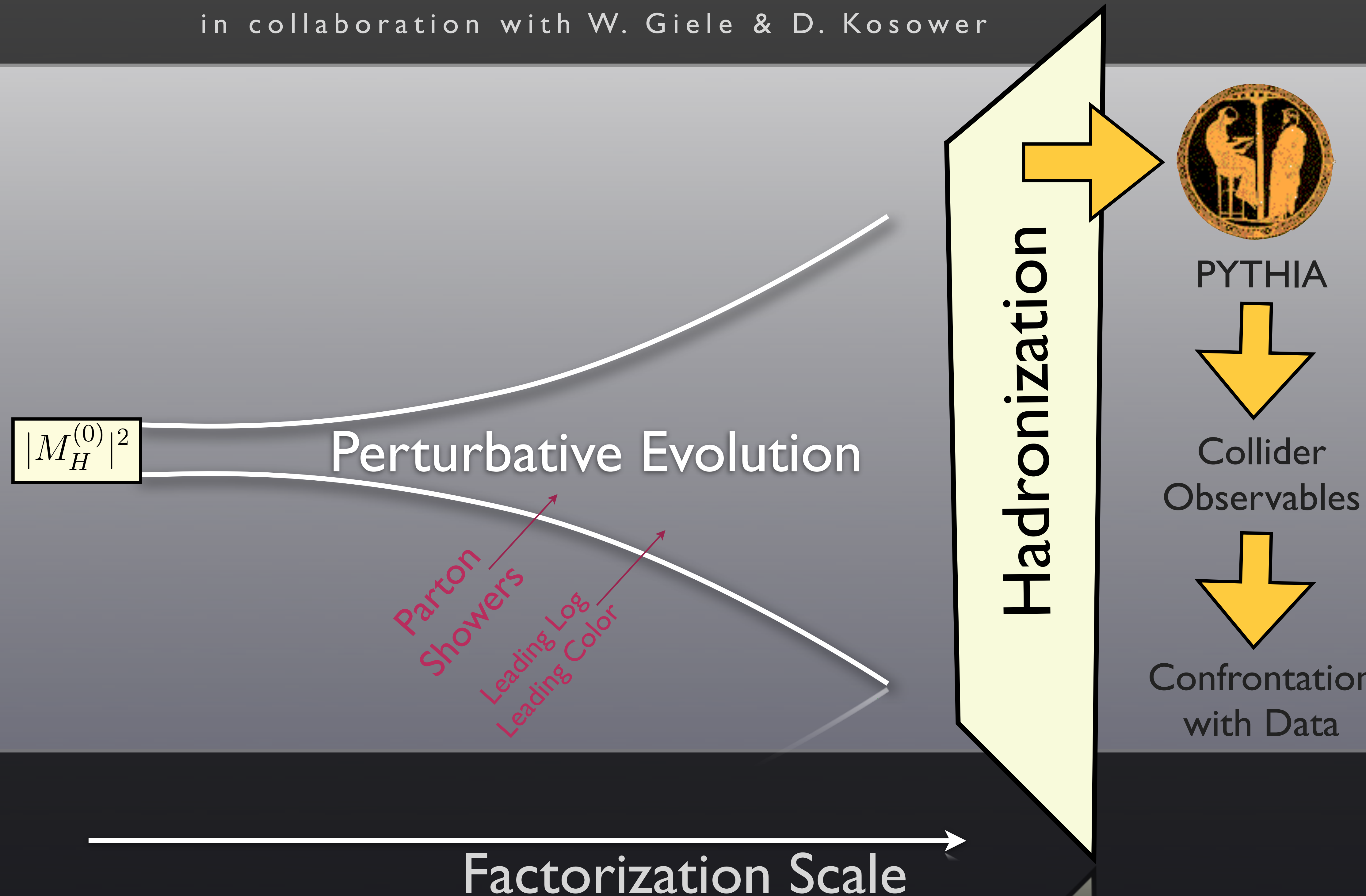
A New Formalism for LO Matching

P. Skands & J. Lopez-Villarejo (CERN)

in collaboration with W. Giele & D. Kosower



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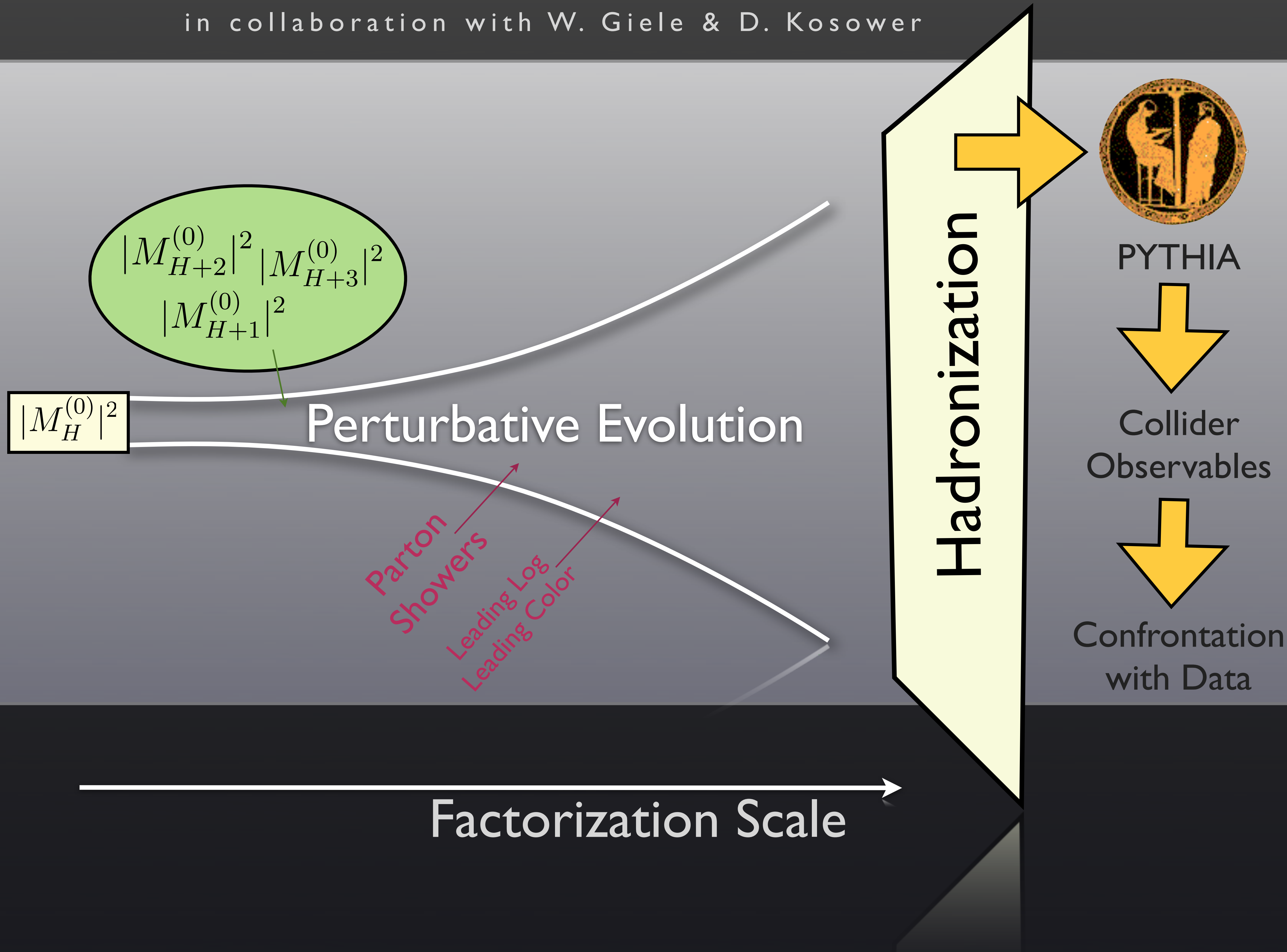

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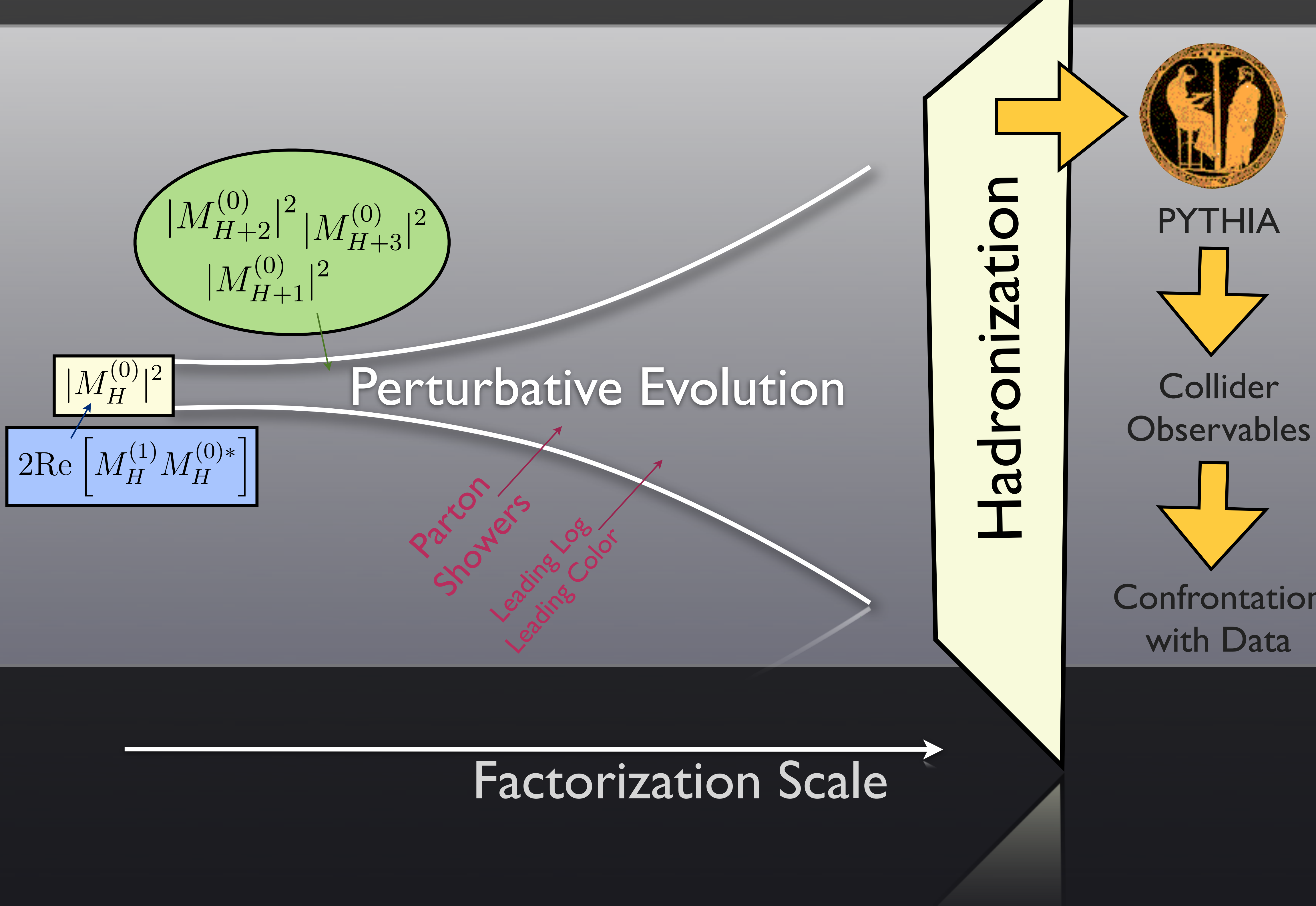

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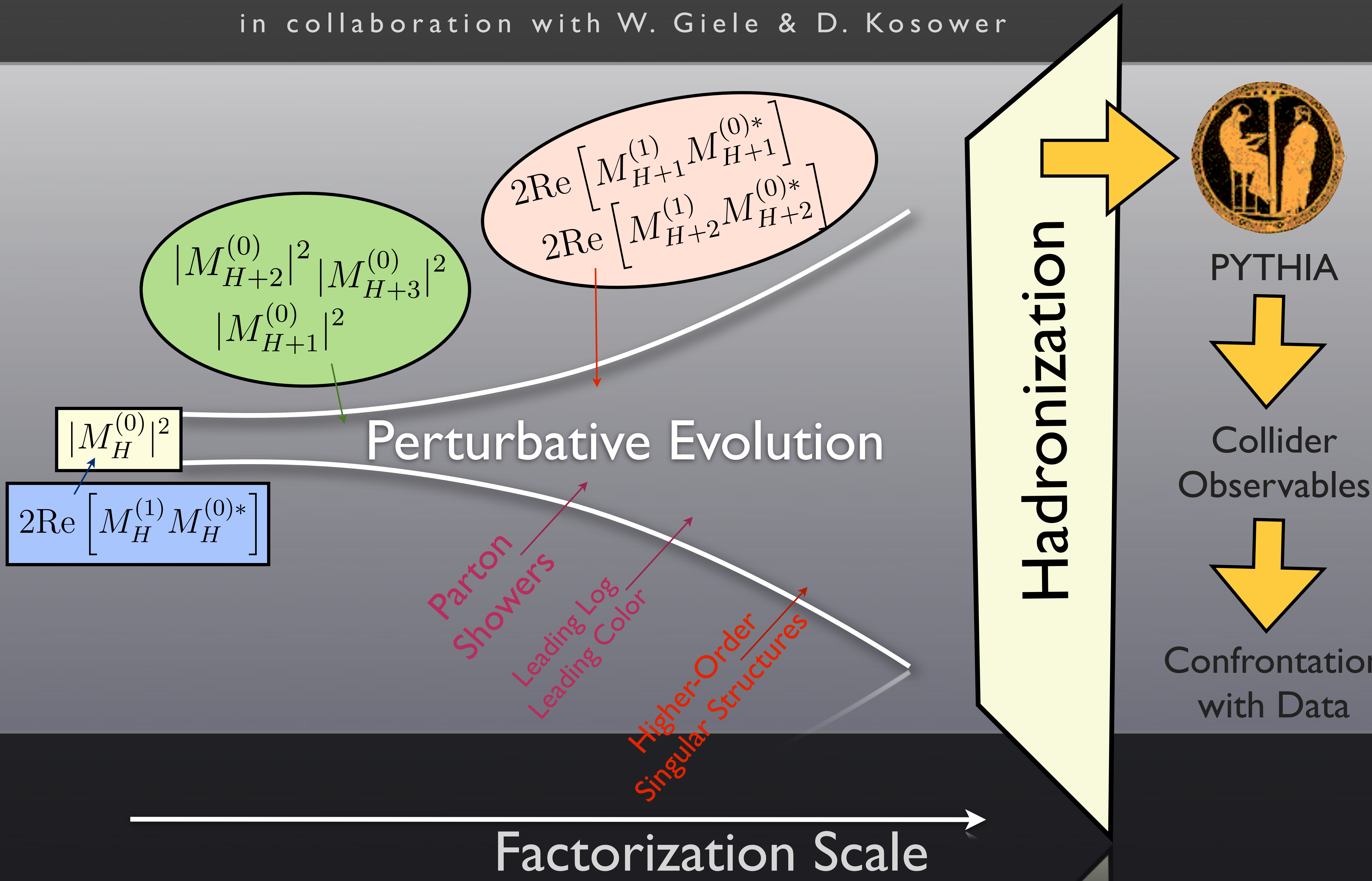


"New" ?

For matching to the first emission:

= PYTHIA scheme Sjöstrand & Bengtsson, Phys.Lett. B185 (1987) 435, Nucl.Phys. B289 (1987) 810

(reformulated for antennae)

For matching to the first loop:

= POWHEG scheme Nason, JHEP 0411 (2004) 040; Nason, Ridolfi, JHEP 0608 (2006) 077; …

(real-emission part same as PYTHIA, hence compatible)

What is new (apart from antennae): Giele, Kosower, Skands, arXiv:1102.2126 (accepted, PRD)

Repeating this for the next emission, and the next, …

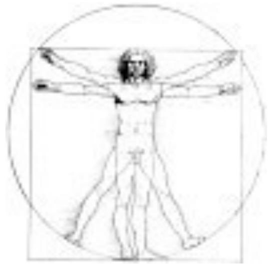
GKS ~ multileg scheme (unitary) that reduces to PYTHIA/POWHEG at 1st order

Unitarity → No "matching scale" needed

Substantially faster than MLM, CKKW (no initialization, no separate n-parton phase-spaces)

The calculation also yields ~10 automatic uncertainty estimates at a moderate speed penalty (less than running the program twice)

VINCIA



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?

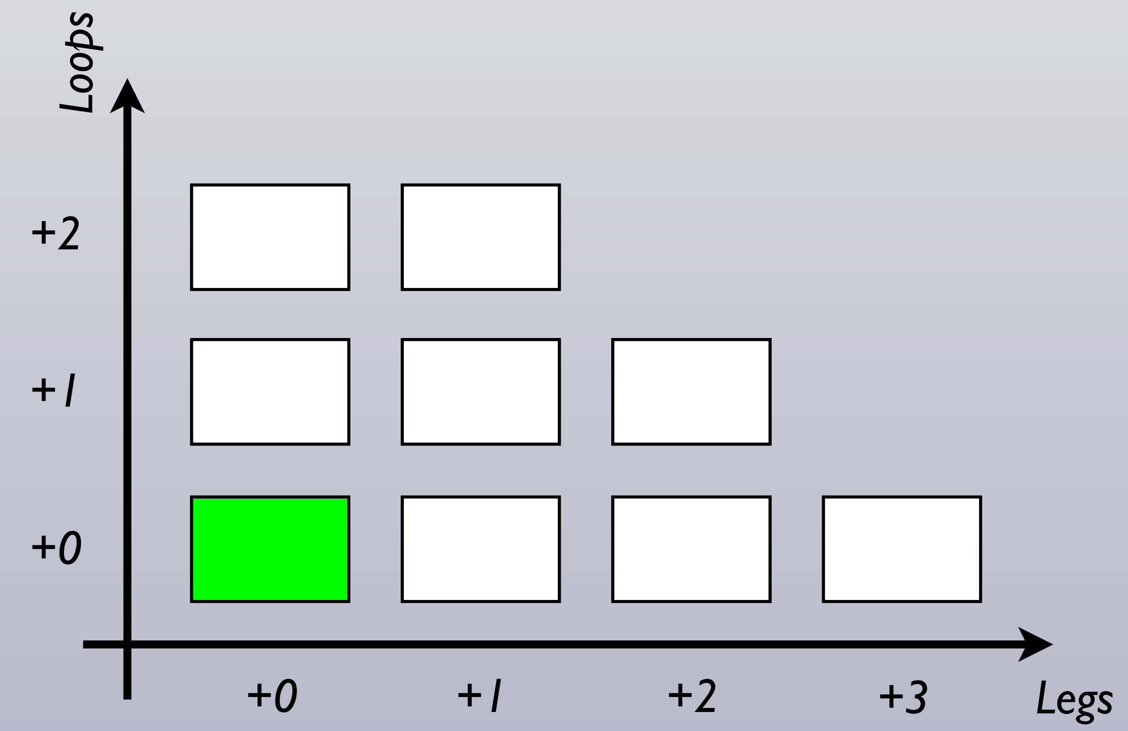
GEEKS: Giele, Kosower, Skands

+ Collaborations with Gehrmann-de-Ridder & Ritzmann *(mass effects)*, Lopez-Villarejo *(“sector showers”)*, Hartgring & Laenen *(NLO multileg)*, Diana *(ISR)*, Larkoski *(Polarization)*, Bravi & Volunteers *(Tuning)*

Markov pQCD

Start at Born level

$$|M_F|^2$$



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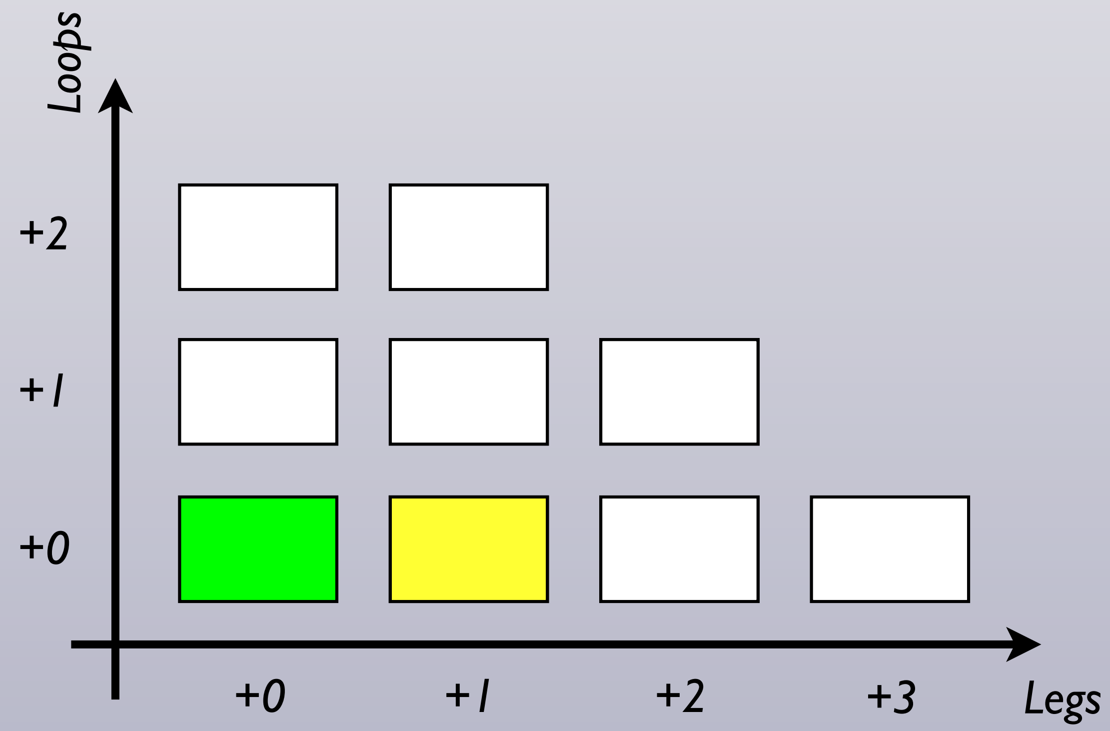
$$|M_{F+1}|^2 \overset{LL}{\sim} \sum_{i\in \mathrm{ant}} a_i \, |M_F|^2$$



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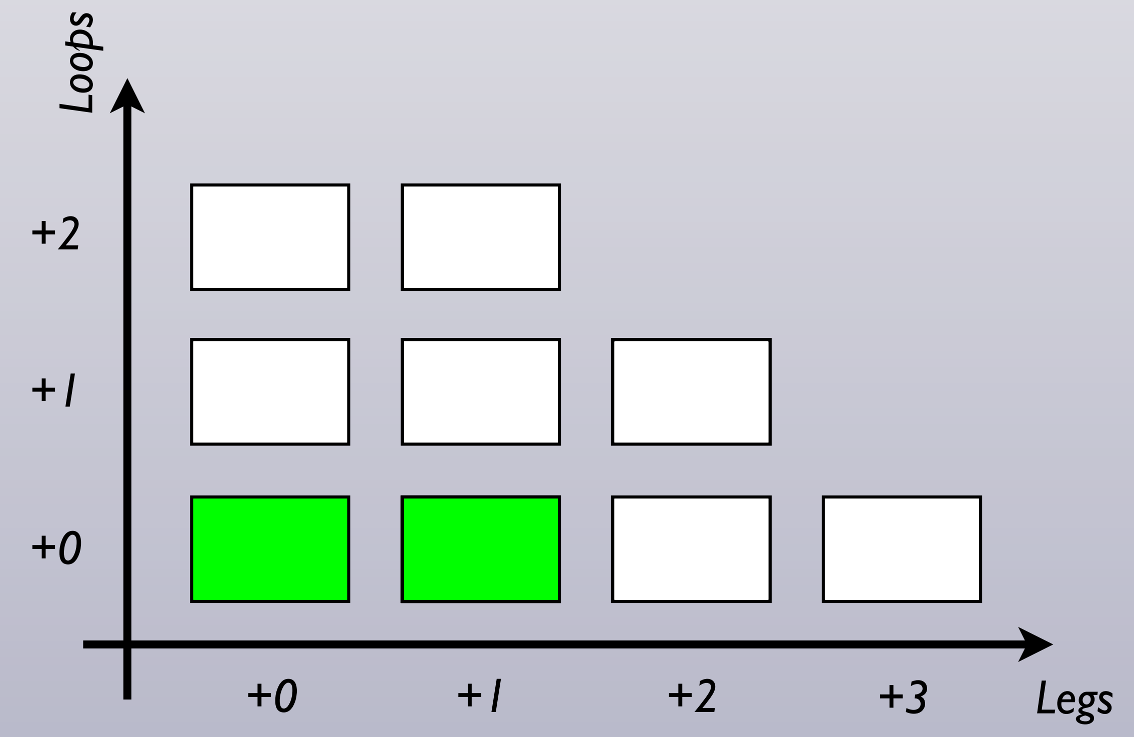
Correct to Matrix Element

PYTHIA trick

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



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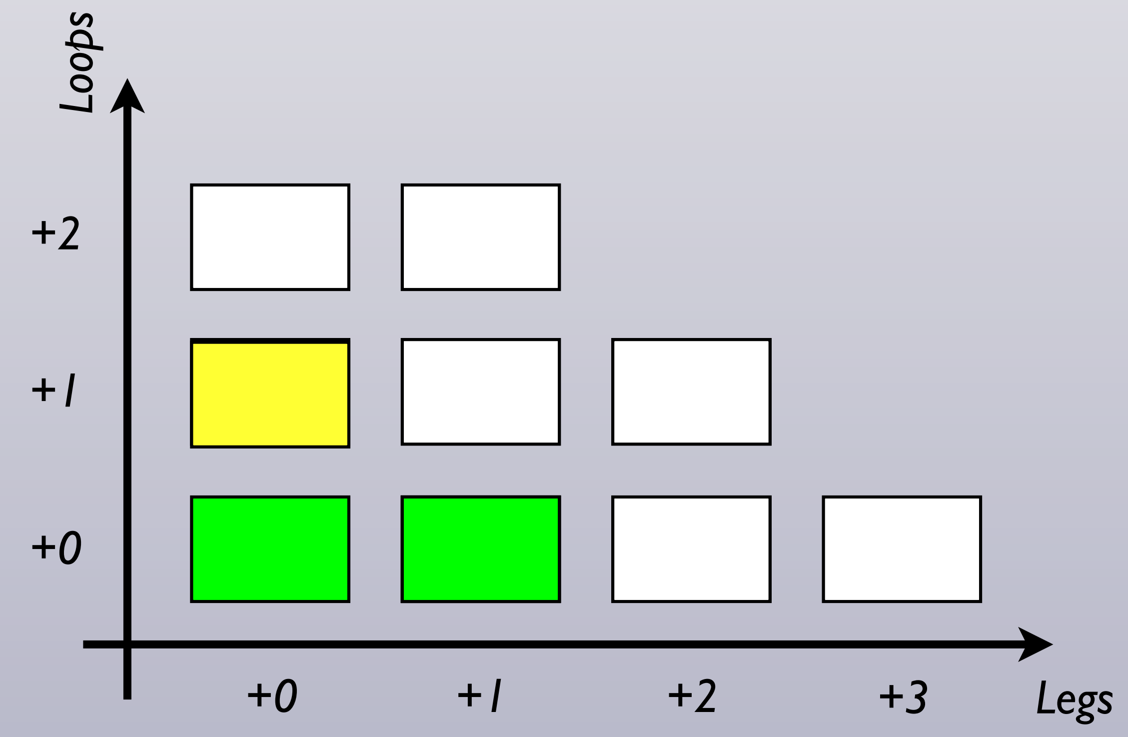
Unitarity of Shower

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



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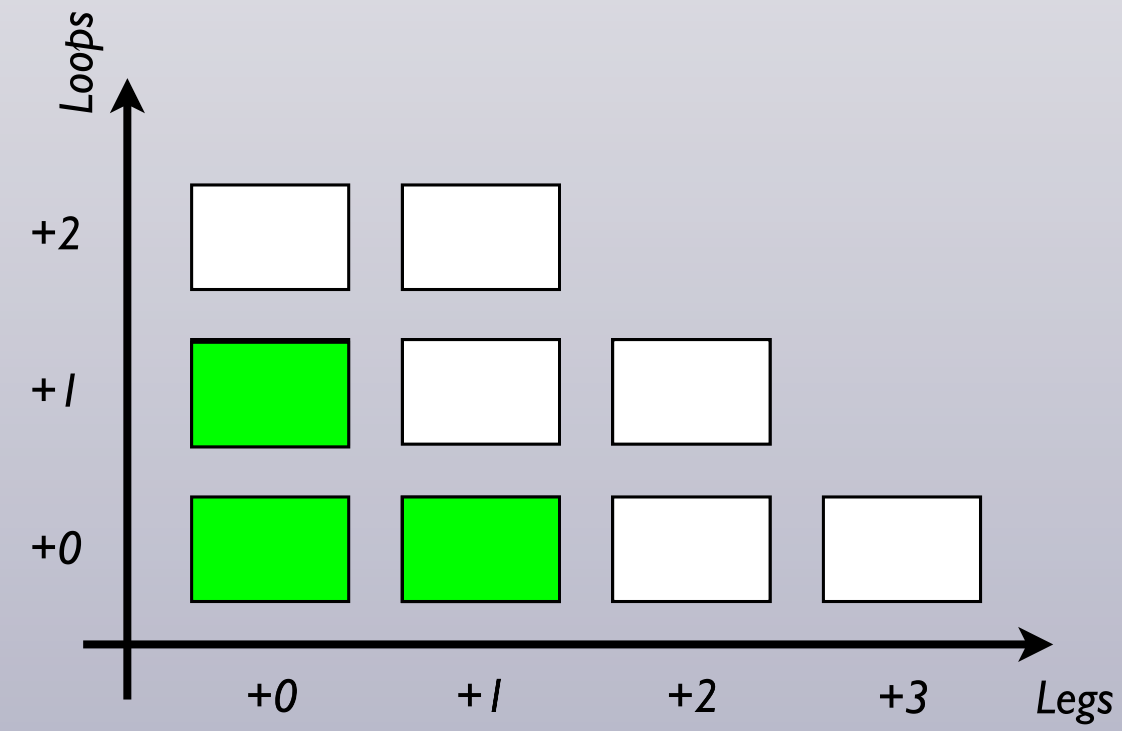

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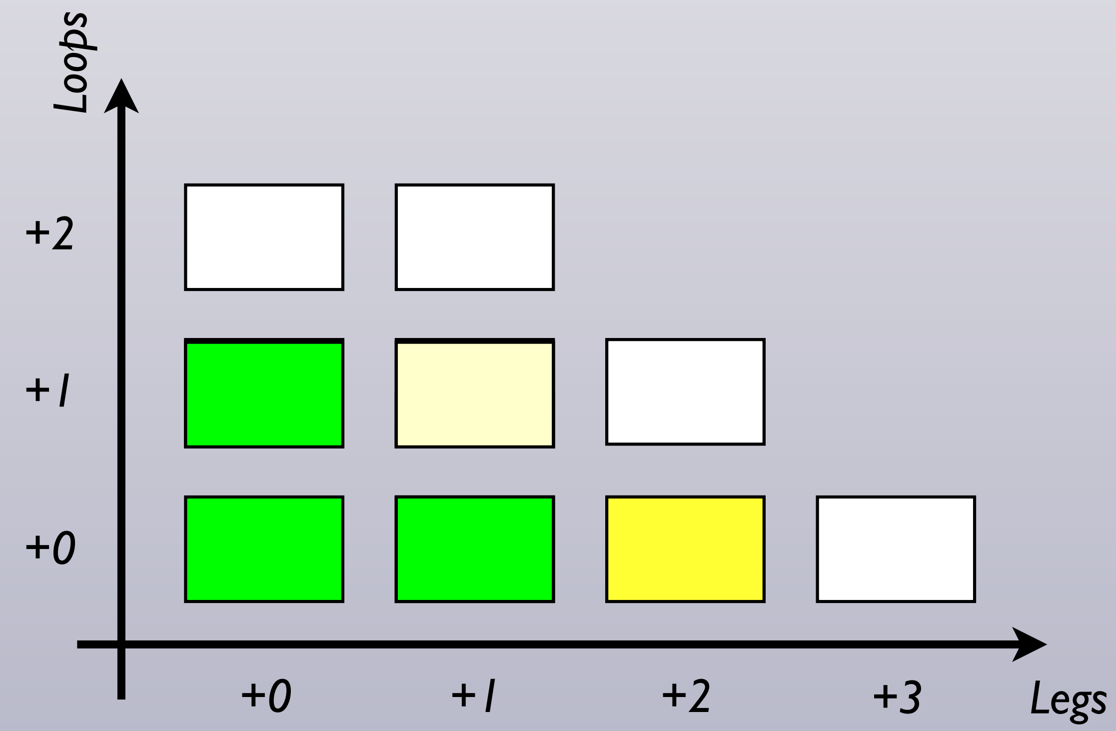

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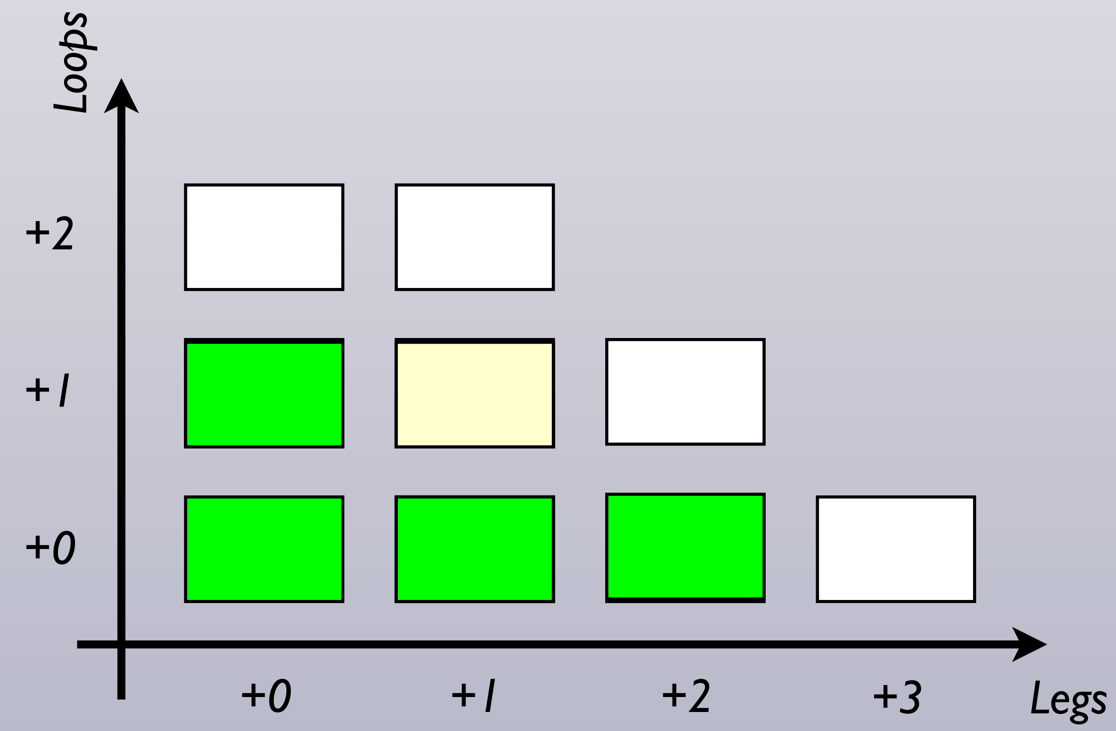

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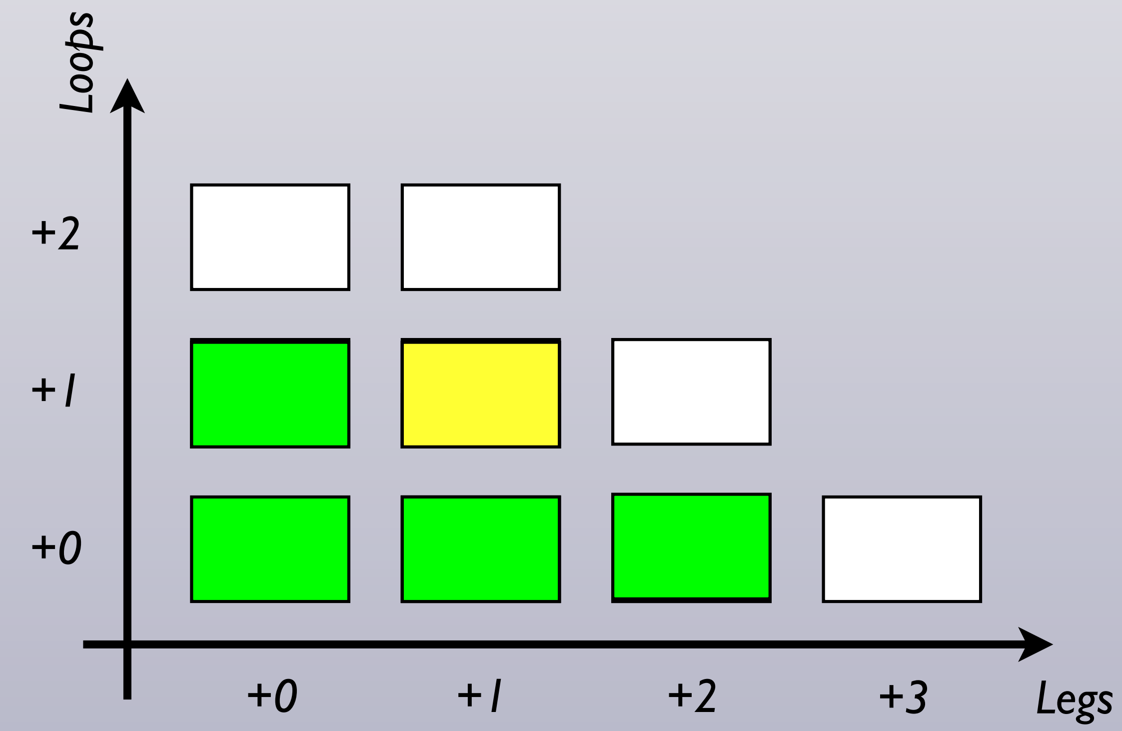

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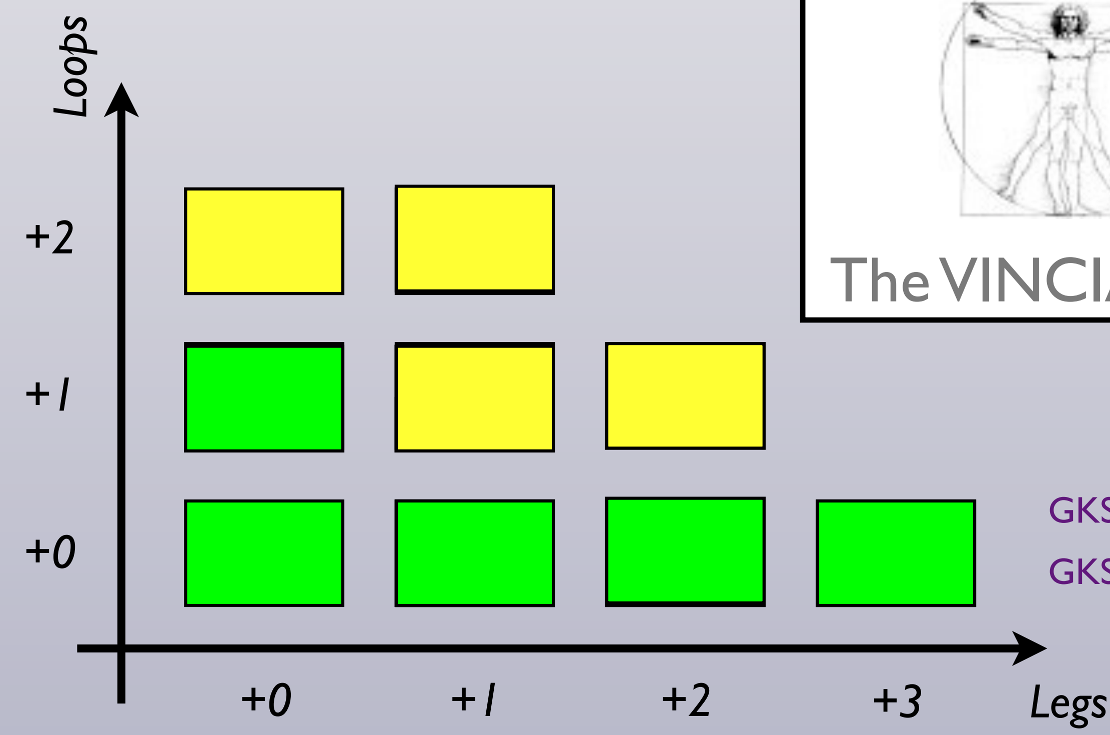
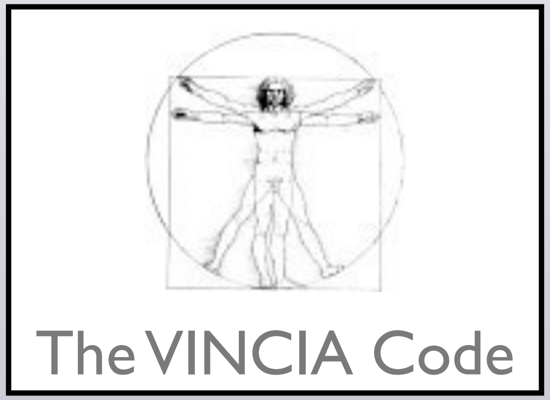


GKS, PRD78(2008)014026

GKS, arXiv:1102.2126



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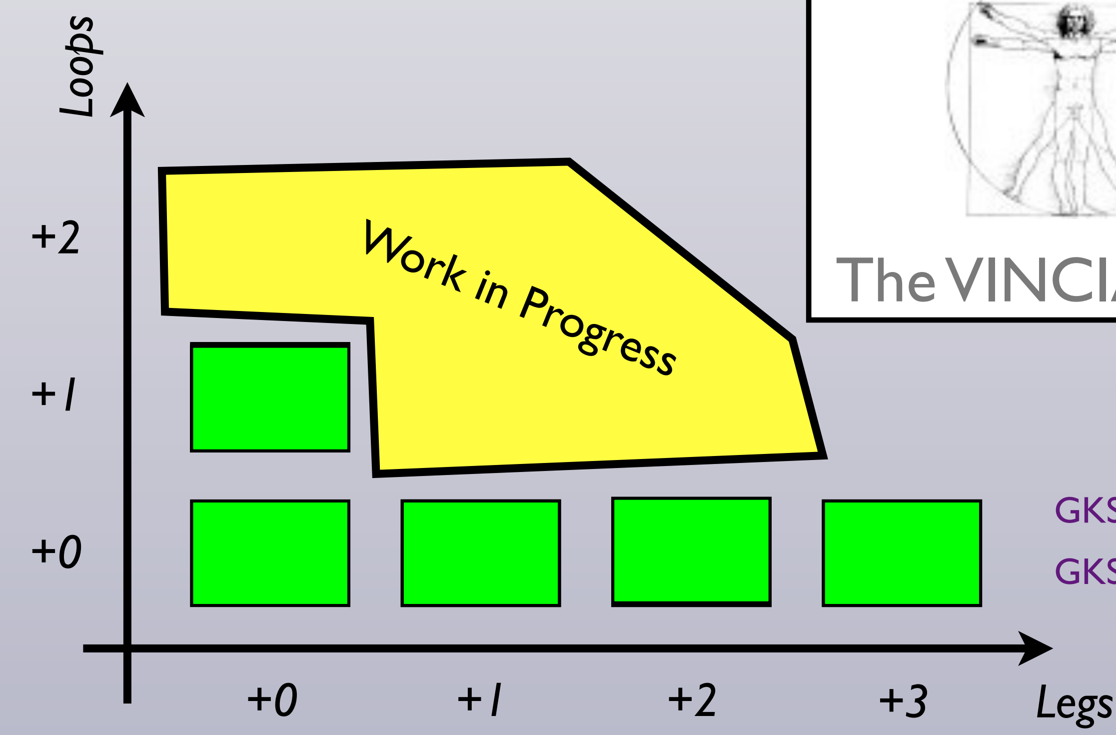

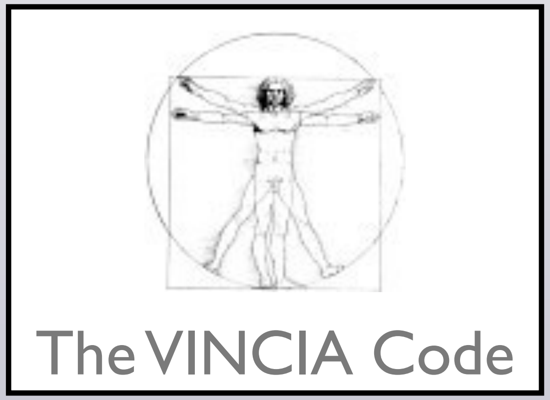

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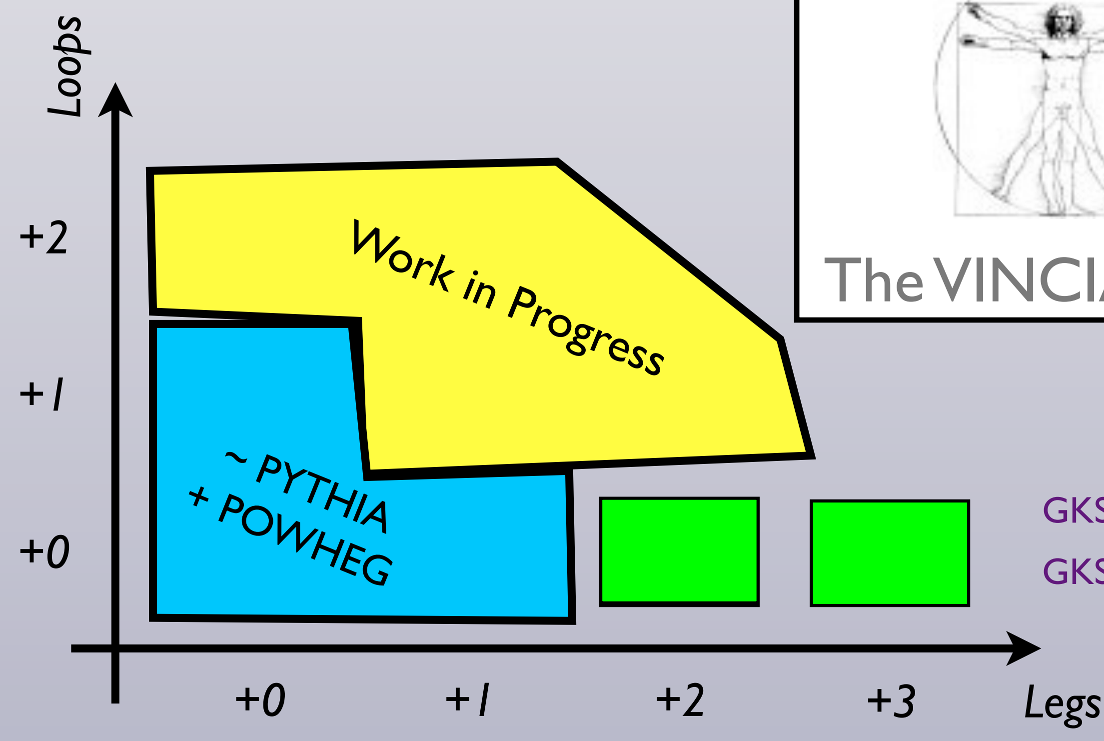

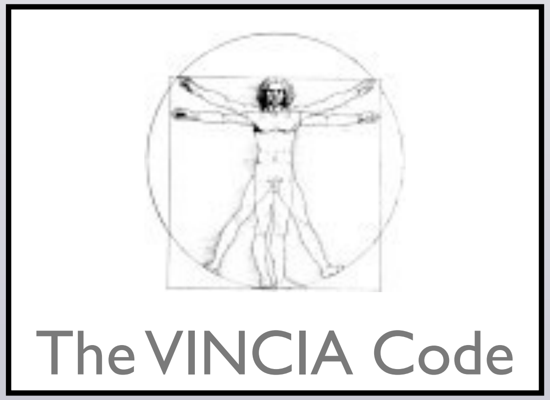

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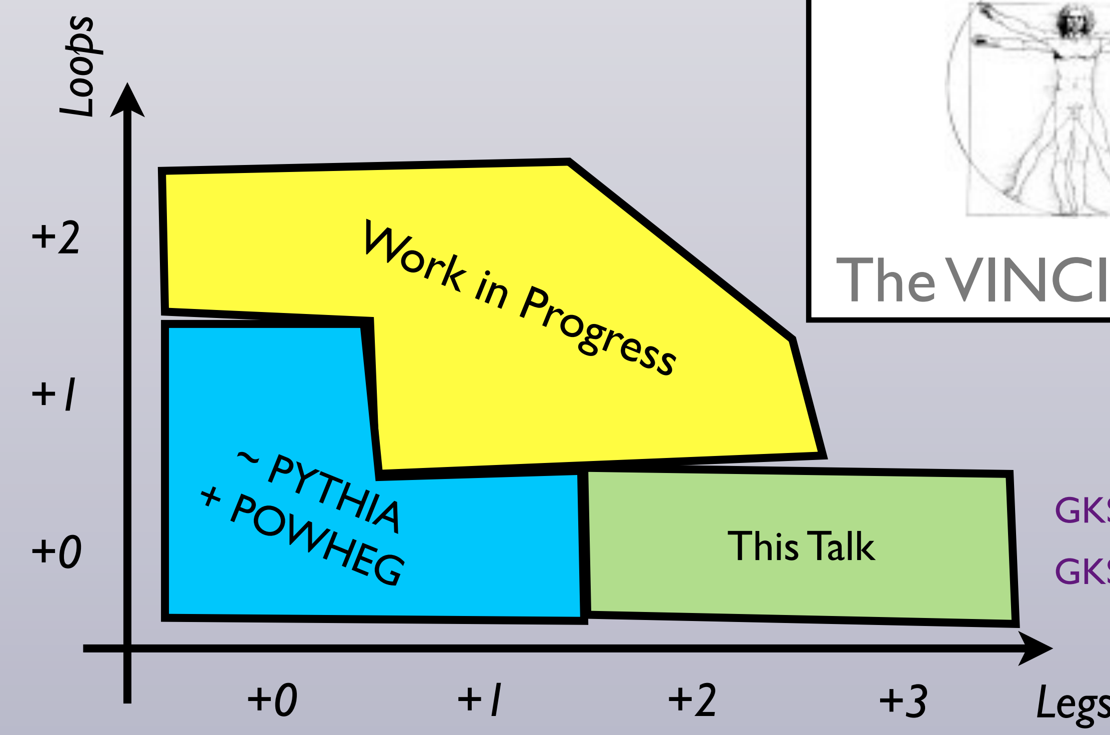

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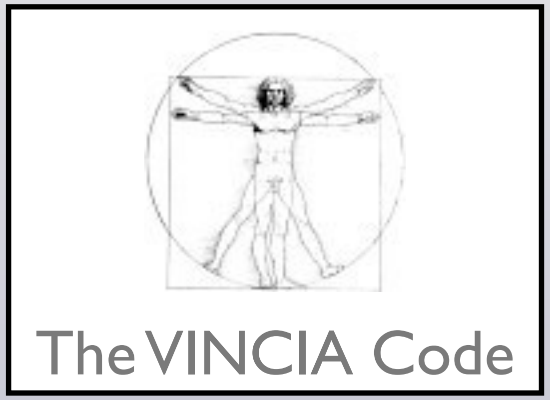

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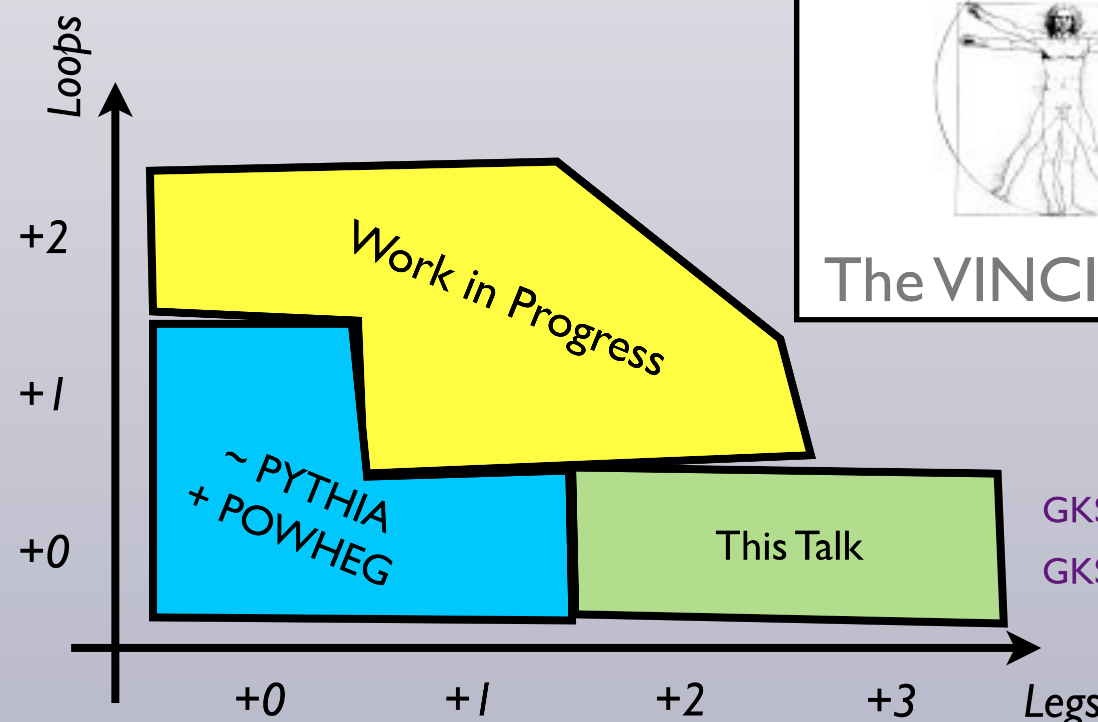

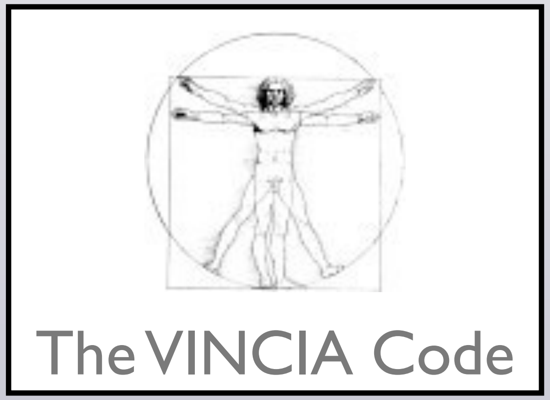

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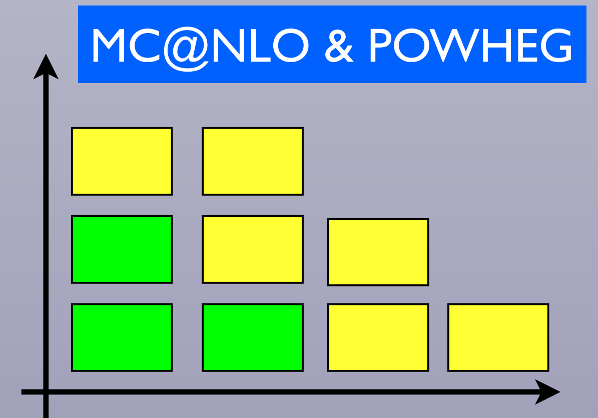
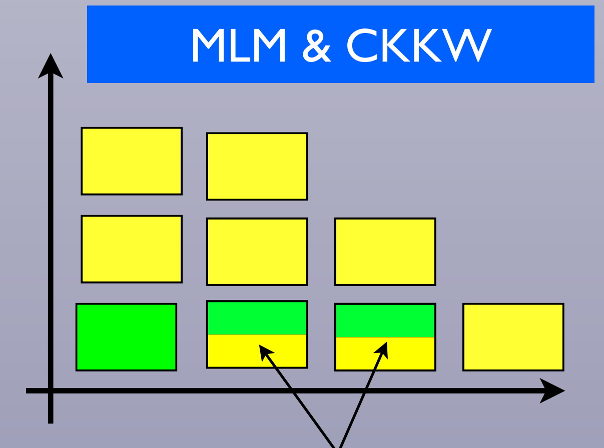


LO for 1st emission
LL for 2nd emission and beyond



"Matching Scale"
→ hierarchies not matched

The Denominator

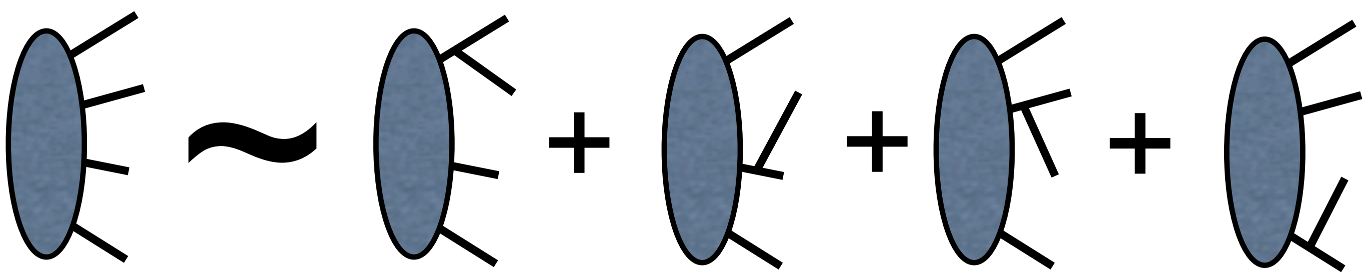
$$a_i \rightarrow \frac{|M_{F+1}|^2}{\sum a_i |M_F|^2}$$

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

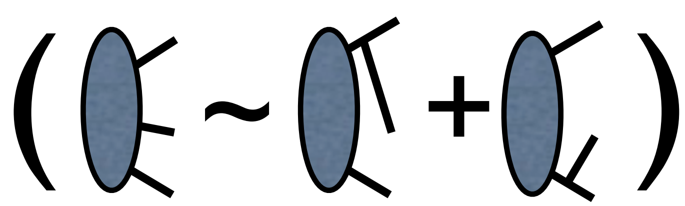
Existing parton showers are *not* really Markov Chains

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

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



j = 2
→ 4 terms



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

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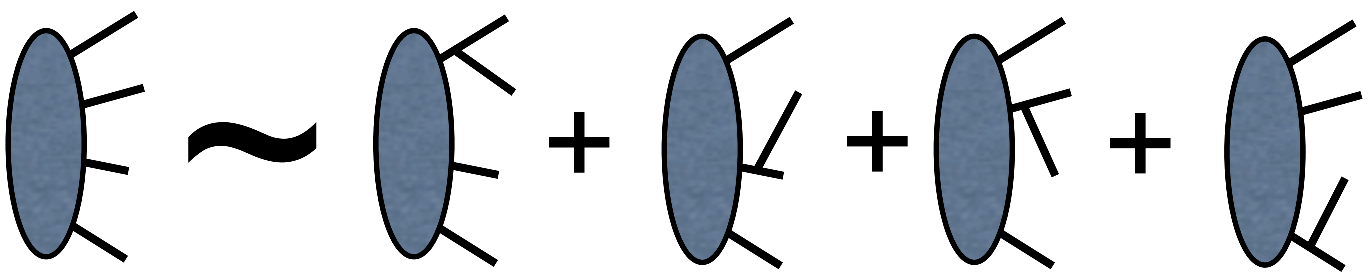

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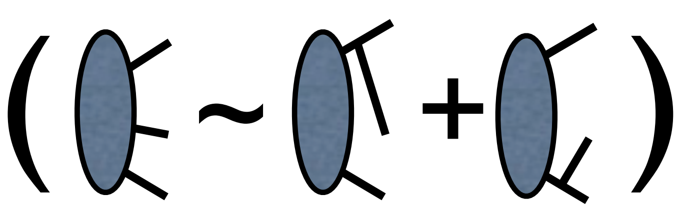

j = 1
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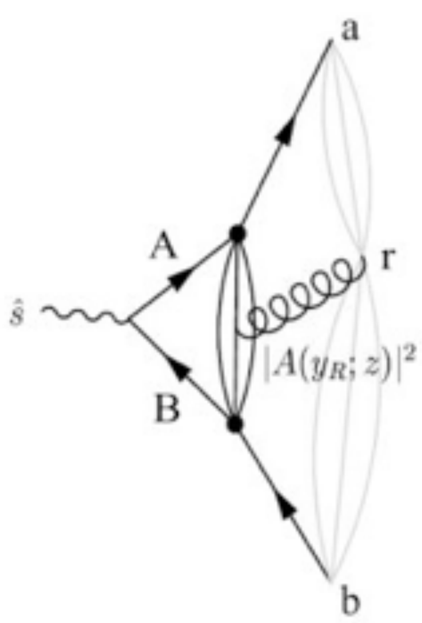
Parton- (or Catani-Seymour) Shower:
After 2 branchings: 8 terms
After 3 branchings: 48 terms
After 4 branchings: 384 terms

(+ 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* **$2^n n! \to n!$**



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

+ Change "shower restart" to Markov criterion:

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

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

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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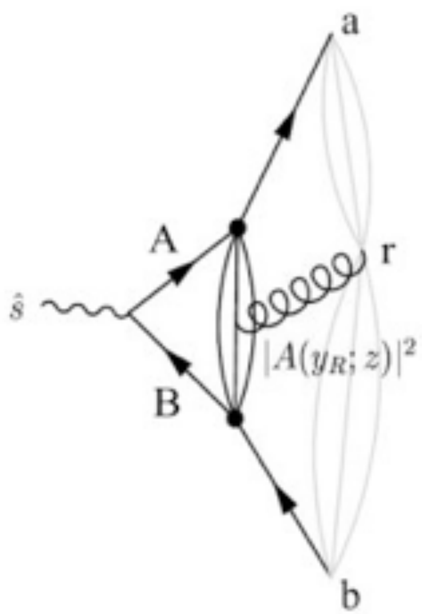

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Matched Markovian Antenna Shower:
After 2 branchings: 2 terms
After 3 branchings: 3 terms
After 4 branchings: 4 terms

+ J. Lopez-Villarejo → 1 term at *any* order

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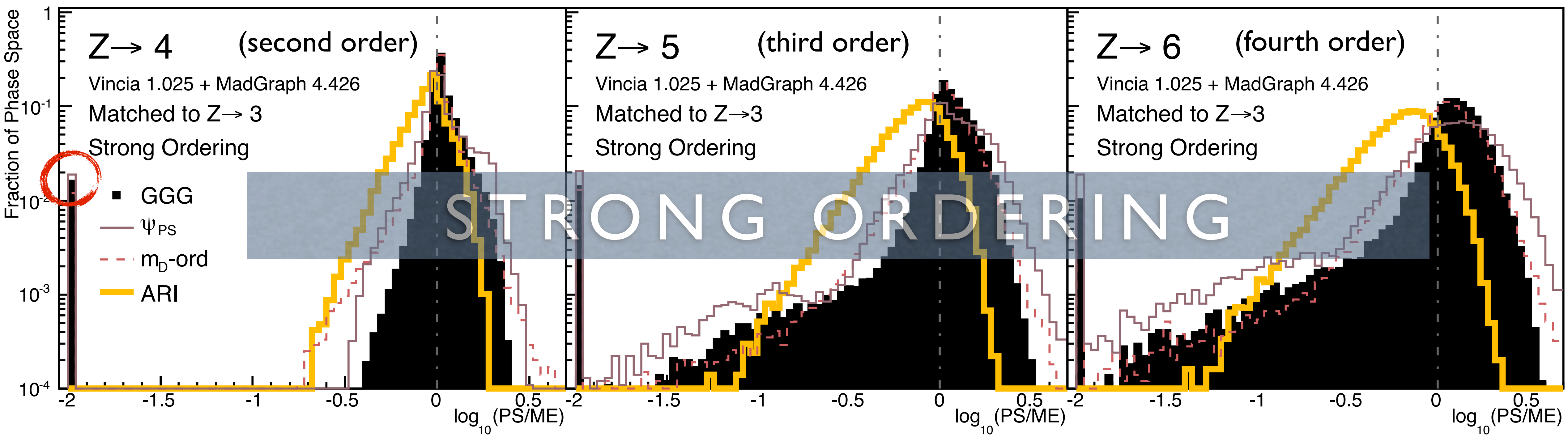
Approximations

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

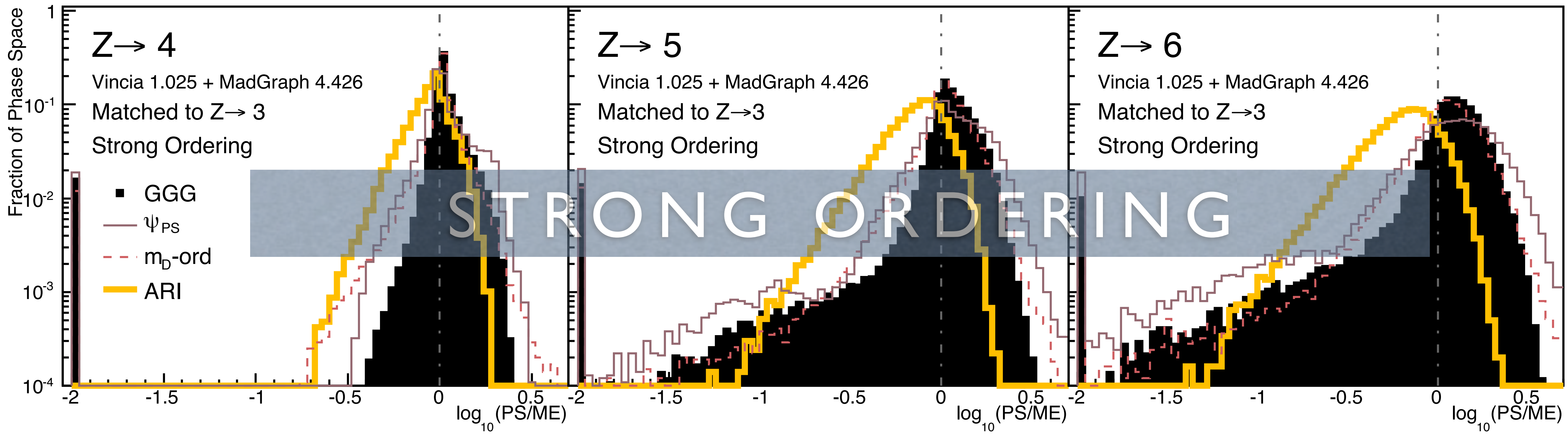


Dead Zone: 1-2% of phase space have no strongly ordered paths leading there*

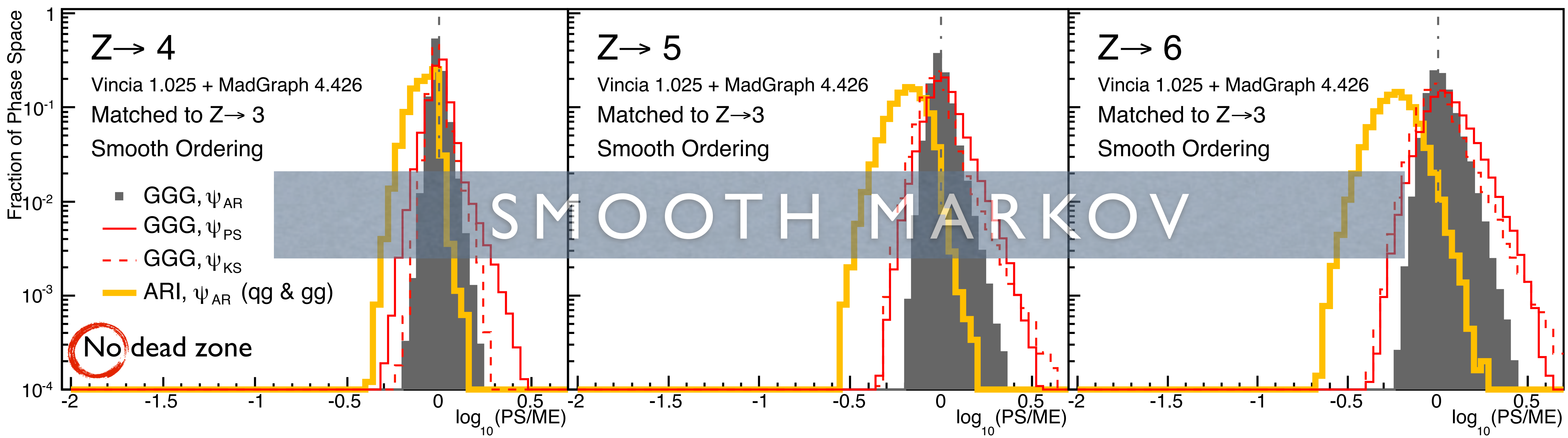
*fine from strict LL point of view: those points correspond to "unordered" non-log-enhanced configurations

→ 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)



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

2→4

Generate Trials *without* imposing strong ordering

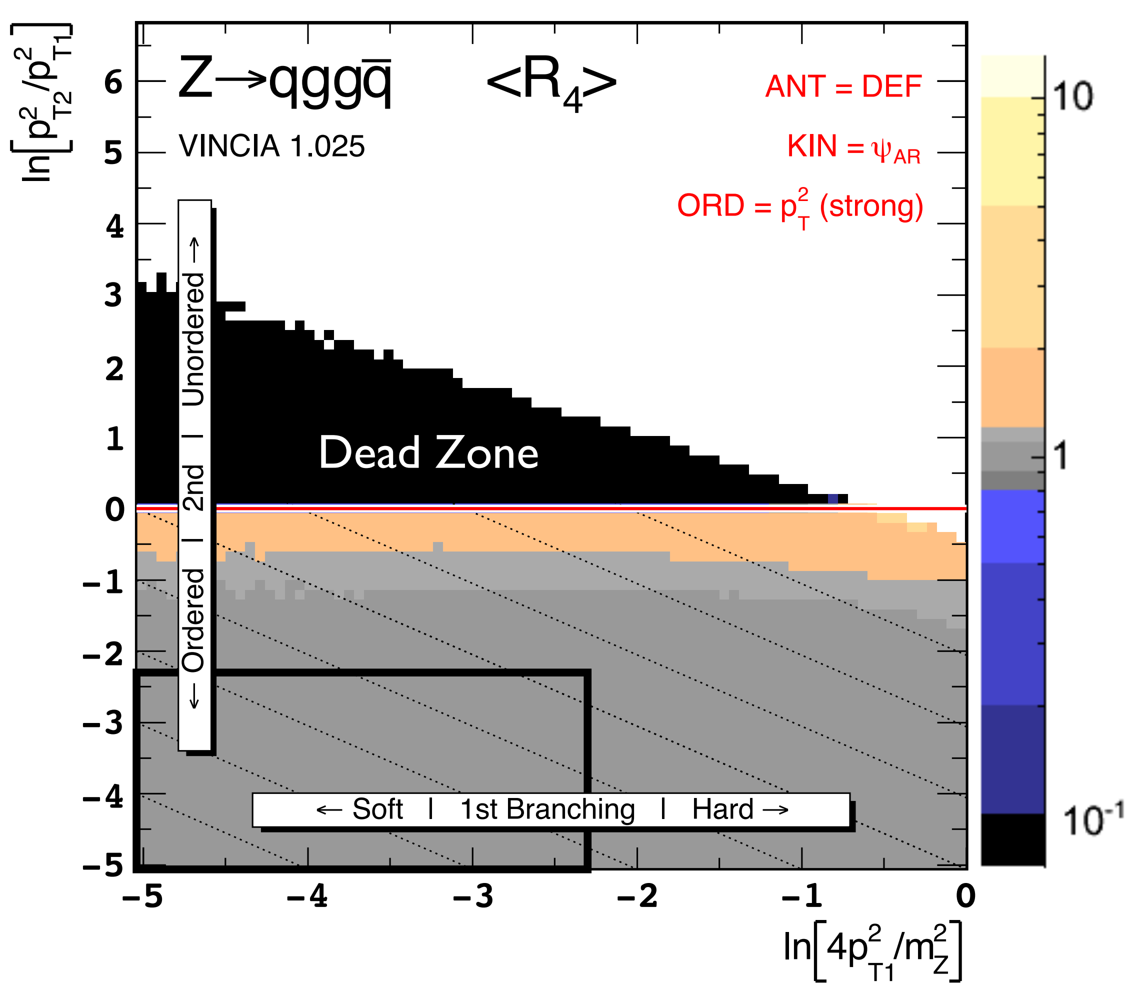
At each step, each dipole allowed to fill its entire phase space

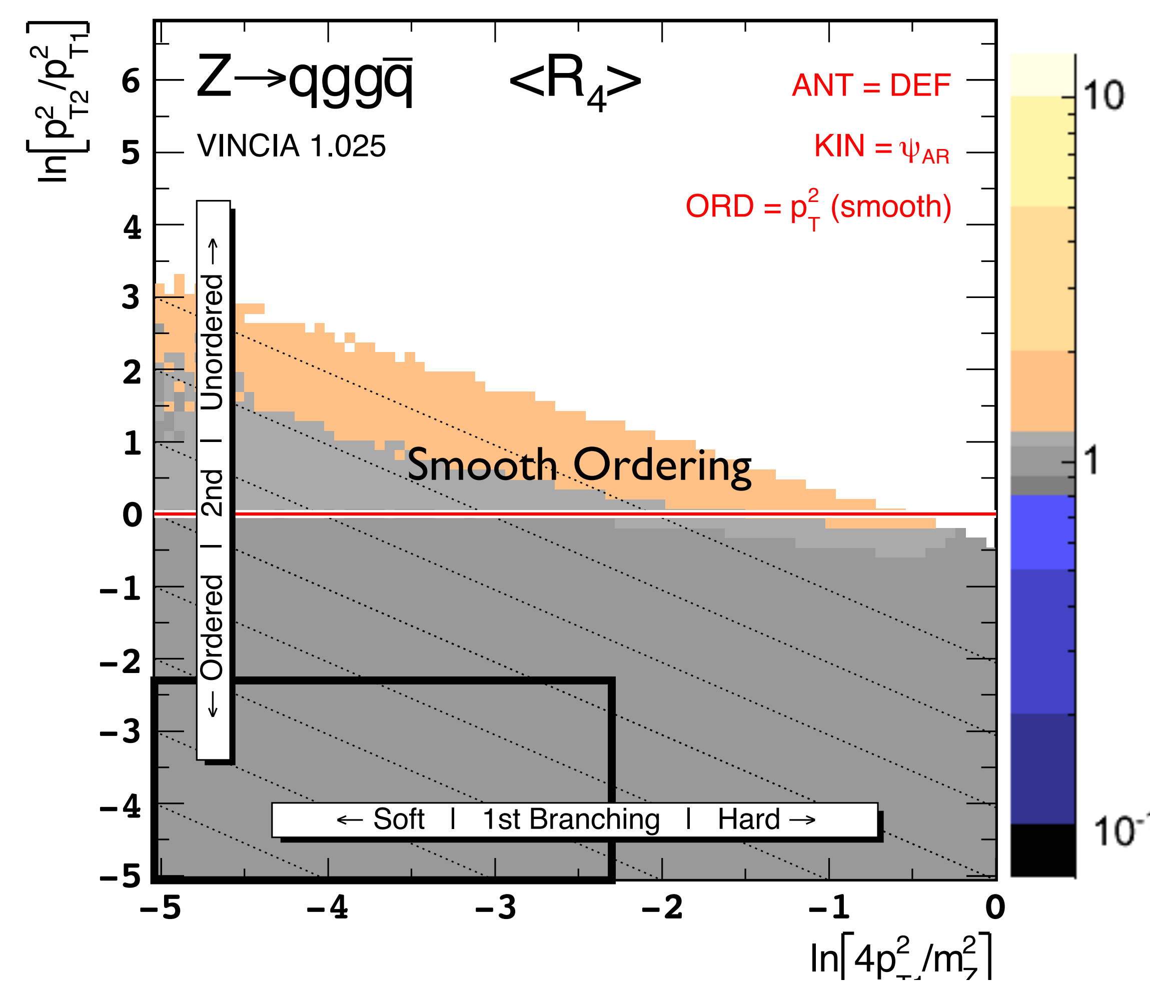
Overcounting removed by matching

+ smooth ordering beyond matched multiplicities

$$\frac{\hat{p}_\perp^2}{\hat{p}_\perp^2 + p_\perp^2} P_{\mathrm{LL}}$$

$\hat{p}_\perp^2$ last branching
$p_\perp^2$ current branching





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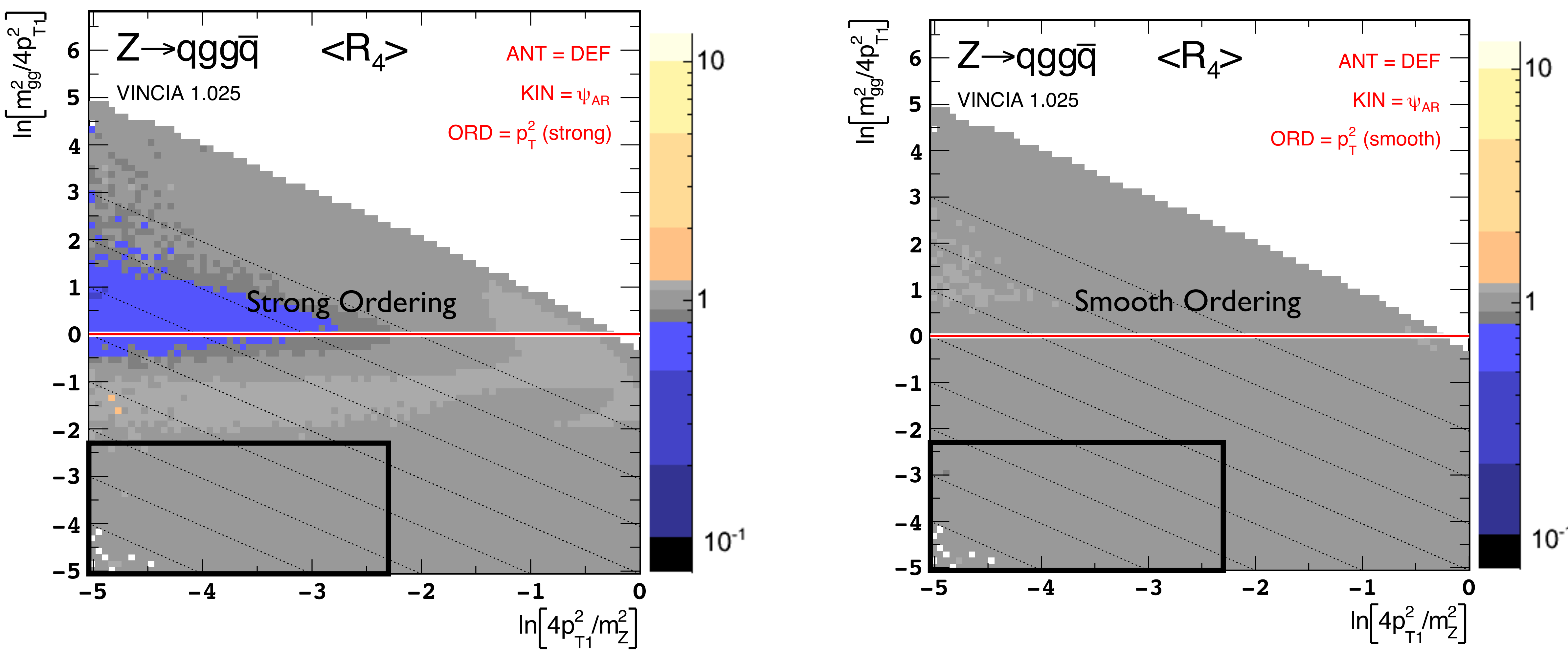
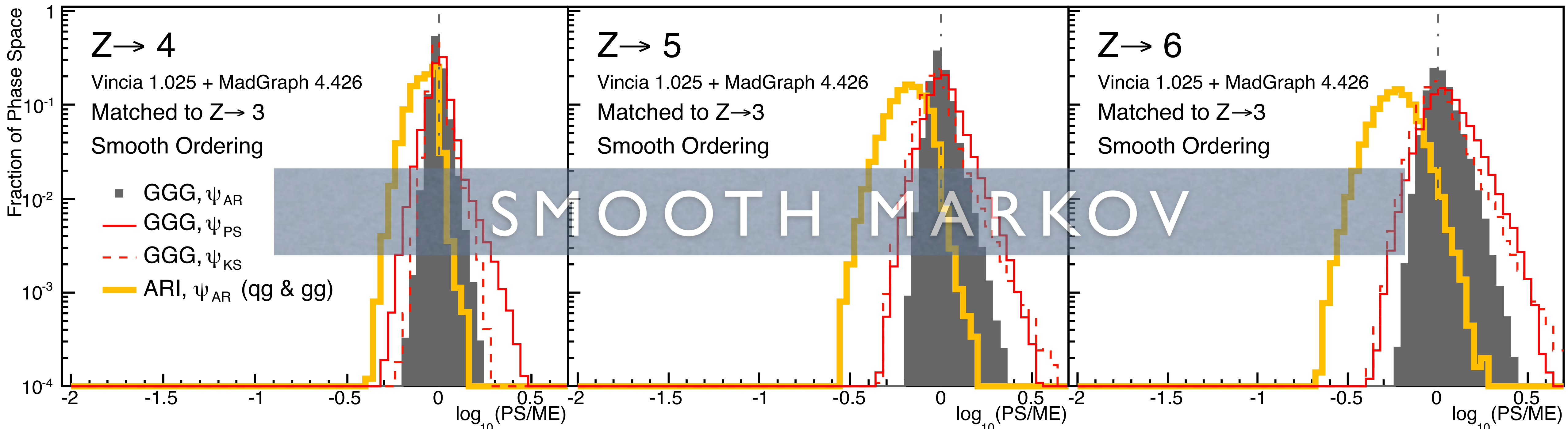
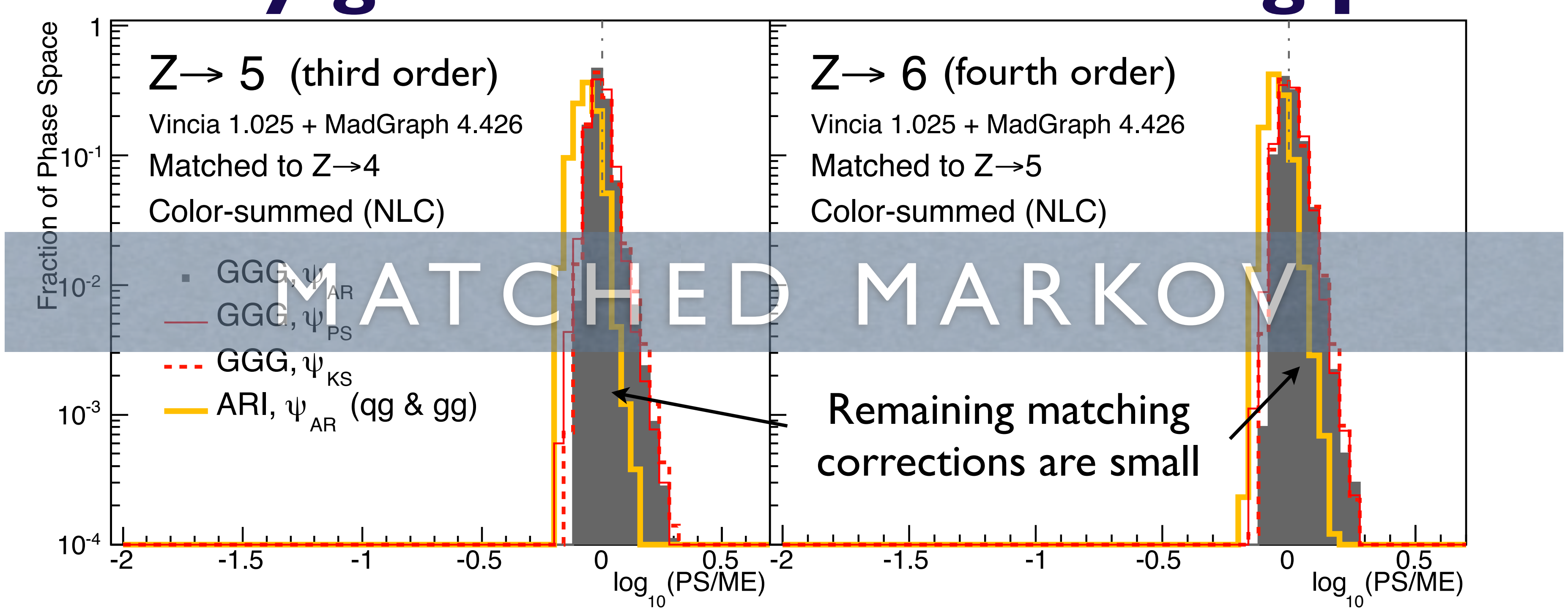


+ Matching (+ full colour)



→ A very good all-orders starting point




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

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	$P_2 = \frac{\alpha_{s2} a_2}{\alpha_{s1} a_1} P_1$

Uncertainties

For each branching, recompute weight for:

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

+ Unitarity

For each *failed* branching:

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

Uncertainties

For each branching, recompute weight for:

- Different renormalization scales
- Different antenna functions
- Different ordering criteria
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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…)

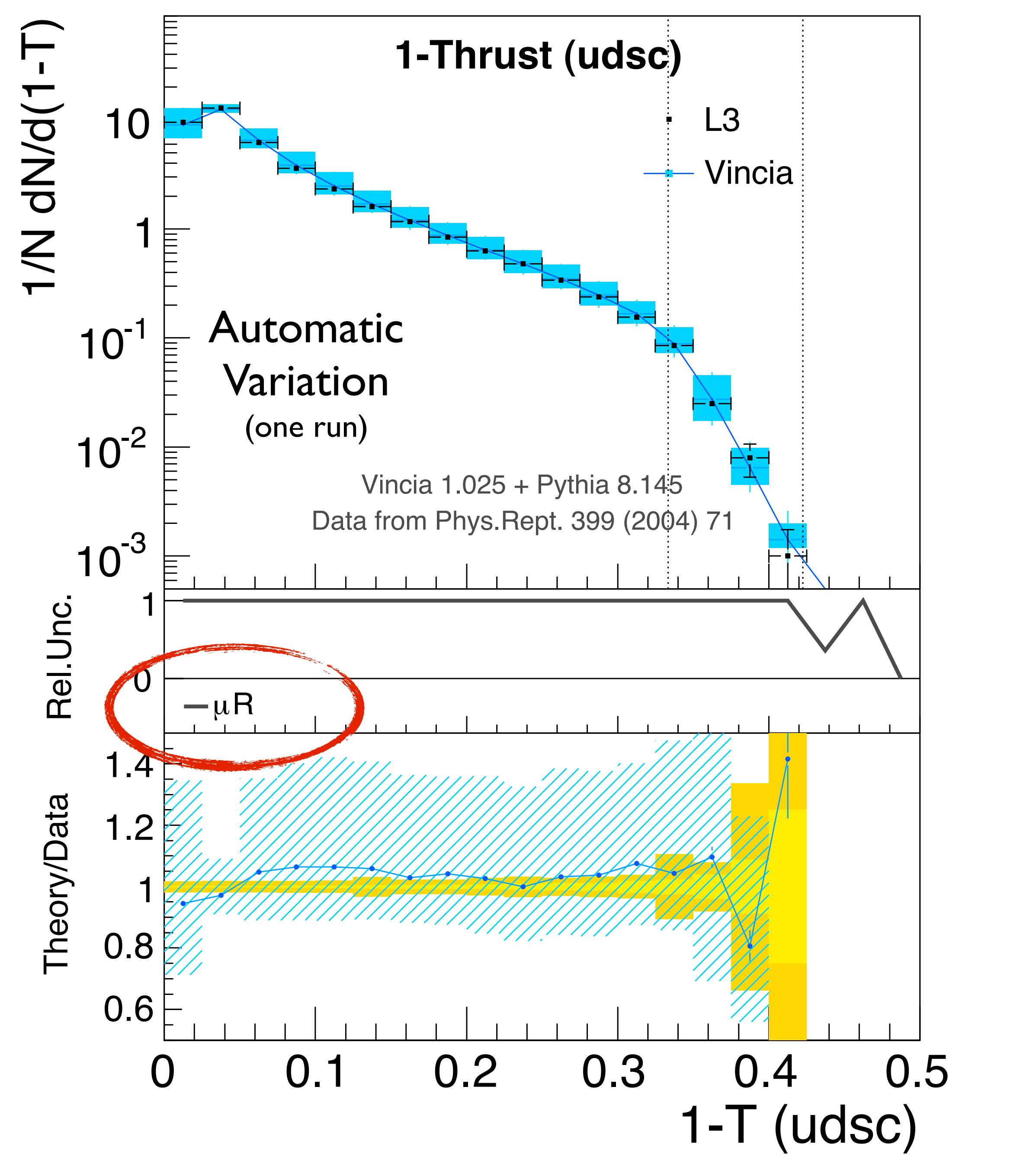
+ Unitarity

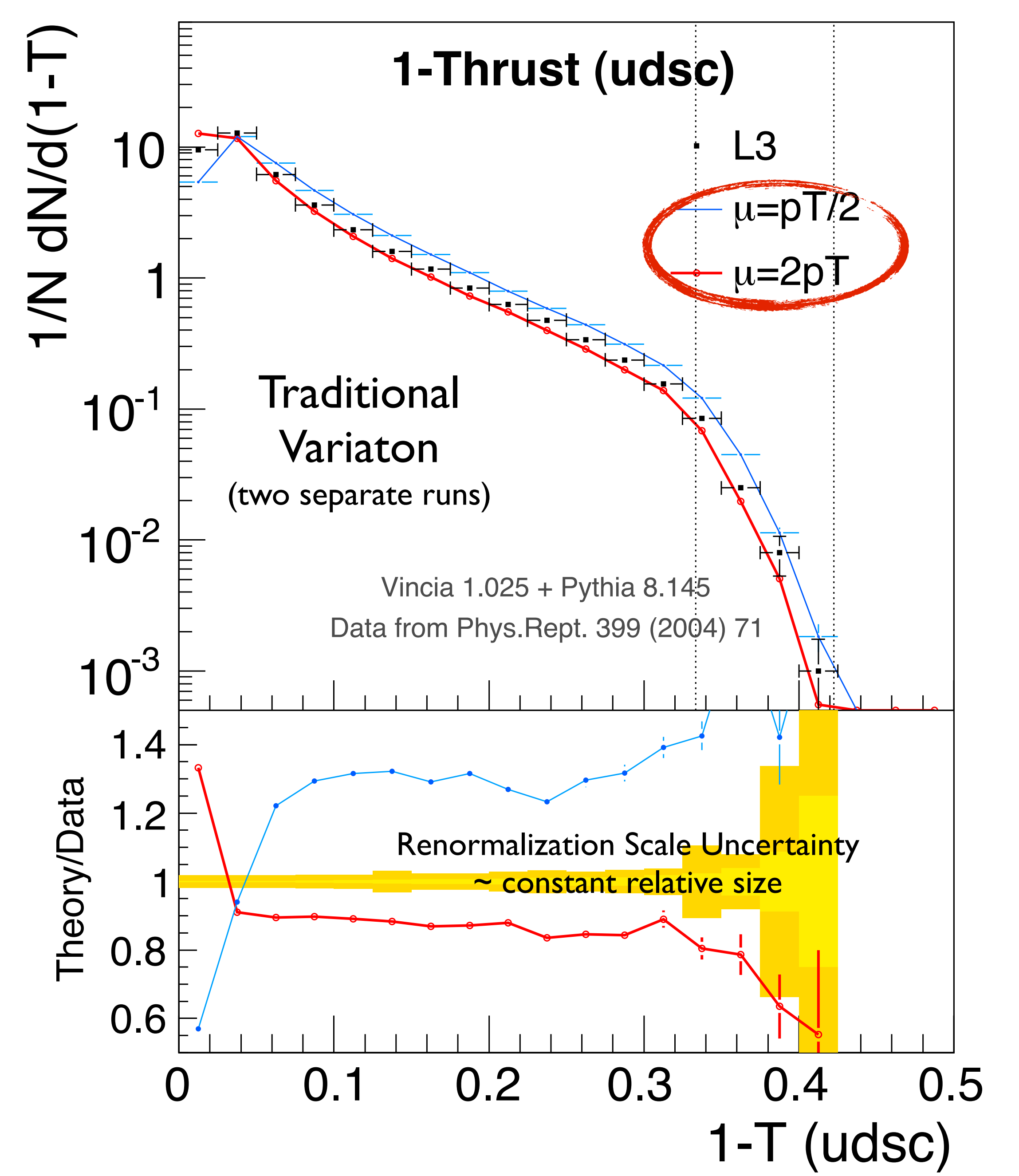
For each *failed* branching:

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

Automatic Uncertainties

Vincia:uncertaintyBands = on

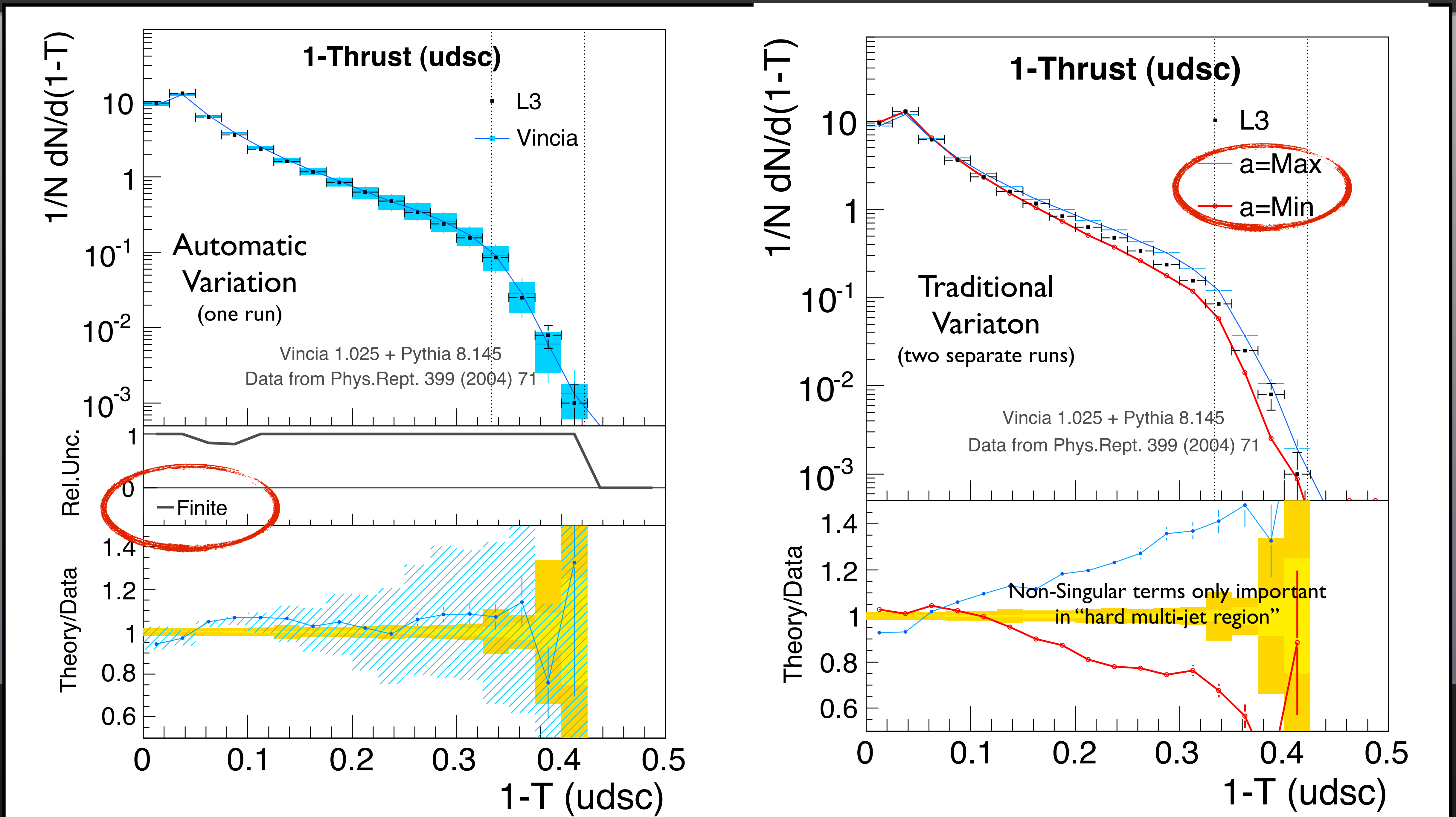




Variation of renormalization scale (no matching)

Automatic Uncertainties

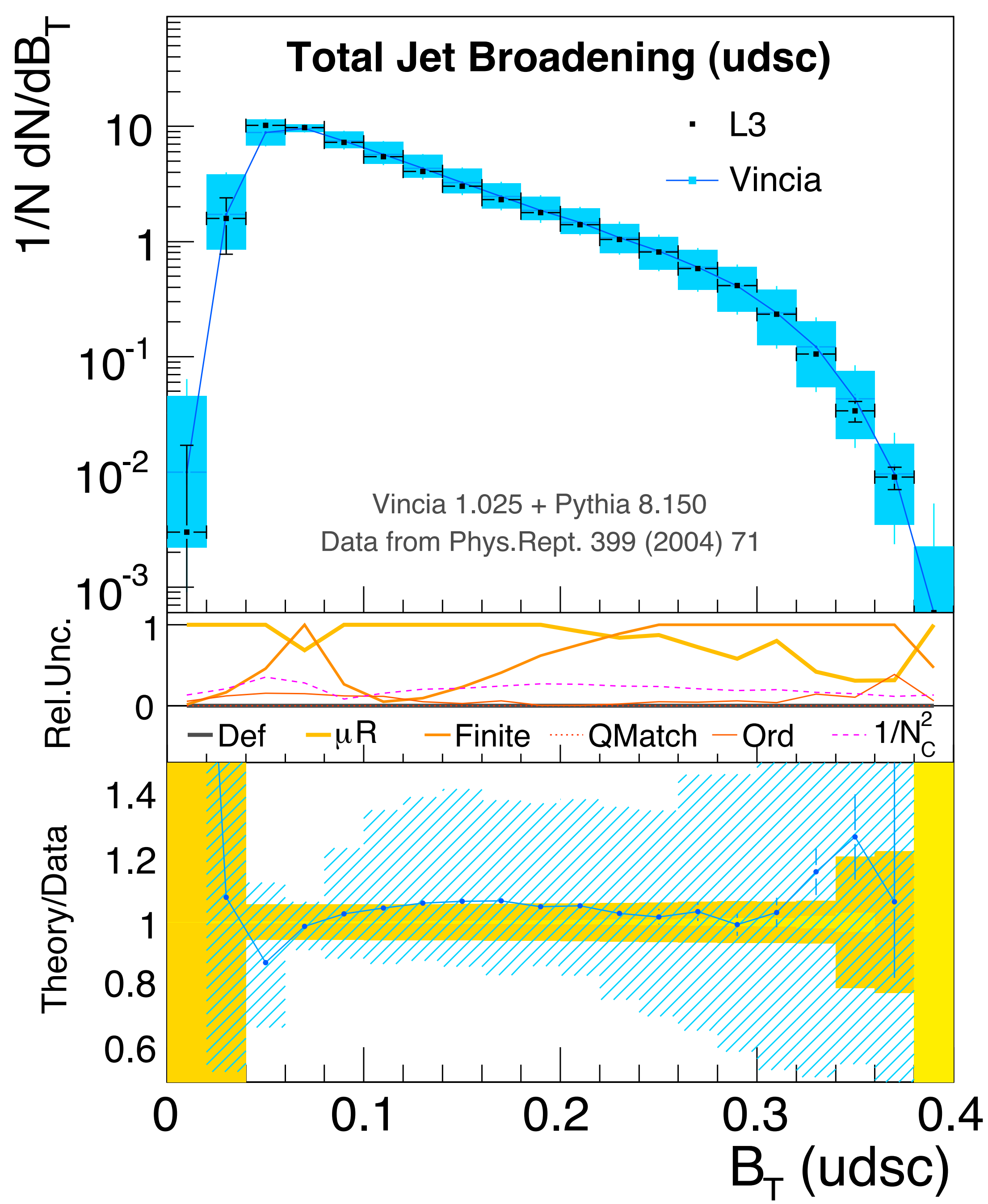
Vincia:uncertaintyBands = on



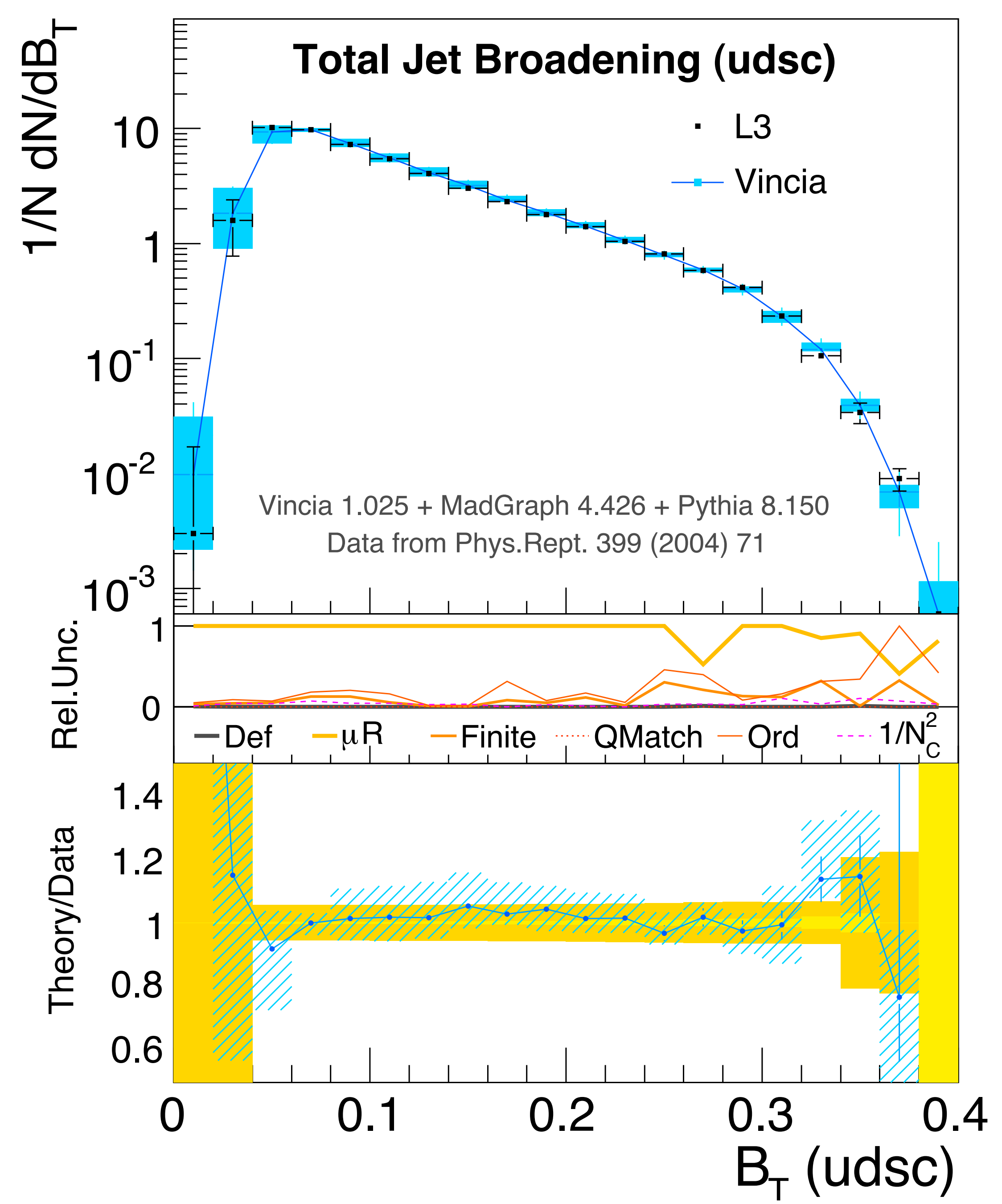
Variation of "finite terms" (no matching)

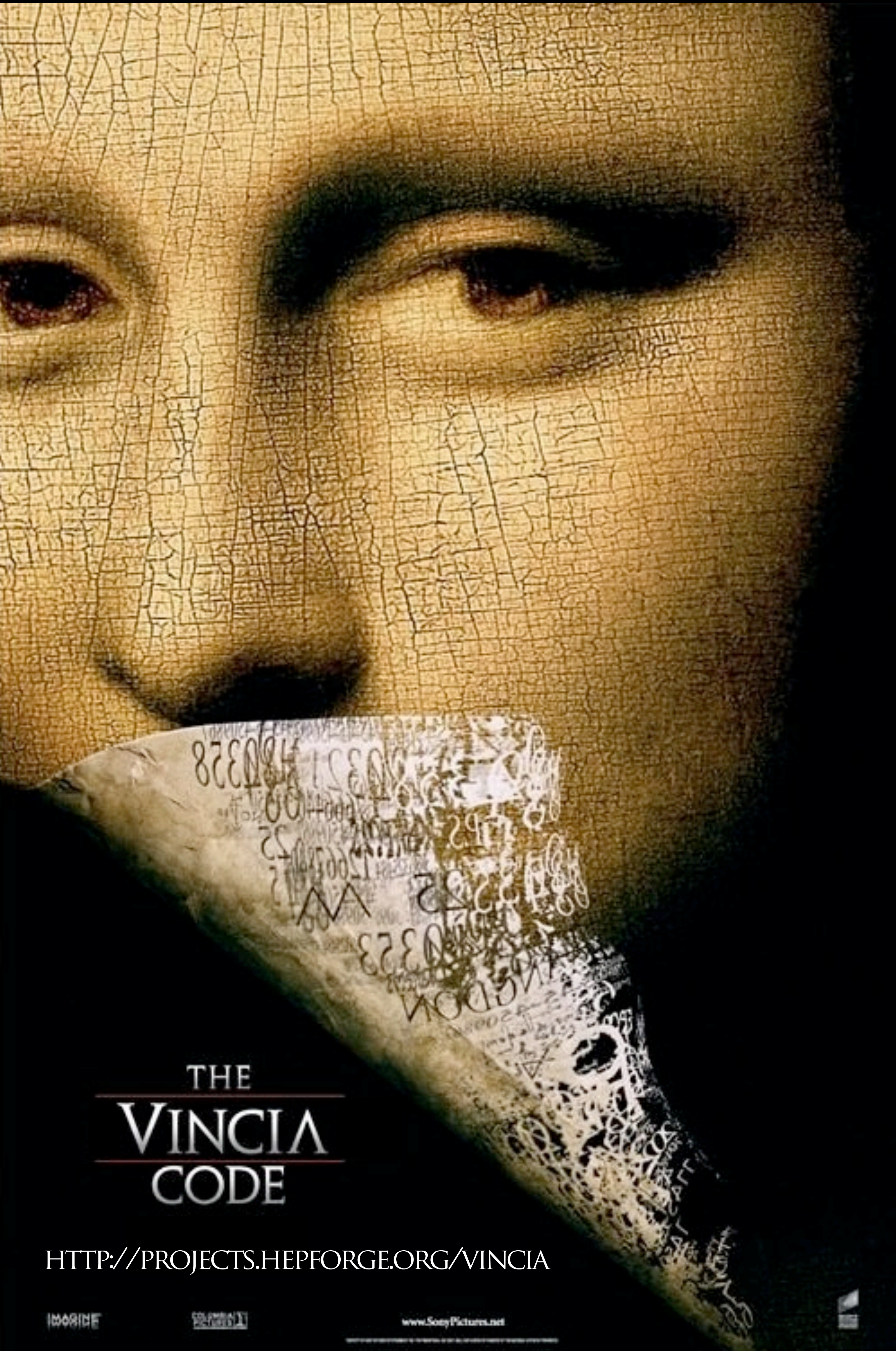
Putting it Together

VinciaMatching:order = 0



VinciaMatching:order = 3





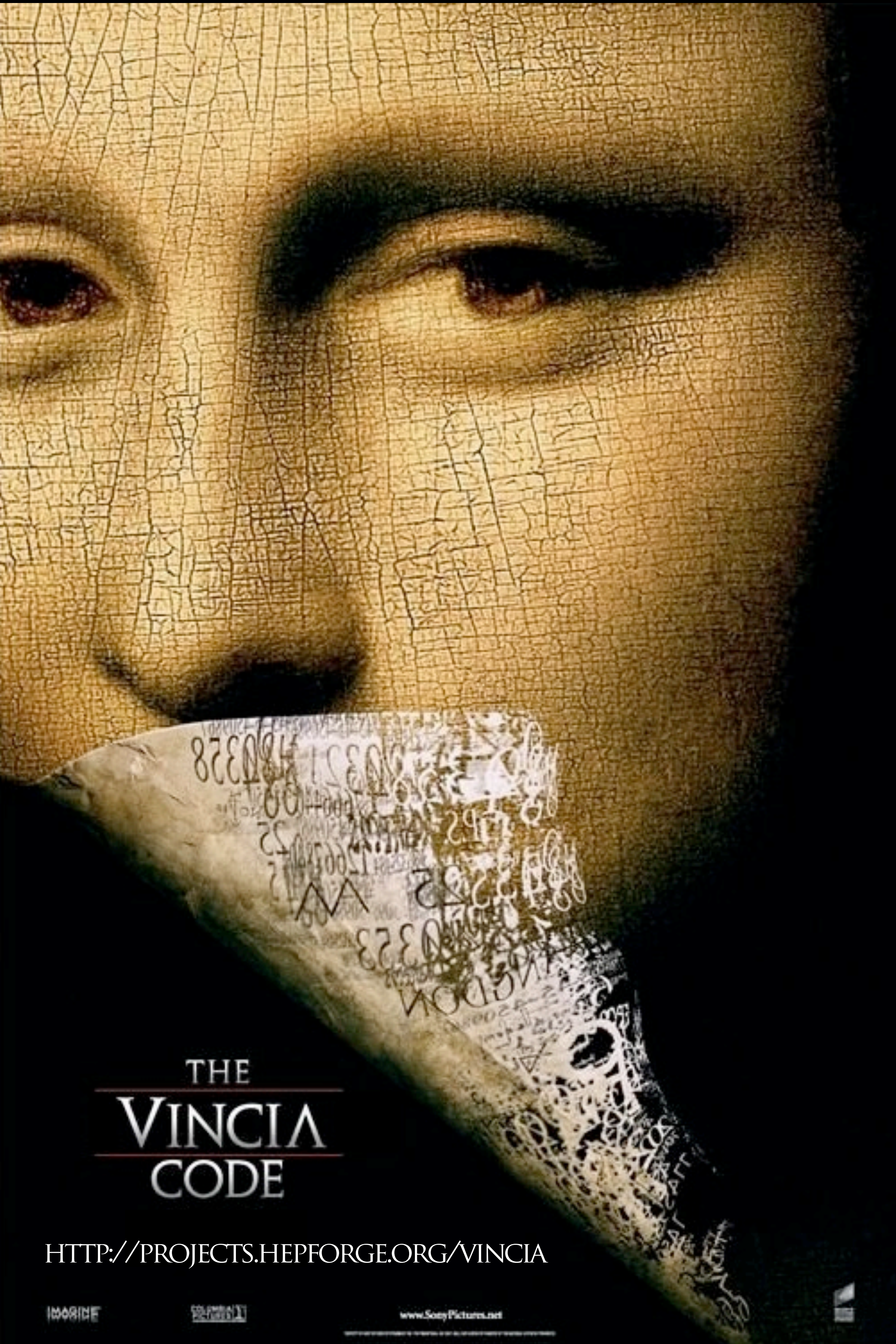
GKS : arXiv:1102.2126

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)
- Polarized Showers (with A. Larkoski, SLAC, & J. Lopez-Villarejo, CERN)
- → Initial-State Showers (with W. Giele, D. Kosower, G. Diana, …)



HTTP://PROJECTS.HEPFORGE.ORG/VINCIA

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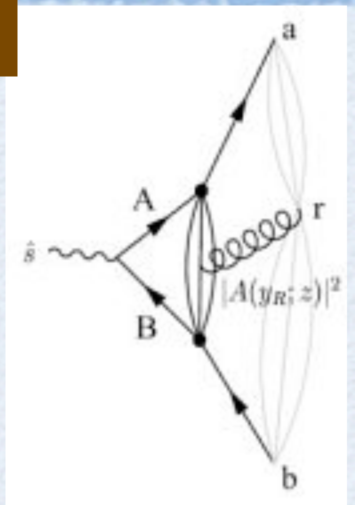
Sector Showers

Kosower, D. A. Phys.Rev. D57 (1998) 5410-5416 ; Gehrmann-De Ridder, A. et al. JHEP 0509 (2005) 056 ; G. Gustafson Phys.Lett. B175 (1986) 453



*)shows Global *without* any ordering condition imposed → overcounting

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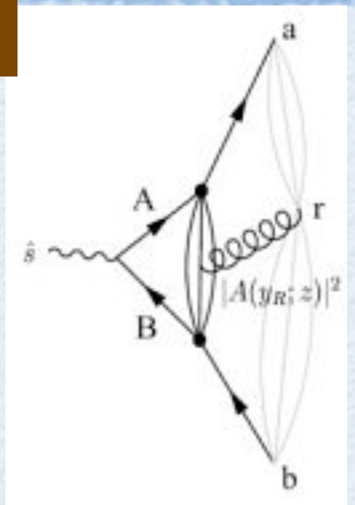

- Dipole-antenna formalism (2 -> 3)

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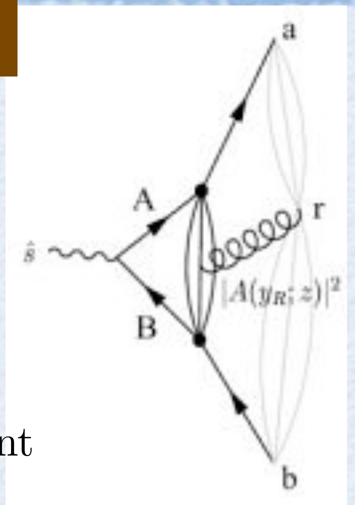
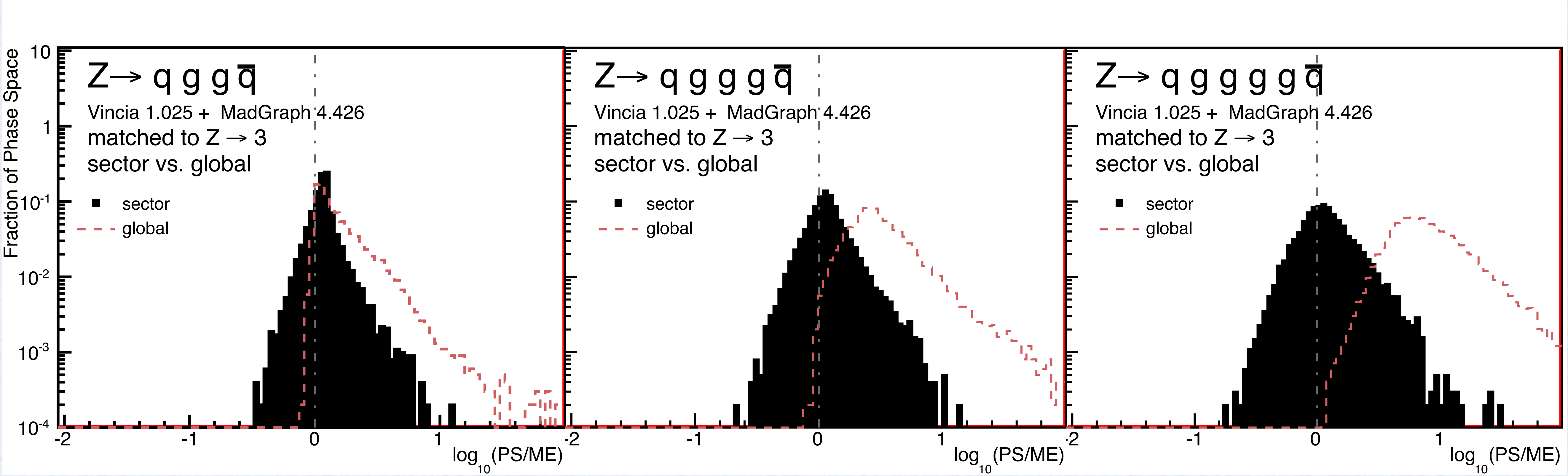


- Dipole-antenna formalism (2 -> 3)
- Two types:
  - Global: $|M^{(n)}|^2 \sim \sum_{i\in \text{clust.}} a_i |M_i^{(n-1)}|^2$ for any P.S. point
  - Sector: $|M^{(n)}|^2 \sim \sum_{i\in \text{clust.}} \tilde{a}_i |M_i^{(n-1)}|^2 \, \Theta_i(\text{P.S.}) \sim \tilde{a}_j |M_j^{(n-1)}|^2$ for some clust. j



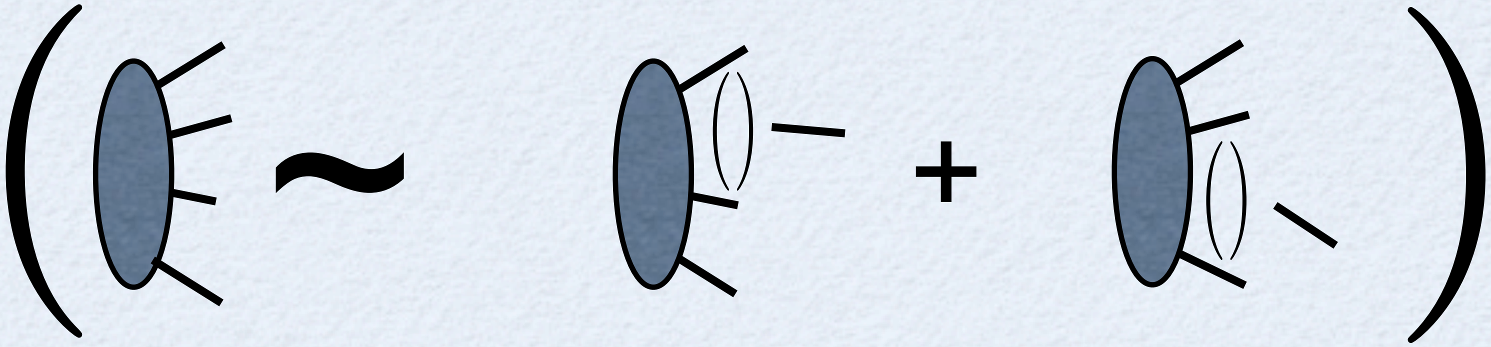
*)shows Global *without* any ordering condition imposed → overcounting

Number of Terms

Global FSR shower (default VINCIA)

	"Traditional" parton shower	Vincia Markov global antenna shower	Vincia Markov sector antenna shower
# of terms produced in the shower	$2^N N!$	N	1

N = number of emitted partons



3→4
2 terms per phase-space point

Number of terms

→ Sector shower

	"Traditional" parton shower	Vincia Markov global antenna shower	Vincia Markov sector antenna shower
# of terms produced in the shower	$2^N N!$	N	1

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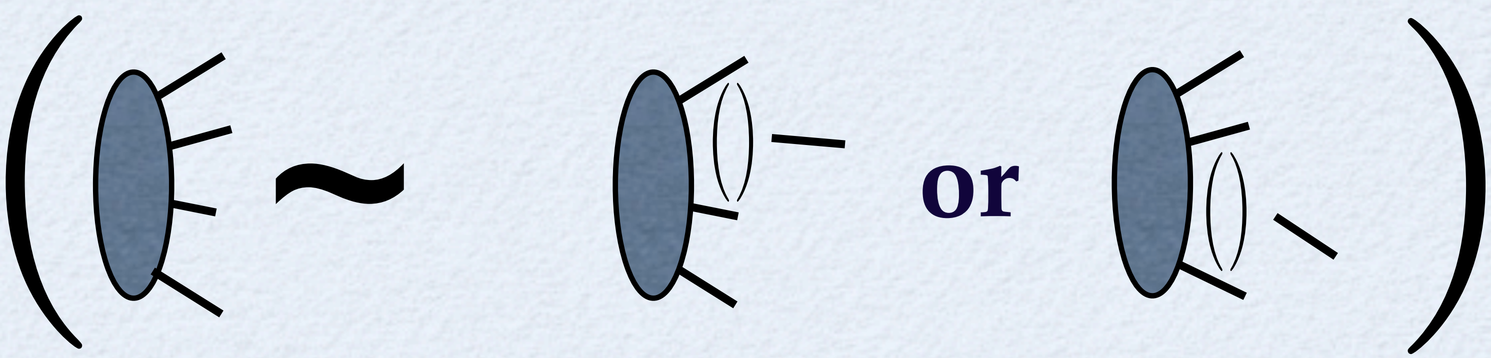


3→4
1 term per phase-space point

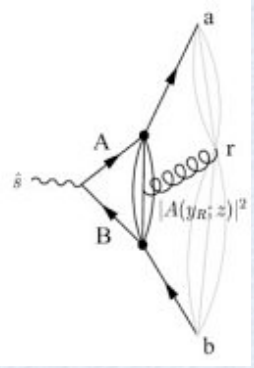
Sector Implementation

Sector implementation

- Implementation based on the global shower setup.

Sector implementation

- Implementation based on the global shower setup.
- Antenna functions are different than in the global case.
  → Challenges (partitioning of collinear radiation singularities)



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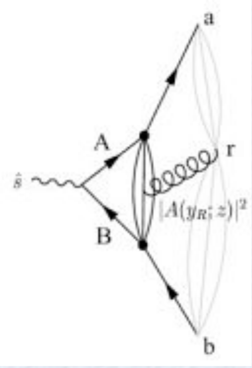
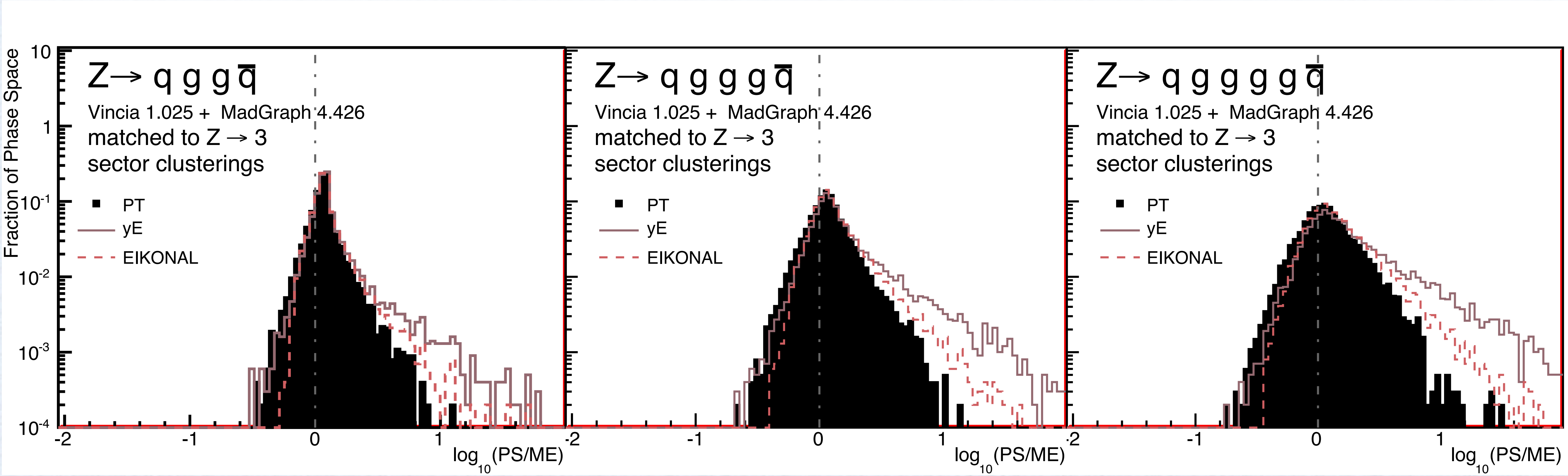


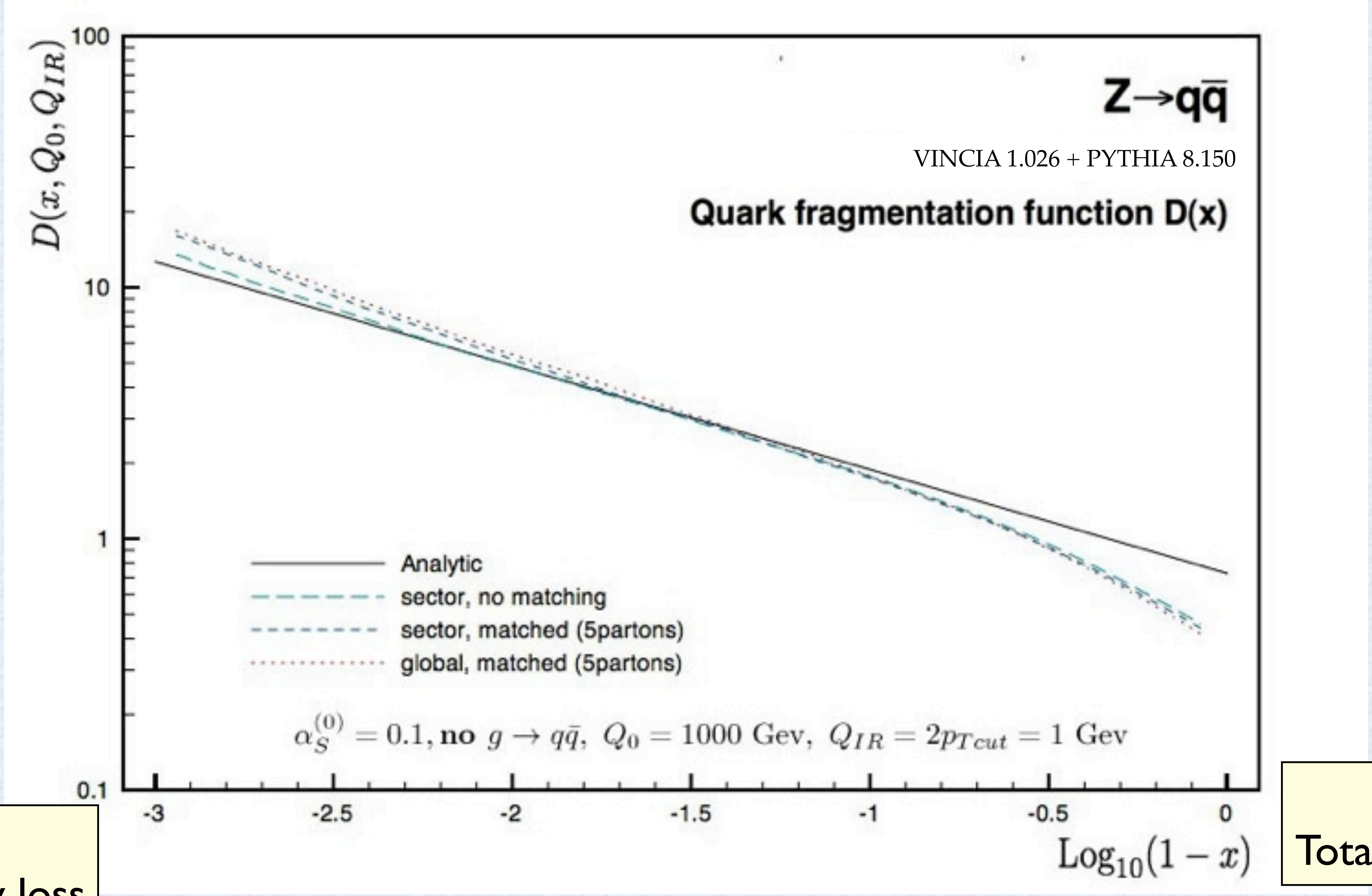
- Different criteria for separating sectors in phase space
  Looking for "best" sub-LL behavior.



RESULTS->FF

Skands, Weinzierl: Phys.Rev.D79 (2009) ; Nagy, Zoltan et al. JHEP 0905 (2009) 088

Test: fragmentation function for a quark



x→1
No energy loss

x→0
Total energy loss

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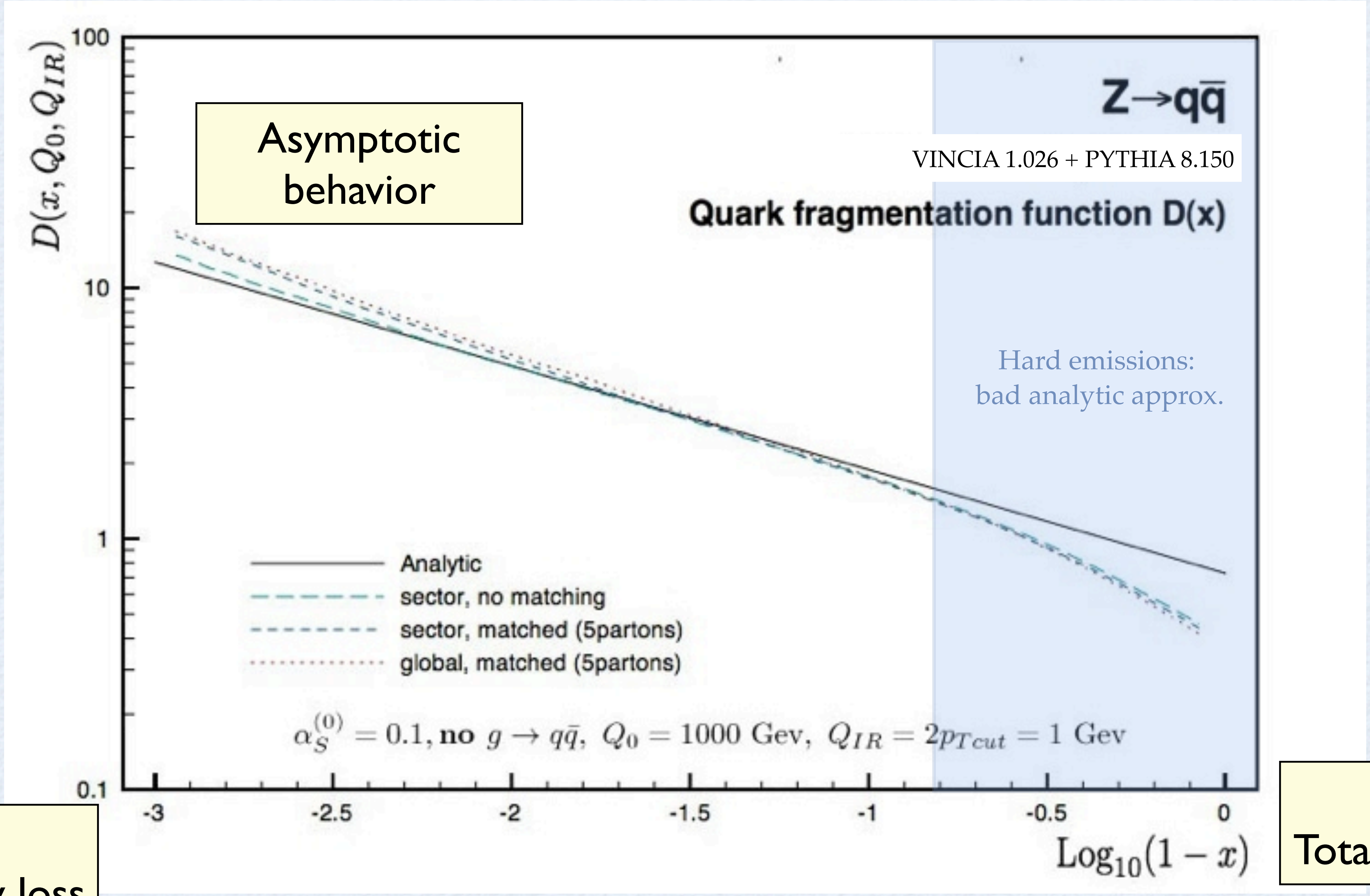

Asymptotic behavior

$x \to 1$
No energy loss

$x \to 0$
Total energy loss

Results -> Speed

Matched through:	$Z\to3$	$Z\to4$	$Z\to5$	$Z\to6$
Pythia 6	0.20	ms/event		
Pythia 8	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 Global	0.30	0.77	6.40	130.00
Vincia Sector	0.27	0.63	6.90	52.00
Vincia Global *(Q_{match} = 5 GeV)*	0.29	0.60	2.40	20.00
Vincia Sector *(Q_{match} = 5 GeV)*	0.26	0.50	1.40	6.70
Sherpa *(Q_{match} = 5 GeV)*	5.15*	53.00*	220.00*	400.00*
* + *initialization time*	1.5 minutes	7 minutes	22 minutes	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)*

J.J. Lopez-Villarejo & Peter Z. Skands. "Efficient matrix-element matching with sector showers":

Arxiv soon ...

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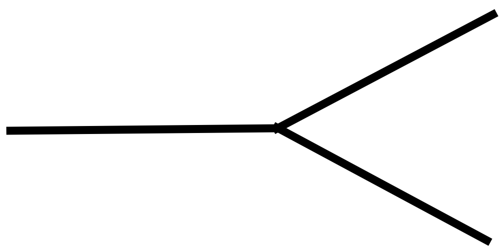
Arxiv soon ...

Next steps: ISR, polarization, NLO, faster MEs? (now using MadGraph), etc. …

Backup Slides

pQCD as Markov Chain

Start from Born Level:



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

Born-Level Phase Space

Born-Level Matrix Element

On-Shell Momentum Configuration

H = Arbitrary hard process

pQCD as Markov Chain

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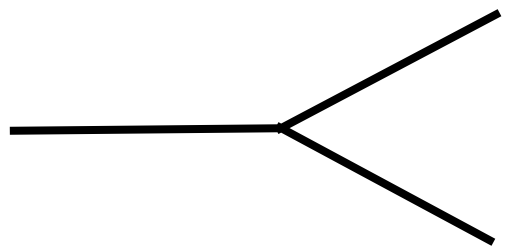

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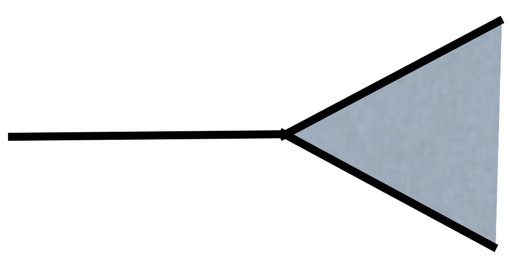
Insert Evolution Operator, *S*:

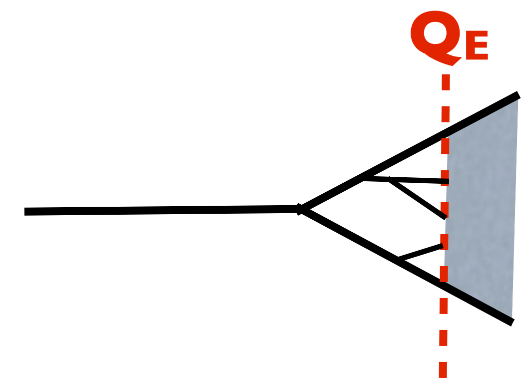


Evolution operator

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

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

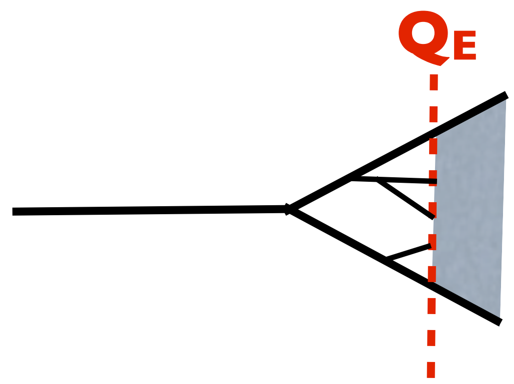
Legend:

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



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(Expand S to First Order)

Equivalent to Sjöstrand/POWHEG

"NLO" virtual correction   Sudakov Expansion

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

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

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

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$c - c'$

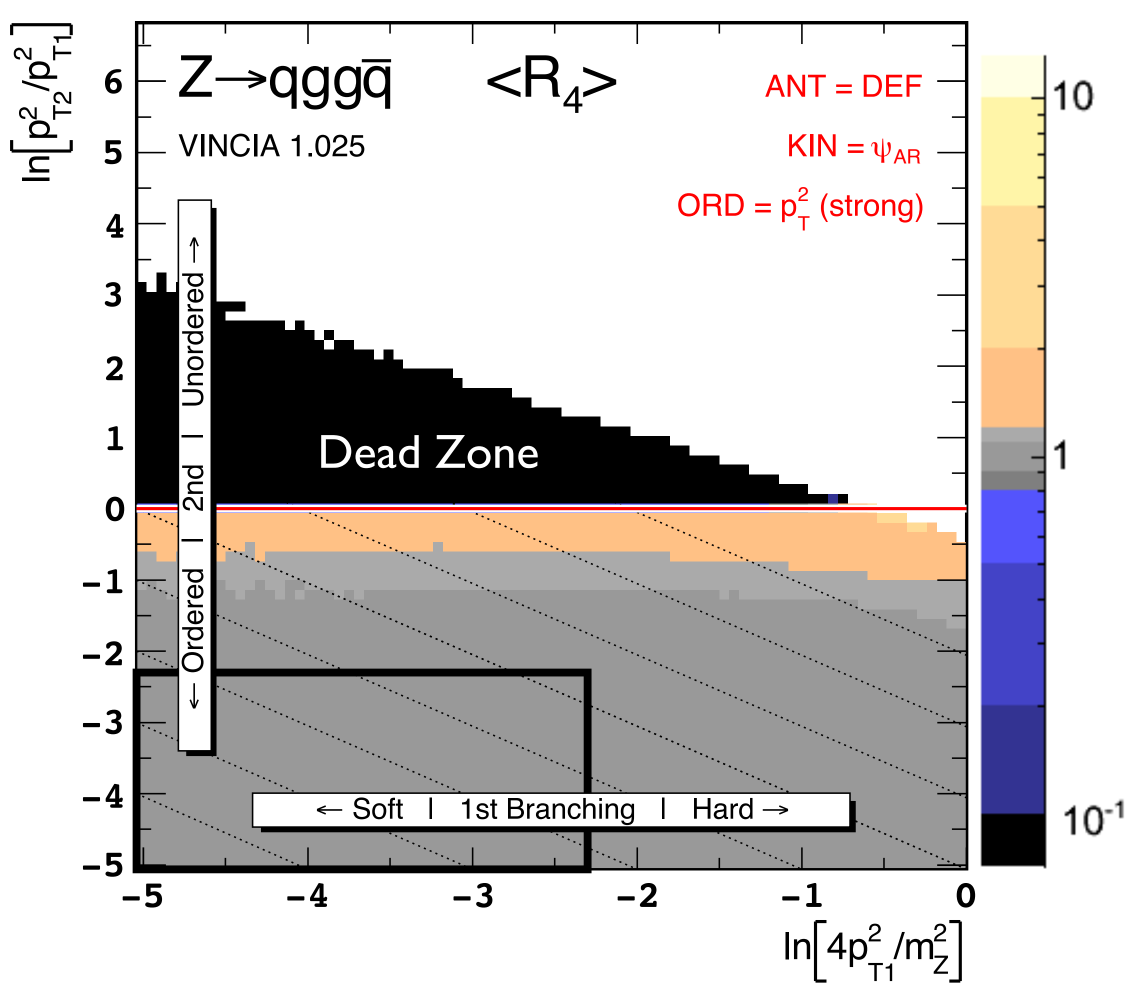
Simple Solution

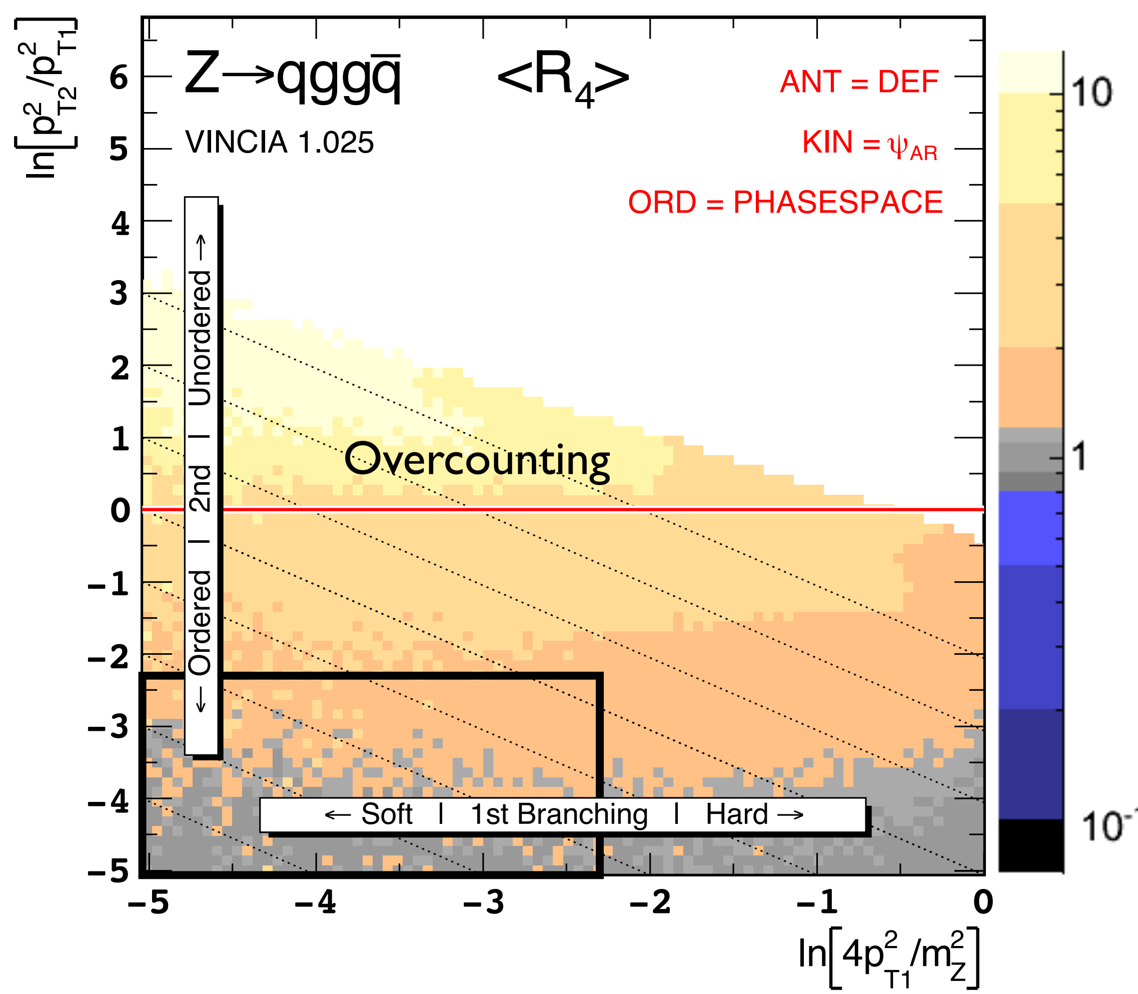
Generate Trials *without* imposing strong ordering

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

Overcounting removed by matching

(revert to strong ordering beyond matched multiplicities)



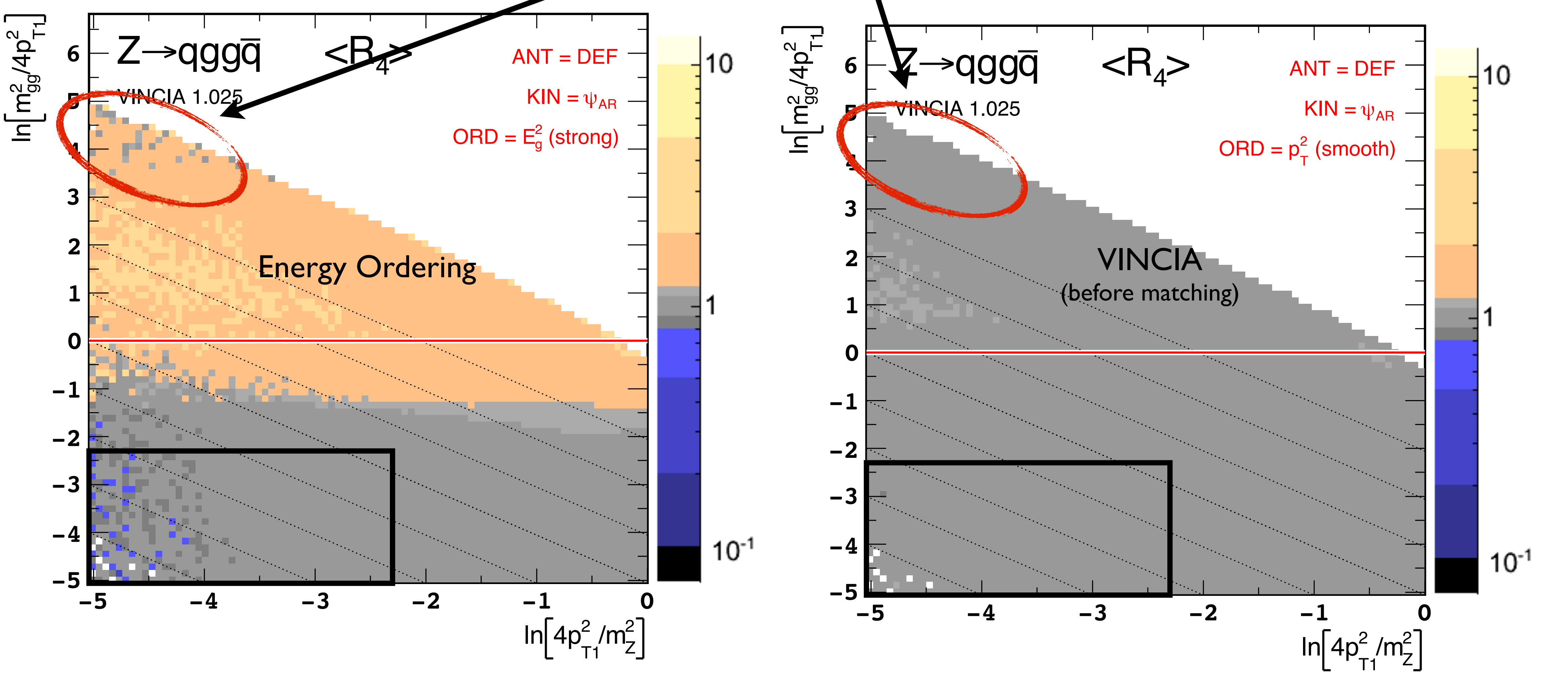


(Subleading Singularities)

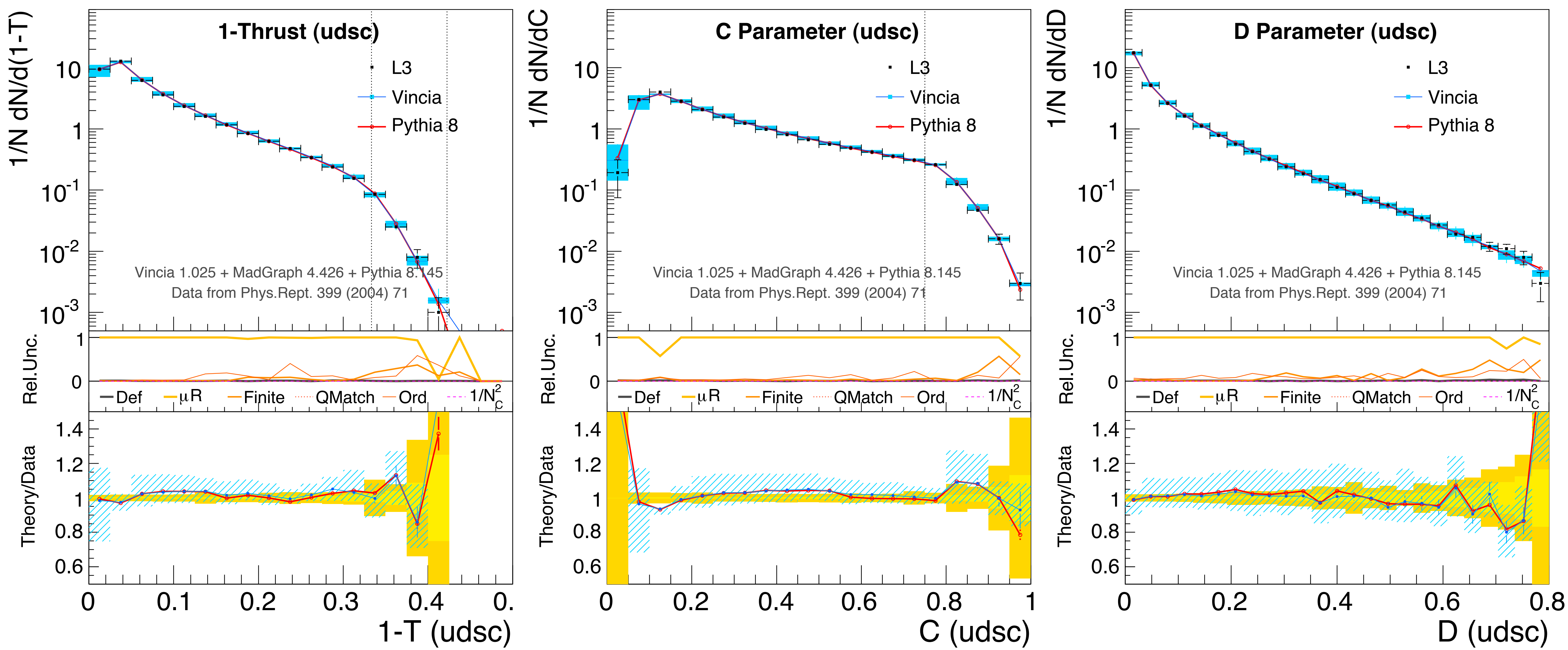
Isolate double-collinear region:

$\alpha_s^2 \ln^2$

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



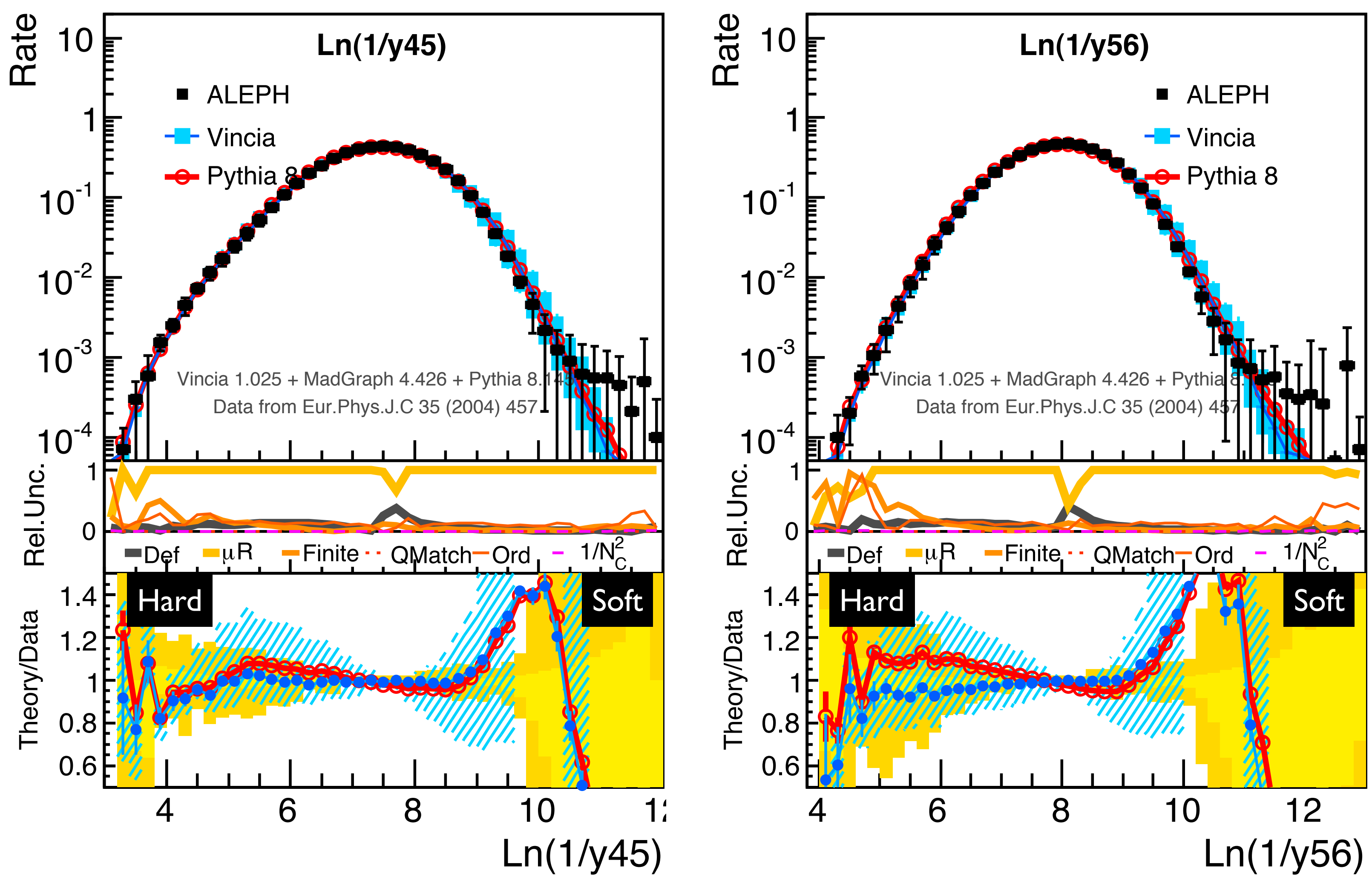
LEP event shapes



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

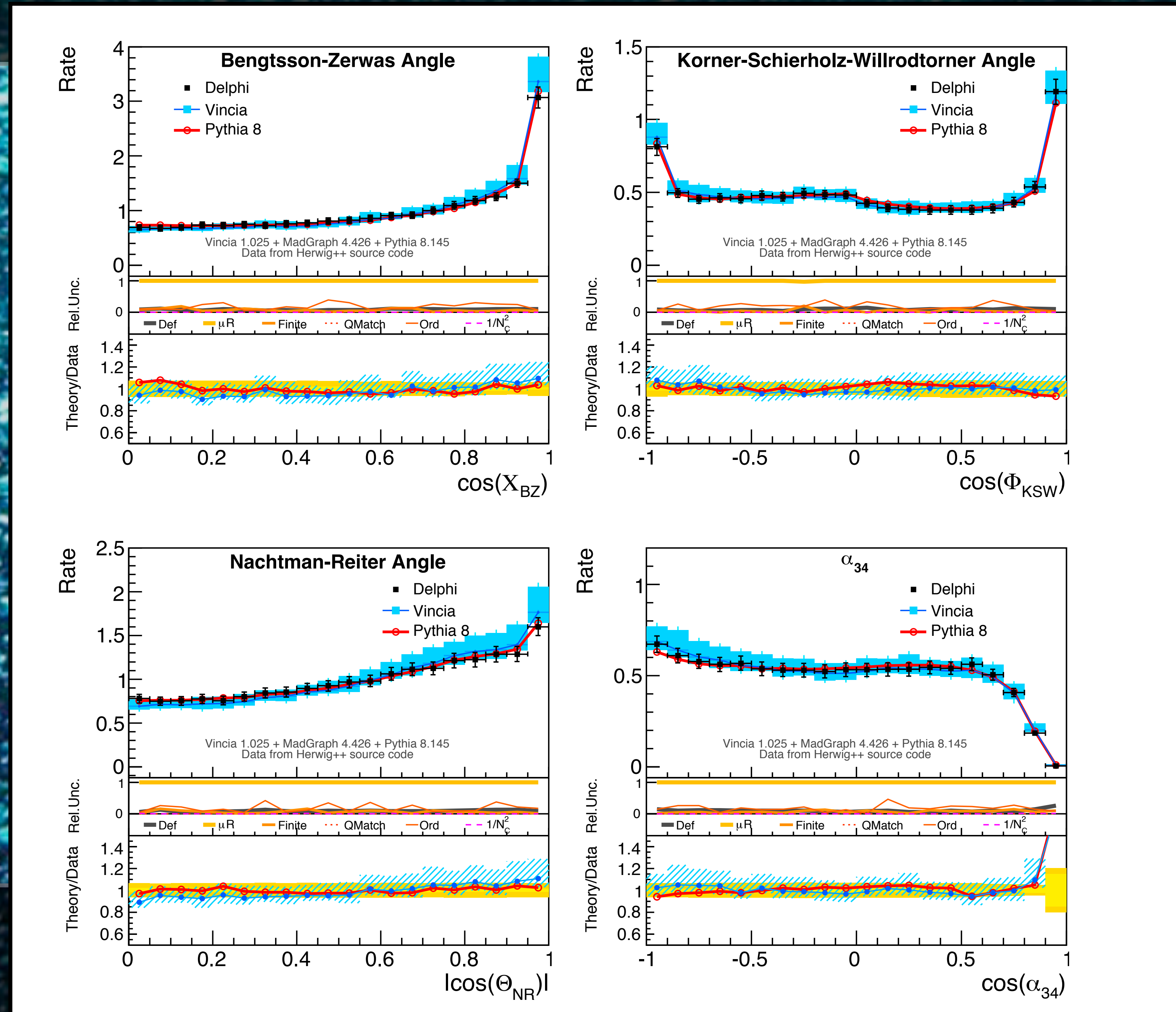
- Sensitive to polarization effects

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?