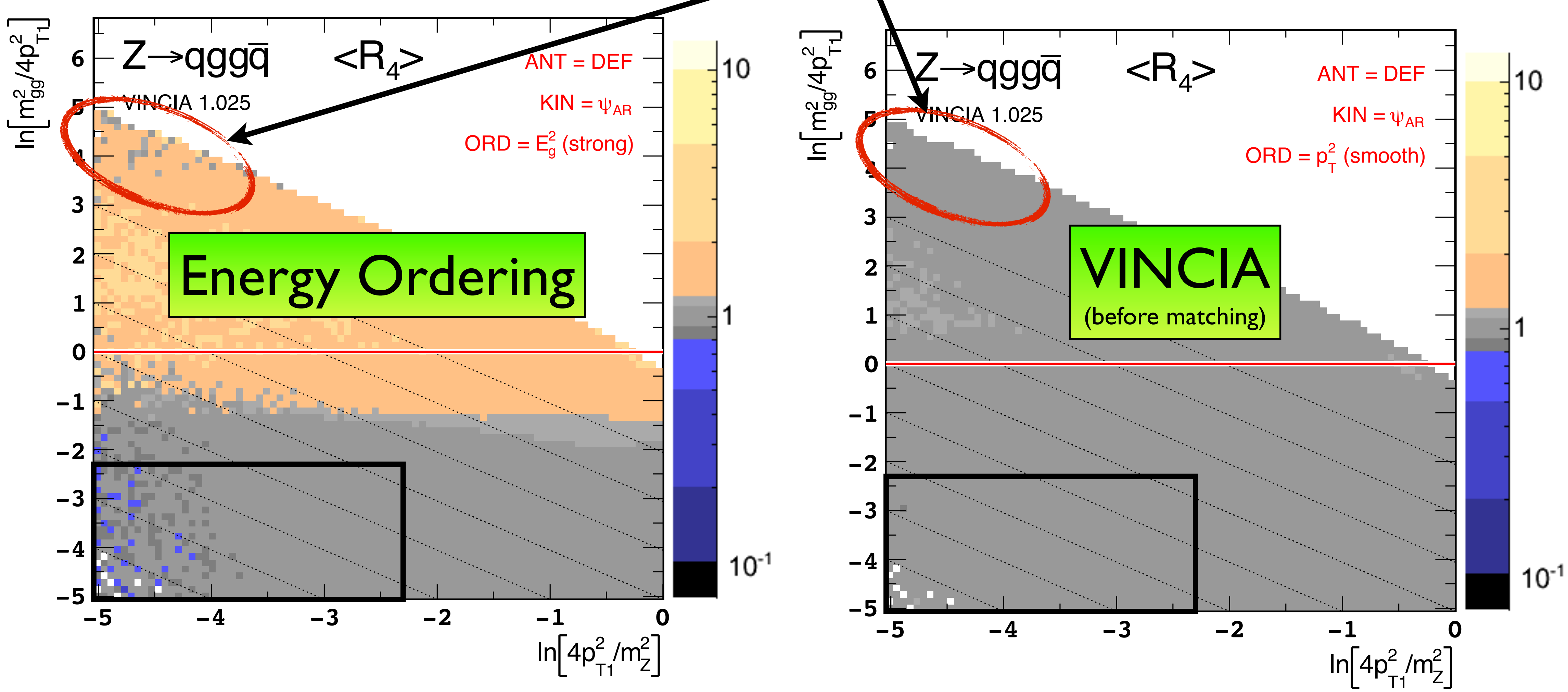


(Subleading Singularities)

Isolate double-collinear region:

$\alpha_s^2 \ln^2$

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



Markov Showers

Change restart to Markov criterion:

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

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

Unique restart scale, independently of how it was produced

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

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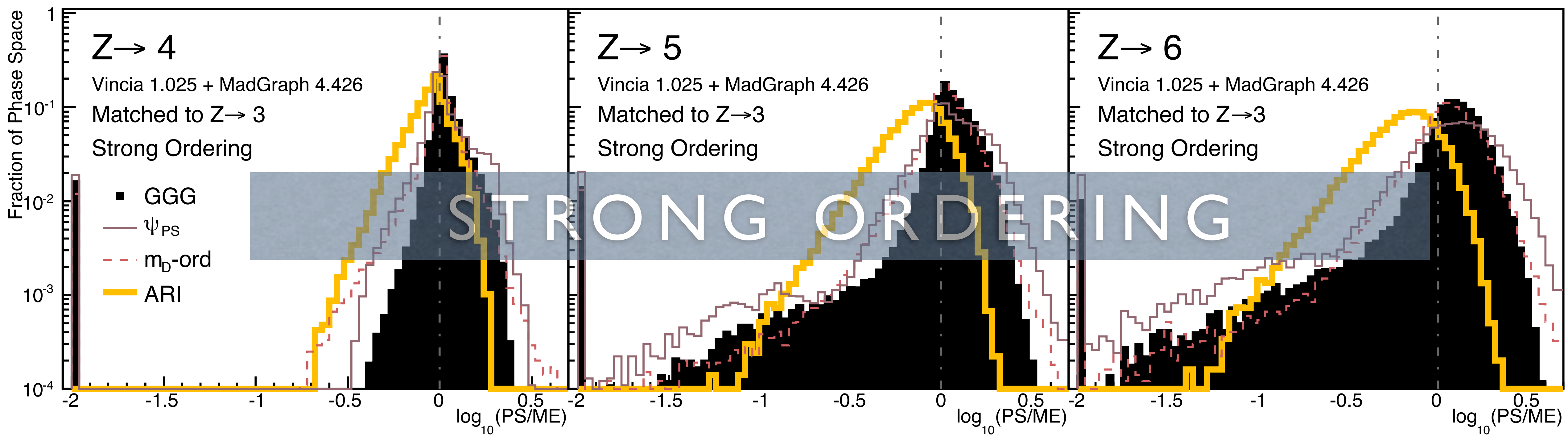
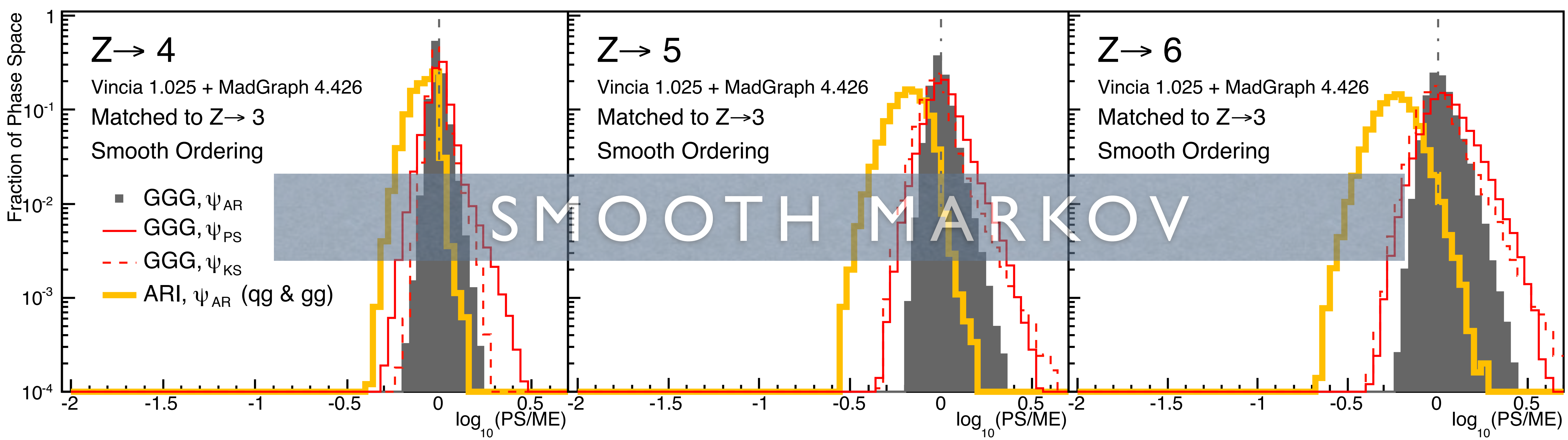
$|M_n|^2$: *Unique weight, independently of how it was produced*

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

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

Better Approximations



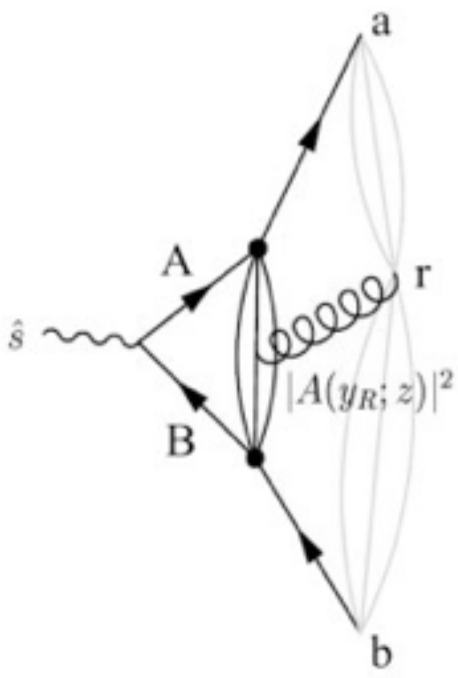


(Subleading Colour: Shower)

Leading Singularity Structure of [q,g,…,g,qbar]

= Sum over LC antennae + [q,qbar] antenna with relative colour factor -1/N_c^2

Reference?



Negative sign → cannot treat probabilistically (negative weights)

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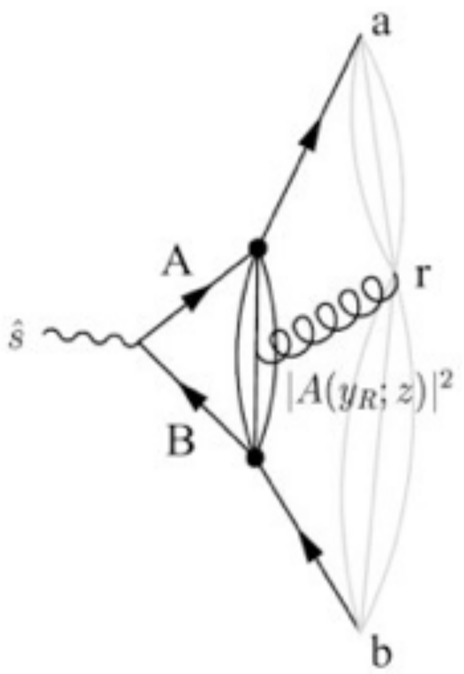

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Gustafson: treat by being careful where you use C_F and where C_A Reference?

Try to be different: partition subleading one into leading ones → "NLC"

$$\sum_{IK\in LC} \tilde{a}_{IK}(y_{ij},y_{jk})\left(1-\frac{f_{IK}}{N_C^2}\frac{\tilde{a}_{NLC}(y_{ij},y_{jk})}{\tilde{a}_{IK}(y_{ij},y_{jk})}\right)$$

$$f_{IK}=\frac{\tilde{a}_{IK}(y_{ij},y_{jk})}{\sum_{AB\in LC}\tilde{a}_{AB}(y_{ar},y_{rb})}$$

Partition of unity?

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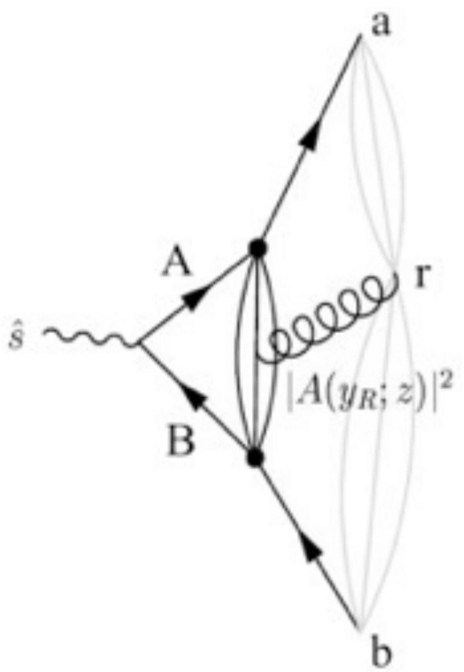

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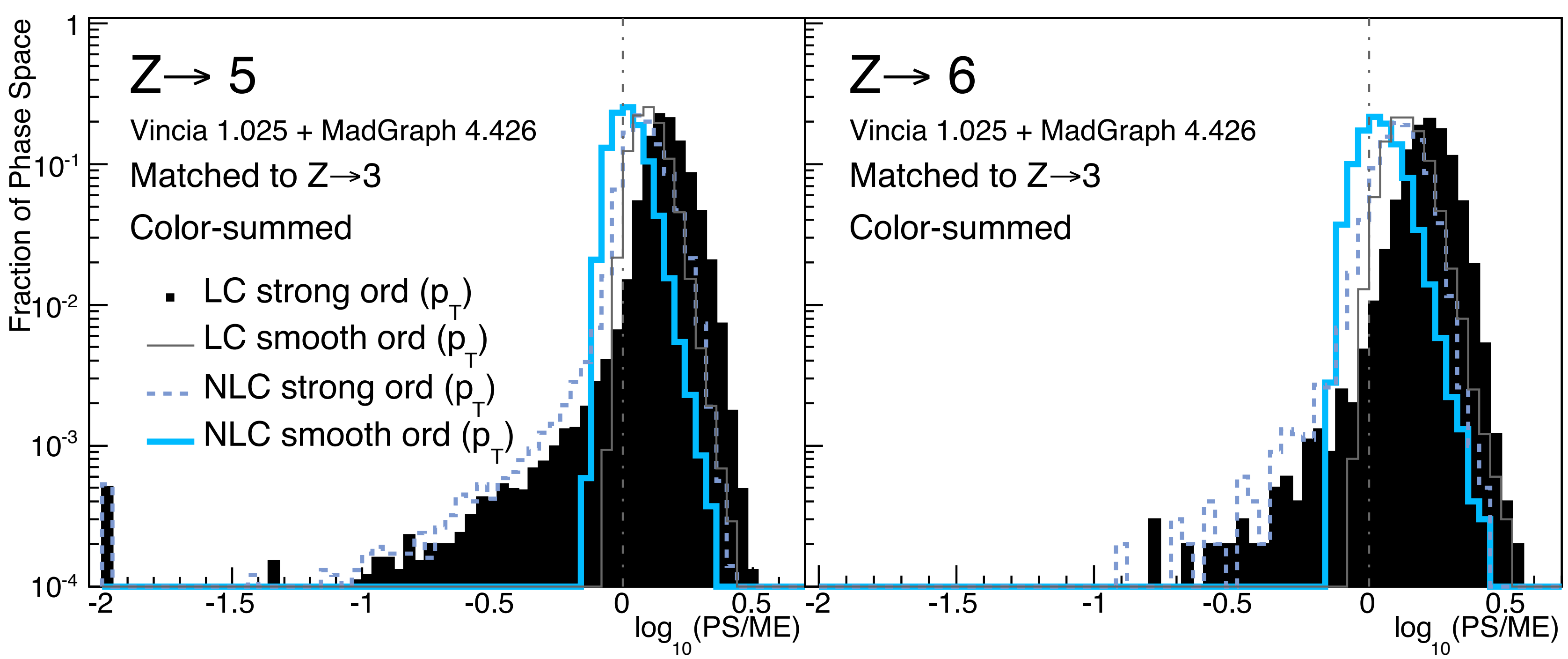


The Full Deal: GeeKS

Why GeeKS? Many people with G, K, and S
Giele, Kosower, Skands + Sjöstrand, Gustafson, GGG, …

Match to full-color matrix elements

Replace LC matrix elements by

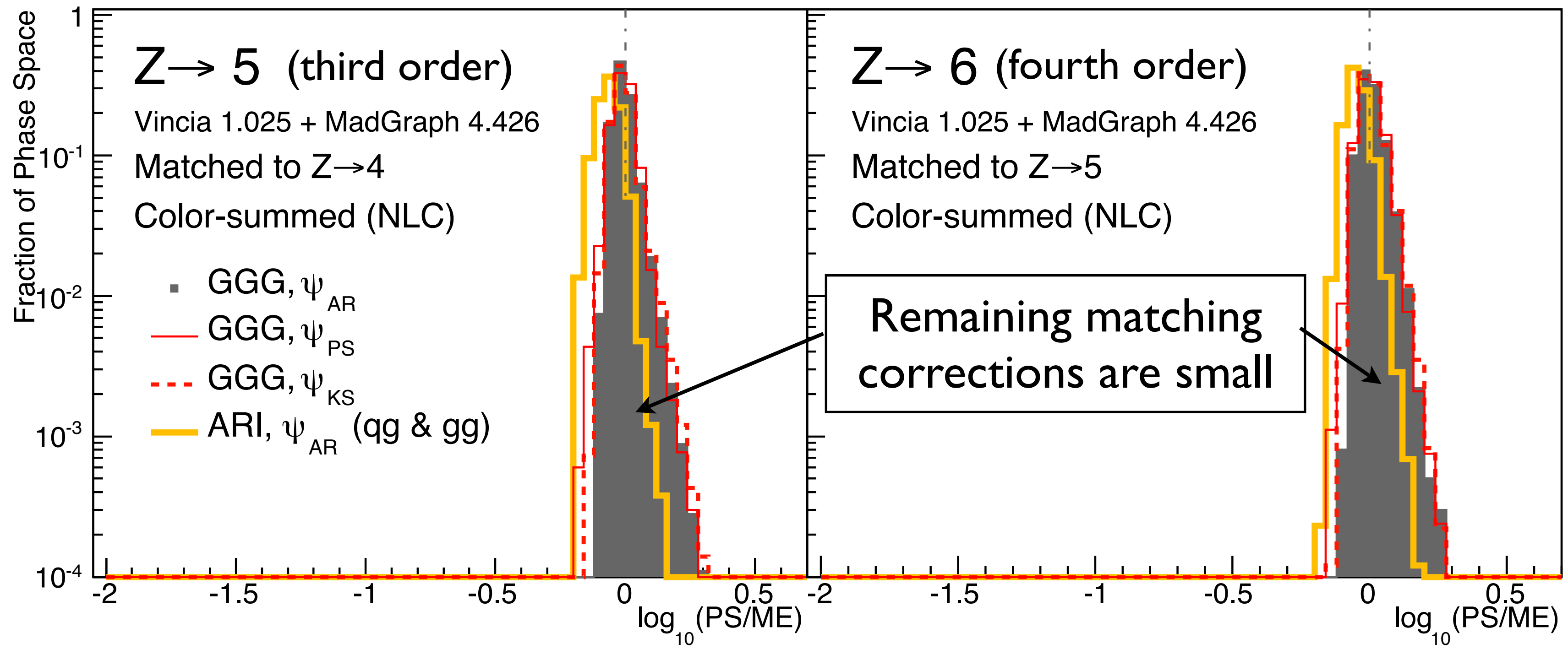
$$|M_i|^2 \quad \rightarrow \quad |M_i|^2 + \frac{|M_i|^2}{\sum_j |M_j|^2} \sum_{j \neq k} M_j M_k^*$$

$$= \quad |M_i|^2 \left(\frac{\sum_{j,k} M_j M_k^*}{\sum_j |M_k|^2} \right)$$

Full-Color Matrix Element

Leading-Color Matrix Element

→ A very good all-orders starting point



What is the matching scale?

Matching corrections well-behaved over all of phase space

→ *Can match over all of phase space*

→ *forget about "matching scales" (set = 0)*

(can still impose a (small) one for high multiplicities, for speed)

(will also make multi-leg NLO matching possible/easier)

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Reason is:

Matching at each preceding order + unitarity

→ *Subleading divergencies of matrix-element corrections are resummed, order by order, up to matched multiplicities*

(we are not yet sure they are CORRECTLY resummed)

How many separate samples must I generate?

Matching corrections applied directly to Markov chain as it evolves, phase-space-point-by-phase-space-point

→ One single event sample

(Effectively, n-parton samples use parton shower itself as phase space generator = highly efficient "multi-channel" integration)

similar to SARGE?

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How about weighted events? Negative weights?

Unitarity → unit weights (no negative)

(more specifically: Born-level weights preserved, so can still pre-weight Born distribution if desired)

Uncertainties

Uncertainty Variations

A result is only as good as its uncertainty

- VINCIA has been designed with *a lot* of flexibility for this
- 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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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

GKS: all events have weight = 1

Recompute *unitary* weights for many different assumptions

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

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

Uncertainties

For each branching, recompute weight for:

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

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

+ Matching

Differences explicitly matched out

(Up to matched orders)

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

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

Does not work

Unitarity Again

Uncertainty weights:

Emission probabilities different, but Sudakovs unchanged

→ not unitary

→ *runaway products!*

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How to modify Sudakovs?

Analytic?

Trial Showers?

Learn from our failures … ?

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How to modify Sudakovs?

Analytic? Intractable

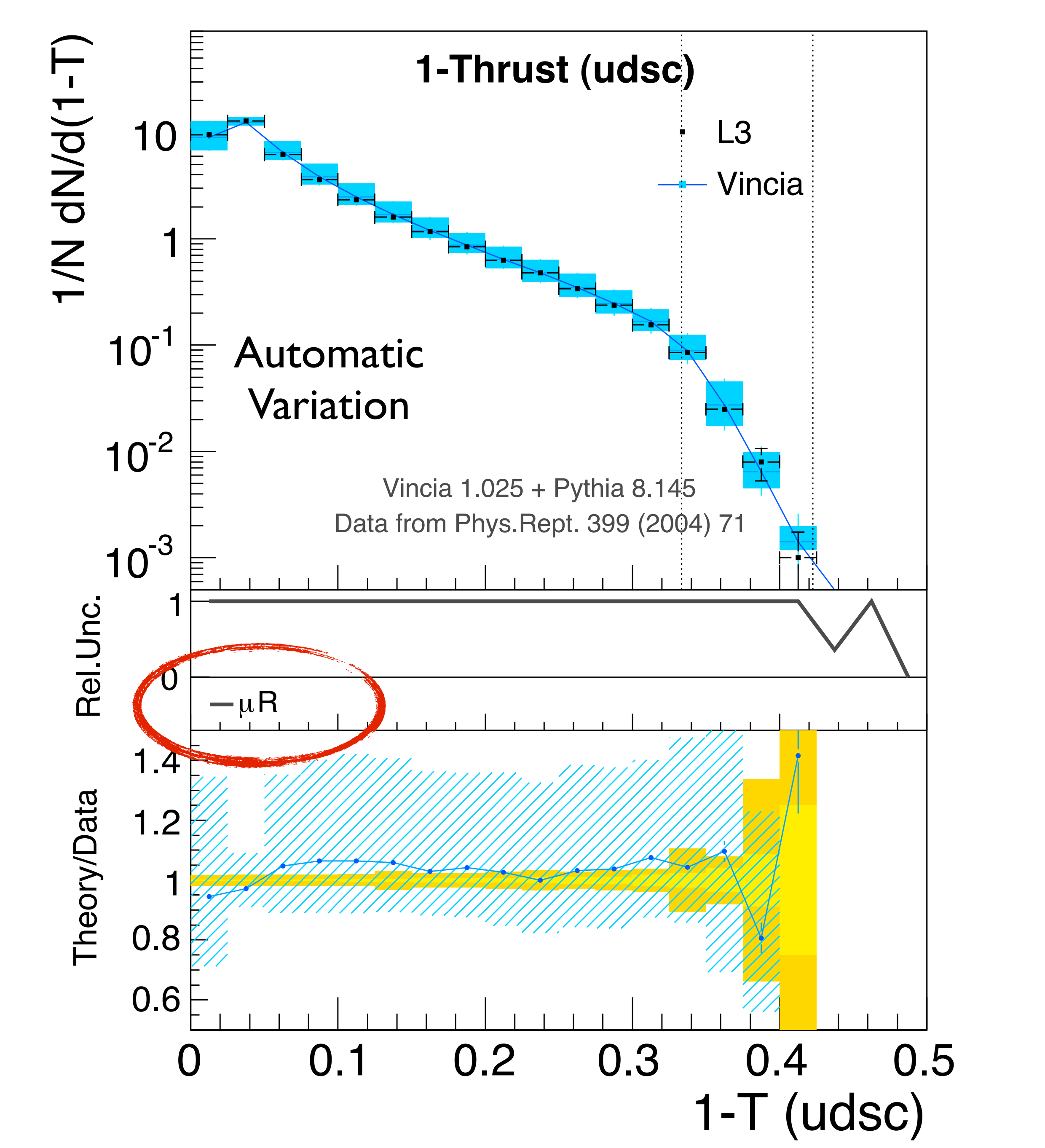
Trial Showers? Too slow

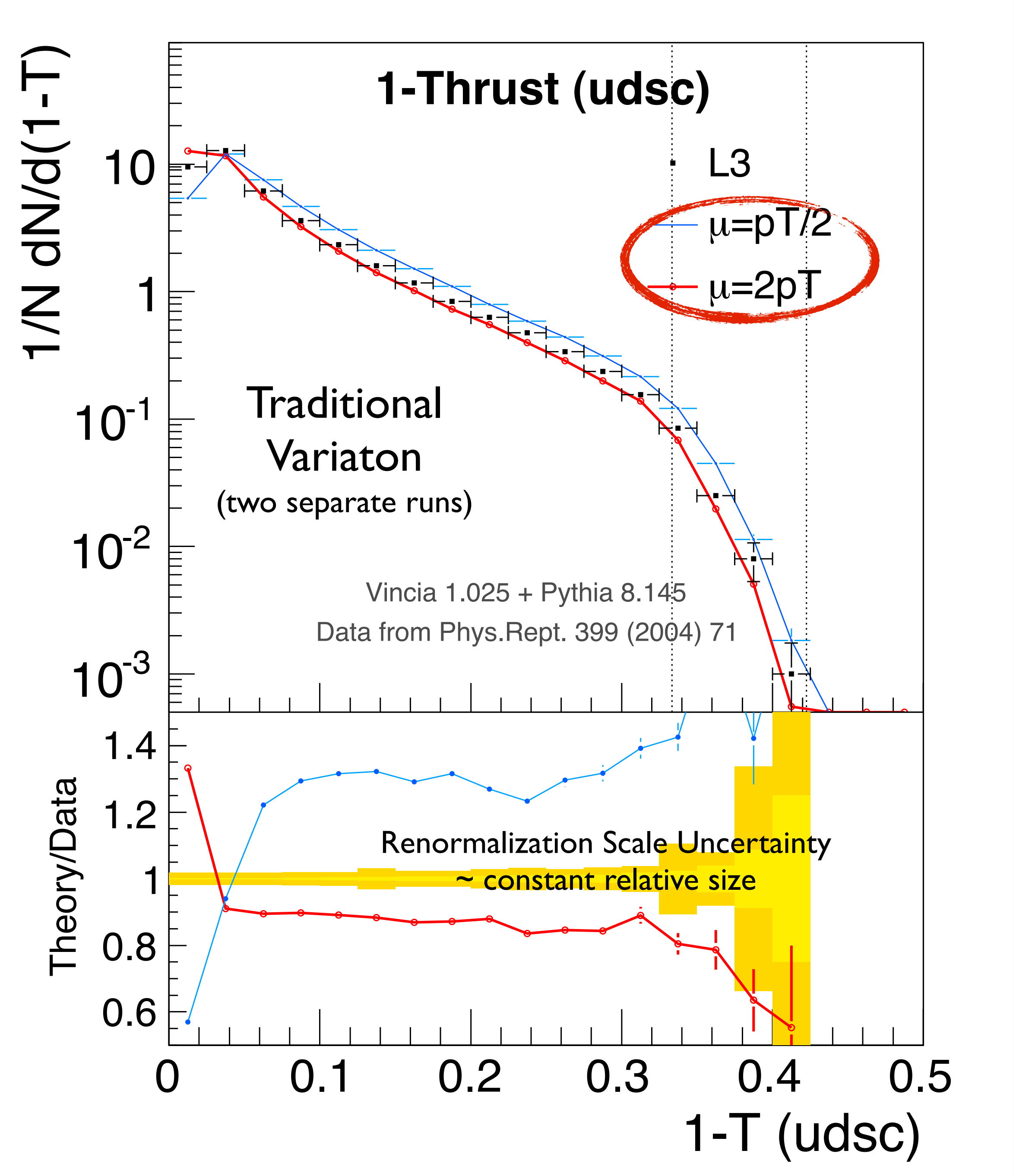
Learn from our failures … ? Yes

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





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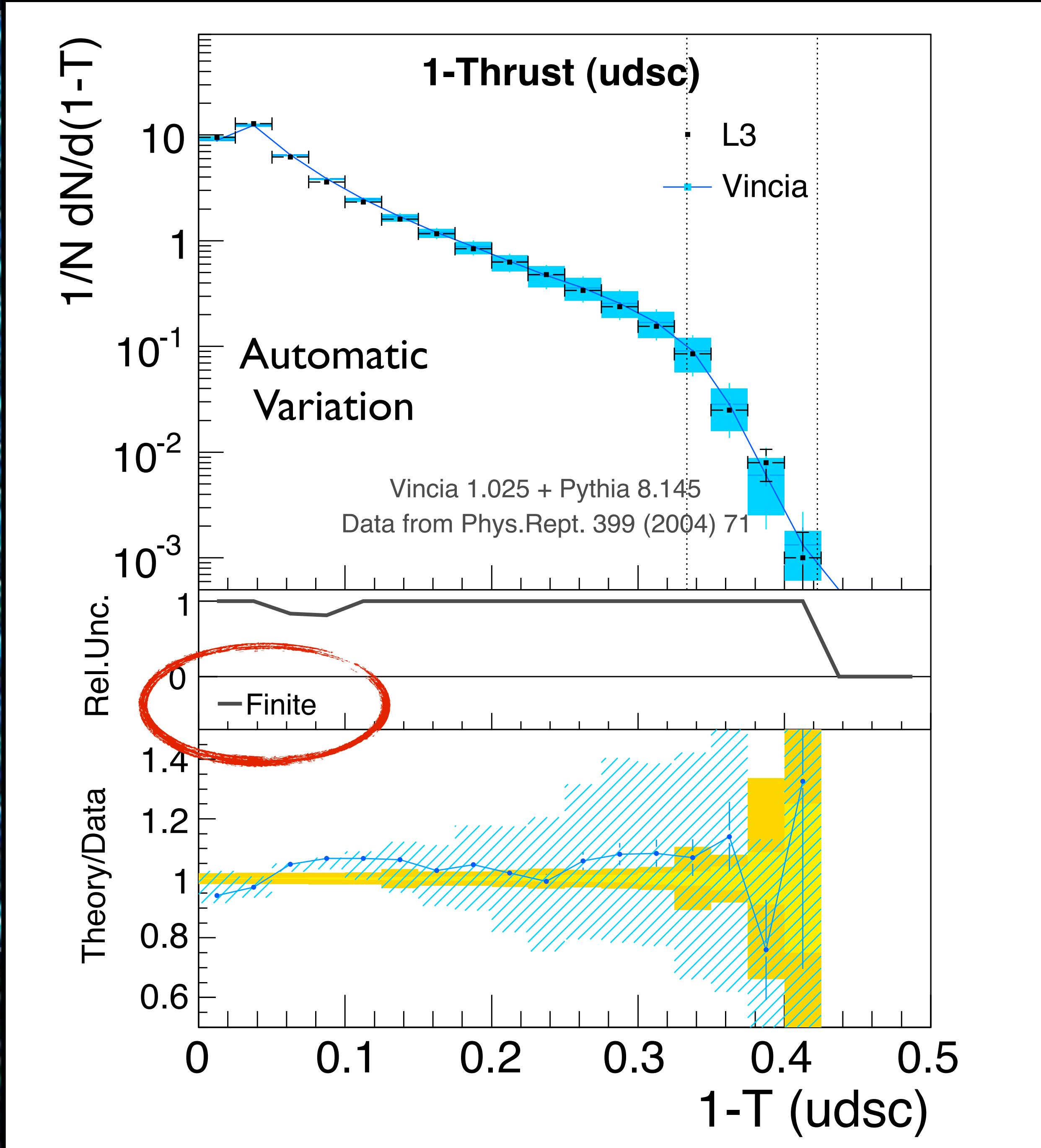
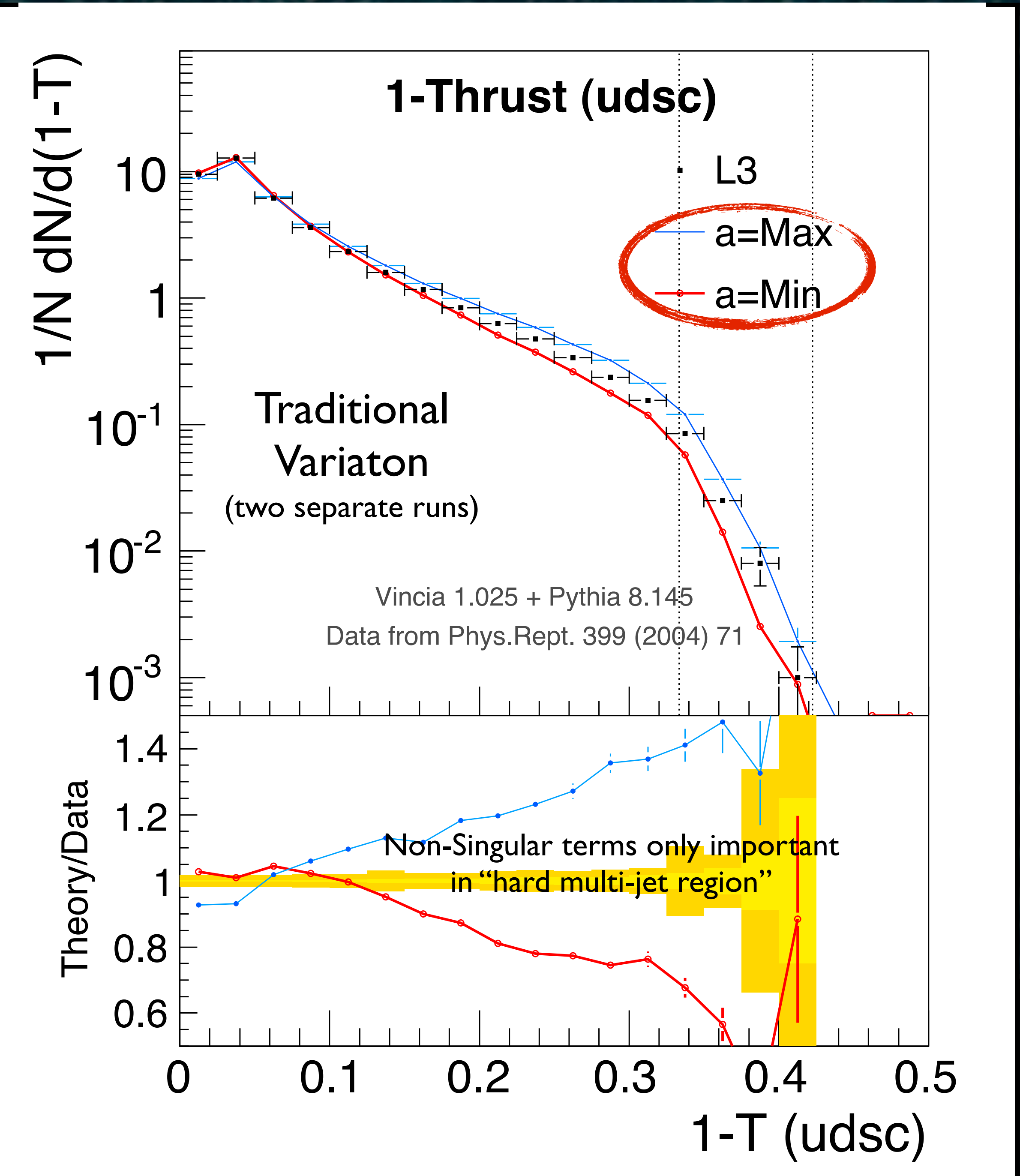
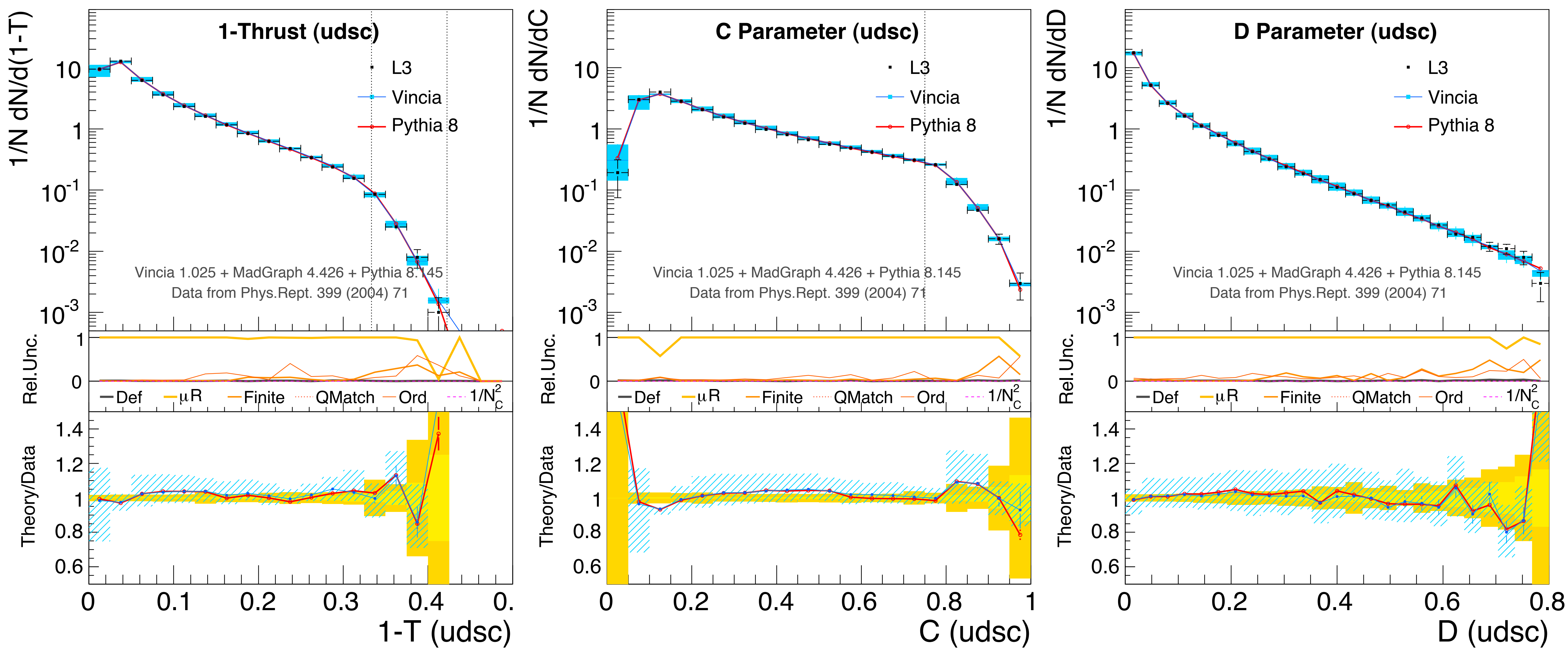




The Proof of the …

… lies in the eating

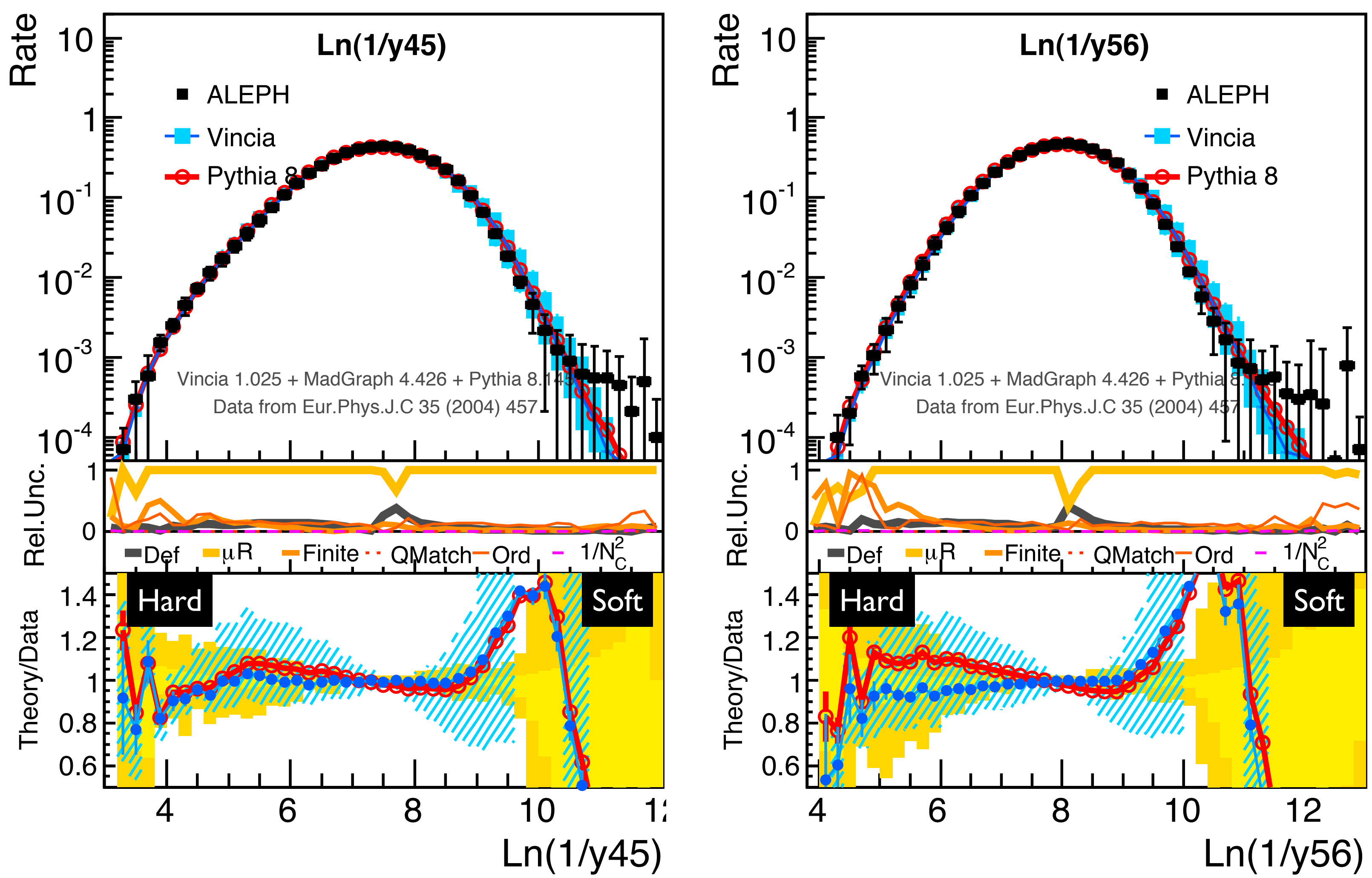
LEP event shapes



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

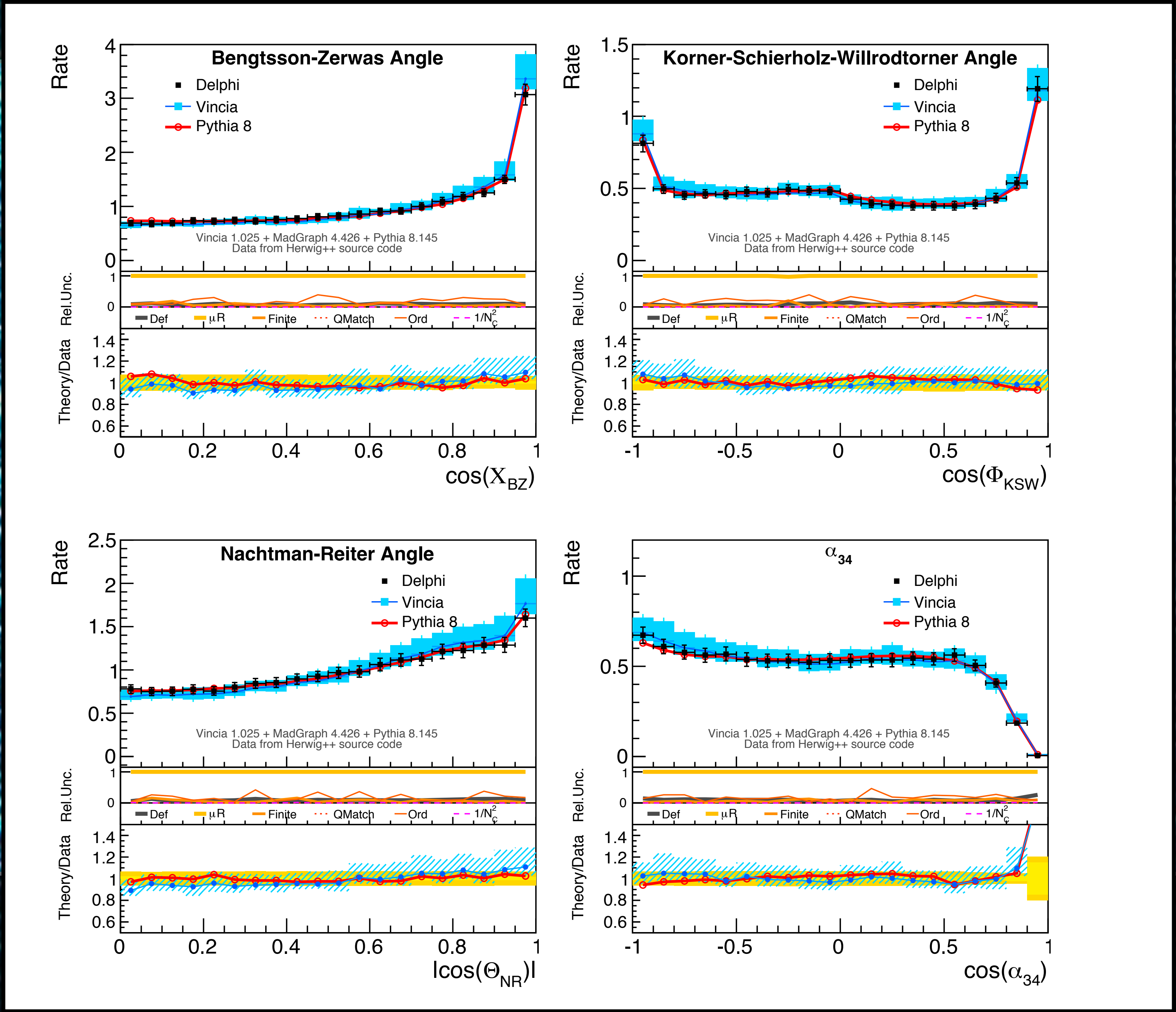
Good News

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?

Summary

VINCIA Status

Stable and reliable for LEP observables

Automatic matching and uncertainty bands

+ some improvements in shower (smooth ordering, NLC)

Paper on massless implementation ~ ready (2010?)

Mass corrections implemented, expect paper early 2011

Next steps

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

"Sector Showers" (with J. Lopez-Villarejo, CERN)

→ Initial-State Showers

Plug-in to PYTHIA 8

http://home.fnal.gov/~skands/vincia/