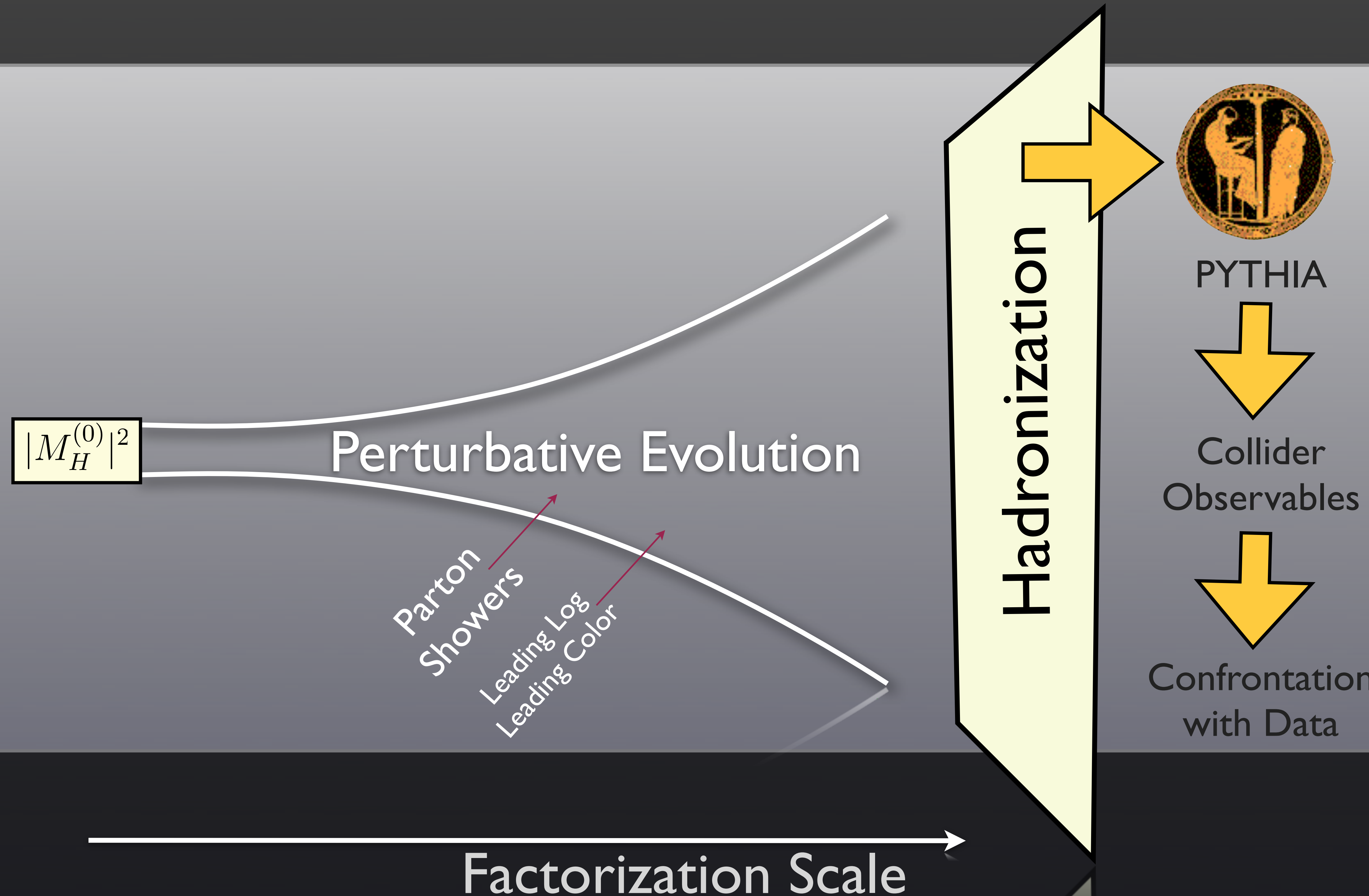
New Developments in Parton Showers

P. Skands



Work in collaboration with W. Giele, D. Kosower, J. Lopez-Villarejo,
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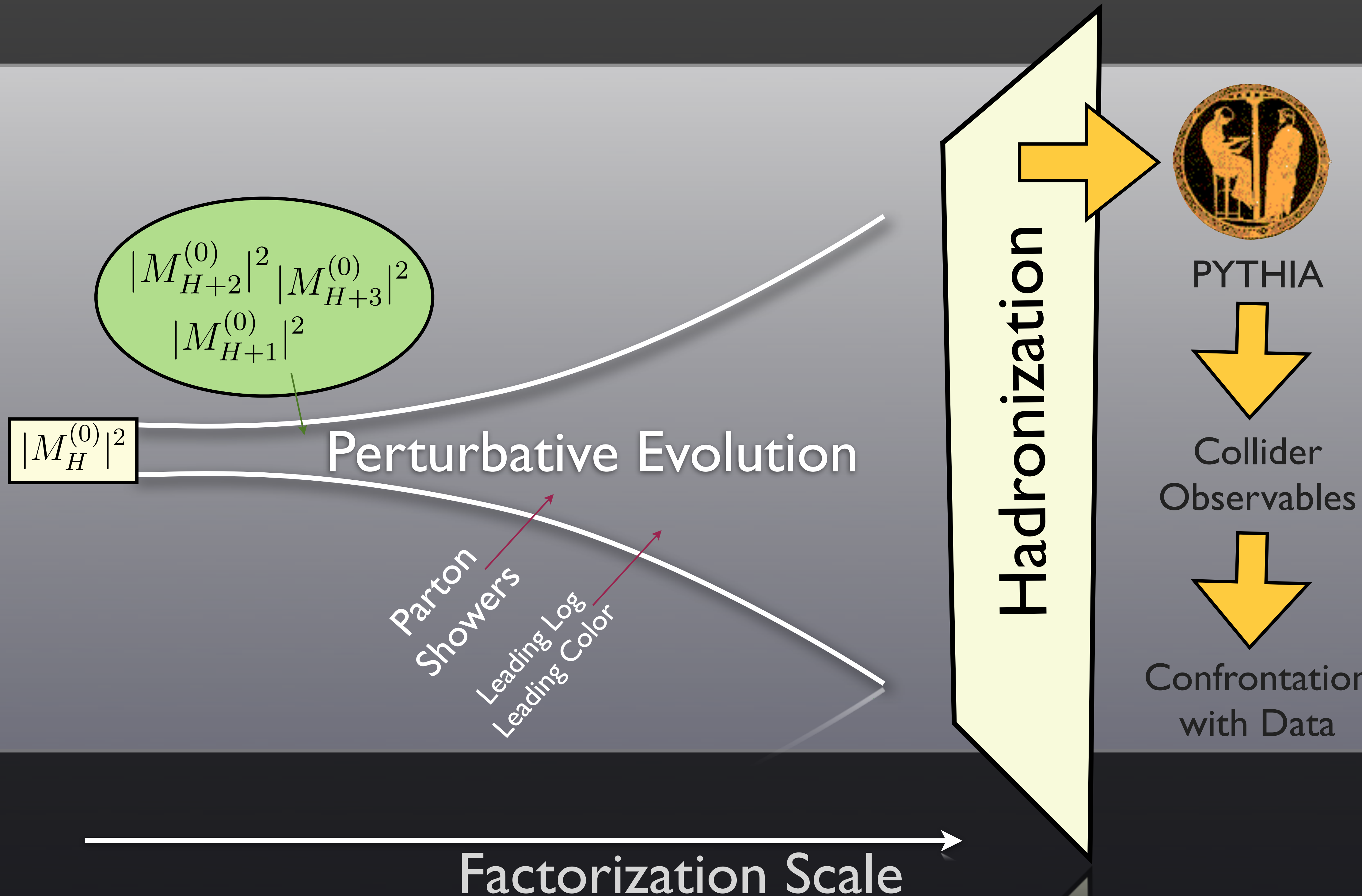

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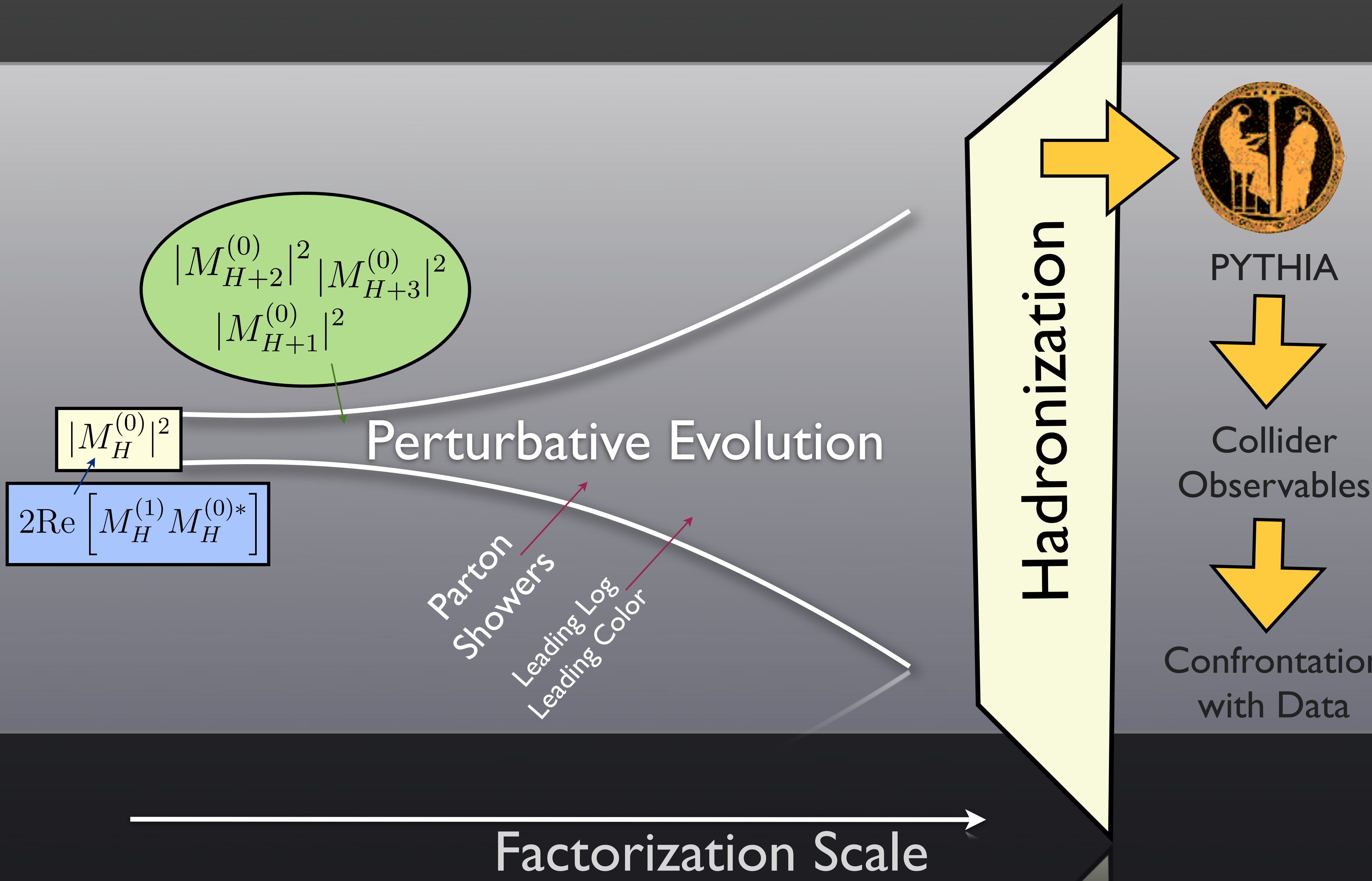

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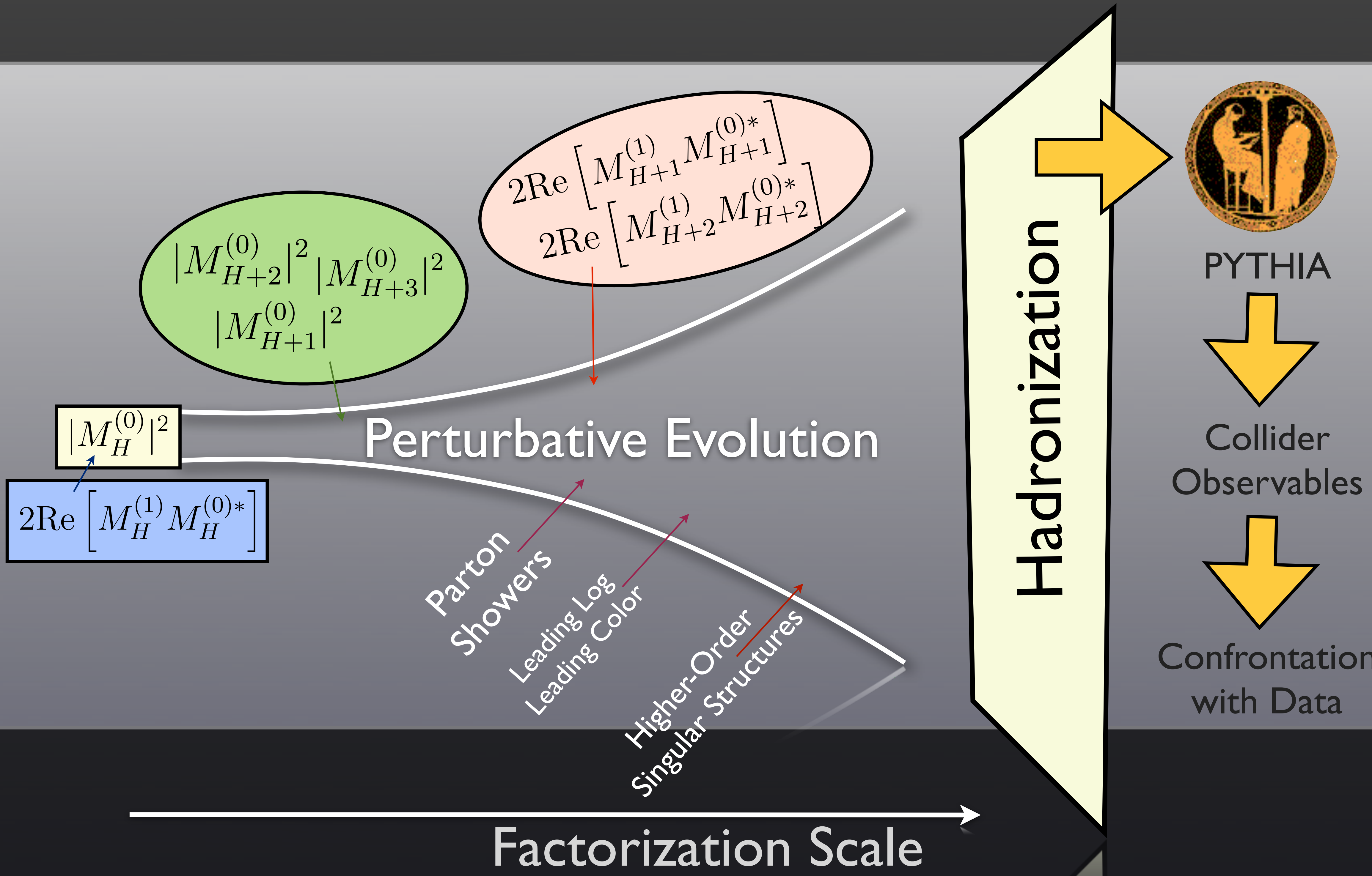

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“New” ?

For matching to the first emission:

= PYTHIA scheme Sjöstrand & Bengtsson, PLB 185 (1987) 435, NPB 289 (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)

Lund, Mueller, Catani-Seymour, St Petersburg, Kosower, Gehrmann-Glover, …
“Global” : Gustafson & Pettersson, NPB 306 (1988) 746 + Gehrmann et al. (2005)
“Sector” : Kosower. PRD 57 (1998) 5410

What is new (apart from antennae): Giele, Kosower, PS, PRD 84 (2011) 054003

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

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

Calculation also yields ~10 automatic uncertainty estimates at a moderate speed penalty

1^{st} Order: PYTHIA and POWHEG

PYTHIA

FSR: Sjöstrand & Bengtsson, PLB185(1987)435, NPB289(1987)810
Drell-Yan: Miu & Sjöstrand, PLB449(1999)313

Real Radiation:

$$\left.\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}}\right|_{\mathrm{PS}} = \left.\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}}\right|_{\mathrm{PS1}} + \left.\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}}\right|_{\mathrm{PS2}} = \frac{\sigma_0}{\hat{s}}\,\frac{\alpha_{\mathrm{s}}}{2\pi}\,\frac{4}{3}\,\frac{\hat{s}^2+m_{\mathrm{W}}^4}{\hat{t}\hat{u}}\;.$$

(for qg→q'W)

Use PS as overestimate. Correct to R/B via veto:

$$R_{\mathrm{qg}\to\mathrm{q'W}}(\hat{s},\hat{t}) = \frac{(\mathrm{d}\hat{\sigma}/\mathrm{d}\hat{t})_{\mathrm{ME}}}{(\mathrm{d}\hat{\sigma}/\mathrm{d}\hat{t})_{\mathrm{PS}}} = \boxed{\frac{\hat{s}^2+\hat{u}^2+2m_{\mathrm{W}}^2\hat{t}}{\hat{s}^2+2m_{\mathrm{W}}^2(\hat{t}+\hat{u})}}$$

(+analogous for qq→gW)

Unitarity → Modified Sudakov Factor:

$$\exp\left(-\int_t^{t_{\max}}\mathrm{d}t'\,\frac{\alpha_{\mathrm{s}}(t')}{2\pi}\sum_a\int_x^1\mathrm{d}z\,\frac{x' f_a(x',t')}{x f_b(x,t')}\,P_{a\to bc}(z)\right)$$

Inclusive Cross Section (at fixed underlying Born variables):

Unitarity + no normalization correction → remains σ_0

$$\rightarrow\; B = \sigma_0 = |M_{\mathrm{Born}}|^2$$

Cancels when normalizing to $1/\sigma$ and integrating over Born

Note: → tuning of standalone PYTHIA done with this matching scheme
Should be OK for POWHEG, but could give worries for MLM
B. Cooper et al, arXiv:1109.5295

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POWHEG

Nason, JHEP 11(2004)040
Drell-Yan: Alioli et al., JHEP 07(2008)060

Real Radiation:

$$R_{g\bar{q},q} + R_{qg,\bar{q}} = \left.\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}}\right|_{\mathrm{ME}} = \frac{\sigma_0}{\hat{s}}\frac{\alpha_\mathrm{s}}{2\pi}\frac{4}{3}\frac{\hat{t}^2+\hat{u}^2+2m_\mathrm{W}^2\hat{s}}{\hat{t}\hat{u}}$$

(for qg→q'W) (using Sjöstrand's notation)

Use R/B as splitting kernels (via overestimate + veto)

(+analogous for qq→gW)

Unitarity → Sudakov Factor:

(explicit formula only for final-state in org paper → no PDF factors here)

$$\Delta_R^{(\mathrm{NLO})}(p_\mathrm{T}) = e^{-\int d\Phi_r \frac{R(v,r)}{B(v)}\theta(k_\mathrm{T}(v,r)-p_\mathrm{T})}$$

= LL'

(not needed if shower ordered in p_T, though watch out, see next)

Inclusive Cross Section (at fixed underlying Born variables):

Include correction to NLO inclusive level → becomes σ_{NLO}

$$\to \quad \bar{B}(v) = B(v) + V(v) + \int (R(v,r) - C(v,r))\,d\Phi_r$$

Cancels when normalizing to $1/\sigma$ and integrating over Born

Differences?

Slide from T. Sjöstrand, TH-LPCC workshop, August 2011, CERN

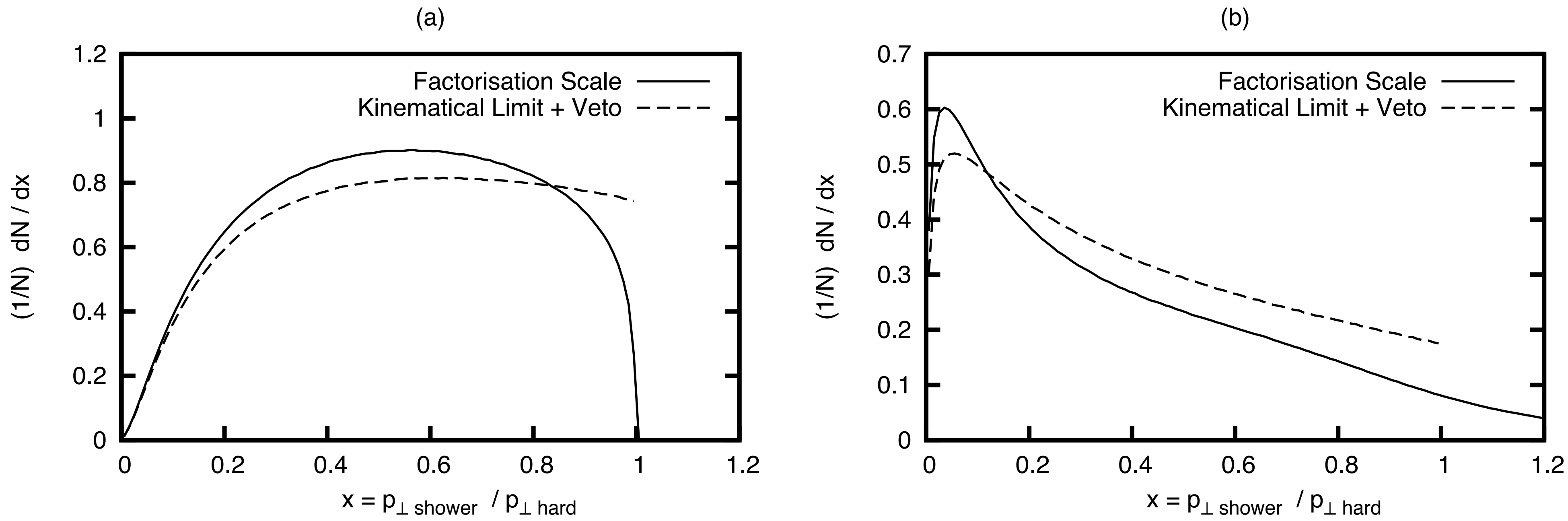
Standard Les Houches interface (LHA, LHEF) specifies startup scale SCALUP for showers, so “trivial” to interface any external program, including POWHEG.
Problem: for ISR

$$p_\perp^2 = \mathrm{p}_{\perp\mathrm{evol}}^2 - \frac{\mathrm{p}_{\perp\mathrm{evol}}^4}{p_{\perp\mathrm{evol,max}}^2}$$

$$\int d\Phi_r \frac{R(v,r)}{B(v)} \theta(k_\mathrm{T}(v,r) - p_\mathrm{T})$$

not needed if shower ordered in p_T?

i.e. $p_\perp$ decreases for $\theta^* > 90^\circ$ but $\mathrm{p}_{\perp\mathrm{evol}}$ monotonously increasing.
Solution: run “power” shower but kill emissions above the hardest one, by POWHEG’s definition.

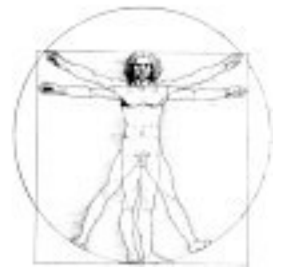


Available for ISR-dominated, coming for QCD jets with FSR issues.

in PYTHIA 8

Note: Other things that may differ in comparisons: PDFs (NLO vs LO), Scale Choices

VINCIA



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")

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?

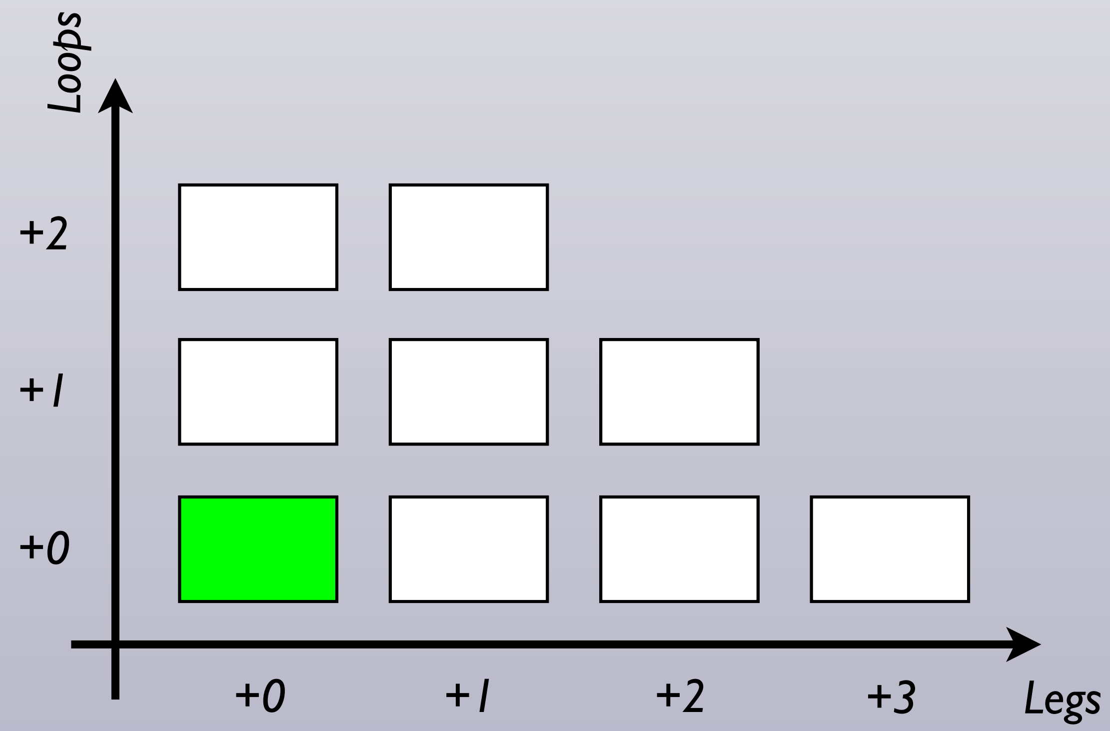
GEEKS: Giele, Kosower, PS

+ Collaborations with Sjostrand *(Pythia 8 interface)*, Gehrmann-de-Ridder & Ritzmann *(mass effects)*, Lopez-Villarejo & Larkoski *(sector showers, helicity-dependence)*, Hartgring & Laenen *(NLL/NLO multileg)*, Diana *(ISR)*, Volunteers *(Tuning)*

Markov pQCD

Start at Born level

$$|M_F|^2$$



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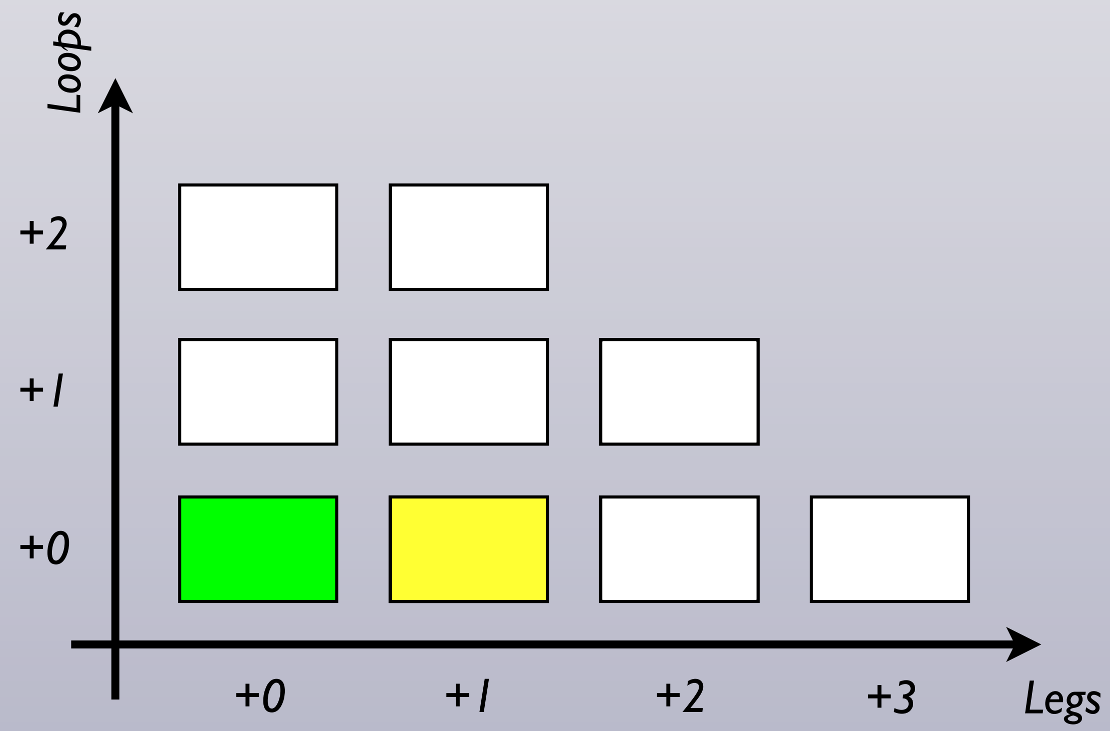
Generate "shower" emission

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



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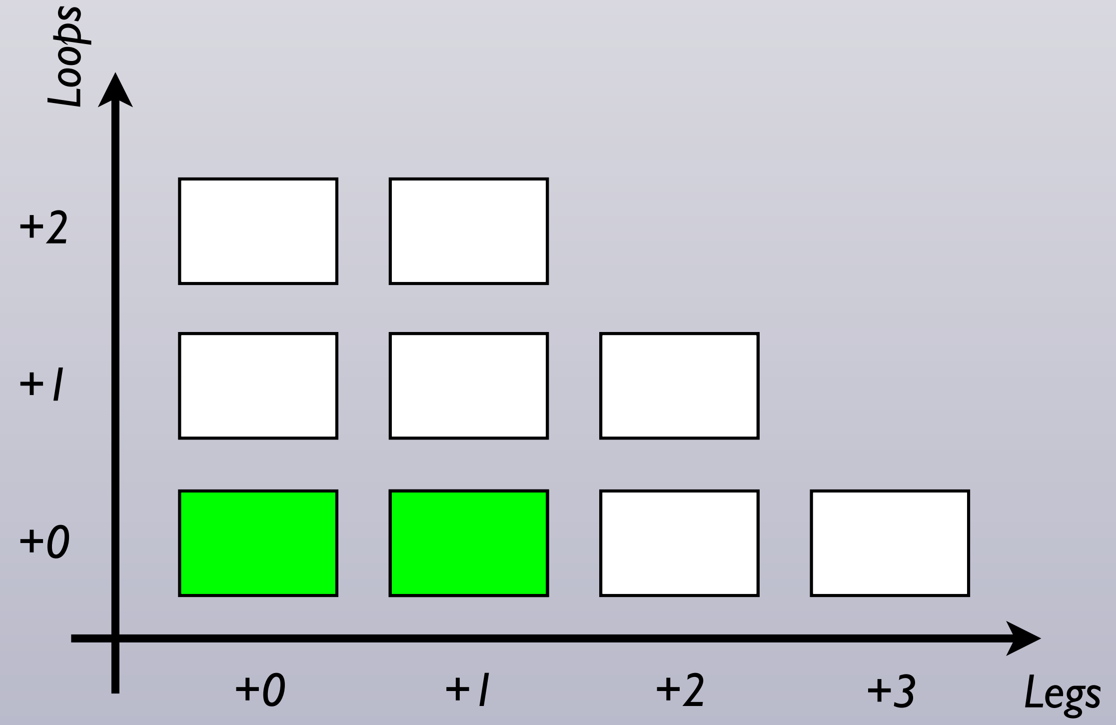
Correct to Matrix Element

PYTHIA trick

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



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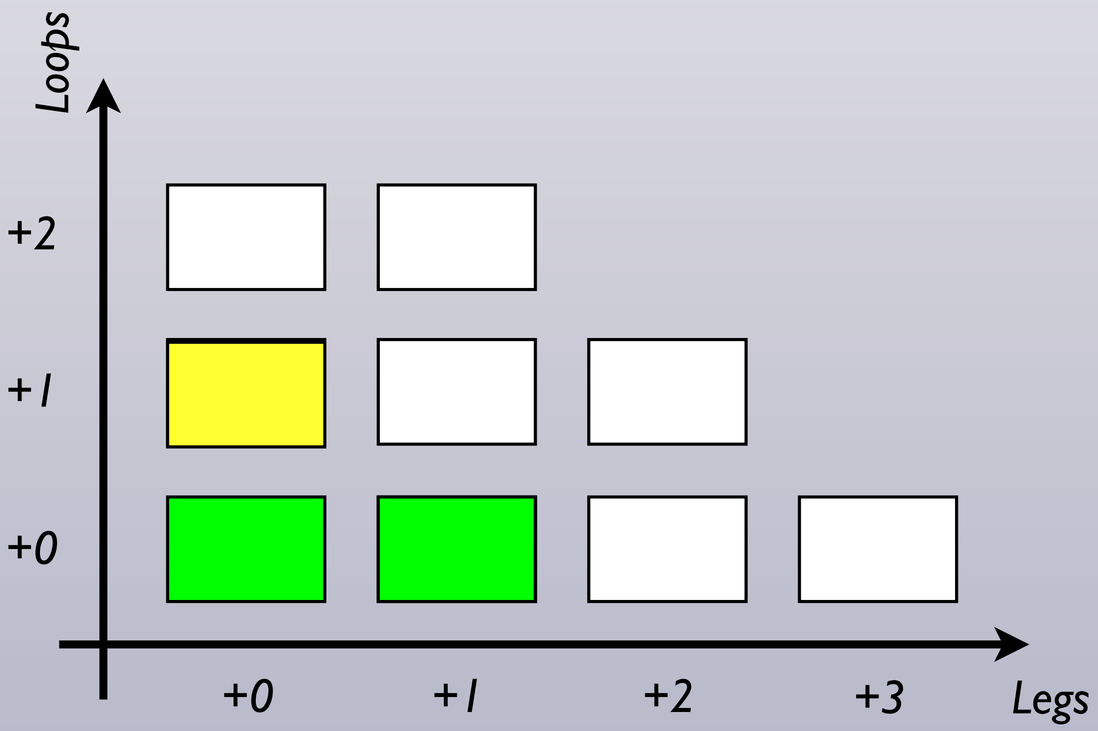
Unitarity of Shower

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



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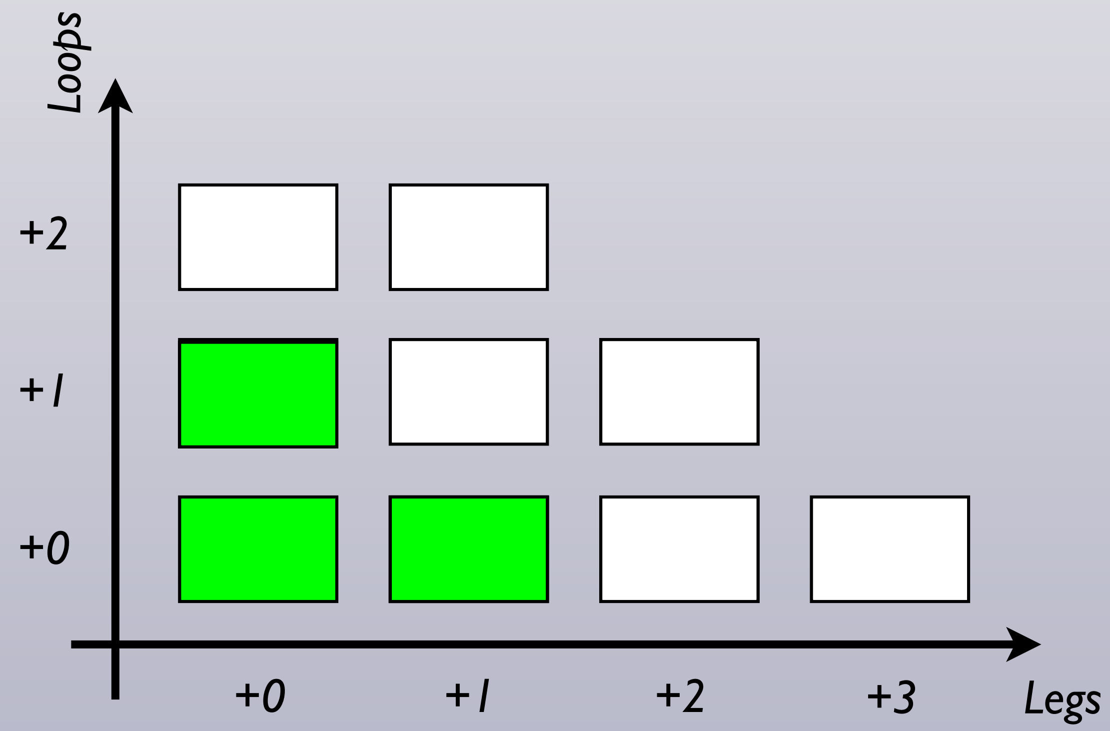

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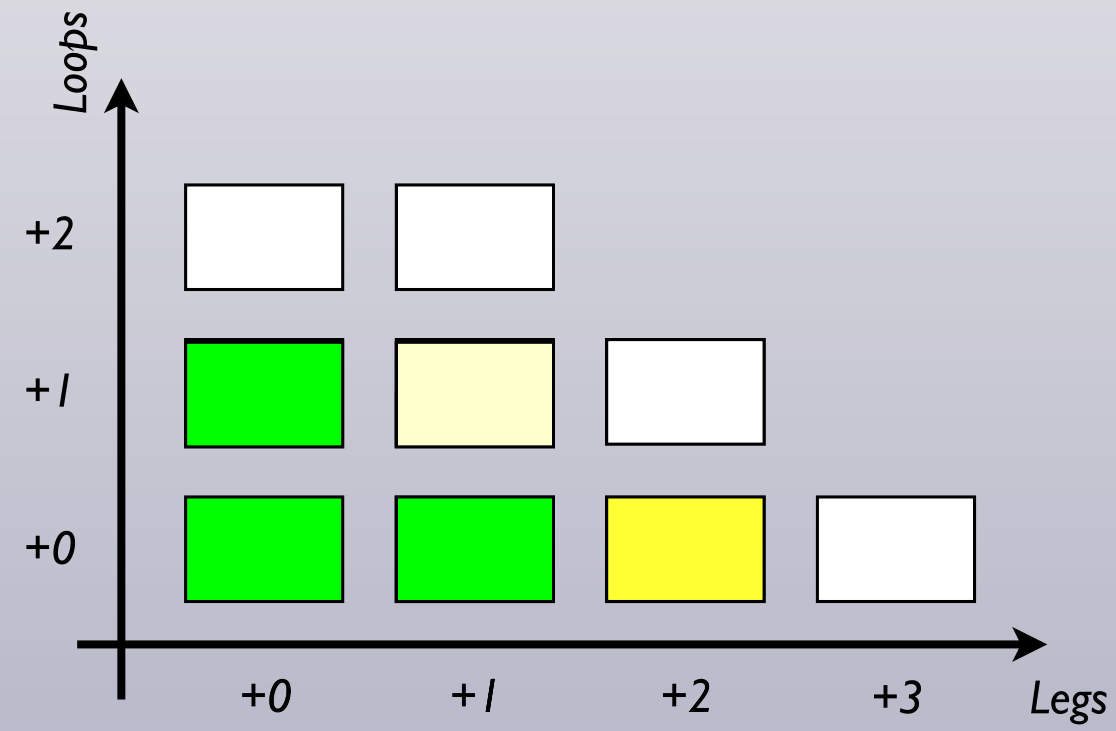

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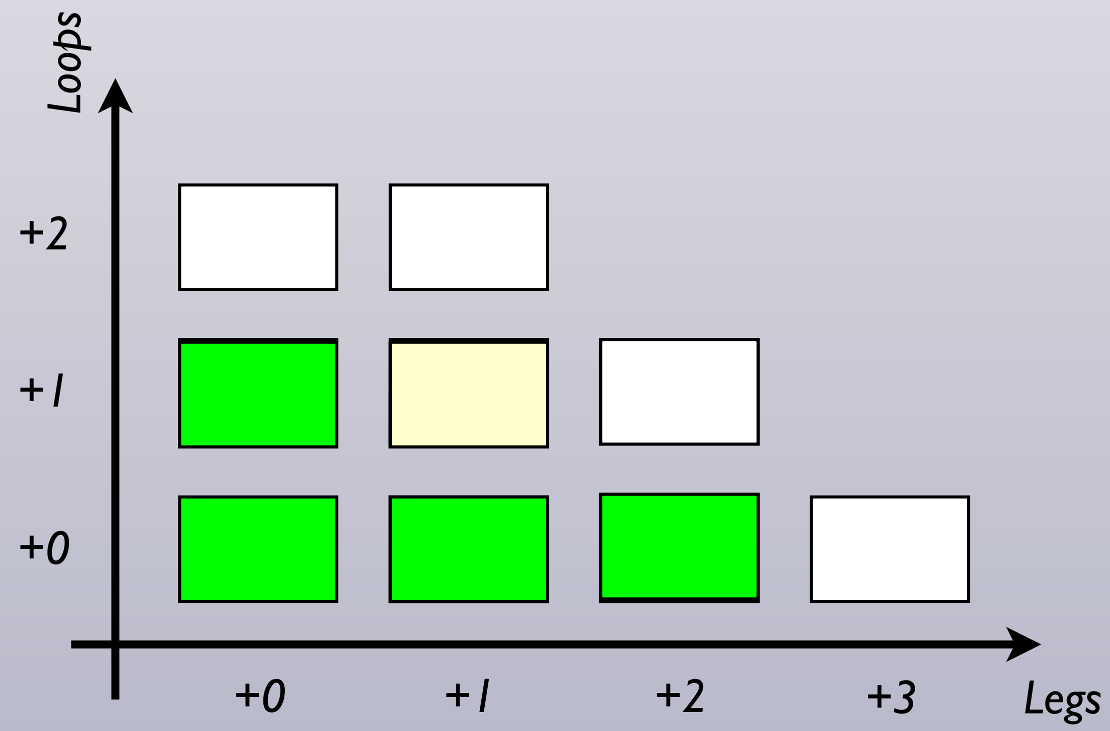

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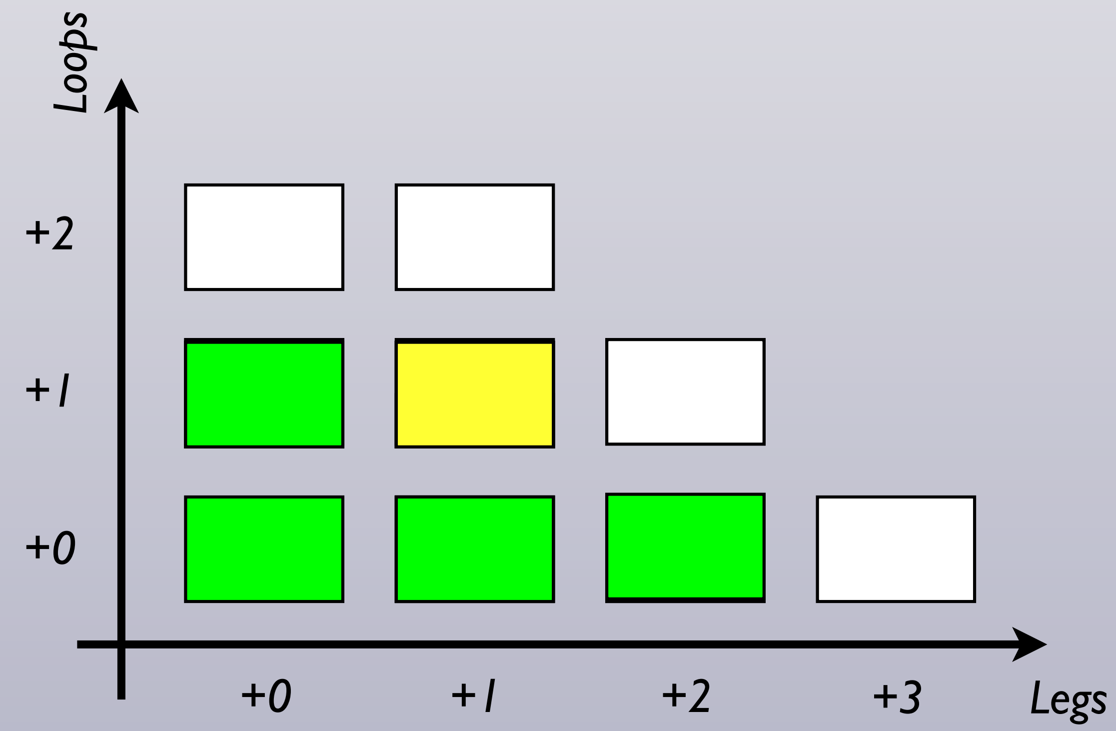

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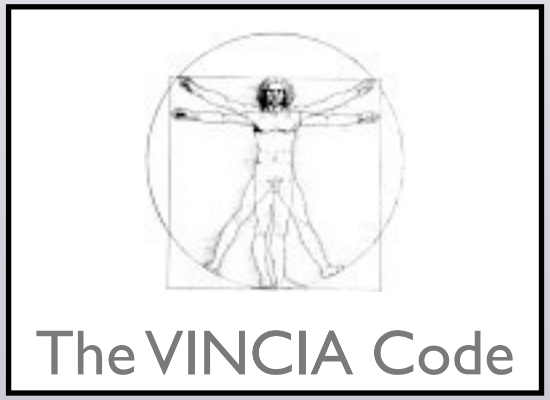

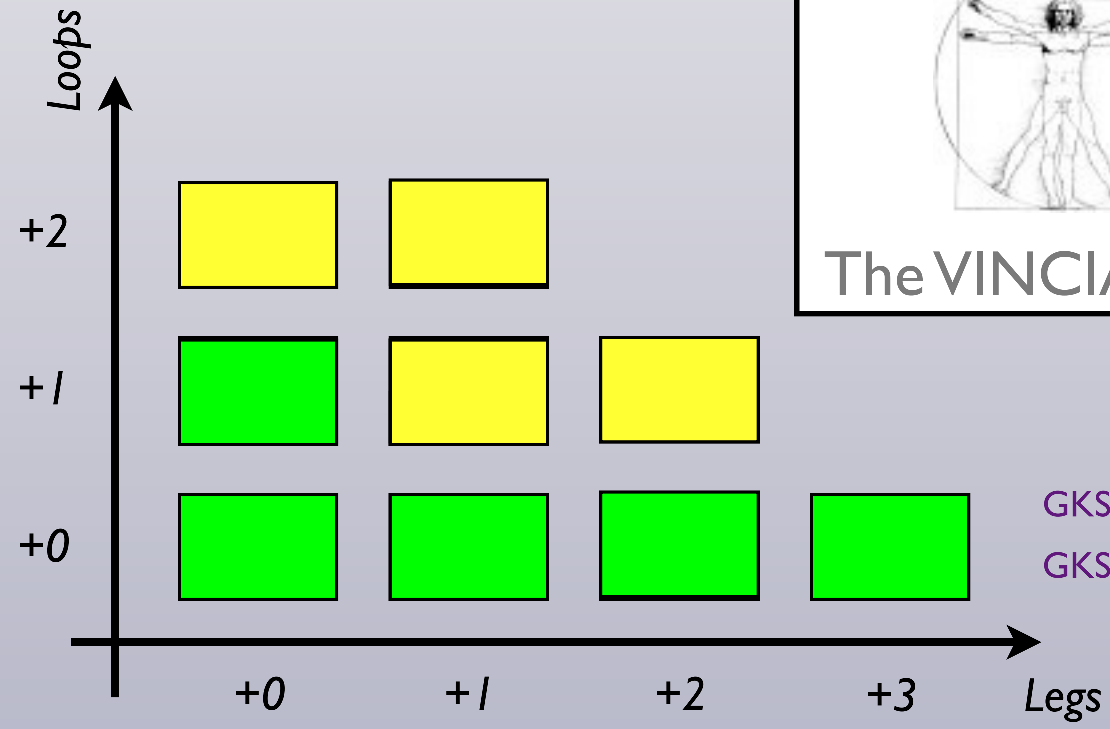

GKS, PRD78(2008)014026

GKS, PRD84(2011)054003

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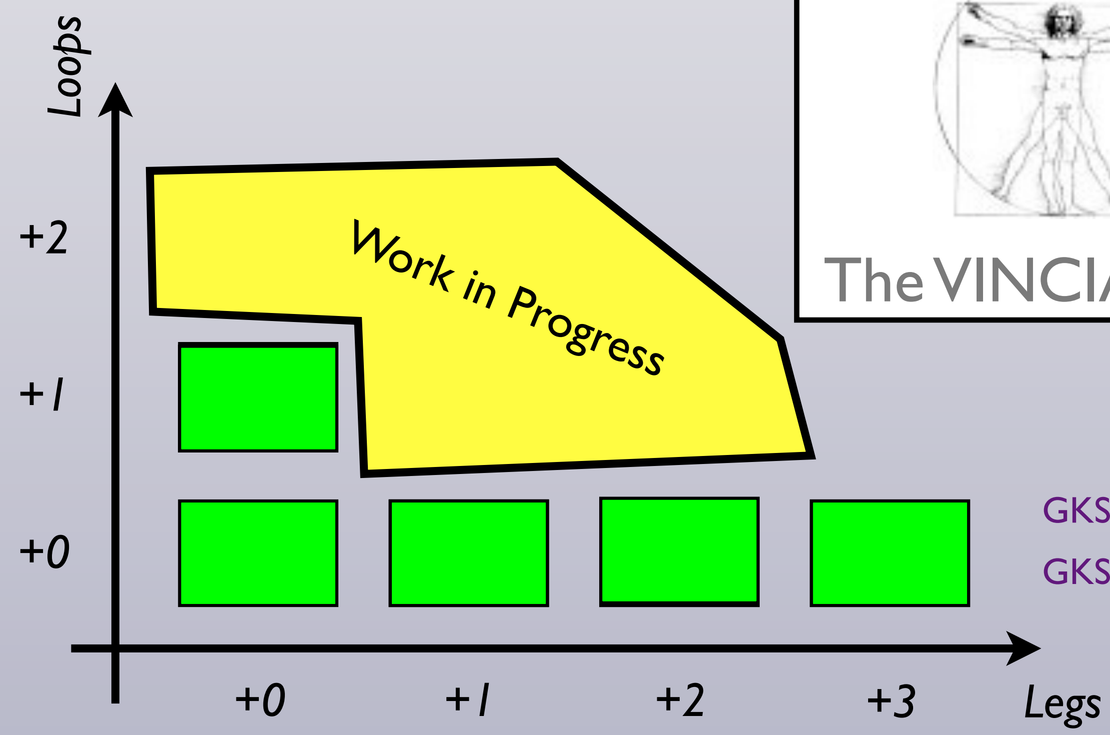

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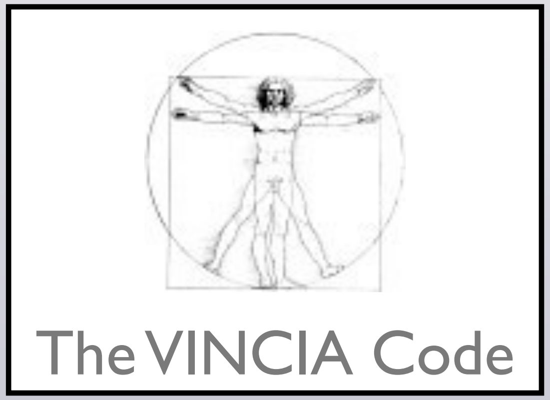

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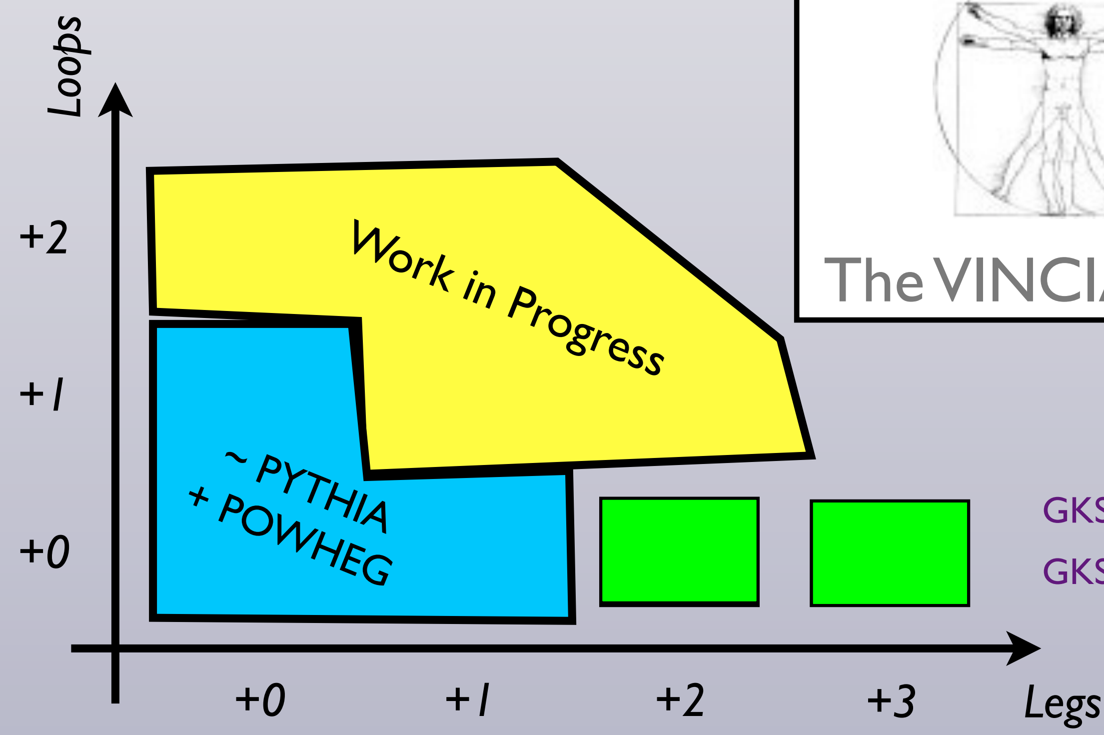

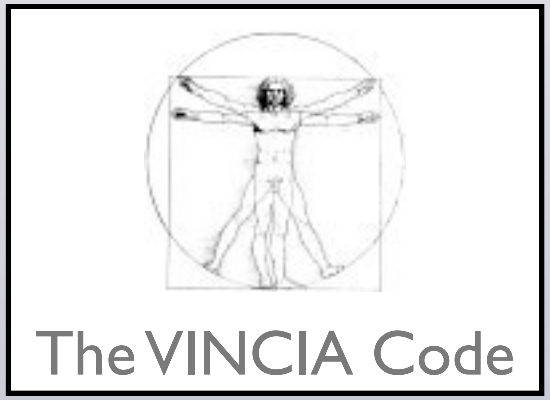

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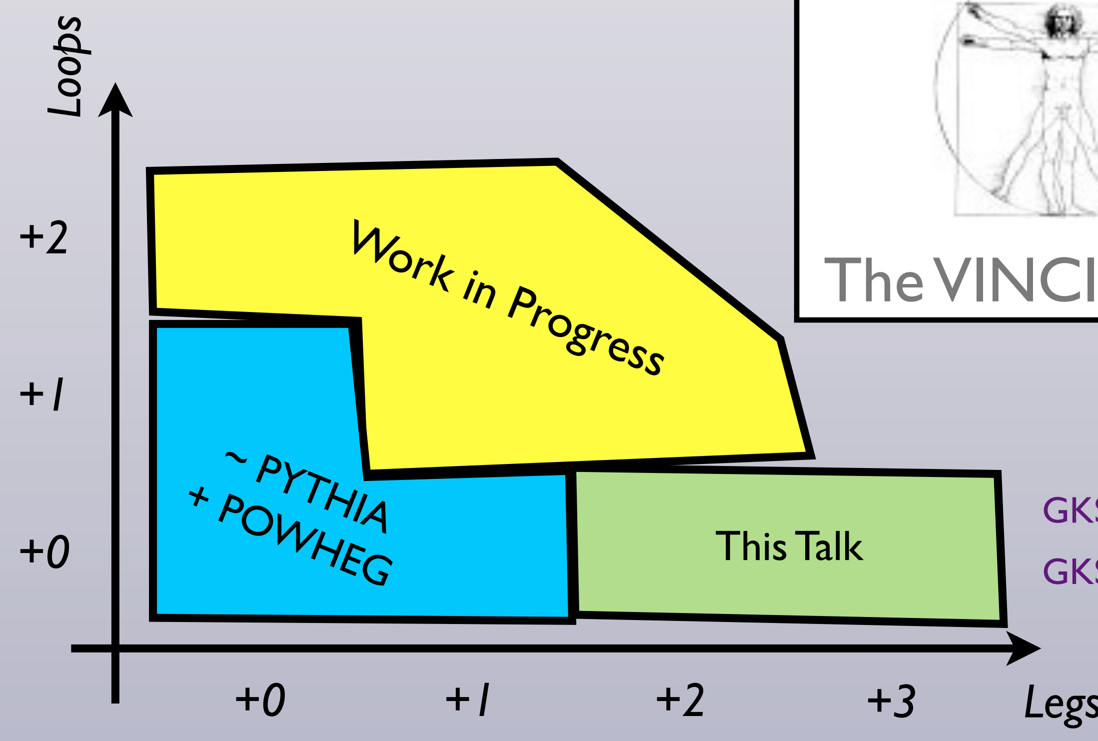

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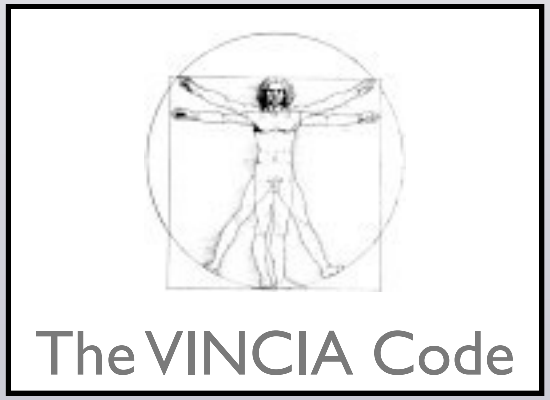

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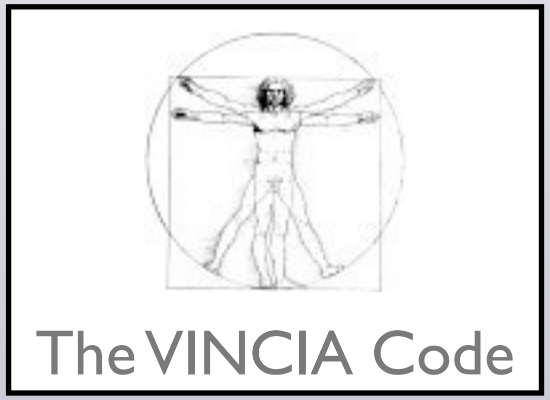

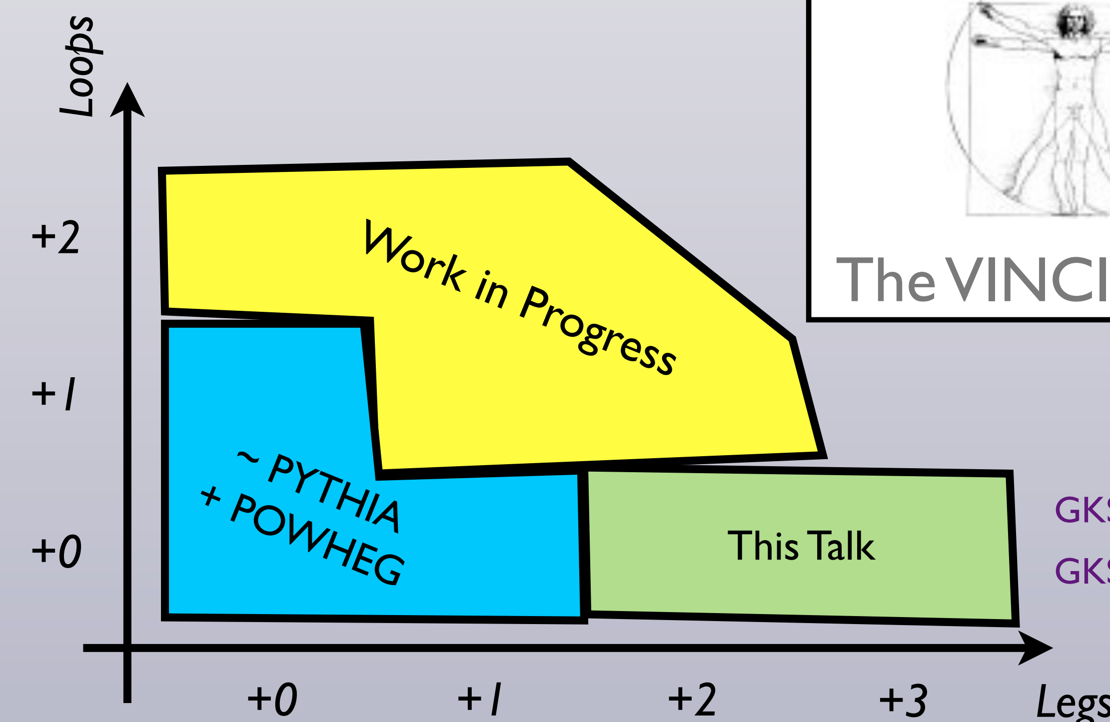

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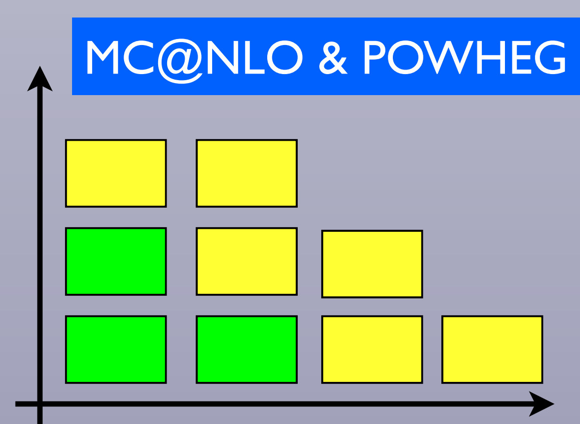
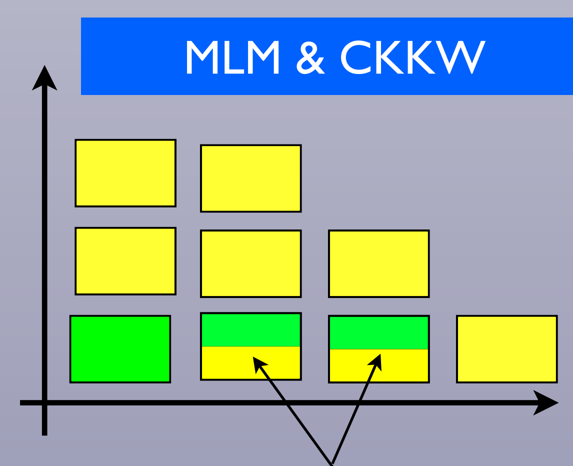


LO for 1st emission
LL for 2nd emission and beyond



"Matching Scale"
→ hierarchies not matched

The Denominator

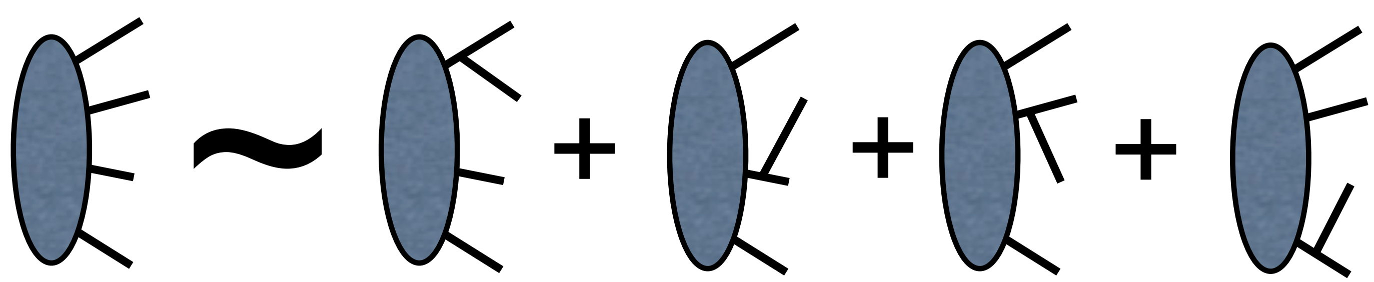
$$a_i \rightarrow \frac{|M_{F+1}|^2}{\sum a_i |M_F|^2}$$

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

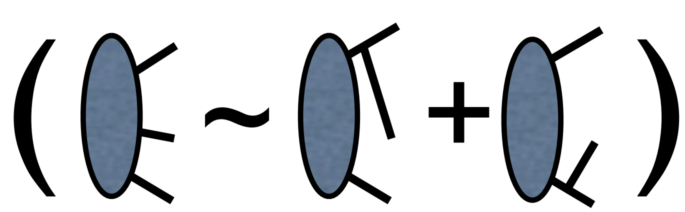
Existing parton showers are *not* really Markov Chains

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

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



j = 2
→ 4 terms



j = 1
→ 2 terms

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

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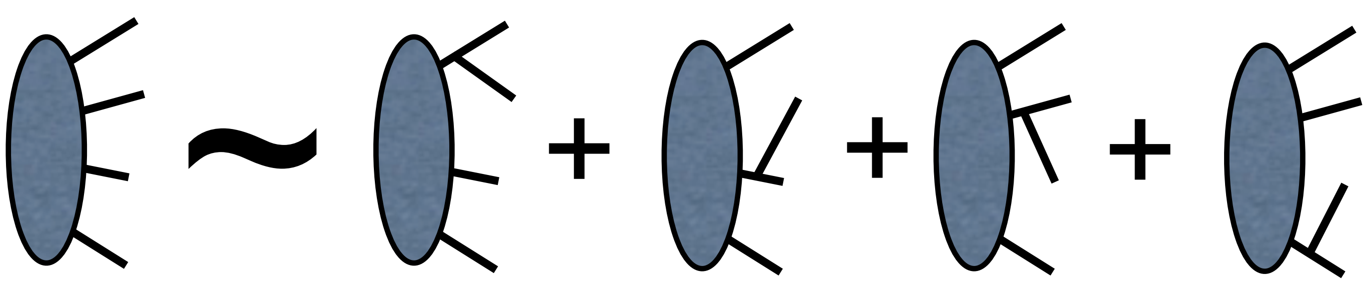
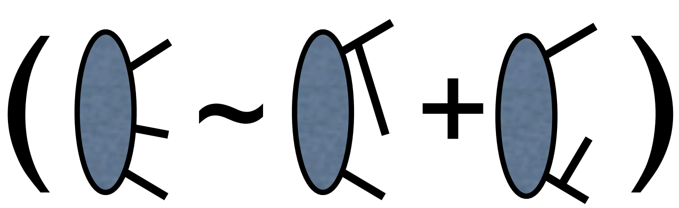
Further evolution (restart scale) depends on which branching happened last
→ proliferation of terms

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



j = 2
→ 4 terms



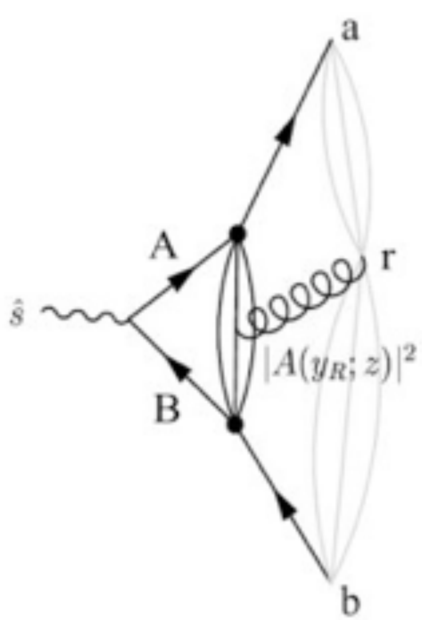
j = 1
→ 2 terms

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** $2^n n! \rightarrow n!$



(+ 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

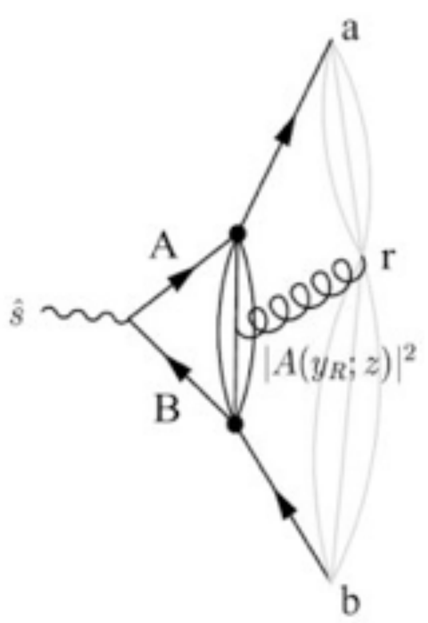
+ Matching: $n! \rightarrow n$

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

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

Matched Markovian Antenna Showers

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



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

+ Change "shower restart" to Markov criterion:

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

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

Unique restart scale, independently of how it was produced

+ Matching: $n! \rightarrow n$

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

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

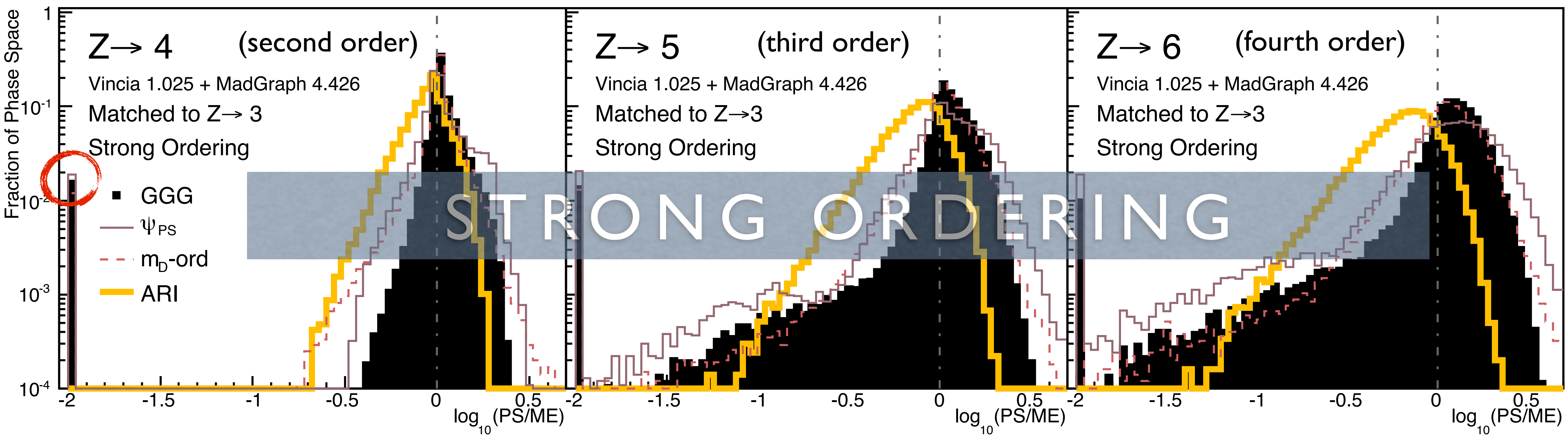
Matched Markovian Antenna Shower:
After 2 branchings: 2 terms
After 3 branchings: 3 terms
After 4 branchings: 4 terms

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

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

Approximations

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

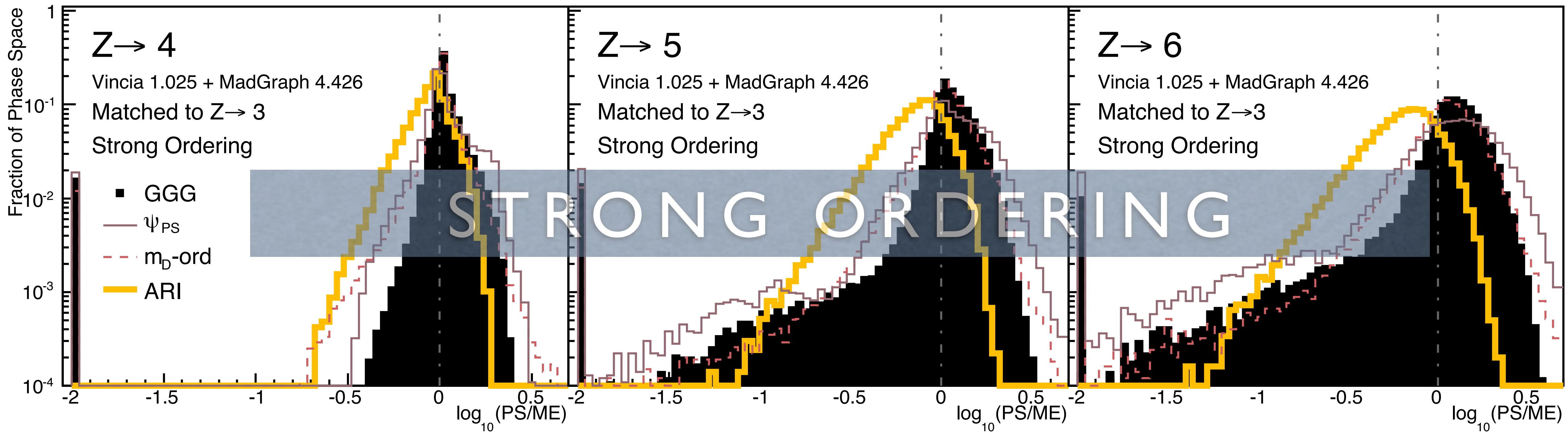


Dead Zone: 1-2% of phase space have no strongly ordered paths leading there*

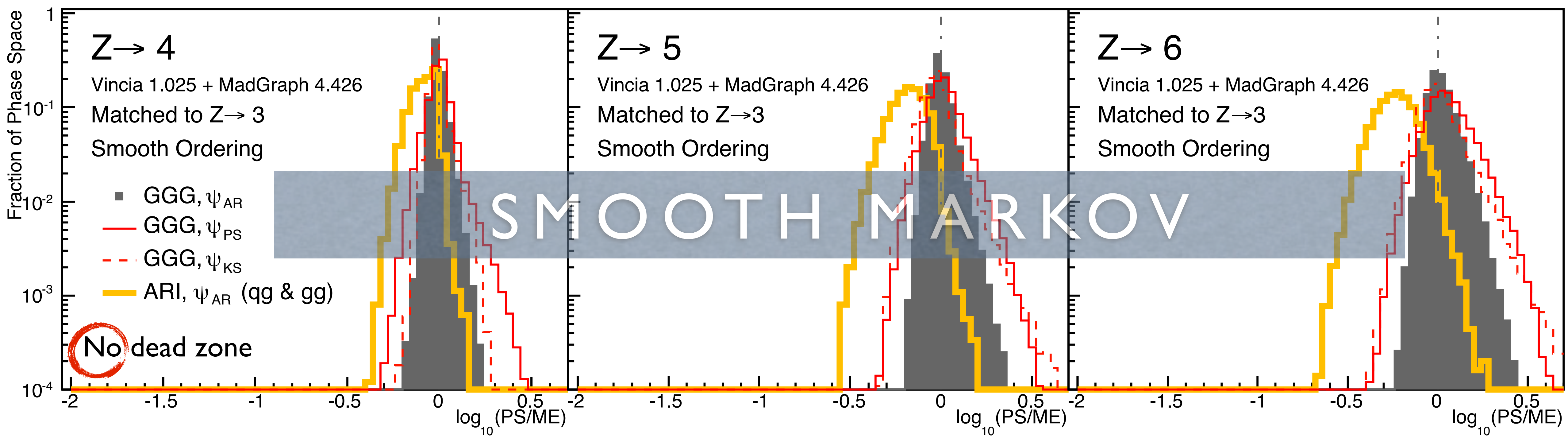
*fine from strict LL point of view: those points correspond to "unordered" non-log-enhanced configurations

→ 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)



2→4

Generate Trials *without* imposing strong ordering

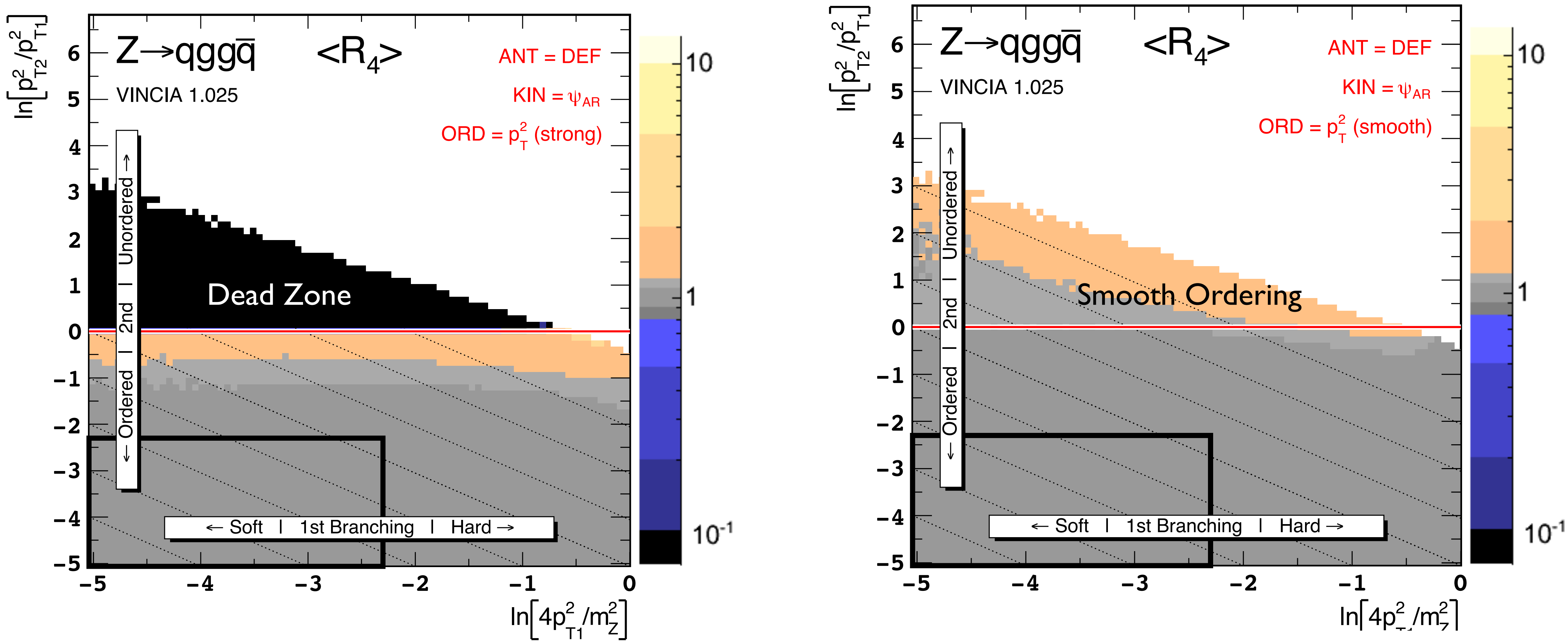
At each step, each dipole allowed to fill its entire phase space

Overcounting removed by matching

+ smooth ordering beyond matched multiplicities

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

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



2→4

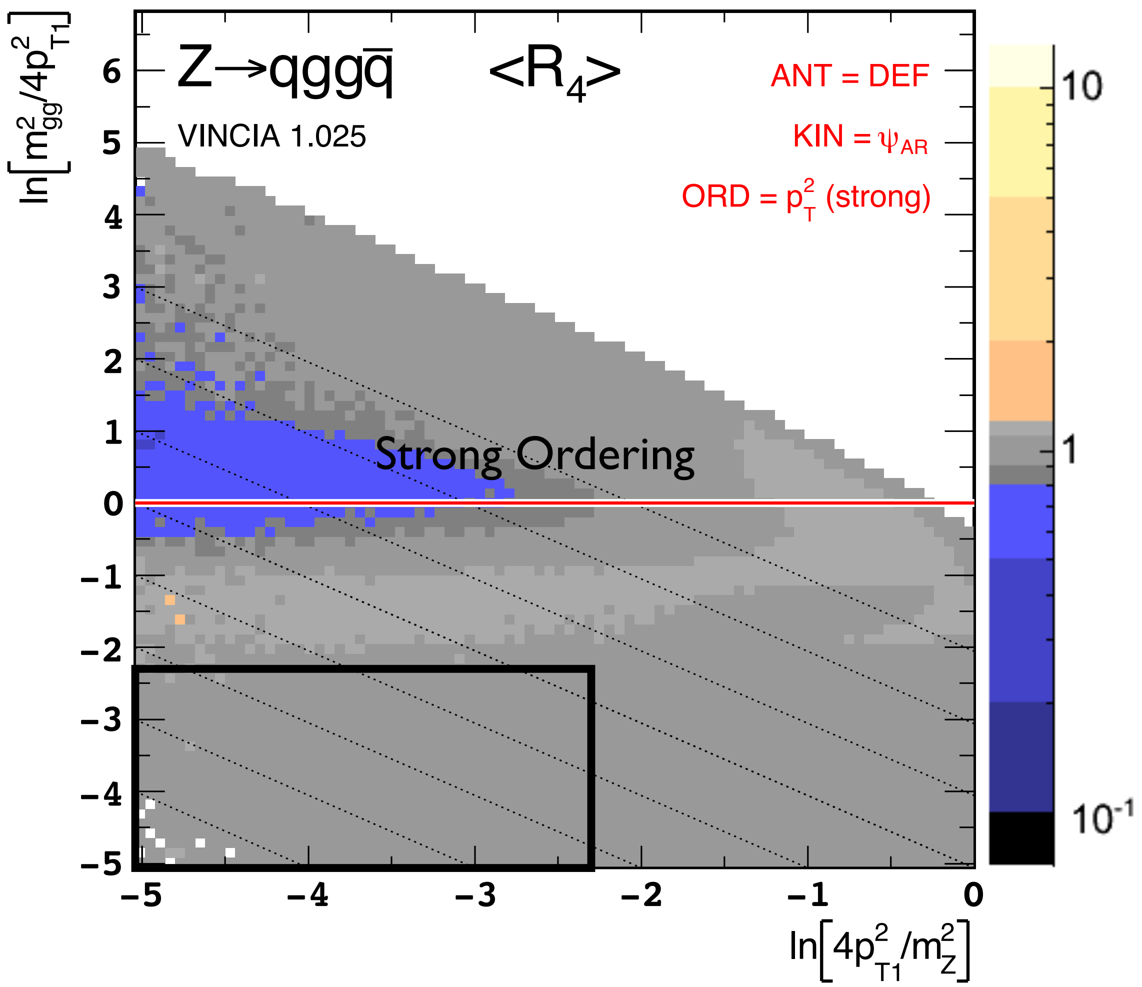
Generate Trials *without* imposing strong ordering

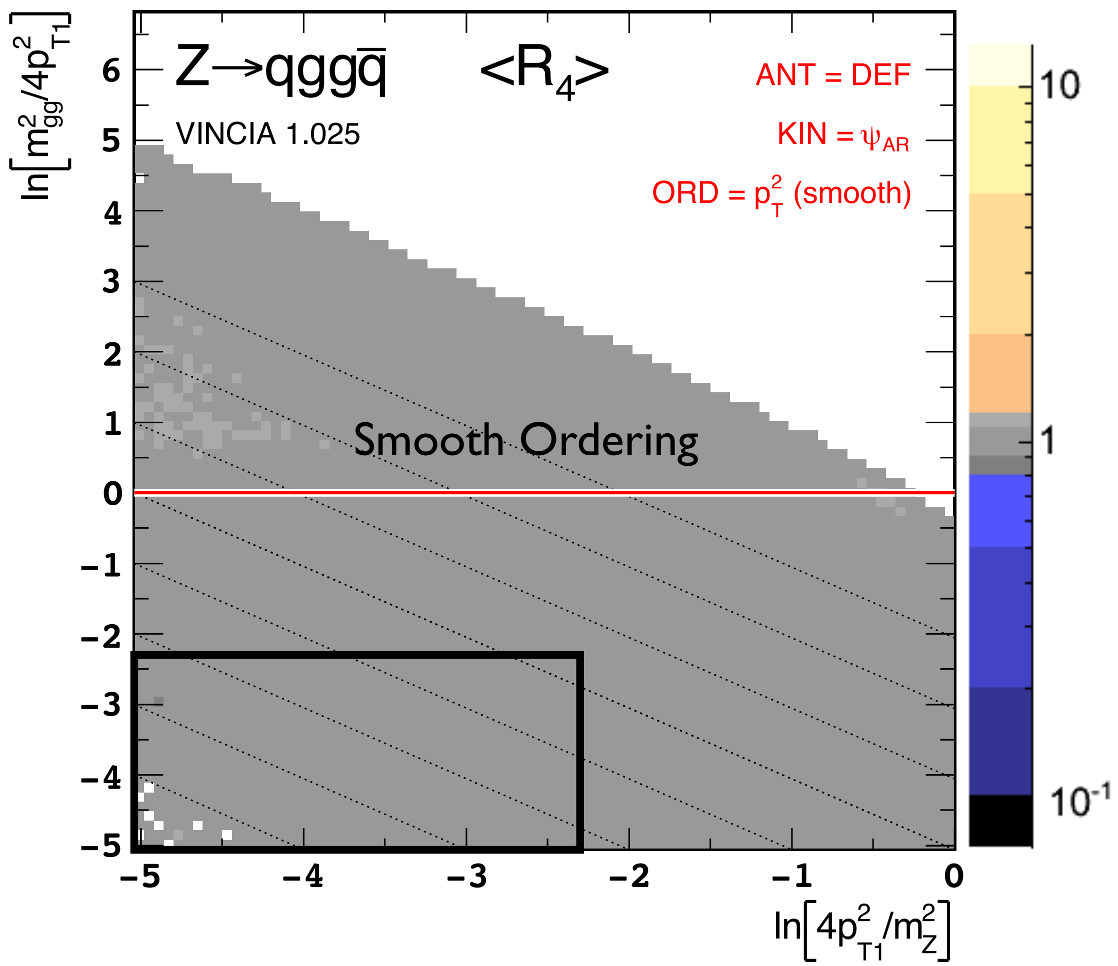
At each step, each dipole allowed to fill its entire phase space

Overcounting removed by matching

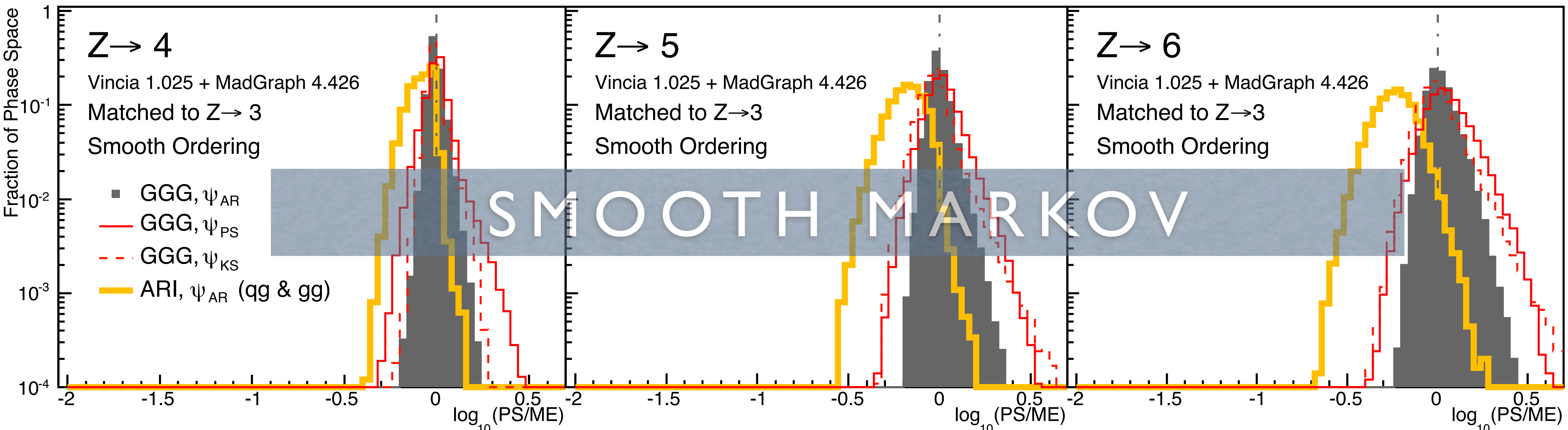
+ smooth ordering beyond matched multiplicities

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

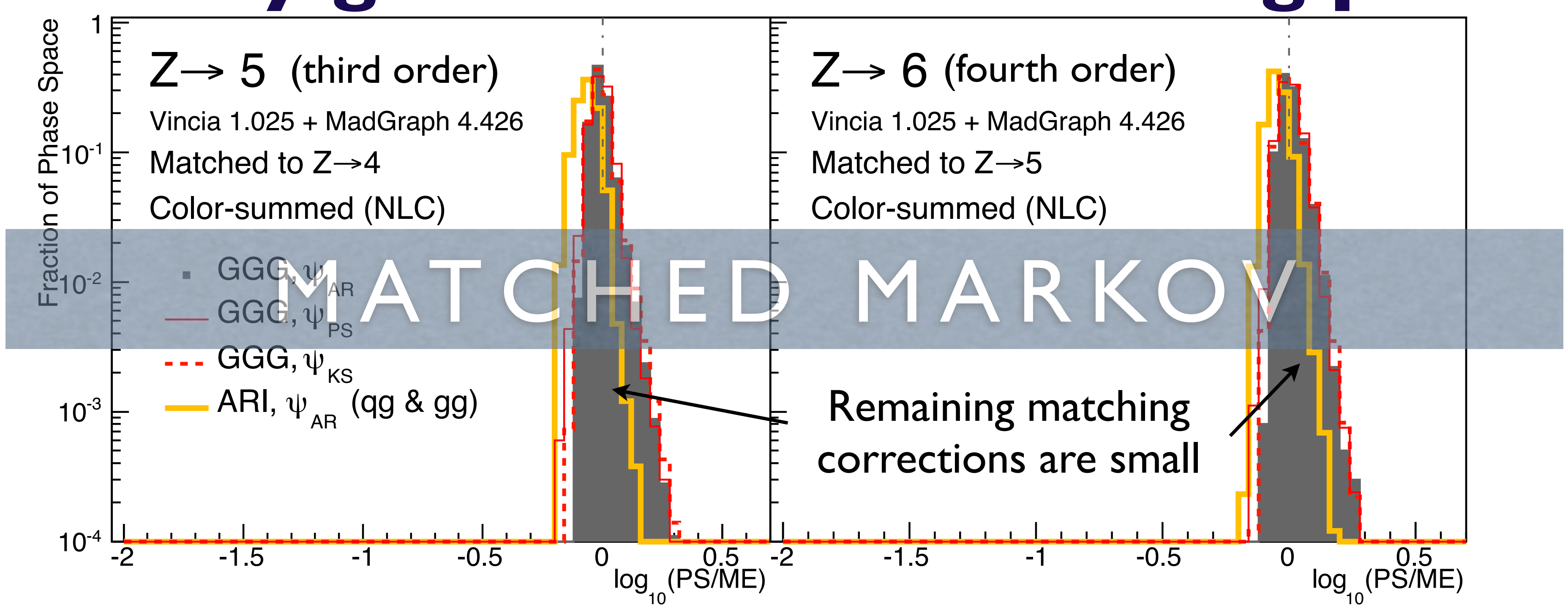




+ Matching (+ full colour)



→ **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:

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

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

+ 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
- 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…)

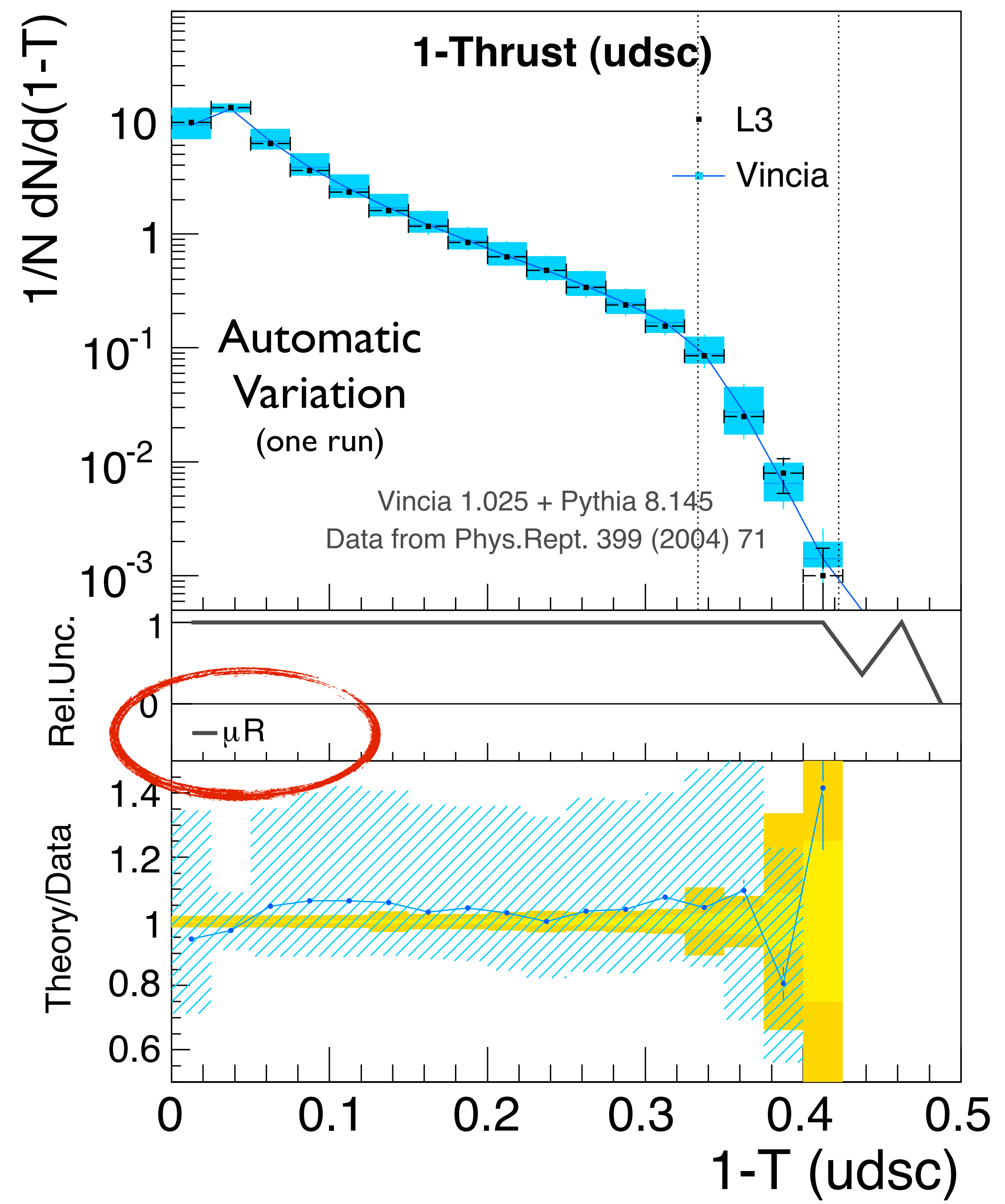
+ Unitarity

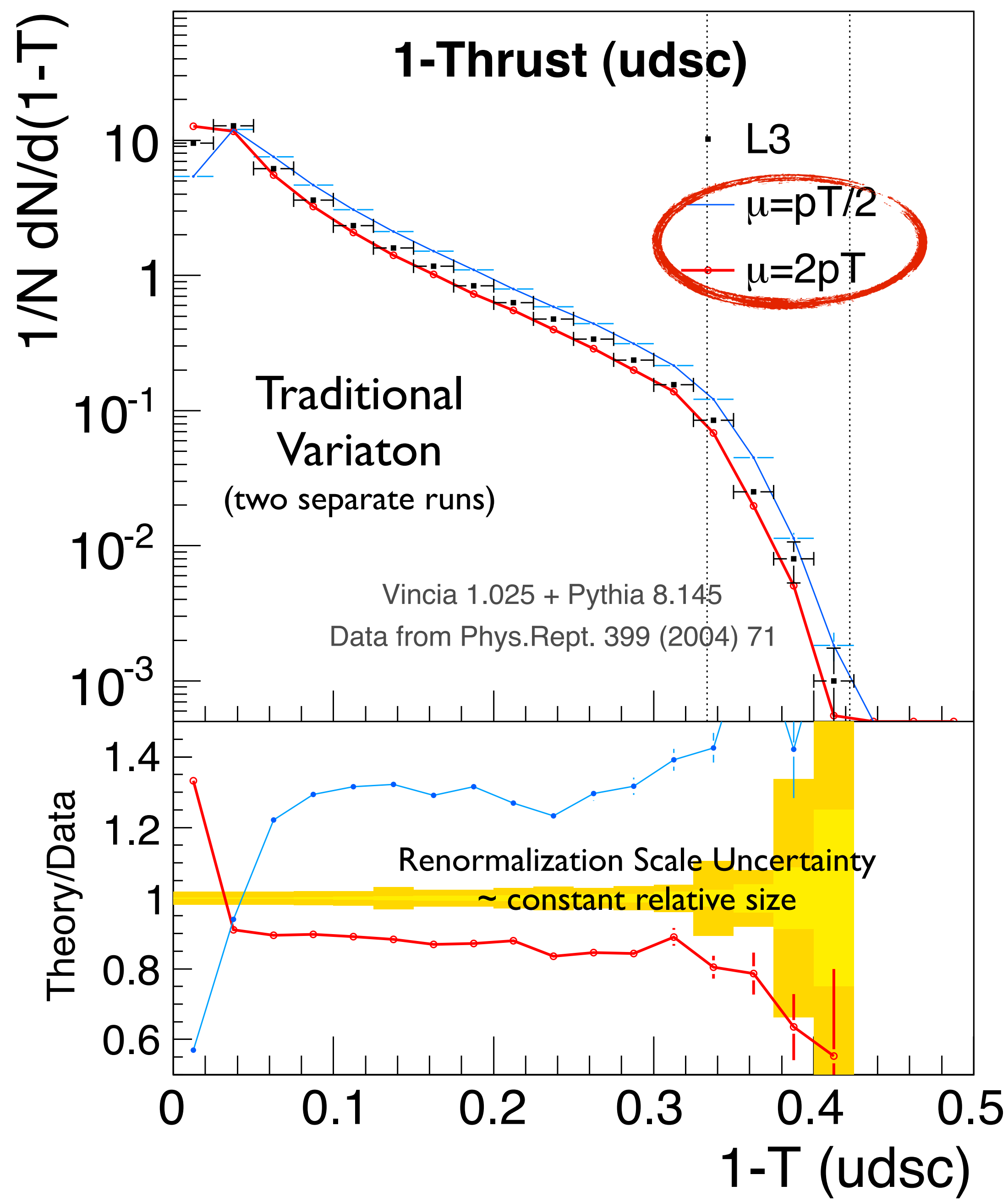
For each *failed* branching:

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

Automatic Uncertainties

Vincia:uncertaintyBands = on

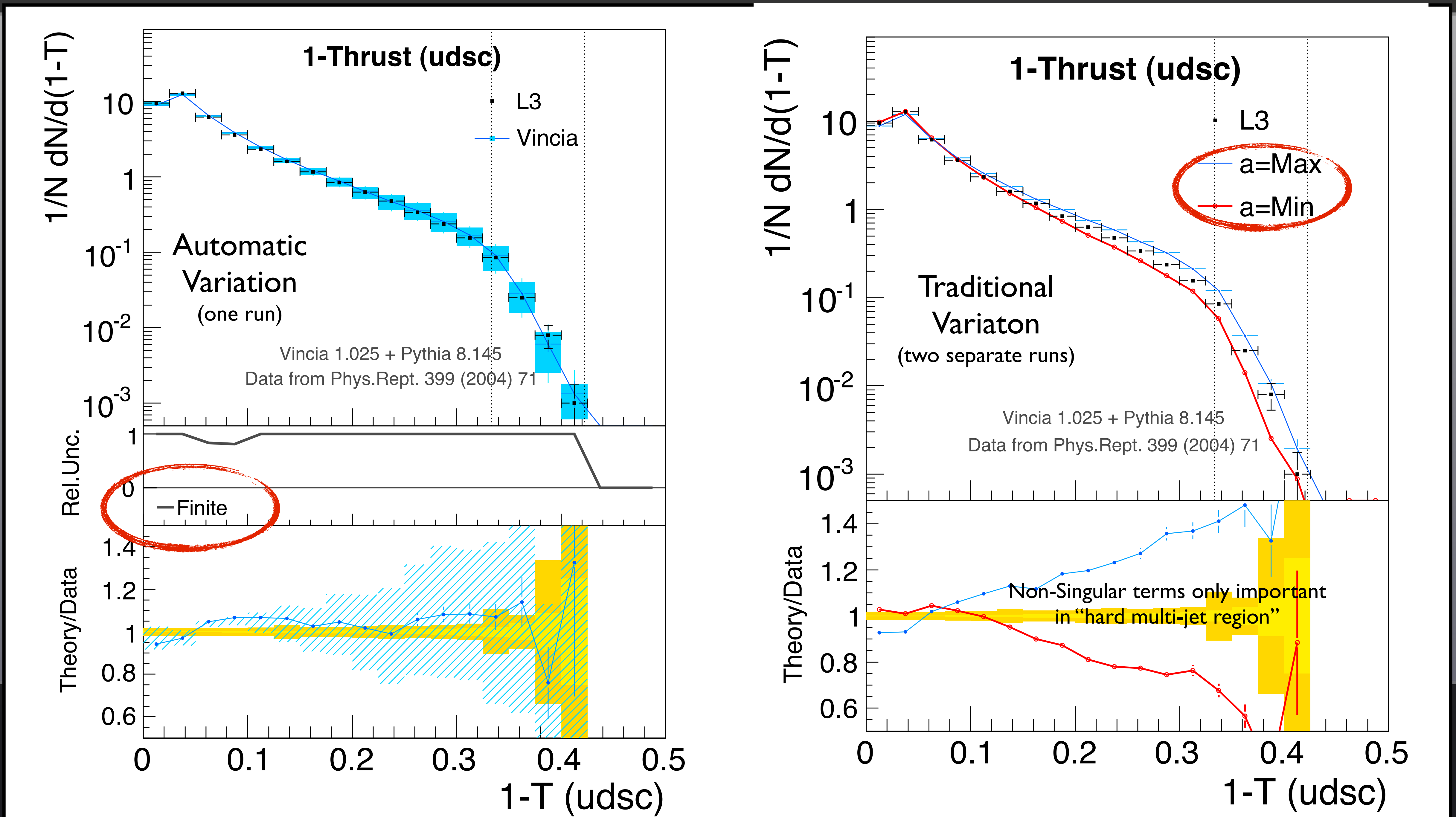




Variation of renormalization scale (no matching)

Automatic Uncertainties

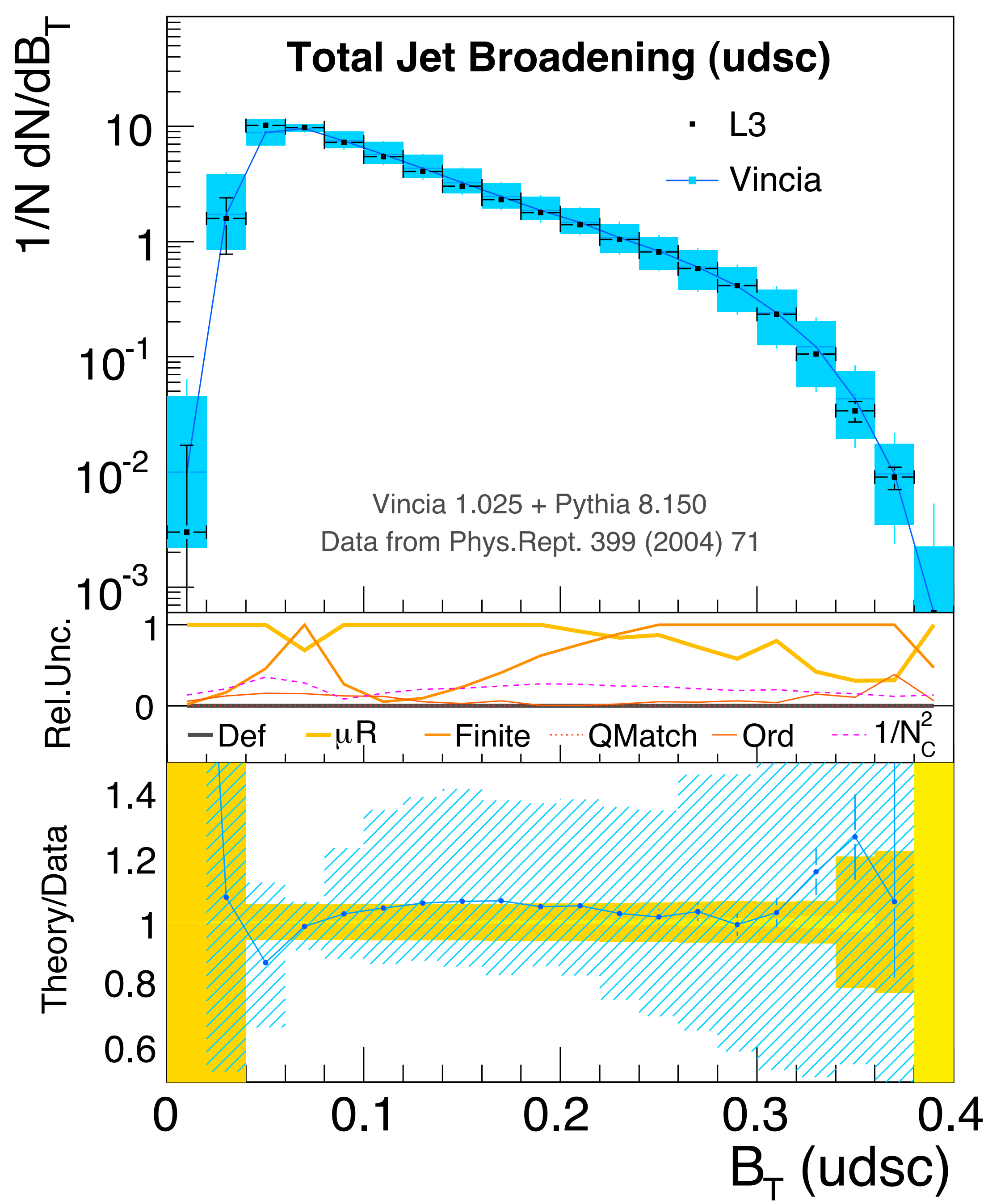
Vincia:uncertaintyBands = on



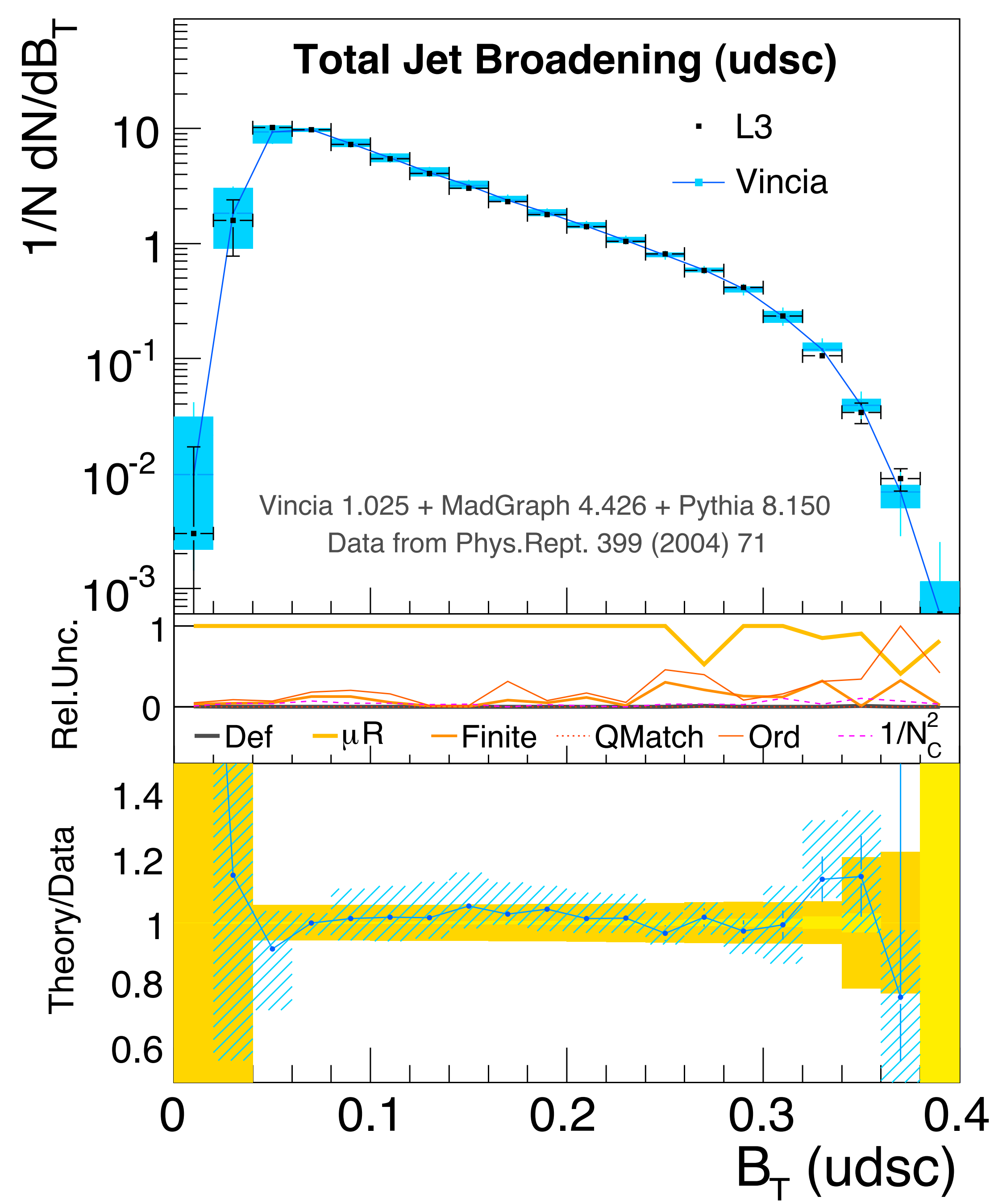
Variation of "finite terms" (no matching)

Putting it Together

VinciaMatching:order = 0



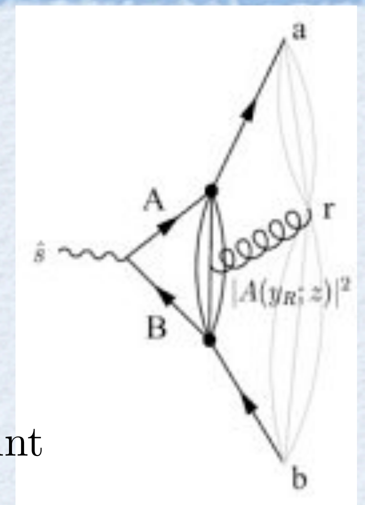
VinciaMatching:order = 3



Sector Showers

J. Lopez-Villarejo & PS, arXiv:1109.3608

Also discussed in Larkoski & Peskin, PRD81(2010)054010, PRD84 (2011)034034



- Dipole-antenna formalism (2 -> 3)
- Two types:
  - Global (Lund, GGG, GKS): $|M^{(n)}|^2 \sim \sum_{i \in \text{clust.}} a_i |M_i^{(n-1)}|^2$ for any P.S. point
  - Sector (Kosower PRD 57 (1998) 5410): $|M^{(n)}|^2 \sim \sum_{i \in \text{clust.}} \tilde{a}_i |M_i^{(n-1)}|^2 \; \Theta_i(\text{P.S.}) \sim \tilde{a}_j |M_j^{(n-1)}|^2$

Sector Showers

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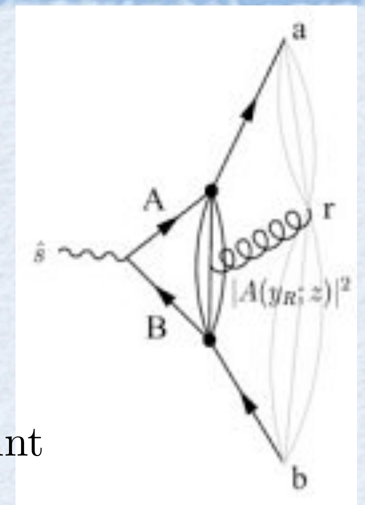
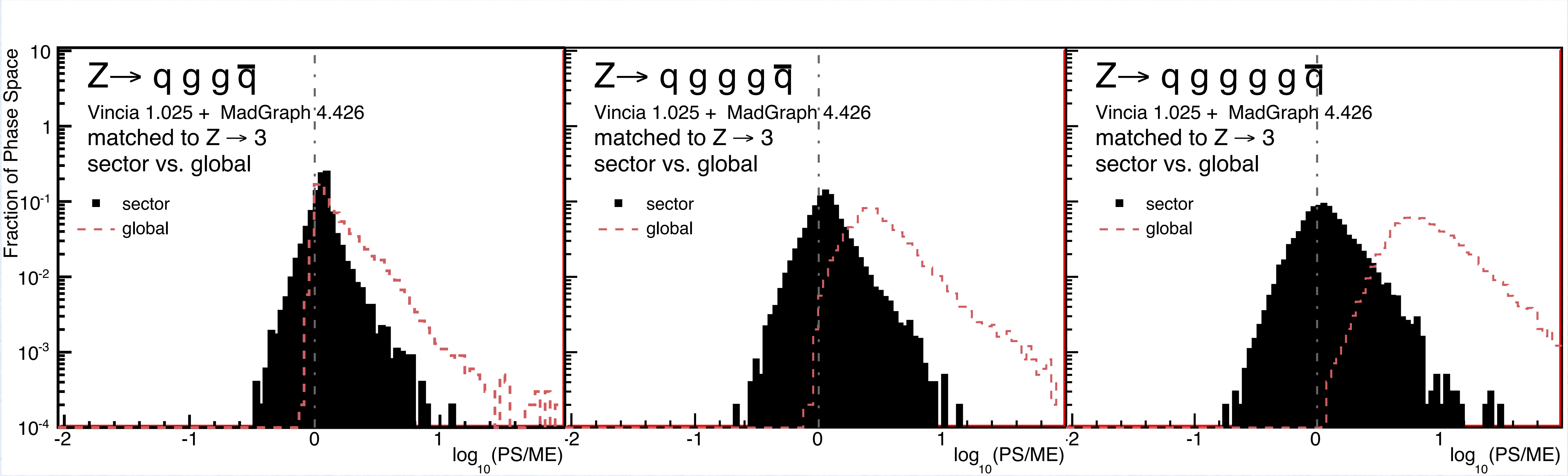


- Dipole-antenna formalism (2 -> 3)
- Two types:
  - Global (Lund, GGG, GKS): $|M^{(n)}|^2 \sim \sum_{i\in\mathrm{clust.}} a_i |M_i^{(n-1)}|^2$ for any P.S. point
  - Sector (Kosower PRD 57 (1998) 5410): $|M^{(n)}|^2 \sim \sum_{i\in\mathrm{clust.}} \tilde{a}_i |M_i^{(n-1)}|^2 \, \Theta_i(\mathrm{P.S.}) \sim \tilde{a}_j |M_j^{(n-1)}|^2$



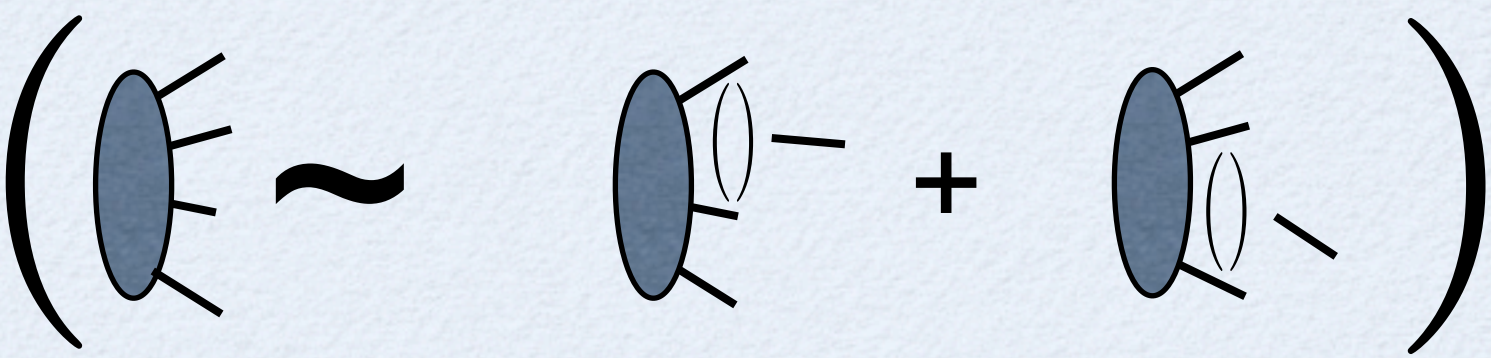
*) shows Global *without* any ordering condition imposed → overcounting

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



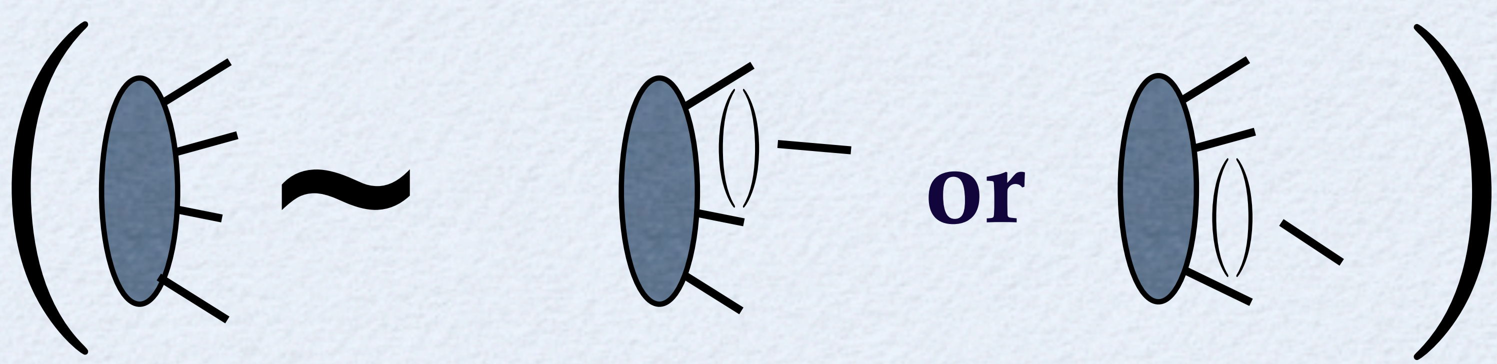
3→4
2 terms per phase-space point

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

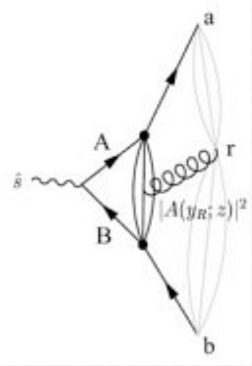
N = number of emitted partons



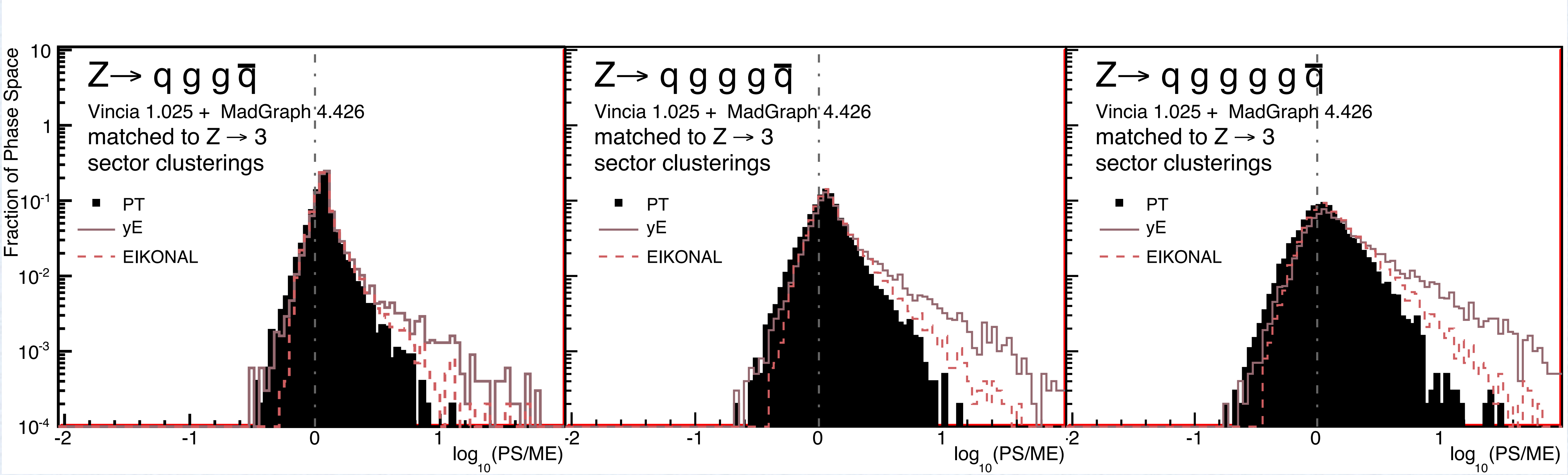
3→4
1 term per phase-space point

Sector Implementation

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



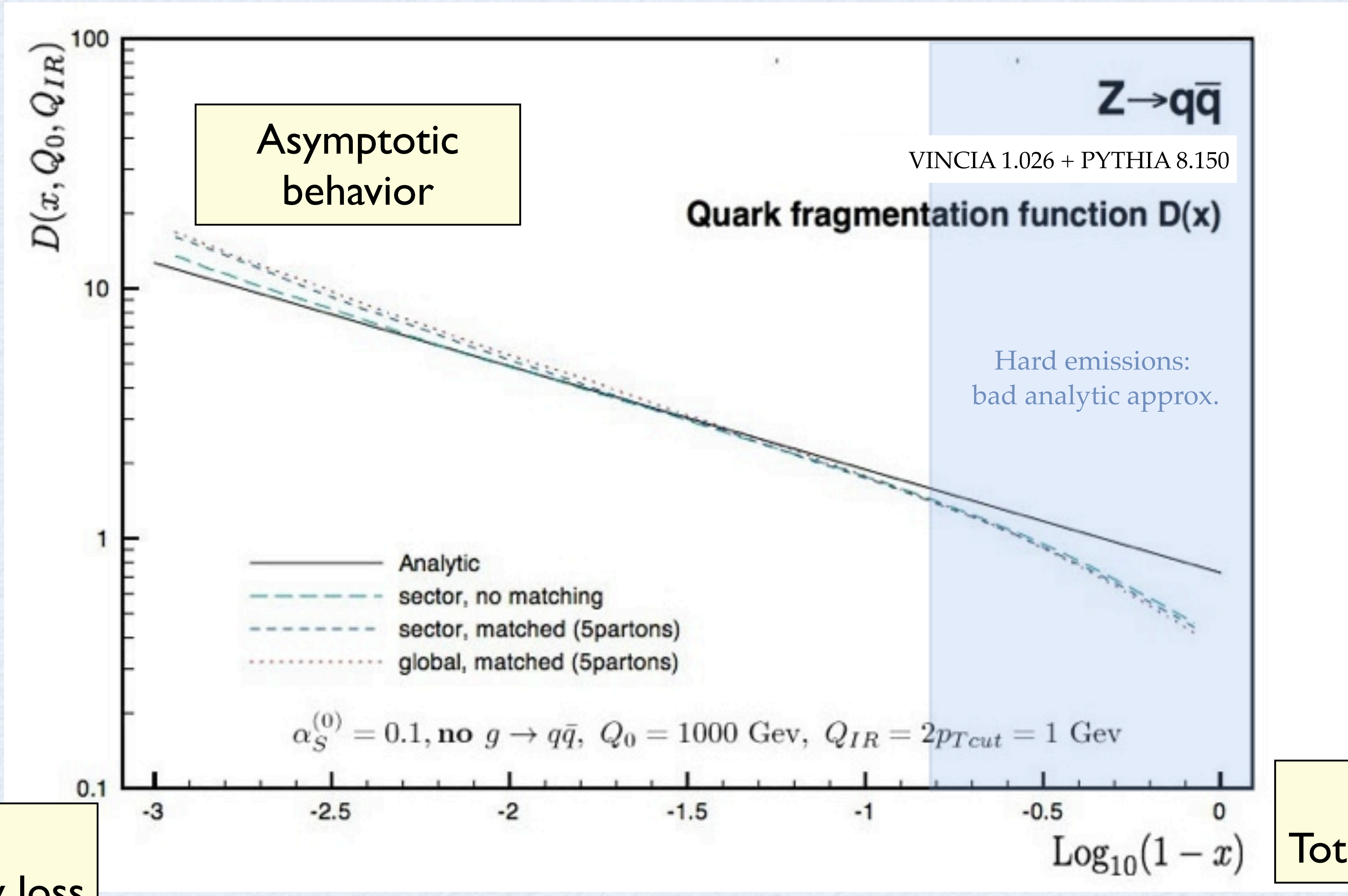
- Different criteria for separating sectors in phase space
  Looking for "best" sub-LL behavior.



Results->FF

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

Test: fragmentation function for a quark



x→1
No energy loss

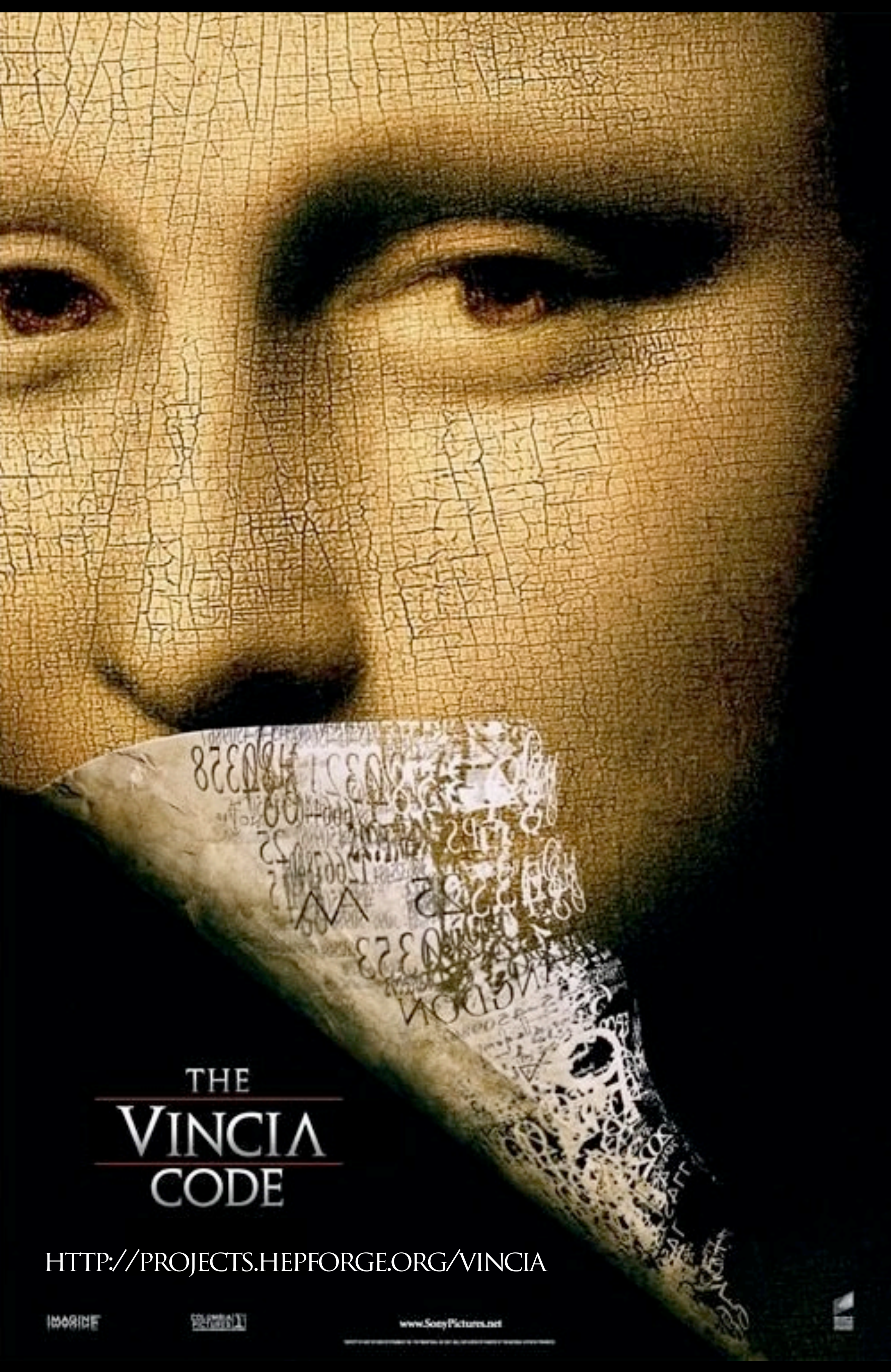
x→0
Total energy loss

Results -> Speed

Matched through:	Z→3	Z→4	Z→5	Z→6
Pythia 6	0.20	ms/event Z→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*		
Pythia 8	0.22			
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)* * + *initialization time*	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)*

J. Lopez-Villarejo & PS, arXiv:1109.3608



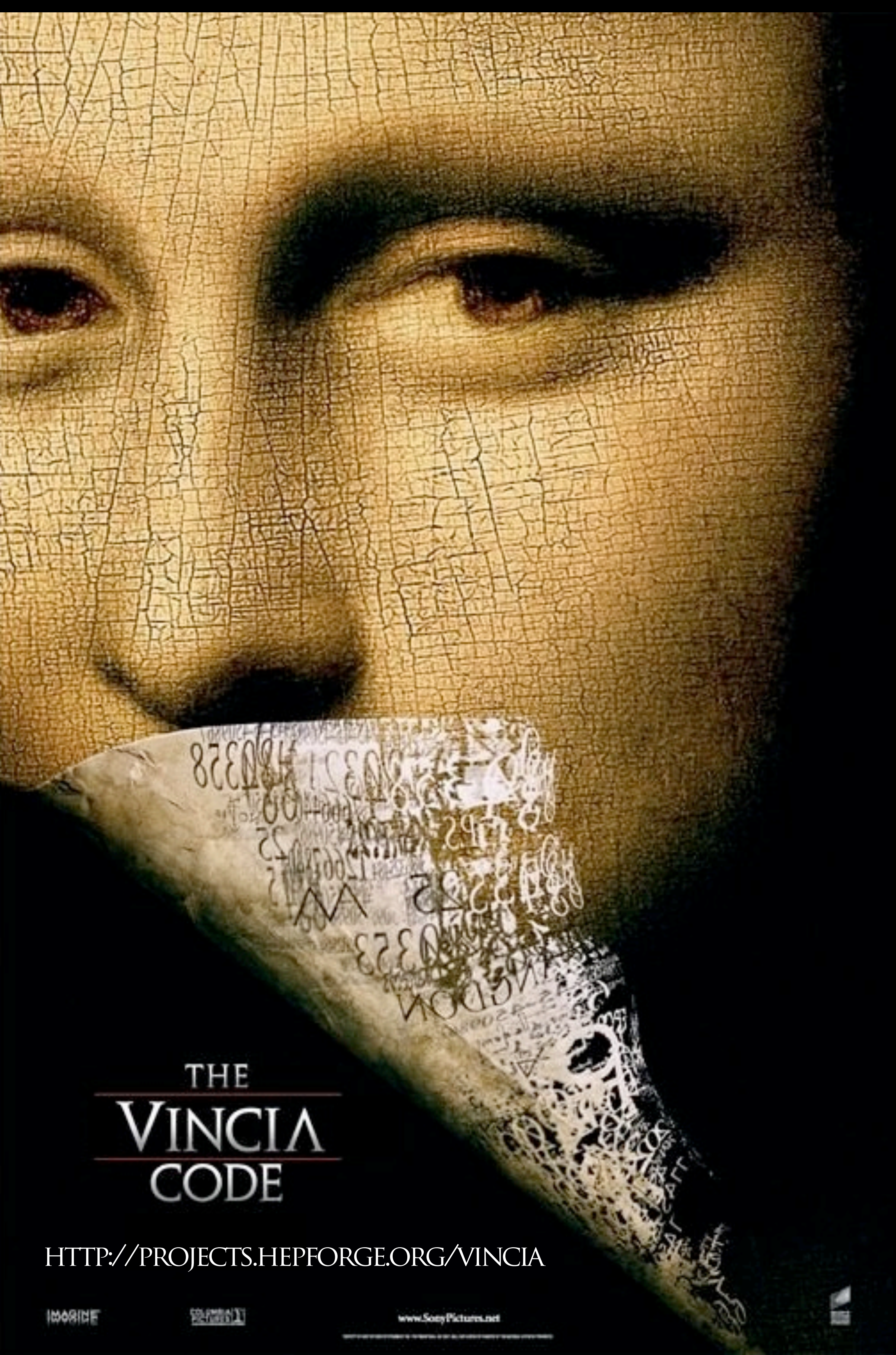
HTTP://PROJECTS.HEPFORGE.ORG/VINCIA

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



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VINCIA Status

Next steps

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

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

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

Backup Slides

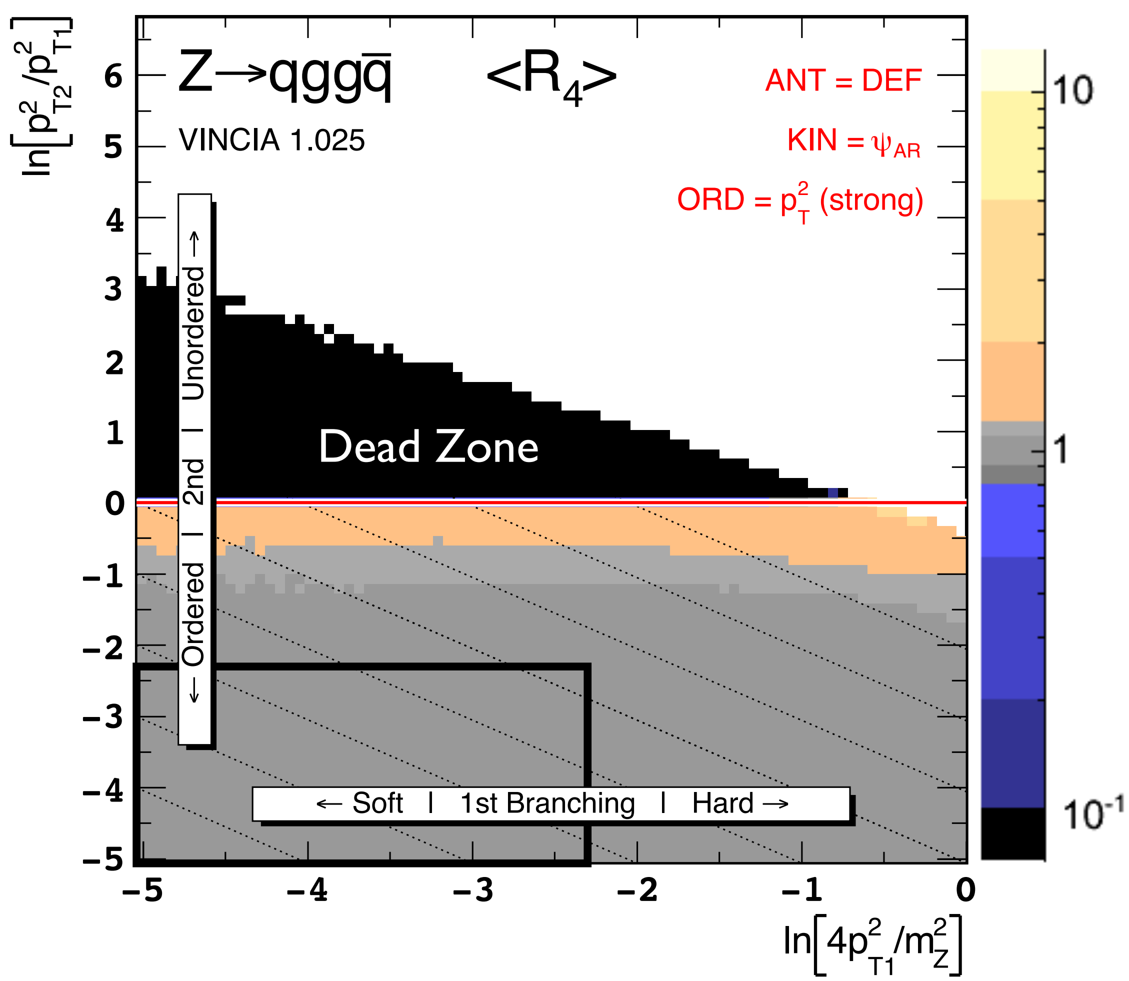
Simple Solution

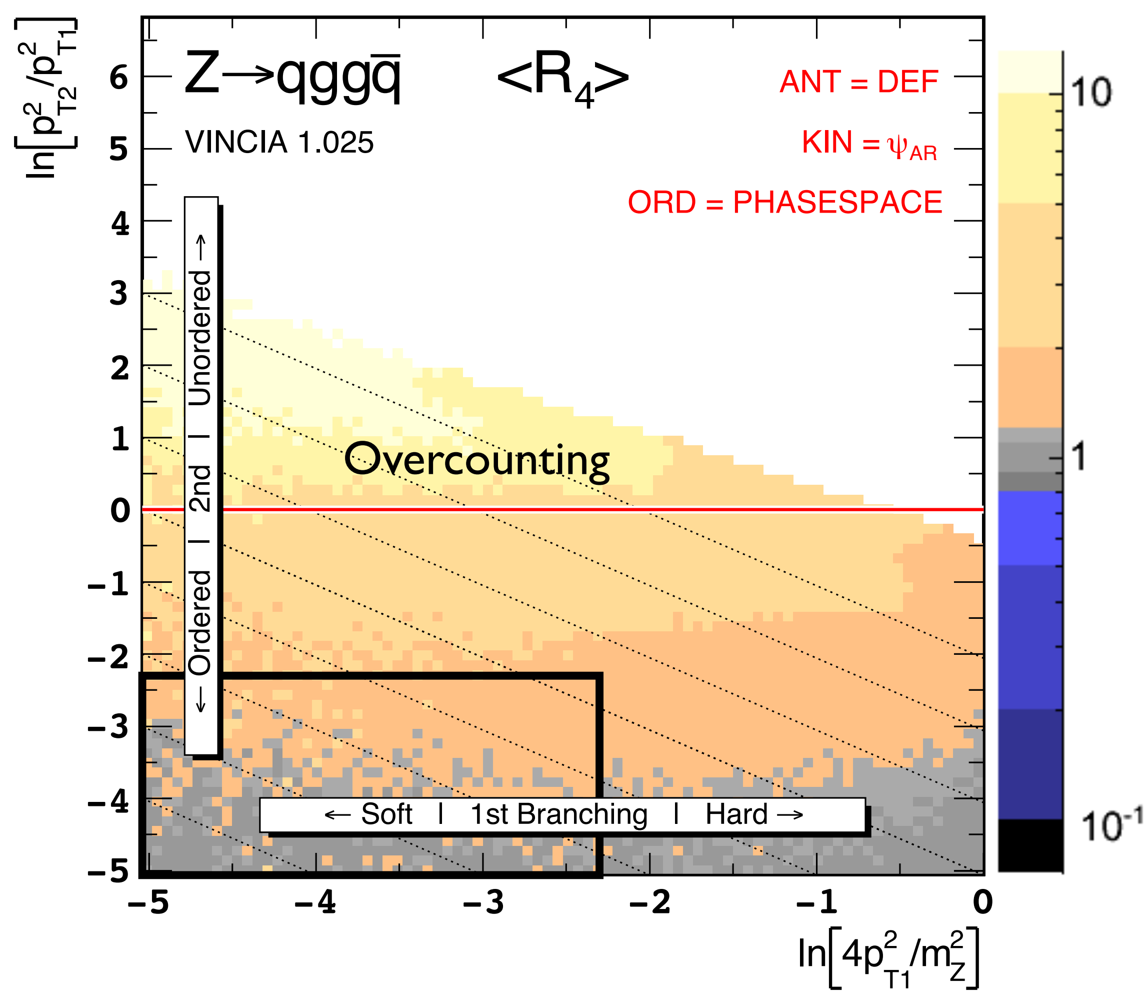
Generate Trials *without* imposing strong ordering

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

Overcounting removed by matching

(revert to strong ordering beyond matched multiplicities)



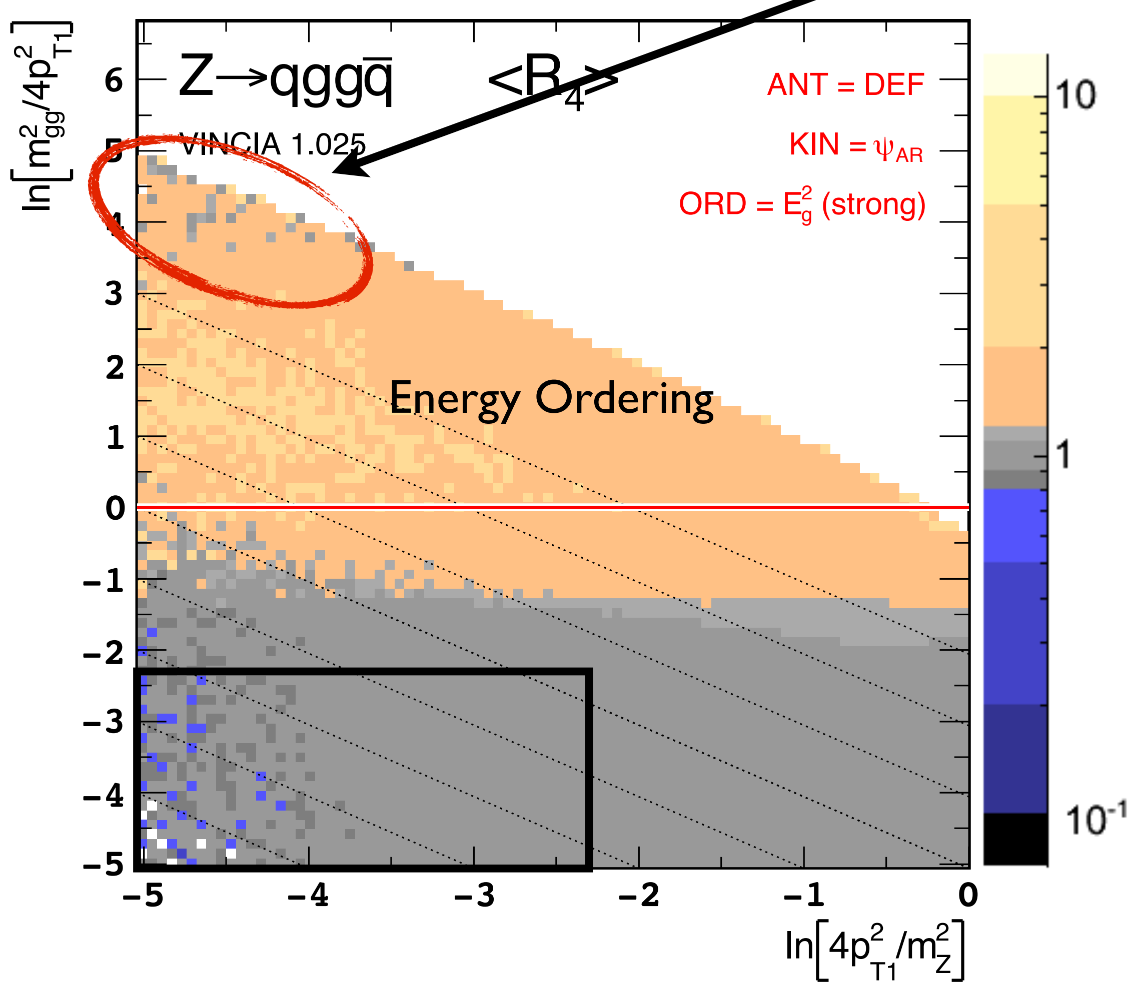


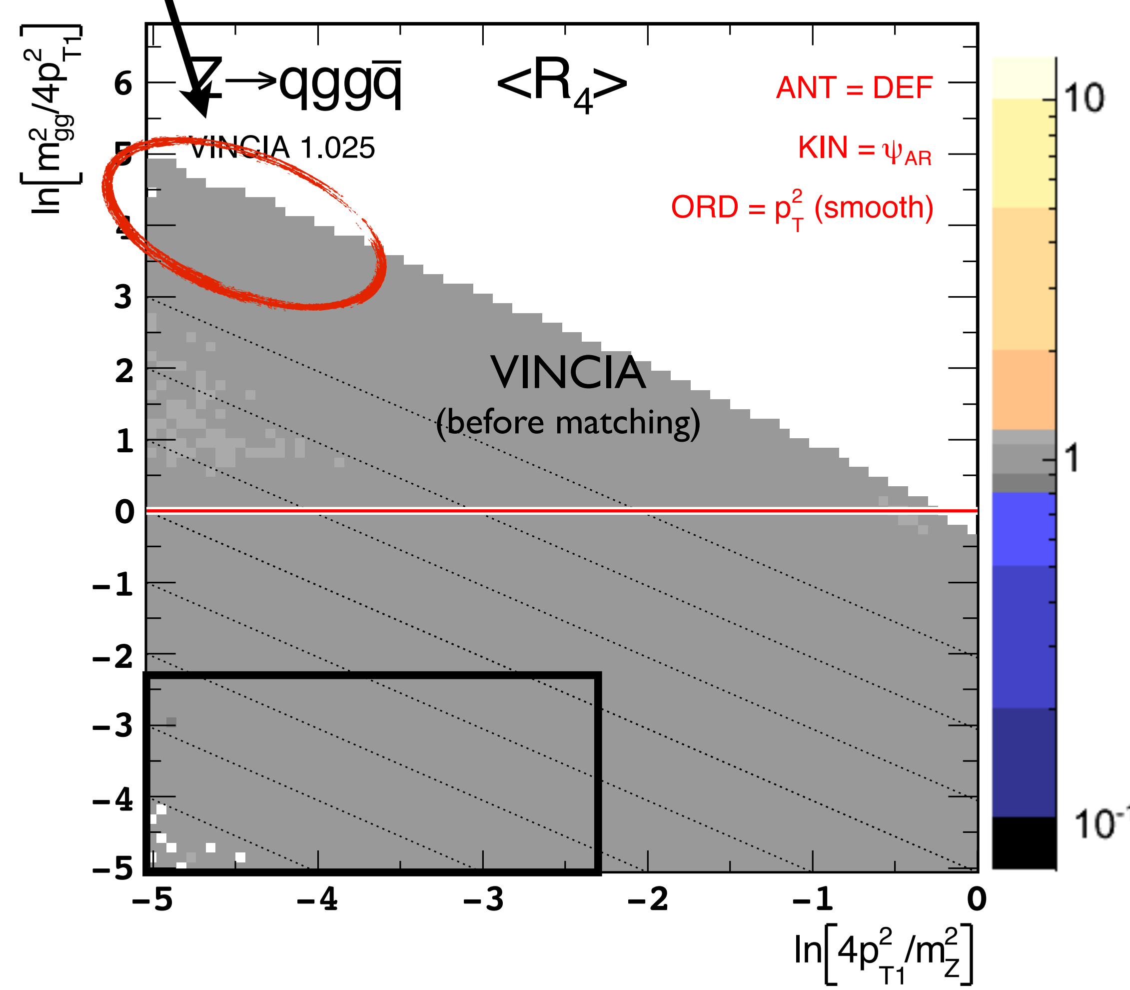
(Subleading Singularities)

Isolate double-collinear region:

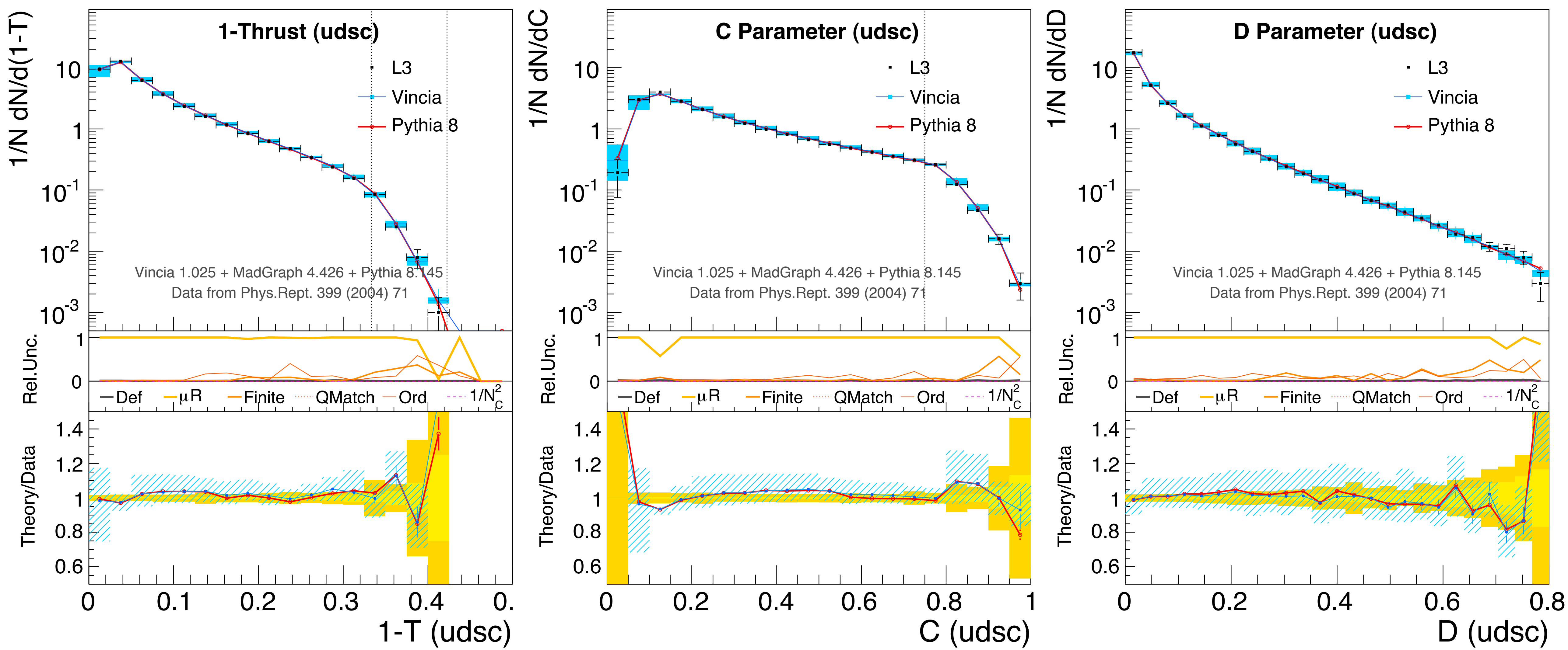
$\alpha_s^2 \ln^2$

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



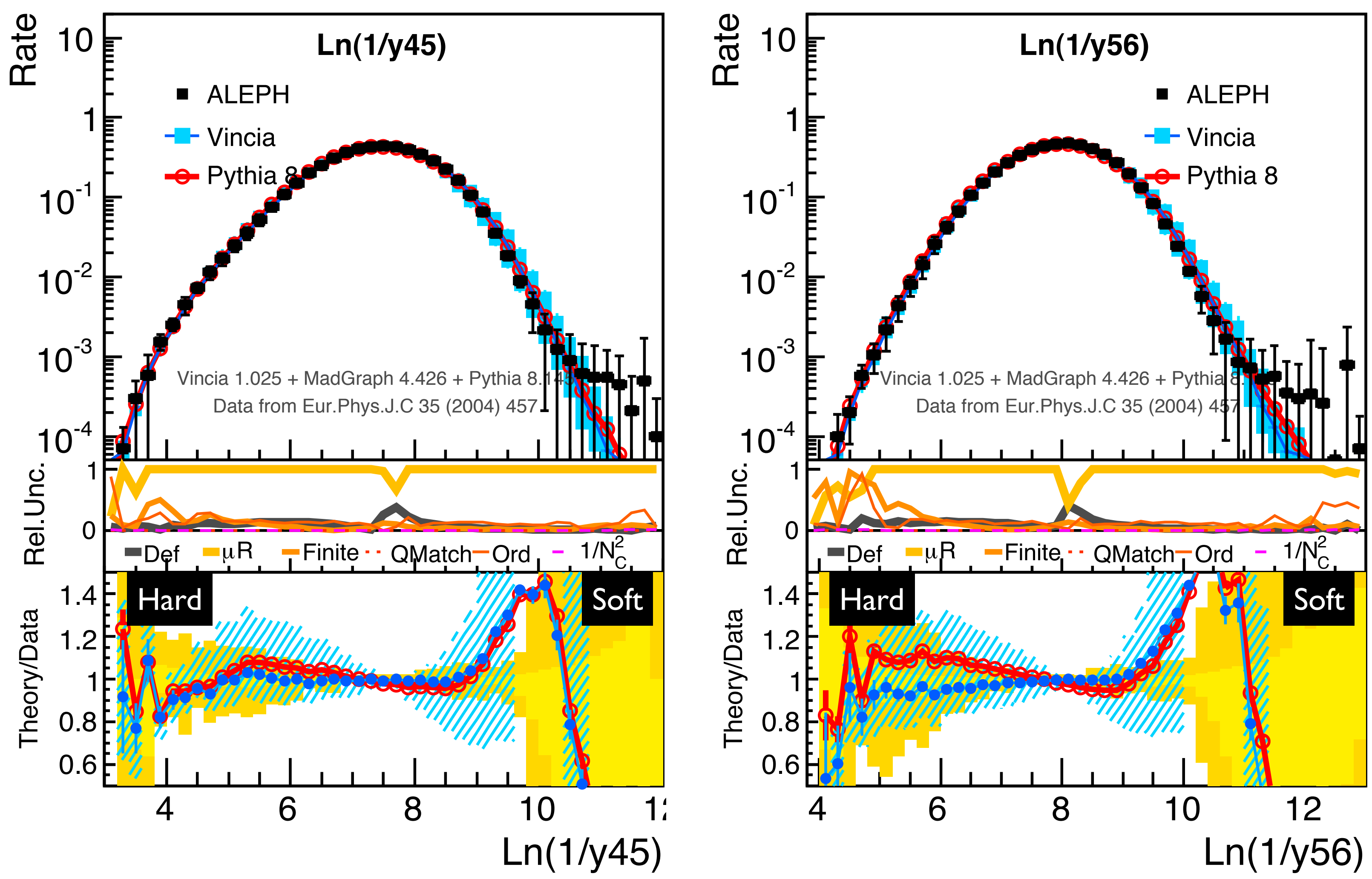


LEP event shapes



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

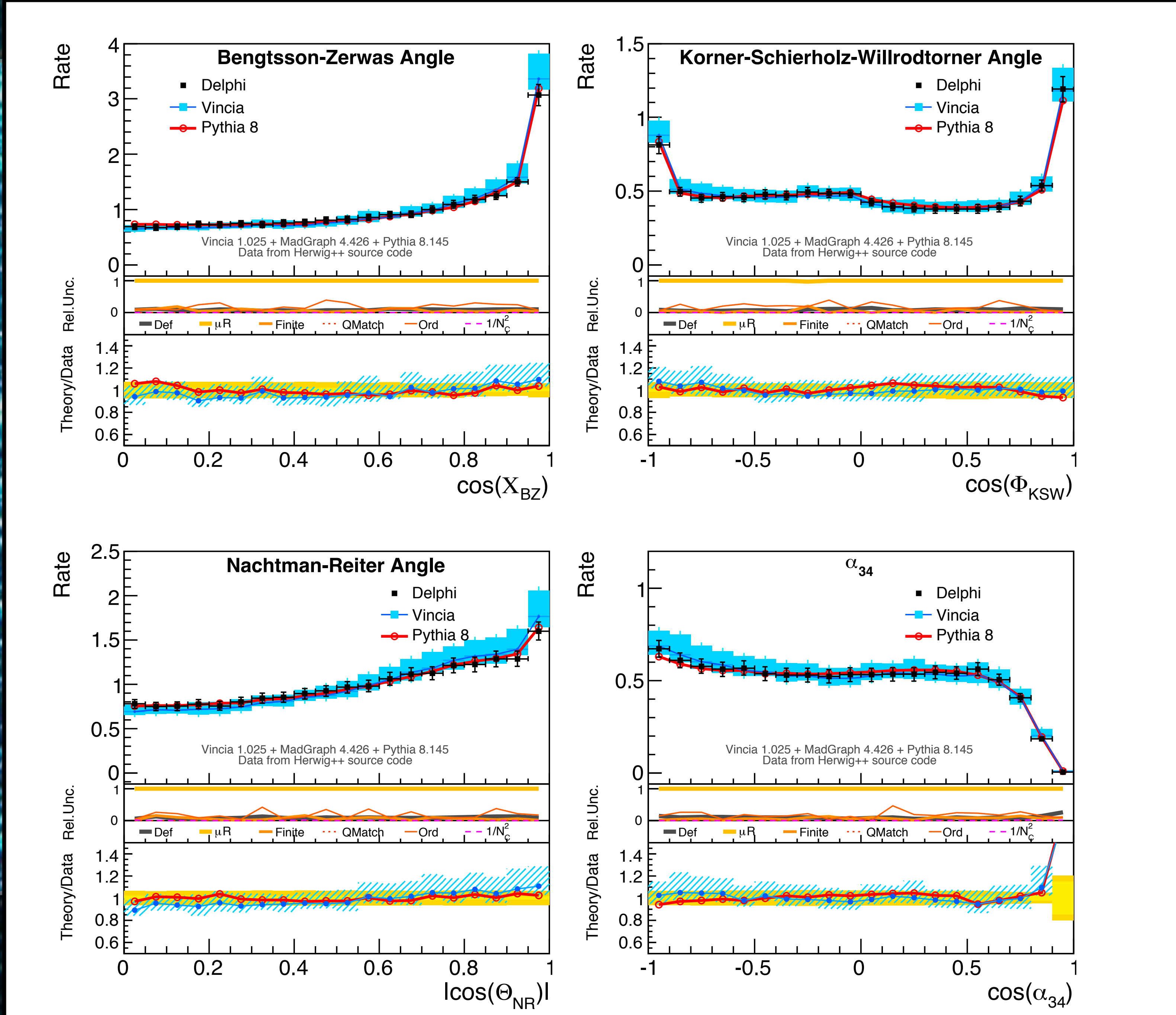
- Sensitive to polarization effects

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?