GenEvA

A New Framework for Event Generation

Jesse Thaler (Berkeley)

with Christian Bauer and Frank Tackmann

Monte Carlo in LHC Era

All experimental searches and measurements are (in one way or another) Monte Carlo sensitive.

How will we understand BSM backgrounds?

$$pp \to W + \text{jets} \qquad pp \to Z + \text{jets}$$

$$pp \to t\bar{t} + \text{jets}$$

Heavy resonances + QCD radiation.
Multiple scales and potentially large logarithms.

TeVatron Example

(conversations with Beate Heinemann)

$$p\bar{p} \to Z + b \; / \; p\bar{p} \to Z$$

|

0.0023 (“NLO”)

|

0.0035 (“LO”)

This is important calibration for heavy flavor.

TeVatron Example

(conversations with Beate Heinemann)

$$p\bar{p} \to Z + b \;/\; p\bar{p} \to Z$$

0.0037 ± 0.0006 (CDF)

0.0023 (“NLO”)

0.0035 (“LO”)

This is important calibration for heavy flavor.

Scorecard

"NLO" = MCFM w/ Pythia UE + Had.	"LO" = Pythia Out-of-the-Box
+ Order α_s^2	– Order αs
– Some Leading Logarithms	+ All Leading Logarithms
+ Proper Bottom Mass Treatment	– Ad Hoc Bottom Mass Treatment
– No PS/ME merging	+ "Normalized" PS/ME merging
+ All Angular Correlations	– Some Angular Correlations

Two fundamentally different approaches, each with benefits and drawbacks.

Fixed-Order Calculations

Parton Showers

Fixed-Order Calculations

Perturbative α_s Expansion

Fixed n-body Phase Space

Parton Showers

Fixed-Order Calculations

Perturbative
α_s Expansion

Fixed n-body
Phase Space

Soft Collinear
Limit

Recursive
Phase Space

Parton
Showers

Fixed-Order Calculations

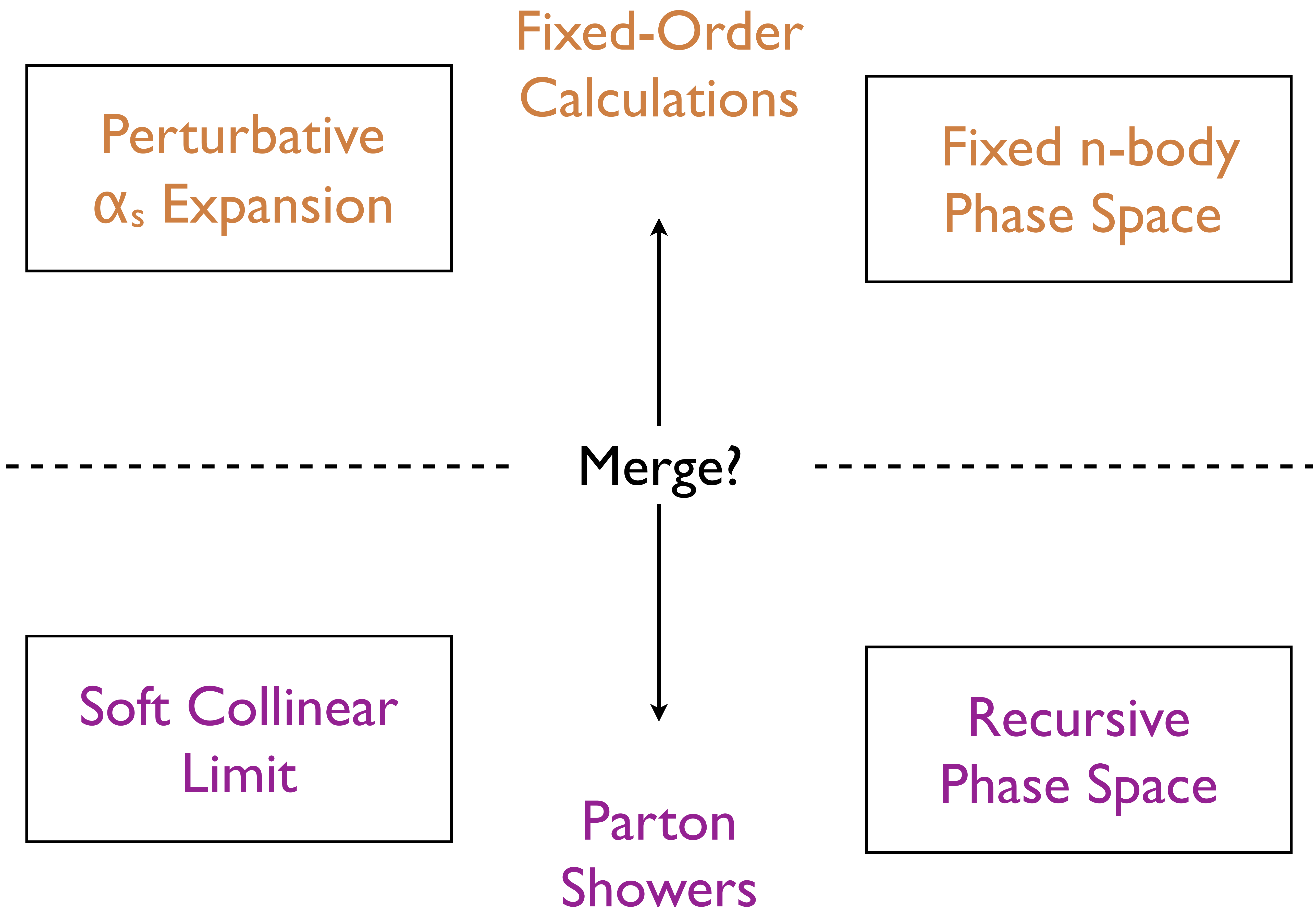
Perturbative α_s Expansion

Fixed n-body Phase Space

Soft Collinear Limit

Recursive Phase Space

Parton Showers



Fixed-Order
Calculations
Perturbative
α_s Expansion
Fixed n-body
Phase Space
Merge?
Soft Collinear
Limit
Recursive
Phase Space
Parton
Showers

Existing Tools

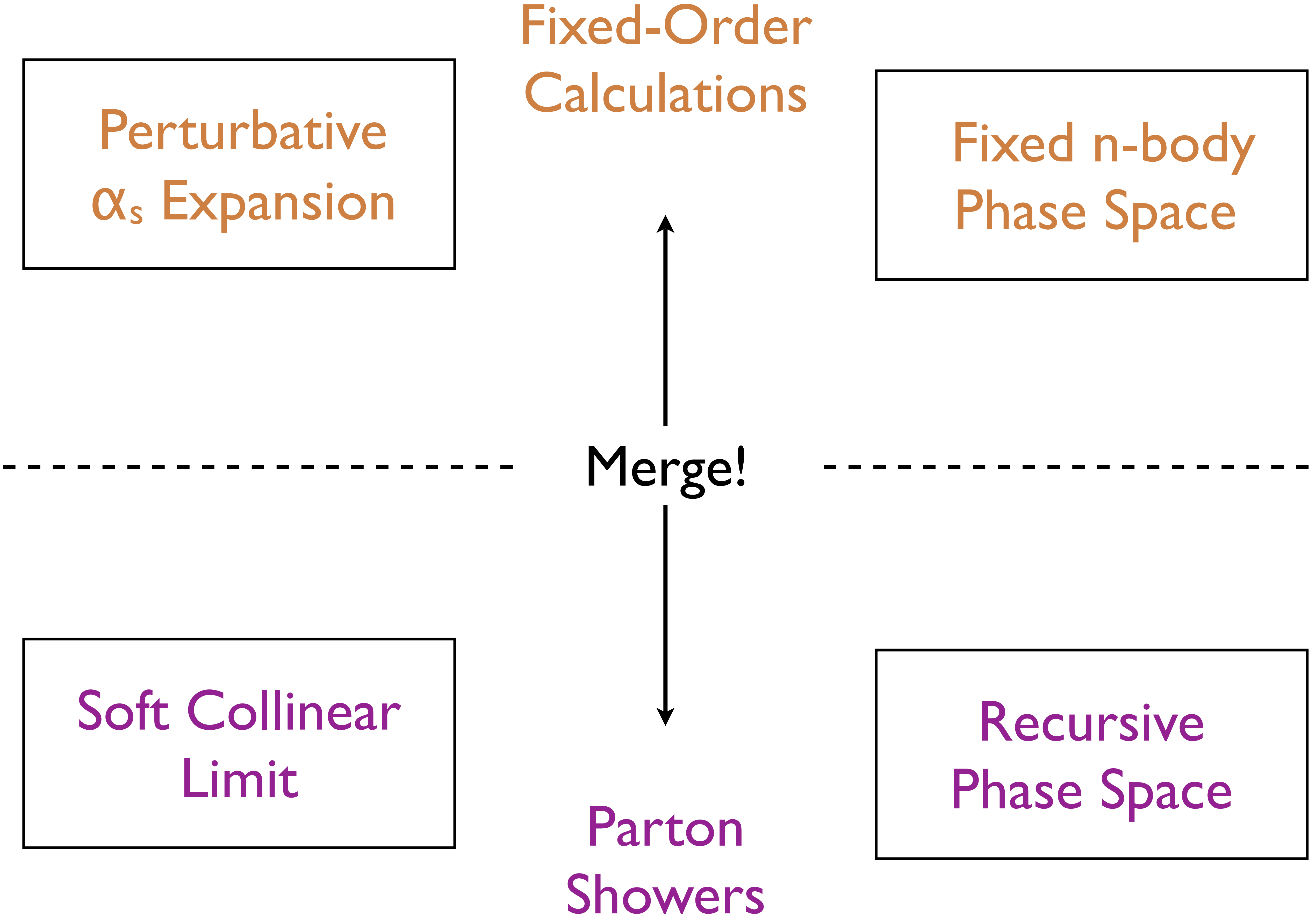
Merge successes of fixed-order calculations with successes of parton showers?

PS/ME Merging

Supplement Tree-Level Matrix Elements with Sudakov Information (CKKW, MLM, Lönnblad...)

MC@NLO

Combine Loop-Level Matrix Elements with Sudakov Information (FW, POWHEG...)


Fixed-Order
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Merge!
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Perturbative
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Fixed n-body
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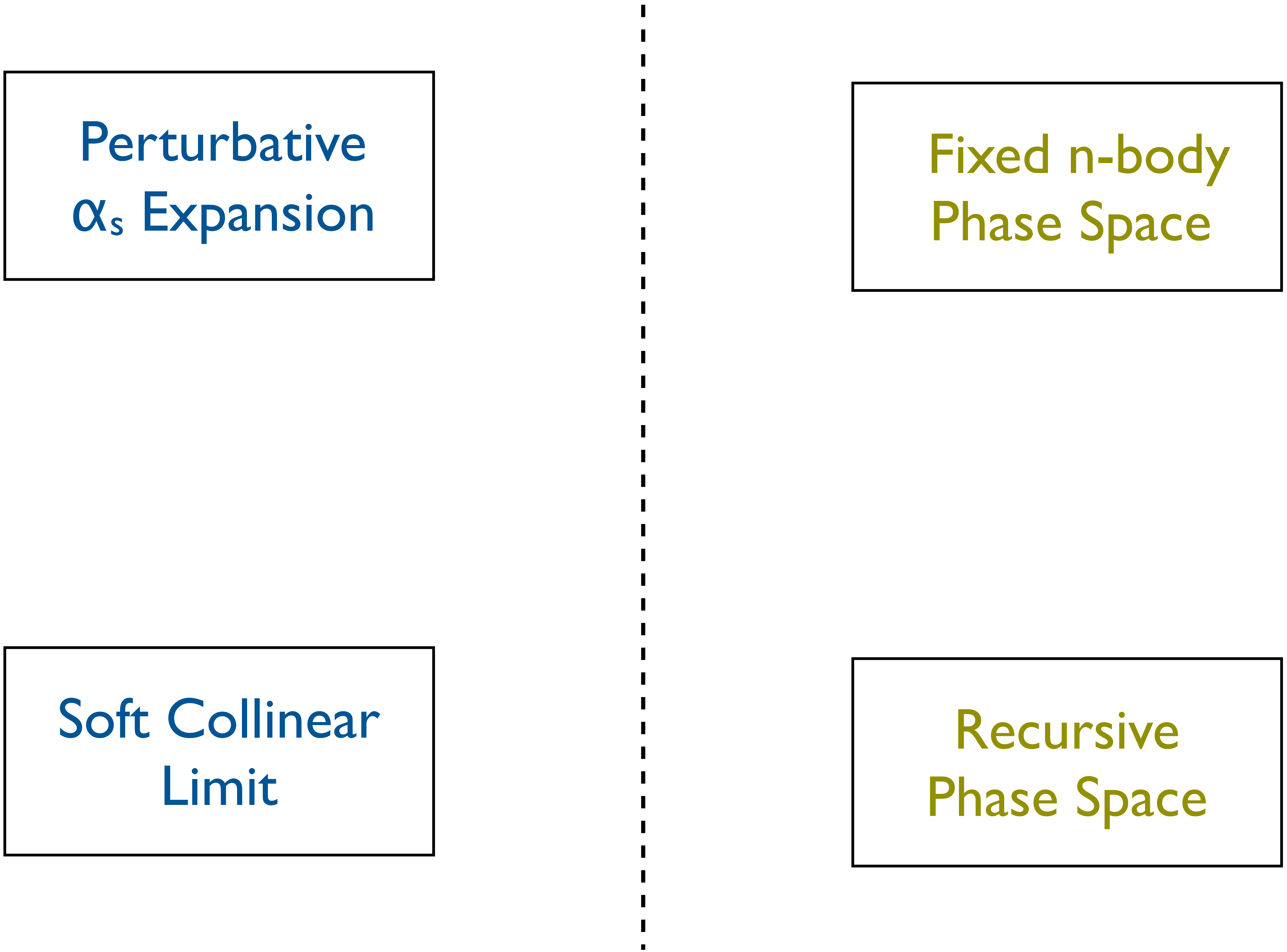
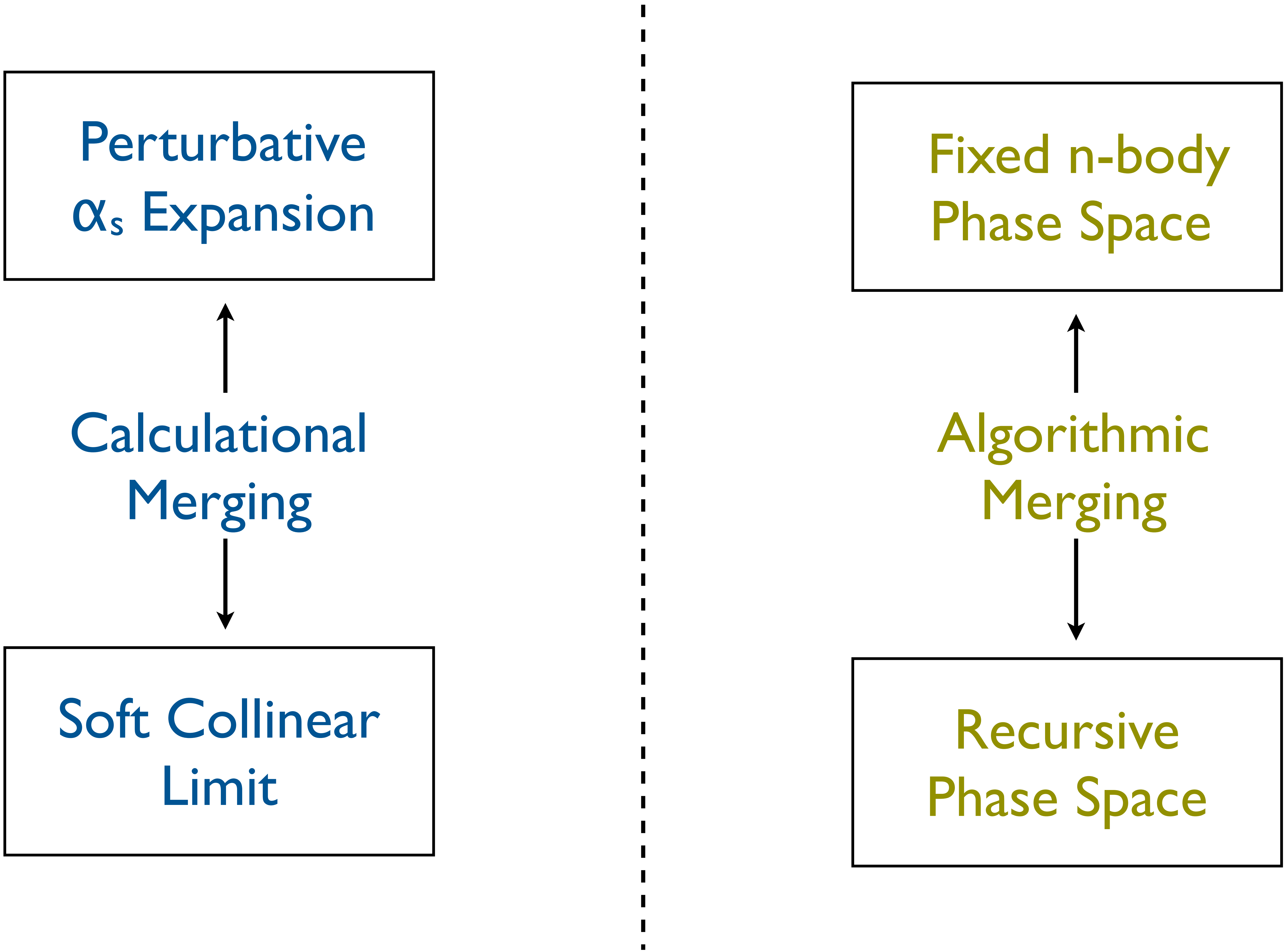

Perturbative α_s Expansion
Fixed n-body Phase Space
Soft Collinear Limit
Recursive Phase Space


Perturbative
α_s Expansion
Calculational
Merging
Soft Collinear
Limit
Fixed n-body
Phase Space
Algorithmic
Merging
Recursive
Phase Space

The GenEvA Framework

$$d\sigma = \left|\mathcal{M}(\mu)\right|^2 \, d\mathrm{MC}(\mu)$$

No dead zones, no double counting,
no negative weights, no incalculable ambiguities.

The GenEvA Framework

Calculations | Algorithms

$$d\sigma = |\mathcal{M}(\mu)|^2 \, d\mathrm{MC}(\mu)$$

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The GenEvA Framework

Calculations | Algorithms

$$d\sigma = |\mathcal{M}(\mu)|^2 \, d\mathrm{MC}(\mu)$$

Matching Scale

No dead zones, no double counting,
no negative weights, no incalculable ambiguities.

GENerate EVents Analytically

- Algorithmic Side
  - A New Approach to Phase Space
  - What is the Parton Shower?
- Calculational Side
  - LO/LL Merging (Analog of PS/ME Merging)
  - NLO/LL Merging (Analog of MC@NLO)
  - NLO/LO/LL Merging (New!)

*

Ultimate Goal:

Hadronic Collisions with Heavy Resonances

Current Status:

Leptonic Collisions with Massless Partons

$$e^+e^- \to n \text{ jets}$$

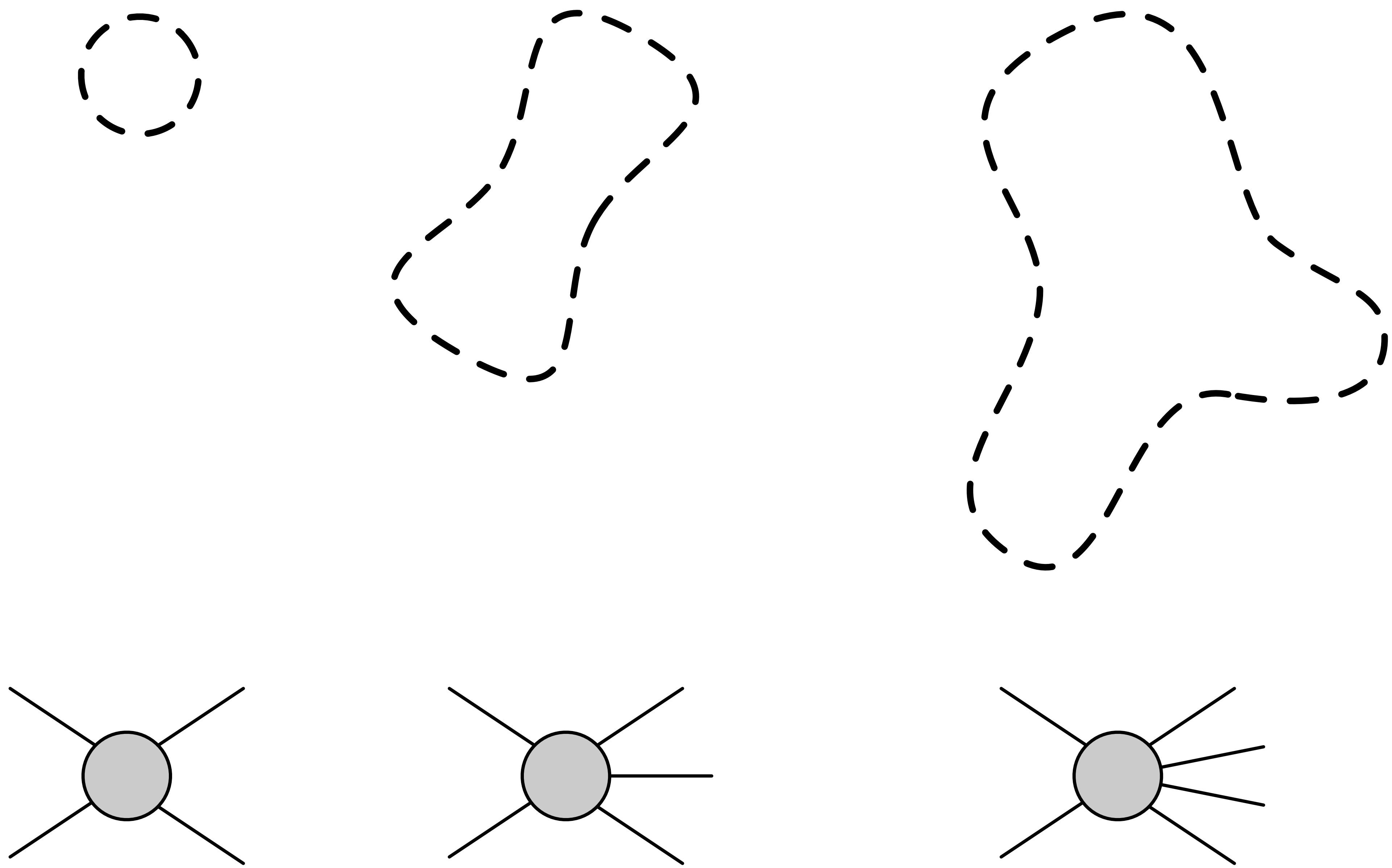
GenEvA Phase Space

Understanding the Effect of the Parton Shower

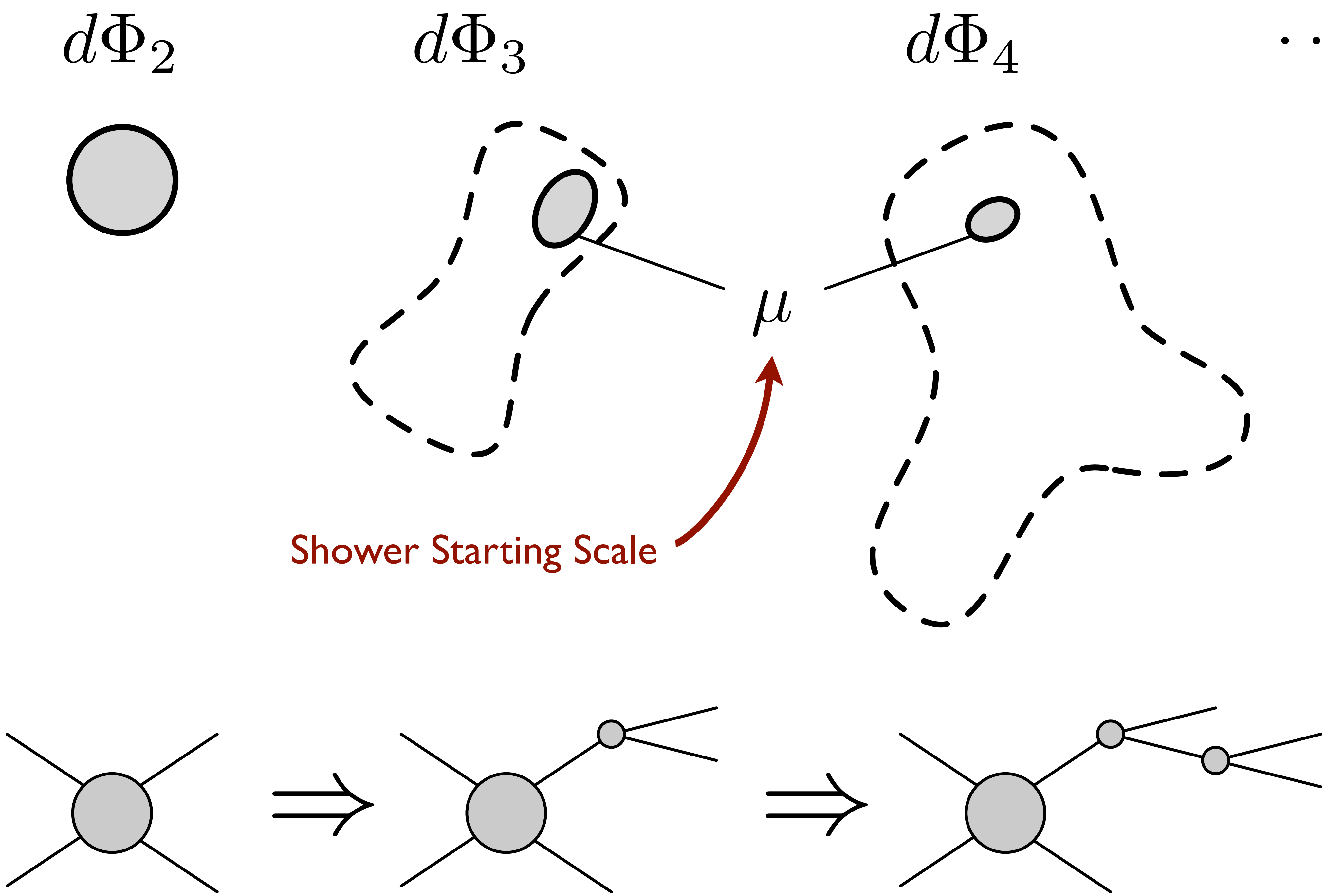
$$d\mathrm{MC}(\mu)$$

Partonic Phase Space

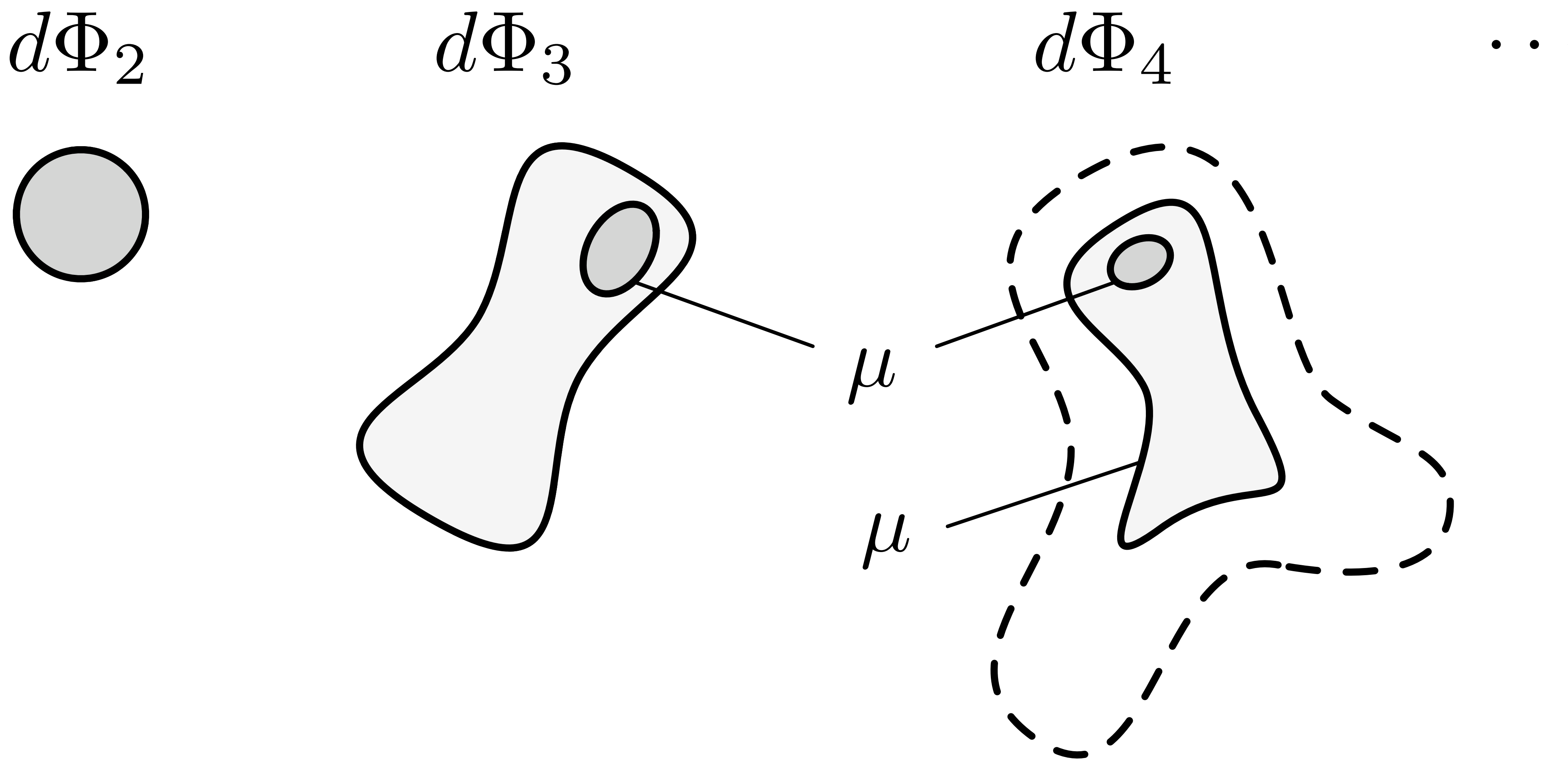
$d\Phi_2$ $d\Phi_3$ $d\Phi_4$ $\cdots$



The Parton Shower



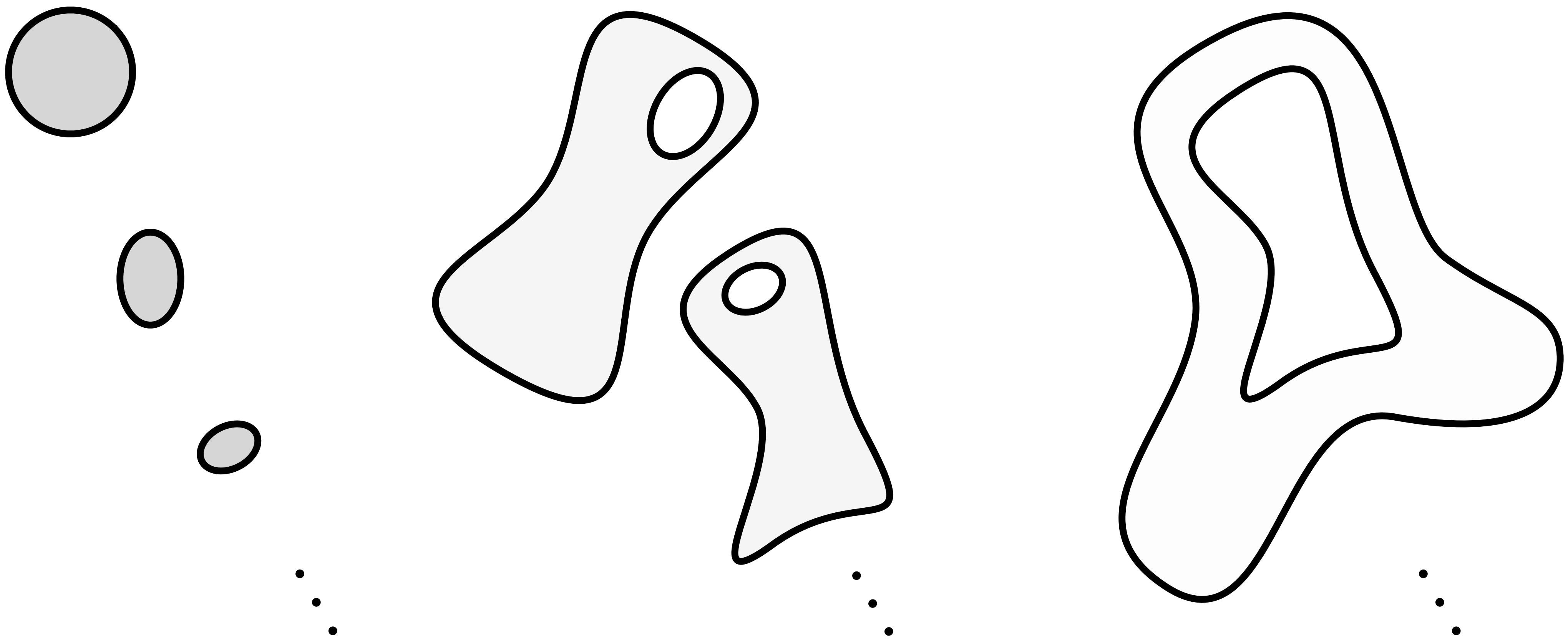
Additional Emissions



How to avoid double counting between 2-body showered and 3-body unshowered?

Monte Carlo Space

$d\mathrm{MC}_2(\mu)$ $d\mathrm{MC}_3(\mu)$ $d\mathrm{MC}_4(\mu)$ $\cdots$



dMC is dΦ organized in terms of showered areas.
Double-counting solved by construction.
Simple to say, technically challenging to implement.

Complete Phase Space

$$\sum_{n=2}^{n_{\max}} d\mathrm{MC}_n(\mu) \Rightarrow \sum_{n=2}^{\infty} d\Phi_n$$

$$d\sigma = \sum_{n=2}^{n_{\max}} \left|\mathcal{M}_n(\mu)\right|^2 d\mathrm{MC}_n(\mu)$$

The amplitude is a function of n-body phase space,
but influences (≥n)-body phase space through shower.

What is the Shower?

Parton shower fills out phase space starting from hard scattering matrix element.

$$d\sigma = \left|\mathcal{M}_2^{\text{hard}}\right|^2 d\text{MC}_2(E_{\text{CM}})$$

What is the Shower?

Parton shower fills out phase space starting from hard scattering matrix element.

$$d\sigma = \left|\mathcal{M}_2^{\text{hard}}\right|^2 d\text{MC}_2(E_{\text{CM}})$$

There must be an equivalent description of same physics with no shower!

$$d\sigma = \sum_{n=2}^{\infty} \left|\mathcal{M}_n^{\text{shower}}\right|^2 d\Phi_n$$

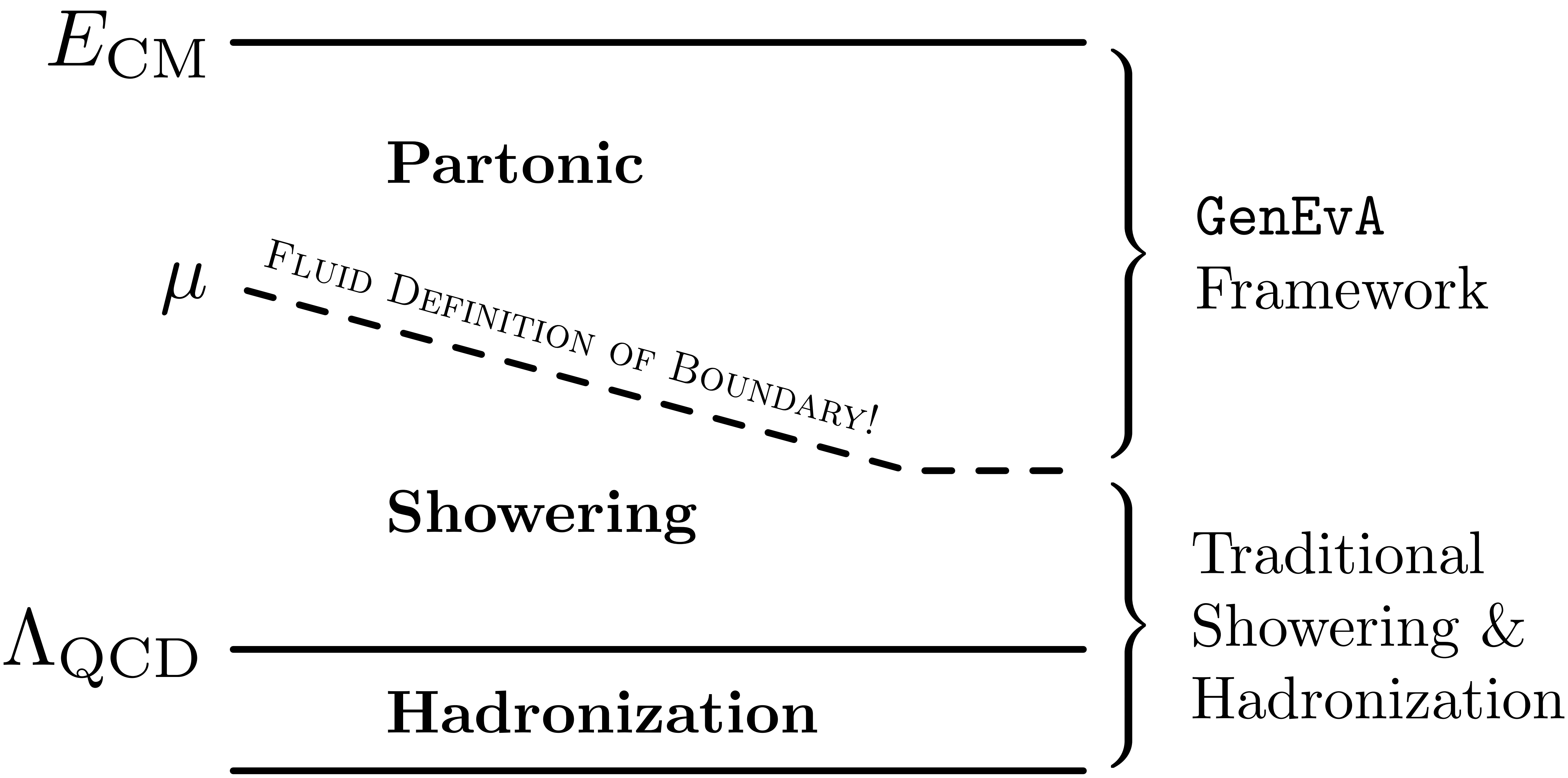
What is the Shower?

There is also an equivalent description of the same physics with part shower, part "matrix element"!

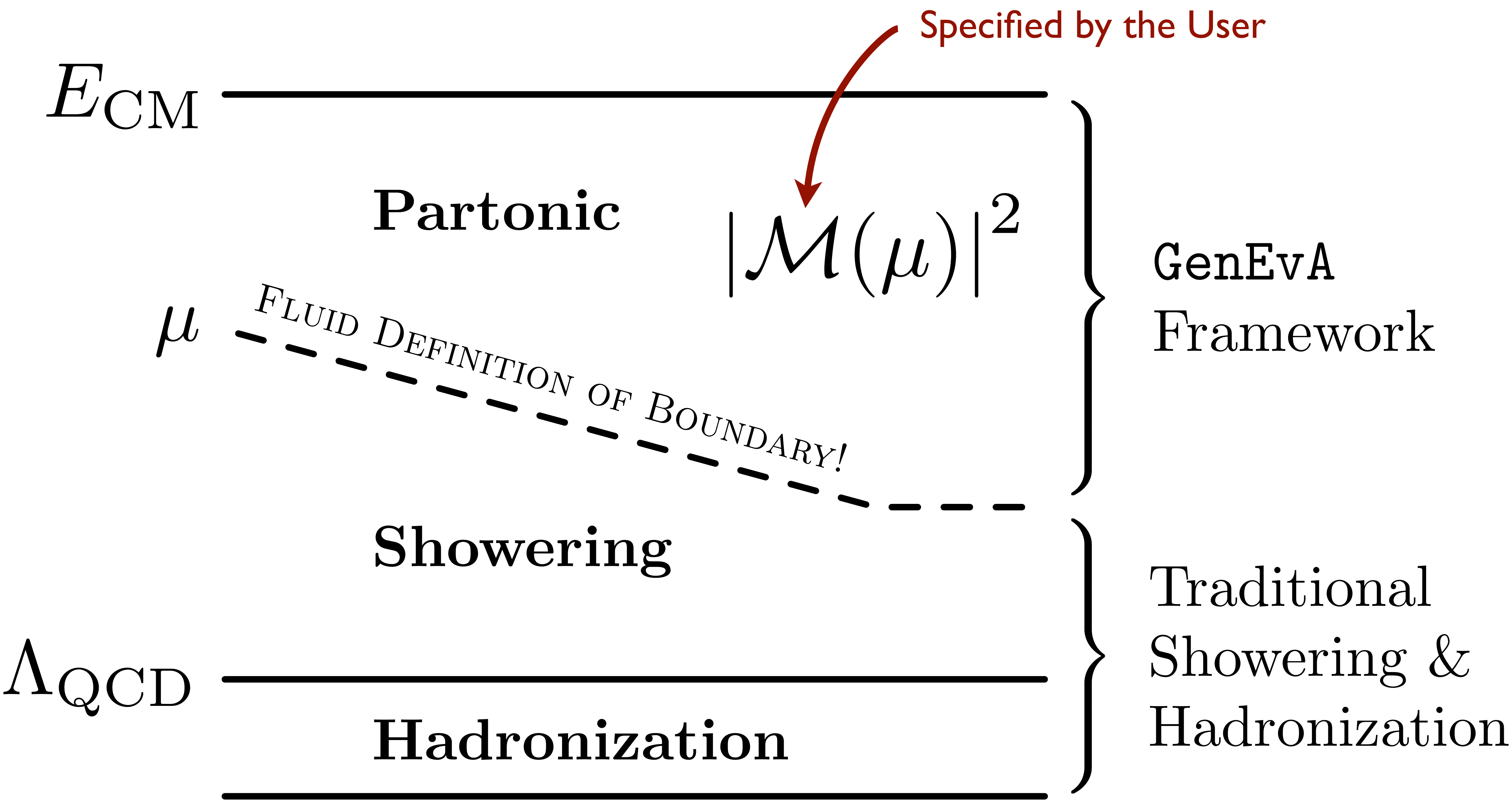
$$d\sigma = \sum_{n=2}^{n_{\max}} \left| \mathcal{M}_n^{\text{shower}}(\mu) \right|^2 d\text{MC}_n(\mu)$$

The scale μ gives this interpolation meaning, by capturing correct leading-logarithmic dependence.

The GenEvA Approach



The GenEvA Approach



Improving Monte Carlo

$$d\sigma = \sum_{n=2}^{n_{\max}} \left|\mathcal{M}_n(\mu)\right|^2 d\mathrm{MC}_n(\mu)$$

Choose the best possible expression for

$$\left|\mathcal{M}_n(\mu)\right|^2$$

and lower μ and raise n_{max} as far as possible.

GenEvA Amplitudes

Comparing Different Expansions of QCD

$$|\mathcal{M}(\mu)|^2$$

Terminology

LL: Leading Logarithms

Correct Sudakov Factors in Soft/Collinear Limit

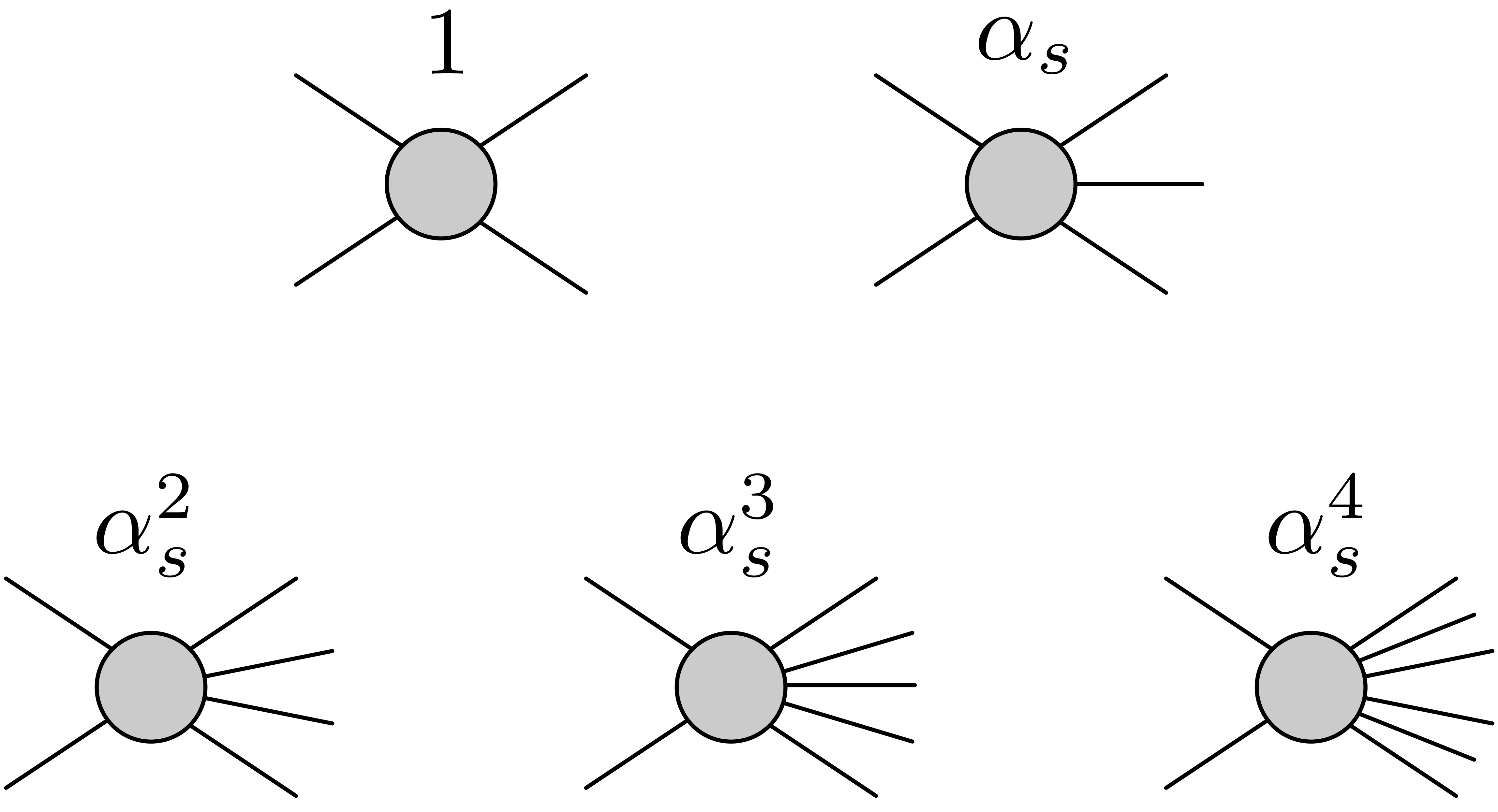
LO: Tree-Level Matrix Elements

Correct Quantum Interference in Large Angle Limit

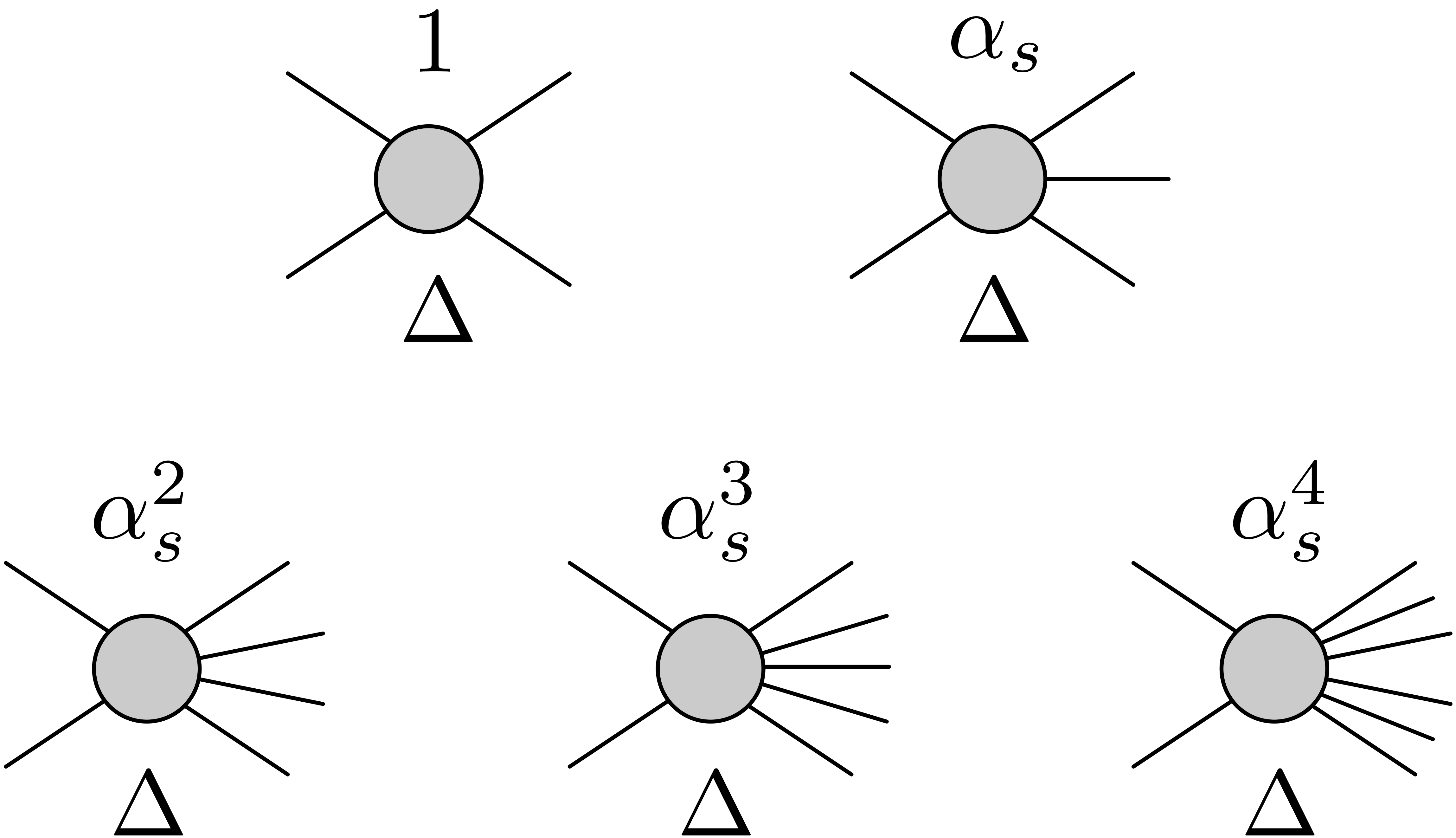
NLO: Next-to-Leading Order

Everything Correct to Order α_s

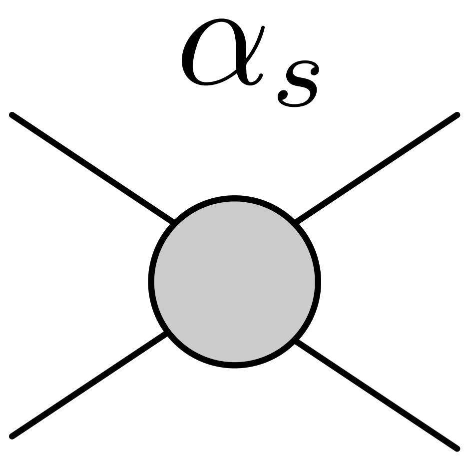
LO Tree-Level Generators

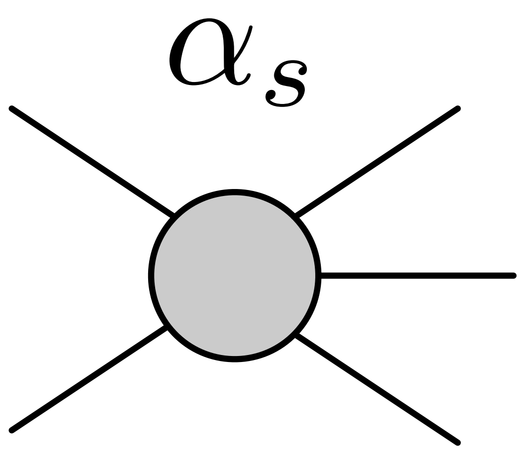


LO/LL Analog of PS/ME Merging

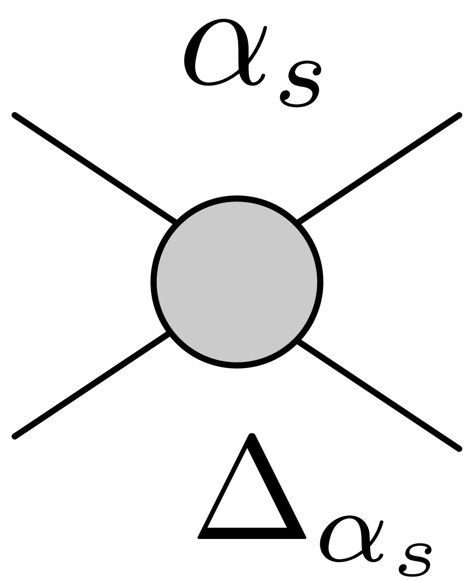


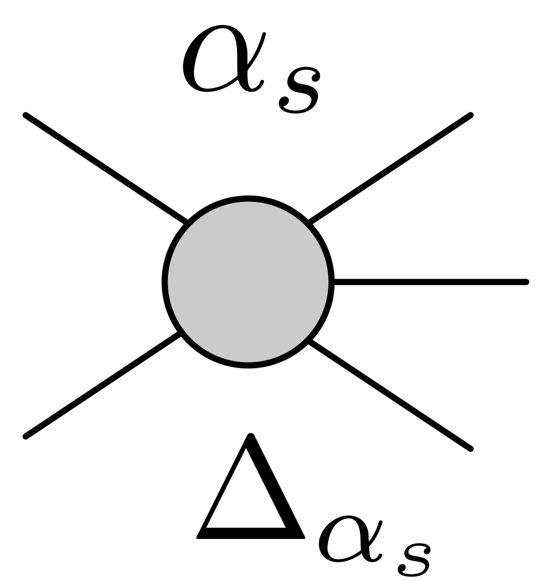
NLO Loop-Level Generators



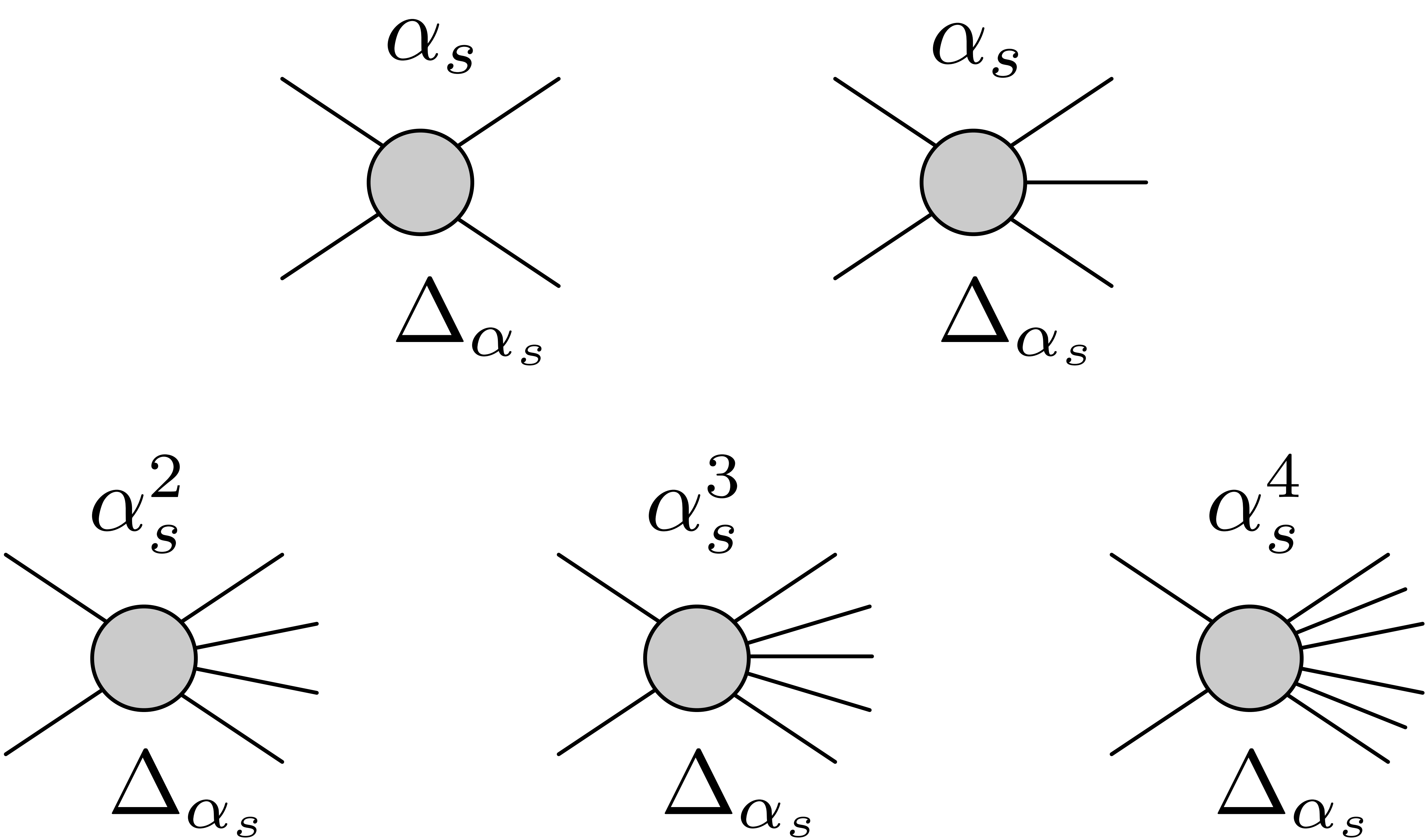


NLO/LL Analog of MC@NLO





NLO/LO/LL GenEvA Best



NLO/LO/LL GenEvA Best

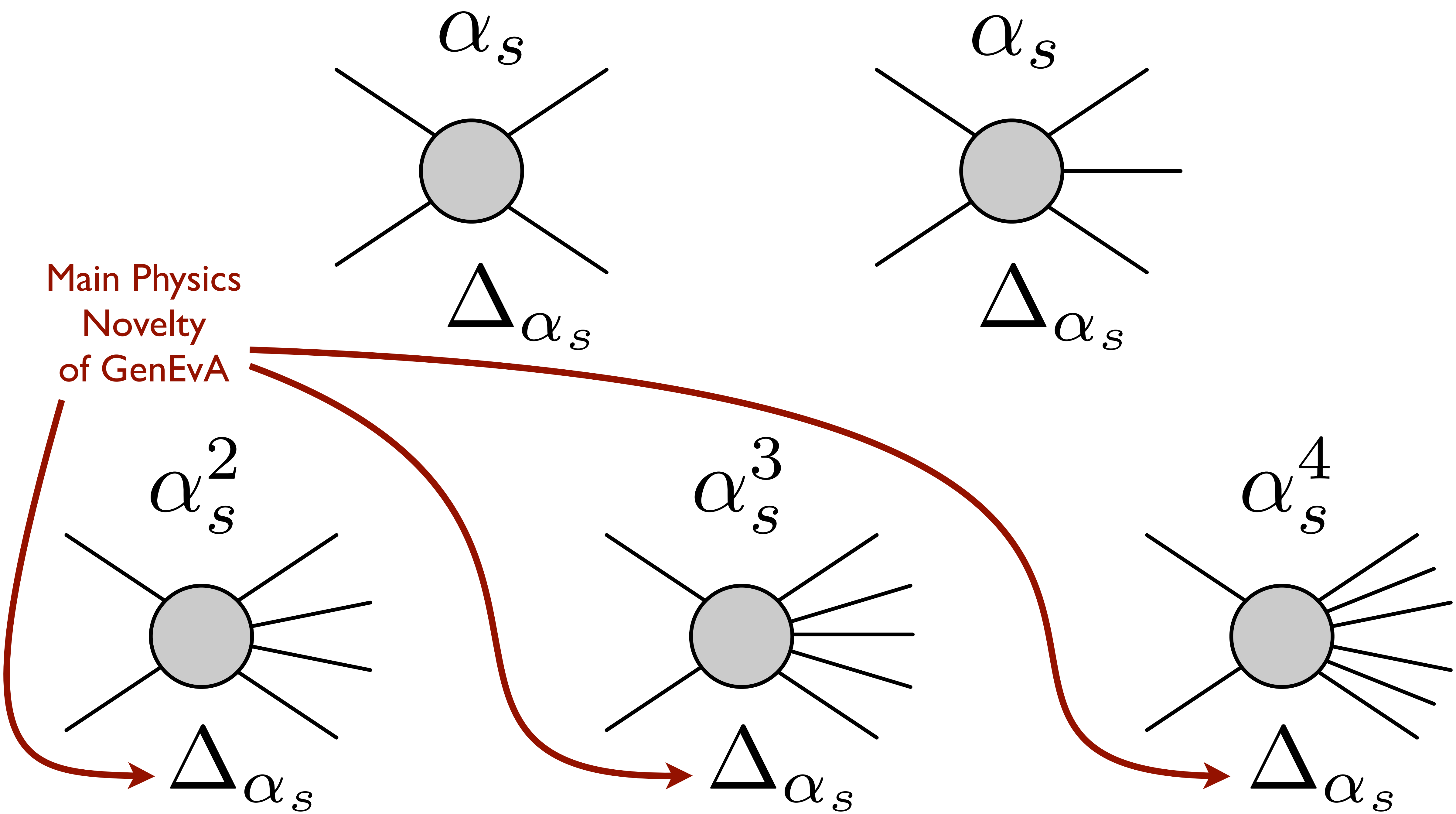


Figure of Merit?

How would you know whether we have actually achieved an NLO/LO/LL sample?

Normalization

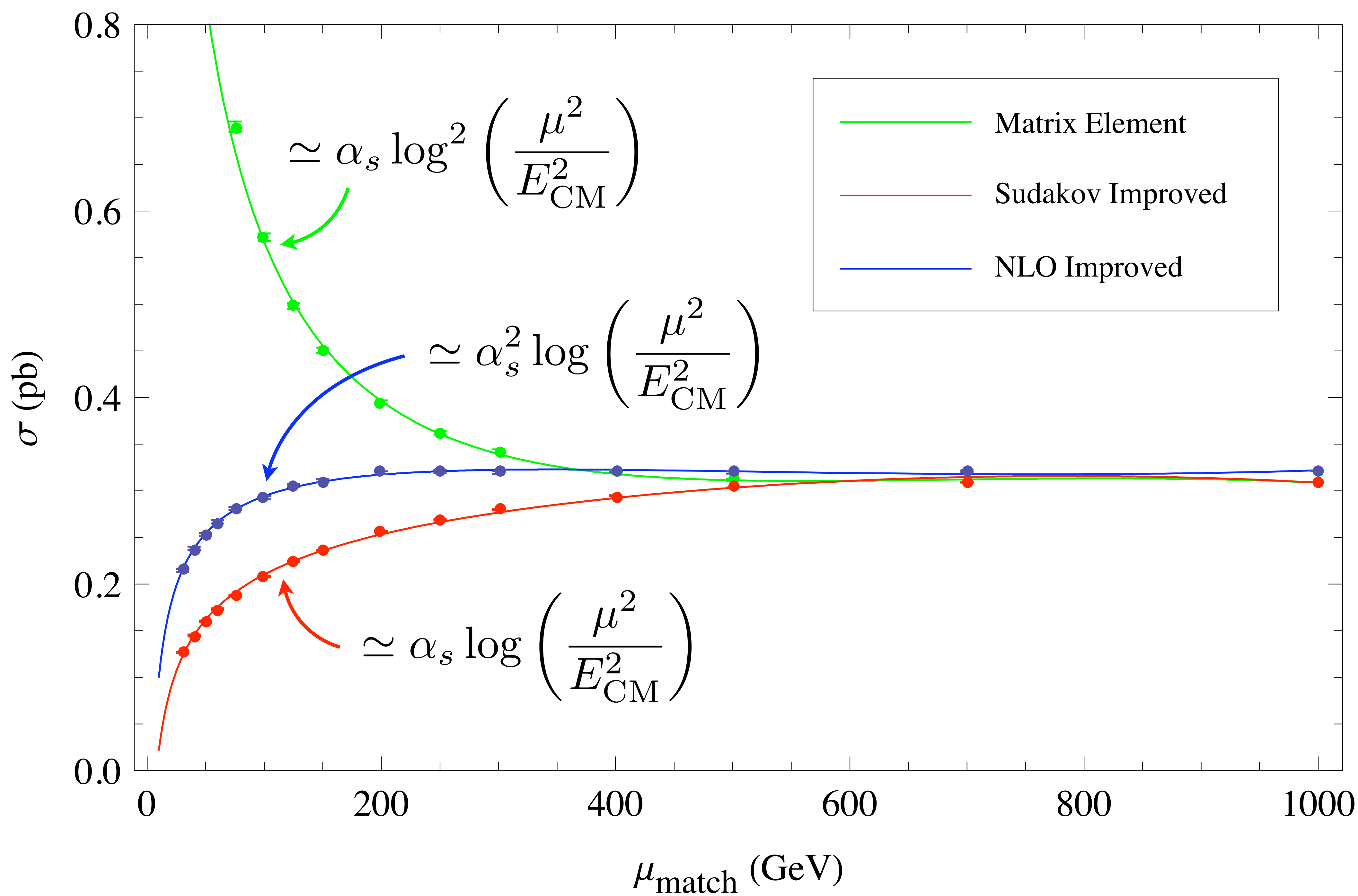
The μ-dependence should scale like

$$\text{No LL: } \alpha_s \log^2 \mu \quad \text{LO/LL: } \alpha_s \log \mu \quad \text{NLO/LL: } \alpha_s^2 \log \mu$$

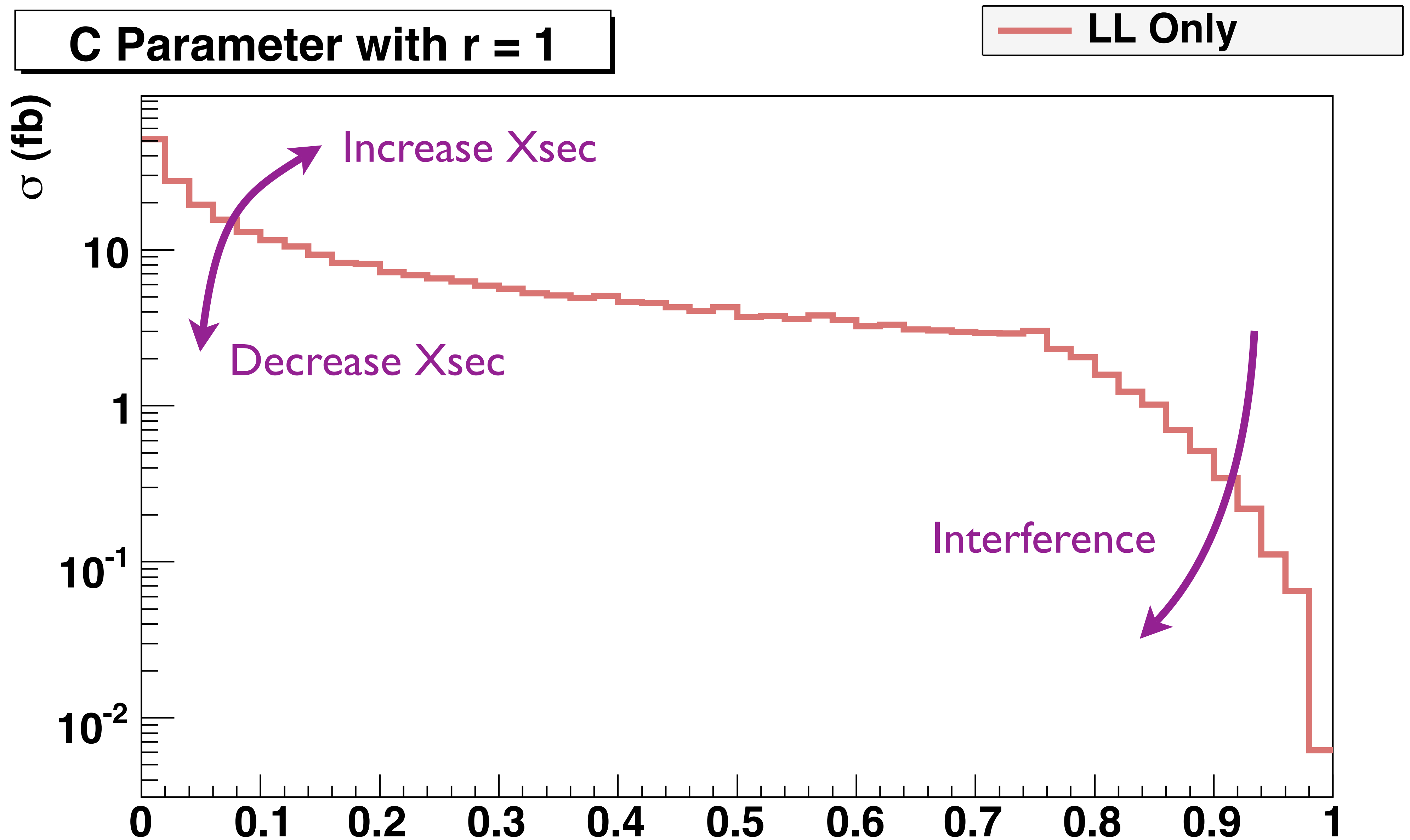
Shape

A merged sample should interpolate between the two underlying differential distributions.

Amplitudes for $n_{max} = 6$



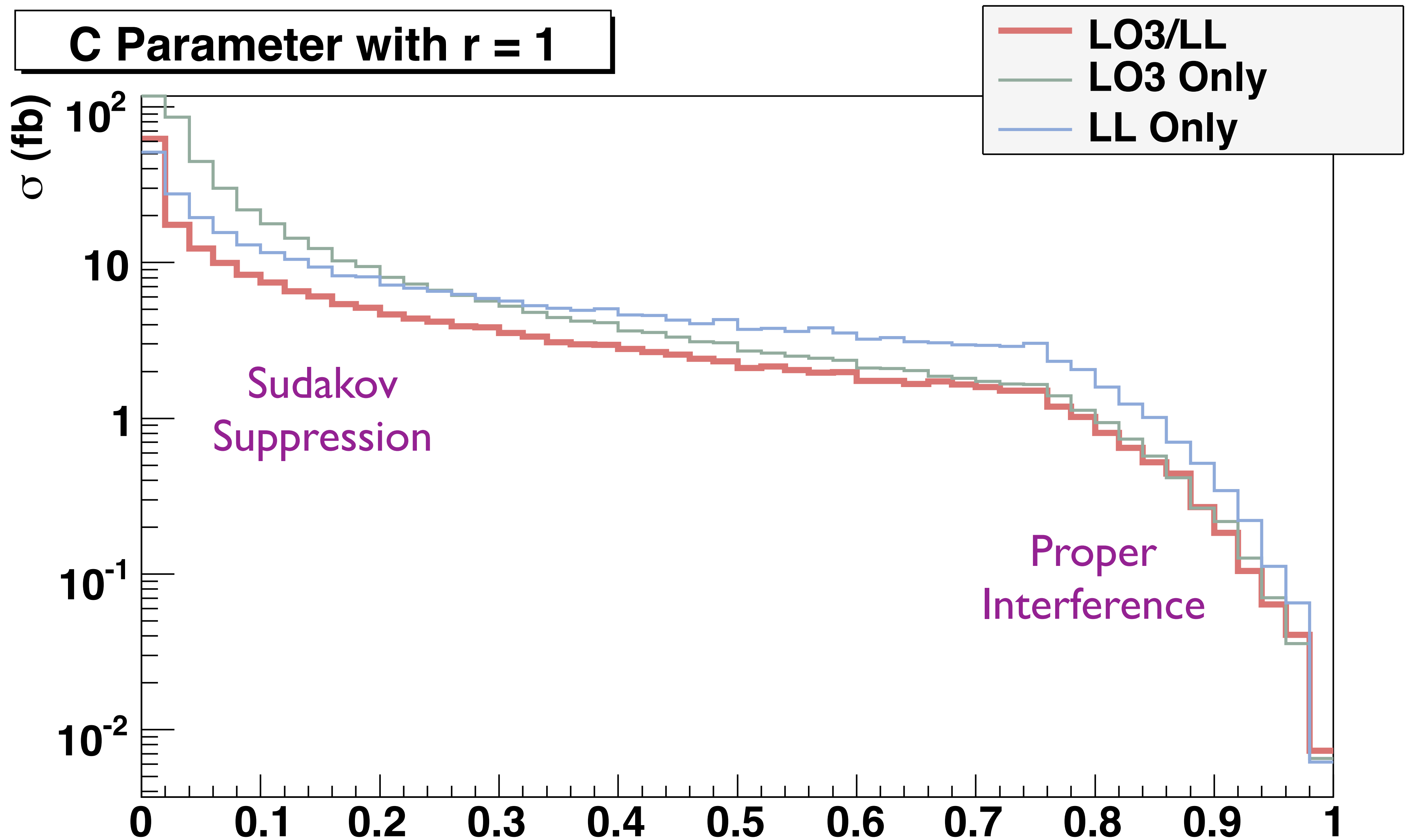
Baseline Shower



2 jet-like

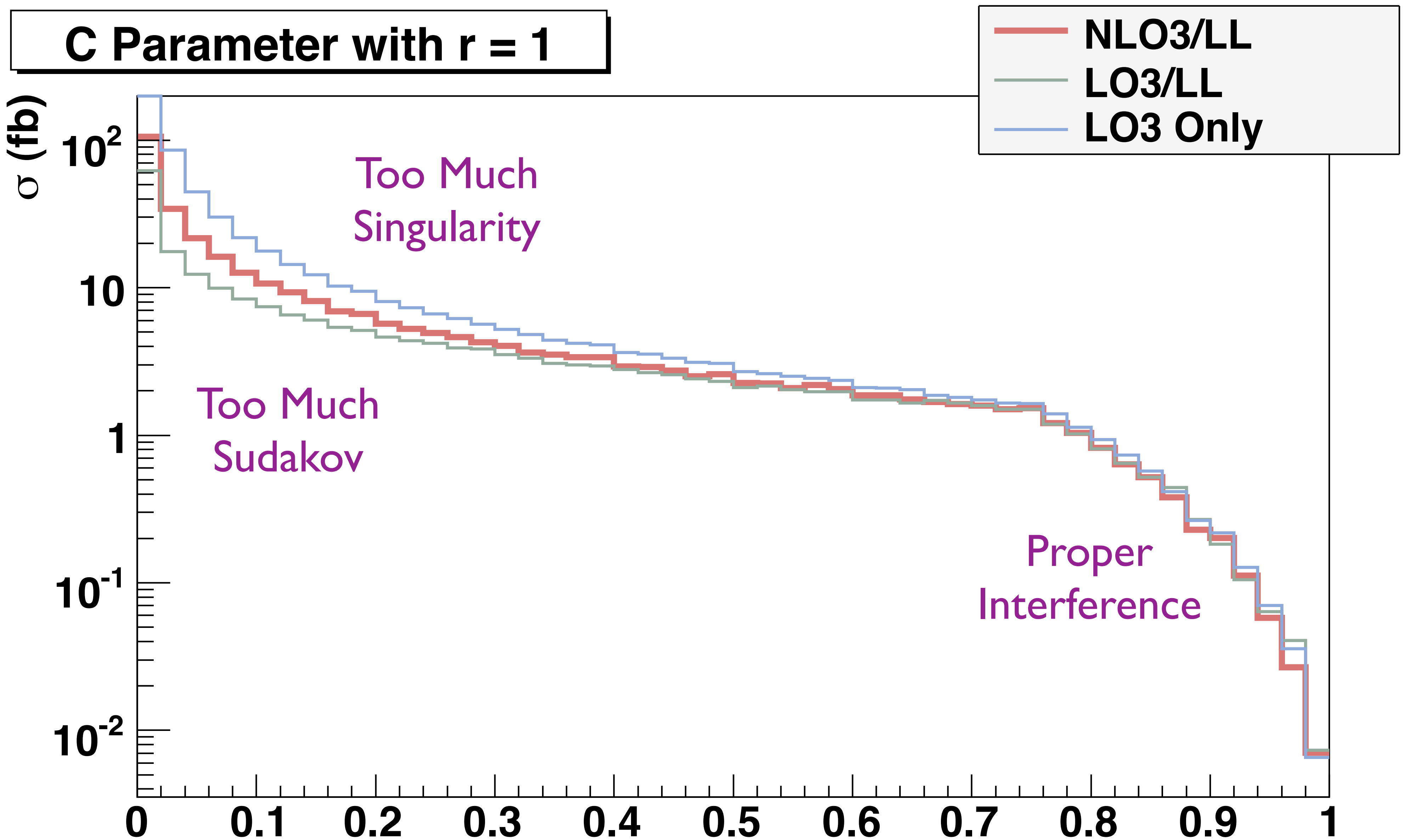
3^+ jet-like

LO/LL Calculation



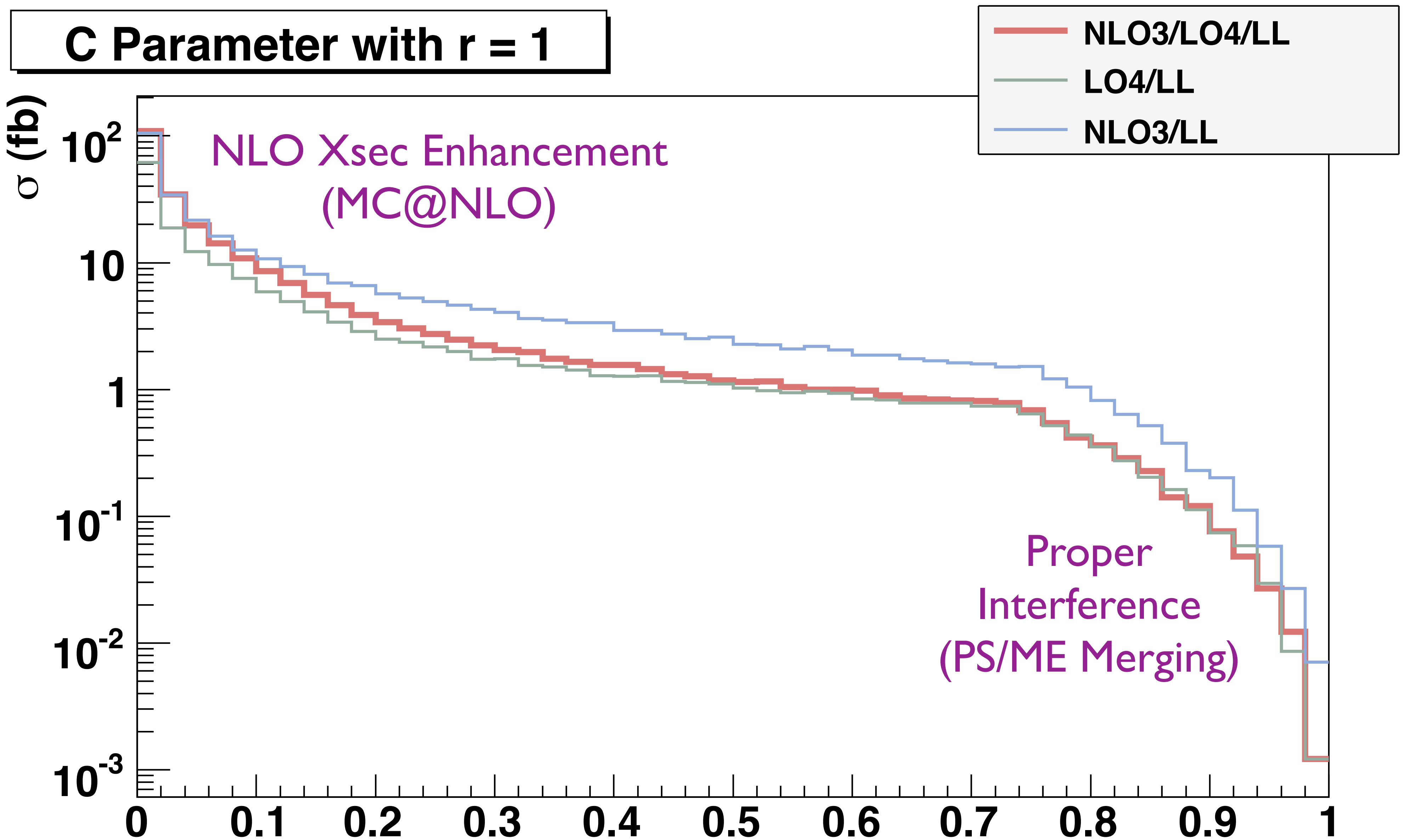
LO/LL answer is smaller than either approximation.

NLO/LL Calculation



A "Goldilocks" Interpolation

NLO/LO/LL Calculation



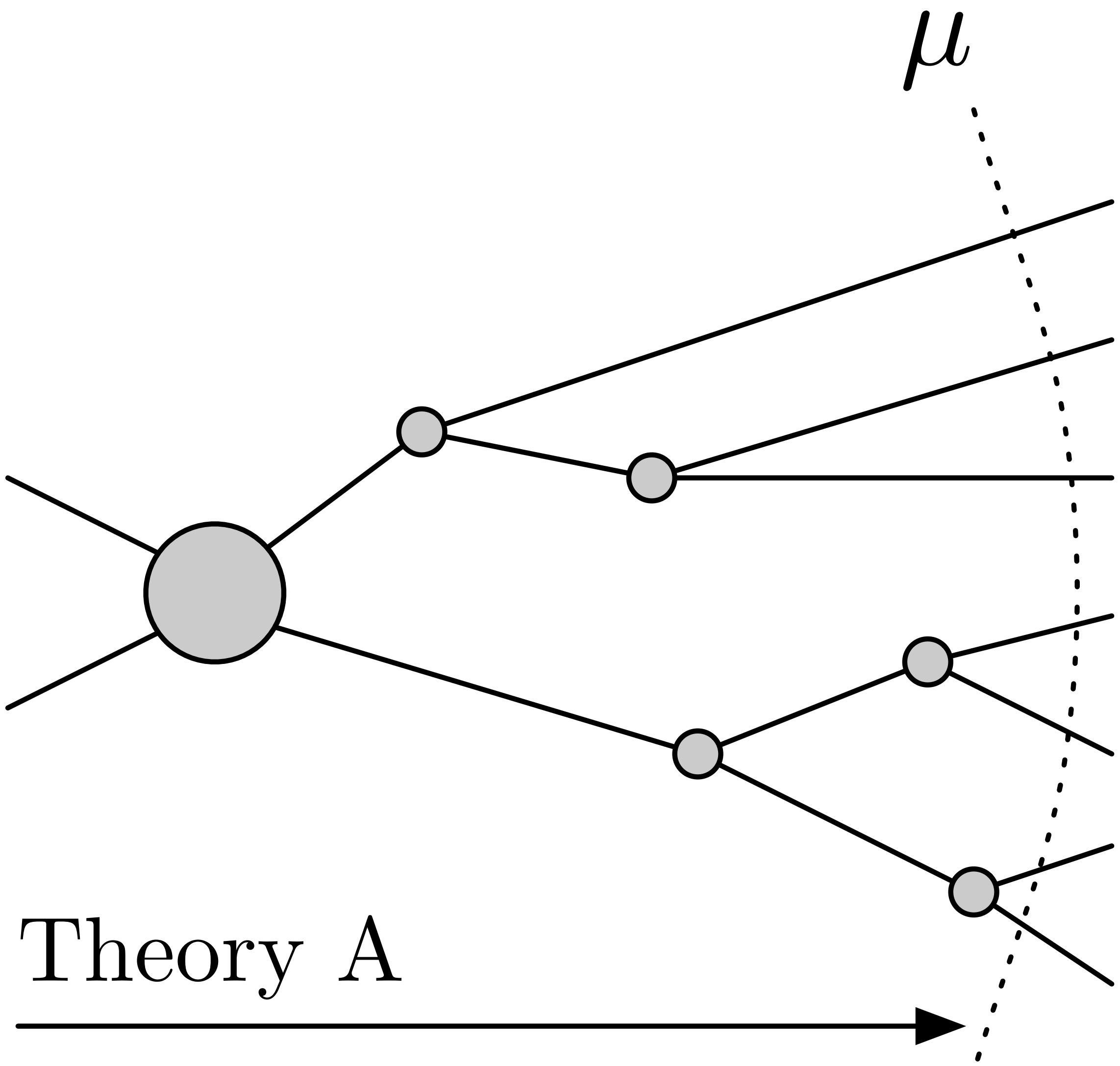
Interpolates between PS/ME Merging and MC@NLO!

GenEvA Details

Strategy to Merge Different Approximation Schemes?

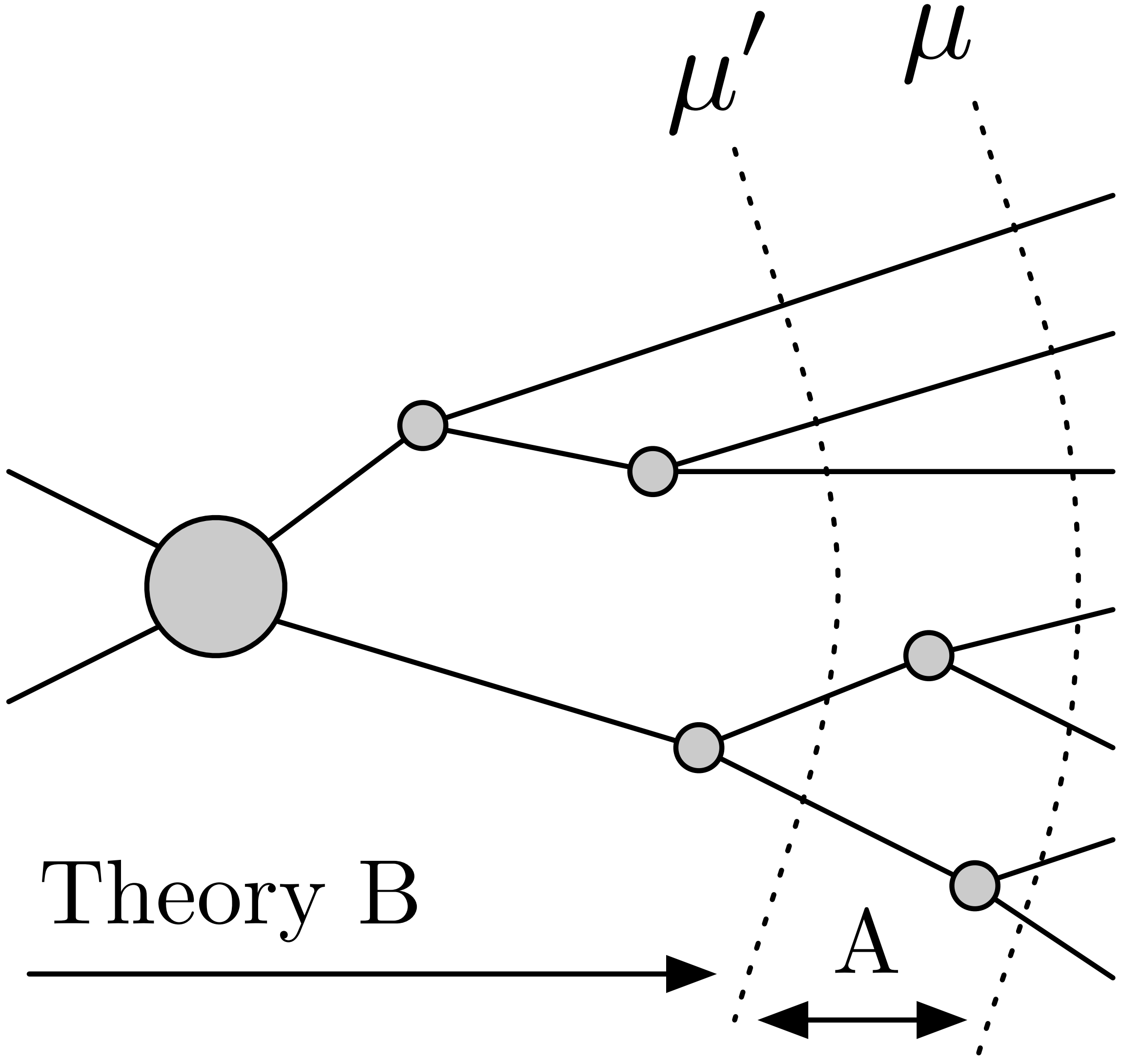
$$\left|\mathcal{M}^{\mathrm{A}}(\mu)\right|^2 \;\; \text{vs.} \;\; \left|\mathcal{M}^{\mathrm{B}}(\mu)\right|^2$$

Nested Mergings



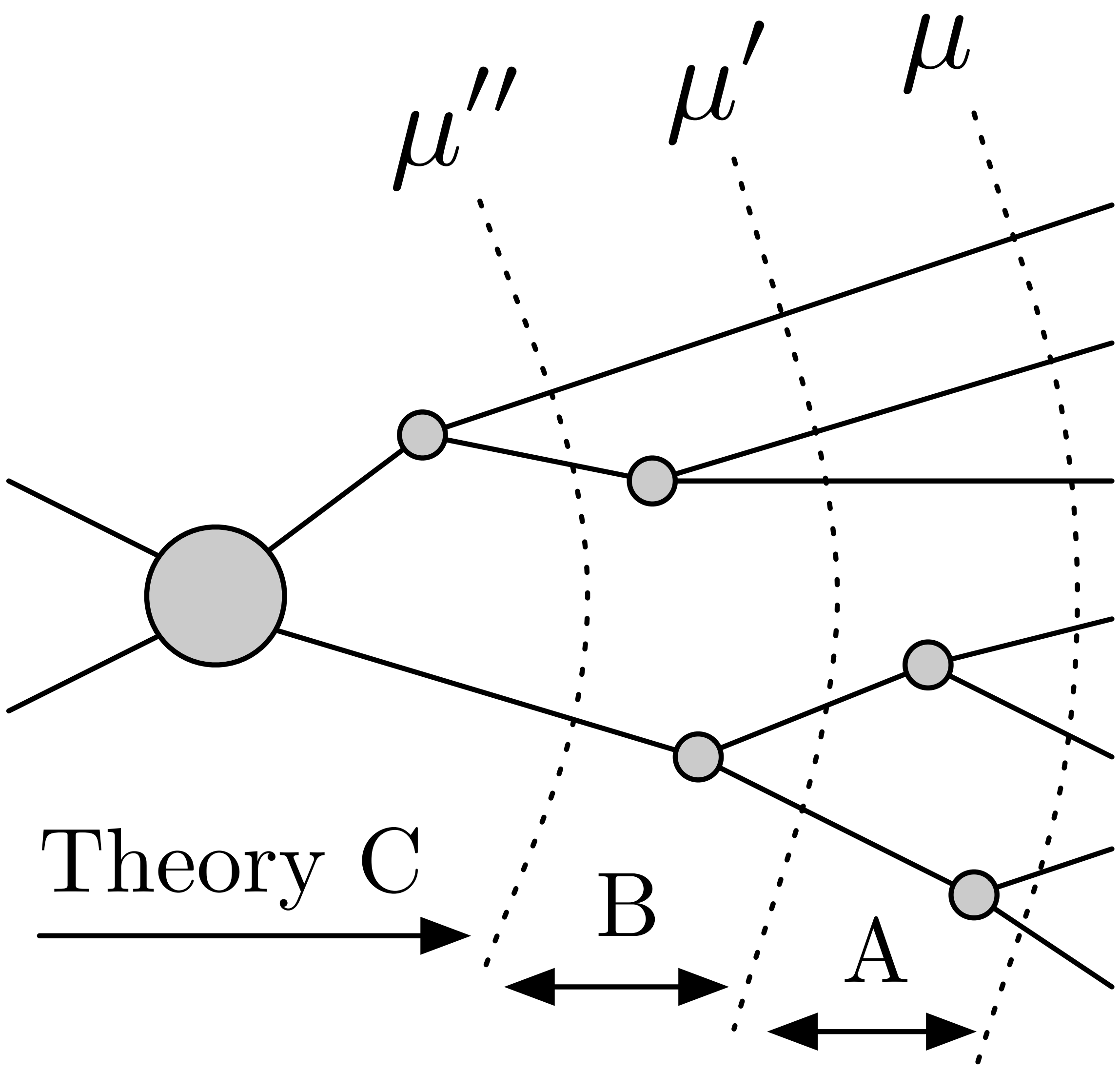
$$\left|\mathcal{M}^{\text{Best}}(\mu)\right|^2 = \left|\mathcal{M}^{\text{A}}(\mu)\right|^2$$

Nested Mergings



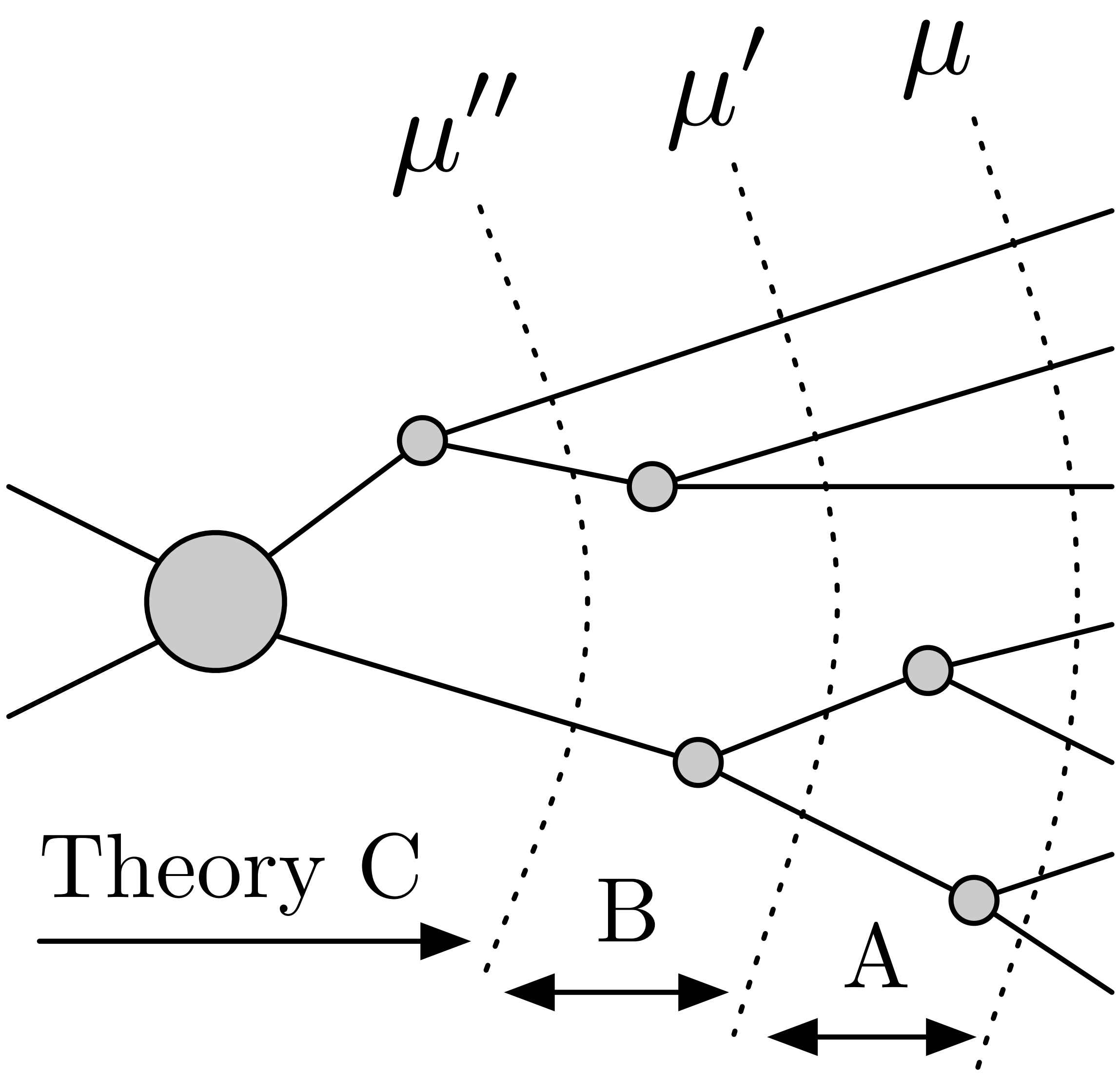
$$\left|\mathcal{M}^{\mathrm{Best}}(\mu)\right|^2 = \left|\mathcal{M}^{\mathrm{A}}(\mu)\right|^2 \times \frac{\left|\mathcal{M}^{\mathrm{B}}(\mu')\right|^2}{\left|\mathcal{M}^{\mathrm{A}}(\mu')\right|^2}$$

Nested Mergings



$$\left|\mathcal{M}^{\mathrm{Best}}(\mu)\right|^2 = \left|\mathcal{M}^{\mathrm{A}}(\mu)\right|^2 \times \frac{\left|\mathcal{M}^{\mathrm{B}}(\mu')\right|^2}{\left|\mathcal{M}^{\mathrm{A}}(\mu')\right|^2} \times \frac{\left|\mathcal{M}^{\mathrm{C}}(\mu'')\right|^2}{\left|\mathcal{M}^{\mathrm{B}}(\mu'')\right|^2}$$

NLO/LO/LL



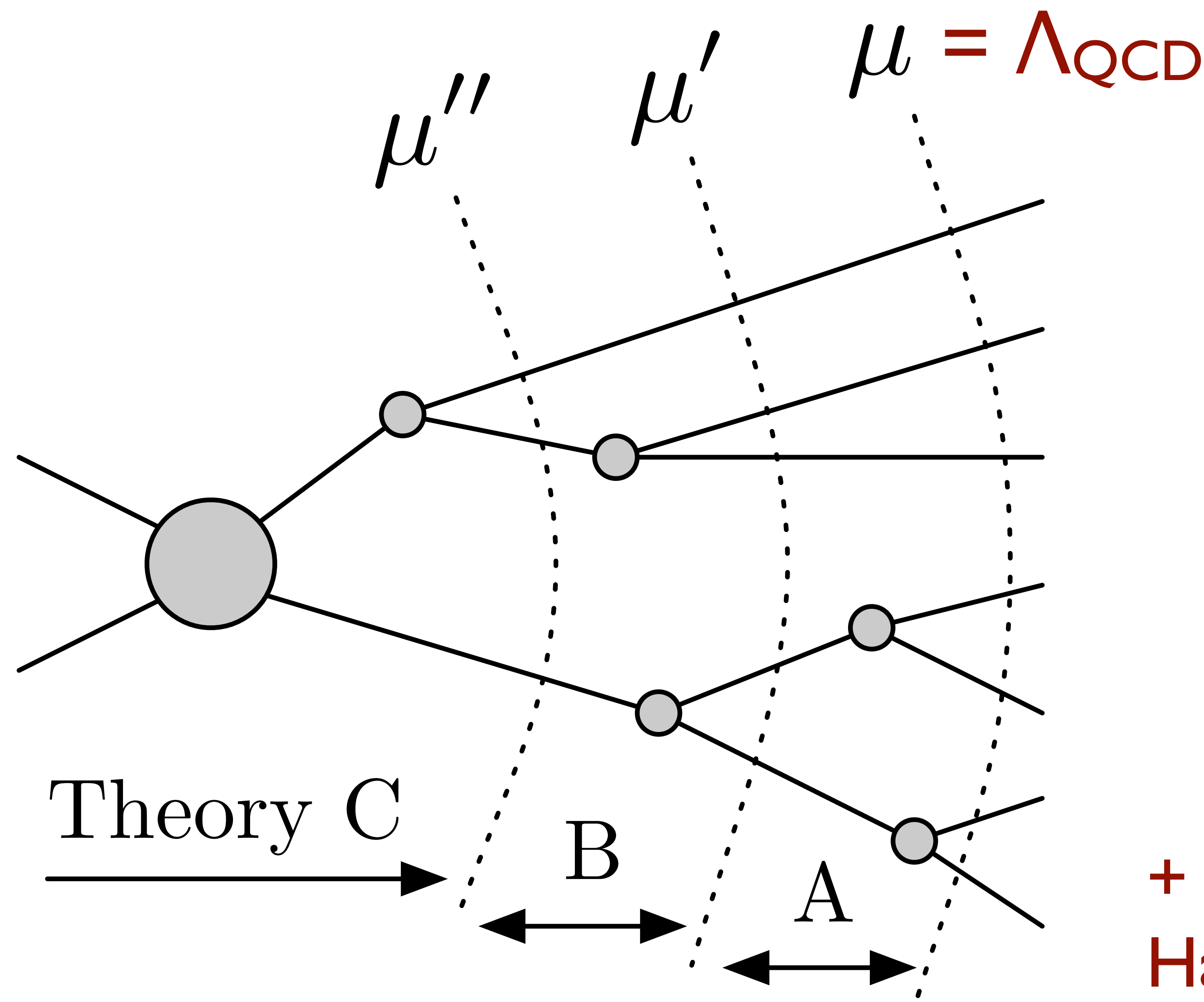
C: NLO/LL
(MC@NLO)

B: LO/LL
(PS/ME Merging)

A: Shower

Putting it all together...

PDFs
+
Secondaries
+
Beam Remnants
+
Pileup
+



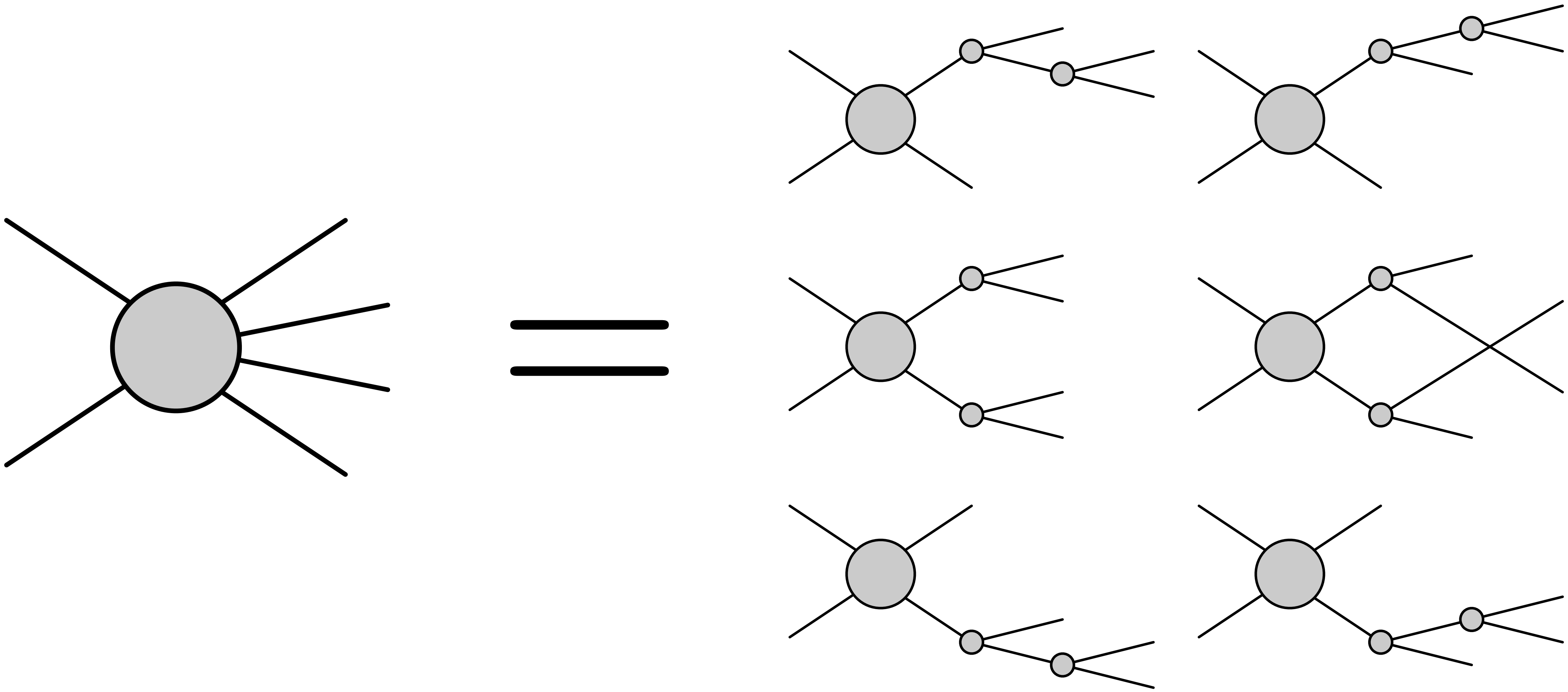
+
Hadronization

C: NLO/LL
(MC@NLO)

B: LO/LL
(PS/ME Merging)

A: Shower

Shower Subtlety



Same four-vectors are determined by multiple shower histories. Dominant history is the most singular one.

LO/LL Merging

$$\left|\mathcal{M}_n^{\text{shower}}(\mu)\right|^2 = \sum_i Q_i \Delta_i(\mu)$$

Splitting Functions

Sudakovs

Shower Histories

In singular regions of phase space:

$$\left|\mathcal{M}_n^{\text{tree}}\right|^2 \to \sum_j Q_j$$

Interference terms in tree-level matrix element with Sudakovs from shower "matrix element"?

LO/LL Merging

$$\left|\mathcal{M}_n^{\mathrm{LO/LL}}(\mu)\right|^2 = \left|\mathcal{M}_n^{\mathrm{tree}}\right|^2 \sum_i \frac{Q_i}{\sum_j Q_j} \Delta_i(\mu)$$

Shower doesn't factorize, but in singular regions:

$$\frac{Q_{\mathrm{dom}}}{\sum_j Q_j} \to 1 \qquad \frac{Q_{\mathrm{other}}}{\sum_j Q_j} \to 0$$

$$\left|\mathcal{M}_n^{\mathrm{LO/LL}}(\mu)\right|^2 \simeq \left|\mathcal{M}_n^{\mathrm{tree}}\right|^2 \Delta_{\mathrm{dom}}(\mu)$$

Equivalent to CKKW in singular regions.

NLO/LL Merging

$$\sigma_2(\mu) \;=\; \sigma_{\rm NLO}\Delta_R(\mu)$$

$$\frac{d\sigma_3(t)}{dt} \;=\; \sigma_{\rm NLO}R(t)\Delta_R(t)$$

$$= \frac{d\sigma_3^{\rm tree}(t)}{dt} + \mathcal{O}(\alpha_s^2)$$

Inspired by POWHEG, turn NLO calculation into "shower" with novel "splitting function".
By construction, cross section is correct to NLO.

GenEvA Outlook

Hadronic Collisions, Heavy Resonances,
Advanced Matrix Elements

The GenEvA Framework

Calculations | Algorithms

$$d\sigma = |\mathcal{M}(\mu)|^2 \, d\mathrm{MC}(\mu)$$

Matching Scale

No dead zones, no double counting,
no negative weights, no incalculable ambiguities.

GenEvA IL or CH

To be relevant for the LHC, we need...

Calculations	Algorithms

$$d\sigma = |\mathcal{M}(\mu)|^2 \; d\mathrm{MC}(\mu)$$

Calculations	Algorithms
Proper Fact./Renorm. Scale Treatment	Proper Mass Treatment
Parton Distribution Functions	Interface with $p_\perp$ Showers
ISR/FSR Interference	ISR/FSR Double Counting
	Resonance/Showerer

These are technical issues, not conceptual ones.
Consequence of μ appearing in both calculations and algorithms.

Theory Challenge

$$\left|\mathcal{M}^{\mathrm{Best}}(\mu)\right|^2$$

SCET Matrix Elements

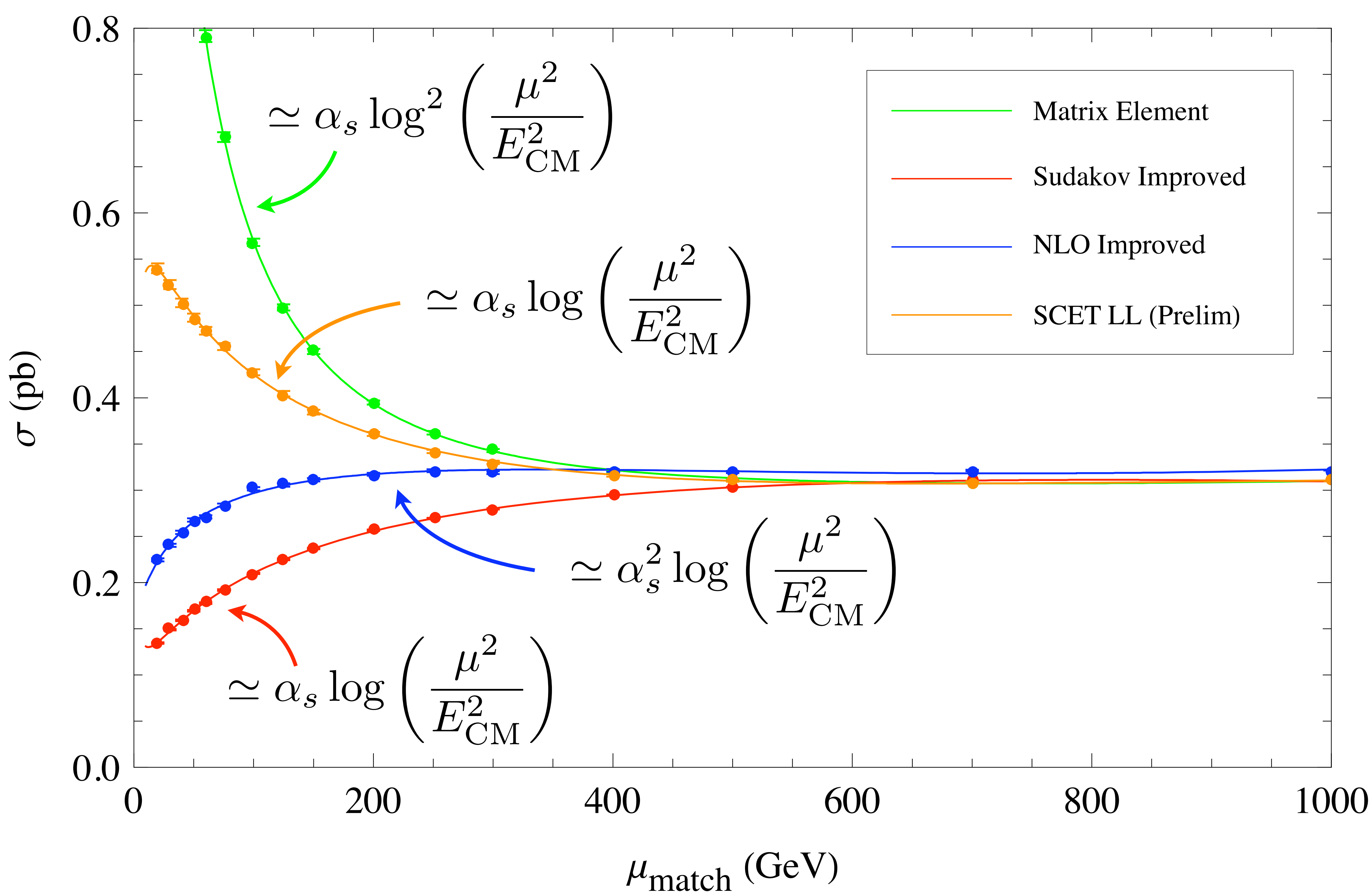
Subleading-logarithmic treatment of multiple scales?

NNLO/NLO/LO/NLL/LL

Describe N^iLO observables accurate to N^iLO and N^jLL observables accurate to N^jLL, simultaneously?

Preliminary SCET Work

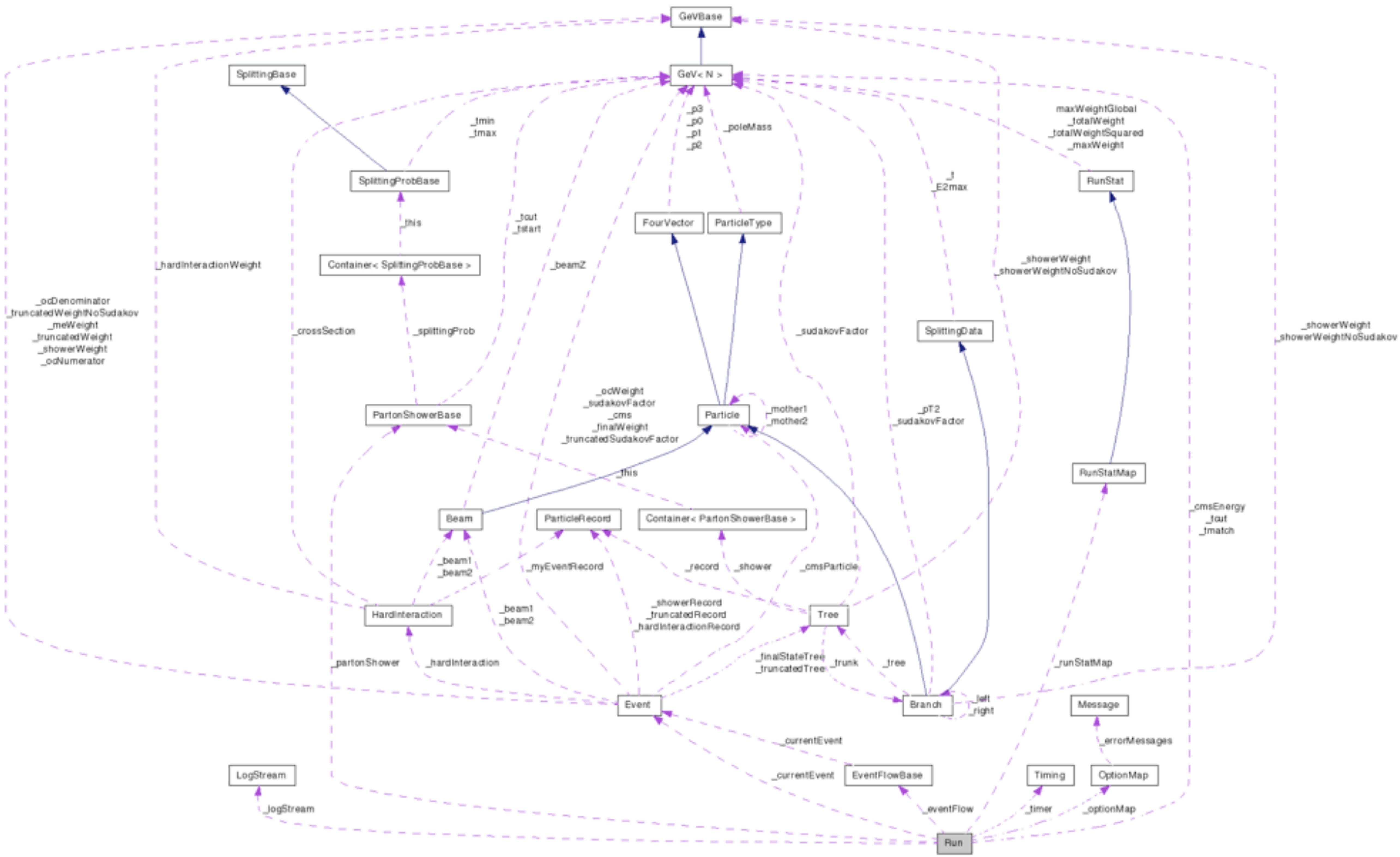
(Matrix Elements from Matthew Schwartz)




$d\sigma$
$|\mathcal{M}(\mu)|^2 \, d\mathrm{MC}(\mu)$

Backup Slides

In case you were wondering...



There is real code....

```
+-----------------------------------------------------------+
|  GenEvA --- GENerate EVents Analytically                  |
+-----------------------------------------------------------+
|  Version: 0.1.95 (November 6, 2007)                       |
|  Authors: Christian Bauer, Frank Tackmann & Jesse Thaler  |
|    arXiv: 0801.xxxx                                       |
+-----------------------------------------------------------+

     +-----  Command Line
     |  GenEvA --cms 1000 --cut 10 --numStat 10000 --best 6 50
     +----------

     +-----  Event Generation Information
     |                 Process: e- e+ -> j j
     |   Center-of-Mass Energy: 1000 GeV
     |          Matching Scale: 50 GeV with maximum multiplicity 6
     |           Shower Cutoff: 10 GeV
     |              Generation: Events are matched to NLO/LO matrix element.
     +----------

     +-----  Run Statistics
     |  Process:    NumGen  NumKept  NumStat StatEff   NumUnw  UnwEff      Sigma +/- dS (pb)   (error%)
     |   Global:     19771    18674  10000.3   0.536   6485.0   0.347   0.253007 +/- 0.001779  ( 0.70%)
     |       2j:      2303     2303   2303.0   1.000   2303.0   1.000   0.089849 +/- 0.001760  ( 1.96%)
     |       3j:      8480     7383   6406.3   0.868   3539.7   0.479   0.129731 +/- 0.001333  ( 1.03%)
     |       4j:      5629     5629   3351.1   0.595    905.4   0.161   0.029322 +/- 0.000462  ( 1.57%)
     |       5j:      2492     2492   1187.3   0.476    254.1   0.102   0.003693 +/- 0.000104  ( 2.81%)
     |       6j:       867      867    326.1   0.376     82.2   0.095   0.000412 +/- 0.000023  ( 5.49%)
     +----------

+-----  Thank you for running GenEvA
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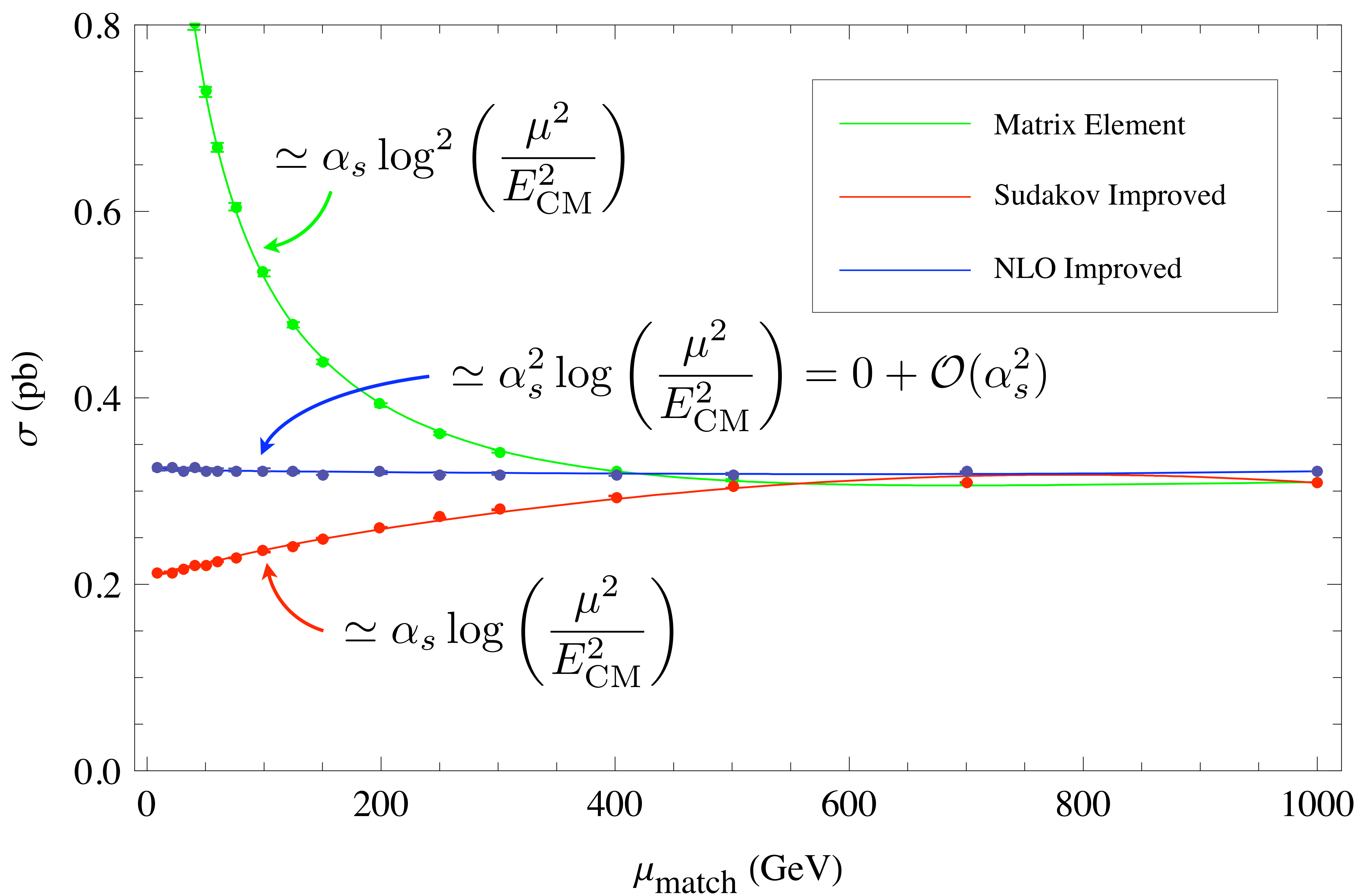
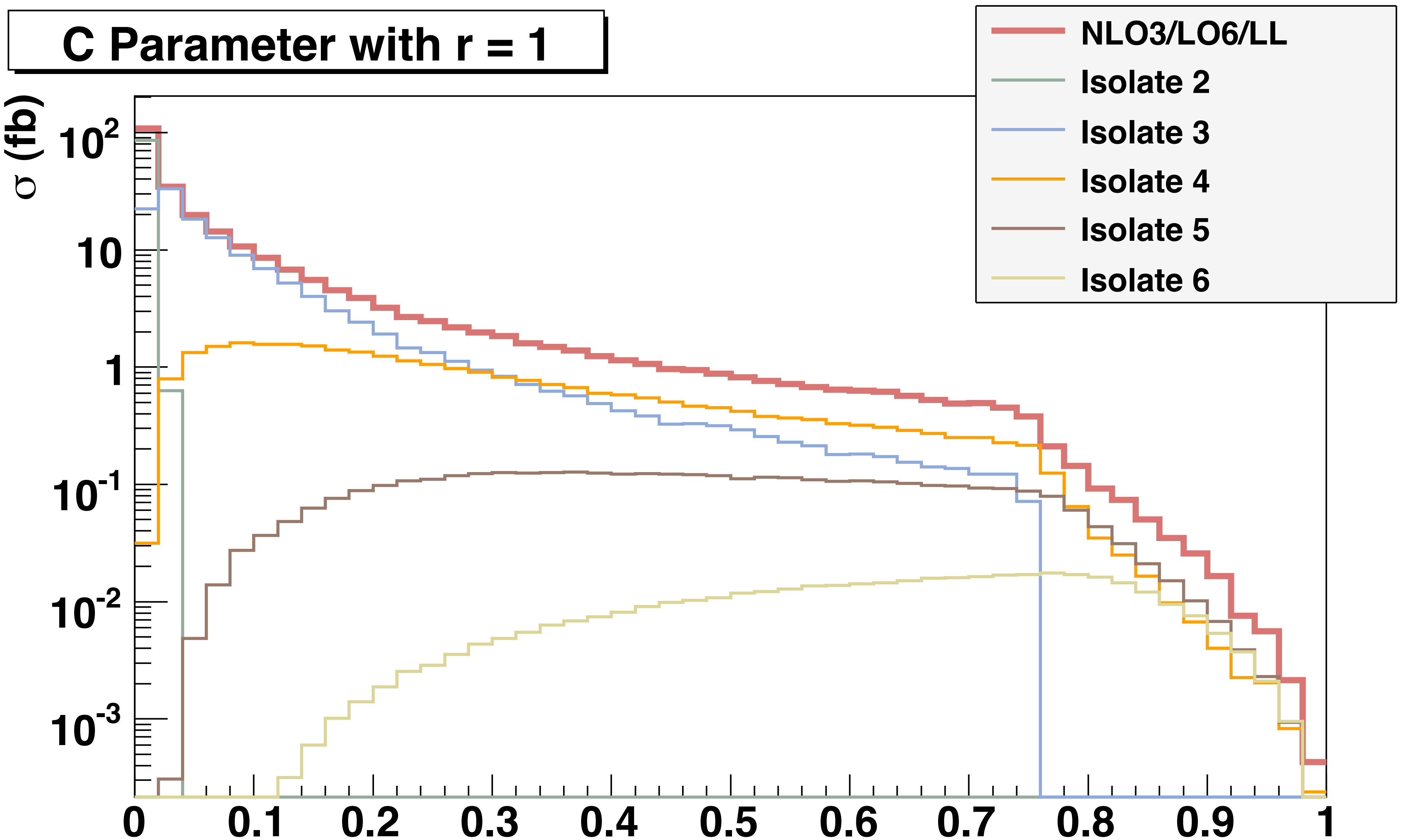
....and it's reasonably user-friendly.

Amplitudes for $n_{max} = 3$



Isolated Components



Non-trivial combination of five different samples.