

Combining NLO Calculations with Parton Showers

SLAC Seminar
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Measurements @ LHC

Goal of LHC is to determine the mechanism of EW symmetry breaking

Main question, is the SM sufficient, or do we need physics beyond the standard model (BSM)

By definition BSM is difference between true distributions in nature and SM predictions

$$\sigma_{\text{BSM}} = \sigma_{\text{true}} - \sigma_{\text{SM}}$$

Measurements @ LHC

Problem:

Measured distributions are convolutions of true distributions with detector effects

$$\sigma_{\text{meas}} = d\sigma_{\text{true}} \otimes \text{detector}$$

For a meaningful comparison between σ_{meas} and SM predictions, need to be able to calculate

$$\sigma_{\text{pred}} = d\sigma_{\text{SM}} \otimes \text{detector}$$

Why parton showers?

Detector effects depend on details of the fully hadronic events (π^+ vs π^0 , details of jets)

Need $d\sigma_{SM}$ including full hadronization effects

Only known way to generate exclusive distributions is using parton shower Monte Carlos (Pythia/Herwig)

$$d\sigma_{SM} = (\text{Calc}) \otimes \text{Pythia/Herwig}$$

In order to use LHC data...

For the perturbative part, NLO calculations are the state of the art and should be viewed as mandatory

- Several processes only available at NLO
- Scale dependence only under control starting at NLO
- NLO calculations required to get to $O(10\%)$ uncertainty

Combine NLO calculations with parton showers

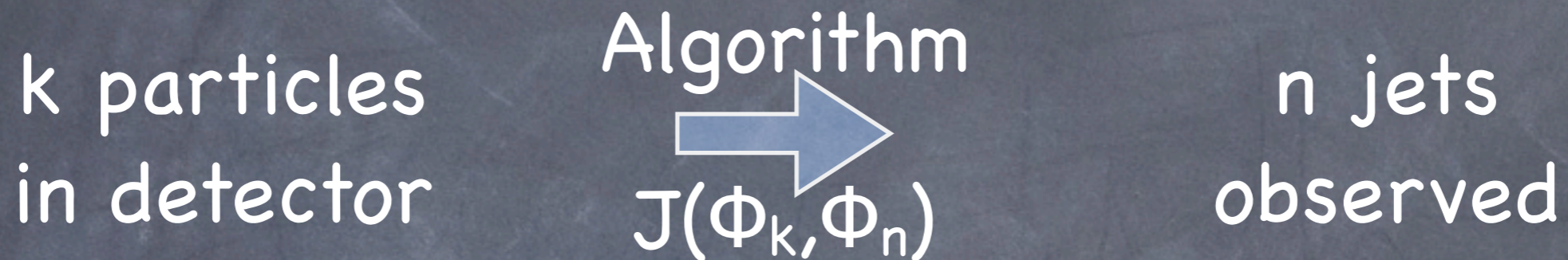
Outline

- Jet Observables and Monte Carlo
- The Parton Shower Algorithm
- Generics of combining with fixed order calculations
 - LO Accuracy
 - NLO Accuracy
- Some details of our calculation
- Conclusions

Jet observables and Monte Carlo

Jet cross sections

Defined with help of jet algorithm



If jet algorithm is infrared safe, can calculate
perturbatively

$$\frac{d\sigma_n^{\text{jet}}}{d\Phi_n} = \sum_{i \geq n} \int d\Phi'_i \frac{d\sigma_i^{\text{parton}}}{d\Phi'_i} \mathcal{J}(\Phi'_i, \Phi_n)$$

Jet cross sections

Problem 1:

- Each term in sum separately divergent (cancels in sum)
- In general can only do this calculation numerically by integrating over each term in sum separately

How do we deal with the IR divergences numerically?

$$\frac{d\sigma_n^{\text{jet}}}{d\Phi_n} = \sum_{i \geq n} \int d\Phi'_i \frac{d\sigma_i^{\text{parton}}}{d\Phi'_i} J(\Phi'_i, \Phi_n)$$

Jet cross sections

Problem 2:

- Partonic calculations calculated in fixed order PT
- Presence of large ratios in phase space variables gives large logarithmic terms that destroy convergence of PT

How do we sum large logs for all i ?

$$\frac{d\sigma_n^{\text{jet}}}{d\Phi_n} = \sum_{i \geq n} \int d\Phi'_i \frac{d\sigma_i^{\text{parton}}}{d\Phi'_i} J(\Phi'_i, \Phi_n)$$

Jet cross sections

Problem 3:

- Partonic calculations can only be obtained for small i
- The jet algorithm depends in general on phase space cuts and efficiencies which requires fully exclusive events

How to get expression for large i ?

$$\frac{d\sigma_n^{\text{jet}}}{d\Phi_n} = \sum_{i \geq n} \int d\Phi'_i \frac{d\sigma_i^{\text{parton}}}{d\Phi'_i} J(\Phi'_i, \Phi_n)$$

Jet cross sections

Problem 4:

- Partonic calculations only give partons in final state
- Efficiencies and experimental cuts can depend on the type of hadronic final state, as well as other NP effects

How to get fully hadronized events?

$$\frac{d\sigma_n^{\text{jet}}}{d\Phi_n} = \sum_{i \geq n} \int d\Phi'_i \frac{d\sigma_i^{\text{parton}}}{d\Phi'_i} J(\Phi'_i, \Phi_n)$$

Summary of the 4 problems

1. How do we implement KLN cancellation numerically?
2. How do we get expressions that resum leading logarithms?
3. How do we get expressions for large number of particles?
4. How do we get fully hadronized events?

Solution to the problems

Define "Monte Carlo cross sections"

$$\frac{d\sigma_n^{\text{MC}}}{d\Phi_n} = \sum_{i \geq n} \int d\Phi'_i \frac{d\sigma_i^{\text{parton}}}{d\Phi'_i} J_{\text{MC}}(\Phi'_i, \Phi_n)$$

And define a jet cross section calculated from these

$$\frac{d\sigma_n^{\text{jet,MC}}}{d\Phi_n} = \sum_{i \geq n} \int d\Phi'_i \frac{d\sigma_i^{\text{MC}}}{d\Phi'_i} J_{\text{MC}}(\Phi'_i, \Phi_n)$$

Need to define $d\sigma_i^{\text{MC}}$ such that gives measured jet cross section and solves all 4 problems

Deal with Problem 1

Divide phase space in singular and non-singular regions

$$\mathcal{J}(\Phi'_i, \Phi_n) = \mathcal{J}(\Phi'_i, \Phi_n) \Theta(\Phi'_i = \text{sing}) + \mathcal{J}(\Phi_i, \Phi_n) \Theta(\Phi'_i = \text{non-sing})$$

$$\mathcal{J}_{\text{MC}}(\Phi'_i, \Phi_n)$$

$$\mathcal{J}_{\overline{\text{MC}}}(\Phi'_i, \Phi_n)$$

Define "Monte Carlo cross sections"

$$\frac{d\sigma_n^{\text{MC}}}{d\Phi_n} = \sum_{i \geq n} \int d\Phi'_i \frac{d\sigma_i^{\text{parton}}}{d\Phi'_i} \mathcal{J}_{\text{MC}}(\Phi'_i, \Phi_n)$$

Since integrate over singular phase space, KLN
cancellation guaranteed

Deal with Problem 2

Calculate leading logarithms to $d\sigma_n^{MC}$ to all orders in perturbation theory

Main idea is to use ideas of Sudakov factors and no-branching probabilities to construct $d\sigma_n^{MC}$

Straightforward task to obtain LL resummed result, and combination of NLO and LL can be obtained by matching

Deal with Problems 3-4

Parton shower algorithms generate phase space recursively ($\Phi_2 \rightarrow \Phi_3 \rightarrow \Phi_4 \rightarrow \dots$)

- Each step in recursion simple \Rightarrow generate arbitrarily complicated final states
- Simple known ways to implement with models of hadronization
- Gets the collinear and soft limit correct
- Does not change total cross sections

If $d\sigma_n^{\text{MC}}$ is merged with parton shower,
solve all 4 Problems

Combining fixed order calculations with Parton showers

Pictorial phase space

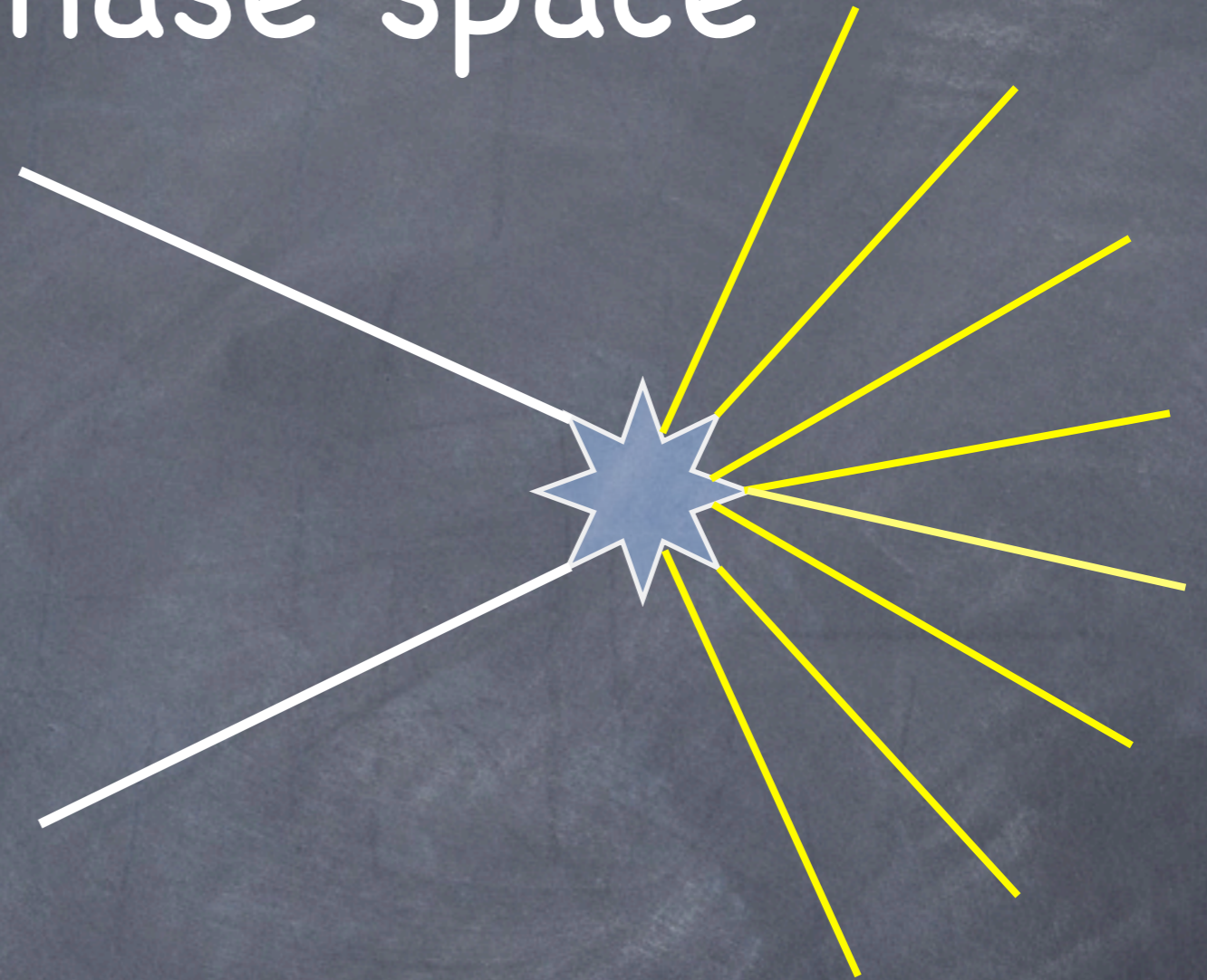
$d\Phi_n$



$d\Phi_{n+1}$



$d\Phi_{n+2}$



Pictorial phase space

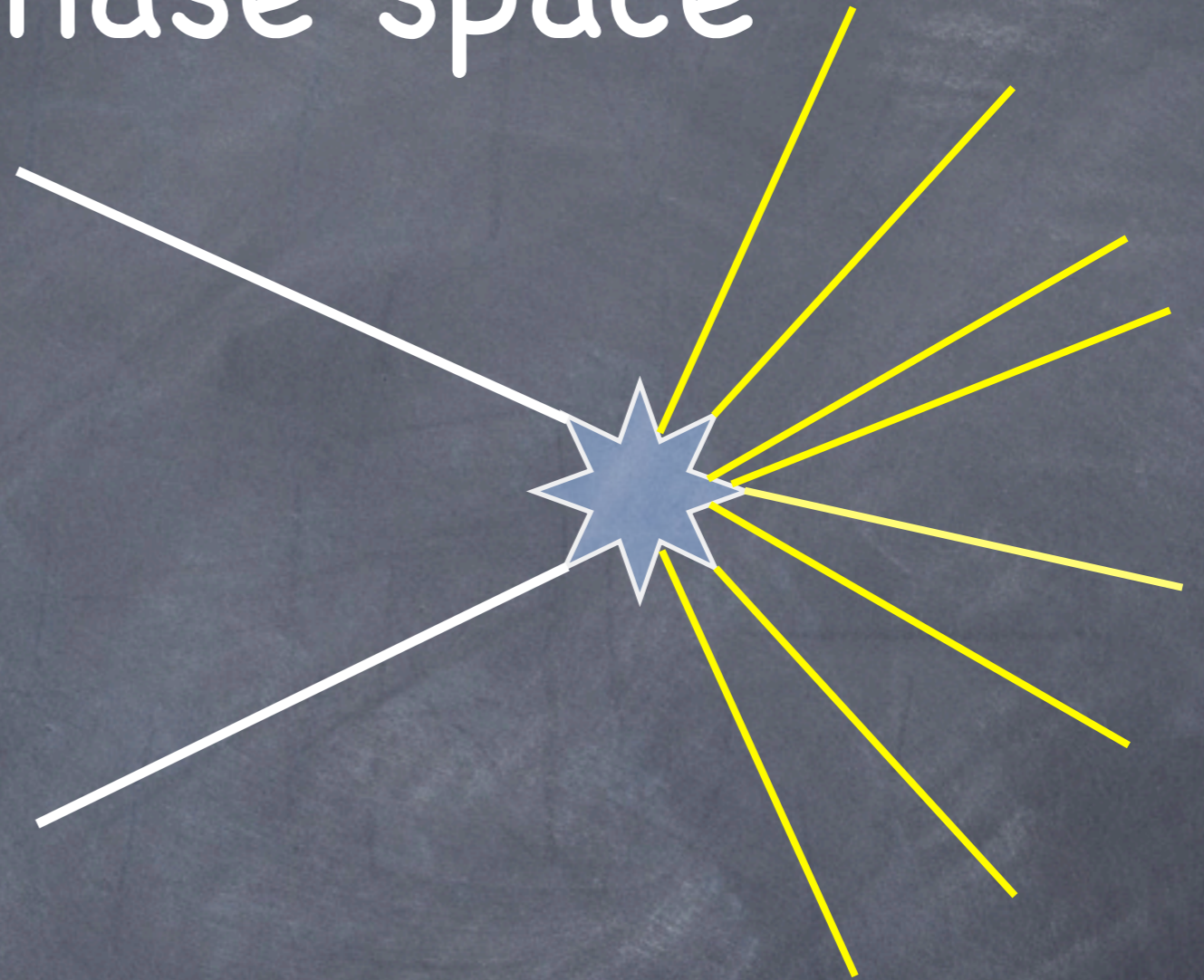
$d\Phi_n$



$d\Phi_{n+1}$

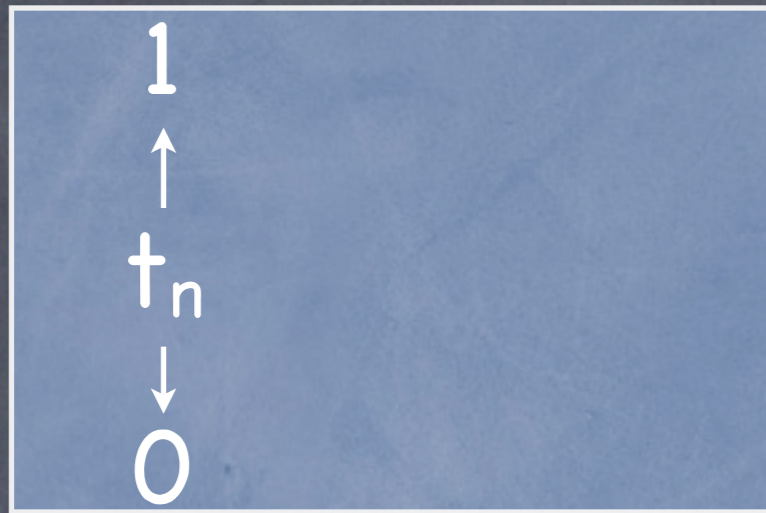


$d\Phi_{n+2}$

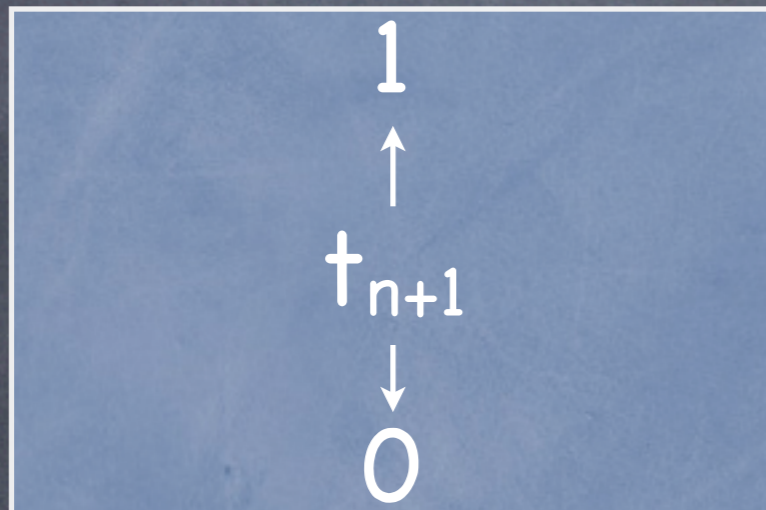


Pictorial phase space

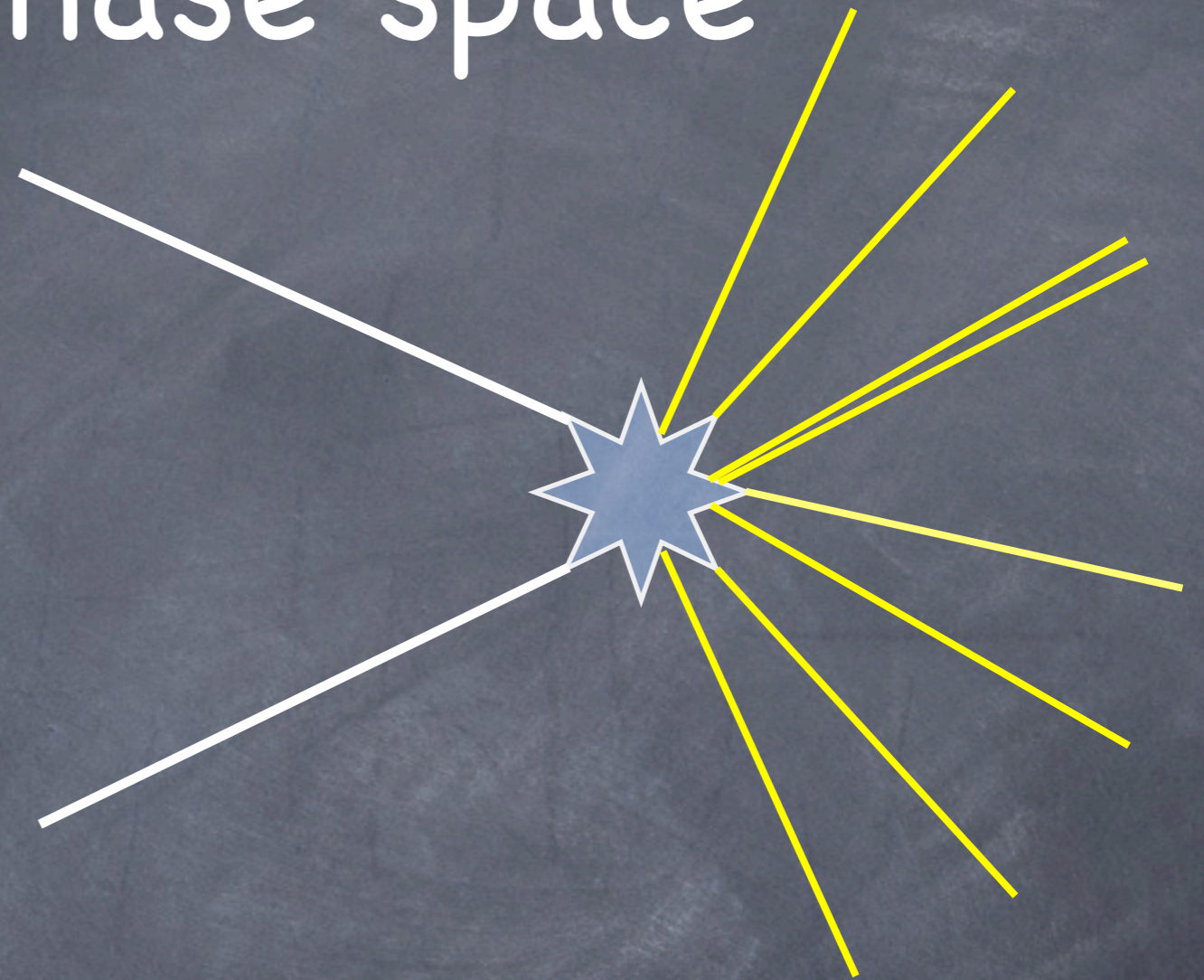
$d\Phi_n$



$d\Phi_{n+1}$



$d\Phi_{n+2}$

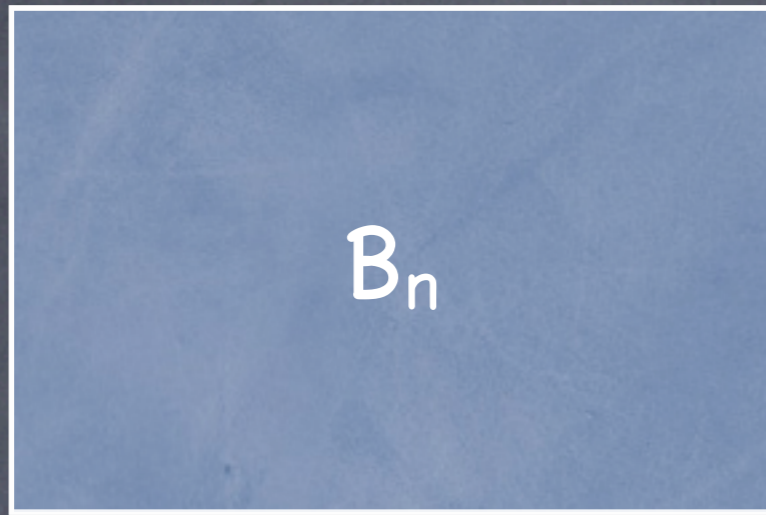


Region of Φ_n looks like Φ_{n-1}

Define resolution variable t_n
($t_n \rightarrow 0$ in collinear region)

The parton shower

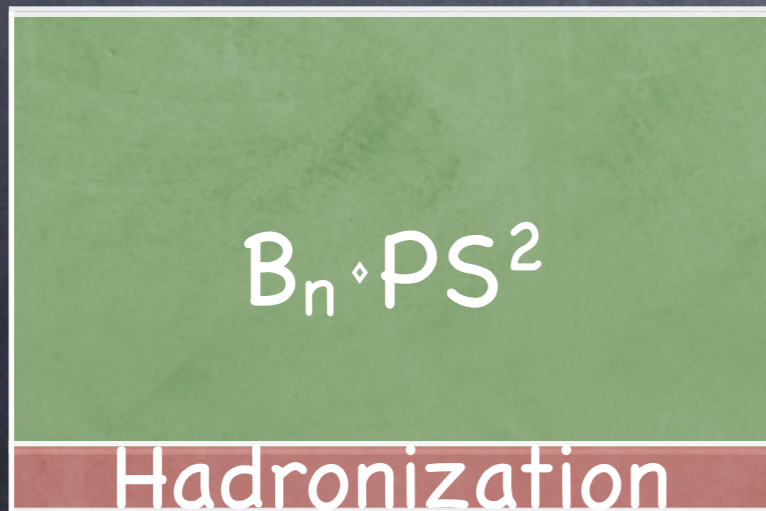
$d\Phi_n$



$d\Phi_{n+1}$



$d\Phi_{n+2}$

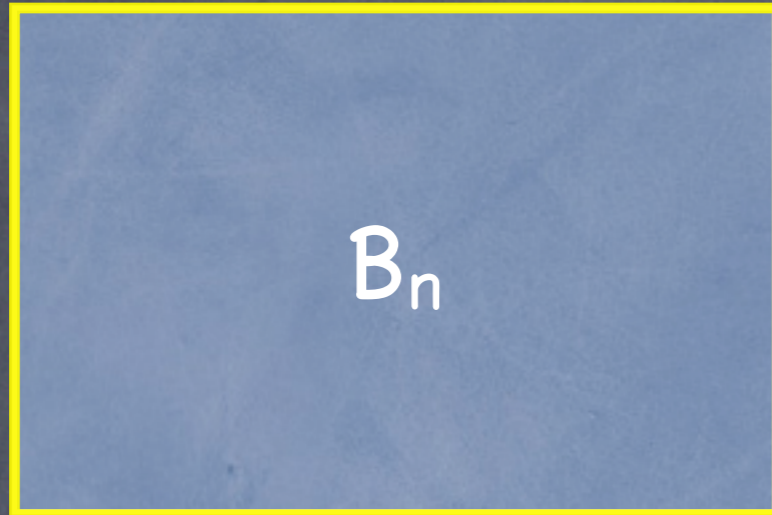


- Starts from known B_n
- Adds extra emissions via simple algorithm
- Is probabilistic (always sums to the answer started from)
- Simple way to attach hadronization at t_{had}

Solves Problems 3-4 as advertised

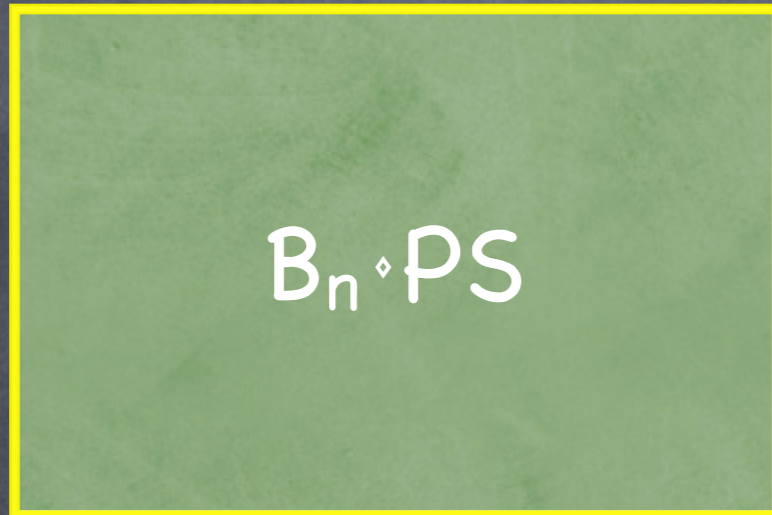
Combining with LO

$d\Phi_n$

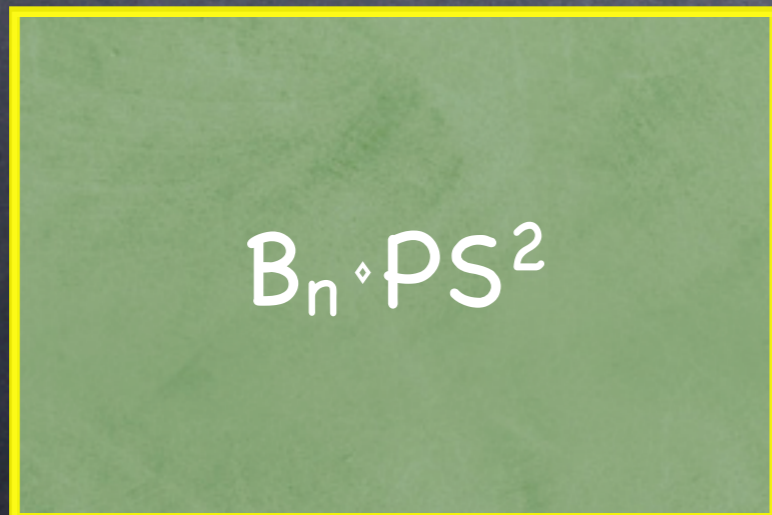


How do we correct higher dim phase space to LO results?

$d\Phi_{n+1}$



$d\Phi_{n+2}$



Double up phase space

$d\Phi_n$

$$B_n$$

How do we correct higher dim phase space to LO results?

$d\Phi_{n+1}$

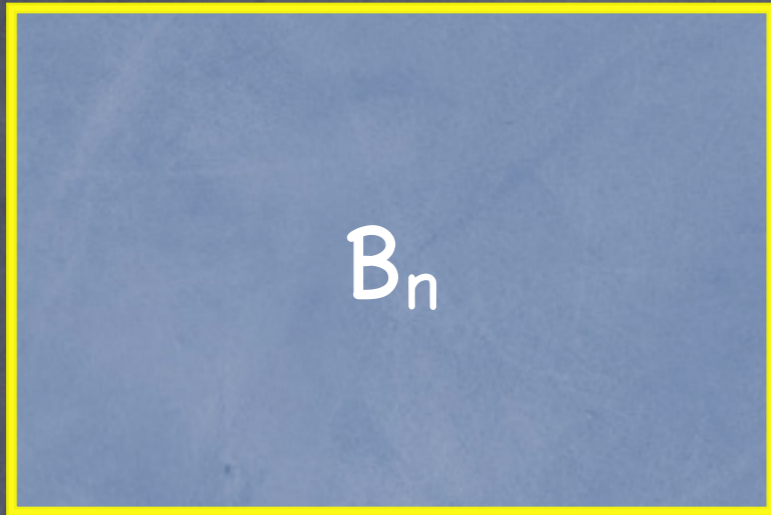
$B_n \diamond PS$	$B_{n+1} - B_n \diamond PS$
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$d\Phi_{n+2}$

$B_n \diamond PS^2$	$[B_{n+1} - B_n \diamond PS] \diamond PS$	$B_{n+2} - [B_{n+1} - B_n \diamond PS] \diamond PS - B_n \diamond PS^2$
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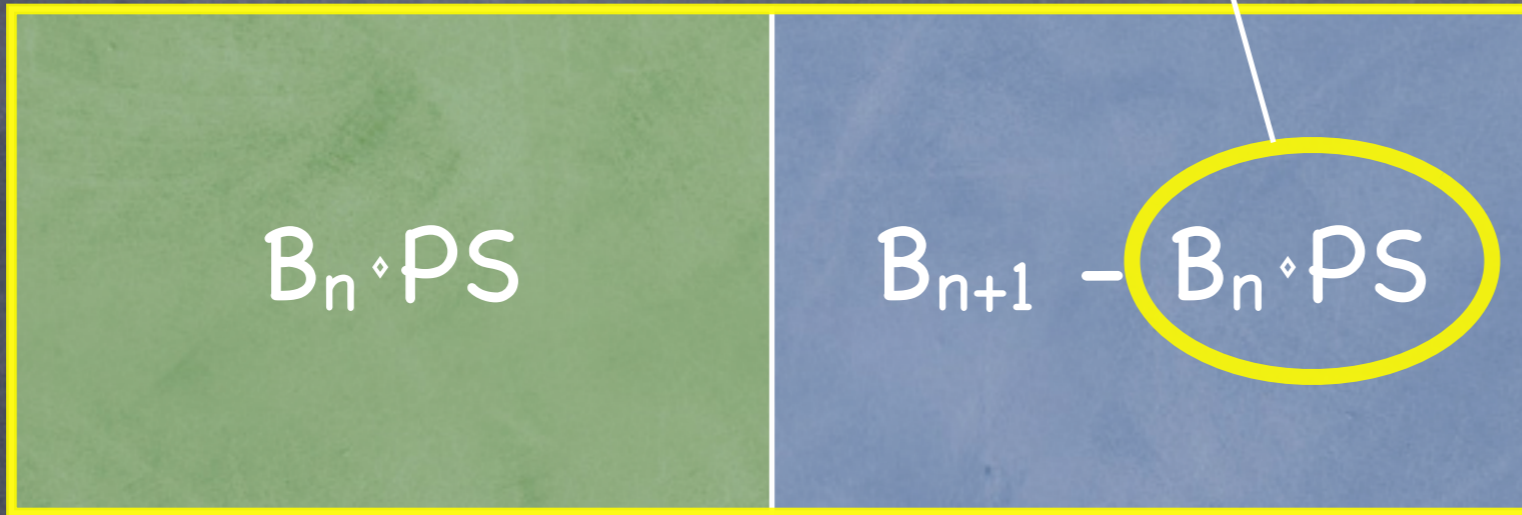
Double up phase space

$d\Phi_n$

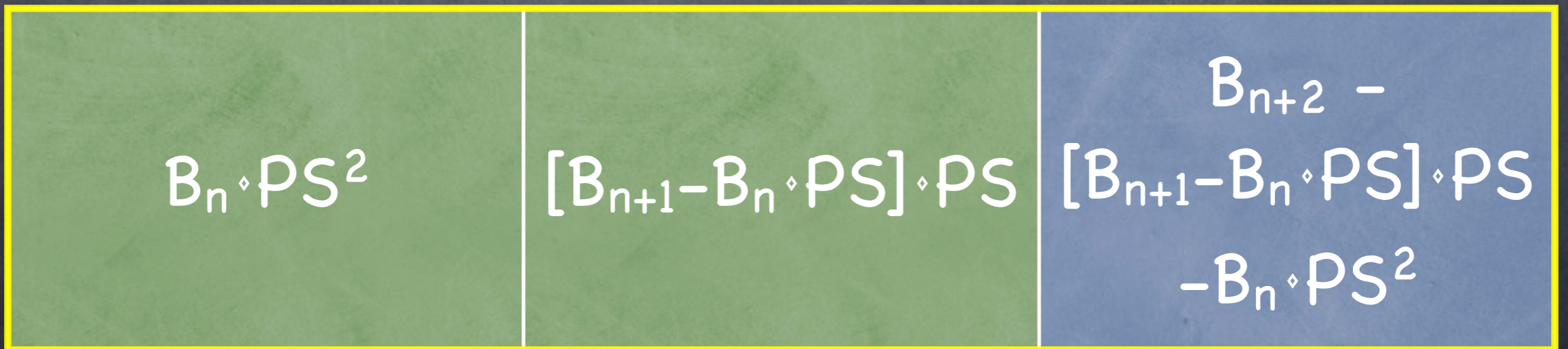


Need Shower analytically

$d\Phi_{n+1}$



$d\Phi_{n+2}$



Double up phase space

$d\Phi_n$

$$B_n$$

Need Shower analytically

Gives negative weights

$d\Phi_{n+1}$

$B_n \diamond PS$	$B_{n+1} - B_n \diamond PS$
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$d\Phi_{n+2}$

$B_n \diamond PS^2$	$[B_{n+1} - B_n \diamond PS] \diamond PS$	$B_{n+2} - [B_{n+1} - B_n \diamond PS] \diamond PS - B_n \diamond PS^2$
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Double up phase space

$d\Phi_n$

$$B_n$$

Need Shower analytically
Gives negative weights
Almost impossible to extend

$d\Phi_{n+1}$

$B_n \diamond PS$	$B_{n+1} - B_n \diamond PS$
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$d\Phi_{n+2}$

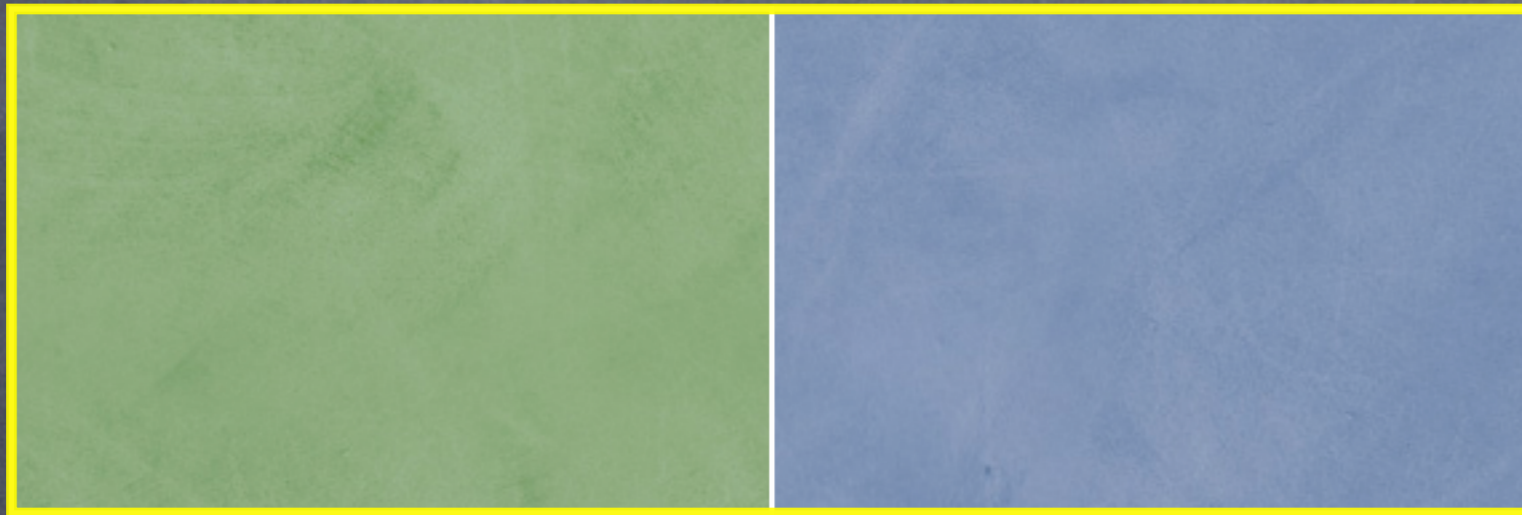
$B_n \diamond PS^2$	$[B_{n+1} - B_n \diamond PS] \diamond PS$	$B_{n+2} - [B_{n+1} - B_n \diamond PS] \diamond PS - B_n \diamond PS^2$
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Double up phase space

$d\Phi_n$



$d\Phi_{n+1}$



$d\Phi_{n+2}$

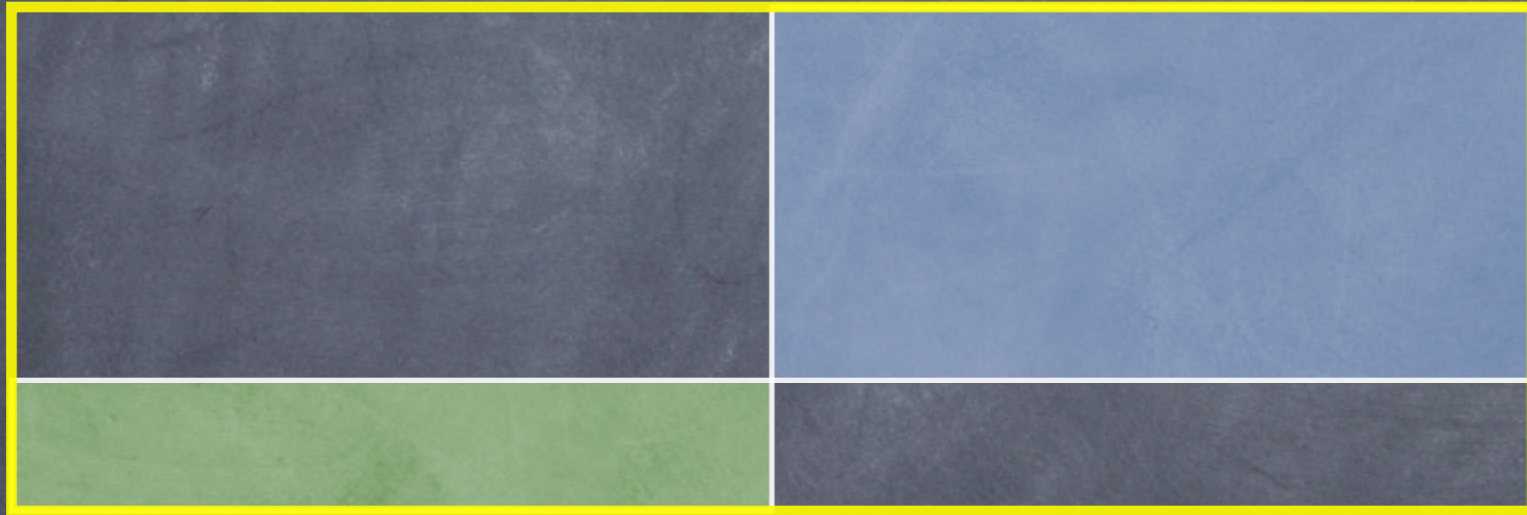


Separate phase space

$d\Phi_n$



$d\Phi_{n+1}$



μ_n

$d\Phi_{n+2}$

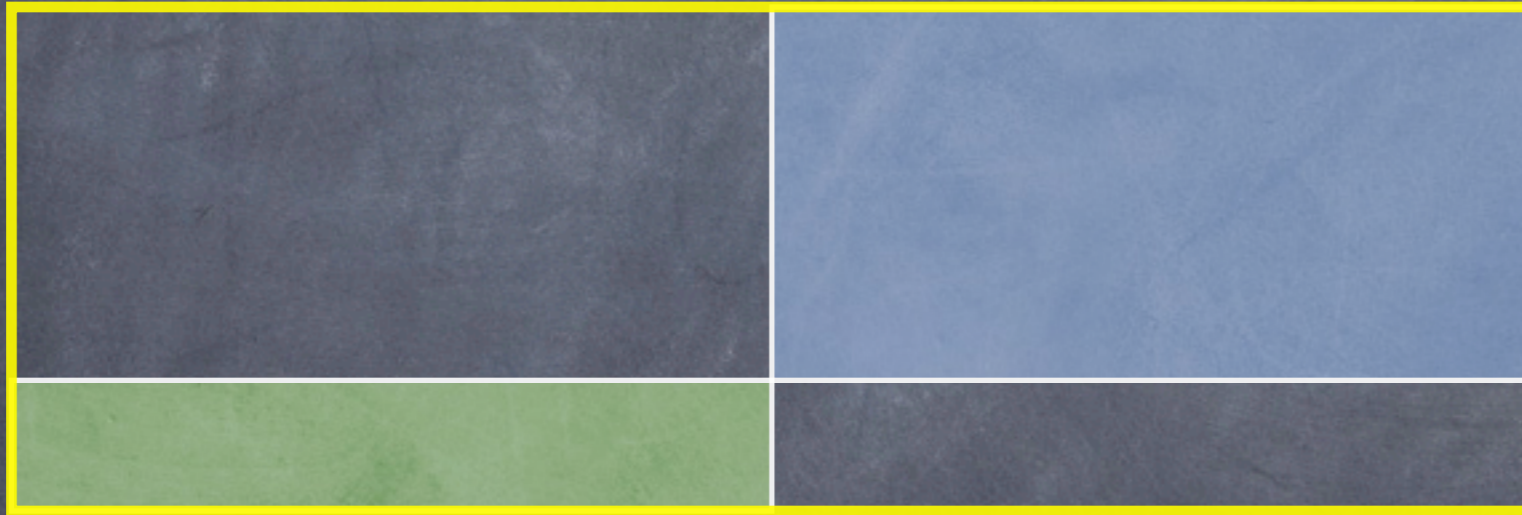


Separate phase space

$d\Phi_n$

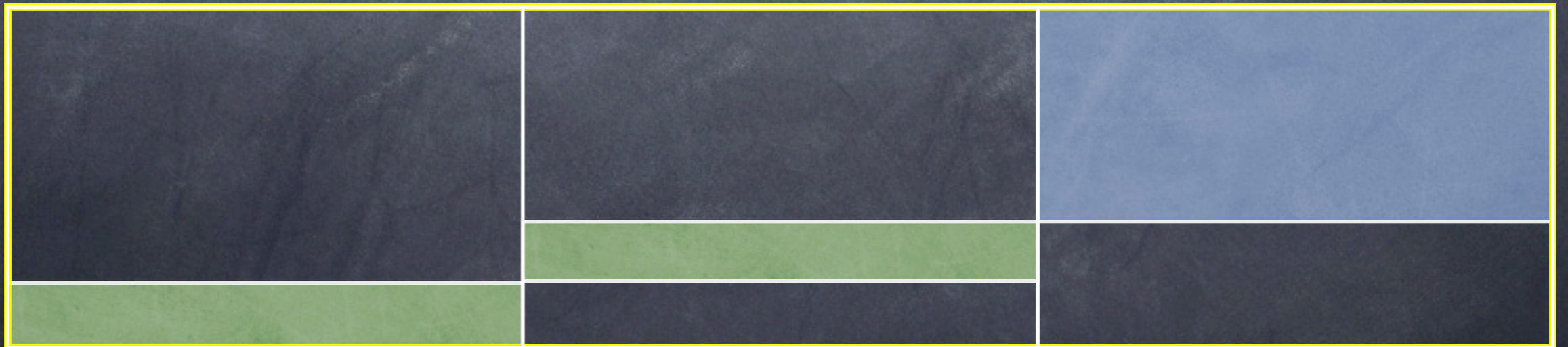


$d\Phi_{n+1}$



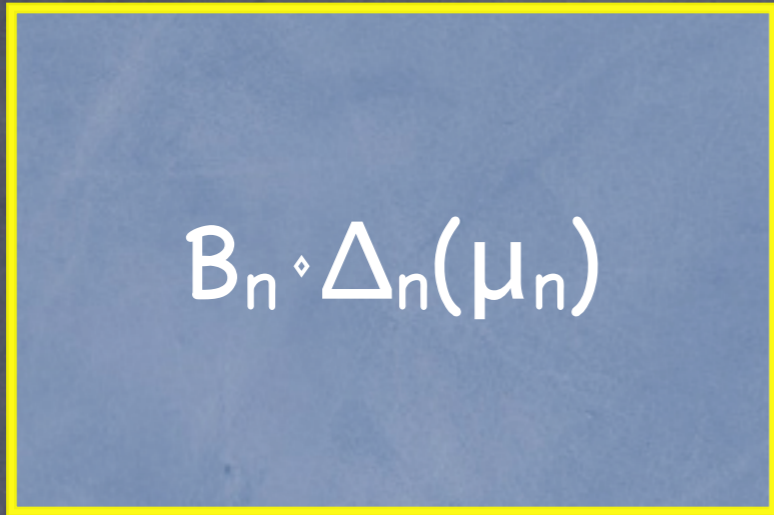
μ_n

$d\Phi_{n+2}$



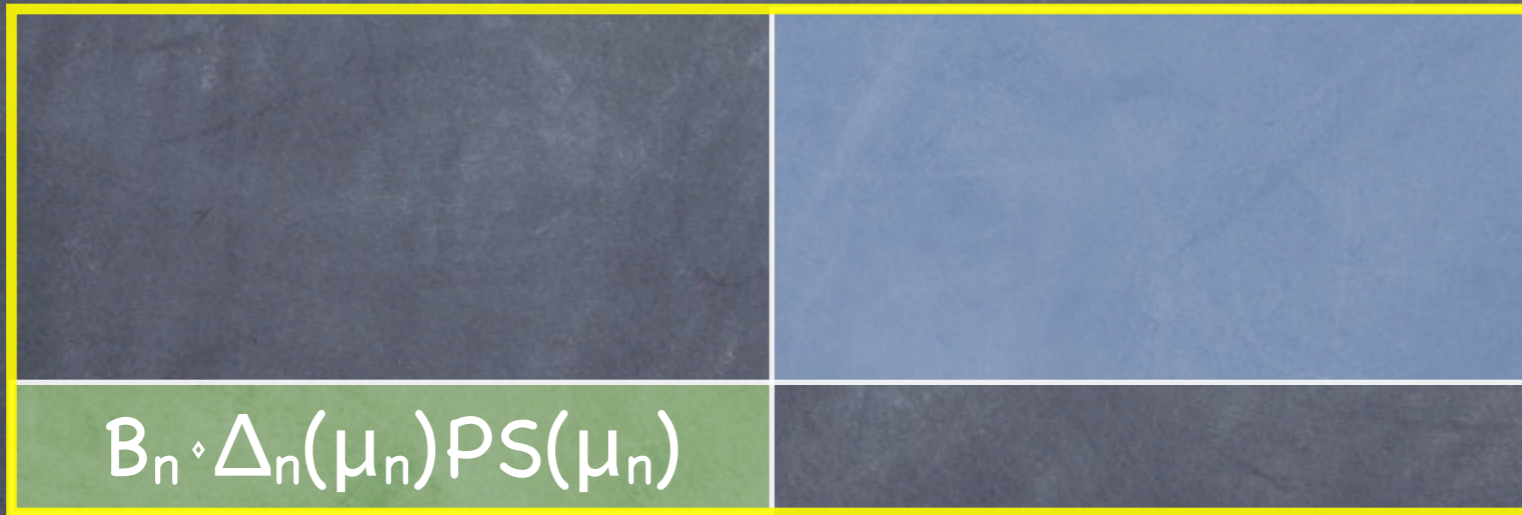
Separate phase space

$d\Phi_n$

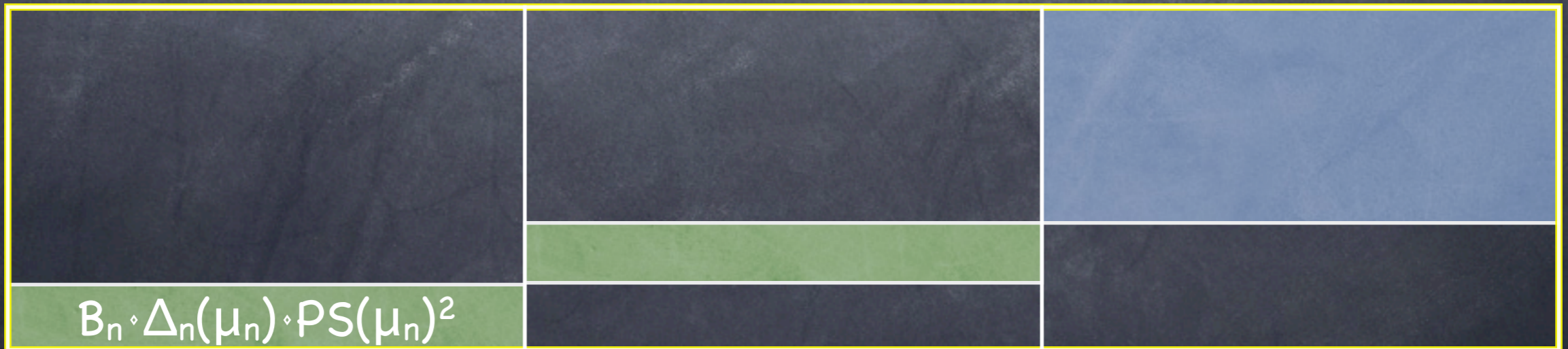


Add new samples to fill the empty regions with fixed order calculations

$d\Phi_{n+1}$



$d\Phi_{n+2}$



Separate phase space

$d\Phi_n$

$$B_n \diamond \Delta_n(\mu_n)$$

Add new samples to fill the empty regions with fixed order calculations

$d\Phi_{n+1}$

$$B_n \diamond \Delta_n(\mu_n) PS(\mu_n)$$

$$B_{n+1} \diamond \Delta_{n+1}(\mu_{n+1})$$

$d\Phi_{n+2}$

$$B_n \diamond \Delta_n(\mu_n) \diamond PS(\mu_n)^2$$

$$B_{n+1} \diamond \Delta_{n+1}(\mu_{n+1}) \diamond PS(\mu_{n+1})$$

$$B_{n+2}(\Phi_{n+2}) \diamond \Delta_{n+2}(\mu_{n+2})$$

Separate phase space

$d\Phi_n$

$$B_n \diamond \Delta_n(\mu_n)$$

Each correct @ LO/LL

Gives inclusive @ LO

$d\Phi_{n+1}$

	$B_{n+1} \diamond \Delta_{n+1}(\mu_{n+1})$
$B_n \diamond \Delta_n(\mu_n) PS(\mu_n)$	

*CKKW
MLM*

$d\Phi_{n+2}$

		$B_{n+2}(\Phi_{n+2}) \diamond \Delta_{n+2}(\mu_{n+2})$
	$B_{n+1} \diamond \Delta_{n+1}(\mu_{n+1}) \diamond PS(\mu_{n+1})$	
$B_n \diamond \Delta_n(\mu_n) \diamond PS(\mu_n)^2$		

The same at NLO

Naive attempt

$d\Phi_n$

$B_n + V_n$

Both columns separately div.

$d\Phi_{n+1}$

B_{n+1}

$d\Phi_{n+2}$

Double up phase space

$d\Phi_n$

B_{n+V_n}

Both columns separately div.
(n+1) row does not sum up

$d\Phi_{n+1}$

$[B_{n+V_n}] \diamond PS$

B_{n+1}

$d\Phi_{n+2}$

Double up phase space

$d\Phi_n$

$B_n + V_n$

Both columns separately div.
 $(n+1)$ row does not sum up

$d\Phi_{n+1}$

$[B_n + V_n] \diamond PS$

B_{n+1}

$d\Phi_{n+2}$

Naive attempt

$d\Phi_n$

$$B_{n+1} + V_n$$

Both columns separately div.

✓ (n+1) row does not sum up

$d\Phi_{n+1}$

$$[B_{n+1} + V_n] \cdot PS$$

$$B_{n+1} - B_n \cdot PS$$

$d\Phi_{n+2}$

Double up phase space

$d\Phi_n$

$$B_{n+1} + V_{n+1} + \int B_n \diamond PS$$

- ✓ Both columns separately div.
- ✓ $(n+1)$ row does not sum up

$d\Phi_{n+1}$

$$[B_{n+1} + V_{n+1} + \int B_n \diamond PS] \diamond PS$$

$$B_{n+1} - B_n \diamond PS$$

MC@NLO

$d\Phi_{n+2}$

Double up phase space

$d\Phi_n$

$$B_{n+1} + V_{n+1} + \int B_n \diamond PS$$

Need Shower analytically

Gives negative weights

Almost impossible to extend

$d\Phi_{n+1}$

$$[B_{n+1} + V_{n+1} + \int B_n \diamond PS] \diamond PS$$

$$B_{n+1} - B_n \diamond PS$$

MC@NLO

$d\Phi_{n+2}$

Separate phase space

$d\Phi_n$

$$\sigma_n^{\text{incl}} \diamond \Delta_n(\mu_n)$$

What do I need for
(n+1)-body phase space?

$d\Phi_{n+1}$

	$\frac{\sigma_n^{\text{incl}}}{B_n} B_{n+1} \diamond \Delta_n^B(t_{n+1})$
$\sigma_n^{\text{incl}} \diamond \Delta_n(\mu_n) \diamond PS(\mu_n)$	

$d\Phi_{n+2}$

Separate phase space

$d\Phi_n$

$$\sigma_n^{\text{incl}} \diamond \Delta_n(\mu_n)$$

choose $Q^B(\Phi_{\text{rad}}) = \frac{B_{n+1}}{B_n}$

$$\int d\Phi_{\text{rad}} \frac{B_{n+1}}{B_n} \Delta_n^B(t_{\text{rad}}) \theta(1 > t_{\text{rad}} > \mu) = 1 - \Delta_n^B(\mu)$$

$d\Phi_{n+1}$

	$\frac{\sigma_n^{\text{incl}}}{B_n} B_{n+1} \diamond \Delta_n^B(t_{n+1})$
$\sigma_n^{\text{incl}} \diamond \Delta_n(\mu_n) \diamond PS(\mu_n)$	

$d\Phi_{n+2}$

Separate phase space

$d\Phi_n$

$$\sigma_n^{\text{incl}} \diamond \Delta_n^B(\mu_n)$$

choose $Q^B(\Phi_{\text{rad}}) = \frac{B_{n+1}}{B_n}$

$$\int d\Phi_{\text{rad}} \frac{B_{n+1}}{B_n} \Delta_n^B(t_{\text{rad}}) \theta(1 > t_{\text{rad}} > \mu) = 1 - \Delta_n^B(\mu)$$

$d\Phi_{n+1}$

	$\frac{\sigma_n^{\text{incl}}}{B_n} B_{n+1} \diamond \Delta_n^B(t_{n+1})$
$\sigma_n^{\text{incl}} \diamond \Delta_n(\mu_n) \diamond PS(\mu_n)$	

$d\Phi_{n+2}$

POWHEG

Separate phase space

$d\Phi_n$

$\sigma_n^{\text{incl}} \cdot \Delta_n^B(\mu_n)$

Need to calculate integral

$d\Phi_{n+1}$

	$\frac{\sigma_n^{\text{incl}}}{B_n} B_{n+1} \cdot \Delta_n^B(t_{n+1})$
$\sigma_n^{\text{incl}} \cdot \Delta_n(\mu_n) \cdot PS(\mu_n)$	

$d\Phi_{n+2}$

POWHEG

Separate phase space

Need to calculate integral

$d\Phi_n$

$$\sigma_n^{\text{inc}} \diamond \Delta_n^B(\mu_n)$$

Need to calculate Sudakov

$d\Phi_{n+1}$

	$\frac{\sigma_n^{\text{incl}}}{B_n} B_{n+1} \diamond \Delta_n^B(t_{n+1})$
$\sigma_n^{\text{incl}} \diamond \Delta_n(\mu_n) \diamond PS(\mu_n)$	

POWHEG

$d\Phi_{n+2}$

Separate phase space

$d\Phi_n$

$$\sigma_n^{\text{incl}} \diamond \Delta_n^{\text{B}}(\mu_n)$$

Need to calculate integral
Need to calculate Sudakov

Broken the symmetry

$d\Phi_{n+1}$

	$\frac{\sigma_n^{\text{incl}}}{B_n} B_{n+1} \diamond \Delta_n^{\text{B}}(t_{n+1})$
$\sigma_n^{\text{incl}} \diamond \Delta_n(\mu_n) \diamond PS(\mu_n)$	

POWHEG

$d\Phi_{n+2}$



Separate phase space

$d\Phi_n$

$$\sigma_n^{\text{incl}} \cdot \Delta_n^{\text{B}}(\mu_n)$$

Need to calculate integral
Need to calculate Sudakov
Difficult to extend

$d\Phi_{n+1}$

	$\frac{\sigma_n^{\text{incl}}}{B_n} B_{n+1} \cdot \Delta_n^{\text{B}}(t_{n+1})$
$\sigma_n^{\text{incl}} \cdot \Delta_n(\mu_n) \cdot PS(\mu_n)$	

POWHEG

$d\Phi_{n+2}$

Our Method

$d\Phi_n$

$$\frac{d\sigma_n^{\text{excl}}(\mu_n)}{d\Phi_n}$$

Each correct @ NLO/LL

Gives inclusive @ NLO

No gratuitous num integrals

$d\Phi_{n+1}$

$$\frac{d\sigma_{n+1}^{\text{excl}}(\mu_{n+1})}{d\Phi_{n+1}}$$

----- μ_n

$d\Phi_{n+2}$

$$\frac{d\sigma_{n+2}^{\text{excl}}(\mu_{n+2})}{d\Phi_{n+2}}$$

Determining the σ^{excl}

- Obtain the correct expression at fixed order
 - Need careful definition of J_{MC} to have analytical results
- Write expression that has correct logarithmic structure
 - Use parton shower ideas as a guideline
- Combine the two results by a simple matching

Fixed order results

Deriving a generic expression

$$\frac{d\sigma_n^{\text{excl}}(\mu_n)}{d\Phi_n} = \frac{d\sigma_n^{\text{parton}}}{d\Phi_n} + \int d\Phi'_{n+1} \frac{d\sigma_{n+1}^{\text{parton}}}{d\Phi_n} J_{\text{MC}}(\Phi'_{n+1}, \Phi_n, \mu_n)$$



Final result for small μ_n

$$\frac{d\sigma_n^{\text{excl}}(\mu_n)}{d\Phi_n} = B_n(\Phi_n) + V_n(\Phi_n) + \int d\Phi'_{n+1} S_{n+1}(\Phi'_{n+1}) J_{\text{MC}}(\Phi'_{n+1}, \Phi_n, \mu_n)$$

Fixed order results

$$\frac{d\sigma_n^{\text{excl}}(\mu_n)}{d\Phi_n} = B_n(\Phi_n) + V_n(\Phi_n) + \int d\Phi'_{n+1} S_{n+1}(\Phi'_{n+1}) J_{\text{MC}}(\Phi'_{n+1}, \Phi_n, \mu_n)$$

Need to choose J_{MC} such that analytically calculable

Write S as sum over different terms

$$S_{n+1}(\Phi'_{n+1}) = \sum_i S_{n+1}^{(i)}(\Phi'_{n+1})$$

For each i can find $J_{\text{MC}}^{(i)}$ that allows to integrate

$$\int d\Phi_{n+1} S_{n+1}^{(i)}(\Phi_{n+1}) J_{\text{MC}}^{(i)}(\Phi_{n+1}, \Phi_n, \mu_n)$$

Therefore, can choose

$$J_{\text{MC}}(\Phi'_{n+1}, \Phi_n, \mu_n) = \sum_i \frac{S_{n+1}^{(i)}(\Phi'_{n+1})}{S_{n+1}(\Phi'_{n+1})} J_{\text{MC}}^{(i)}(\Phi'_{n+1}, \Phi_n, \mu_n)$$

Example: Catani-Seymour

Different term for each of three partons [(i) → ij,k]


singularity $p_i \cdot p_j \rightarrow 0$
with k recoil

$$\sum_i \equiv \sum_{ij,k}$$

Factorization for
each {ij,k}

$$S_{n+1}^{(i)}(\Phi_{n+1}) \equiv \mathcal{D}_{n+1}^{ij,k}(\Phi_{n+1})$$

$$d\Phi_{n+1} \equiv d\Phi_n^{ij,k} d\Phi_{\text{rad}}^{ij,k}$$

$$dy^{ij,k} dz^{ij,k} d\phi^{ij,k}$$


This allows to define

$$J_{\text{MC}}^{ij,k}(\Phi_{n+1}, \Phi_n, \mu_n) = \delta(\Phi_n - \Phi_n^{ij,k}) \Theta(y^{ij,k} < \mu_n)$$

Gives rise to analytically calculable integrals

Nagy, Trocsanyi ('98)

Correct logarithmic structure

Use the fact that parton shower resums
leading logarithmic terms

Write cross section in recursive form

$$\left[\frac{d\sigma_n^{\text{PS}}}{d\Phi_n} \right] = \left[\frac{d\sigma_{n-1}^{\text{PS}}}{d\Phi_{n-1}} \right] \times PS$$

Several subtleties, but can be done

Combine results

Use slightly generalized LL result

$$\left[\frac{d\sigma_n^{\text{MC}}(\mu_n)}{d\Phi_n} \right] = \sum_i \left(\left[\frac{d\sigma_{n-1}^{\text{MC}}}{d\Phi_{n-1}} \right] Q^{(i)}(\Phi_{n-1 \rightarrow n}) + M_n^{(i)}(\Phi_n) \right) \Delta_n(\mu_n)$$

Choose splitting functions as

$$Q^{(i)}(\Phi_{n-1 \rightarrow n}) = \frac{S_n^{(i)}(\Phi_n)}{B_{n-1}(\Phi_{n-1})}$$

Determine matching coefficient by explicit comparison
with previous NLO result

Determining the σ^{excl}

By expanding to NLO order and comparing with known results, can obtain M_n

$$M_n^{i_n, (0)}(\Phi_n) = S_n^{i_n}(\Phi_n) \left(\frac{B_n(\Phi_n)}{S_n(\Phi_n)} - 1 \right)$$

$$M_n^{i_n, (1)}(\Phi_n) = S_n^{i_n} \left(\frac{V_n^S(\Phi_n, \mu_n)}{S_n(\Phi_n)} - \frac{V_{n-1}^S(\Phi_{n-1}^{i_n}, t_n^{i_n})}{B_{n-1}(\Phi_{n-1}^{i_n})} - \Delta_n^{(1)}(t_n^{i_n}, \mu_n) \right)$$

The tree
level
diagrams

Known
subtraction
functions

The virtual
(1-loop)
diagrams

Expansion of
the Sudakov
function

Everything known analytically!

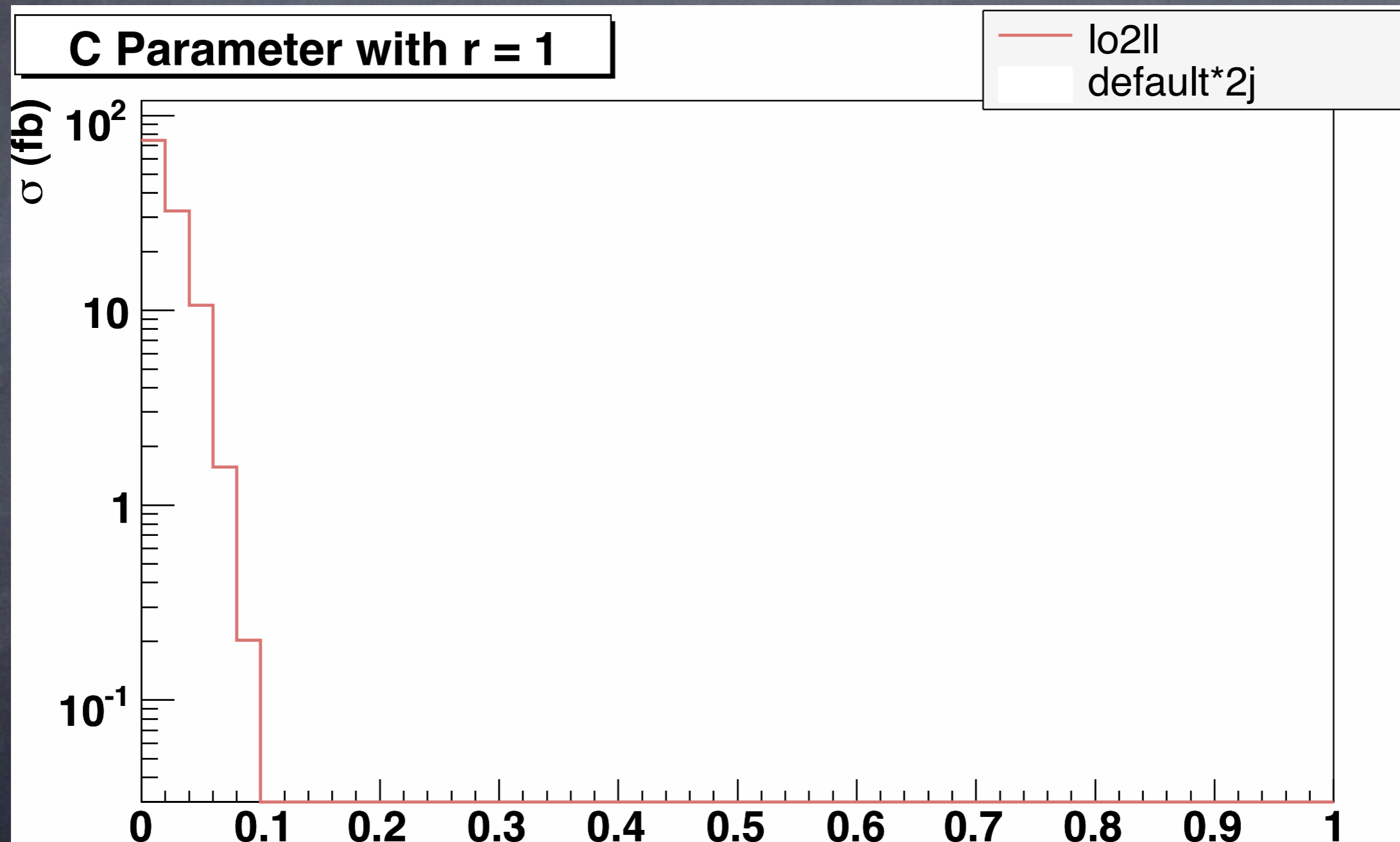
Status of the work?

Have all the analytical results
worked out in detail for e^+e^-

Currently debugging implementation
in GenEvA for e^+e^-

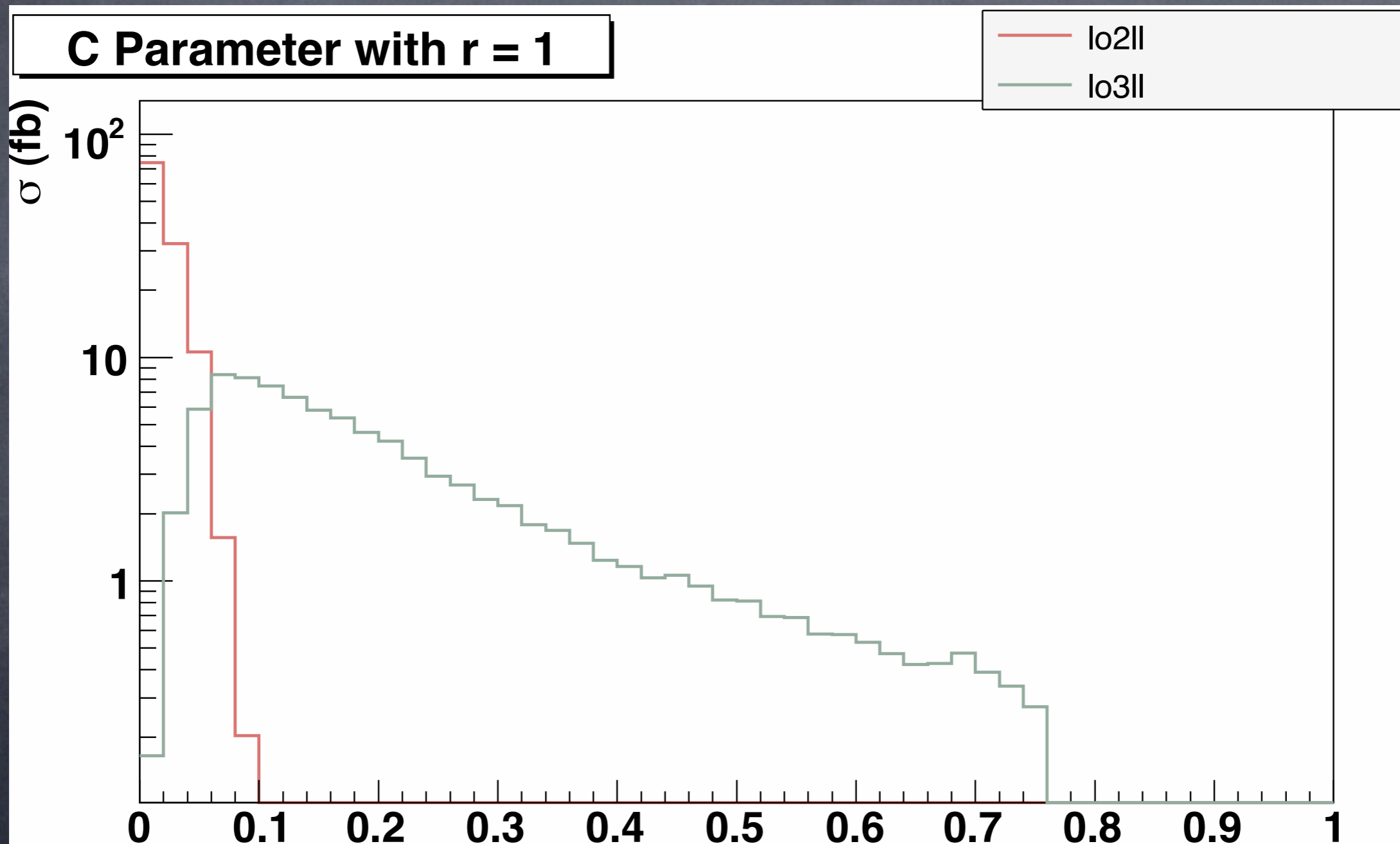
Implementation in GenEvA

Just 2-body LO matrix element, NLO improved



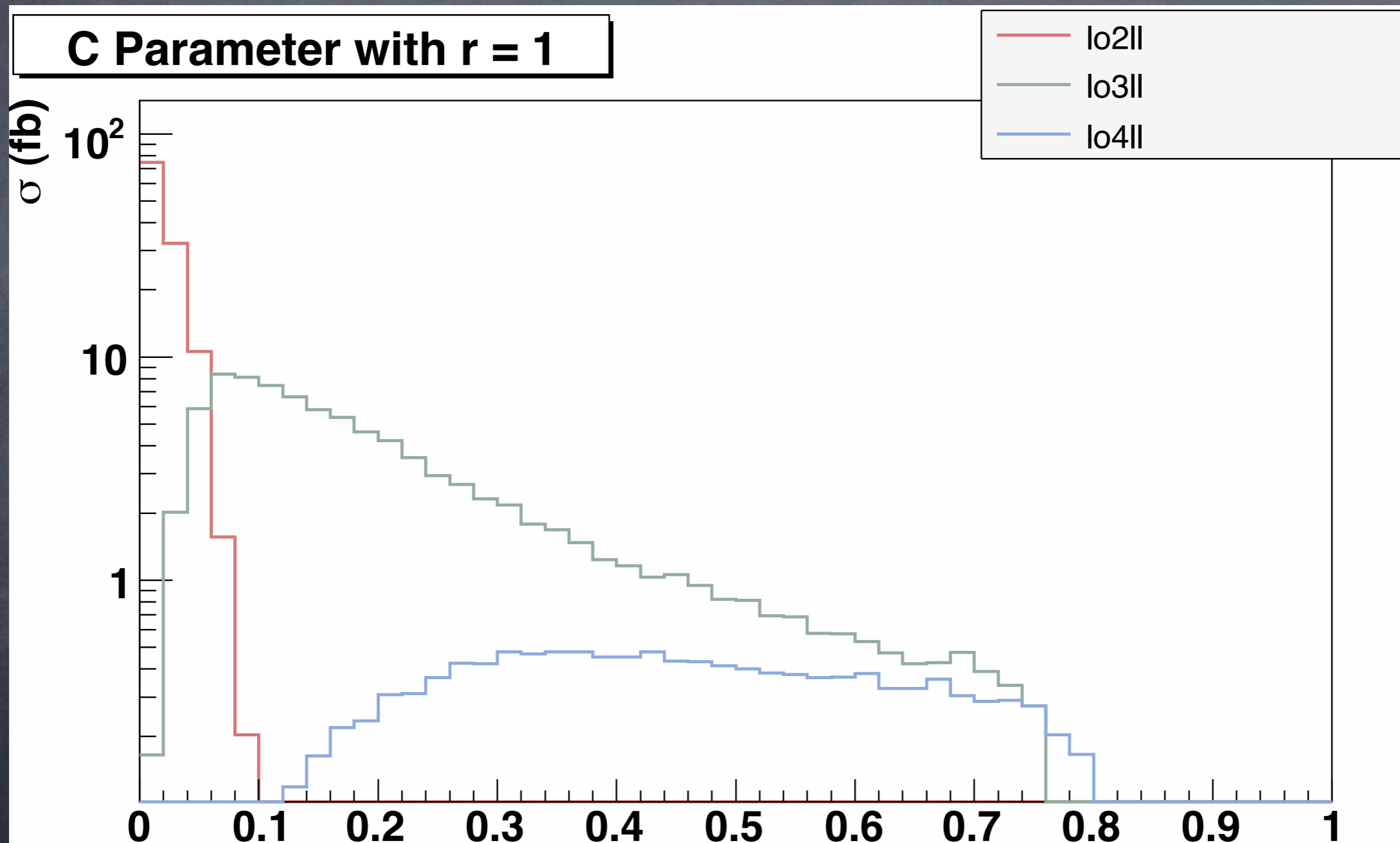
Implementation in GenEvA

Add 3-body LO matrix element



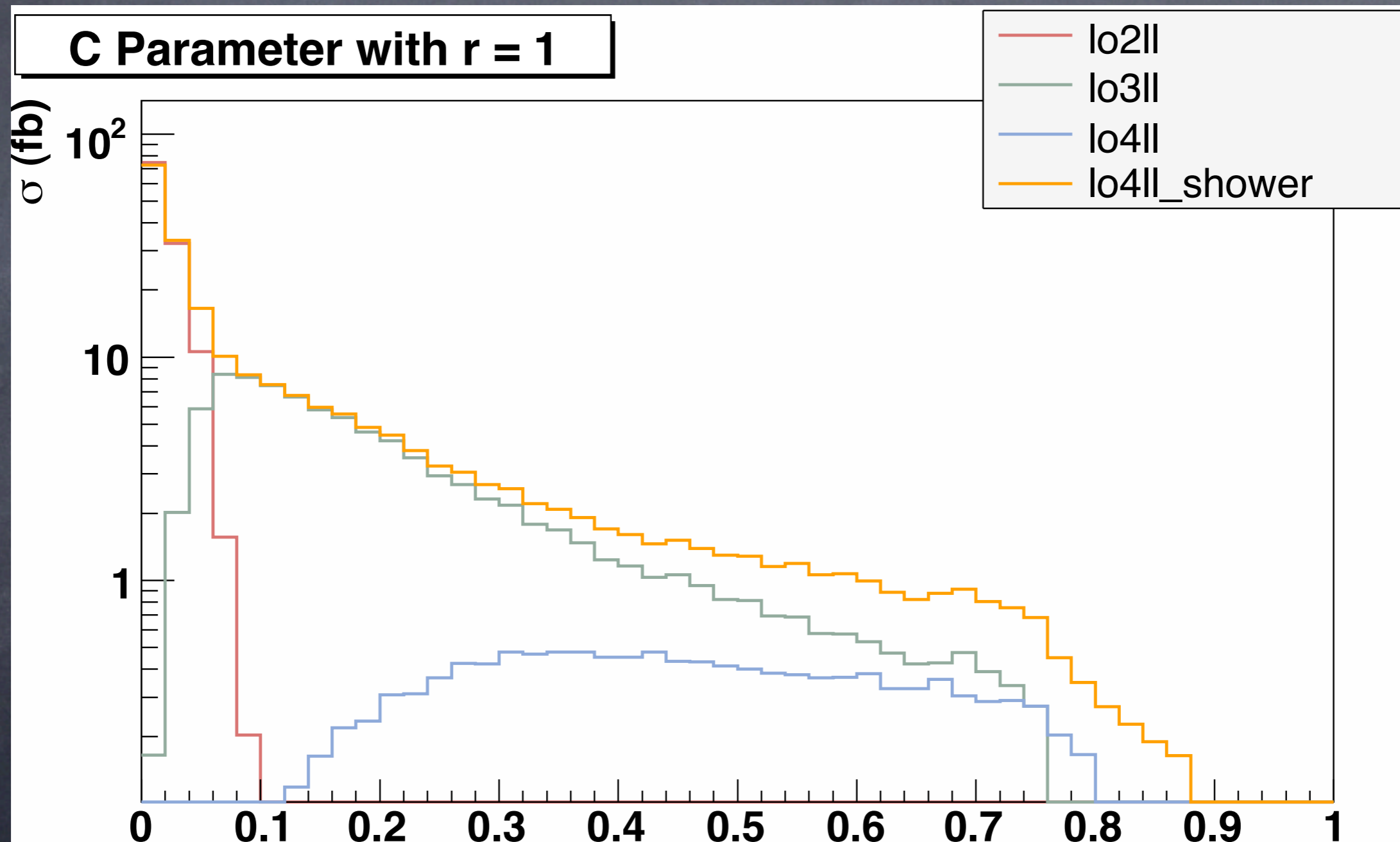
Implementation in GenEvA

Add 4-body LO matrix element



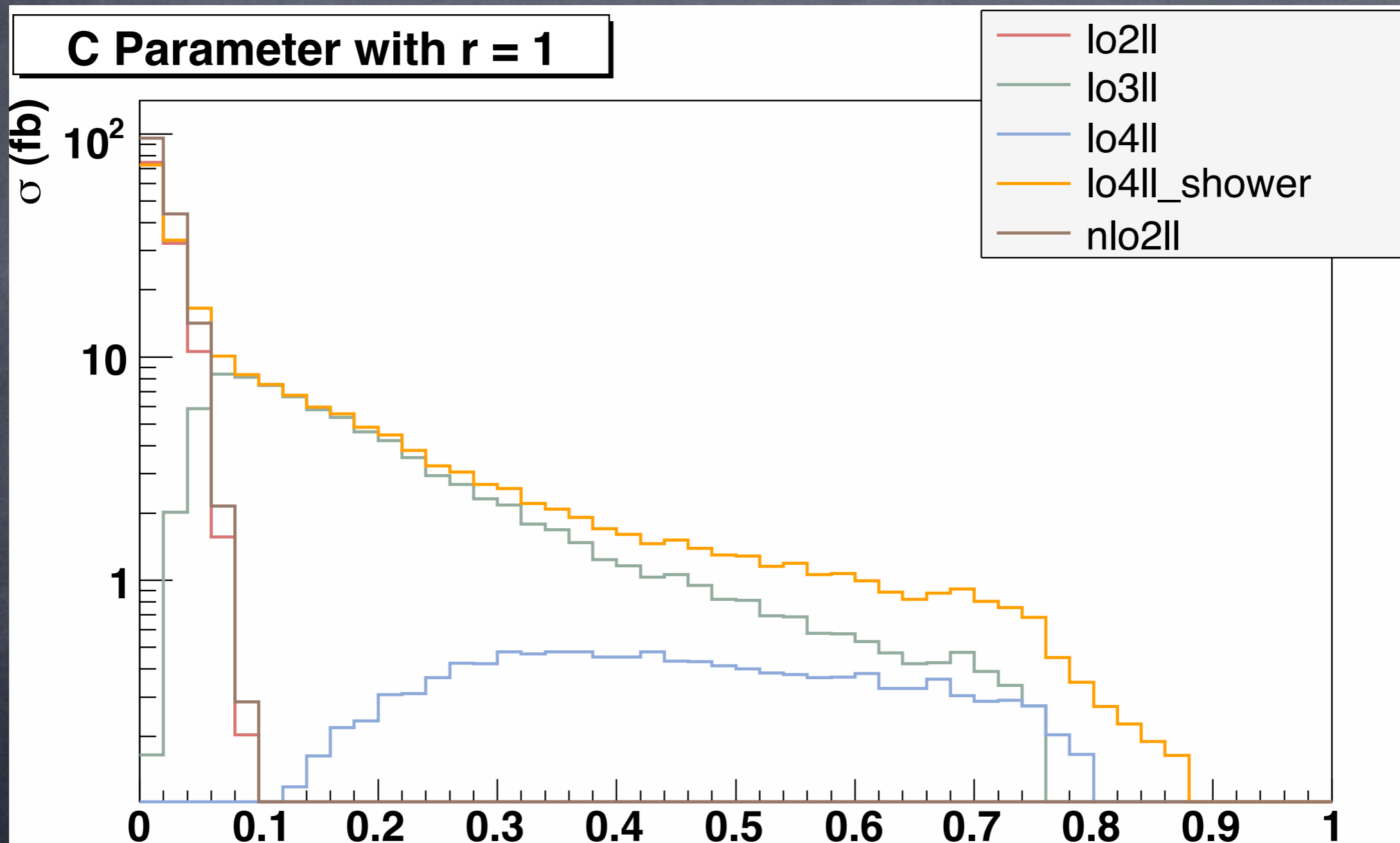
Implementation in GenEvA

Combine together and add parton shower



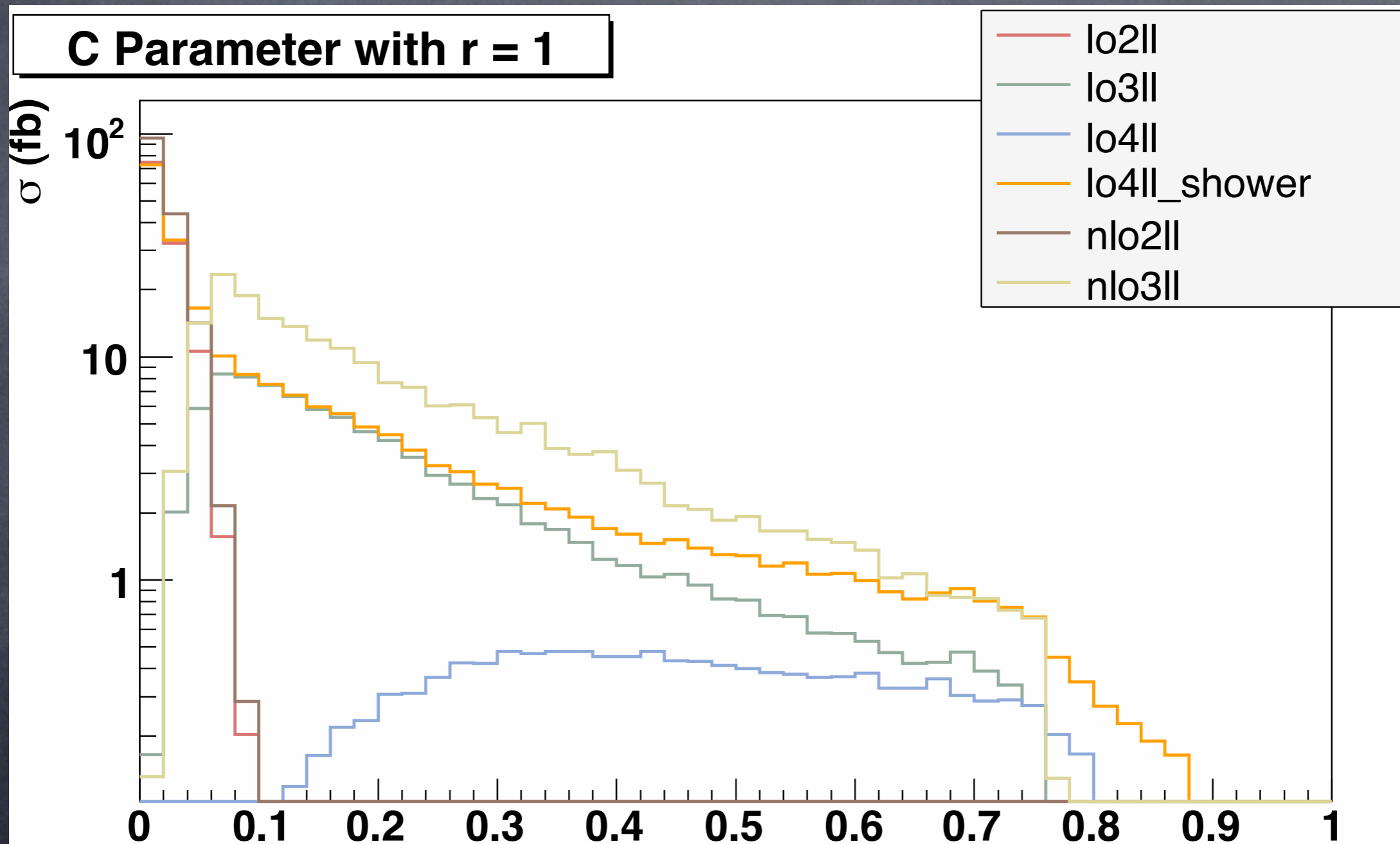
Implementation in GenEvA

Use NLO for 2-body process



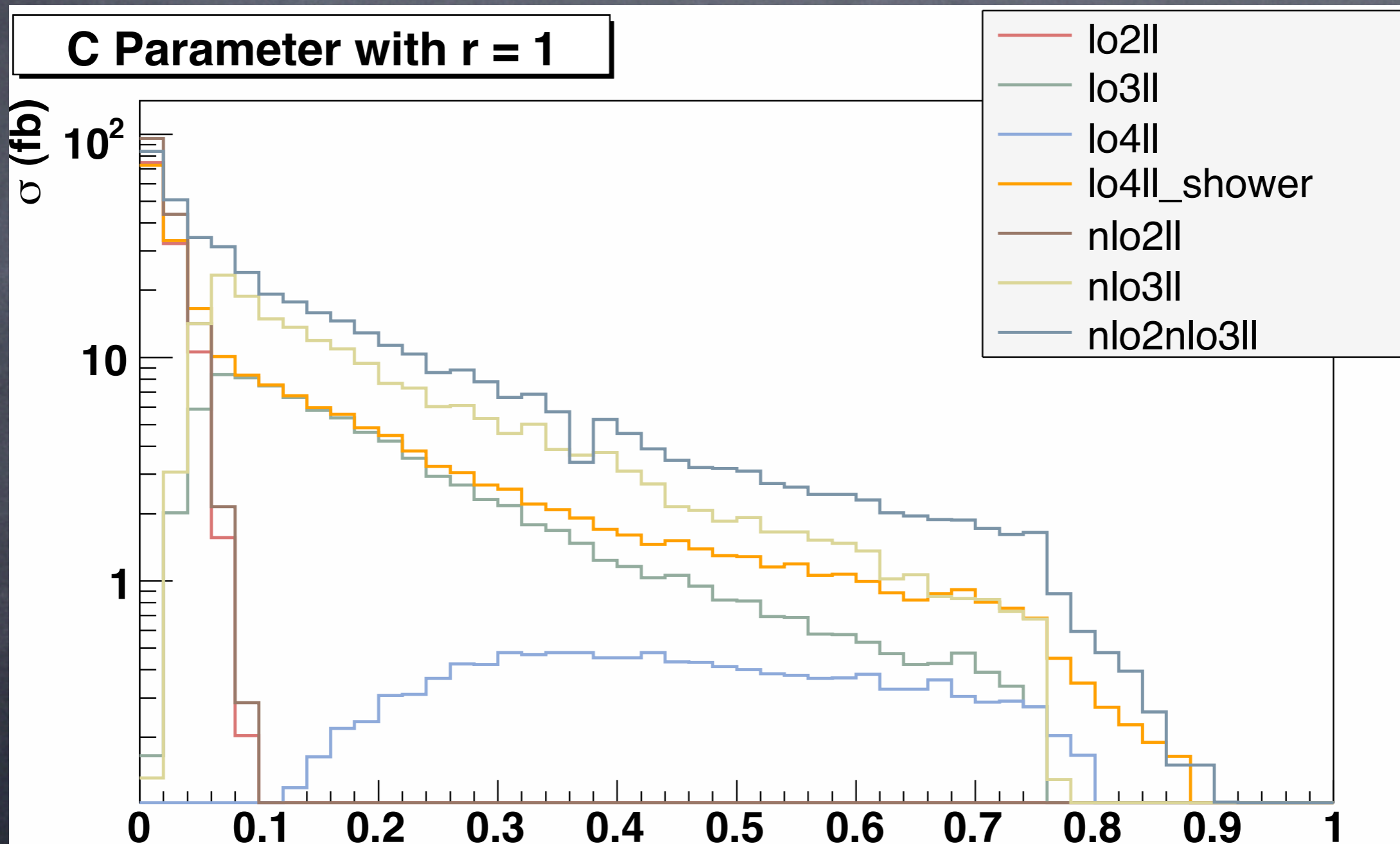
Implementation in GenEvA

Use NLO for 3-body process



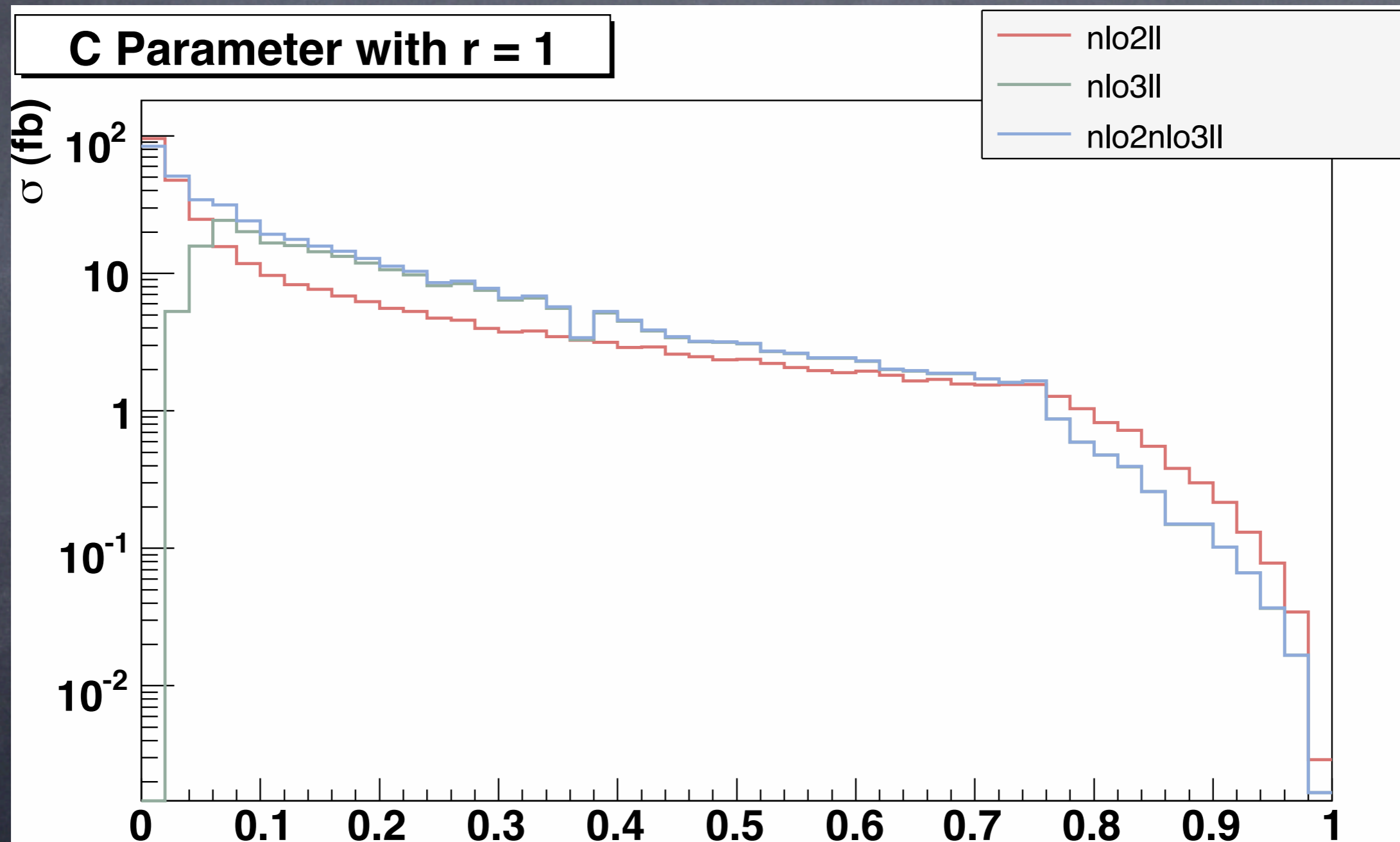
Implementation in GenEvA

Combine together and add parton shower



Implementation in GenEvA

Show NLO Cascade with lower cut on shower



Status of the work?

Have all the analytical results
worked out in detail for e^+e^-

Currently debugging implementation
in GenEvA for e^+e^-

Working on extension to allow for
hadron colliders

**Hope to have first numerical results by
the summer**

Conclusions

- Both NLO calculations and parton shower algorithms crucial to have detailed understanding of signals and backgrounds
- Need to merge the two approaches to get reliable and trustworthy results
- Four main problems that need to be addressed
- Believe we have a fast and efficient algorithm that should give us first results by the summer