GenEvA

A New Framework for Event Generation

Jesse Thaler (Berkeley)

with Christian Bauer and Frank Tackmann

arXiv:0801.4026 [Physics]
arXiv:0801.4028 [Techniques]

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.

+ Order α_s^2
– Some Leading Logarithms
+ Proper Bottom Mass Treatment
– No PS/ME merging
+ All Angular Correlations

“LO” = Pythia Out-of-the-Box

– Order αs
+ All Leading Logarithms
– Ad Hoc Bottom Mass Treatment
+ “Normalized” PS/ME merging
– 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

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Fixed n-body Phase Space

Soft Collinear Limit

Recursive Phase Space

Parton Showers

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Fixed-Order Calculations

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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, ...)

Traditional Approach

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

Dead zones? Double counting?
Negative weights? Ambiguities?

Traditional Approach

Vetoed Showers, Modified Scale Choices

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

Dead zones? Double counting?
Negative weights? Ambiguities?

Traditional Approach

Vetoed Showers, Modified Scale Choices

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

Subtractions, Sudakovs, Multiple Samples

Dead zones? Double counting?
Negative weights? Ambiguities?

Fixed-Order Calculations

Perturbative α_s Expansion

Fixed n-body Phase Space

Merge!

Soft Collinear Limit

Recursive Phase Space

Parton Showers

Perturbative
α_s Expansion

Fixed n-body
Phase Space

Soft Collinear
Limit

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Phase Space

Perturbative
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Fixed n-body
Phase Space

Soft Collinear
Limit

Recursive
Phase Space

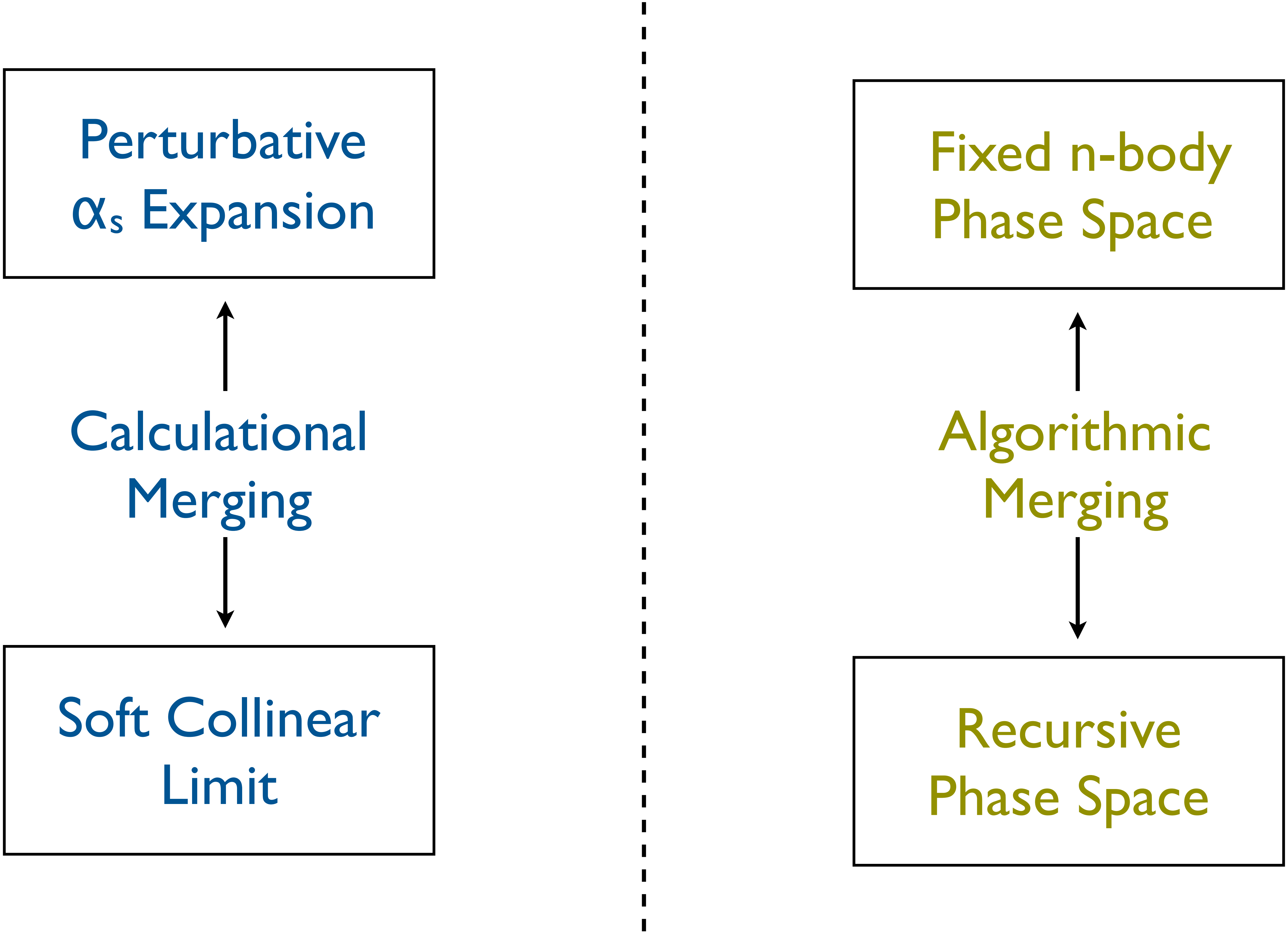
Perturbative
α_s Expansion

Calculational
Merging

Soft Collinear
Limit

Fixed n-body
Phase Space

Recursive
Phase Space



Perturbative
αs 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

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

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The GenEvA Framework

Calculations | Algorithms

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

Matching Scale

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

GENerate EVents Analytically

- Algorithmic Side
  - "Deriving" the Master Formula
  - A New Approach to Phase Space
- Calculational Side
  - Proof-of-Concept Amplitudes
    - LO/LL Merging (Analog of PS/ME Merging)
    - NLO/LL Merging (Analog of MC@NLO)
    - NLO/LO/LL Merging (New!)
  - Technical Details
- GenEvA at the LHC

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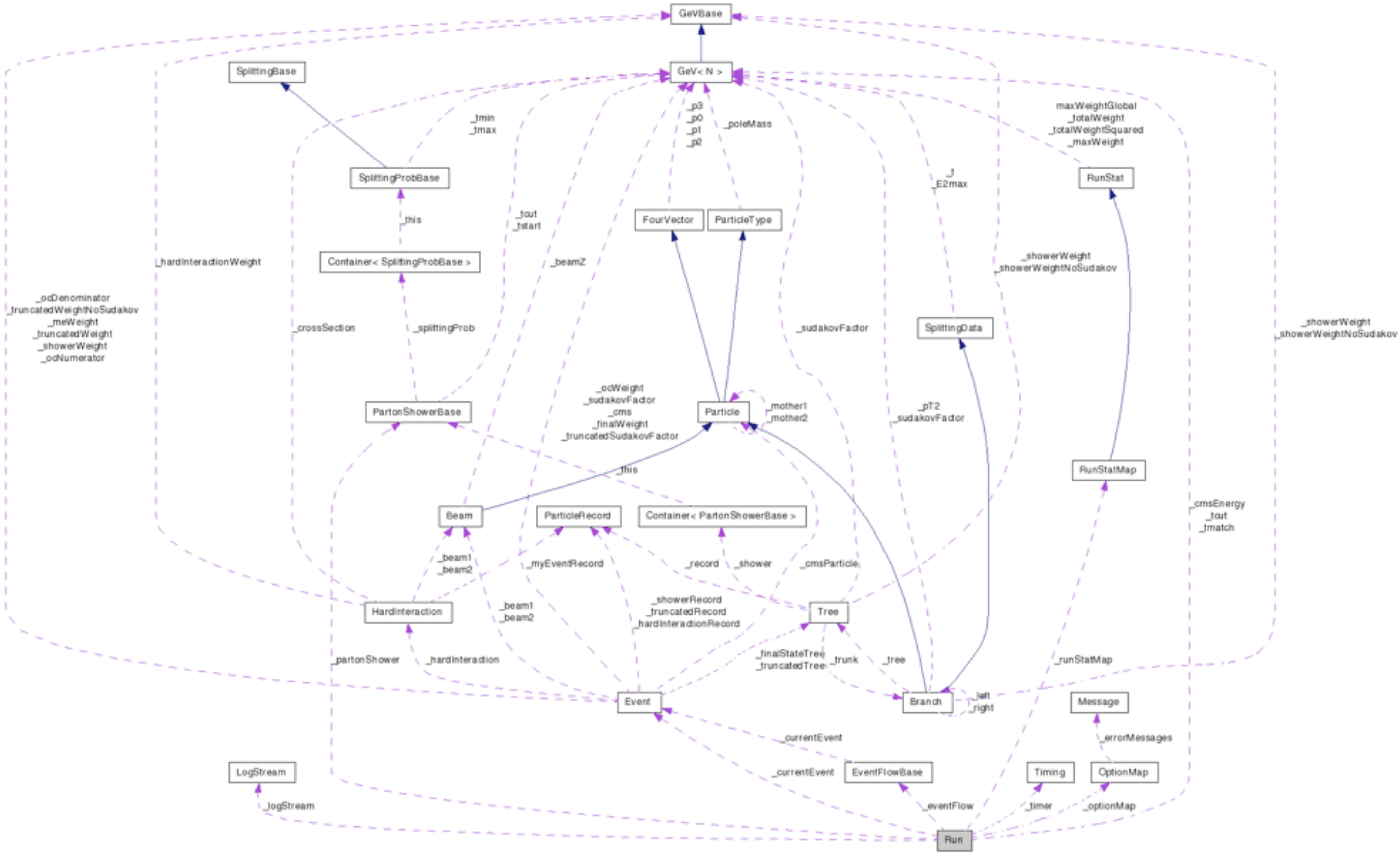
Ultimate Goal:

Hadronic Collisions with Heavy Resonances

Current Status:

Leptonic Collisions with Massless Partons

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



There is real code....

```
+------------------------------------------------------------+
|  GenEvA --- GENerate EVents Analytically                   |
+------------------------------------------------------------+
|  Version: 0.1.104 (January 24, 2008)                       |
|  Authors: Christian Bauer, Frank Tackmann & Jesse Thaler   |
|    arXiv: 0801.4026 & 0801.4028                            |
+------------------------------------------------------------+

     +-----  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
```

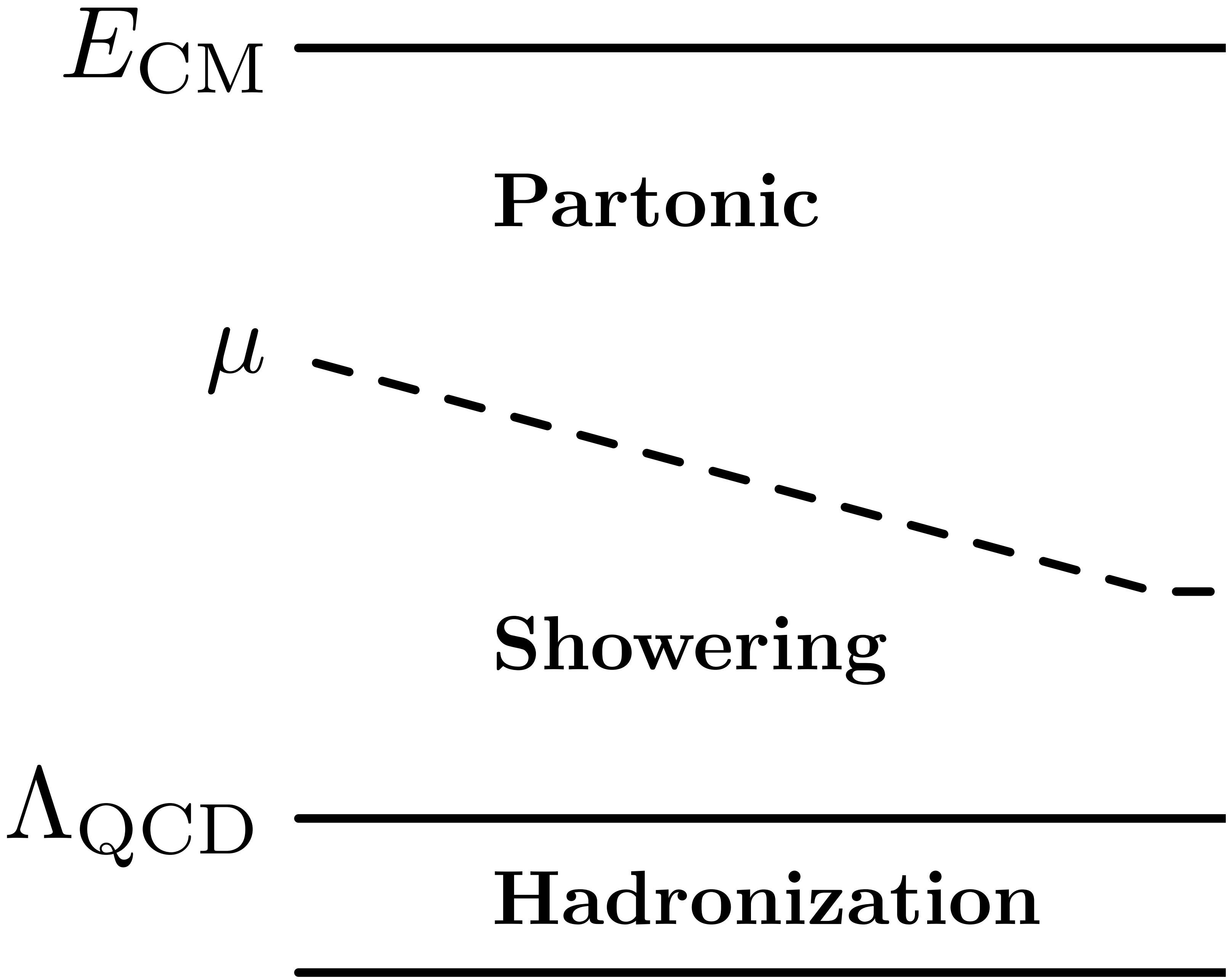
....and it's reasonably user-friendly.

GenEvA Master Formula

Generic Solution to Merging Fixed-Order Calculations with Parton Showers

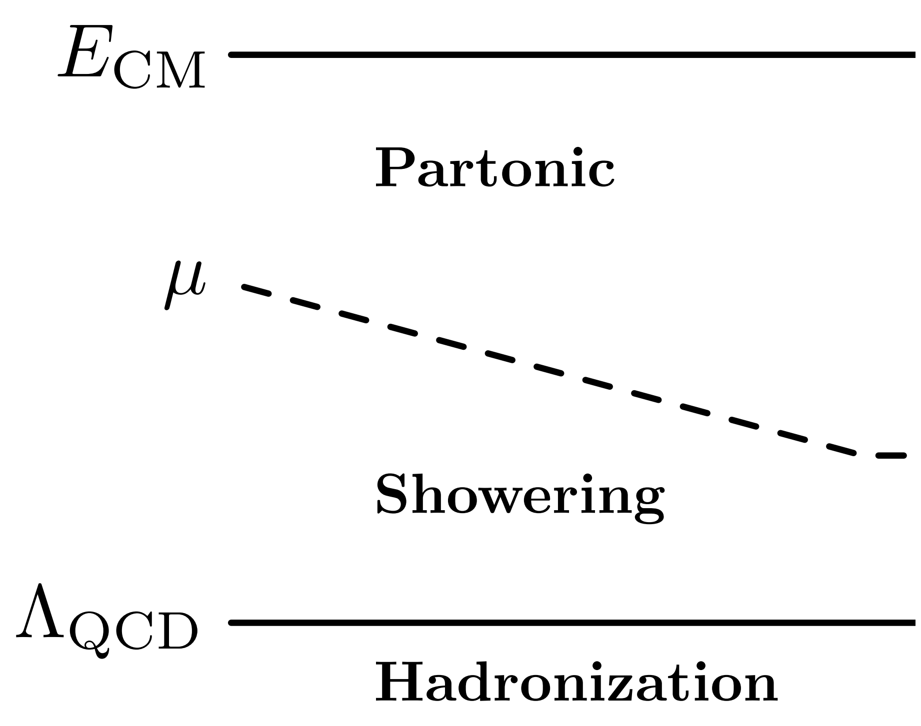
$$d\sigma = \left|\mathcal{M}(\mu)\right|^2 d\mathrm{MC}(\mu)$$

General Picture



Traditional Approach

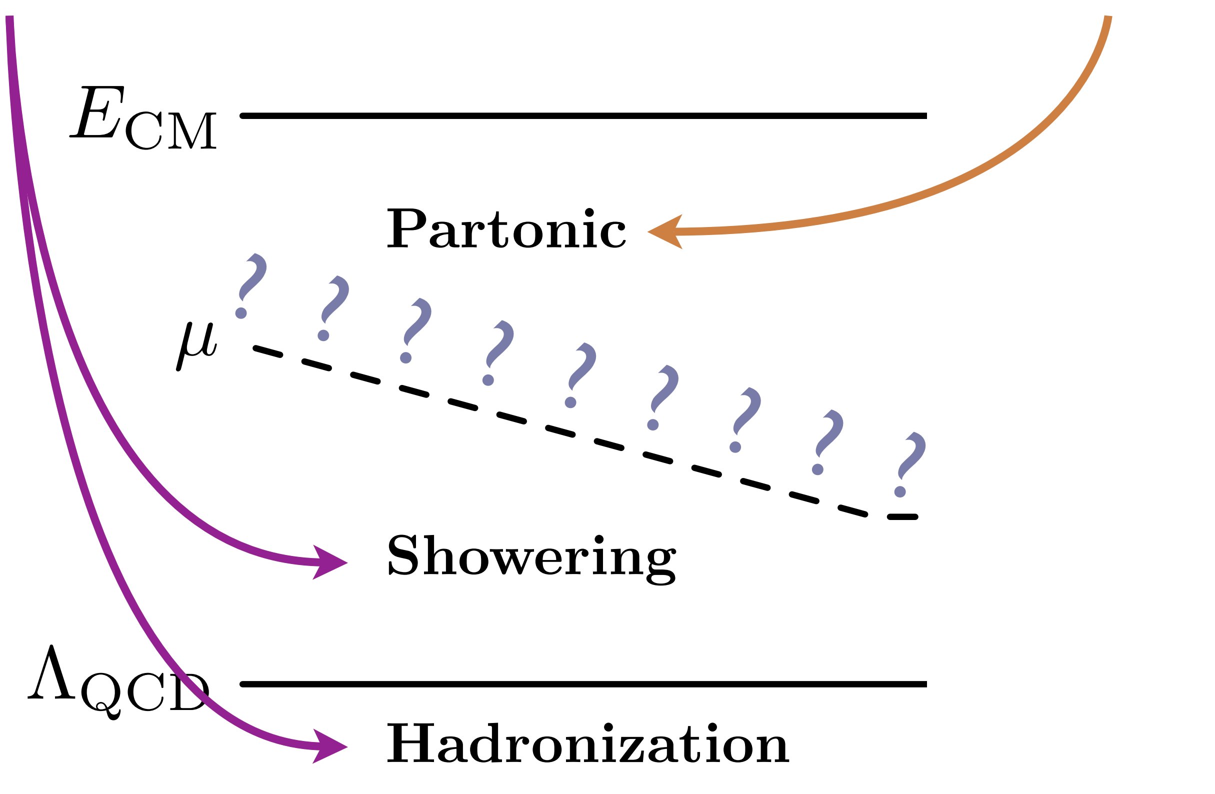
$$d\sigma = \mathrm{MC}\left(|\mathcal{M}|^2 \, d\Phi\right)$$



Traditional Approach

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

(Pythia, Herwig, ...) (ALPGEN, MadEvent, ...)



Traditional Approach

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

Three Technical Problems

1. Infrared Divergences
2. Scale Dependence
3. Double Counting

GenEvA Framework

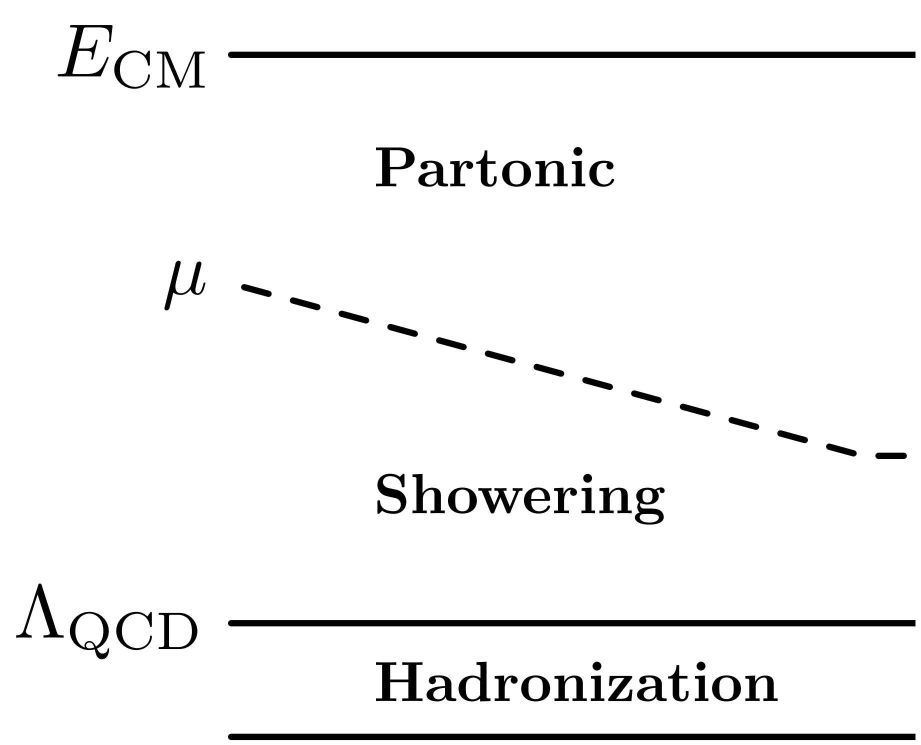
$$d\sigma = \left|\mathcal{M}(\mu)\right|^2 d\mathrm{MC}(\mu)$$

Three Conceptual Solutions

1. Infrared Divergences? → Merge QCD Approximations
2. Scale Dependence? → Merge Calc. with Pheno. Models
3. Double Counting? → Merge Phase Space Algorithms

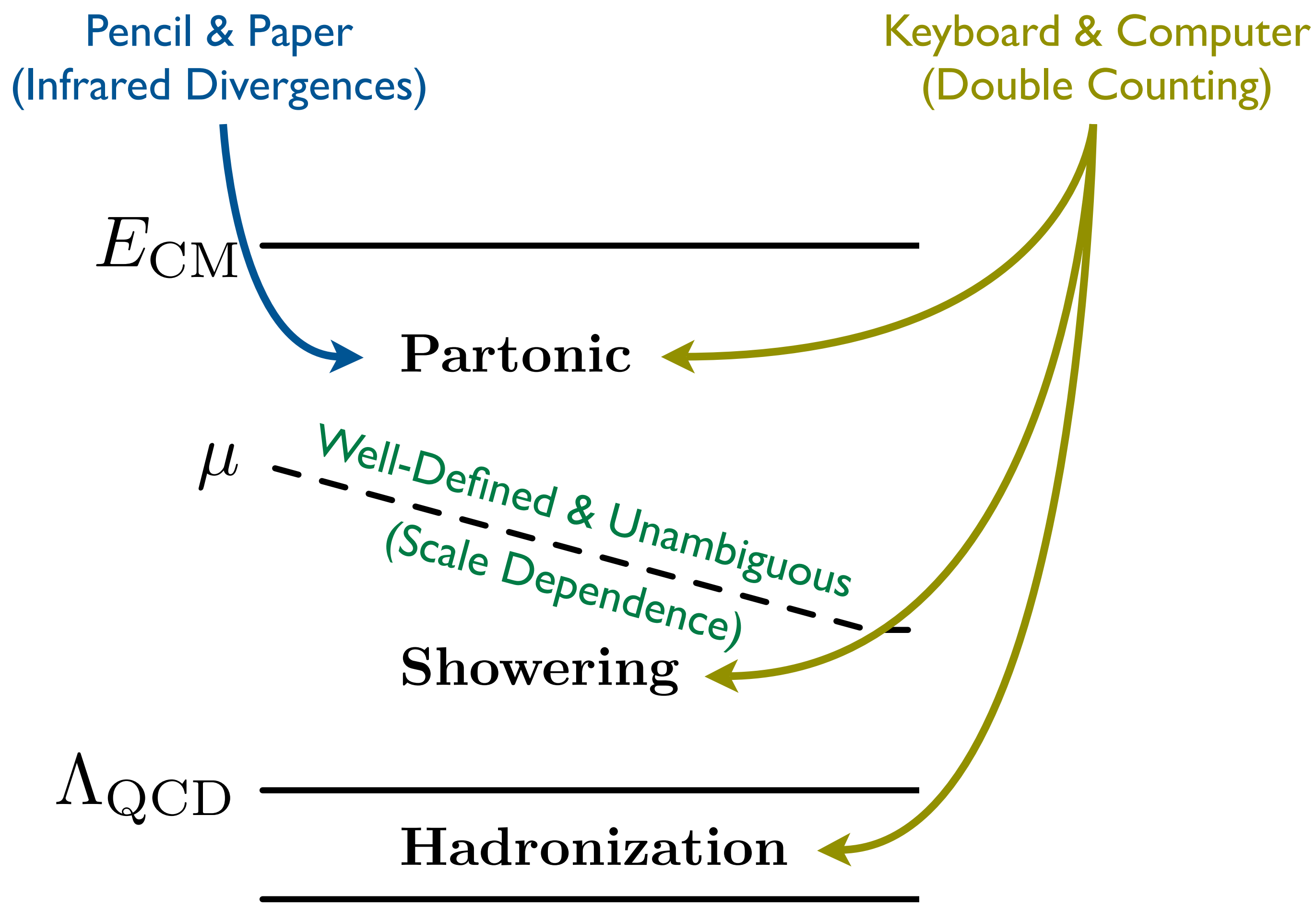
GenEvA Framework

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



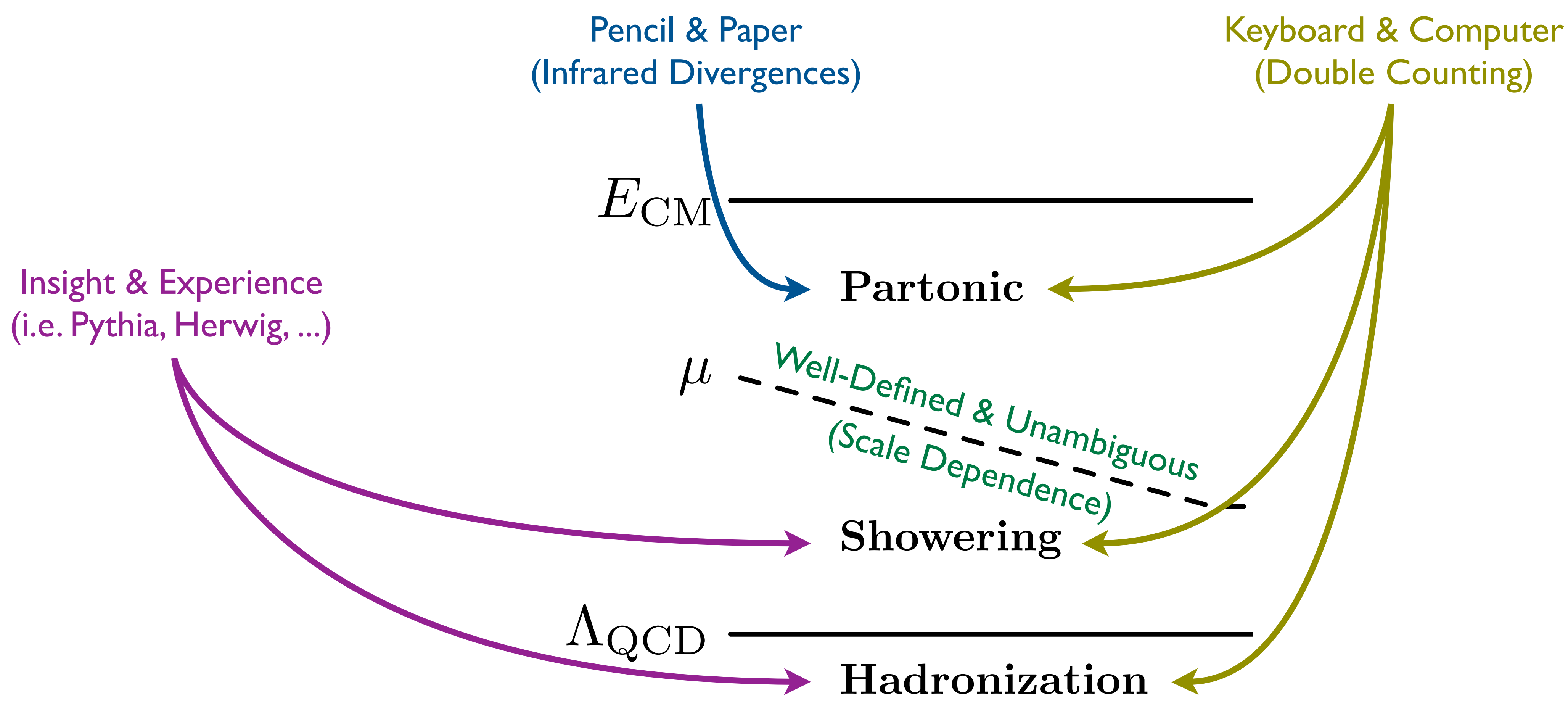
GenEvA Framework

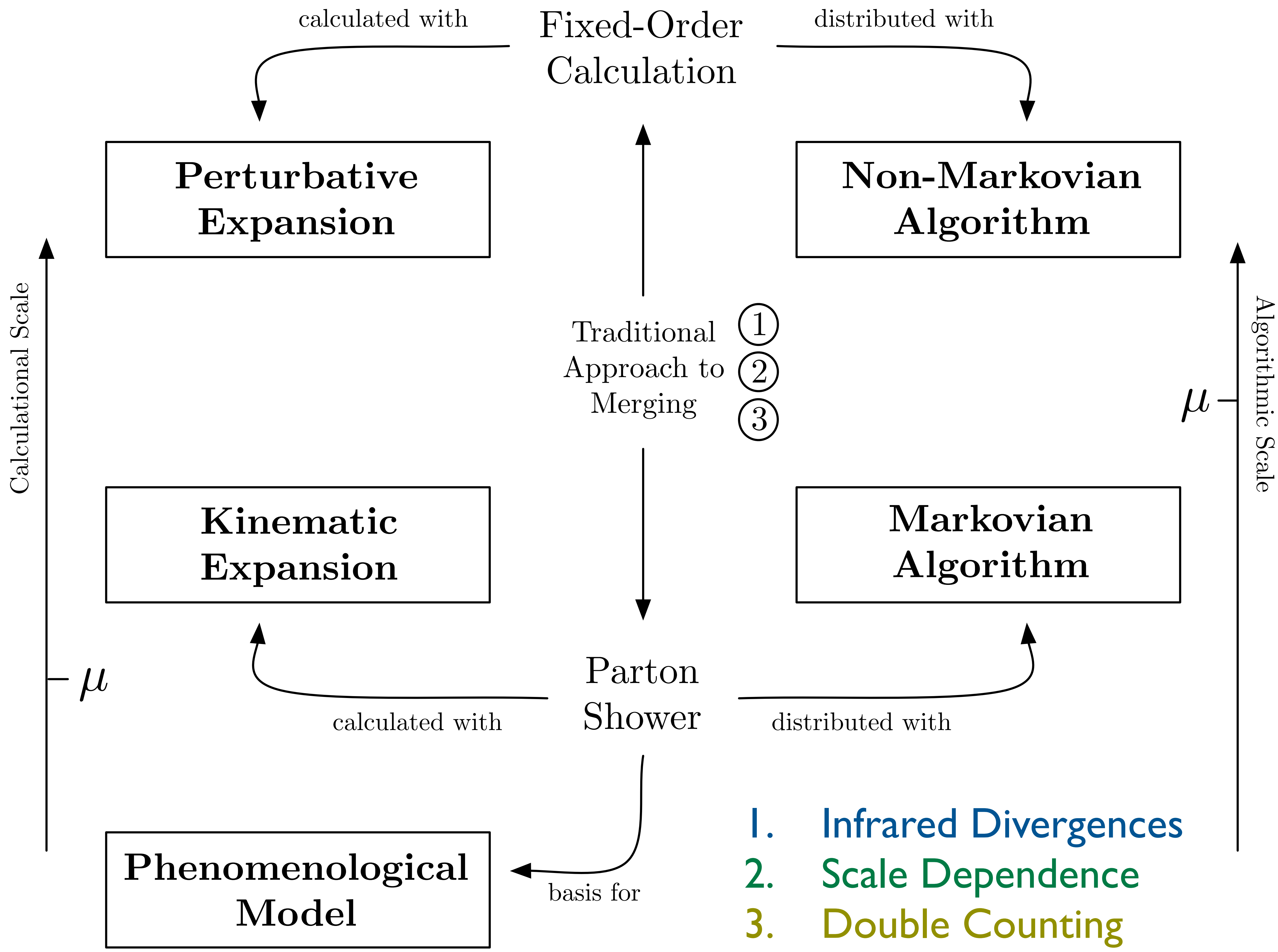
$$d\sigma = |\mathcal{M}(\mu)|^2 \, d\mathrm{MC}(\mu)$$



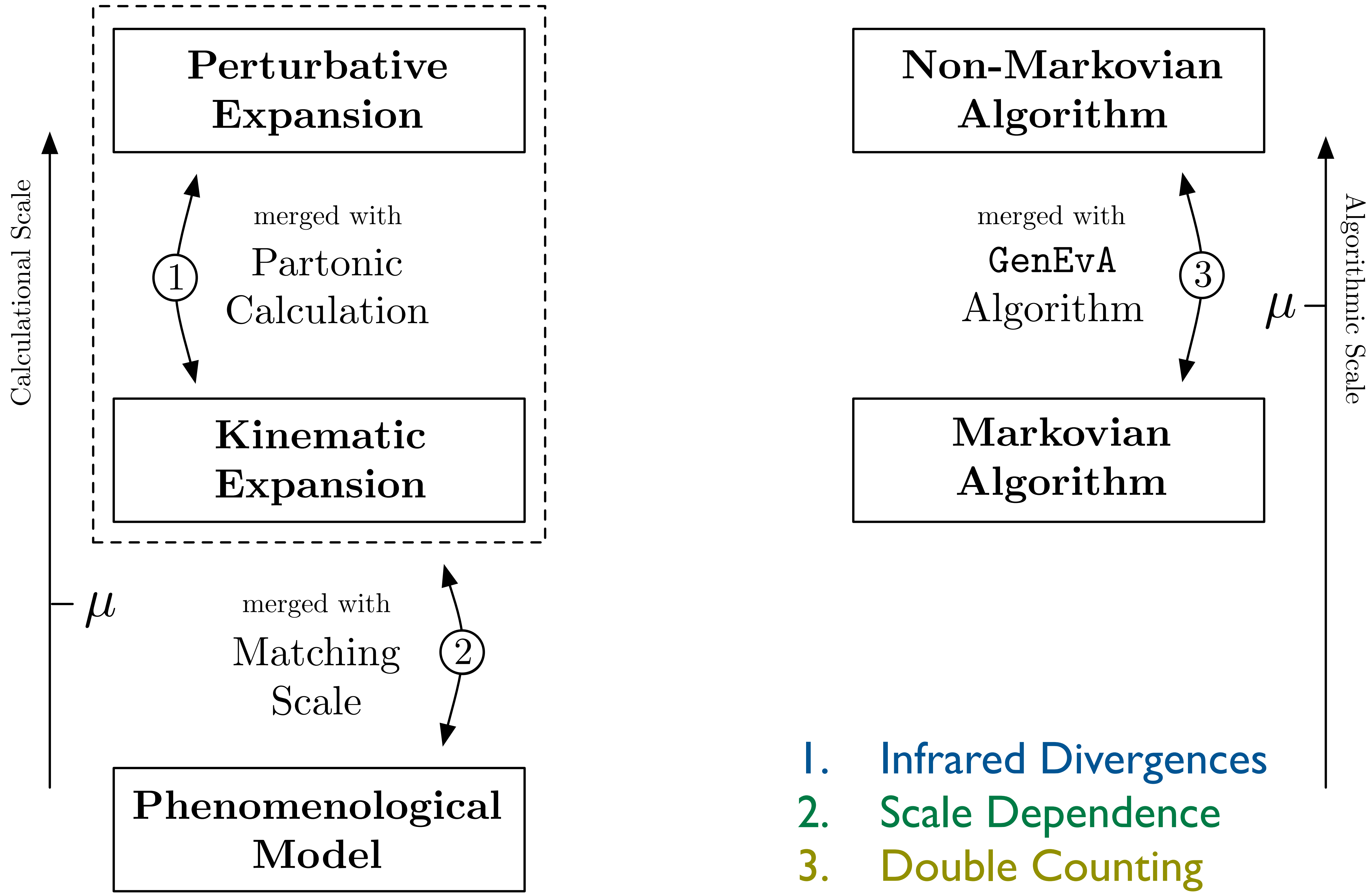
GenEvA Framework

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

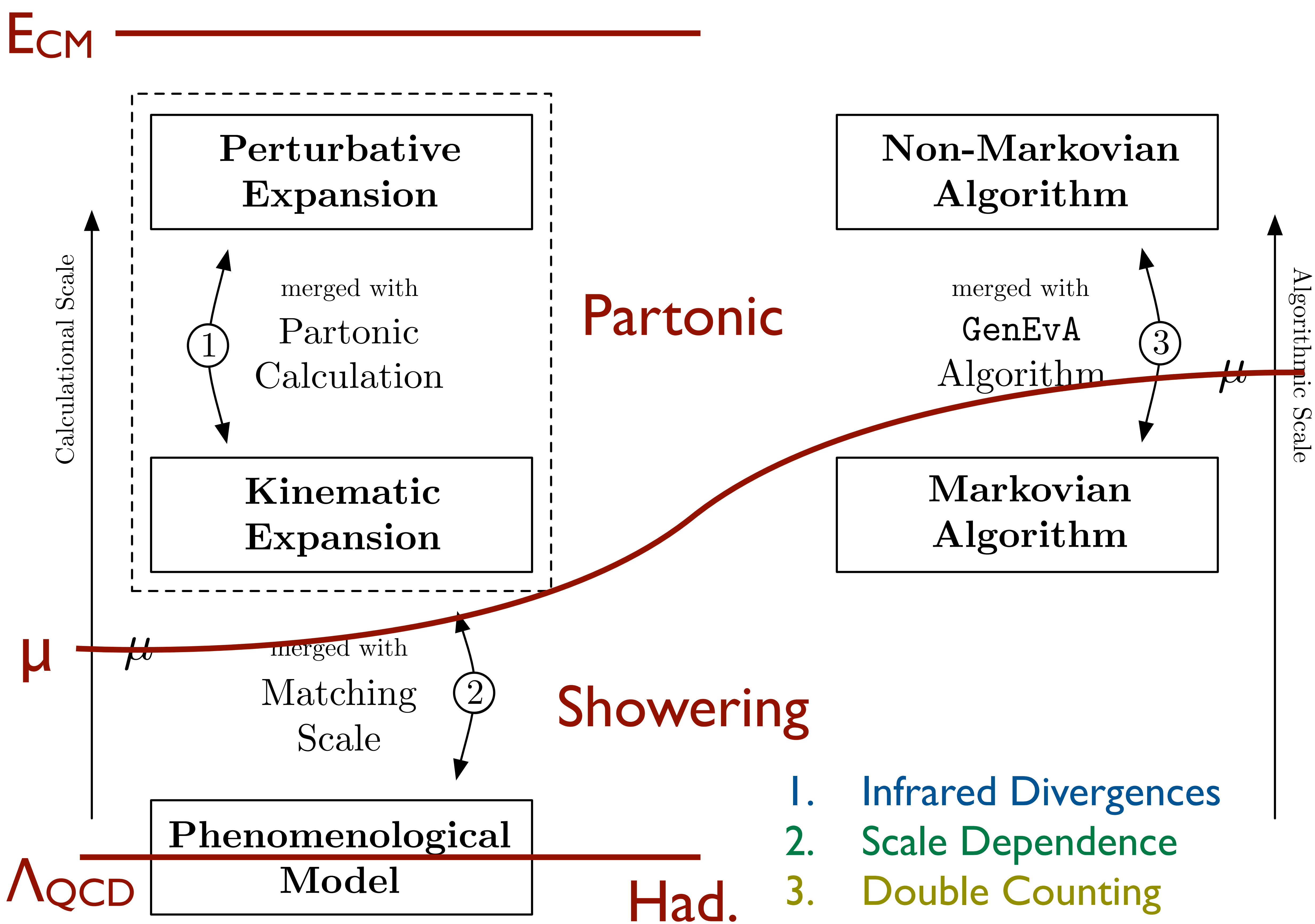




Fixed-Order Calculation
calculated with
distributed with
Perturbative Expansion
Non-Markovian Algorithm
Calculational Scale
Algorithmic Scale
μ
Traditional Approach to Merging
1
2
3
Kinematic Expansion
Markovian Algorithm
μ
Parton Shower
calculated with
distributed with
basis for
Phenomenological Model
1. Infrared Divergences
2. Scale Dependence
3. Double Counting



1. Infrared Divergences
2. Scale Dependence
3. Double Counting



ECM
Perturbative Expansion
merged with
Partonic Calculation
Kinematic Expansion
Calculational Scale
Partonic
Non-Markovian Algorithm
merged with
GenEvA Algorithm
Markovian Algorithm
Algorithmic Scale
μ
μ
merged with
Matching Scale
Showering
Phenomenological Model
ΛQCD
Had.
1. Infrared Divergences
2. Scale Dependence
3. Double Counting

1. Different QCD Approx.

We have Fixed Order Expansion in α_s.

We have (Sub-)Leading Logarithms in Soft-Collinear Limit.

Infrared Divergences should Cancel between Trees and Loops.

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

Infrared divergences cancelled in definition of "amplitude".
Infrared scale $\tilde{\mu}$ needed to resum $\alpha_s \log^2 r$ terms.

Partonic Calculations

$$|\mathcal{M}^{\mathrm{CKKW}}(\tilde{\mu})|^2 \simeq |\mathcal{M}^{\mathrm{tree}}|^2\,\Delta(E_{\mathrm{CM}},\tilde{\mu})$$

$$|\mathcal{M}_n^{\mathrm{NLO}}(\tilde{\mu})|^2 \simeq |\mathcal{M}_n^{\mathrm{tree+loop}}|^2 + \int_{\tilde{\mu}} |\mathcal{M}_{n+1}^{\mathrm{tree}}|^2$$

$$|\mathcal{M}^{\mathrm{MC@NLO}}(\tilde{\mu})|^2 \neq |\mathcal{M}^{\mathrm{NLO}}(\tilde{\mu})|^2\Delta(E_{\mathrm{CM}},\tilde{\mu})$$

2. Calculations vs. Models

Calculations Available for Finite Number of Particles.

Need Parton Shower to fill out Phase Space.

Need Hadronization Model for Detector Simulation.

$$\tilde{\mu} \longrightarrow \mu$$

If "amplitude" has correct leading logarithms, interface with parton shower will be smooth if μ scale is the same.

3. Phase Space Algorithms

Field Theory Calculations need Fixed Number of Final States.

Parton Showers need Variable Number of Final States.

Want Every Phase Space Point Covered Once and Only Once.

$$\mathrm{MC}\left(d\Phi\right) \longrightarrow d\mathrm{MC}(\mu)$$

Replace two event generation frameworks with one master framework that solves double counting by construction.

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

Infrared Divergences $\quad |\mathcal{M}|^2 \longrightarrow |\mathcal{M}(\tilde{\mu})|^2 \quad$ Merge QCD Approx.

Scale Dependence $\quad \tilde{\mu} \longrightarrow \mu \quad$ Merge Calc. w/ Model

Double Counting $\quad \mathrm{MC}\,(d\Phi) \longrightarrow d\mathrm{MC}(\mu) \quad$ Merge Algorithms

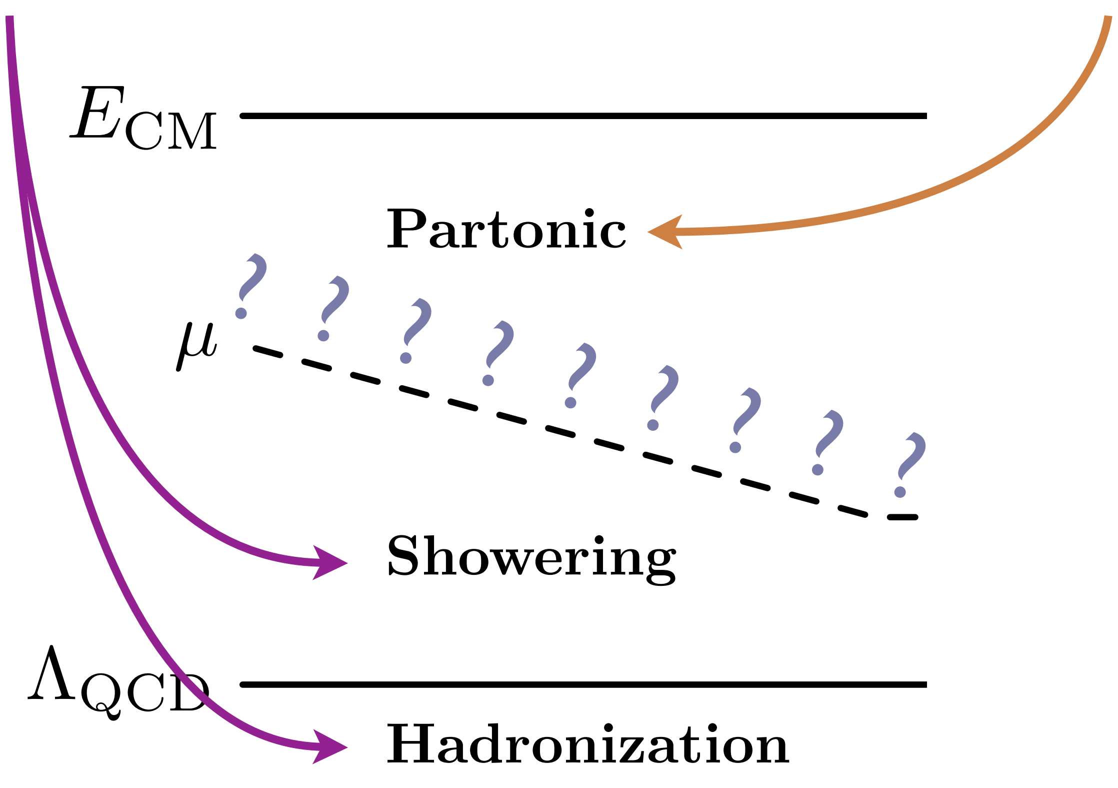
$$d\sigma = |\mathcal{M}(\mu)|^2 \, d\mathrm{MC}(\mu)$$

Traditional Approach

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

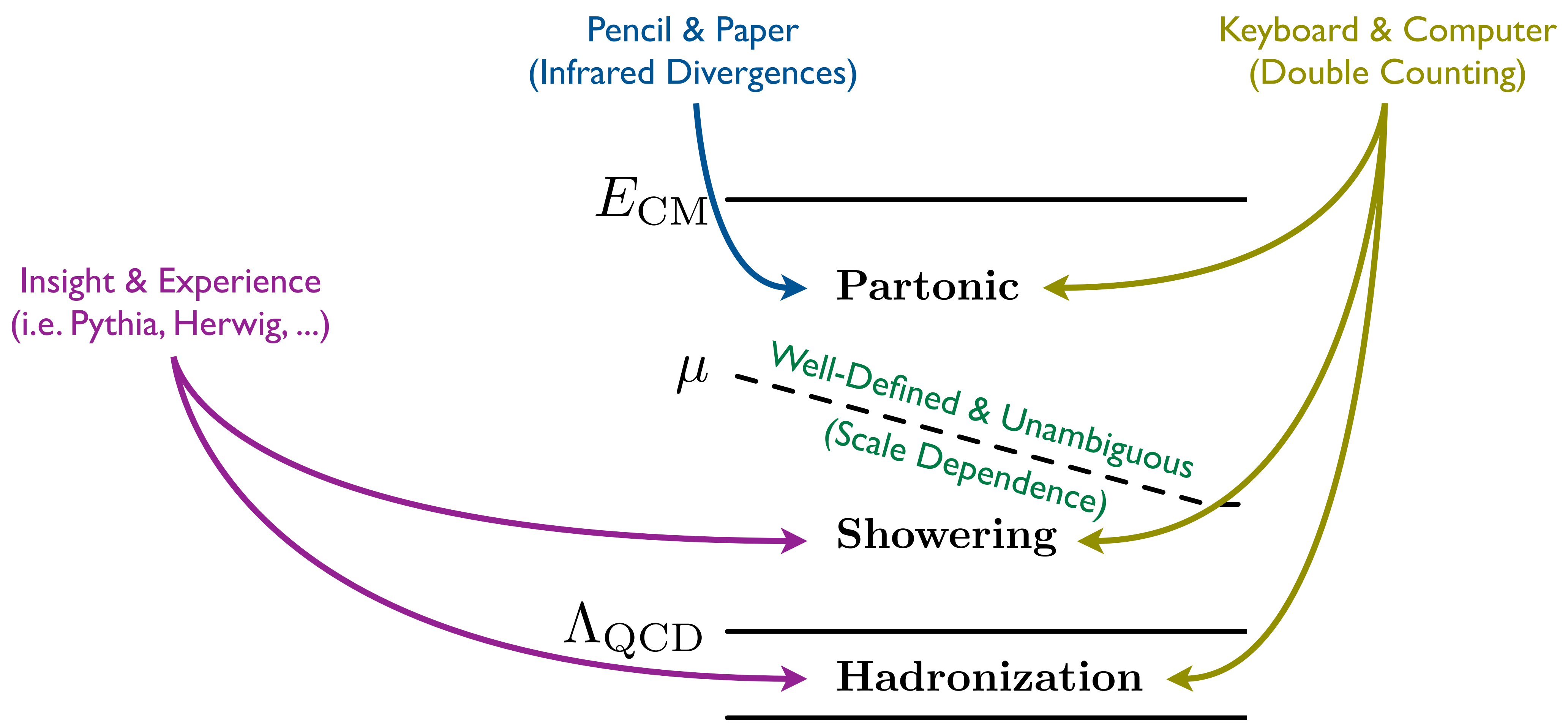
(Pythia, Herwig, ...)

(ALPGEN, MadEvent, ...)



GenEvA Framework

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



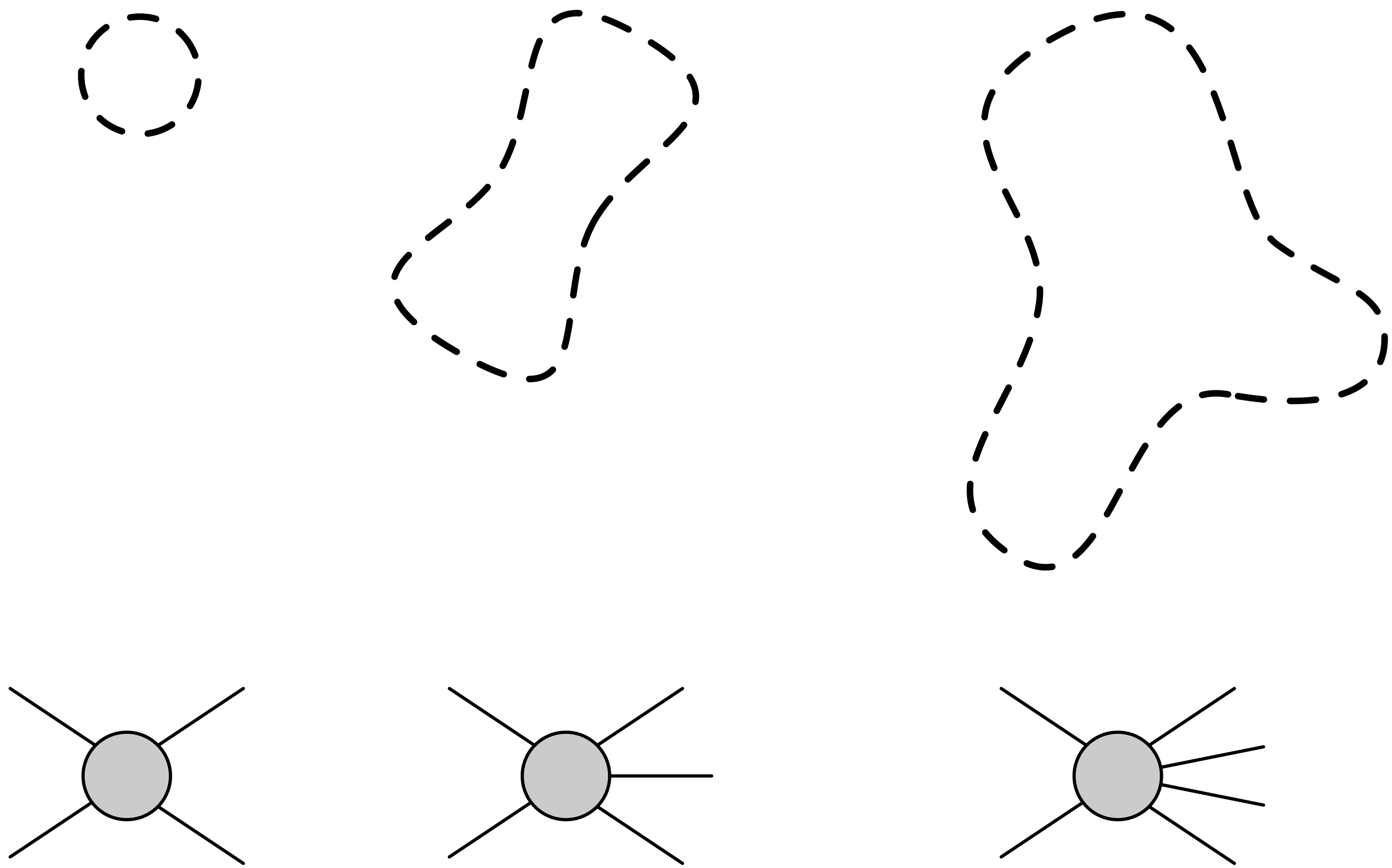
GenEvA Phase Space

Understanding the Effect of the Parton Shower

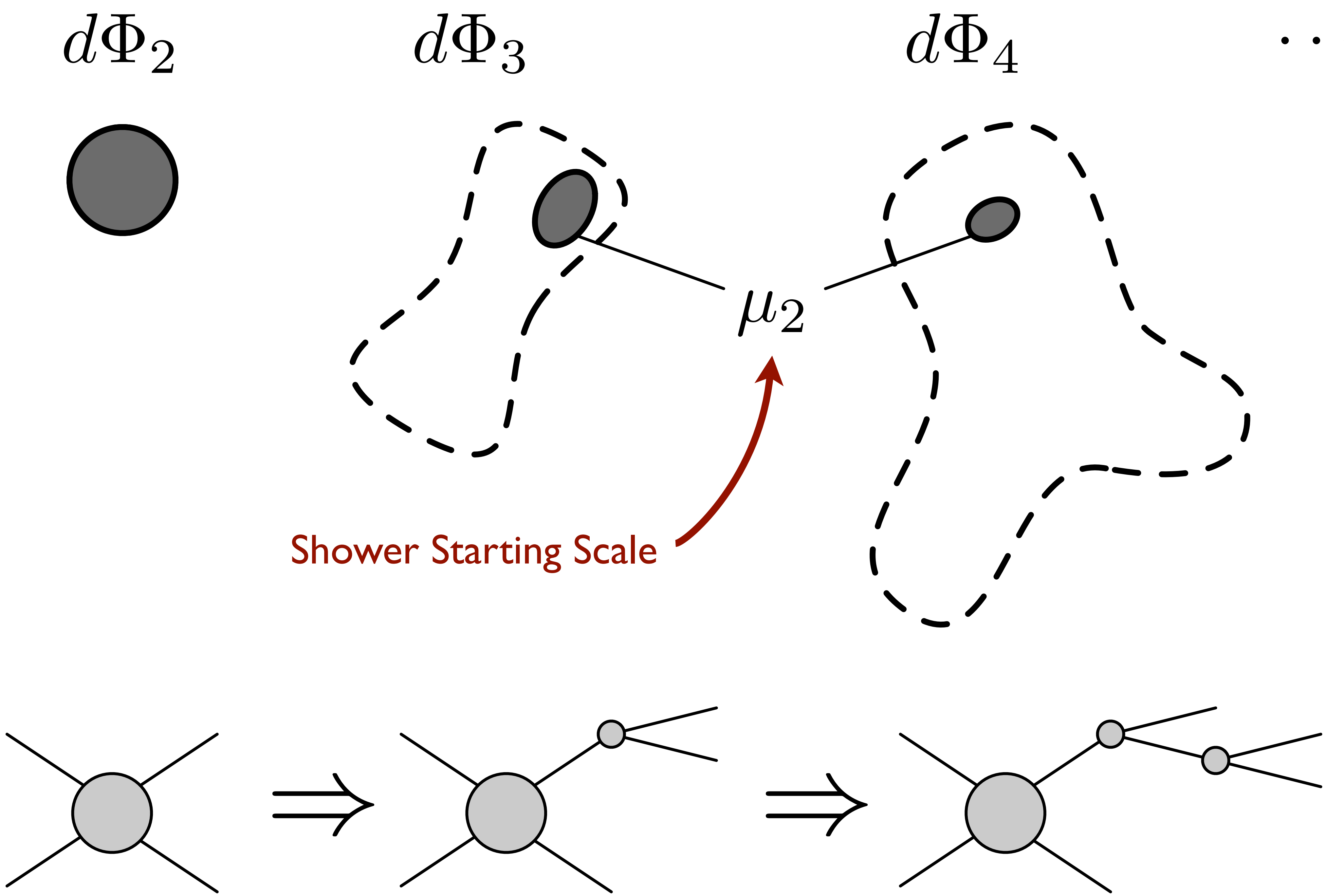
$$d\mathrm{MC}(\mu)$$

Partonic Phase Space

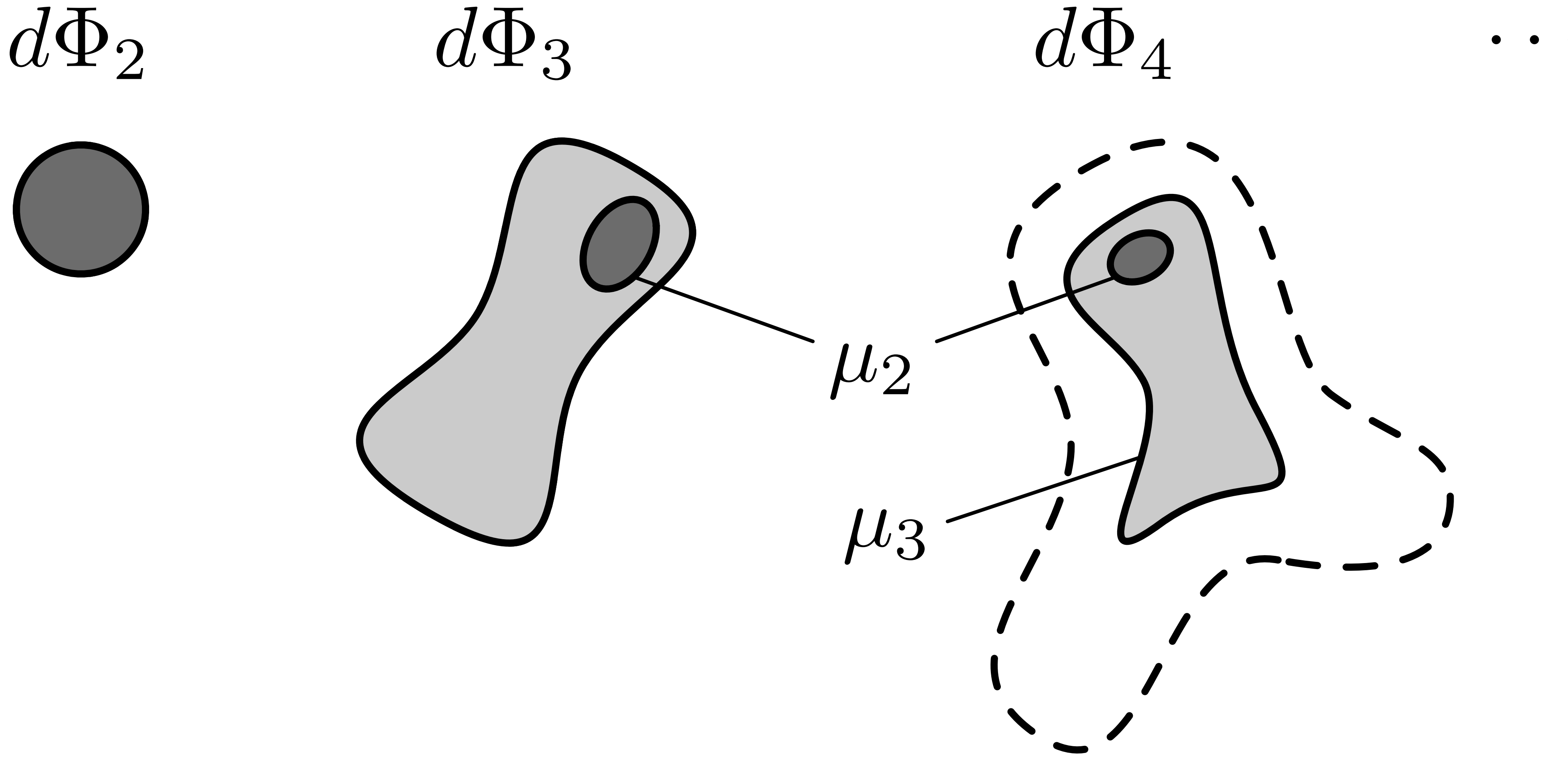
$d\Phi_2$ $\quad$ $d\Phi_3$ $\quad$ $d\Phi_4$ $\quad$ $\cdots$



The Parton Shower



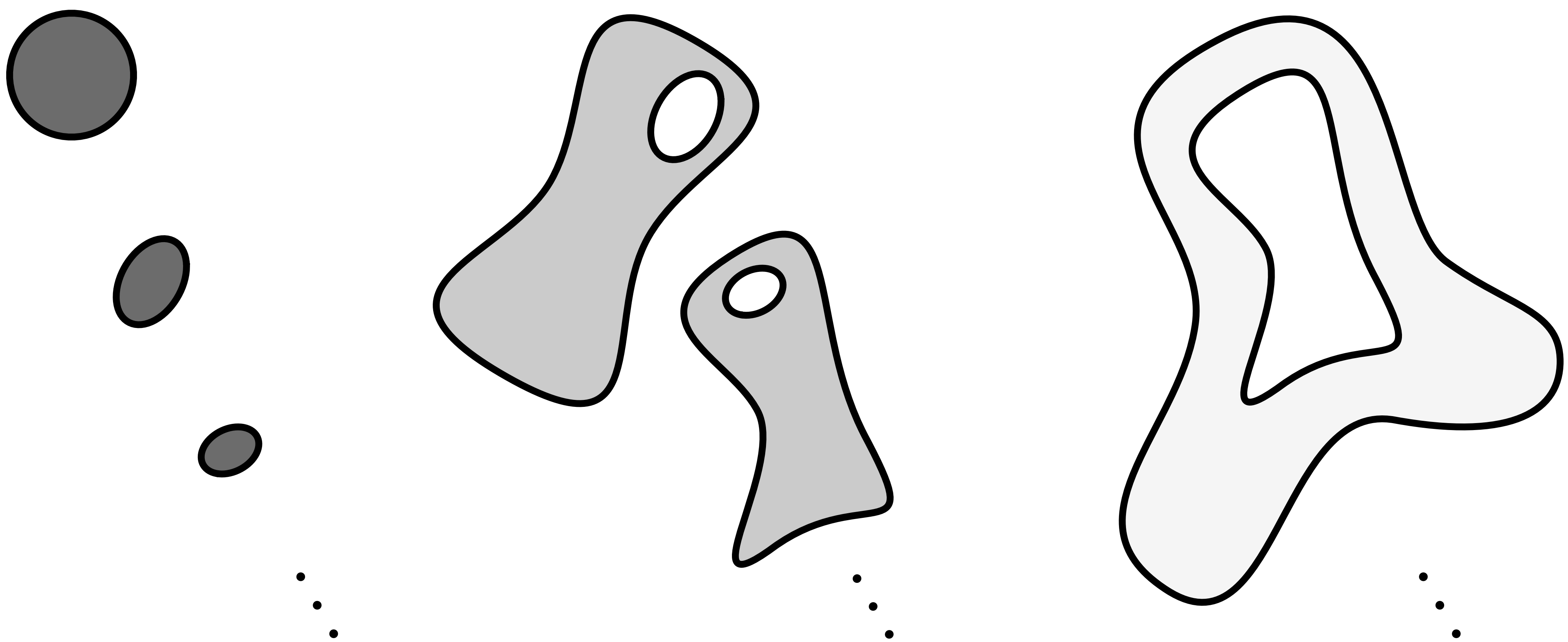
Additional Emissions



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.

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

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!

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

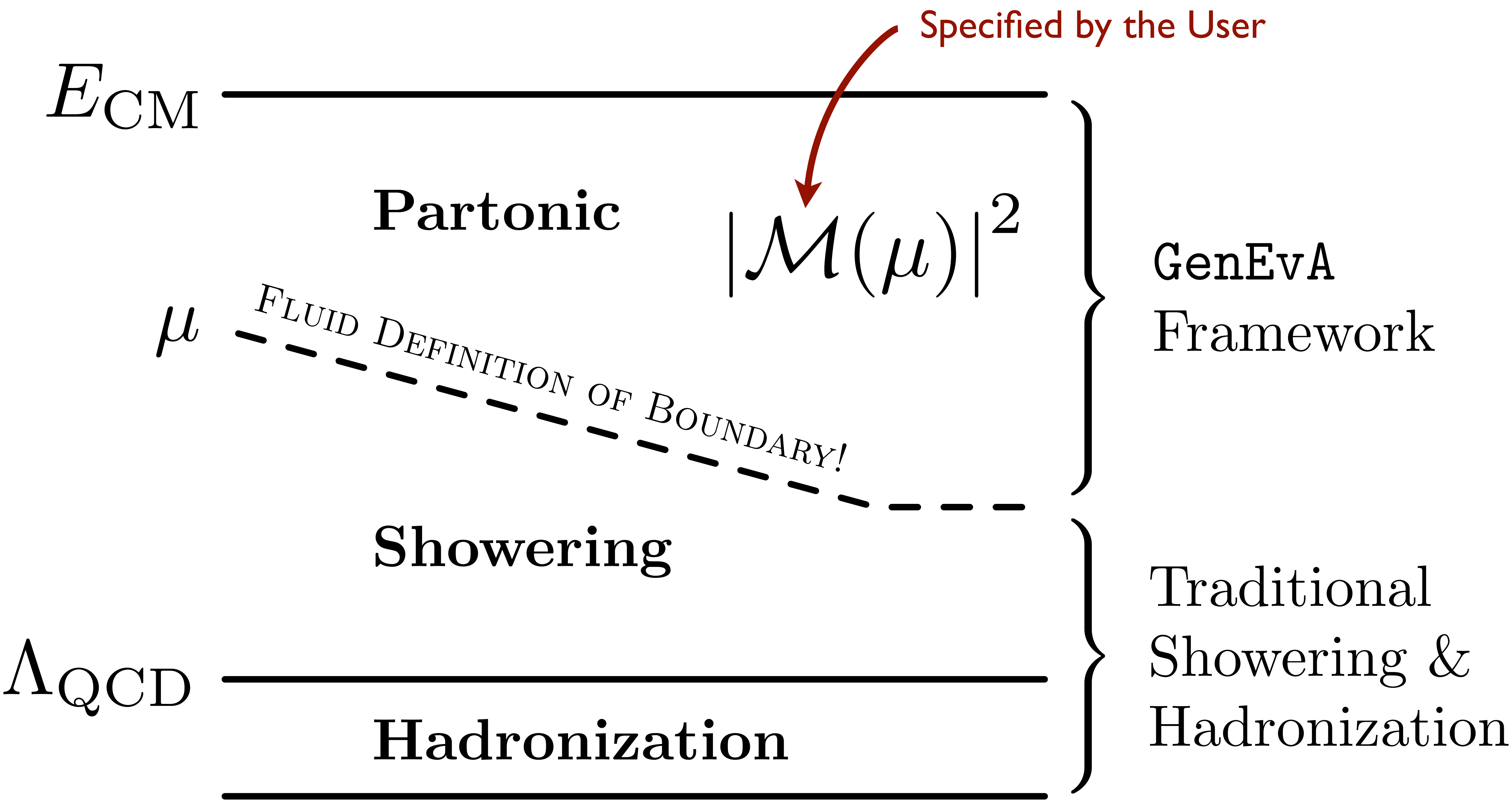
What is the Shower?

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

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

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

The GenEvA Approach



Improving Monte Carlo

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

Choose the best possible expression for

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

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

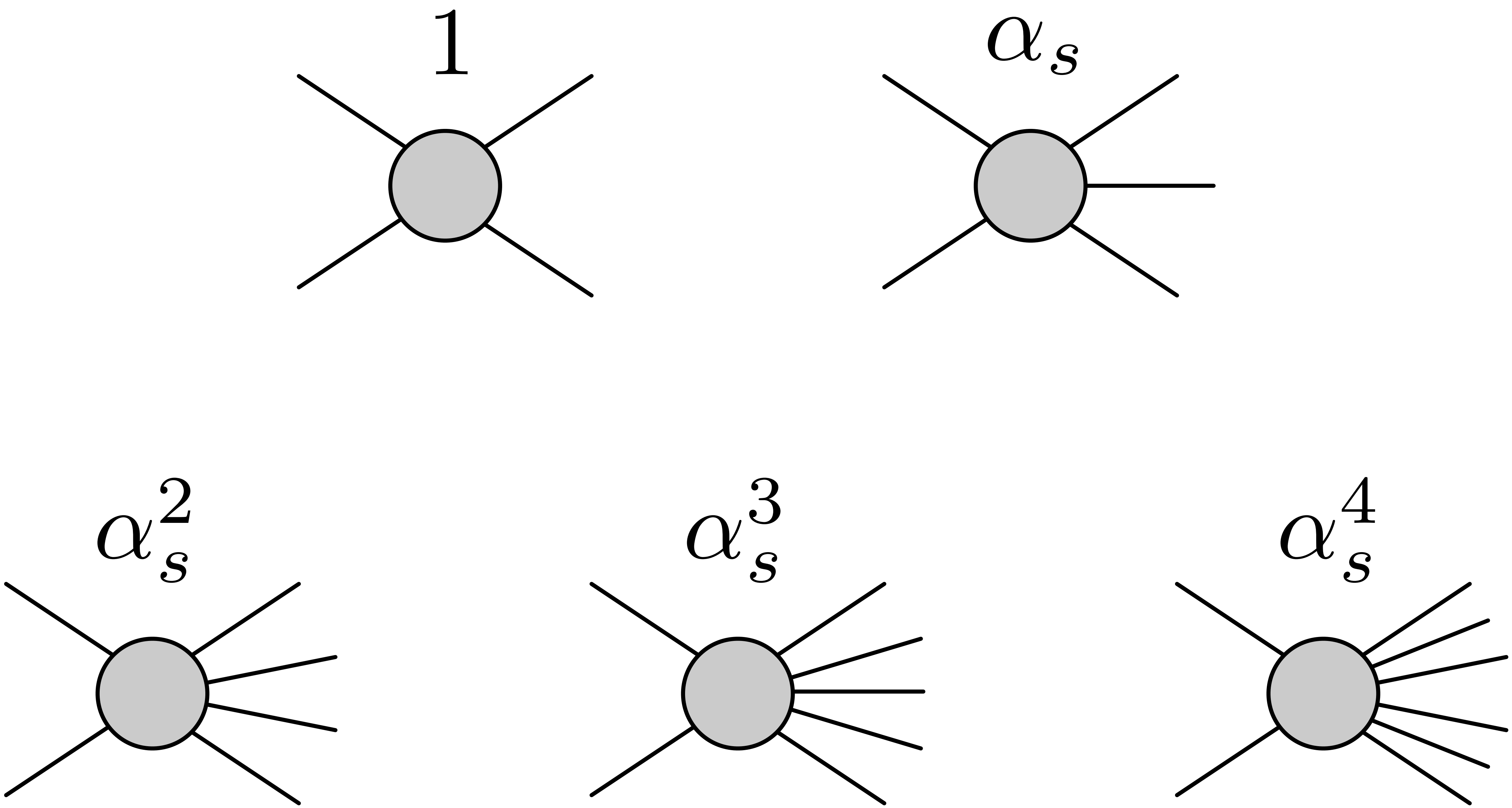
Correct Quantum Interference in Large Angle Limit

NLO: Next-to-Leading Order

Everything Correct to Order α_s

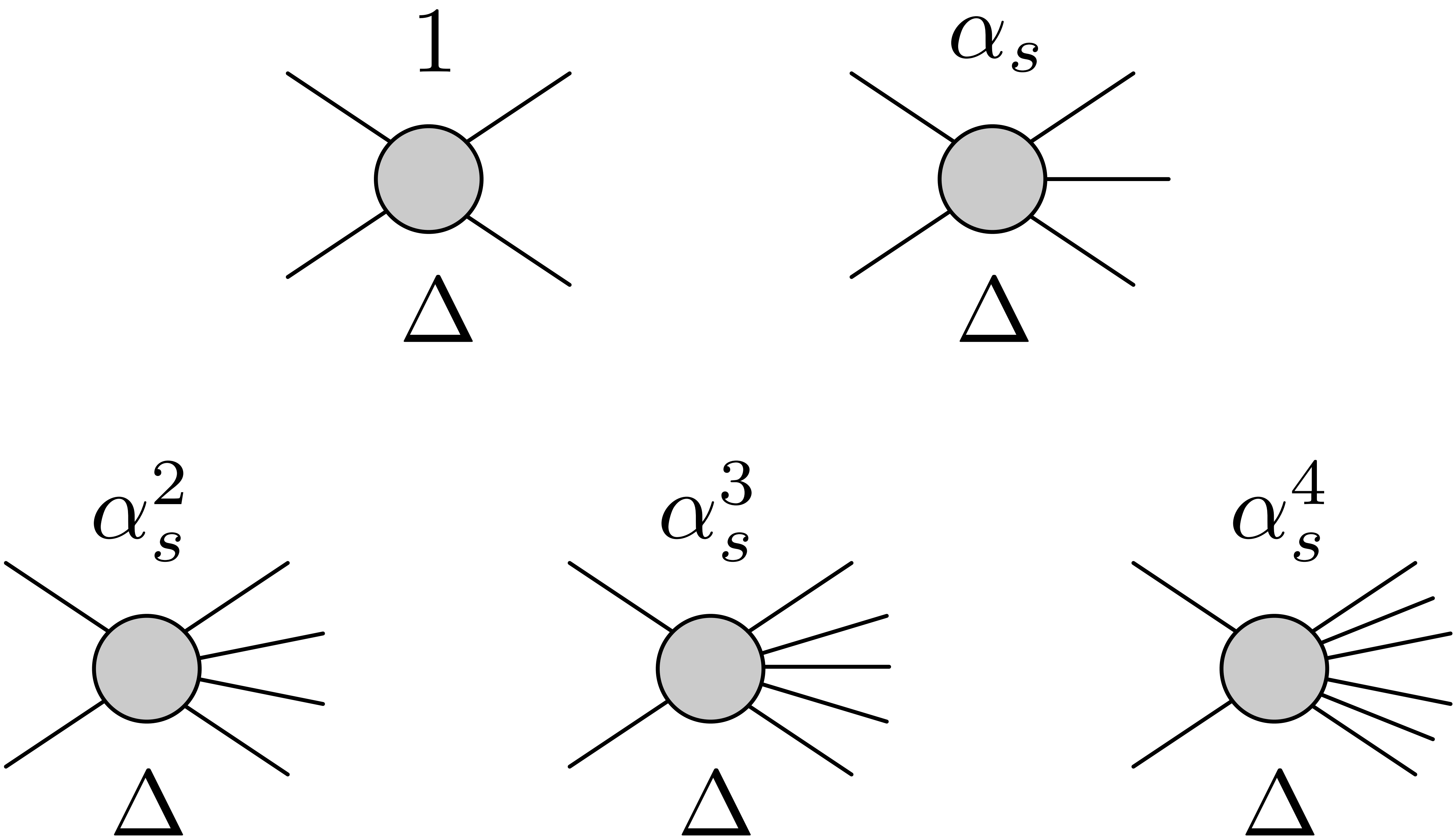
LO Tree-Level Generators

(ALPGEN, MadEvent, CompHep, Apacic, Whizard, Helac, ...)



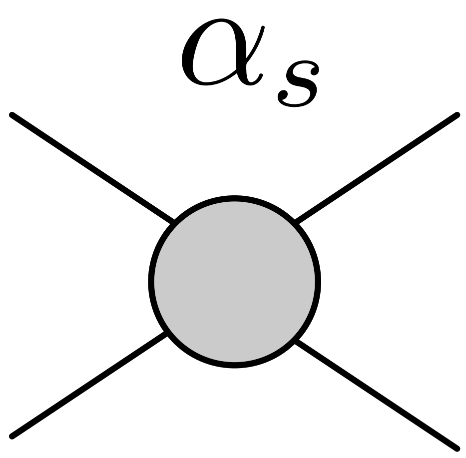
LO/LL Analog of PS/ME Merging

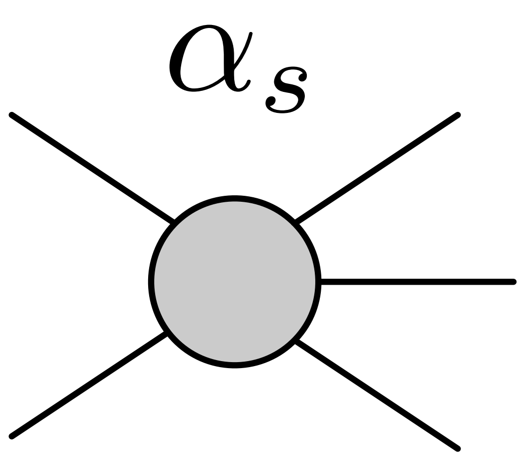
(CKKW, MLM, Lönnblad, ...)



NLO Loop-Level Generators

(MCFM, NLOJet, PHOX, ...)

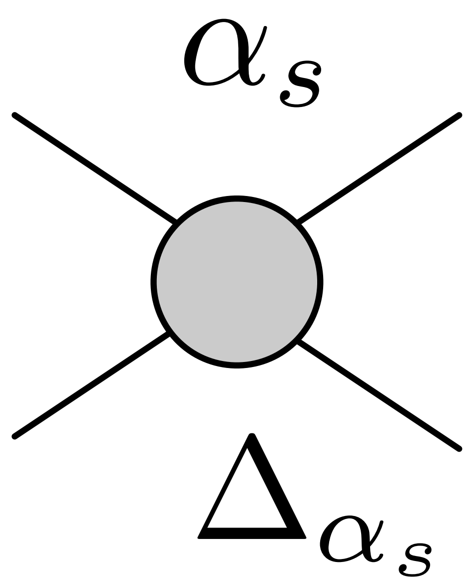


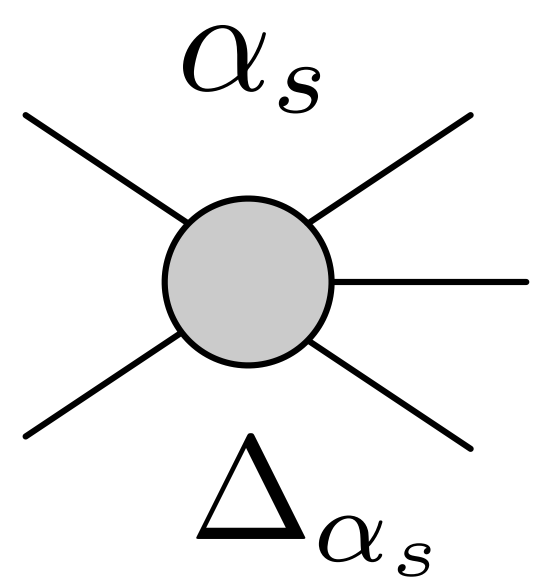


NLO/LL

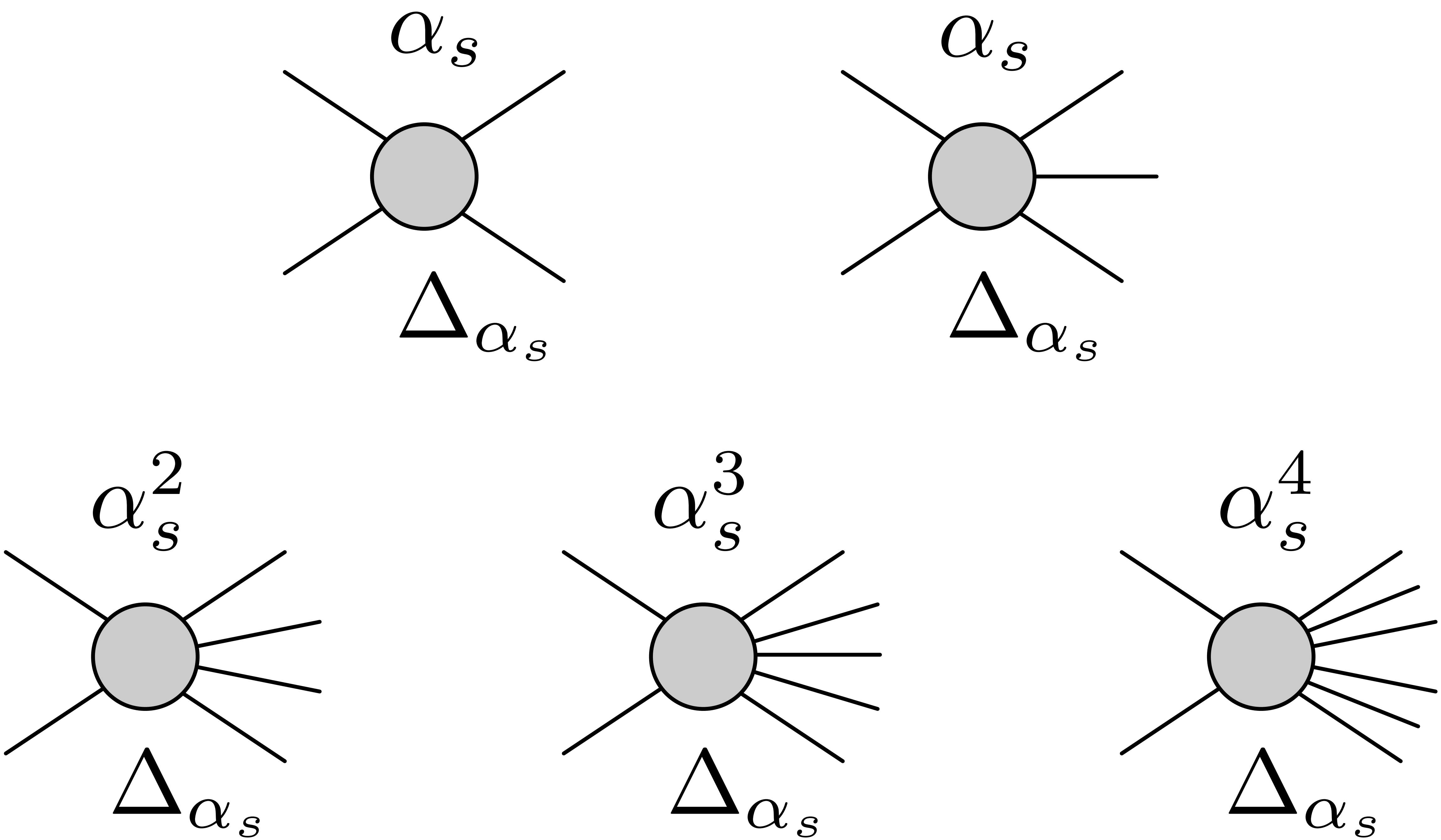
Analog of MC@NLO

(FW, POWHEG, ...)





NLO/LO/LL GenEvA Best
(New!)



NLO/LO/LL GenEvA Best
(New!)

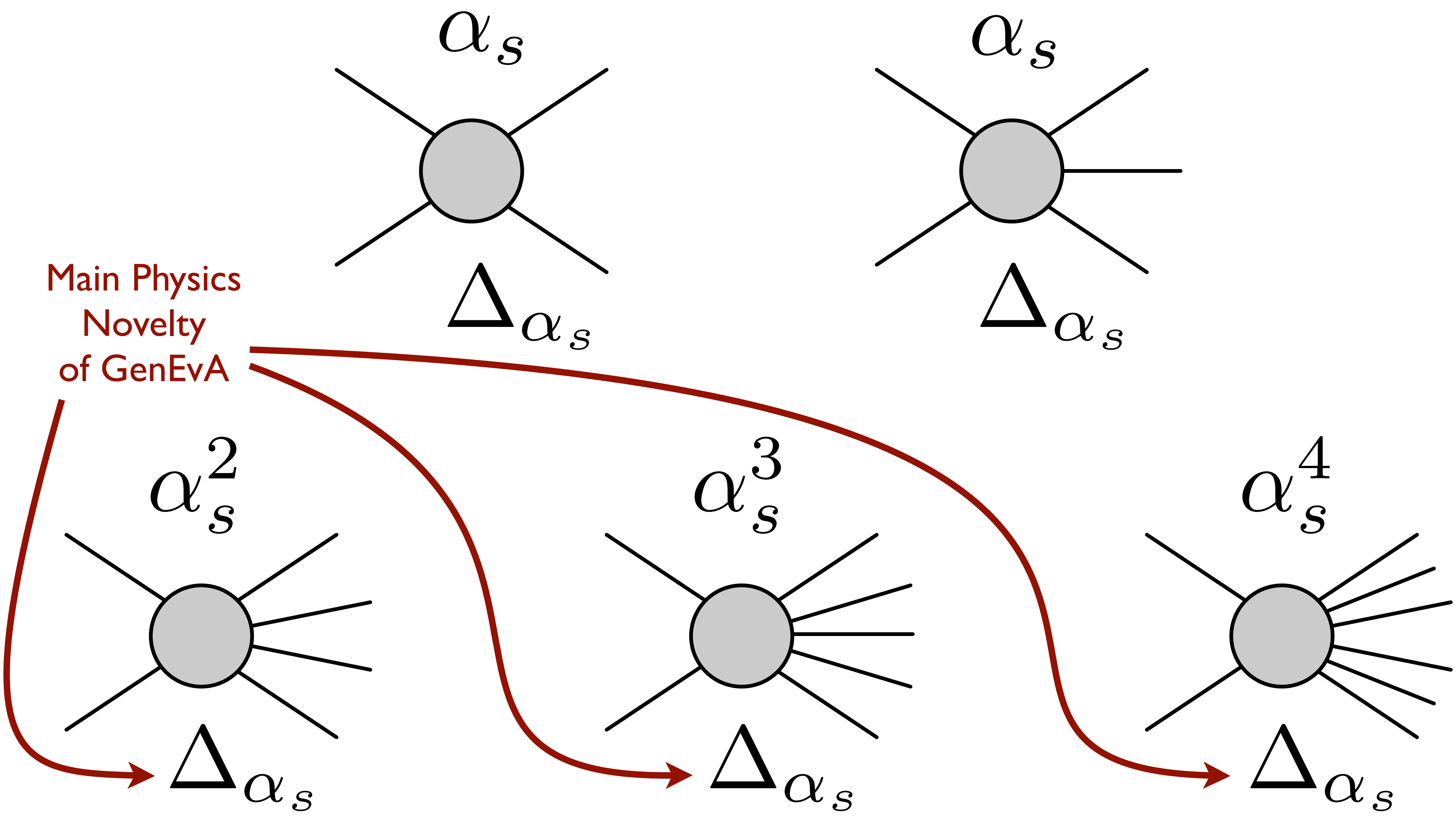


Figure of Merit?

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

Normalization

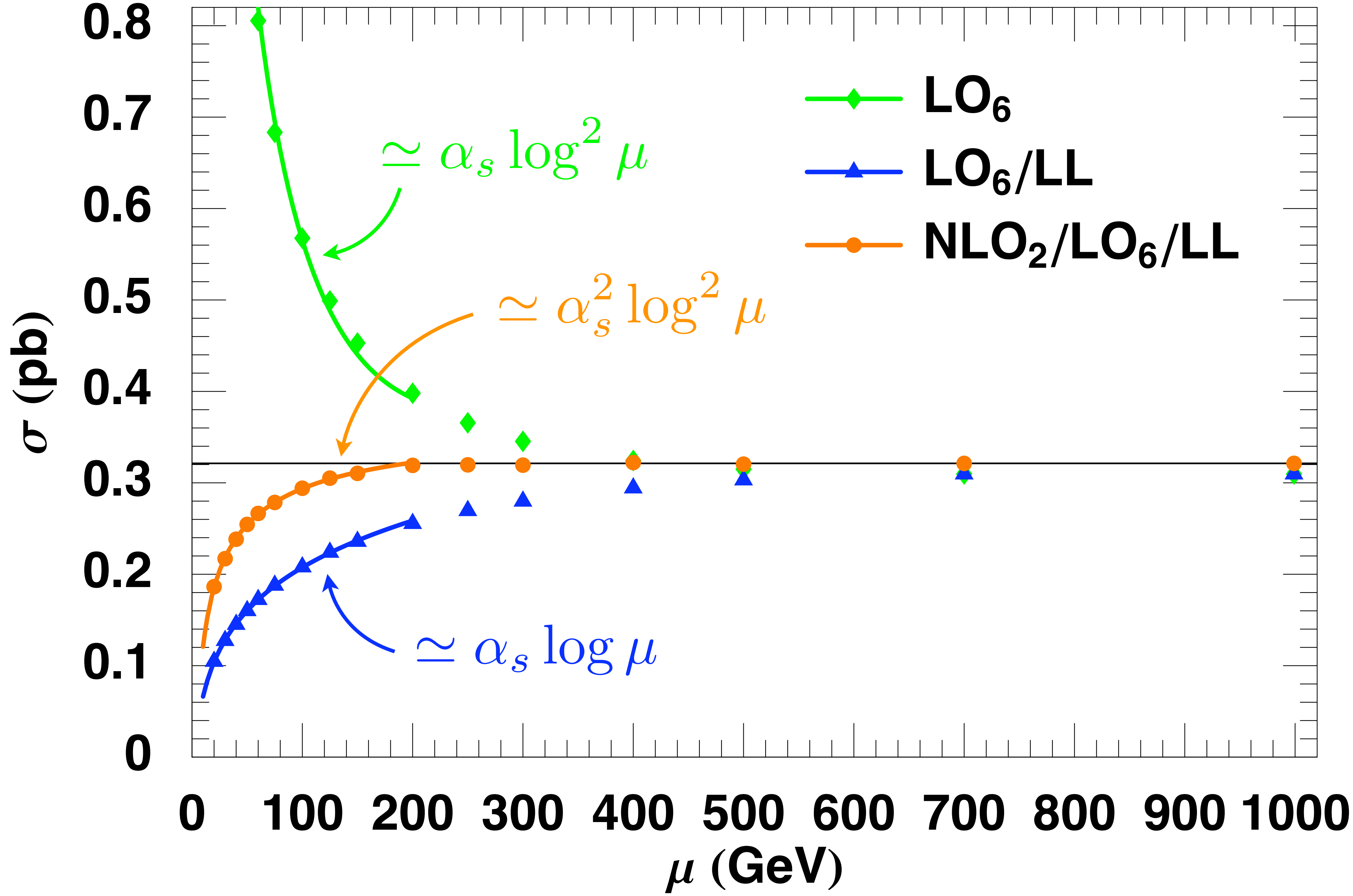
The μ-dependence should scale like

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

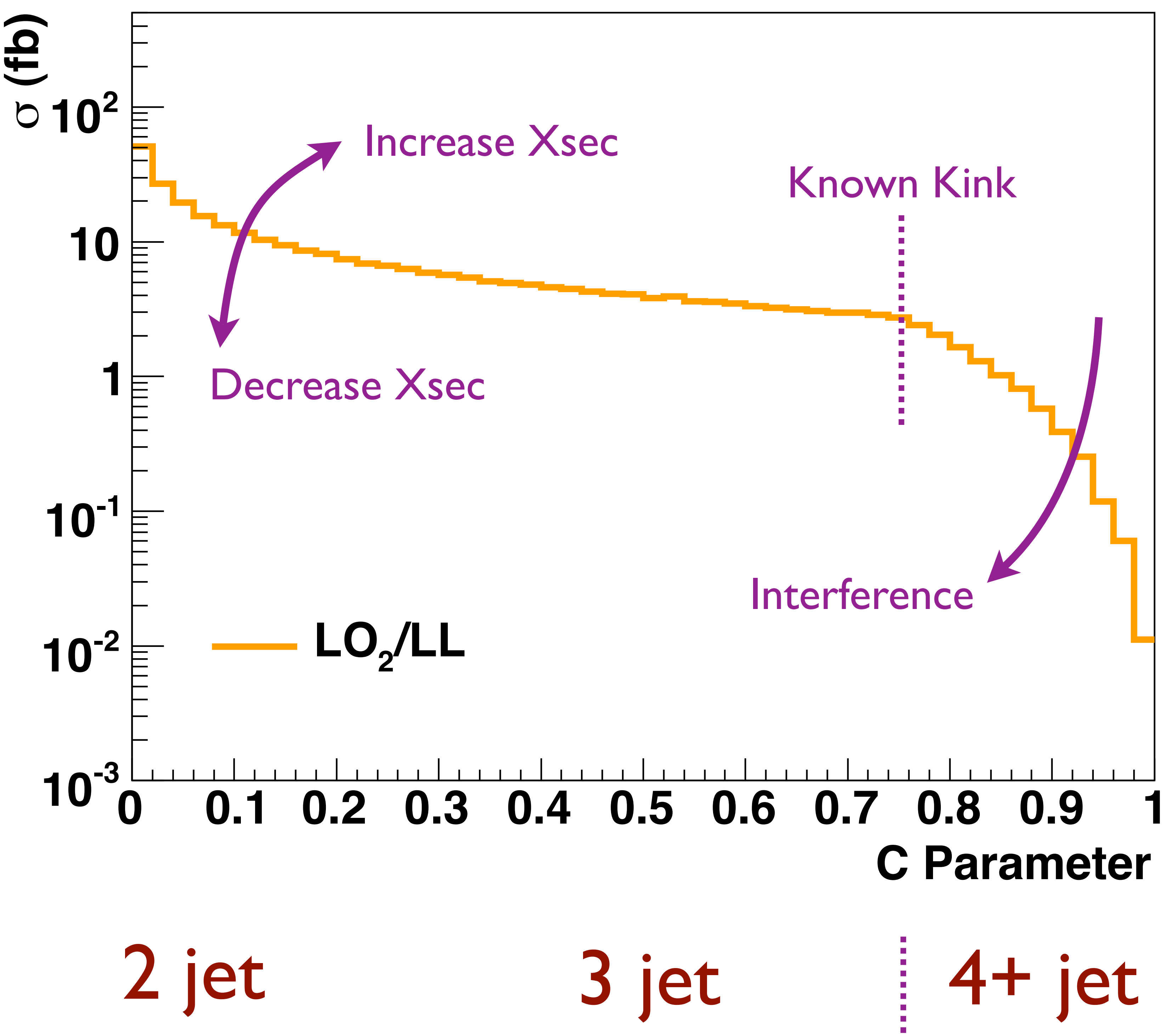
Shape

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

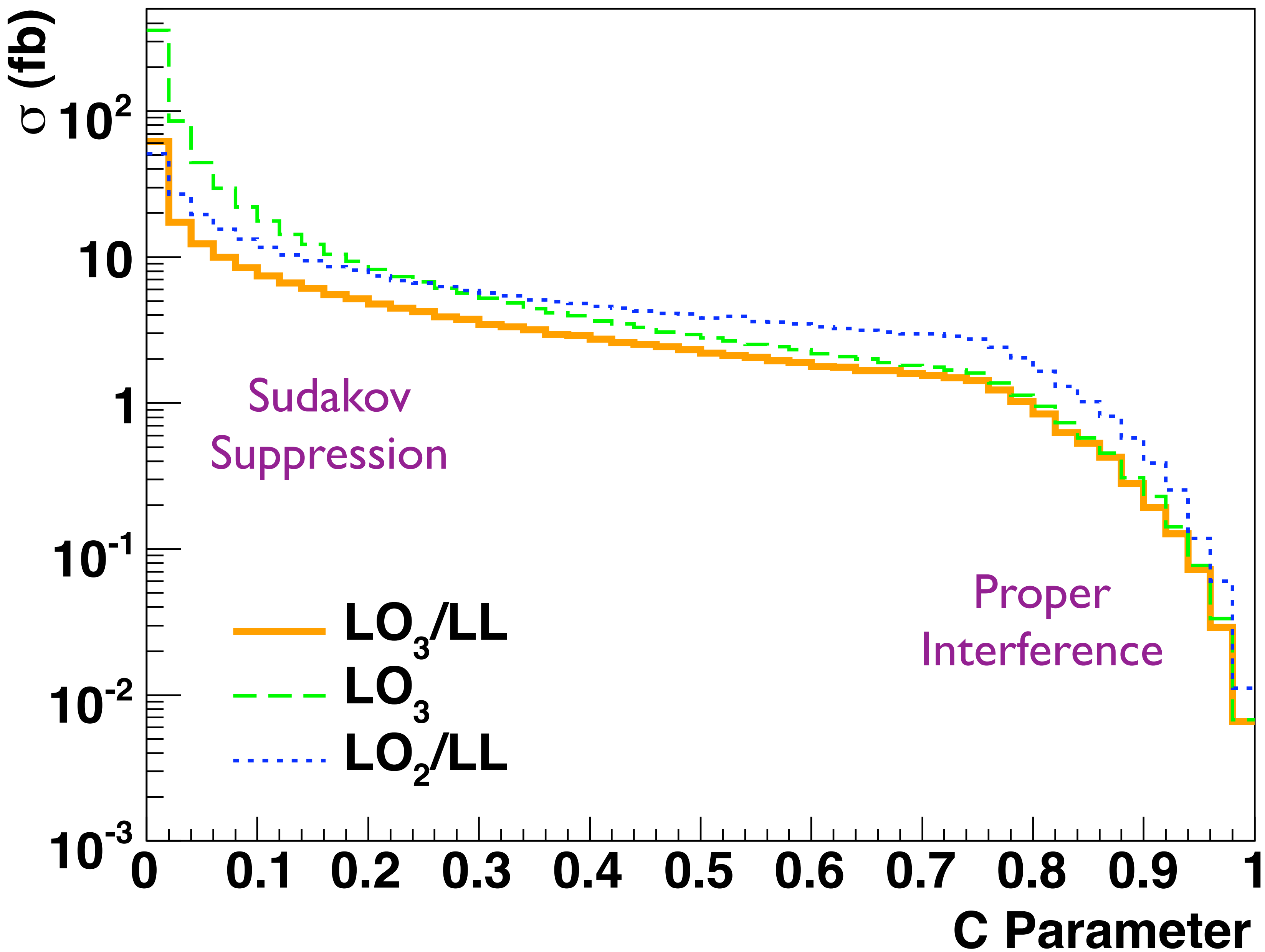
Cross Section Scaling



Baseline Shower

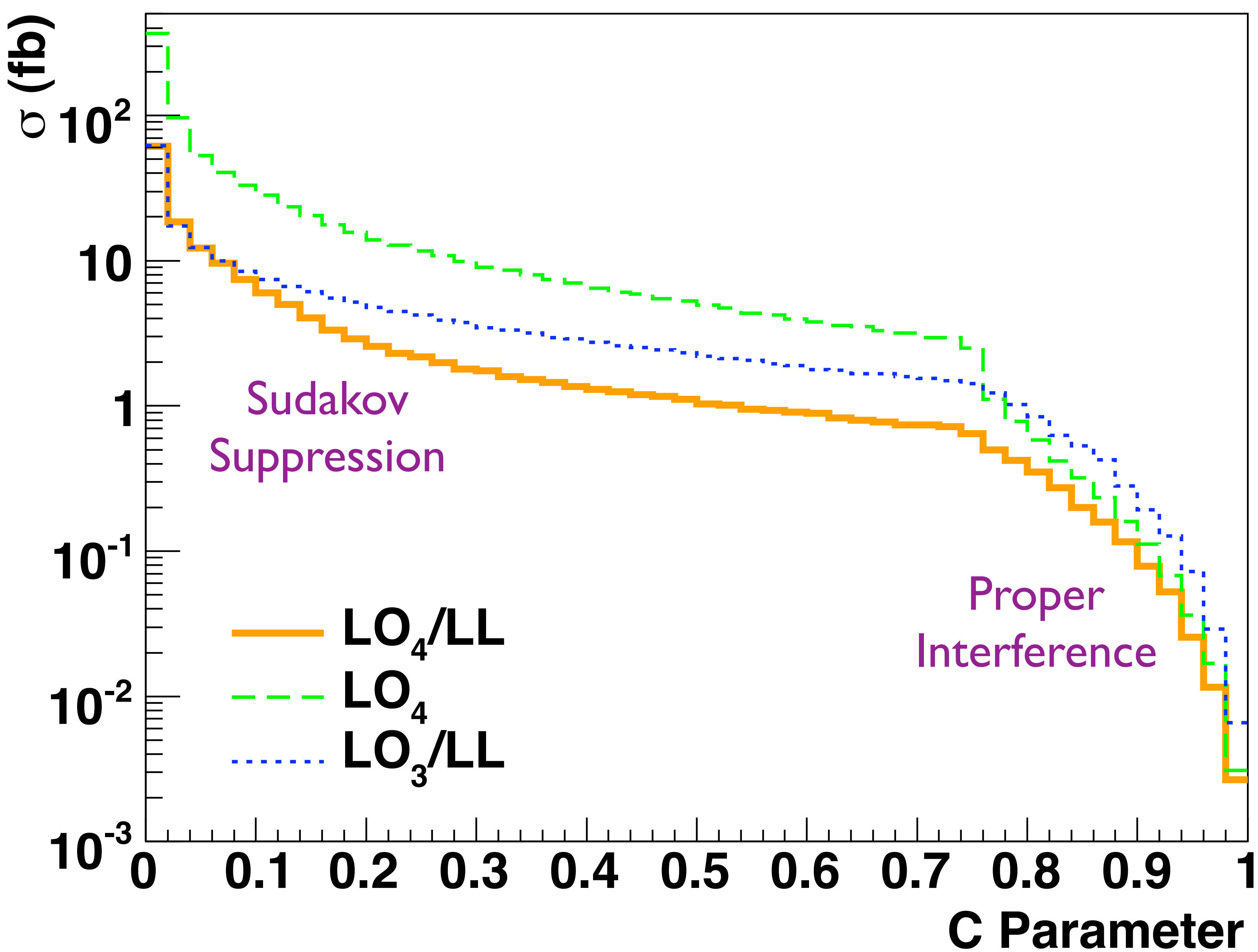


LO/LL Calculation



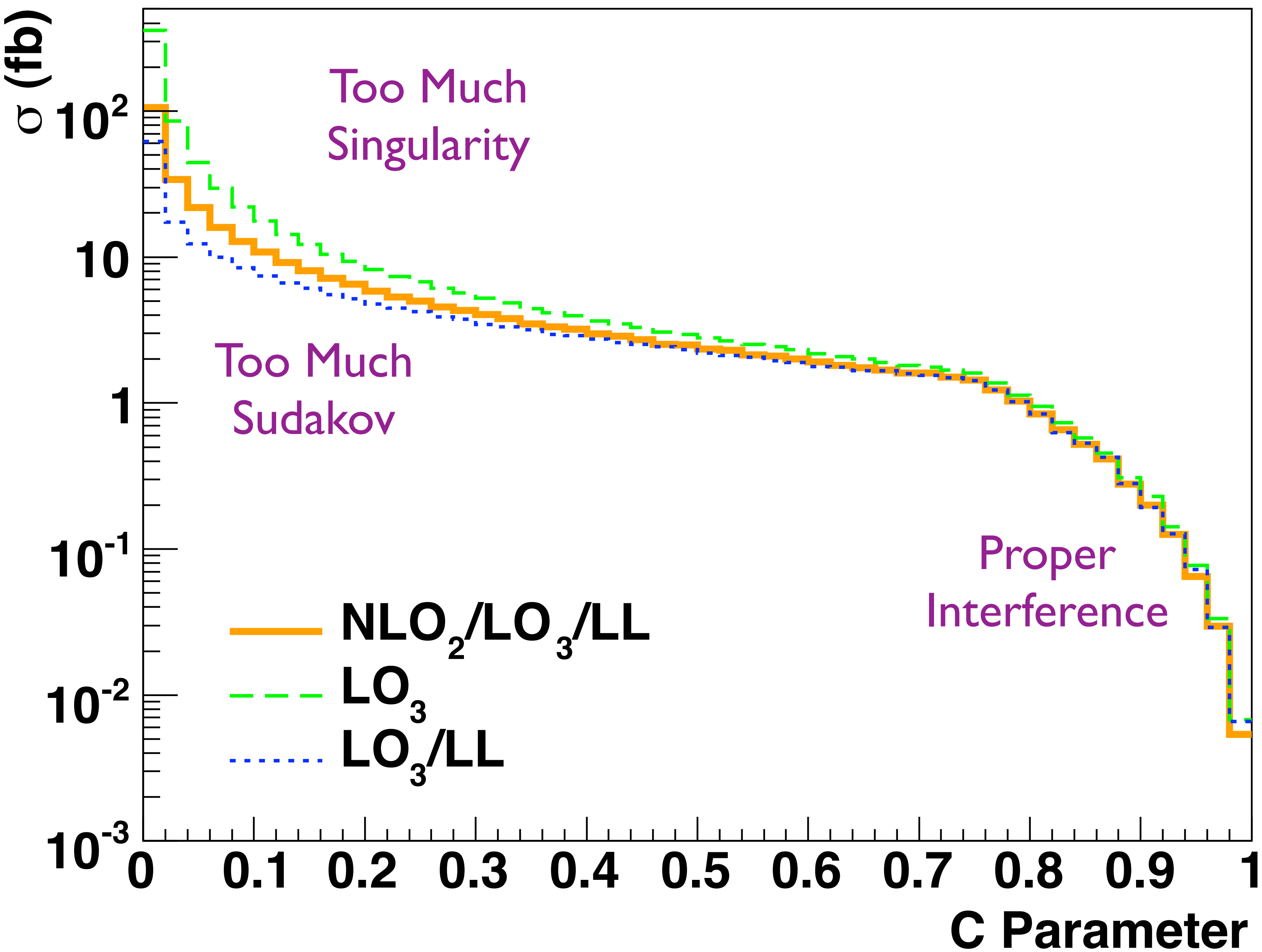
LO/LL answer is smaller than either approximation.

LO/LL Calculation



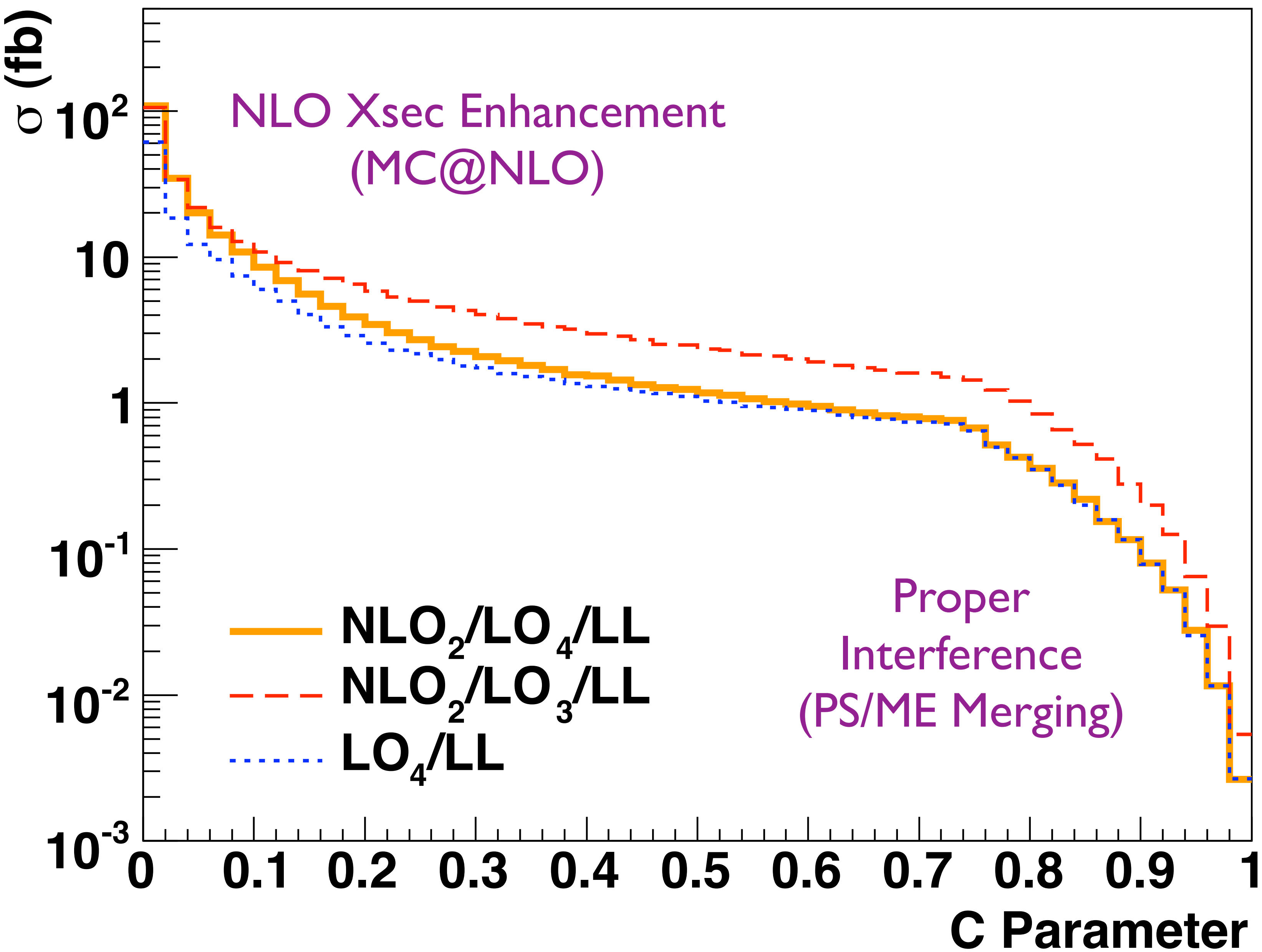
LO/LL answer is smaller than either approximation.

NLO/LL Calculation



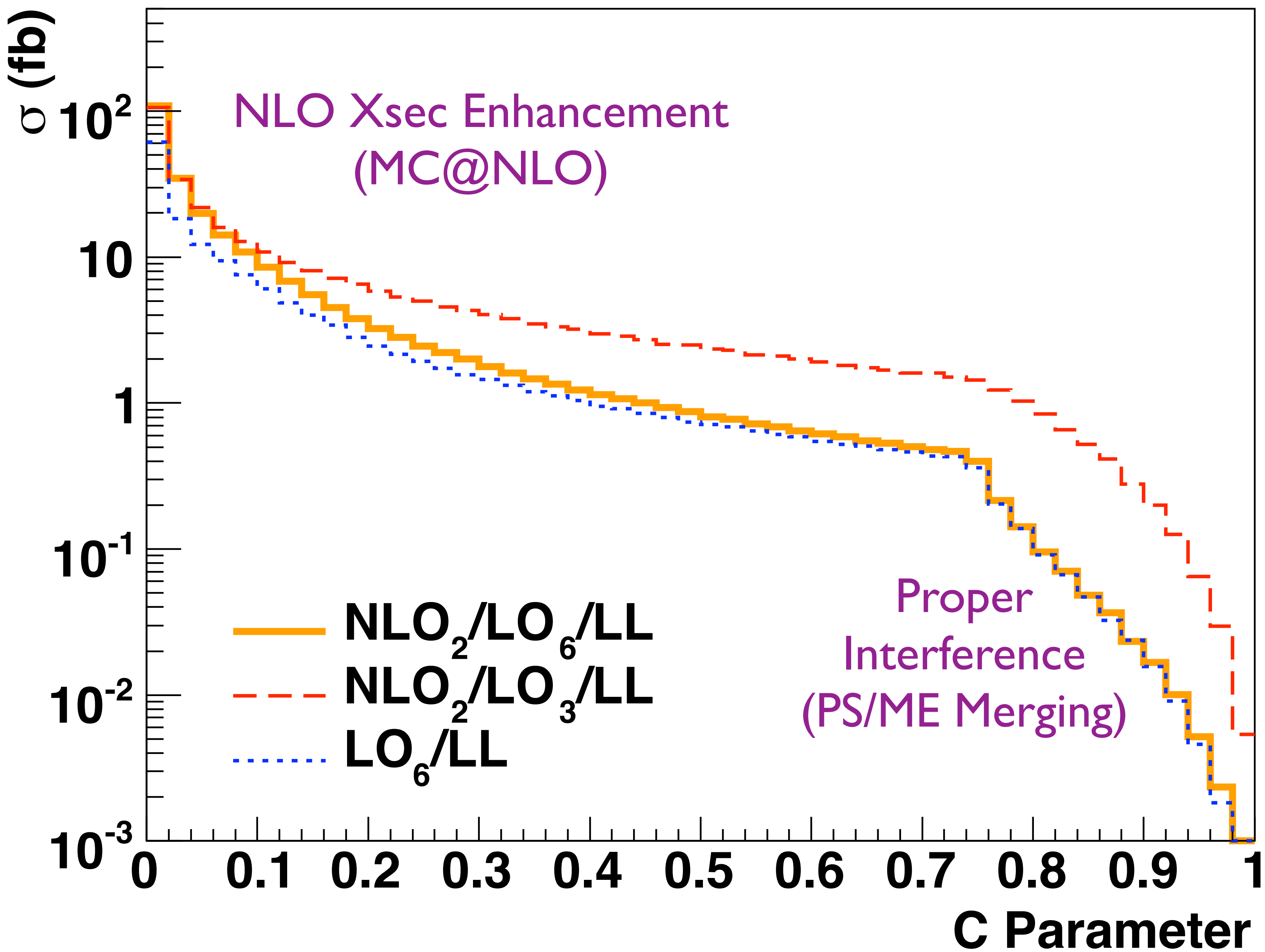
A "Goldilocks" Interpolation

NLO/LO/LL Calculation



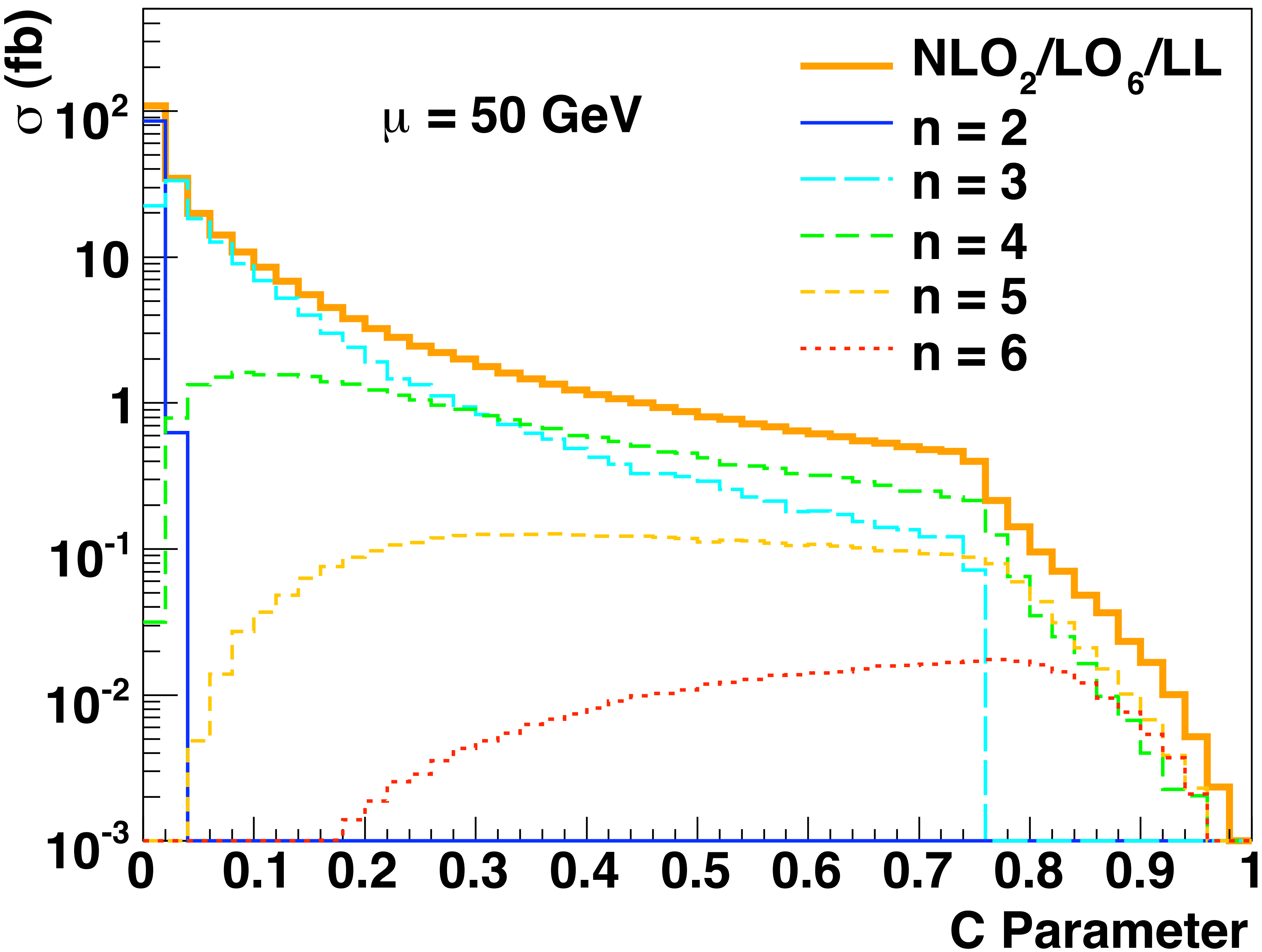
Interpolates between PS/ME Merging and MC@NLO!

NLO/LO/LL Calculation



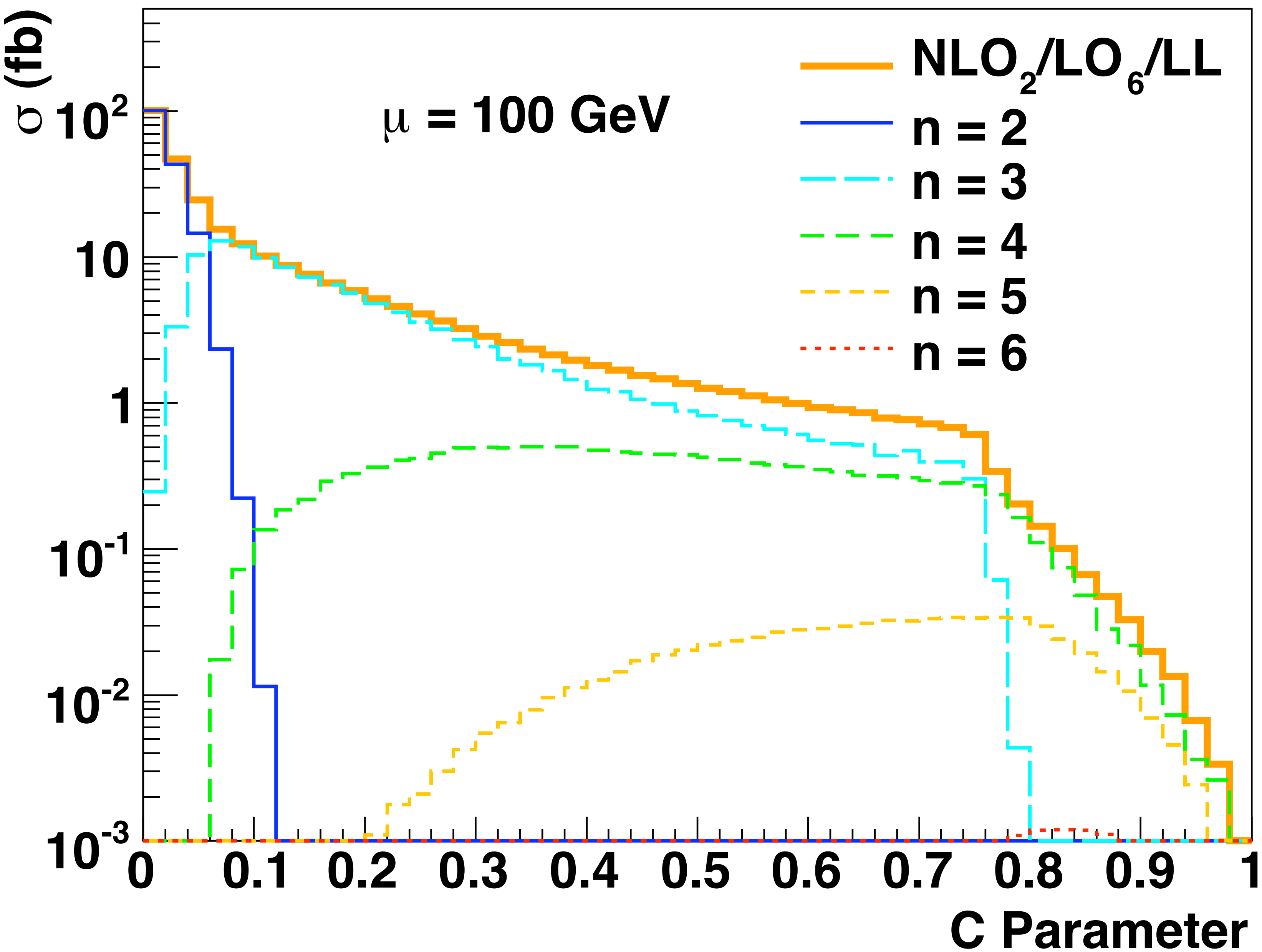
Interpolates between PS/ME Merging and MC@NLO!

Isolated Components



Non-trivial combination of five different samples.

Isolated Components



Only single-logarithmic change in total distribution.

“Data” Comparison

GenEvA Should Not Reproduce Small Angle Tune (Showering Regime)

GenEvA Should Reproduce Large Angle Tune (Partonic Regime)

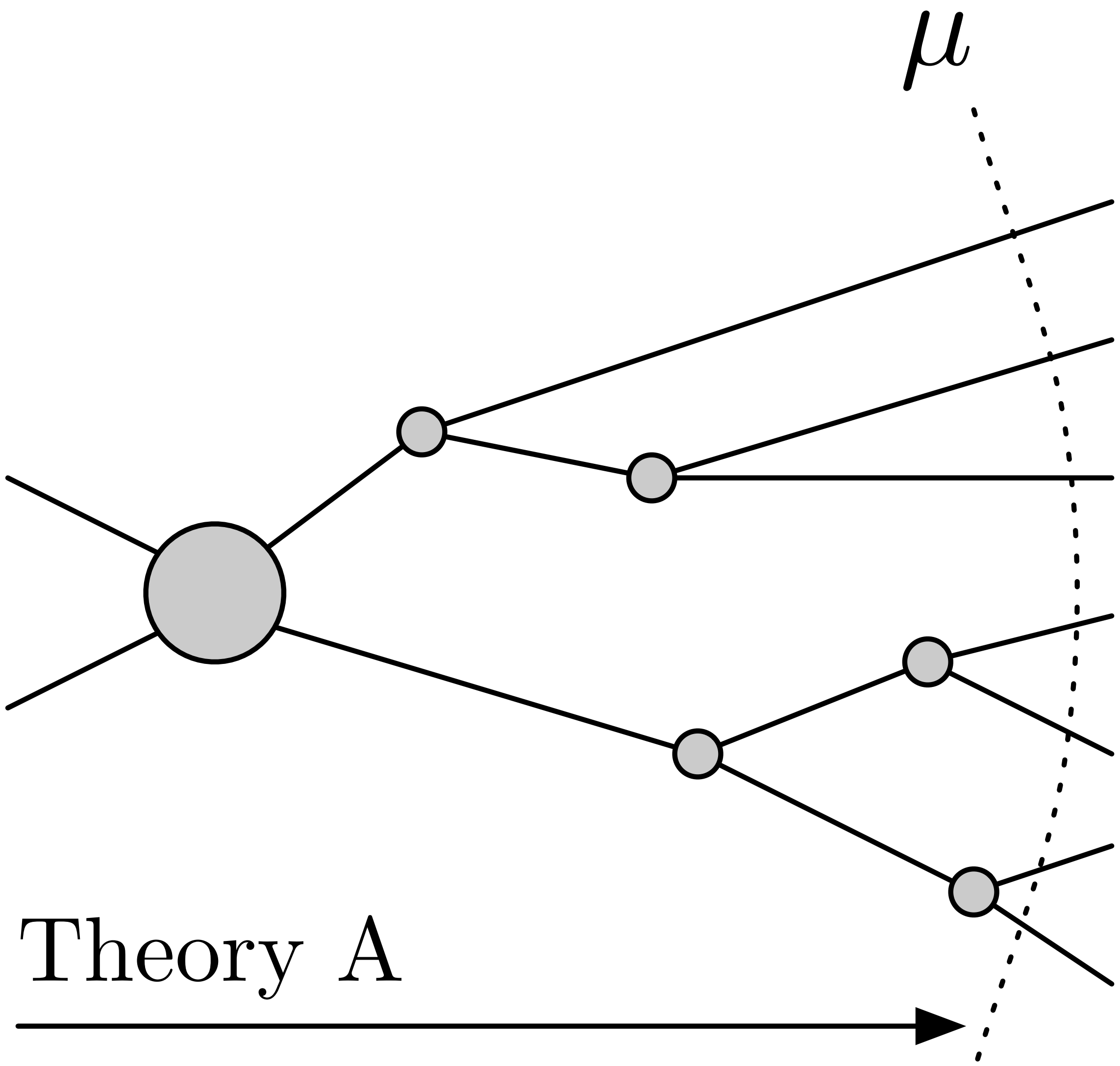
PRELIMINARY

GenEvA Details

Strategy to Merge Different Approximation Schemes

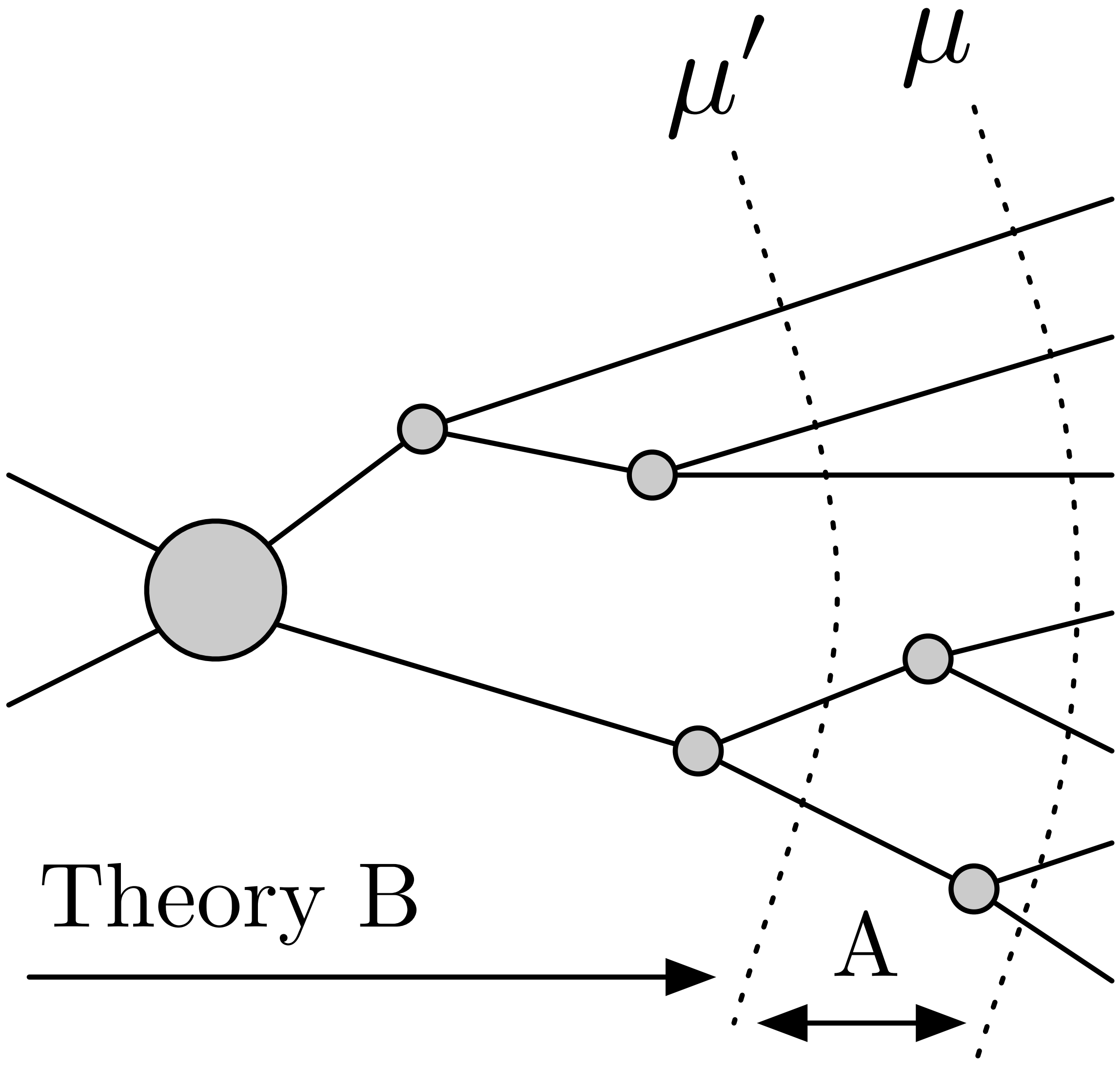
$$\left|\mathcal{M}^{\mathrm{A}}(\mu)\right|^2 \ \text{vs.}\ \left|\mathcal{M}^{\mathrm{B}}(\mu)\right|^2$$

Nested Mergings



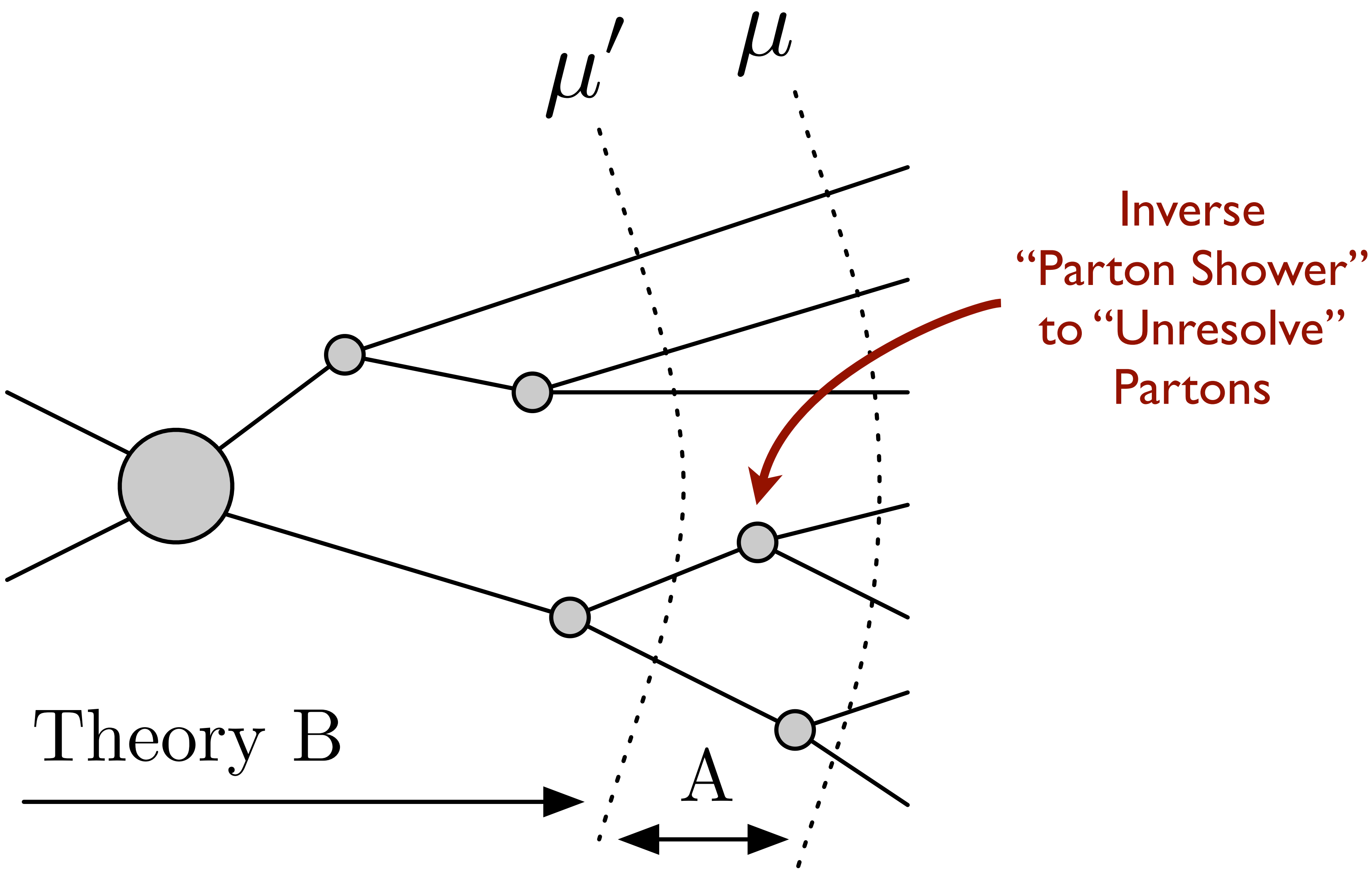
$$\left|\mathcal{M}^{\text{Best}}(\mu)\right|^2 = \left|\mathcal{M}^{\text{A}}(\mu)\right|^2$$

Nested Mergings



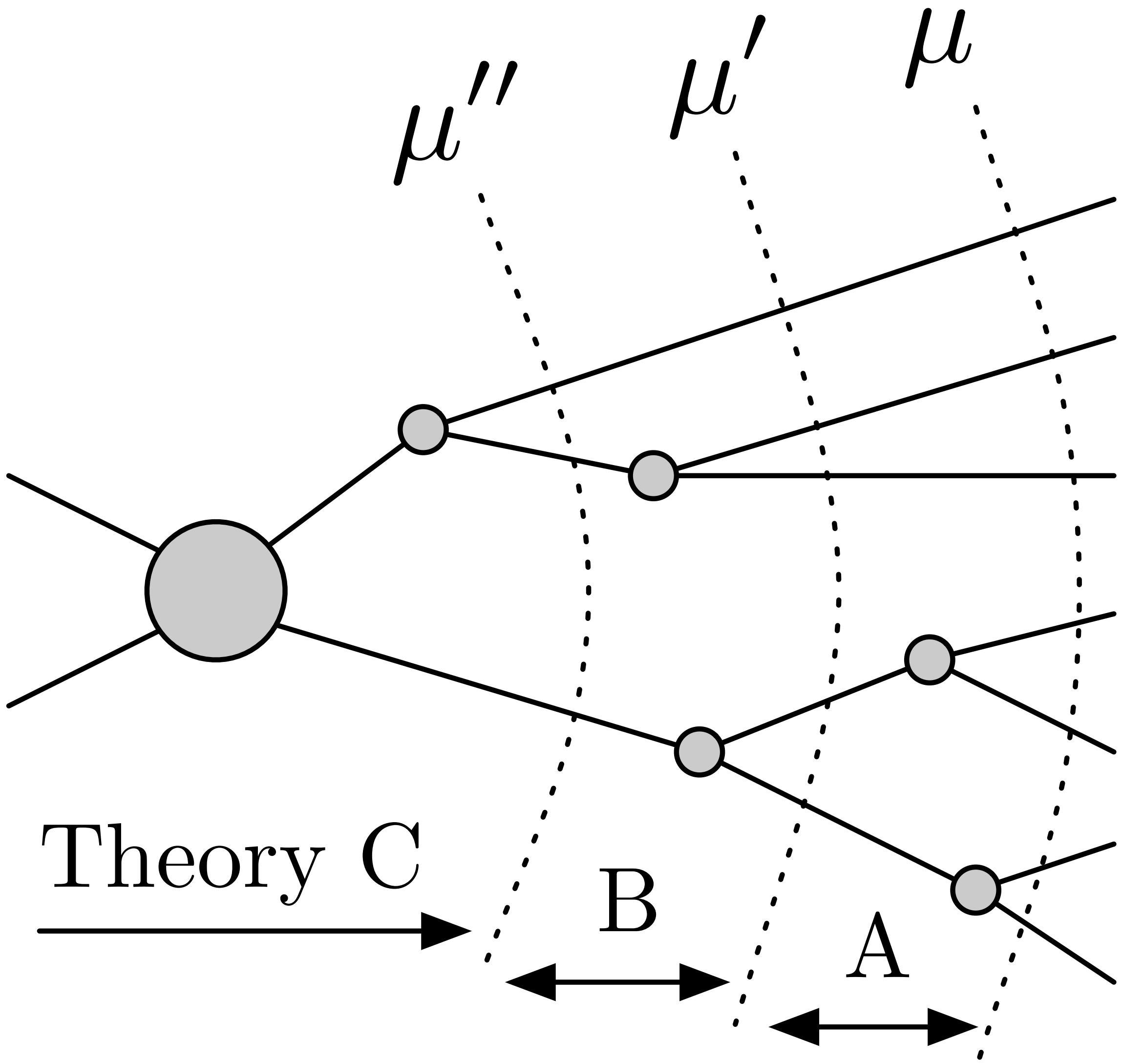
$$\left|\mathcal{M}^{\mathrm{Best}}(\mu)\right|^2 = \left|\mathcal{M}^{\mathrm{A}}(\mu)\right|^2 \times \frac{\left|\mathcal{M}^{\mathrm{B}}(\mu')\right|^2}{\left|\mathcal{M}^{\mathrm{A}}(\mu')\right|^2}$$

Nested Mergings



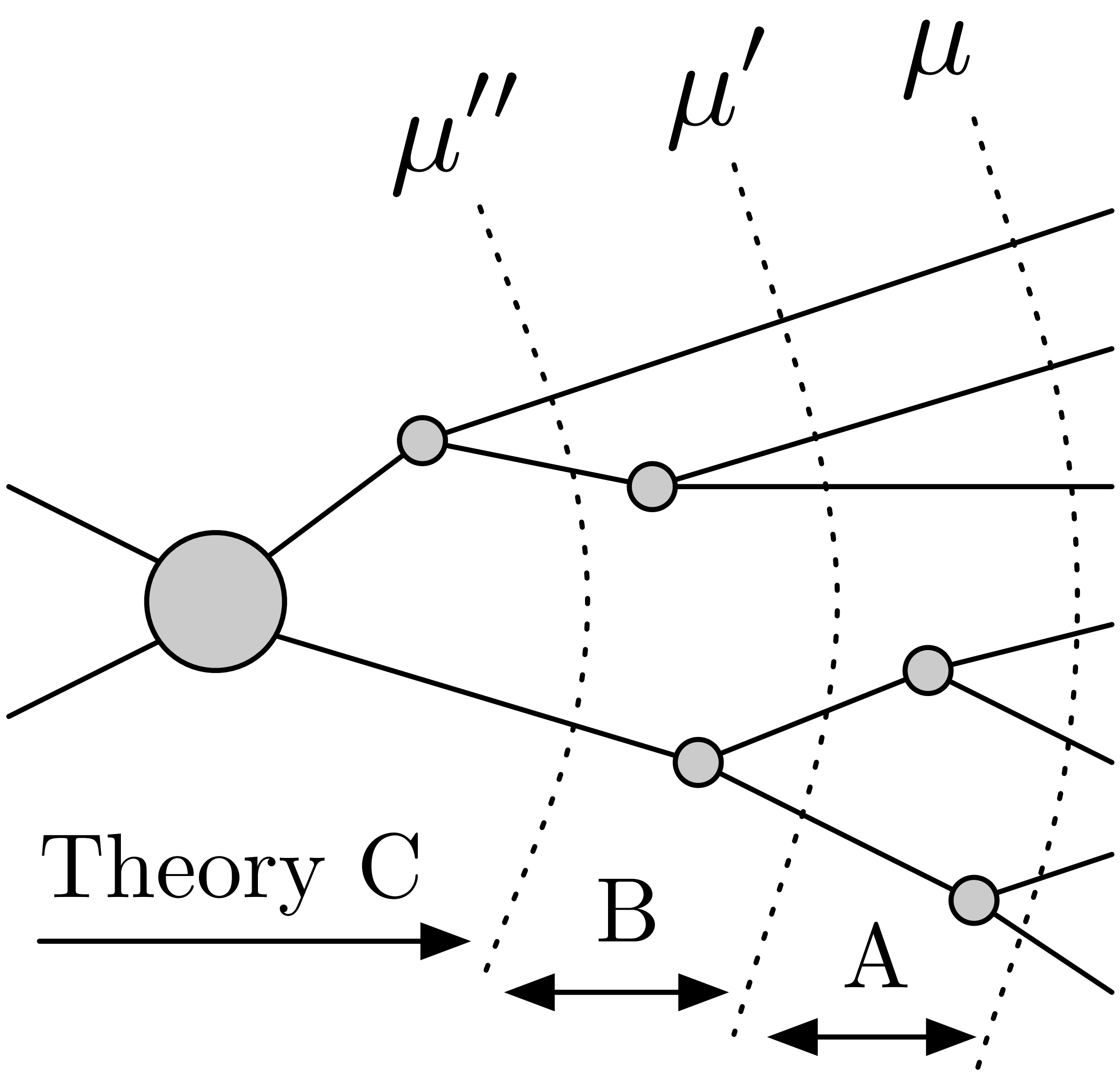
$$\left|\mathcal{M}^{\mathrm{Best}}(\mu)\right|^2 = \left|\mathcal{M}^{\mathrm{A}}(\mu)\right|^2 \times \frac{\left|\mathcal{M}^{\mathrm{B}}(\mu')\right|^2}{\left|\mathcal{M}^{\mathrm{A}}(\mu')\right|^2}$$

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



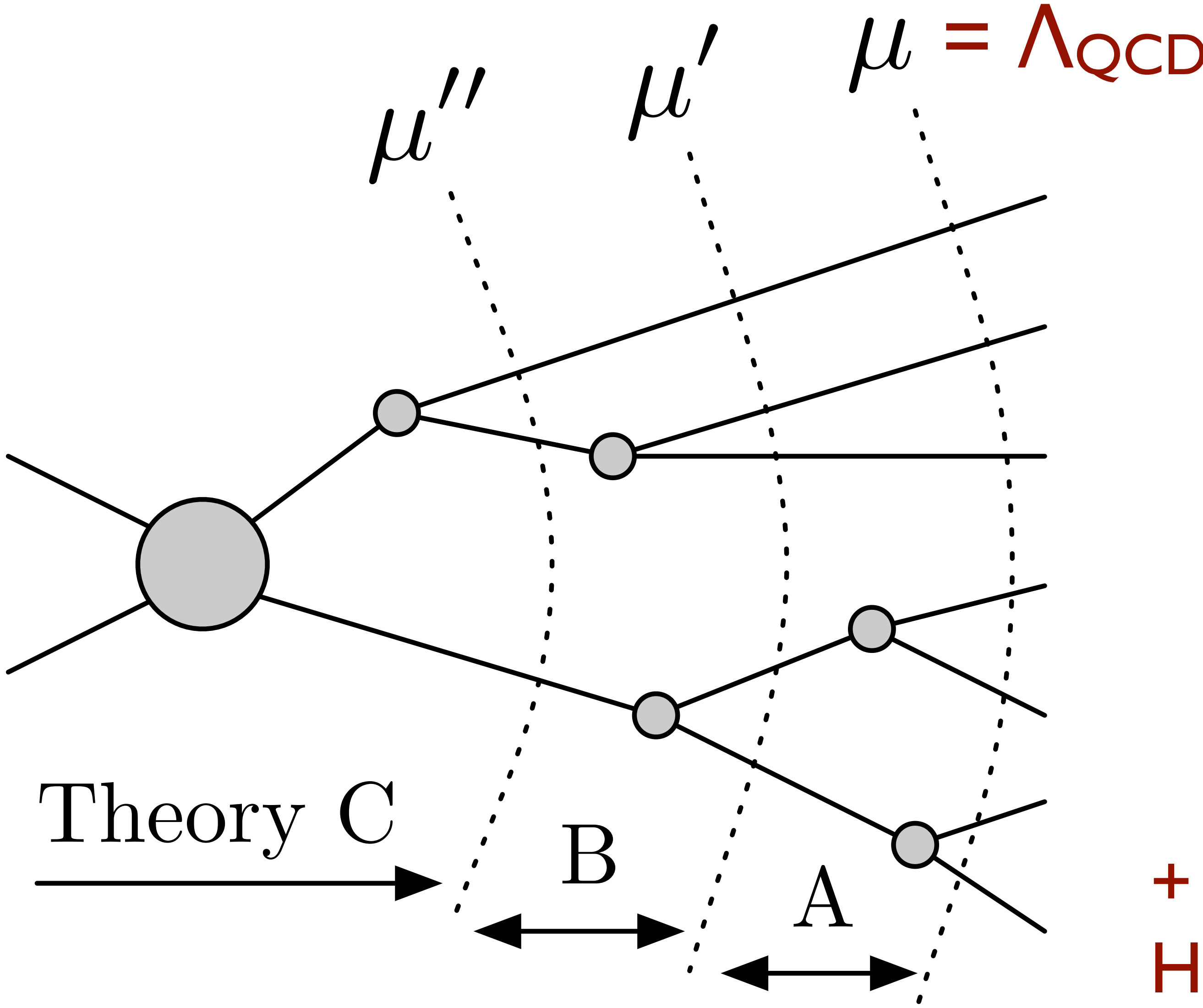
C: NLO/LL
(MC@NLO)

B: LO/LL
(PS/ME Merging)

A: Shower

Putting it all together...

PDFs
+
Secondaries
+
Beam Remnants
+
Pileup
+



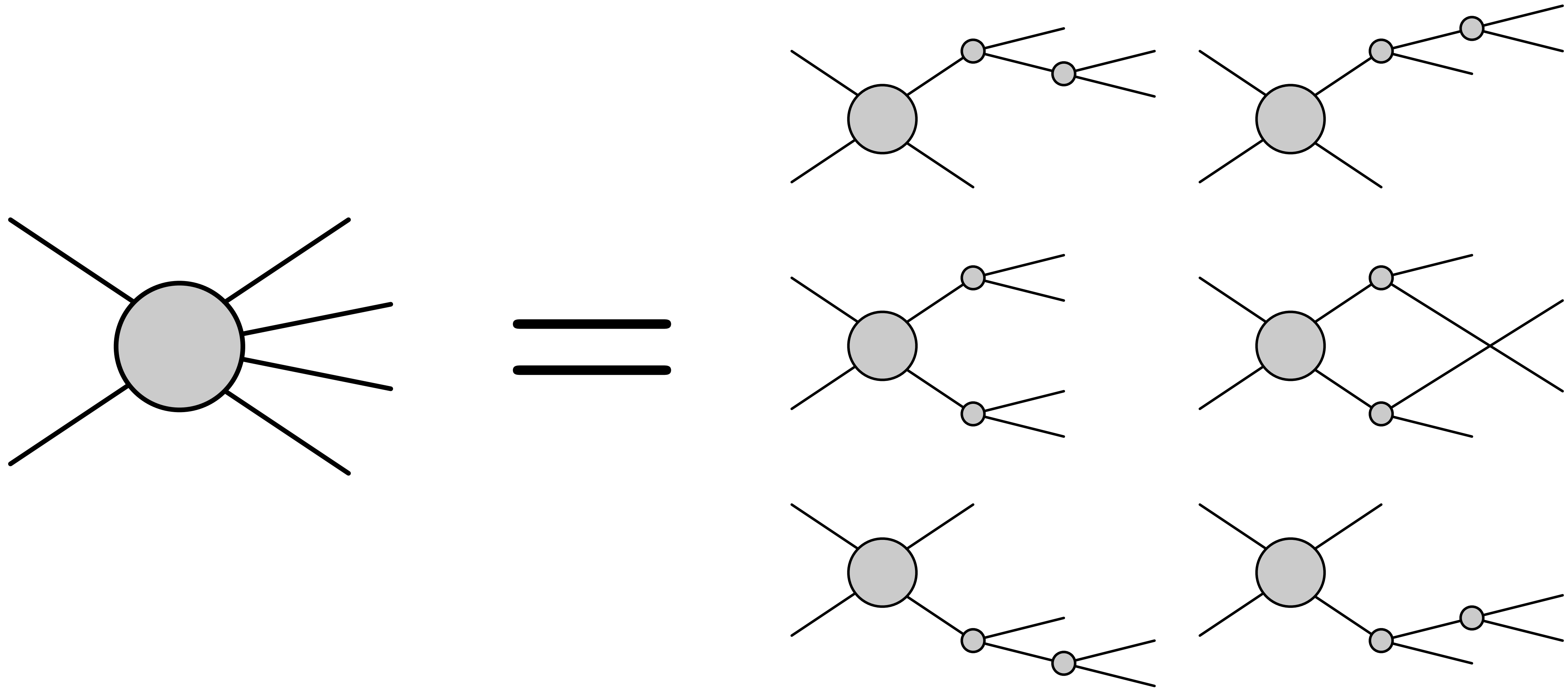
+
Hadronization

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

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

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

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

As shown 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
$d\sigma = \lvert\mathcal{M}(\mu)\rvert^2$	$d\mathrm{MC}(\mu)$
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

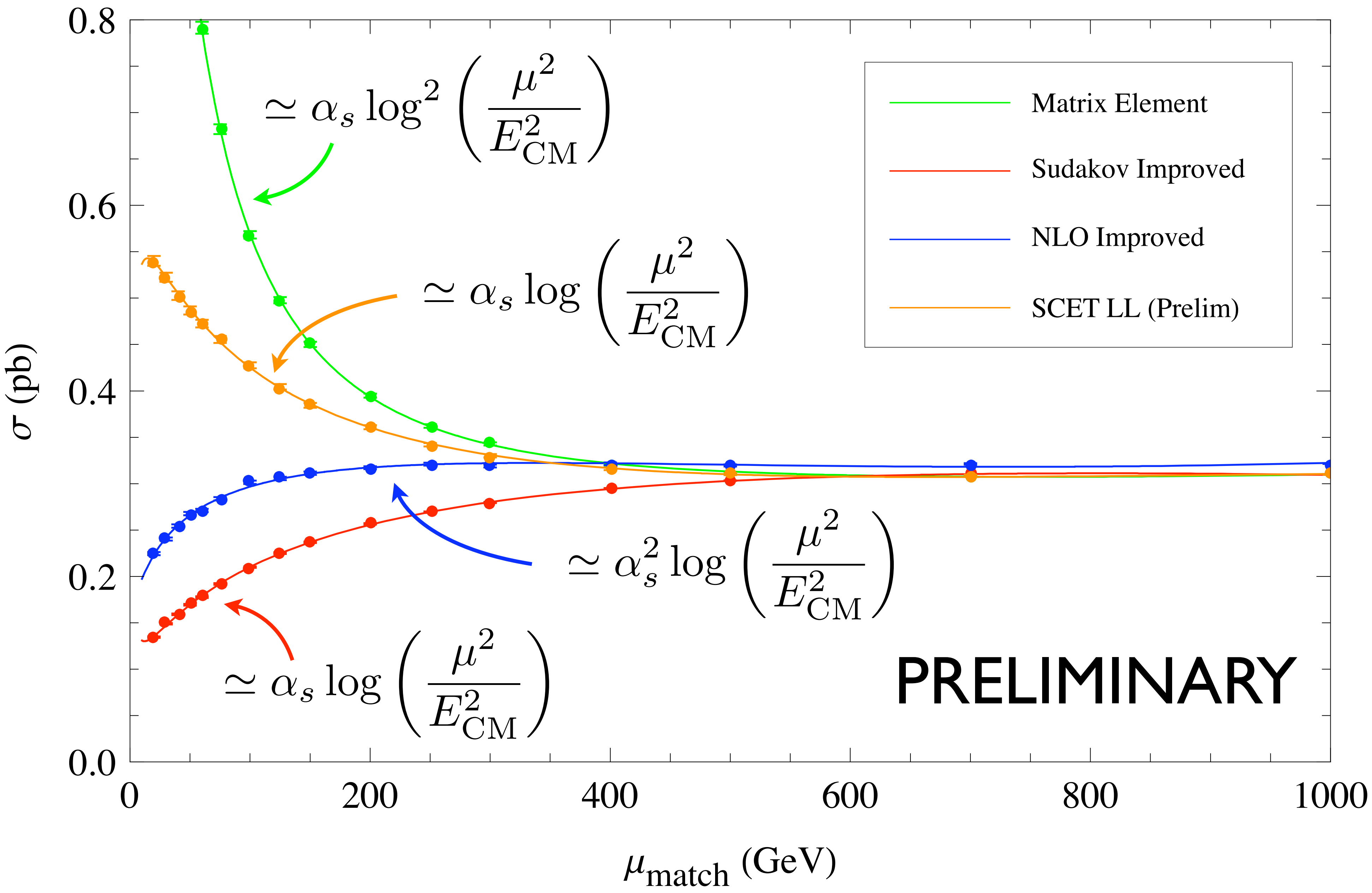
Subleading-logarithmic treatment of multiple scales?

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)

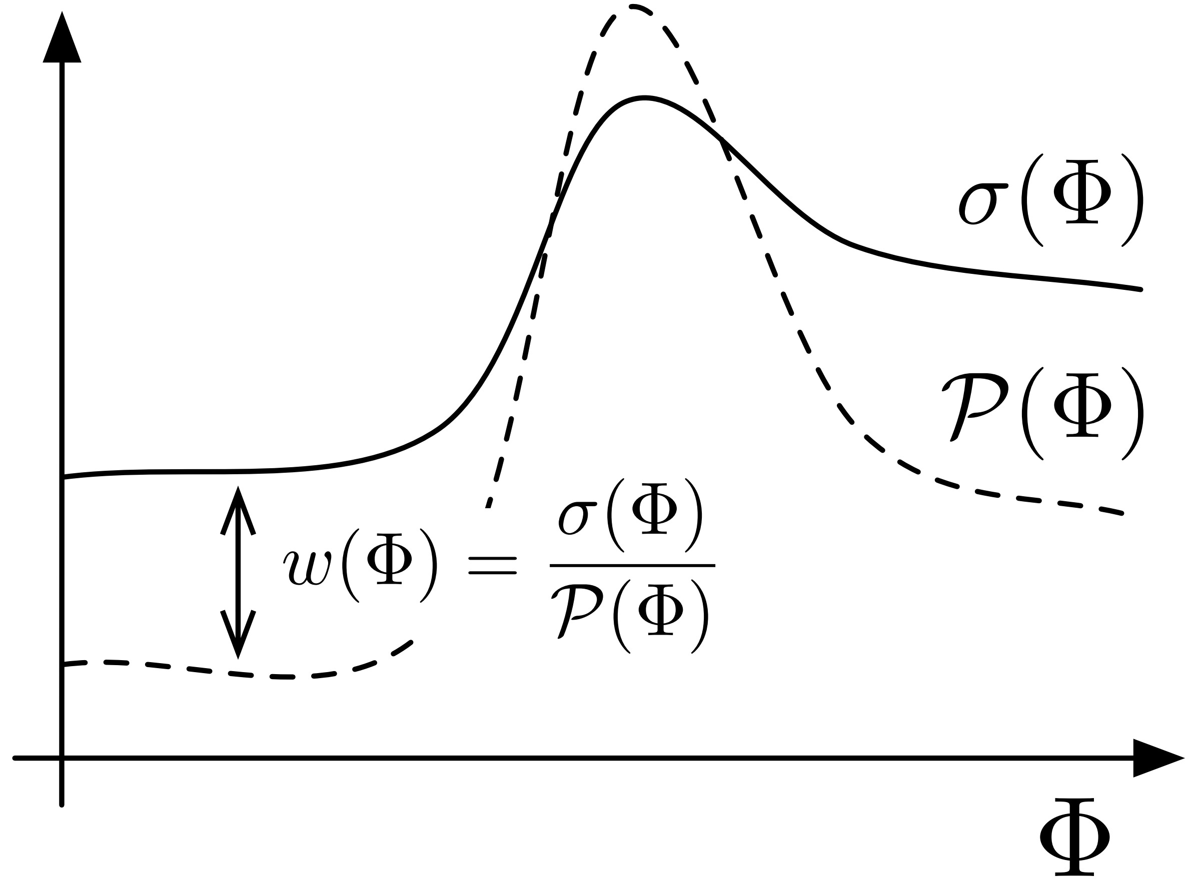



$d\sigma$
$|\mathcal{M}(\mu)|^2\, d\mathrm{MC}(\mu)$

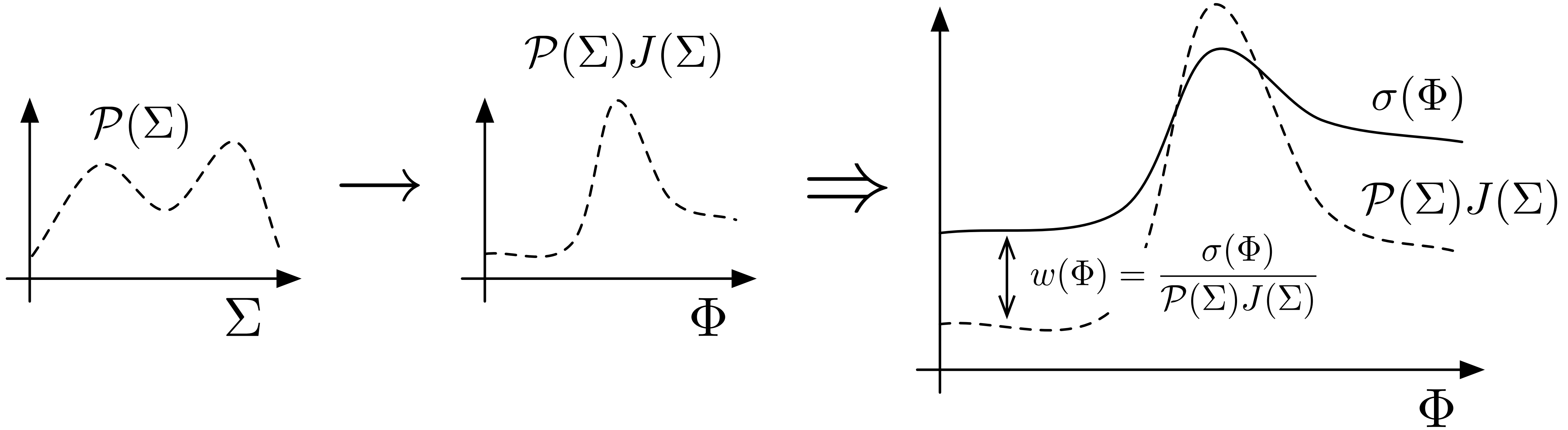
Backup Slides

In Case You Were Wondering...

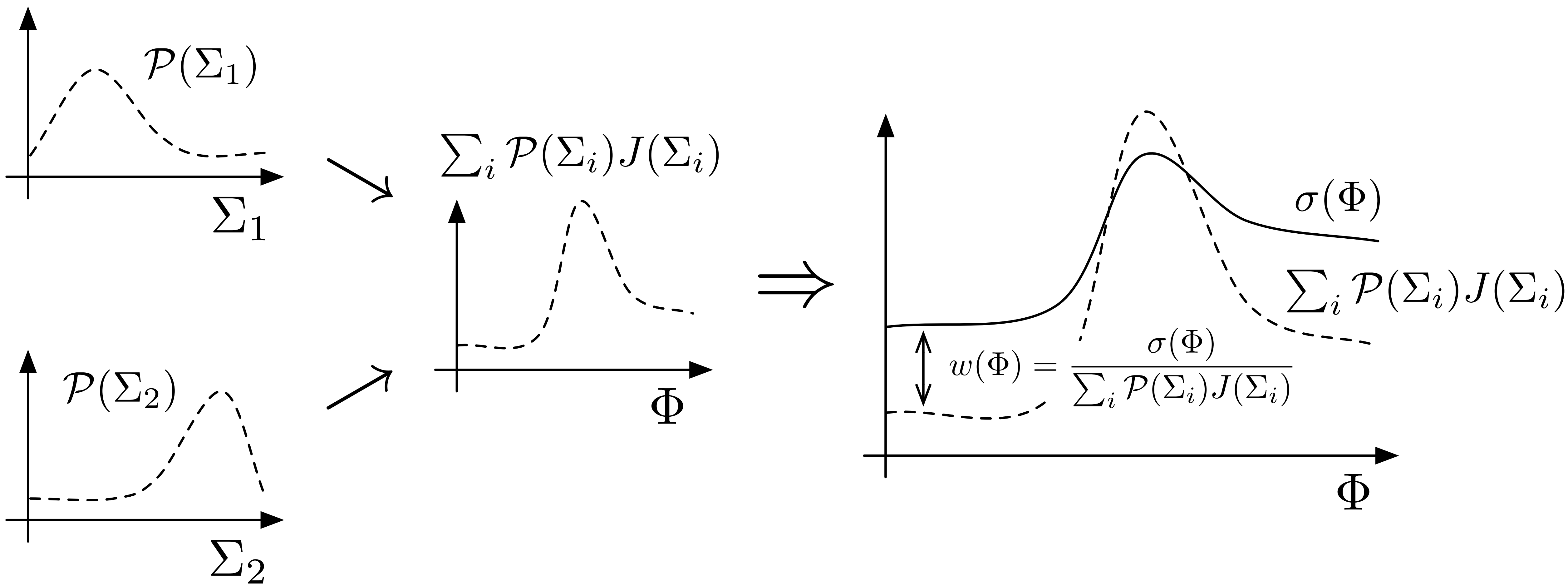
Reweighting (Simple)



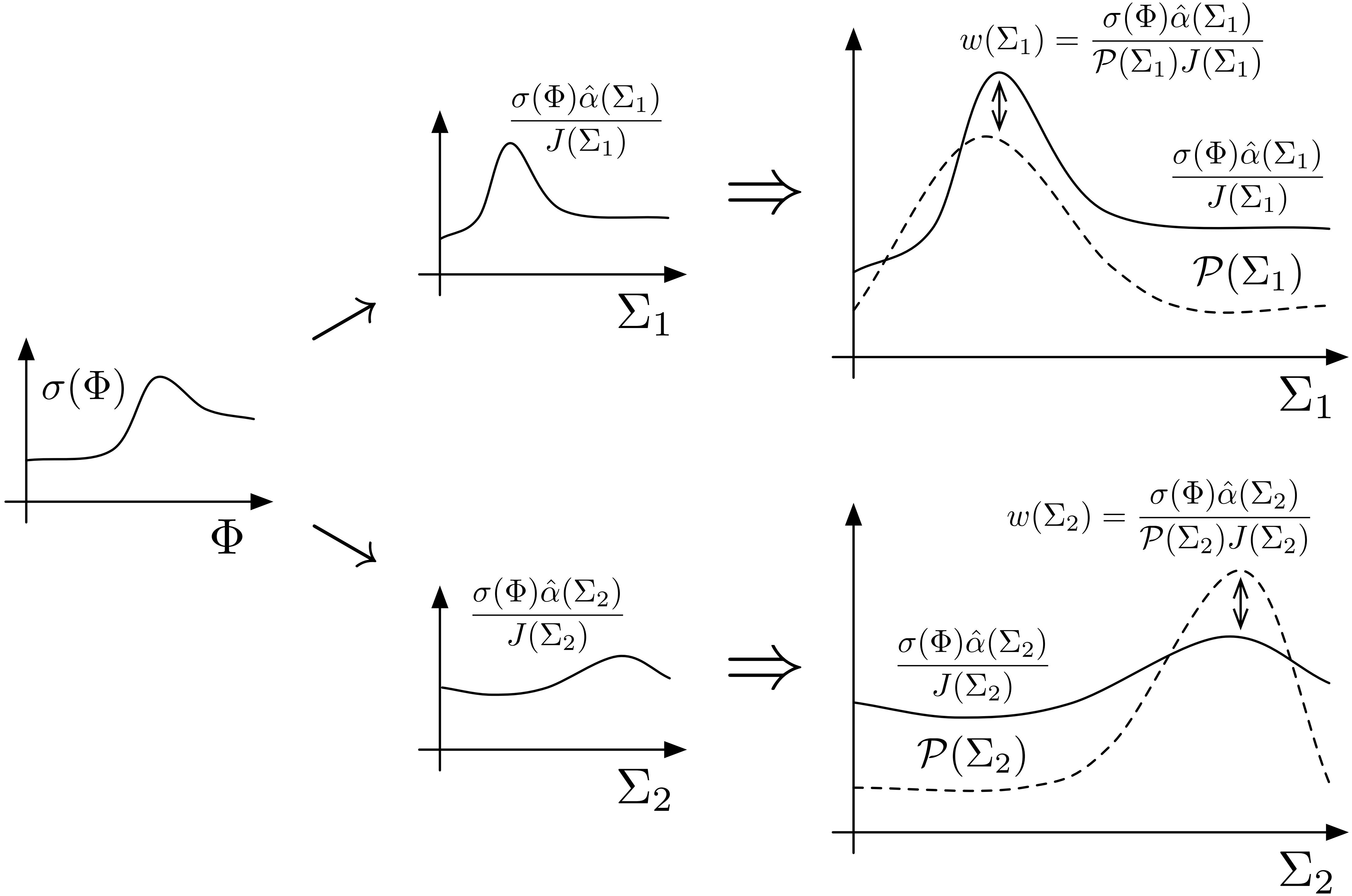
Reweighting (Jacobian)



Reweighting (Not 1-1)



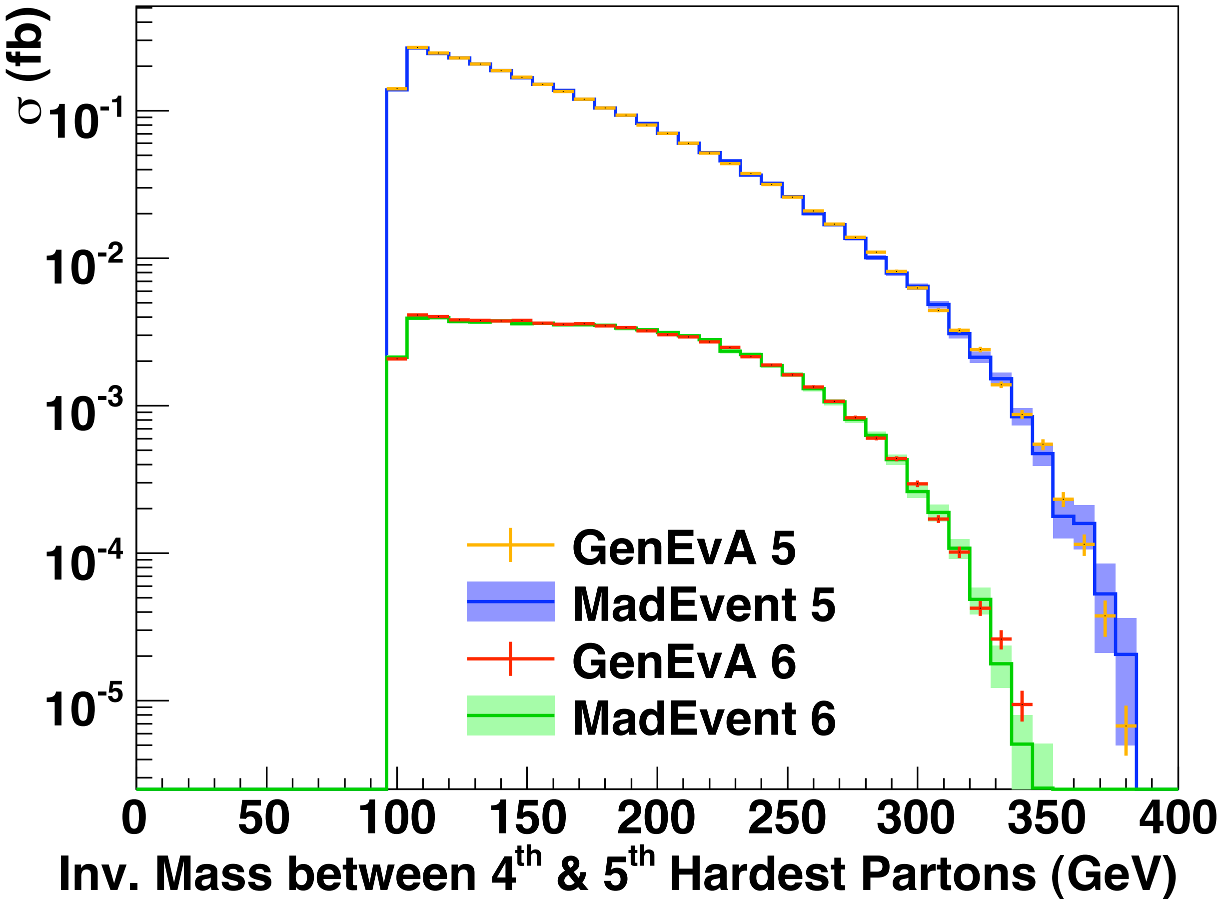
Reweighting (GenEvA)

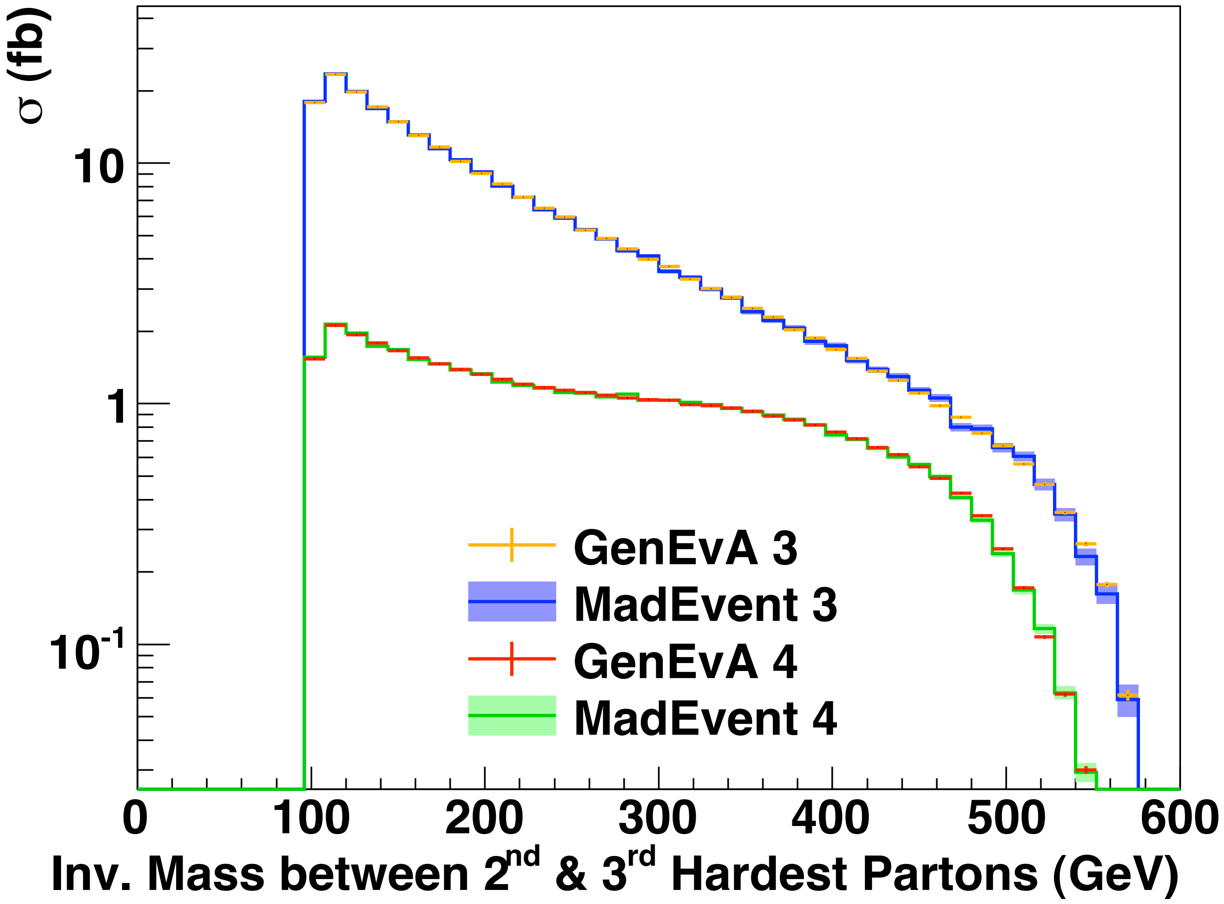


MadEvent Comparison

process	`MadEvent`	`GenEvA`	process	`MadEvent`	`GenEvA`
LO 3 (fb)	216.71 ± 0.21	216.77 ± 0.22	LO 5 (ab)	2542 ± 3	2543 ± 3
$u\bar{u}g$	86.62 ± 0.13	86.60 ± 0.18	$u\bar{u}ggg$	912 ± 2	912 ± 2
$d\bar{d}g$	21.75 ± 0.07	21.55 ± 0.10	$d\bar{d}ggg$	227.5 ± 0.9	228.3 ± 0.8
$s\bar{s}g$	21.63 ± 0.06	21.73 ± 0.10	$u\bar{u}d\bar{d}g$	33.8 ± 0.2	34.3 ± 0.4
$c\bar{c}g$	86.71 ± 0.13	86.70 ± 0.18	$u\bar{u}u\bar{u}g$	25.6 ± 0.2	25.7 ± 0.3
LO 4 (fb)	36.44 ± 0.04	36.49 ± 0.04	LO 6 (ab)	67.9 ± 0.3	68.0 ± 0.2
$u\bar{u}gg$	14.00 ± 0.03	14.00 ± 0.02	$u\bar{u}gggg$	22.41 ± 0.09	22.29 ± 0.12
$d\bar{d}gg$	3.504 ± 0.013	3.511 ± 0.011	$u\bar{u}u\bar{u}gg$	1.117 ± 0.006	1.14 ± 0.03
$u\bar{u}d\bar{d}$	0.175 ± 0.001	0.180 ± 0.003	$u\bar{u}u\bar{u}u\bar{u}$	$0.005 \pm 0.001^{-}$	0.005 ± 0.001
$u\bar{u}u\bar{u}$	0.132 ± 0.001	0.132 ± 0.002	$u\bar{u}d\bar{d}s\bar{s}$	$0.019 \pm 0.001^{-}$	0.020 ± 0.005

MadEvent Comparison

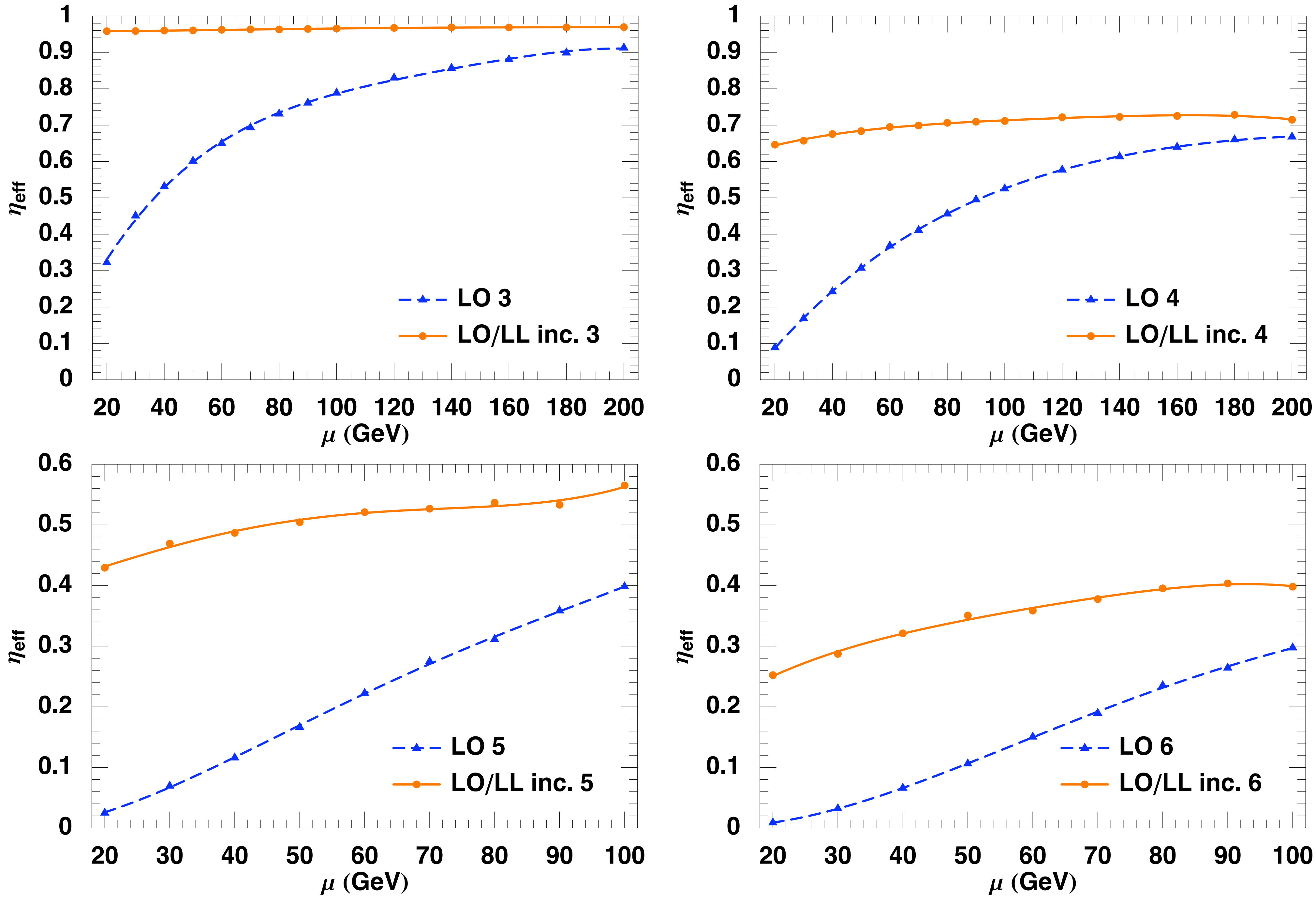




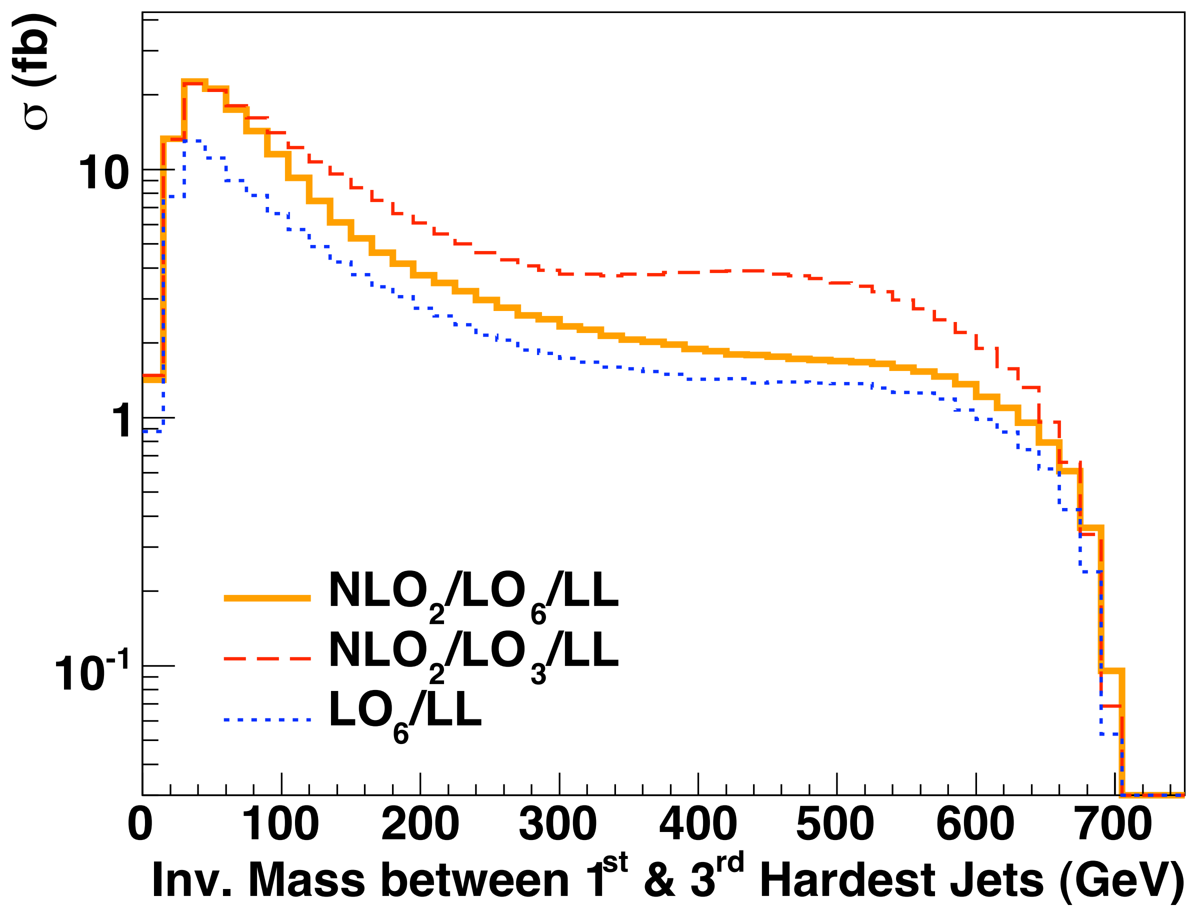
MadEvent Comparison

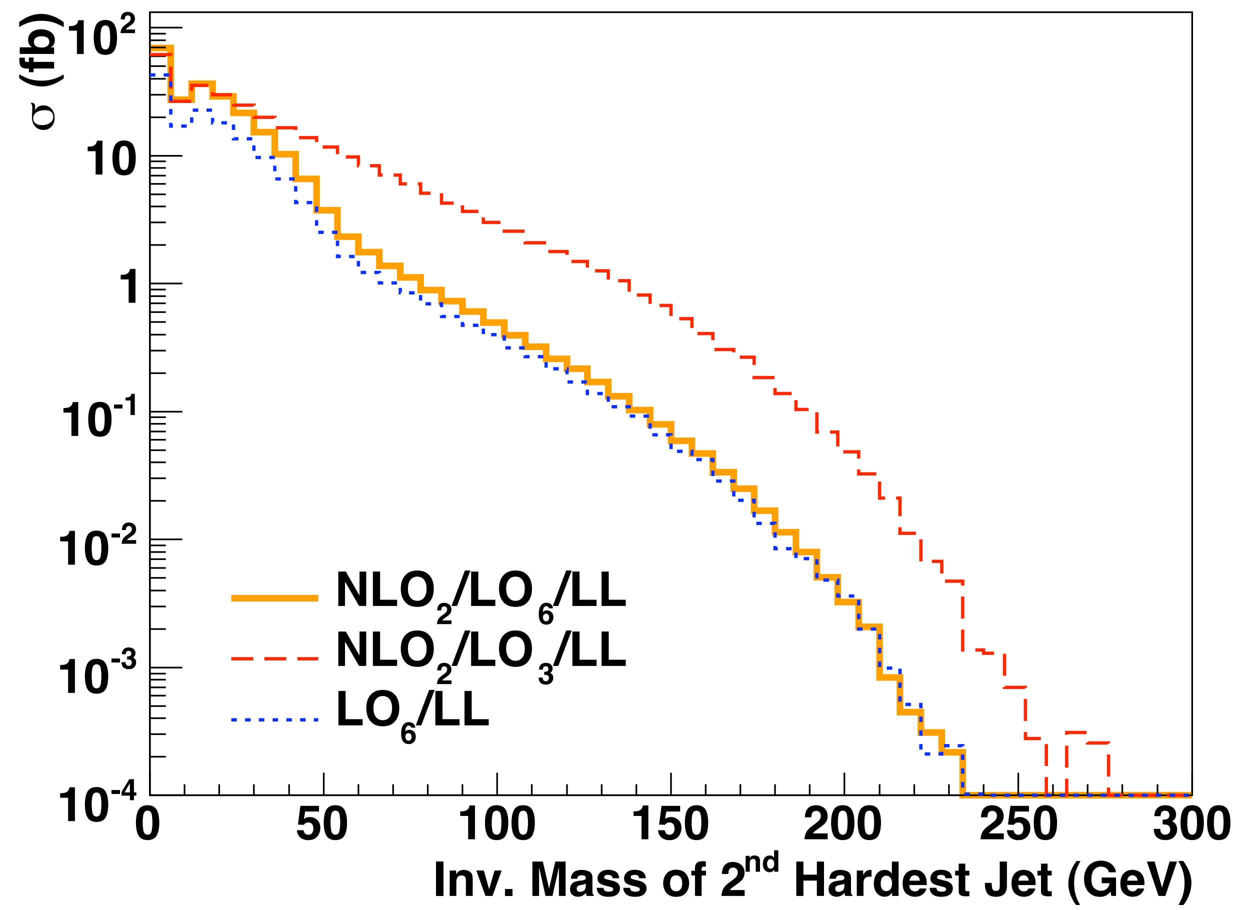
	η_{eff}	T_{eff} (msec)	$T_{0.9}$ (msec)
`GenEvA` LO 3	0.789	0.57	0.62
`GenEvA` LO/LL inc. 3	0.965	0.47	$<$ 0.47
`MadEvent` 3	0.982	2.6	$<$ 2.6
`MadEvent` $u\bar{u}g$	0.994	3.0	$<$ 3.0
`GenEvA` LO 4	0.525	1.7	2.2
`GenEvA` LO/LL inc. 4	0.713	1.3	1.5
`MadEvent` 4	0.809	11.1	11.4
`MadEvent` $u\bar{u}gg$	0.752	5.4	5.7
`GenEvA` LO 5	0.390	10.0	15
`GenEvA` LO/LL inc. 5	0.557	8.6	10.8
`MadEvent` 5	0.843	62	64
`MadEvent` $u\bar{u}ggg$	0.833	27	27
`GenEvA` LO 6	0.298	160	250
`GenEvA` LO/LL inc. 6	0.396	150	230
`MadEvent` 6	0.809	1900	2300
`MadEvent` $u\bar{u}gggg$	0.784	330	350

GenEvA Efficiency

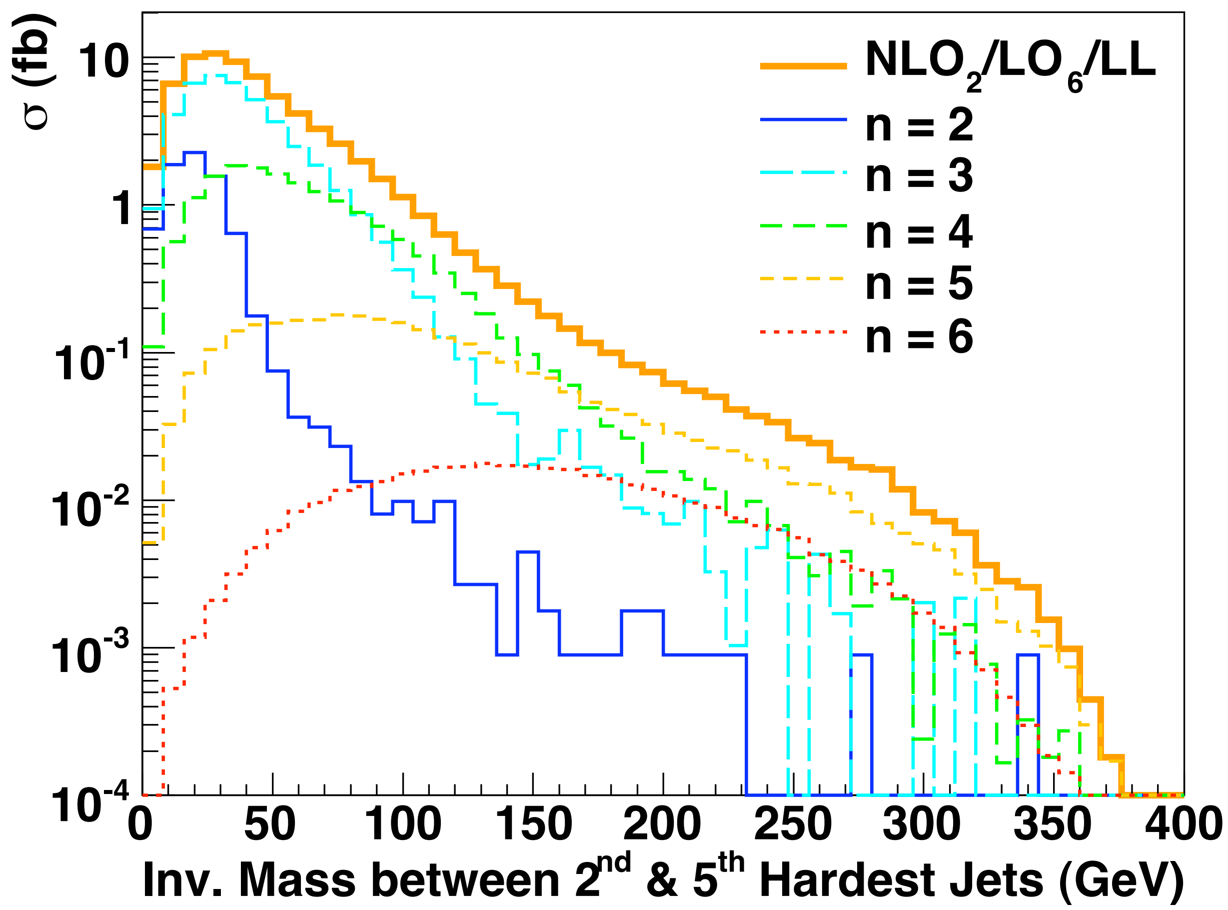


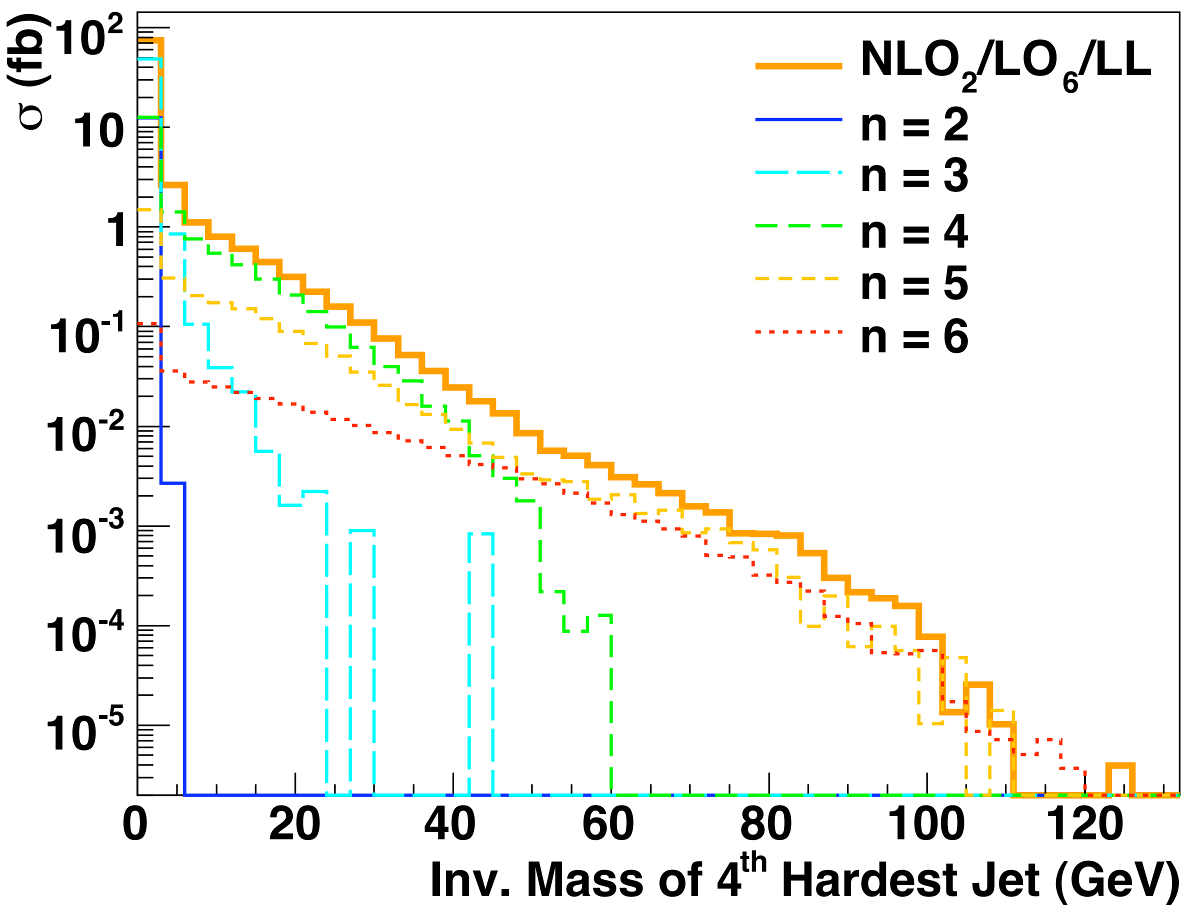
More Interpolations



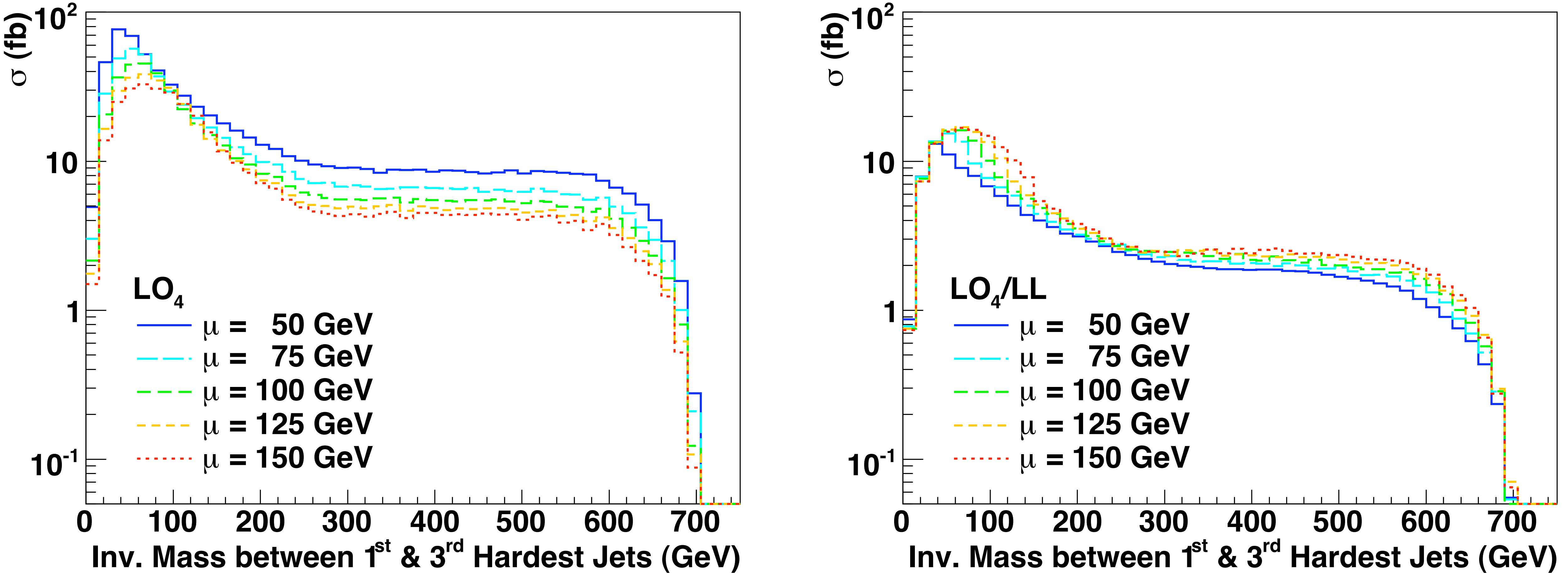


More Components





Differential Scaling



Differential Scaling