MadGraph5

Olivier Mattelaer

Aim of the Lecture

- Get you acquainted with the concepts and techniques used in event generation
- Give you hands-on experience
- Answer as many of your questions as I can

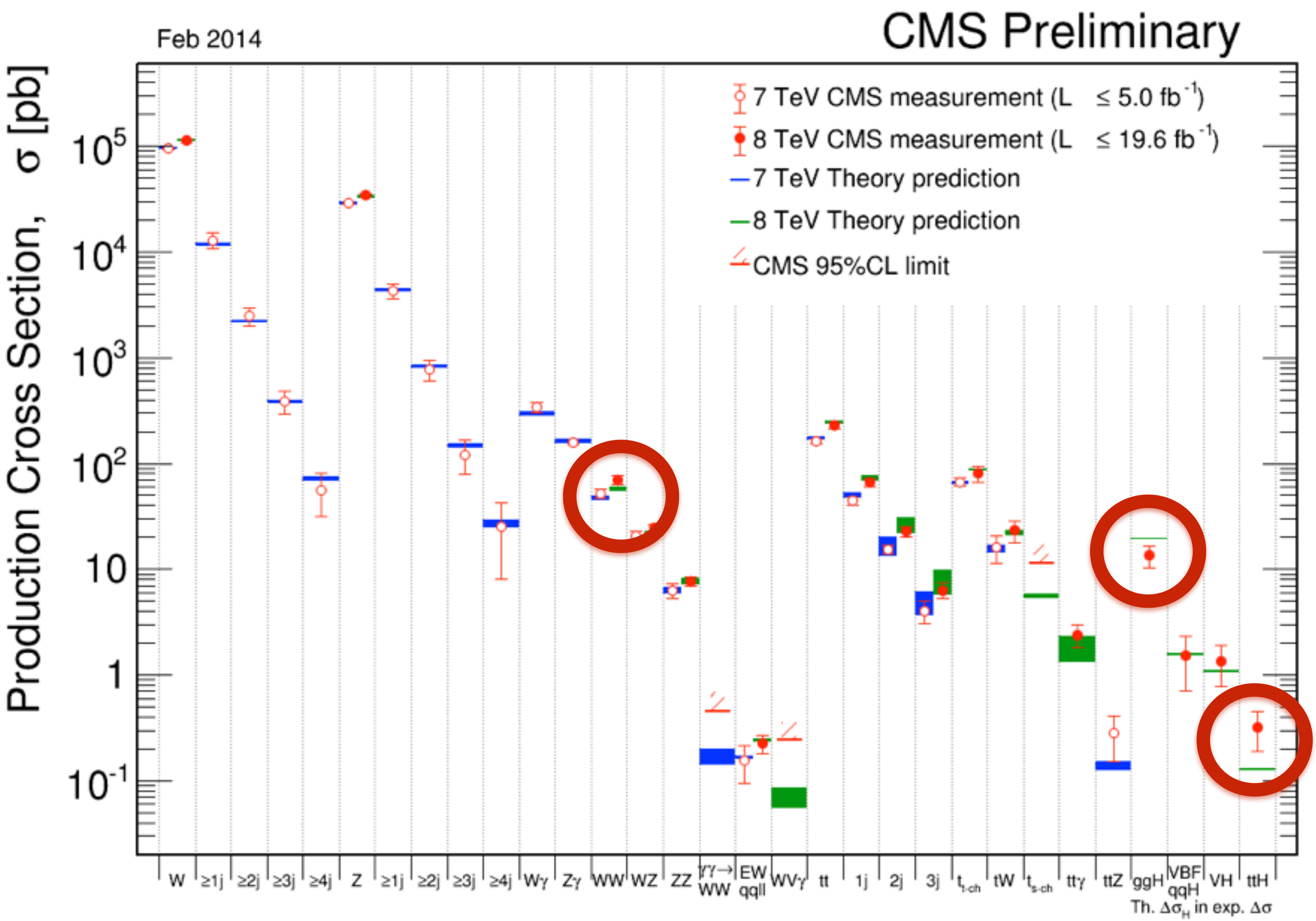
Lecture I

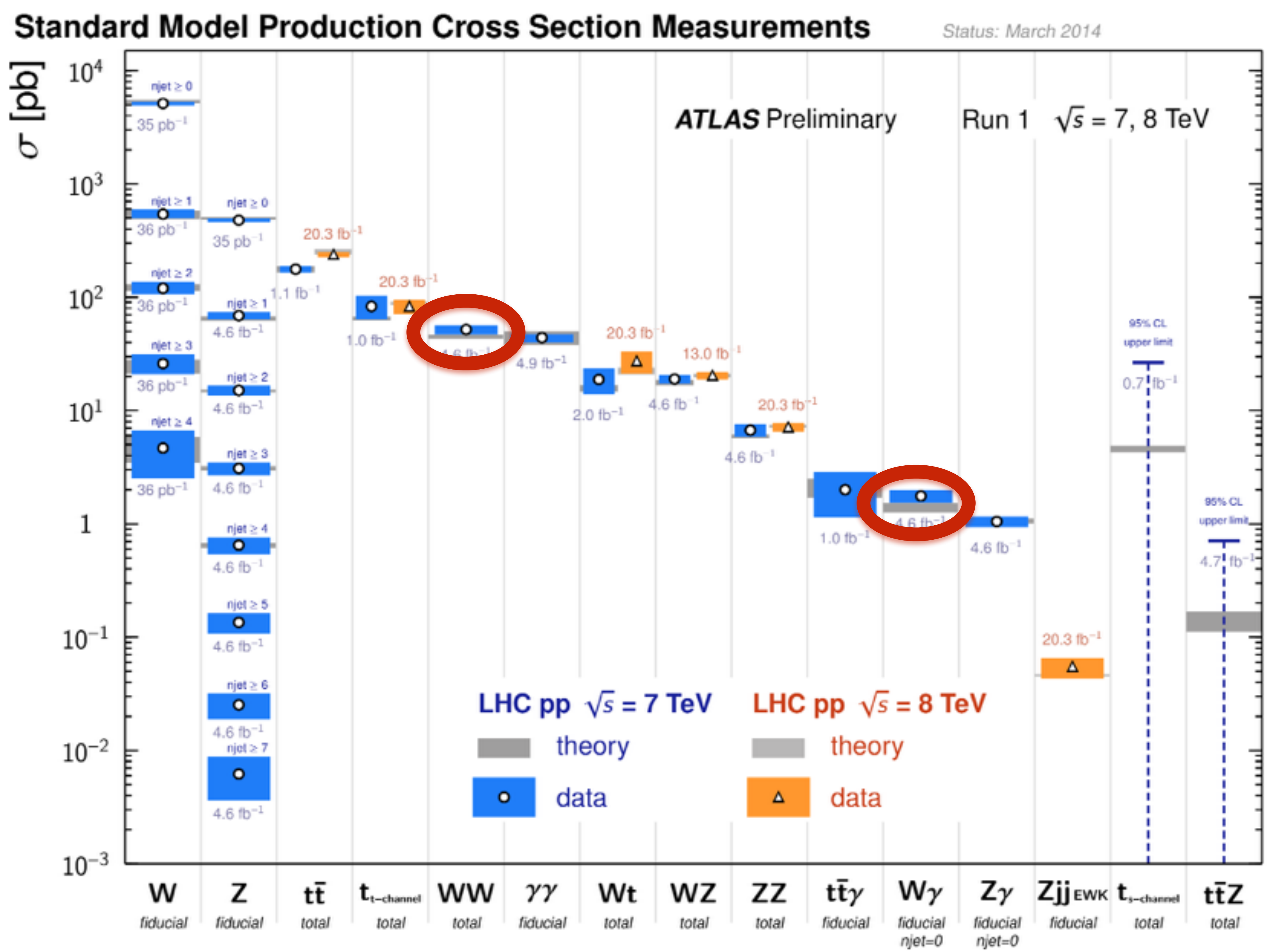
- Introduction
- Evaluation of Matrix Element
- Integration of the cross-section/ events generation

Lecture II

- Shower Monte-Carlo
- Matching/Merging

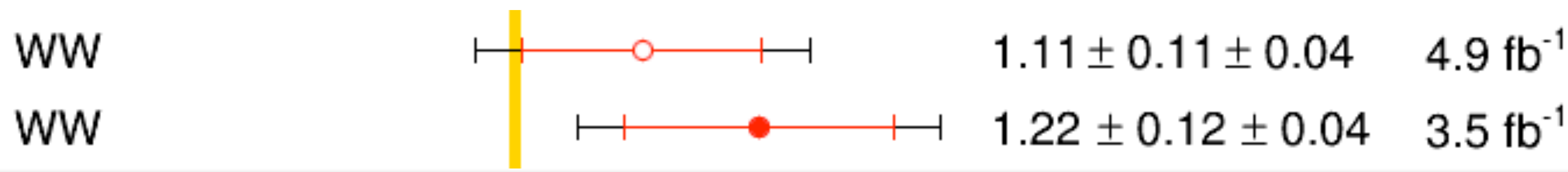
Standard Model





Standard Model Production Cross Section Measurements
Status: March 2014
ATLAS Preliminary
Run 1 √s = 7, 8 TeV
σ [pb]
LHC pp √s = 7 TeV
theory
data
LHC pp √s = 8 TeV
theory
data
W fiducial
Z fiducial
tt̄ total
t t-channel total
WW total
γγ fiducial
Wt total
WZ total
ZZ total
tt̄γ fiducial
Wγ fiducial njet=0
Zγ fiducial njet=0
Zjj EWK fiducial
t s-channel total
tt̄Z total
95% CL upper limit

CMS

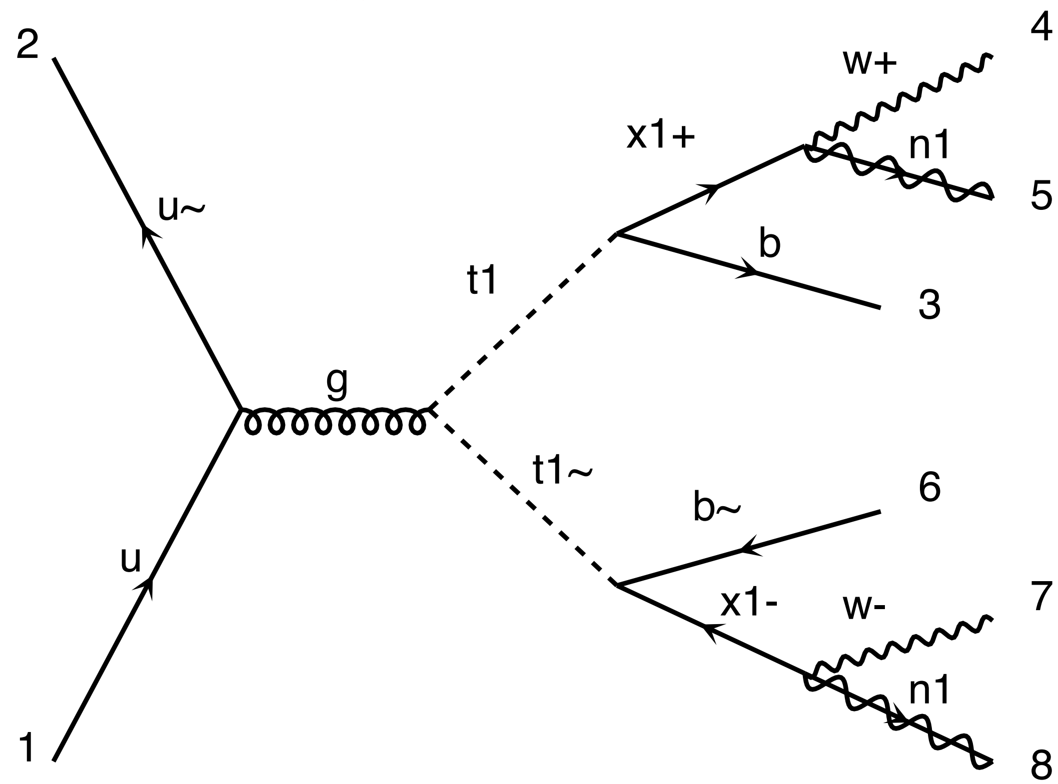


ATLAS

COMBINE

- Both seems indicates a 15-20% excess
- Not significant at all
- Need more data / theoretical precision

SUSY Like Explanation



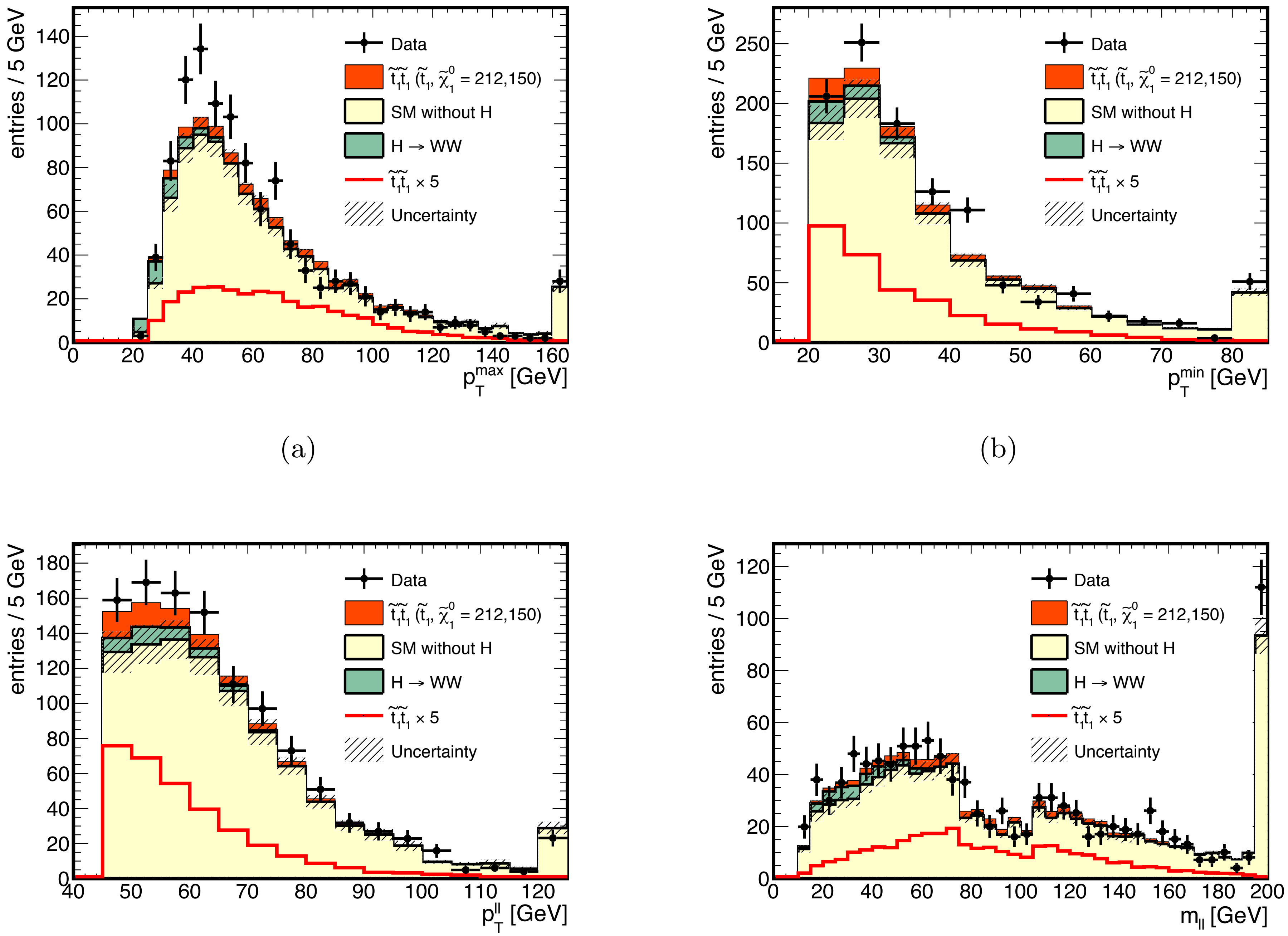
Kim, Rolbiecki, sakurai, Tattersal [1406.0858]

Compressed Spectrum $M_{\tilde{t}} \approx M_{\chi^+}$

- Soft b/b~
  - ➡ not observed
- evade direct searches constraints

Check the model!

- Monte-Carlo!



Kim, Rolbiecki, Sakurai, Tattersal [1406.0858]

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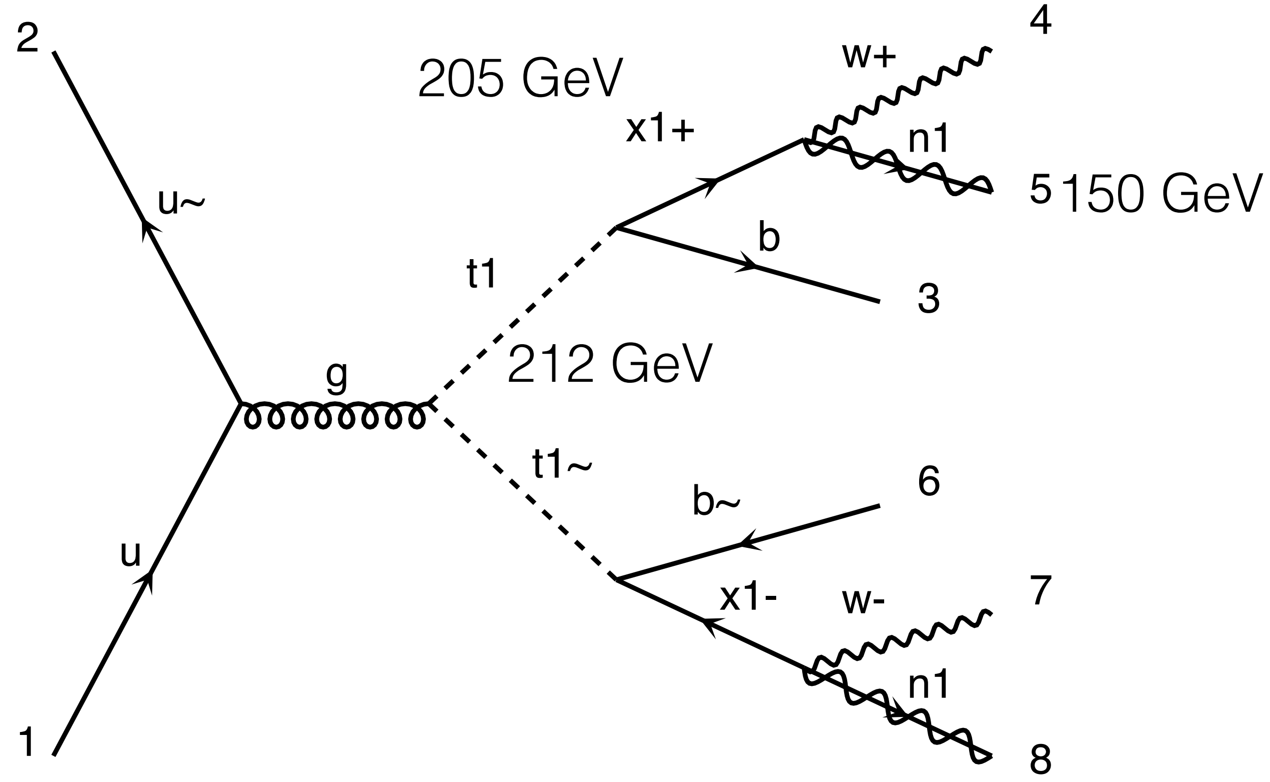

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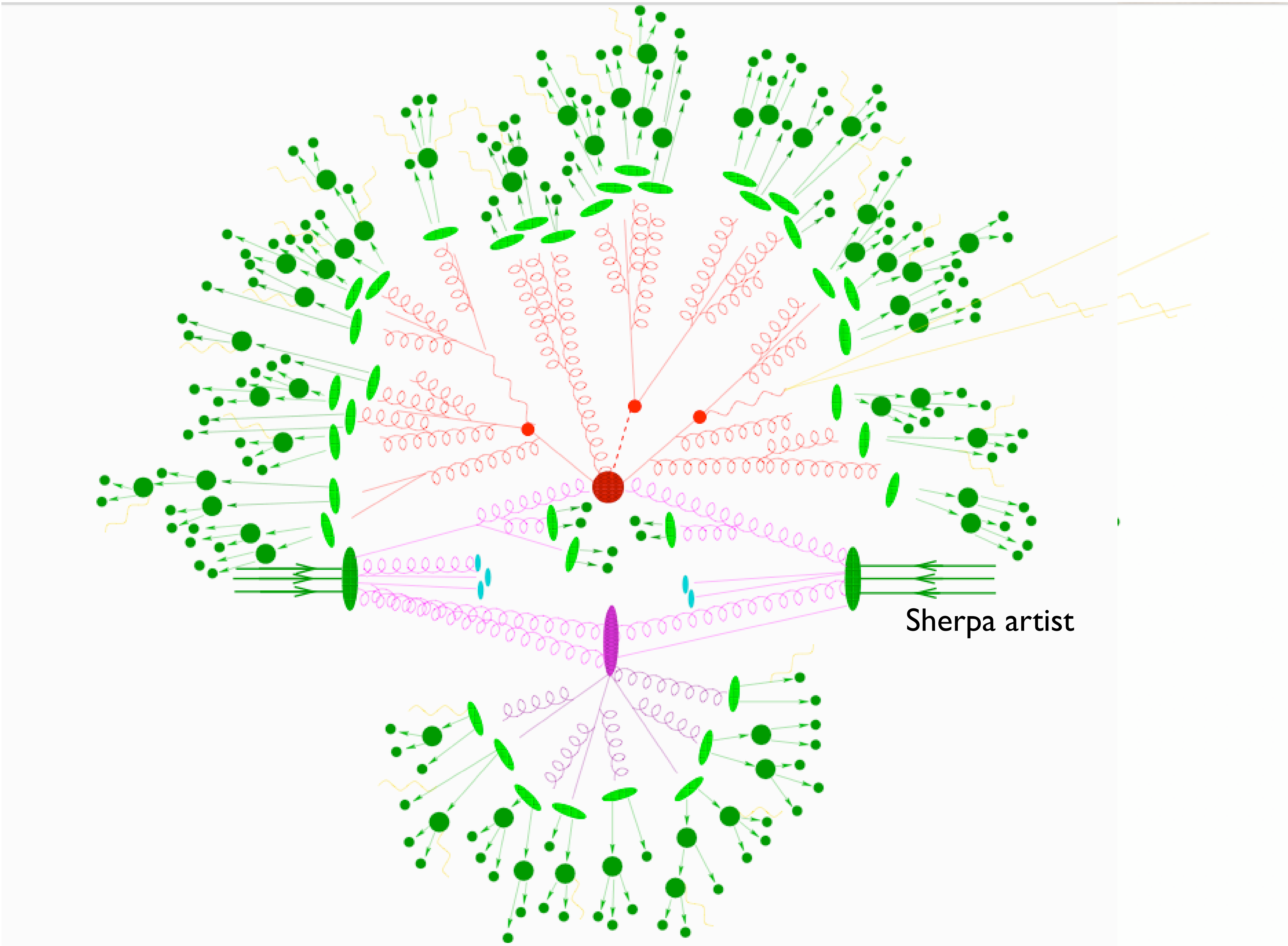
4. Find range of model parameters that can explain excess
   - ➡ Typically, using Monte Carlo simulations
5. Find other observables (collider as well as flavor/EWP/cosmology) where the explanation can be verified/falsified
   - ➡ Note that indirect constraints (flavor/EWP/cosmology) typically modified by additional particles in the spectrum

Simulation of collider events

What are the MC for?

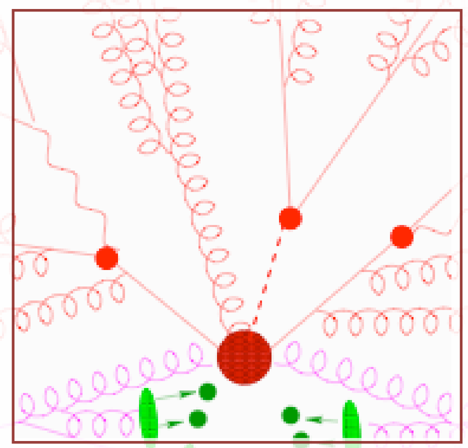


What are the MC for?

1. High-Q^2 Scattering

2. Parton Shower

☞ where new physics lies



☞ process dependent

☞ first principles description

☞ it can be systematically improved

3. Hadronization

4. Underlying Event

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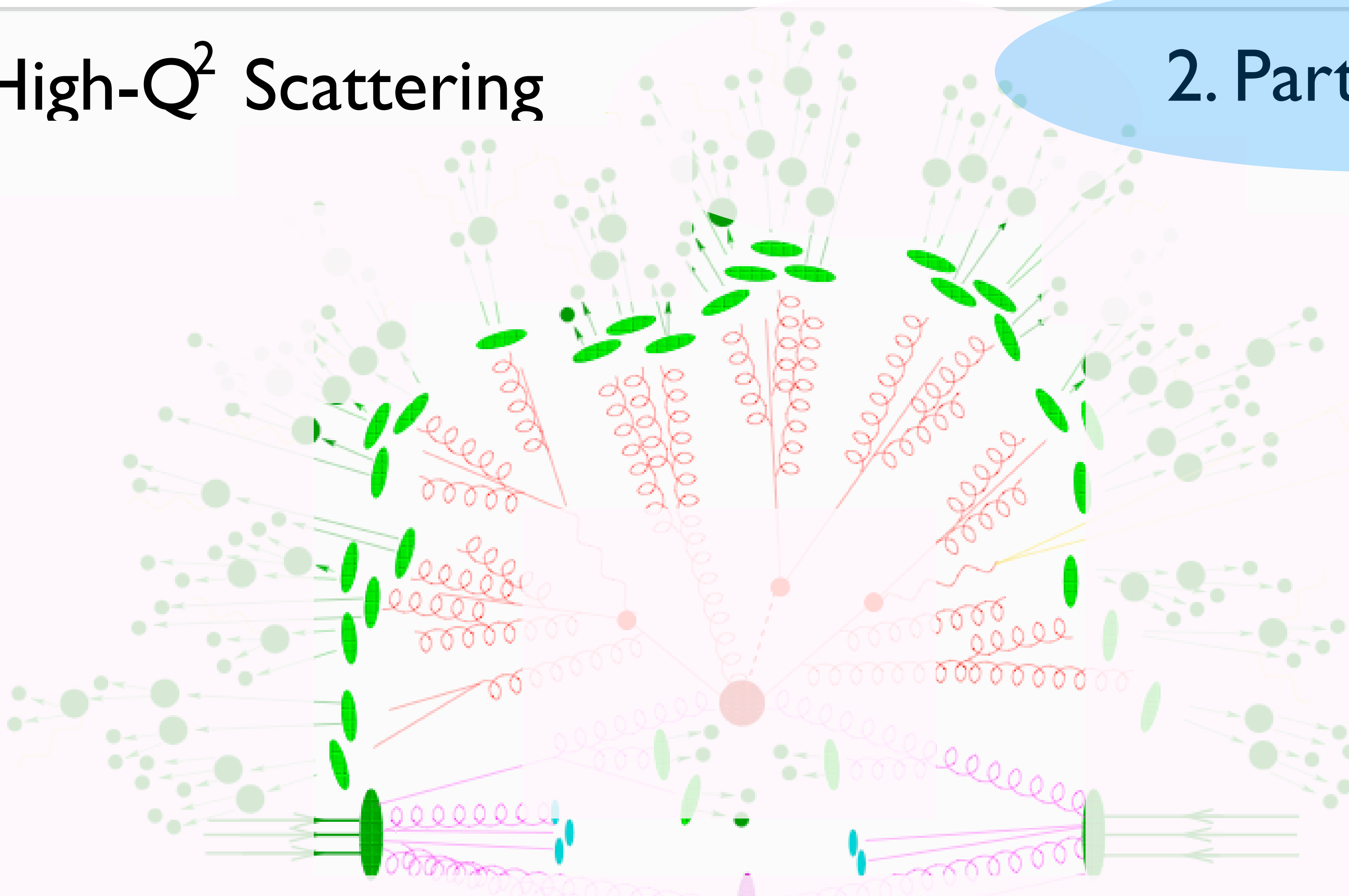

- ☞ QCD -"known physics"
- ☞ universal/ process independent
- ☞ first principles description

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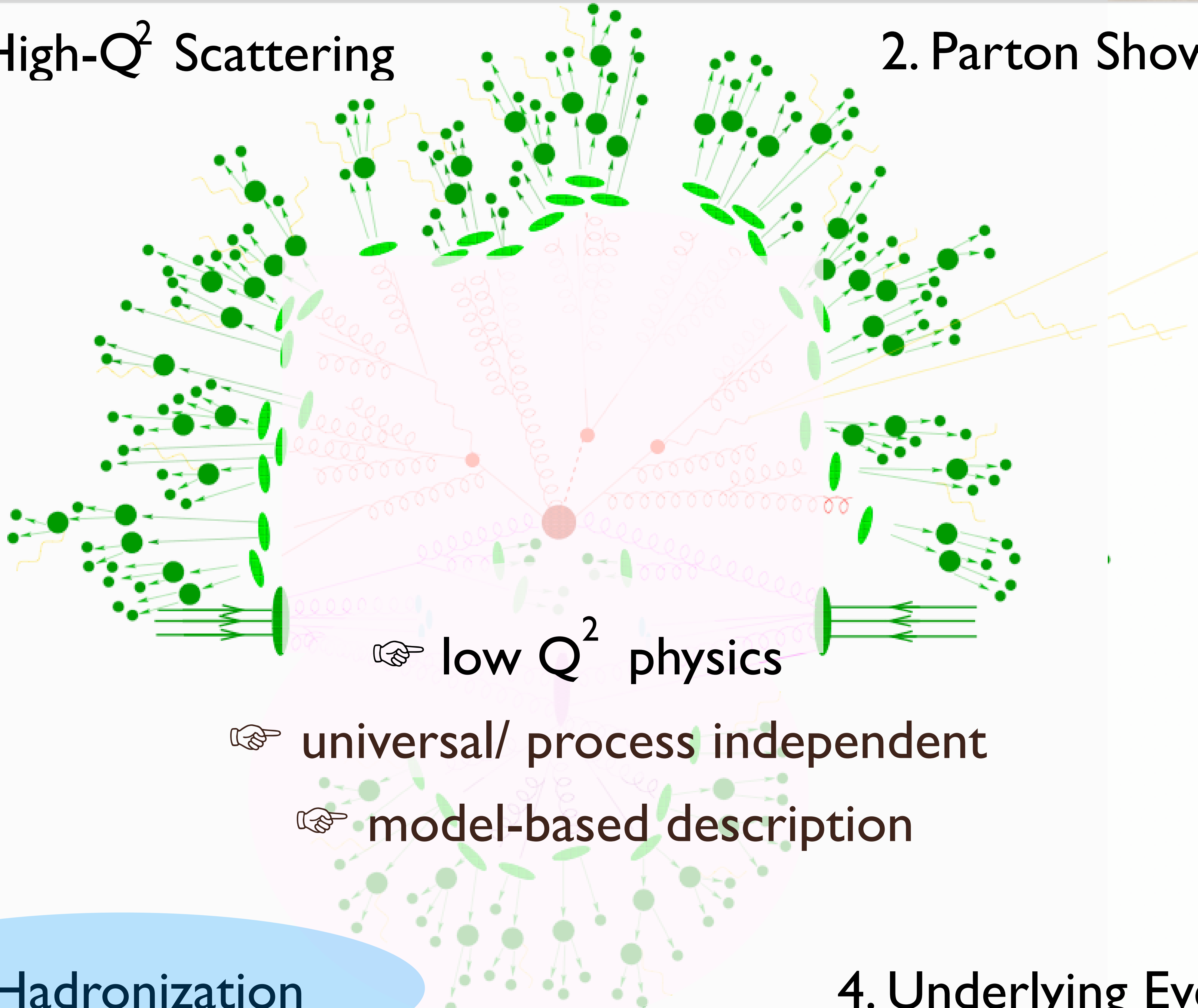

- ☞ low Q^2 physics
- ☞ universal/ process independent
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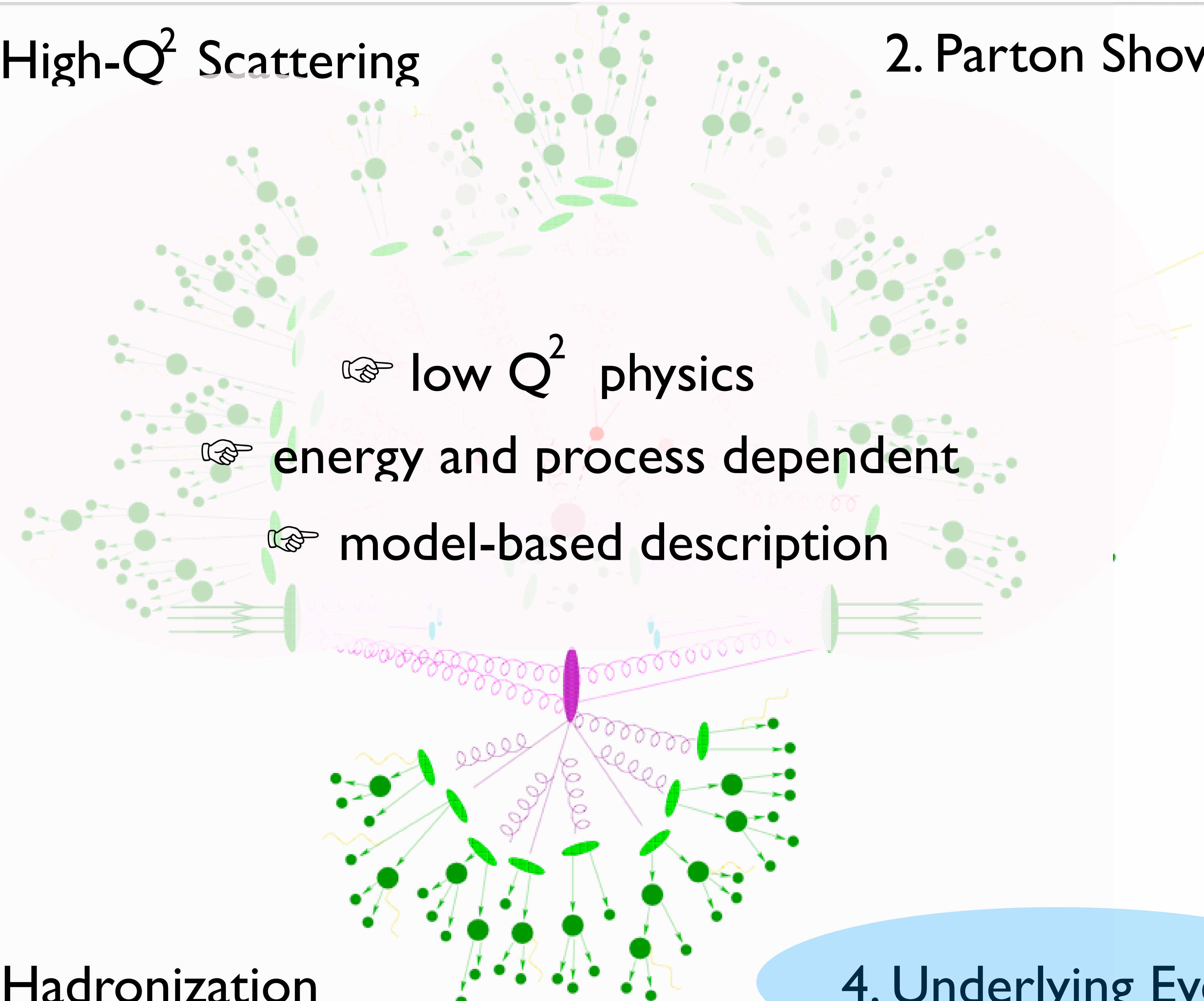

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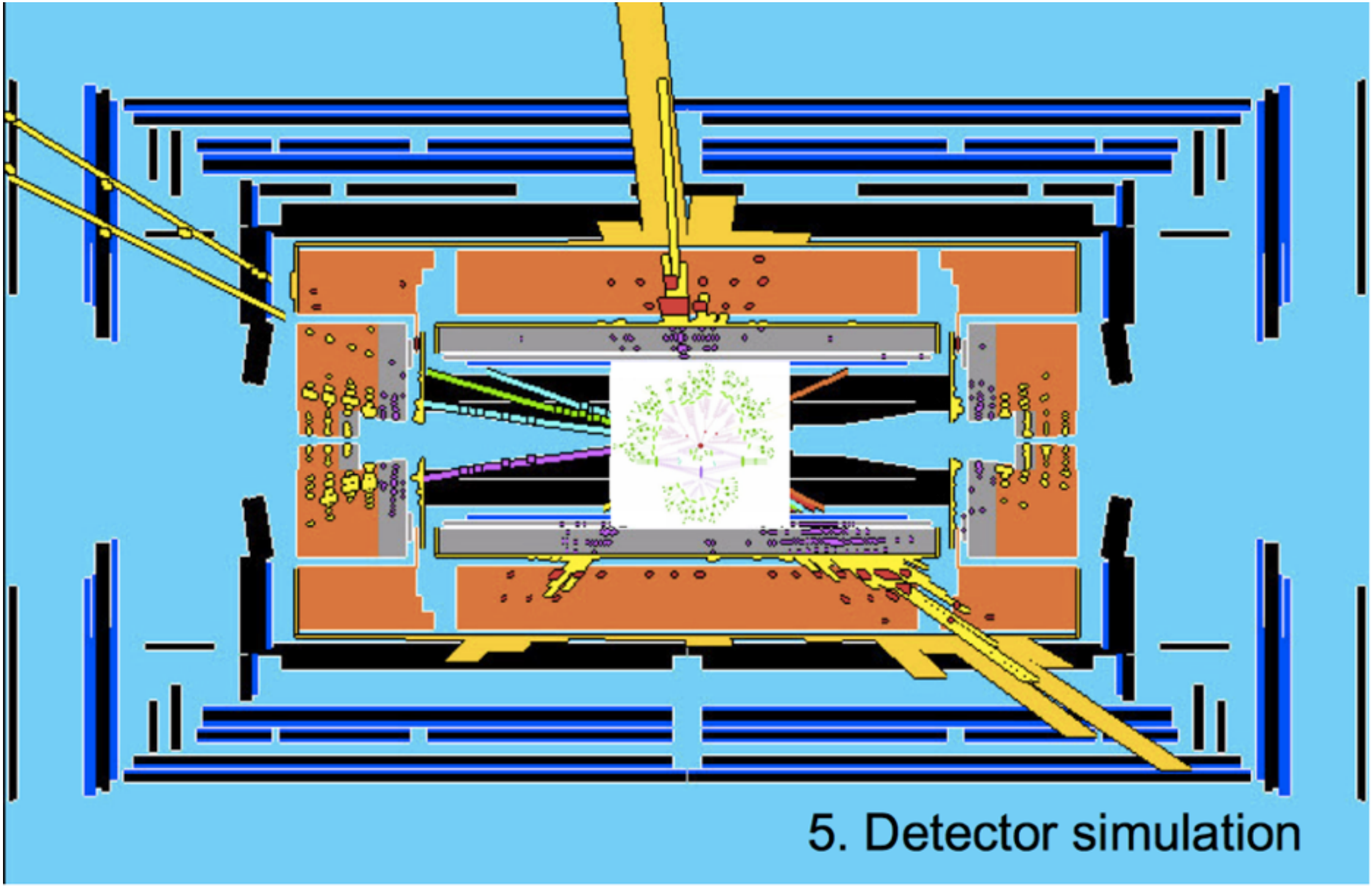

Tevatron vs. the LHC

- Tevatron: 2 TeV proton-antiproton collider
  - ➡ Most important: q-$\bar{q}$ annihilation (85% of $t\bar{t}$)
- LHC: 8-14 TeV proton-proton collider
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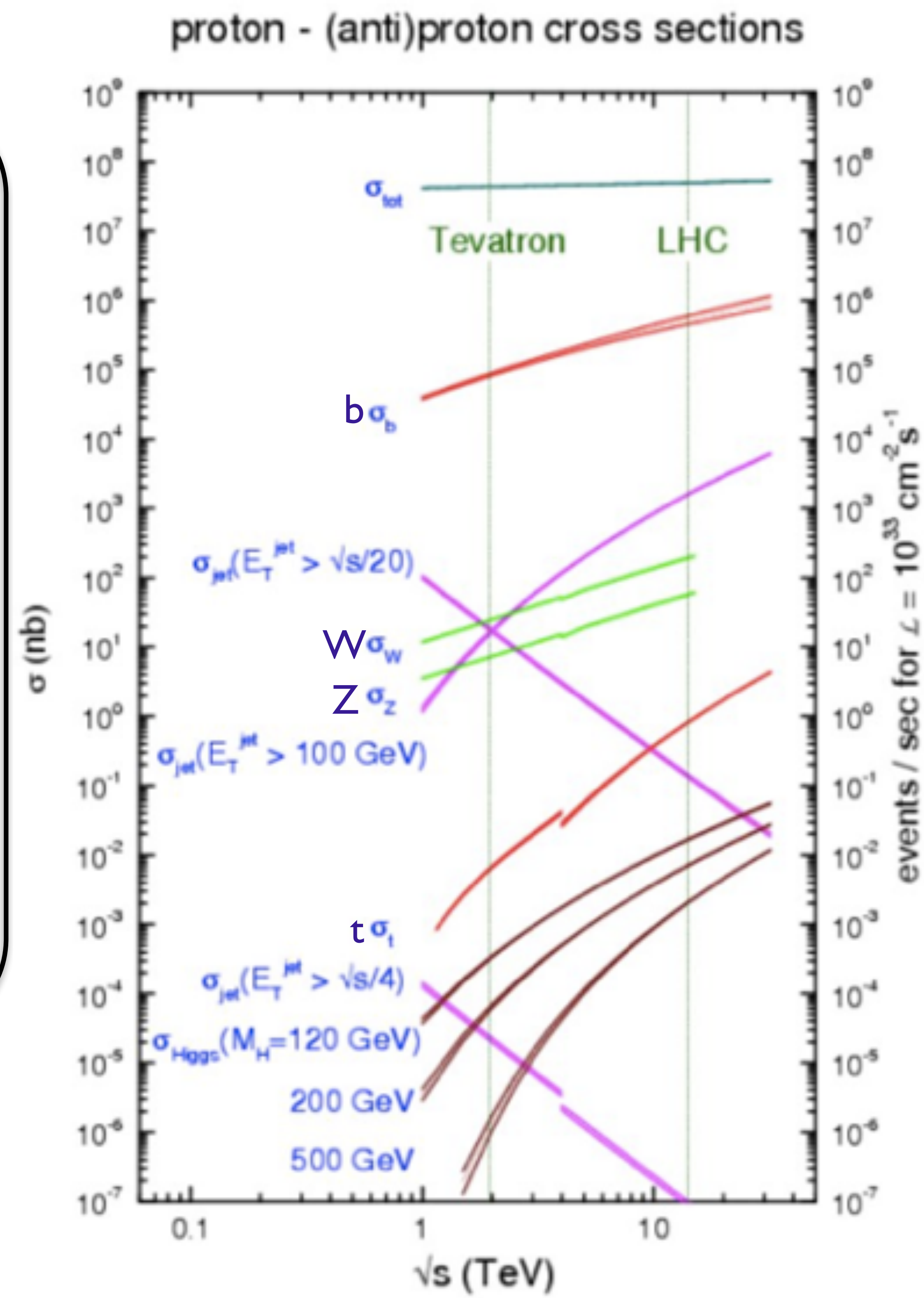
Hadron Colliders

First: Understand our processes!

Cross sections at a collider depend on:

- Coupling strength
- Coupling to what?
  (light quarks, gluons, heavy quarks, EW gauge bosons?)
- Mass
- Single production/pair production



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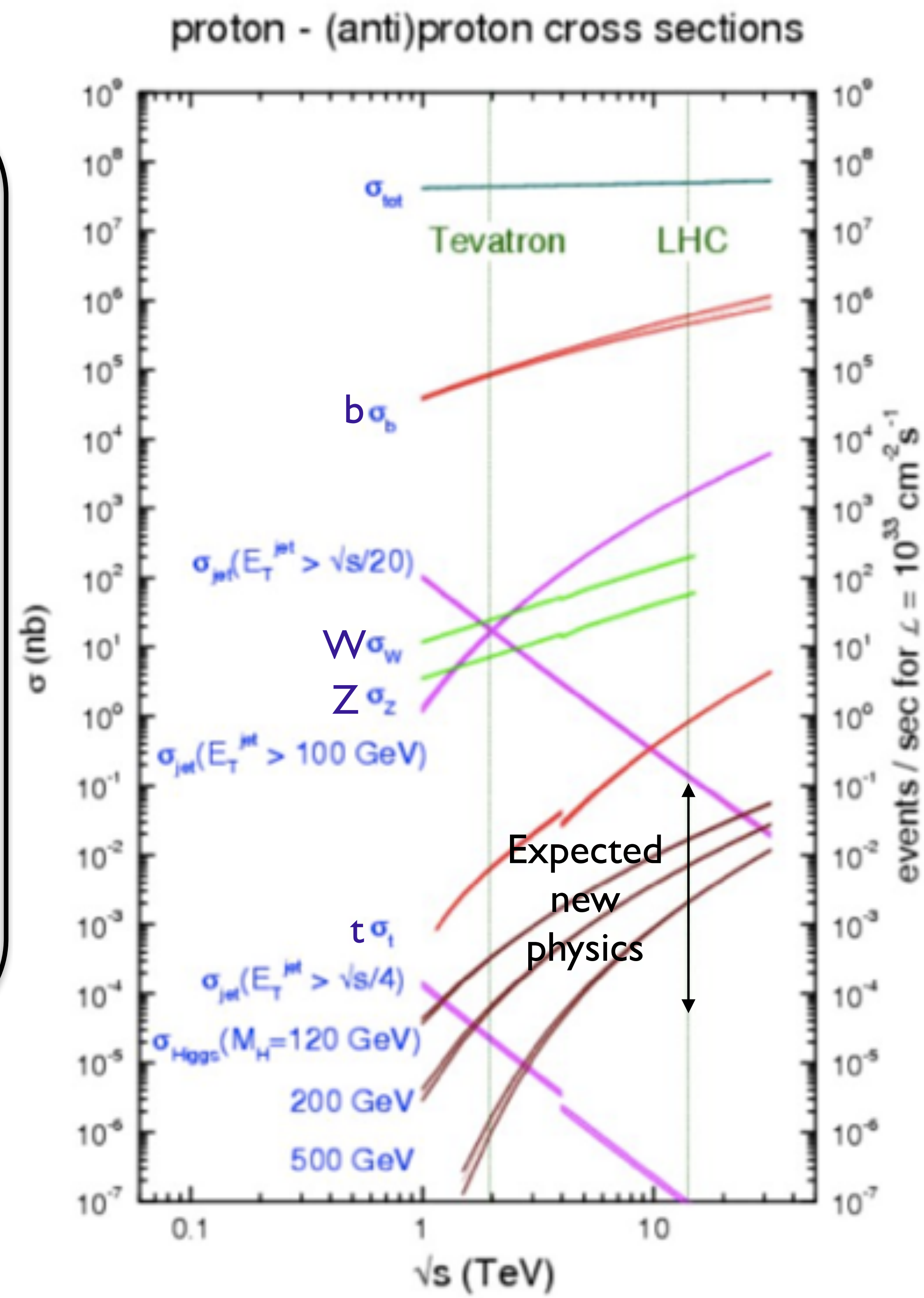
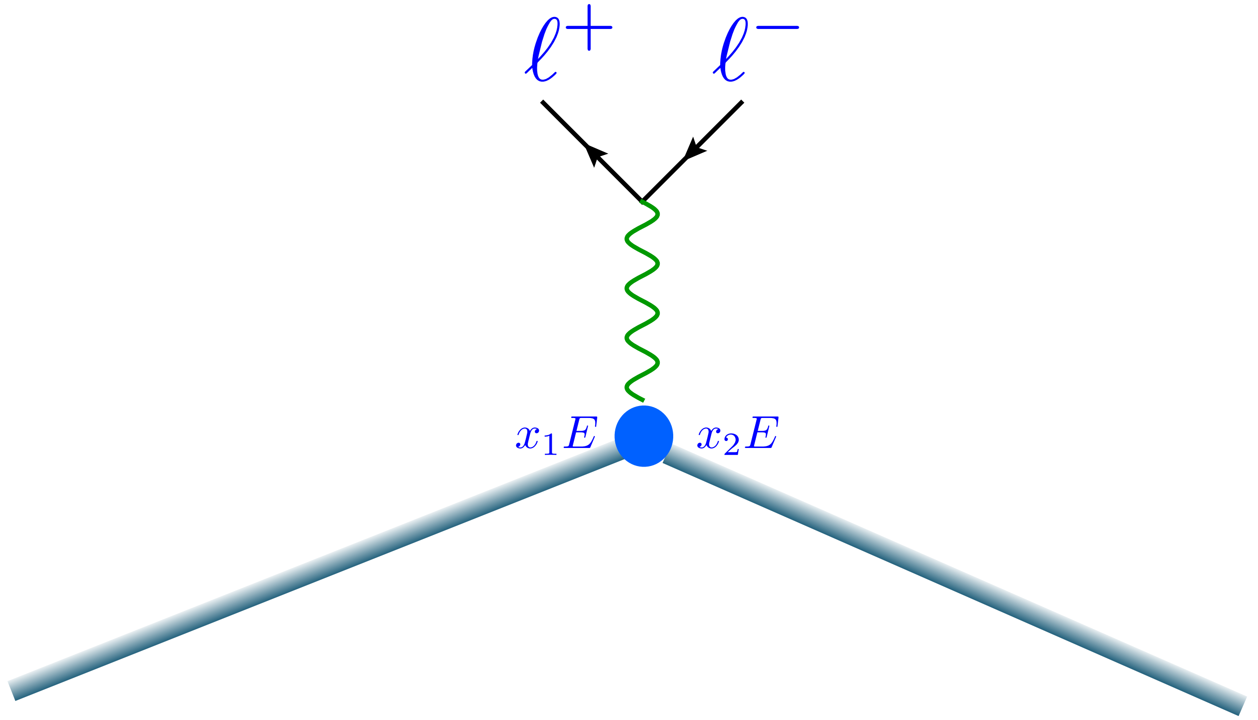
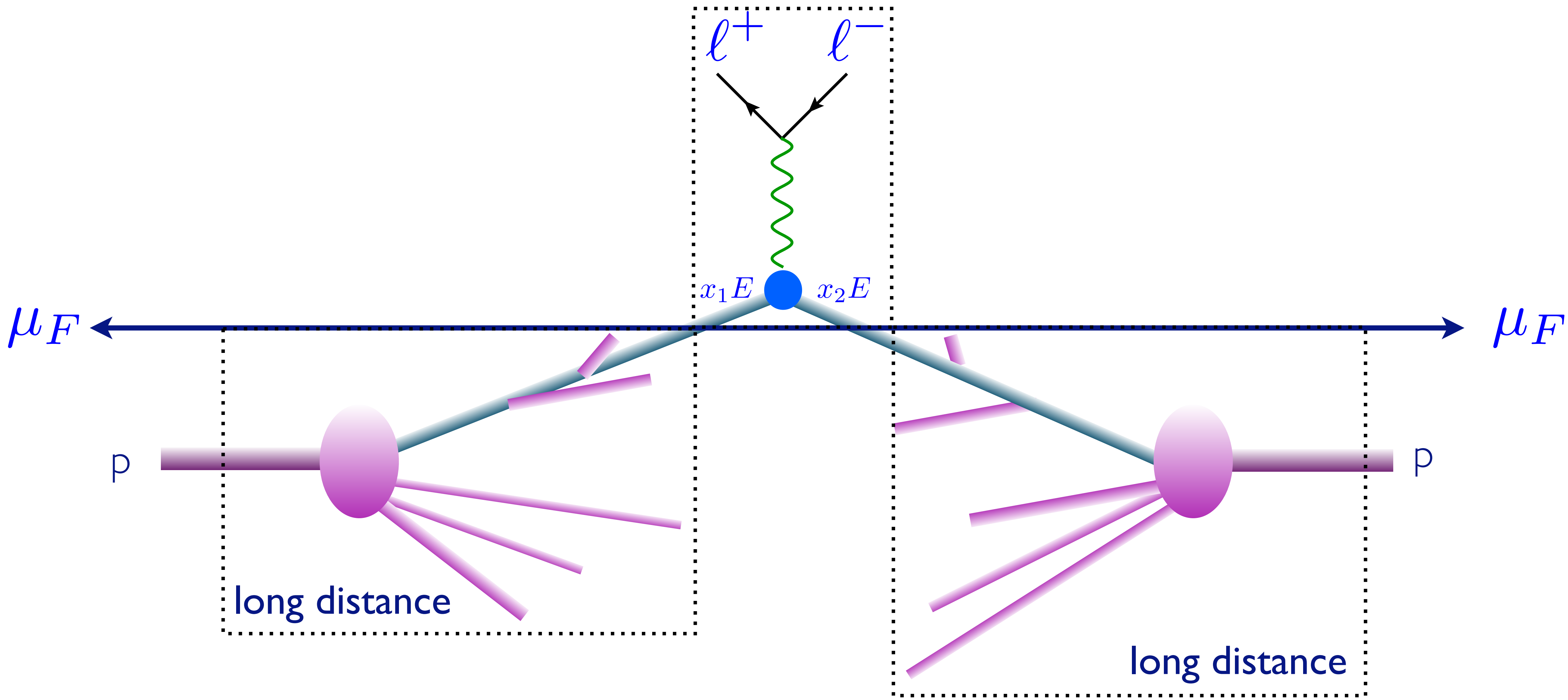




$$\hat{\sigma}_{ab \to X}(\hat{s}, \mu_F, \mu_R)$$

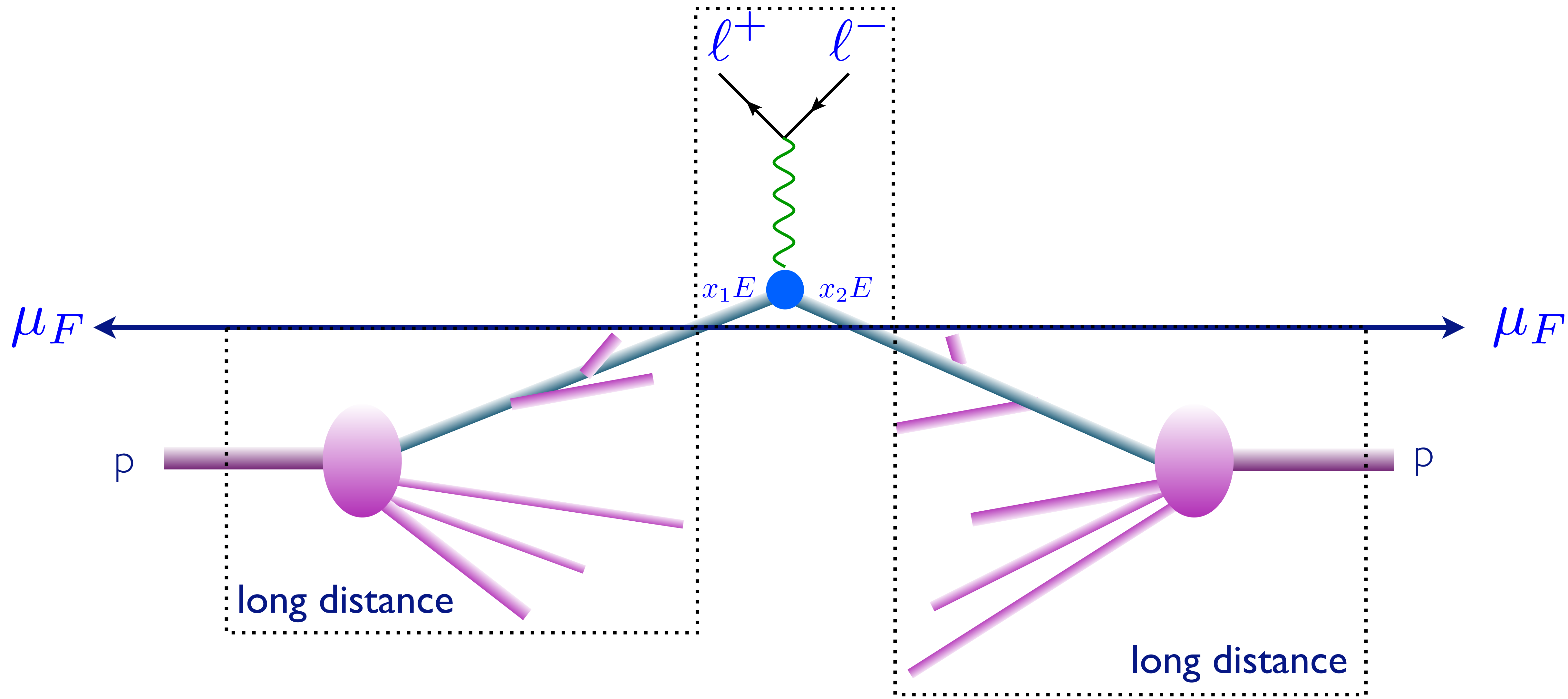
Parton-level cross section



$$f_a(x_1, \mu_F) f_b(x_2, \mu_F)\, \hat{\sigma}_{ab\to X}(\hat{s}, \mu_F, \mu_R)$$

Parton density functions

Parton-level cross section



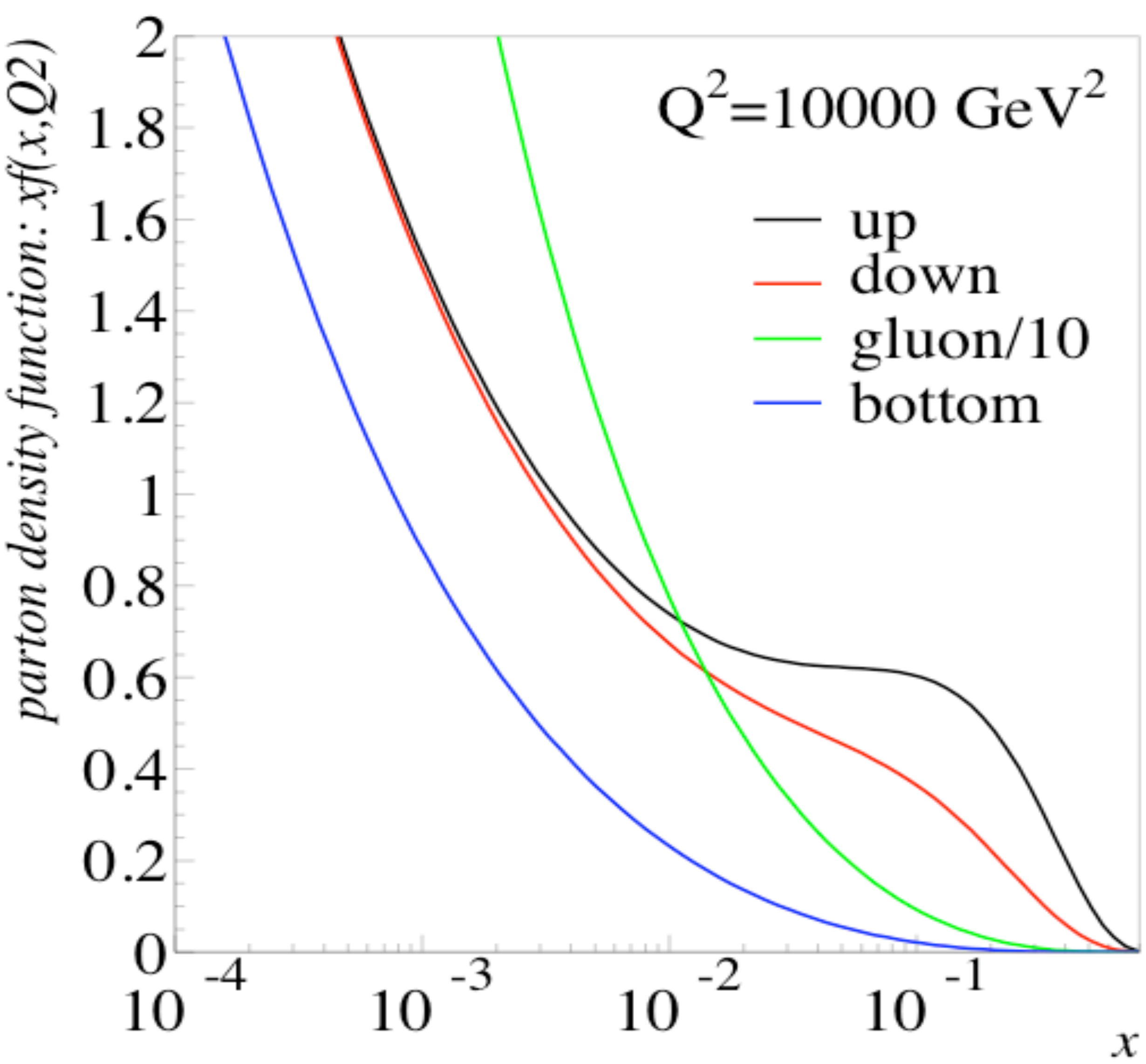
$$\sum_{a,b} \int dx_1 dx_2 d\Phi_{\mathrm{FS}}\, f_a(x_1,\mu_F) f_b(x_2,\mu_F)\, \hat{\sigma}_{ab\to X}(\hat{s},\mu_F,\mu_R)$$

Phase-space integral

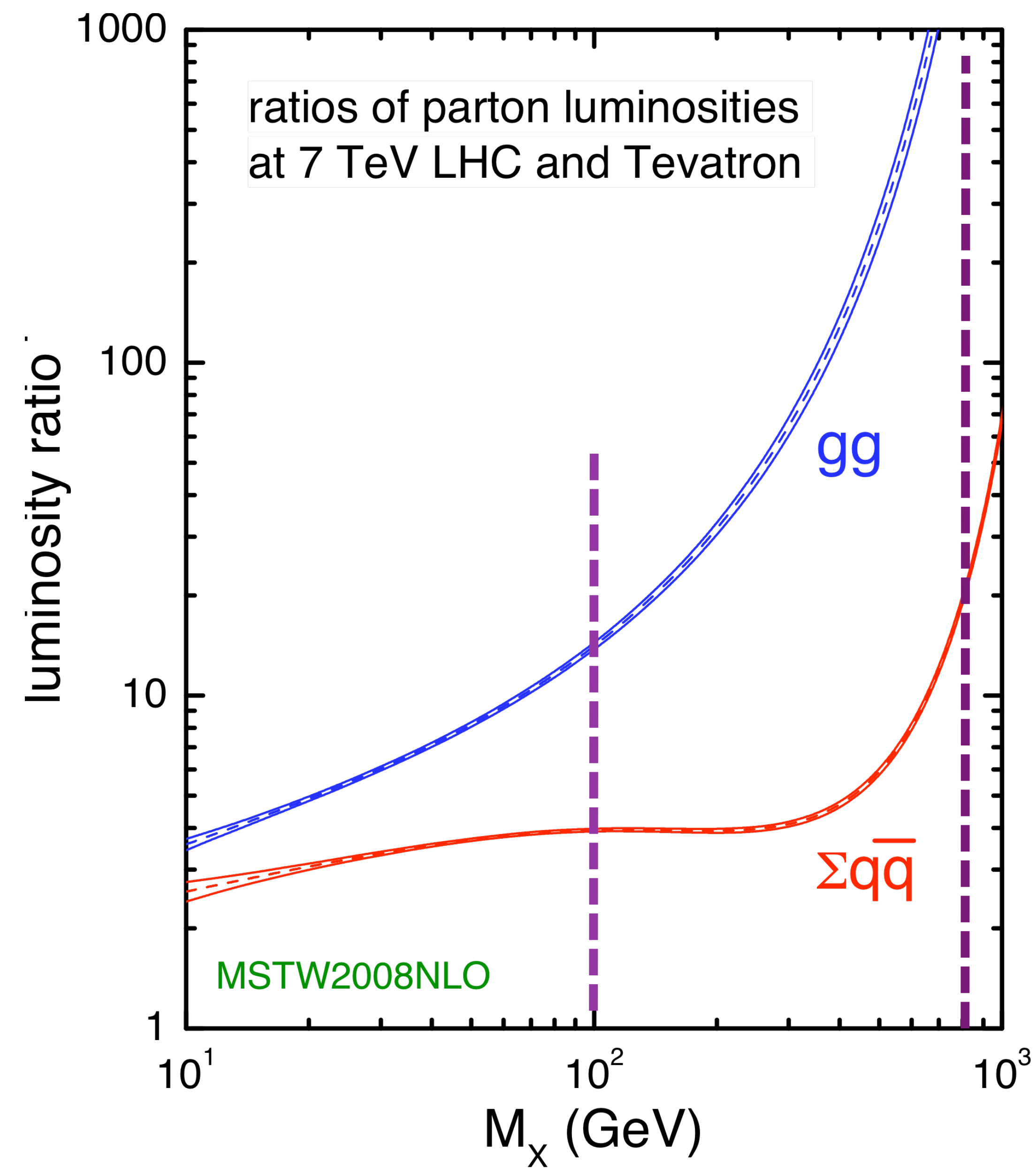
Parton density functions

Parton-level cross section

Parton densities

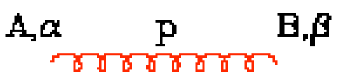


At small x (small ŝ), gluon domination.
At large x valence quarks

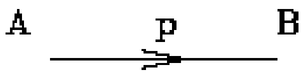


LHC formidable at large mass –
For low mass, Tevatron backgrounds smaller

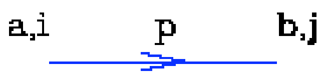
The Matrix Element



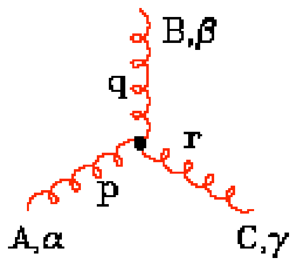
$$\delta^{AB}\,\left[-g^{\alpha\beta}+(1-\lambda)\frac{p^{\alpha}p^{\beta}}{p^{2}+i\epsilon}\right]\frac{i}{p^{2}+i\epsilon}$$



$$\delta^{AB}\,\frac{i}{(p^{2}+i\epsilon)}$$

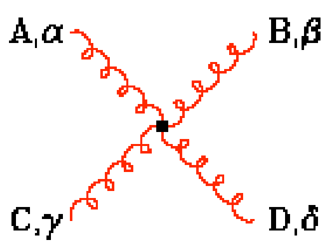


$$\delta^{ab}\,\frac{i}{(\not p-m+i\epsilon)_{ji}}$$

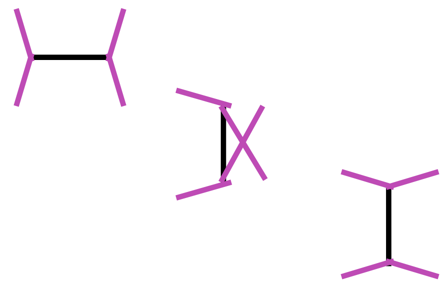


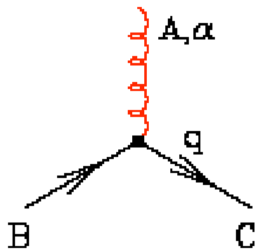
$$-g\;f^{ABC}[(p-q)^{\gamma}g^{\alpha\beta}+(q-r)^{\alpha}g^{\beta\gamma}+(r-p)^{\beta}g^{\gamma\alpha}]$$

(all momenta incoming)

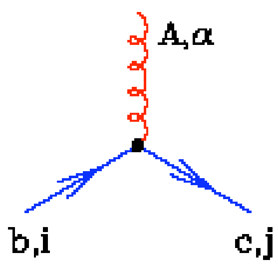


$$-ig^{2}\;f^{XAC}f^{XBD}\;[g^{\alpha\beta}g^{\gamma\delta}-g^{\alpha\delta}g^{\beta\gamma}]$$
$$-ig^{2}\;f^{XAD}f^{XBC}\;[g^{\alpha\beta}g^{\gamma\delta}-g^{\alpha\gamma}g^{\beta\delta}]$$
$$-ig^{2}\;f^{XAB}f^{XCD}\;[g^{\alpha\gamma}g^{\beta\delta}-g^{\alpha\delta}g^{\beta\gamma}]$$



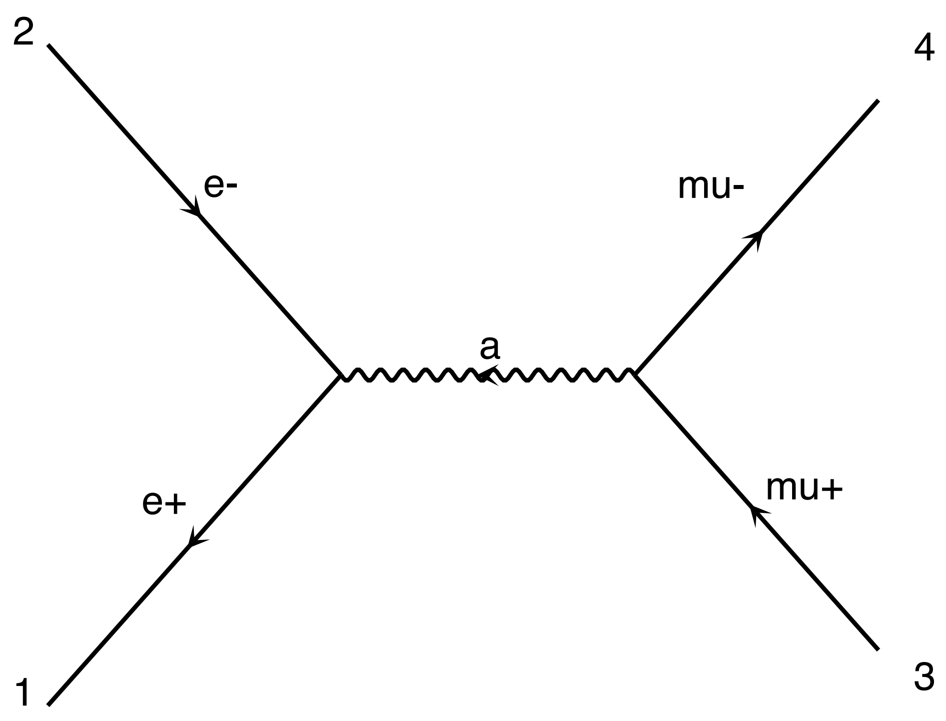


$$g\;f^{ABC}q^{\alpha}$$



$$-ig\;(t^{A})_{cb}\;(\gamma^{\alpha})_{ji}$$

Matrix Element



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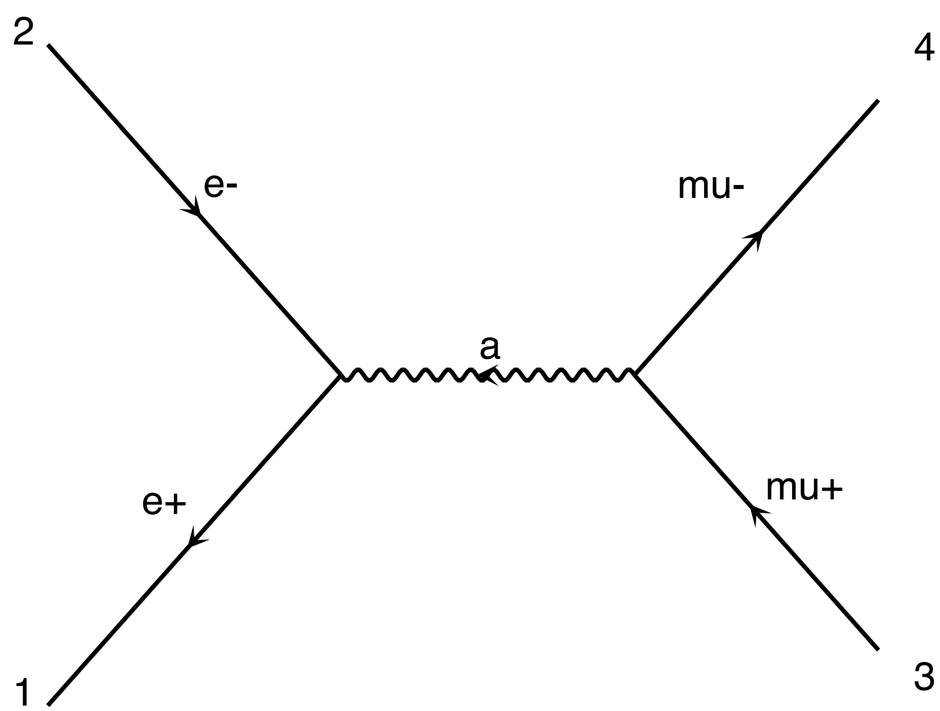
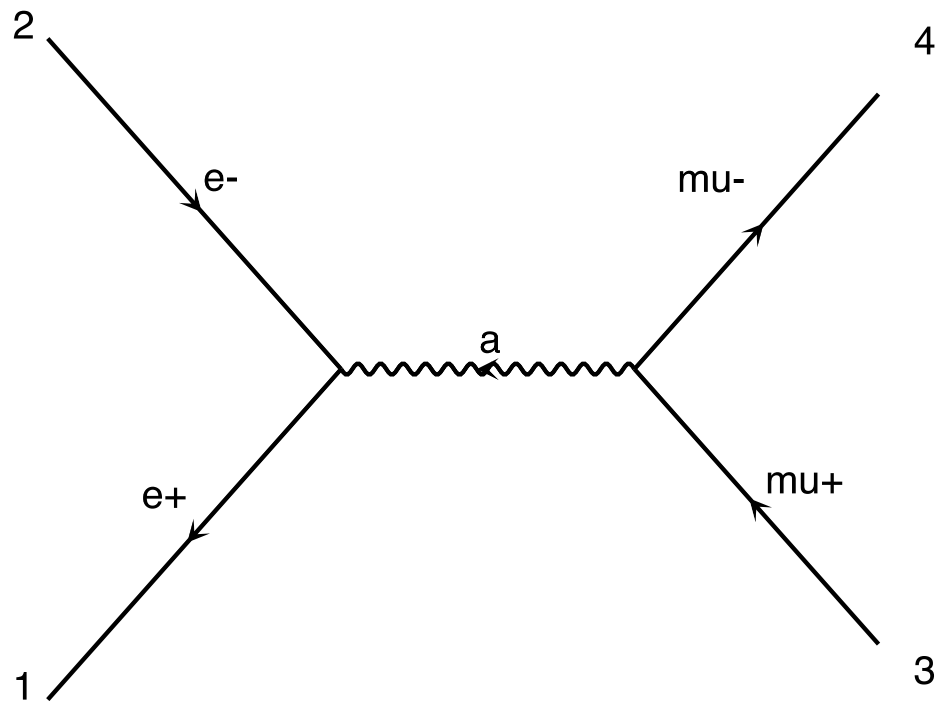


$$\mathcal{M} = e^2 (\bar{u}\gamma^\mu v) \frac{g_{\mu\nu}}{q^2} (\bar{u}\gamma^\nu v)$$

Matrix Element



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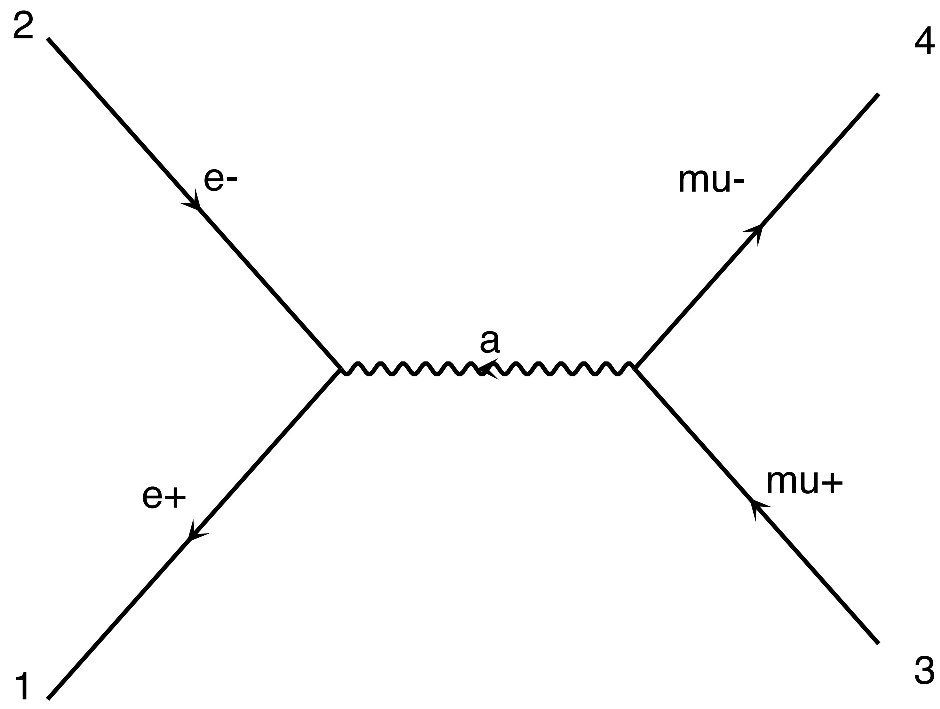
$$\frac{1}{4}\sum_{pol}|\mathcal{M}|^2 = \frac{1}{4}\sum_{pol}\mathcal{M}^*\mathcal{M}$$



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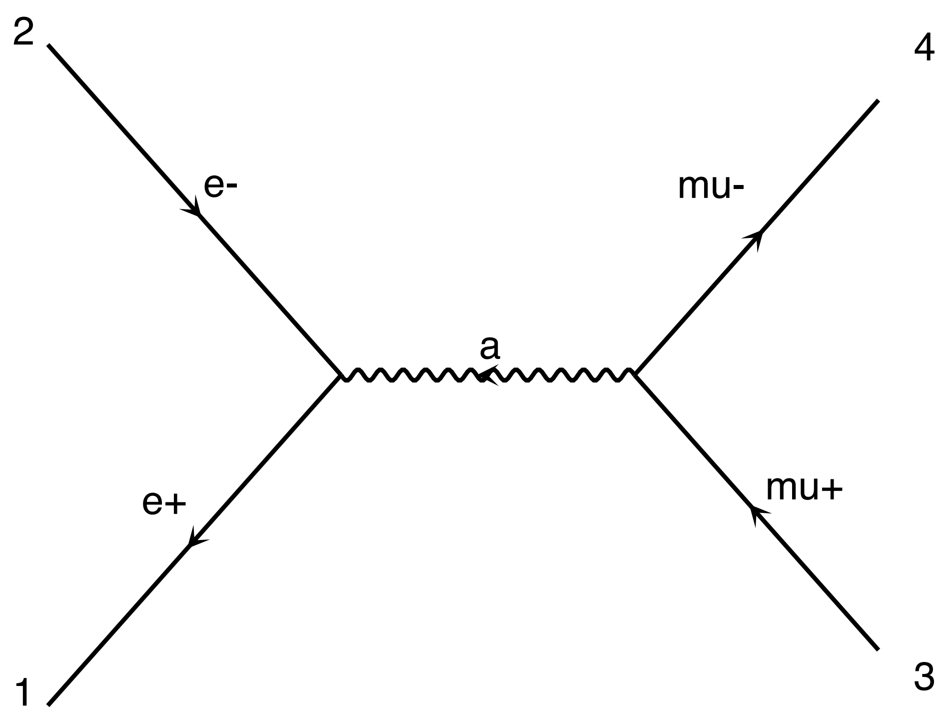

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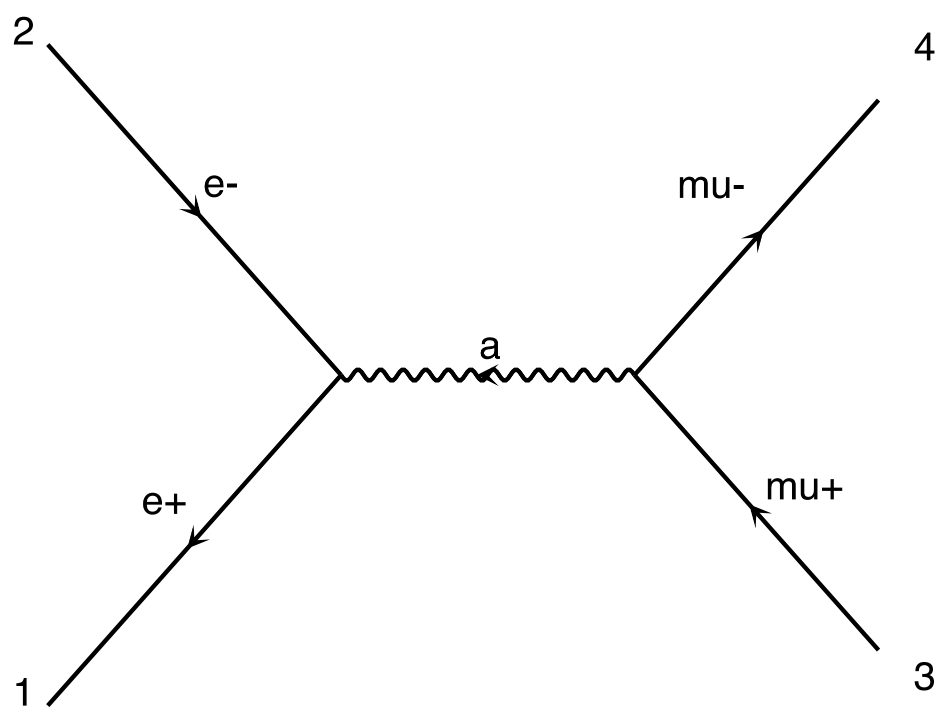
$$\rightarrow \frac{e^4}{4q^4} Tr[\not{p}_1\gamma^\mu\not{p}_2\gamma^\nu] Tr[\not{p}_3\gamma_\mu\not{p}_4\gamma_\nu]$$

Matrix Element



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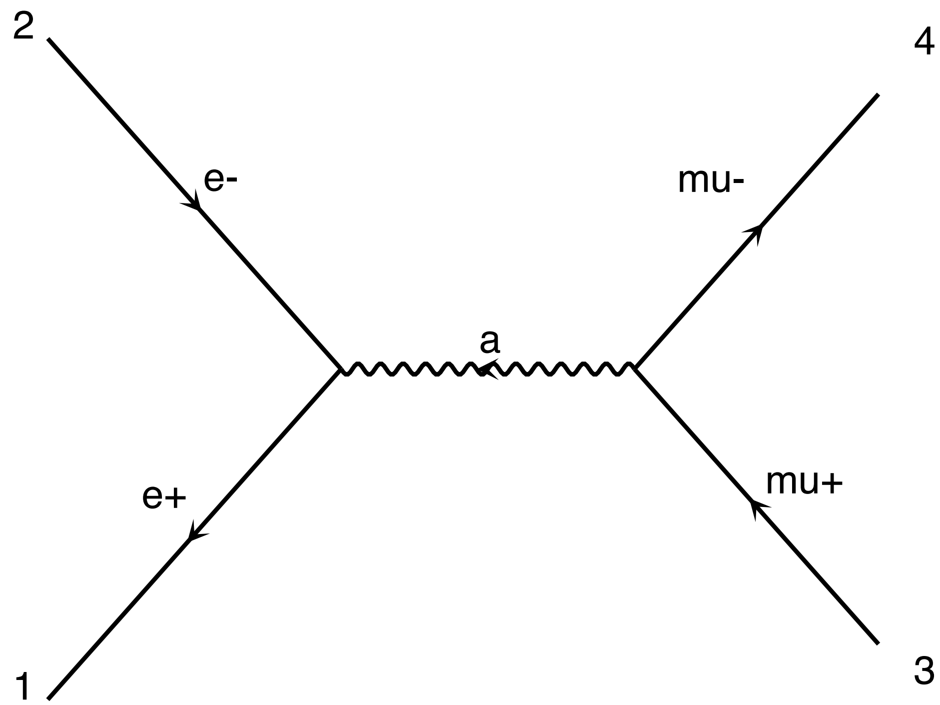
Very Efficient !!!

Matrix Element



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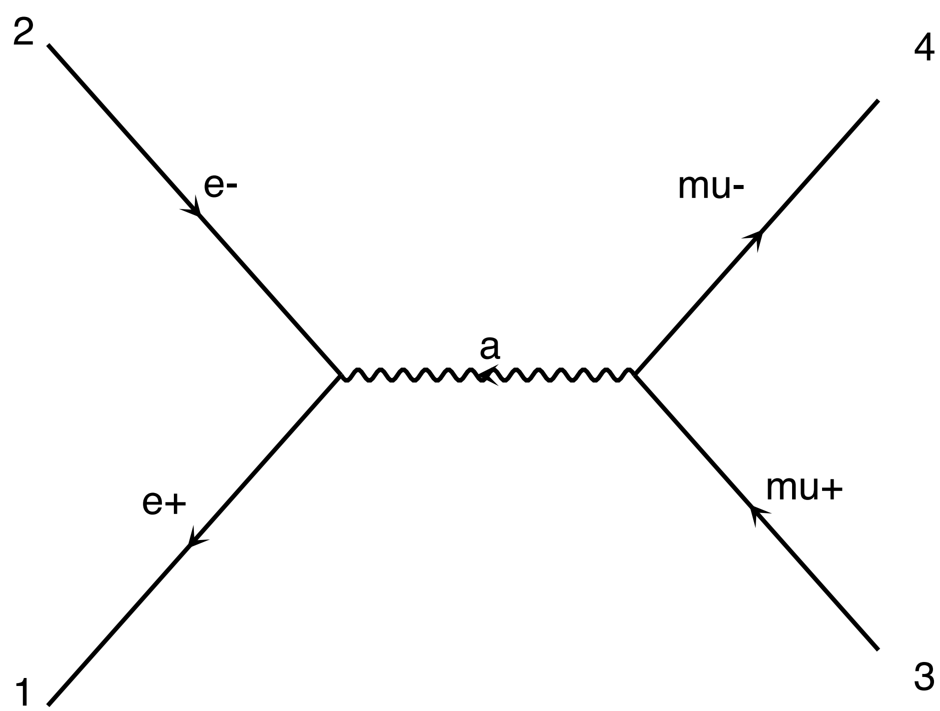
Matrix Element



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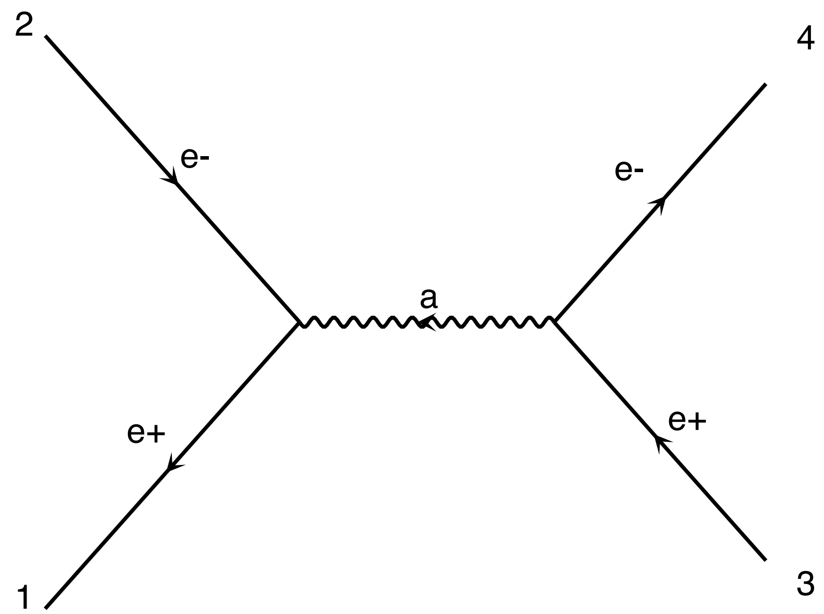
But the number of terms rises as N^2

Only for 2→2 and 2→3

- Idea: Evaluate $\mathcal{M}$ for fixed helicity of external particles
  - ➡ Multiply $\mathcal{M}$ with $\mathcal{M}^*$ -> |$\mathcal{M}$|^2
  - ➡ Loop on Helicity and sum the results



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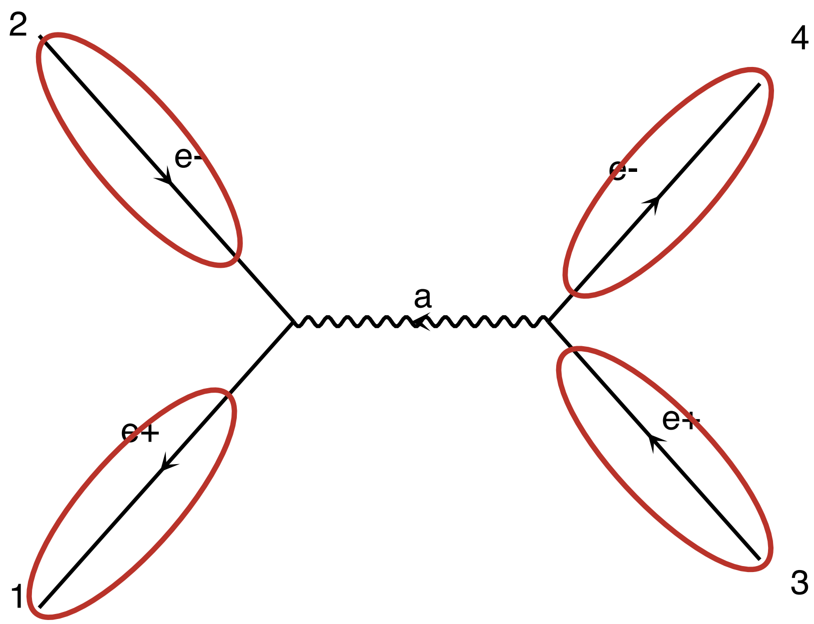

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Numbers for given helicity and momenta

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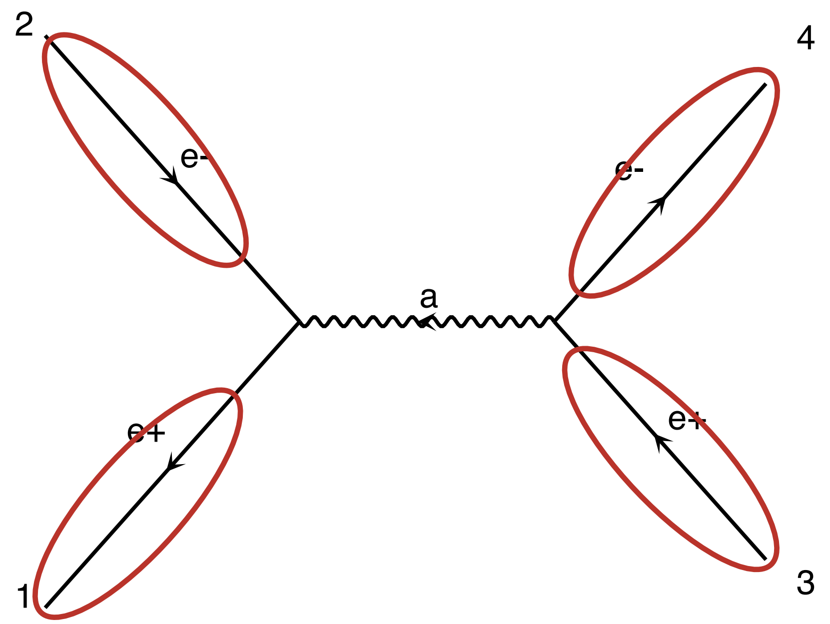

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Numbers for given helicity and momenta

```
CALL OXXXXX(P(0,1),ZERO,NHEL(1),-1*IC(1),W(1,1))
CALL IXXXXX(P(0,2),ZERO,NHEL(2),+1*IC(2),W(1,2))
CALL IXXXXX(P(0,3),ZERO,NHEL(3),-1*IC(3),W(1,3))
CALL OXXXXX(P(0,4),ZERO,NHEL(4),+1*IC(4),W(1,4))
```

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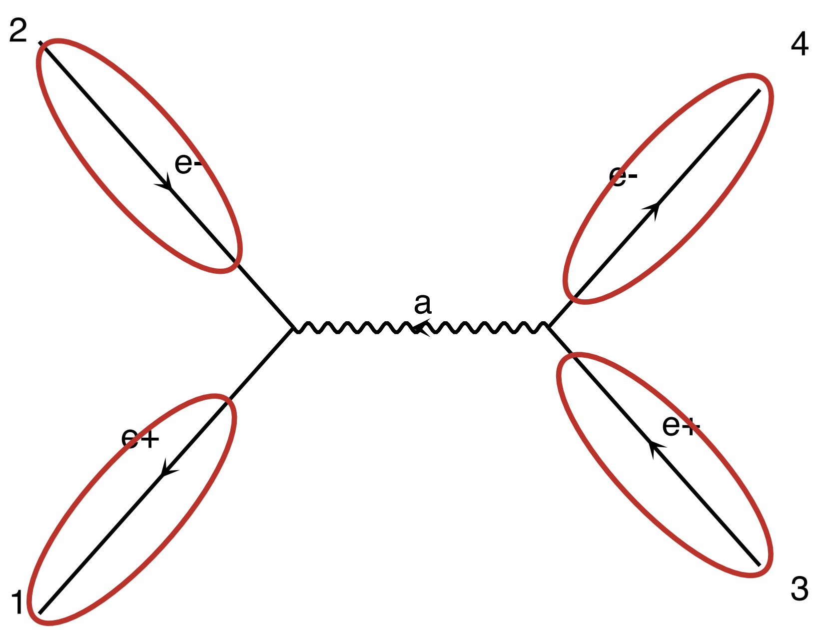

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Input: momenta, mass, helicity

Ouput: Wavefunction (given by an analytical formula)

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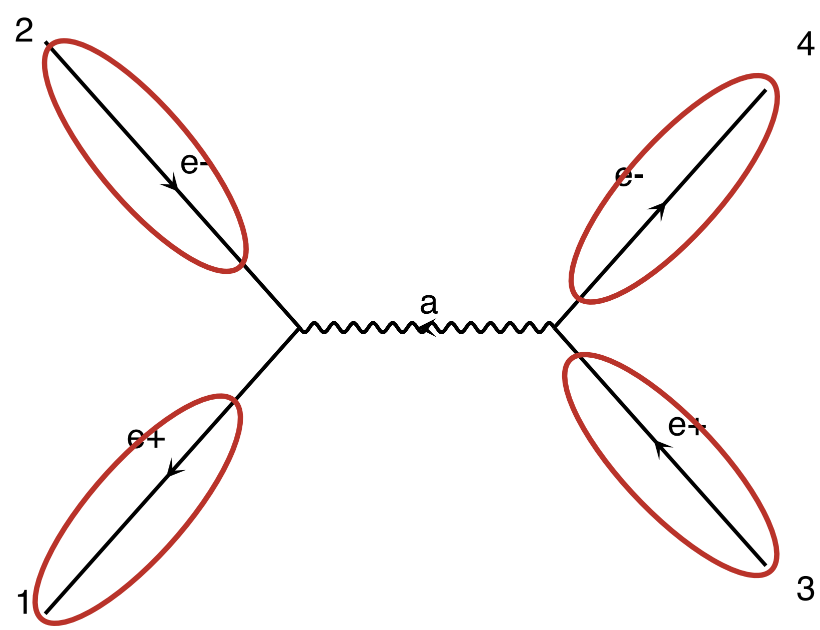

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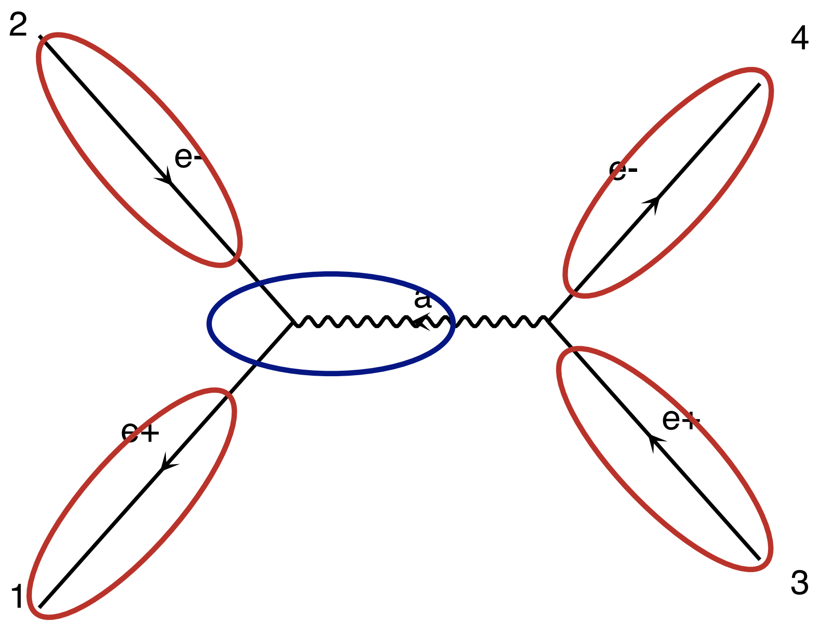

$$\mathcal{M} = \bar{u}\gamma^{\mu} v P_{\mu\nu} \bar{u}\gamma^{\nu} v$$

Numbers for given helicity and momenta

Calculate propagator wavefunctions

```
CALL OXXXXX(P(0,1),ZERO,NHEL(1),-1*IC(1),W(1,1))
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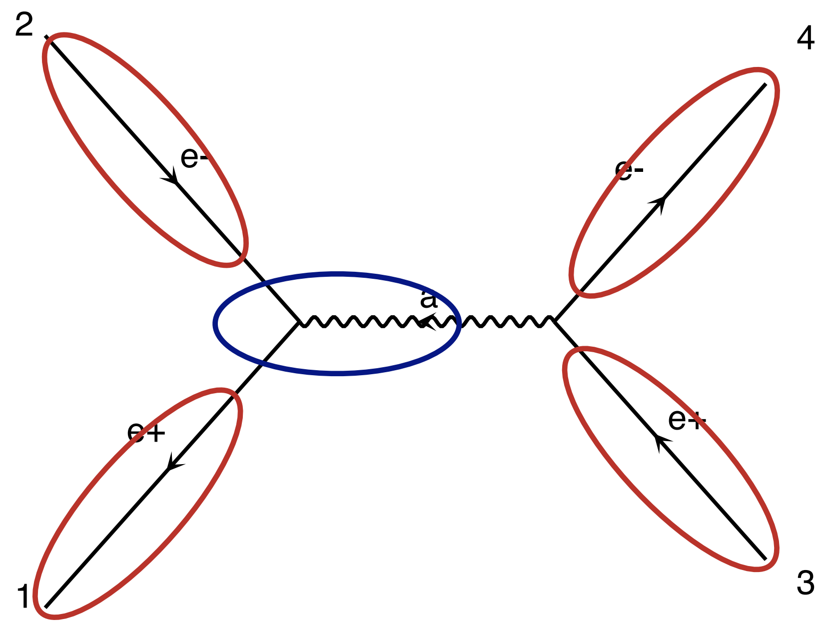
CALL OXXXXX(P(0,4),ZERO,NHEL(4),+1*IC(4),W(1,4))

CALL JIOXXX(W(1,2),W(1,1),GAL,ZERO,ZERO,W(1,5))
```

- Idea: Evaluate $\mathcal{M}$ for fixed helicity of external particles
    - ➡ Multiply $\mathcal{M}$ with $\mathcal{M}^*$ -> |$\mathcal{M}$|^2
    - ➡ Loop on Helicity and sum the results



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```

Input: Wavefunctions, mass, width, coupling

```
CALL JIOXXX(W(1,2),W(1,1),GAL,ZERO,ZERO,W(1,5))
```

Ouput: Wavefunction (given by an analytical formula)

- Idea: Evaluate $\mathcal{M}$ for fixed helicity of external particles
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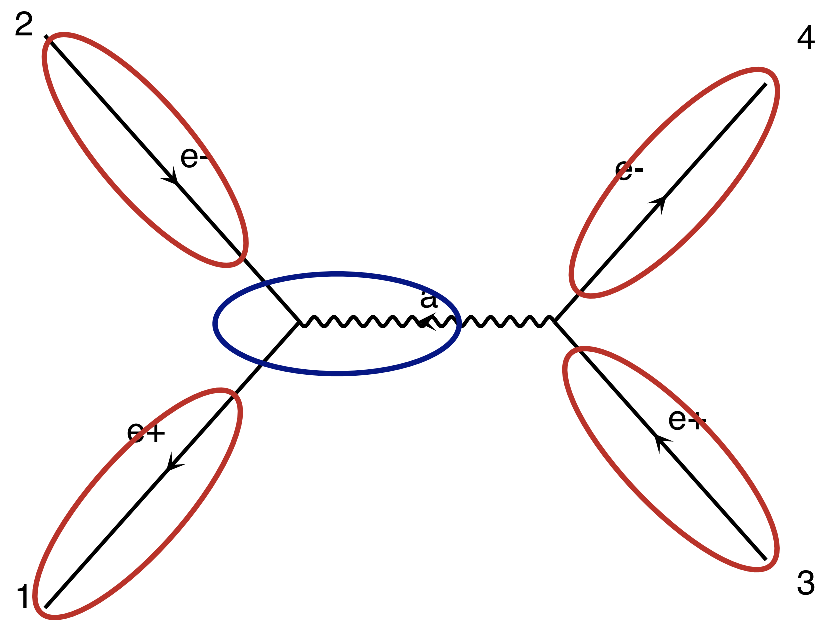

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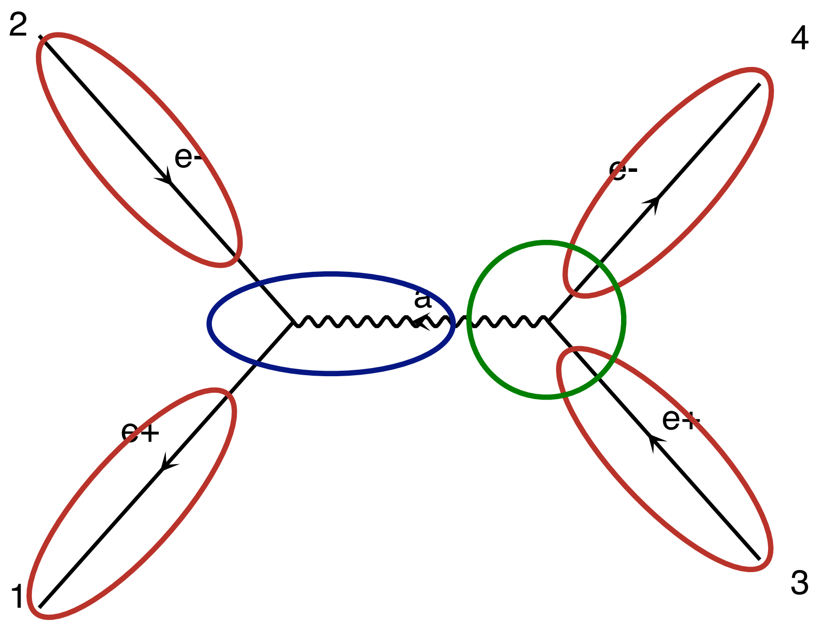

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Numbers for given helicity and momenta

Calculate propagator wavefunctions

Finally evaluate amplitude (c-number)

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CALL IOVXXX(W(1,3),W(1,4),W(1,5),GAL,AMP(1))
```

- Idea: Evaluate $\mathcal{M}$ for fixed helicity of external particles
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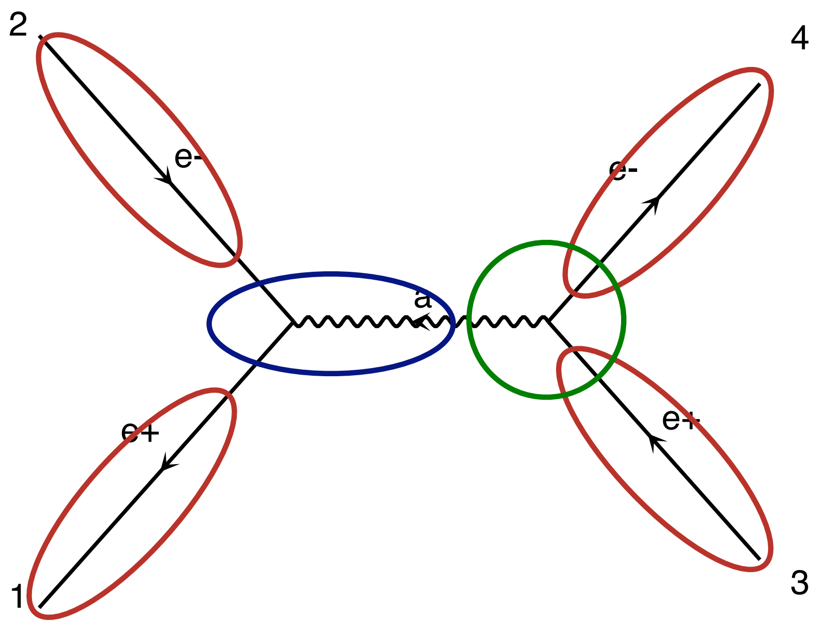

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CALL OXXXXX(P(0,4),ZERO,NHEL(4),+1*IC(4),W(1,4))
```

Input: Wavefunctions, coupling

```
CALL IOVXXX(W(1,3),W(1,4),W(1,5),GAL,AMP(1))
```

Ouput: Amplitude

- Idea: Evaluate $\mathcal{M}$ for fixed helicity of external particles
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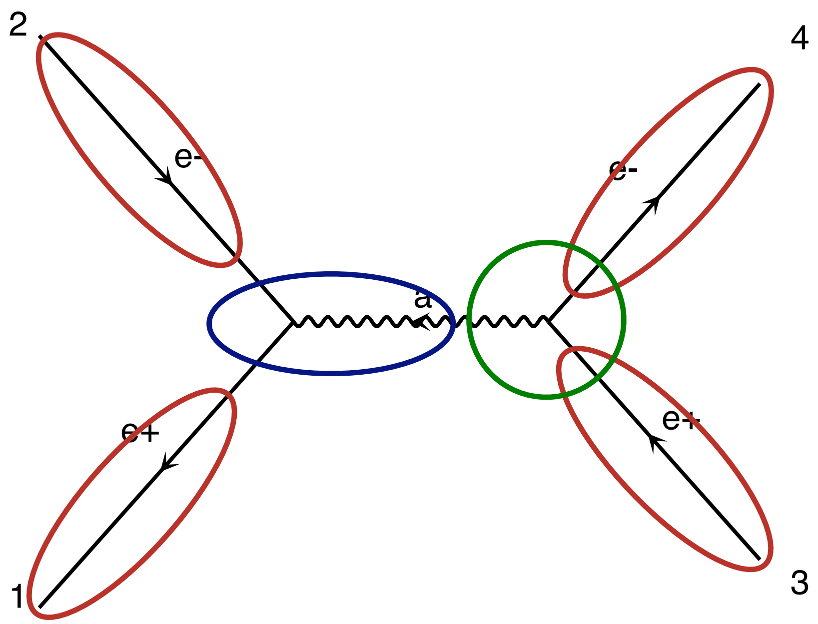

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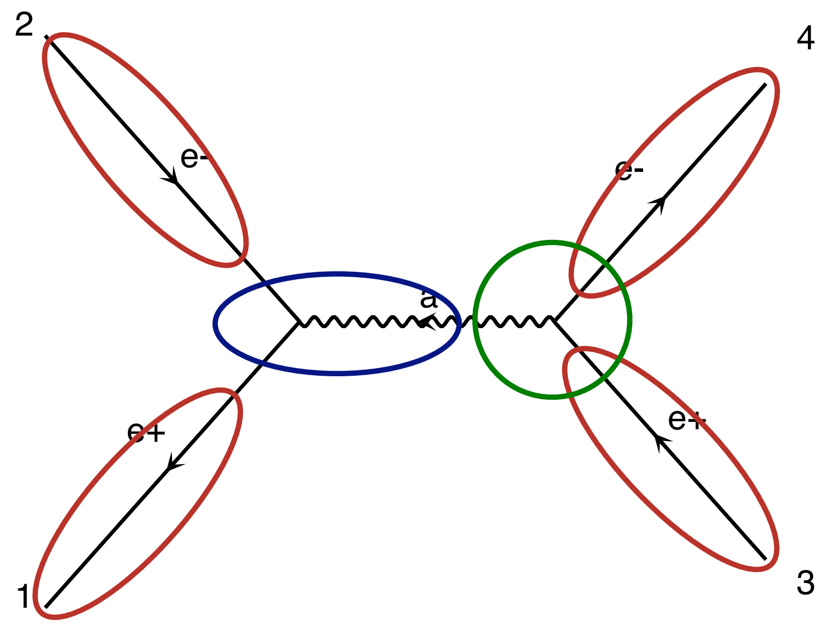

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Numbers for given helicity and momenta

Calculate propagator wavefunctions

Finally evaluate amplitude (c-number)

Helicity amplitude calls written by MadGraph

```
CALL OXXXXX(P(0,1),ZERO,NHEL(1),-1*IC(1),W(1,1))
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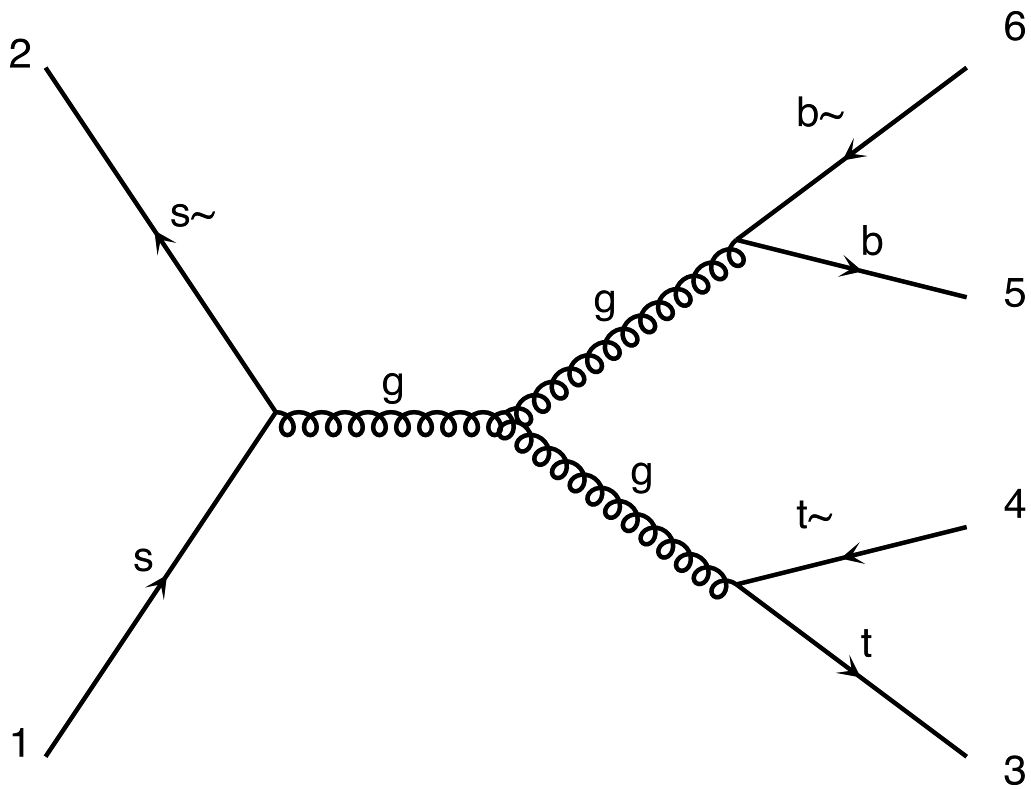
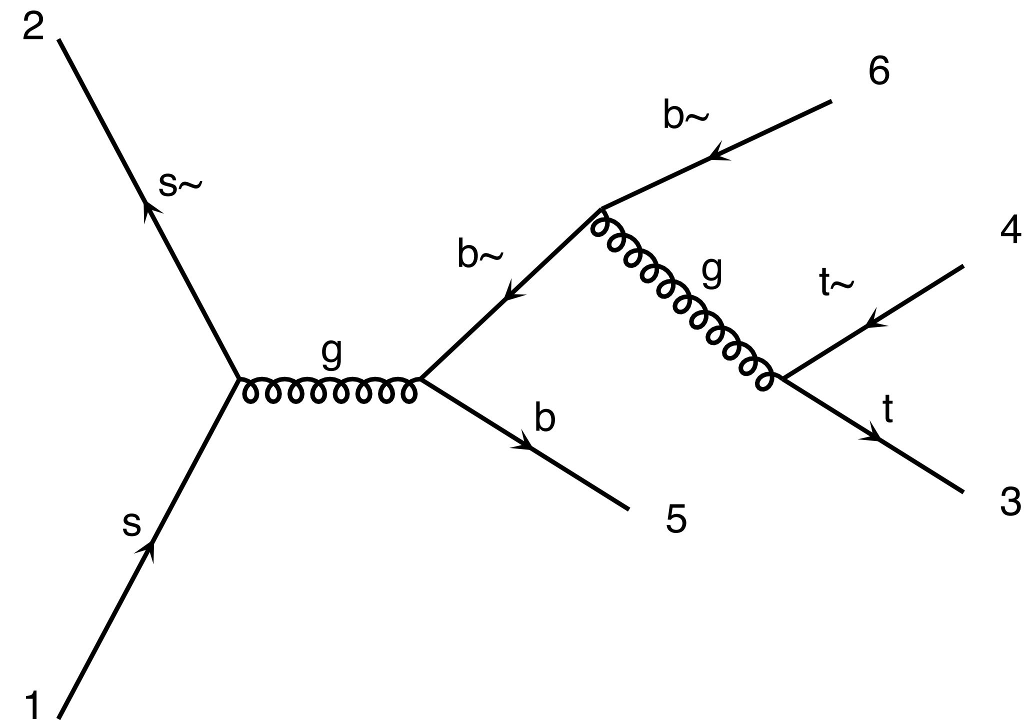
CALL JIOXXX(W(1,2),W(1,1),GAL,ZERO,ZERO,W(1,5))
CALL IOVXXX(W(1,3),W(1,4),W(1,5),GAL,AMP(1))
```

Known





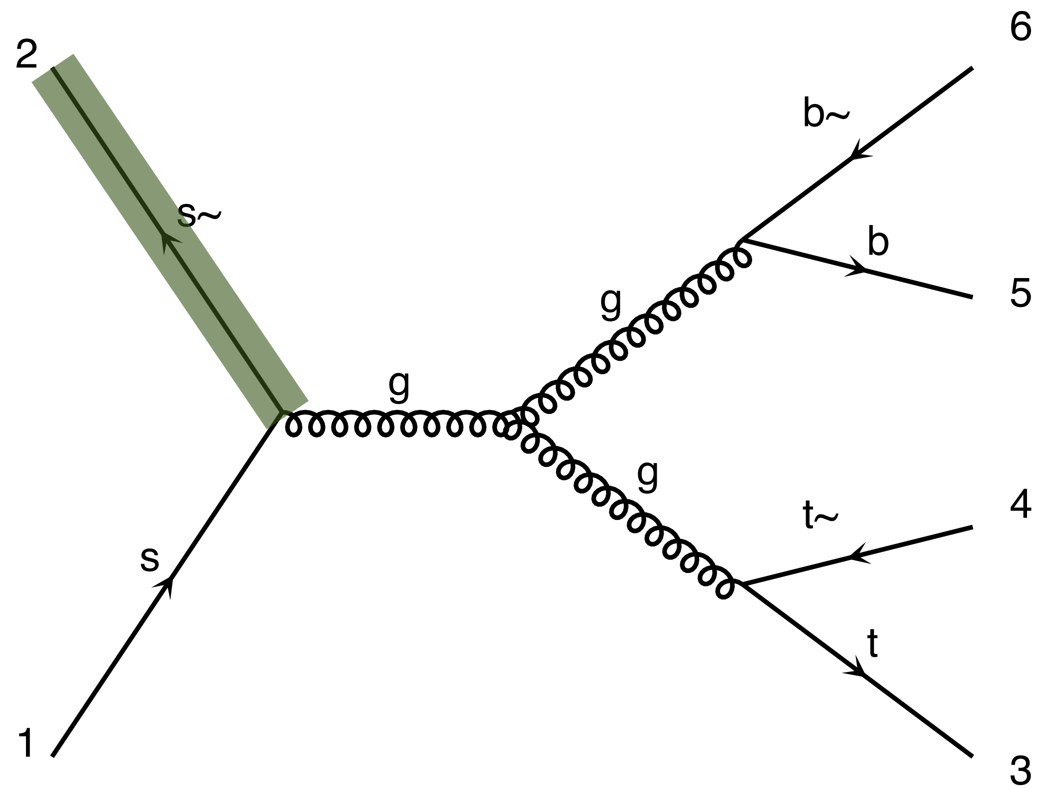
Number of routines: 0

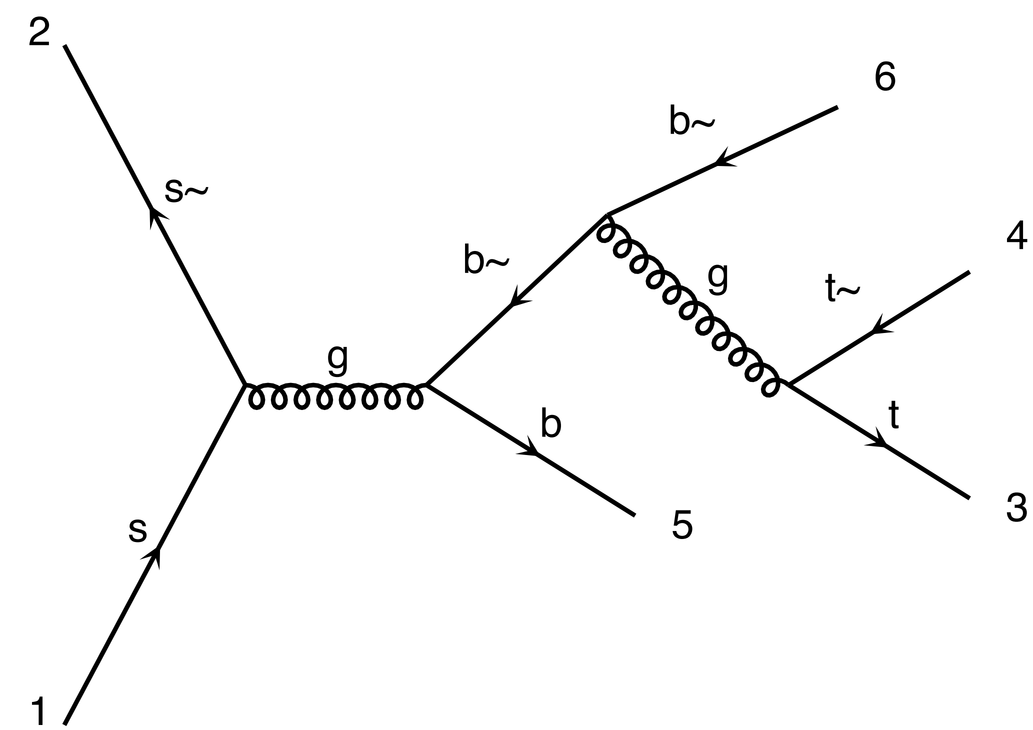
Number of routines: 0

Number of routines for both: 0

Real case

Known





Number of routines: 1

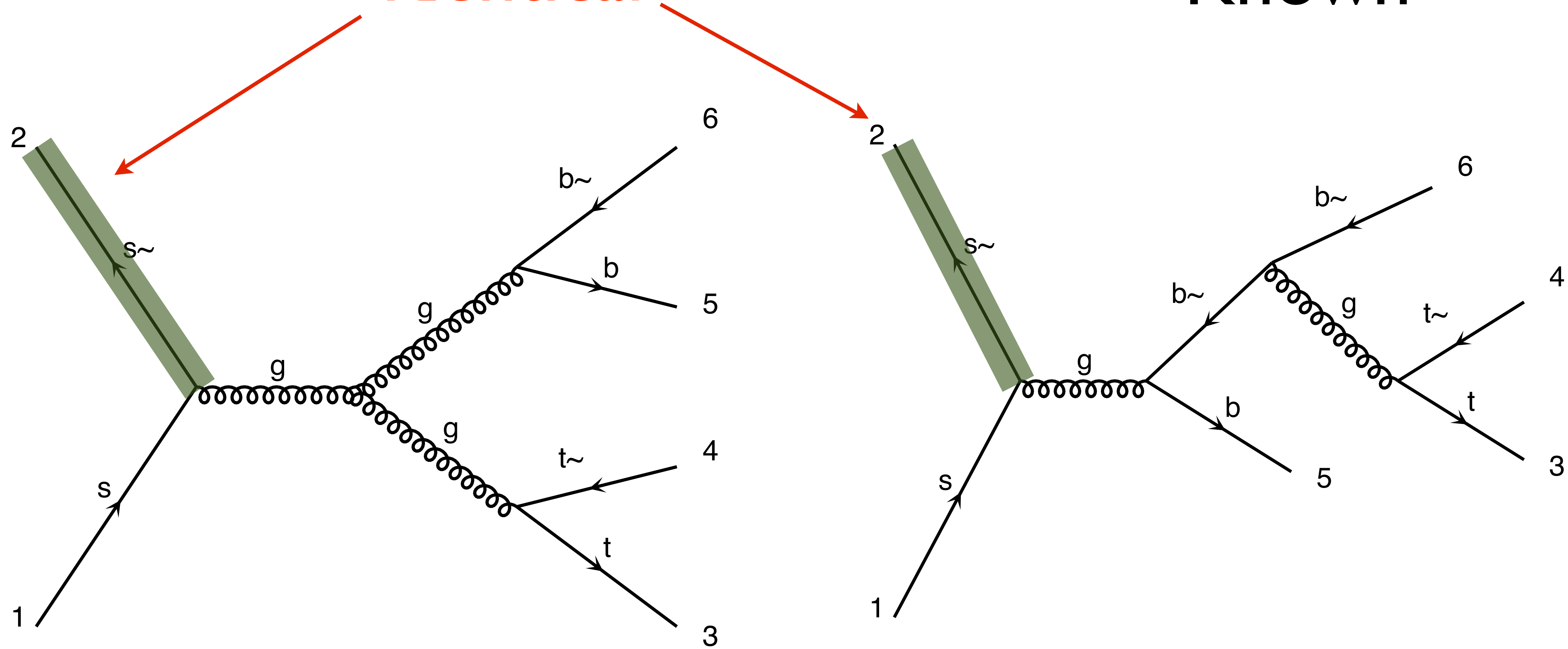
Number of routines: 0

Number of routines for both: 1

Real case

Identical

Known

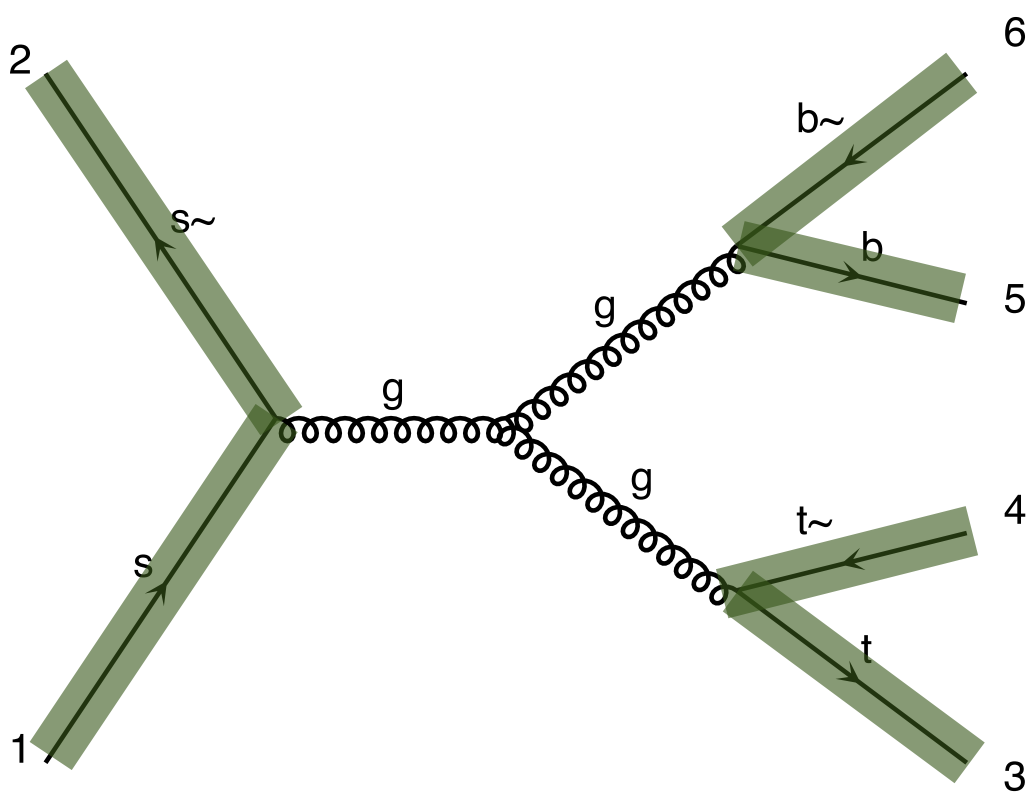


Number of routines: 1

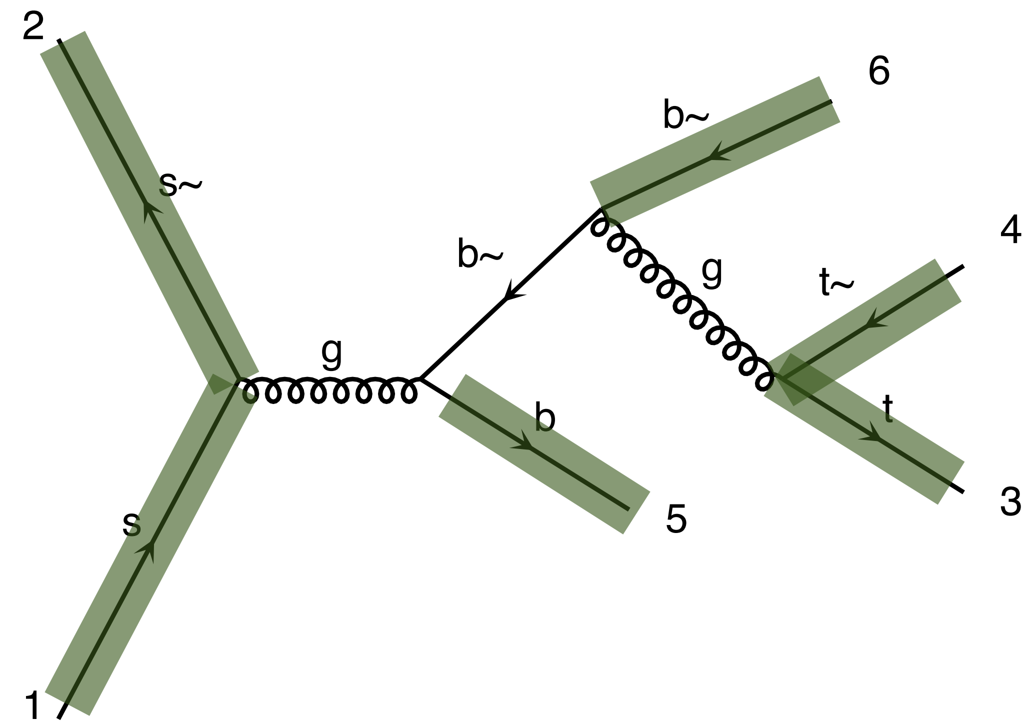
Number of routines: 1

Number of routines for both: 1

Real case



Number of routines: 6

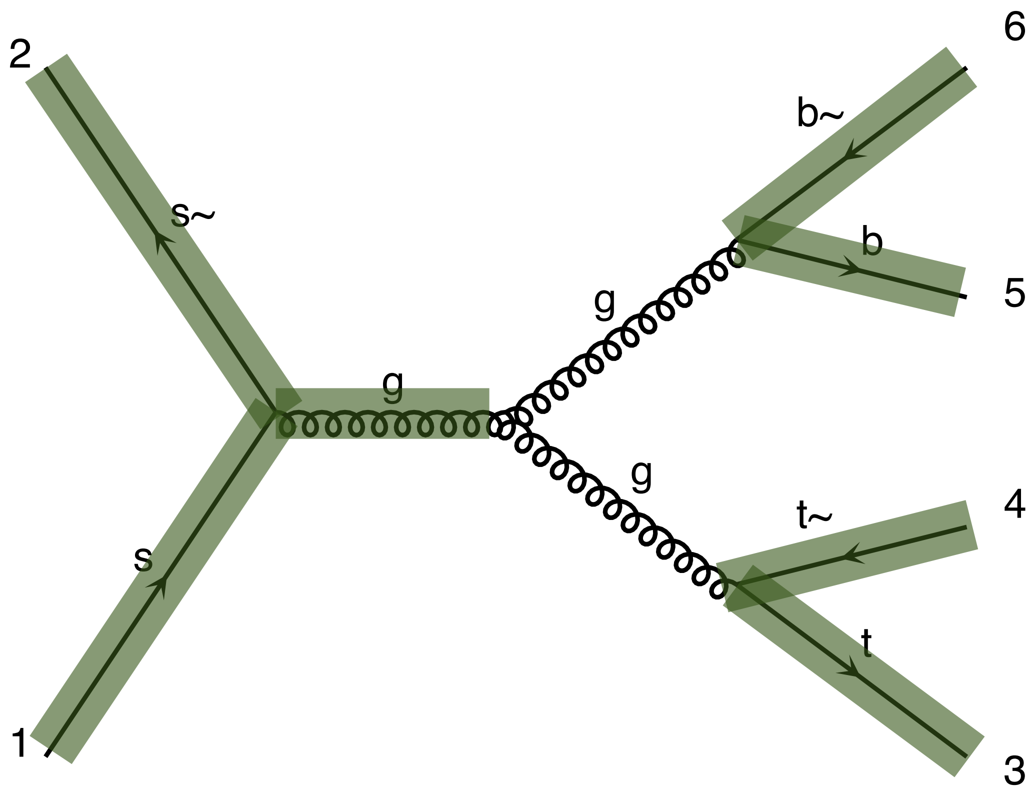


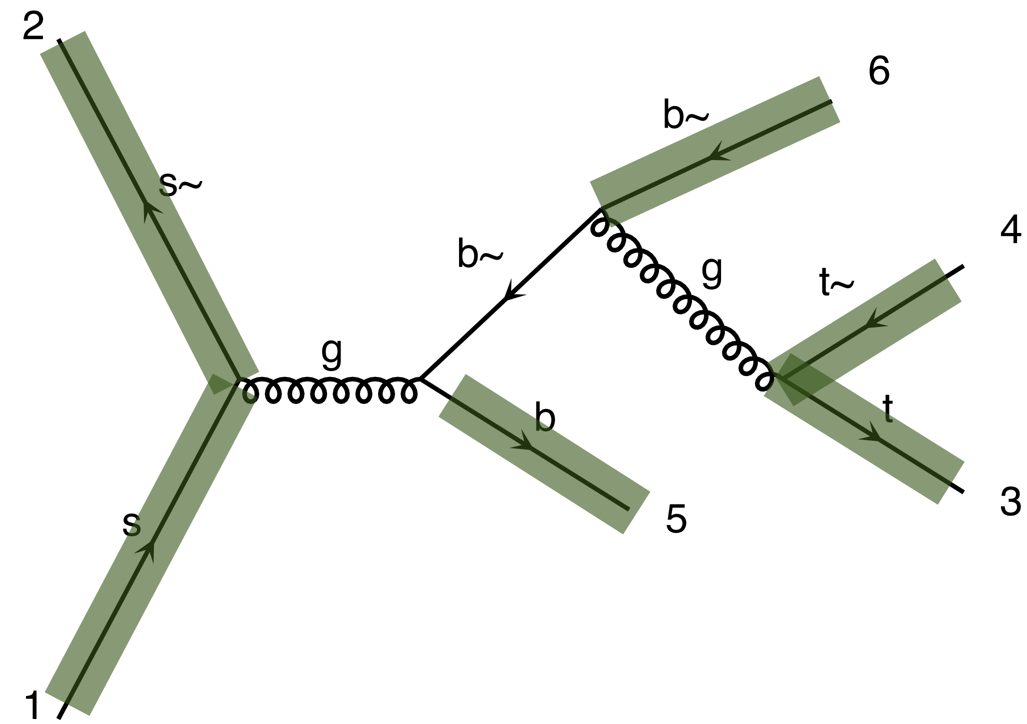
Number of routines: 6

Number of routines for both: 6

Real case

Known



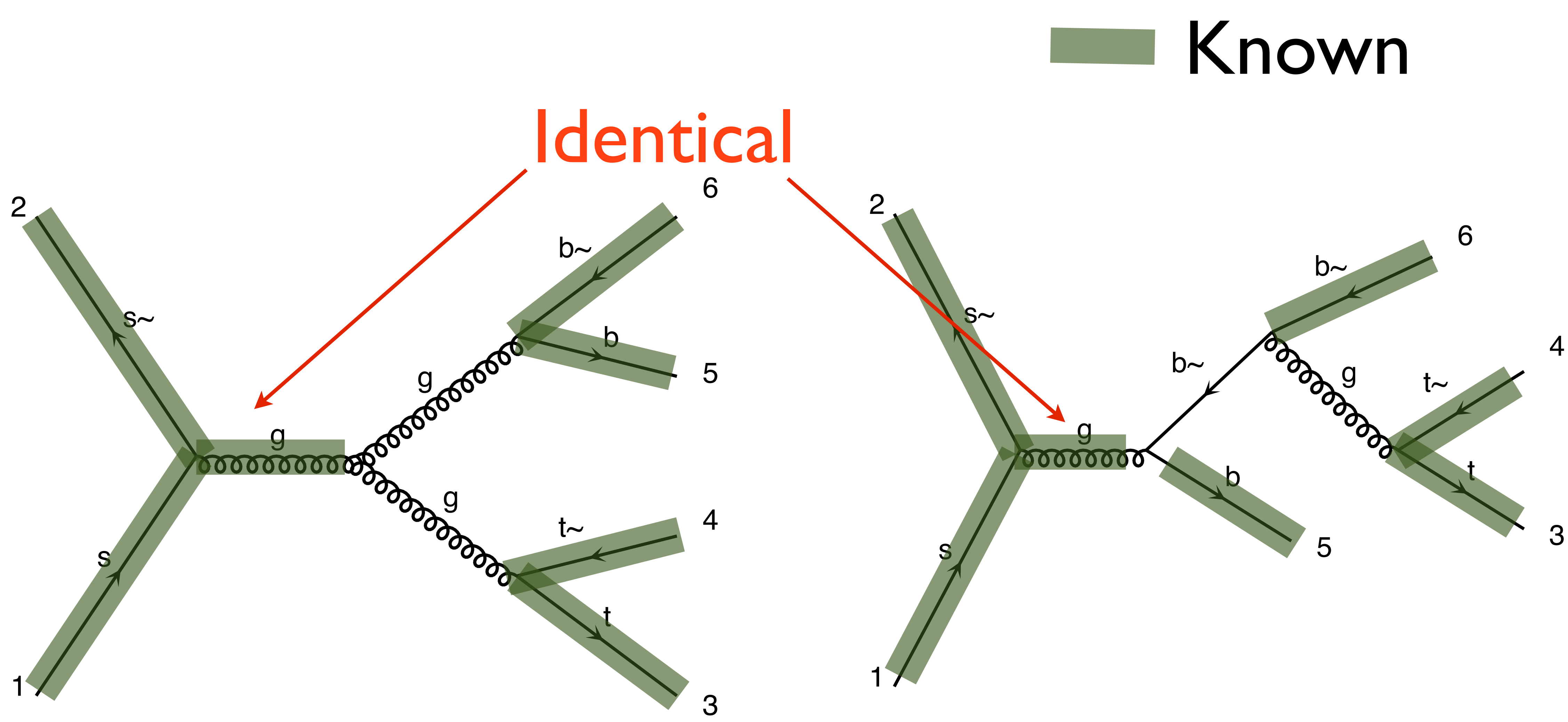


Number of routines: 7

Number of routines: 6

Number of routines for both: 7

Real case

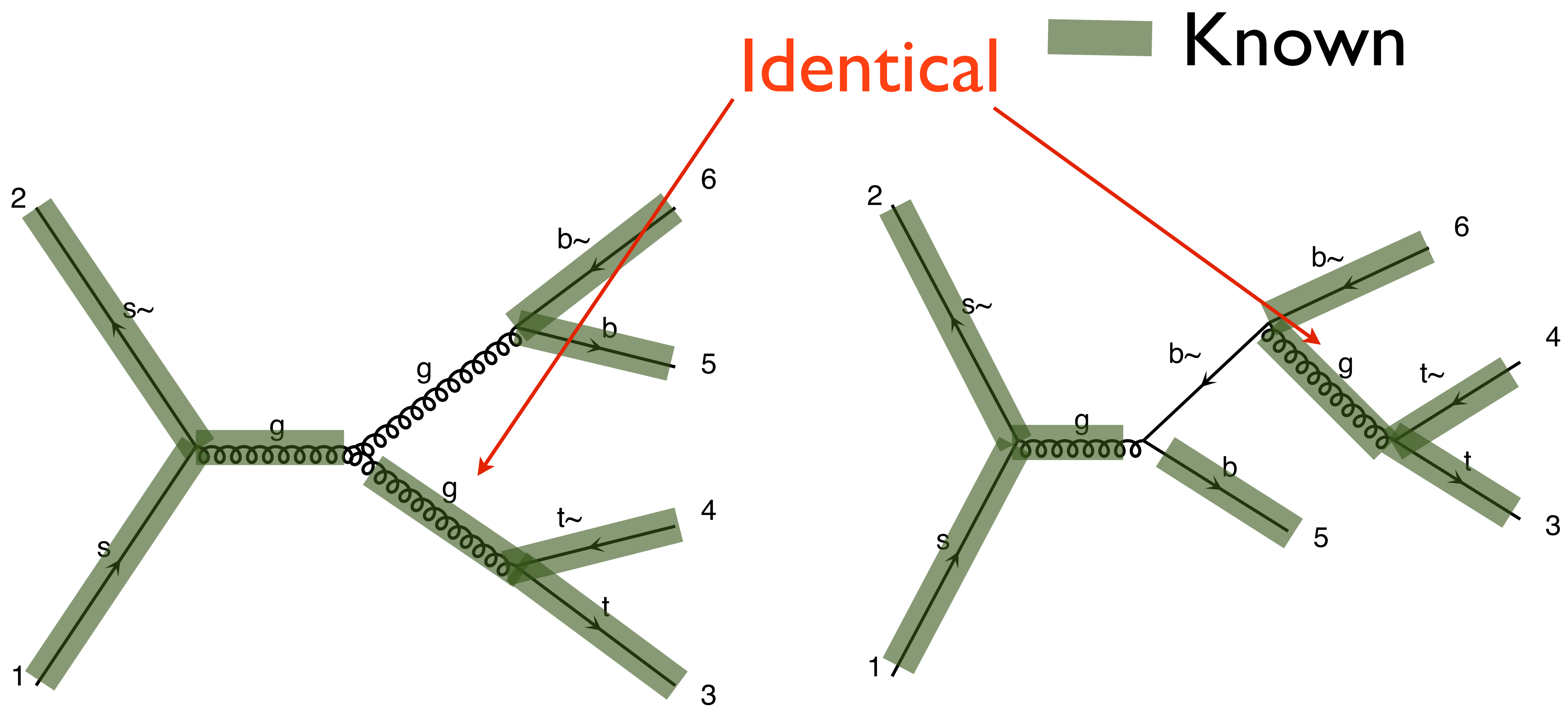


Number of routines: 7

Number of routines: 7

Number of routines for both: 7

Real case



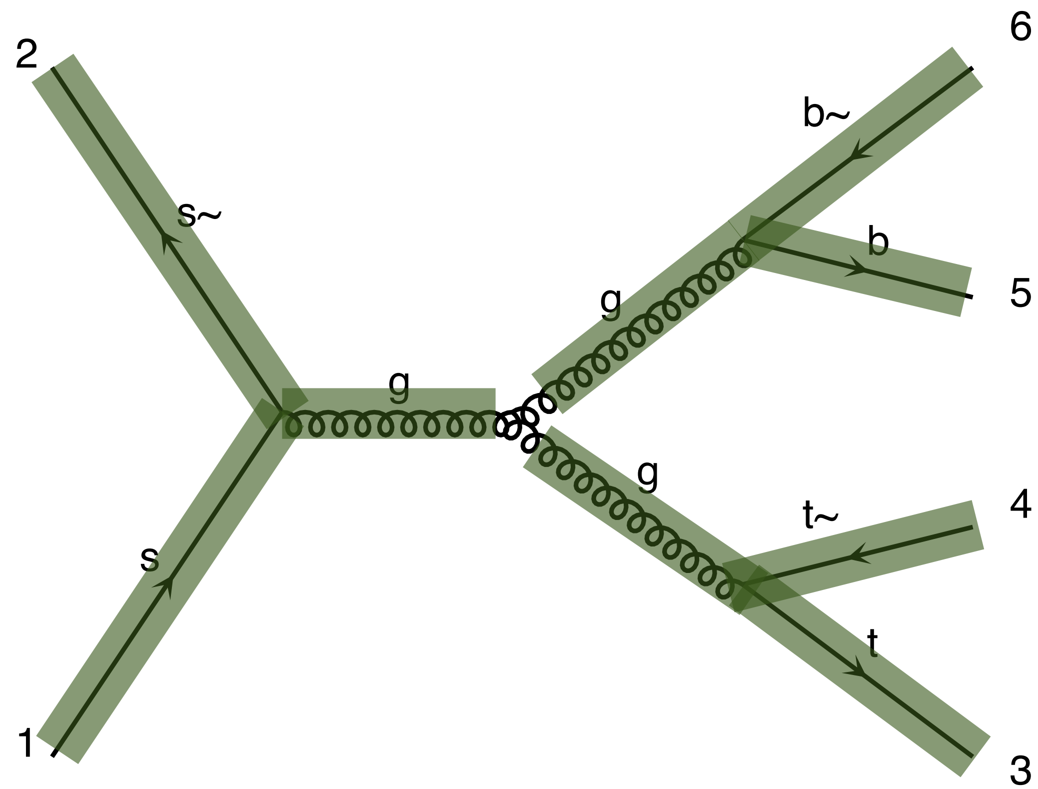
Number of routines: 8

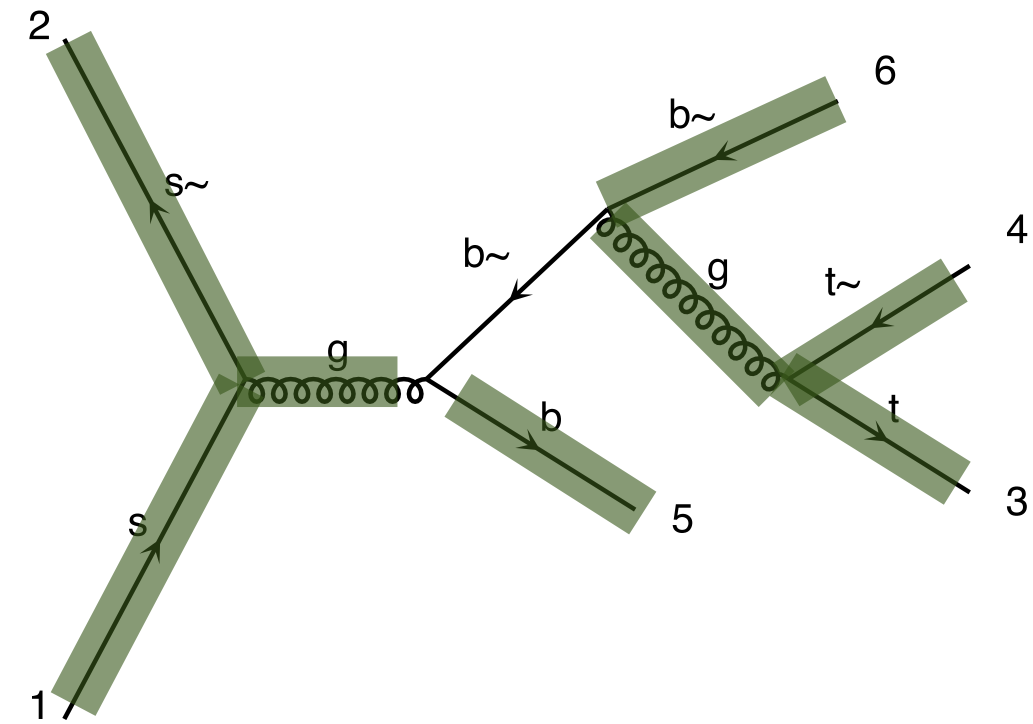
Number of routines: 8

Number of routines for both: 8

Real case

Known





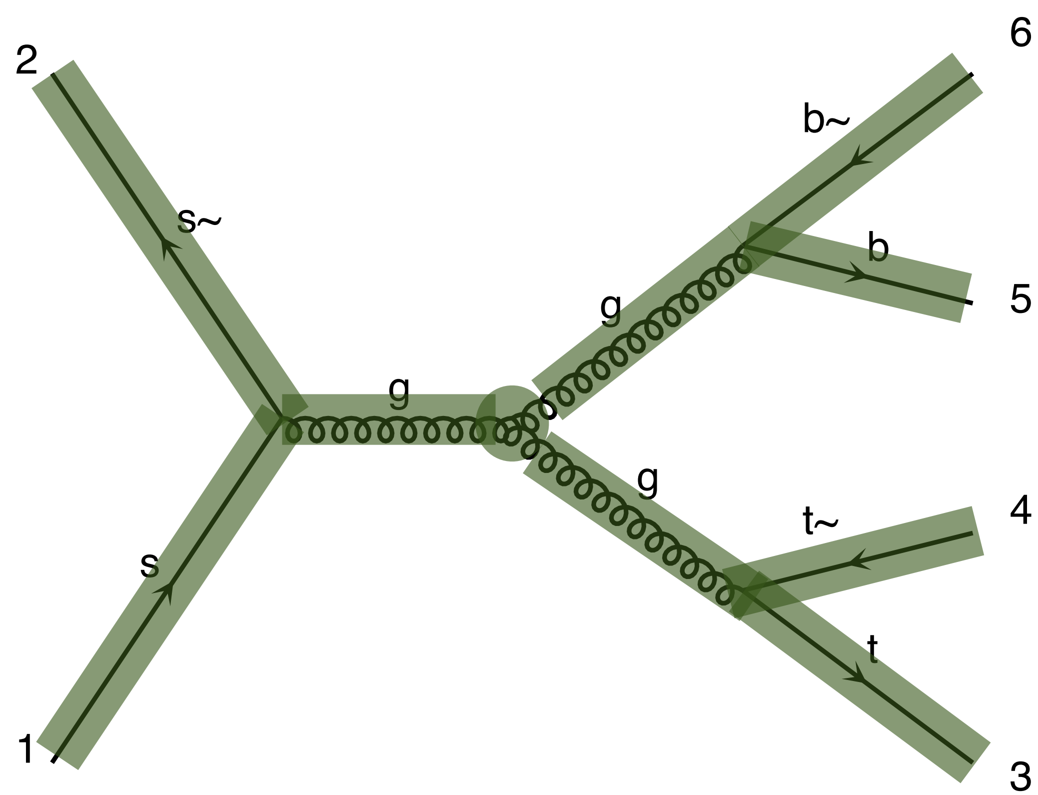
Number of routines: 9

Number of routines: 8

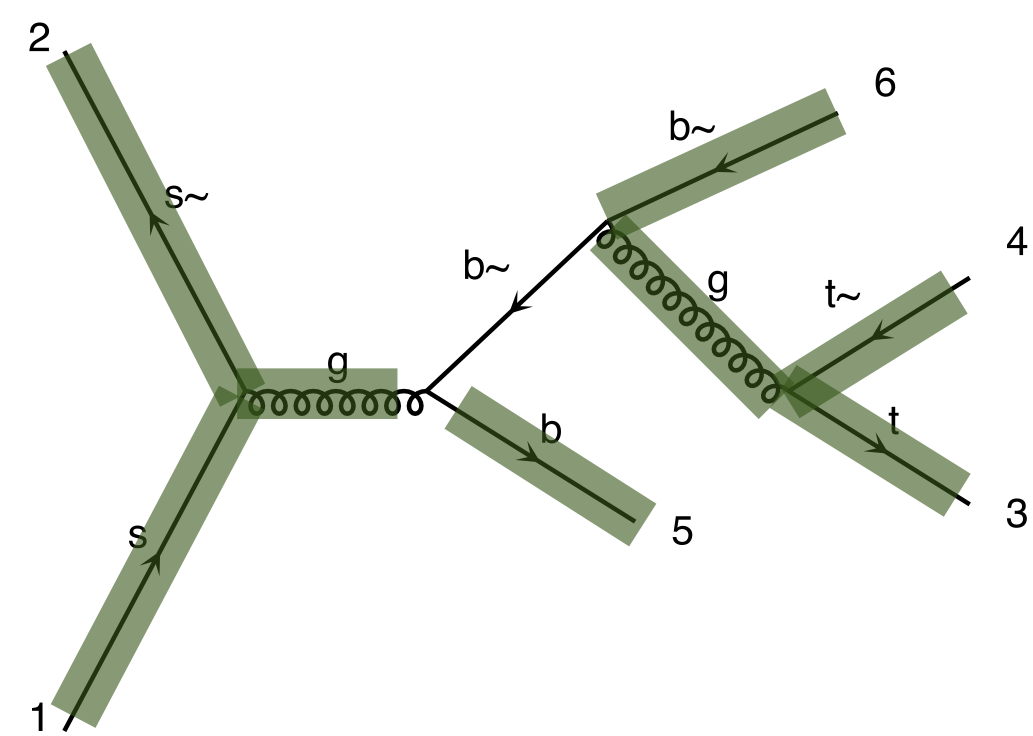
Number of routines for both: 9

Real case

Known



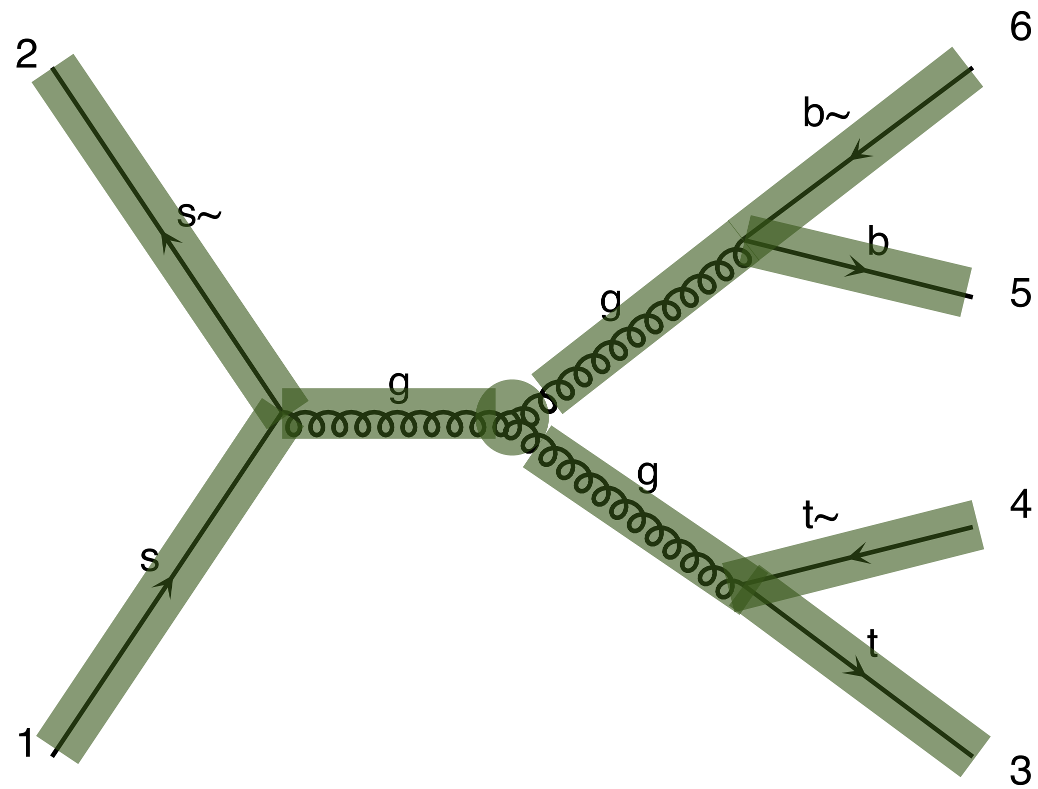
Number of routines: 10

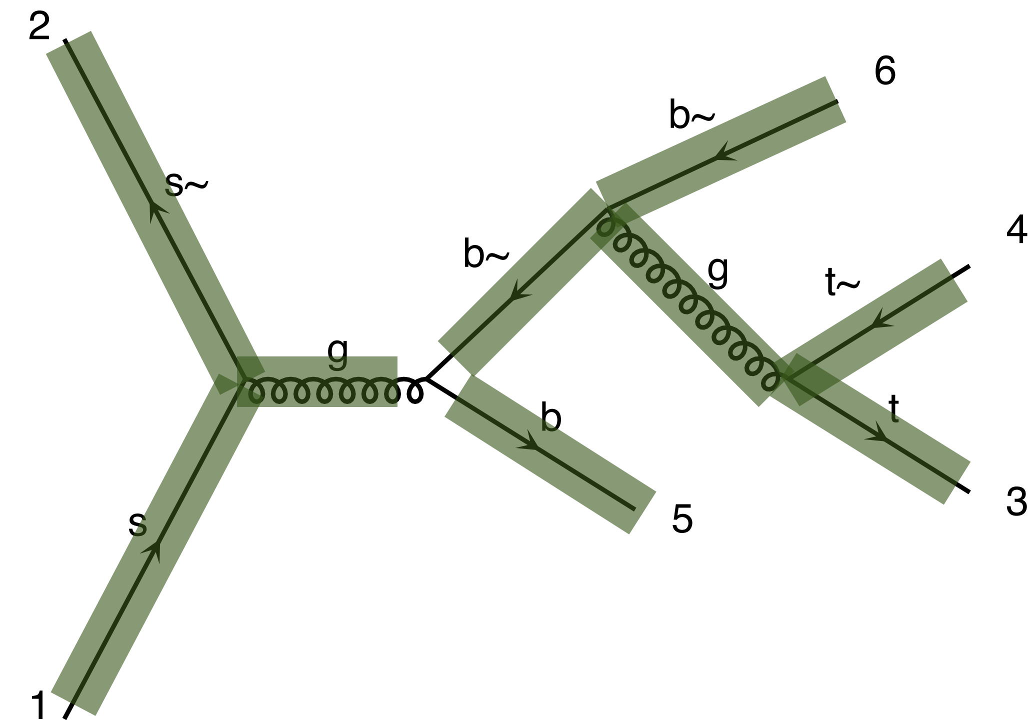


Number of routines: 8

Number of routines for both: 10

Real case



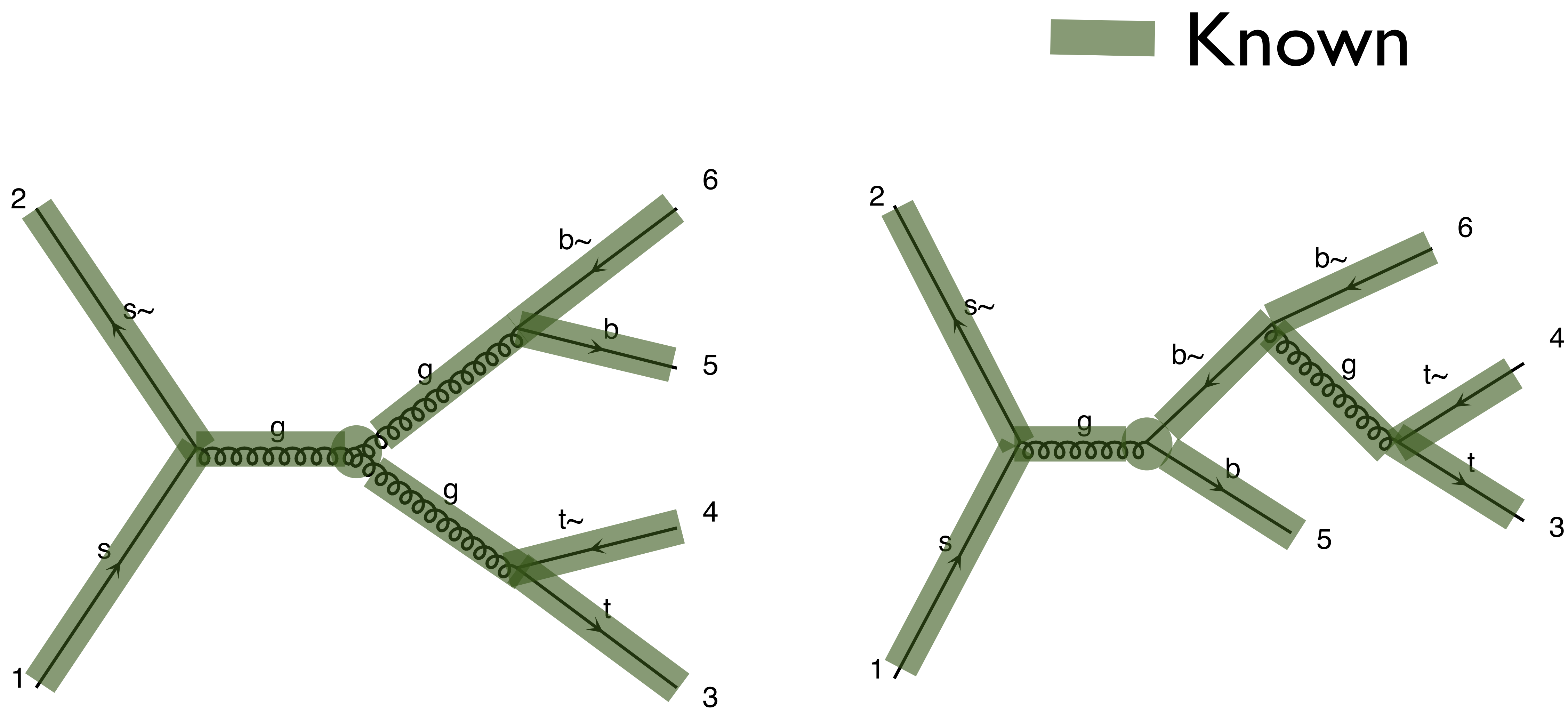


Number of routines: 10

Number of routines: 9

Number of routines for both: 11

Real case



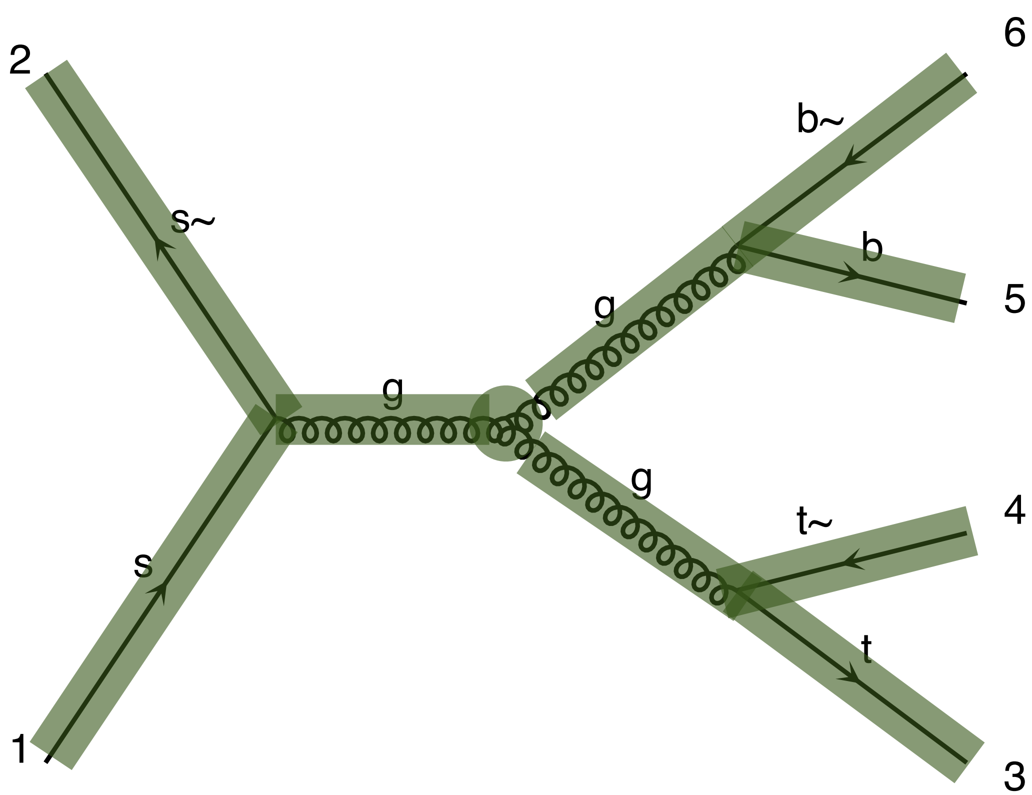
Number of routines: 10

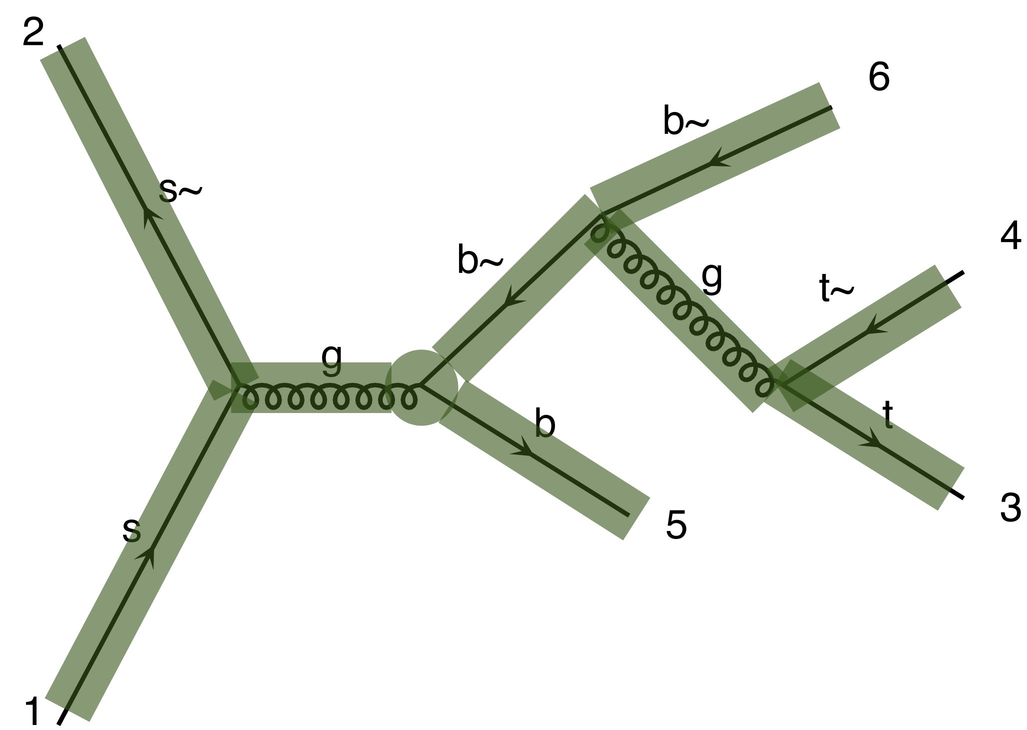
Number of routines: 10

Number of routines for both: 12

Real case

Known





Number of routines: 10

2(N+1)

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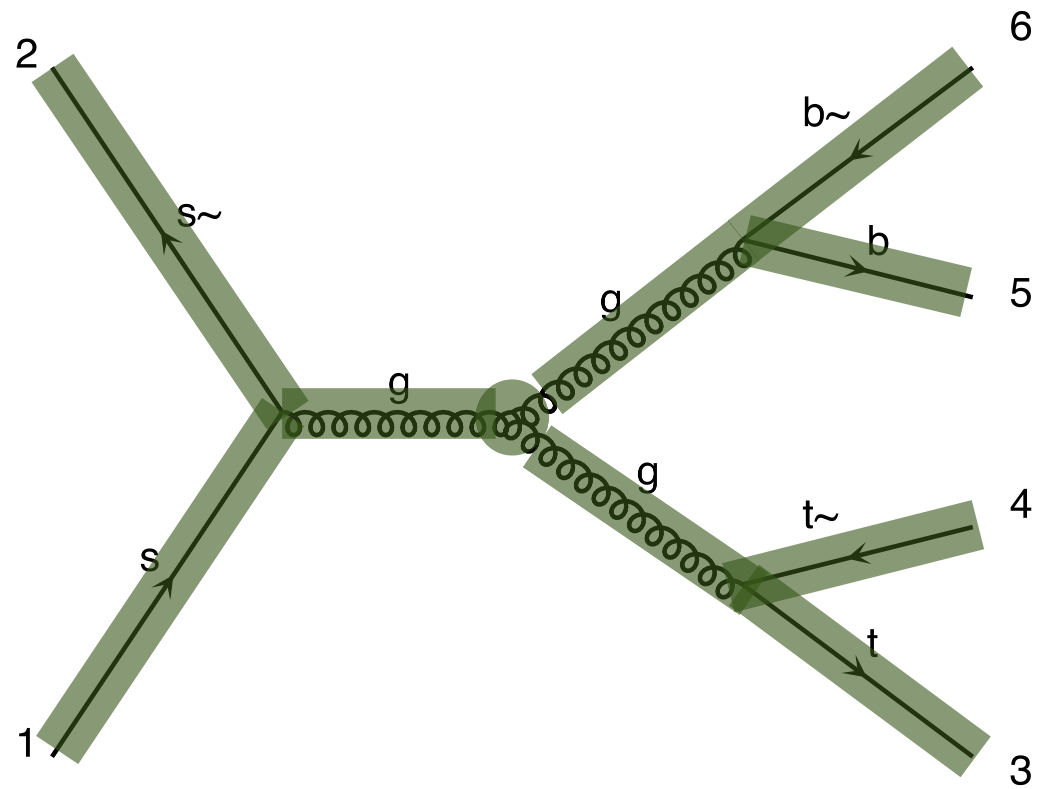
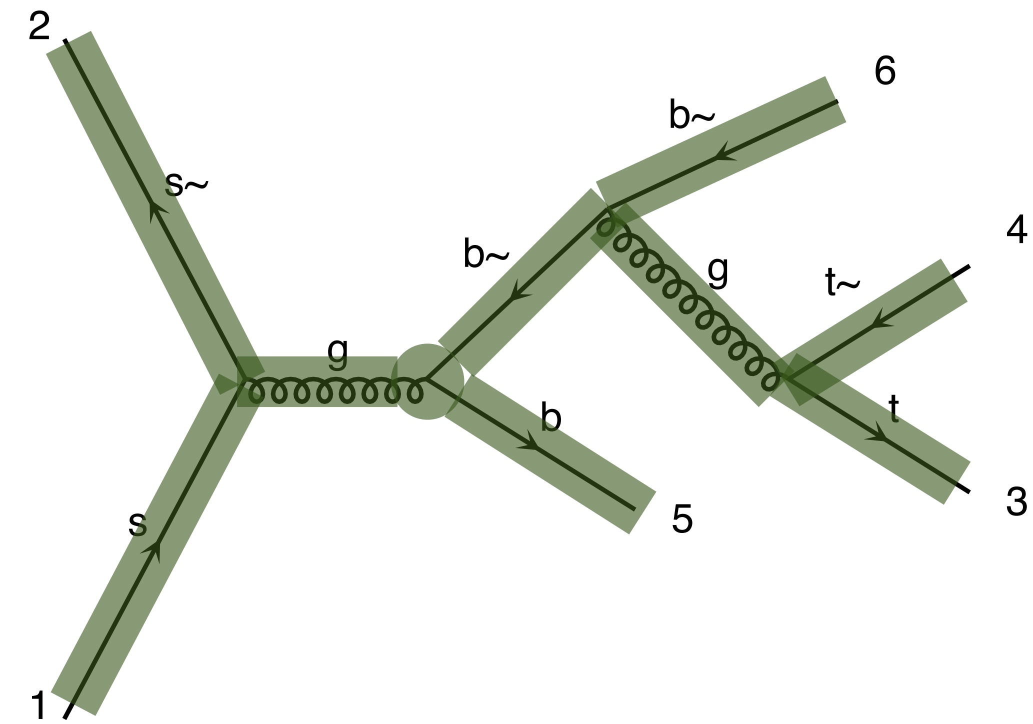
Number of routines for both: 12

Real case

Known





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2(N+1)

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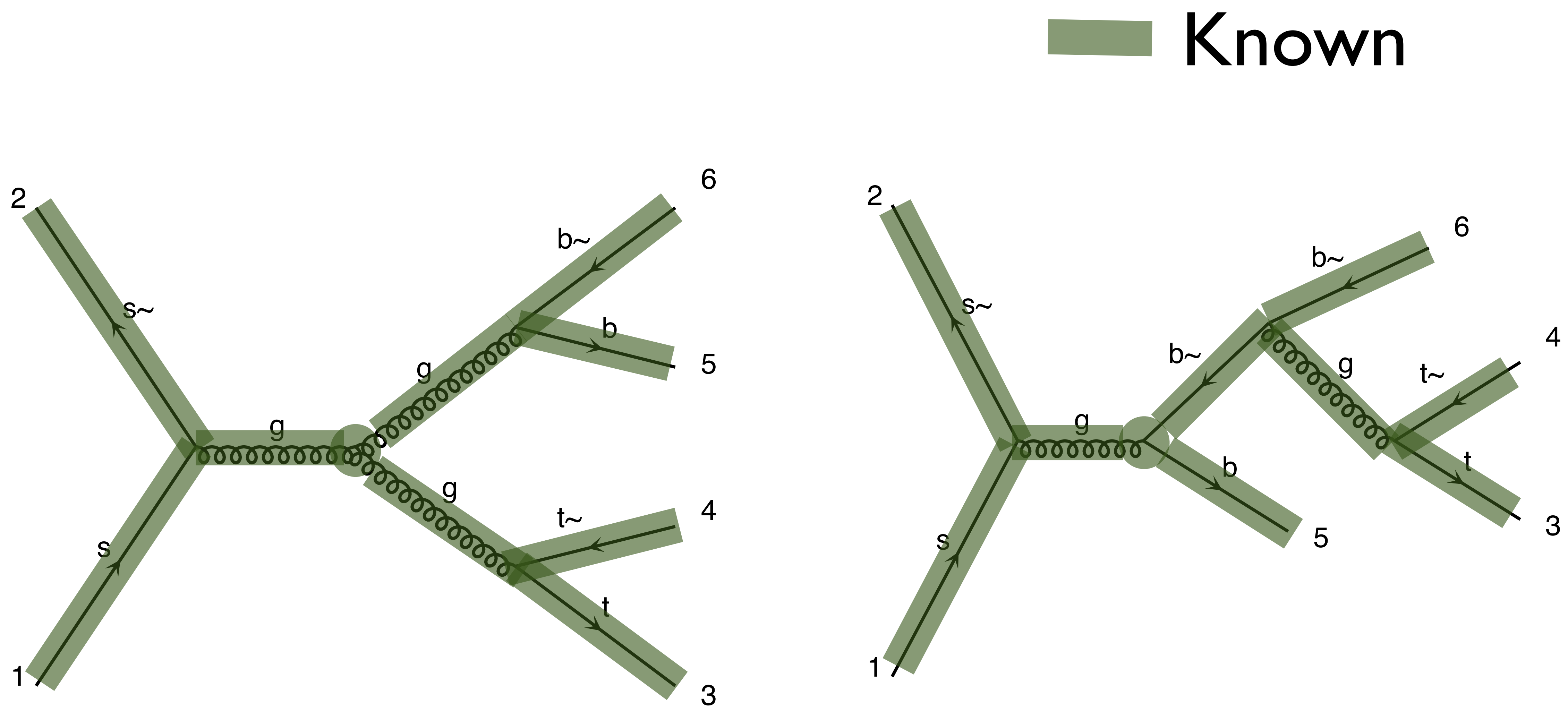
2(N+1)

Number of routines for both: 12

N!*2(N+1) ⟶ N!

Real case



Number of routines: 10

2(N+1)

Number of routines: 10

2(N+1)

Number of routines for both: 12

N!*2(N+1) → N! —in progress→ 2^N

Helicity amplitudes

- Thanks to new diagram generation algorithm, wf recycling much more efficient in MG5 than MG4

Process	Amplitudes	Wavefunctions		Run time		
		MG 4	MG 5	MG 4	MG 5	no recycling
$u\bar{u} \to e^+e^-$	2	6	6	$< 6\mu s$	$< 6\mu s$	
$u\bar{u} \to e^+e^-e^+e^-$	48	62	32	0.22 ms	0.14 ms	
$u\bar{u} \to e^+e^-e^+e^-e^+e^-$	3474	3194	301	46.5 ms	19.0 ms	300,000
$u\bar{u} \to d\bar{d}$	1	5	5	$< 4\mu s$	$< 4\mu s$	
$u\bar{u} \to d\bar{d}g$	5	11	11	27 μs	27 μs	
$u\bar{u} \to d\bar{d}gg$	38	47	29	0.42 ms	0.31 ms	
$u\bar{u} \to d\bar{d}ggg$	393	355	122	10.8 ms	6.75 ms	
$u\bar{u} \to u\bar{u}gg$	76	84	40	1.24 ms	0.80 ms	
$u\bar{u} \to u\bar{u}ggg$	786	682	174	35.7 ms	17.2 ms	
$u\bar{u} \to d\bar{d}d\bar{d}$	14	28	19	84 μs	83 μs	
$u\bar{u} \to d\bar{d}d\bar{d}g$	132	178	65	1.88 ms	1.15 ms	
$u\bar{u} \to d\bar{d}d\bar{d}gg$	1590	1782	286	141 ms	34.4 ms	
$u\bar{u} \to d\bar{d}d\bar{d}d\bar{d}$	612	758	141	42.5 ms	6.6 ms	5500

Time for matrix element evaluation on a Sony Vaio TZ laptop

HELAS

[Murayama, Watanabe, Hagiwara]

- Original HELicity Amplitude Subroutine library

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Chiral Perturbation

BNV Model

Effective Field Theory

NMSSM

Full HEFT

Chromo-magnetic operator

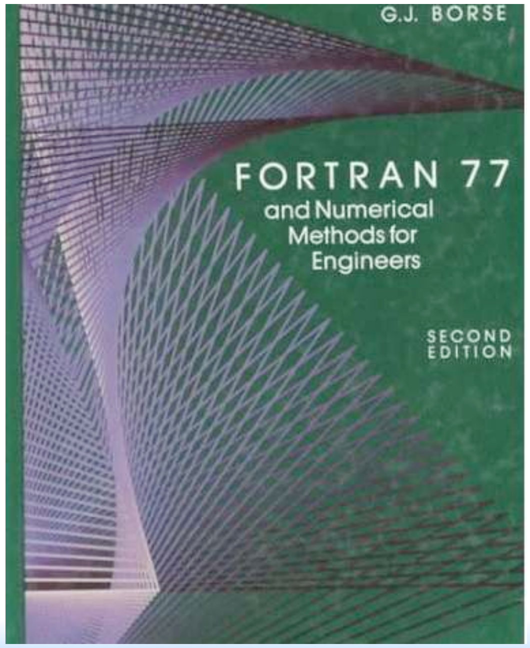
Black Holes

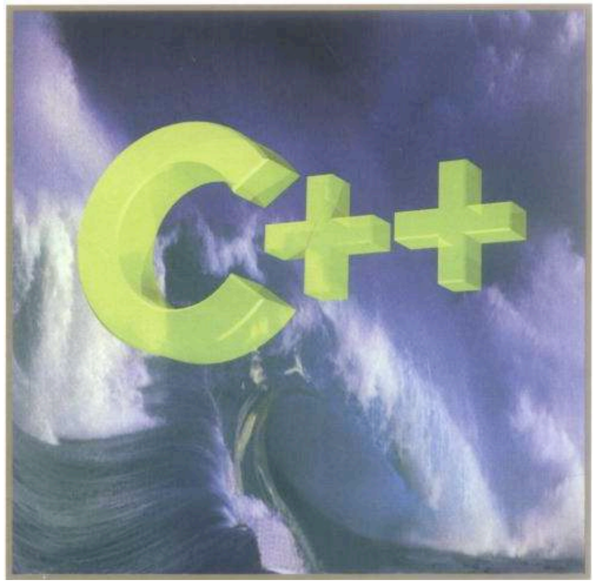
ALOHA

ALOHA
~~Google~~ translate

From: UFO ▾ To: Helicity Translate

Type text or a website address or translate a document.

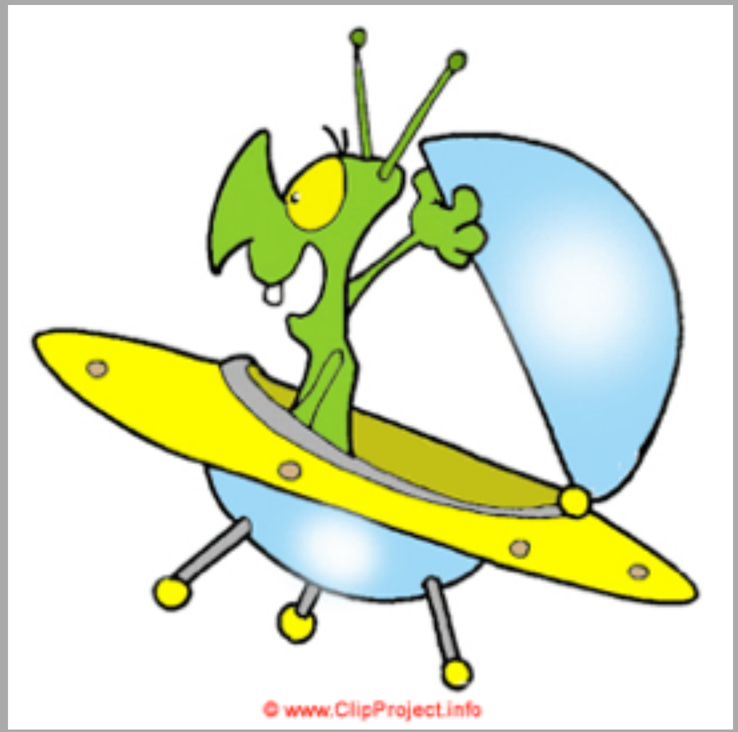




ALOHA

ALOHA ~~Google~~ translate

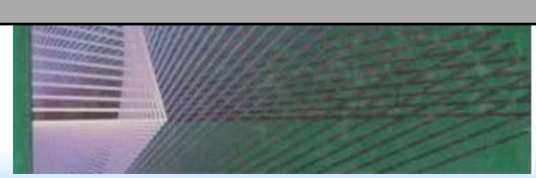
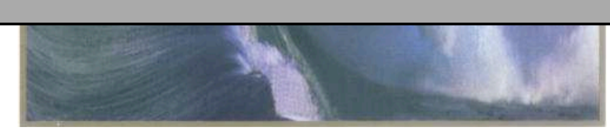
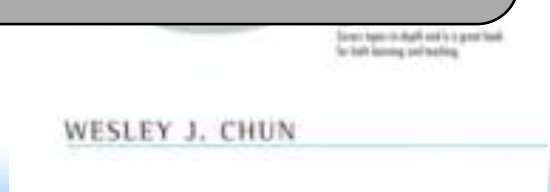
From: UFO To: Helicity Translate



- FeynRules output
- New Model Format
- Gosam/ Herwig++/ MG5
- Fully generic color/Lorentz/…

[Degrande, Duhr, Fuks, Grellscheid, OM, Reiter:108.2040]

Type te

ALOHA

ALOHA ~~Google~~ translate

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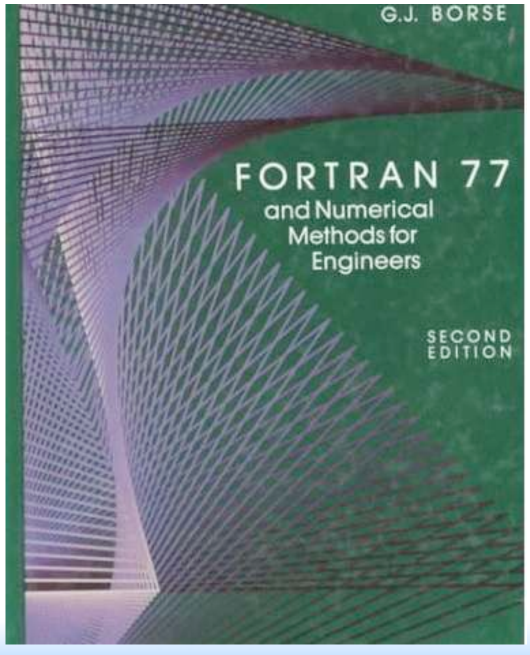
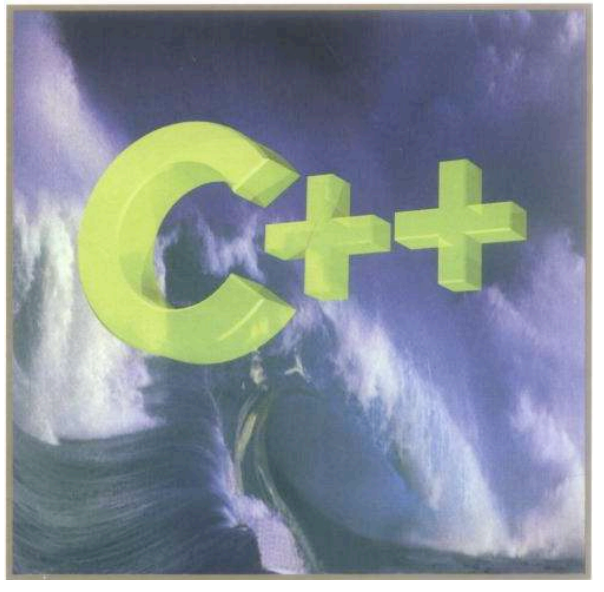
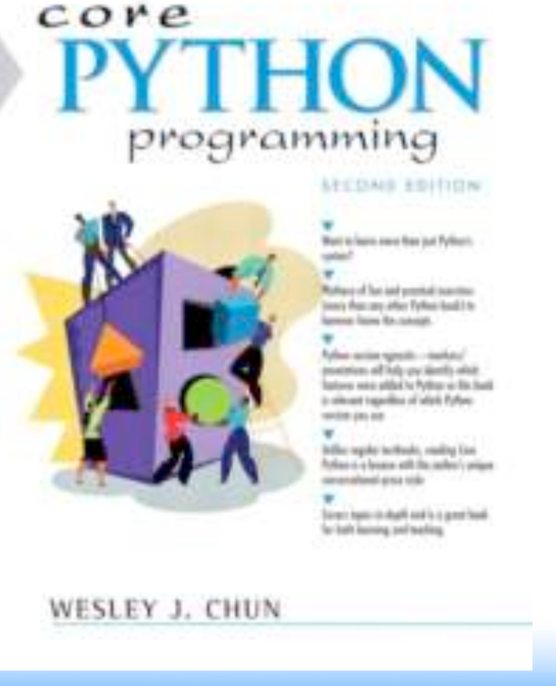
Type text or a website address or translate a document.







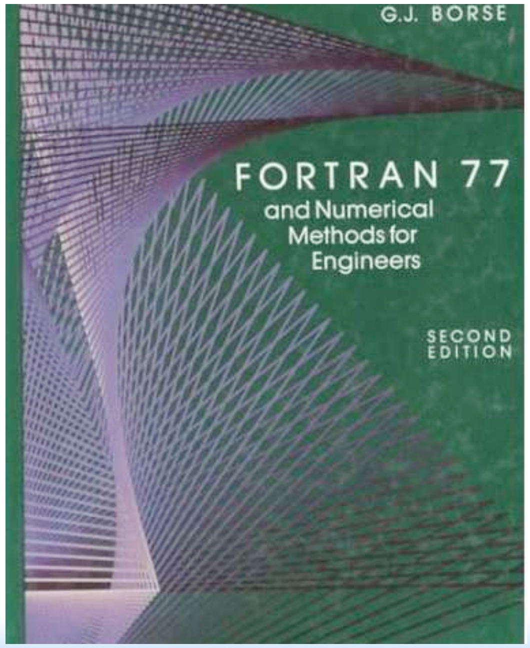
ALOHA

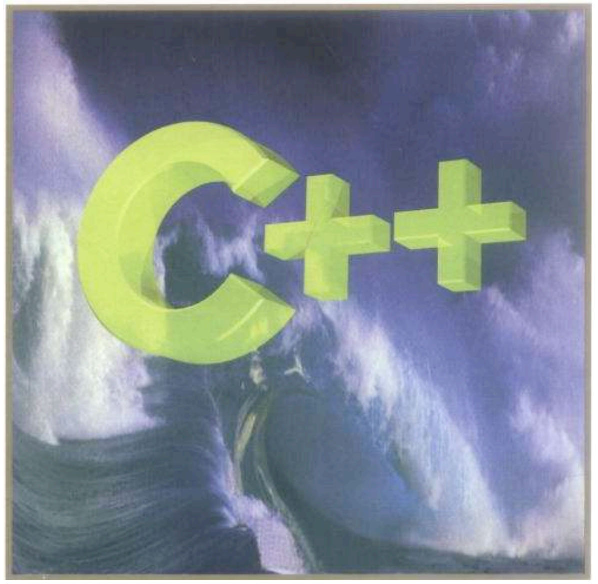
ALOHA
~~Google~~ translate

From: UFO ▾ To: Helicity Translate

Basically Any BSM Model should be working in MG5 out of the box!

Type text or a website address or translate a document.





Monte Carlo Integration and Generation

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Calculations of cross section or decay widths involve integrations over high-dimension phase space of very peaked functions:

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$Dim[\Phi(n)] \sim 3n$

Monte Carlo Integration

Calculations of cross section or decay widths involve integrations over high-dimension phase space of very peaked functions:

$$\sigma = \frac{1}{2s} \int |\mathcal{M}|^2 d\Phi(n)$$

$Dim[\Phi(n)] \sim 3n$

General and flexible method is needed

Integrals as averages

$$I = \int_{x_1}^{x_2} f(x)dx \quad \Rightarrow \quad I_N = (x_2 - x_1)\frac{1}{N}\sum_{i=1}^{N} f(x)$$

$$V = (x_2 - x_1)\int_{x_1}^{x_2} [f(x)]^2 dx - I^2 \quad \Rightarrow \quad V_N = (x_2 - x_1)^2\frac{1}{N}\sum_{i=1}^{N}[f(x)]^2 - I_N^2$$

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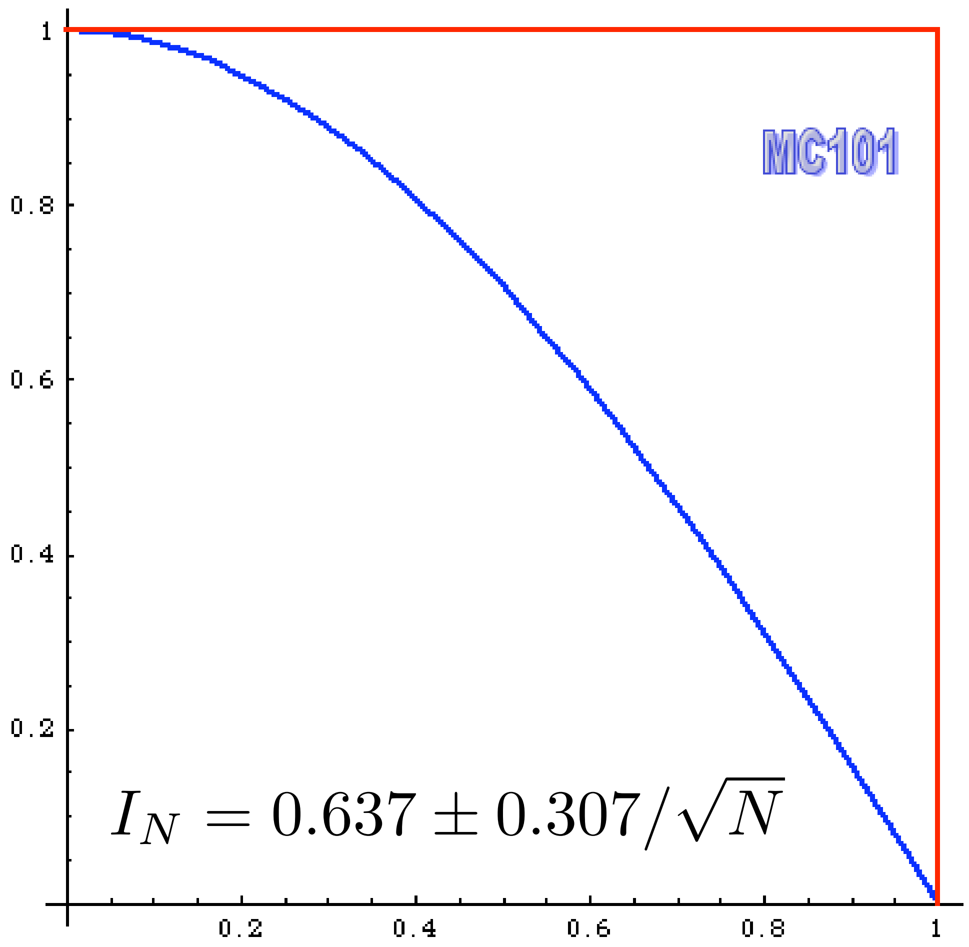
- ☞ Convergence is slow but it can be easily estimated
- ☞ Error does not depend on # of dimensions!
- ☞ Improvement by minimizing V_N.
- ☞ Optimal/Ideal case: $f(x)=C \Rightarrow V_N=0$

Importance Sampling



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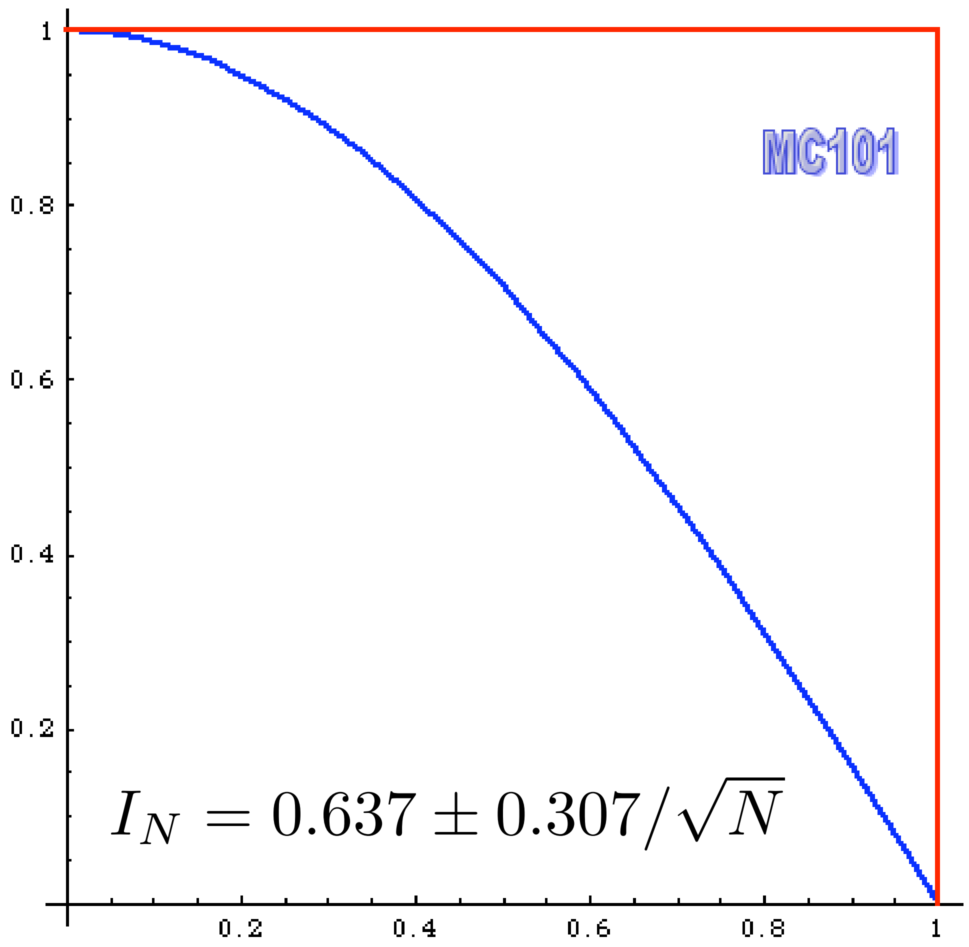
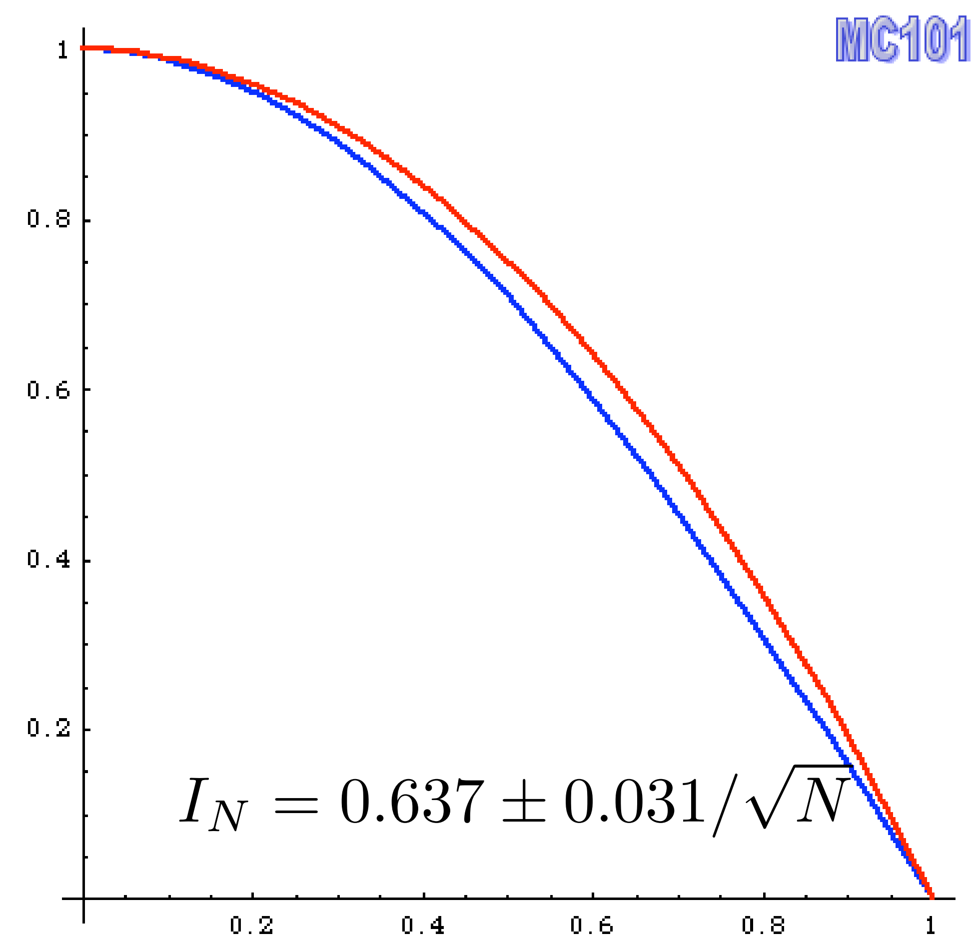
Importance Sampling





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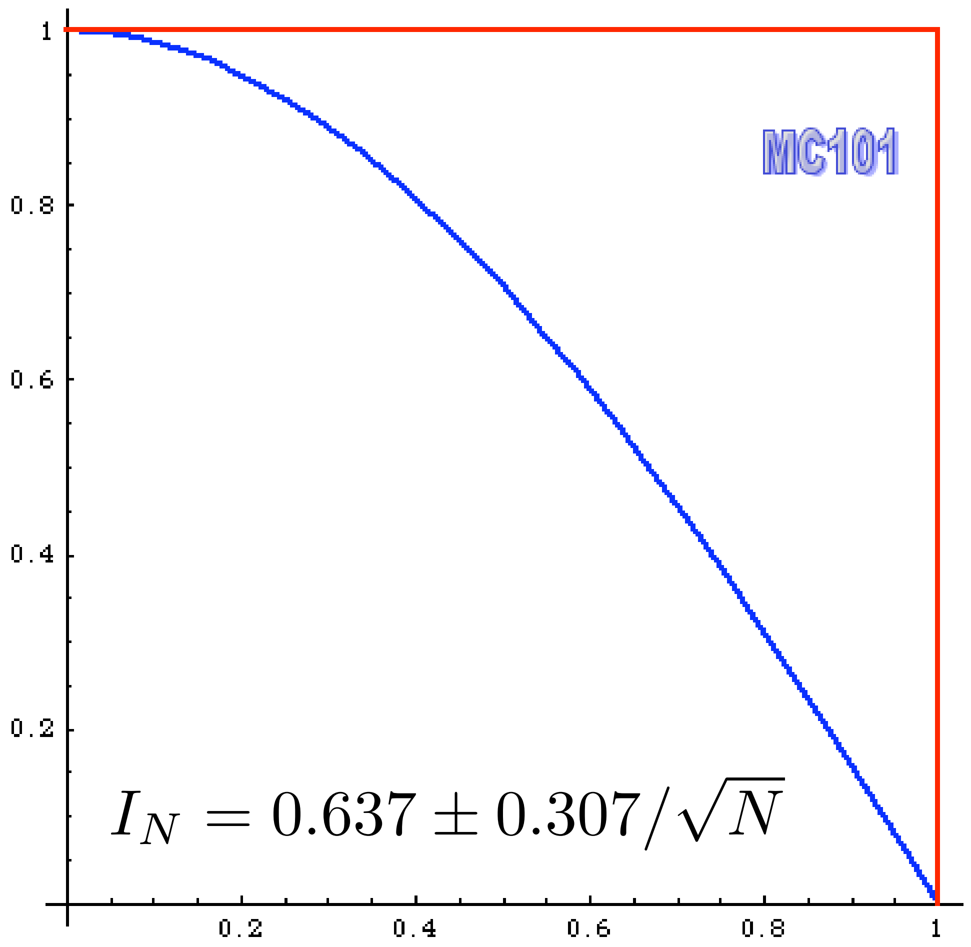

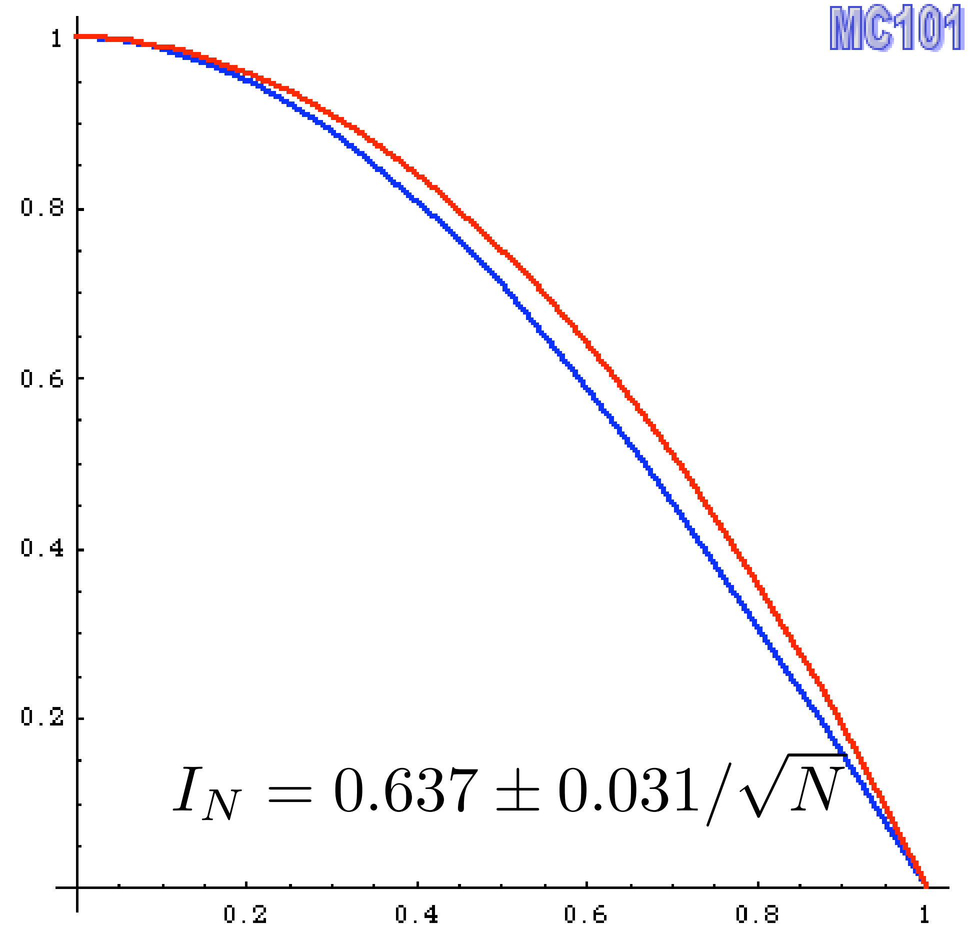

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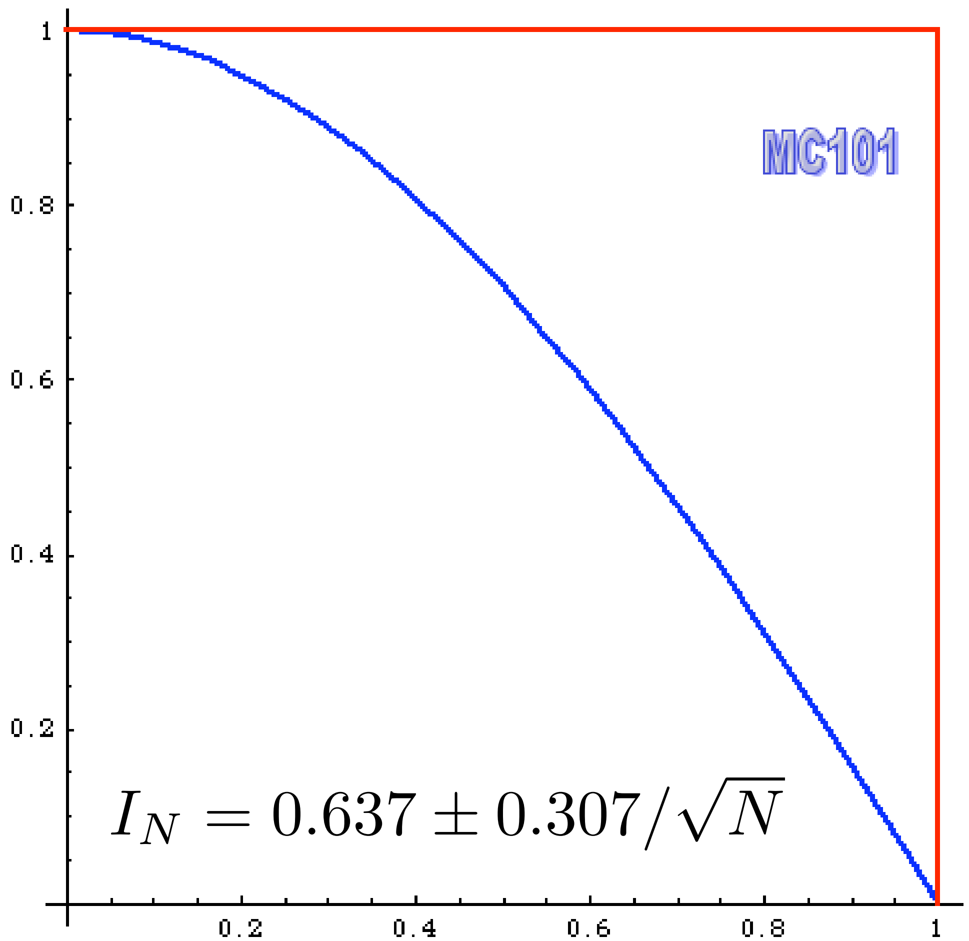
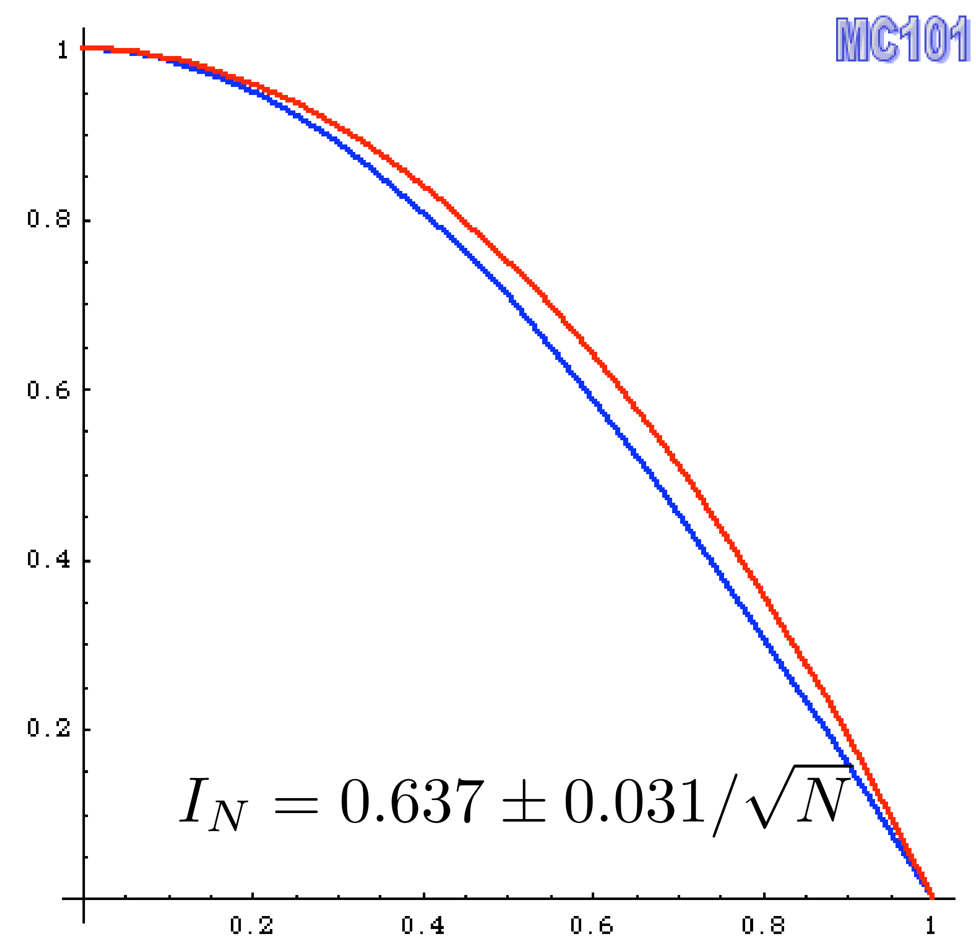
$$= \int_{\xi_1}^{\xi_2} d\xi \frac{\cos \frac{\pi}{2} x[\xi]}{1 - x[\xi]^2}$$

Importance Sampling





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$$= \int_{\xi_1}^{\xi_2} d\xi \frac{\cos\frac{\pi}{2}x[\xi]}{1-x[\xi]^2} \Rightarrow \simeq 1$$

Importance Sampling

but... you need to know a lot about f(x)!

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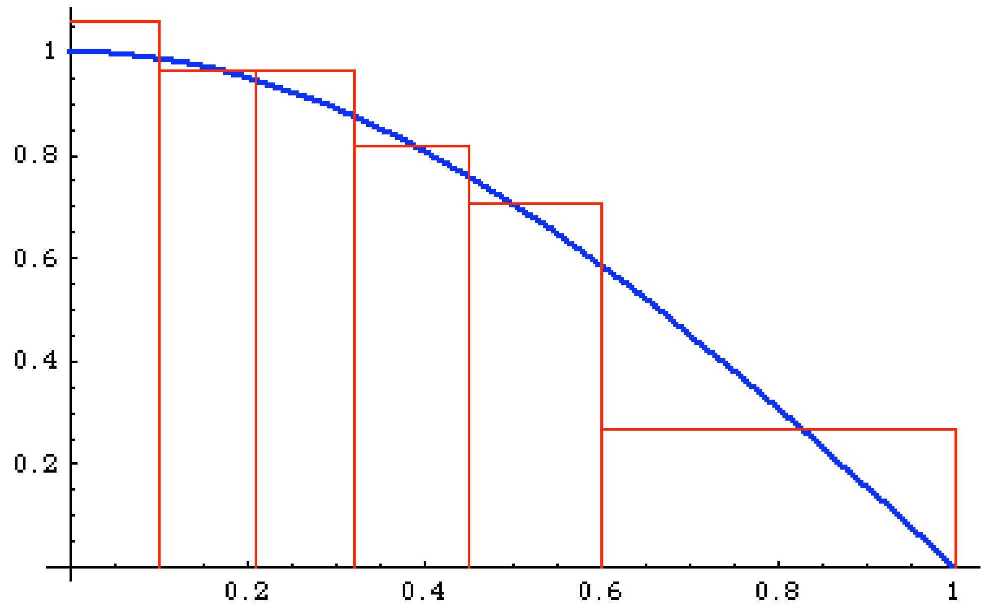
MC101



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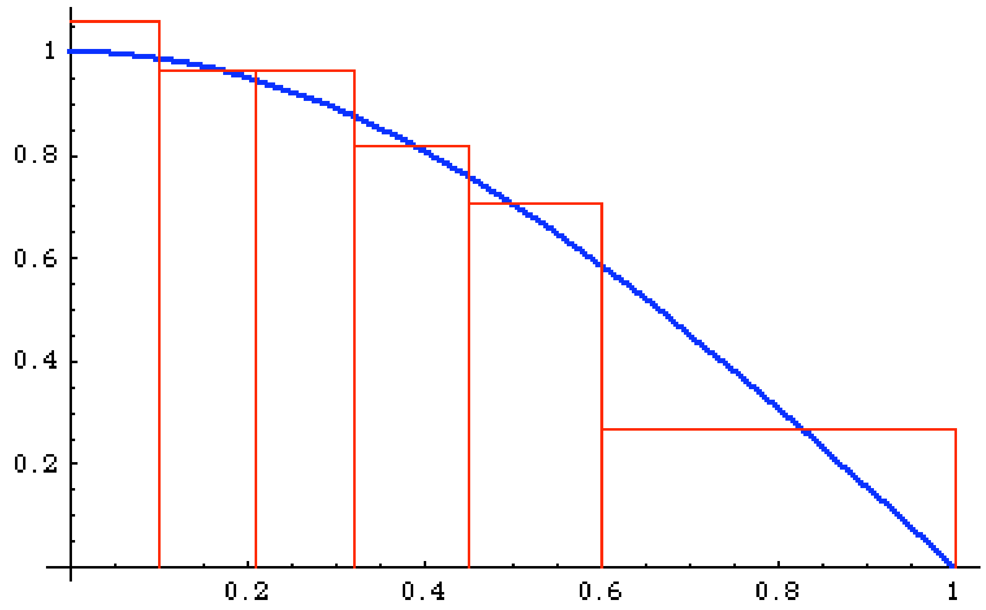

many bins where f(x) is large

$$p(x) = \frac{1}{N_b \Delta x_i}, \quad x_i - \Delta x_i < x < x_i$$

Importance Sampling

can be generalized to n dimensions:

$$\vec{p}(x) = p(x) \cdot p(y) \cdot p(z) \ldots$$

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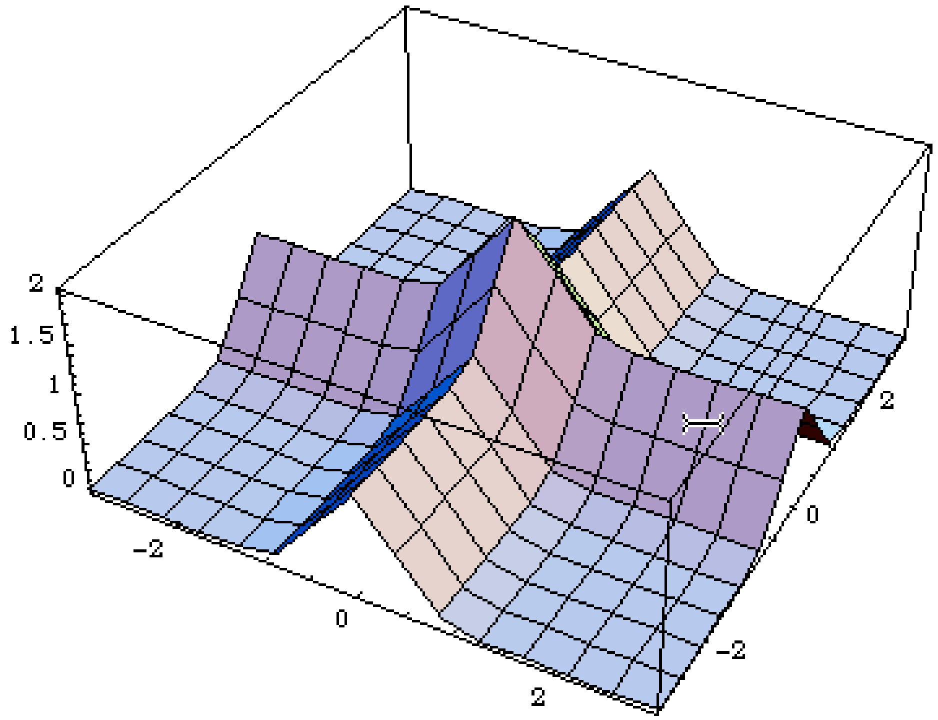

This is ok...

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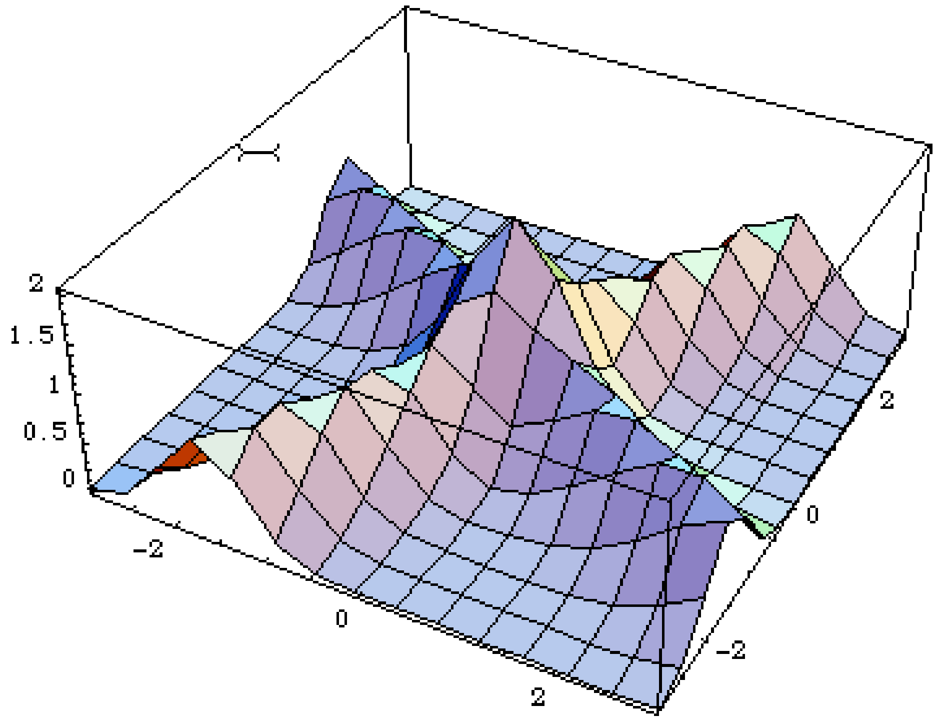

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Importance Sampling

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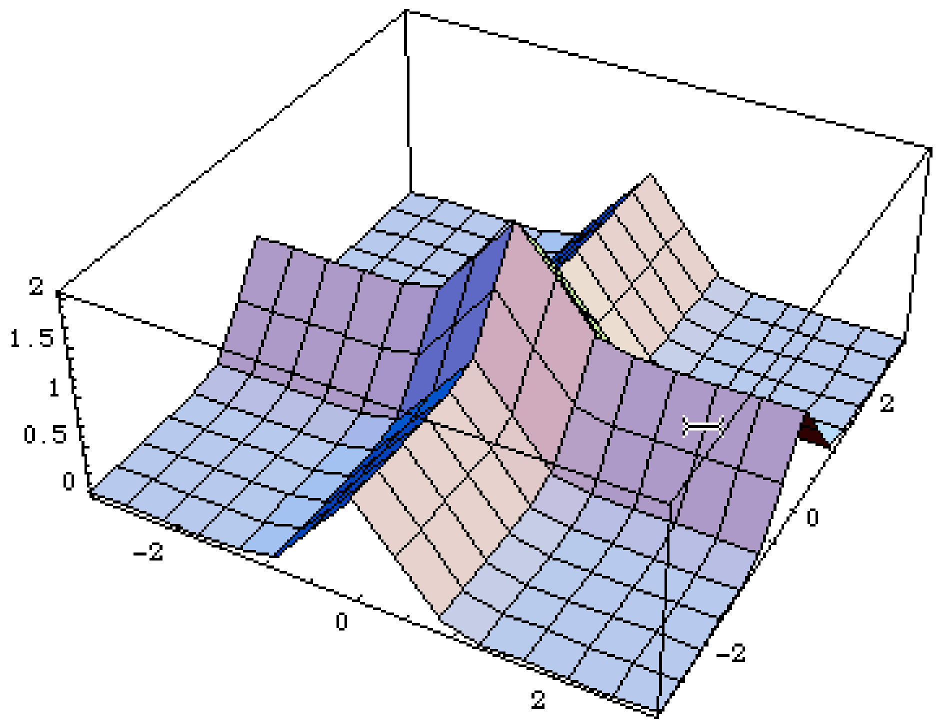
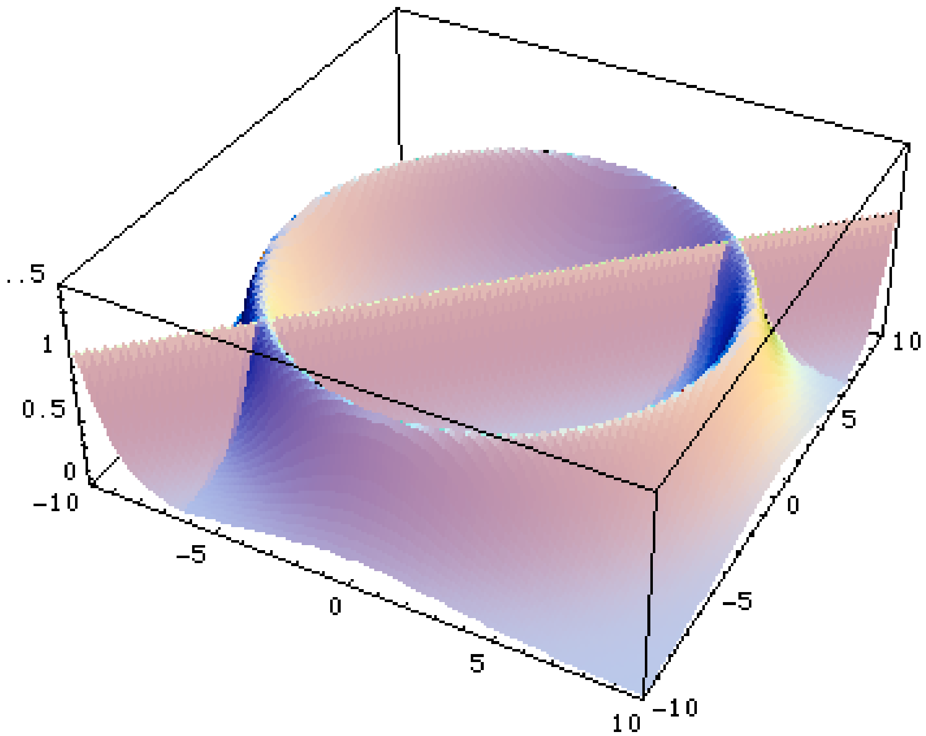


but it is sufficient to make a change of variables!

Multi-channel



What do we do if there is no transformation that aligns all integrand peaks to the chosen axes? Vegas is bound to fail!

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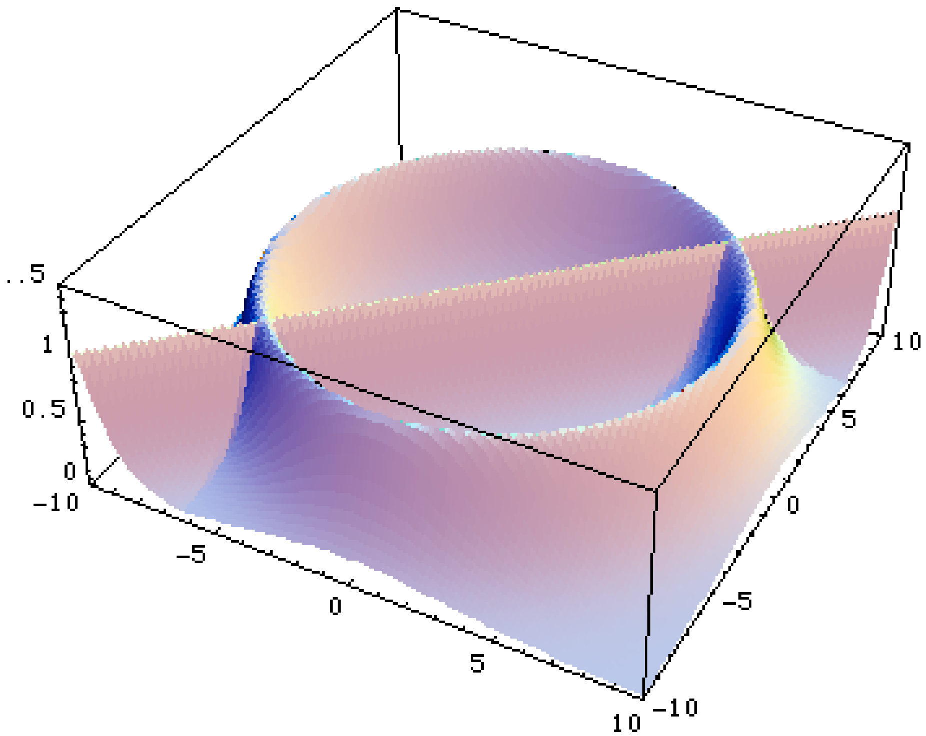


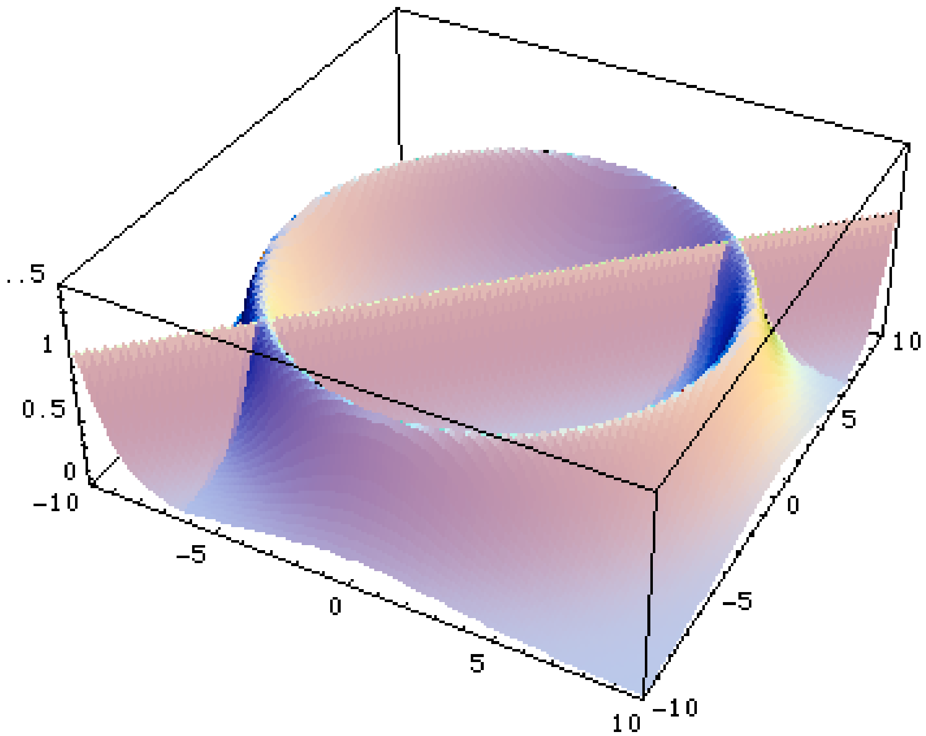
What do we do if there is no transformation that aligns all integrand peaks to the chosen axes?
Vegas is bound to fail!

Solution: use different transformations = channels

$$p(x) = \sum_{i=1}^{n} \alpha_i p_i(x) \qquad \text{with} \qquad \sum_{i=1}^{n} \alpha_i = 1$$

with each $p_i(x)$ taking care of one "peak" at the time

Multi-channel



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with

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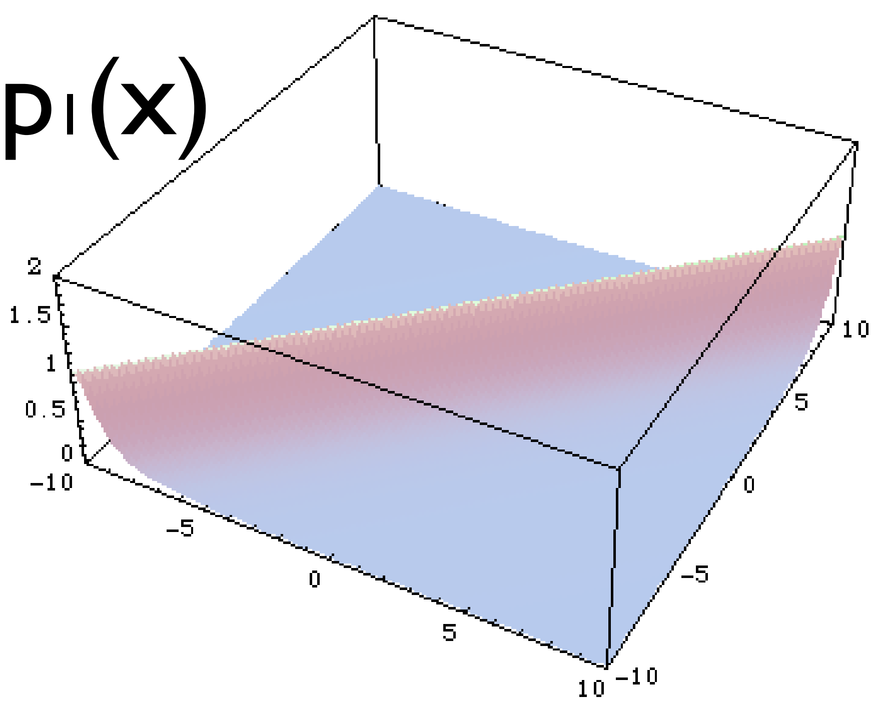
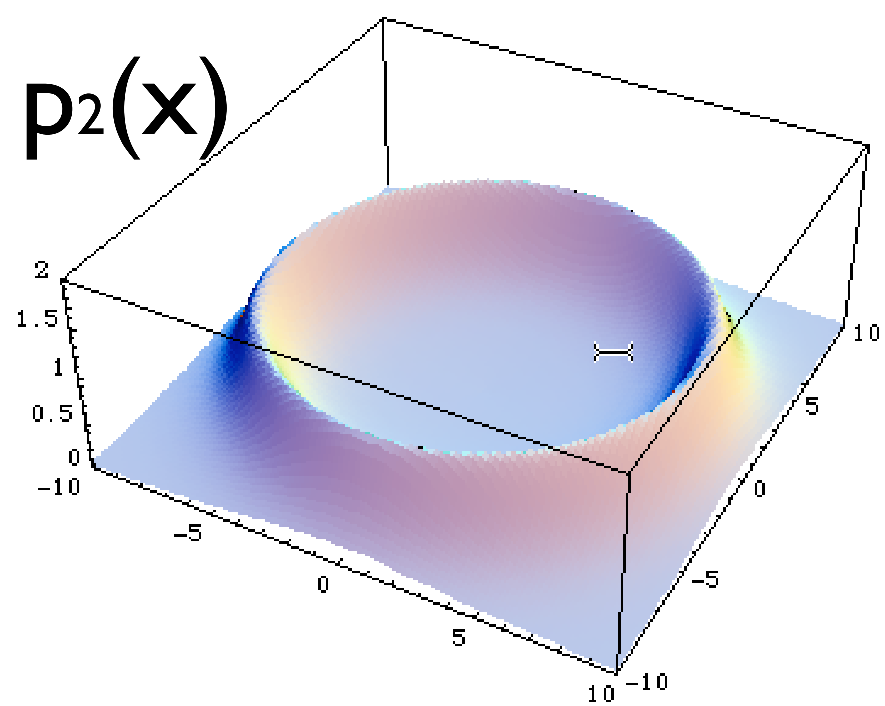
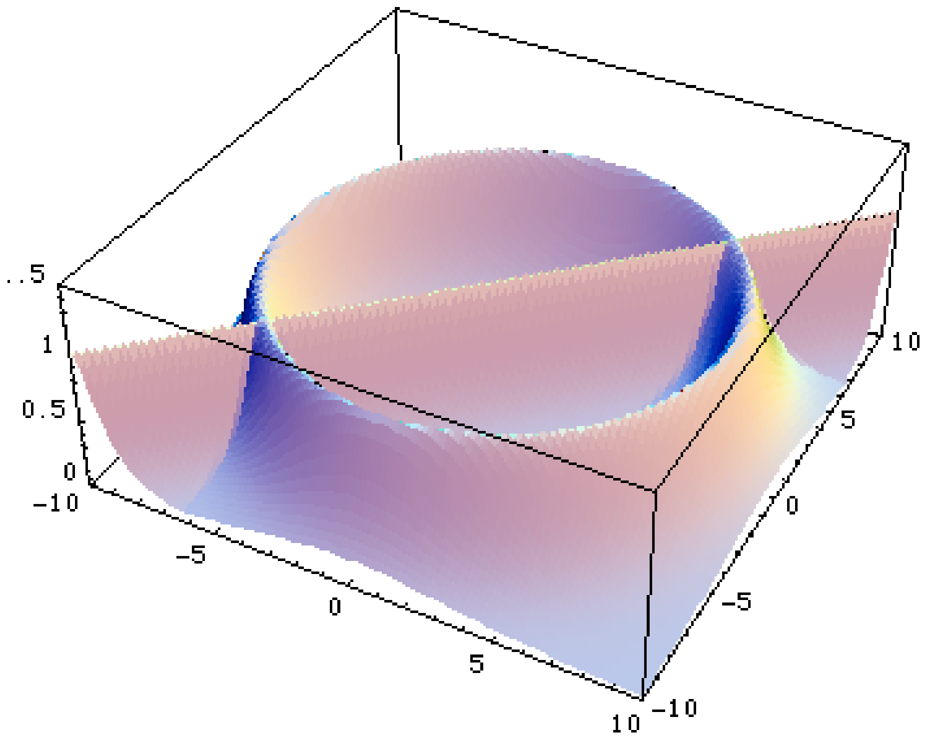
$p_1(x)$



$p_2(x)$



Multi-channel

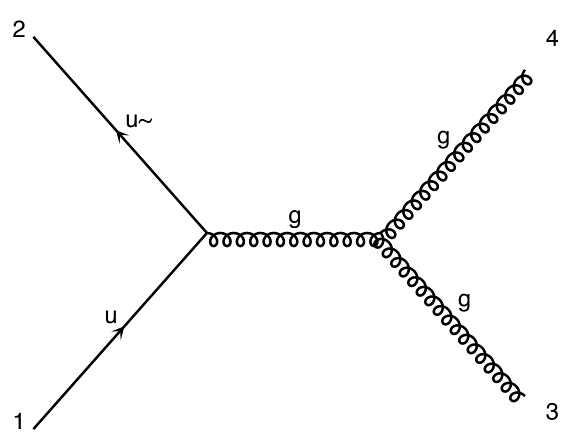


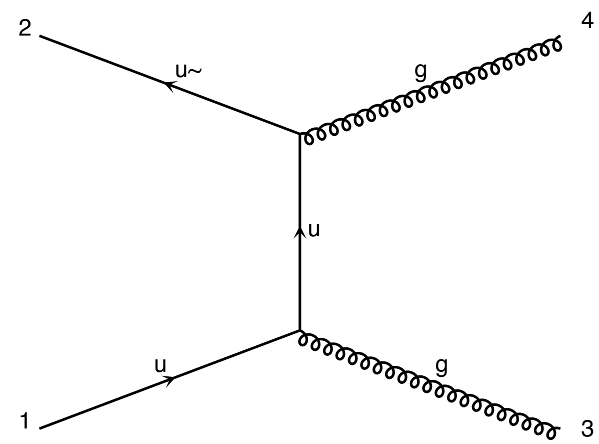
$$p(x) = \sum_{i=1}^{n} \alpha_i p_i(x)$$

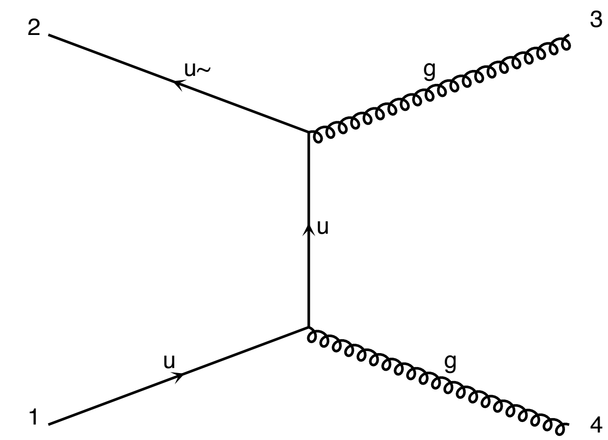
with $$\sum_{i=1}^{n} \alpha_i = 1$$

Then,

$$I = \int f(x)dx = \sum_{i=1}^{n} \alpha_i \int \frac{f(x)}{p(x)} p_i(x) dx$$







$$\propto \frac{1}{\hat{s}} = \frac{1}{(p_1 + p_2)^2} \qquad \propto \frac{1}{\hat{t}} = \frac{1}{(p_1 - p_3)^2} \qquad \propto \frac{1}{\hat{u}} = \frac{1}{(p_1 - p_4)^2}$$

Three very different pole structures contributing to the same matrix element.

Multi-channel

Consider the integration of an amplitude |M|^2 at tree level which many contributing diagrams. We would like to have a basis of functions,

$$f = \sum_{i=1}^{n} f_i \quad \text{with} \quad f_i \geq 0\,, \quad \forall \; i\,,$$

such that:

1. we know how to integrate each one of them,
2. they describe all possible peaks,

giving us the combined integral

$$I = \int d\vec{\Phi} f(\vec{\Phi}) = \sum_{i=1}^{n} \int d\vec{\Phi}\, g_i(\vec{\Phi}) \frac{f_i(\vec{\Phi})}{g_i(\vec{\Phi})} = \sum_{i=1}^{n} I_i\,,$$

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Does such a basis exist?

*Method used in MadGraph

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YES! $$f_i = \frac{|A_i|^2}{\sum_i |A_i|^2} |A_{\text{tot}}|^2$$

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Does such a basis exist?

YES! $f_i = \frac{|A_i|^2}{\sum_i |A_i|^2} |A_{\text{tot}}|^2$ ≈ 1

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Does such a basis exist?

YES! $f_i = \frac{|A_i|^2}{\sum_i |A_i|^2} |A_{\text{tot}}|^2 \approx 1$

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Key Idea

- Any single diagram is "easy" to integrate (pole structures/ suitable integration variables known from the propagators)
- Divide integration into pieces, based on diagrams
- All other peaks taken care of by denominator sum

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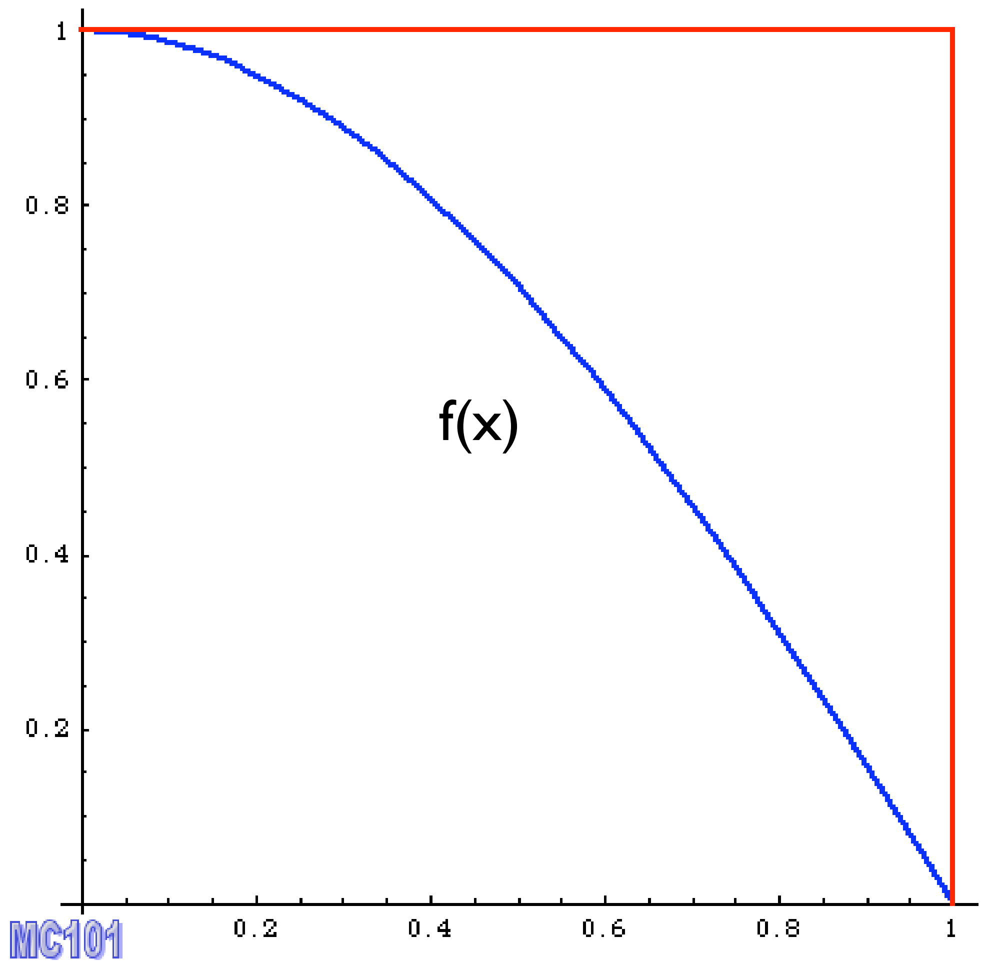
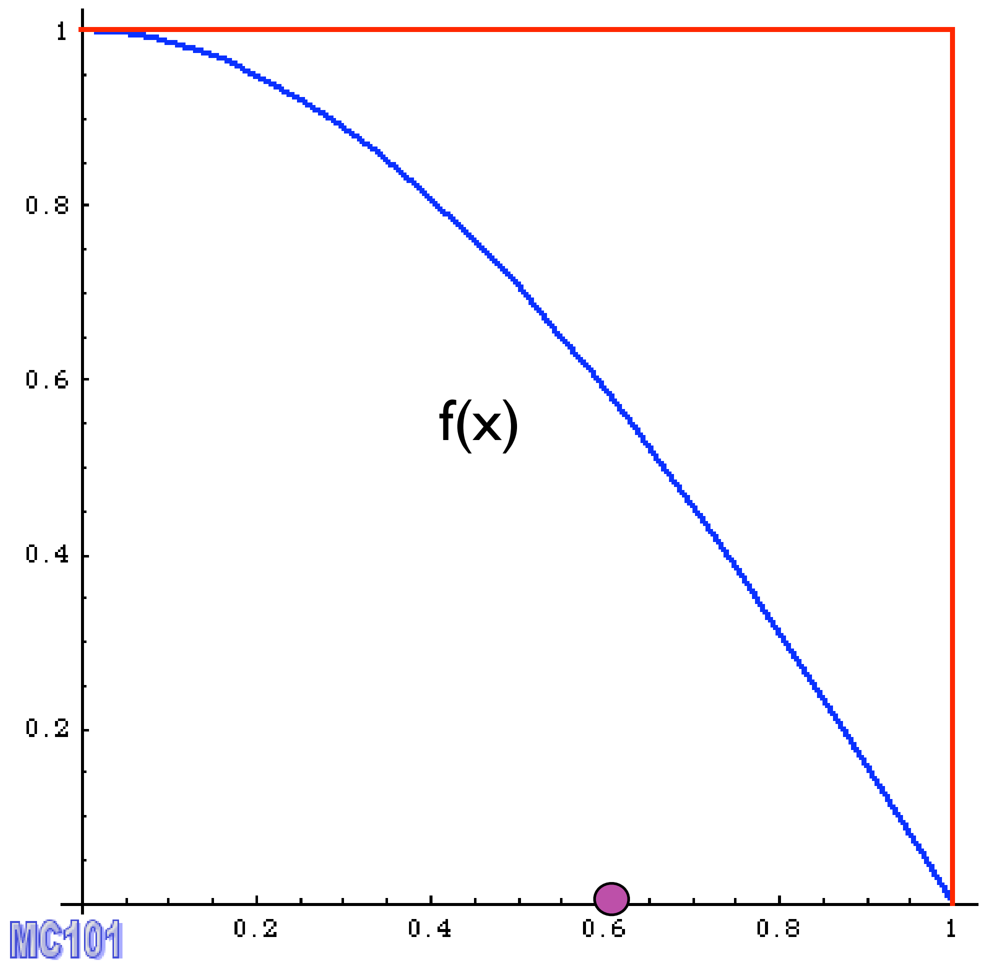
N Integral

- Errors add in quadrature so no extra cost
- "Weight" functions already calculated during $|M|^2$ calculation
- Parallel in nature

Event generation

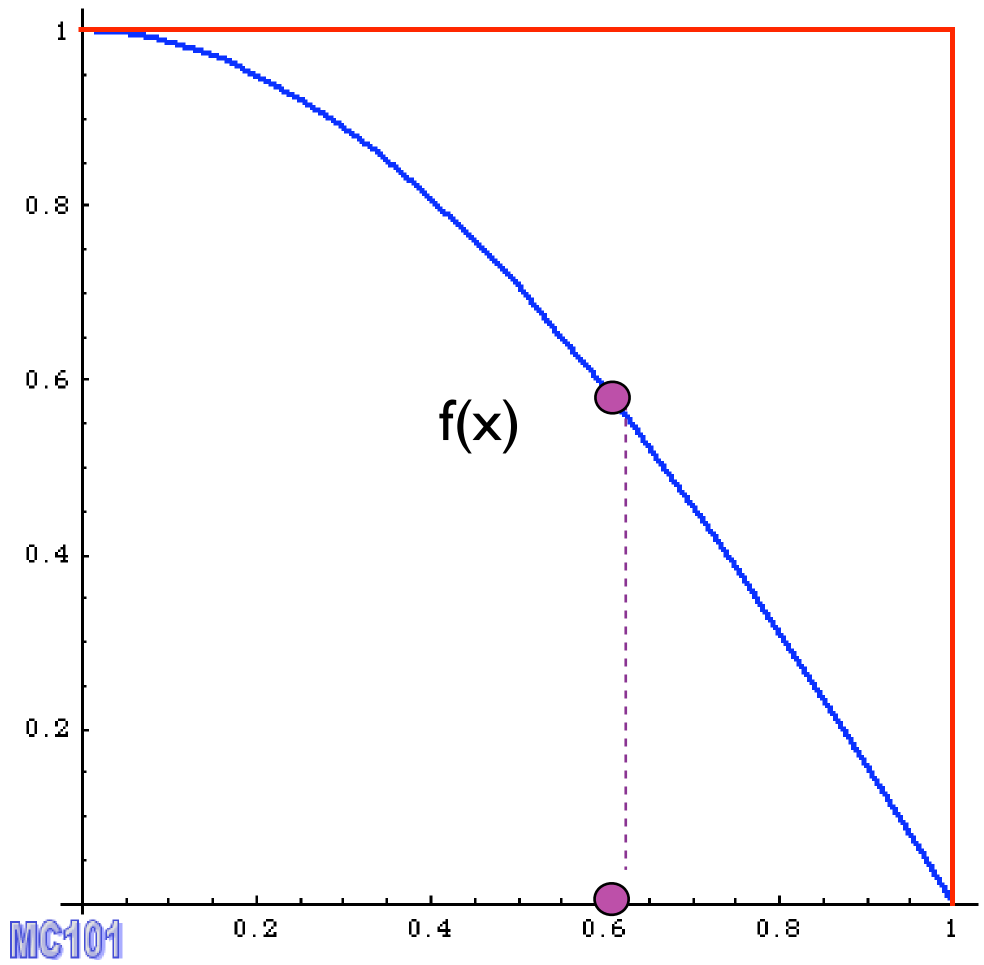


Event generation



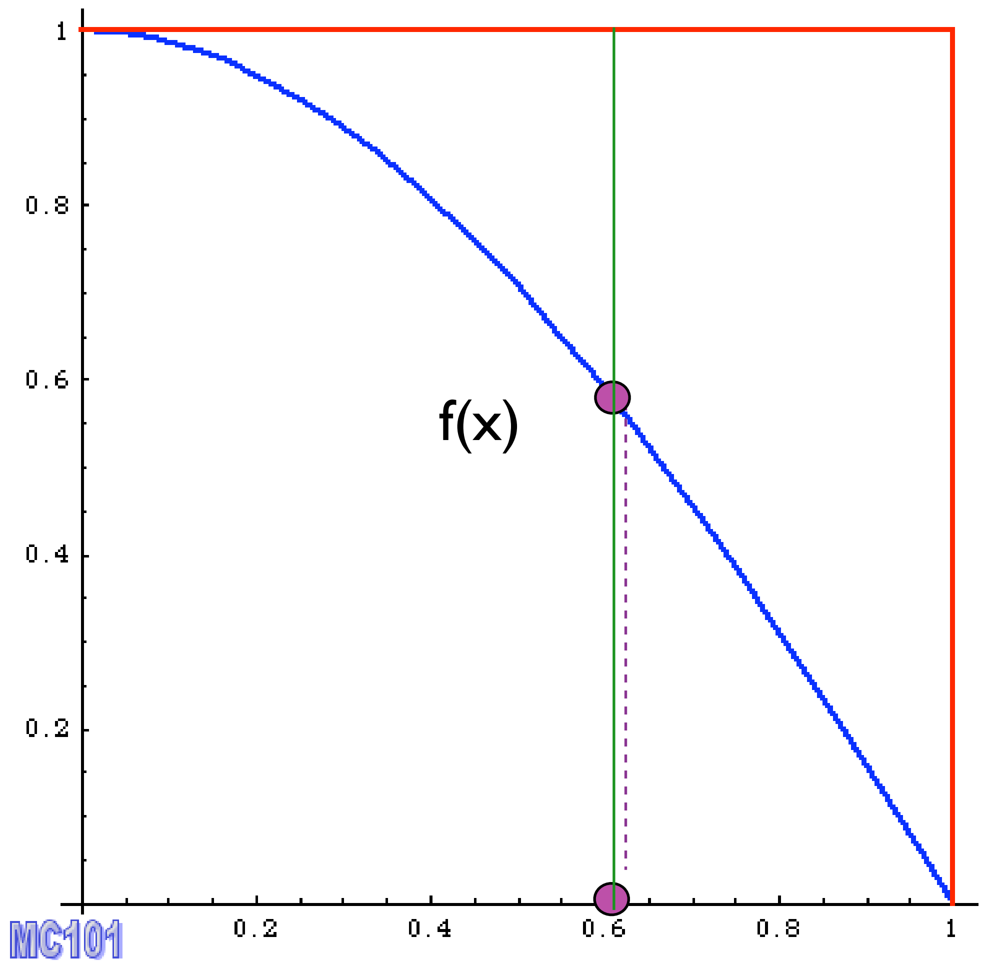
1. pick x

Event generation



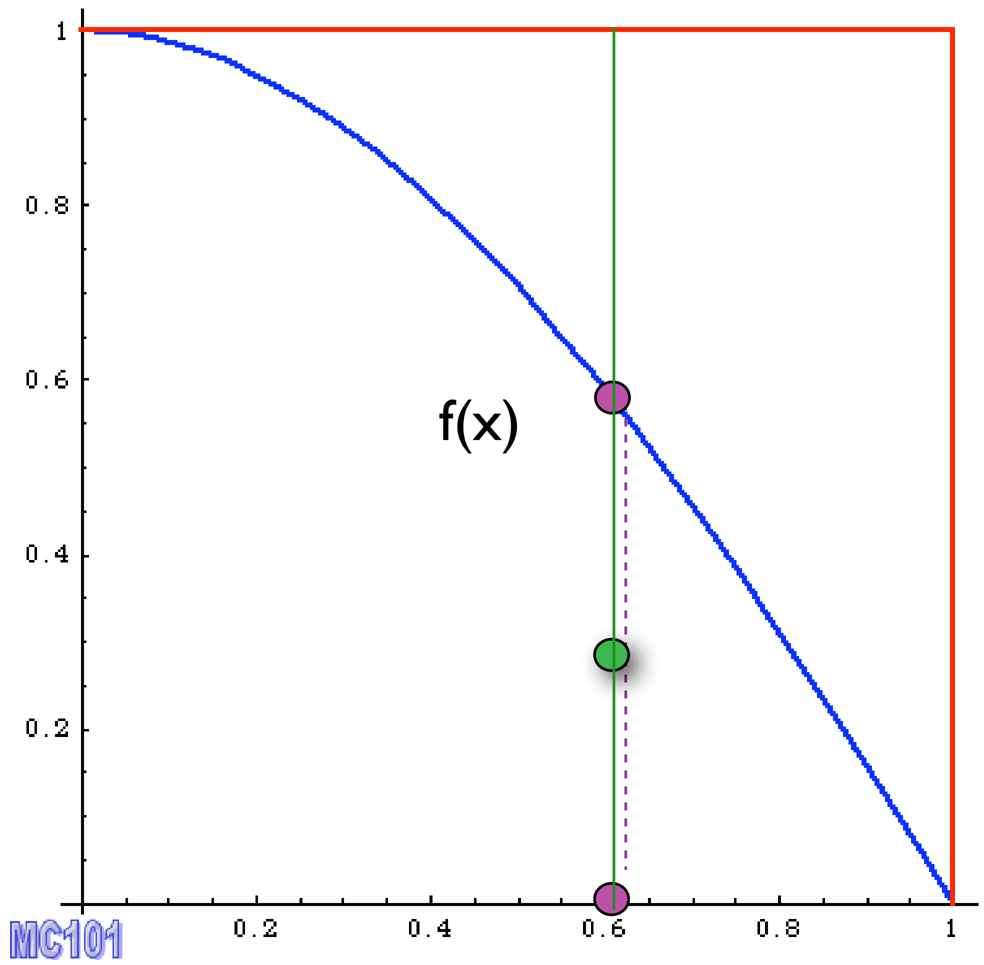
1. pick x
2. calculate f(x)

Event generation



1. pick x
2. calculate f(x)
3. pick 0<y<fmax

Event generation



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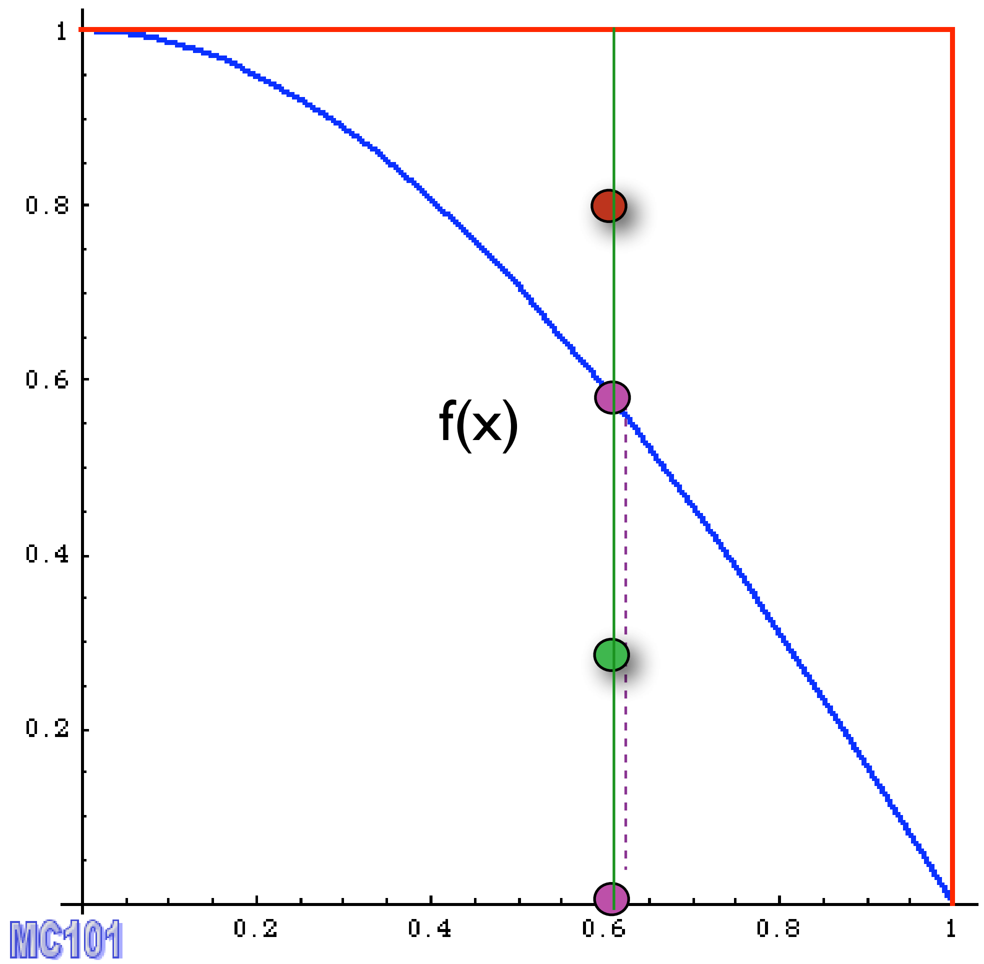
4. Compare:
   if f(x)>y accept event,

Event generation



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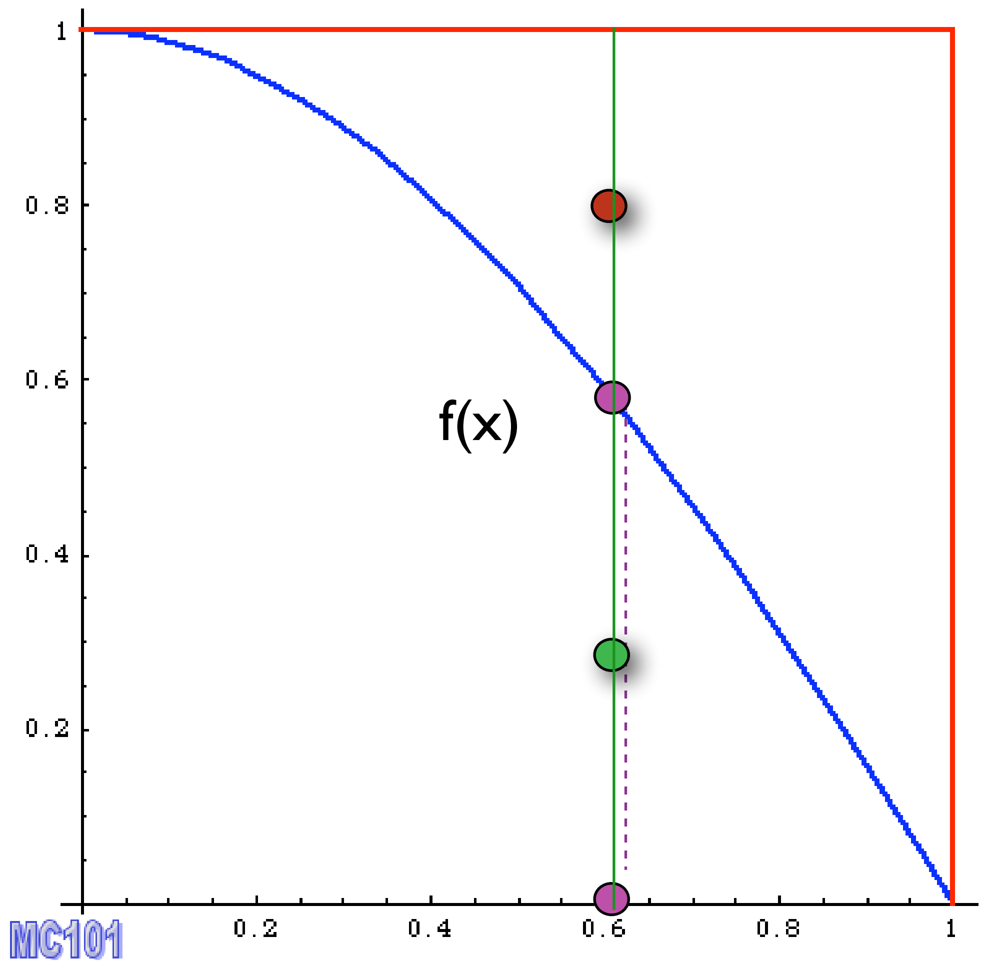

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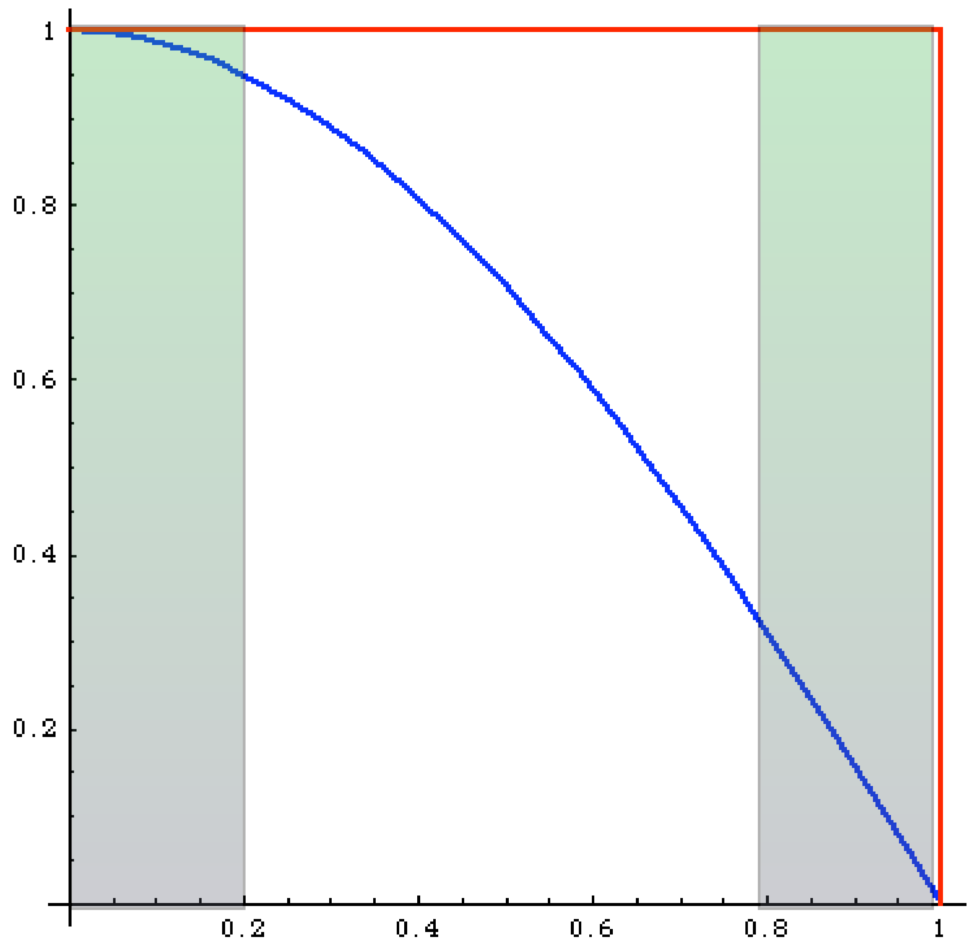
4. Compare:
   if f(x)>y accept event,

   else reject it.

$$I = \frac{\text{accepted}}{\text{total tries}} = \text{efficiency}$$

Event generation

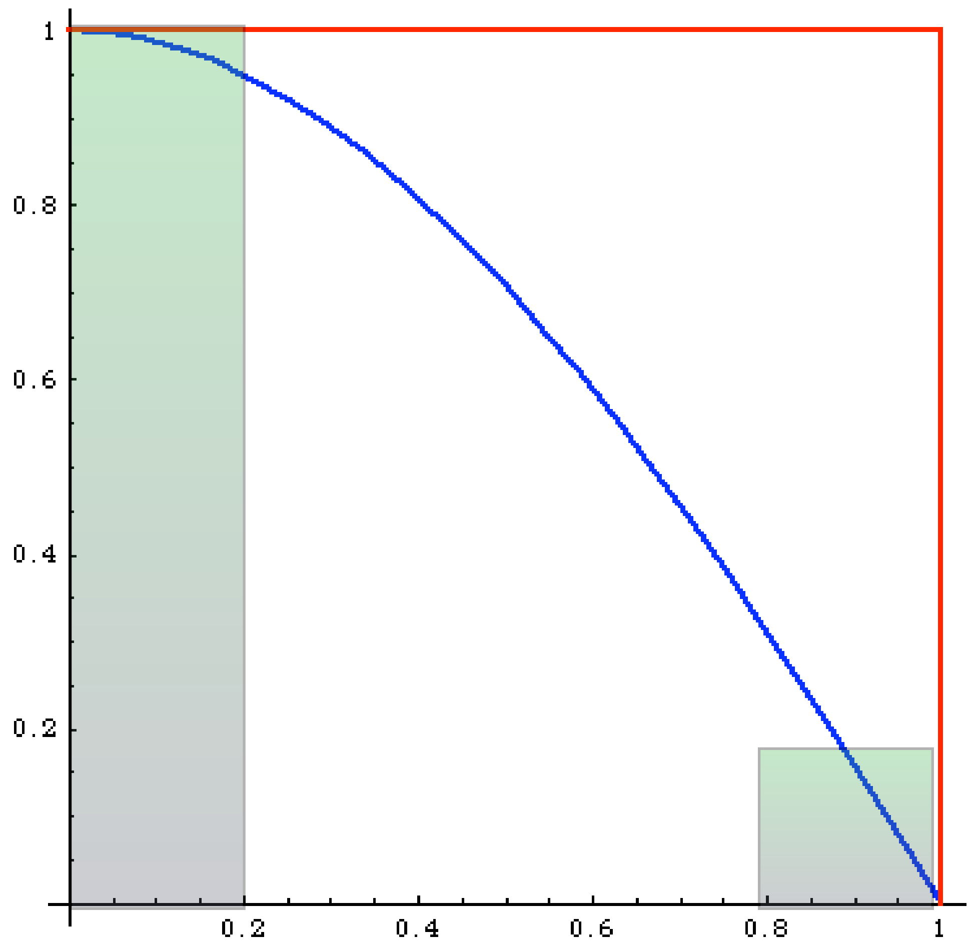


What's the difference between weighted and unweighted?

Weighted:

Same # of events in areas of phase space with very different probabilities: events must have different weights

Event generation



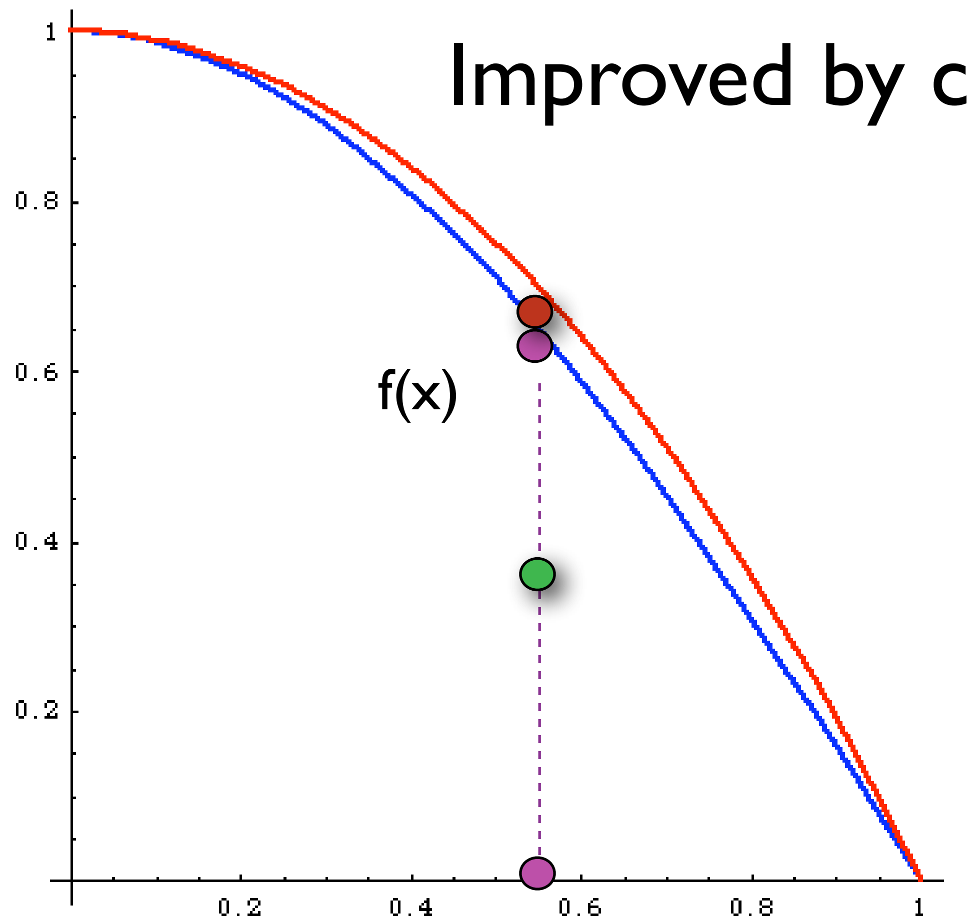
What's the difference between weighted and unweighted?

Unweighted:

events is proportional to the probability of areas of phase space:
events have all the same weight (”unweighted”)

Events distributed as in nature

Event generation



Improved by combining with importance sampling:

1. pick x distributed as p(x)
2. calculate f(x) and p(x)
3. pick 0<y<1
4. Compare:
   if f(x)>y p(x) accept event,

else reject it.

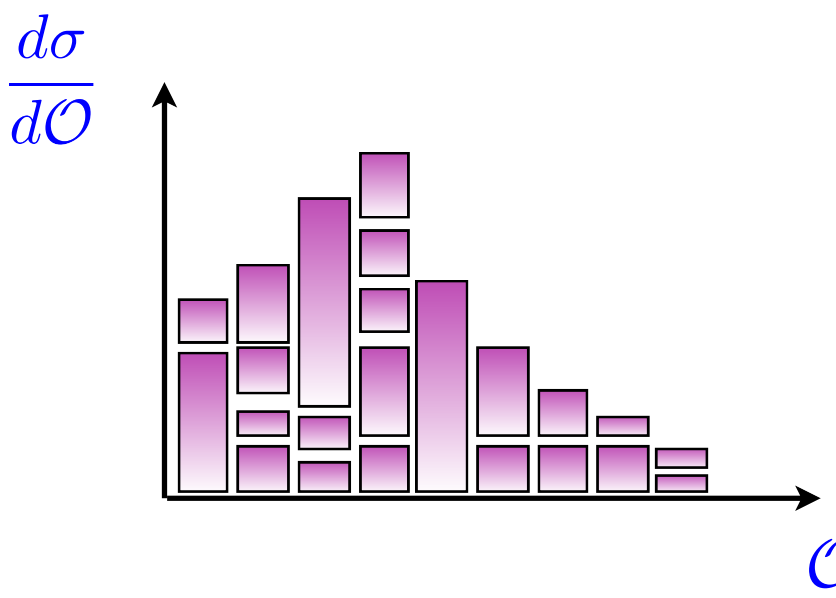
much better efficiency!!!

Event generation

MC integrator

Event generation

MC integrator



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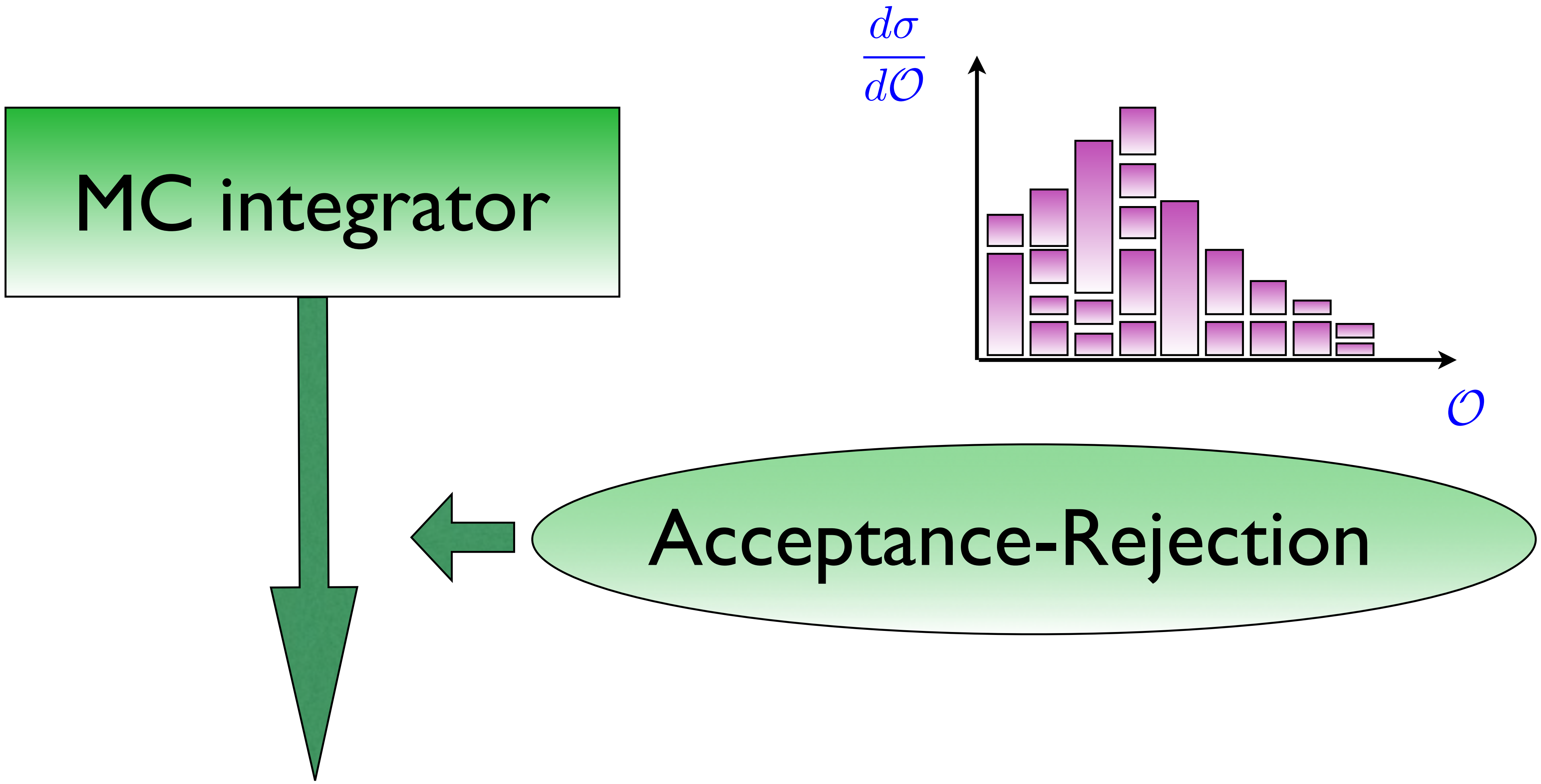

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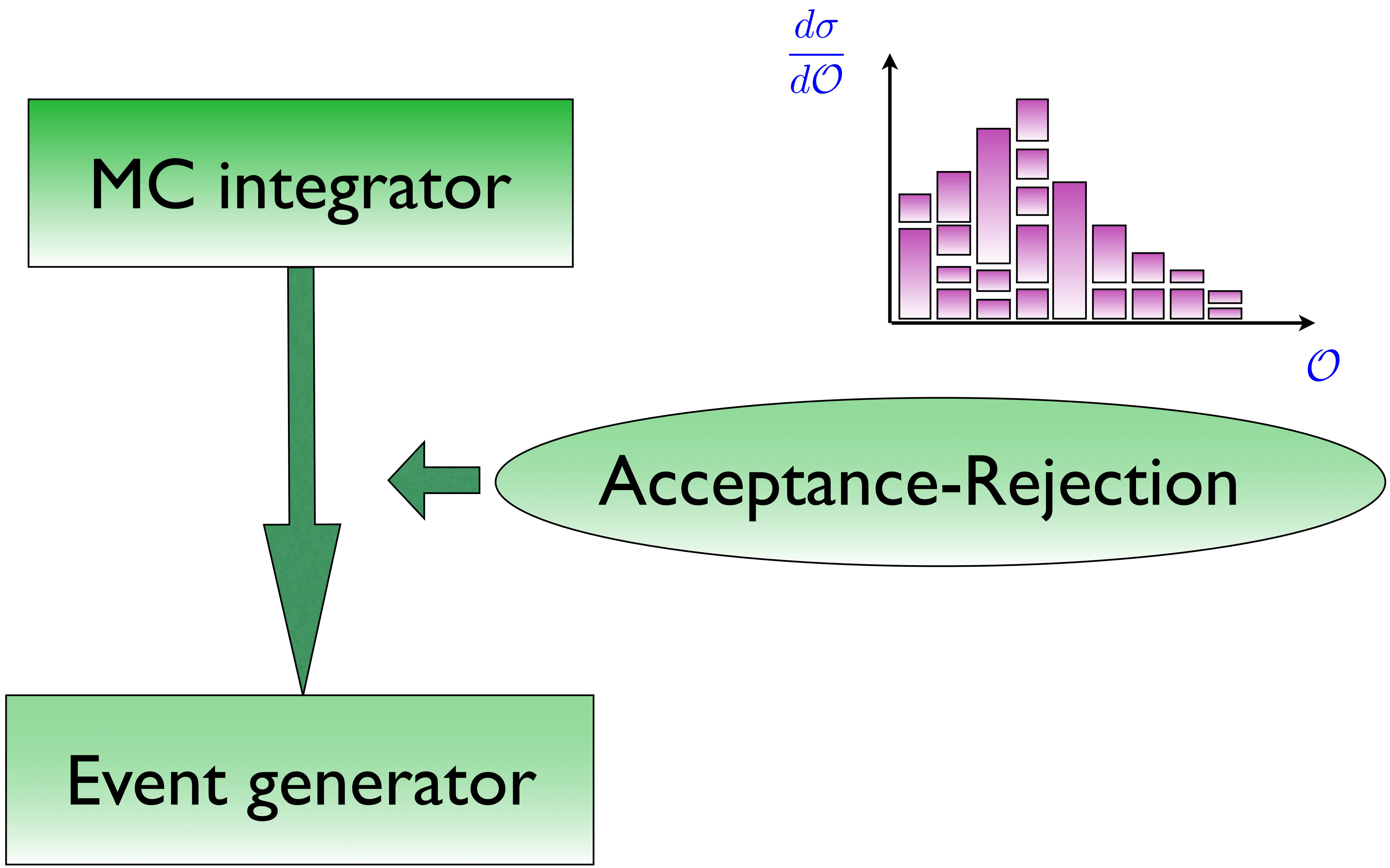

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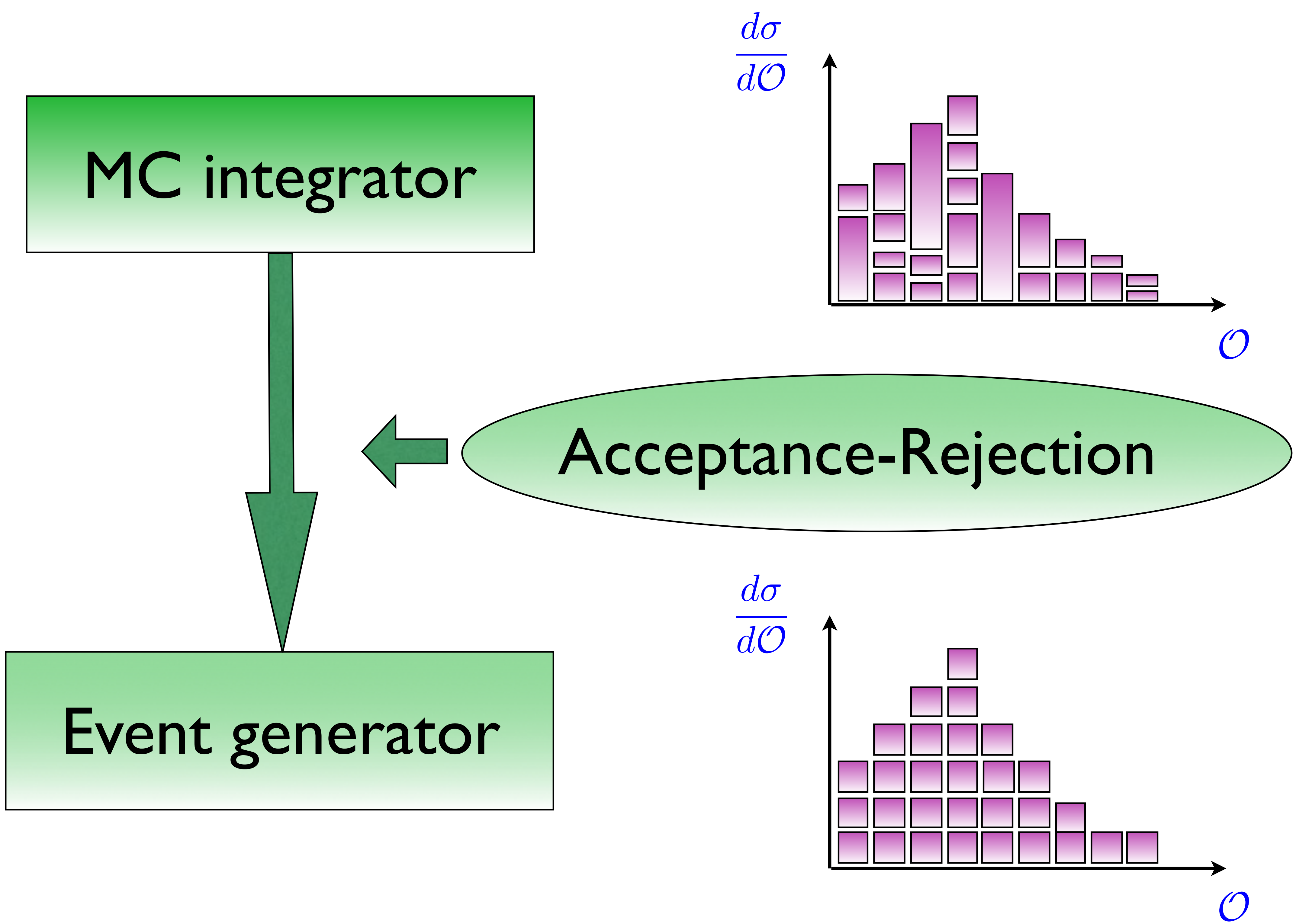
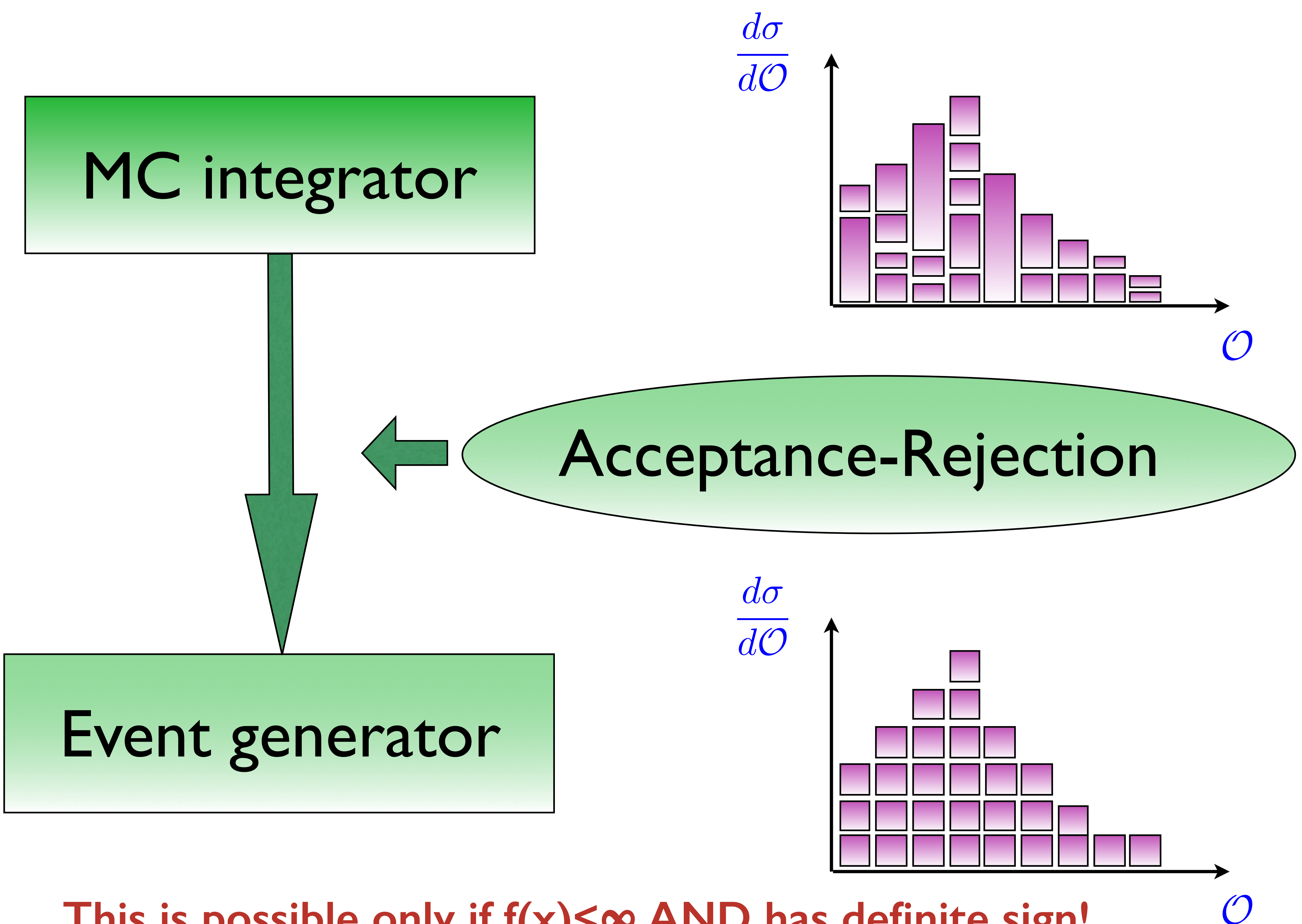


Event generation



☞ **This is possible only if f(x)<∞ AND has definite sign!**

MadGraph5_aMC@NLO

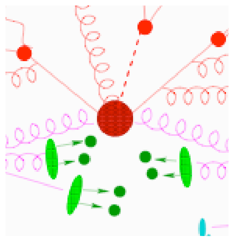
MadGraph

MadGraph

MAD stands for Madison

MadGraph

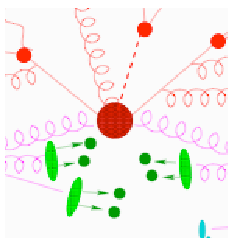
MadGraph



- Original MadGraph by Tim Stelzer was written in Fortran, first version from 1994

hep-ph/9401258

MadGraph



$\int$

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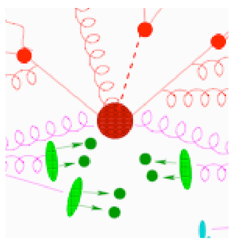
MadGraph



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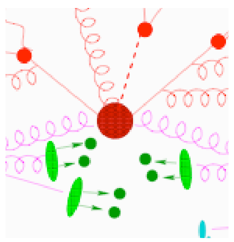
- Support for BSM (and many other improvements) in MG/ME 4 (2006) arXiv:0706.2334

MadGraph



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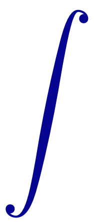
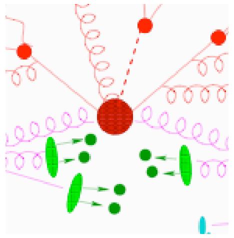


- Event generation by MadEvent using the single diagram enhanced multichannel integration technique in 2002 (Stelzer, Maltoni) — hep-ph/0208156
- Support for BSM (and many other improvements) in MG/ME 4 (2006) — arXiv:0706.2334
- Rewritten in Python in 2011: MG5
  - ➡ Fully Automatic BSM — arXiv:1106.0522

MadGraph



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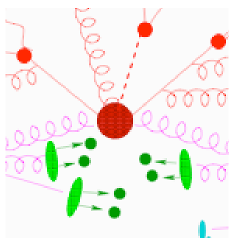
MadGraph



citation

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- Including NLO computation in 2014 — arXiv:1405.0301 — 10

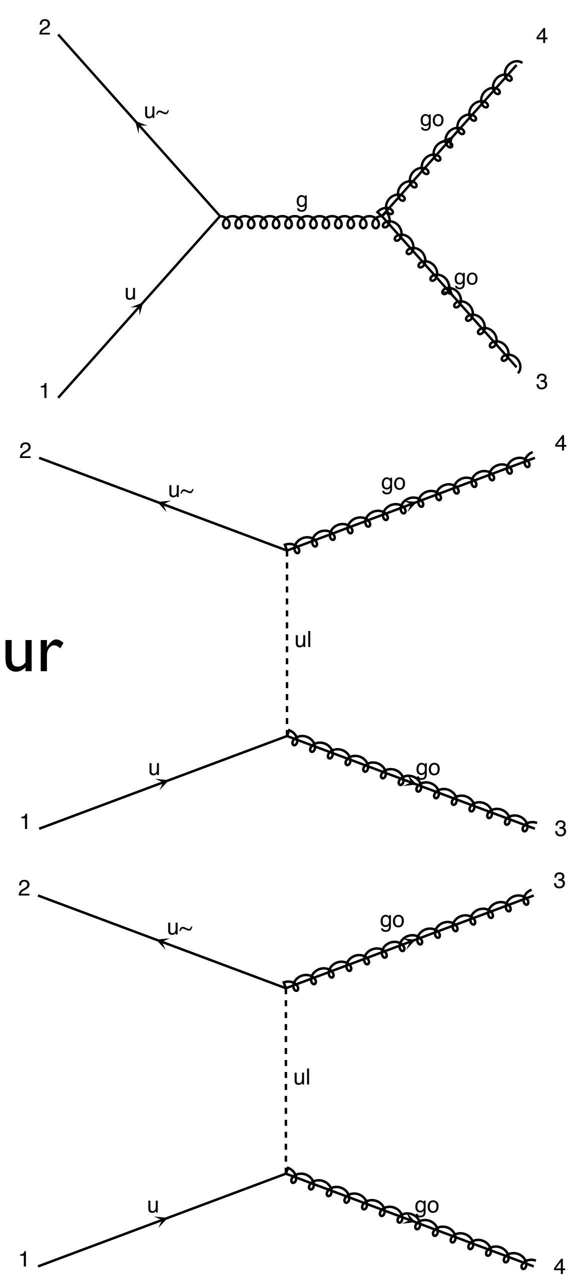
Decay chains

- p p > t t~ w+, (t > w+ b, w+ > l+ vl), \
  (t~ > w- b~, w- > j j), \
  w+ > l+ vl
- Separately generate core process and each decay
  - Decays generated with the decaying particle as resulting wavefunction
- Iteratively combine decays and core processes
- Difficulty: Multiple diagrams in decays

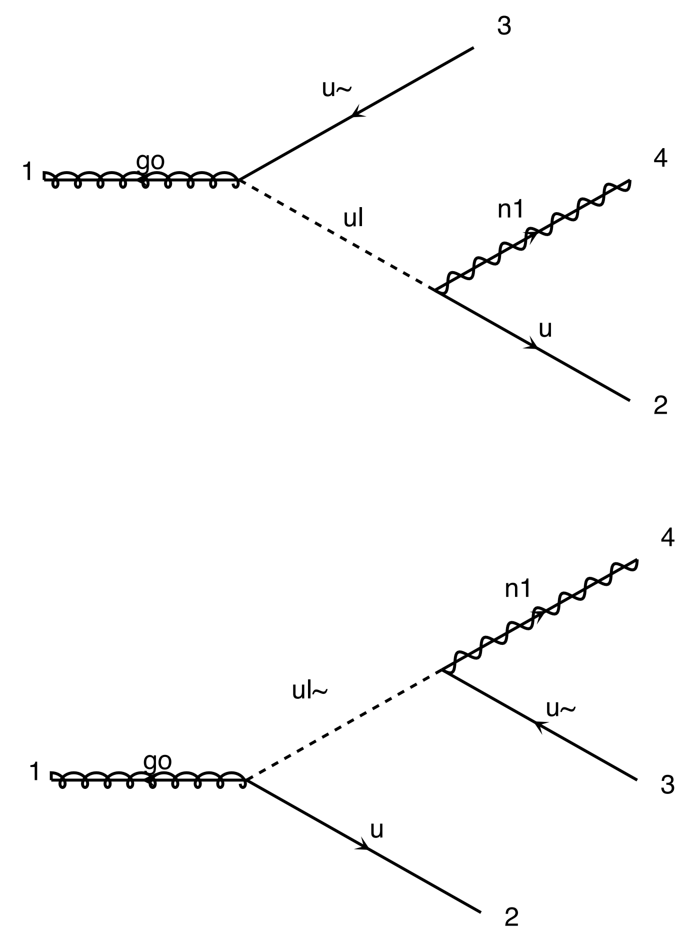
Decay chains

- If multiple diagrams in decays, need to multiply together core process and decay diagrams:

u u~ > go go / ur



x



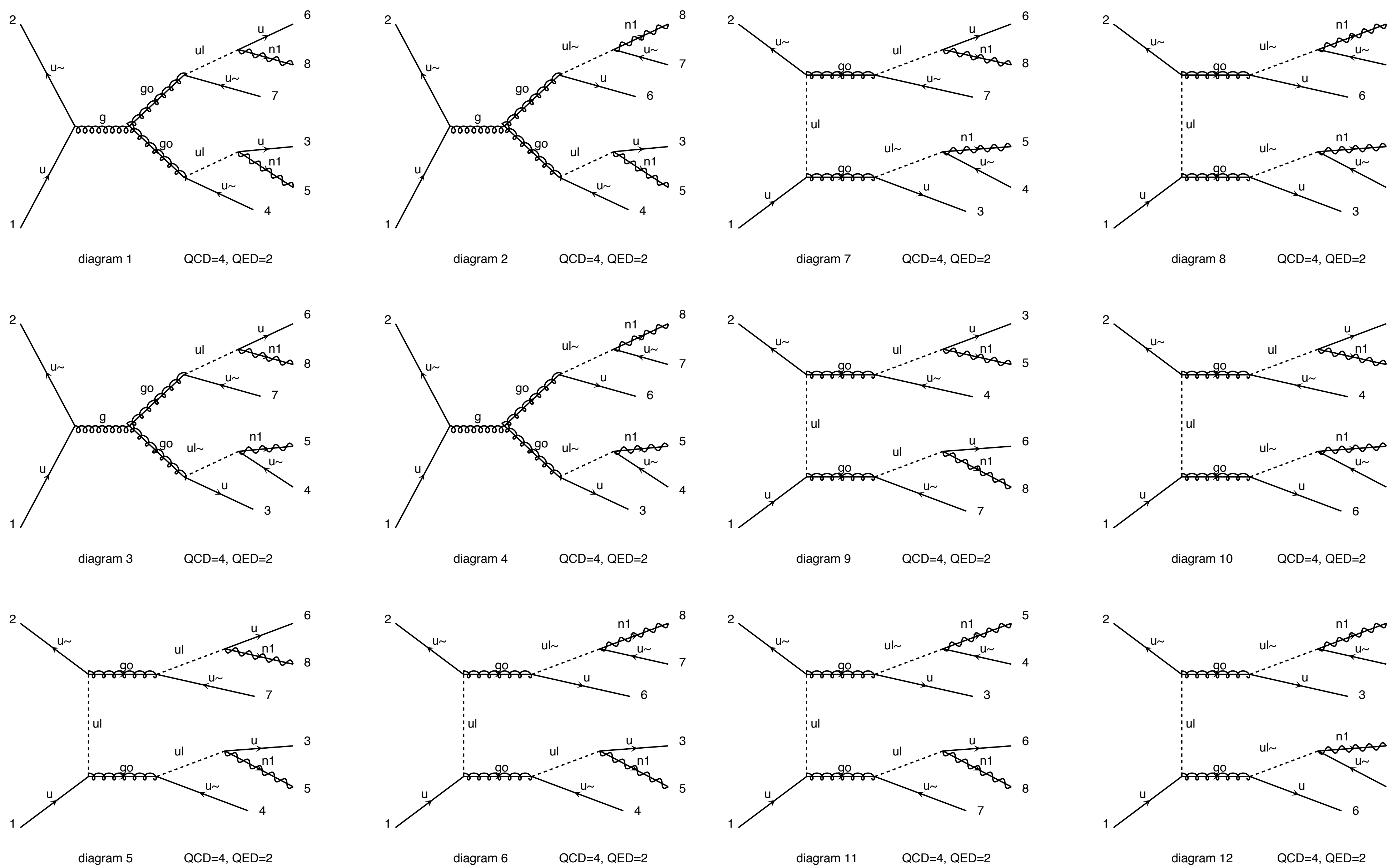
go > u u~ n1 / ur

(to the second power since both gluinos decay)

Decay chains

- If multiple diagrams in decays, need to multiply together core process and decay diagrams:

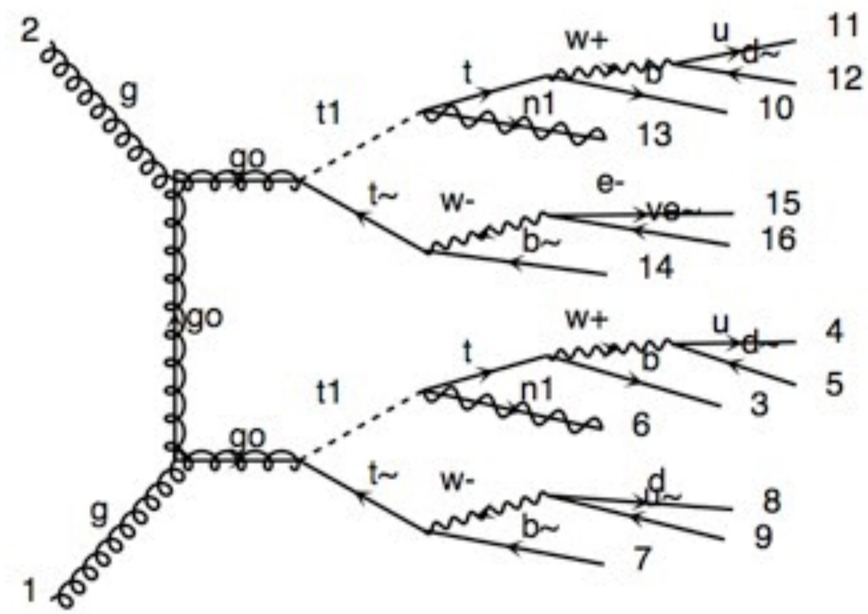
u u~ > go go / ur, go > u u~ n1 / ur



Decay chains

- Decay chains retain **full matrix element** for the diagrams compatible with the decay
- Full spin correlations (within and between decays)
- Full width effects
- However, no interference with non-resonant diagrams
  - ➡ Description only valid close to pole mass
  - ➡ Cutoff at $|m \pm n\Gamma|$ where n is set in run_card.

Decay chains



Online Event Generation

file://localhost/Users/alwall/MadGraph/version_1_0_1/PROC_gogo_t1tx_tn1_ballall/HTML/crossx.html

Results for g g > go go , (go > t1 t~ , t~ > b~ all all / h+ , (t1 > t n1 , t > b all all / h+)) in the mssm

Available Results

Links	Events	Tag	Run	Collider	Cross section (pb)	Events
results banner	Parton-level LHE	fermi	test	p p 7000 x 7000 GeV	.33857E-03	10000

Main Page

Thanks to developments in MadEvent, also (very) long decay chains possible to simulate directly in MadGraph!

Output formats in MadGraph 5

- Thanks to UFO/ALOHA, we now have automatic helicity amplitude routines in any language
  - ➡ So it makes sense to have also matrix element output in multiple languages!
- Presently implemented: Fortran, C++, Python
  - ➡ Fortran - for MadEvent and Standalone
  - ➡ C++ - for Pythia 8 and Standalone
  - ➡ Python - for internal use in MG5 (checks of gauge, perturbation and Lorentz invariance)

Life Demo

Examples shown

- p p > t t~
  This gives only (the dominant) QCD vertices, and ignores (the negligible) QED vertices.
- p p > t t~ QED=2
  This gives both QED and QCD vertices.
- p p > w+ j j, w+ > l+ vl
  More complicated example.

More syntax examples

- p p > t t~ j QED=2: Generate all combinations of processes for particles defined in multiparticle labels p / j, including up to two QED vertices (and unlimited QCD vertices)
- p p > t t~, (t > b w+, w+ > l+ vl), t~ > b~ j j :
  - Only diagrams compatible with given decay
  - Only t / t~ and W+ close to mass shell in event generation
- p p > w+ w- / h : Exclude any diagrams with h
- p p > w+ w- $ h : Exclude on-shell h in event generation (but retain interference effects)

Summary

$$\int \hat{\sigma}_{ab\to X}(\hat{s},\ldots)\, f_a(x_1) f_b(x_2)\, dx_1 dx_2 d\Phi_{FS}$$

Parton level cross section | Parton density functions | Phase space integral

- MadGraph use Numerical method for the matrix element
  - ➡ Faster than analytical formula
  - ➡ Available For ANY BSM (thanks to UFO/ALOHA)
- Numerical integration is not trivial
  - ➡ We use Monte-Carlo integration
  - ➡ Return physical sample of events!
- MG5
  - ➡ decay chains
  - ➡ nice interface
  - ➡ several output formats