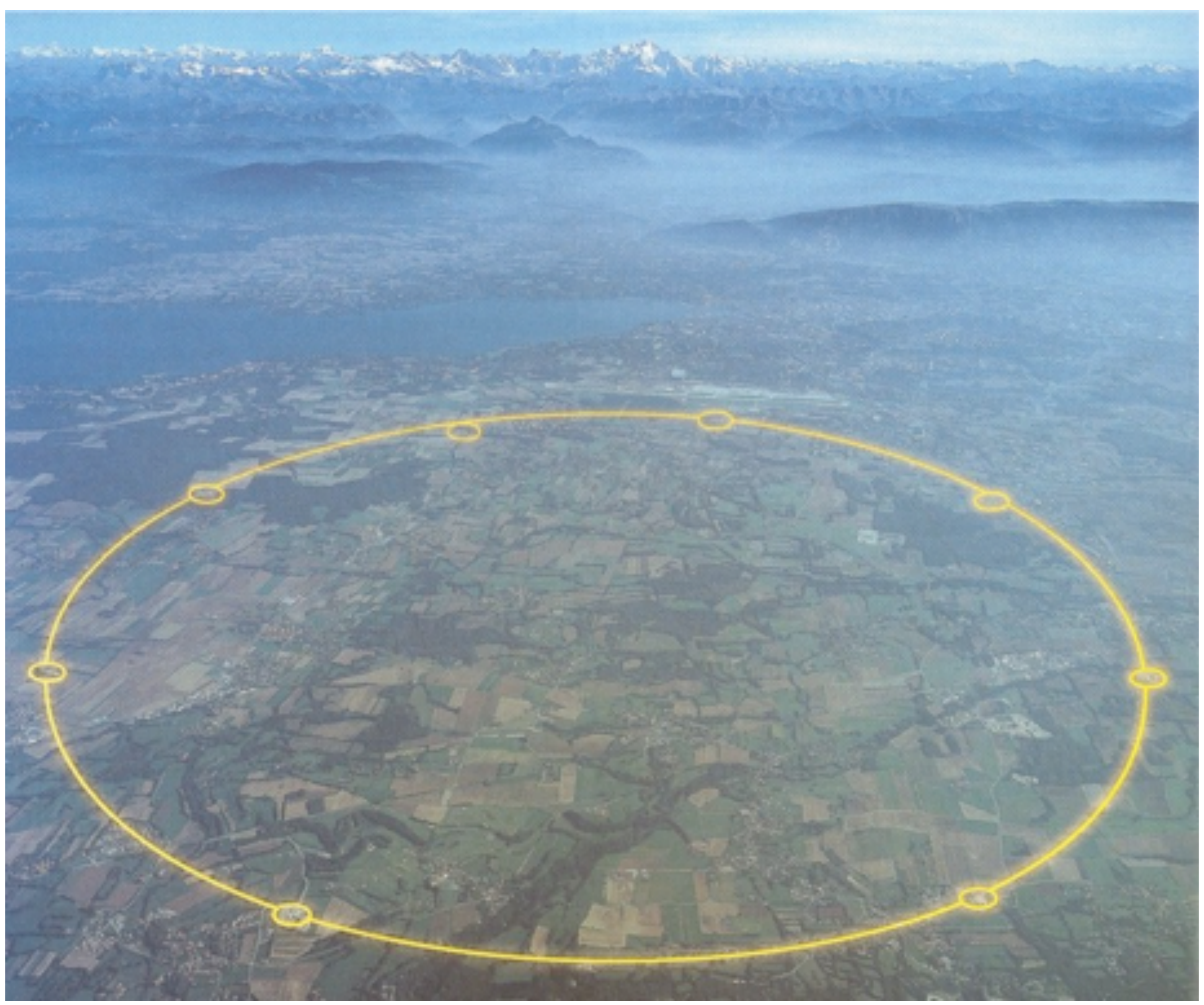
Monte-Carlo Generation

Olivier Mattelaer
IPPP/Durham

Introduction

Topic

- Collider Physics



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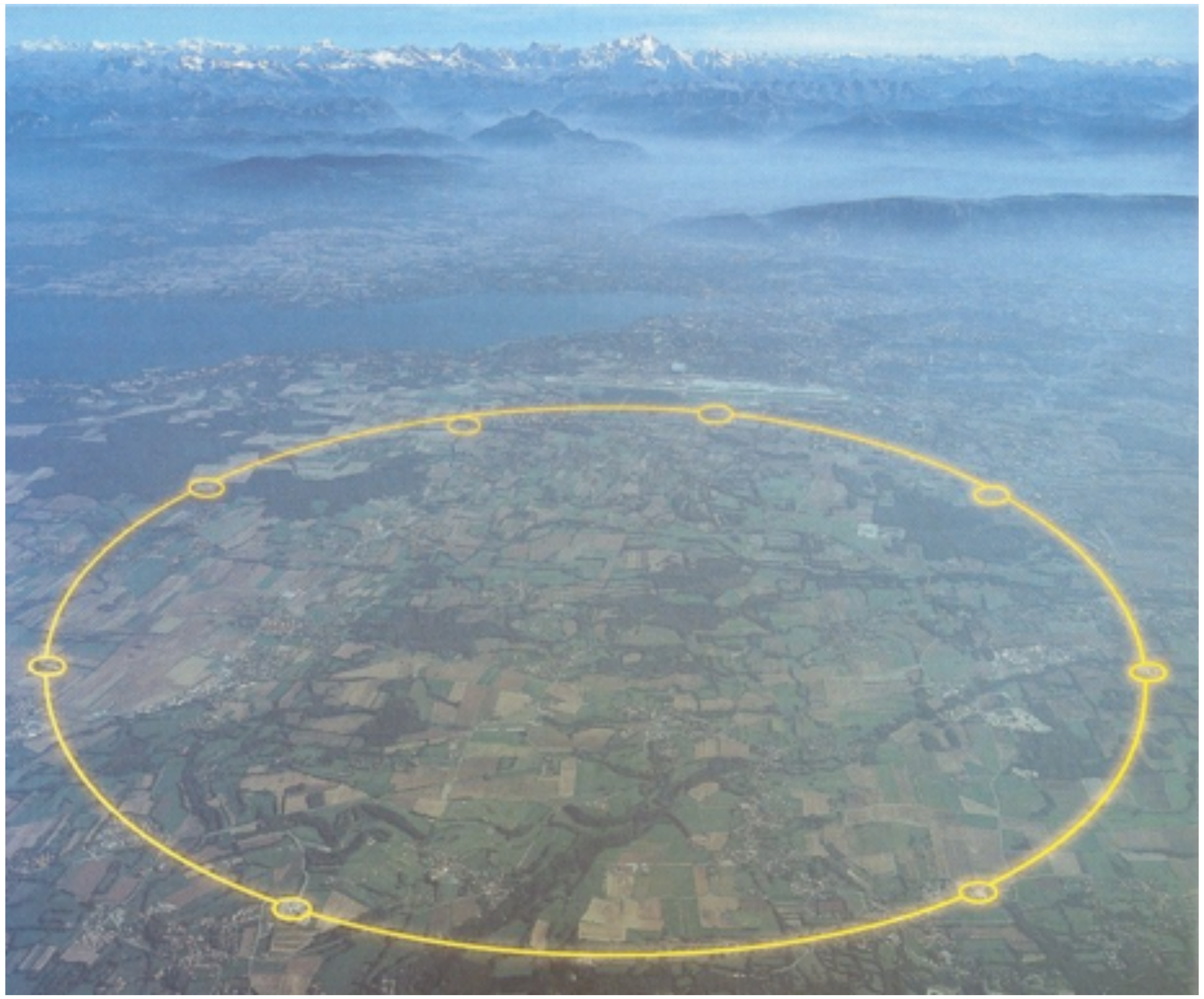
  - accelerating particle -> High Energy collision



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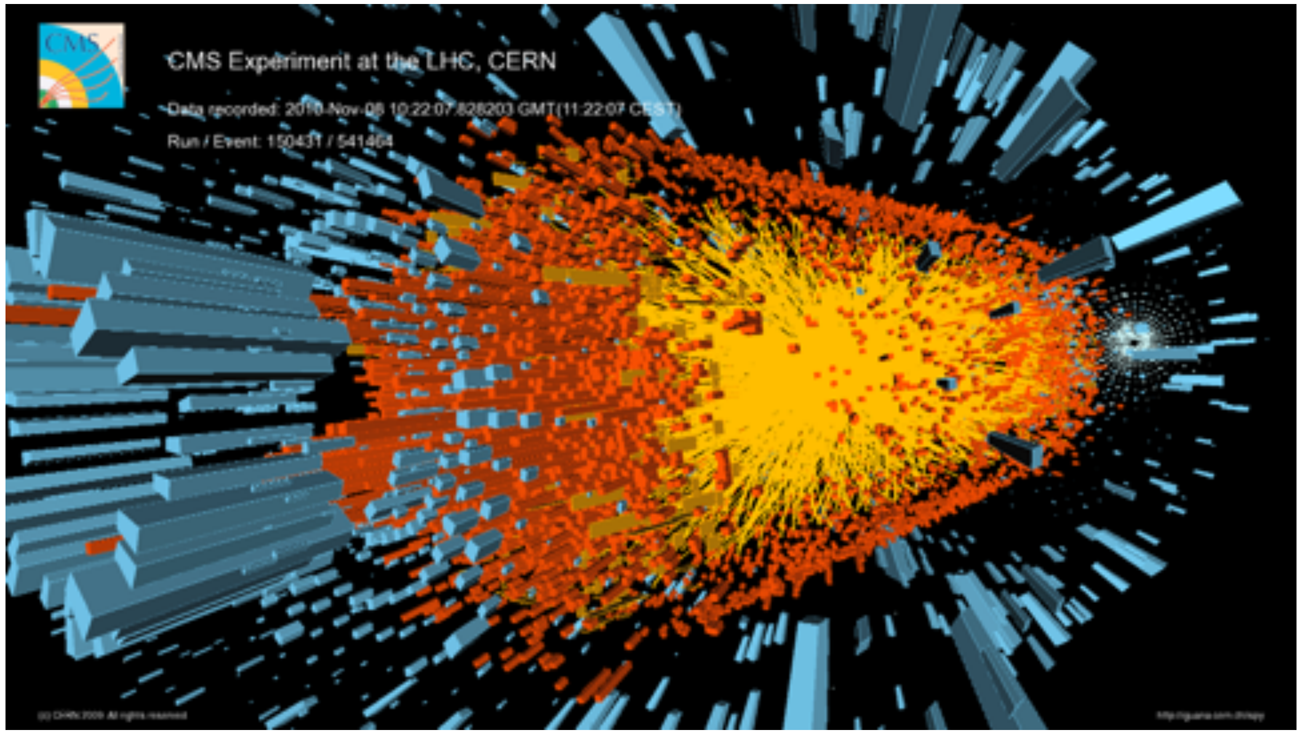
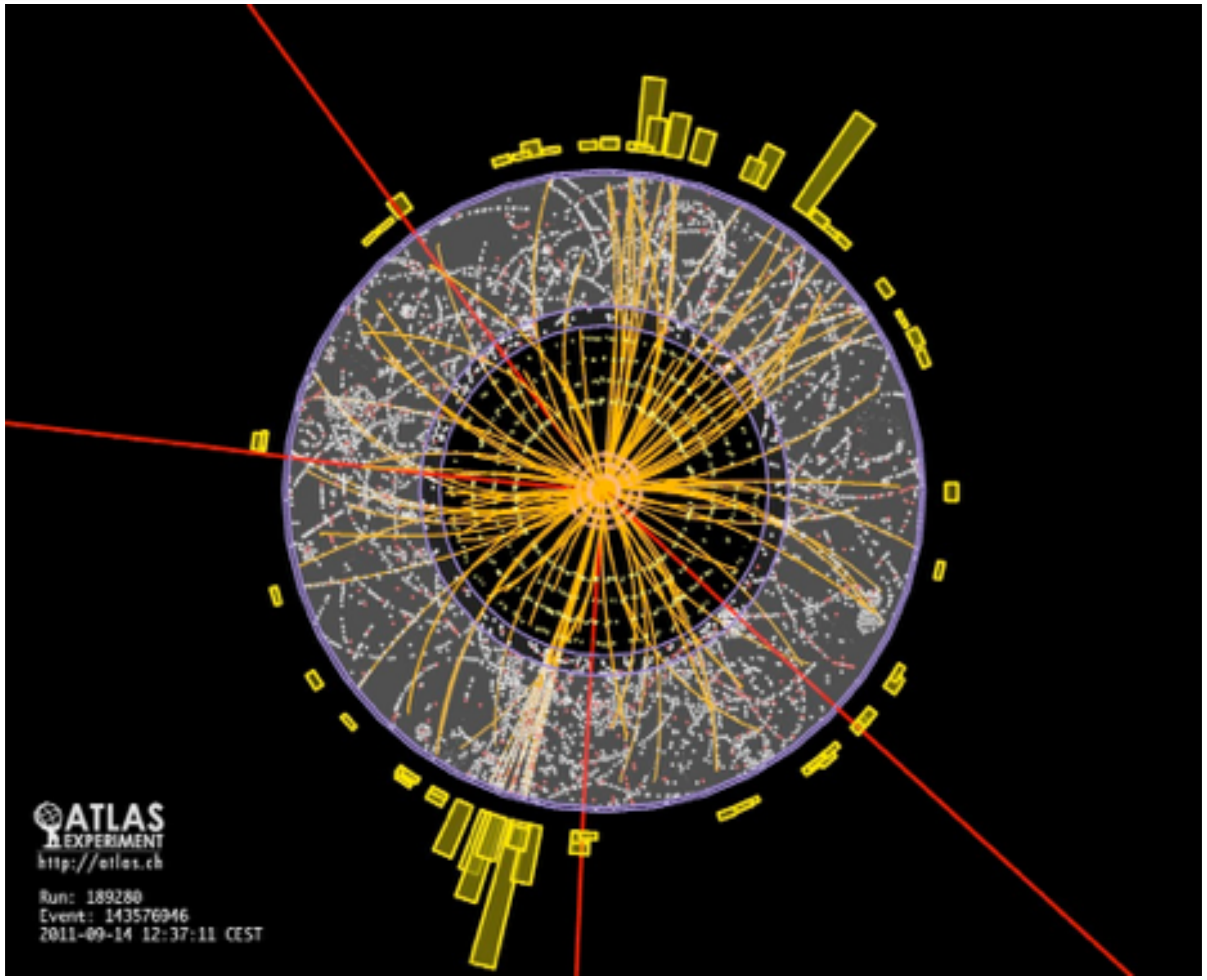
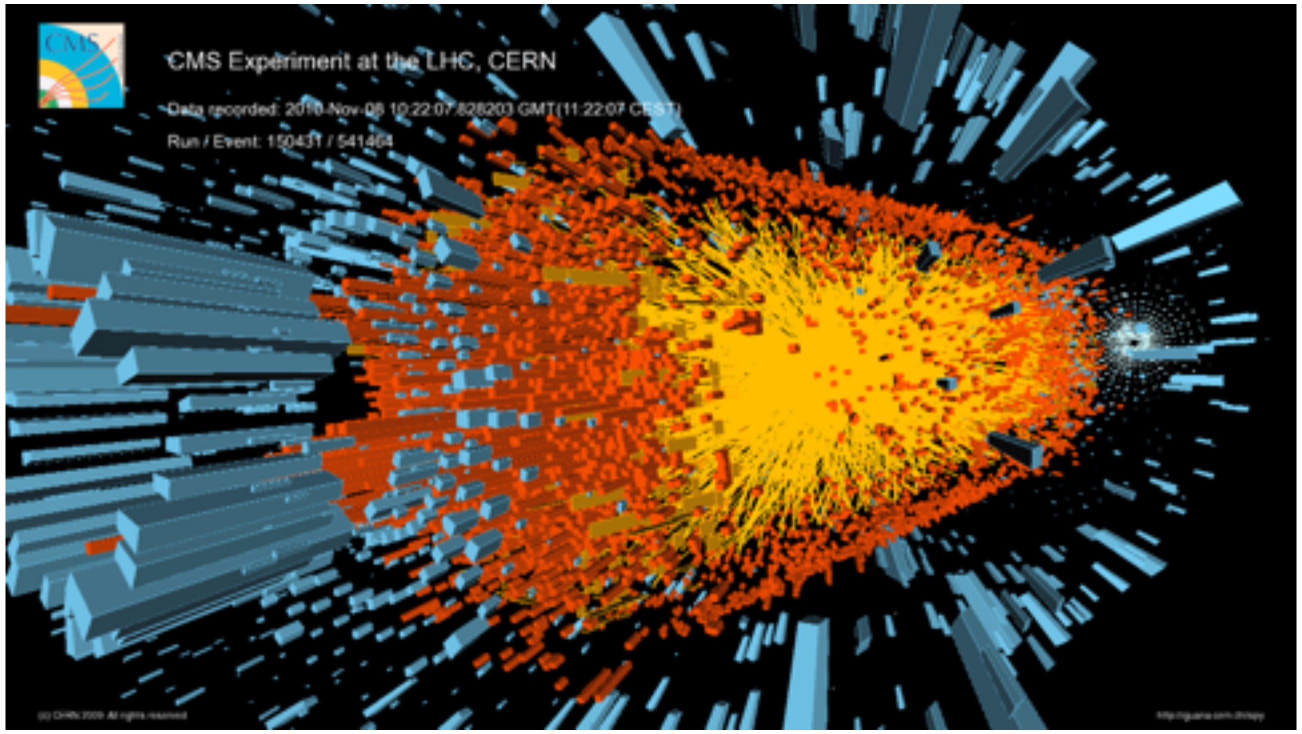


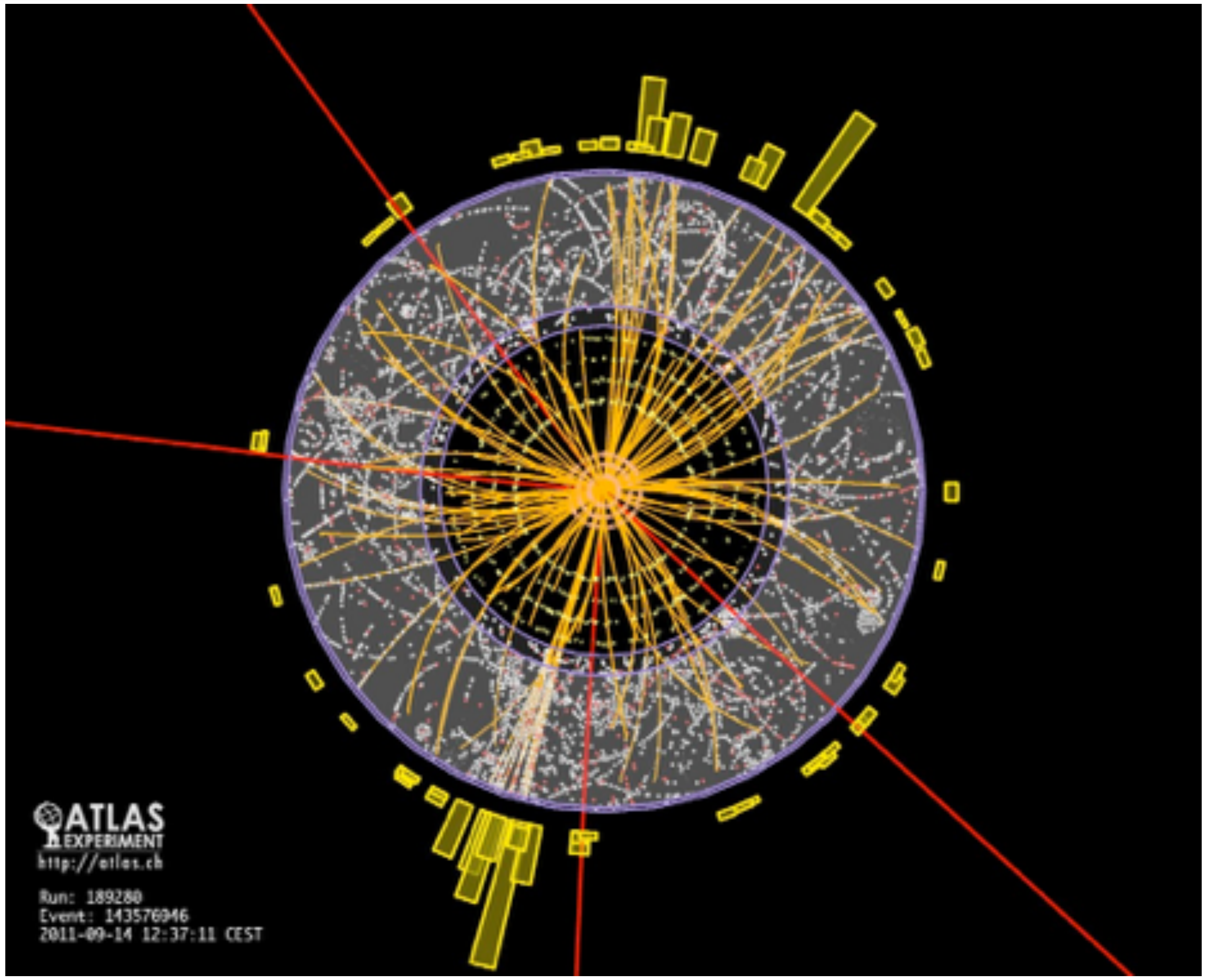


Introduction

Topic

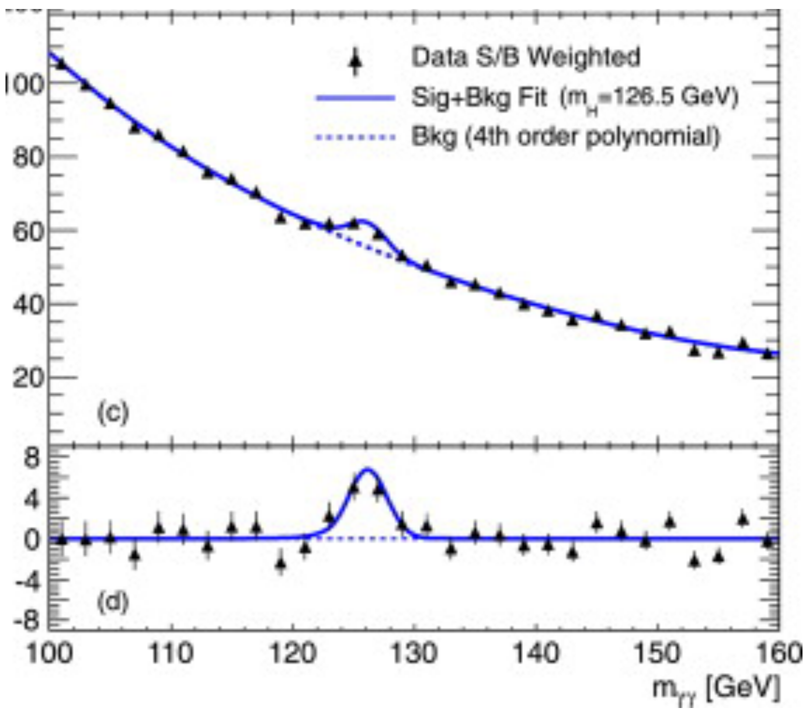
- Collider Physics
  - accelerating particle -> High Energy collision
- What do we need to predict/understand such collision?





Kind of measurement

Peak



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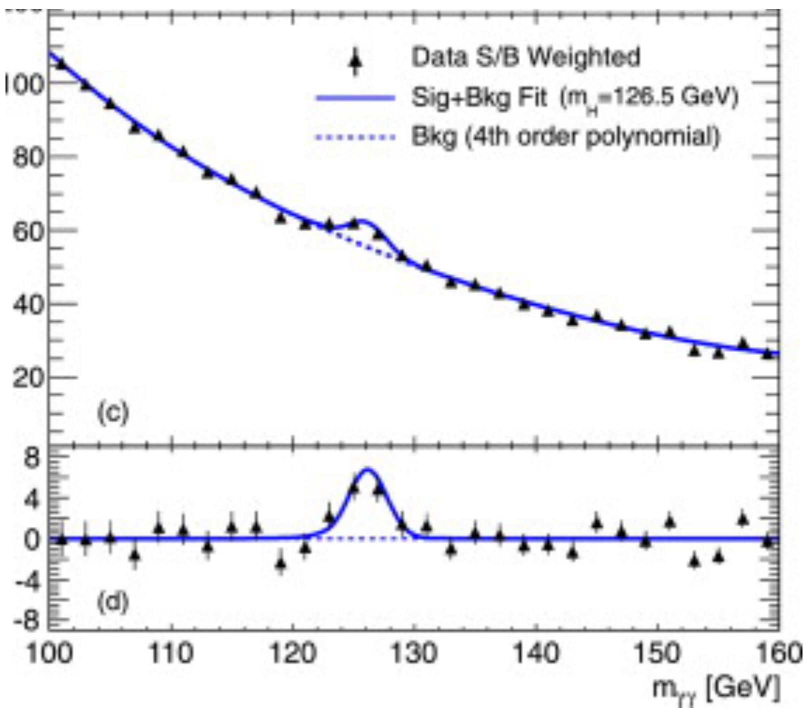
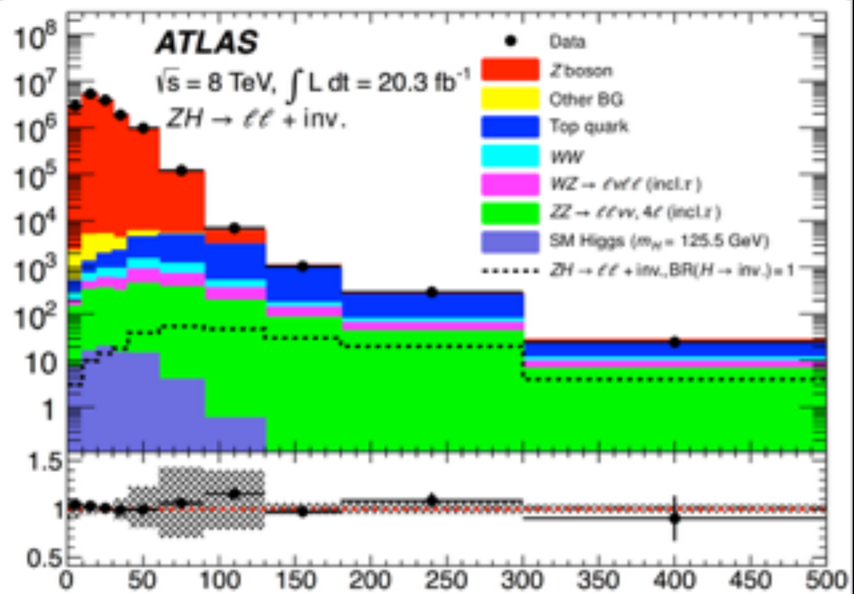


Shape



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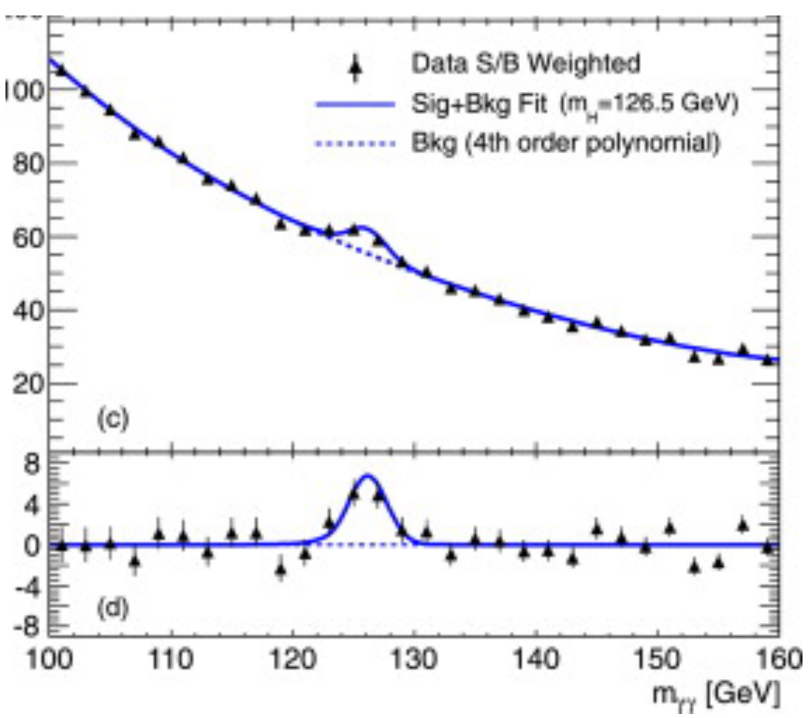

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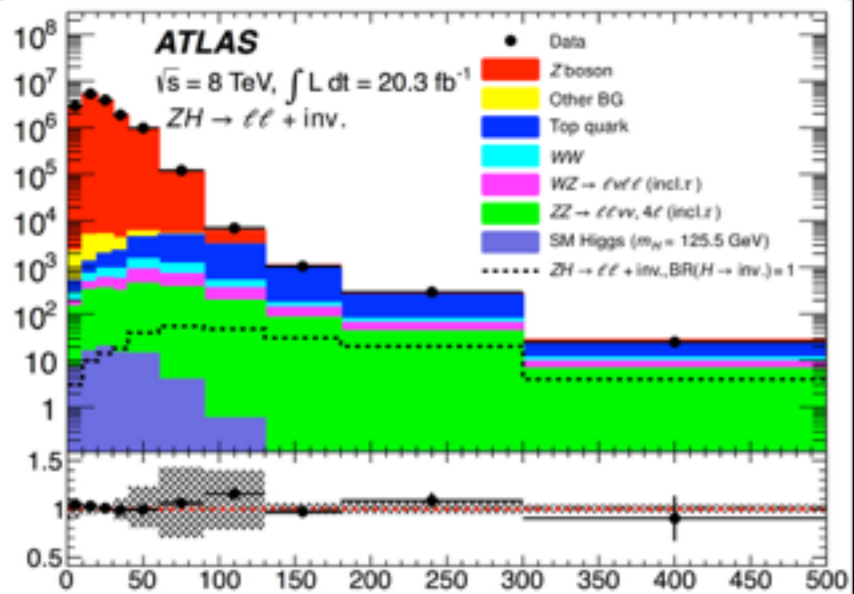
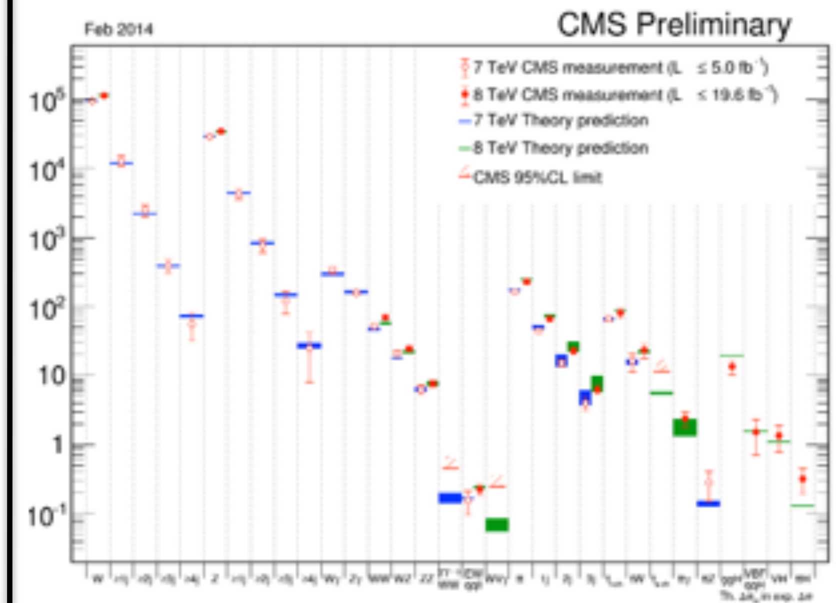


Rate



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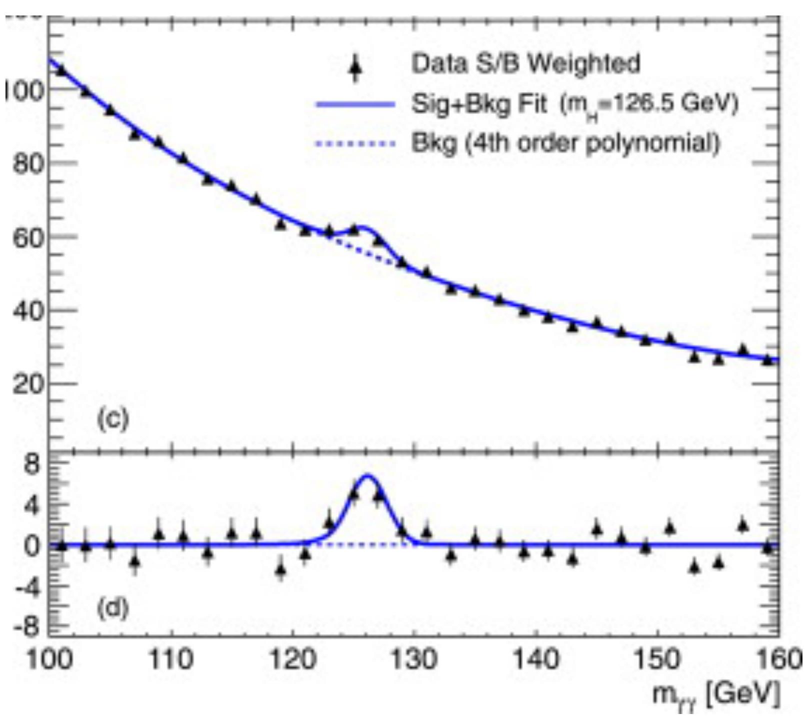
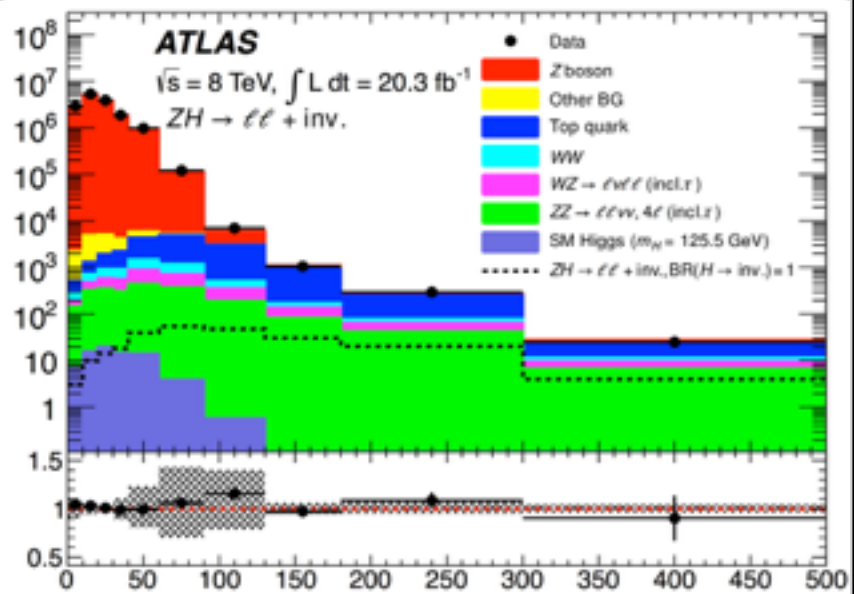


“EASY”

Shape



“HARD”

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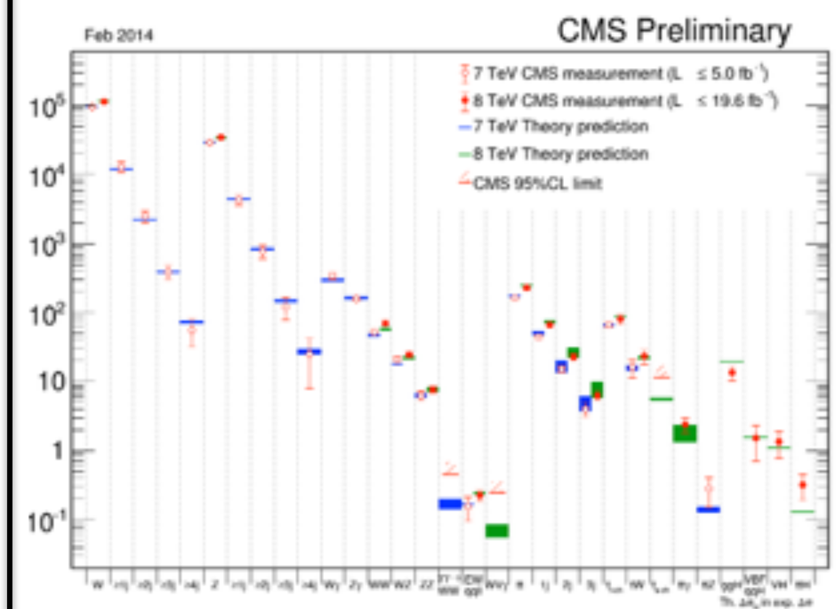

“VERY HARD”

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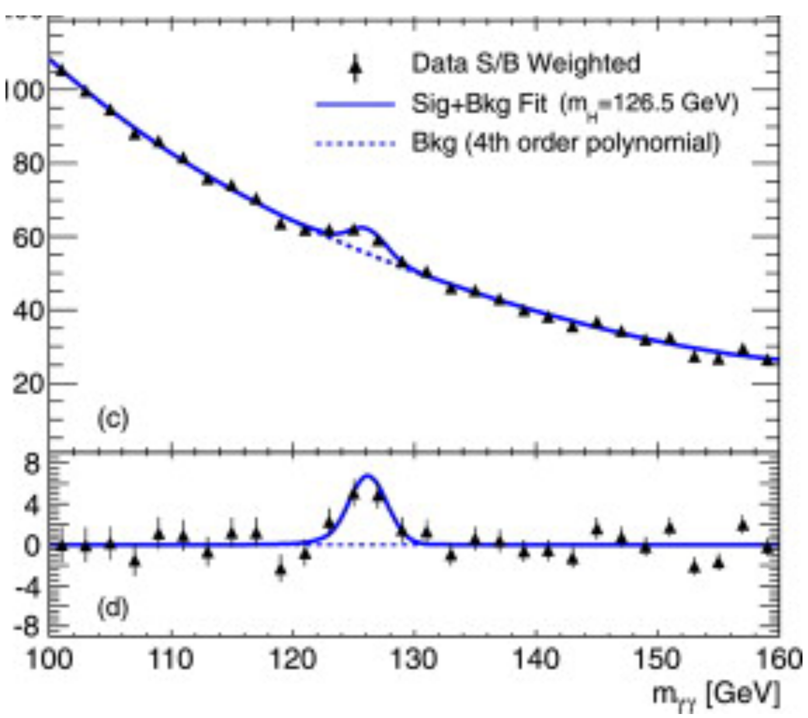

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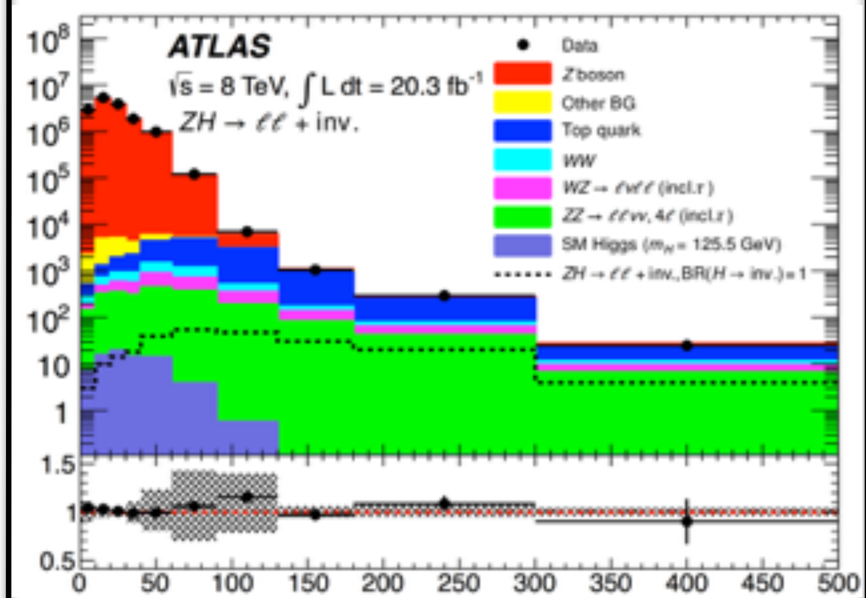
Background directly measured from **data**. Theory needed only for parameter extraction

Shape



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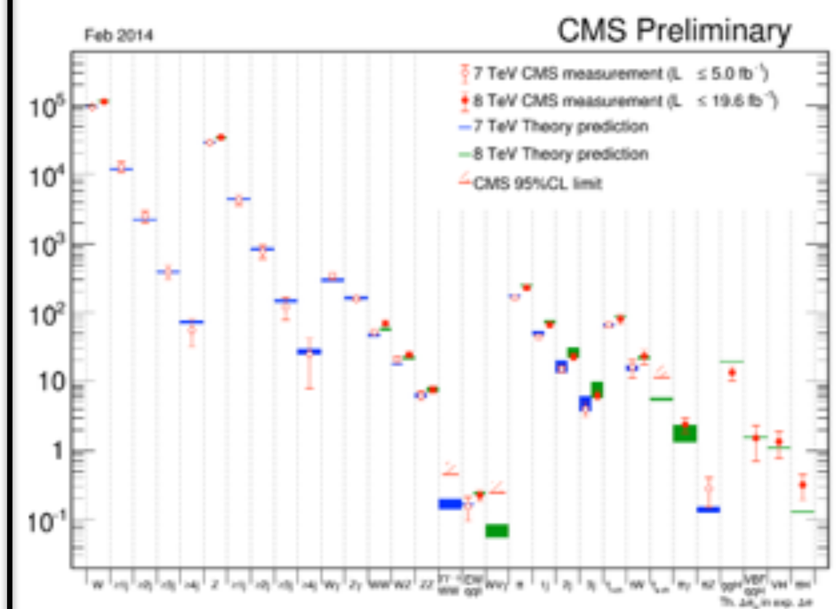

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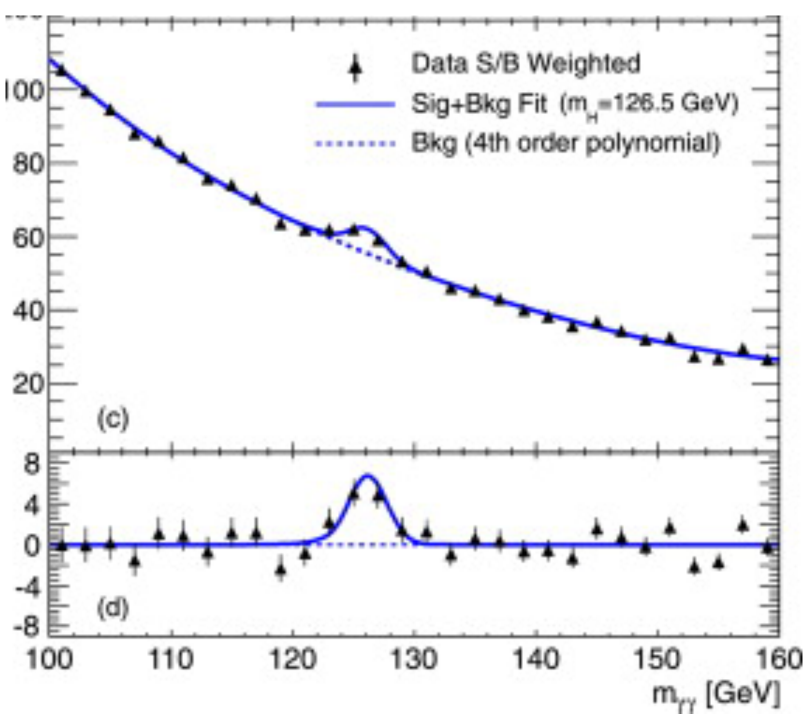

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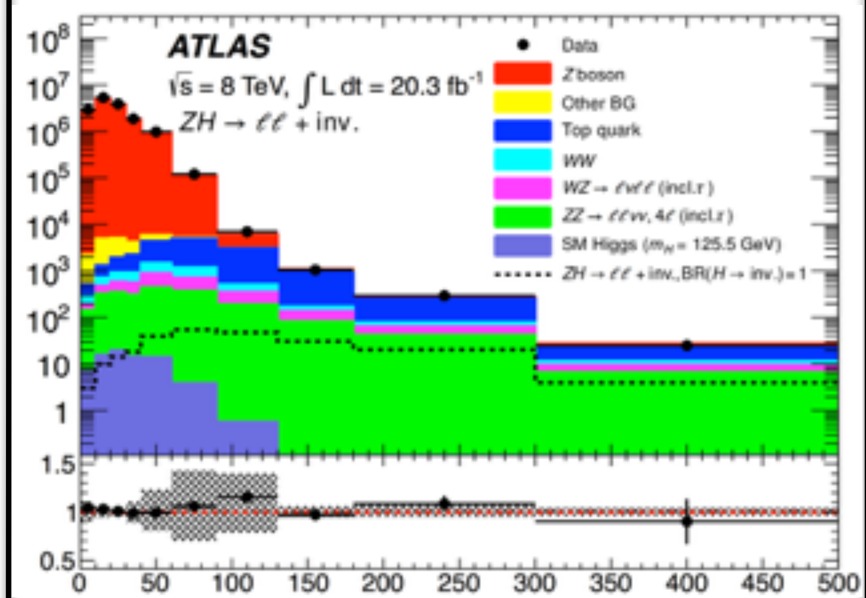
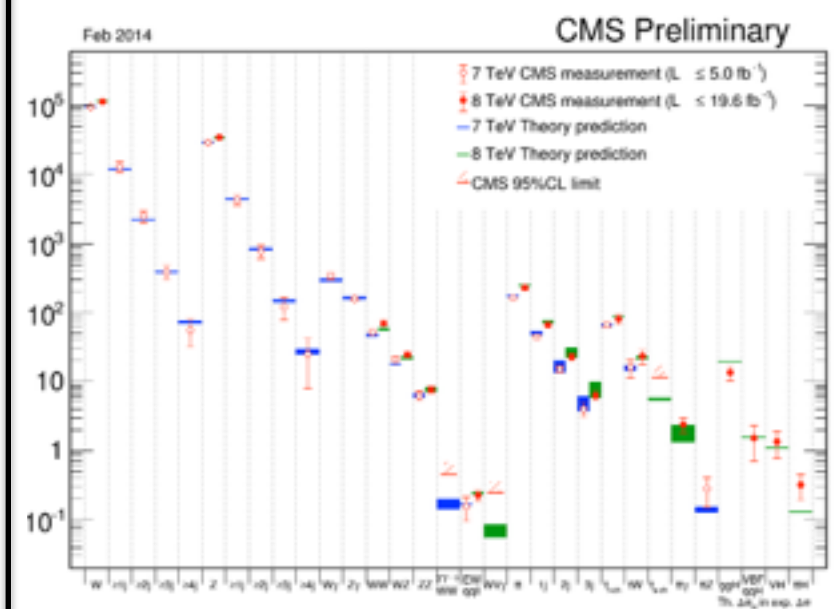


“HARD”

Background **SHAPE** needed. Flexible MC for both signal and background validated and tuned to data

Rate



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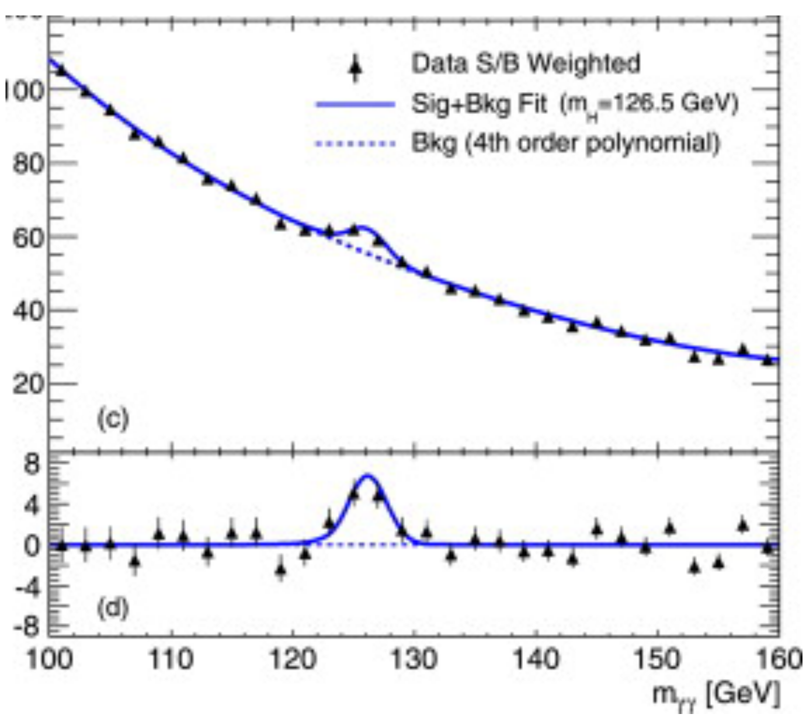

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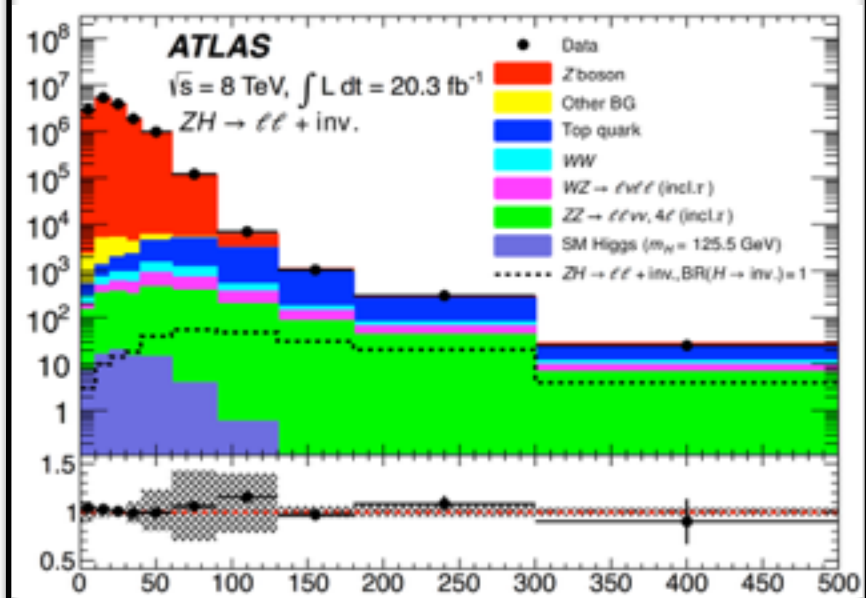

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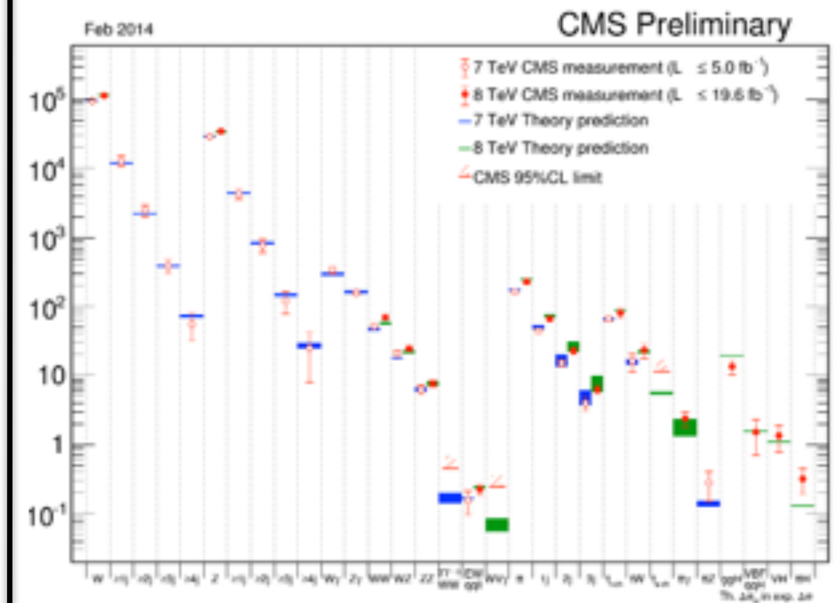
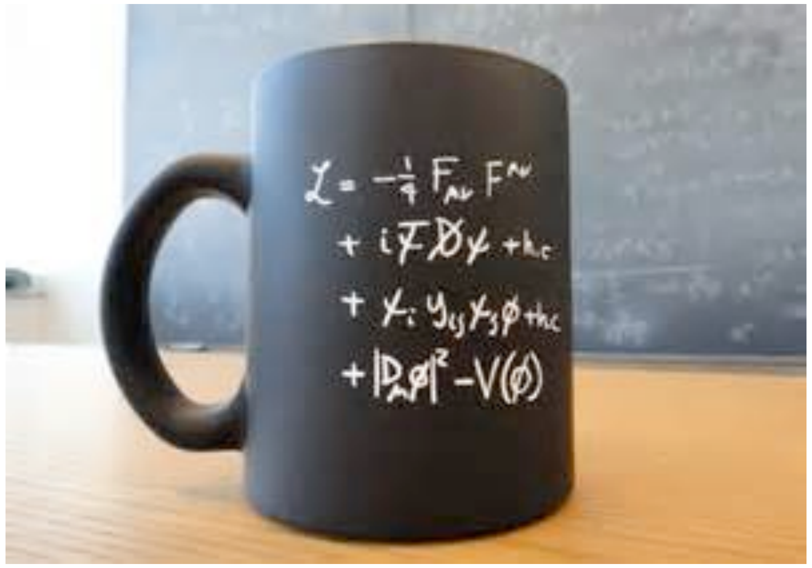


“VERY HARD”

Relies on prediction for both **shape** and **normalization**. Complicated interplay of best simulations and data

Theory side

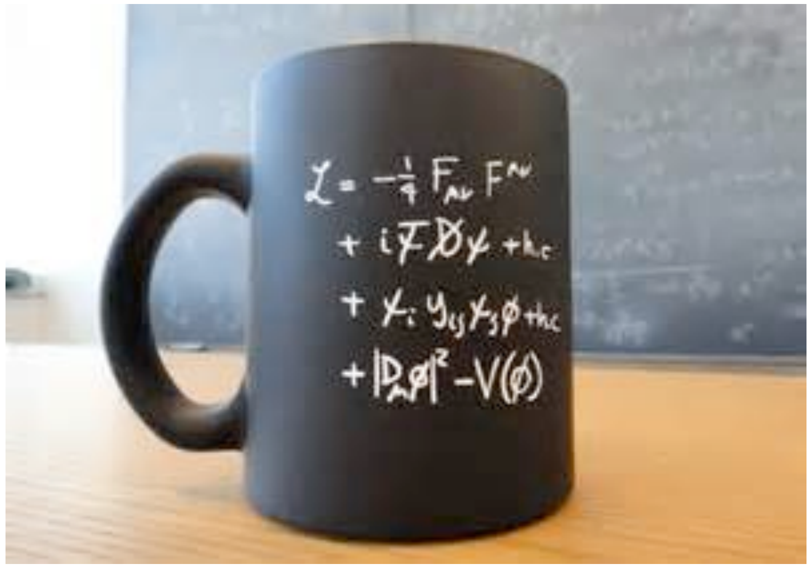
Lagrangian



- This is Where the new idea are expressed

Theory side

Lagrangian



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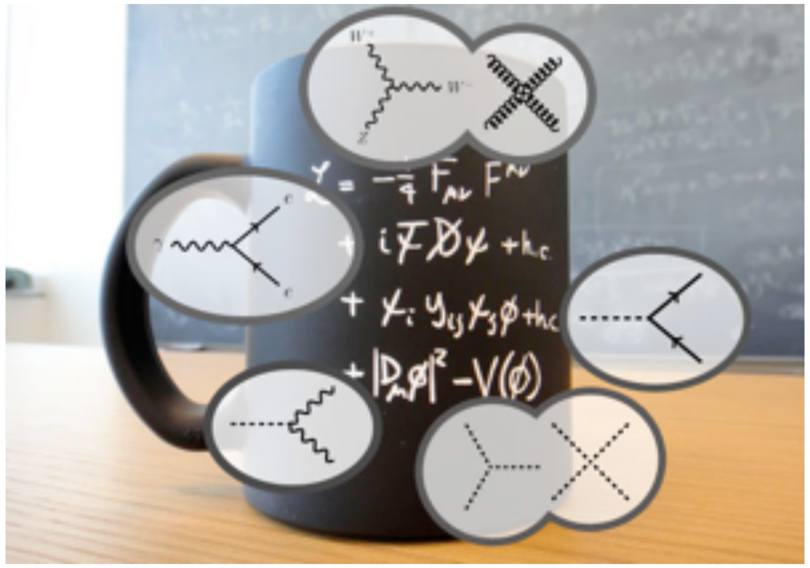
Feynman Rule

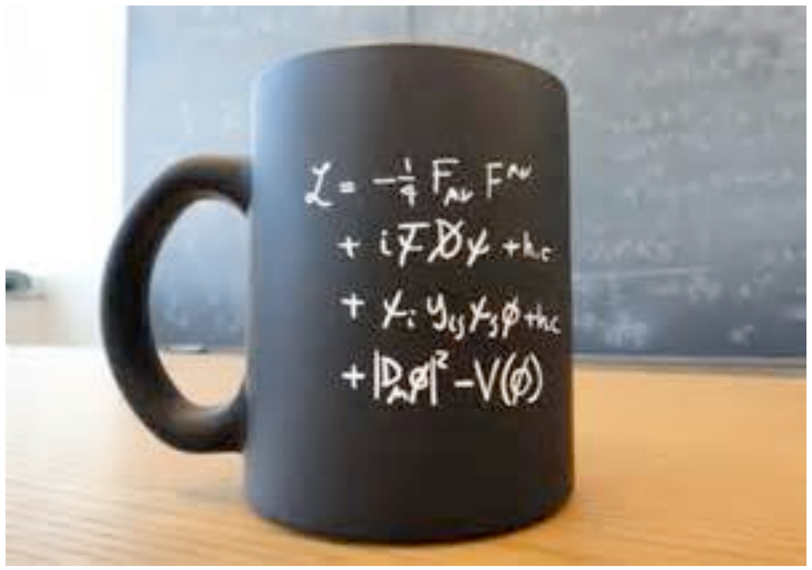


- Same information as the Lagrangian

FeynRules

Theory side

Lagrangian



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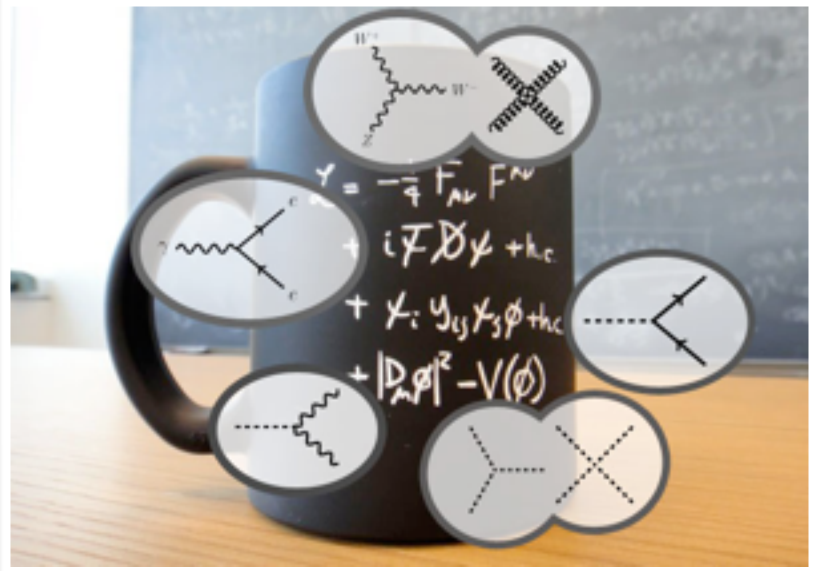
Feynman Rule

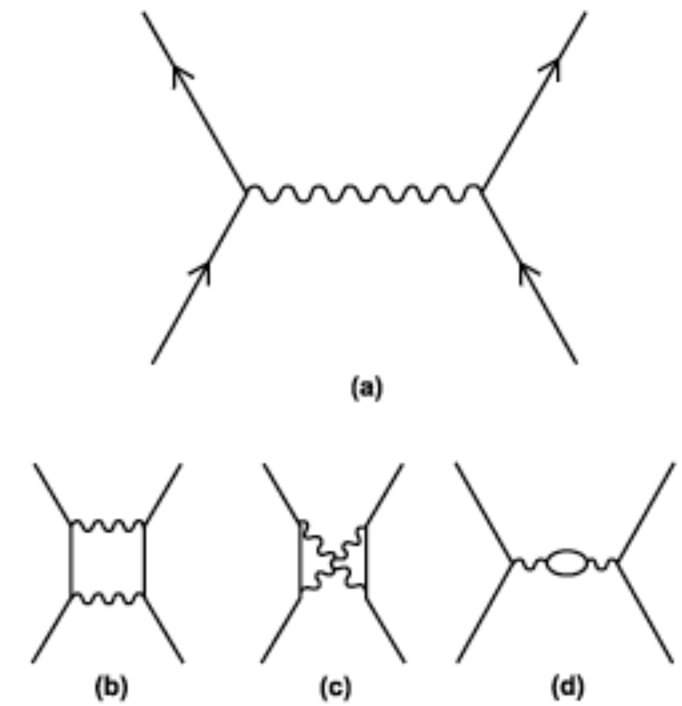


- Same information as the Lagrangian

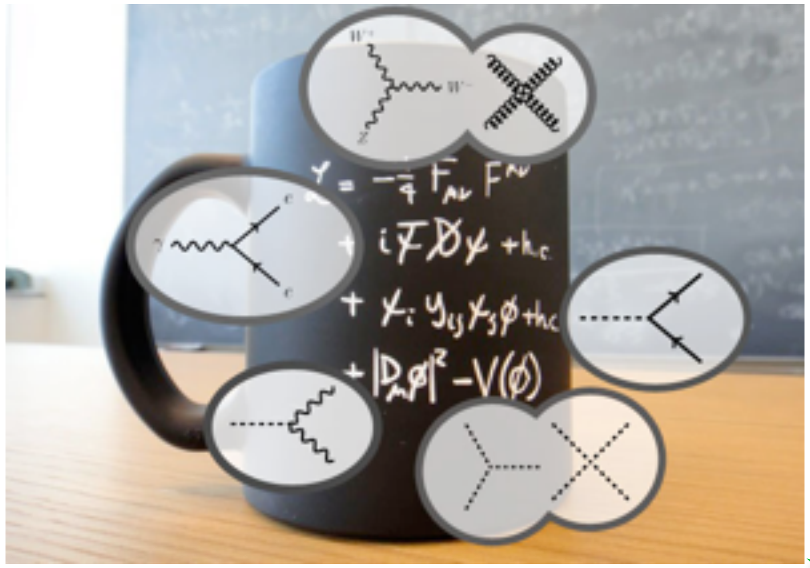
FeynRules

Cross-section

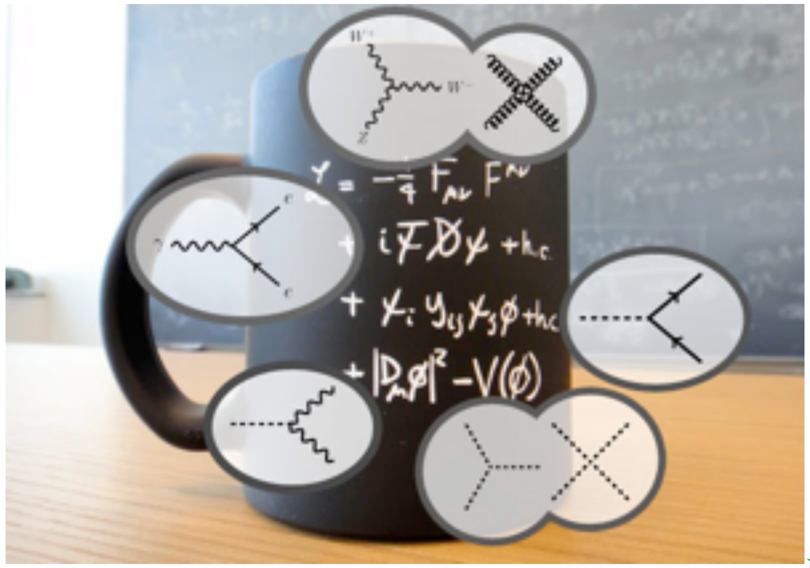
$$\frac{d\sigma}{d\ \cos\theta} = \left(\frac{d\sigma}{d\ \cos\theta}\right)_R \frac{(1+\cos\theta)/2}{\left[1+\frac{(1-\cos\theta)KE}{Mc^2}\right]}$$



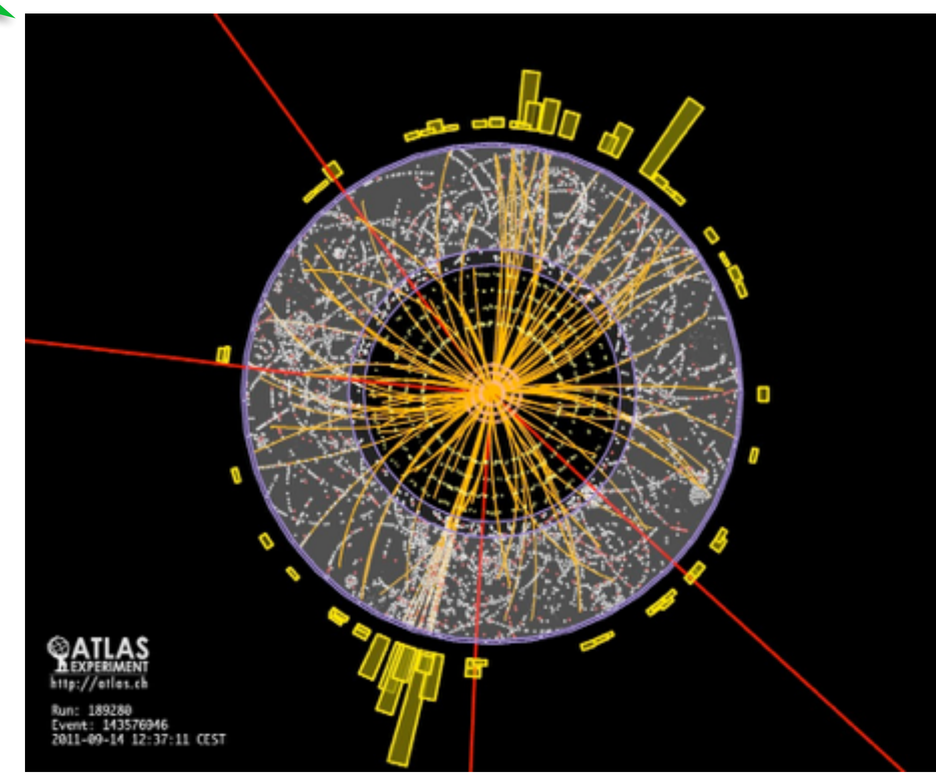
- What is the precision?



Monte-Carlo Physics

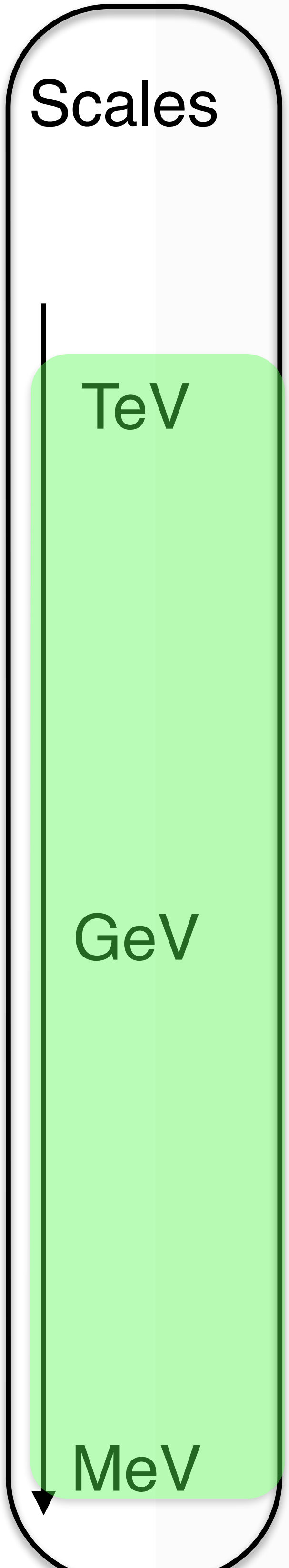


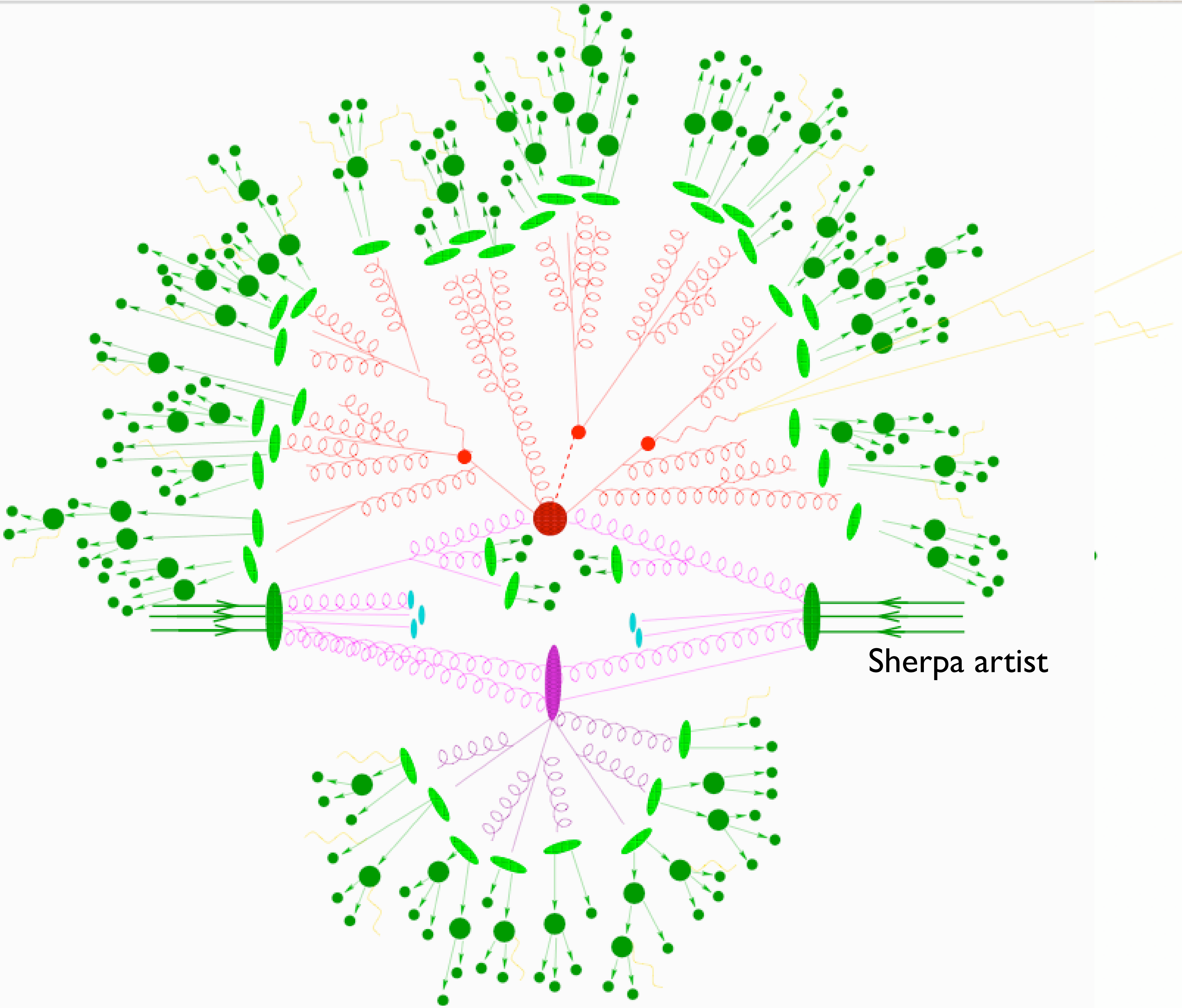
Monte-Carlo Physics



Simulation of collider events

What are the MC for?





What are the MC for?

Scales

TeV

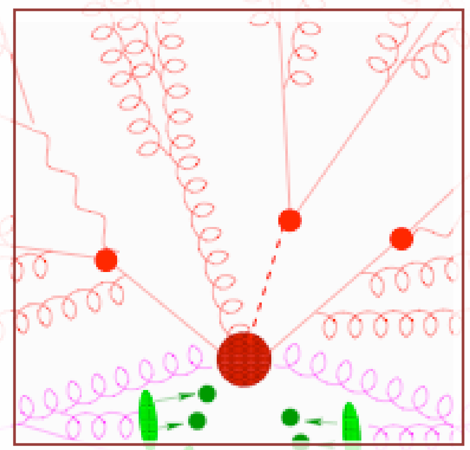
GeV

MeV

1. High-Q^2 Scattering

2. Parton Shower

☞ where BSM physics lies



☞ process dependent

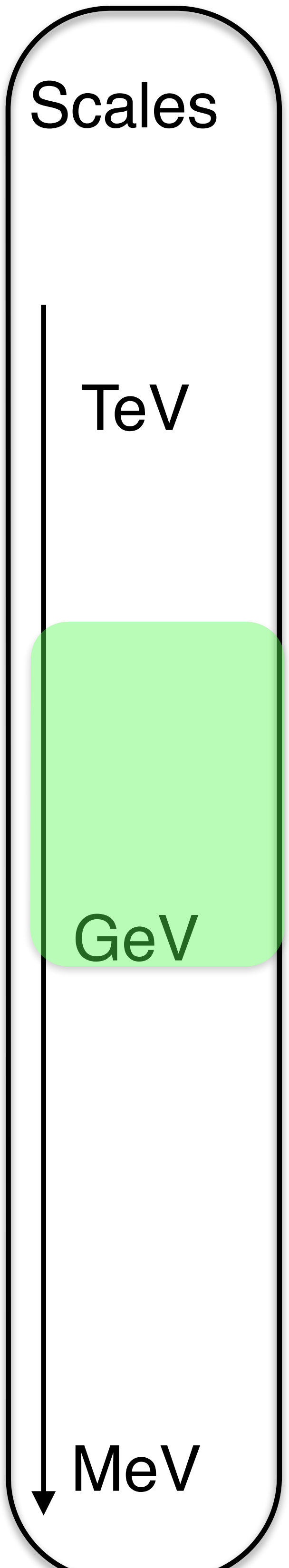
☞ first principles description

☞ it can be systematically improved

3. Hadronization

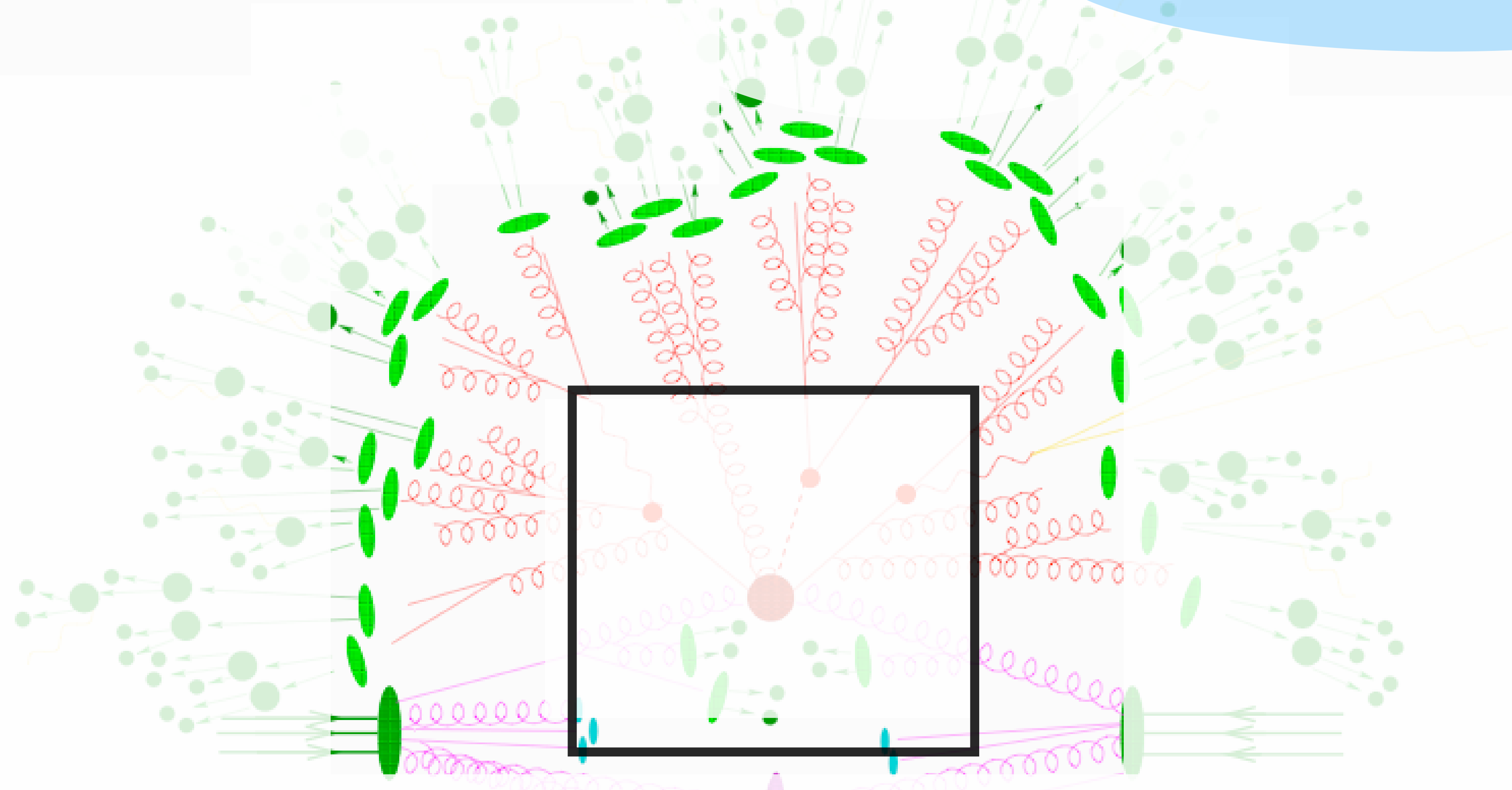
4. Underlying Event

What are the MC for?



1. High-Q^2 Scattering

2. Parton Shower

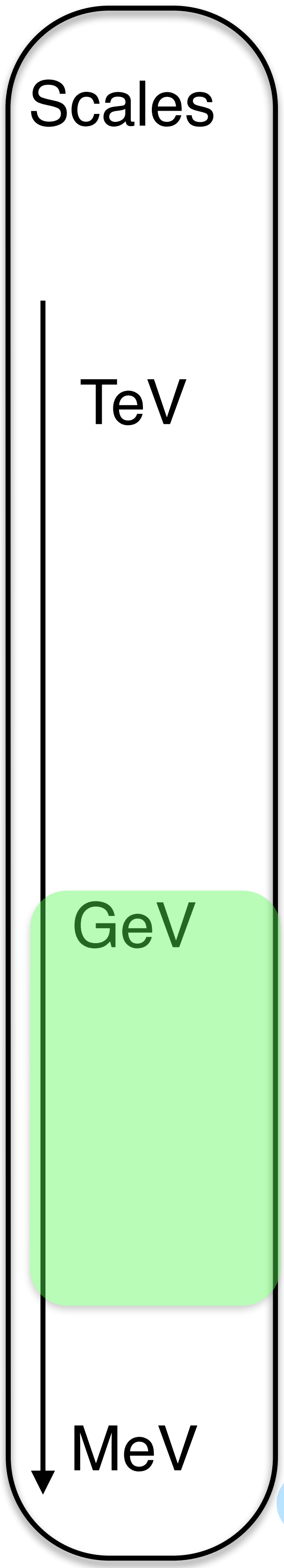


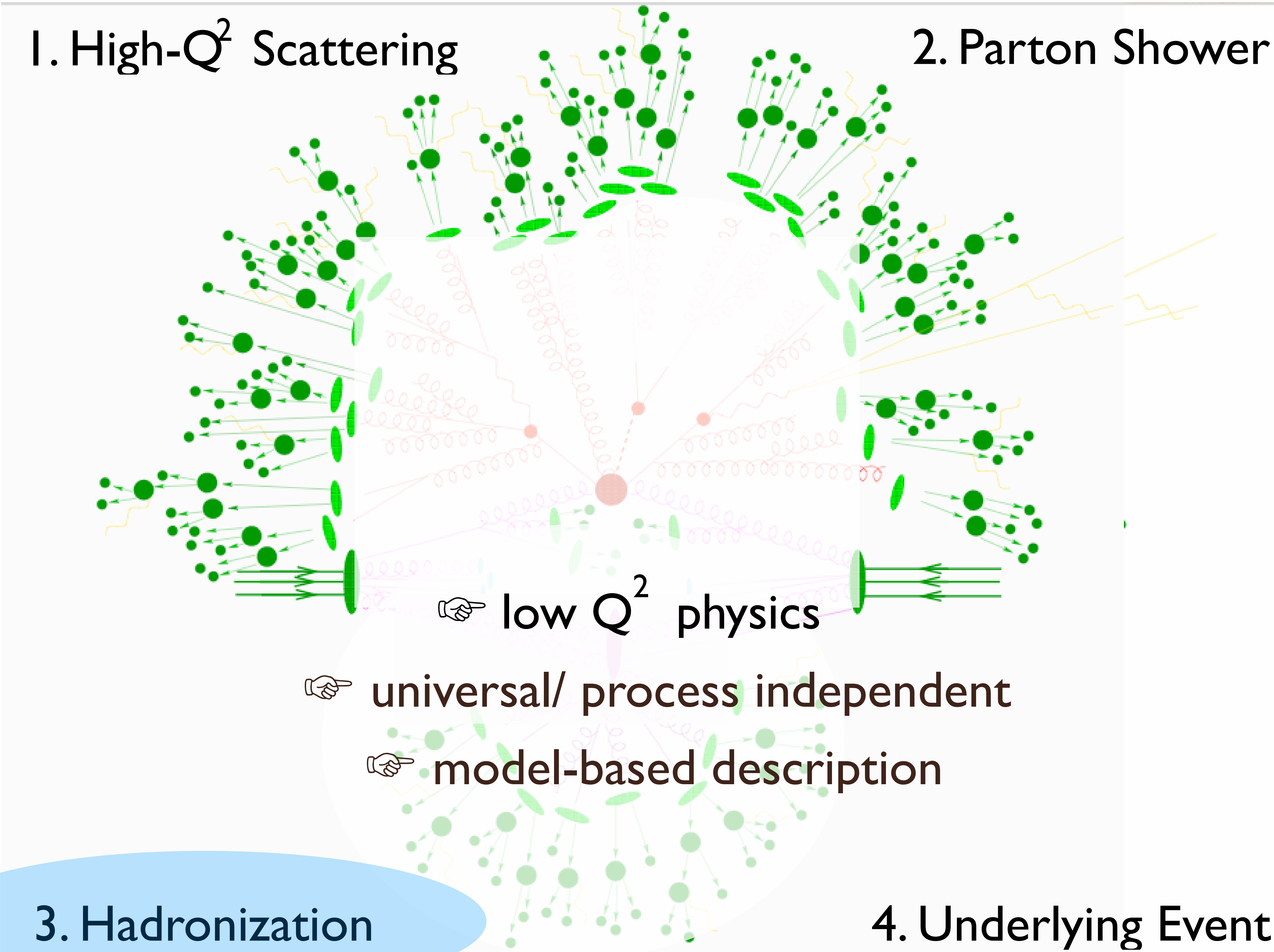
- QCD -"known physics"
- universal/ process independent
- first principles description

3. Hadronization

4. Underlying Event

What are the MC for?





What are the MC for?

Scales

TeV

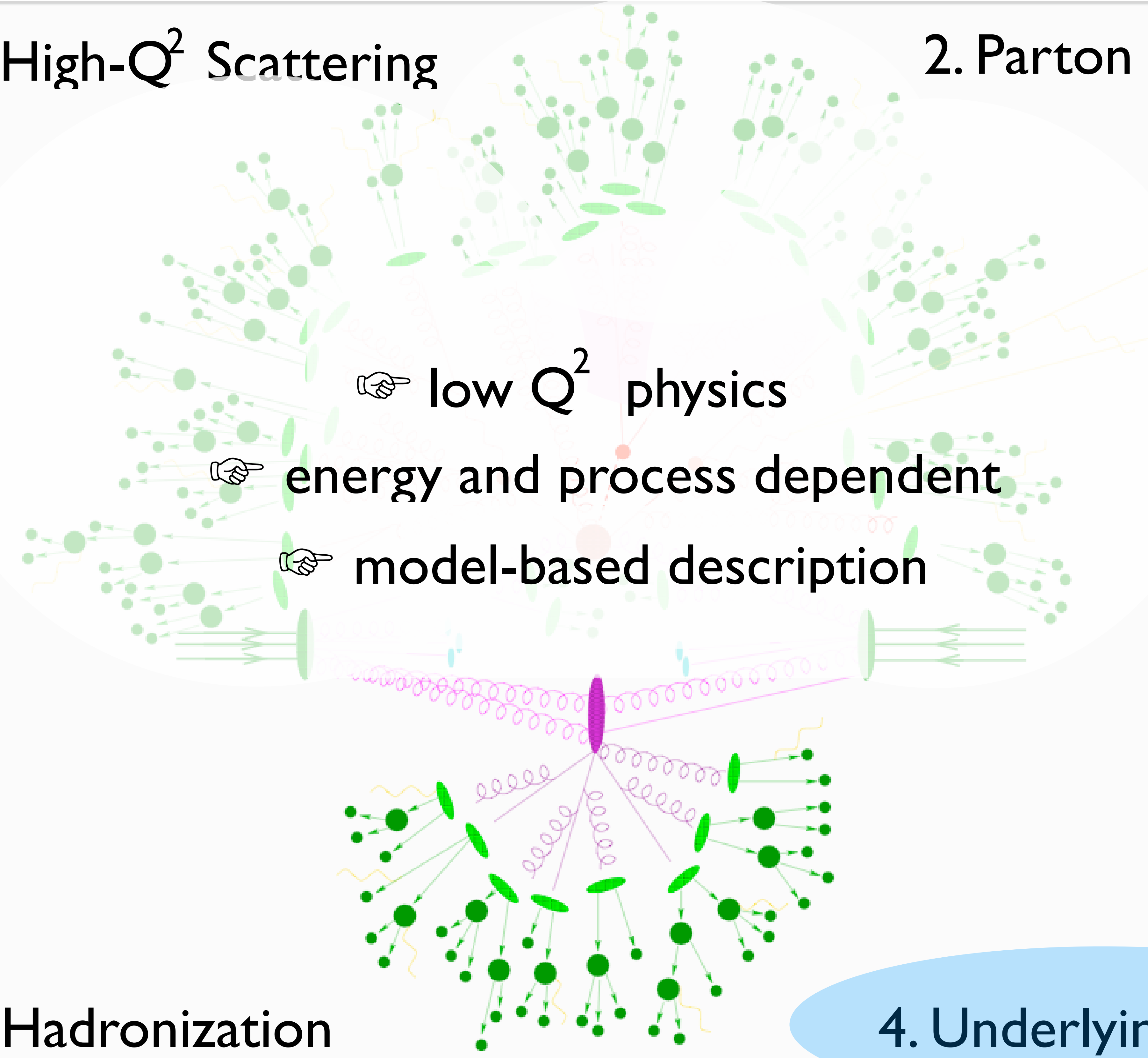
GeV

MeV

1. High-Q^2 Scattering

2. Parton Shower

- ☞ low Q^2 physics
- ☞ energy and process dependent
- ☞ model-based description



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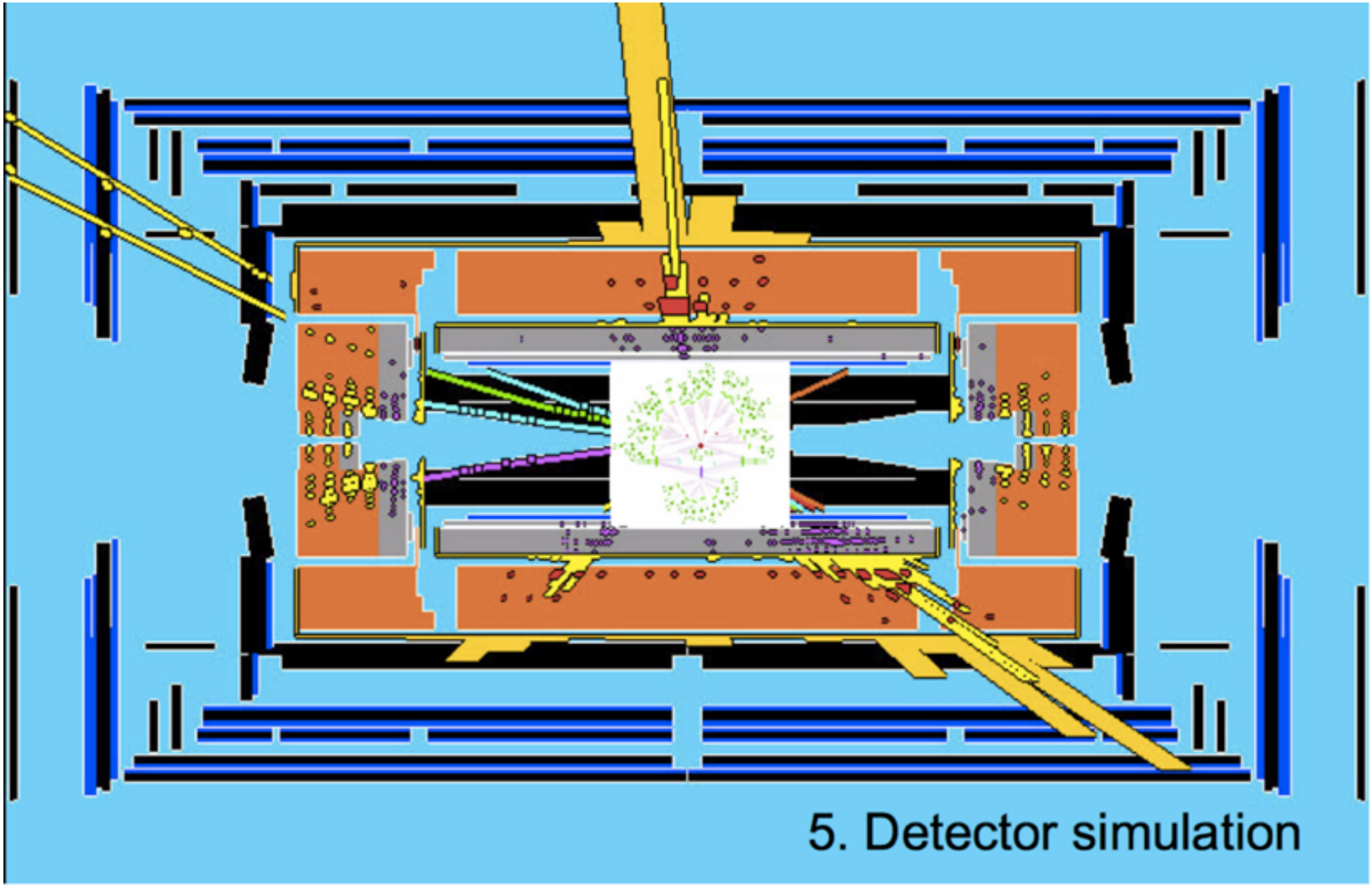
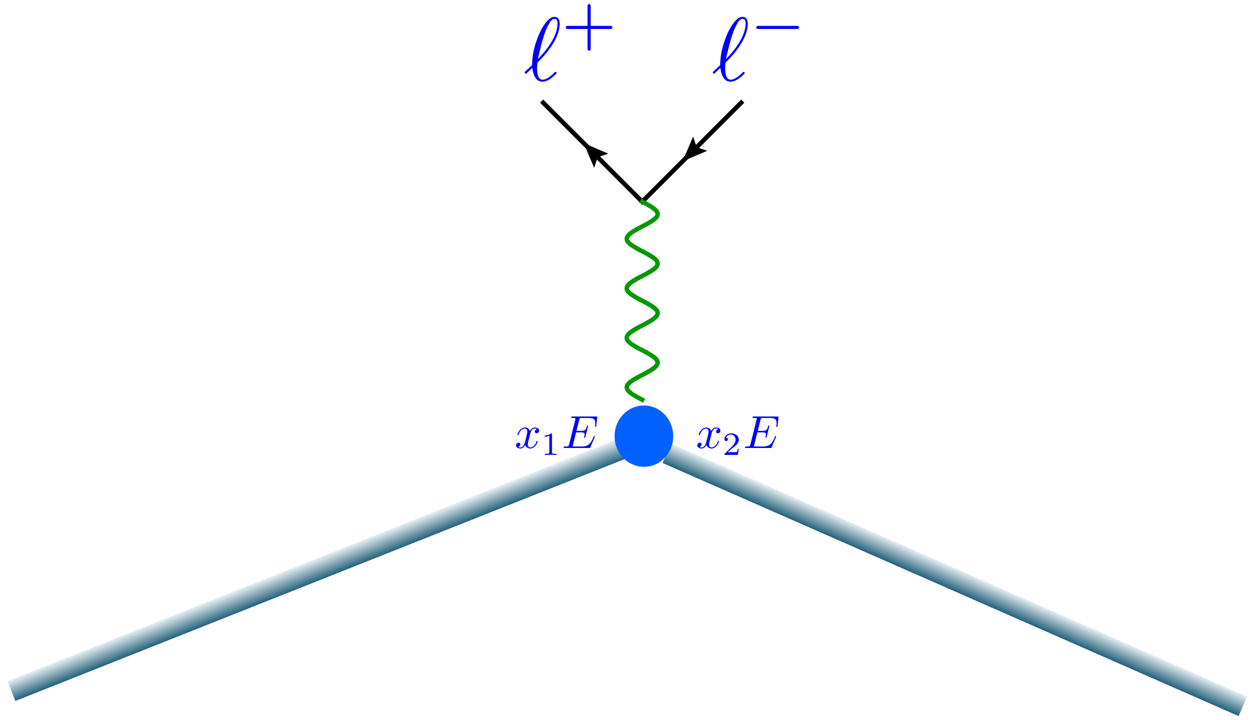


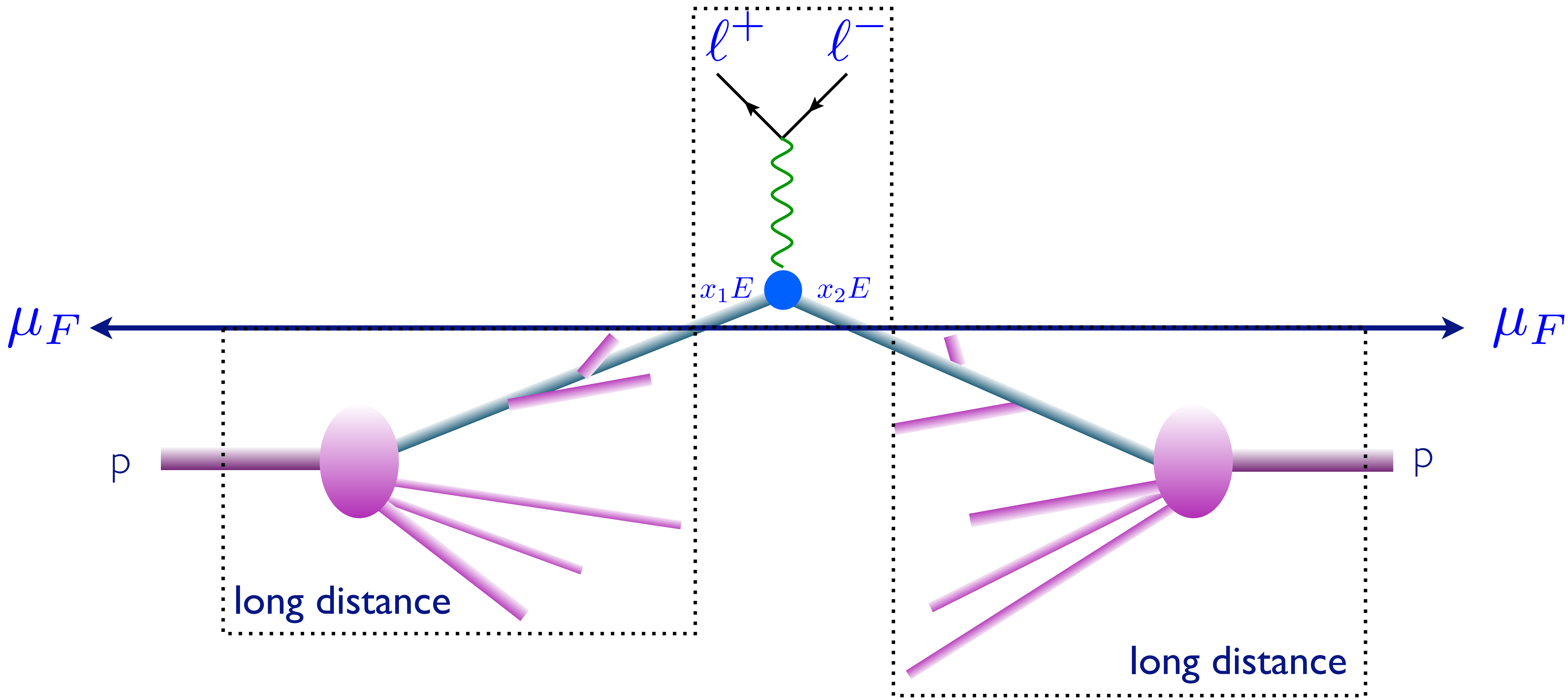
To Remember

- Multi-scale problem
  - ➡ New physics visible only at High scale
  - ➡ Problem split in different scale



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

Parton-level cross section

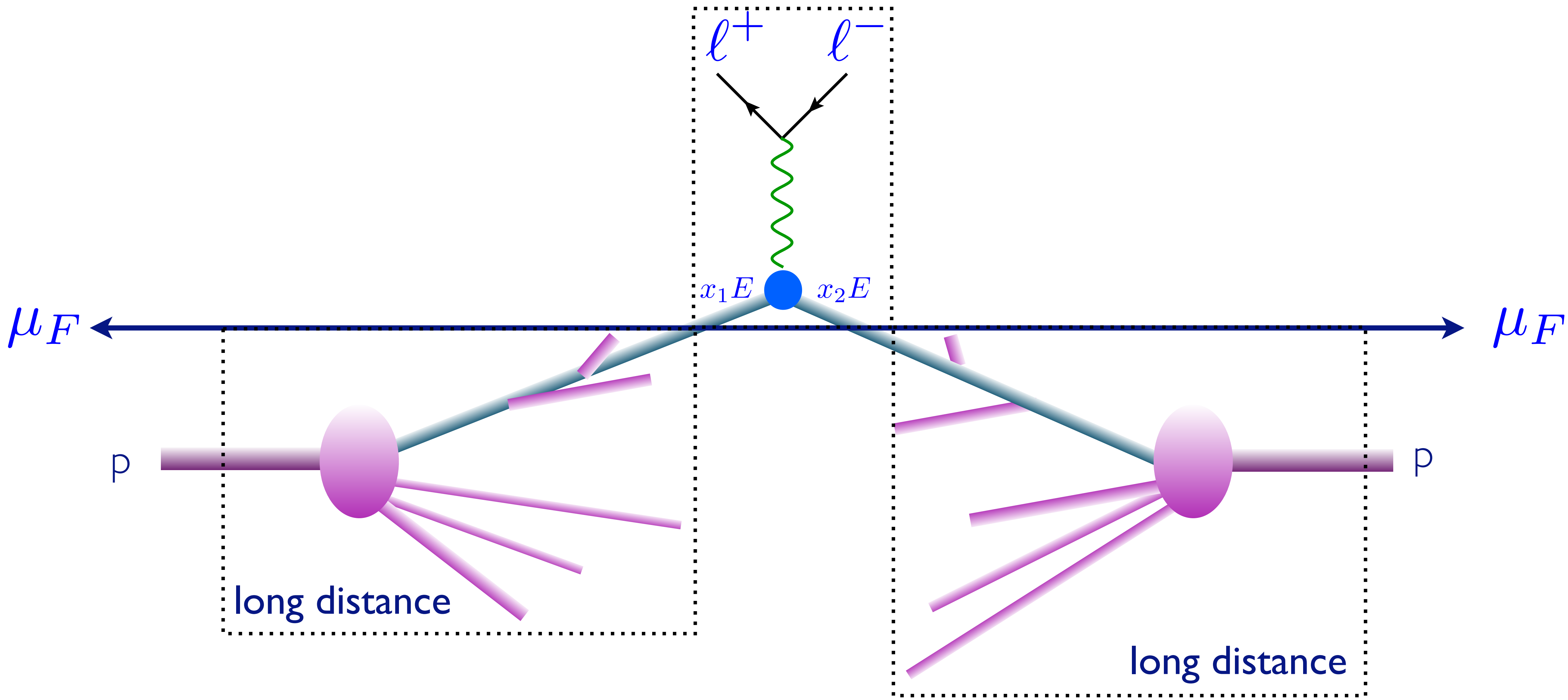


$$f_a(x_1,\mu_F)f_b(x_2,\mu_F)\,\hat{\sigma}_{ab\to X}(\hat{s},\mu_F,\mu_R)$$

Parton density functions

Parton-level cross section

Master formula for the LHC



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

Phase-space integral

Parton density functions

Parton-level cross section

Perturbative expansion

$d\hat{\sigma}_{ab\to X}(\hat{s},\mu_F,\mu_R)$ **Parton-level cross section**

- The parton-level cross section can be computed as a series in perturbation theory, using the coupling constant as an expansion parameter, schematically:

$$\hat{\sigma} = \sigma^{\rm Born}\left(1+\frac{\alpha_s}{2\pi}\sigma^{(1)}+\left(\frac{\alpha_s}{2\pi}\right)^2\sigma^{(2)}+\left(\frac{\alpha_s}{2\pi}\right)^3\sigma^{(3)}+\dots\right)$$

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LO predictions

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LO predictions

NLO corrections

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LO predictions

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LO predictions

NLO corrections

NNLO corrections

N3LO or NNNLO corrections

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LO predictions | NLO corrections | NNLO corrections | N3LO or NNNLO corrections

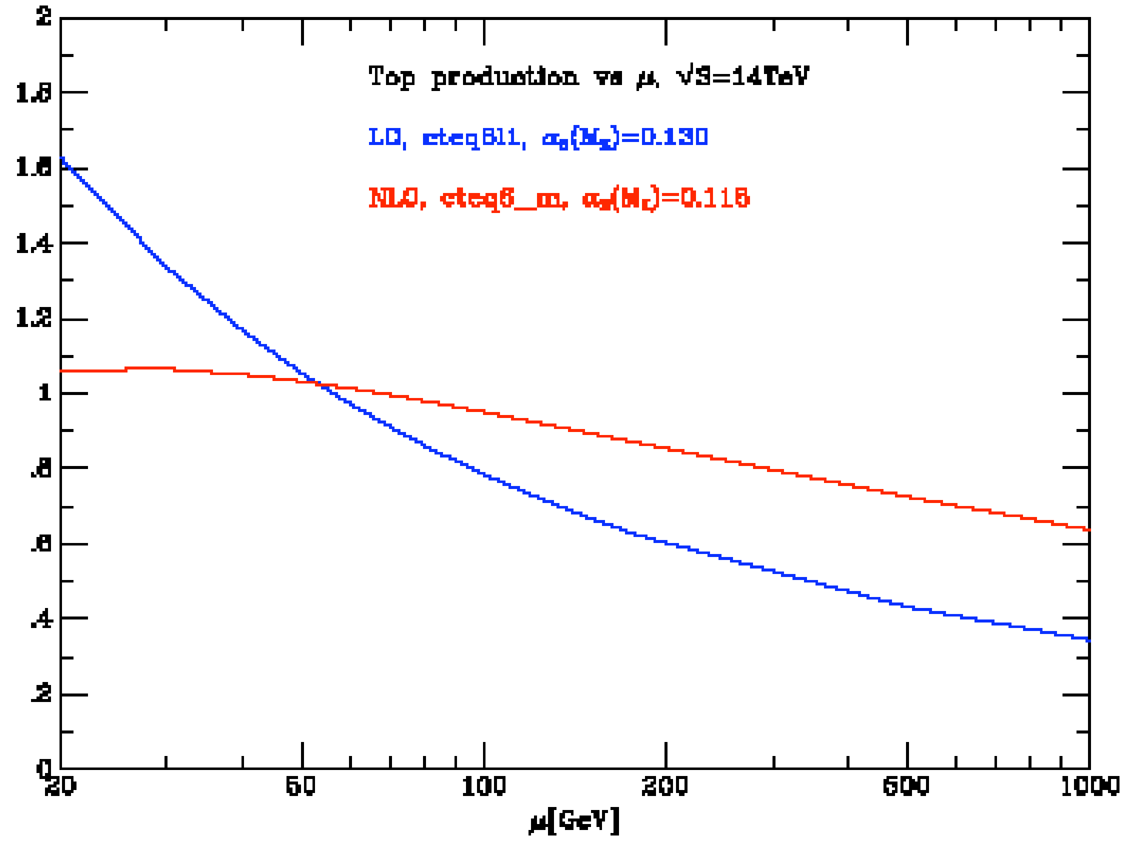
- Including higher corrections improves predictions and reduces theoretical uncertainties

Improved predictions

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

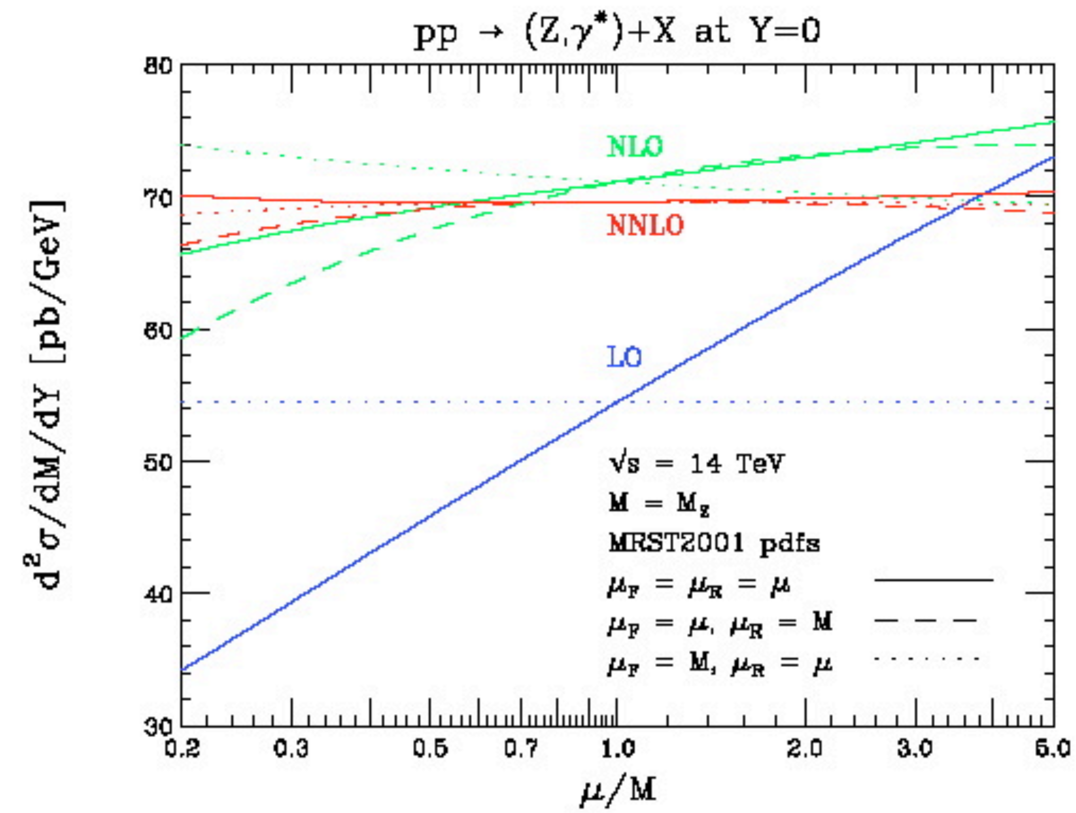
$$\hat{\sigma} = \sigma^{\text{Born}} \left(1 + \frac{\alpha_s}{2\pi}\sigma^{(1)} + \left(\frac{\alpha_s}{2\pi}\right)^2 \sigma^{(2)} + \left(\frac{\alpha_s}{2\pi}\right)^3 \sigma^{(3)} + \ldots \right)$$

- Leading Order predictions can depend strongly on the renormalization and factorization scales
- Including higher order corrections reduces the dependence on these scales



Going NNLO...?

- **NNLO is the current state-of-the-art. There are only a few results available: Higgs, Drell-Yan, ttbar**
- **Why do we need it?**
  - control of the uncertainties in a calculation
  - It is "mandatory" if NLO corrections are very large to check the behavior of the perturbative series



  - It is needed for Standard Candles and very precise tests of perturbation theory, exploiting all the available information, e.g. for determining NNLO PDF sets

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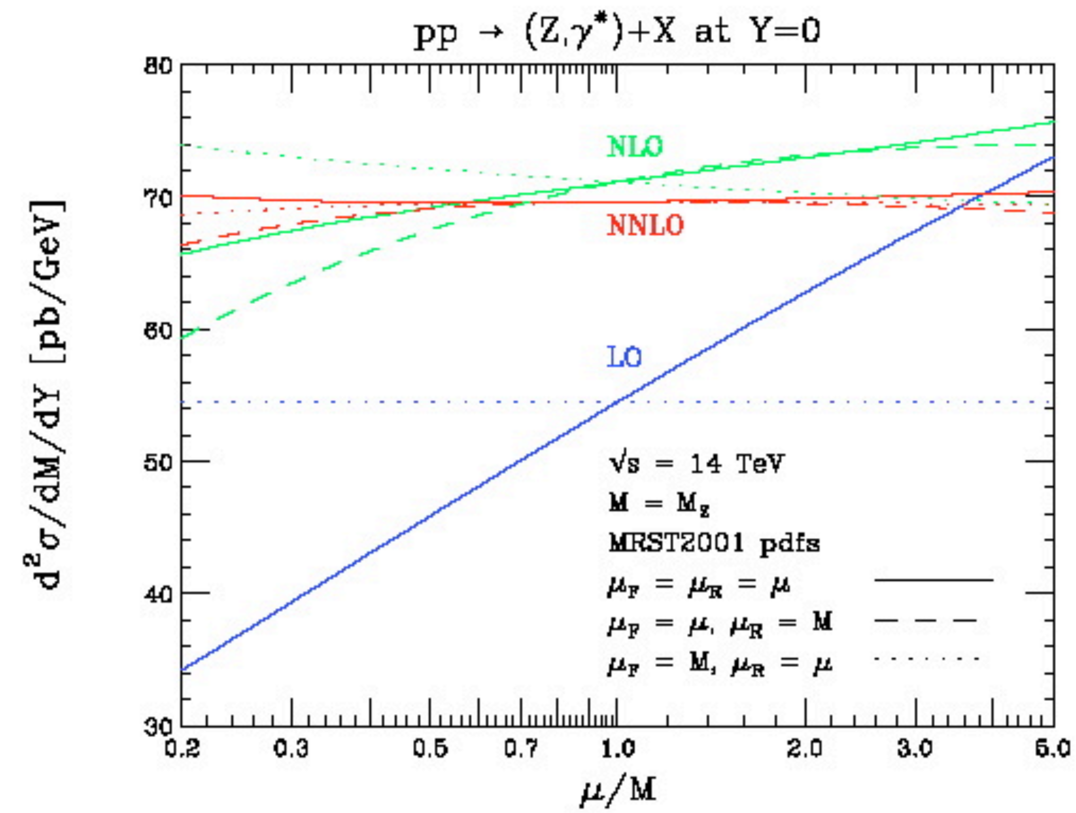

Let's focus on LO

Hadron Colliders

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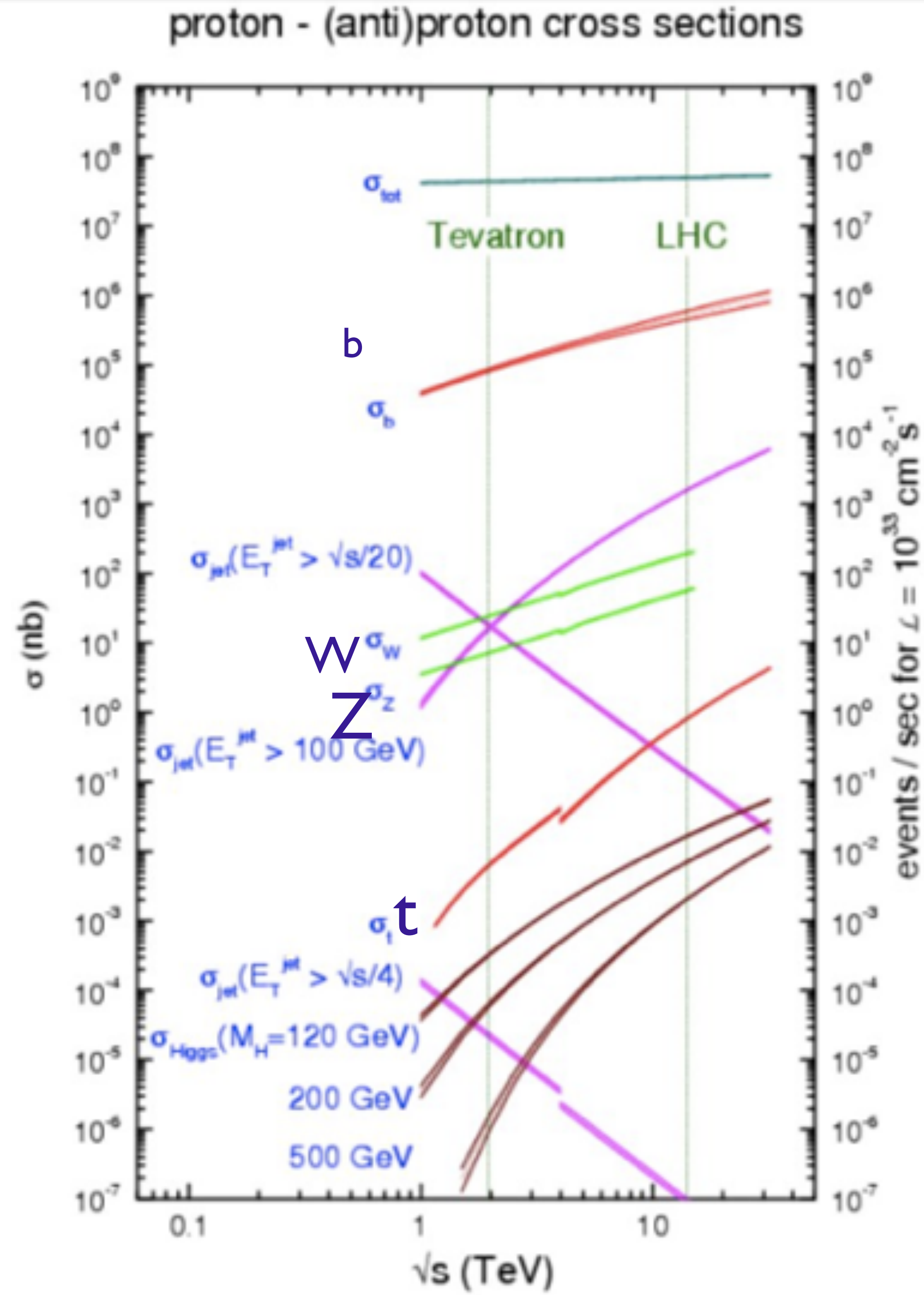
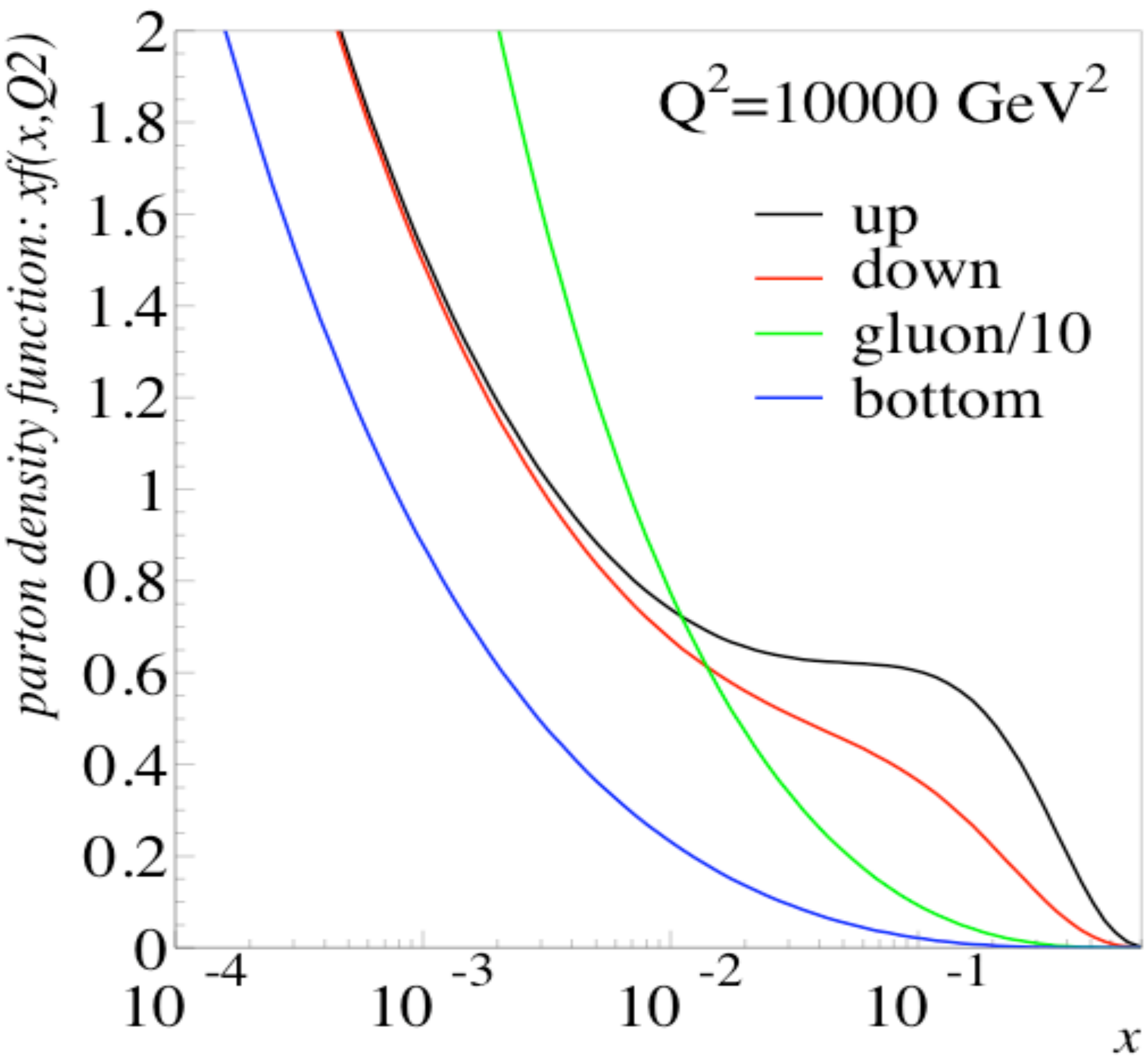
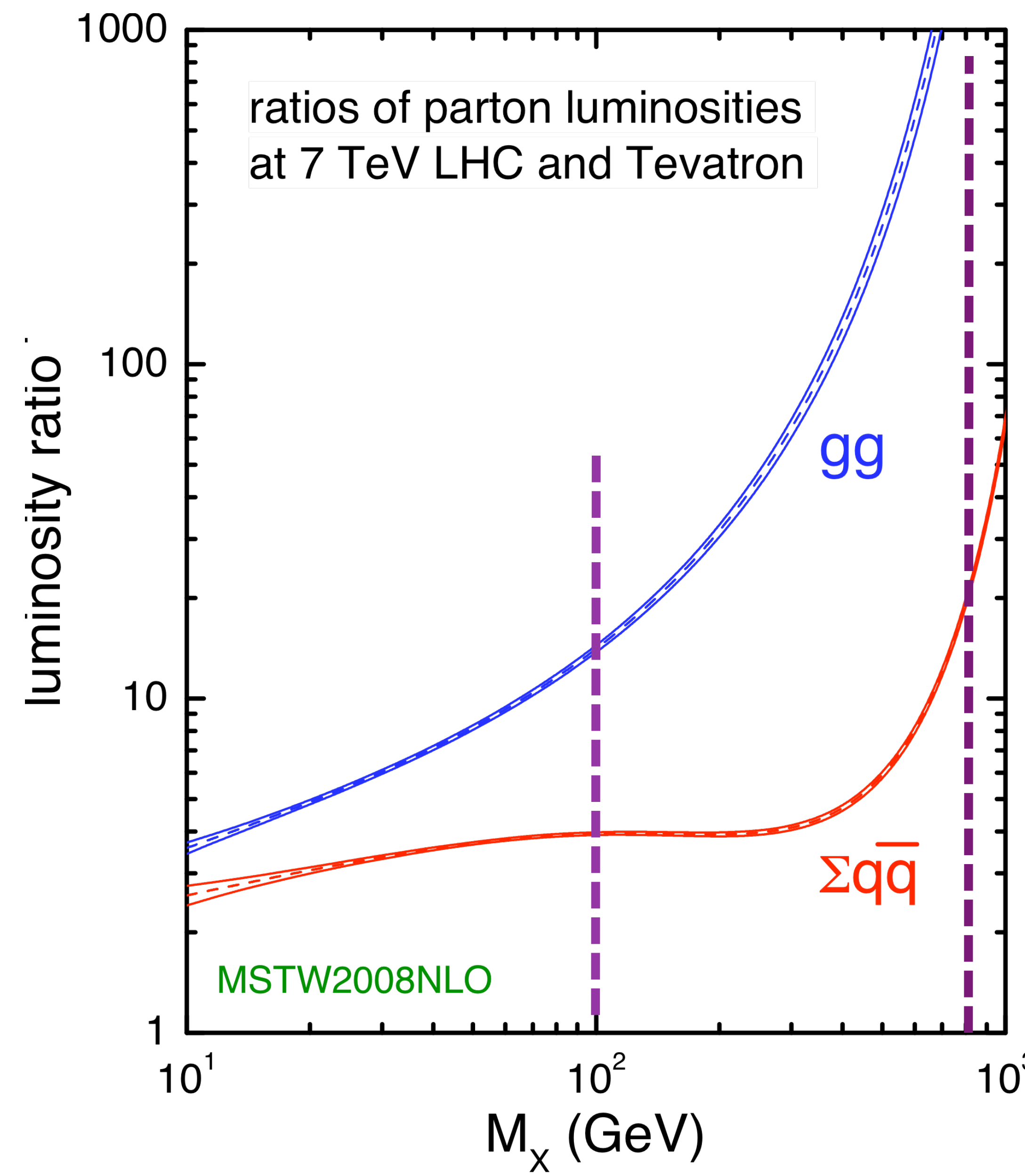


Parton densities

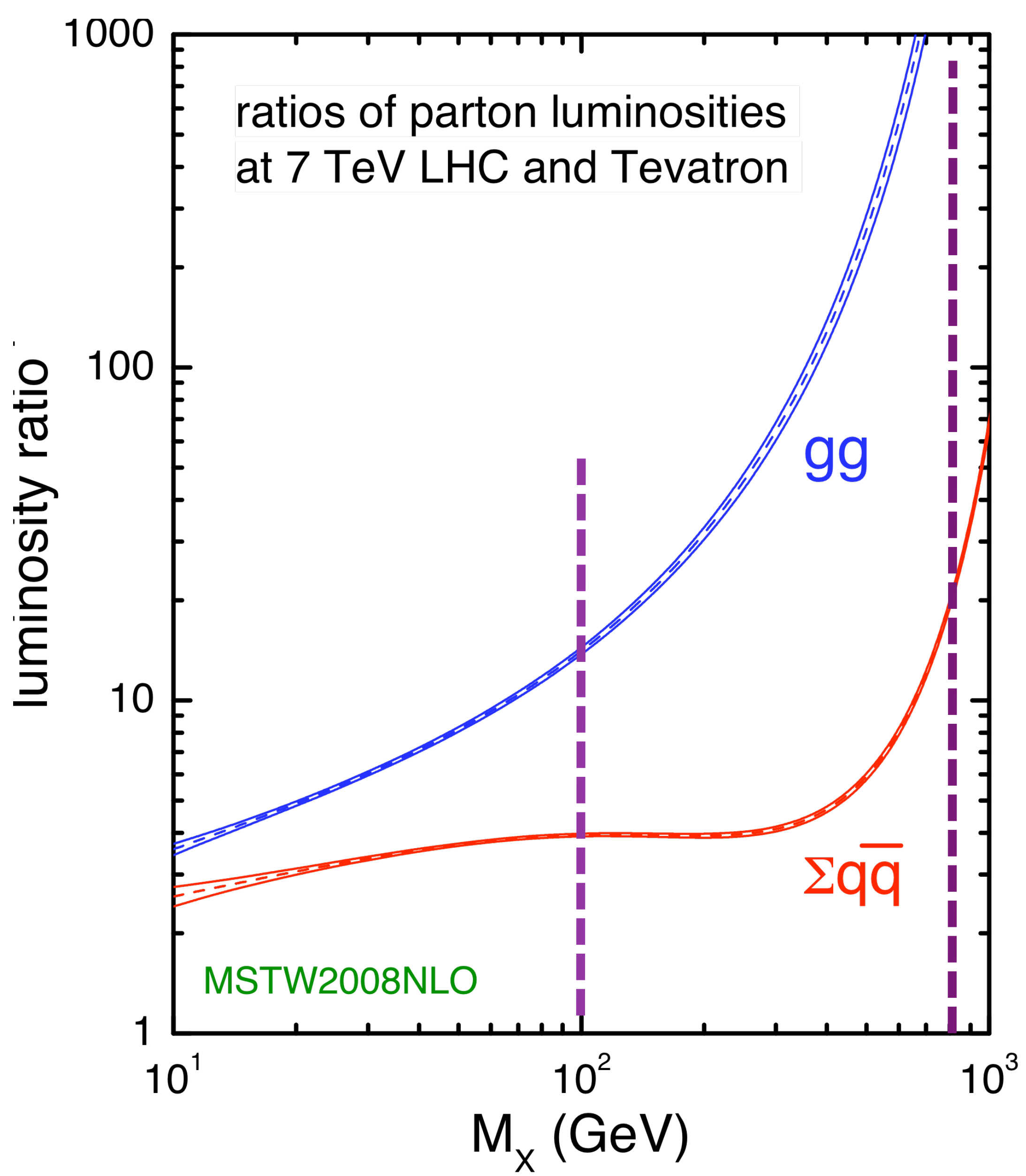


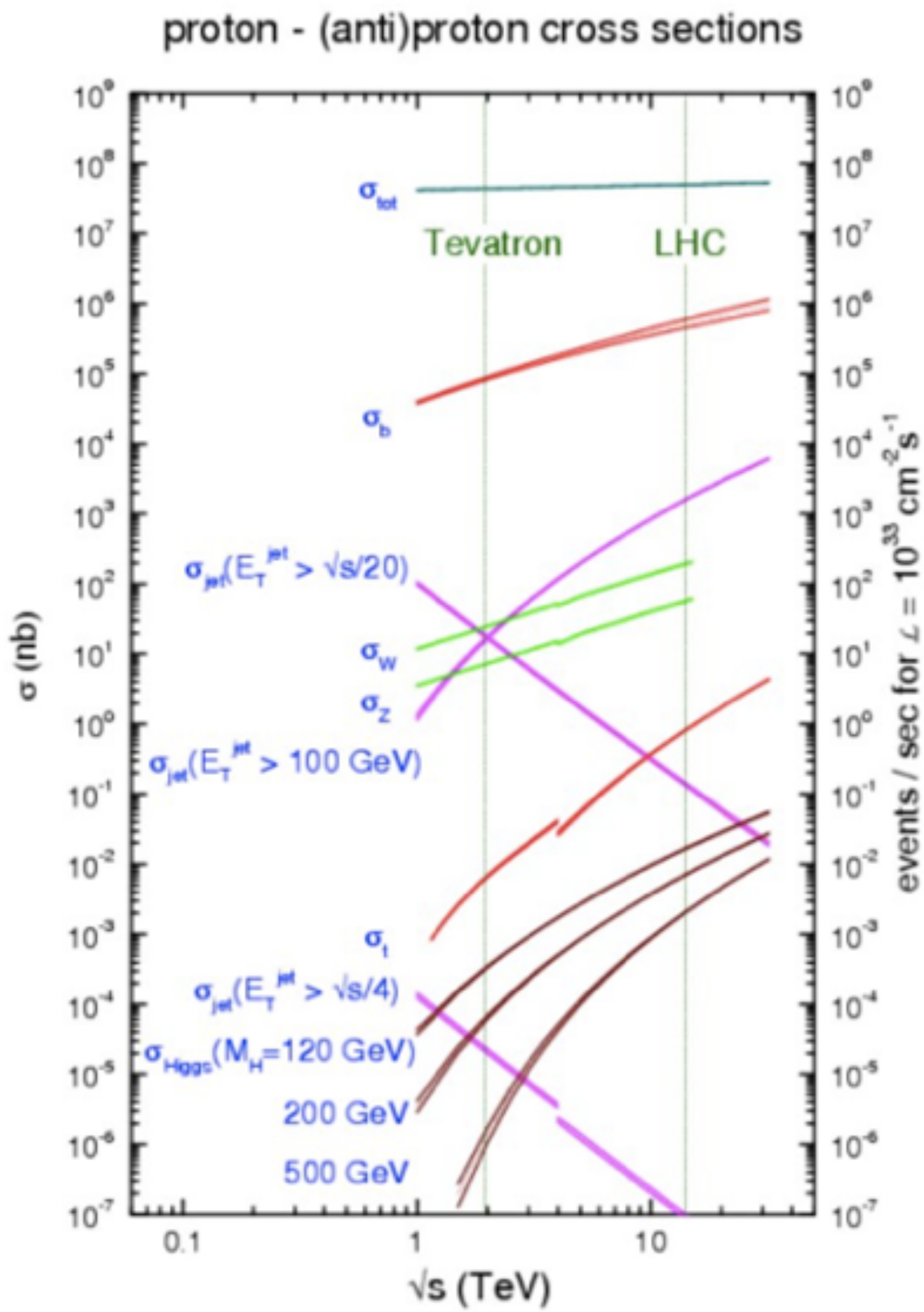
At small x (small $\hat{s}$), gluon domination.
At large x valence quarks

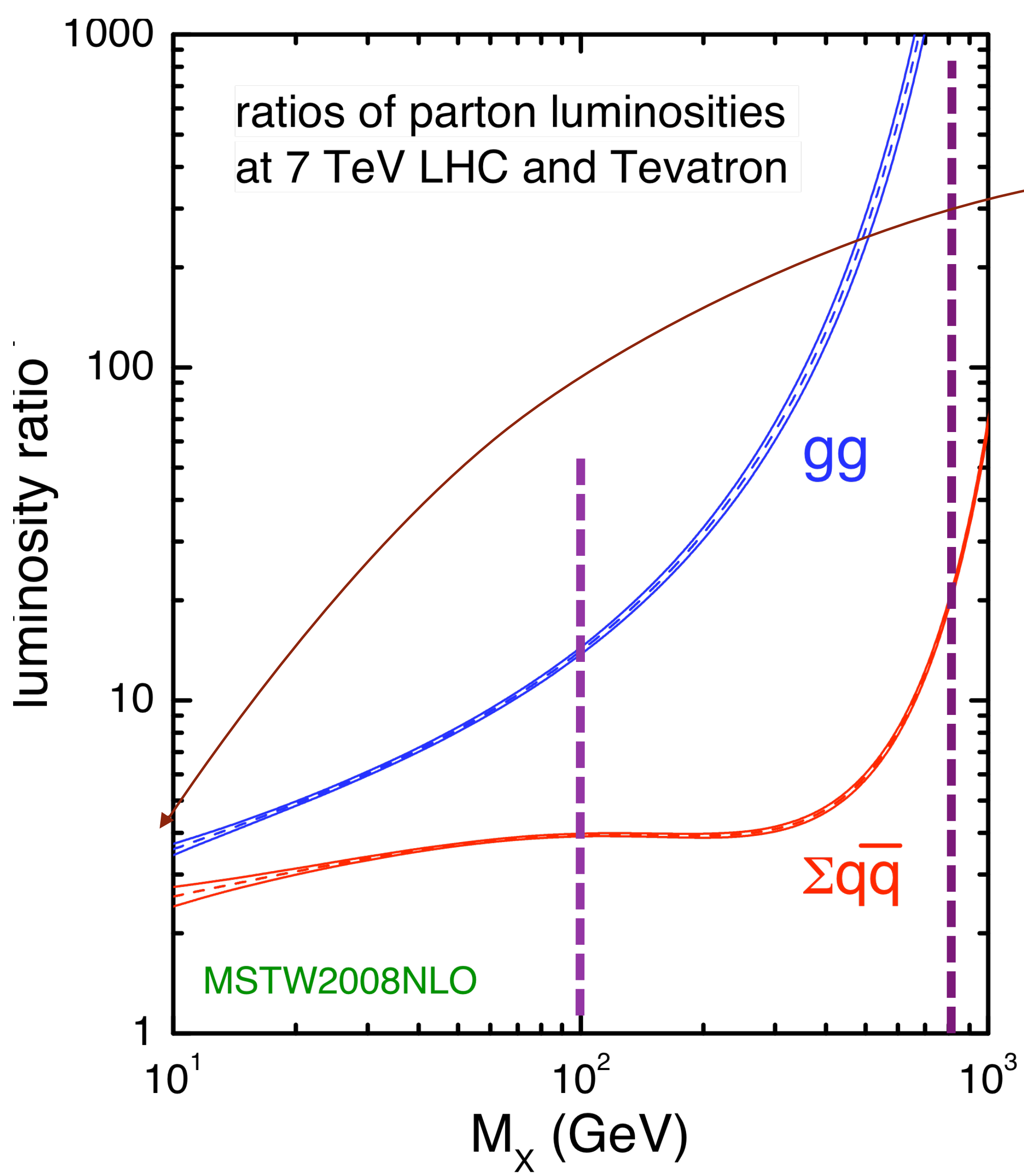


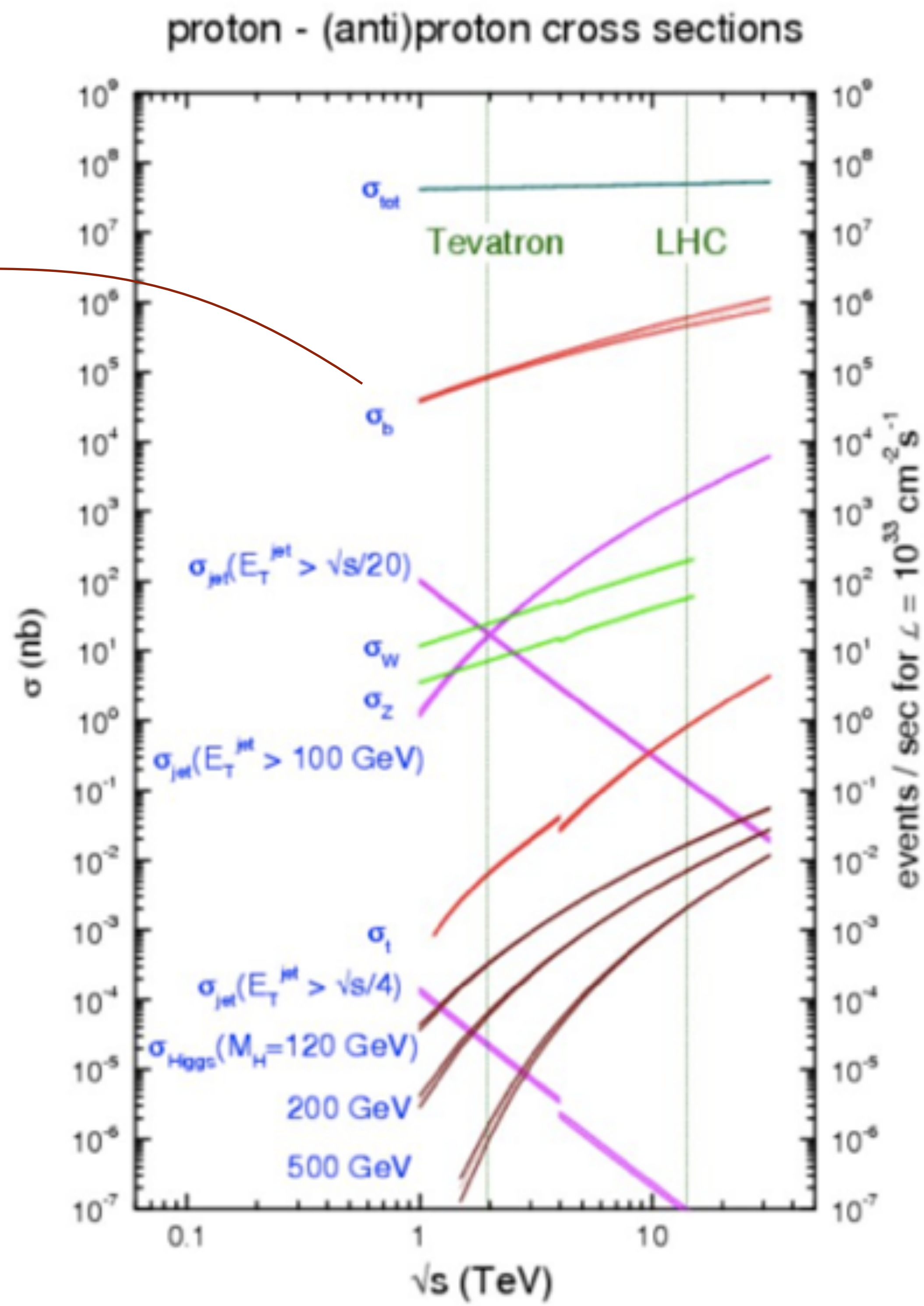
LHC formidable at large mass –
For low mass, Tevatron backgrounds smaller

Back to the processes

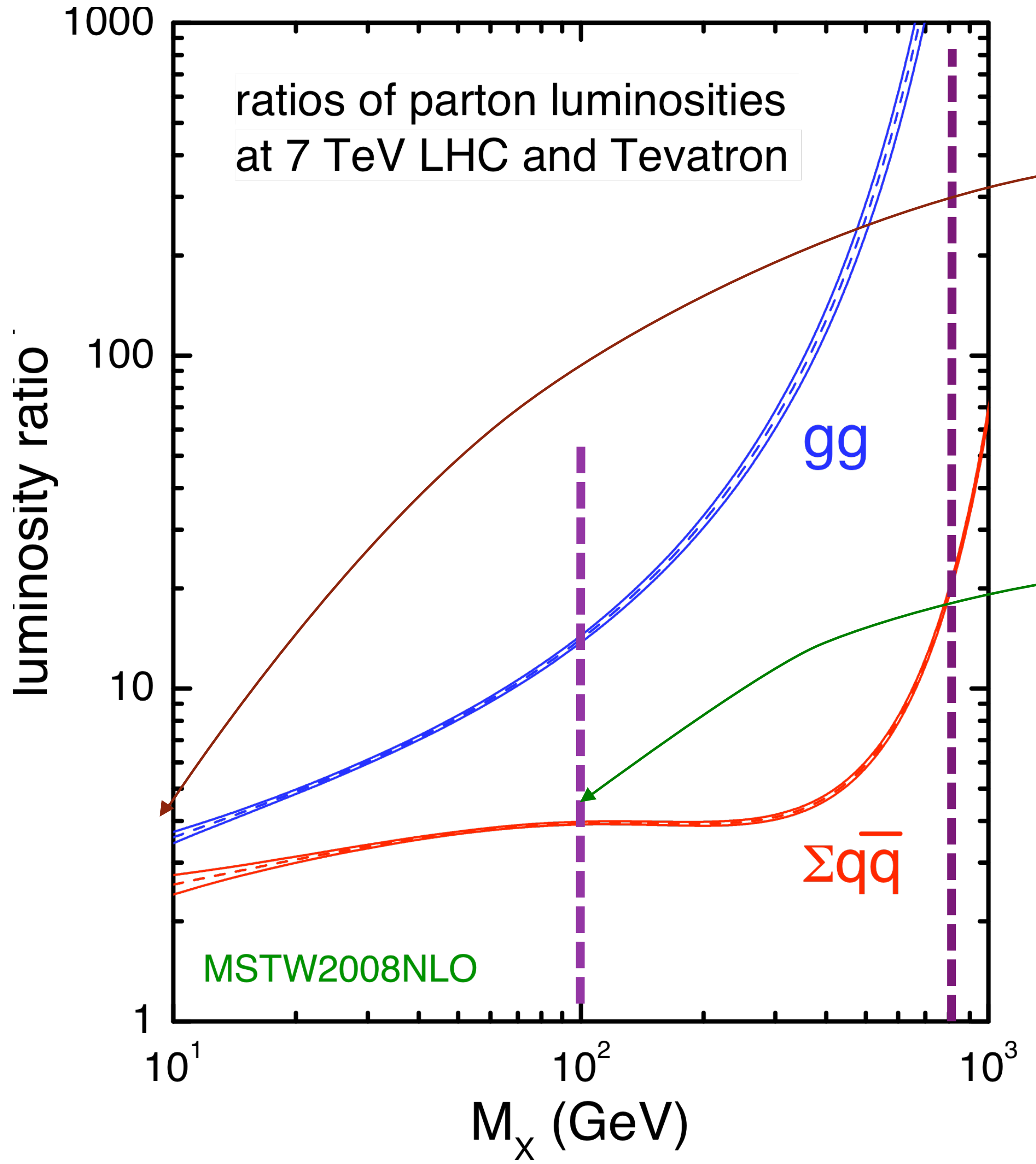


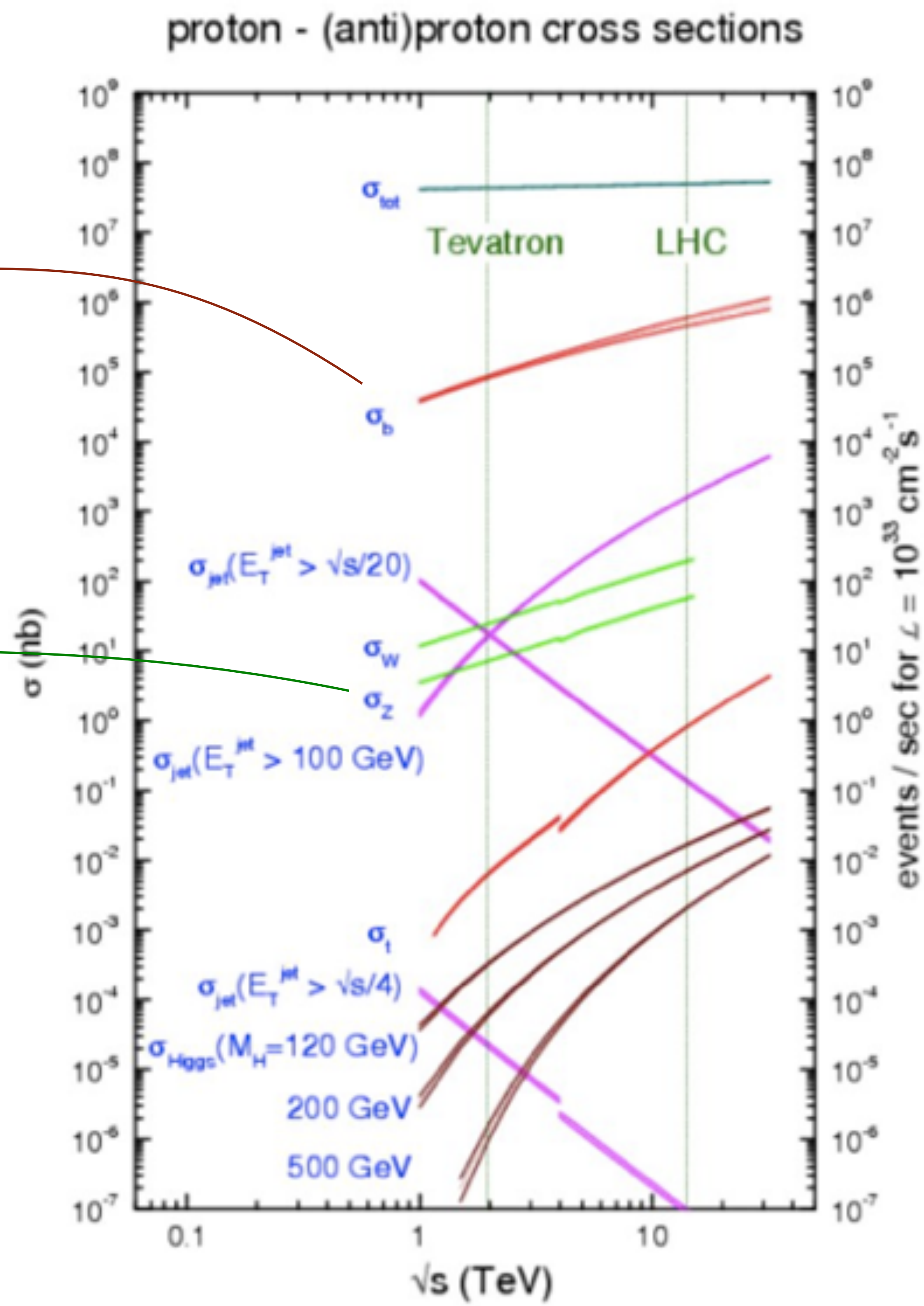



ratios of parton luminosities
at 7 TeV LHC and Tevatron
luminosity ratio
1000
100
10
1
gg
Σqq̄
MSTW2008NLO
10^1
10^2
10^3
M_X (GeV)

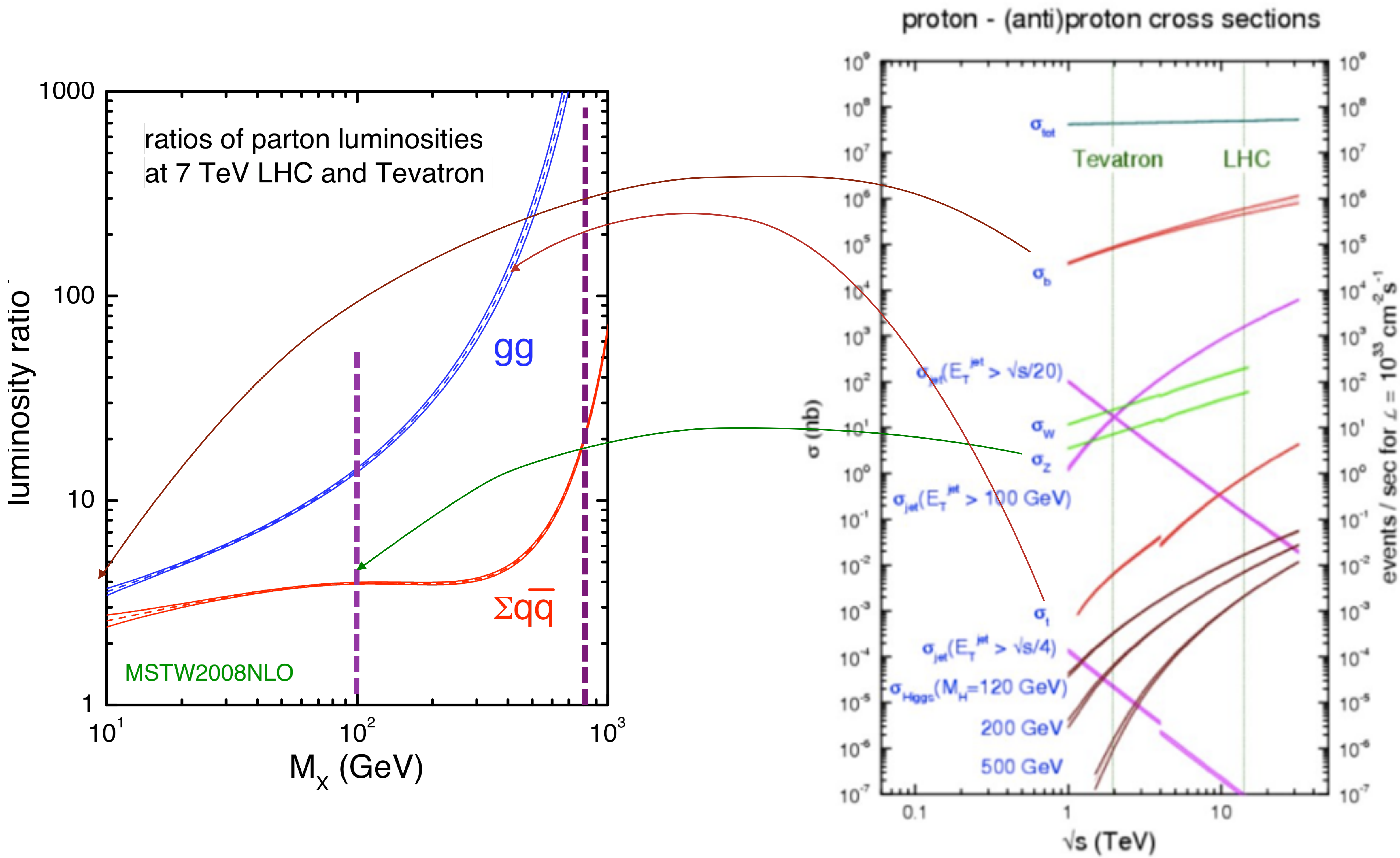

proton - (anti)proton cross sections
σ_tot
Tevatron
LHC
σ_b
σ_jet(E_T^jet > √s/20)
σ_W
σ_Z
σ_jet(E_T^jet > 100 GeV)
σ_t
σ_jet(E_T^jet > √s/4)
σ_Higgs(M_H=120 GeV)
200 GeV
500 GeV
σ (nb)
events / sec for L = 10^33 cm^-2 s^-1
0.1
1
10
√s (TeV)

Back to the processes





Back to the processes



To Remember

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

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

- PDF: content of the proton
  - ➡ Define the physics/processes that will dominate on your accelerator
- NLO/NNLO: Reduce scale uncertainty linked to your division of your multi-scale problem

Matrix-Element

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

- Determine the production mechanism

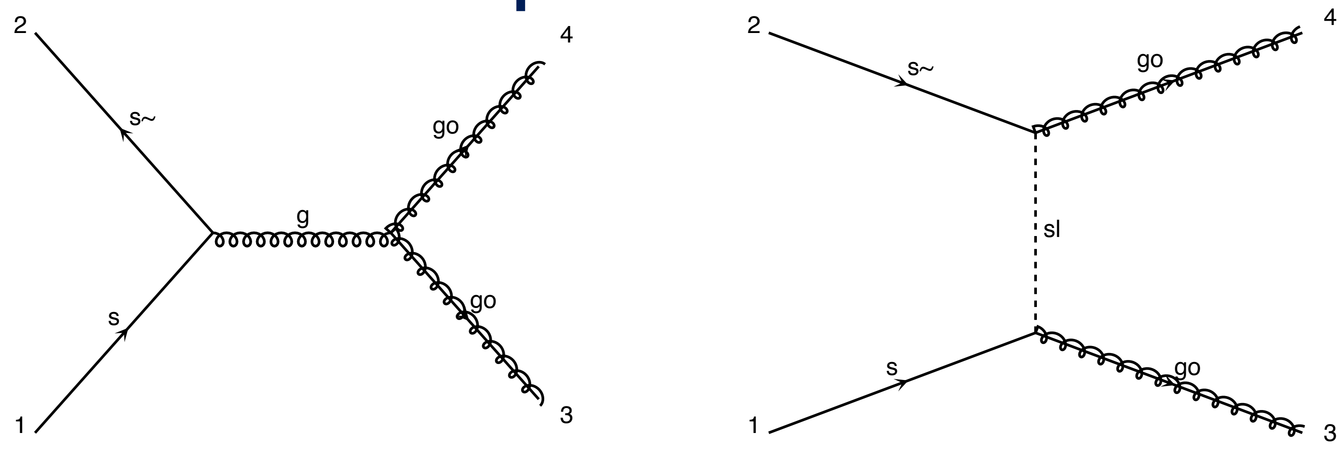


diagram 1 QCD=2, QED=0

diagram 2 QCD=2, QED=0

- Evaluate the matrix-element

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

- Phase-Space Integration

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

Monte Carlo Integration and Generation

Monte Carlo Integration

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

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

Monte Carlo Integration

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

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

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

Monte Carlo Integration

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

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

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

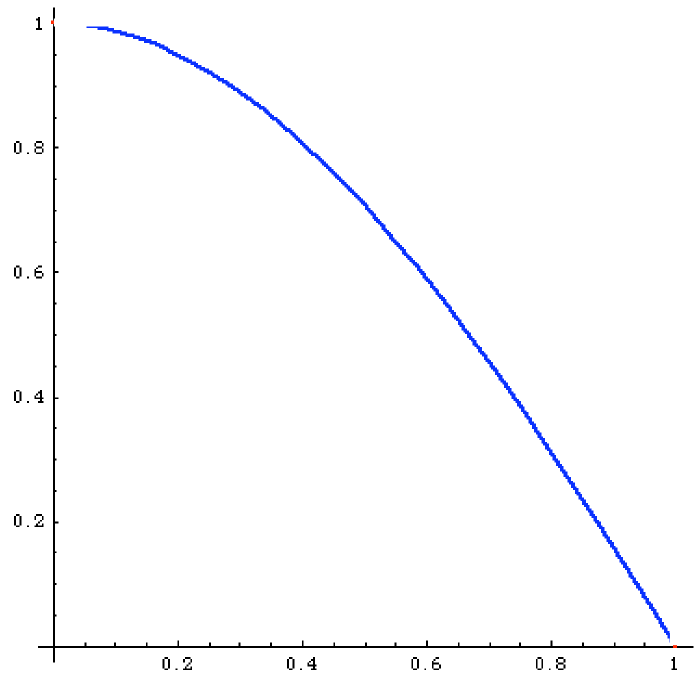
General and flexible method is needed

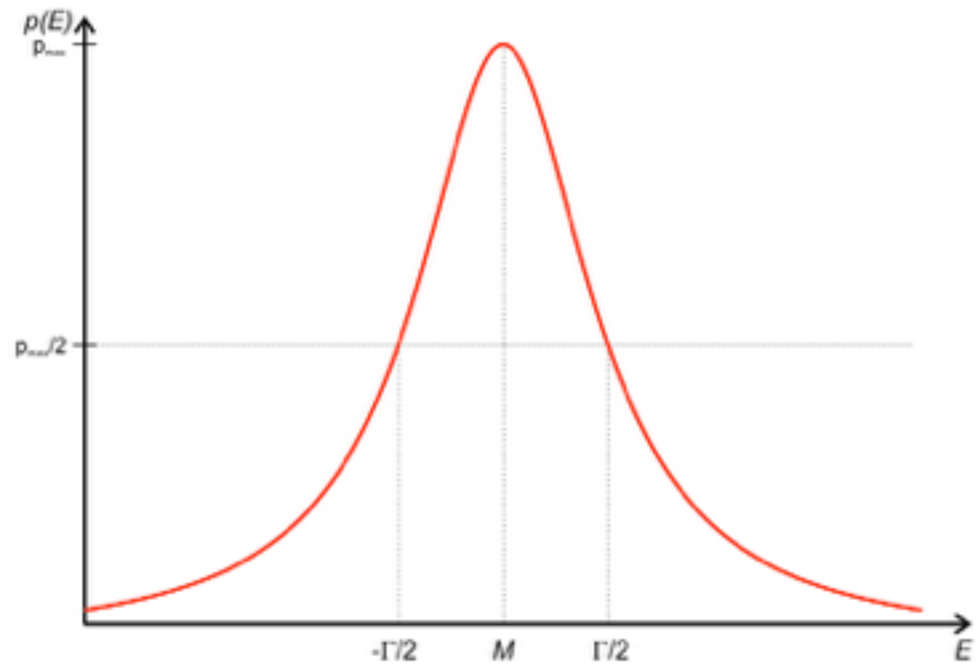
Integration

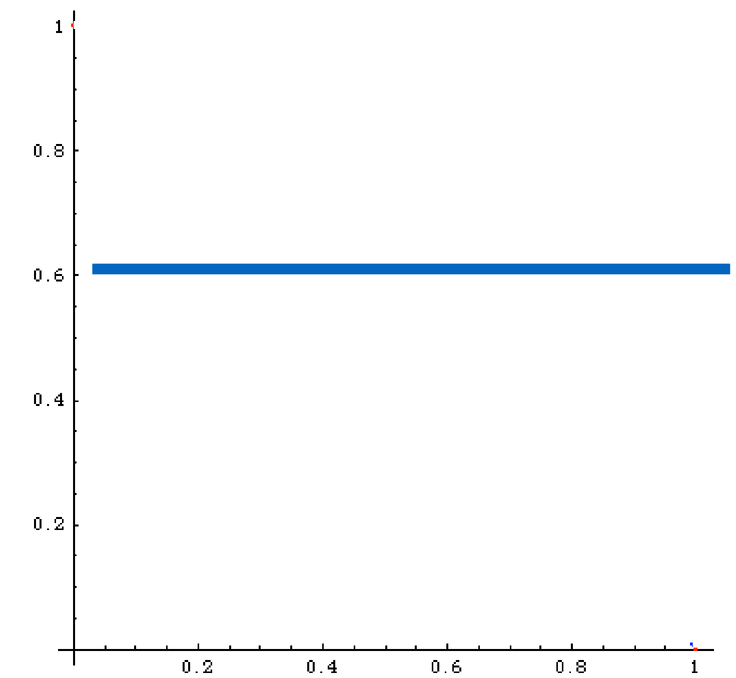
$$I = \int_0^1 dx \cos \frac{\pi}{2} x$$

$$\int \frac{dq^2}{(q^2 - M^2 + iM\Gamma)^2}$$

$$\int dx\, C$$

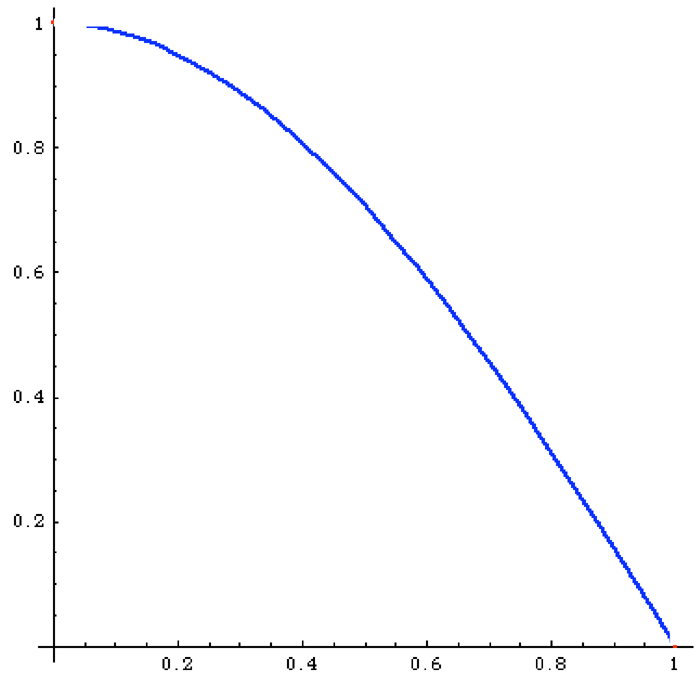




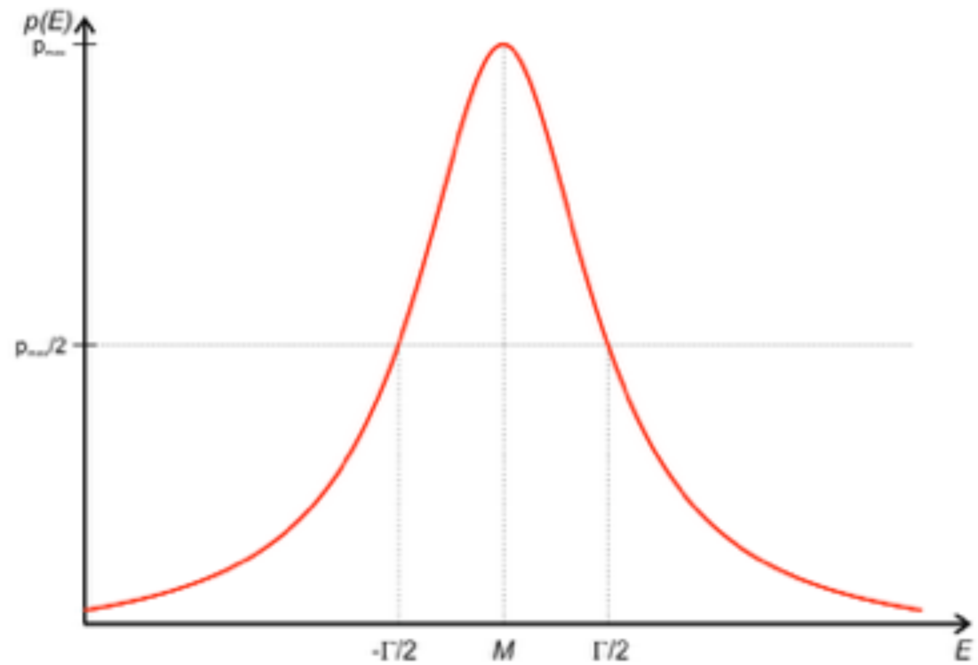


Integration

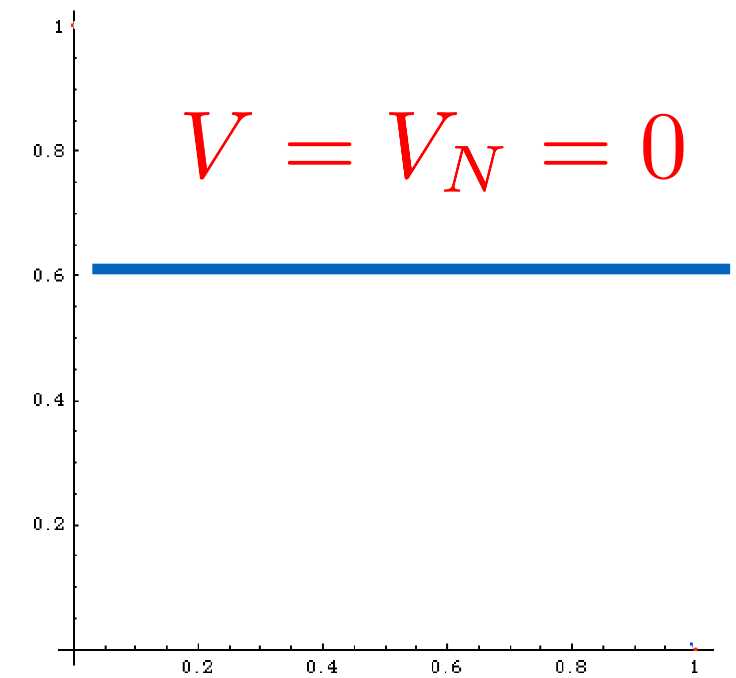
$$I = \int_0^1 dx \cos\frac{\pi}{2}x$$



$$\int \frac{dq^2}{(q^2 - M^2 + iM\Gamma)^2}$$



$$\int dx\, C$$



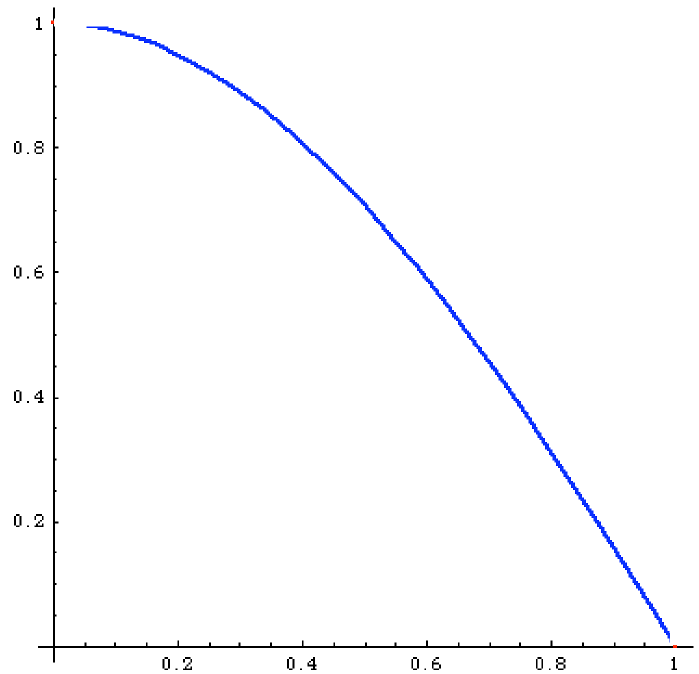
$$V = V_N = 0$$

Method of evaluation

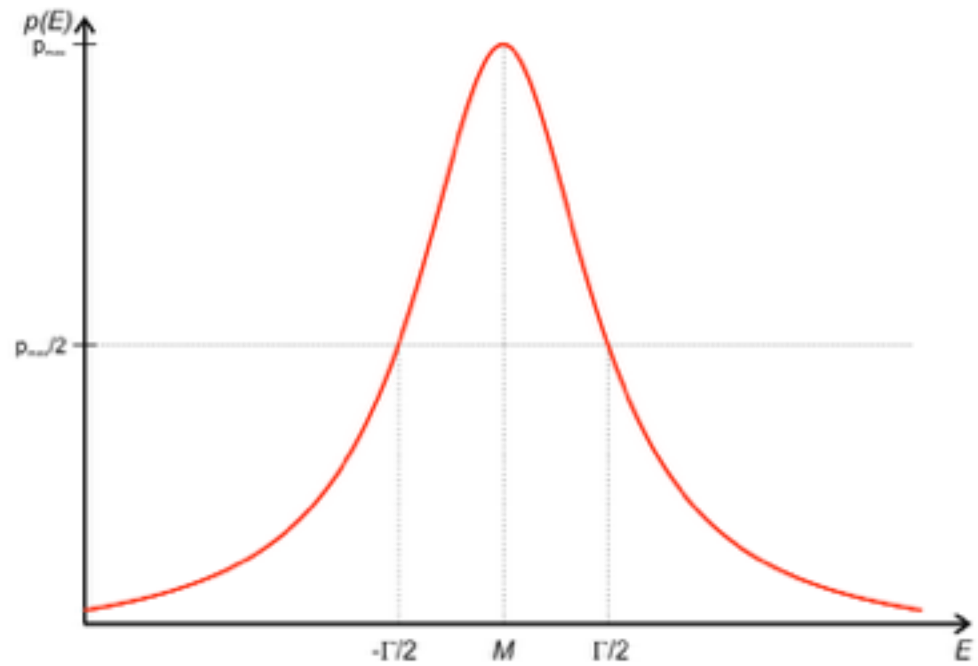
- MonteCarlo $1/\sqrt{N}$
- Trapezium $1/N^2$
- Simpson $1/N^4$

Integration

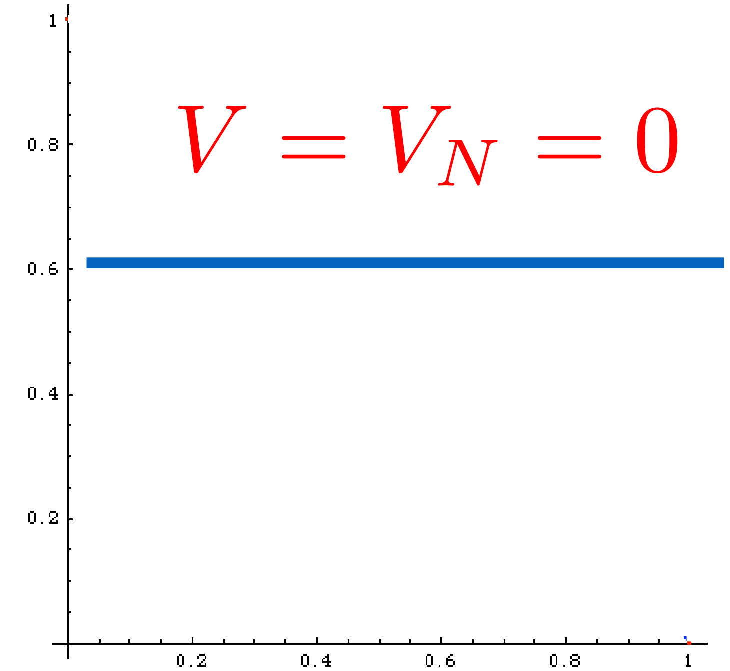
$$I = \int_0^1 dx \cos\frac{\pi}{2}x$$



$$\int \frac{dq^2}{(q^2 - M^2 + iM\Gamma)^2}$$



$$\int dx\, C$$



	simpson	MC
3	0,638	0,3
5	0,6367	0,8
20	0,63662	0,6
100	0,636619	0,65
1000	0,636619	0,636

Method of evaluation

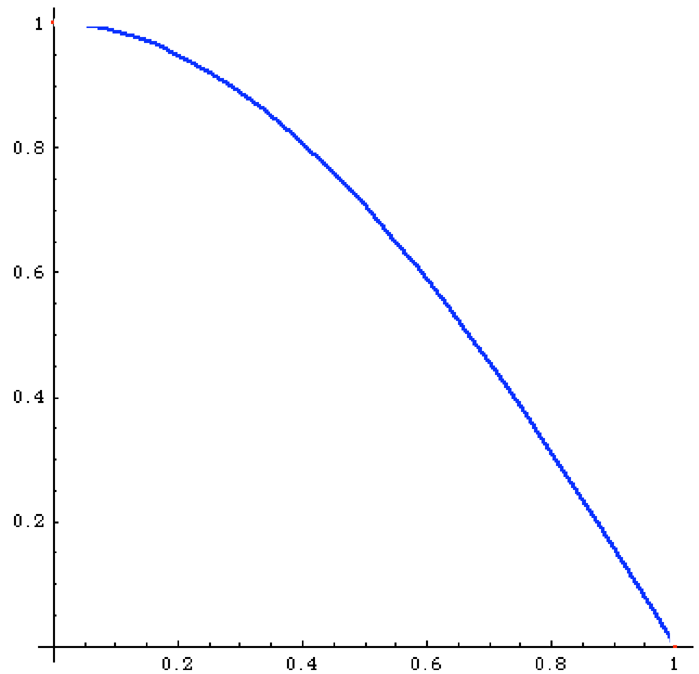
- MonteCarlo $1/\sqrt{N}$
- Trapezium $1/N^2$
- Simpson $1/N^4$

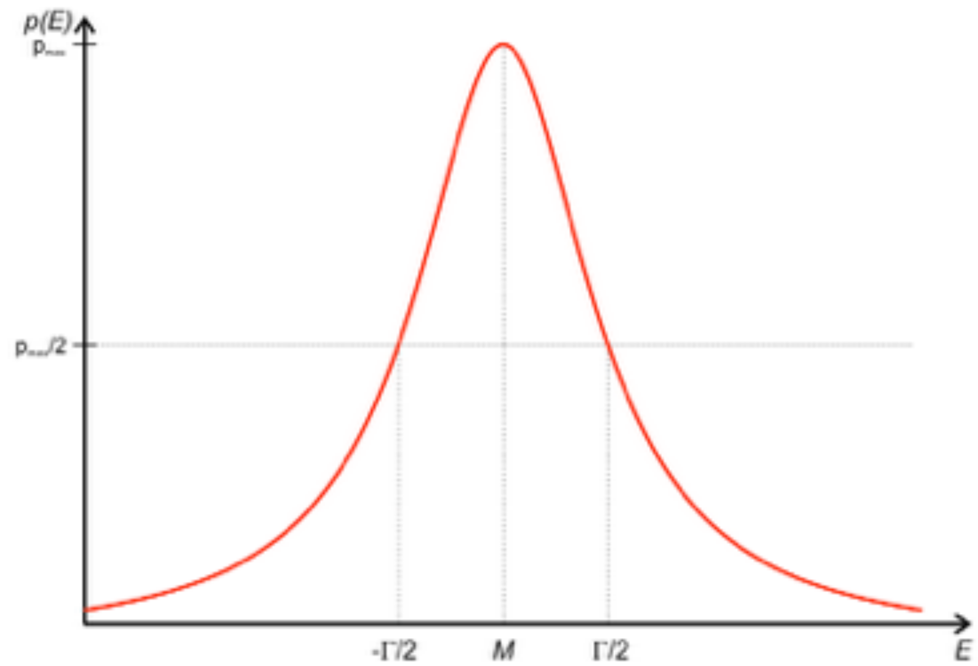
Integration

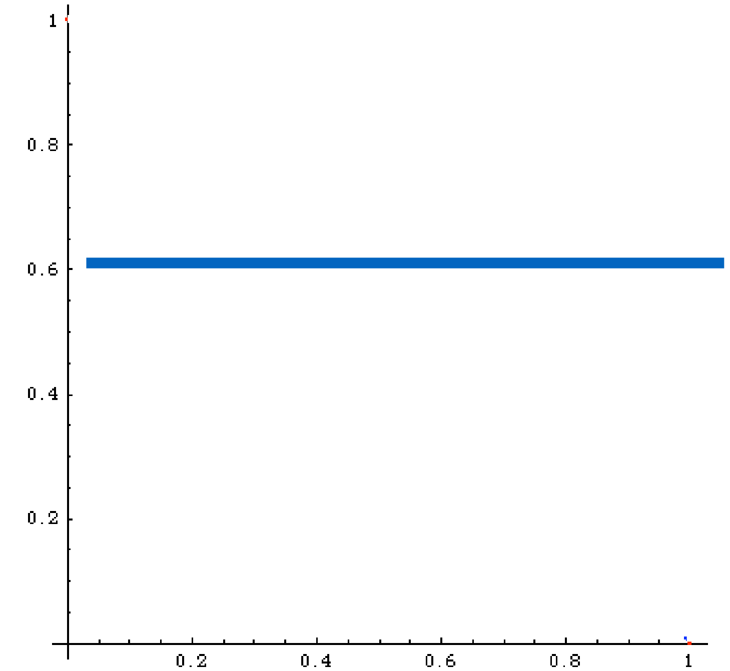
$$I = \int_0^1 dx \cos\frac{\pi}{2}x$$

$$\int \frac{dq^2}{(q^2 - M^2 + iM\Gamma)^2}$$

$$\int dx\, C$$







Method of evaluation

- MonteCarlo $1/\sqrt{N}$
- Trapezium $1/N^2$
- Simpson $1/N^4$

More Dimension

$1/\sqrt{N}$

$1/N^{2/d}$

$1/N^{4/d}$

To Remember

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

P0_gg_hqq

s= 0.44288 ± 0.00268 (pb)

Graph	Cross-Section ↓	Error	Events (K)	Unwgt	Luminosity
G7	0.1263	0.00102	8.002	256.0	2.03e+03
G6	0.1225	0.00132	16.002	760.0	6.21e+03
G2	0.08464	0.0011	32.002	1931.0	2.28e+04
G4	0.08122	0.00169	32.002	101.0	1.25e+03
G1	0.02821	0.000563	8.002	144.0	5.1e+03

What have we learned!

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

Phase-space integral

Parton density functions

Parton-level cross section

- The Importance of PDF
  - ➡ Defines the physics
- Evaluation of Matrix Element
  - ➡ Numerical method faster than analytical formula
  - ➡ cross-section prediction needs NLO
- Phase Space Integration
  - ➡ Need to know in advance what we integrate. Be careful with strong cuts!

Learning MG5_aMC

Today: LO
Next Week: NLO

Minimal tutorial

- Launch the code
  - ➡ ./bin/mg5_aMC
    - Run by default python3 (need 3.7+)
    - Also compatible with python2.7 via
      - Python2.7 ./bin/mg5_aMC
- Type the word “tutorial” in the shell
  - ➡ Follow instructions

What are those cards?

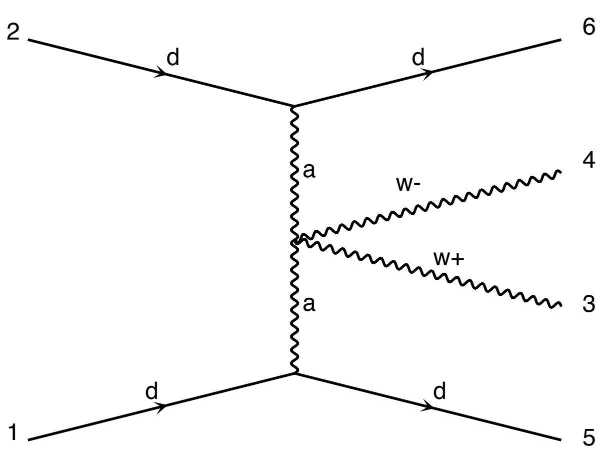
- Read the Cards and identify what they do
  - ➡ param_card: model parameters
  - ➡ run_card: beam/run parameters and cuts
    - https://answers.launchpad.net/madgraph5/+faq/2014

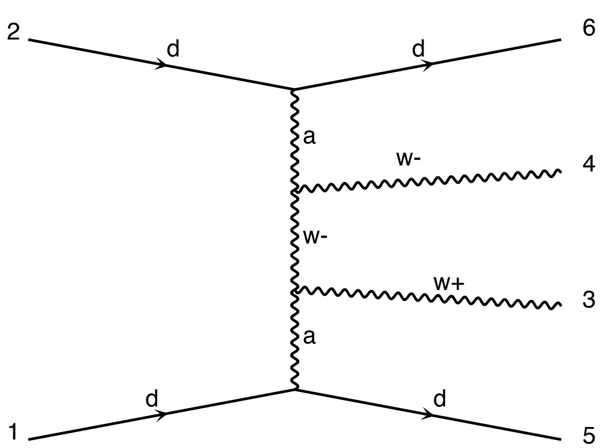
Exercise II: Cards Meaning

- How do you change
  - ➡ top mass
  - ➡ top width
  - ➡ W mass
  - ➡ beam energy
  - ➡ pt cut on the lepton

Exercise II : Syntax

- What's the meaning of the order QED/QCD
- What's the difference between
  - ➡ p p > t t~
  - ➡ p p > t t~ QED=2
  - ➡ p p > t t~ QED=0
- Compute the cross-section for each of those and check the diagram
  - ➡ p p > t t~ QCD=0
  - ➡ p p > t t~ QED<=2
  - ➡ p p > t t~ QCD^2==2
- Generate VBF process





Exercise IV: Top pair production at LO

- Basic questions:
  - Generate the process
  - Which partonic subprocesses contribute?
  - How many Feynman diagrams has each subprocess?
  - Output the code
  - Compute the cross-section at the LHC (8 TeV) for m_t=170 GeV
- Extra questions:
  - Are b-quarks included in the initial state? If not, how can I include them?
  - Recompute the $t\bar{t}$ cross-section for m_t=170, 172, 174 … 180 GeV
  - Add the top decay and redo the mass scan. Anything strange?

Exercise IV: hint

- Compute the cross-section for the top pair production for 3 different mass points.
  - ➡ Do NOT use the interactive interface
    - hint: you can edit the param_card/run_card via the "set" command [After the launch]
    - hint: All command [including answer to question] can be put in a file. (run ./bin/mg5 PATH_TO_FILE)

Examples

File:

```
import model EWDim6
generate p p > z z
ouput TUTO_DIM6
launch
  set nevents 5000
  set MZ 100
```

How to Run: `./bin/mg5_amc PATH`

Solution Learning MG5_aMC

Exercise II: Cards Meaning

- How do you change
  - ➡ top mass
  - ➡ top width
  - ➡ W mass
  - ➡ beam energy
  - ➡ pt cut on the lepton

Param_card

Run_card

- top mass

```
###################################
## INFORMATION FOR MASS
###################################
Block mass
    6 1.730000e+02 # MT
   23 9.118800e+01 # MZ
   25 1.200000e+02 # MH
## Dependent parameters, given by model restrictions.
## Those values should be edited following the
## analytical expression. MG5 ignores those values
## but they are important for interfacing the output of MG5
## to external program such as Pythia.
  1 0.000000 # d : 0.0
  2 0.000000 # u : 0.0
  3 0.000000 # s : 0.0
  4 0.000000 # c : 0.0
  11 0.000000 # e- : 0.0
  12 0.000000 # ve : 0.0
  13 0.000000 # nu- : 0.0
  14 0.000000 # vm : 0.0
  16 0.000000 # vt : 0.0
  21 0.000000 # g : 0.0
  22 0.000000 # a : 0.0
  24 80.419002 # w+ : cmath.sqrt(MZ__exp__2/2. + cmath.sqrt(MZ__exp__4/4. - (aEW*cmath.pi*MZ__exp__2)/(Gf*sqrt__2)))
```

```
######################################
## INFORMATION FOR MASS
######################################
Block mass
    5 4.700000e+00 # MB
    6 1.730000e+02 # MT
   15 1.777000e+00 # MTA
   23 9.118800e+01 # MZ
   25 1.200000e+02 # MH
## Dependent parameters, given by model restrictions.
## Those values should be edited following the
## analytical expression. MG5 ignores those values
## but they are important for interfacing the output of MG5
## to external program such as Pythia.
  1 0.000000 # d : 0.0
  2 0.000000 # u : 0.0
  3 0.000000 # s : 0.0
  4 0.000000 # c : 0.0
  11 0.000000 # e- : 0.0
  12 0.000000 # ve : 0.0
  13 0.000000 # nu- : 0.0
  14 0.000000 # vm : 0.0
  16 0.000000 # vt : 0.0
  21 0.000000 # g : 0.0
  22 0.000000
  24 80.419002 # w+ : cmath.sqrt(MZ__exp__2/2. + cmath.sqrt(MZ__exp__4/4. - (aEW*cmath.pi*MZ__exp__2)/(Gf*sqrt__2)))
```

W Mass is an internal parameter!

MG5 didn't use this value!

So you need to change MZ or Gf or alpha_EW

Solution I : Syntax

- What's the meaning of the order QED/QCD
  - ➡ By default MG5 takes the lowest order in QED!
  - ➡ p p > t t~ => p p > t t~ QED=0
  - ➡ p p > t t~ QED=2
    - additional diagrams (photon/z exchange)

p p > t t~

Cross section (pb)
555 ± 0.84

p p > t t~ QED=2

Cross section (pb)
555.8 ± 0.91

No significant QED contribution

Exercise 1: Extra questions:

- Are diagrams with photons/z included? If not, how can I include them? How much does the cross-section change? What is that 'WEIGHTED'?
  - `> display diagrams`
  - No photon/z appear.
  - Are we missing anything important?

Exercise 1: Extra questions:

- Are diagrams with photons/z included? If not, how can I include them? How much does the cross-section change? What is that 'WEIGHTED'?
  - > `display diagrams`
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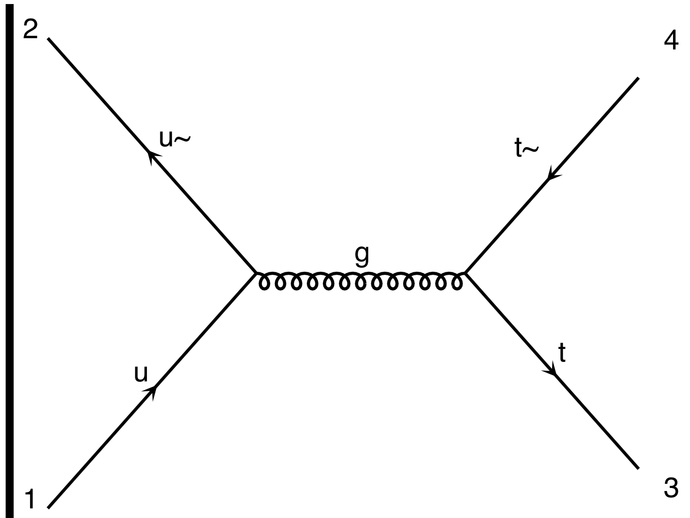
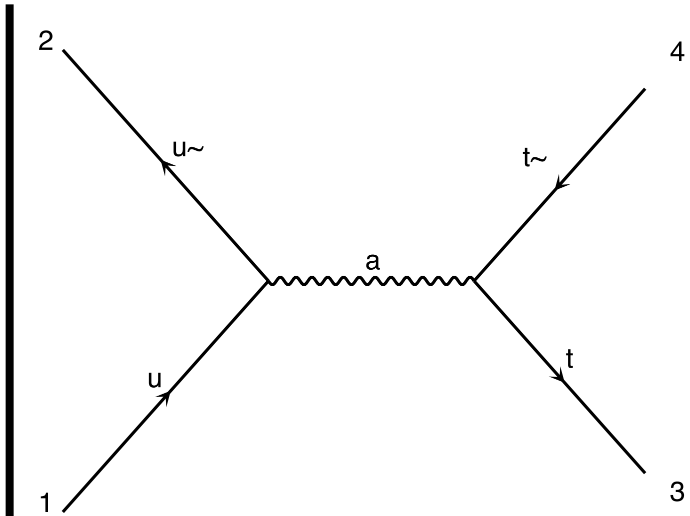


$$\left|\ \cdot\ \right|^2 \sim \alpha_s^2$$



$$\left|\ \cdot\ \right|^2 \sim \alpha_e^2$$

Exercise 1:
Extra questions:

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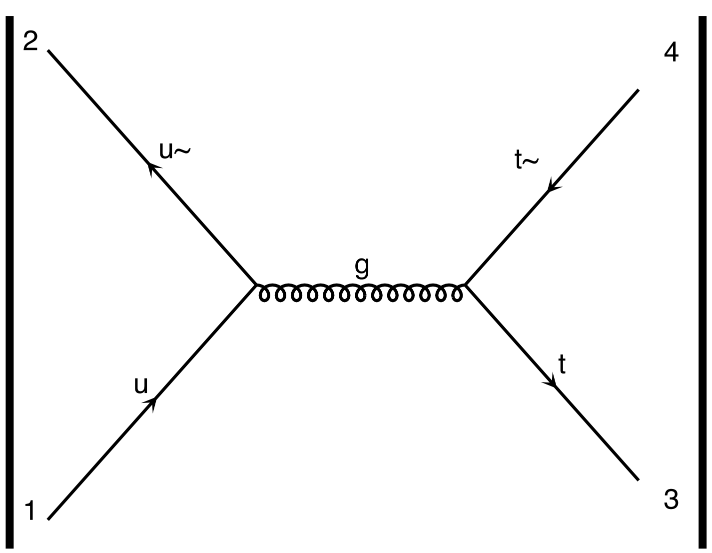
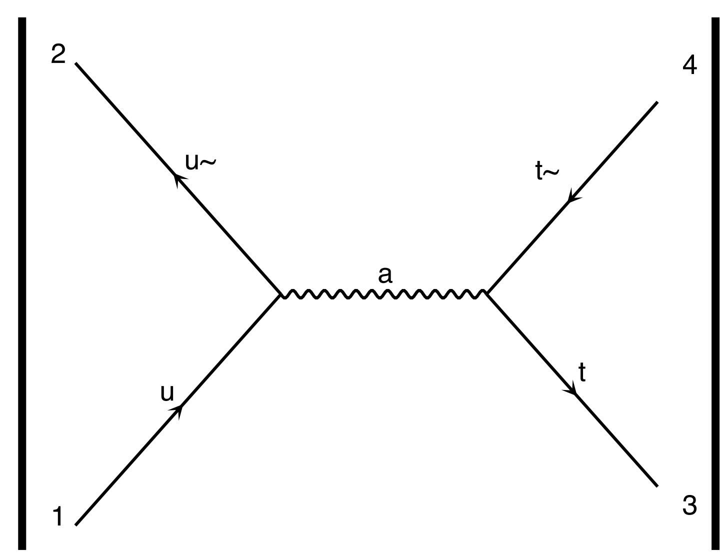


$$\Big|\ \cdots\ \Big|^2 \sim \alpha_s^2$$



$$\Big|\ \cdots\ \Big|^2 \sim \alpha_e^2 \quad \frac{\alpha_e}{\alpha_s} \lesssim 0.1$$

Exercise 1:
Extra questions:

- Are diagrams with photons/z included? If not, how can I include them? How much does the cross-section change?
  What is that 'WEIGHTED'?
  - `> display diagrams`
  - No photon/z appear.
  - Are we missing anything important? Does not seem the case
  - How to have them anyway?
  - MG5 exploits the hierarchy between QCD and QED couplings in order to give the leading (i.e. with most QCD) contribution to the cross-section by default
  - It assign WEIGHTED order =1(=2) to QCD (QED) vertices and generates the process with minimum WEIGHTED order

Exercise 1: Extra questions:

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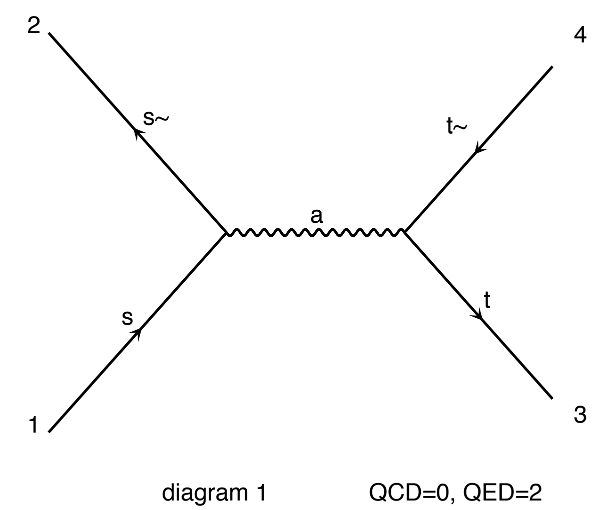
Exercise 1:
Extra questions:

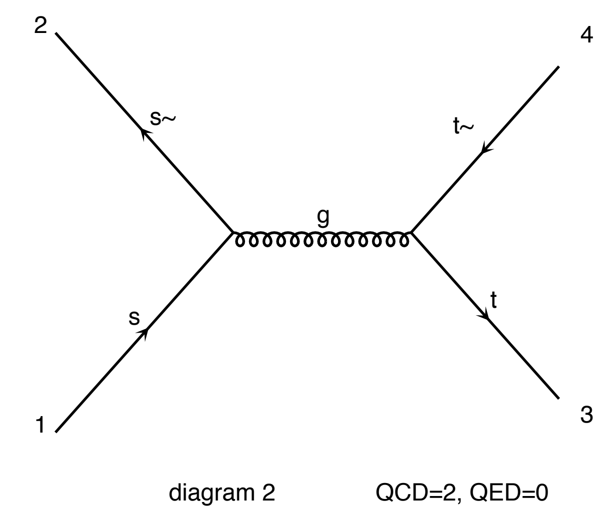
Exercise 1:
Extra questions:

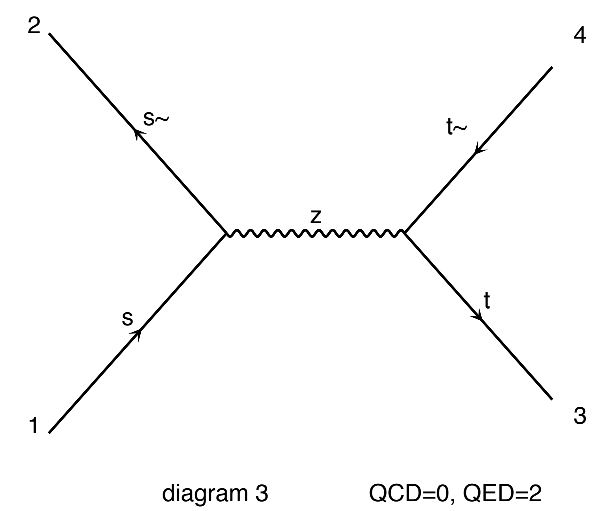
- Are diagrams with photons/z included? If not, how can I include them? How much does the cross-section change?
  - > `generate p p > t t~ WEIGHTED=4`
  - > `display diagrams`
  - > `output …`

Exercise 1:
Extra questions:

- Are diagrams with photons/z included? If not, how can I include them? How much does the cross-section change?
  - > `generate p p > t t~ WEIGHTED=4`
  - > `display diagrams`
  - > `output ...`

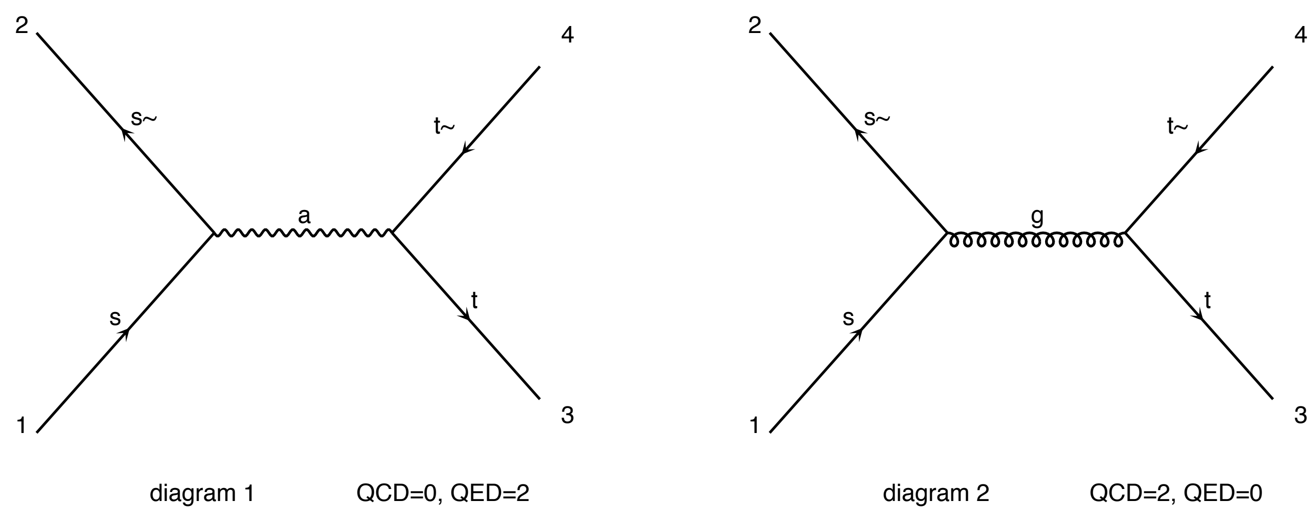


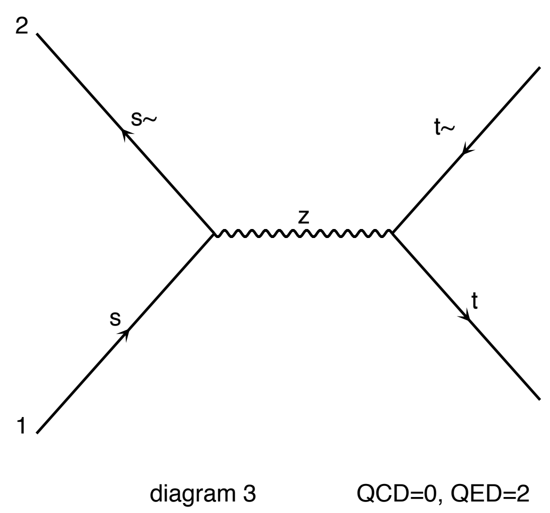




Exercise 1:
Extra questions:

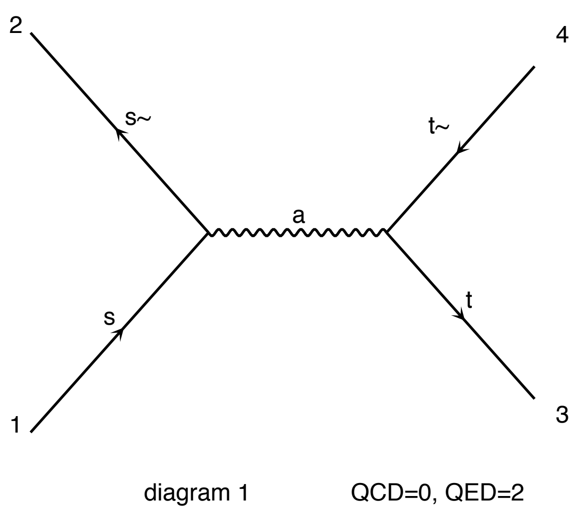
- Are diagrams with photons/z included? If not, how can I include them? How much does the cross-section change?
  - > generate p p > t t~ WEIGHTED=4
  - > display diagrams
  - > output …
  - > launch
  - > …

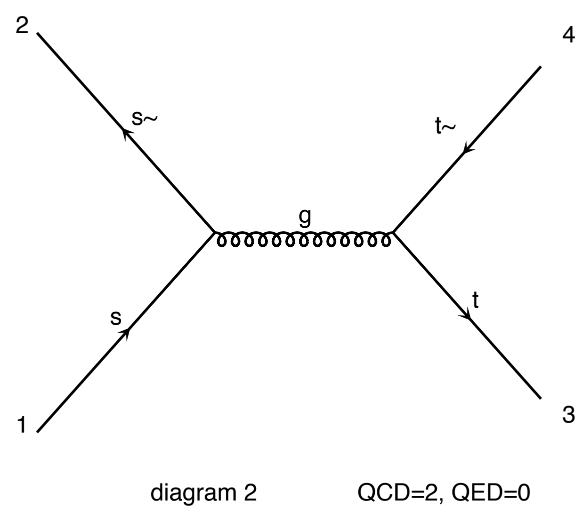




Exercise 1:
Extra questions:

- Are diagrams with photons/z included? If not, how can I include them? How much does the cross-section change?
  - > generate p p > t t~ WEIGHTED=4
  - > display diagrams
  - > output ...
  - > launch
  - > ...

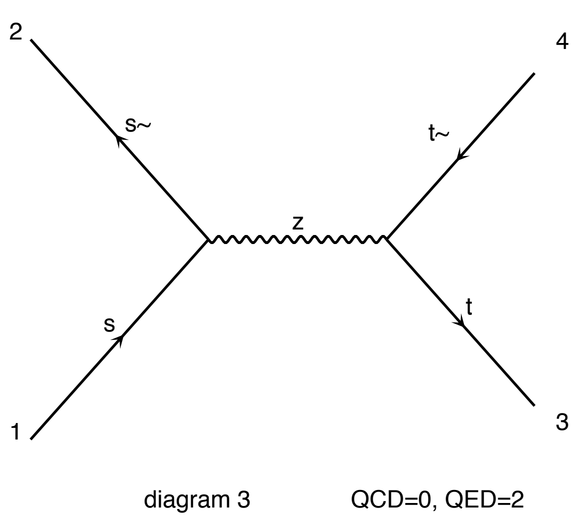





```
Cross-section :   160.8 +- 0.1999 pb
Nb of events :  10000
```

WEIGHTED=2

```
Cross-section :   160.4 +- 0.231 pb
Nb of events :  10000
```



Exercise 1:
Extra questions:

- Recompute the $t\bar{t}$ cross-section for m_t=170, 172, 174 … 180 GeV
- Be smart! Script it!
- Create a txt file `myttbar_scan.txt`

```
generate p p > t t~
output mytestdir2
launch
set ebeam1 4000
set ebeam2 4000
set MT 170
launch
set MT 172
launch
set MT 174
launch
set MT 176
launch
set MT 178
launch
set MT 180
```

- `./bin/mg5_aMC myttbar_scan.txt`

Exercise 1: Extra questions:

- Recompute the $t\bar{t}$ cross-section for m_t=170, 172, 174 … 180 GeV
- Be smart! Script it!
- You can also launch an existing folder, without regenerating the code

```
launch mytestdir2
set ebeam1 4000
set ebeam2 4000
set MT 170
launch
set MT 172
launch
set MT 174
launch
set MT 176
launch
set MT 178
launch
set MT 180
```

Exercise 1:
Extra questions:

- Recompute the $t\bar{t}$ cross-section for m_t=170, 172, 174 … 180 GeV

Results in the sm for p p > t t~

Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 4000 x 4000 GeV	tag_1	169.8 ± 0.24	10000	parton madevent	LHE	remove run · launch detector simulation
run_02	p p 4000 x 4000 GeV	tag_1	160.1 ± 0.28	10000	parton madevent	LHE	remove run · launch detector simulation
run_03	p p 4000 x 4000 GeV	tag_1	151.1 ± 0.2	10000	parton madevent	LHE	remove run · launch detector simulation
run_04	p p 4000 x 4000 GeV	tag_1	142.9 ± 0.18	10000	parton madevent	LHE	remove run · launch detector simulation
run_05	p p 4000 x 4000 GeV	tag_1	134.7 ± 0.19	10000	parton madevent	LHE	remove run · launch detector simulation
run_06	p p 4000 x 4000 GeV	tag_1	127.3 ± 0.16	10000	parton madevent	LHE	remove run · launch detector simulation

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Exercise 1:
Extra questions:

- Recompute the $t\bar{t}$ cross-section for m_t=170, 172, 174 … 180 GeV

Results in the sm for p p > t t~

Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 4000 x 4000 GeV	tag_1	169.8 ± 0.24	10000	parton madevent	LHE	remove run / launch detector simulation
run_02	p p 4000 x 4000 GeV	tag_1	160.1 ± 0.28	10000	parton madevent	LHE	remove run / launch detector simulation
run_03	p p 4000 x 4000 GeV	tag_1	151.1 ± 0.2	10000	parton madevent	LHE	remove run / launch detector simulation
run_04	p p 4000 x 4000 GeV	tag_1	142.9 ± 0.18	10000	parton madevent	LHE	remove run / launch detector simulation
run_05	p p 4000 x 4000 GeV	tag_1	134.7 ± 0.19	10000	parton madevent	LHE	remove run / launch detector simulation
run_06	p p 4000 x 4000 GeV	tag_1	127.3 ± 0.16	10000	parton madevent	LHE	remove run / launch detector simulation

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which folder is what?

Exercise 1: Extra questions:

- Recompute the $t\bar{t}$ cross-section for m_t=170, 172, 174 … 180 GeV
- Be smart! Script it!
- You can specify the name (instead of `run_01...`) with `-n NAME`

```
launch mytestdir2 -n run_MT170
set ebeam1 4000
set ebeam2 4000
set MT 170
launch -n run_MT172
set MT 172
launch -n run_MT174
set MT 174
launch -n run_MT176
set MT 176
launch -n run_MT178
set MT 178
launch -n run_MT180
set MT 180
```

Exercise 1:
Extra questions:

- Since recently, multiple values can be specified for parameters. Just set in the `param_card`, instead of the top mass
  `6 scan:[170,172,174,176,178]`

Exercise 1:
Extra questions:

- Recompute the $t\bar{t}$ cross-section for m_t=170, 172, 174 … 180 GeV

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 4000 x 4000 GeV	tag_1	169.8 ± 0.24	10000	parton madevent	LHE	remove run launch detector simulation
run_02	p p 4000 x 4000 GeV	tag_1	160.1 ± 0.28	10000	parton madevent	LHE	remove run launch detector simulation
run_03	p p 4000 x 4000 GeV	tag_1	151.1 ± 0.2	10000	parton madevent	LHE	remove run launch detector simulation
run_04	p p 4000 x 4000 GeV	tag_1	142.9 ± 0.18	10000	parton madevent	LHE	remove run launch detector simulation
run_05	p p 4000 x 4000 GeV	tag_1	134.7 ± 0.19	10000	parton madevent	LHE	remove run launch detector simulation
run_06	p p 4000 x 4000 GeV	tag_1	127.3 ± 0.16	10000	parton madevent	LHE	remove run launch detector simulation
run_MT170	p p 4000 x 4000 GeV	tag_1	170 ± 0.22	10000	parton madevent	LHE	remove run launch detector simulation
run_MT172	p p 4000 x 4000 GeV	tag_1	159.6 ± 0.22	10000	parton madevent	LHE	remove run launch detector simulation
run_MT174	p p 4000 x 4000 GeV	tag_1	151.1 ± 0.22	10000	parton madevent	LHE	remove run launch detector simulation
run_MT176	p p 4000 x 4000 GeV	tag_1	142.6 ± 0.19	10000	parton madevent	LHE	remove run launch detector simulation
run_MT178	p p 4000 x 4000 GeV	tag_1	134.7 ± 0.18	10000	parton madevent	LHE	remove run launch detector simulation
run_MT180	p p 4000 x 4000 GeV	tag_1	127.2 ± 0.24	10000	parton madevent	LHE	remove run launch detector simulation

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Mass-Scan (with decay)

- Generate p p > t t~, t > w+ b, t~ > w- b~
- Output
- Launch
- Set mt scan:range(170,181,2)

Scan

Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 6500.0 x 6500.0 GeV	tag_1	462.6 ± 0.72 ± systematics	10000	parton madevent	LHE plots	remove run launch detector simulation
run_02	p p 6500.0 x 6500.0 GeV	tag_1	476.2 ± 0.72 ± systematics	10000	parton madevent	LHE plots	remove run launch detector simulation
run_03	p p 6500.0 x 6500.0 GeV	tag_1	488.2 ± 0.86 ± systematics	10000	parton madevent	LHE plots	remove run launch detector simulation
run_04	p p 6500.0 x 6500.0 GeV	tag_1	502.5 ± 0.8 ± systematics	10000	parton madevent	LHE plots	remove run launch detector simulation
run_05	p p 6500.0 x 6500.0 GeV	tag_1	514 ± 0.78 ± systematics	10000	parton madevent	LHE plots	remove run launch detector simulation
run_06	p p 6500.0 x 6500.0 GeV	tag_1	528.6 ± 0.87 ± systematics	10000	parton madevent	LHE plots	remove run launch detector simulation

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- What's wrong?
  - ➡ Why the cross-section increase?

Mass-Scan (with decay)

- The width was not updated. Let's fix it:
  - ➡Generate p p > t t~, t > w+ b, t~ > w- b~
  - ➡Output
  - ➡Launch
  - ➡Set mt scan:range(170,181,2)
  - ➡Set wt auto

- With the LO width

run_07	p p 6500.0 x 6500.0 GeV	tag_1	524.4 ± 0.89 ± systematics	10000	parton madevent	LHE plots	remove run	launch detector simulation
run_08	p p 6500.0 x 6500.0 GeV	tag_1	496.6 ± 0.9 ± systematics	10000	parton madevent	LHE plots	remove run	launch detector simulation
run_09	p p 6500.0 x 6500.0 GeV	tag_1	468.5 ± 0.79 ± systematics	10000	parton madevent	LHE plots	remove run	launch detector simulation
run_10	p p 6500.0 x 6500.0 GeV	tag_1	446 ± 0.79 ± systematics	10000	parton madevent	LHE plots	remove run	launch detector simulation
run_11	p p 6500.0 x 6500.0 GeV	tag_1	421.8 ± 0.81 ± systematics	10000	parton madevent	LHE plots	remove run	launch detector simulation
run_12	p p 6500.0 x 6500.0 GeV	tag_1	400.3 ± 0.63 ± systematics	10000	parton madevent	LHE plots	remove run	launch detector simulation

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