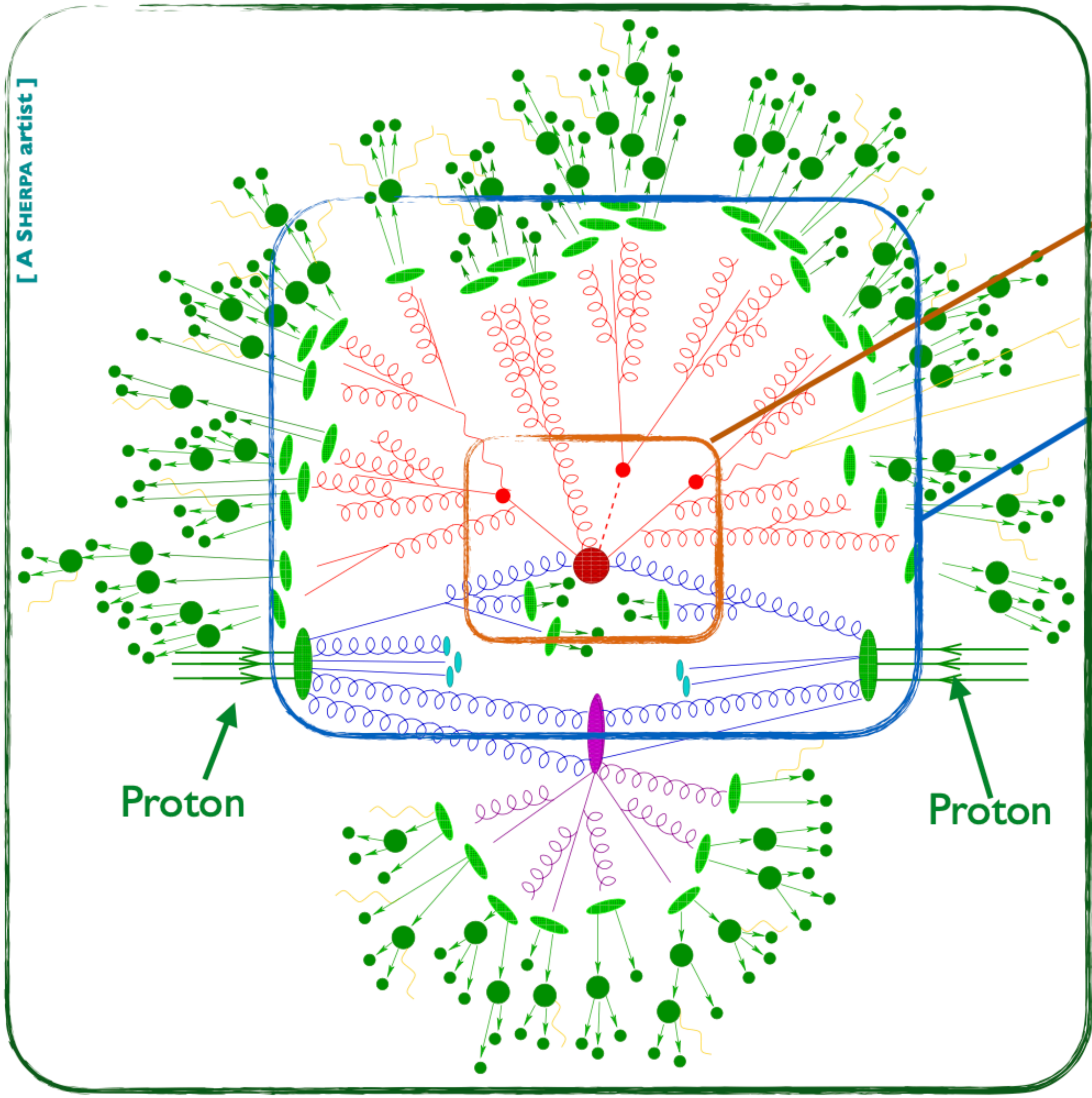
UCLouvain
Institut de recherche en mathématique et physique
Centre de Cosmologie, Physique des Particules et Phénoménologie

MadGraph5_aMC@NLO

Olivier Mattelaer

Collider Physics



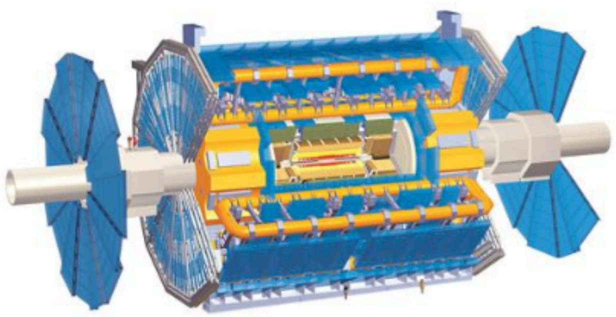
Hard process
- Depends on the model (SM/BSM)
- Perturbative QCD
- Core #1 of this talk

Parton showering
- Universal (QCD)

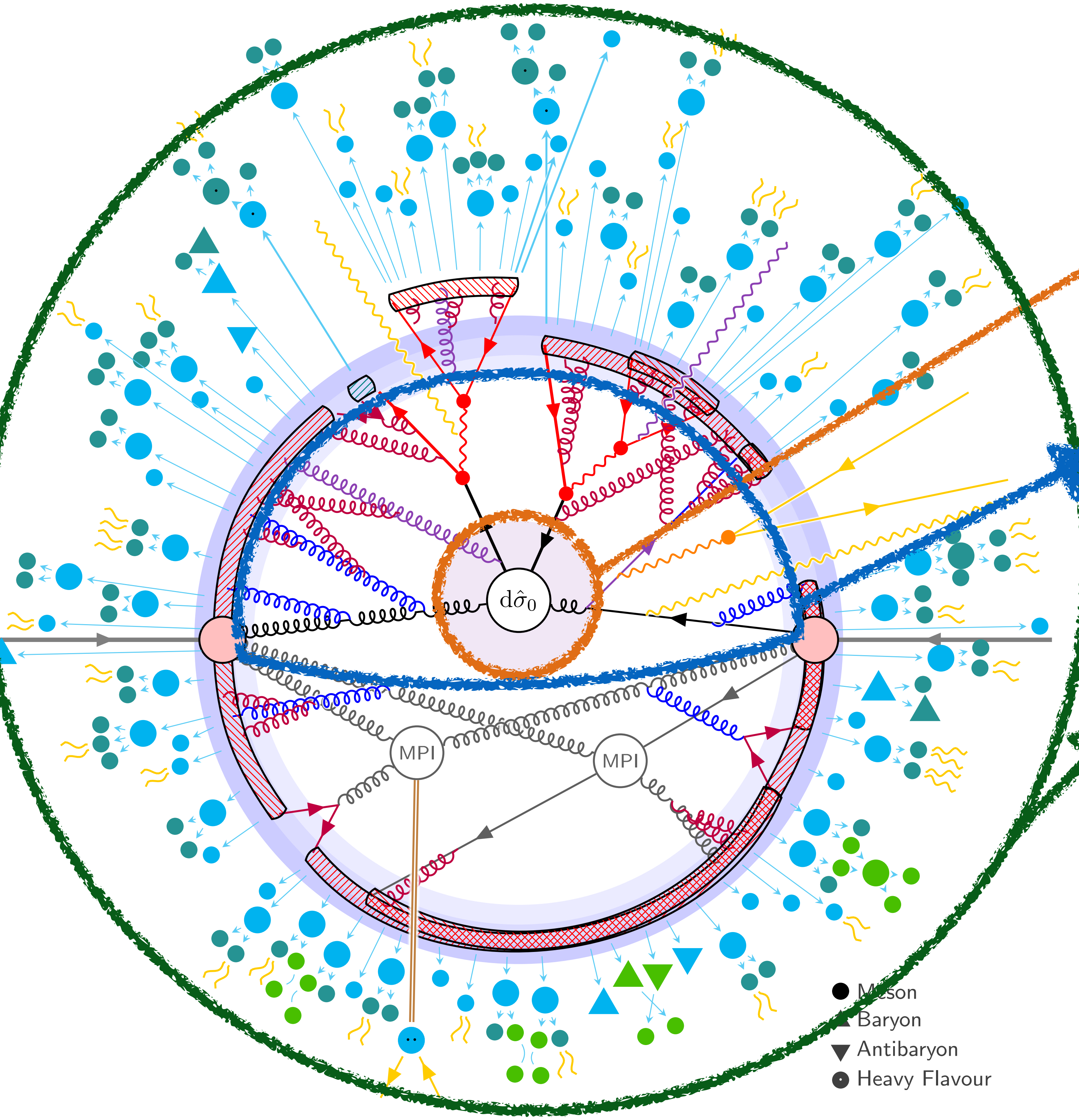
Hadronisation
- Model-based, universal

Underlying event
- Model-based, non-universal

Detector simulation



Collider Physics



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Detector simulation

From pythia8 manual

To Remember

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

Phase-space integral

Parton density functions

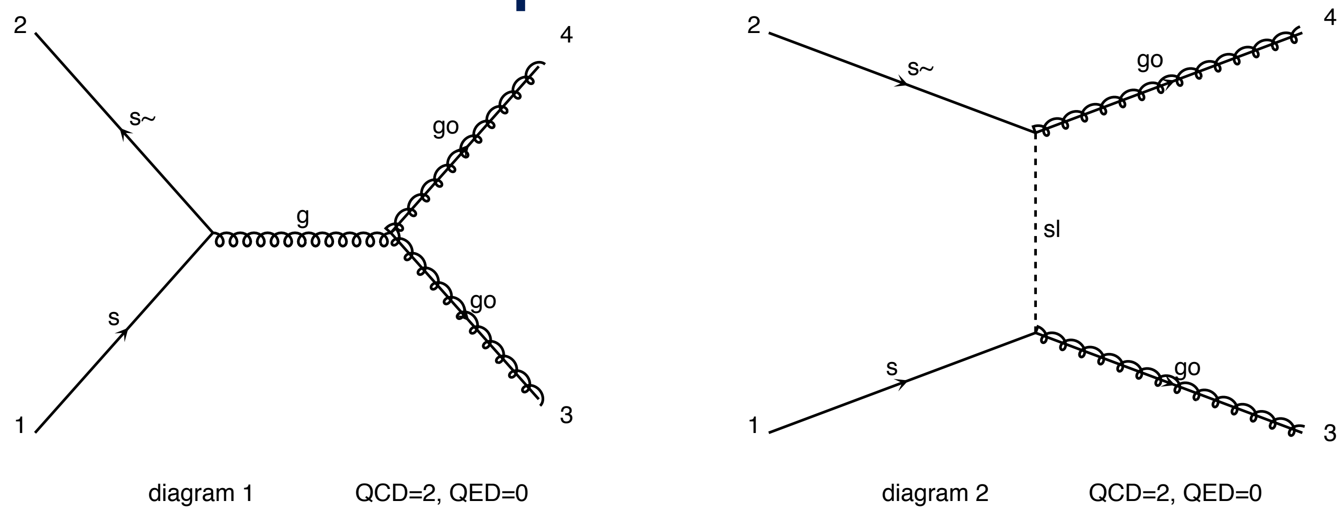
Parton-level cross section

- PDF: content of the proton
  - ➡ Define the physics/processes that will dominate on your accelerator
- LO: good for shape
- NLO/NNLO: Reduce scale uncertainty
- Computation are inclusive (+ any jet) due to renormalization/factorization scale

Matrix-Element

Calculate a given process (e.g. gluino pair)

- Determine the production mechanism



- Evaluate the matrix-element

$|\mathcal{M}|^2$ ➡Need Feynman Rules!

- Phase-Space Integration

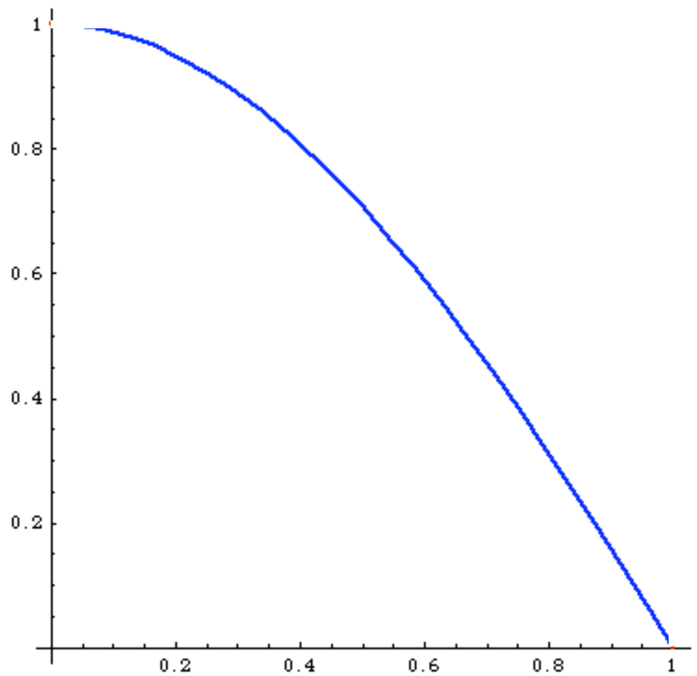
$$\sigma = \frac{1}{2s} \int |\mathcal{M}|^2 d\Phi(n)$$

Easy enough

Hard

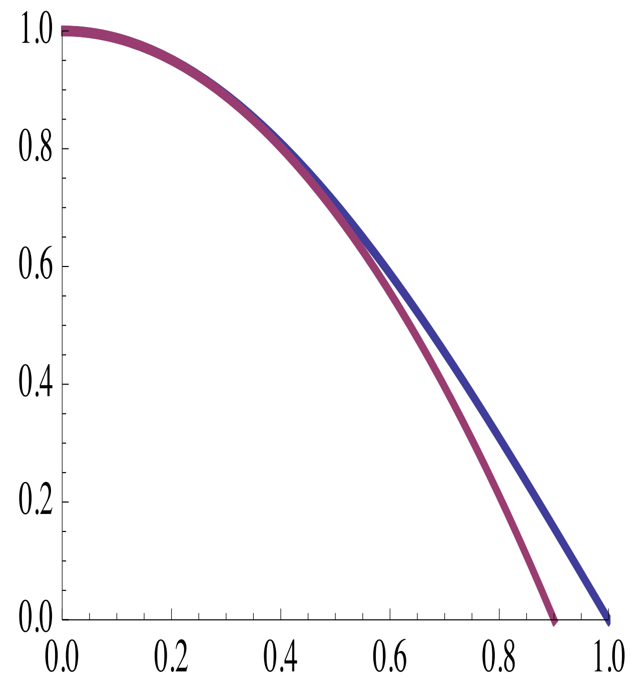
Very Hard (in general)

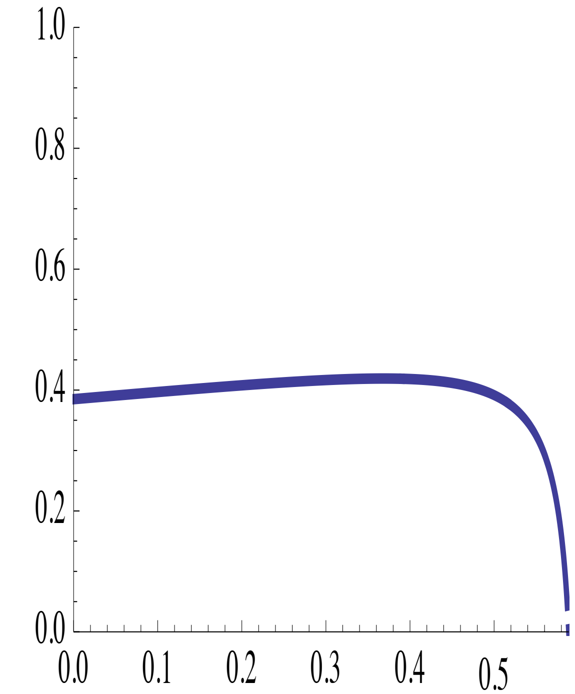
Importance Sampling



$$I = \int_0^1 dx \cos\frac{\pi}{2}x$$

$I_N = 0.637 \pm 0.307/\sqrt{N}$





$$I = \int_0^1 dx(1-cx^2)\frac{\cos\left(\frac{\pi}{2}x\right)}{(1-cx^2)} = \int_{\xi_1}^{\xi_2} d\xi \frac{\cos\frac{\pi}{2}x[\xi]}{1-x[\xi]^2 c}$$

$\simeq 1$

$I_N = 0.637 \pm 0.031/\sqrt{N}$

The Phase-Space parametrization is important to have an efficient computation!

To Remember

- Phase-Space integration is difficult
- We need to know the function
  - ➡ Be careful with cuts
- MadGraph split the integral in different contribution linked to the Feynman Diagram
  - ➡Those are not the contribution of a given diagram

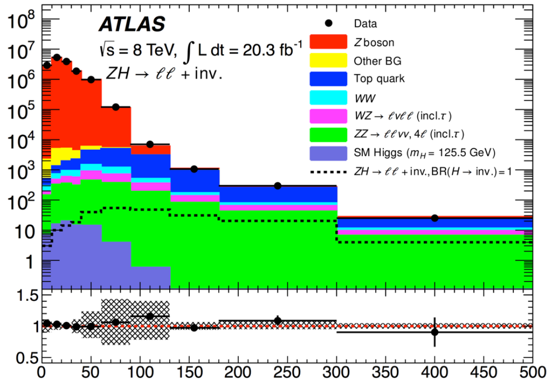
Goal of today

- Event Generation
- Learn how we evaluate (tree-level) matrix-element
- Learn Narrow-width Approximation

Event Generation

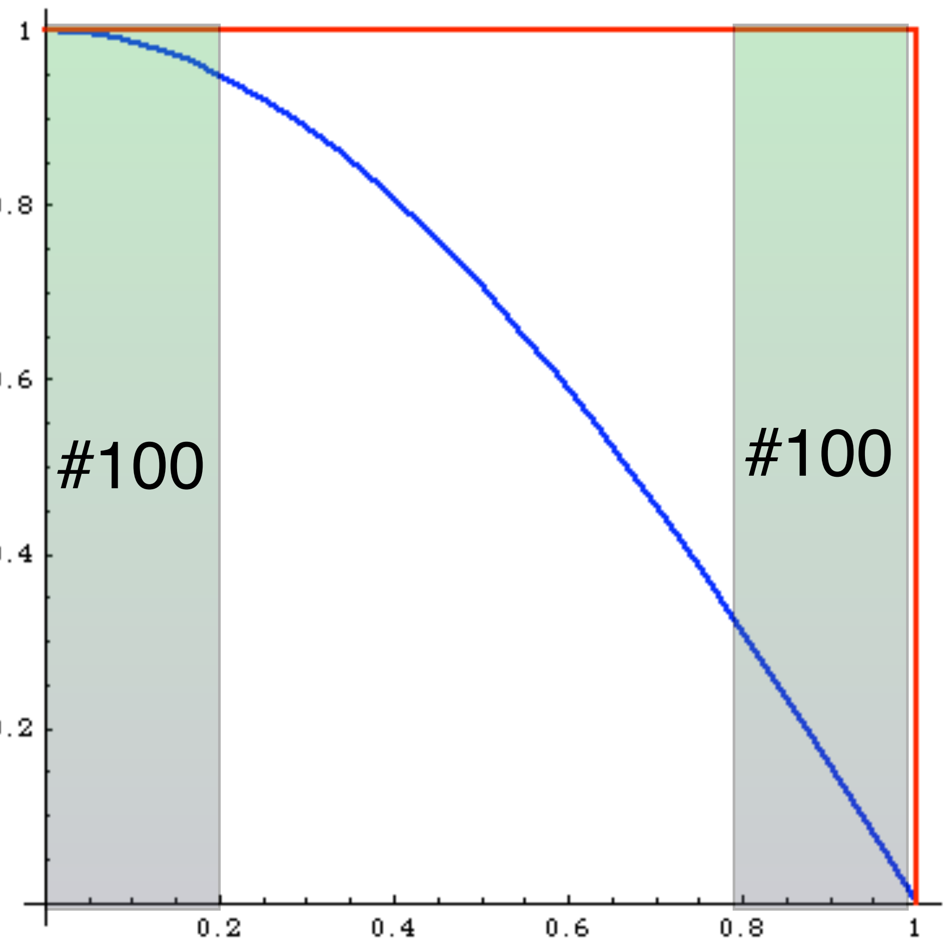
What is the goal?

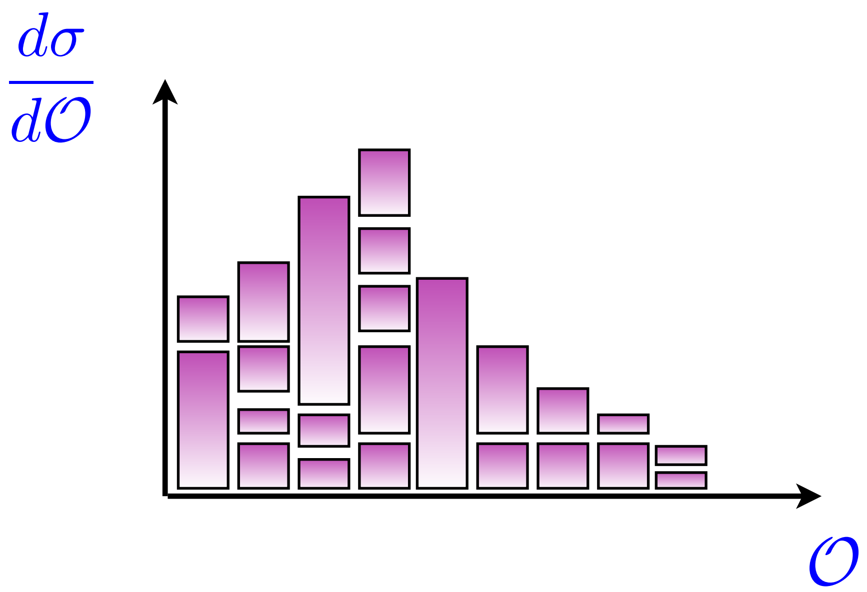
- Cross-section
  - But large theoretical uncertainty



- Differential Cross-Section
  - Provided as sample of events
  - Sample size is problematic
    - Those events will need to have full detector simulation

How to get sample?





- Monte-Carlo integration use random points
  - We can keep those
    - (Uncorrelated) sample

- Points not distributed as the real function
- Need to keep track of the importance of each point (weight)
- Typically a lot of event have low information

Question time

1 Allez sur wooclap.com

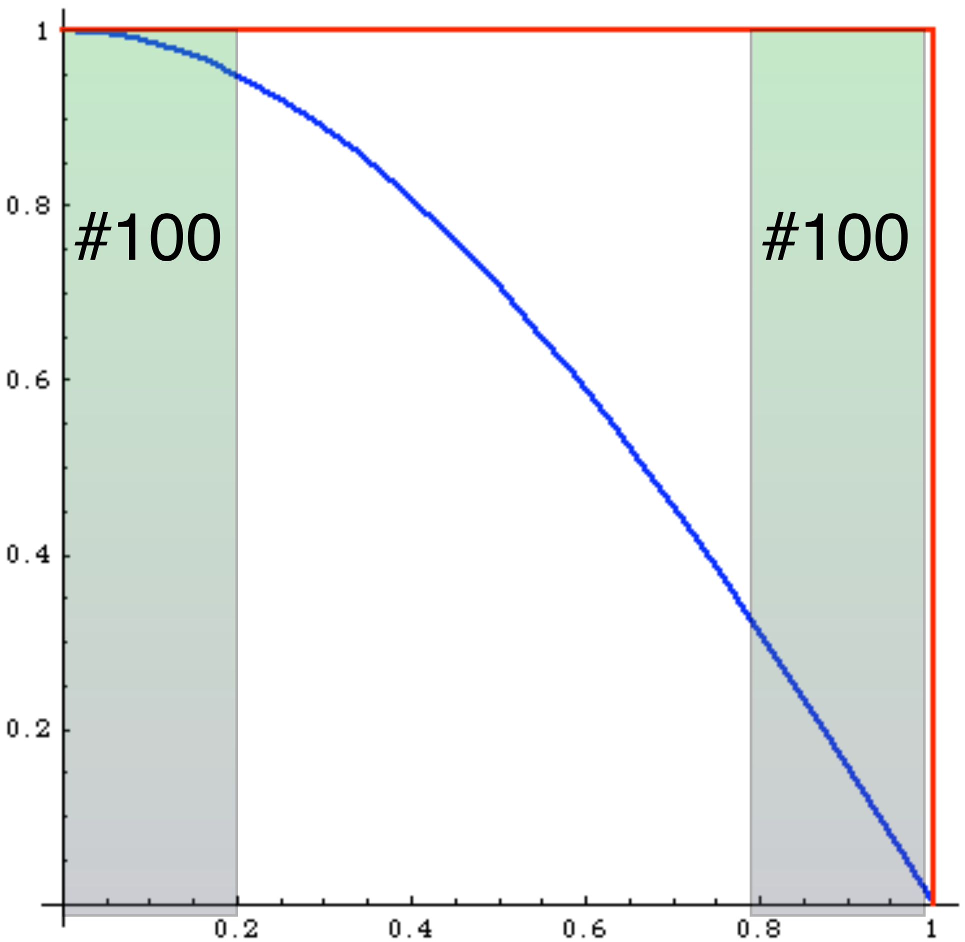
2 Entrez le code d'événement dans le bandeau supérieur

Code d'événement

MADGRAPH

Activer les réponses par SMS

Do we need to keep small weight?



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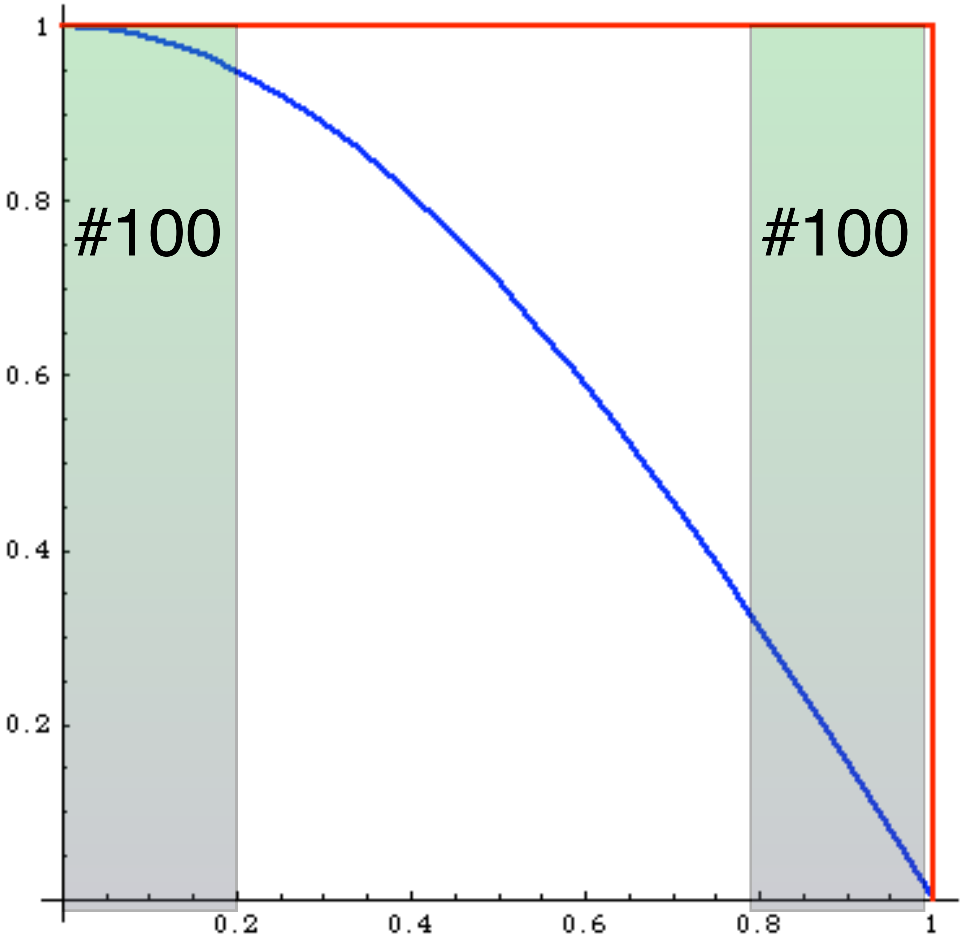
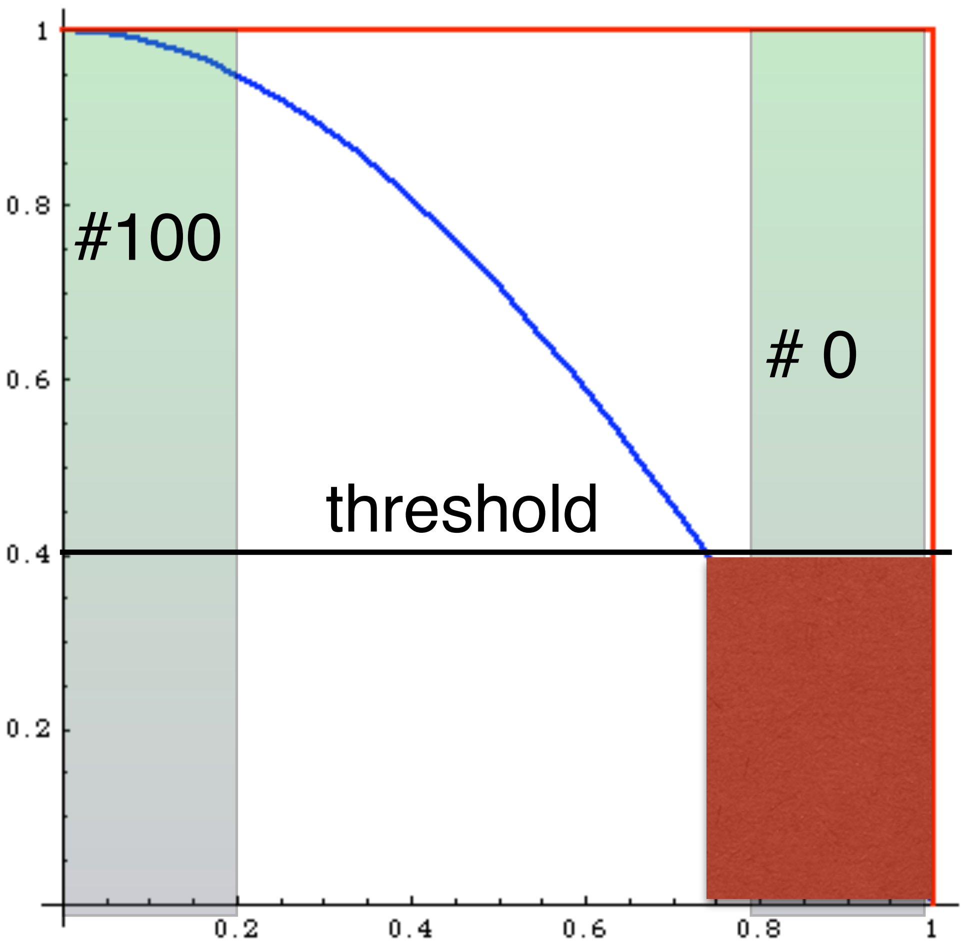


- Let's put a minimum
  - Discard events below the minimum

Do we need to keep small weight?



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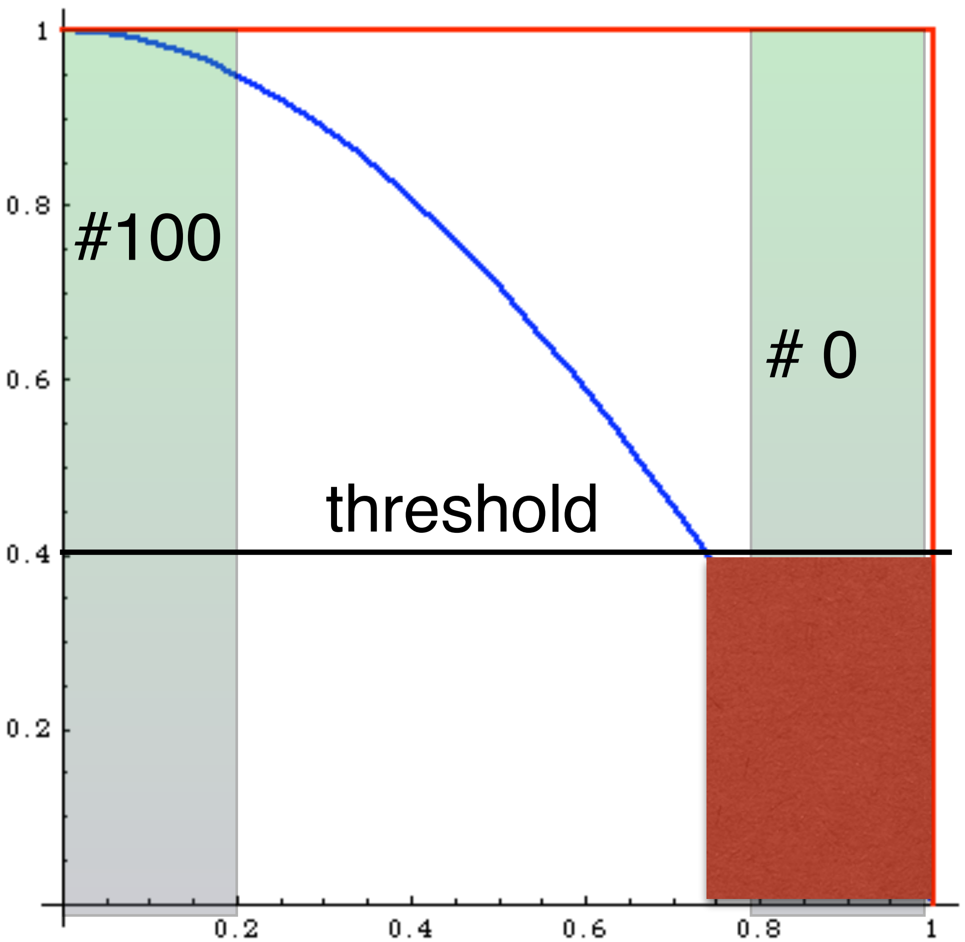

$$\int f(x)dx = \frac{1}{N}\sum_{i=1}^{N} f(x_i)$$

- Let's put a minimum
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  - NO! We loose cross-section/ bias ourself

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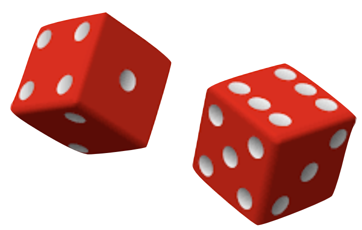

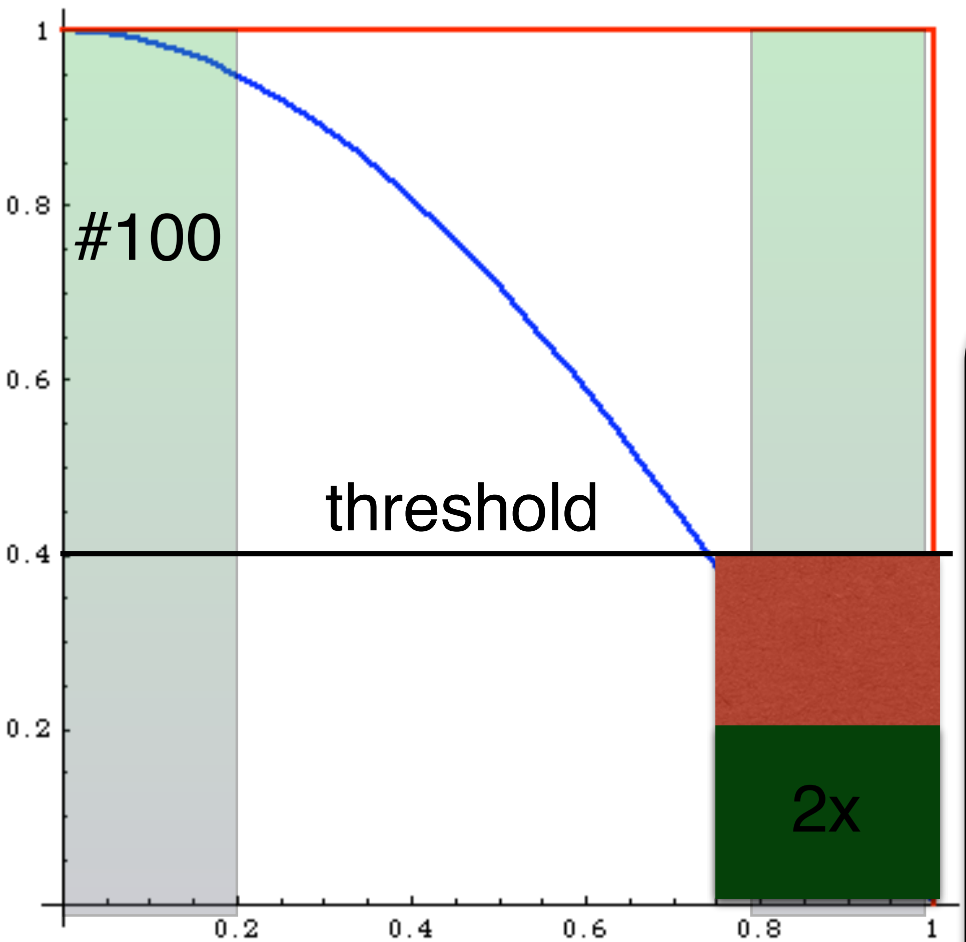

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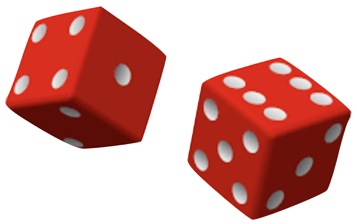
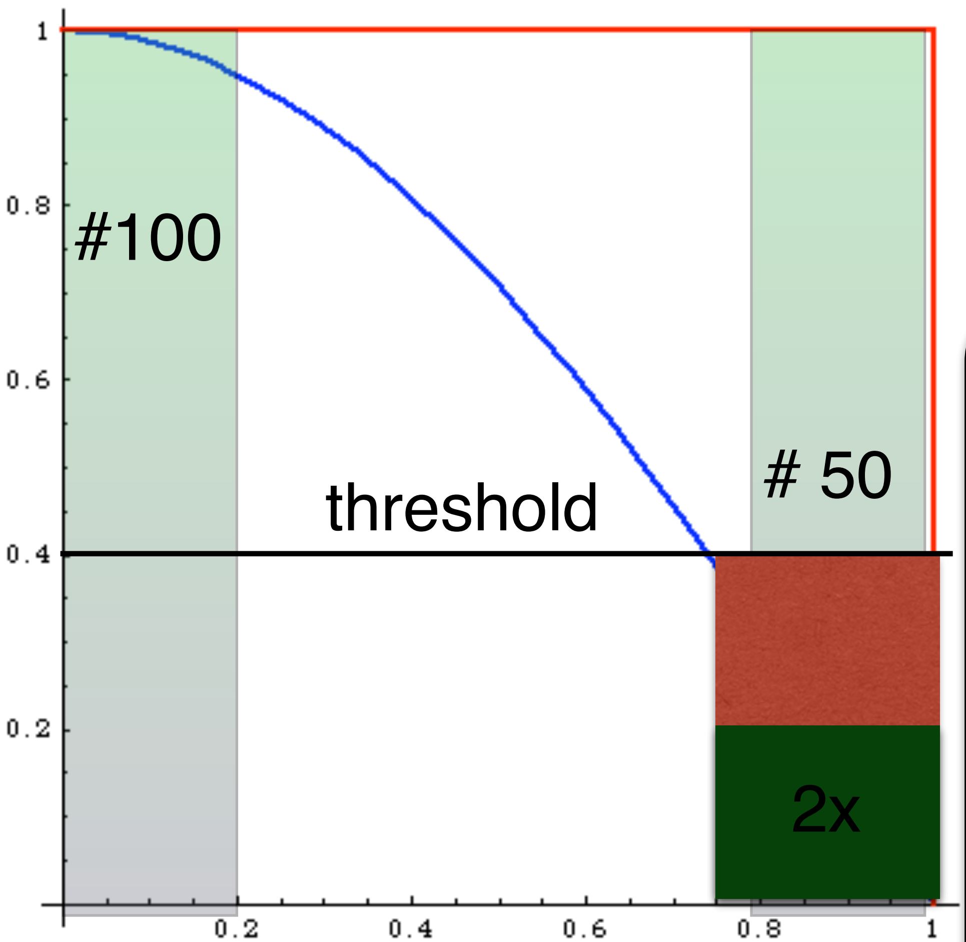
- Let's put a minimum
  - Discard events below the minimum
  - NO! We loose cross-section/ bias ourself

- Let's put a minimum
  - But keep 50% of the events below

Do we need to keep small weight?





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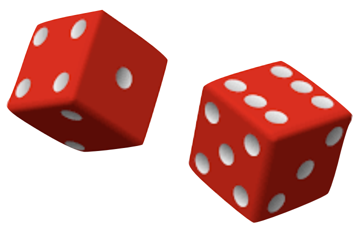

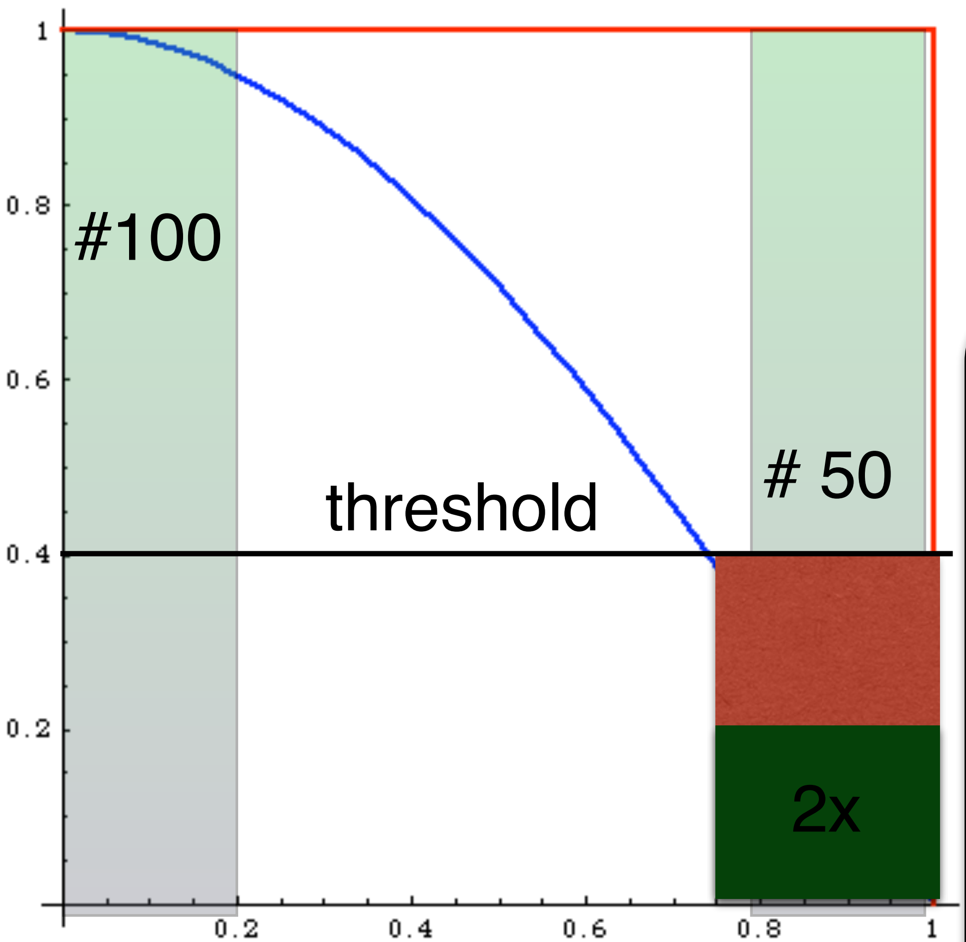

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- Let's put a minimum
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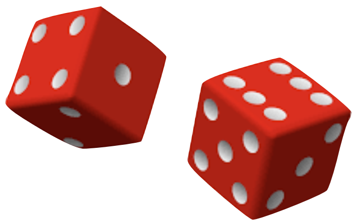
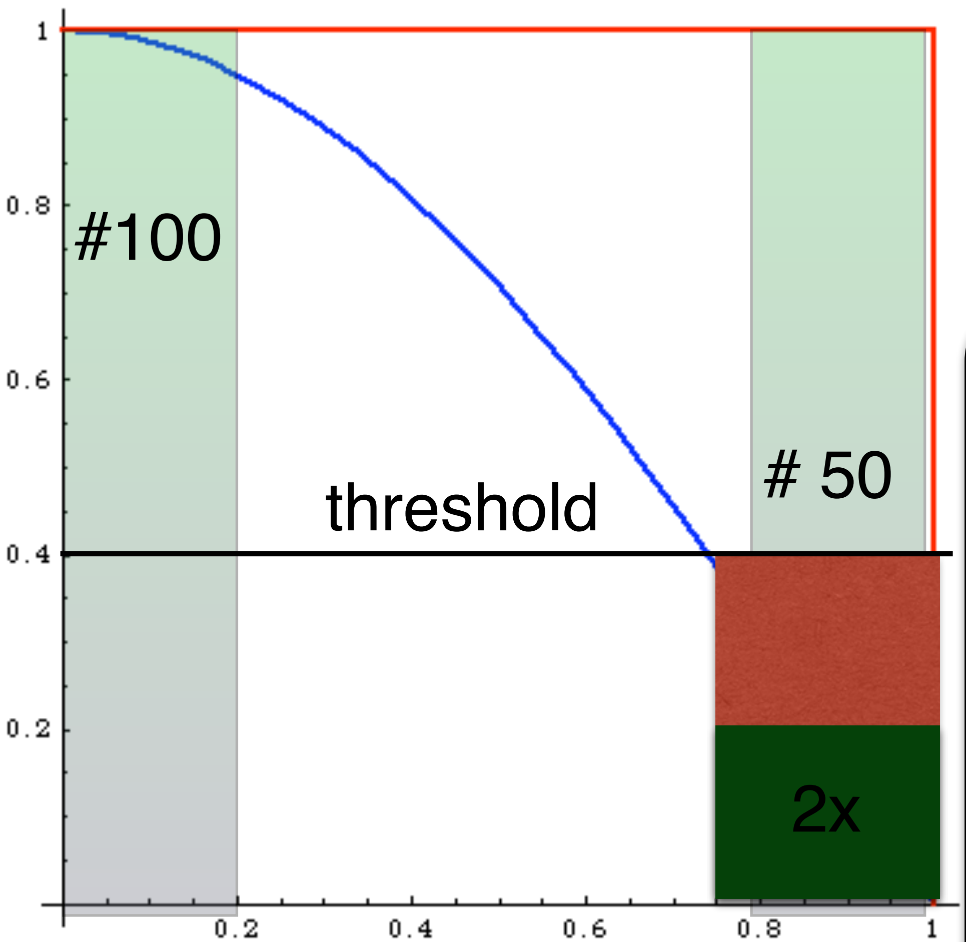
  - Multiply the weight of each event by 2 (preserve cross-section)

Do we need to keep small weight?





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  - NO! We loose cross-section/ bias ourself

- Let's put a minimum
  - But keep 50% of the events below
  - Multiply the weight of each event by 2 (preserve cross-section)
  - We loose information
  - But we gain in file size

Question time

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Code d'événement
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Activer les réponses par SMS

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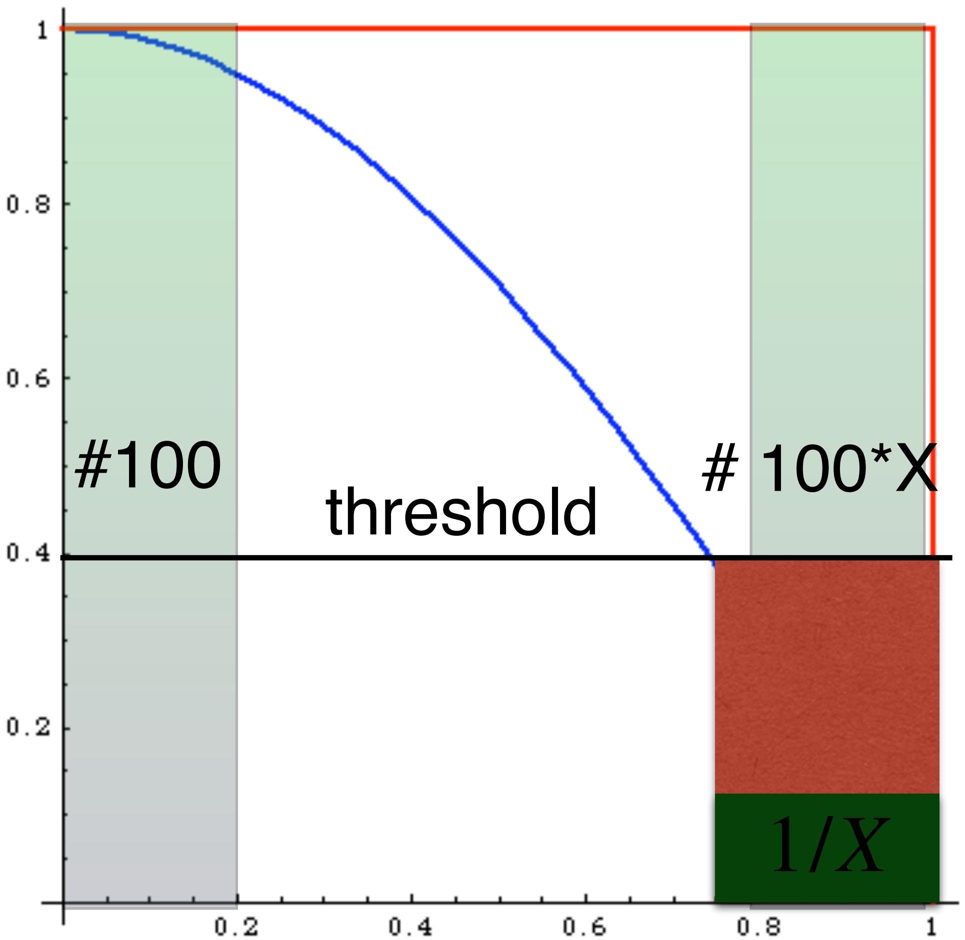

- Let’s put a threshold
  - But keep X*100% of the events below
  - Multiply the weight of each event by 1/X (preserve cross-section)

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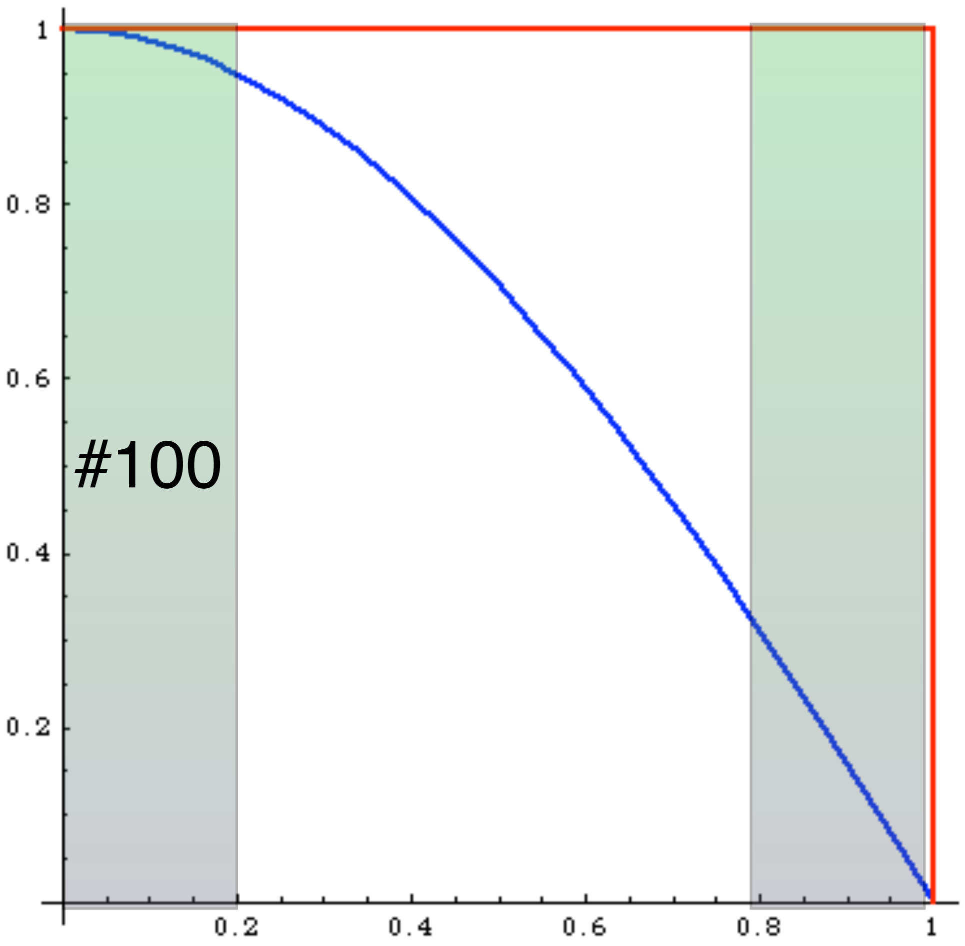

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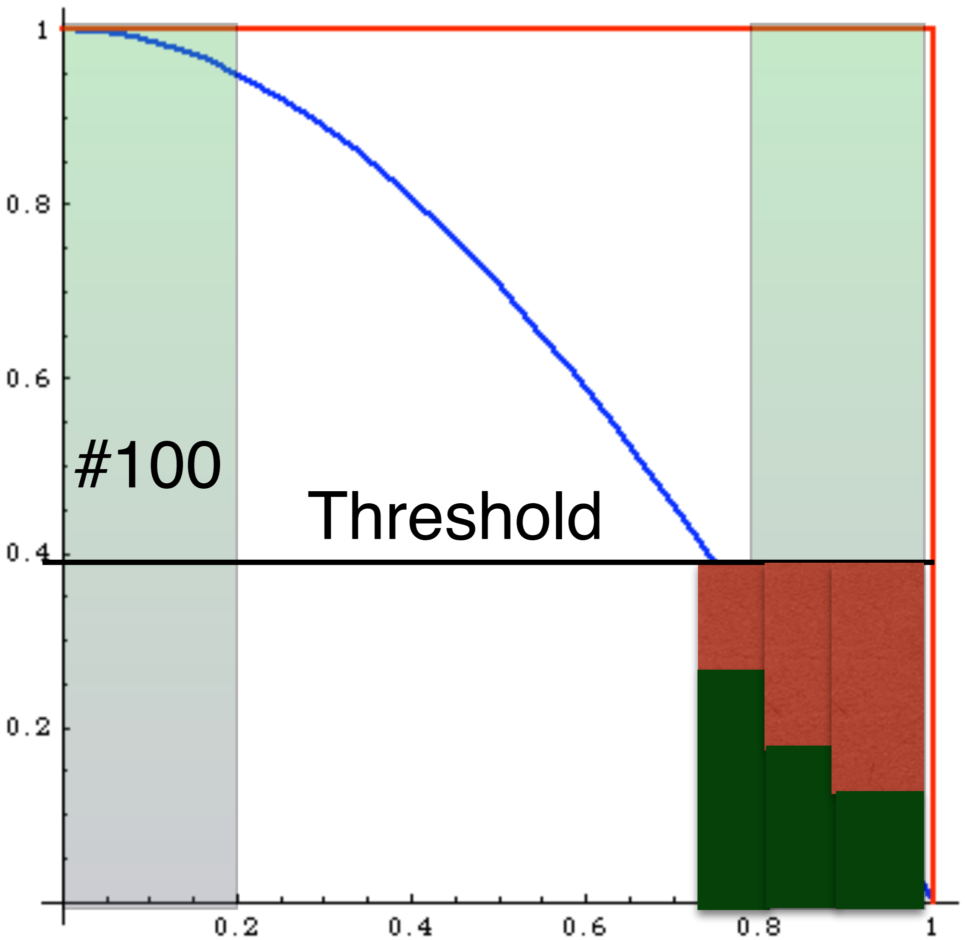

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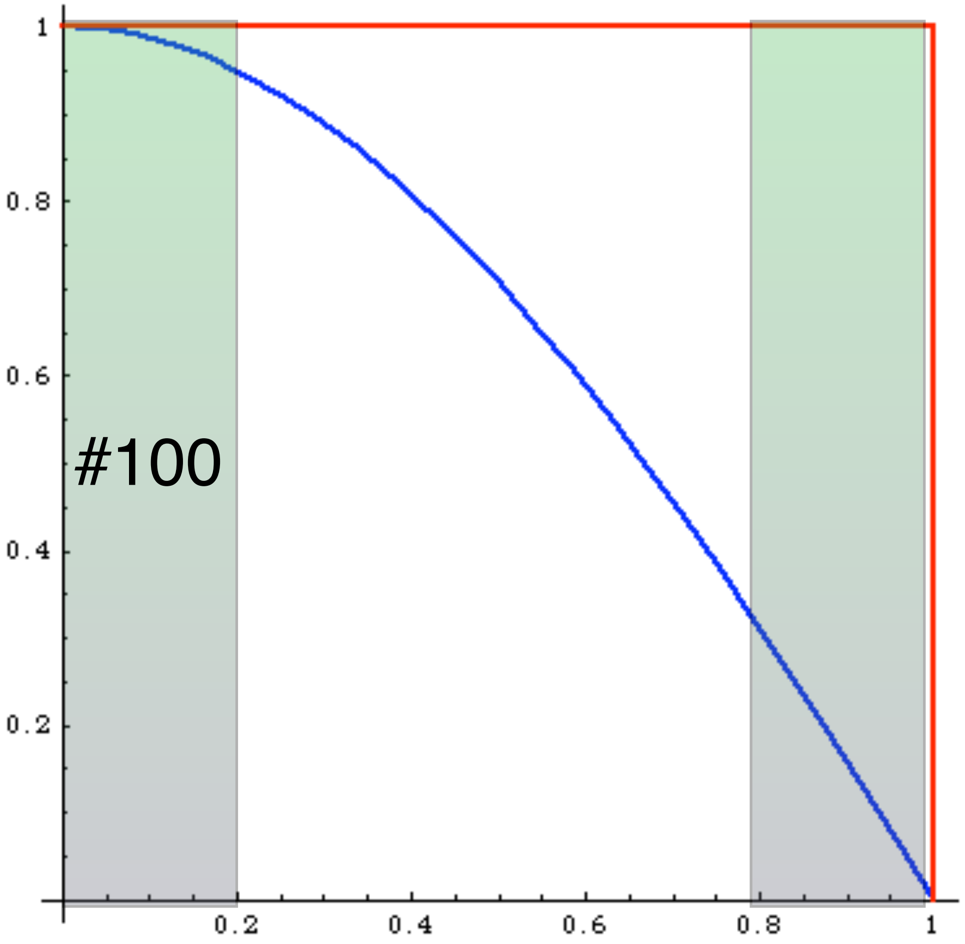
- Let's improve
  - We could reject more event (change X) where the function is small

Do we need to keep small weight?



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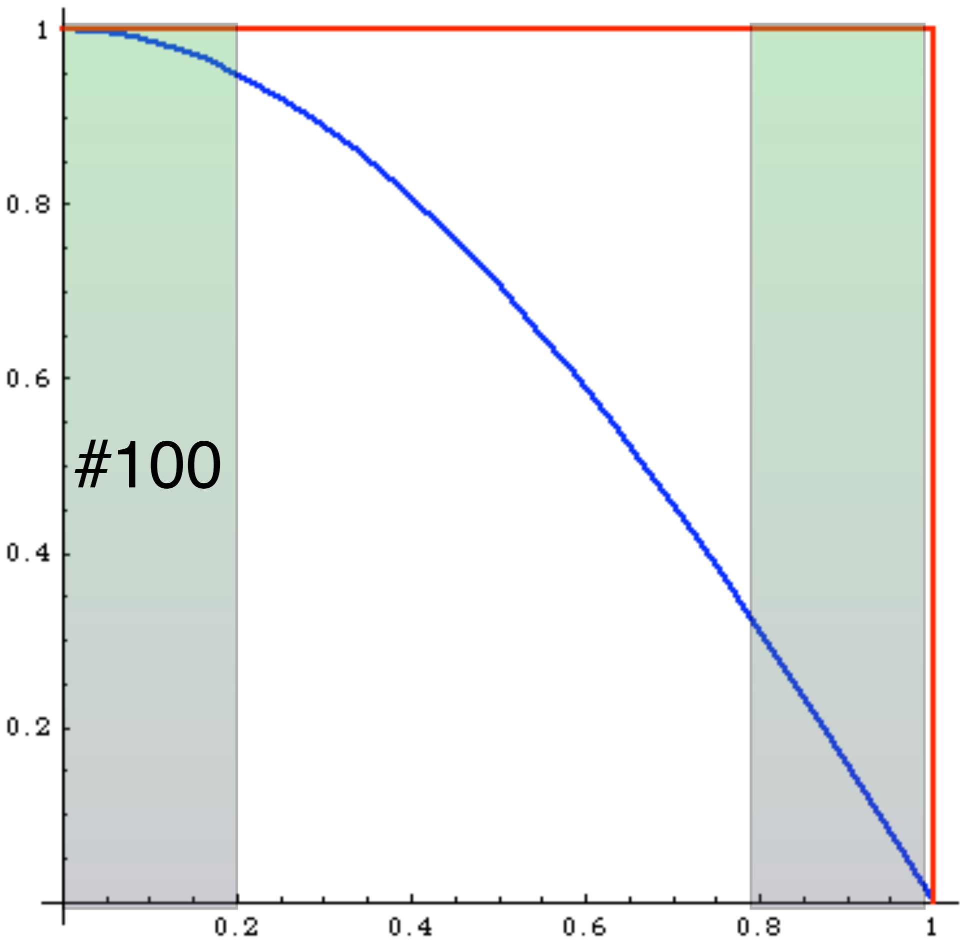

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- Let’s improve
  - Let’s make the threshold proportional to the weight

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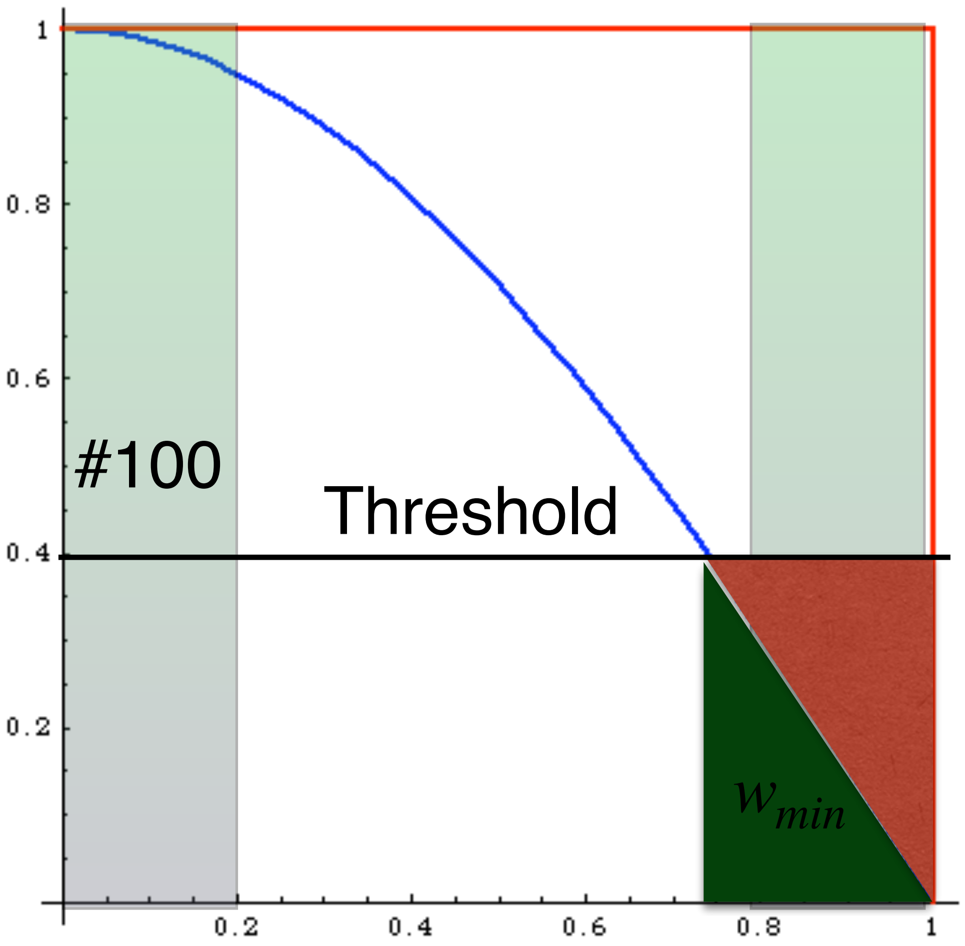

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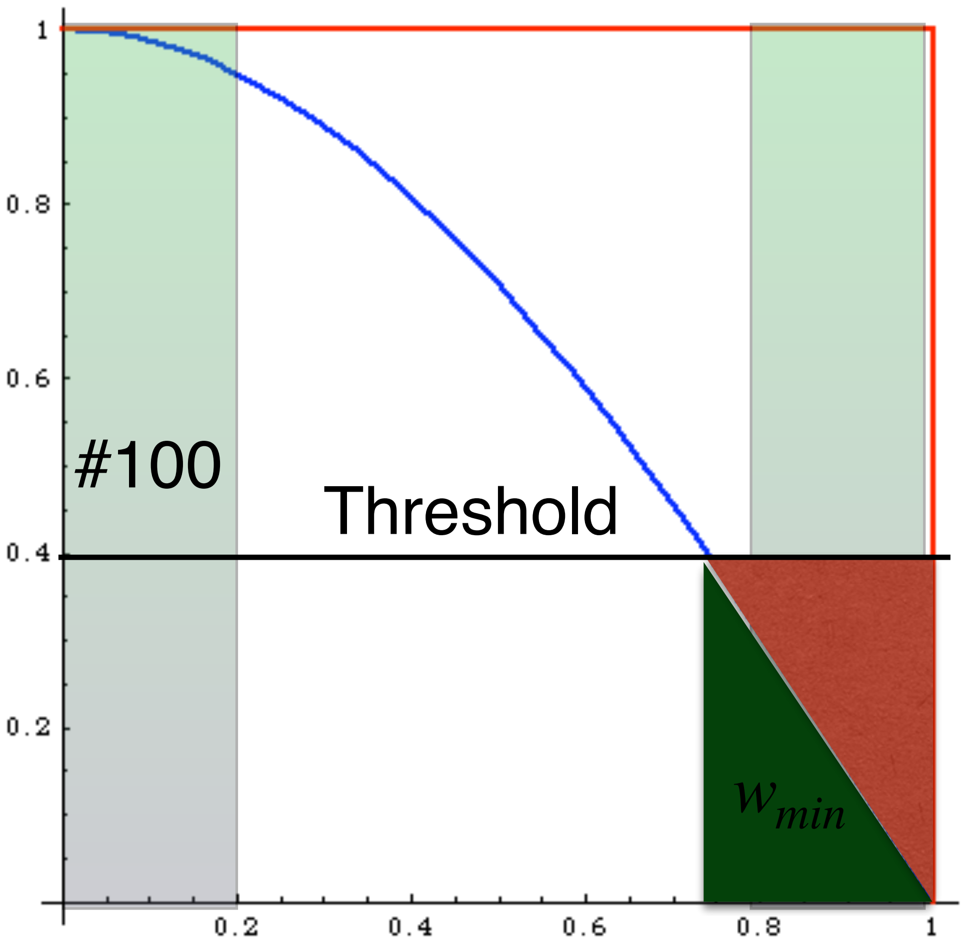

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  - Let's make the threshold proportional to the weight
  - Keep each event with $\frac{100w}{w_{thres}}\%$ probability

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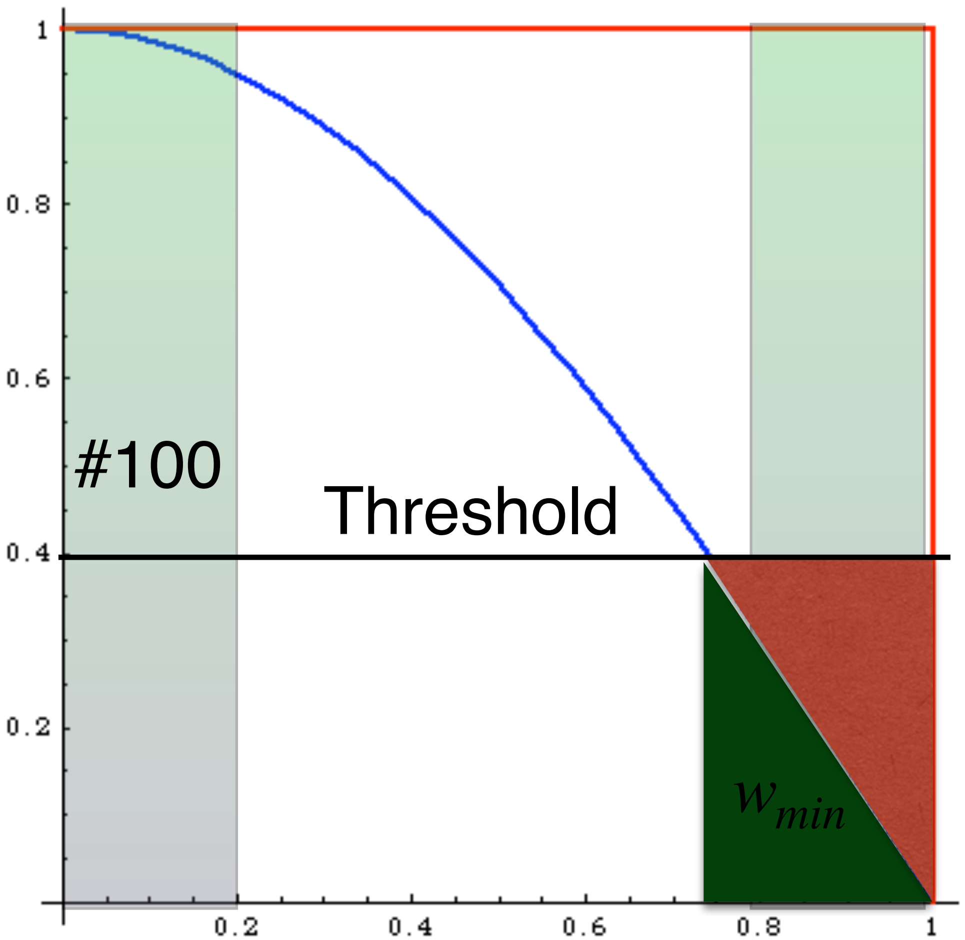

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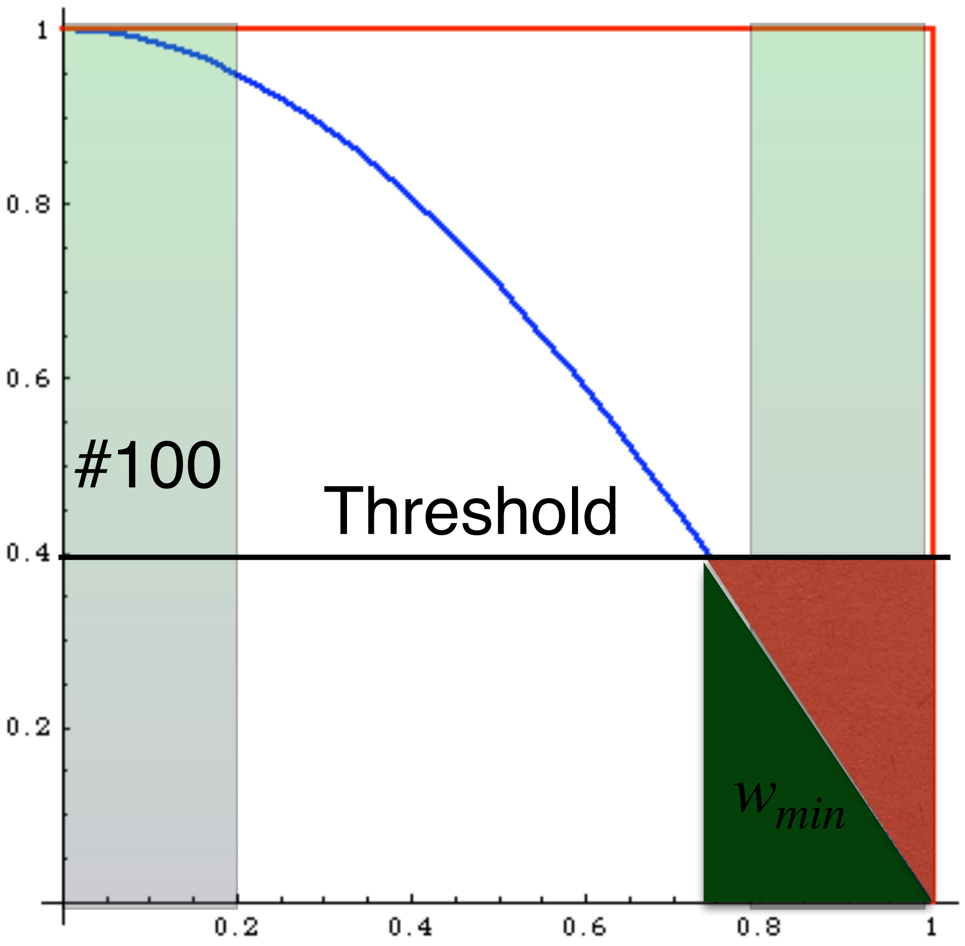
Do we need to keep small weight?



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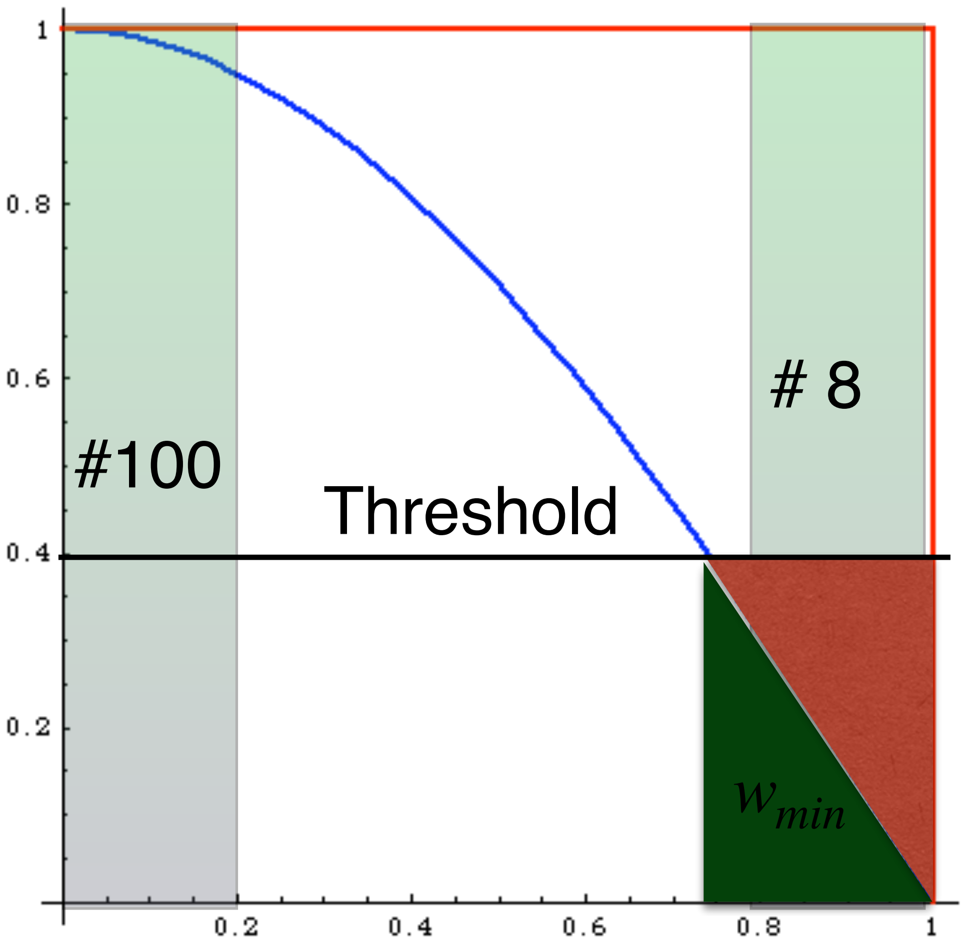
  - So the new weight is w_{thres}

Do we need to keep small weight?



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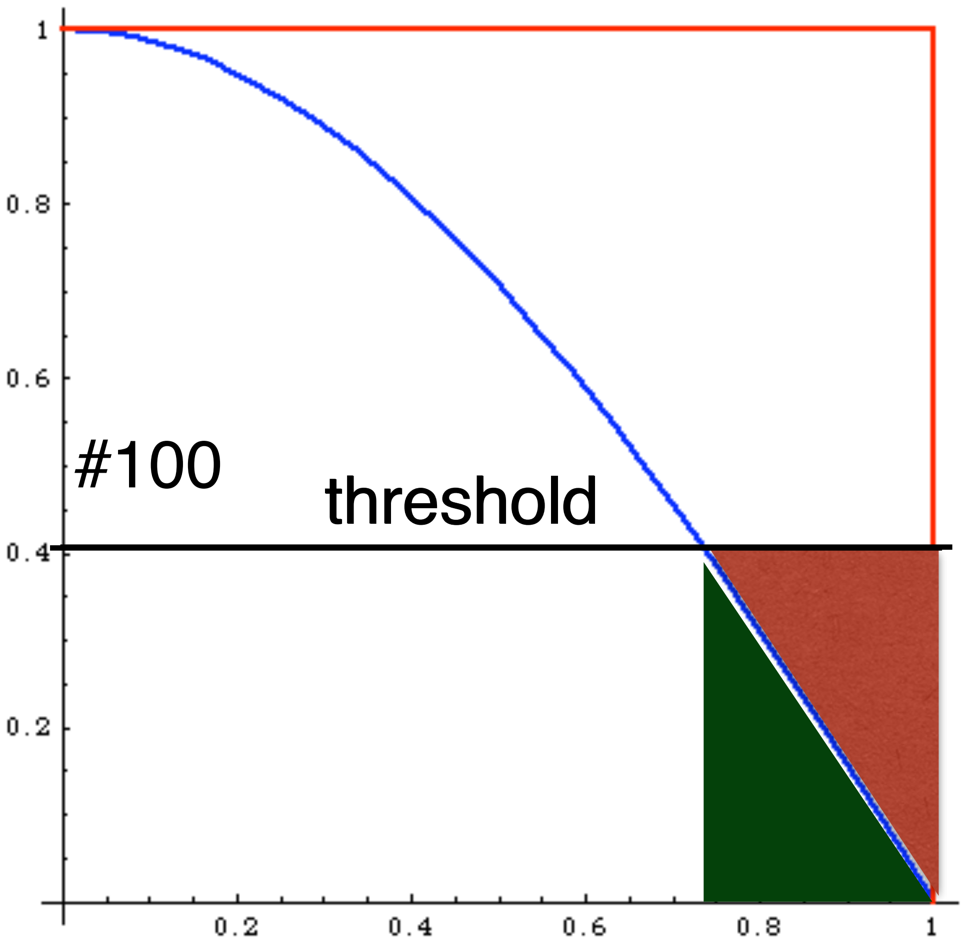

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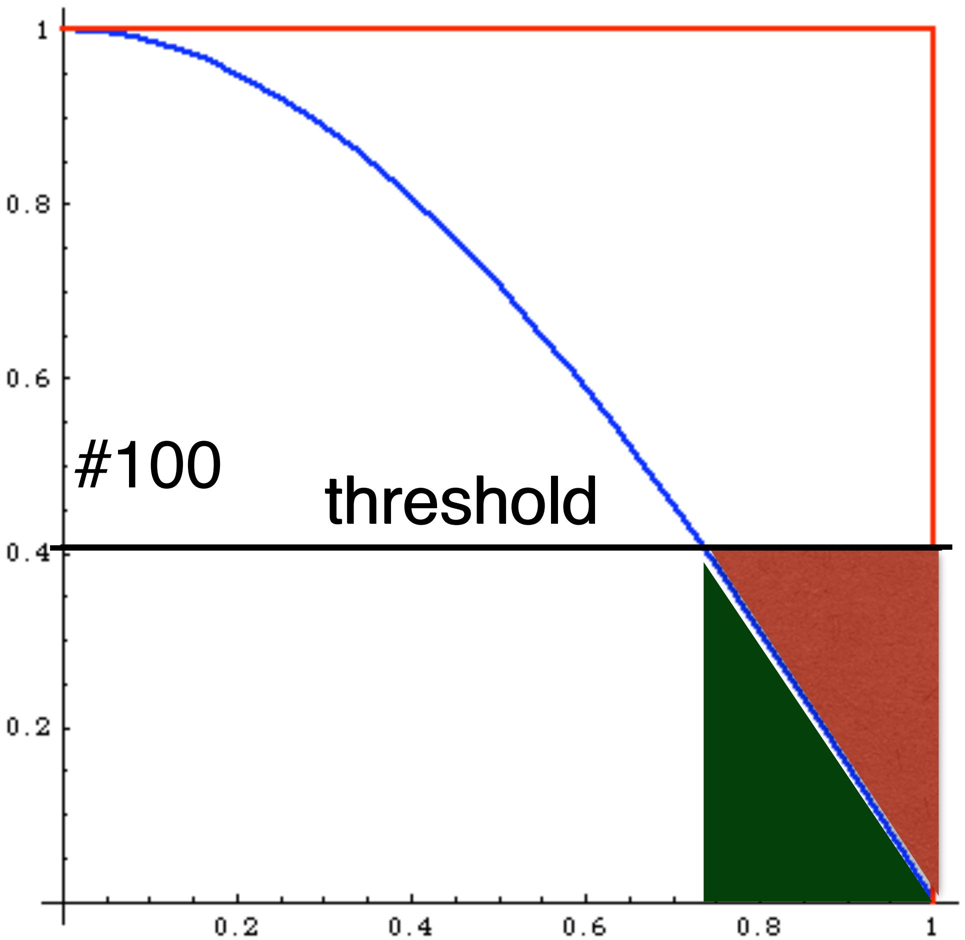

- Let’s improve
  - Let’s make the threshold proportional to the weight
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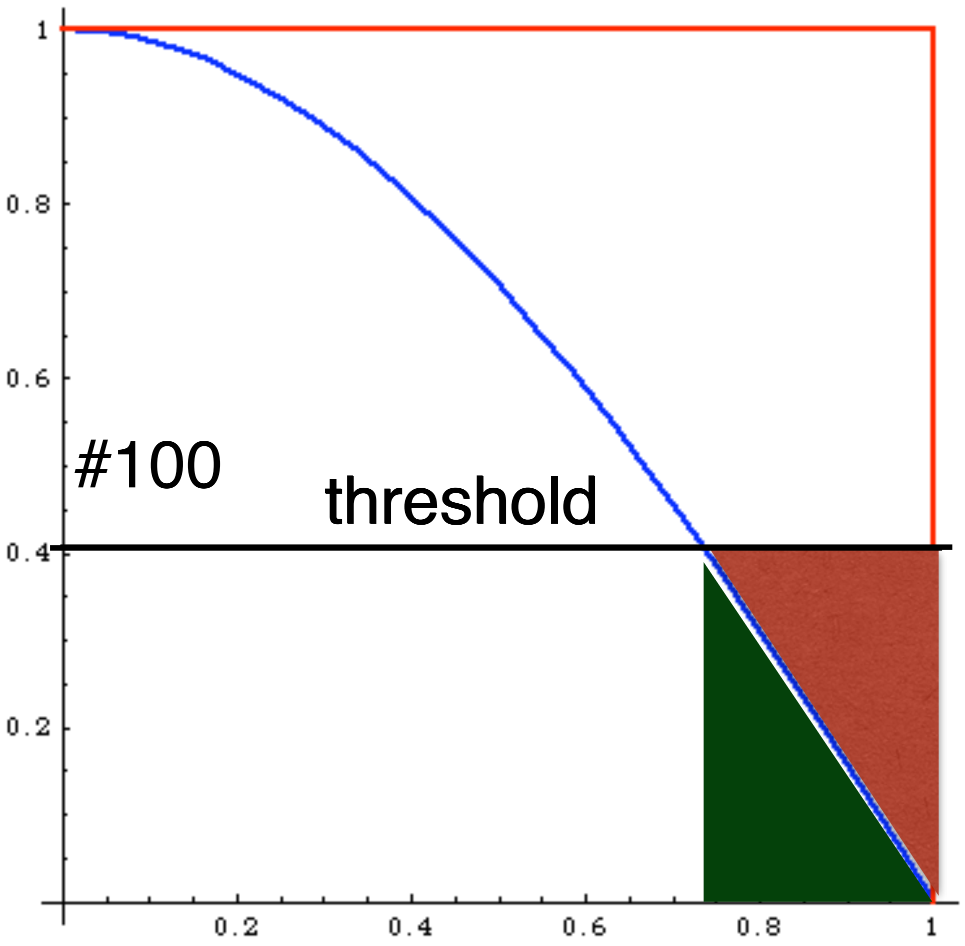
- Let’s all event have the same weight

Do we need to keep small weight?



- Let's improve
  - Let's make the threshold proportional to the weight
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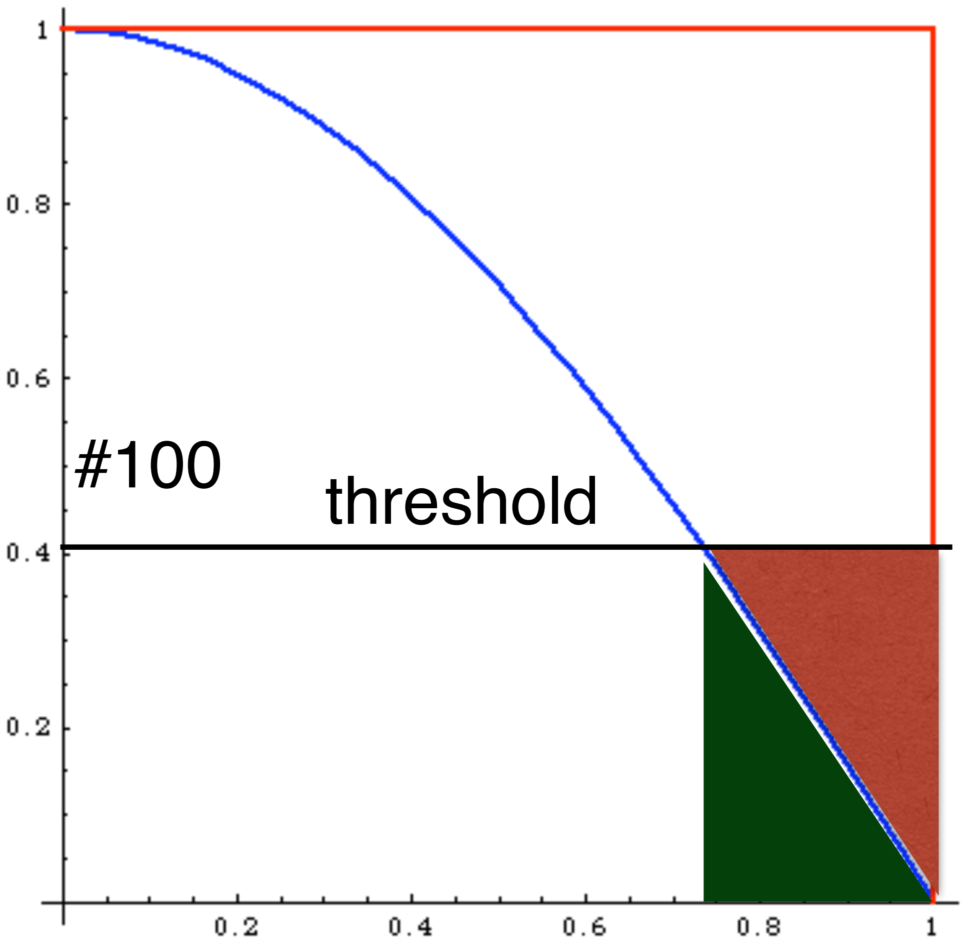
- Let's all event have the same weight
  - So set $w_{thres} > \max(w)$

Do we need to keep small weight?



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- Maximal compression

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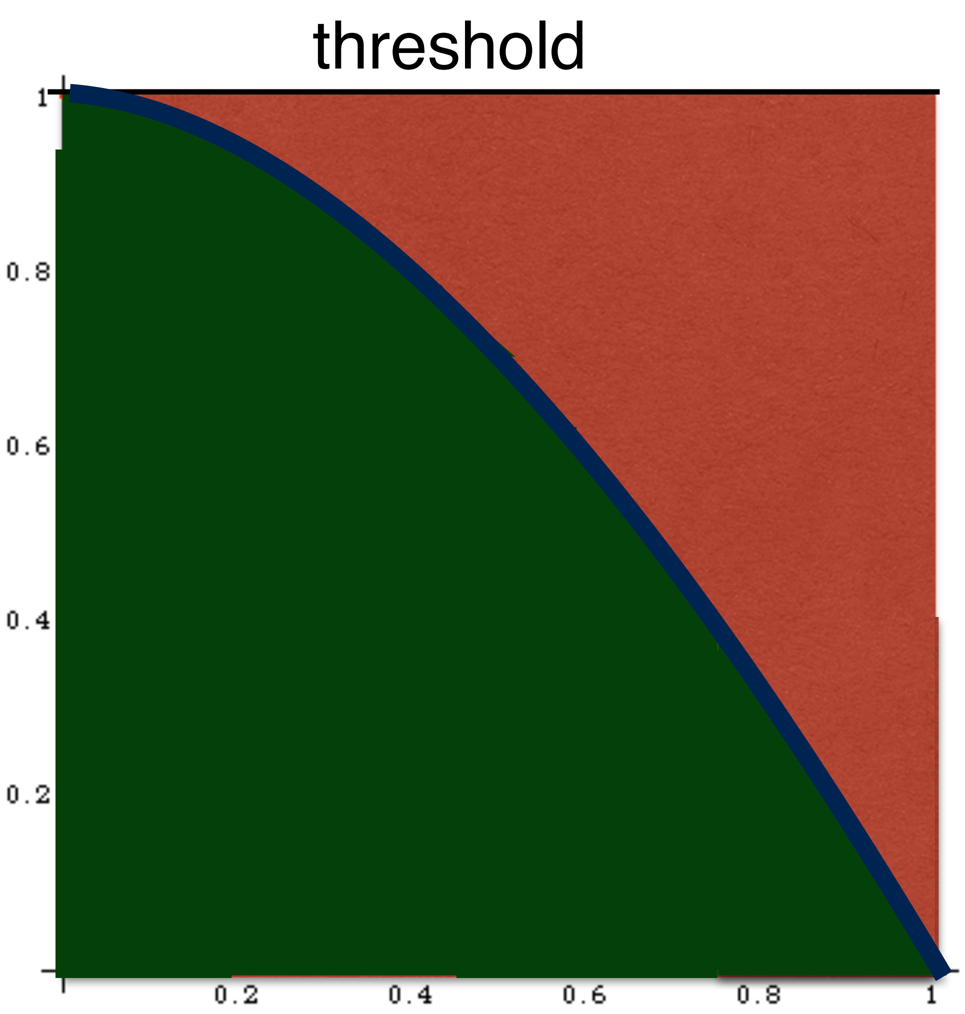

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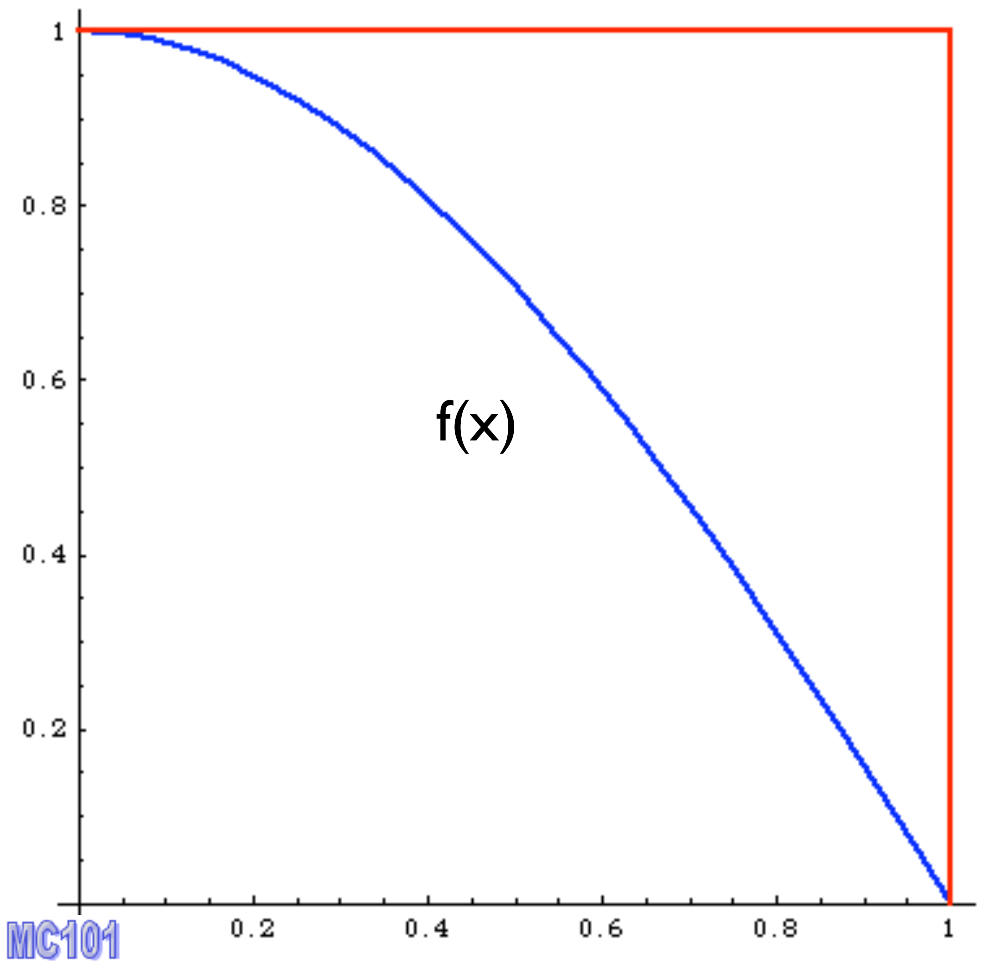
Event generation

$$\int f(x)dx = \frac{1}{N}\sum_{i=1}^{N} f(x_i) = \frac{1}{N}\sum_{i=1}^{N} \frac{f(x_i)}{w_{thres}} w_{thres}$$



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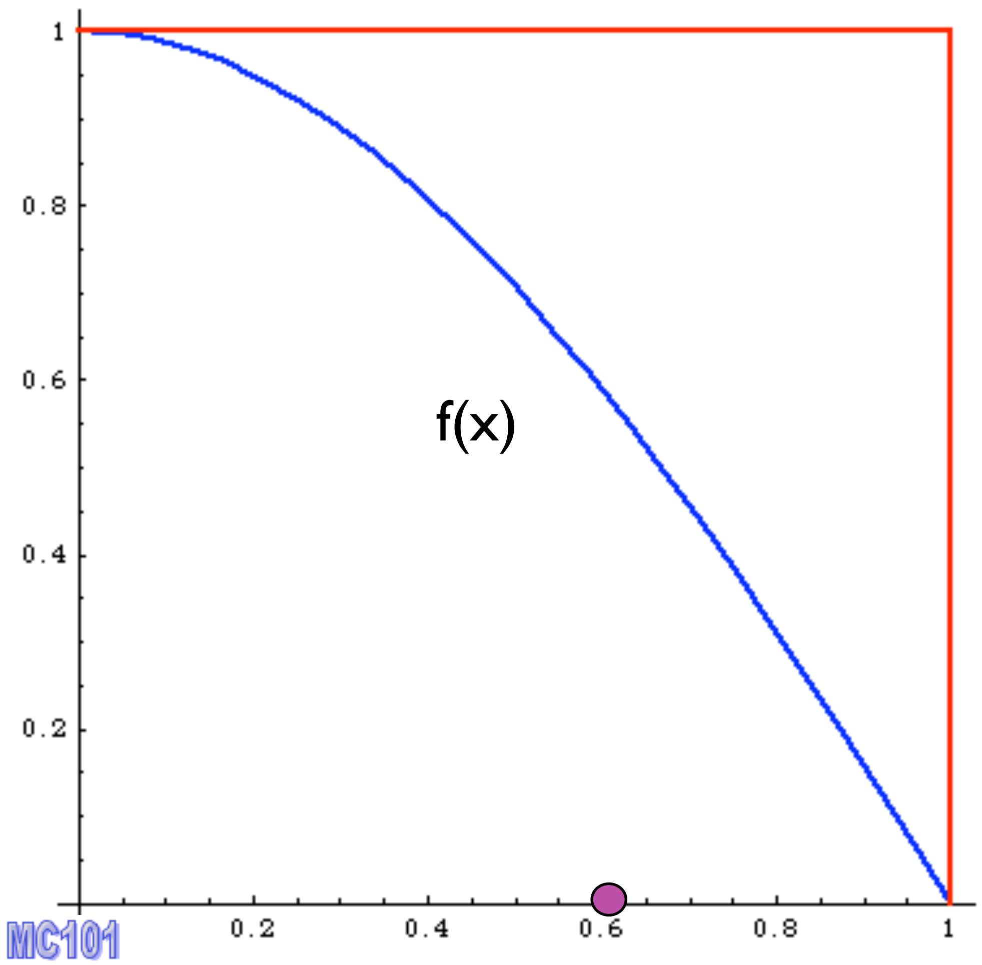
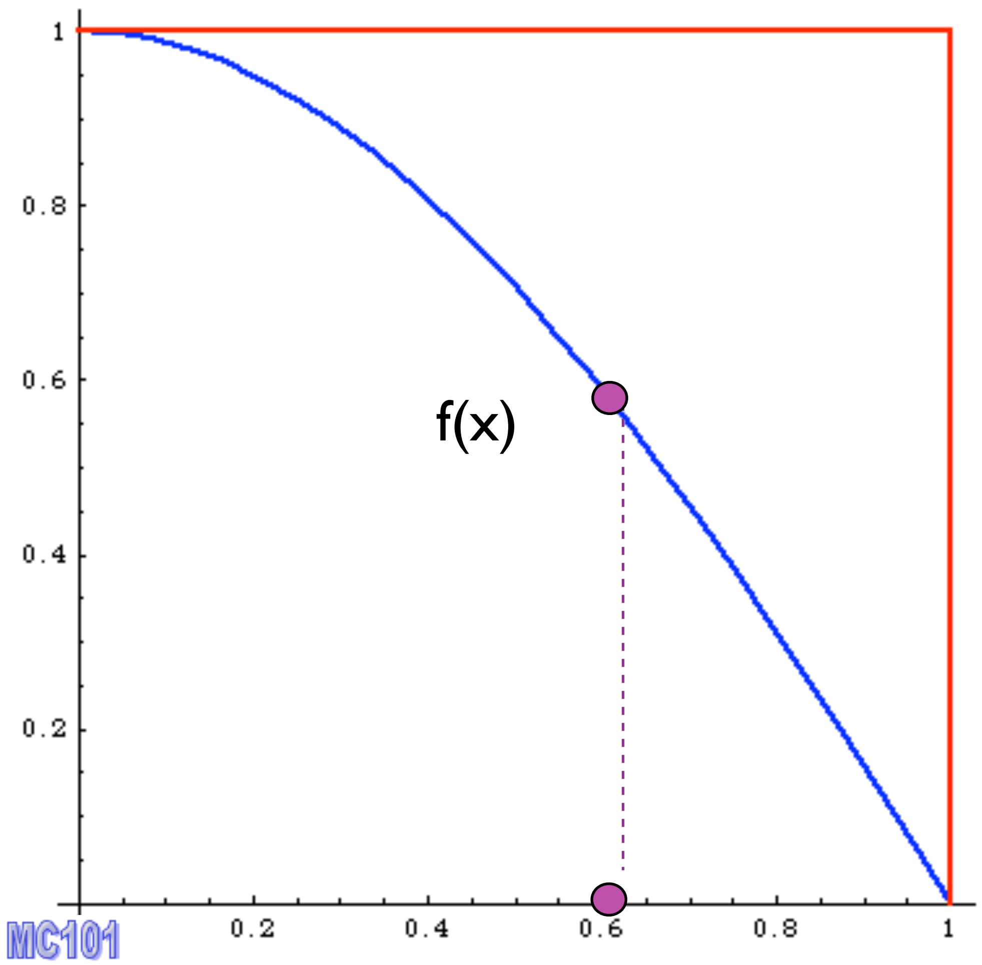


1. pick x_i

Event generation

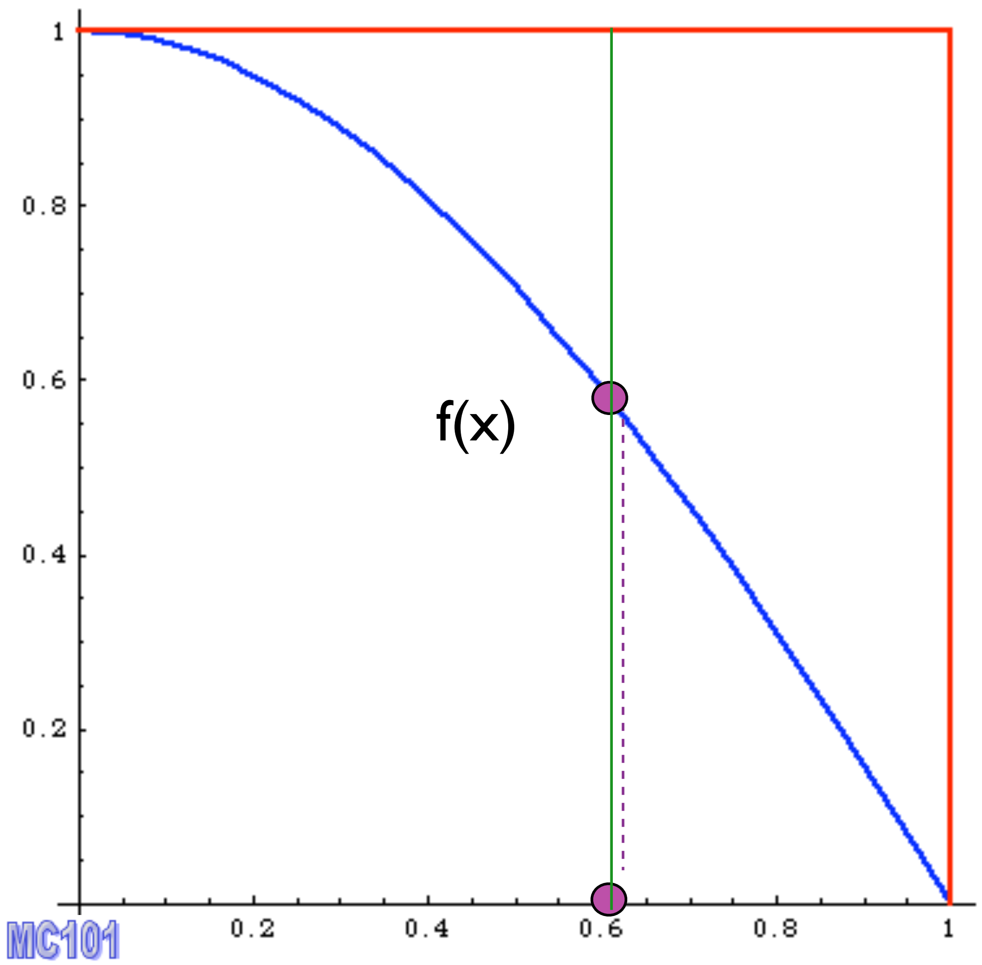
$$\int f(x)dx = \frac{1}{N}\sum_{i=1}^{N} f(x_i) = \frac{1}{N}\sum_{i=1}^{N} \frac{f(x_i)}{w_{thres}} w_{thres}$$



1. pick x_i
2. calculate $f(x_i)$

Event generation

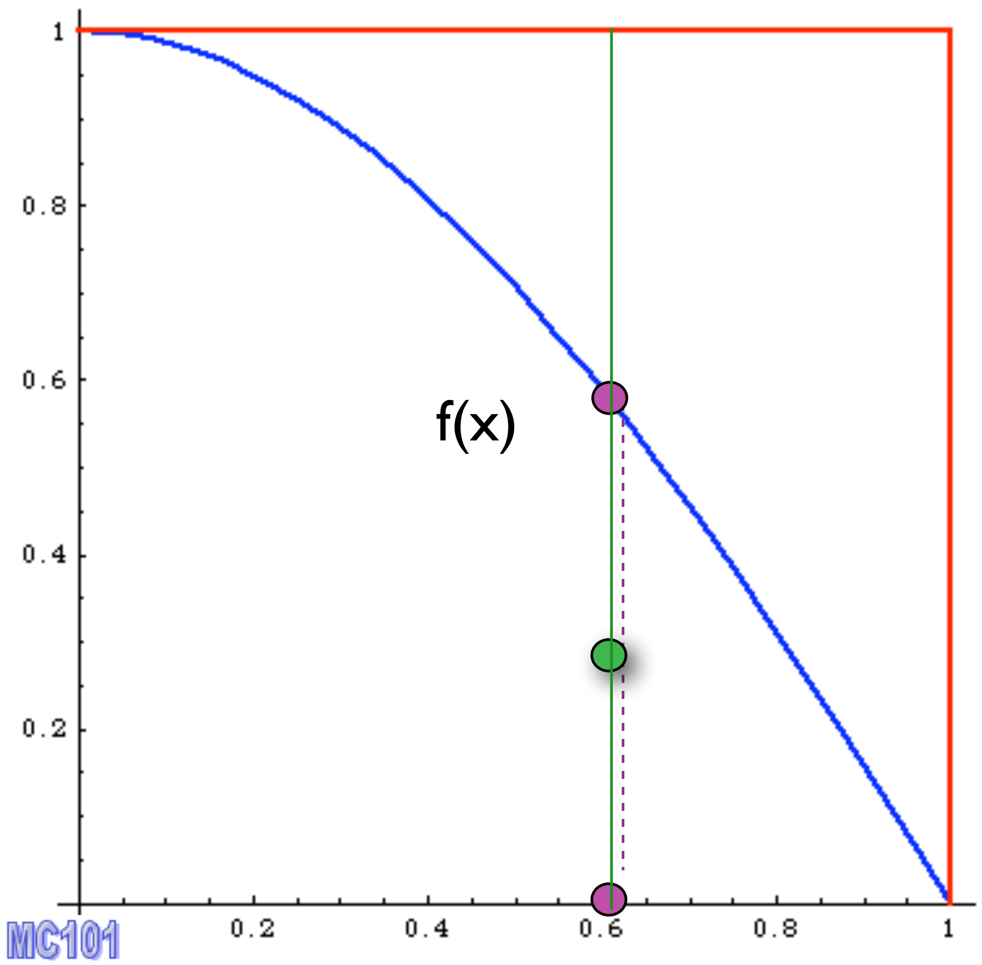
$$\int f(x)dx = \frac{1}{N}\sum_{i=1}^{N} f(x_i) = \frac{1}{N}\sum_{i=1}^{N} \frac{f(x_i)}{w_{thres}} w_{thres}$$



1. pick x_i
2. calculate $f(x_i)$
3. pick $y \in [0, max(f)]$

Event generation

$$\int f(x)dx = \frac{1}{N}\sum_{i=1}^{N} f(x_i) = \frac{1}{N}\sum_{i=1}^{N} \frac{f(x_i)}{w_{thres}} w_{thres}$$



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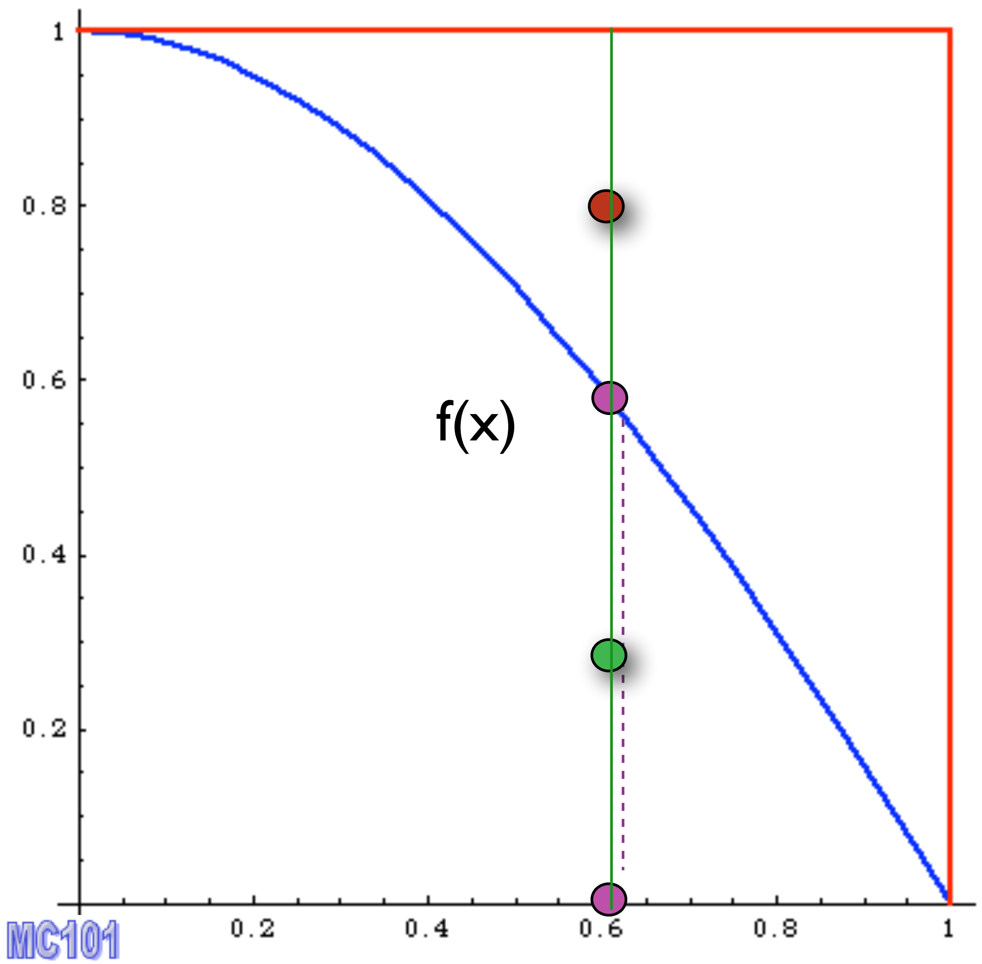
2. calculate $f(x_i)$
3. pick $y \in [0, max(f)]$
4. Compare:
   if $y < f(x_i)$ accept event,

Event generation

$$\int f(x)dx = \frac{1}{N}\sum_{i=1}^{N} f(x_i) = \frac{1}{N}\sum_{i=1}^{N} \frac{f(x_i)}{w_{thres}} w_{thres}$$

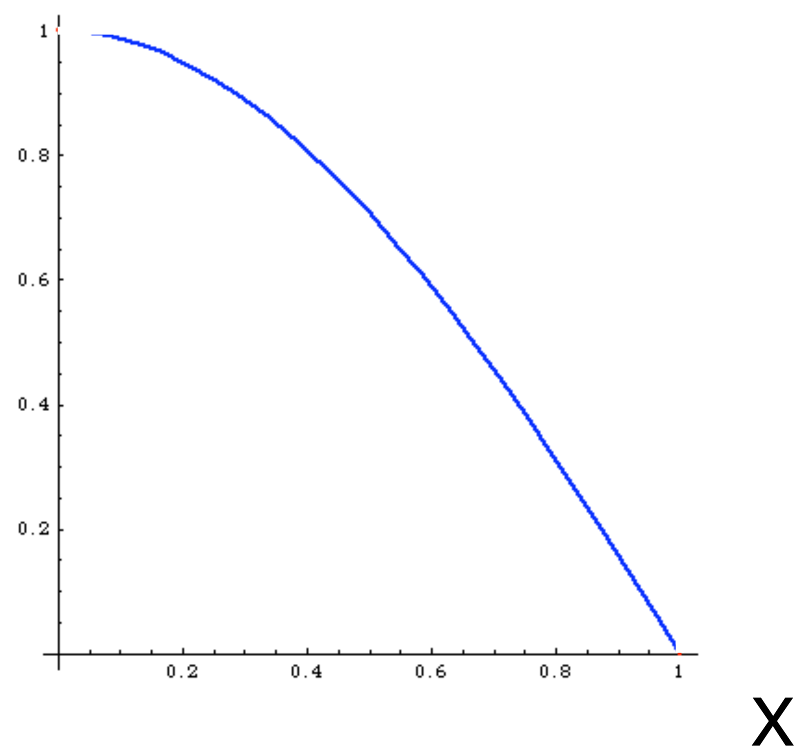


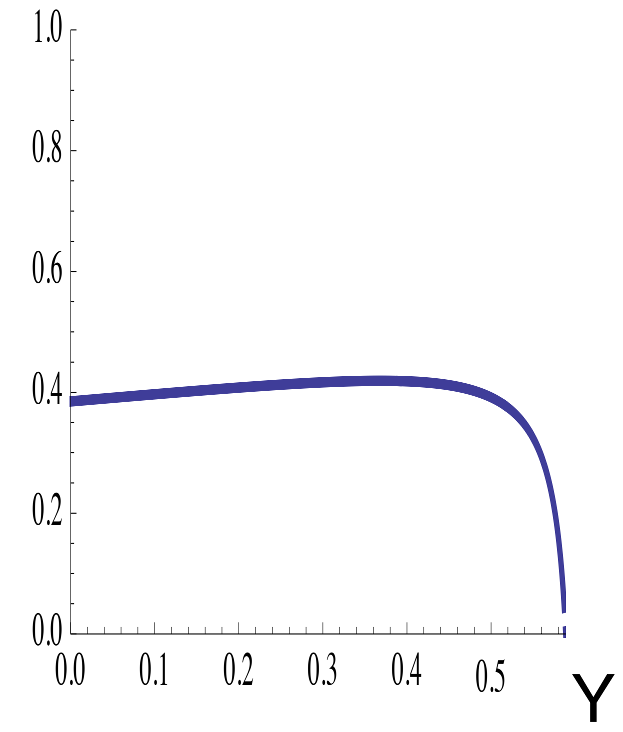
1. pick x_i
2. calculate $f(x_i)$
3. pick $y \in [0, max(f)]$
4. Compare:
   if $y < f(x_i)$ accept event,

   else reject it.

Event generation

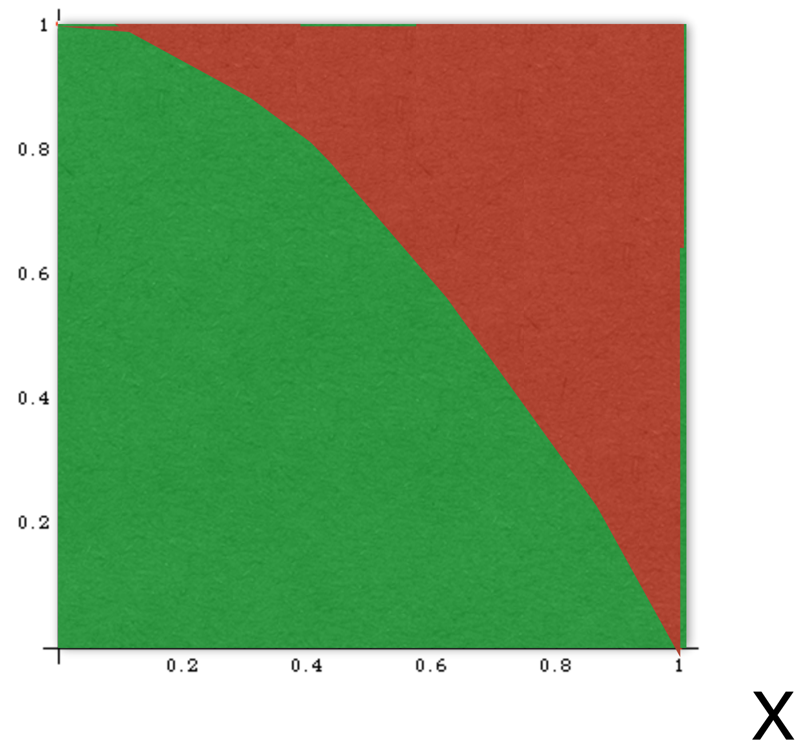
$$\int f(x)dx = \int dy \frac{f(y)}{p(y)} = \frac{1}{N}\sum_{i=1}^{N}\frac{f(y_i)}{p(y_i)} = \frac{1}{N}\sum_{i=1}^{N}\frac{f(y_i)}{p(y_i)\ w_{thres}} w_{thres}$$

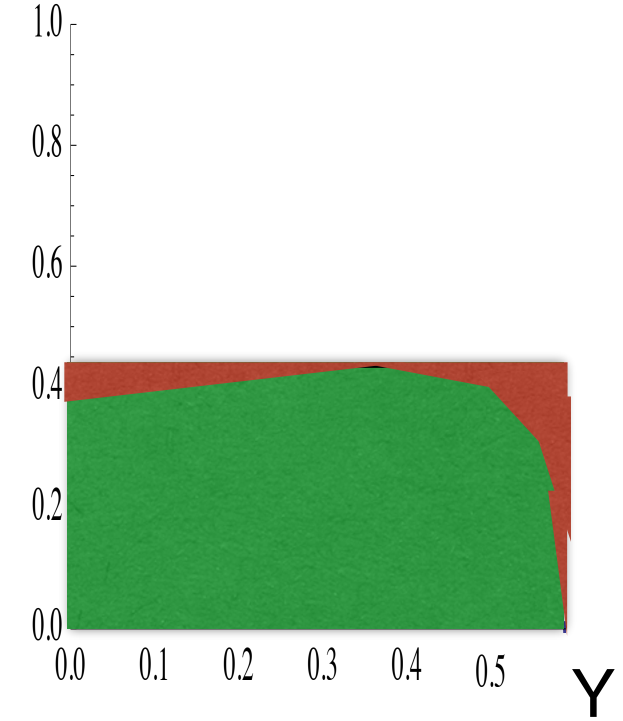




Event generation

$$\int f(x)dx = \int dy \frac{f(y)}{p(y)} = \frac{1}{N}\sum_{i=1}^{N}\frac{f(y_i)}{p(y_i)} = \frac{1}{N}\sum_{i=1}^{N}\frac{f(y_i)}{p(y_i)\ w_{thres}} w_{thres}$$





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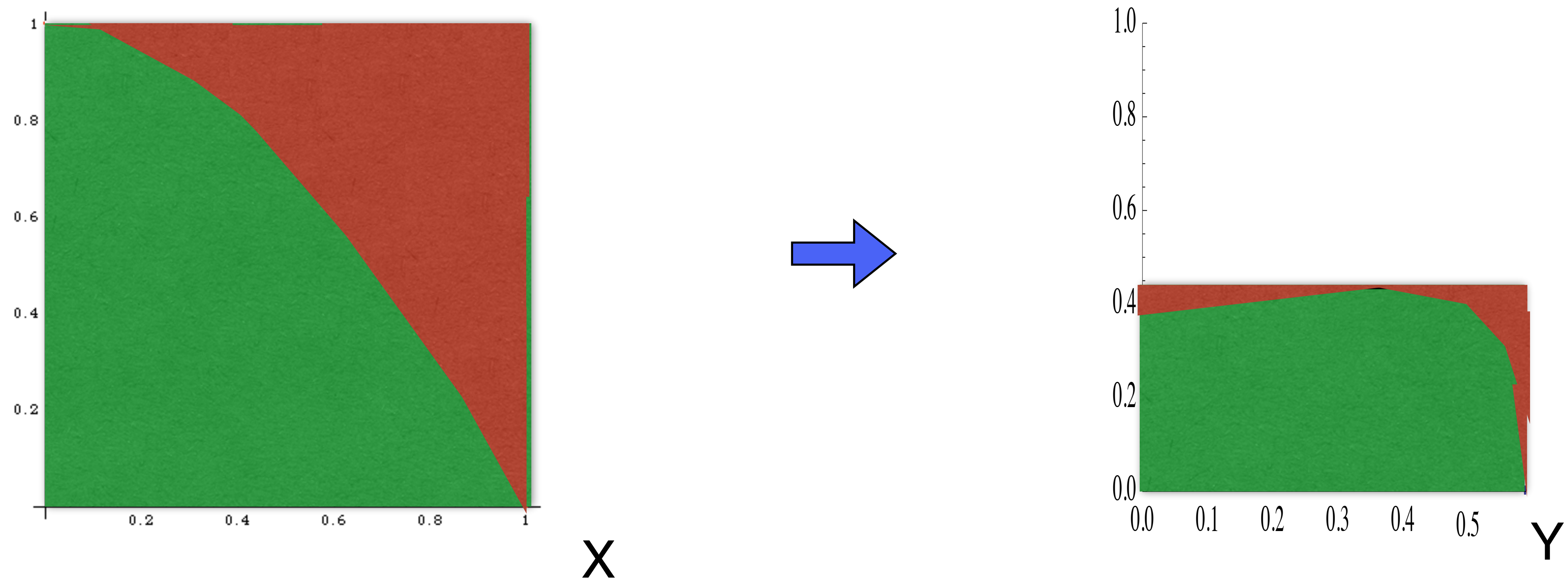


- Having smaller variance (flatter function) also allows to have $\frac{w}{w_{thres}}$ or $\frac{w}{max(w)}$ closer to one and therefore better unweighting efficiency (i.e. faster code)

Question time

1 Allez sur wooclap.com

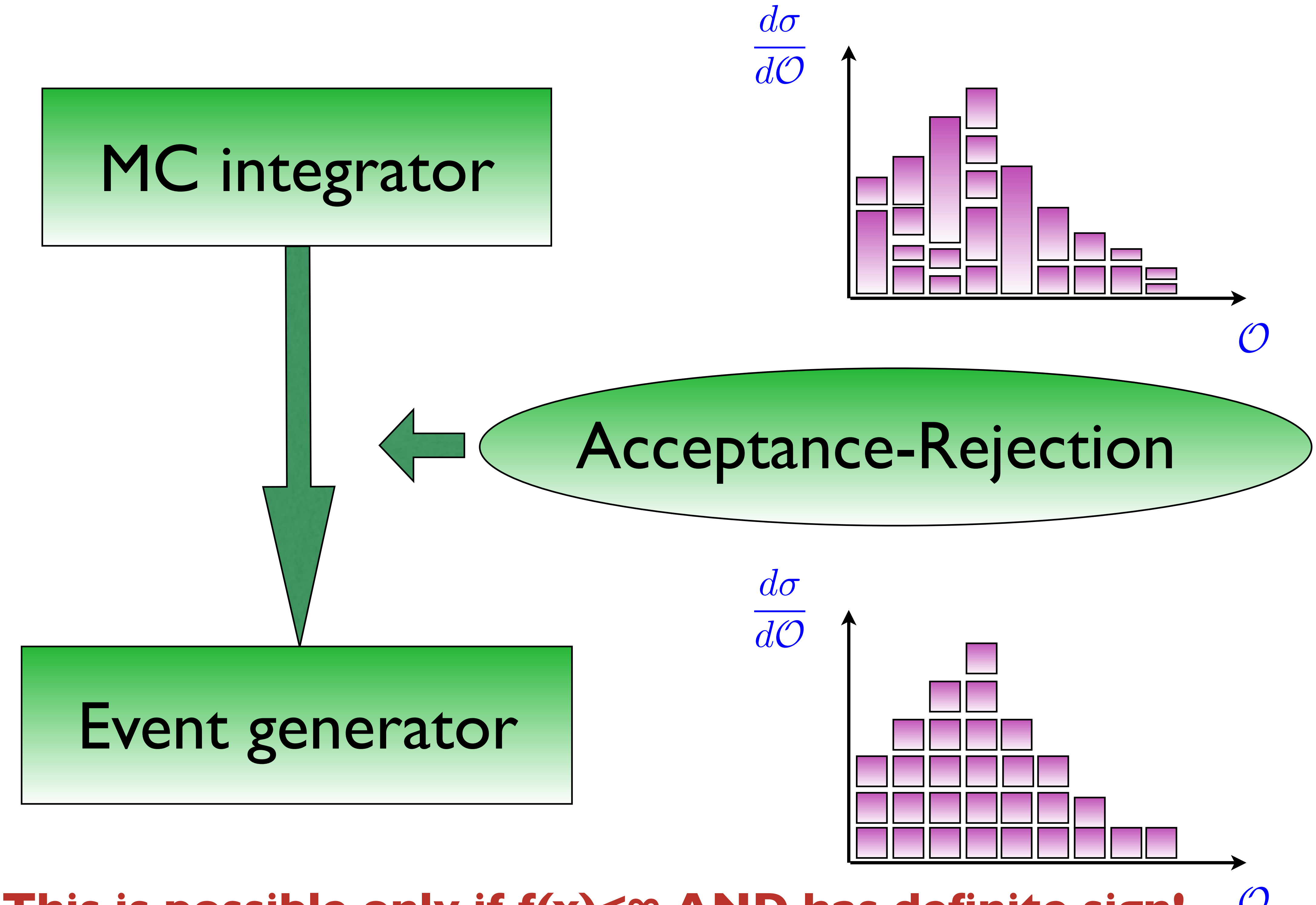
2 Entrez le code d'événement dans le bandeau supérieur

Code d'événement

MADGRAPH

Activer les réponses par SMS

Event generation



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

Monte-Carlo Summary

Bad Point

- Slow Convergence (especially in low number of Dimension)
- Need to know the function
    - Impact on cut

Monte-Carlo Summary

Bad Point

- Slow Convergence (especially in low number of Dimension)
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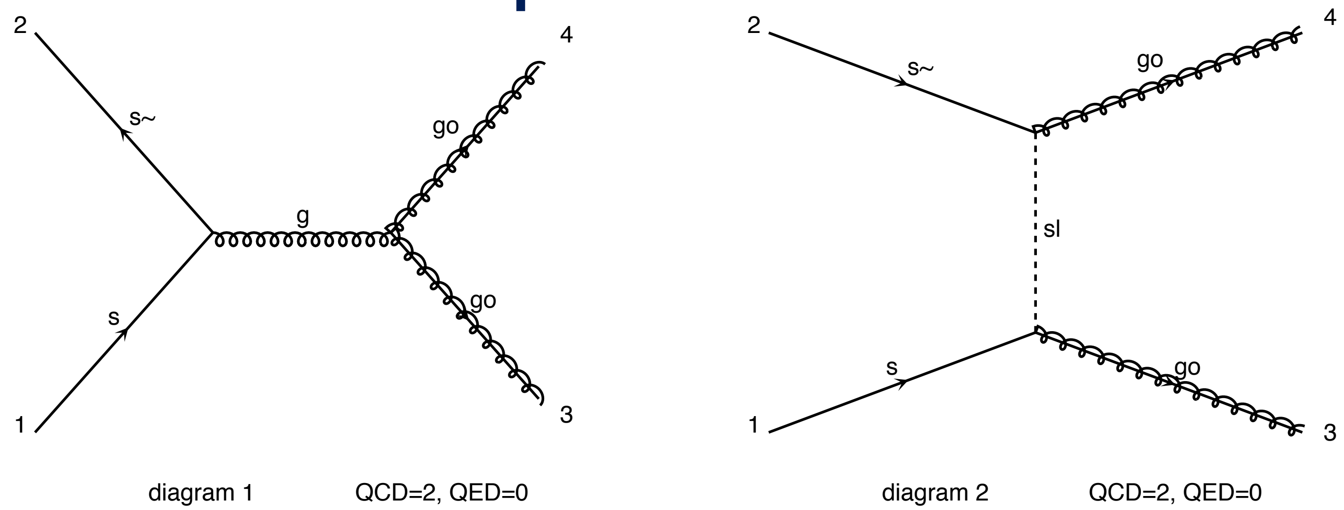
Good Point

- Complex area of Integration
- Easy error estimate
- quick estimation of the integral
- Possibility to have unweighted events

Matrix-Element

Calculate a given process (e.g. gluino pair)

- Determine the production mechanism



- Evaluate the matrix-element

$|\mathcal{M}|^2$ ➡Need Feynman Rules!

- Phase-Space Integration

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

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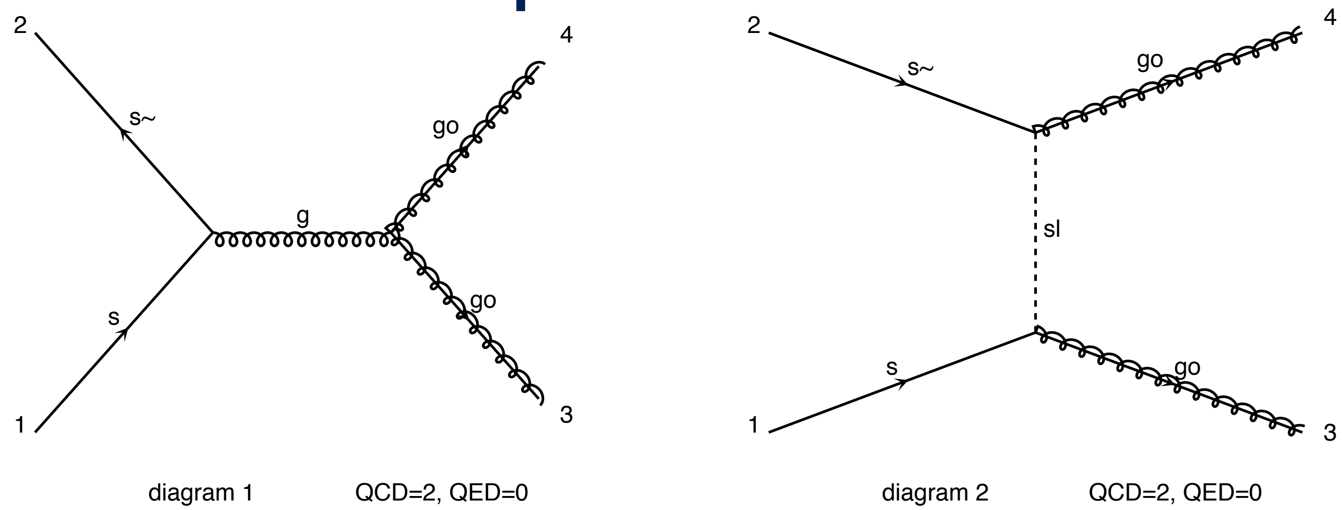

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Easy enough

Hard

Very Hard (in general)

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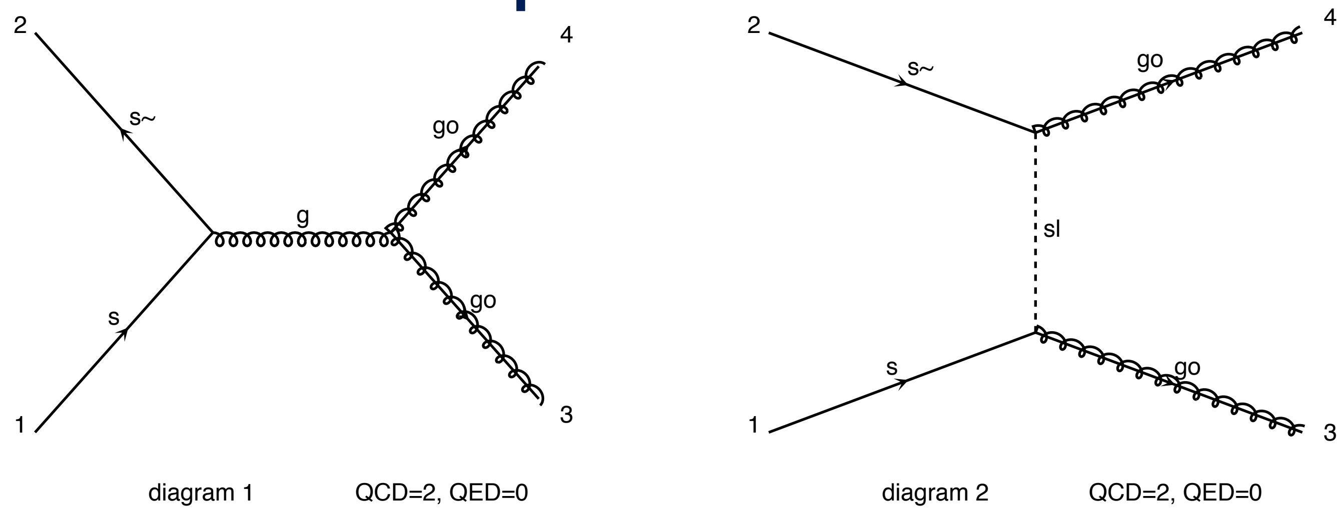

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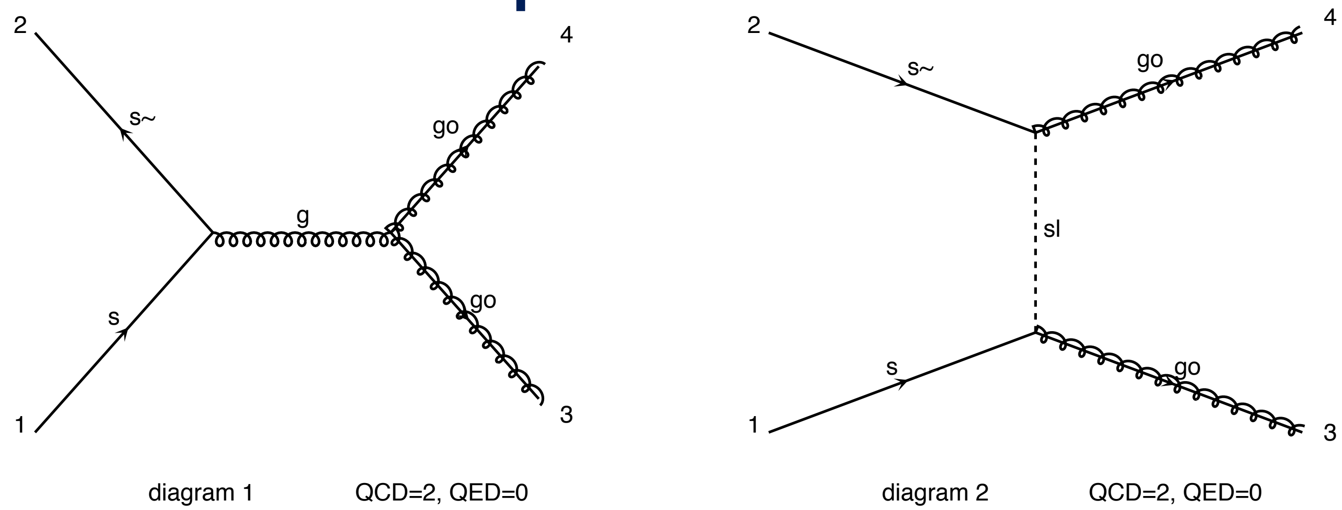

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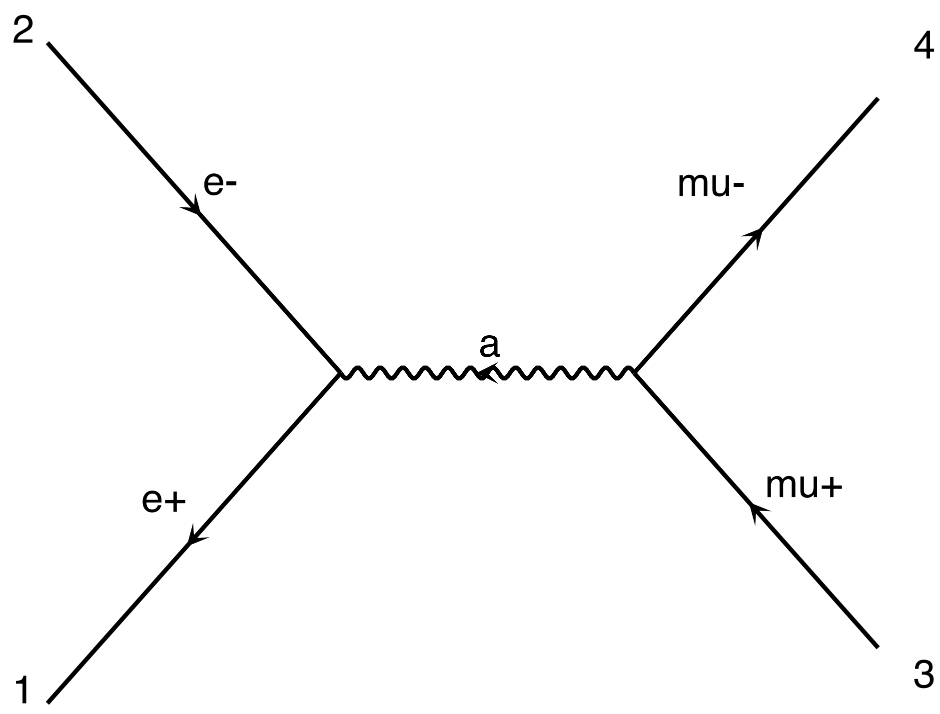
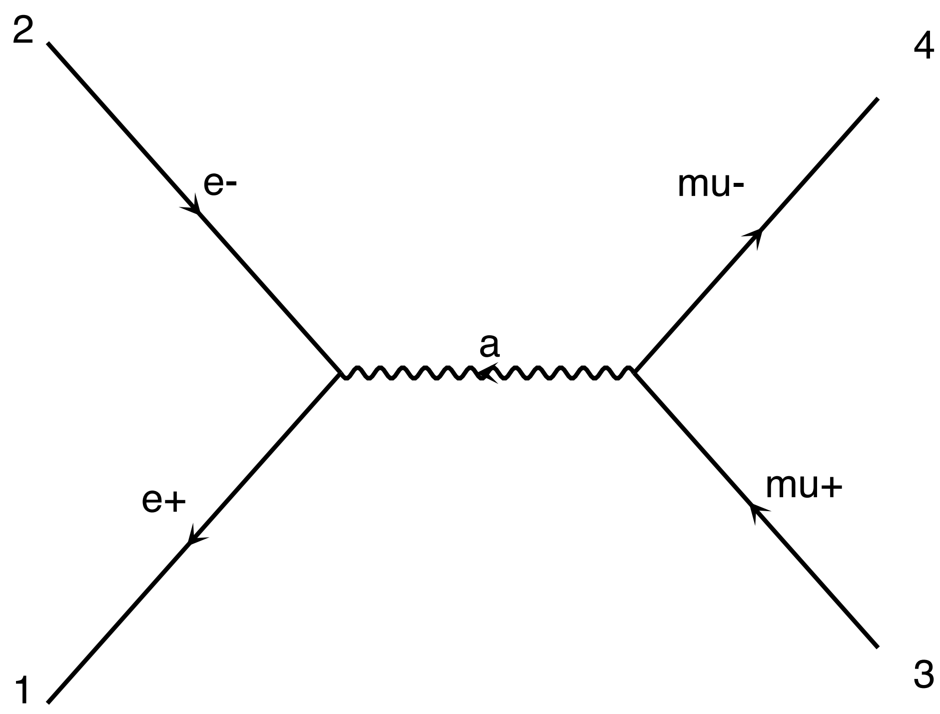


$$\mathcal{M} = e^2(\bar{u}\gamma^\mu v)\frac{g_{\mu\nu}}{q^2}(\bar{v}\gamma^\nu u)$$

Matrix Element



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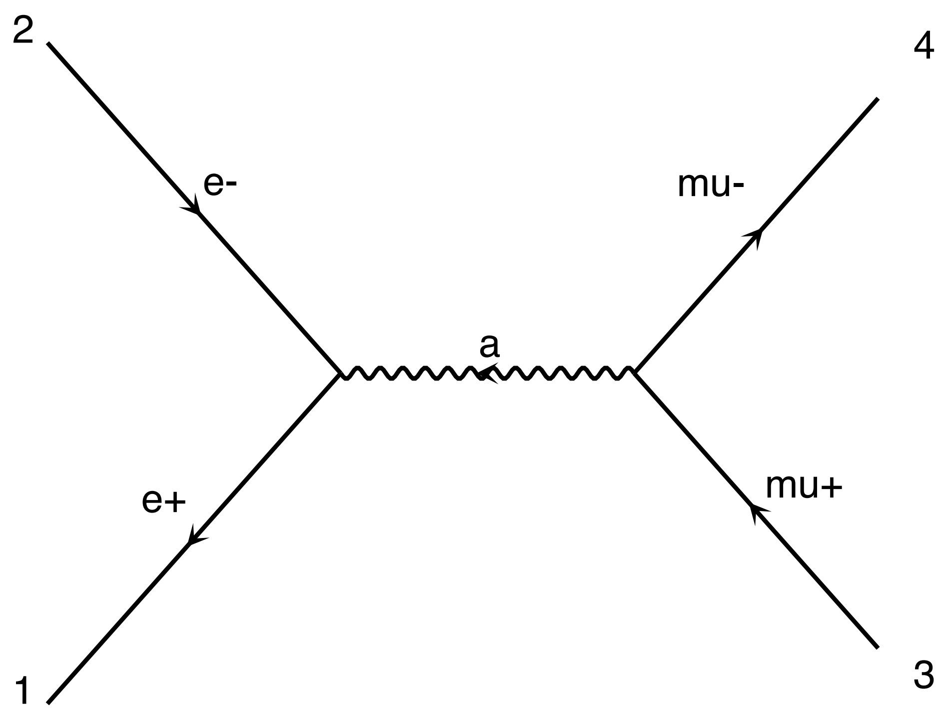
$$\frac{1}{4}\sum_{pol}|\mathcal{M}|^2 = \frac{1}{4}\sum_{pol}\mathcal{M}^*\mathcal{M}$$

Matrix Element



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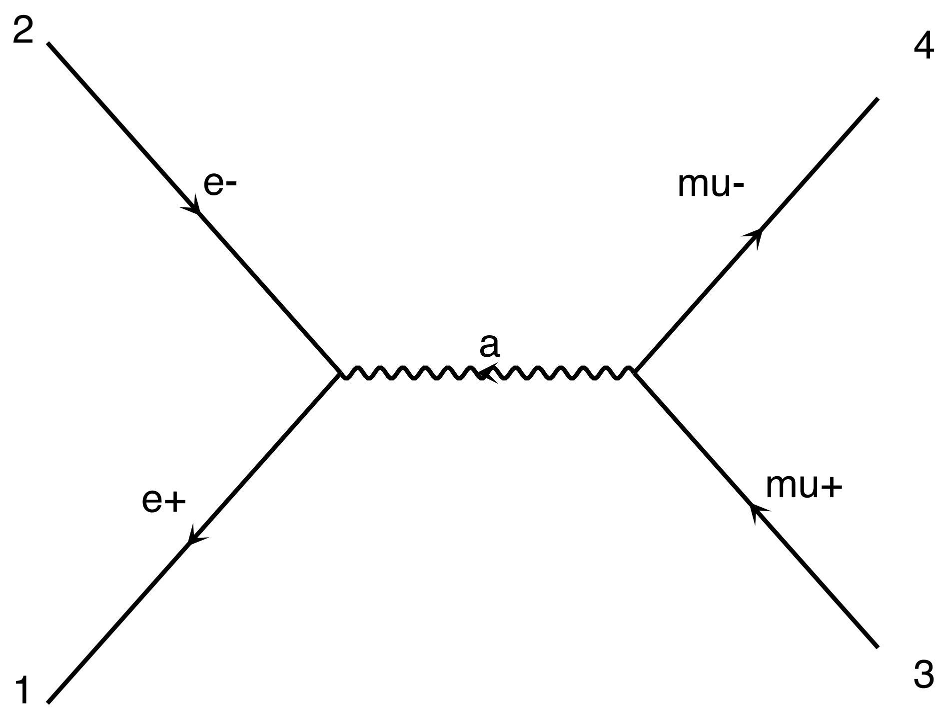
$$\sum_{pol} u\bar{u} = \not{p} + m$$

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

Matrix Element



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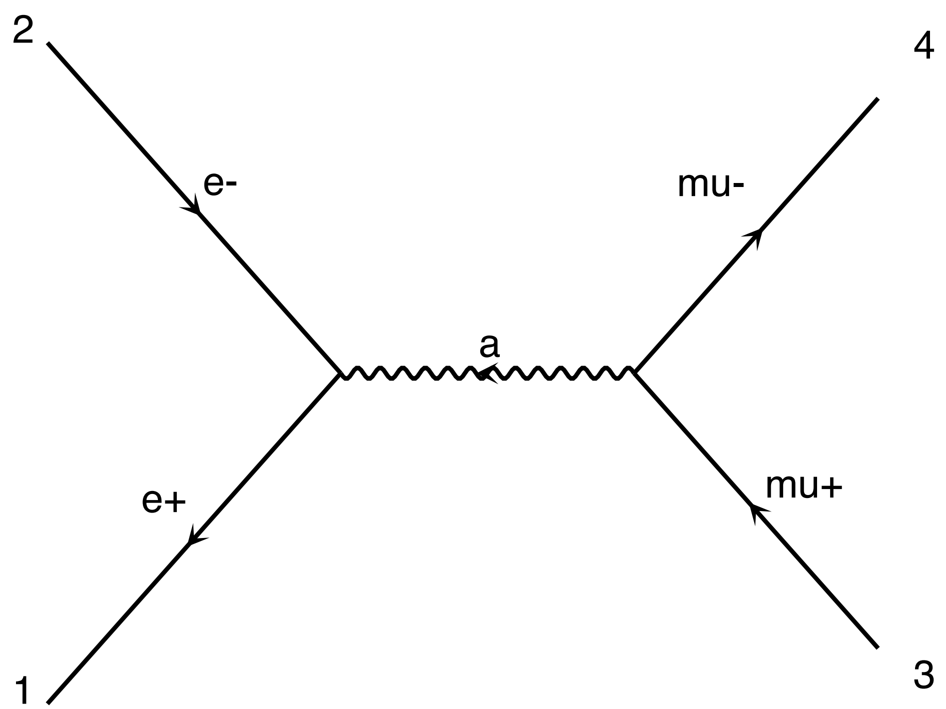
$$\rightarrow \quad \frac{8e^4}{q^4}[(p_1.p_3)(p_2.p_4) + (p_1.p_4)(p_2.p_3)]$$

Matrix Element



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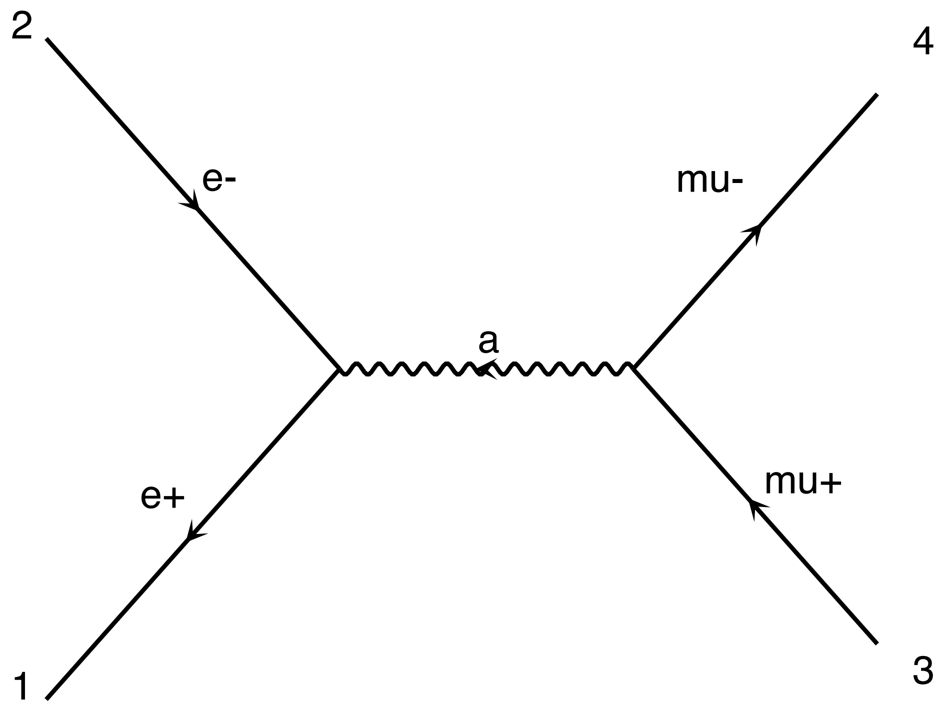
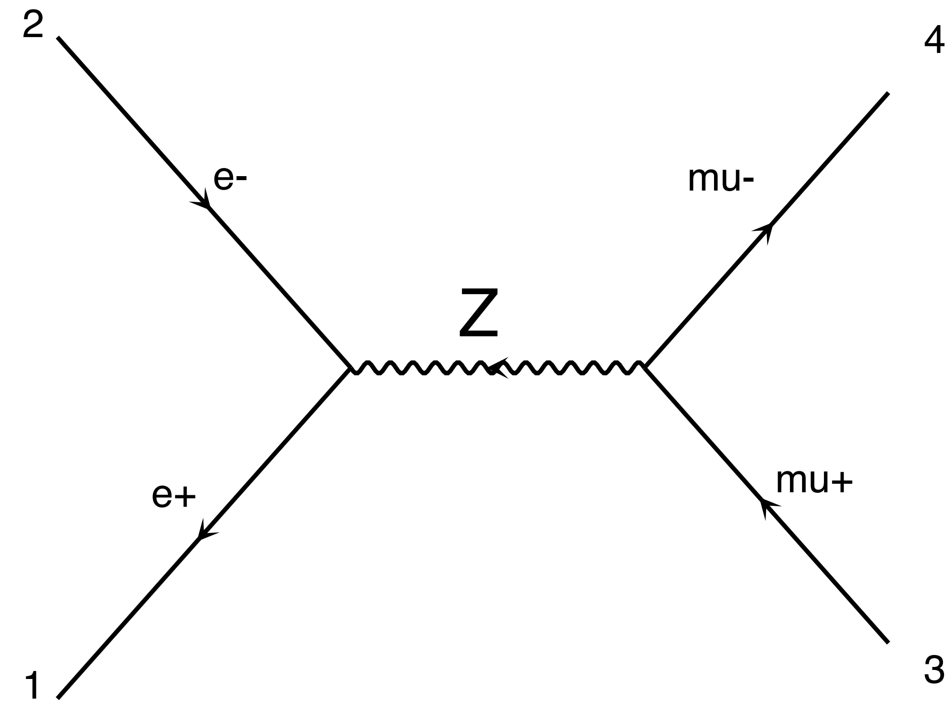
$$\rightarrow \frac{8e^4}{q^4}\left[(p_1.p_3)(p_2.p_4) + (p_1.p_4)(p_2.p_3)\right]$$

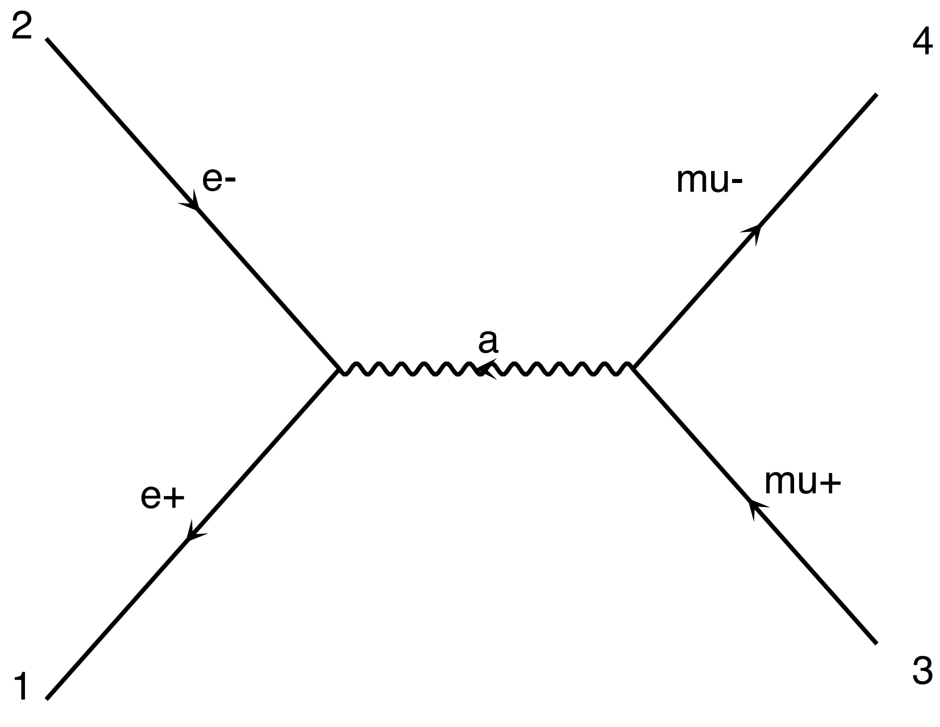
Very Efficient !!!

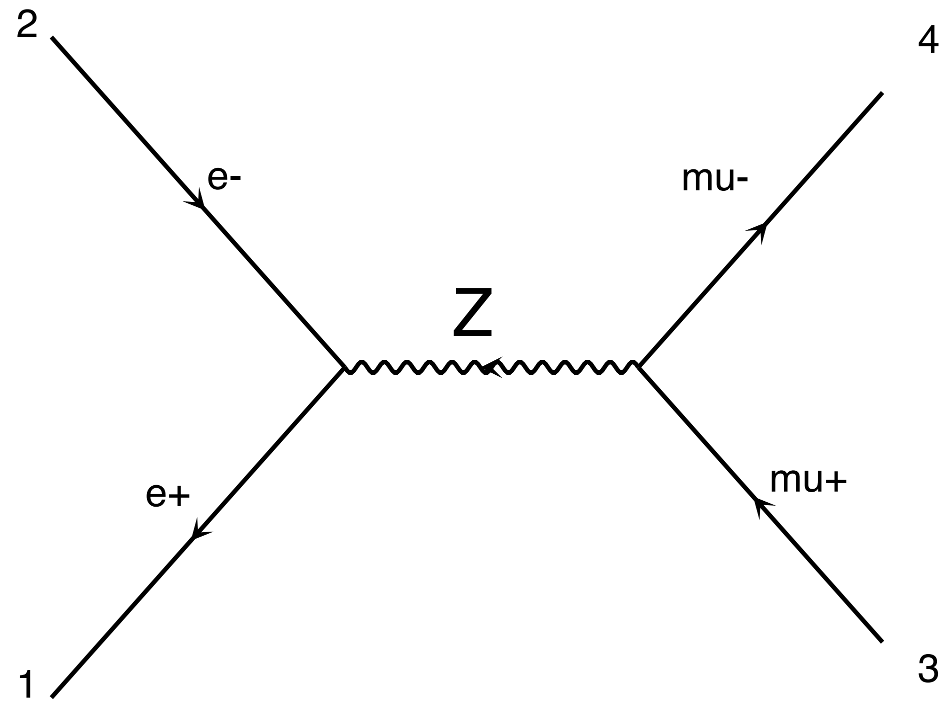


2
e-
4
mu-
a
e+
mu+
1
3

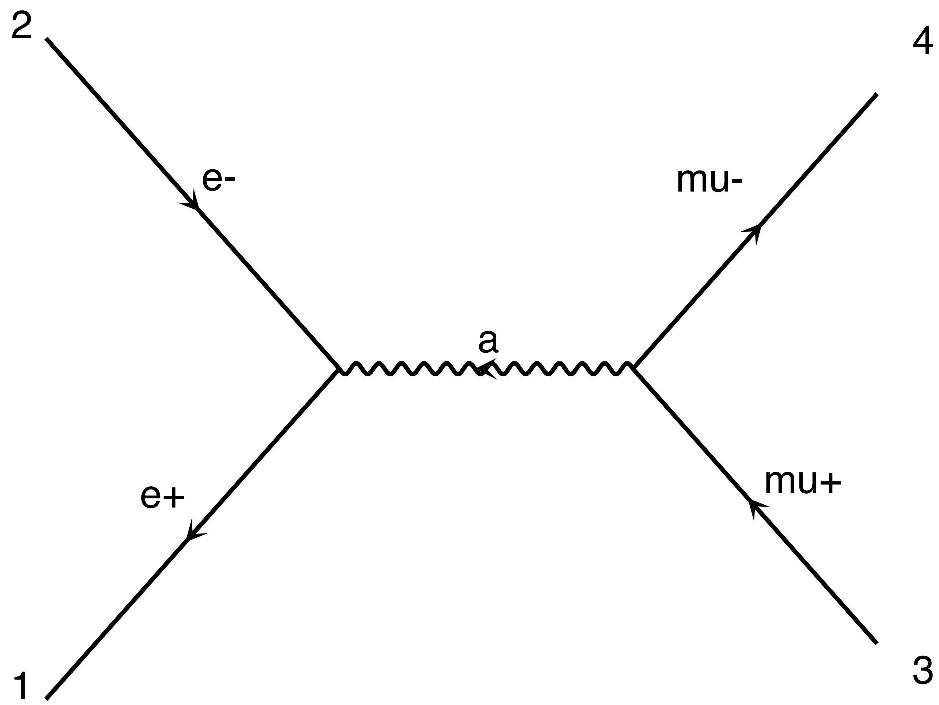


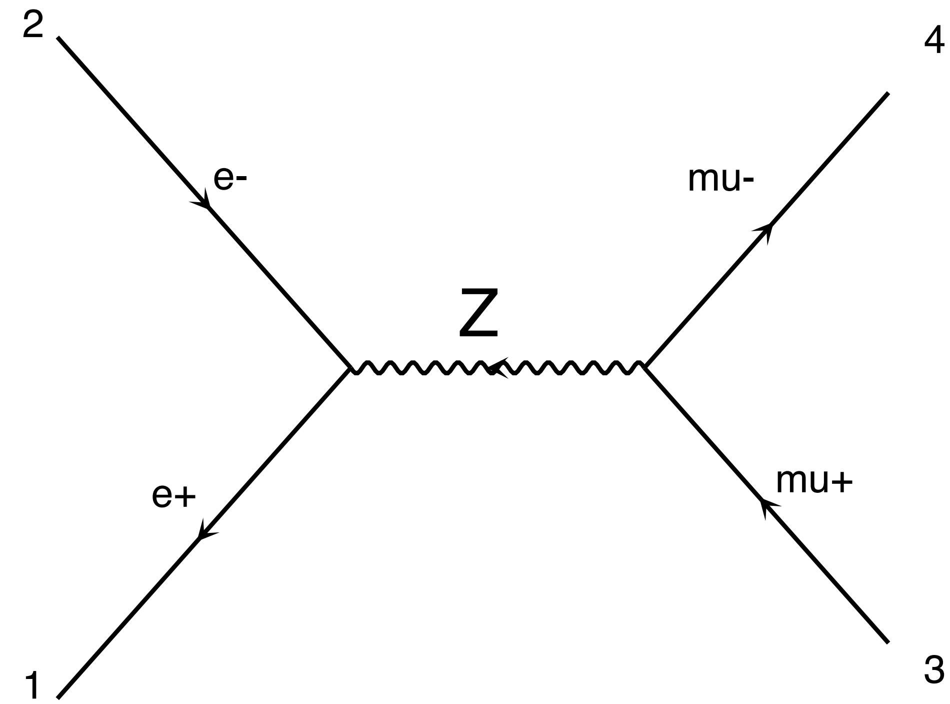
2
e-
4
mu-
Z
e+
mu+
1
3





Need to compute $|M_a|^2$ $|M_z|^2$ $2Re(M_a^* M_z)$





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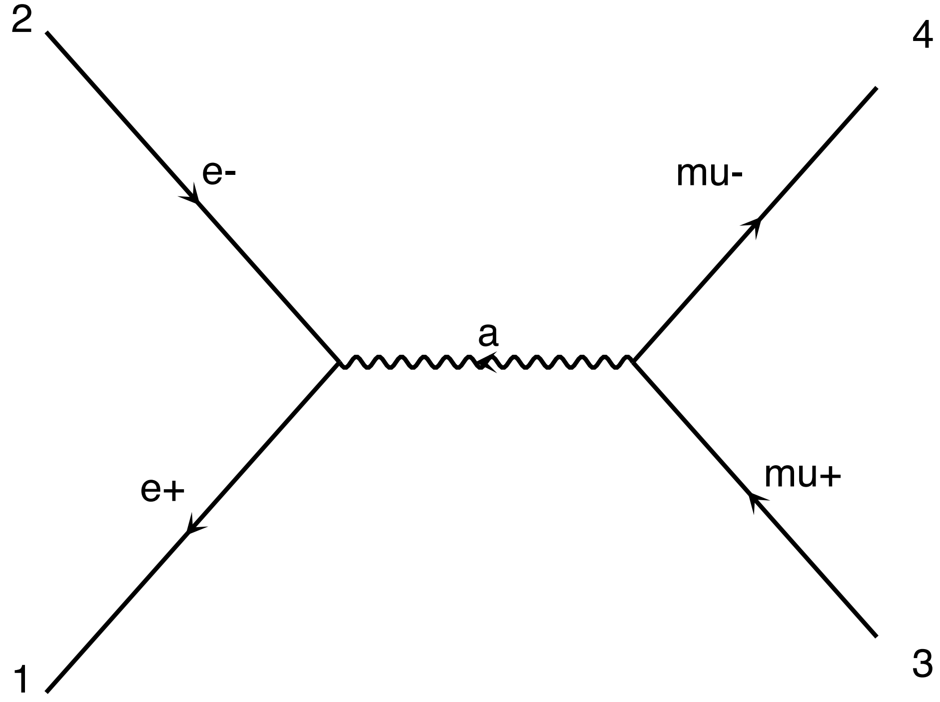
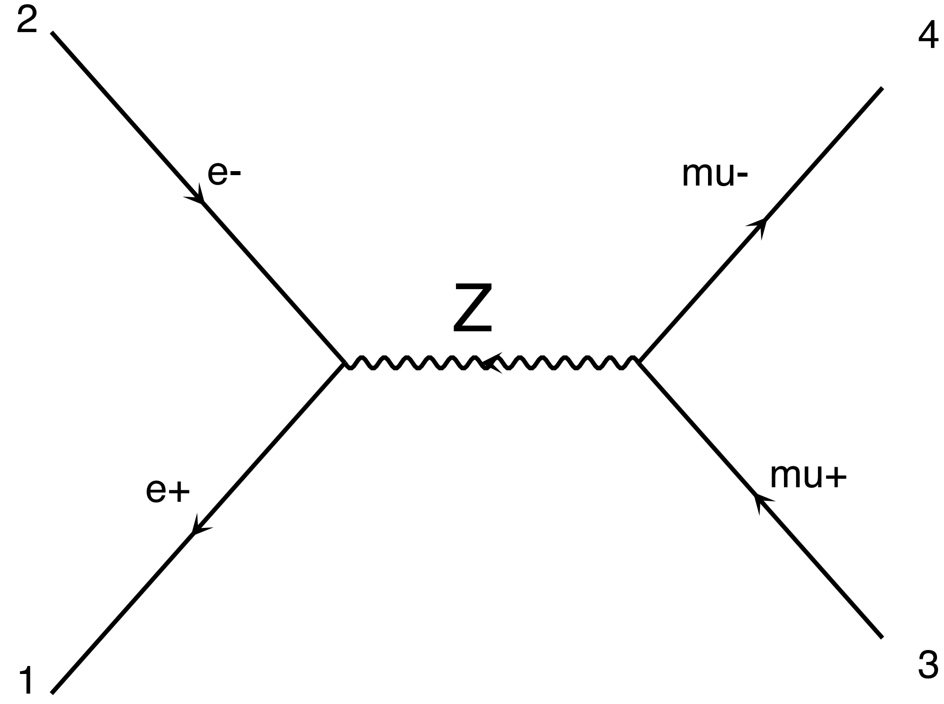
So for M Feynman diagram we need to compute M^2 different term





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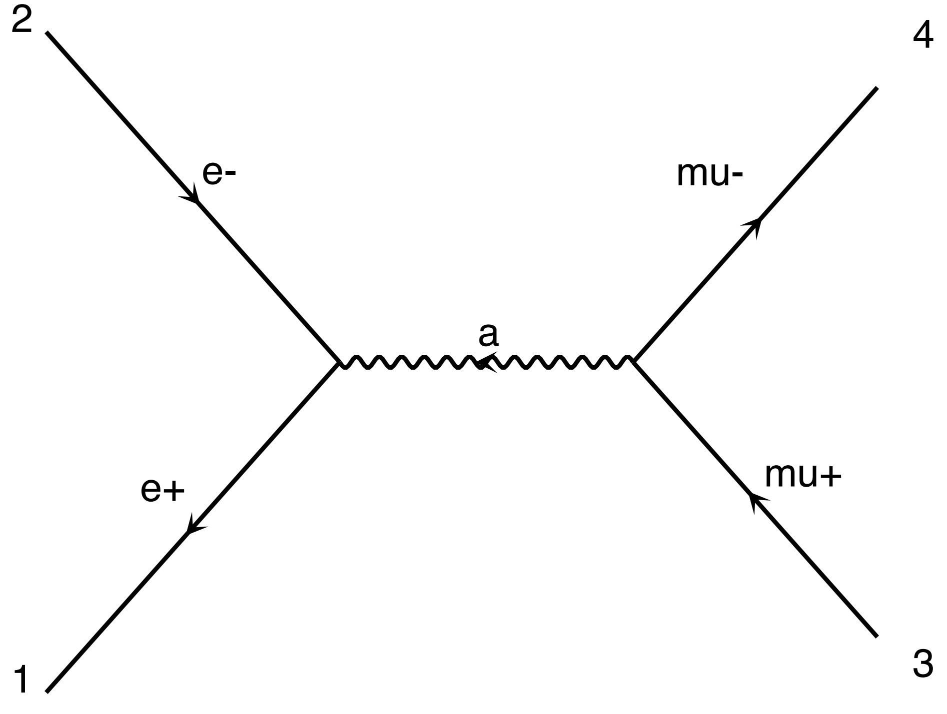
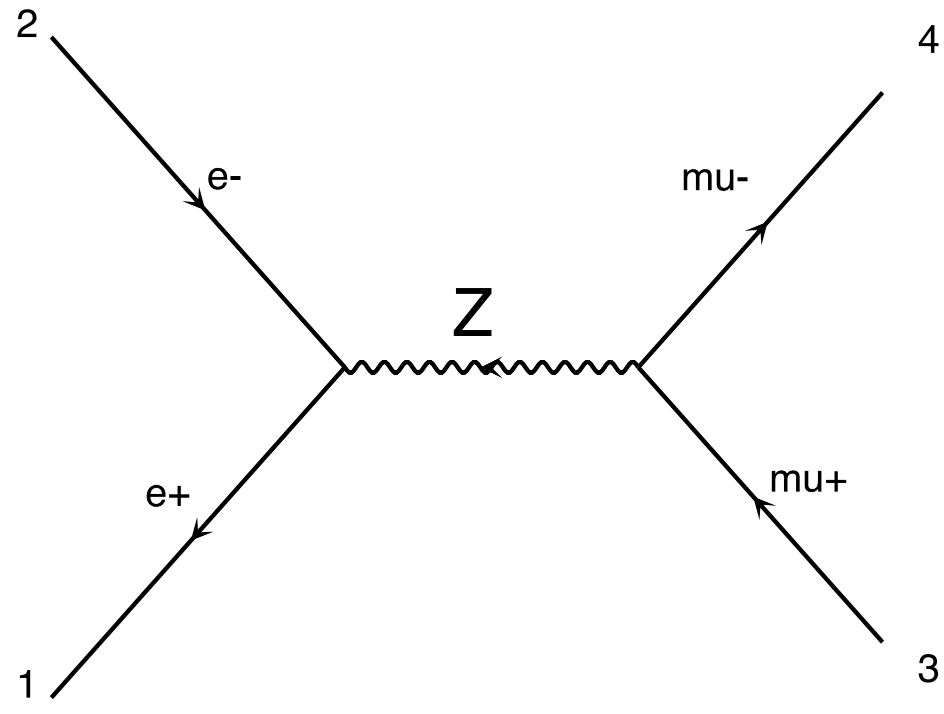
The number of diagram scales factorially with the number of particle





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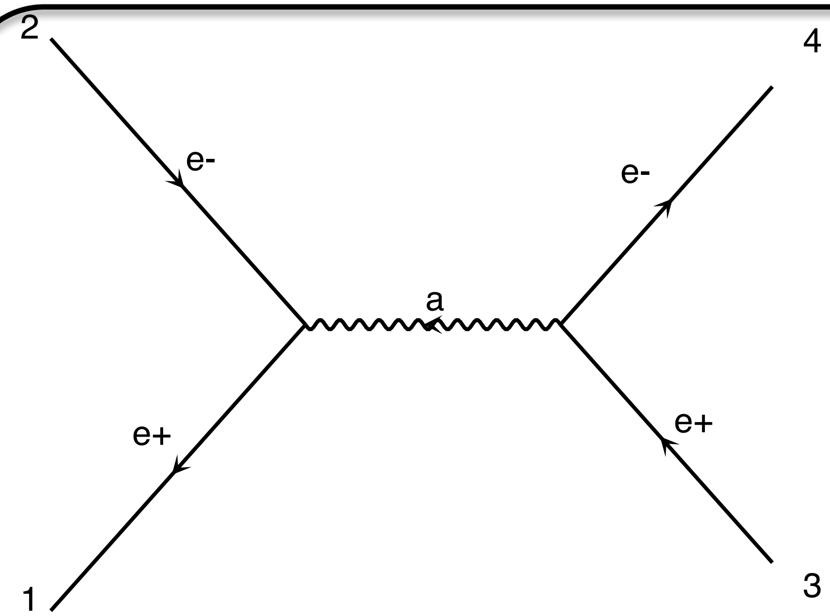
In practise possible up to 2>4

Helicity Amplitude

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



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

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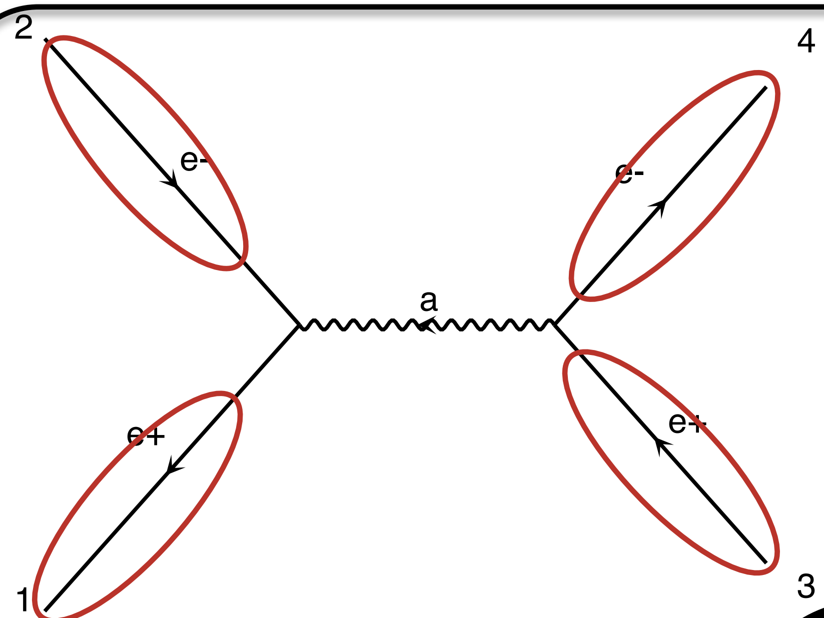

$$\mathcal{M} = ((\bar{u} e \gamma^\mu v)\frac{g_{\mu\nu}}{q^2})(\bar{v} e \gamma^\nu u))$$

Numbers for given helicity and momenta

Lines present in the code.

$$\begin{cases} \bar{v}_1 = fct(\vec{p}_1, m_1) \\ u_2 = fct(\vec{p}_2, m_2) \\ v_3 = fct(\vec{p}_3, m_3) \\ \bar{u}_4 = fct(\vec{p}_4, m_4) \end{cases}$$

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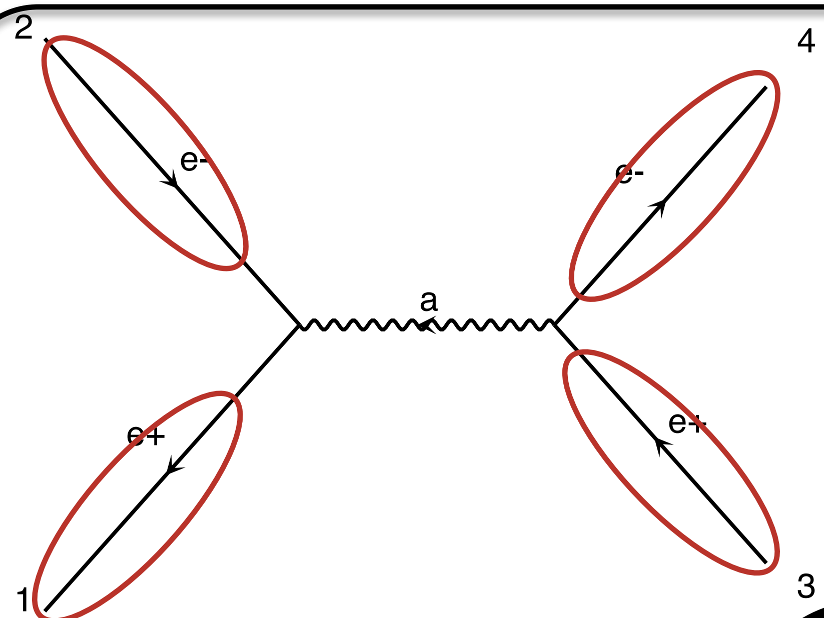

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$$u(p) = \begin{pmatrix} \omega_{-\lambda}(p)\chi_\lambda(\vec{p}) \\ \omega_\lambda(p)\chi_\lambda(\vec{p}) \end{pmatrix}$$

$$\omega_\pm(p) \equiv \sqrt{E \pm |\vec{p}|}.$$

$$\chi_+(\vec{p}) = \frac{1}{\sqrt{2|\vec{p}|(|\vec{p}|+p_z)}} \begin{pmatrix} |\vec{p}|+p_z \\ p_x + ip_y \end{pmatrix},$$

$$\chi_-(\vec{p}) = \frac{1}{\sqrt{2|\vec{p}|(|\vec{p}|+p_z)}} \begin{pmatrix} -p_x + ip_y \\ |\vec{p}|+p_z \end{pmatrix}.$$

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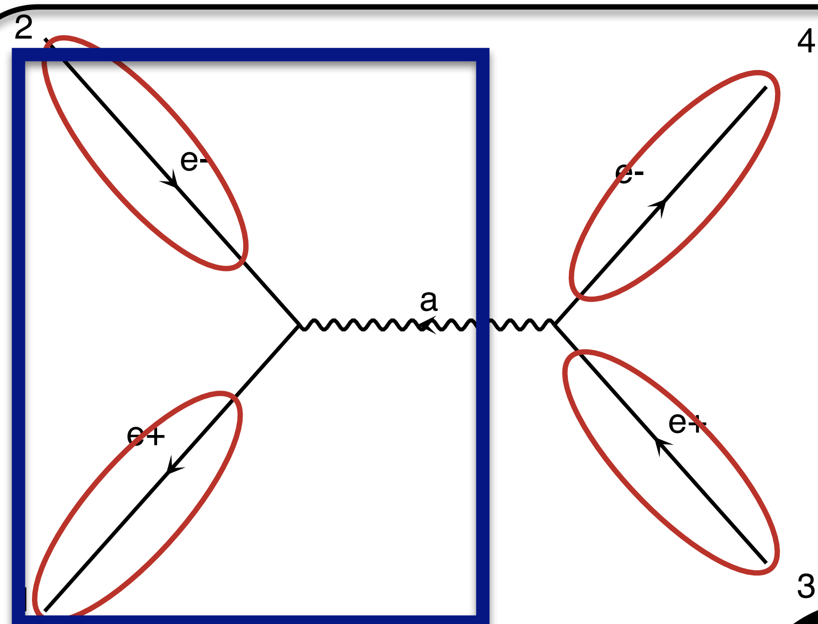

$$\mathcal{M} = ((\bar{u} e \gamma^{\mu} v)\frac{g_{\mu\nu}}{q^2})(\bar{v} e \gamma^{\nu} u))$$

Numbers for given helicity and momenta

Calculate propagator wavefunctions

Lines present in the code.

$$\begin{cases} \bar{v}_1 = fct(\vec{p}_1, m_1) \\ u_2 = fct(\vec{p}_2, m_2) \\ v_3 = fct(\vec{p}_3, m_3) \\ \bar{u}_4 = fct(\vec{p}_4, m_4) \\ W_a = fct(\bar{v}_1, u_2, e, m_a, \Gamma_a) = e\bar{v}_1\gamma^{\mu}u_2\frac{g_{\mu\nu}}{q^2 - m_a^2 + i m_a \Gamma_a} \end{cases}$$

Helicity Amplitude

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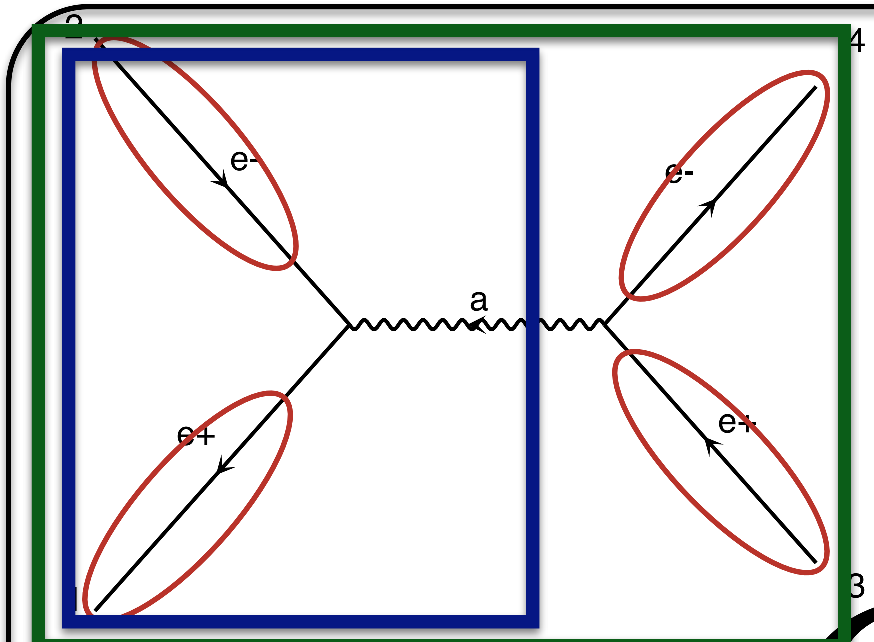

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Numbers for given helicity and momenta

Calculate propagator wavefunctions

Finally evaluate amplitude (c-number)

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$$W_a = fct(\bar{v}_1, u_2, e, m_a, \Gamma_a) = e\bar{v}_1\gamma^{\mu}u_2\frac{g_{\mu\nu}}{q^2 - m_a^2 + im_a\Gamma_a}$$
$$\mathcal{M} = fct(\bar{v}_3, u_4, W_{\nu}^a, e) = e\bar{v}_3\gamma_{\nu}u_4W_{\nu}^a$$

Question time

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Code d'événement
MADGRAPH

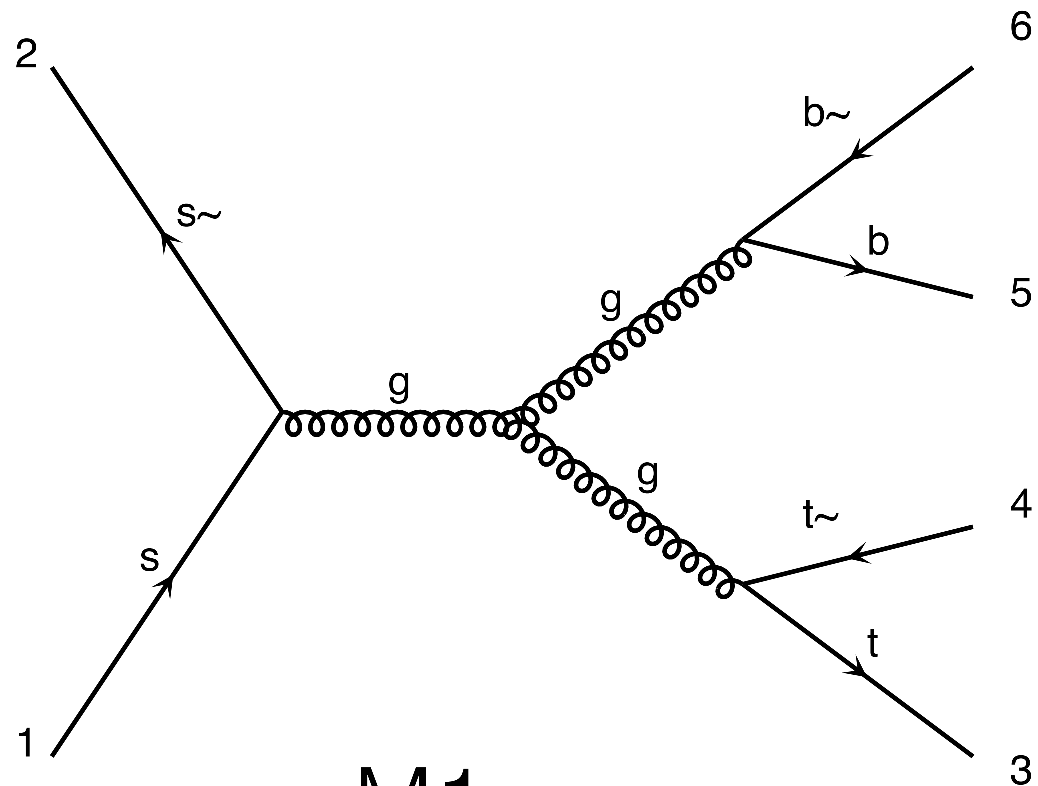
Activer les réponses par SMS

Comparison

	M diag	N particle
Analytical	M^2	$(N!)^2$
Helicity	M	$(N!)\,2^N$

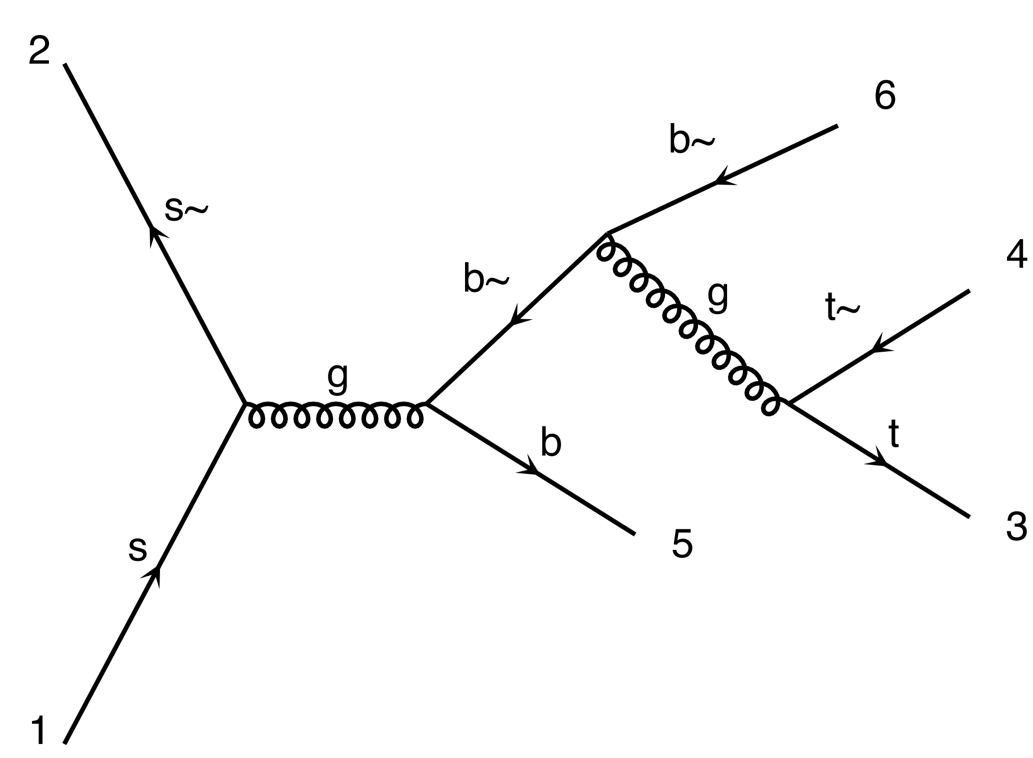
Real case

Known



M1

Number of routines: 0



M2

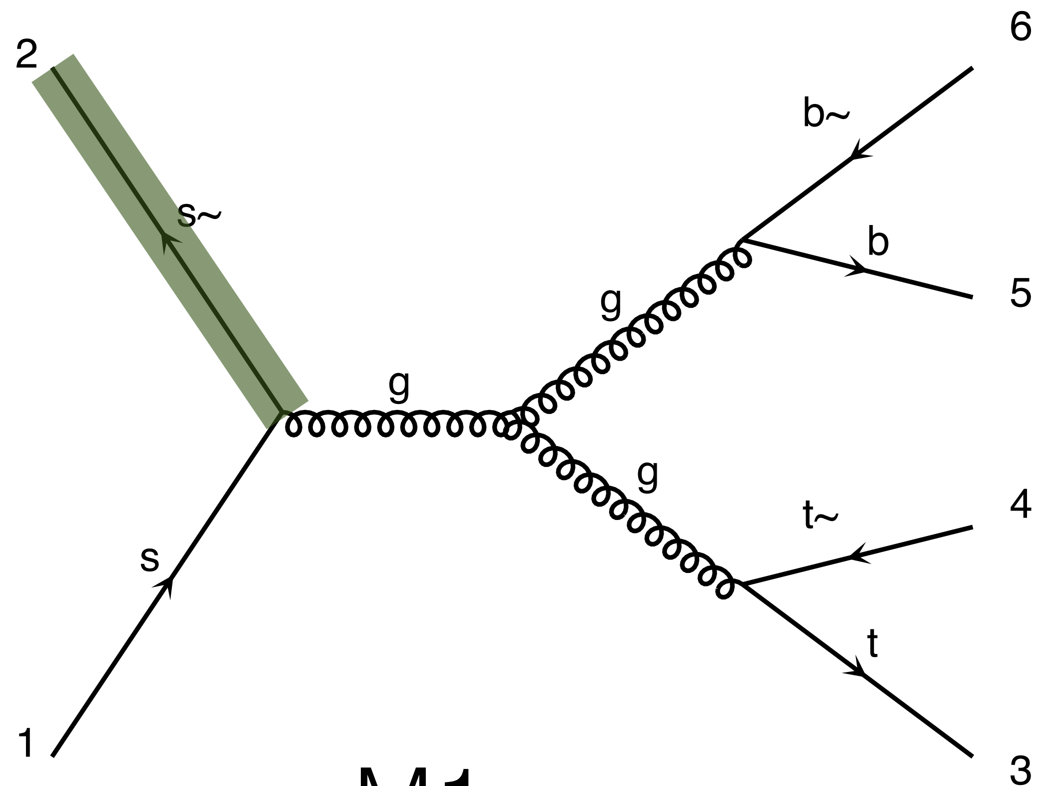
Number of routines: 0

Number of routines for both:0

$$|M|^2 = |M_1 + M_2|^2$$

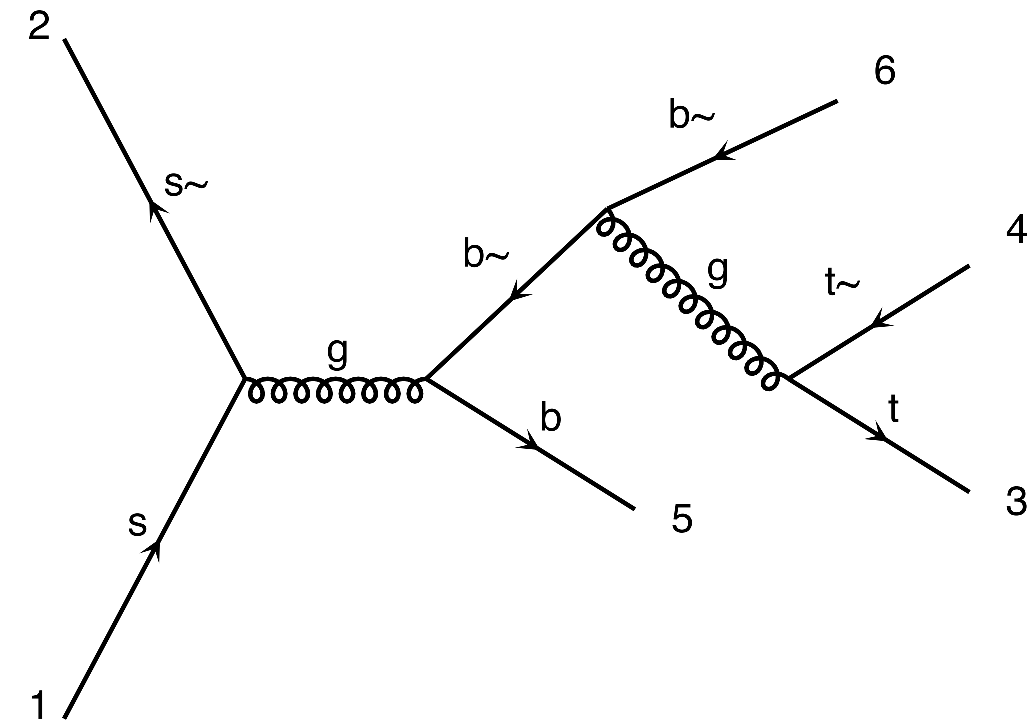
Real case

Known



M1

Number of routines: 1



M2

Number of routines: 0

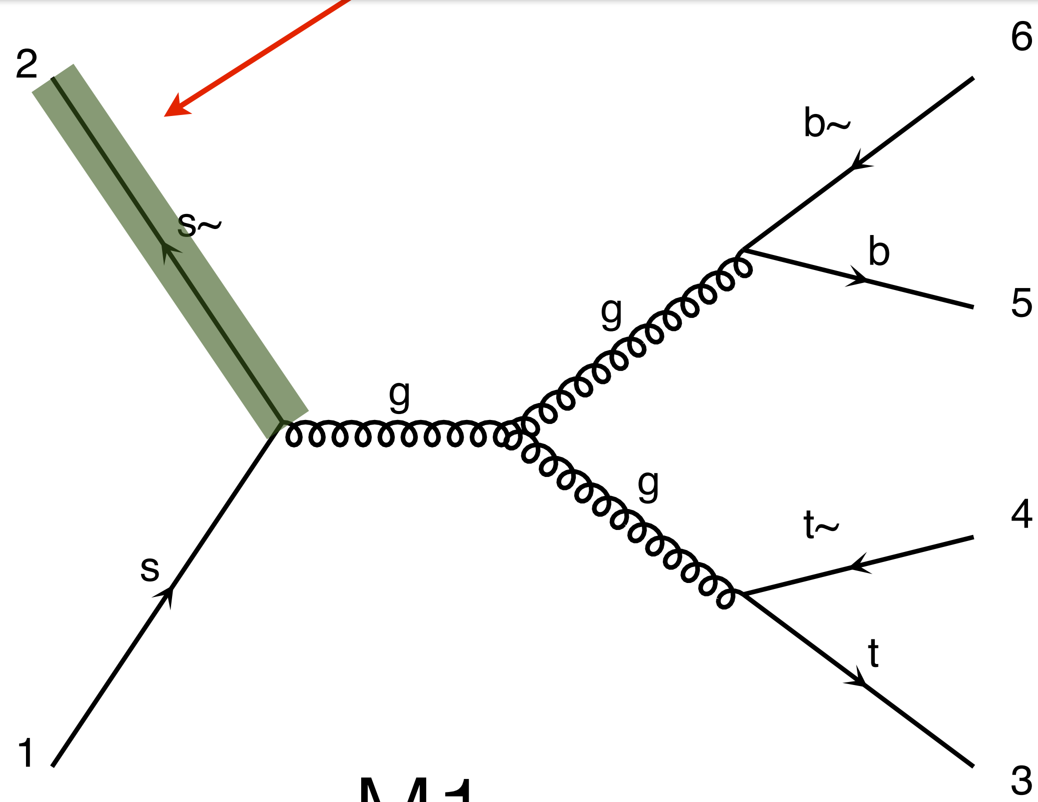
Number of routines for both: 1

$$|M|^2 = |M_1 + M_2|^2$$

Real case

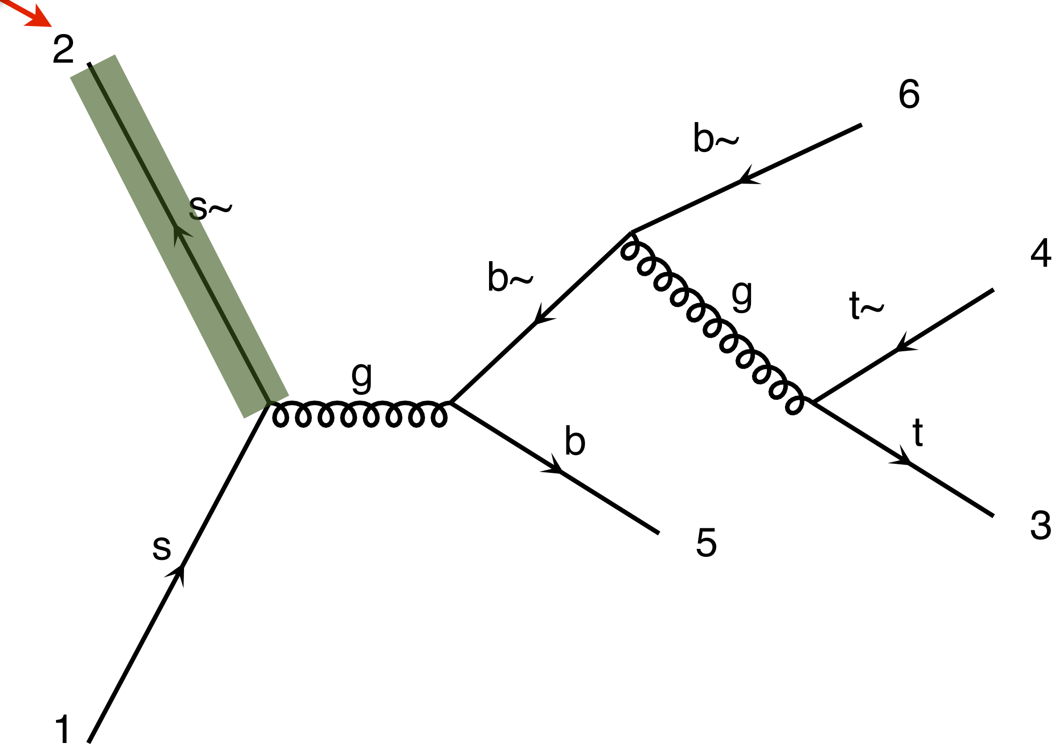
Identical

Known



M1

Number of routines: 1



M2

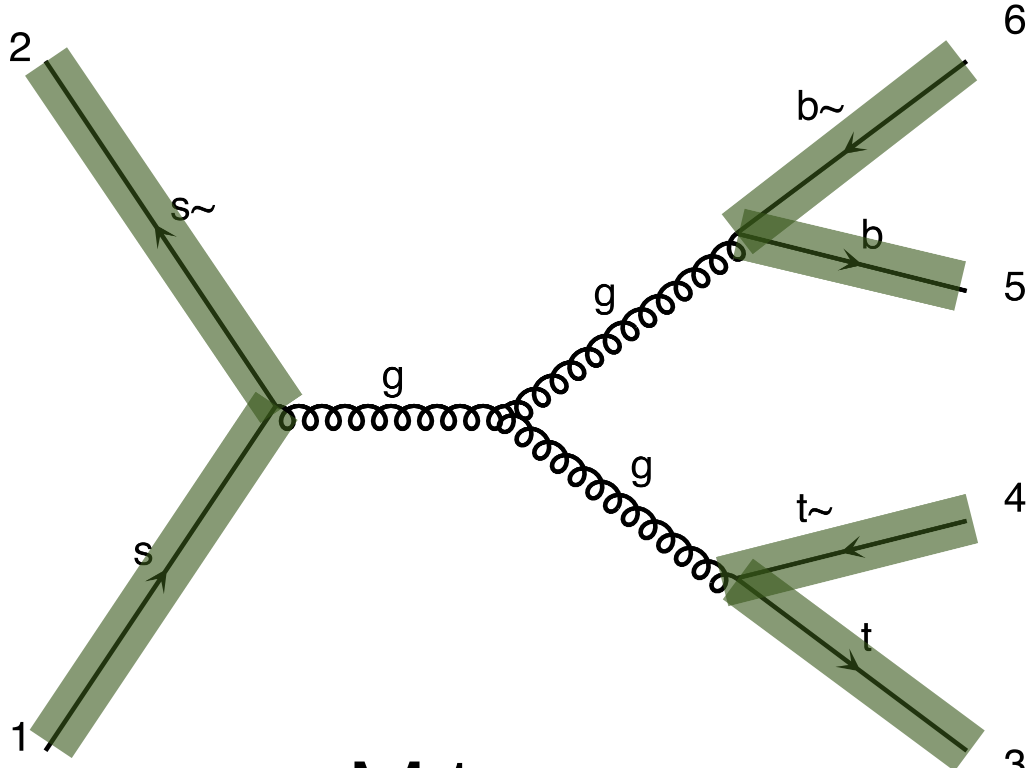
Number of routines: 1

Number of routines for both: 1

$$|M|^2 = |M_1 + M_2|^2$$

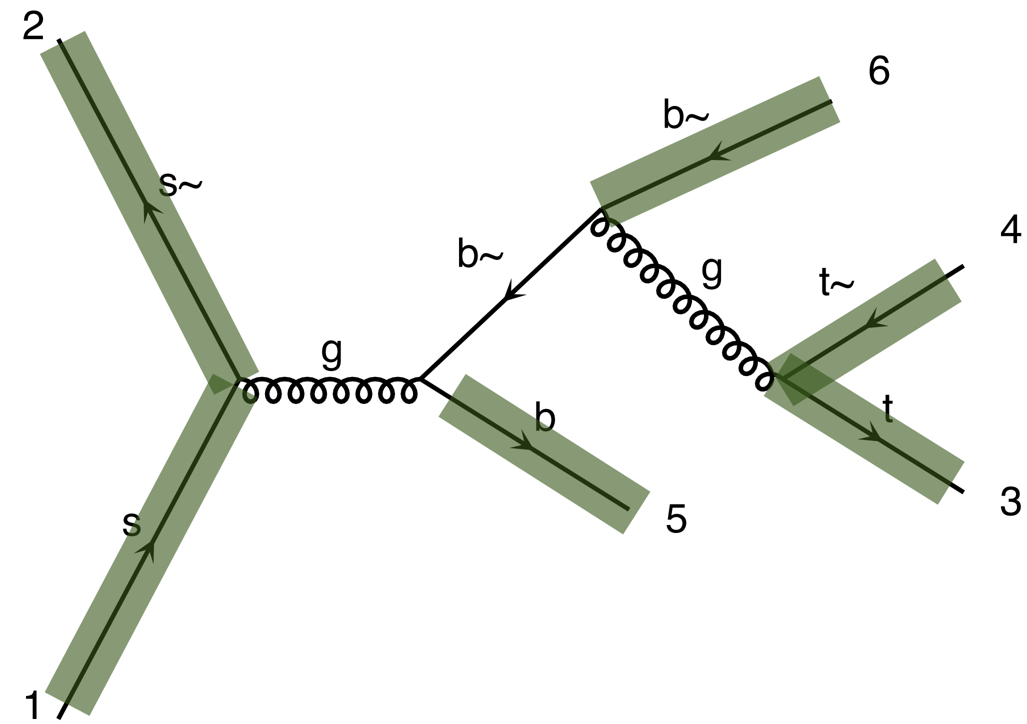
Real case

Known



M1

Number of routines: 6



M2

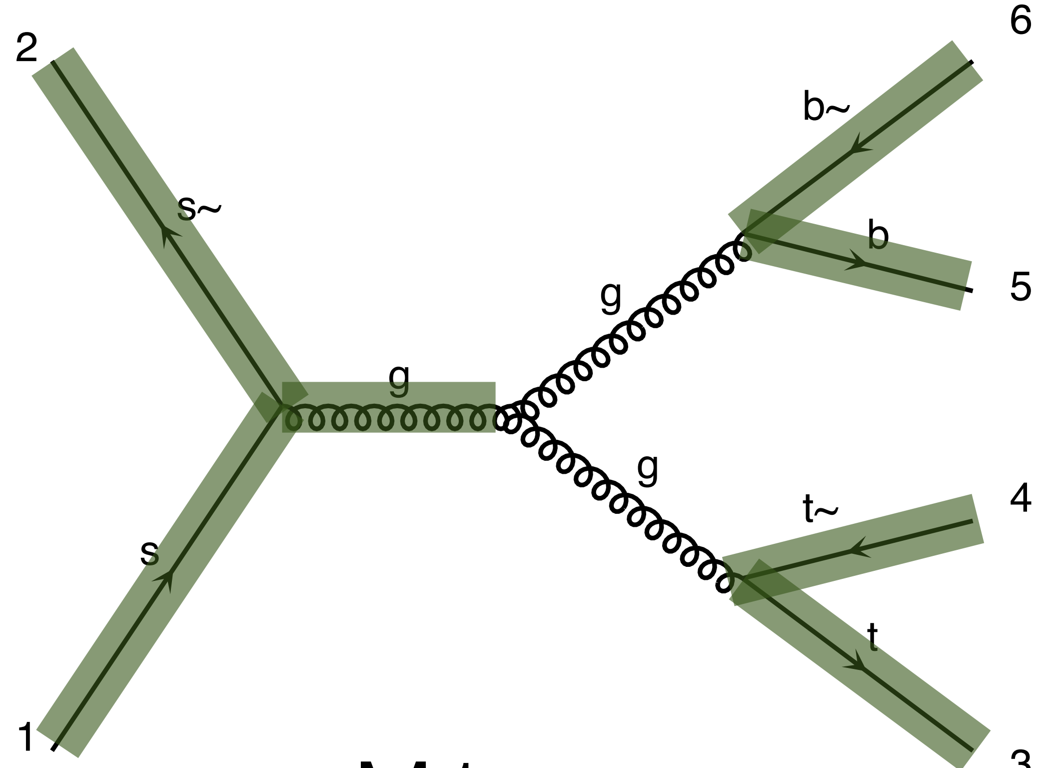
Number of routines: 6

Number of routines for both: 6

$$|M|^2 = |M_1 + M_2|^2$$

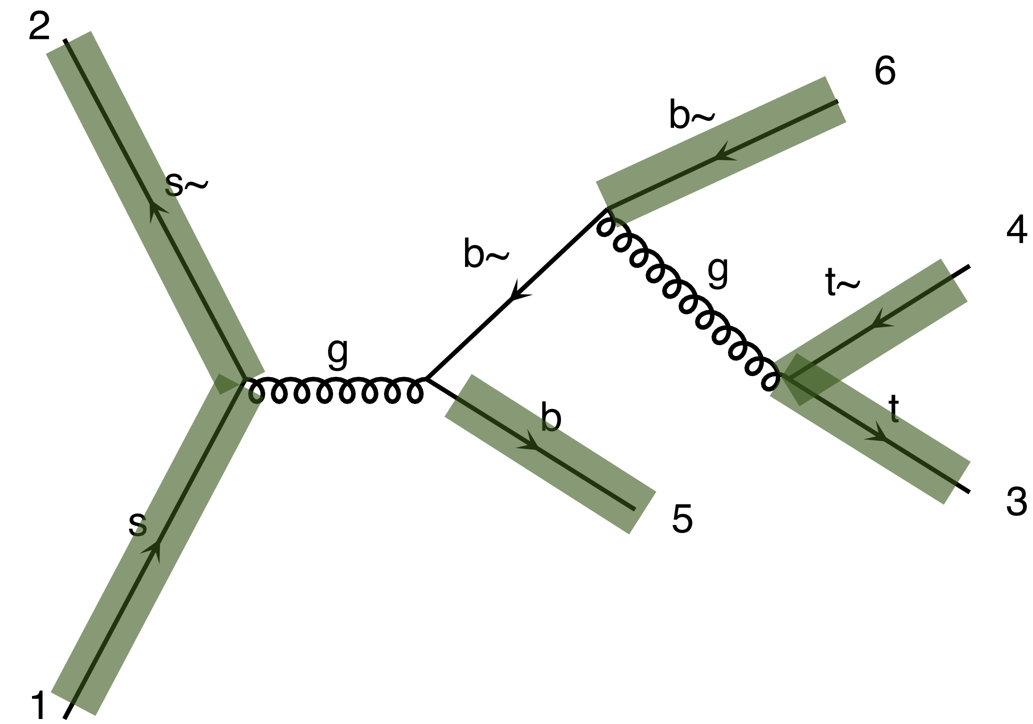
Real case

Known



M1

Number of routines: 7



M2

Number of routines: 6

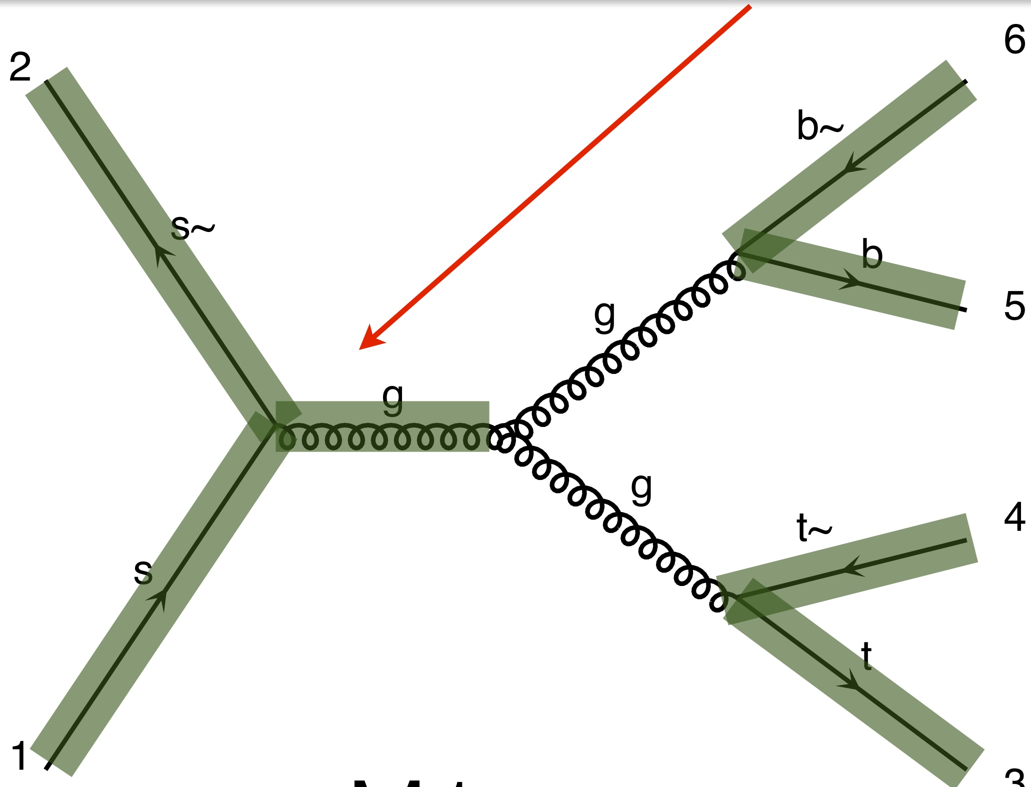
Number of routines for both:7

$$|M|^2 = |M_1 + M_2|^2$$

Real case

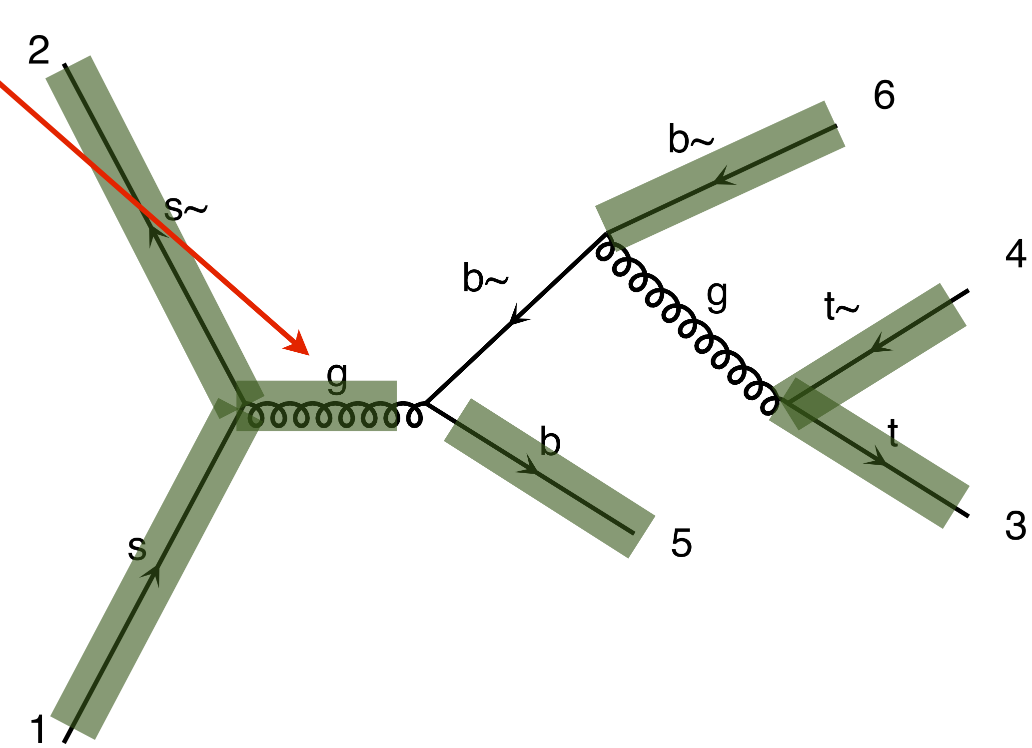
Known

Identical



M1

Number of routines: 7



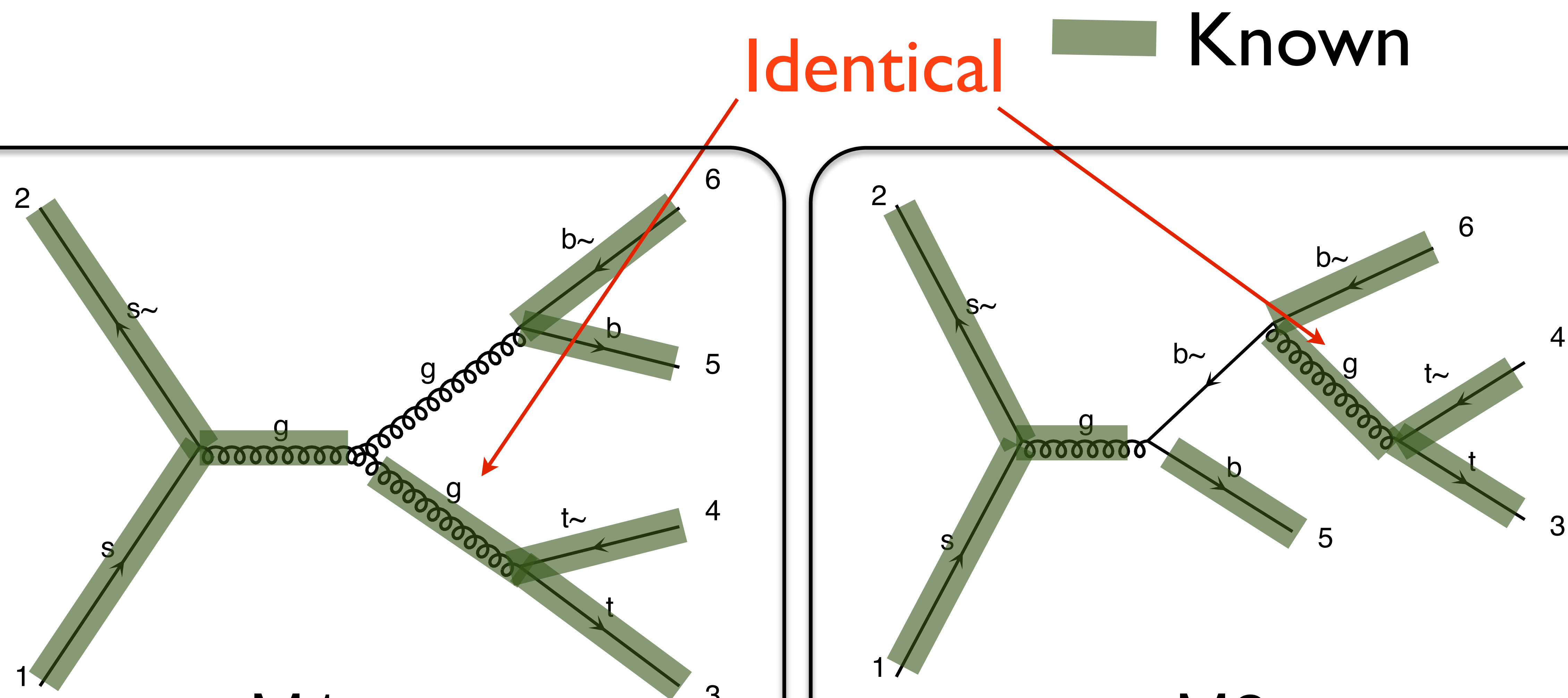
M2

Number of routines: 7

Number of routines for both: 7

$$|M|^2 = |M_1 + M_2|^2$$

Real case



M1

Number of routines: 8

M2

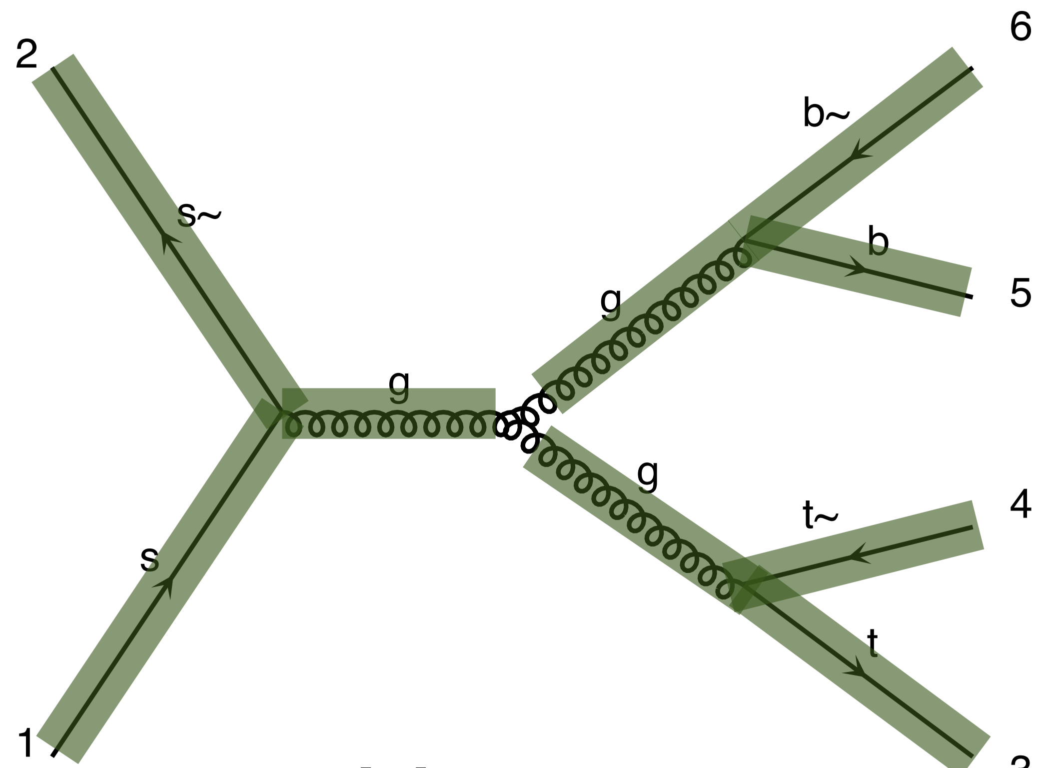
Number of routines: 8

Number of routines for both: 8

$$|M|^2 = |M_1 + M_2|^2$$

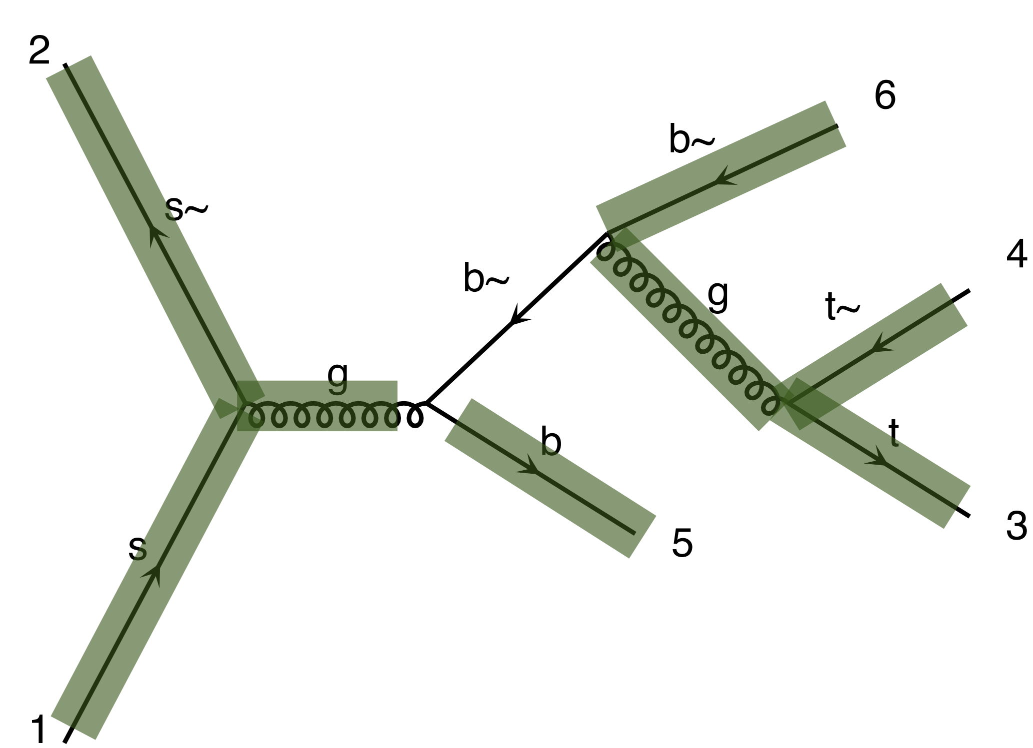
Real case

Known



M1

Number of routines: 9



M2

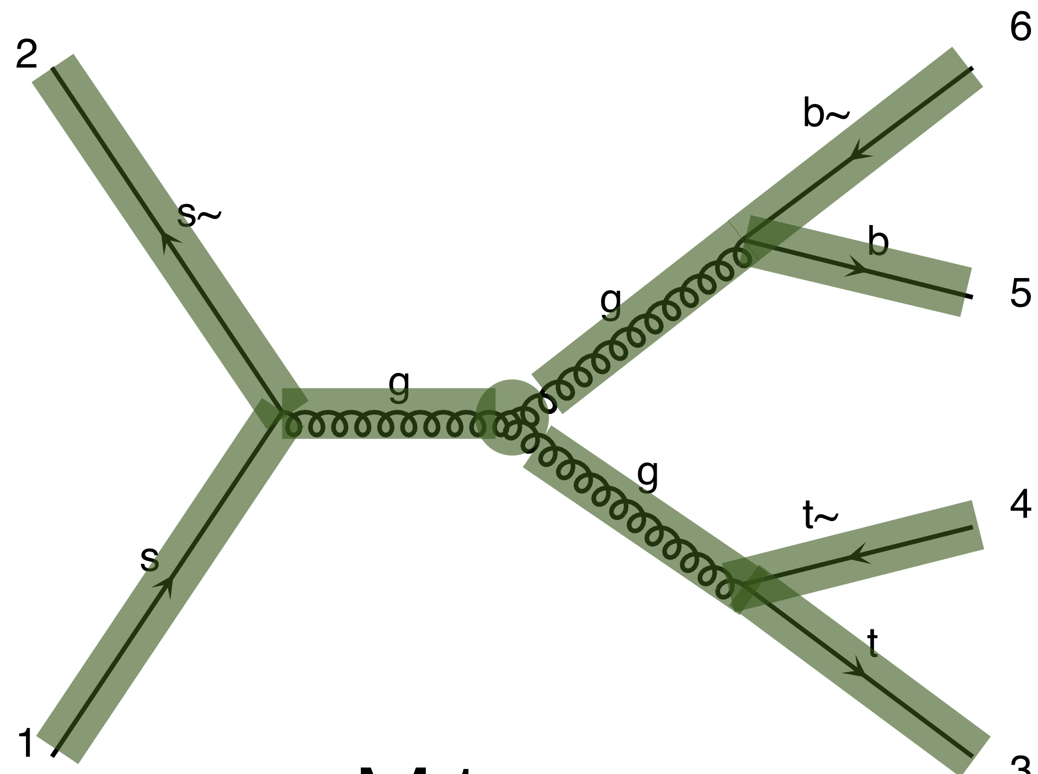
Number of routines: 8

Number of routines for both: 9

$$|M|^2 = |M_1 + M_2|^2$$

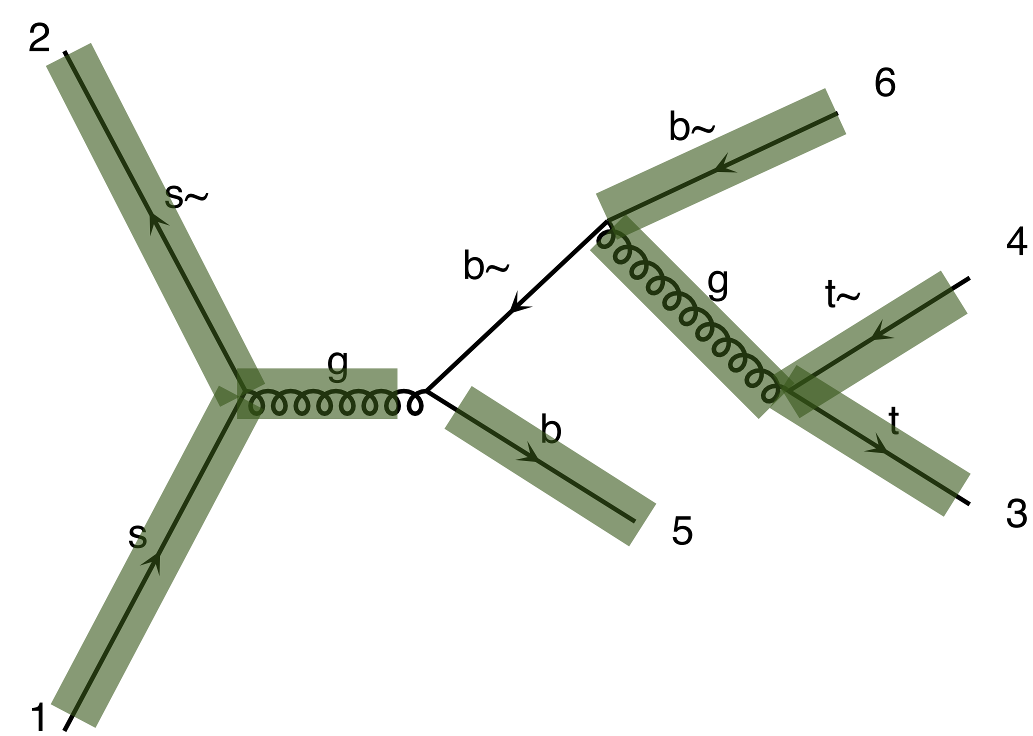
Real case

Known



M1

Number of routines: 10



M2

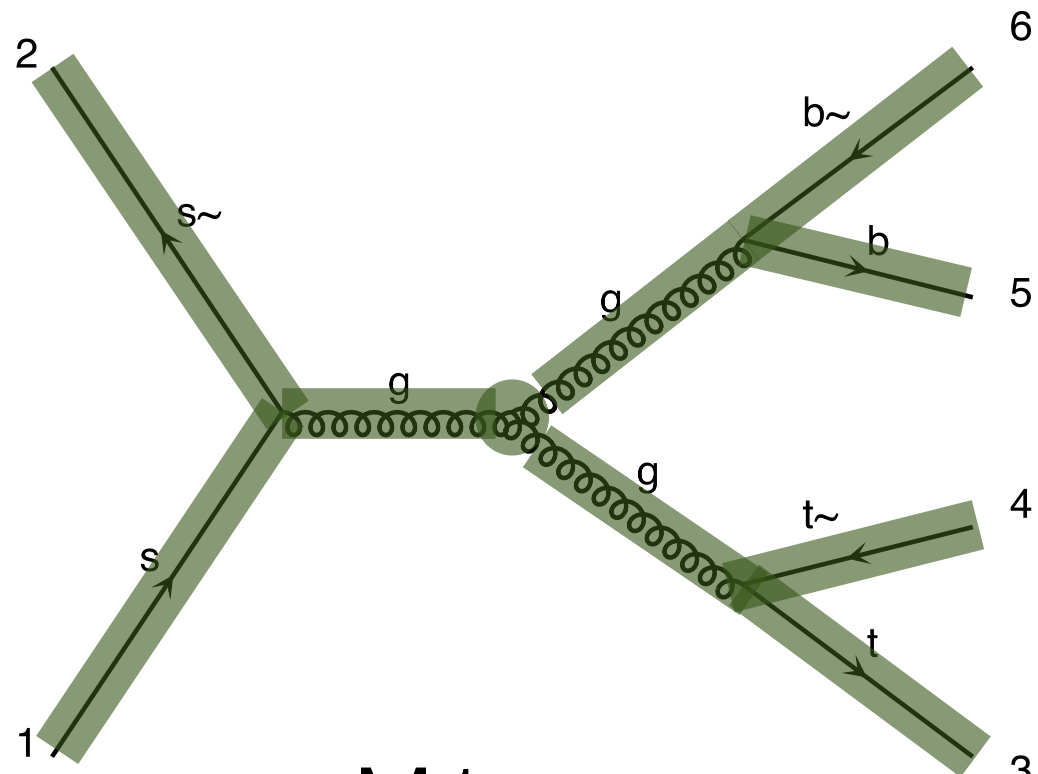
Number of routines: 8

Number of routines for both: 10

$$|M|^2 = |M_1 + M_2|^2$$

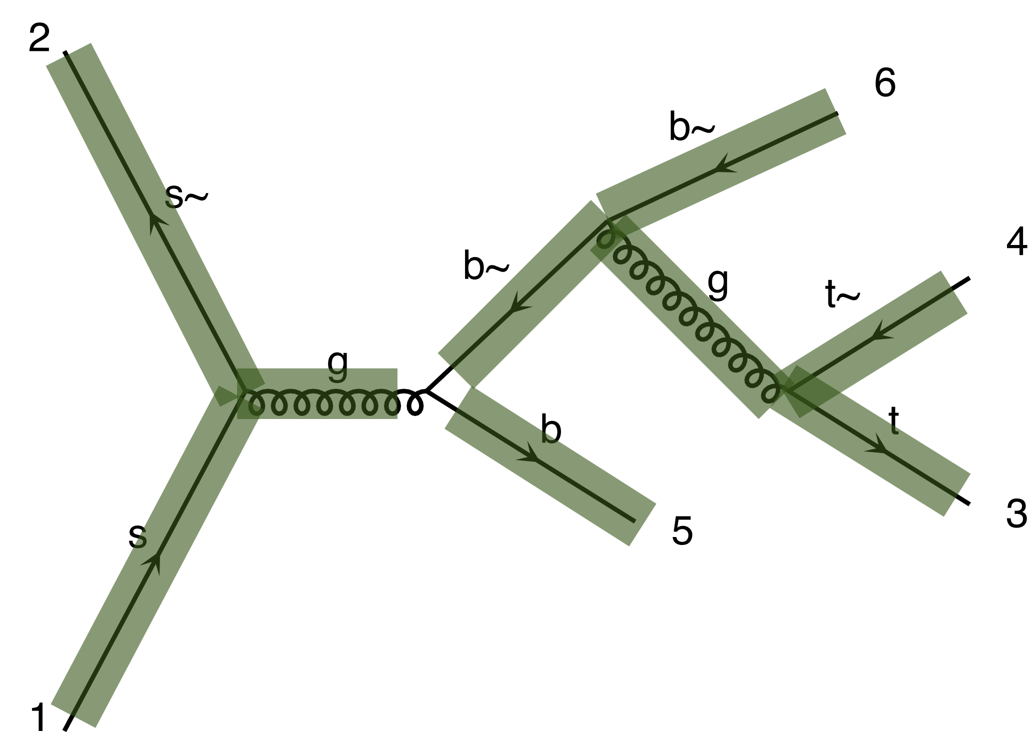
Real case

Known



M1

Number of routines: 10



M2

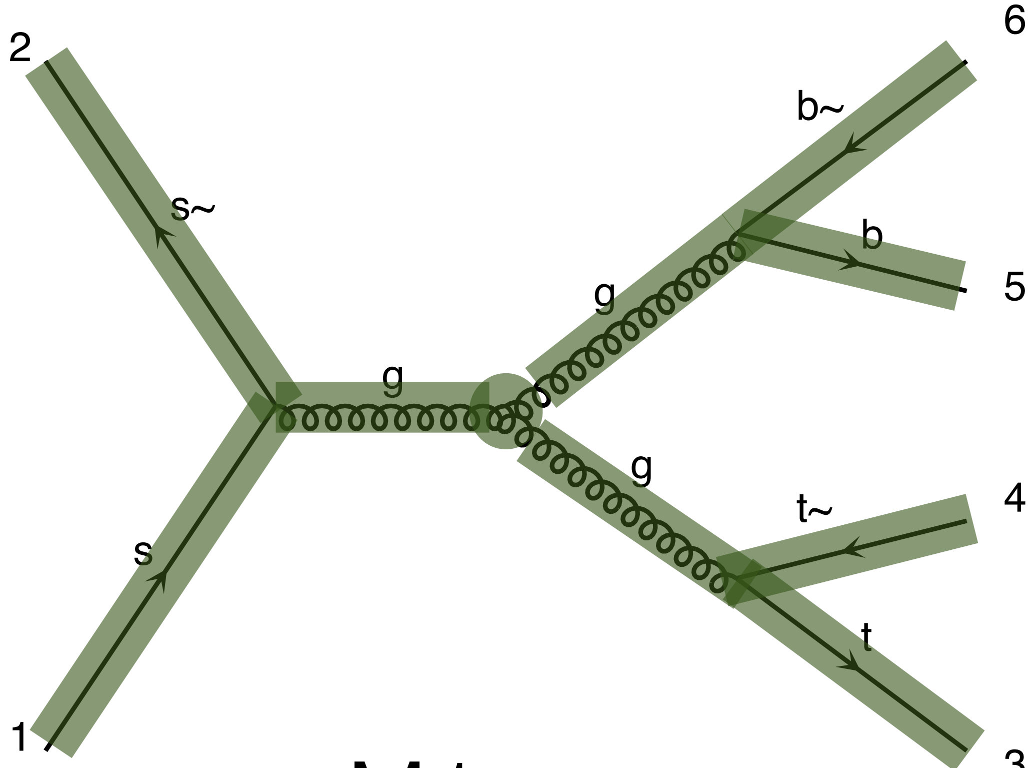
Number of routines: 9

Number of routines for both: 11

$$|M|^2 = |M_1 + M_2|^2$$

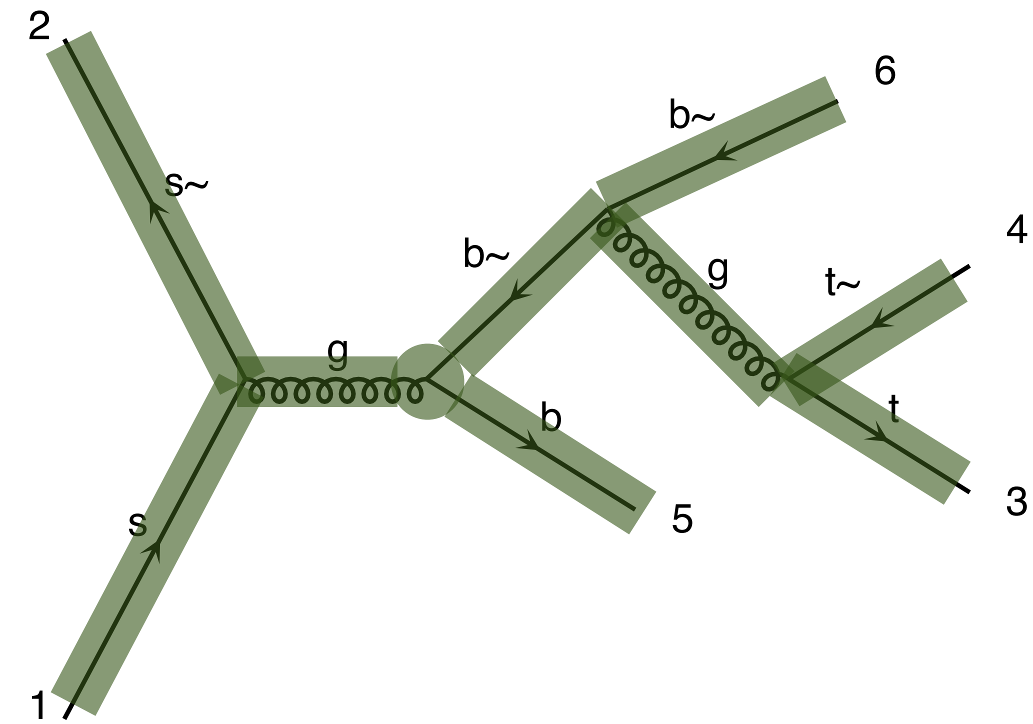
Real case

Known



M1

Number of routines: 10



M2

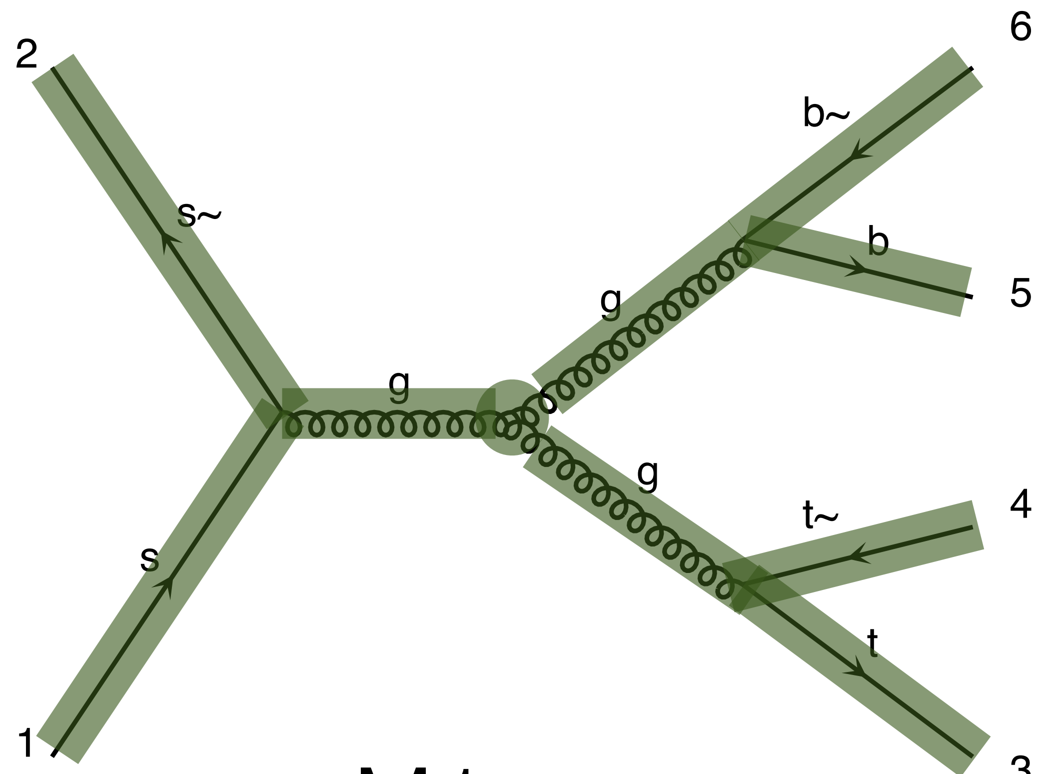
Number of routines: 10

Number of routines for both: 12

$$|M|^2 = |M_1 + M_2|^2$$

Real case

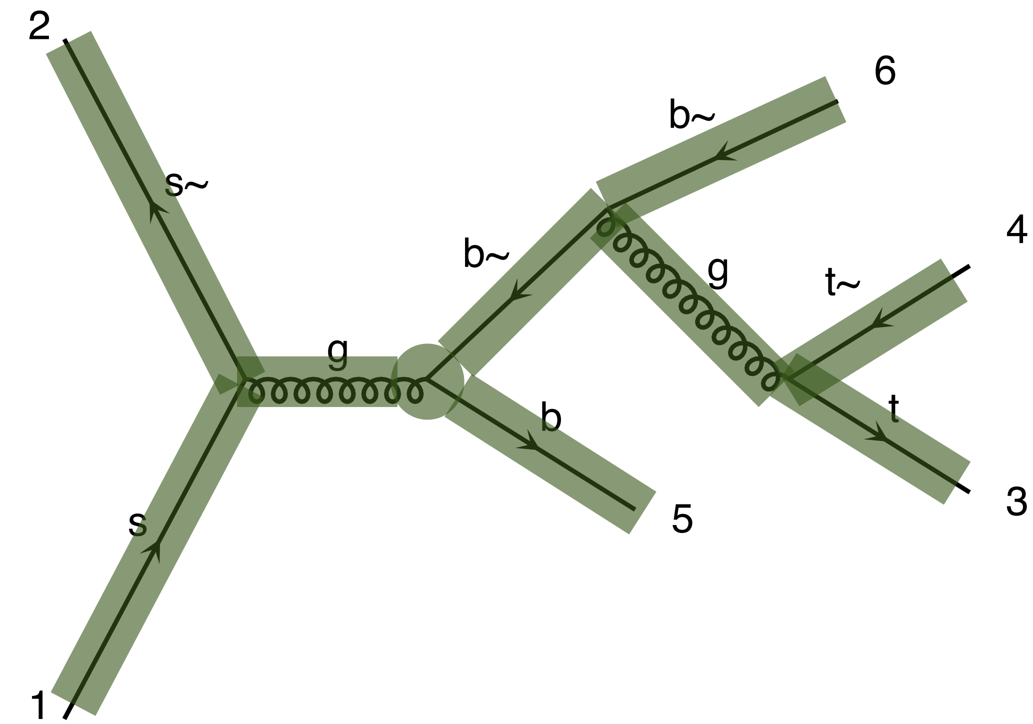
Known



M1

Number of routines: 10

2(N+1)



M2

Number of routines: 10

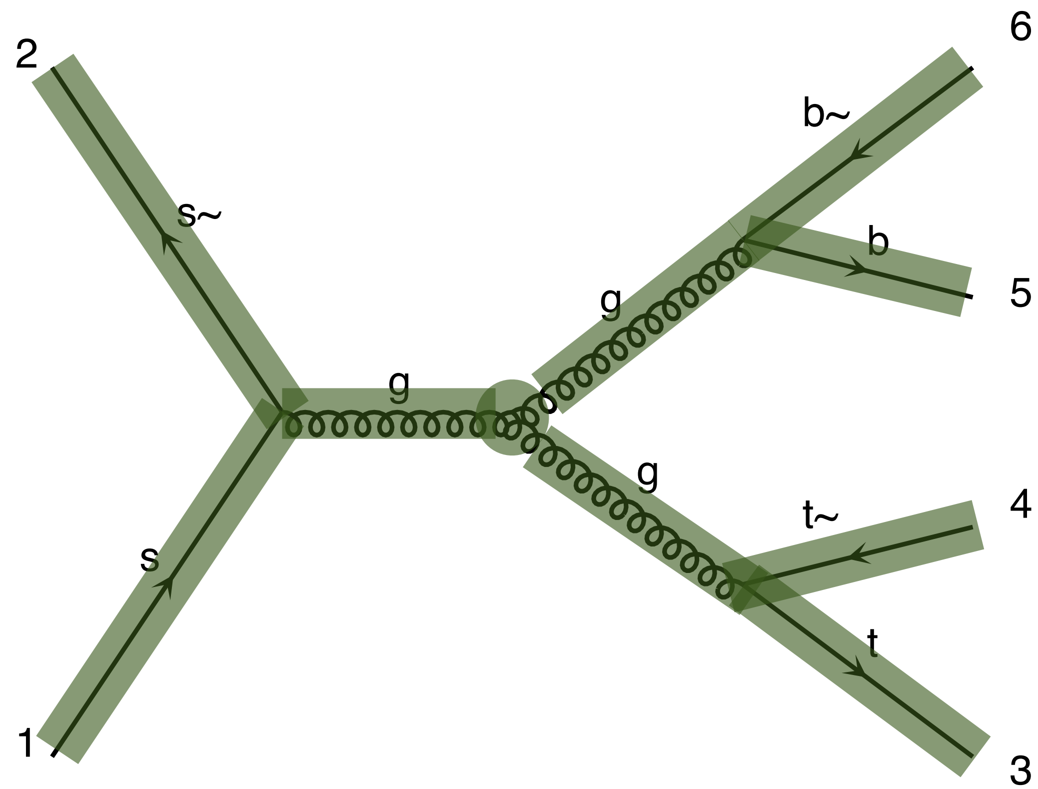
2(N+1)

Number of routines for both: 12

$$|M|^2 = |M_1 + M_2|^2$$

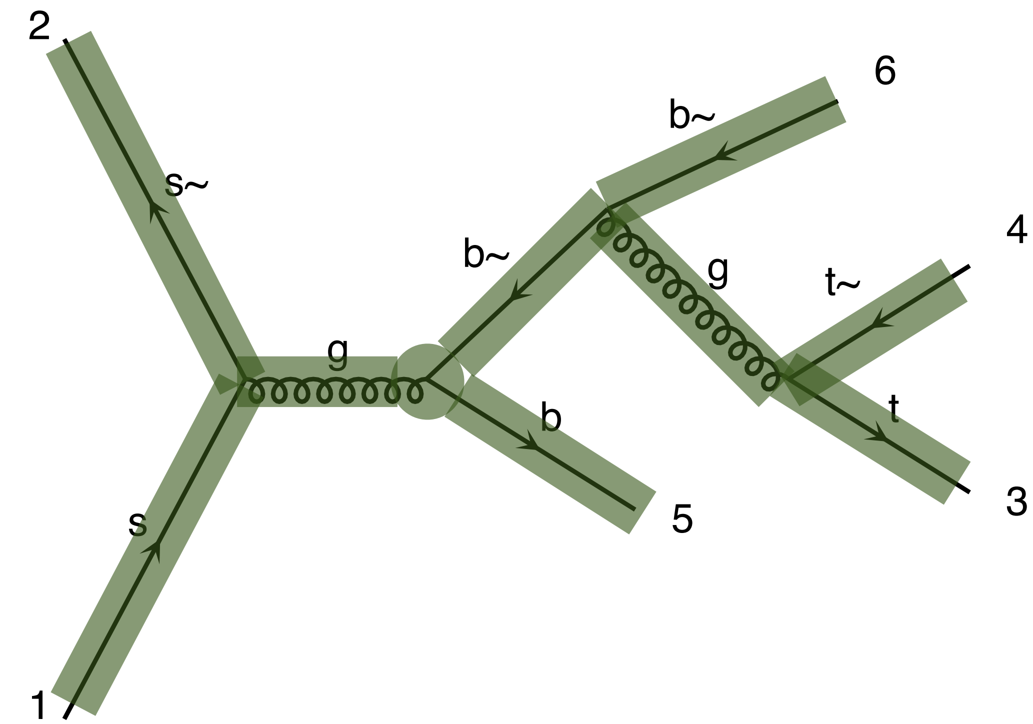
Real case

Known



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!

Comparison

	M diag	N particle
Analytical	M^2	$(N!)^2$
Helicity	M	$(N!)\,2^N$
Recycling	M	$(N-1)!\,2^{(N-1)}$

Color handling

- Can we de the same for colour
  - ➡ Fixed color for final state
  - ➡ Loop over them
- No coherent sum for colour
  - ➡ $gg \to (n-2)g$ scales like 8^{2n}

N	Fixed colour	$((n-1)!)^2$
4	16777216	36
5	1073741824	576
6	68719476736	14400
7	4398046511104	518400
8	281474976710656	25401600

All gluon solution

- Decompose the QCD amplitude on an basis

$$\mathcal{M}(ng) = \sum_{P(2,\ldots,n)} \mathrm{Tr}(t^1 \ldots t^n)\, M(1,\ldots,n) \equiv \sum_{\sigma} F_\sigma M_\sigma$$

➡ Where the sum is over the permutation of index with $(n-1)!$ term

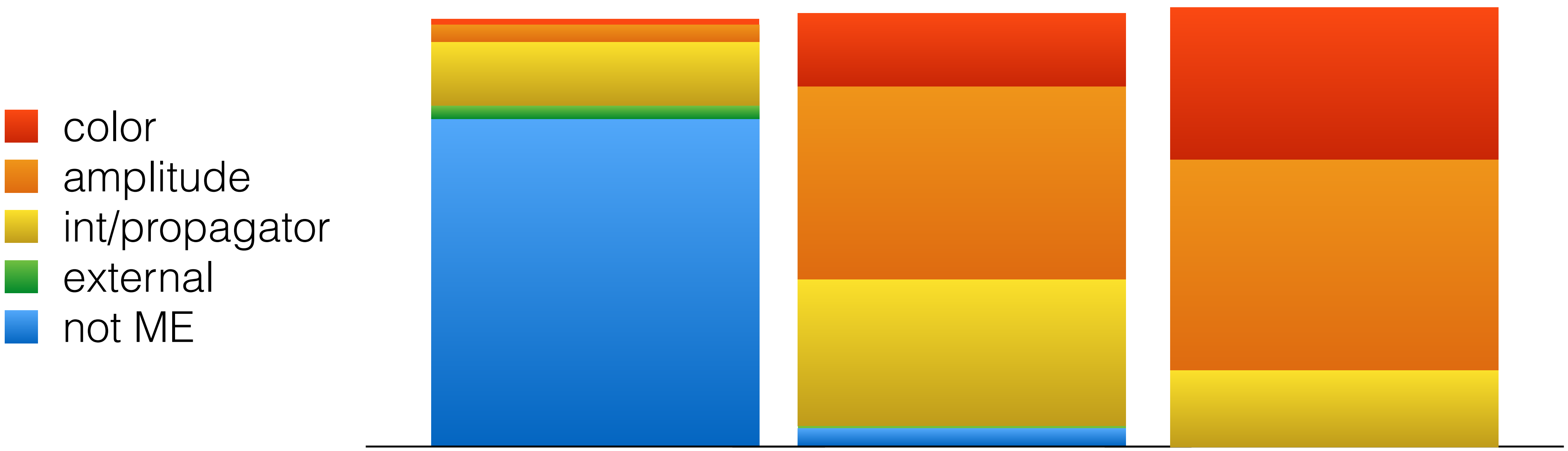
- Amplitude square is then

$$|\mathcal{M}(1,\ldots,n)|^2 = \sum_{\sigma,\sigma'} M_\sigma \underbrace{F_\sigma F^*_{\sigma'}}_{C_{\sigma\sigma'}} M^*_{\sigma'},$$

- $C_{\sigma\sigma'}$ is called the colour matrix

Speed status

	$gg \to t\bar{t}$	$gg \to t\bar{t}gg$	$gg \to t\bar{t}ggg$
madevent	13G	470G	11T
matrix1	3.1G (23%)	450G (96%)	11T (>99%)
↳ ext	450M (3.4%)	3.3G (<1%)	7.3G (<1%)
↳ int	1.9G (14%)	160G (35%)	2T (19%)
↳ amp	530M (4.0%)	210G (44%)	5.5T (51%)



Can we do better? YES

- Recursion relation (used in Sherpa) [WIP]
- New in MG5aMC: Helicity Recycling [2102.00773]
- Feynman Diagram Gauge [2203.10440] [WIP]
- Not full color computation [2210.07267] [WIP]

- 2102.00773 [hep-ph]

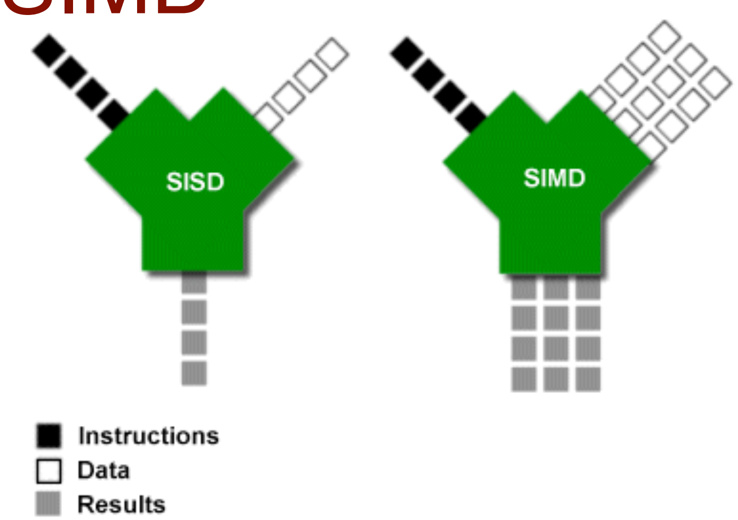
	M diag	N particle
Analytical	M^2	$(N!)^2$
Helicity	M	$(N!)\,2^N$
Recycling	M	$(N-1)!\,2^{(N-1)}$
Hel Recycling	M	$\approx (N-1)!2^{N/2}$

Can we go faster? YES

GPU

- ➡ Was first done a while ago (cuda)
  arXiv:0908.4403,arXiv:1305.0708v2
- ➡ New recent focus in this direction
  - ➡ Not only cuda:
  - ➡ Kokkos, syCL, tensorflow
- ➡ Good performance

SIMD



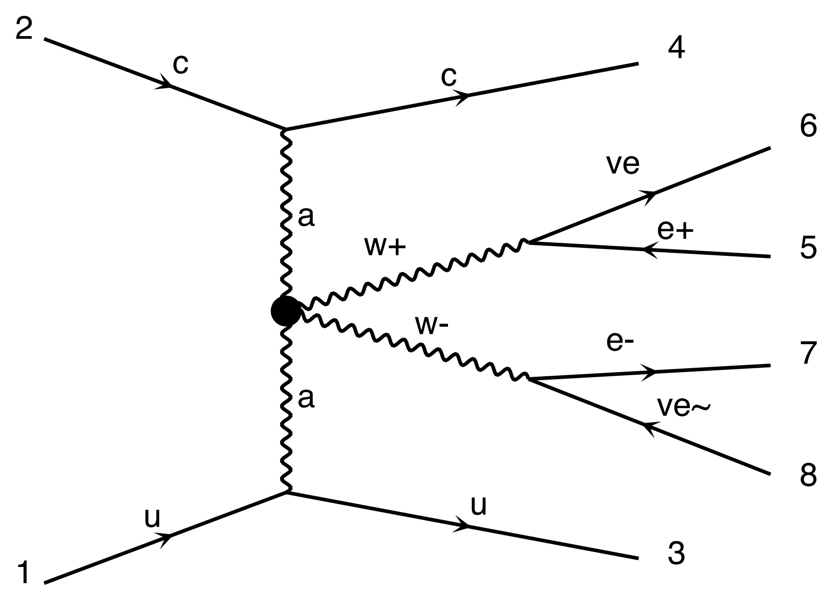
- ➡ Modern CPU can act as a baby GPU
- ➡ They can perform N identical operation as fast as one
- ➡ Close to be released

To Remember

- Numerical computation faster than analytical computation
- We are able to compute matrix-elment
  - ➡ for large number of final state
  - ➡ for any BSM theory
  - ➡ actually also for loop

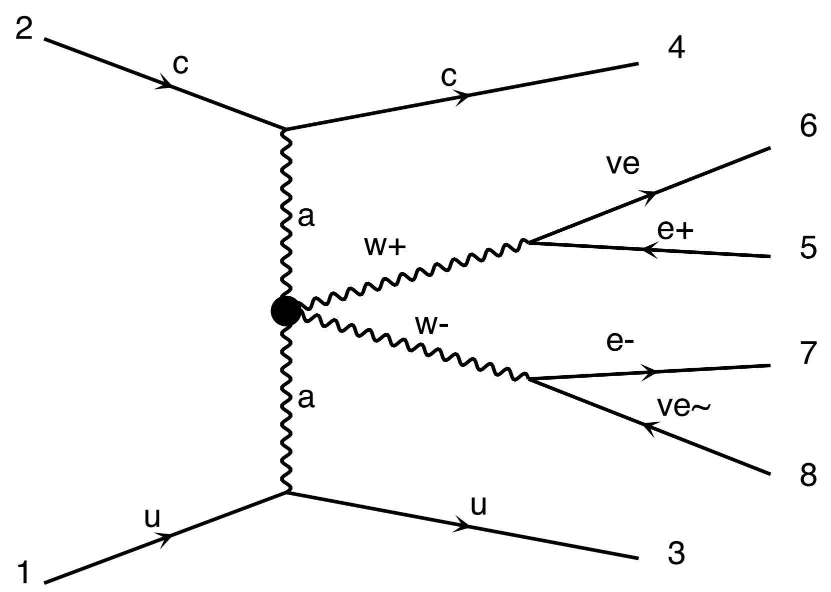
Decay

Resonant Diagram

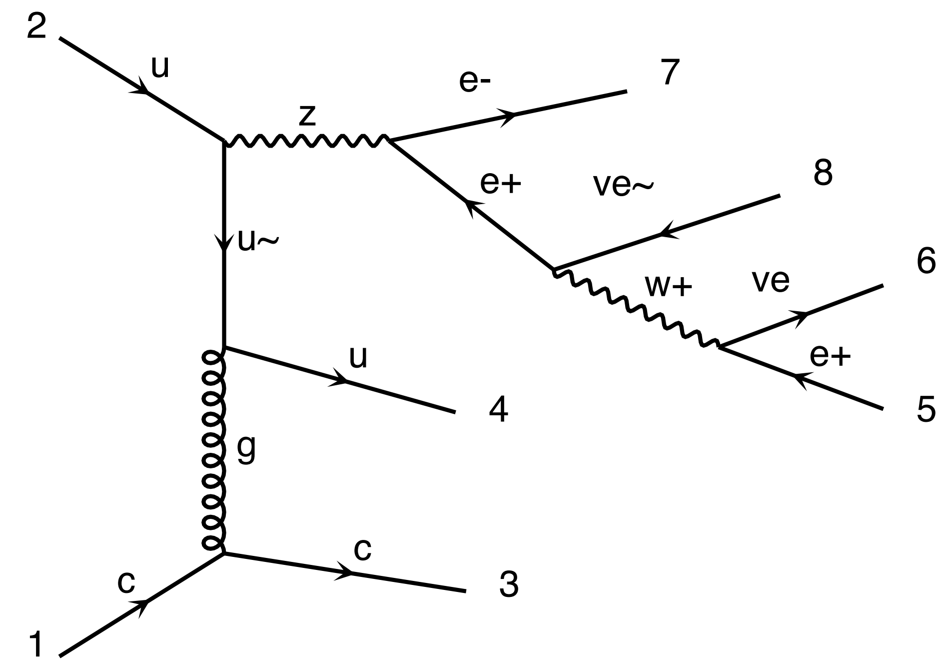


Decay

Resonant Diagram



Non Resonant Diagram



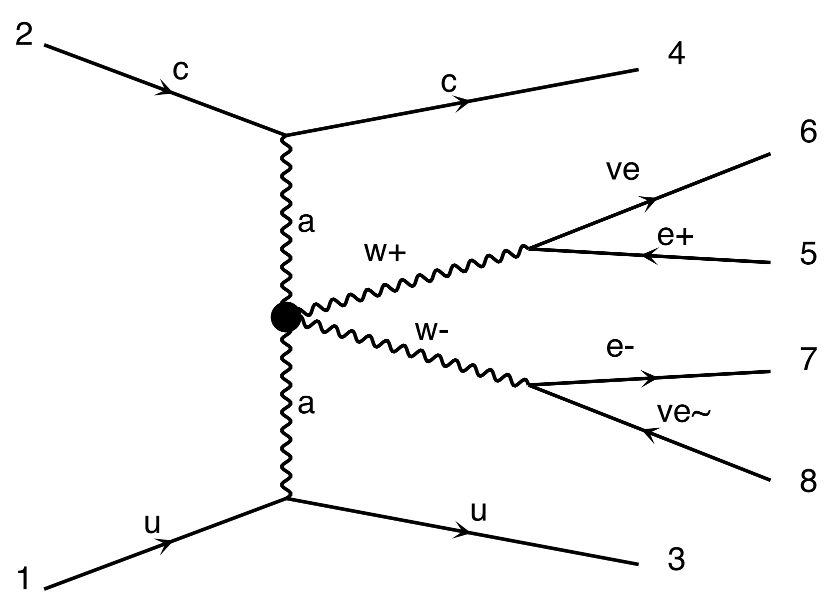
Problem

- Process complicated to have the full process

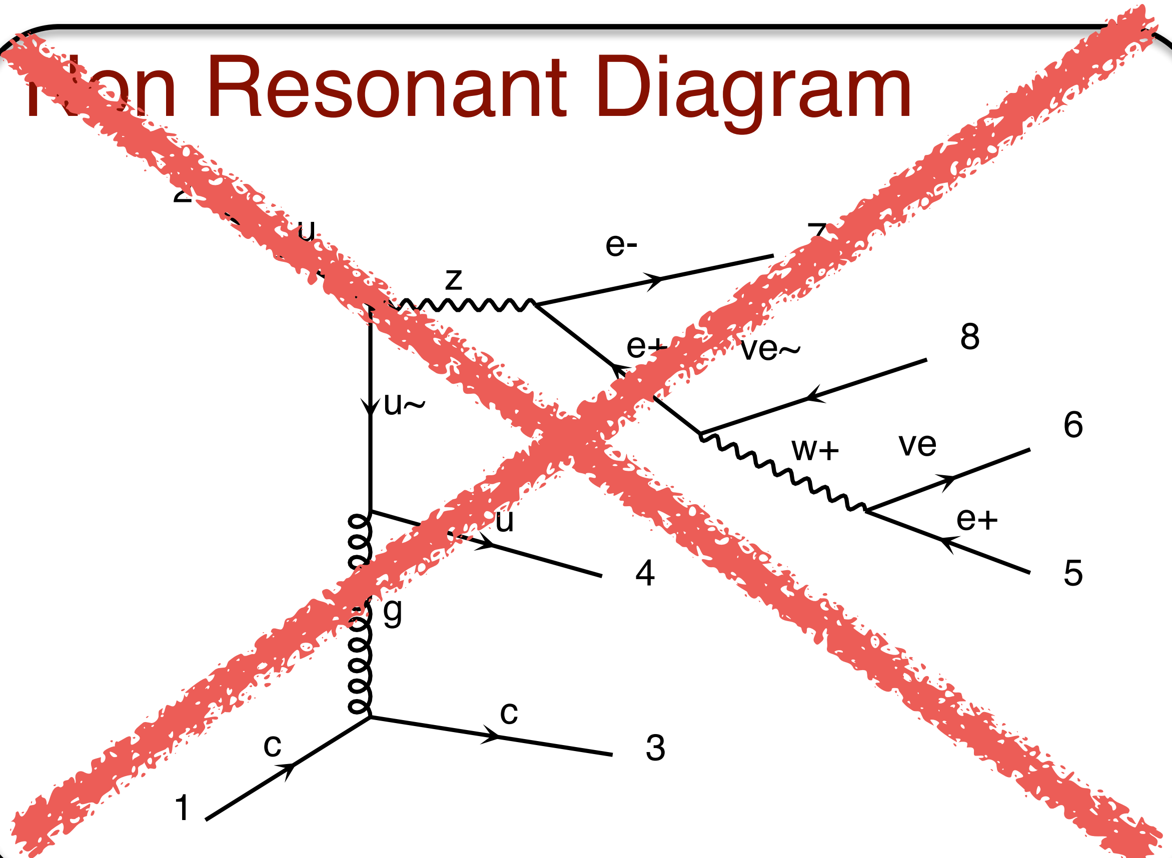
➡Including off-shell contribution

Decay

Resonant Diagram



Non Resonant Diagram



Problem

- Process complicated to have the full process

➡Including off-shell contribution

Solution

- Only keep on-shell contribution

Narrow-Width Approx.

Theory

$$\int dq^2 \left| \frac{1}{q^2 - M^2 + iM\Gamma} \right|^2 \approx \frac{\pi}{M\Gamma} \; \delta(q^2 - M^2)$$

$$\sigma_{full} = \sigma_{prod} * (BR + \mathcal{O}(\frac{\Gamma}{M}))$$

Comment

Narrow-Width Approx.

Theory

$$\int dq^2 \left| \frac{1}{q^2 - M^2 + iM\Gamma} \right|^2 \approx \frac{\pi}{M\Gamma}\ \delta(q^2 - M^2)$$

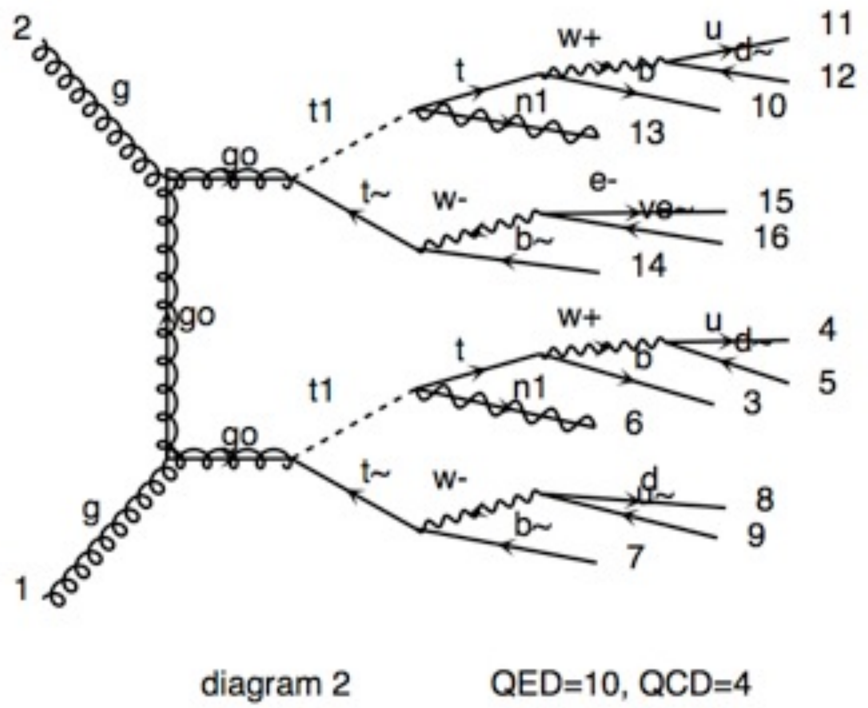
$$\sigma_{full} = \sigma_{prod} * (BR + \mathcal{O}(\frac{\Gamma}{M}))$$

Comment

- This is an Approximation!
- This force the particle to be on-shell!
  - Recover by re-introducing the Breit-wigner up-to a cut-off
- The loop is not a free parameter

Decay chain

- p p > t t~ w+, (t > w+ b, w+ > l+ vl), \
  (t~ > w- b~, w- > j j), \
  w+ > l+ vl



very long
decay chains possible to simulate
directly in MadGraph!

Decay chain

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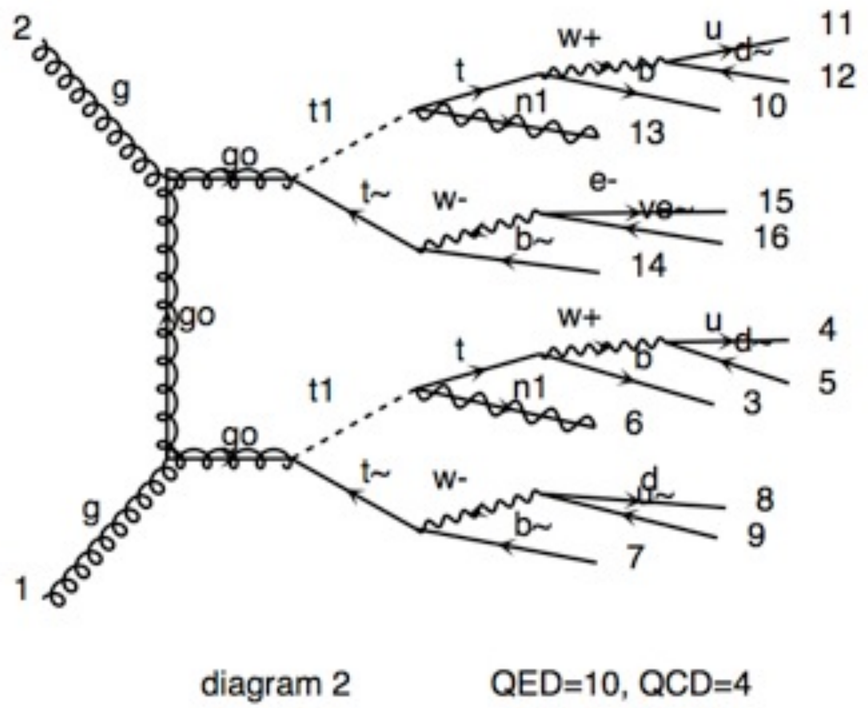


very long
decay chains possible to simulate
directly in MadGraph!

- This syntax has an invariant mass cut associated to t/t~/W
- Other syntax/tools exists for NWA (like MadSpin)

Question time

1 Allez sur wooclap.com

2 Entrez le code d'événement dans le bandeau supérieur

Code d'événement
MADGRAPH

Activer les réponses par SMS

Thin to keep in mind!

- Computation has to be perturbative.
- Do not assume that MG5aMC has good default for you. (We do try)
  - We do have cuts by default.
- We compute inclusive cross-section (production plus any number of jets.)
- Theoretical uncertainty are large.
- Always check that MG5 produces the diagrams you want.
- The width is not a free parameter.
  - Critical in narrow-width approximation

To Remember

- We do assume factorisation into different scale
- Perturbative theory
  - ➡ LO good for shape
  - ➡ Higher order good for cross-section
- We are able to compute matrix-element
  - ➡ for any BSM theory
  - ➡ Also for loop
  - ➡ Not fast enough (we need your help)
- Loop computation need dedicated model

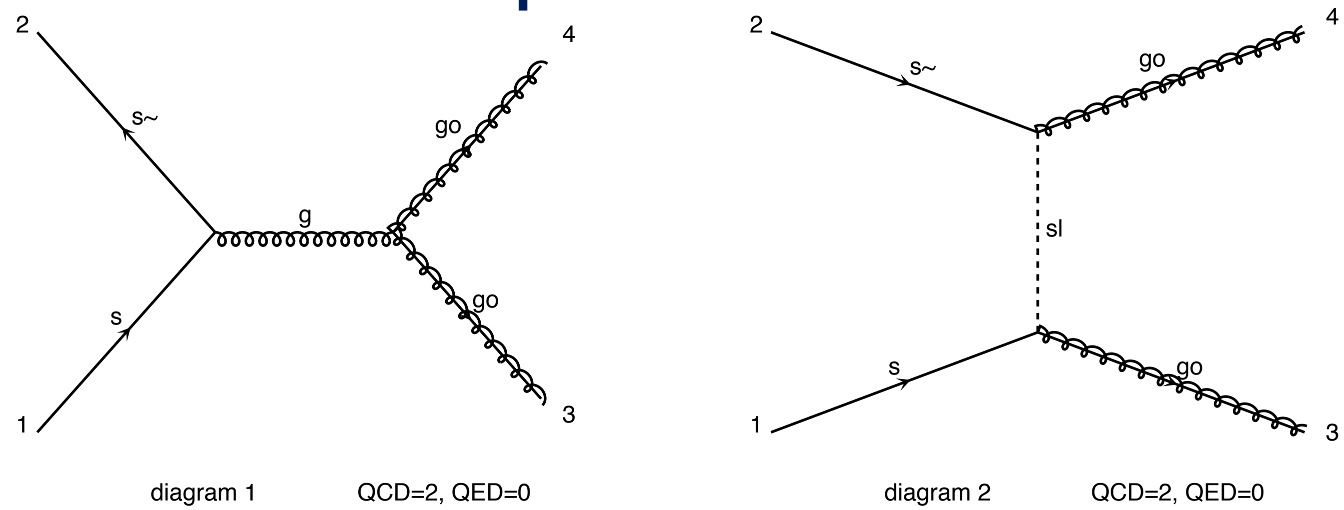
What to remember

- Analytical computation can be slower than numerical method
- Any BSM model are supported (at LO)
- Phase Space integration are slow
  - need knowledge of the function
  - cuts can be problematic
- Event generation are from free.
- All this are automated in MG5_aMC@NLO
- Important to know the physical hypothesis

Matrix-Element

Calculate a given process (e.g. gluino pair)

- Determine the production mechanism



- Evaluate the matrix-element

$|\mathcal{M}|^2$ ➡Need Feynman Rules!

- Phase-Space Integration

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

Matrix-Element

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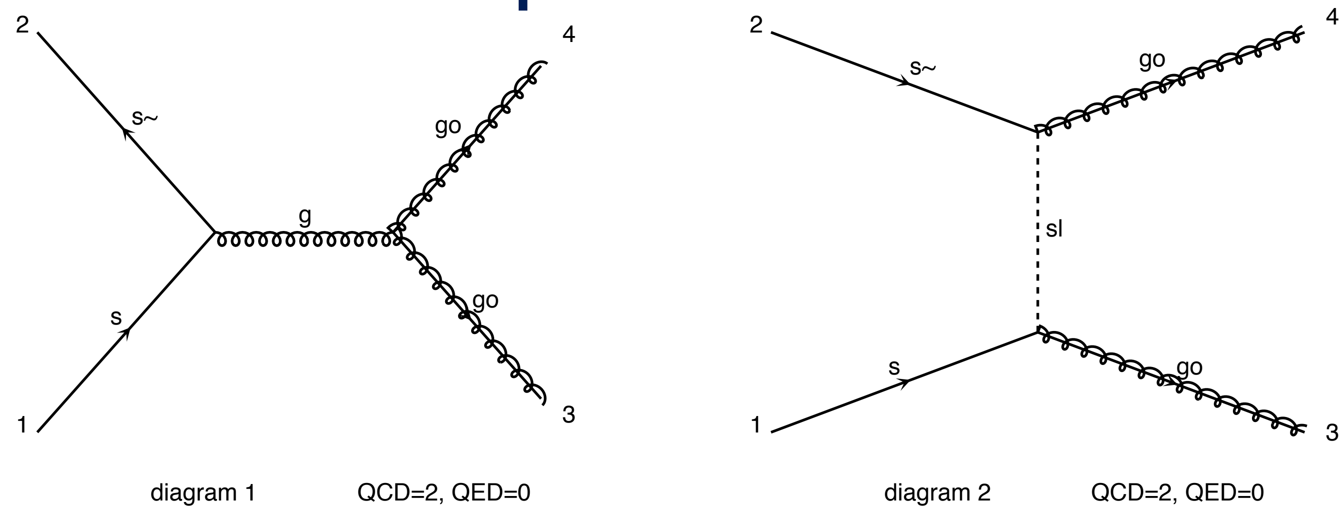

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Easy enough

Hard

Very Hard (in general)

Matrix-Element

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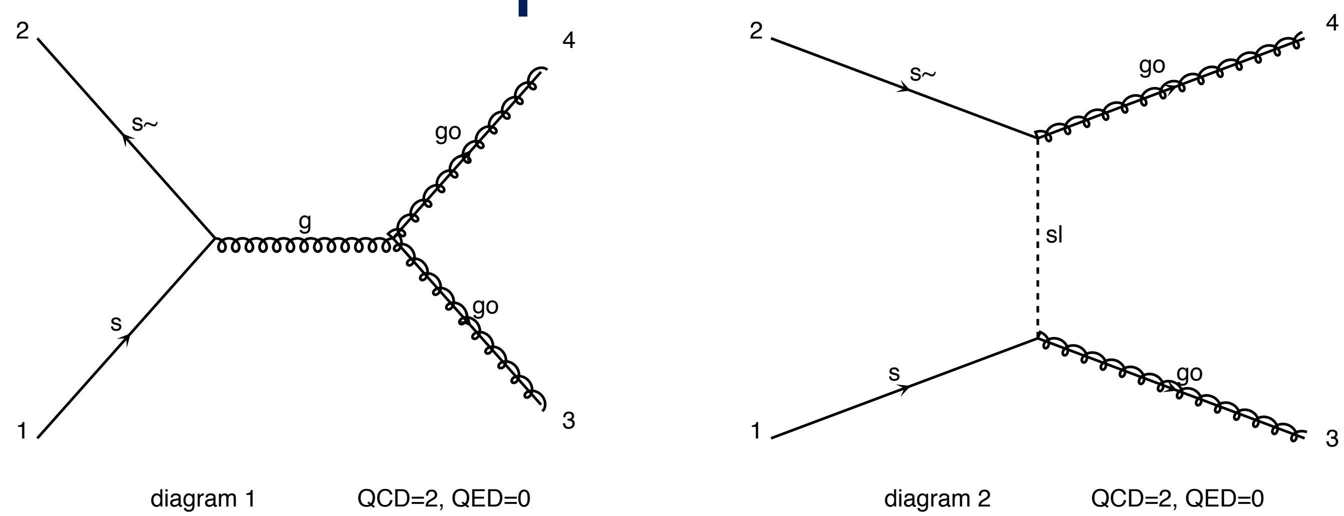

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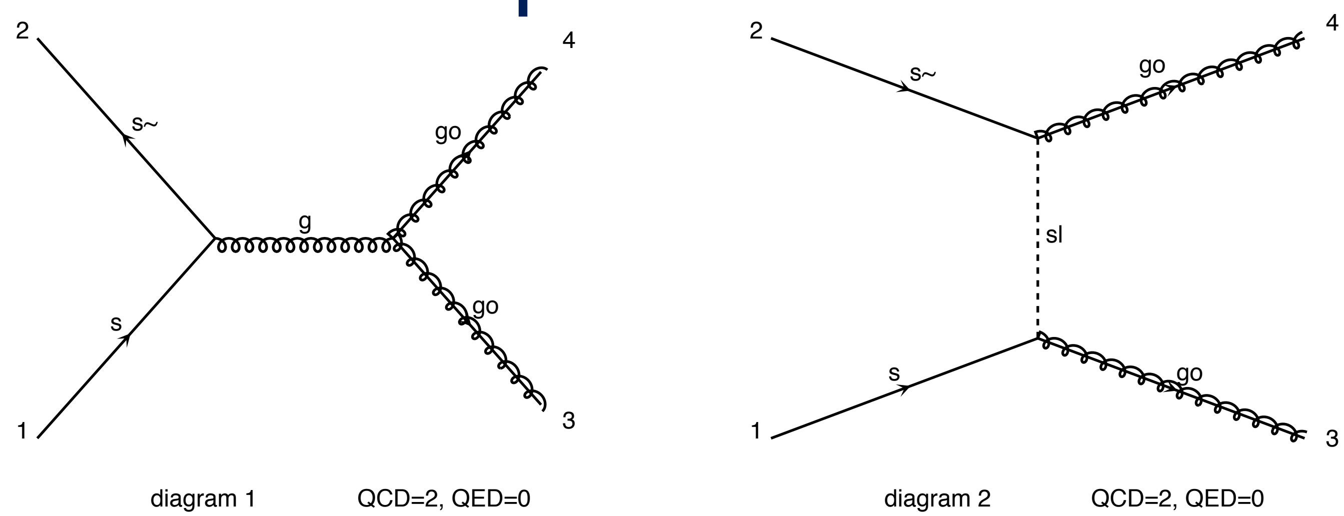

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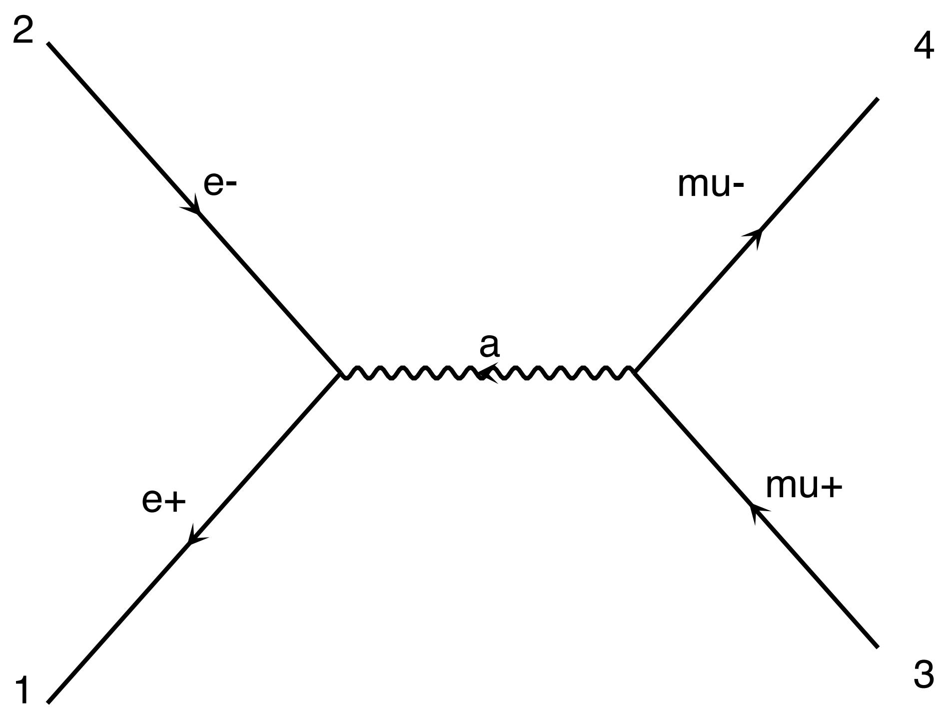
Easy enough

Hard

Tommorow

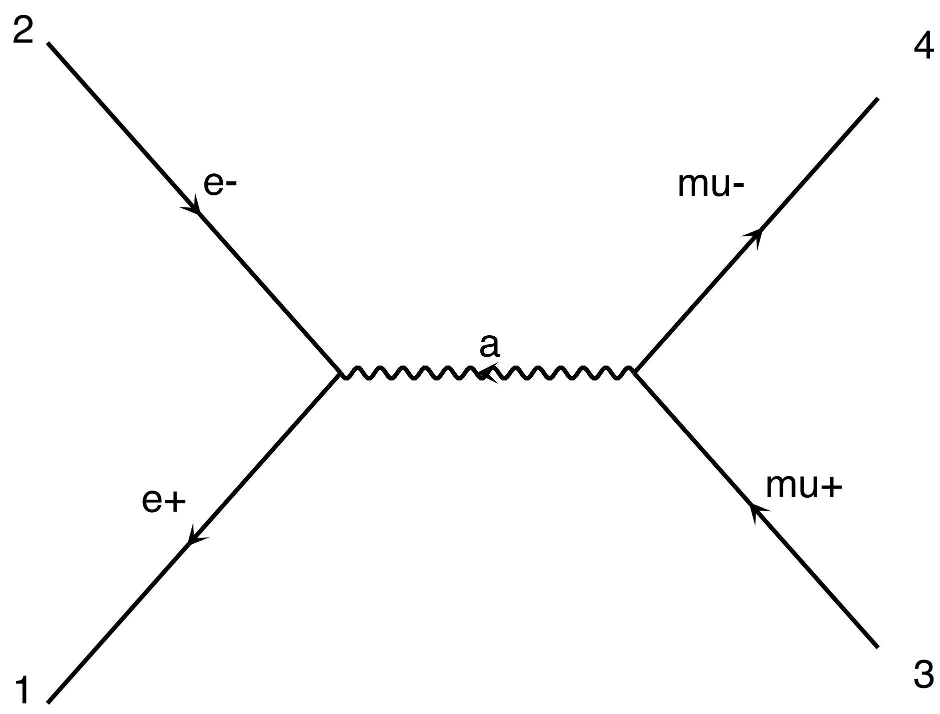
Very Hard (in general)

Matrix Element



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

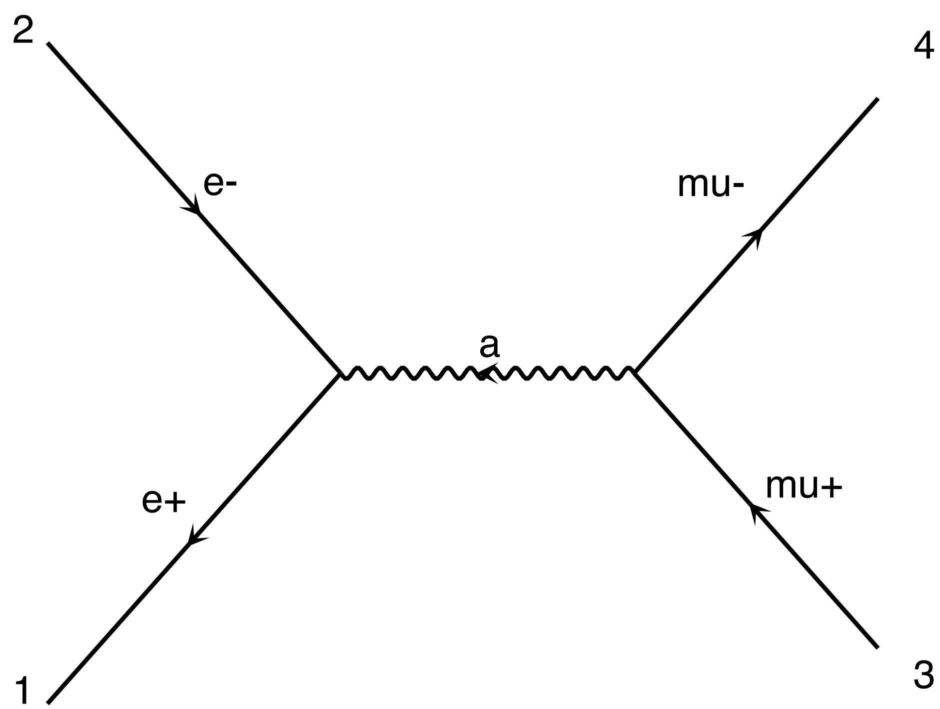
Matrix Element



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

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

Matrix Element



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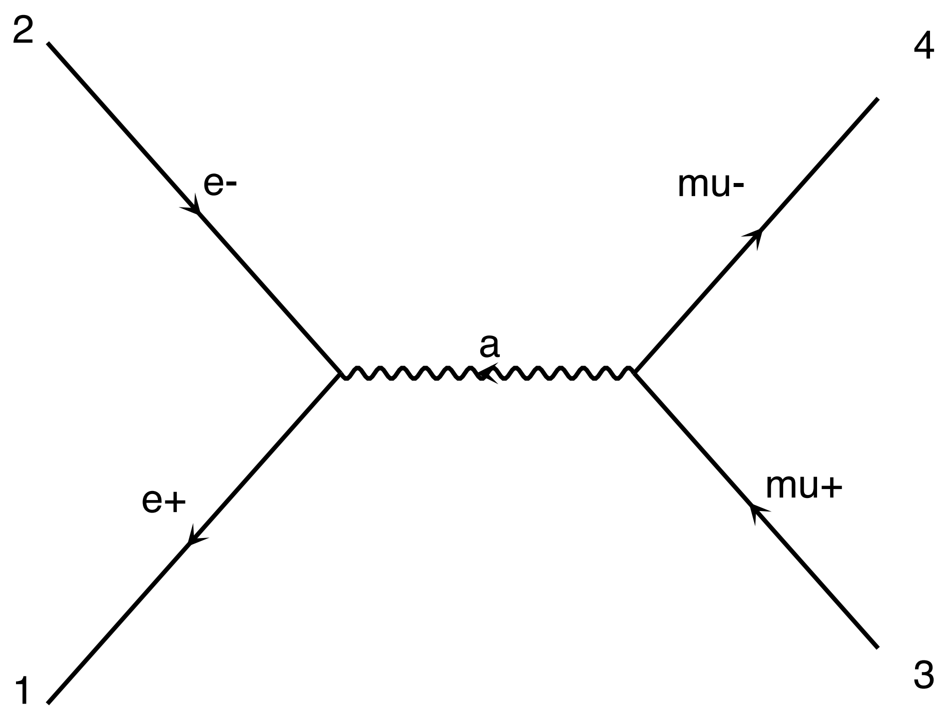
$$\sum_{pol} u\bar{u} = \not{p} + m$$

Matrix Element



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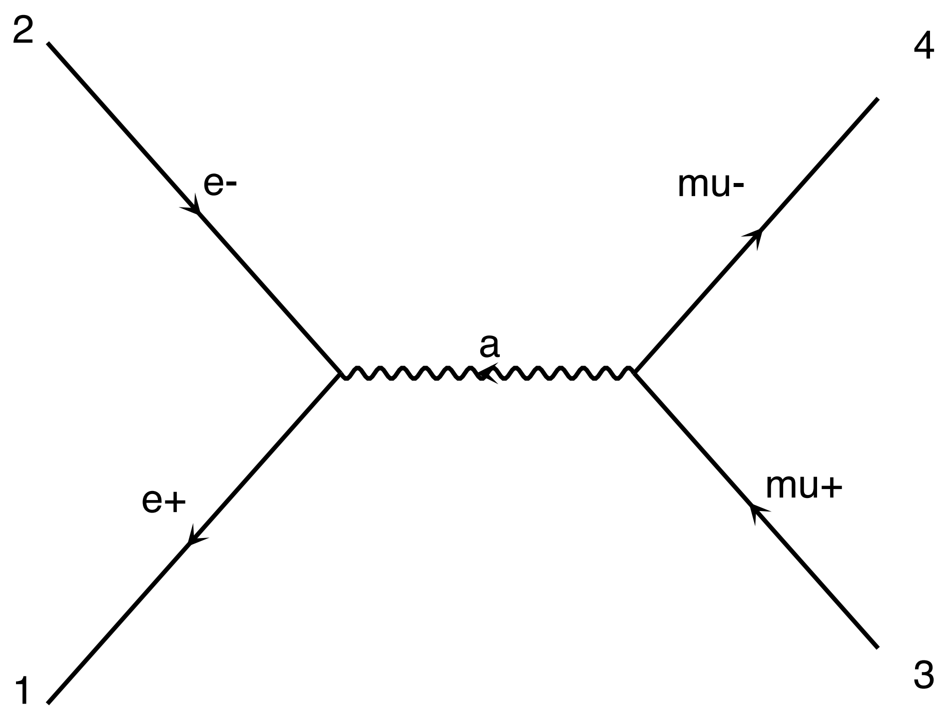
$$\frac{1}{4}\sum_{pol}|\mathcal{M}|^2 = \frac{1}{4}\sum_{pol}\mathcal{M}^*\mathcal{M}$$

$$\sum_{pol} u\bar{u} = \not{p} + m$$

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

Matrix Element



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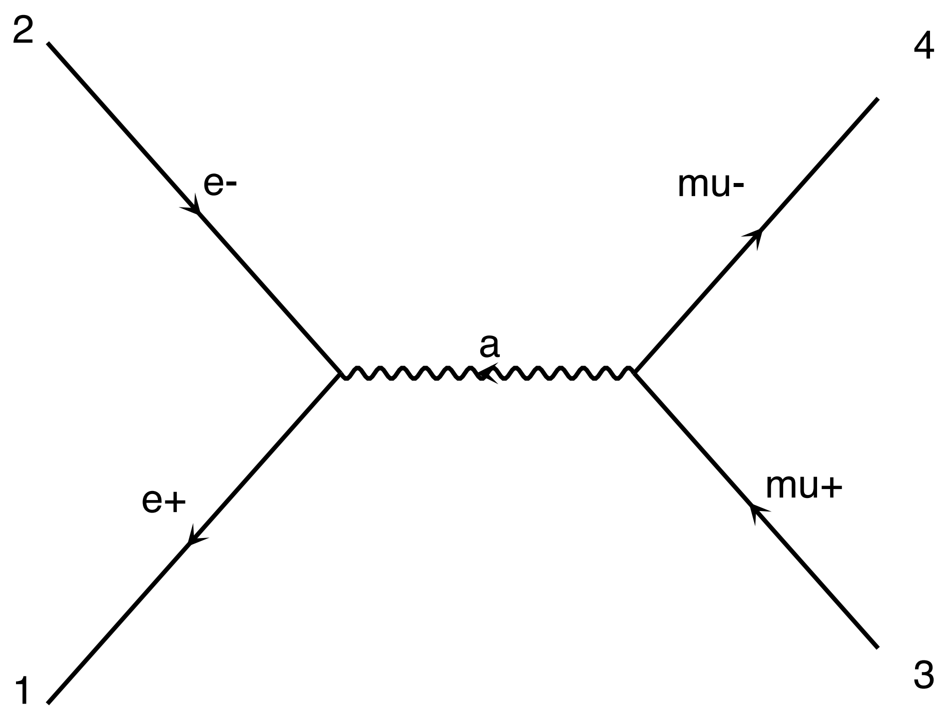
$$\rightarrow \frac{e^4}{4q^4} Tr[\not{p}_1 \gamma^\mu \not{p}_2 \gamma^\nu] Tr[\not{p}_3 \gamma_\mu \not{p}_4 \gamma_\nu]$$

$$\rightarrow \frac{8e^4}{q^4} [(p_1.p_3)(p_2.p_4) + (p_1.p_4)(p_2.p_3)]$$

Matrix Element



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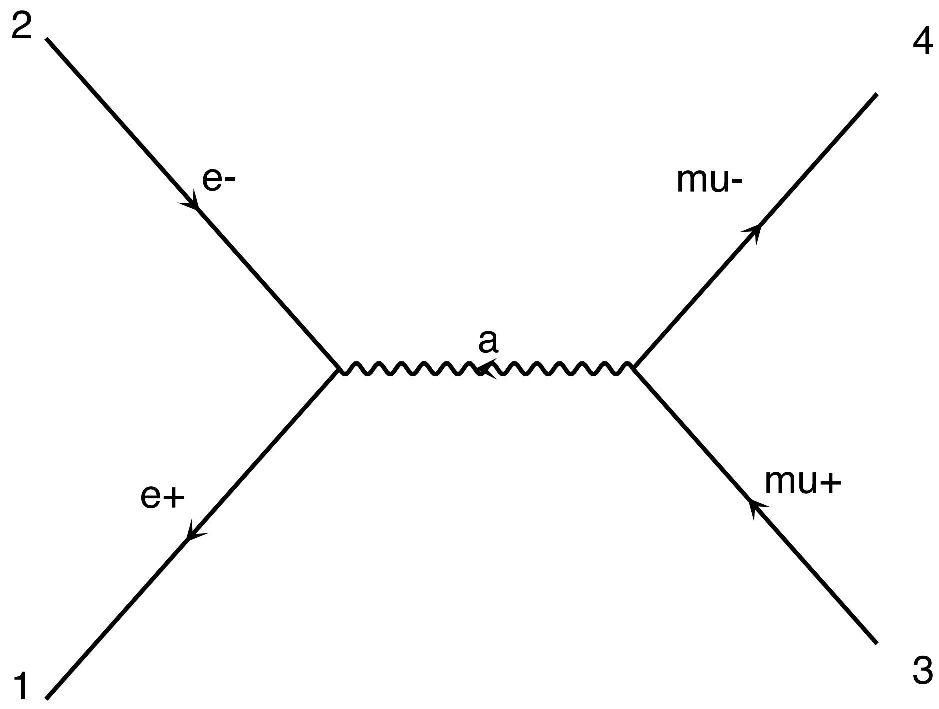
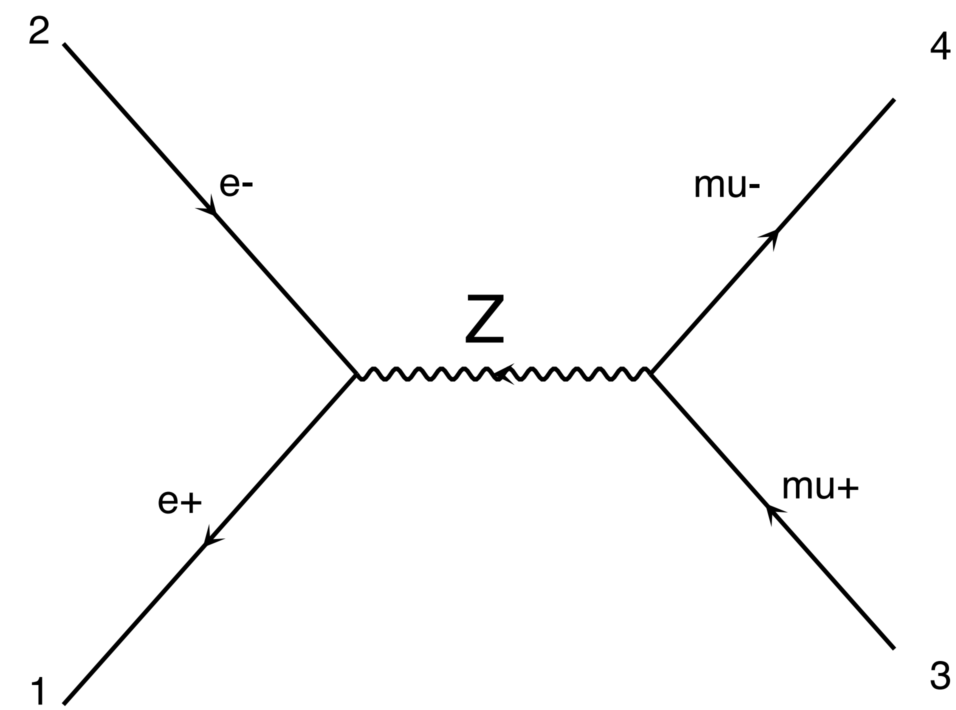
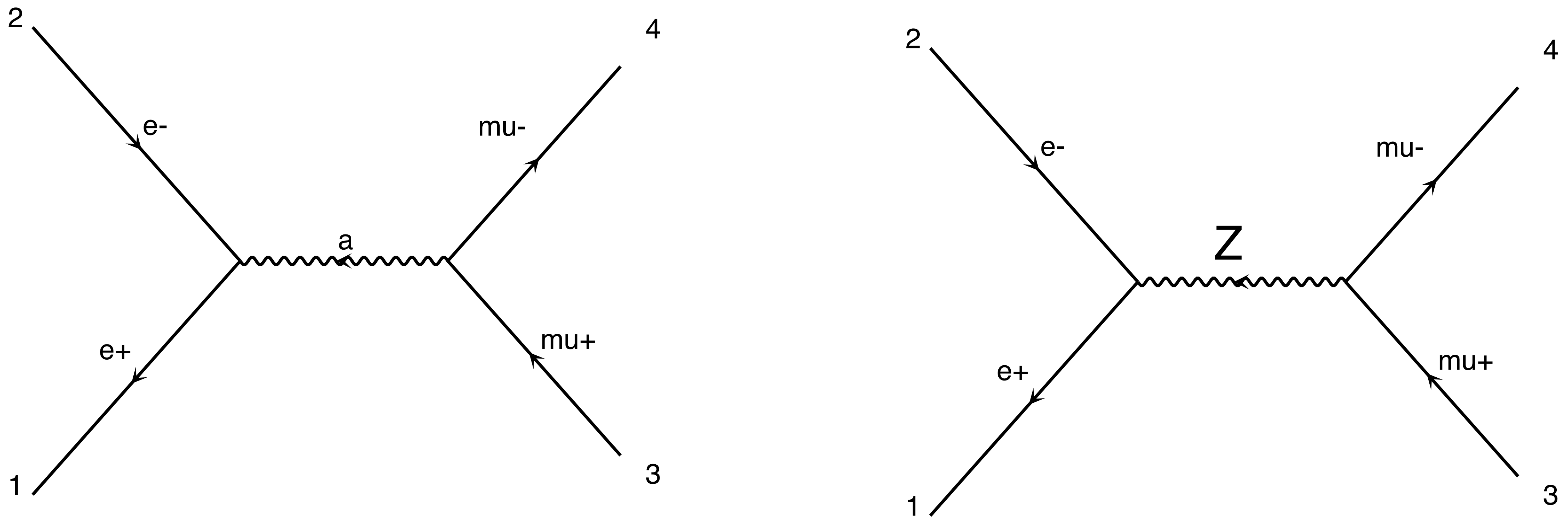
$$\rightarrow \frac{8e^4}{q^4}\left[(p_1.p_3)(p_2.p_4) + (p_1.p_4)(p_2.p_3)\right]$$

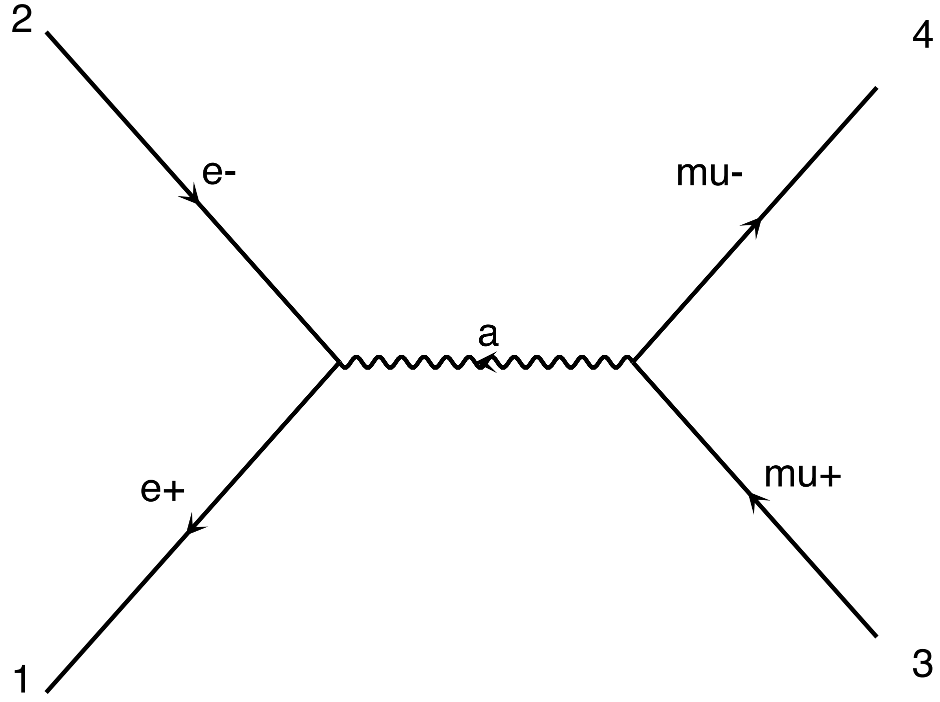
Very Efficient !!!

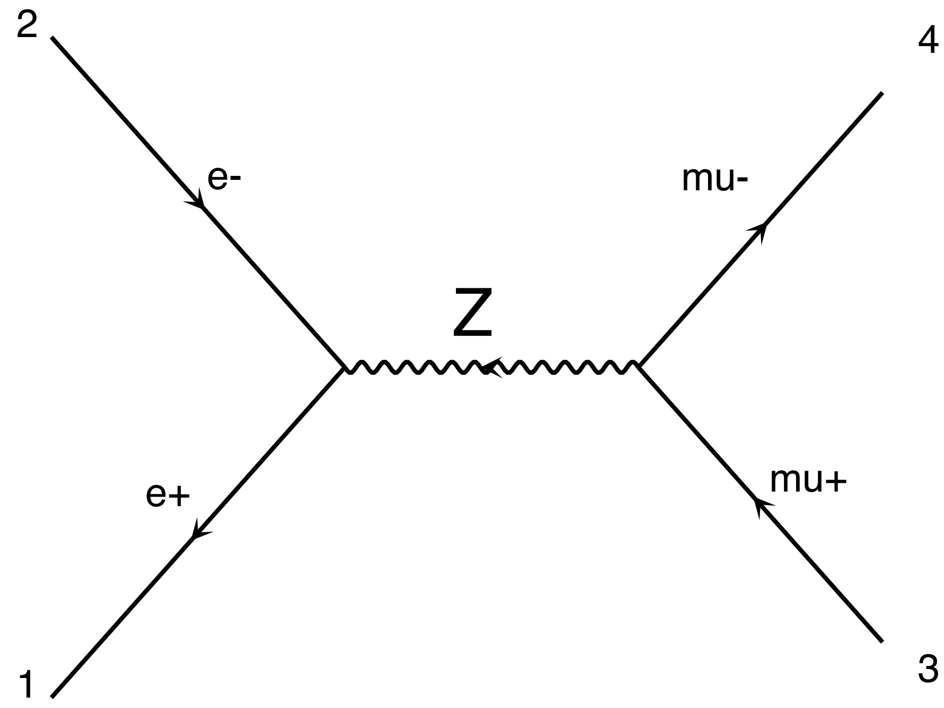

2
e-
4
mu-
a
e+
mu+
1
3


2
e-
4
mu-
Z
e+
mu+
1
3



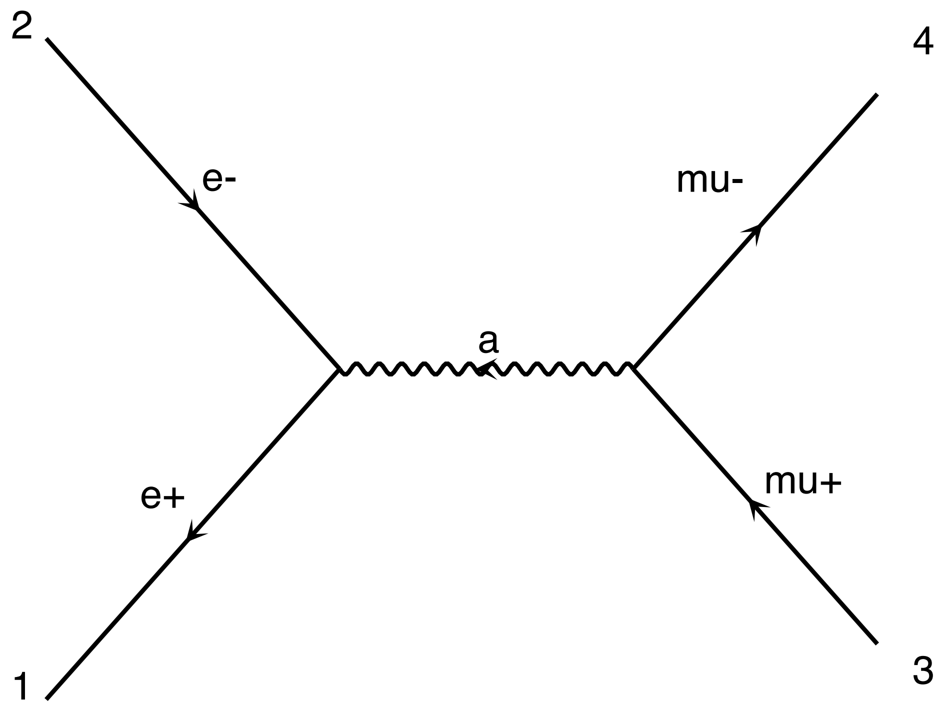
Need to compute $|M_a|^2 \quad |M_z|^2 \quad 2Re(M_a^* M_z)$

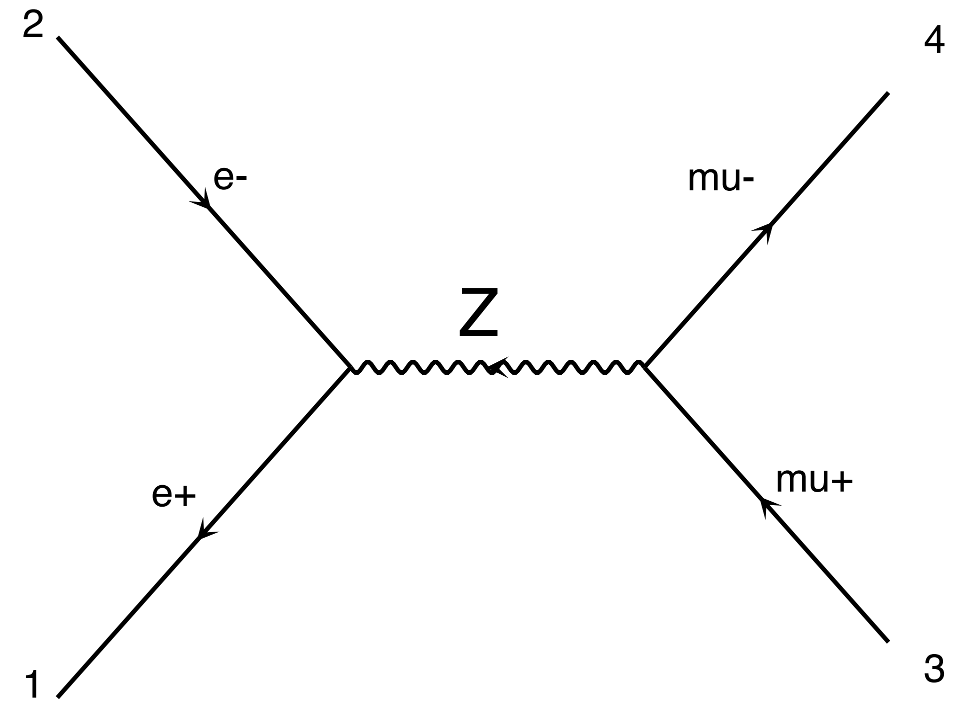




Need to compute $|M_a|^2$ $|M_z|^2$ $2Re(M_a^* M_z)$

So for M Feynman diagram we need to compute M^2 different term





Need to compute $|M_a|^2$ $|M_z|^2$ $2Re(M_a^* M_z)$

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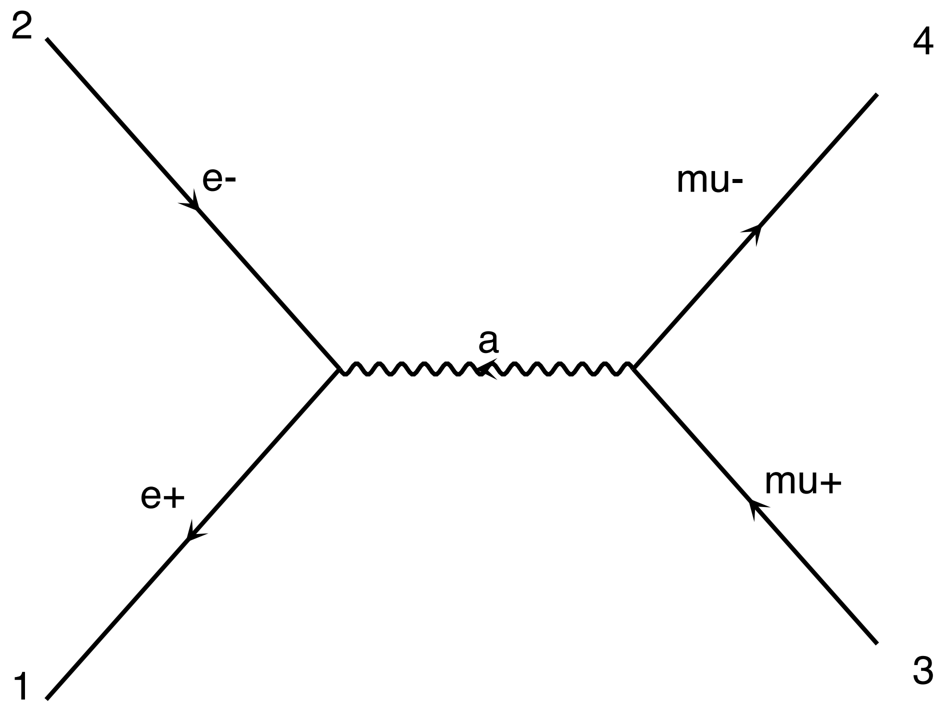
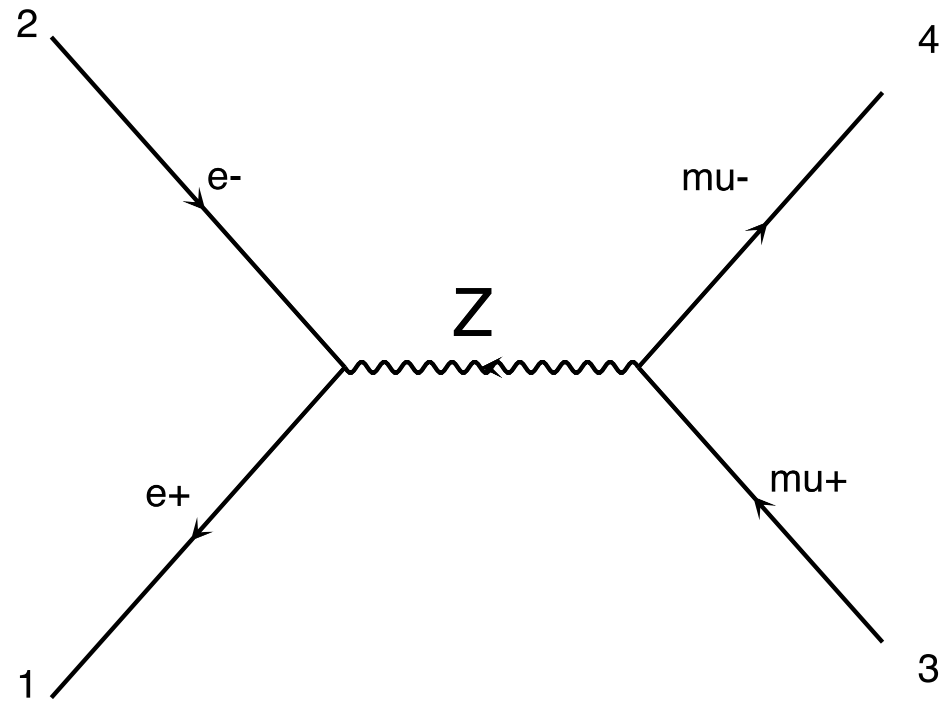
The number of diagram scales factorially with the number of particle





Need to compute $|M_a|^2$ $|M_z|^2$ $2Re(M_a^* M_z)$

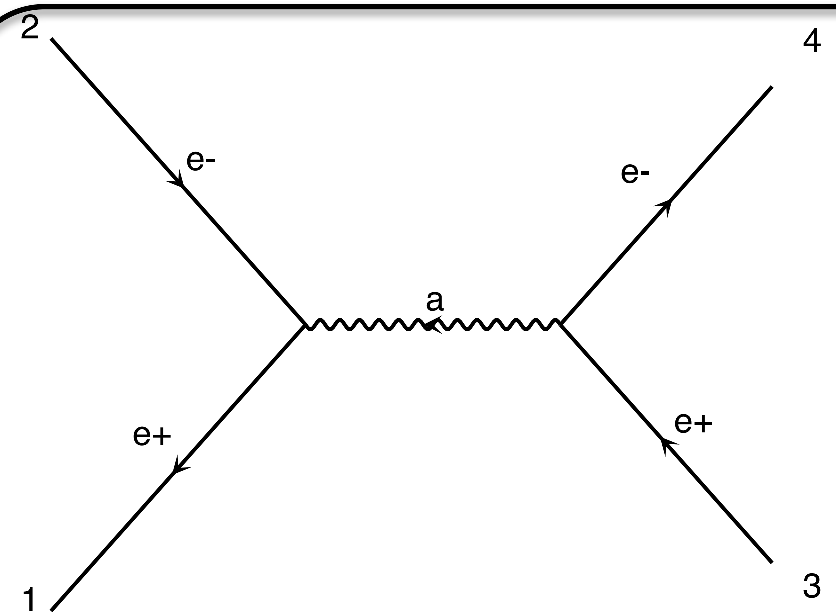
So for M Feynman diagram we need to compute M^2 different term

The number of diagram scales factorially with the number of particle

In practise possible up to 2>4

Helicity Amplitude

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



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

Helicity Amplitude

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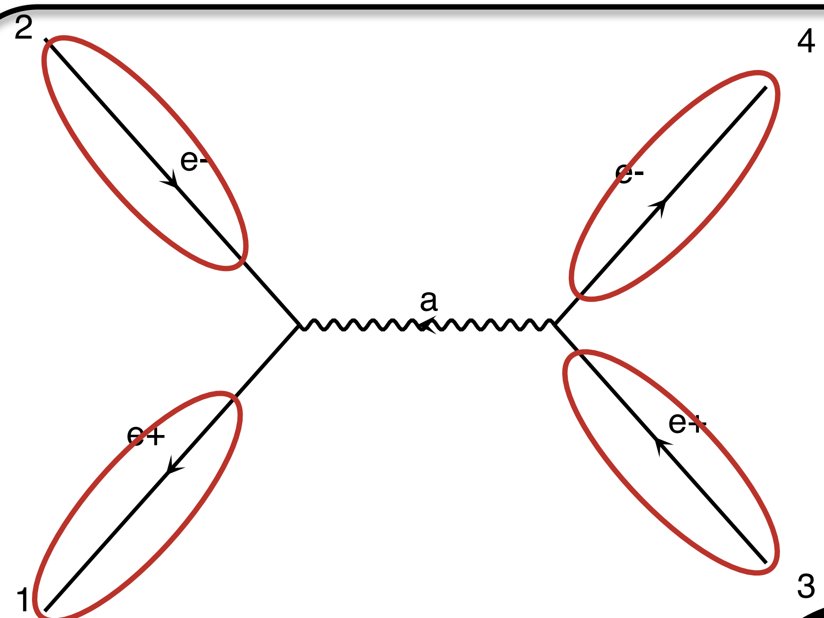

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Numbers for given helicity and momenta

Lines present in the code.

$$\left\{ \begin{array}{l} \bar{v}_1 = fct(\vec{p}_1, m_1) \\ u_2 = fct(\vec{p}_2, m_2) \\ v_3 = fct(\vec{p}_3, m_3) \\ \bar{u}_4 = fct(\vec{p}_4, m_4) \end{array} \right.$$

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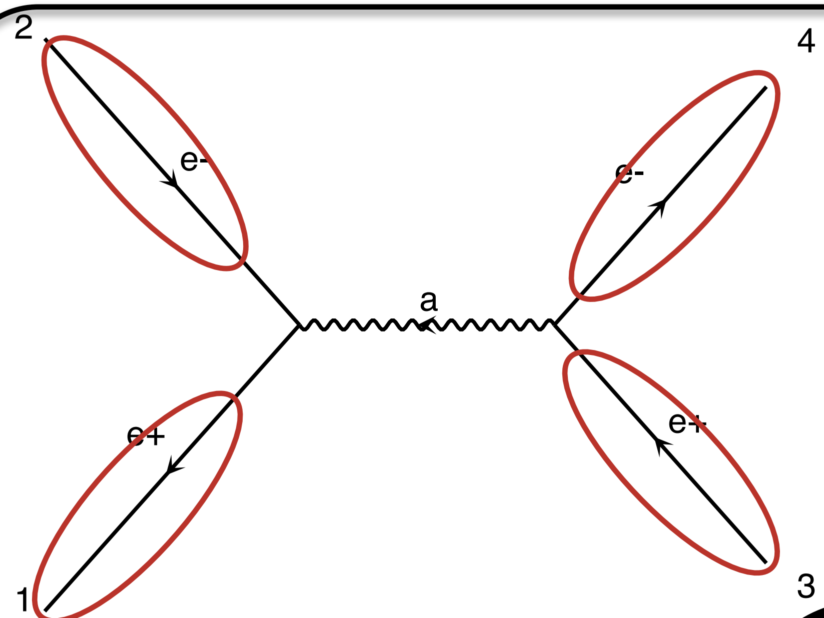

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$$u(p) = \begin{pmatrix} \omega_{-\lambda}(p)\chi_\lambda(\vec{p}) \\ \omega_\lambda(p)\chi_\lambda(\vec{p}) \end{pmatrix}$$

$$\omega_\pm(p) \equiv \sqrt{E \pm |\vec{p}|}.$$

$$\chi_+(\vec{p}) = \frac{1}{\sqrt{2|\vec{p}|(|\vec{p}|+p_z)}} \begin{pmatrix} |\vec{p}|+p_z \\ p_x + ip_y \end{pmatrix},$$

$$\chi_-(\vec{p}) = \frac{1}{\sqrt{2|\vec{p}|(|\vec{p}|+p_z)}} \begin{pmatrix} -p_x + ip_y \\ |\vec{p}|+p_z \end{pmatrix}.$$

Helicity Amplitude

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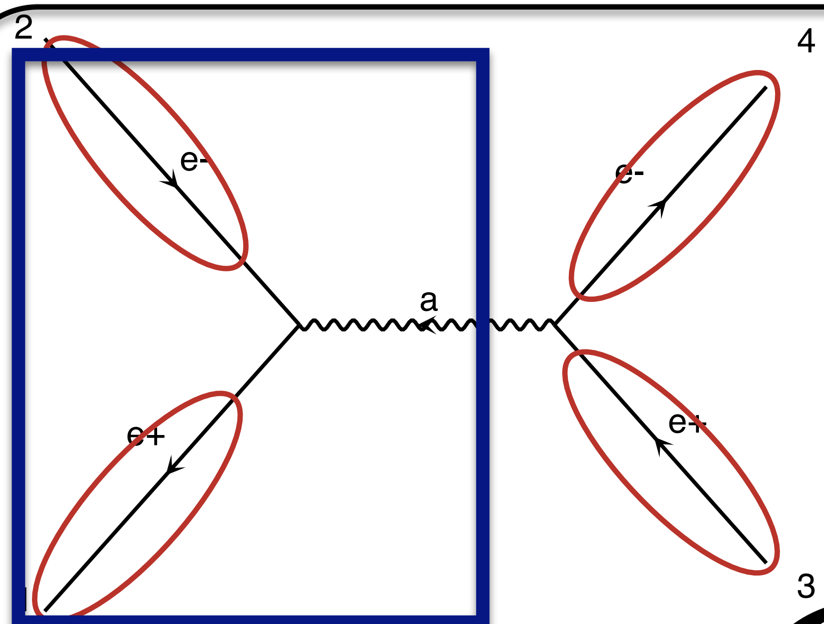

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Numbers for given helicity and momenta

Calculate propagator wavefunctions

Lines present in the code.

$$\left\{\begin{array}{l} \bar{v}_1 = fct(\vec{p}_1, m_1) \\ u_2 = fct(\vec{p}_2, m_2) \\ v_3 = fct(\vec{p}_3, m_3) \\ \bar{u}_4 = fct(\vec{p}_4, m_4) \\ W_a = fct(\bar{v}_1, u_2, e, m_a, \Gamma_a) = e\bar{v}_1\gamma^\mu u_2 \dfrac{\eta_{\mu\nu}}{q^2 - m_a^2 + i m_a \Gamma_a} \end{array}\right.$$

Helicity Amplitude

Idea

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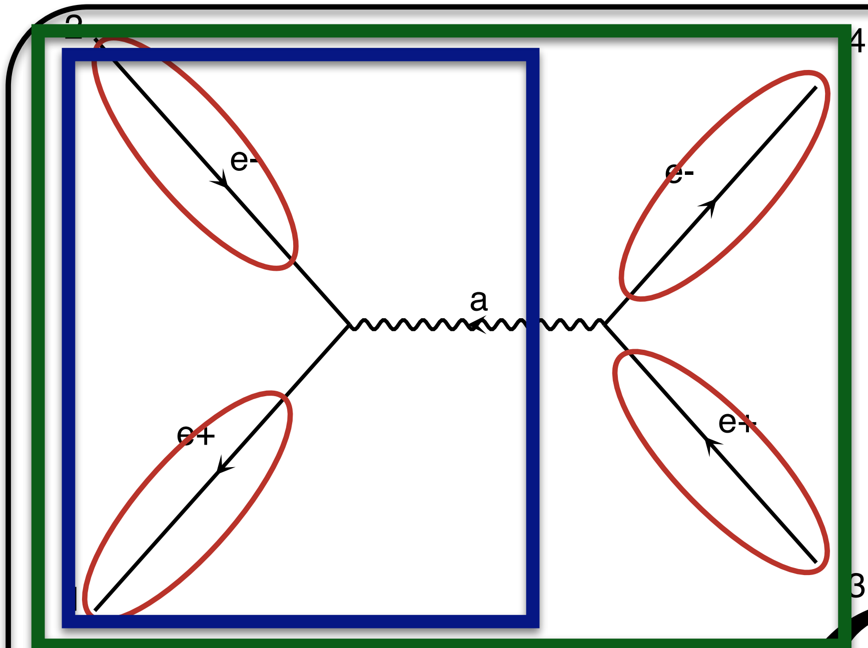

$$\mathcal{M} = ((\bar{u} e \gamma^\mu v)\frac{g_{\mu\nu}}{q^2})(\bar{v} e \gamma^\nu u))$$

Numbers for given helicity and momenta

Calculate propagator wavefunctions

Finally evaluate amplitude (c-number)

Lines present in the code.

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$$u_2 = fct(\vec{p}_2, m_2)$$
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$$W_a = fct(\bar{v}_1, u_2, e, m_a, \Gamma_a) = e\bar{v}_1\gamma^\mu u_2 \frac{\eta_{\mu\nu}}{q^2 - m_a^2 + i m_a \Gamma_a}$$
$$\mathcal{M} = fct(\bar{v}_3, u_4, W_\nu^a, e) = e\bar{v}_3\gamma_\nu u_4 W_\nu^a$$

Comparison

	M diag	N particle
Analytical	M^2	$(N!)^2$
Helicity	M	$(N!)\,2^N$

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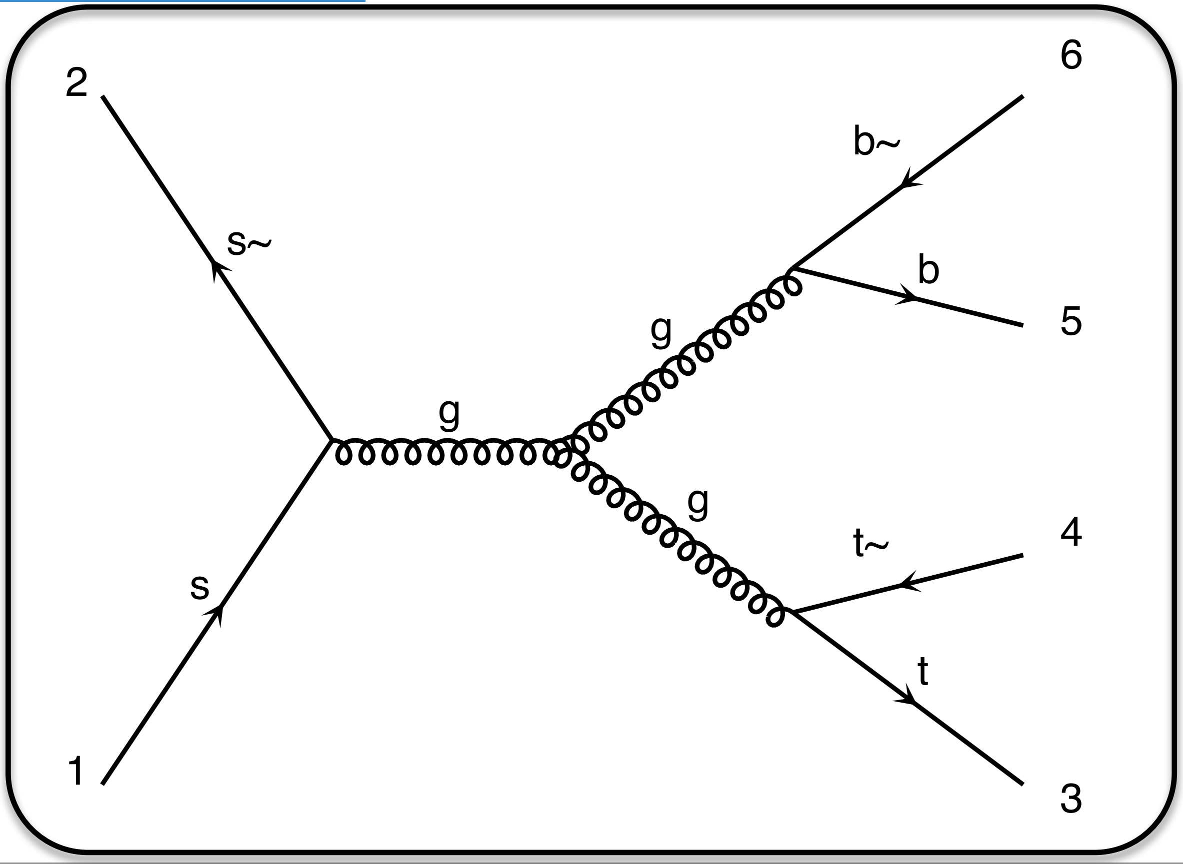

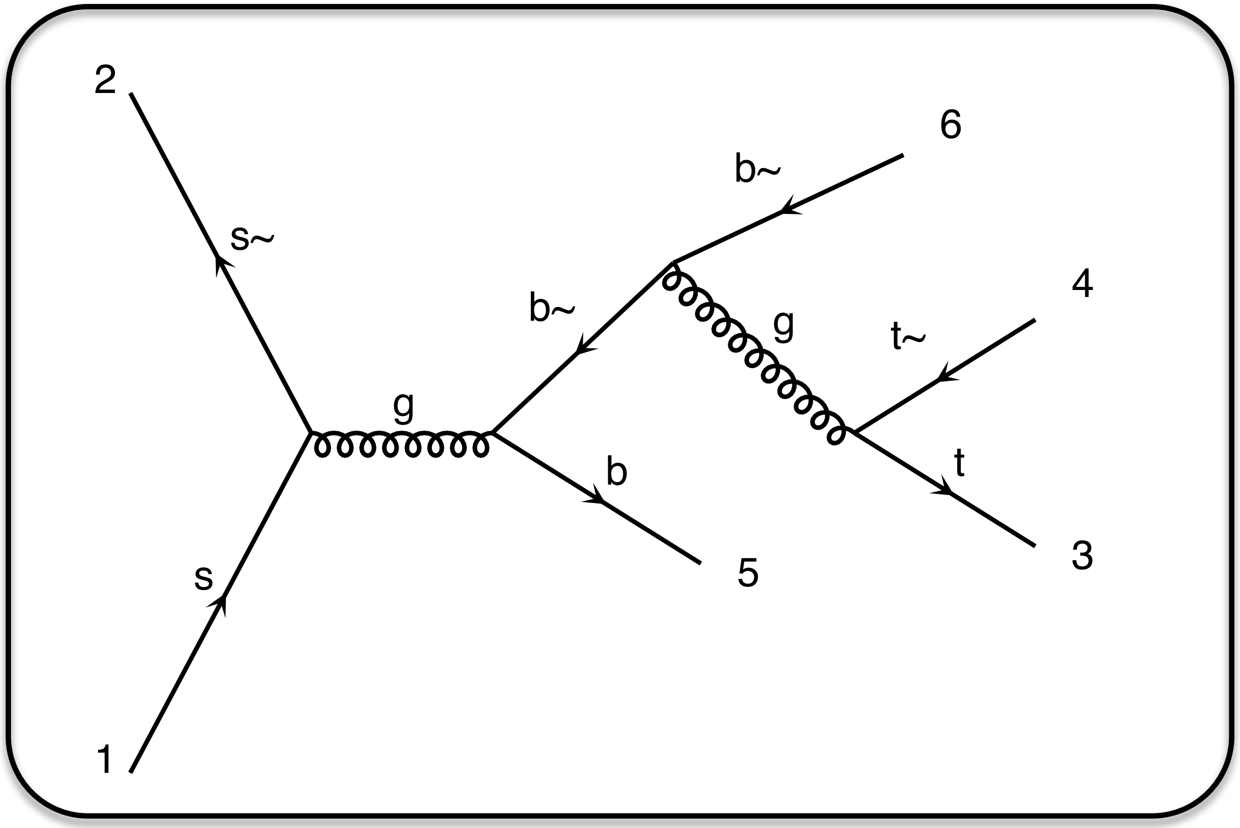

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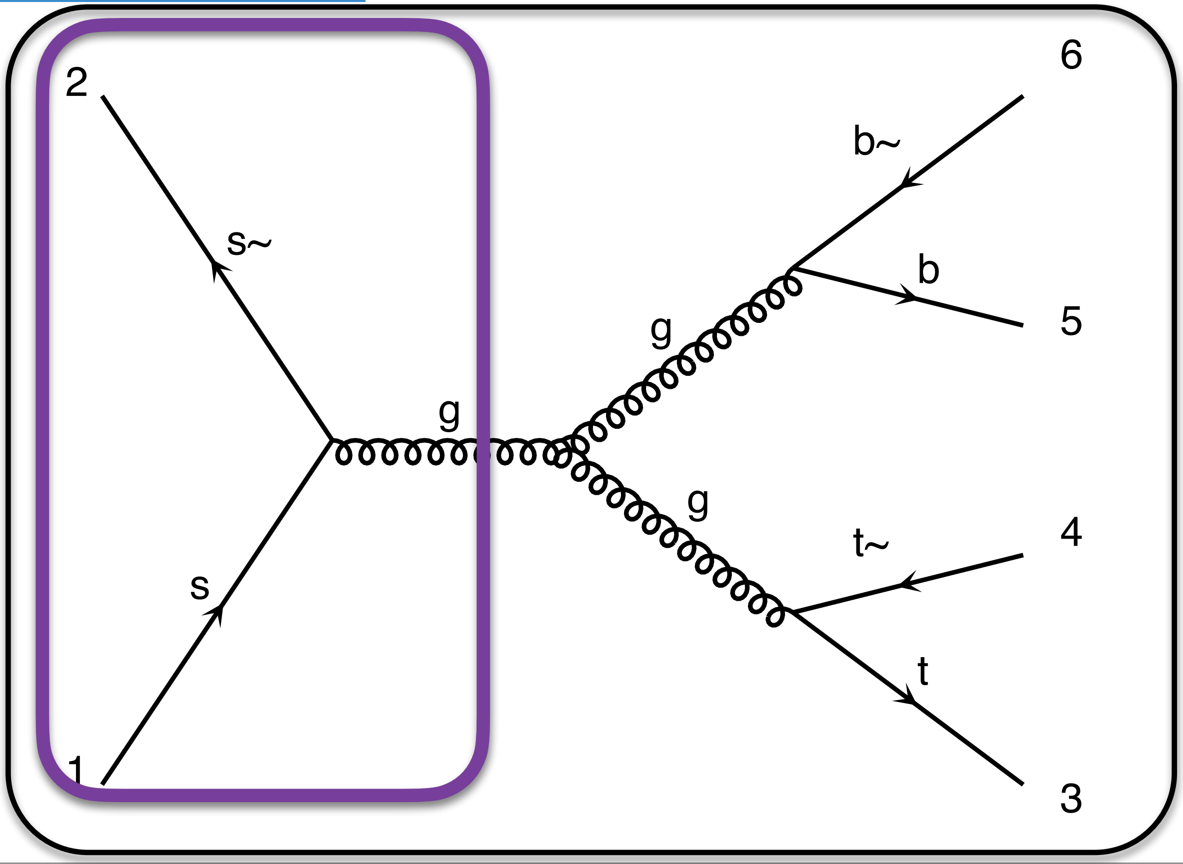

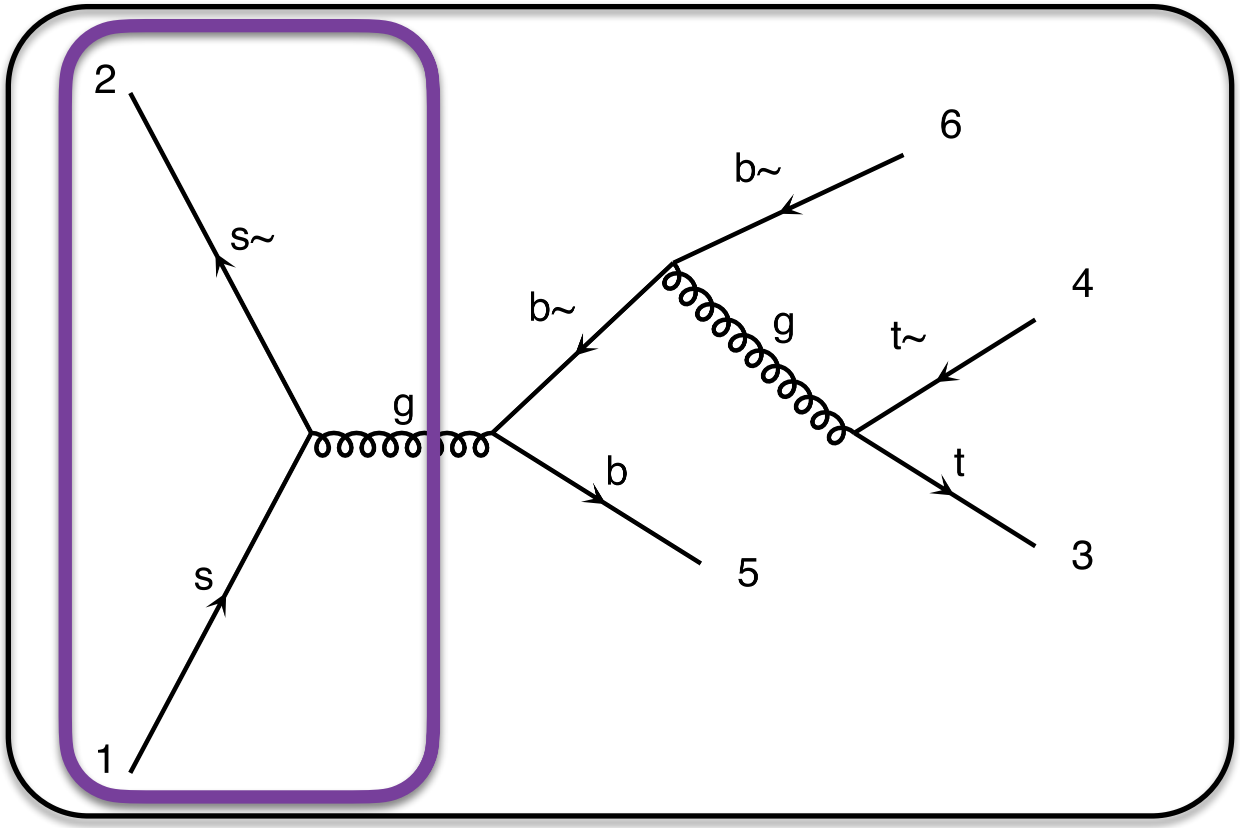

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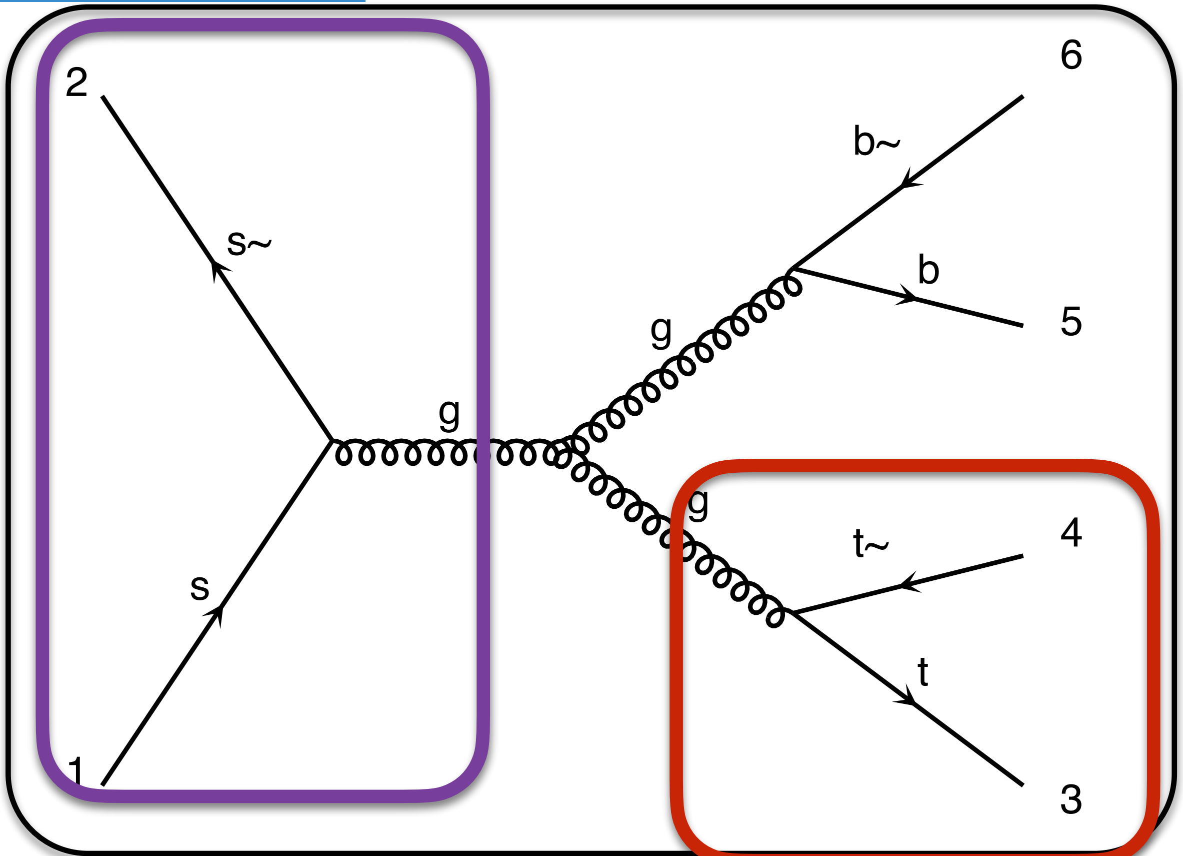
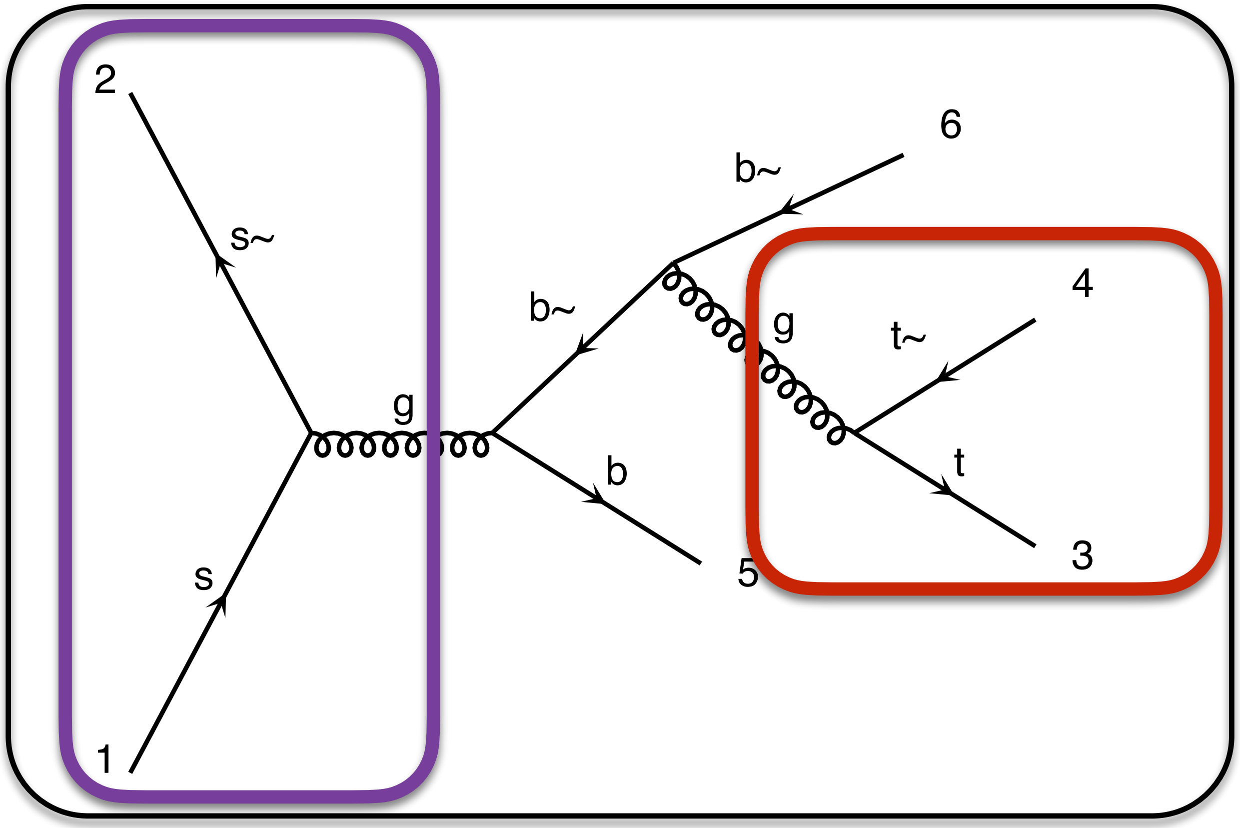




Can we do better? YES

- Recursion relation (used in Sherpa) [WIP]
- New in MG5aMC: Helicity Recycling 2102.00773
- 5 Dimensional helicity wave function 2203.10440
- Not full color computation [WIP]

• 2102.00773 [hep-ph]

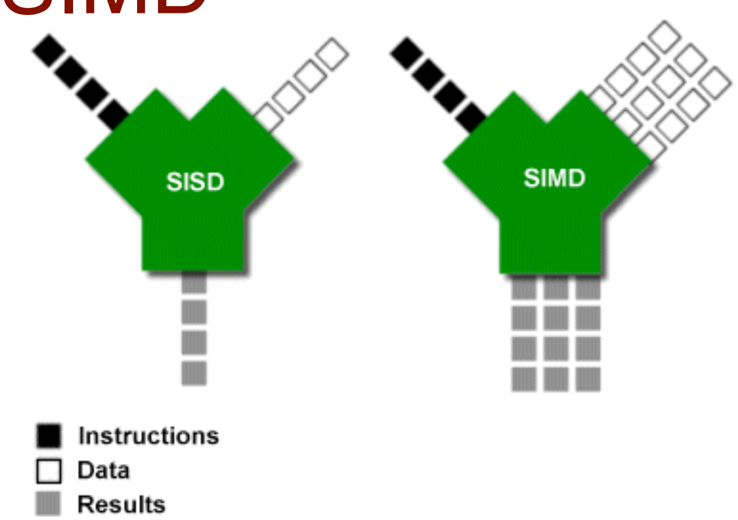
	M diag	N particle
Analytical	M^2	$(N!)^2$
Helicity	M	$(N!)\,2^N$
Recycling	M	$(N-1)!\,2^{(N-1)}$
Hel Recycling	M	$\approx (N-1)!2^{N/2}$

Can we go faster? YES

GPU

- ➡ Was first done a while ago (cuda)
  arXiv:0908.4403,arXiv:1305.0708v2
- ➡ New recent focus in this direction
  - ➡Not only cuda:
  - ➡Kokkos, syCL, tensorflow
- ➡ Good performance but not yet integrated with the phase-space

SIMD



- ➡Modern CPU can act as a baby GPU
- ➡They can perform N identical operation as fast as one

To Remember

- Numerical computation faster than analytical computation
- We are able to compute matrix-element
  - ➡ for large number of final state
  - ➡ for any BSM theory
- Computing the matrix-element is slow
  - ➡ We are still looking for new idea
    - ❑ Physics idea
    - ❑ Better hardware implementation

Intuition for matching and merging

Parton shower

Goal

- We want to an **explicit** description of the SOFT radiation that are **ALREADY** included **implicitly in the LO events** (via the scale)

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  - Such radiations are already included within the event-generator

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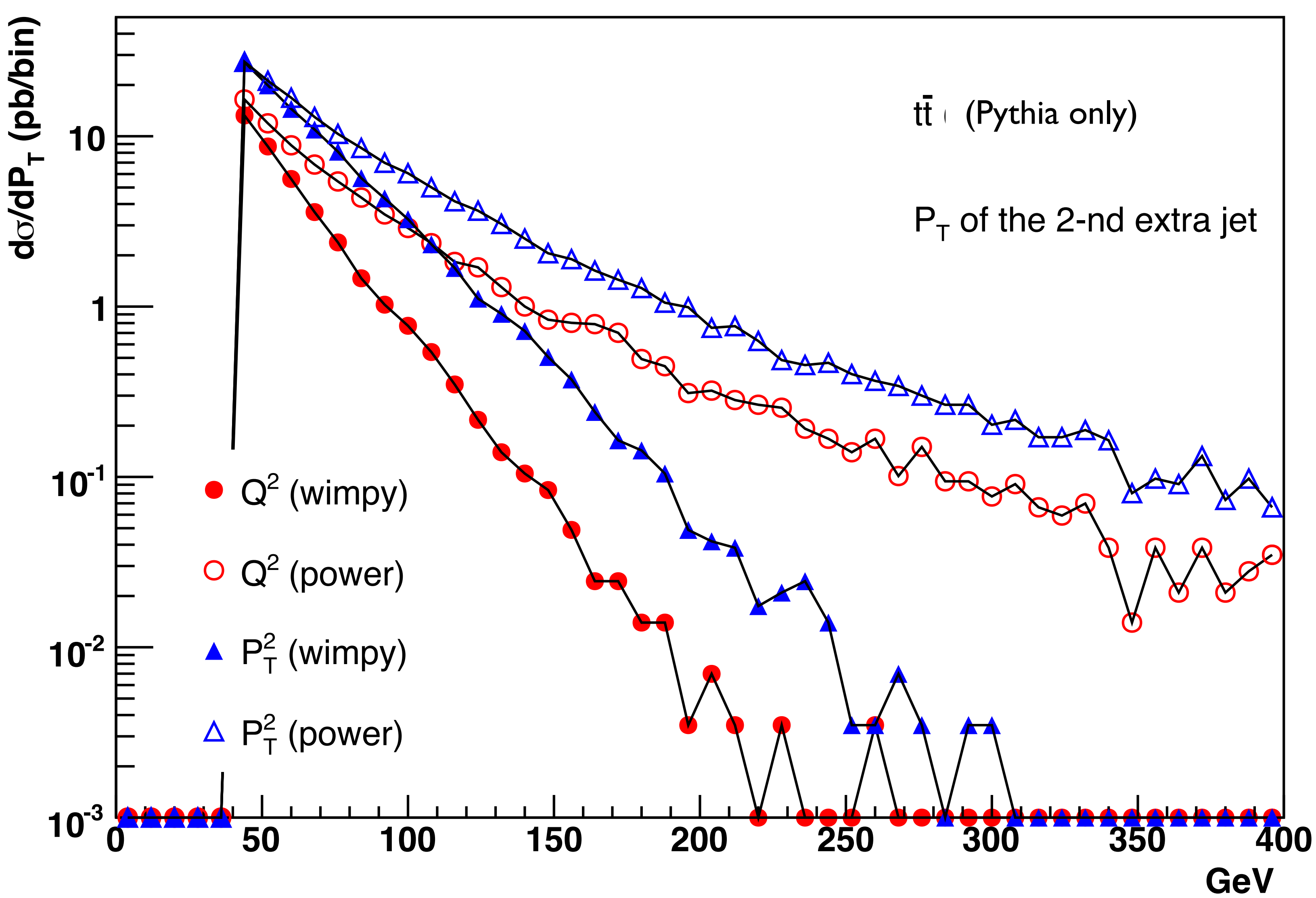
- This effect should be **unitary:** the inclusive cross section shouldn't change when extra radiation is added

PS alone vs matched samples

In the soft-collinear approximation of Parton Shower MCs, parameters are used to tune the result ⇒ Large variation in results (small prediction power)



Matrix Elements vs. Parton Showers

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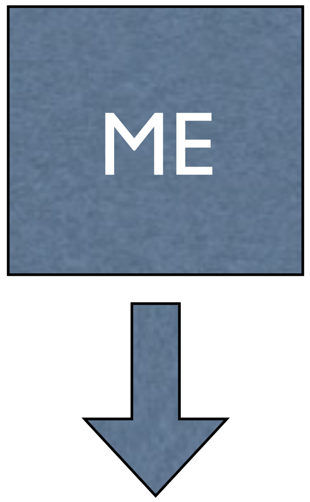

1. Fixed order calculation
2. Computationally expensive
3. Limited number of particles
4. Valid when partons are hard and well separated
5. Quantum interference correct
6. Needed for multi-jet description

Matrix Elements vs. Parton Showers

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Approaches are complementary: merge them!

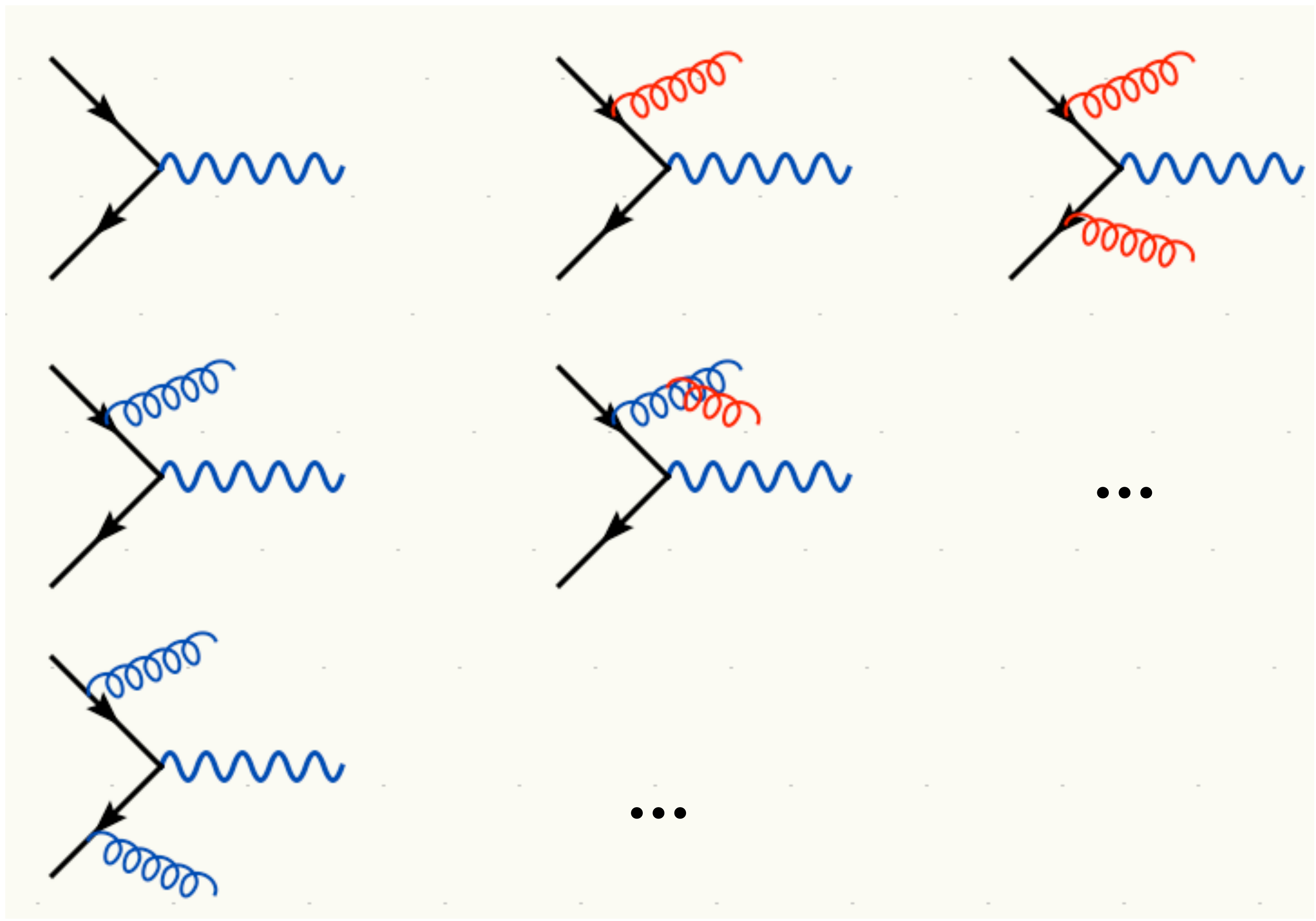
Difficulty: avoid double counting, ensure smooth distributions

Merging ME with PS

[Mangano]
[Catani, Krauss, Kuhn, Webber]
[Lönnblad]

PS →

ME ↓



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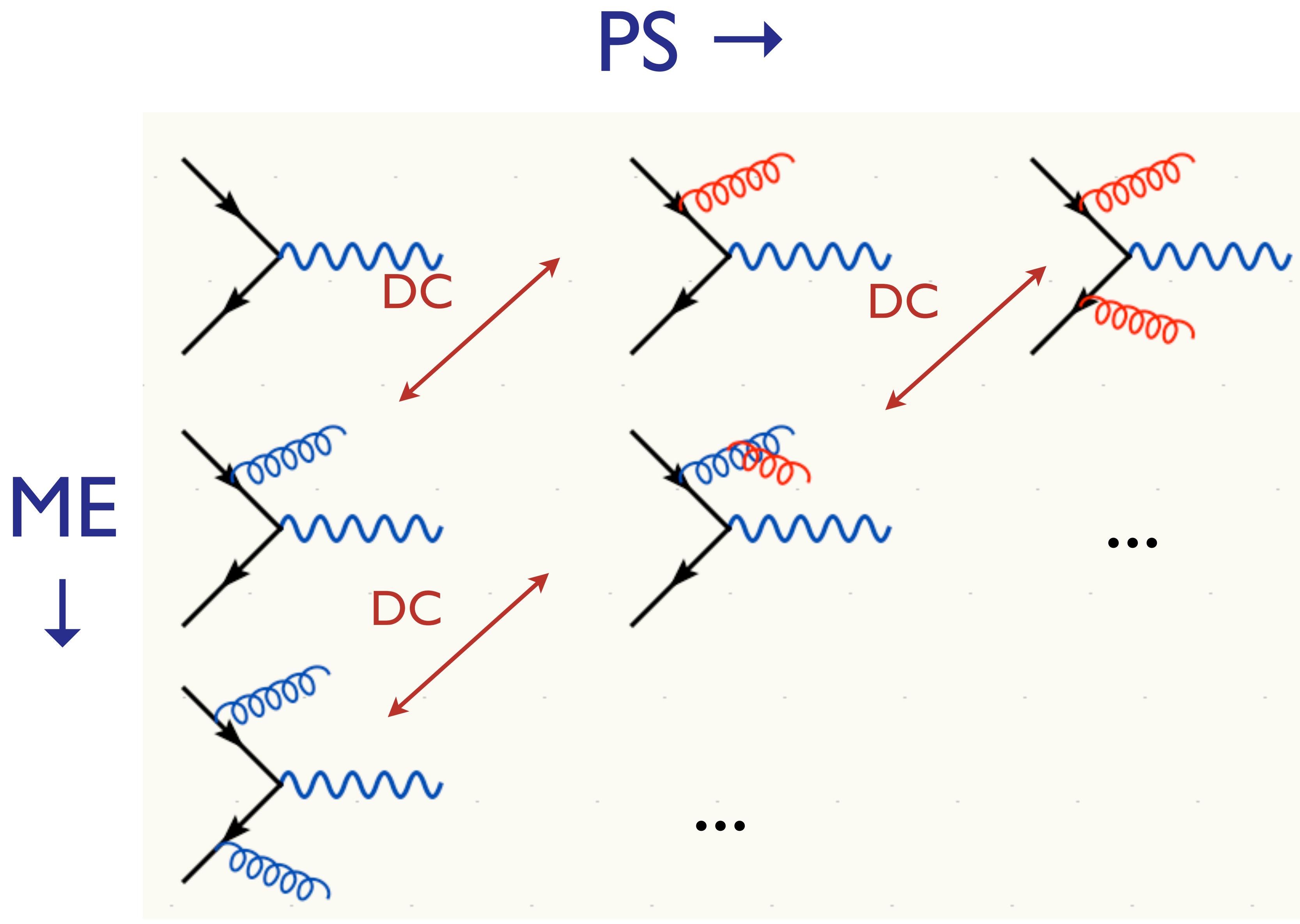

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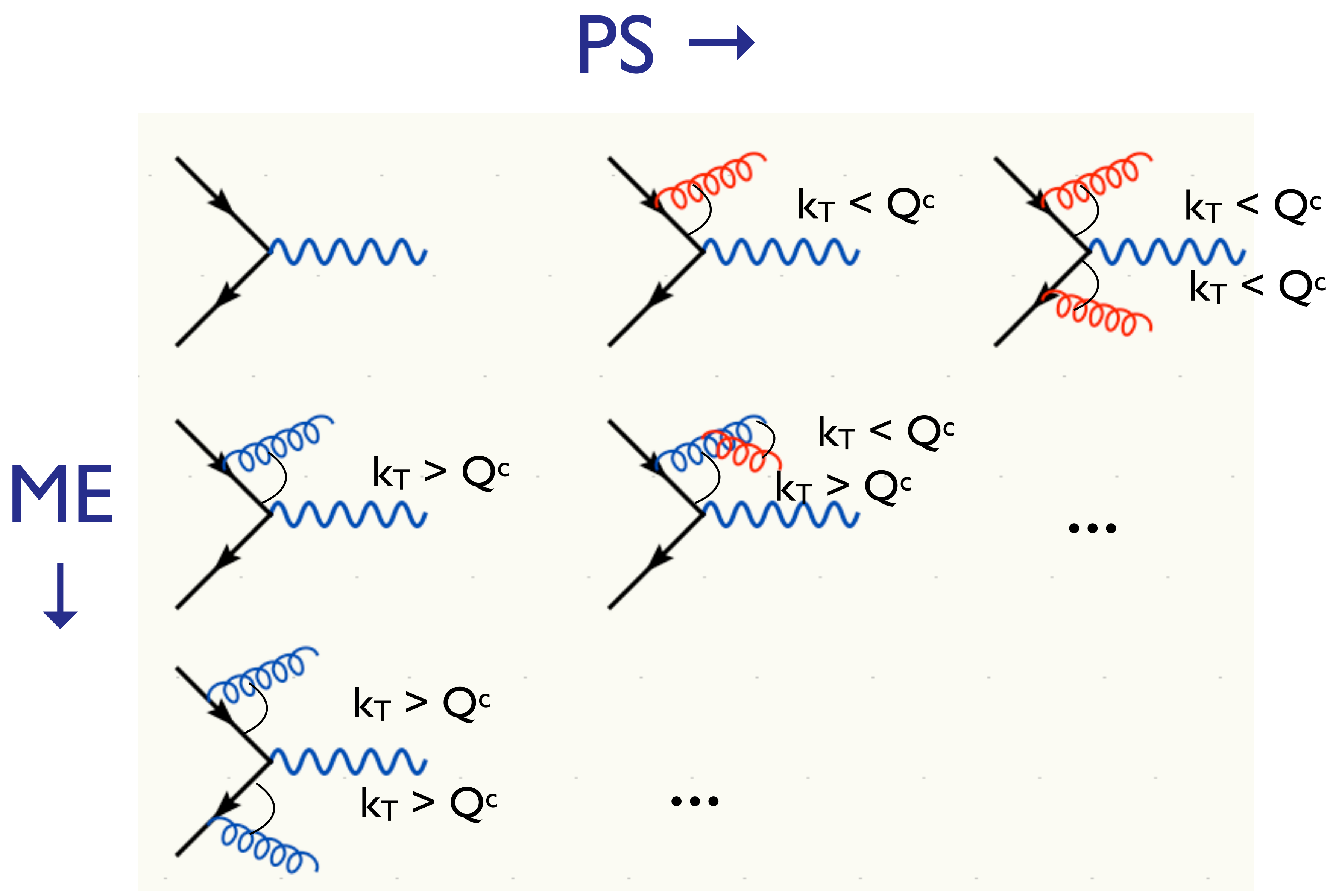

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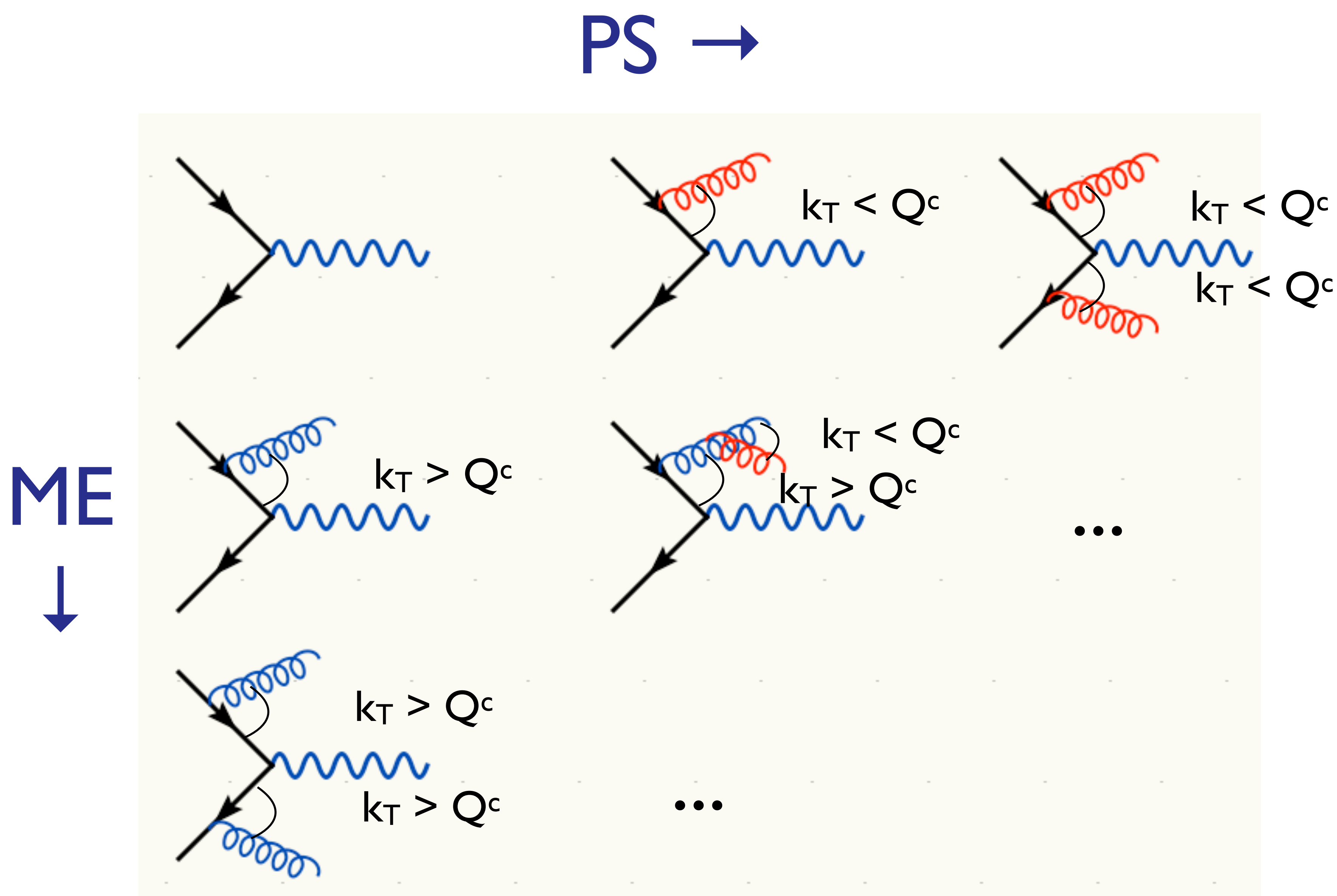
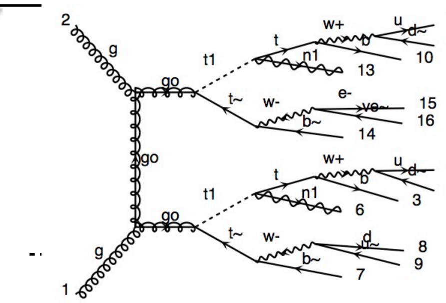
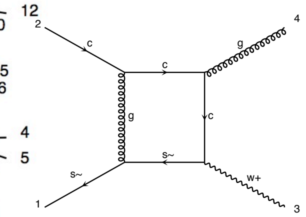


Double counting between ME and PS easily avoided using phase space cut between the two: PS below cutoff, ME above cutoff.

Type of generation

	Tree (B)SM	NLO (QCD) (SM)	NLO (QCD) (BSM)	NLO (EW) (SM)	Loop Induced (B)SM
Fix Order	✓	✓	✓	✓	✓





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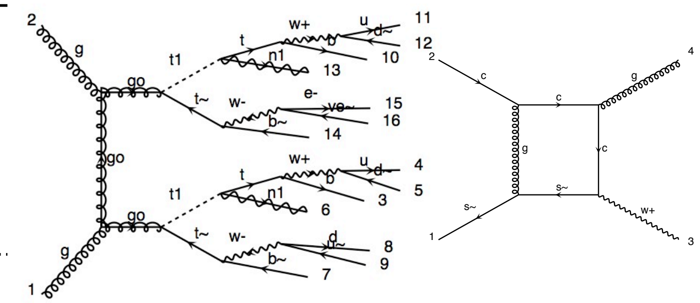
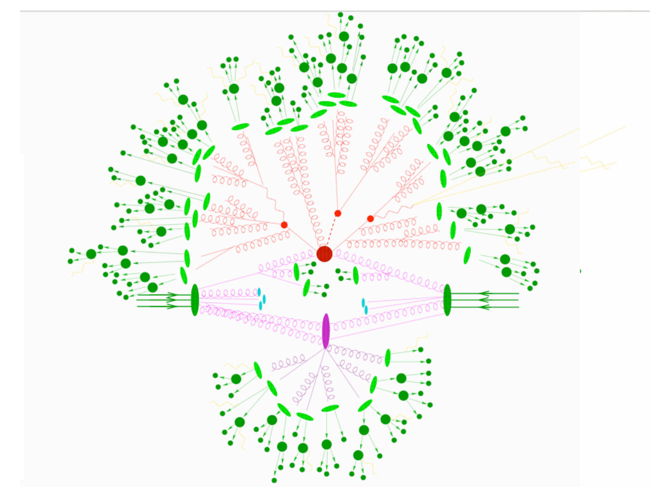
Fix Order	✓	✓	✓	✓	✓
+Parton Shower	✓	✓	✓	✗	✓





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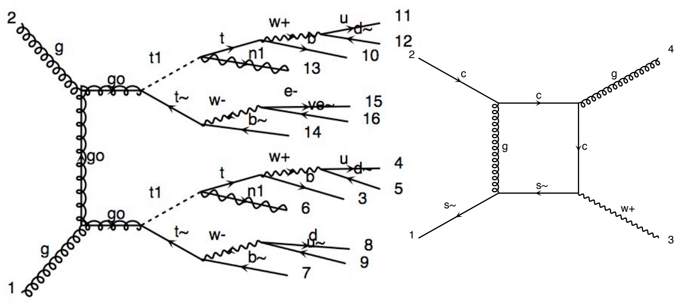
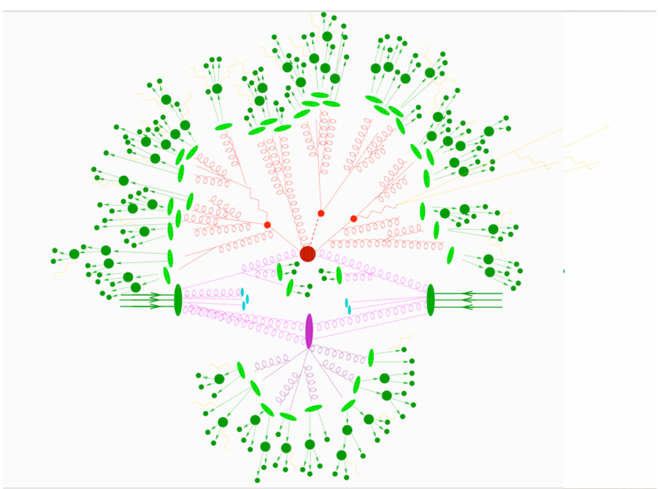
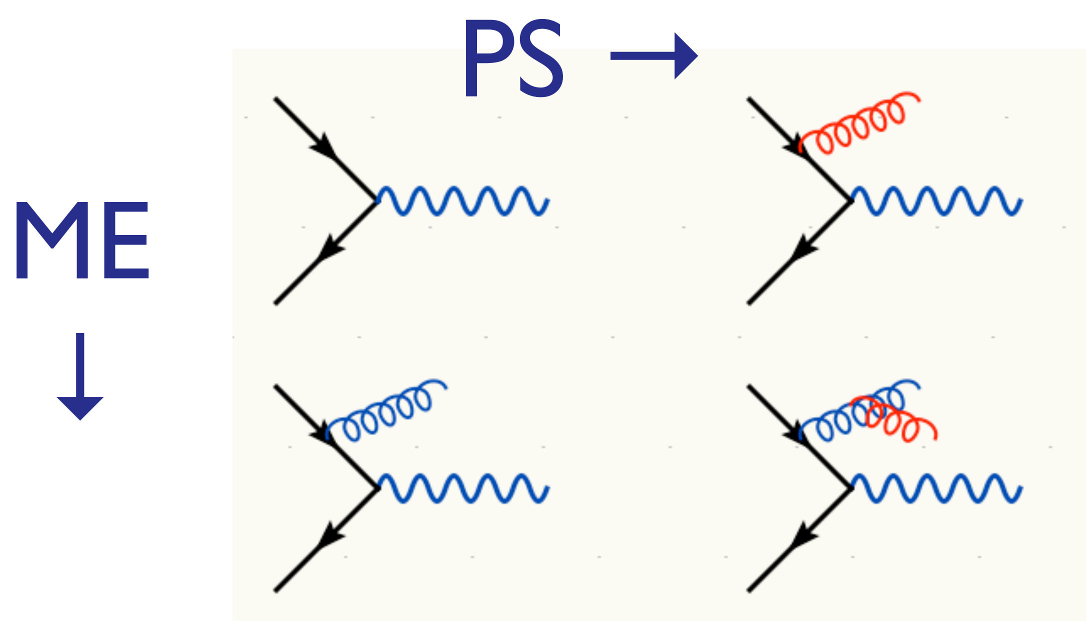
Fix Order	✓	✓	✓	✓	✓
+Parton Shower	✓	✓	✓	✗	✓
Merged Sample	✓	✓	?	✗	✓







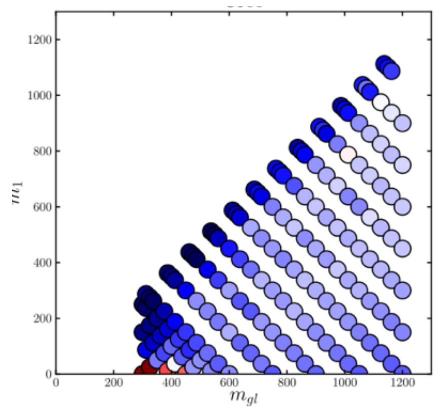
LO Feature

LO Feature

Auto-Width

$$\Gamma = ?$$

Parameter scan



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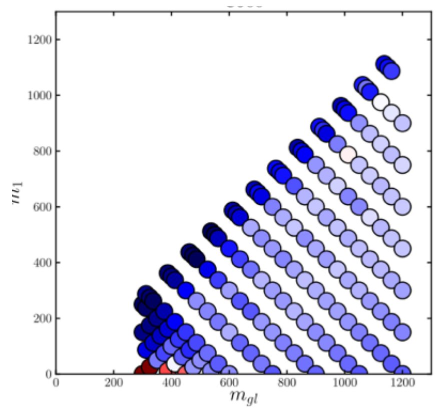
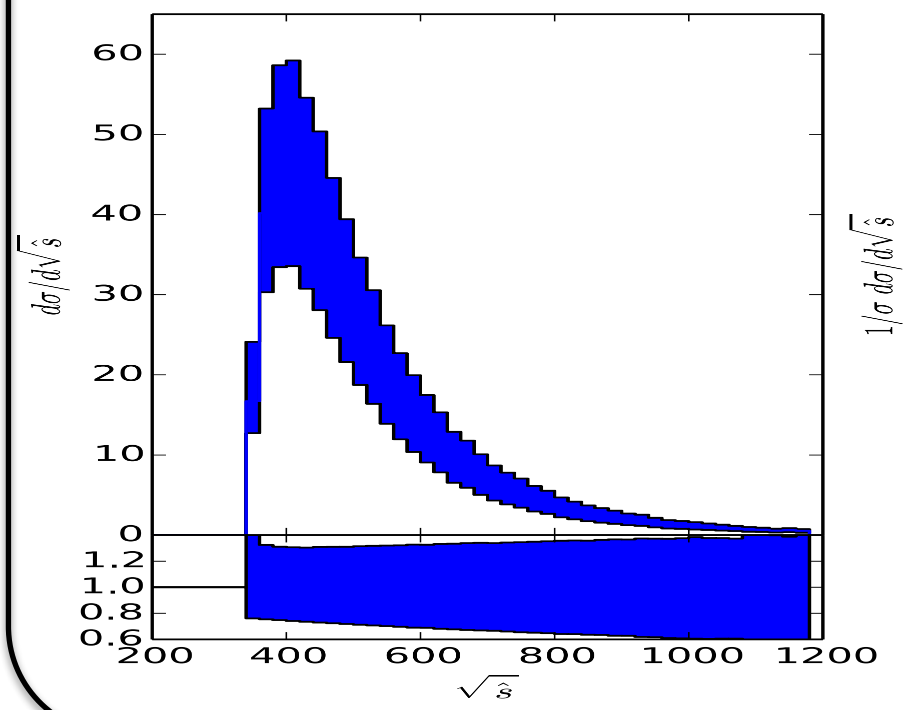
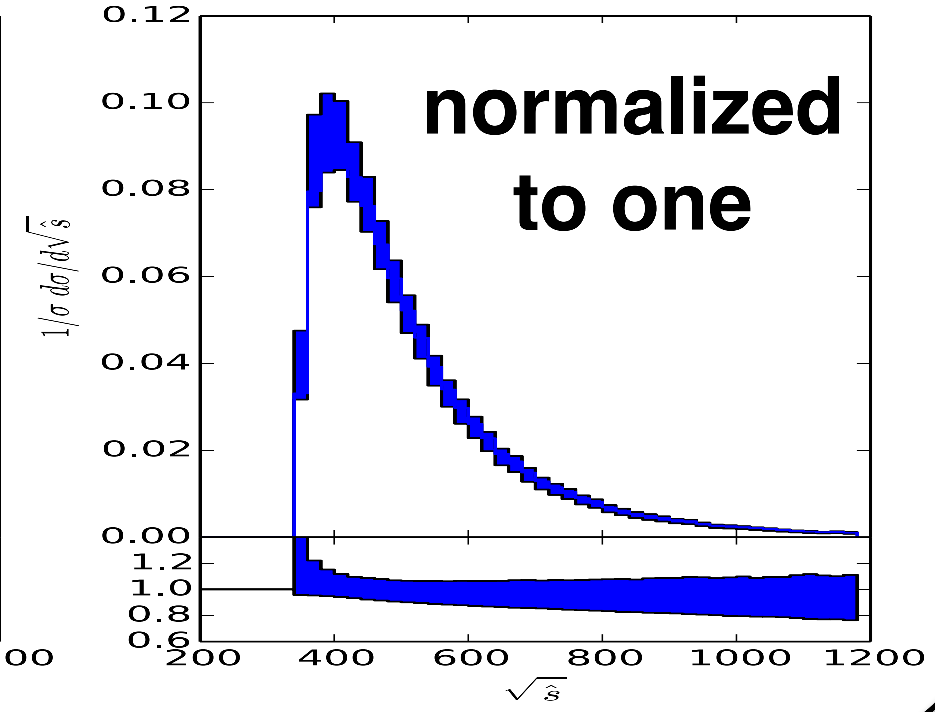


Systematics





BSM re-weighting

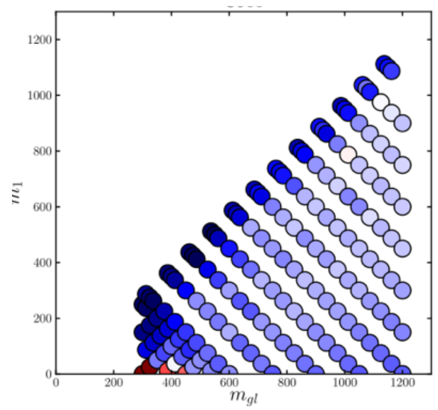
$$|M_{new}|^2 / |M_{old}|^2$$

LO Feature

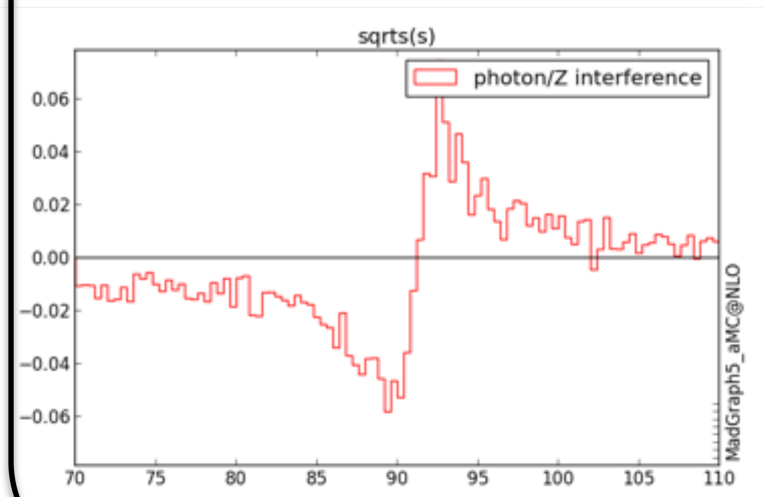
Auto-Width

$$\Gamma = ?$$

Parameter scan



Interference



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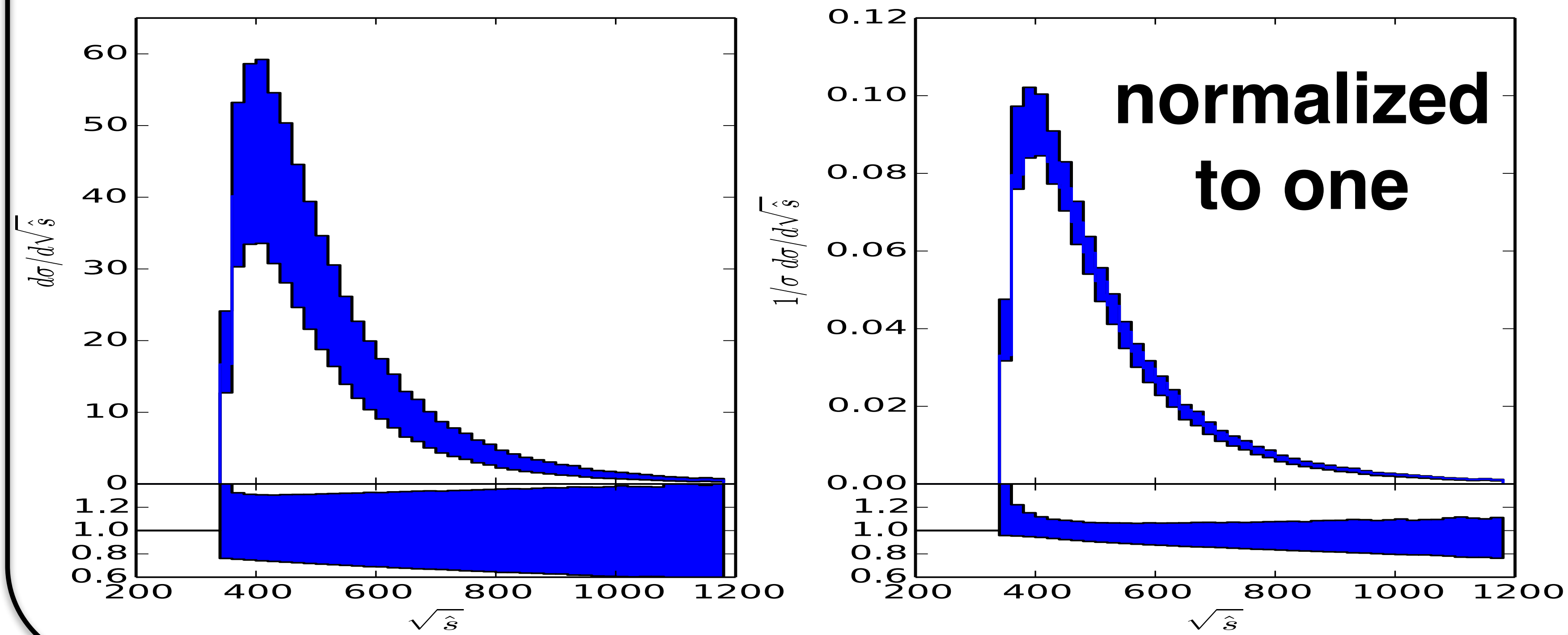

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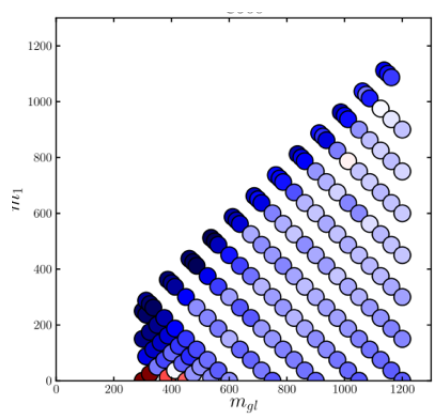

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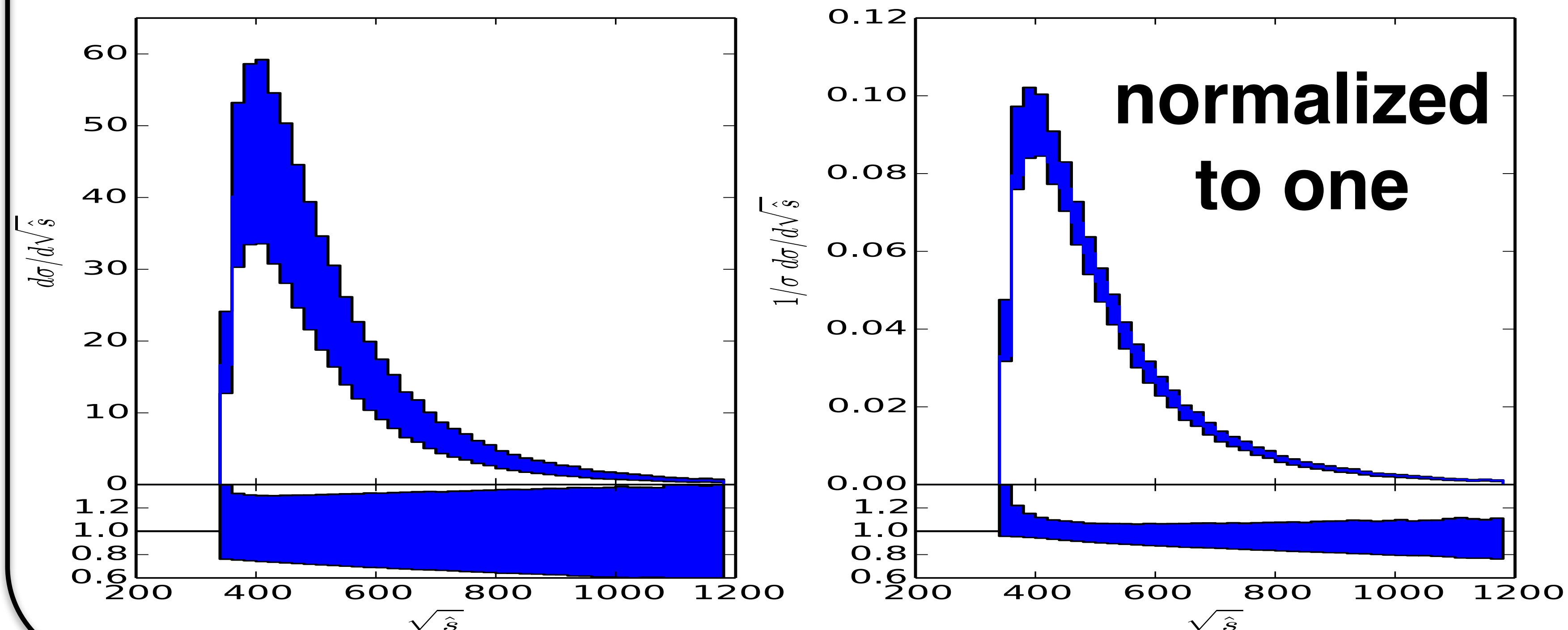
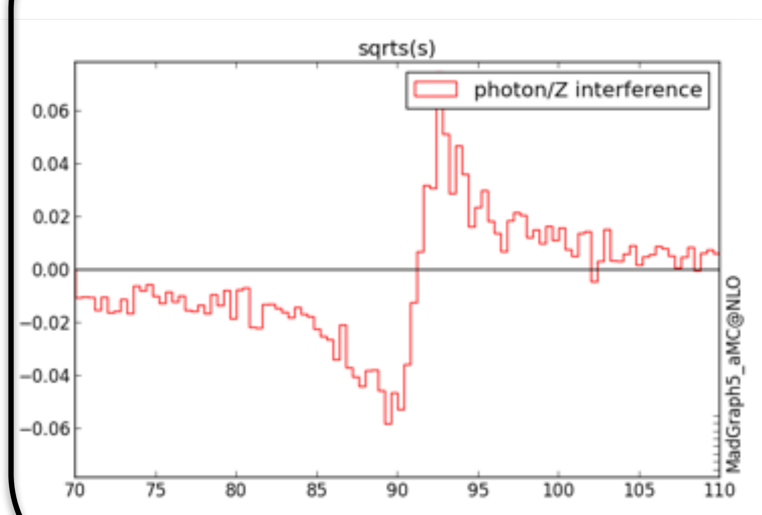
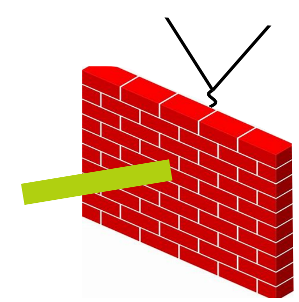


Interference



Plugin



Interface

MAD Analysis 5

BSM re-weighting

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LO Feature

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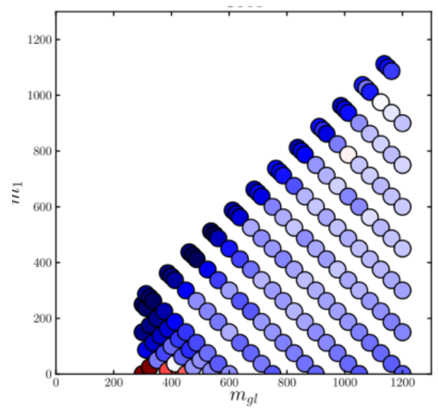
Parameter scan



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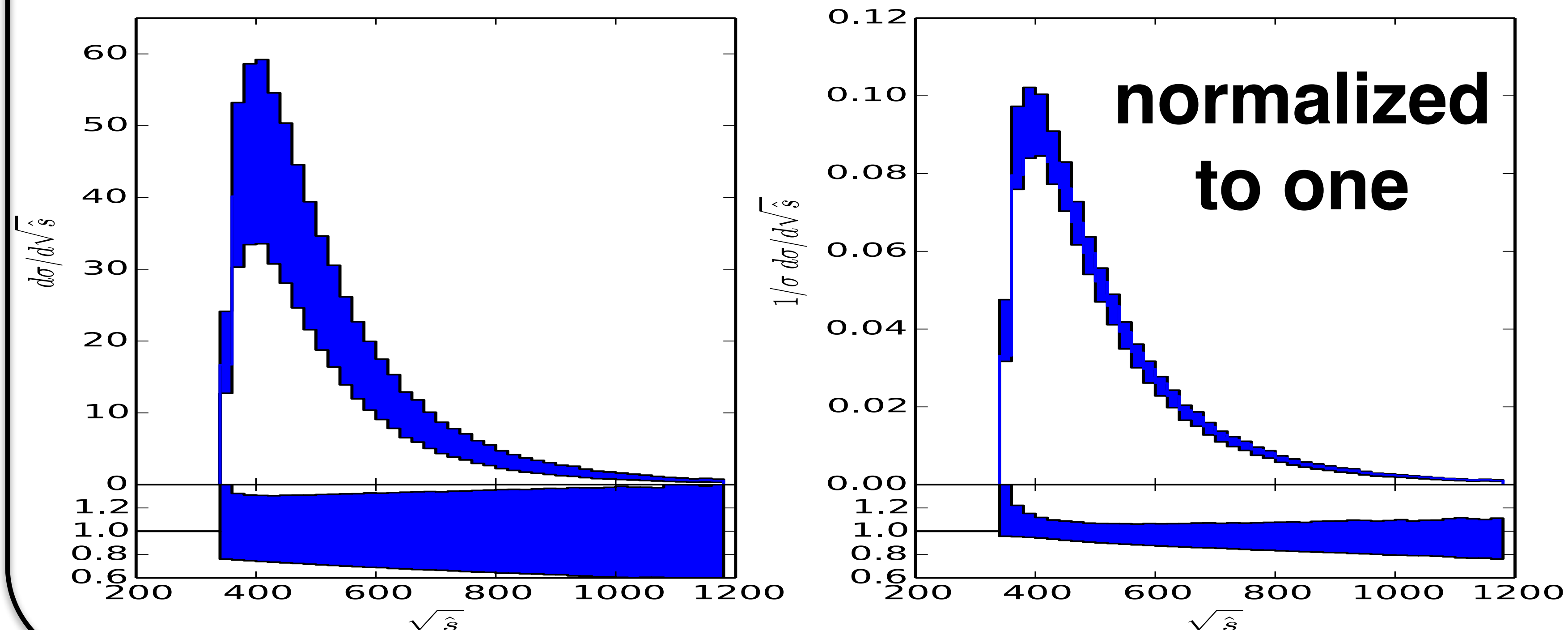

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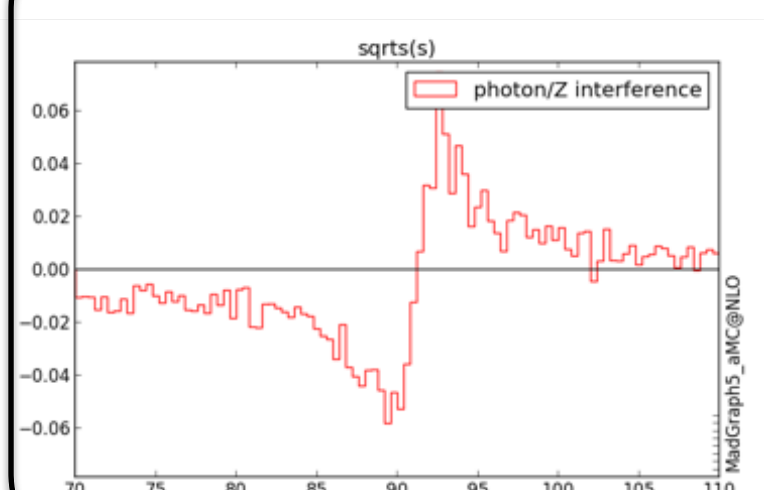
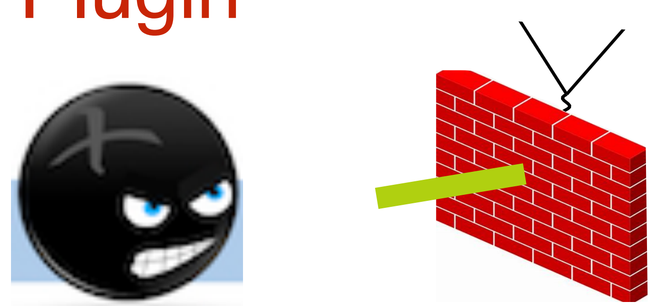
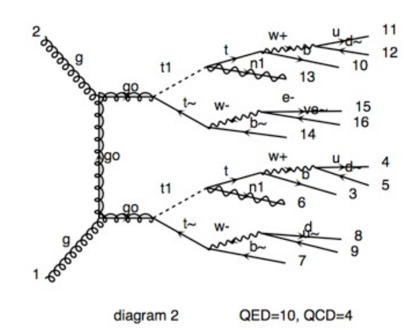


Plugin



Narrow-width



Interface

MADAnalysis 5

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