Getting ready for the LHC: Commissioning the theoretical tools

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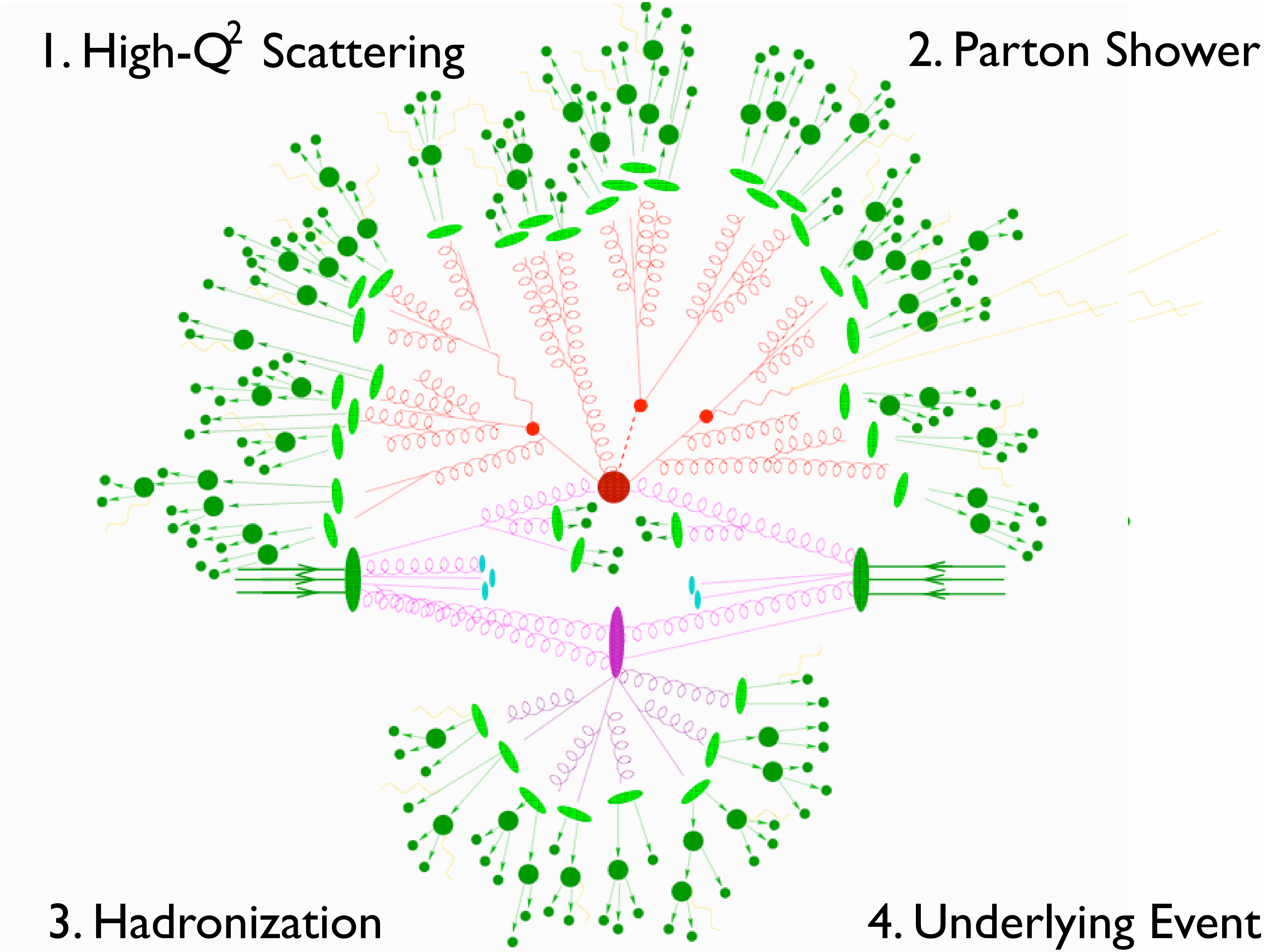
Outline

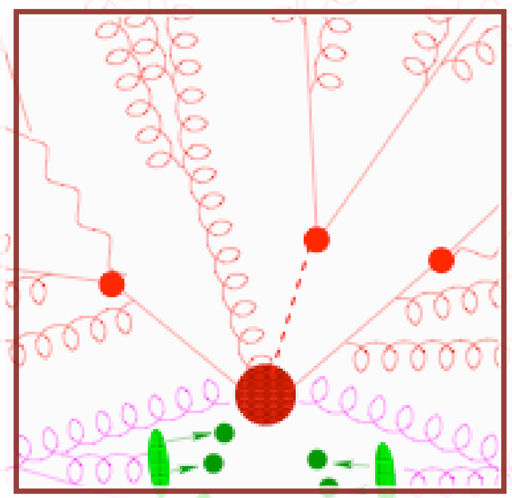
- Theoretical tools?? For what?
- The new generation of simulation tools:
  - Improving the QCD predictions
  - Going BSM
- MG/ME and some physics examples (finally!!)
- Outlook


1. High-Q^2 Scattering
2. Parton Shower
3. Hadronization
4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower

☞ where new physics lies



☞ process dependent

☞ first principles description

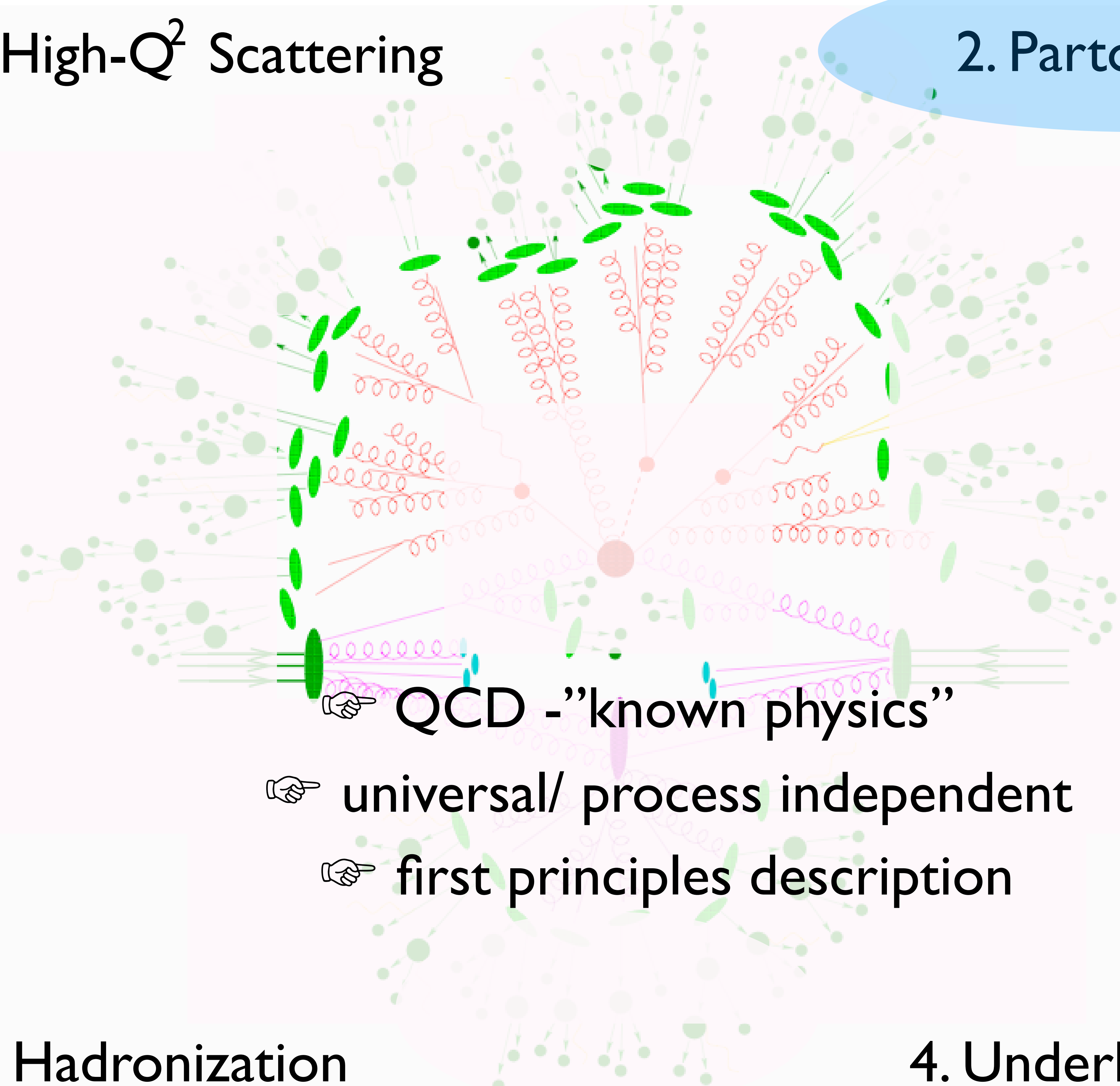
☞ it can be systematically improved

3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower



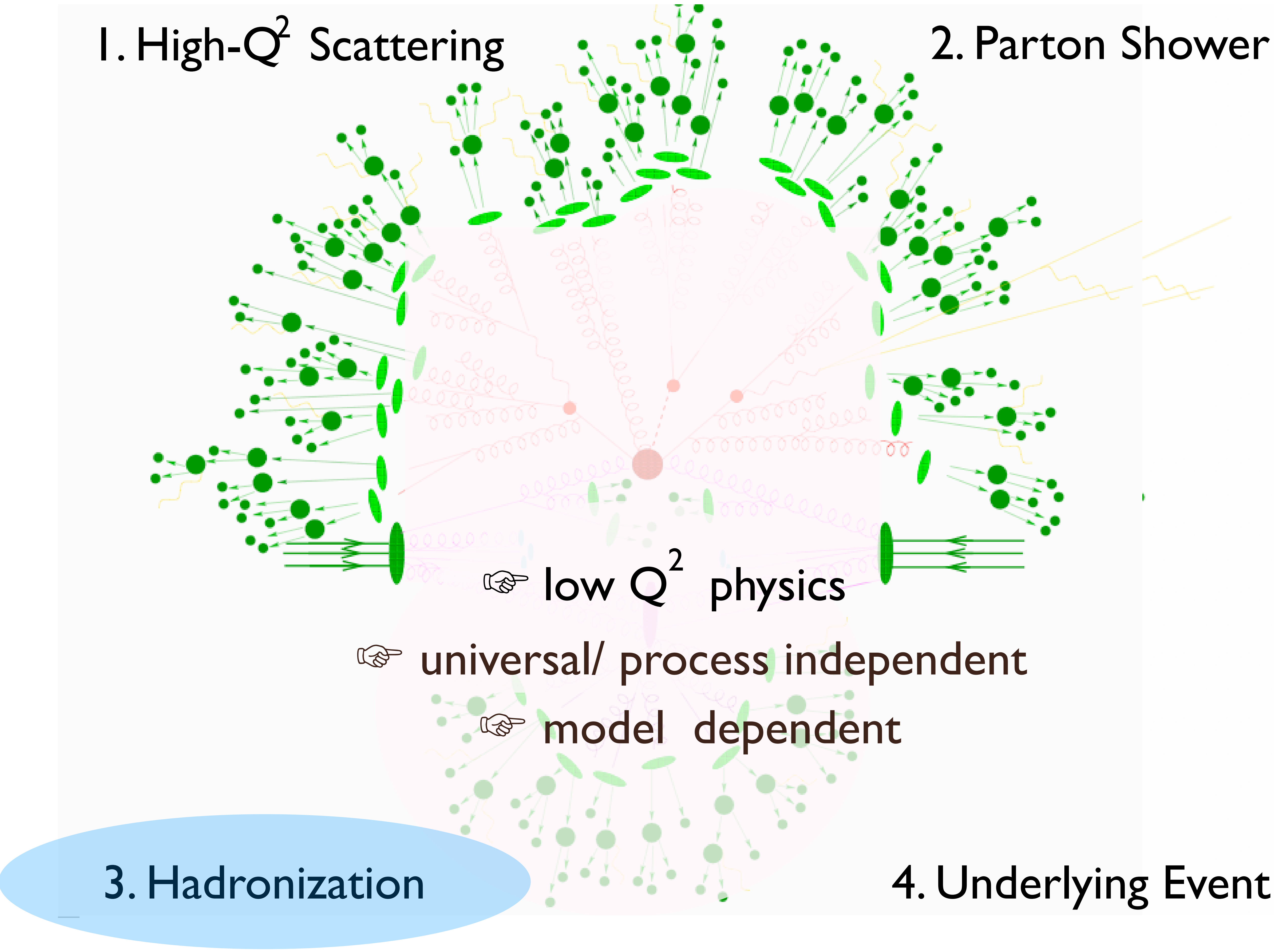
☞ QCD -"known physics"

☞ universal/ process independent

☞ first principles description

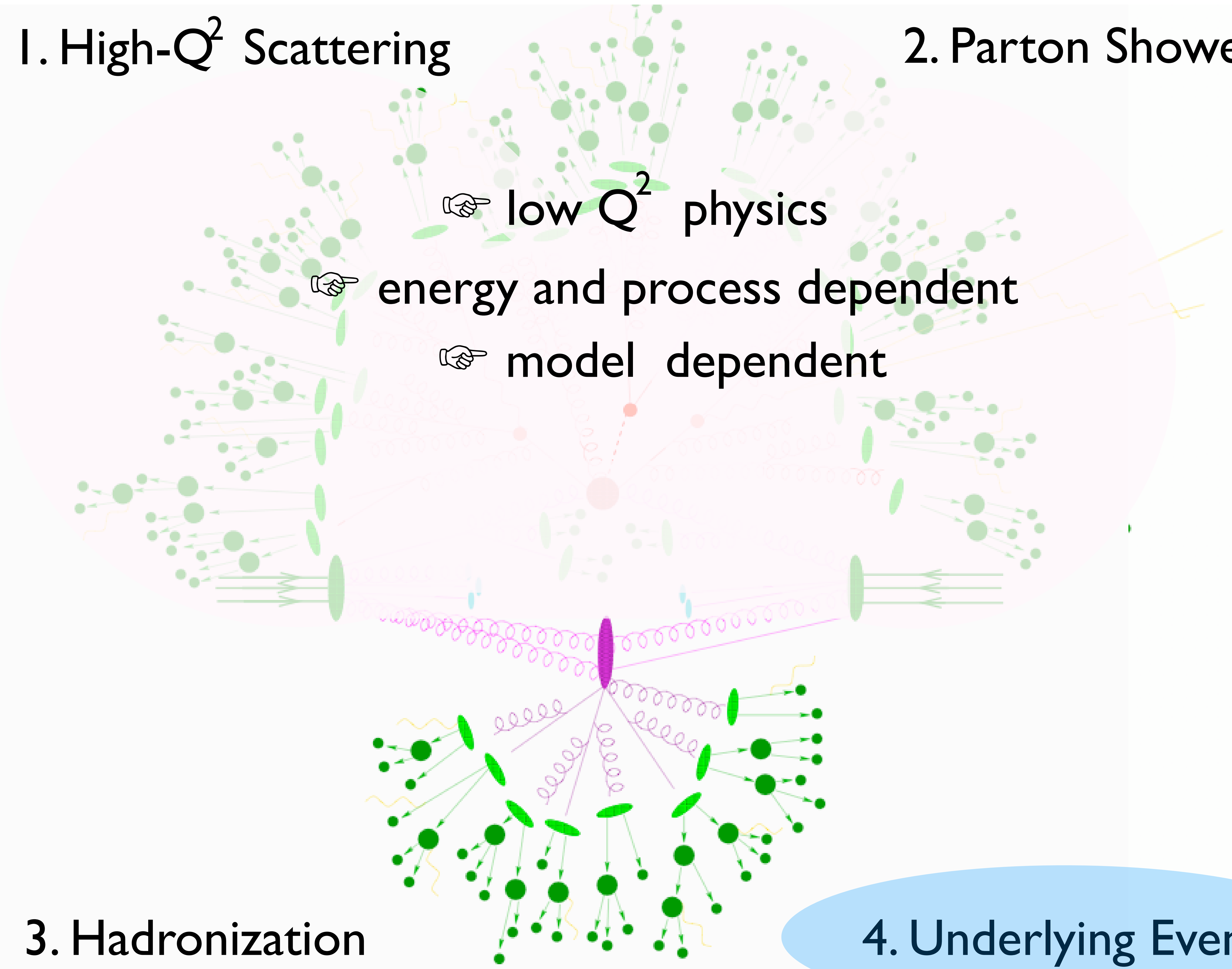
3. Hadronization

4. Underlying Event


1. High-Q^2 Scattering
2. Parton Shower
☞ low Q^2 physics
☞ universal/ process independent
☞ model dependent
3. Hadronization
4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower



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

3. Hadronization

4. Underlying Event

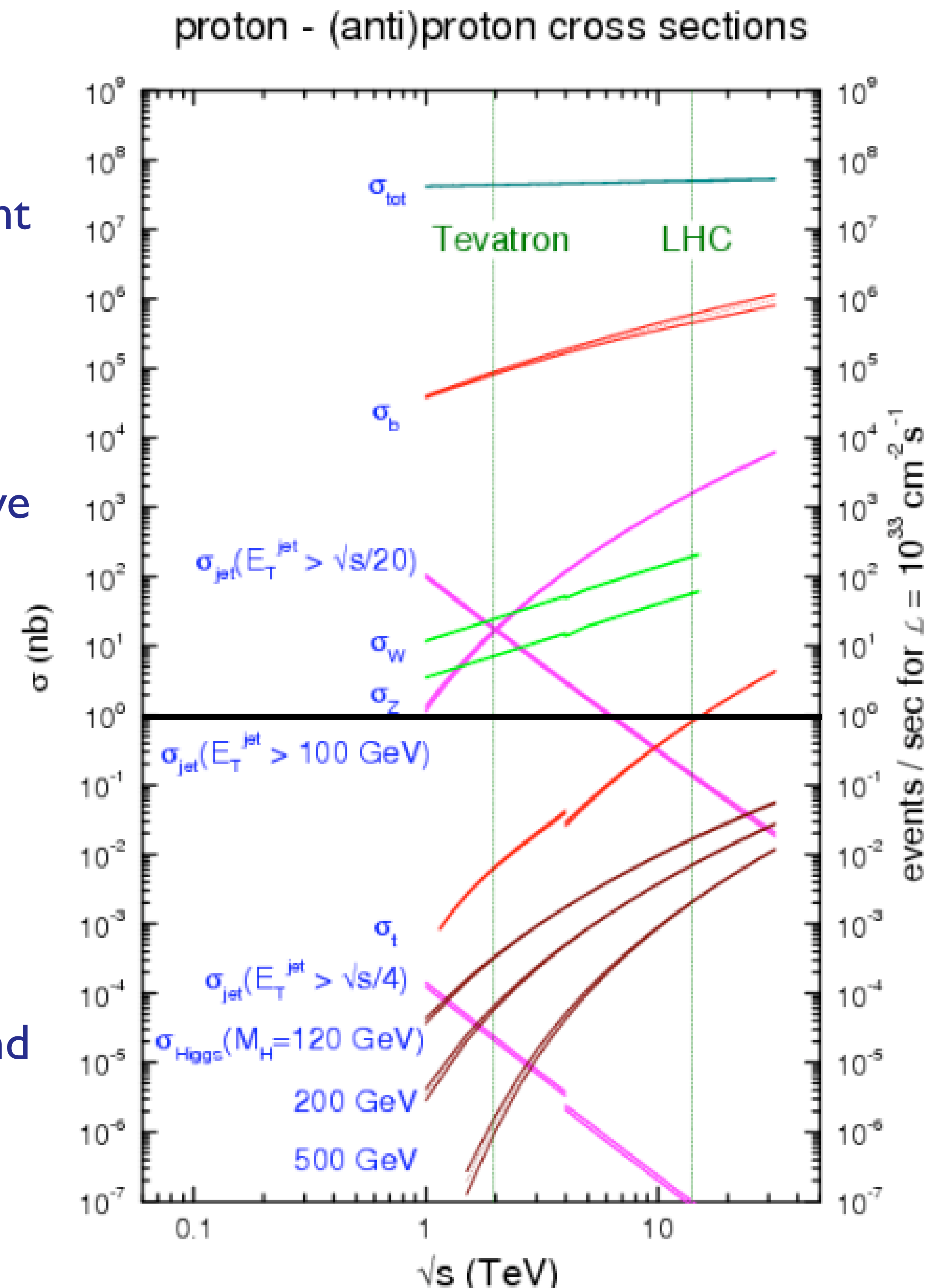
From Tevatron to LHC

- Yields increased by order of magnitudes wrt Tevatron.
- Events with vectors bosons, tops and heavy and light jets with rates >1 Hz.
- Higgs physics down order of magnitudes.
- Need to understand QCD backgrounds well!

QCD factorization theorem for short-distance inclusive processes:

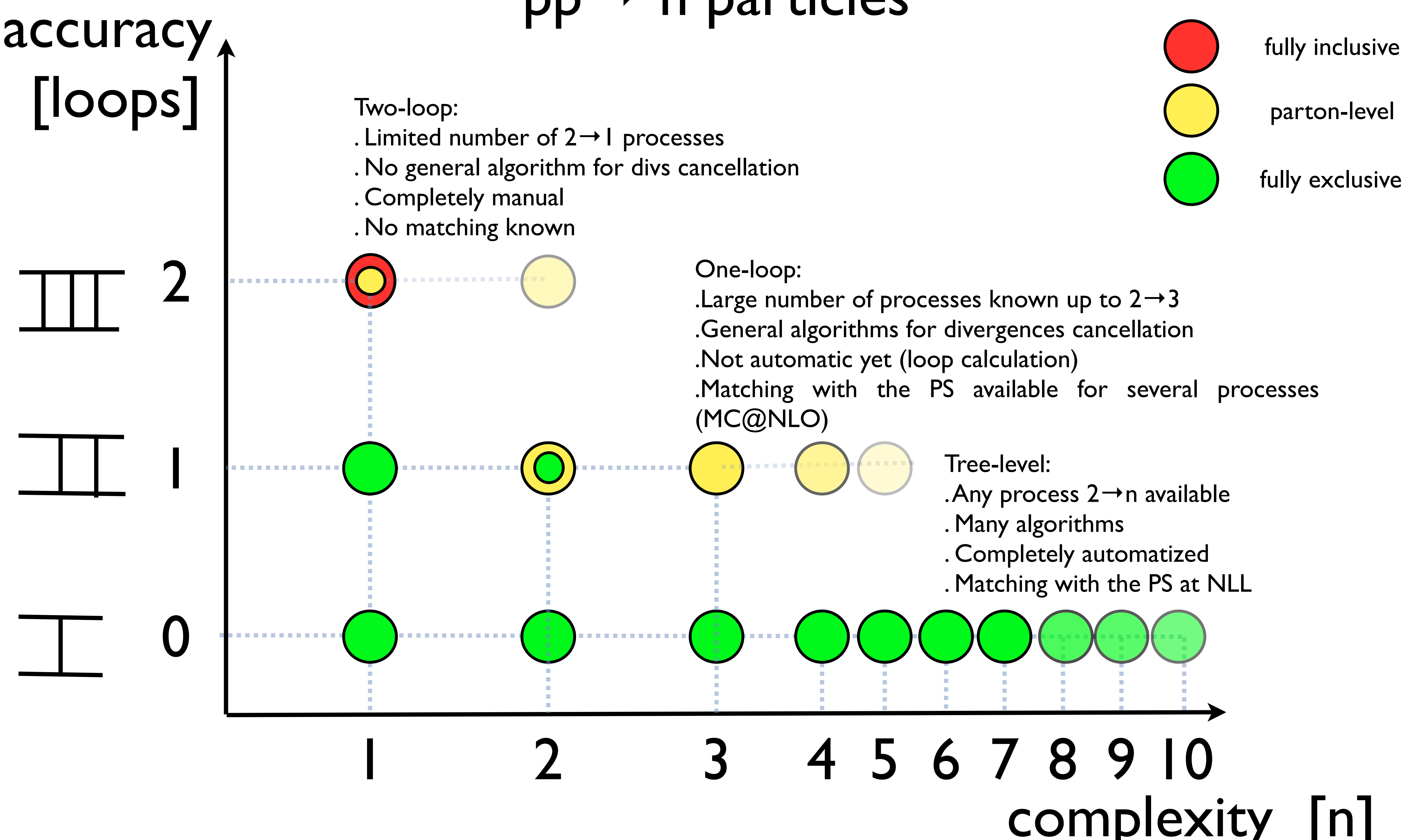
$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab\to X}(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2})$$

Two ingredients necessary:
1. Parton Distribution functions (from exp).
2. Short distance coefficients as an expansion in α_S and possibly with resum. of large logs (from th).



Status

pp→ n particles



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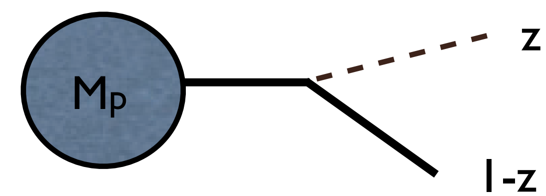
Parton Shower MC event generators

ME involving q →q g (or g → gg) are strongly enhanced when they are close in the phase space:

$$\frac{1}{(p_q+p_g)^2} \simeq \frac{1}{2E_qE_g(1-\cos\theta)}$$



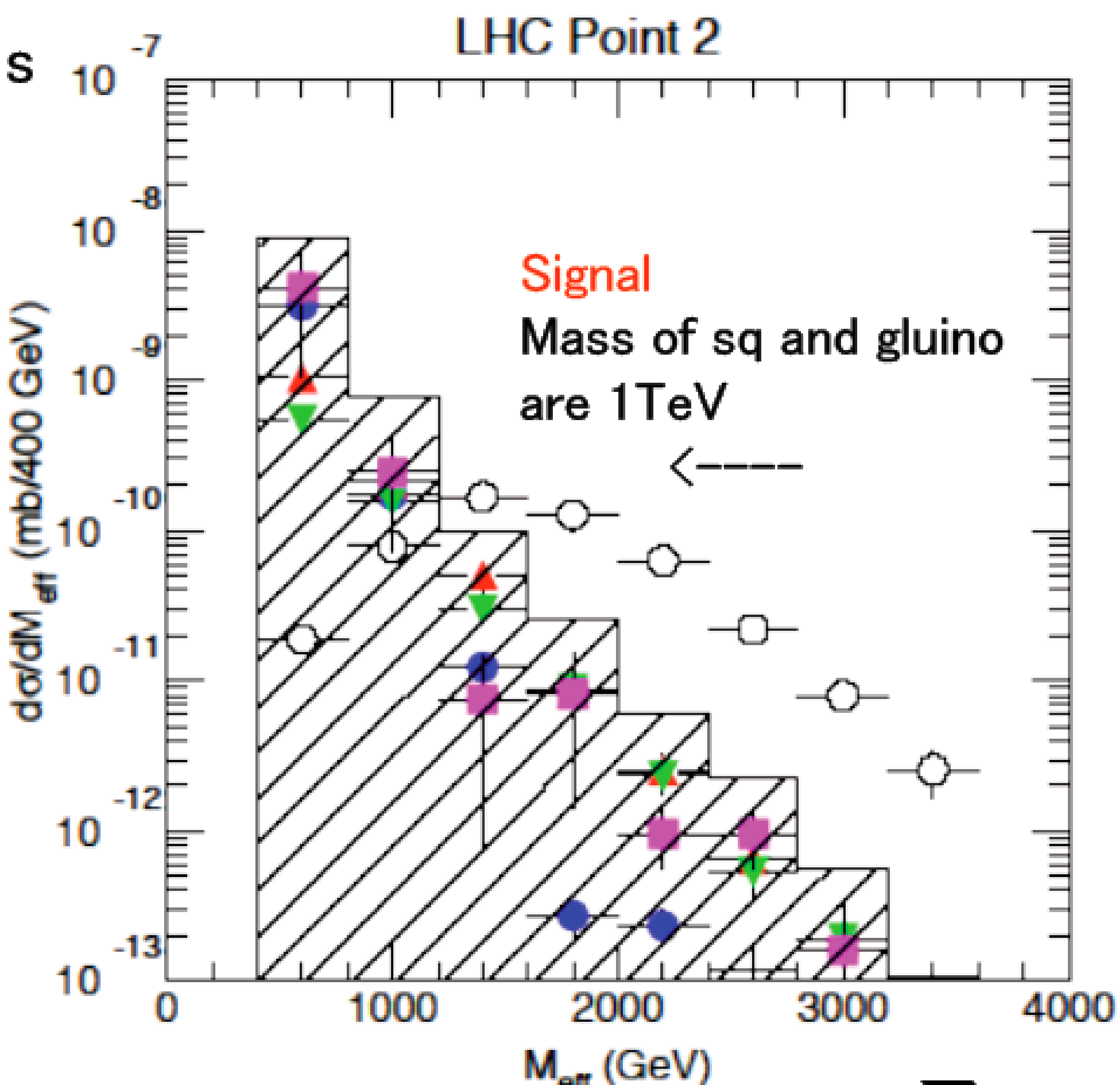
Both soft and collinear divergences: very different nature!

Collinear factorization:

$$|M_{p+1}|^2 d\Phi_{p+1} \simeq |M_p|^2 d\Phi_p \frac{dt}{t}\frac{\alpha_S}{2\pi}P(z)dzd\phi$$

1. Allows for a parton shower (Markov process) evolution
2. The evolution resums the dominant leading-log contributions
3. By adding angular ordering the main quantum (interference) effects are also included

Key example: Inclusive SUSY searches at the LHC



$$= \not{E}_T + \sum P_T$$

The technical challenges

How do we calculate a LO cross section for 3 jets at the LHC?

I. Identify all subprocesses (gg→ggg, qg→qgg....) in

$$\sigma(pp \to 3j) = \sum_{ijk} \int f_i(x_1) f_j(x_2) \hat{\sigma}(ij \to k_1 k_2 k_3)$$

easy

II. For each one, calculate the amplitude:

$$\mathcal{A}(\{p\},\{h\},\{c\}) = \sum_i D_i$$

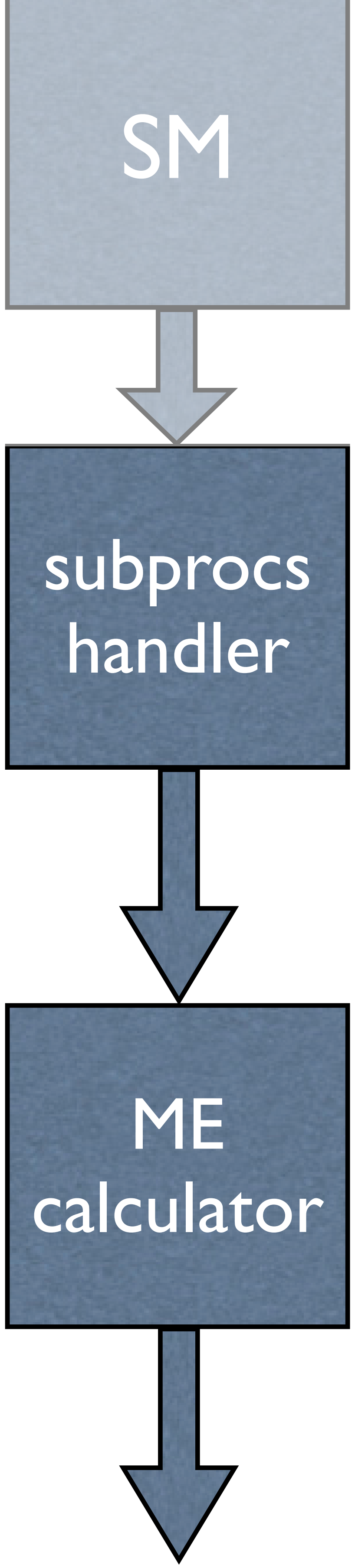
difficult

III. Square the amplitude, sum over spins & color, integrate over the phase space (D ~ 3n)

$$\hat{\sigma} = \frac{1}{2\hat{s}} \int d\Phi_p \sum_{h,c} |\mathcal{A}|^2$$

very hard

General structure

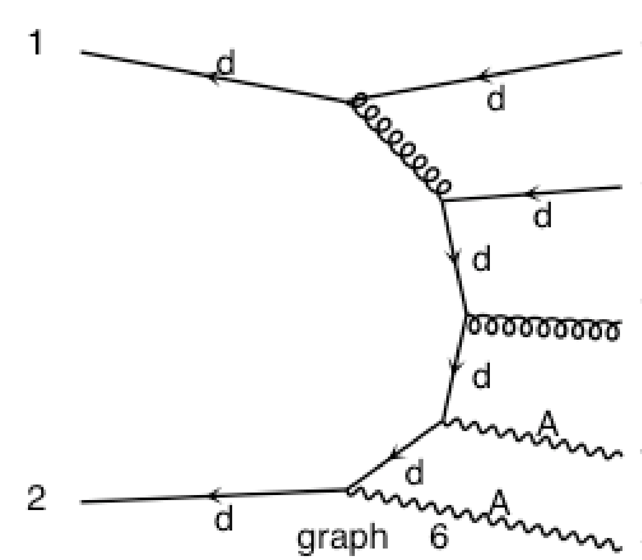


Includes all possible subprocess leading to a given multi-jet final state automatically or manually (done once for all)

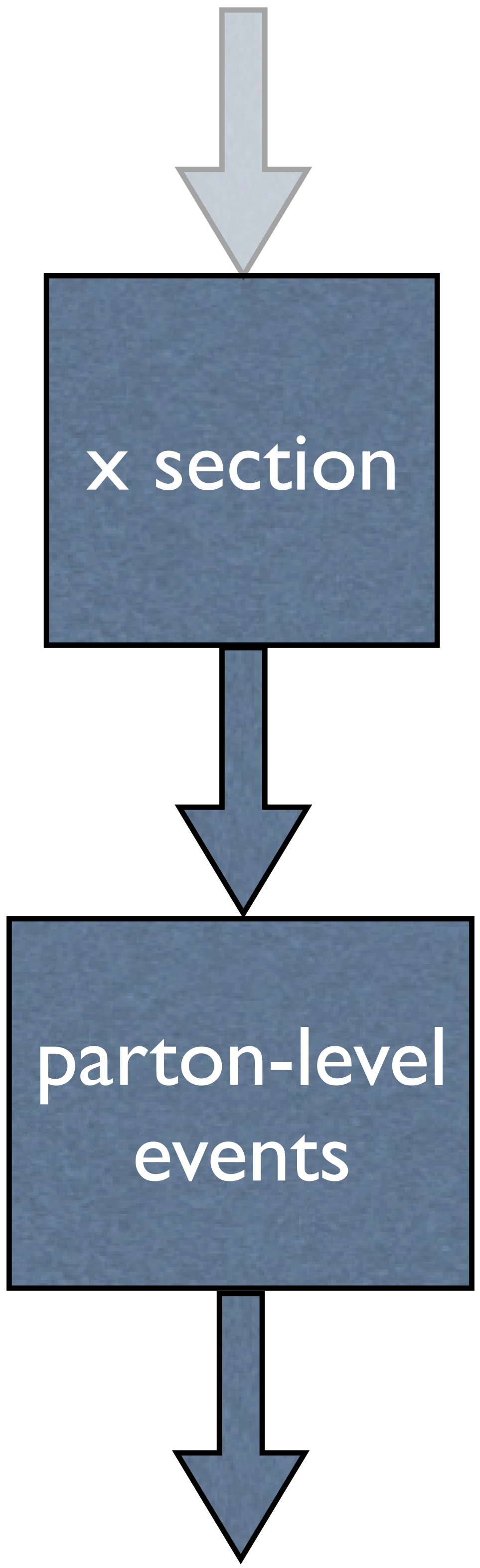
d~ d -> a a u u~ g
d~ d -> a a c c~ g
s~ s -> a a u u~ g
s~ s -> a a c c~ g

<u>"Automatically"</u> generates a code to calculate |M|^2 for arbitrary processes with many partons in the final state.

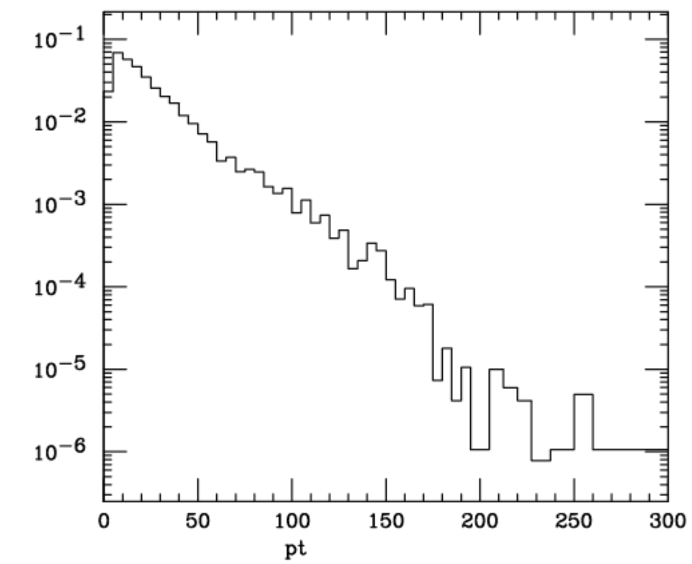
Most use Feynman diagrams w/ tricks to reduce the factorial growth, others have recursive relations to reduce the complexity to exponential. ☺



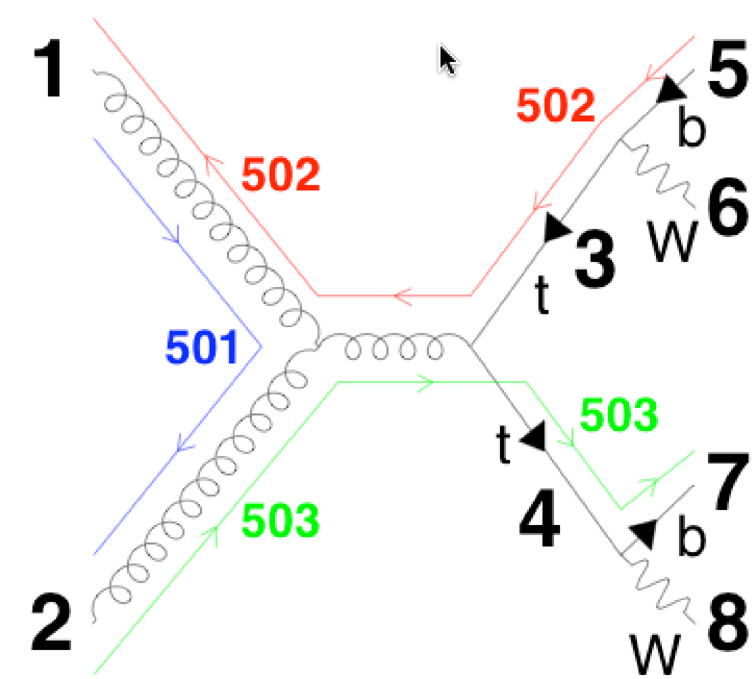
General structure



Integrate the matrix element over the phase space using a multi-channel technique and using parton-level cuts.



Events are obtained by unweighting. These are at the parton-level. Information on particle id, momenta, spin, color is given in the Les Houches format.

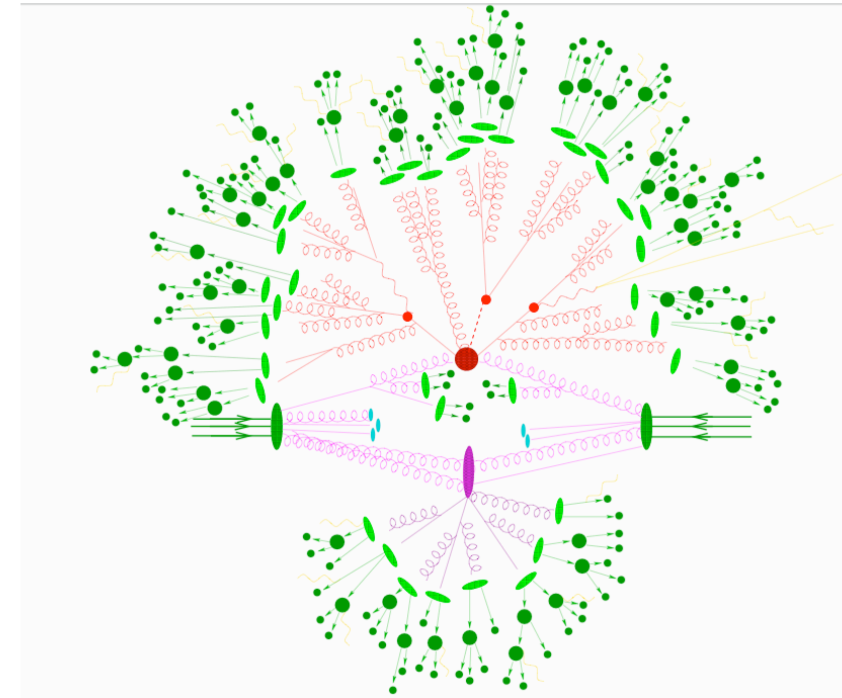


General structure

Shower
&
Hadro

Events in the LH format are passed to the showering and hadronization⇒

high multiplicity hadron-level events

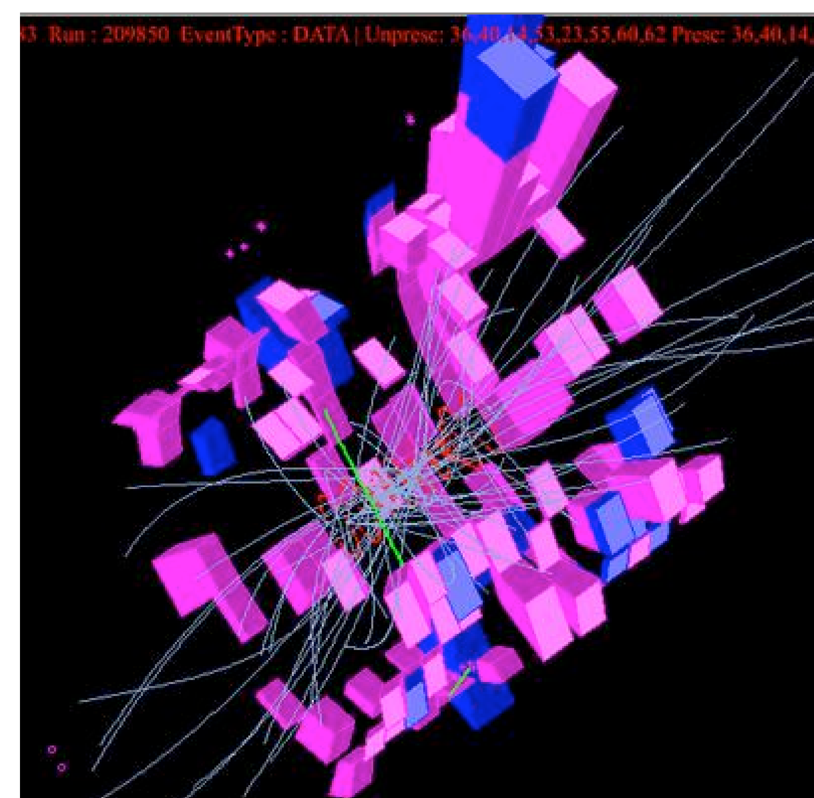


th

exp

Detector simulation & reco

Events in stdhep format are passed through fast or full simulation, and physical objects (leptons, photons, jet, b-jets, taus) are reconstructed.



Aside: Complexity of QCD amplitudes

$$\mathcal{A}_n(g_1,\ldots,g_n) = g^{n-2}\sum_{\sigma\in S_{n-1}} \mathrm{Tr}(\lambda^{a_1}\lambda^{a_{\sigma_2}}\cdots\lambda^{a_{\sigma_n}})A_n(1,\sigma_2,\ldots,\sigma_n)$$

n	full Amp	partial Amp	BG
4	4	3	3
5	25	10	10
6	220	36	35
7	2485	133	70
8	34300	501	126
9	559405	1991	210
10	10525900	7335	330
11	224449225	28199	495
12	5348843500	108280	715
	$(2n)!$	3.8^n	n^4

- New twistor tree-level BCF relations perform WORSE than the "old" Berends-Giele recursive relations for the partial amplitudes even after inserting color back. [C.Duhr, S. Hoeche, F.M., 2006]
- In any case the calculation through partial amplitudes is not as efficient as the direct calculation of the full amplitude at fixed color through numerical recursive relations [Moretti, Caravaglios, Mangano, Pittau, 1998; Draggiotis, Kleiss, Papadopoulos, 1998], which has only an exponential growth.
- Similar results can be obtained through the BG and an improved handling of color [FM, Paul, Stelzer, WIlenbrock 2003].

ME/PS matching

ME

1. parton-level description
2. fixed order calculation
3. quantum interference exact
4. valid when partons are hard and well separated
5. needed for multi-jet description

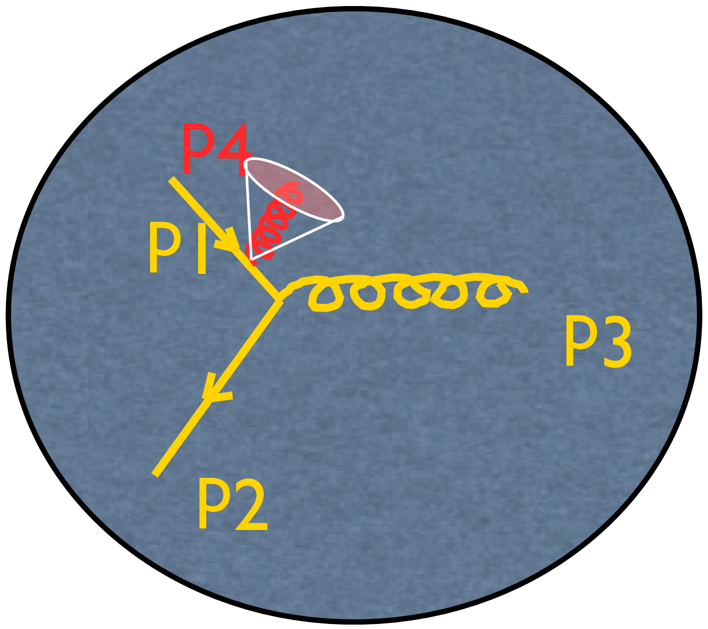
Shower MC

1. hadron-level description
2. resums large logs
3. quantum interference through AA
4. valid when partons are collinear and/or soft
5. nedeed for realistic studies

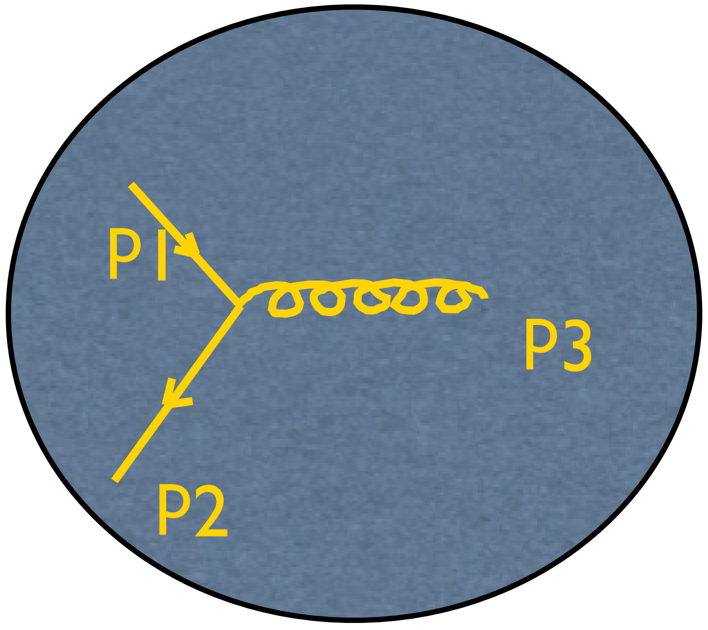
Approaches are complementary!

But double-counting has to be avoided!

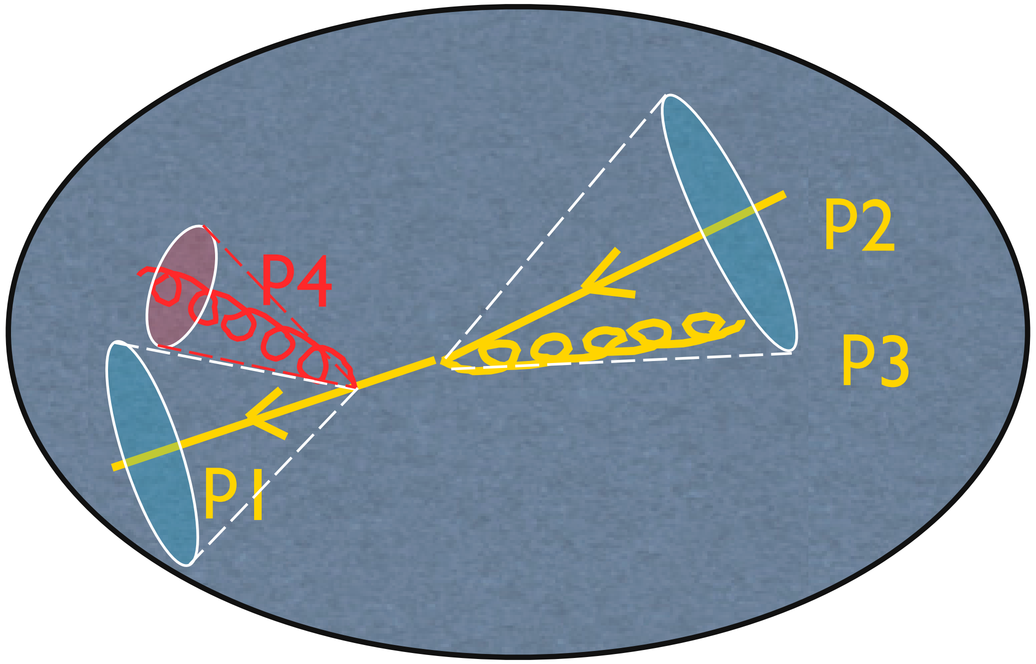
Double counting



is of $O(\alpha_s)$
relative to the
LO process

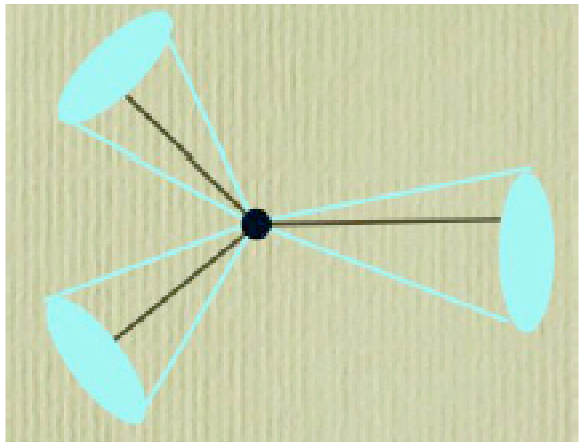


What about this ?

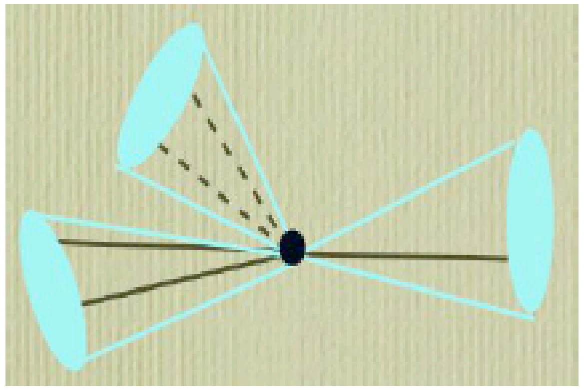


The matching algorithm

Jet-parton matching

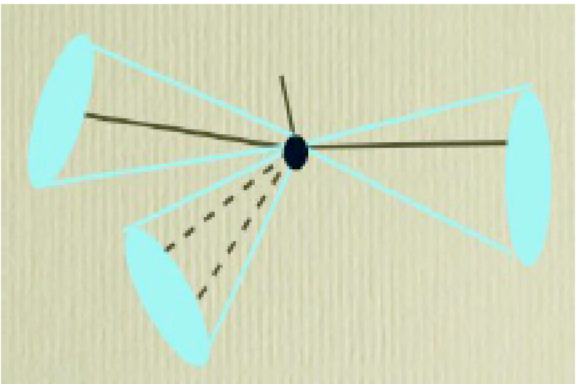


Event matched, $N_{\text{jet}} = N_{\text{part}} = 3$
– Keep event

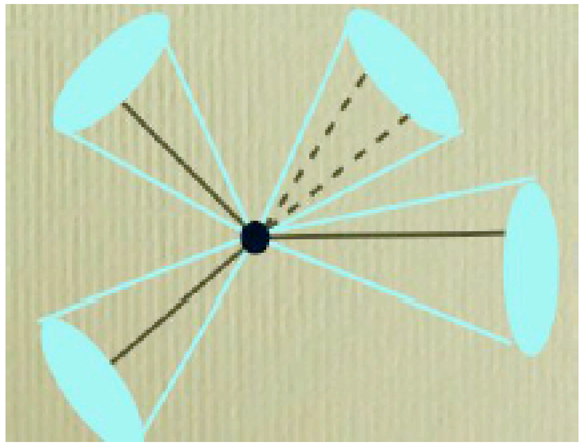


Collinear double-log double counting

Not matched, $N_{\text{jet}} = N_{\text{part}} = 3$
but $N_{\text{matched}} = 2$ – throw away



Soft single-log double counting

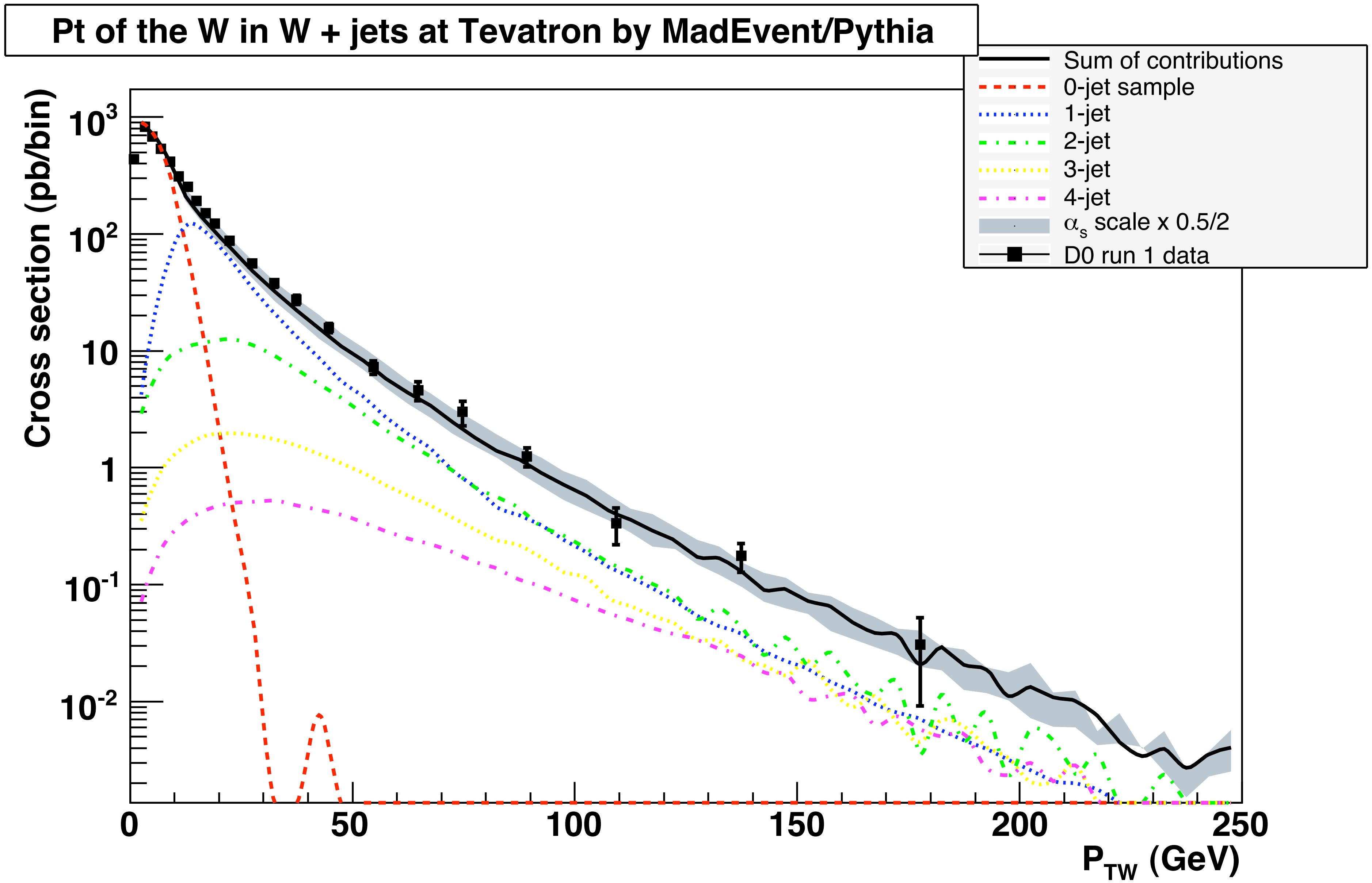


Event matched, but $N_{\text{jet}} > N_{\text{part}}$
– Keep for highest-multiplicity sample only

Solid lines = ME partons   Broken lines = PS partons

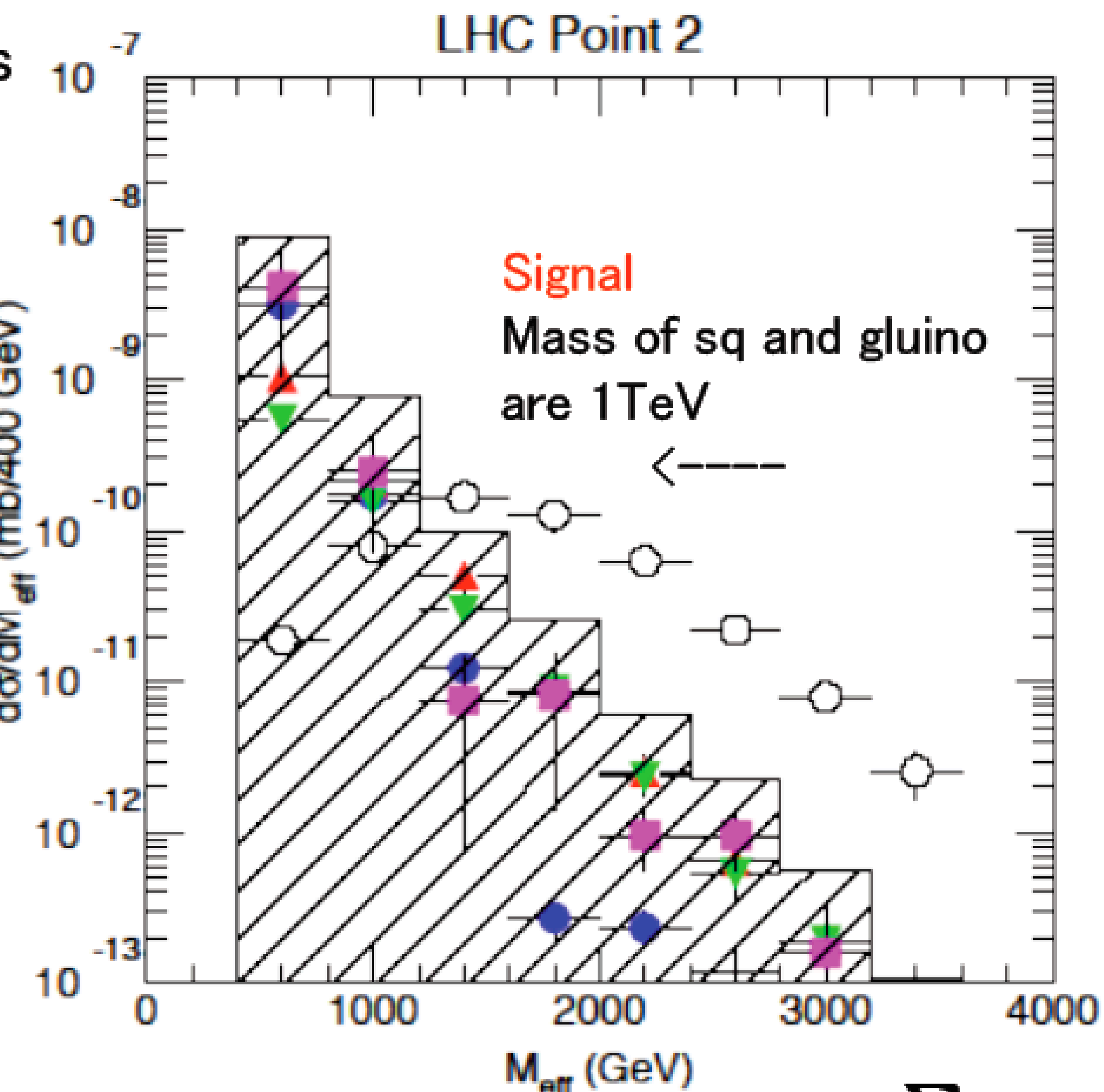
Matching: results

[J. Alwall]

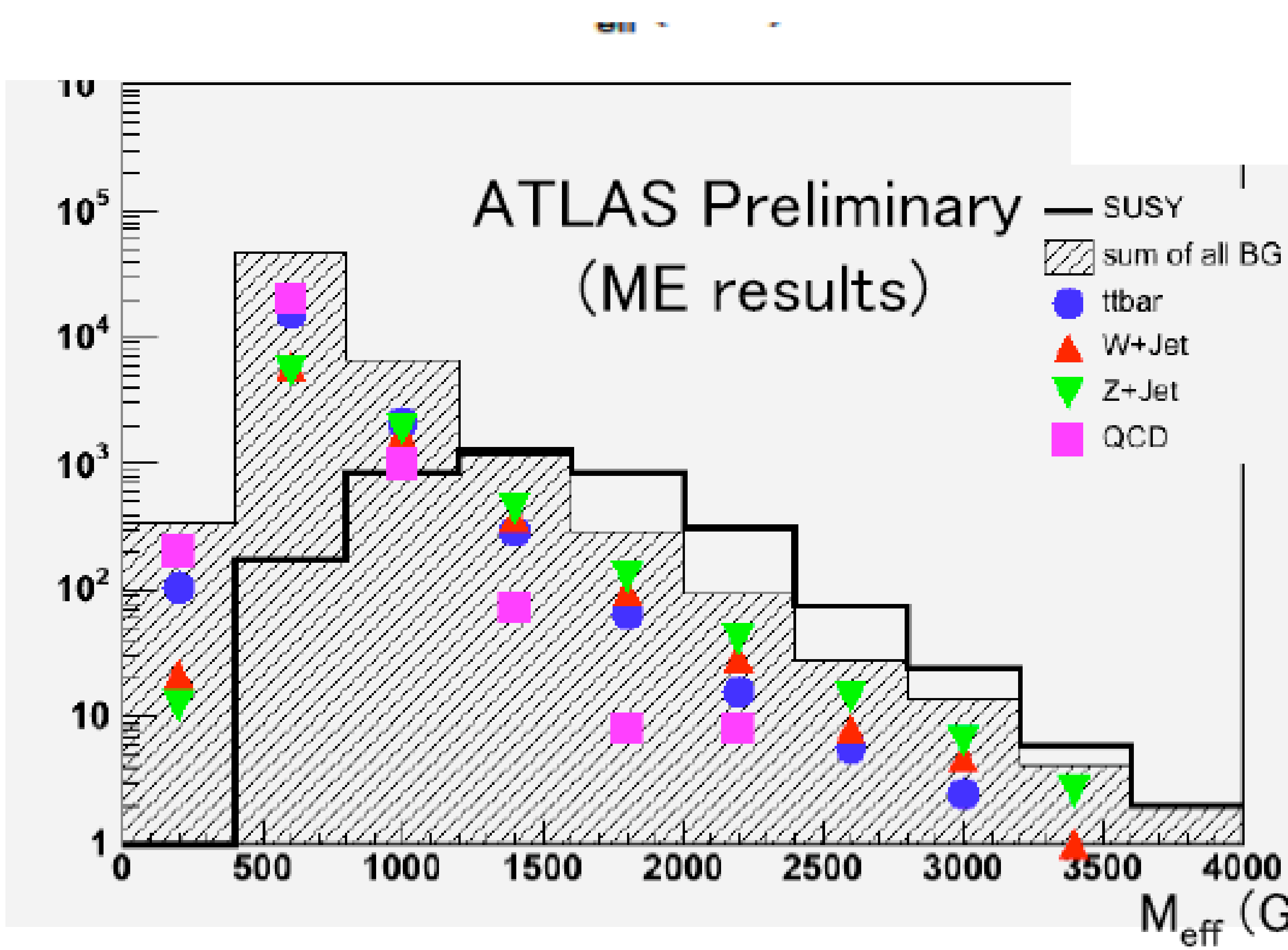


1. The most inclusive observable.
2. All parton multiplicities contribute.
3. Excellent agreement with TeV data (validation)

Key example: Inclusive SUSY searches at the LHC



$$= \not{E}_T + \sum P_T$$



Alpgen+Pythia

1. Simulation for any possible signal of (any) new physics.
2. Accurate and inclusive multi-parton SM backgrounds needed.

[No QCD, No Party!]

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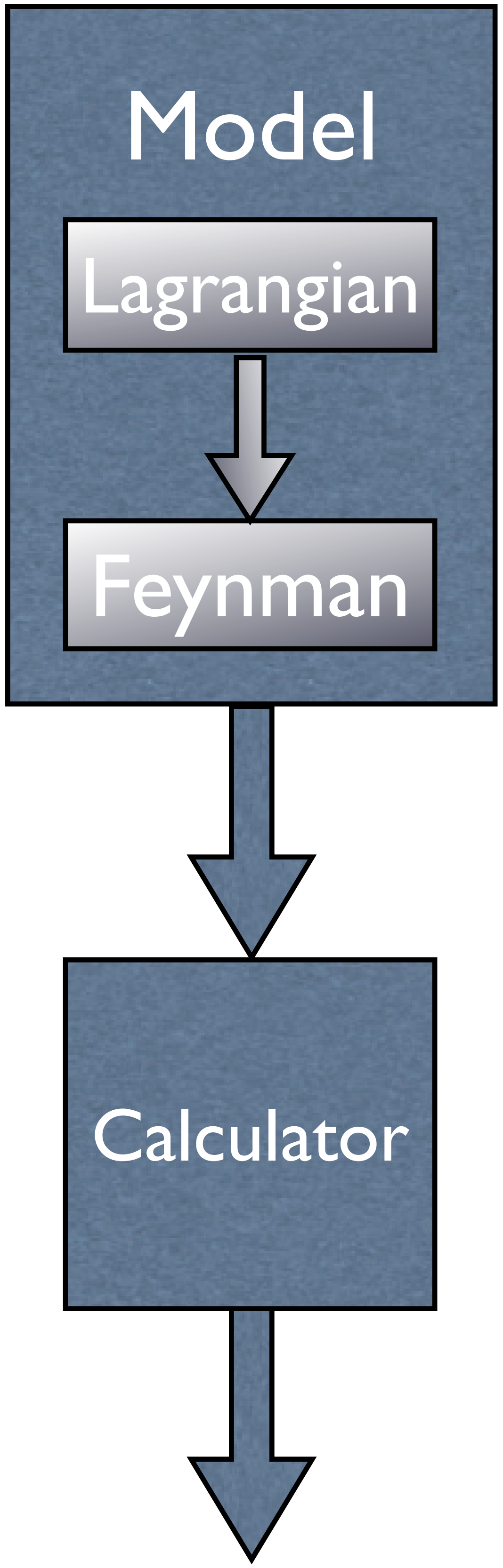
Add-on for BSM



Les Houches interface

Invent a model, renormalizable or not, with new physics. Write the Lagrangian and the Feyman Rules.

The particles content, the type of interactions and the analytic form of the couplings in the Feynman rules define the model at tree level.

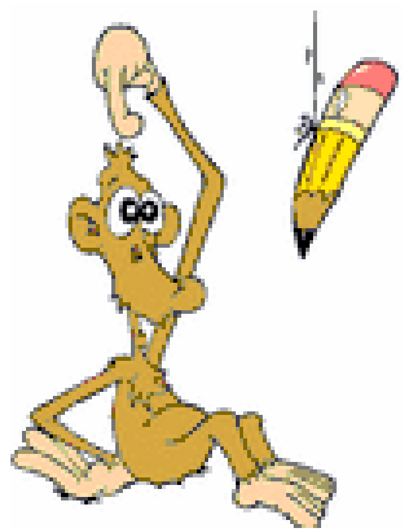
SUSY, Little Higgs, Higgsless, GUT, Extra dimensions (flat, warped, universal,...)

Parameters Calculator.
Given the "primary" couplings, all relevant quantities are calculated: masses, widths and the values of the couplings in the Feynman rules.

Caution: tree-level relations have to be satisfied to avoid gauge violations and/or wrong branching ratios.

FeynHiggs, ISAJET, NMHDecay, SOFTSUSY, SPHENO, SUSPECT, SDECAY...

Communication



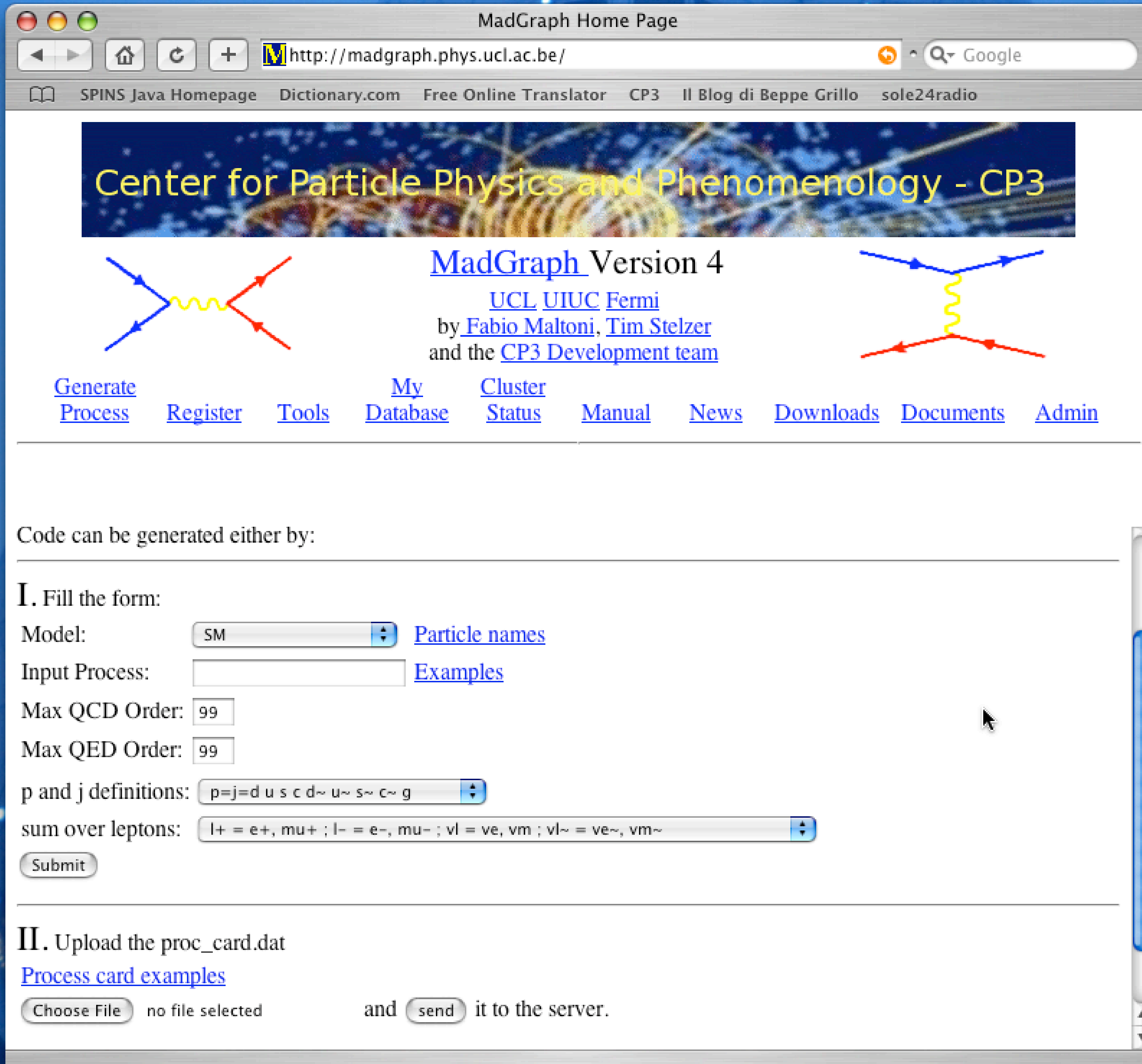
?

Calabi-Yau, Strings, Branes, Monstrous branes, Orientifolds, Kahler geometries, Twistors, SU(5), SO(10), Split SUSY, Little, Higgs, Higgless, Twin Higgs, Extra Dimensions, KK-states, Hierarchy problem, Dark Matter, Dark Energy,...

Radiation hardness, Silicon strips, pixels, Kalman filter, RPC, petals, tracking, calorimeter, muon detectors, CMSSW, Simulation chain, full simulation, fast simulation, tagging efficiency, jet algorithms, Energy flow, neural networks, likelihood, kinematical fits,...

One day, he/she wakes up with an inspired QFT model and would like to know if it could to be tested at the LHC....

One day she/he finds an anomaly in the data and would like to know if there is anything out there that predicts it.


MadGraph Home Page
http://madgraph.phys.ucl.ac.be/
Google
SPINS Java Homepage
Dictionary.com
Free Online Translator
CP3
Il Blog di Beppe Grillo
sole24radio
Center for Particle Physics and Phenomenology - CP3
MadGraph Version 4
UCL UIUC Fermi
by Fabio Maltoni, Tim Stelzer
and the CP3 Development team
Generate Process
Register
Tools
My Database
Cluster Status
Manual
News
Downloads
Documents
Admin
Code can be generated either by:
I. Fill the form:
Model:
SM
Particle names
Input Process:
Examples
Max QCD Order:
99
Max QED Order:
99
p and j definitions:
p=j=d u s c d~ u~ s~ c~ g
sum over leptons:
l+ = e+, mu+ ; l- = e-, mu- ; vl = ve, vm ; vl~ = ve~, vm~
Submit
II. Upload the proc_card.dat
Process card examples
Choose File
no file selected
and
send
it to the server.

Madgraph/MadEvent

[F.M., T. Stelzer]
[CP3 development team:
Johan Alwall,
Pavel Demin,
Simon de Visscher,
Rikkert Frederix,
Michel Herquet]

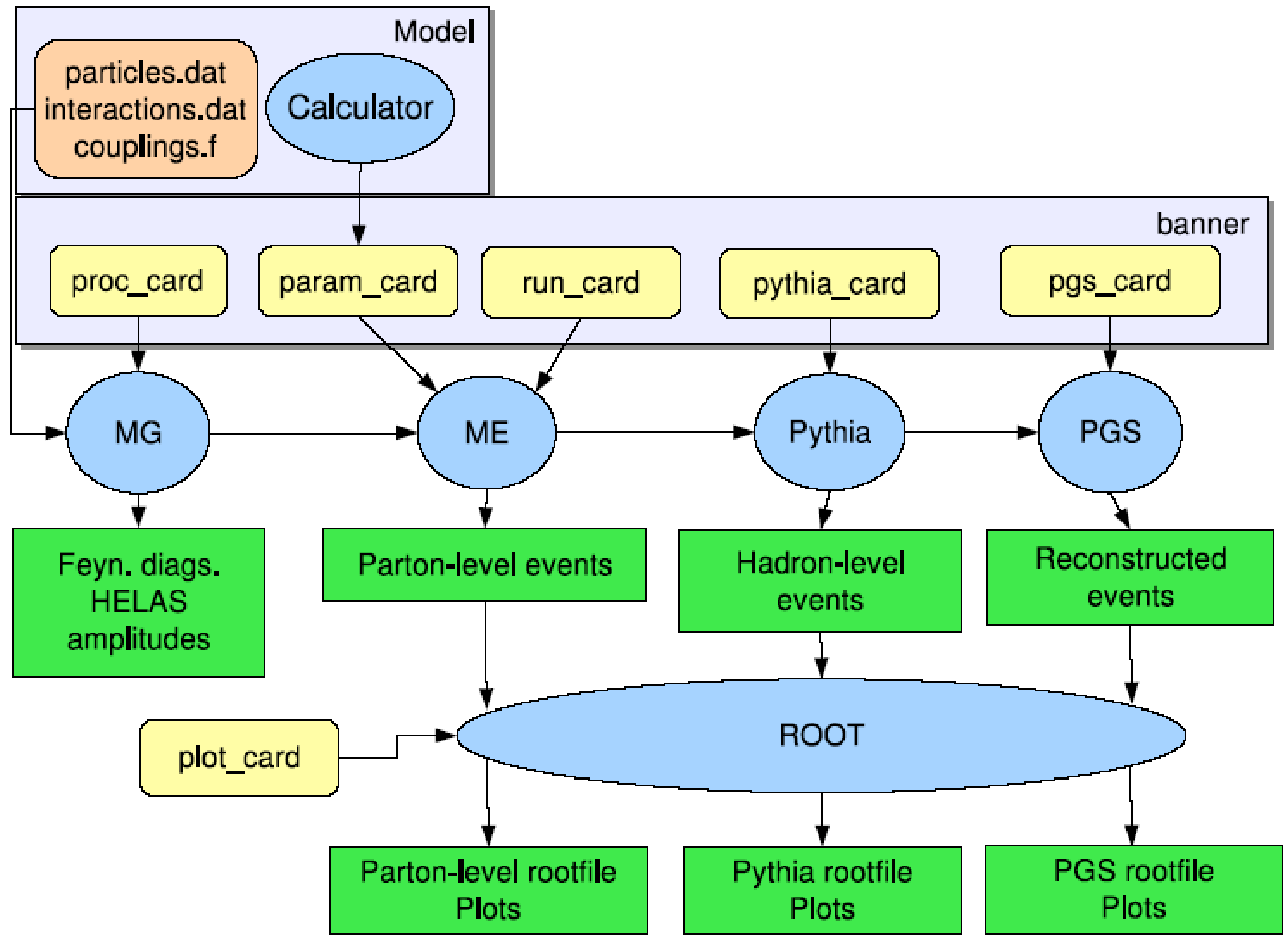
- The new web generation:
  - User inputs model/parameters/cuts.
  - Code runs in parallel on modest farms.
  - Returns cross section, plots, parton-level events.
  - News: BSM physics (MSSM, 2HDM,...) + returns Pythia and PGS events!
- Advantages:
  - Reduces overhead to getting results
  - Events can easily be shared/stored
  - Quick response to user requests and to new ideas!

http://madgraph.phys.ucl.ac.be Belgian

http://madgraph.hep.uiuc.edu U.S.

http://madgraph.roma2.infn.it Italian

FlowChart



Model
particles.dat
interactions.dat
couplings.f
Calculator
banner
proc_card
param_card
run_card
pythia_card
pgs_card
MG
ME
Pythia
PGS
Feyn. diags.
HELAS
amplitudes
Parton-level events
Hadron-level
events
Reconstructed
events
plot_card
ROOT
Parton-level rootfile
Plots
Pythia rootfile
Plots
PGS rootfile
Plots

Models in MadGraph

Previously:

- Standard Model
  (Higgs & backgroun

New models:

- MSSM
- General 2 Higgs Dc
  Model (including Cl
- Higgs EFT

particles.dat

```
#Name anti_Name   Spin    Linetype Mass  Width  Color Label Mod
#xxx   xxxx       SFV      WSDC     str   str   STO    str  PDG
#
# Quarks
#
d       d~         F        S      ZERO  ZERO     T    d     1
u       u~         F        S      ZERO  ZERO     T    u     2
s       s~         F        S      ZERO  ZERO     T    s     3
c       c~         F        S      ZERO  ZERO     T    c     4
b       b~         F        S      BMASS ZERO     T    b     5
t       t~         F        S      TMASS TWIDTH   T    t     6
```

interactions.dat

```
#
# QCD interactions
#
d d g GG QCD
u u g GG QCD
s s g GG QCD
c c g GG QCD
b b g GG QCD
t t g GG QCD

g g g G  QCD
```

- New: General framework for user-defined models

Example #1

Pick up a paper:

W_R identification at hadron colliders

J.-M. Frère [a,b,1] and W.W. Repko [b]

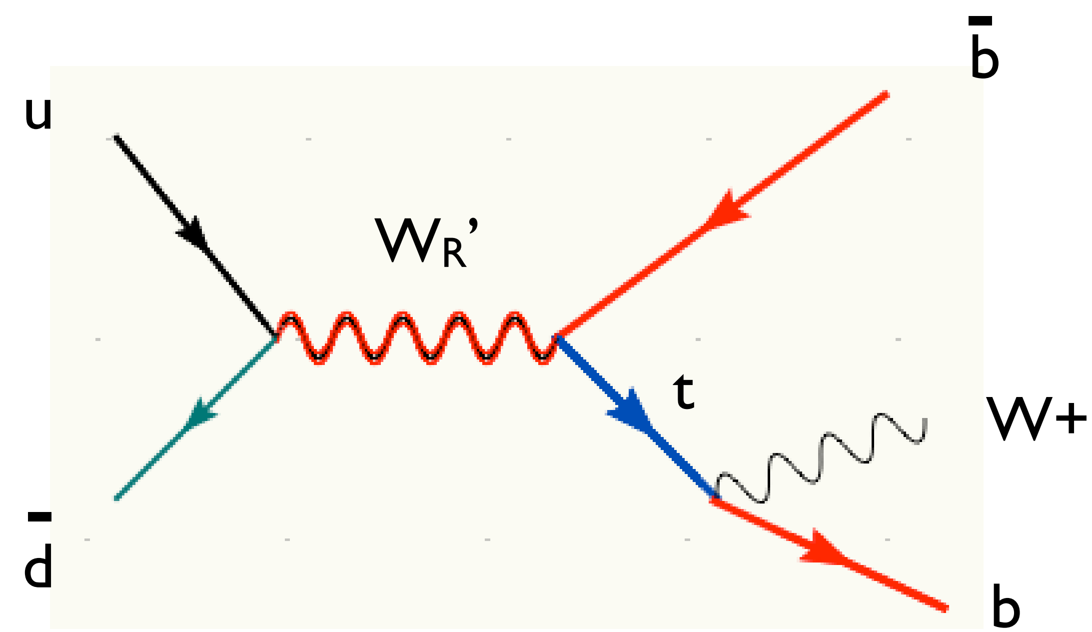
[a] *Physique Théorique, CP225, Université Libre de Bruxelles, B-1050 Brussels, Belgium* [2]

[b] *Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA*

Received 5 November 1990

We study the process pp $(p\bar{p}) \to W_H \to \bar{b}t \to \bar{b}bW_L$, where W_H is a hypothetical heavy gauge boson. The differential cross section $d\sigma/dE_W$ is sensitive to the chiral structure of the W_H coupling. In particular, the heavy W_R expected from $SU(2)_L \times SU(2)_R \times U(1)$ models is clearly distinguishable from an additional W'_L.

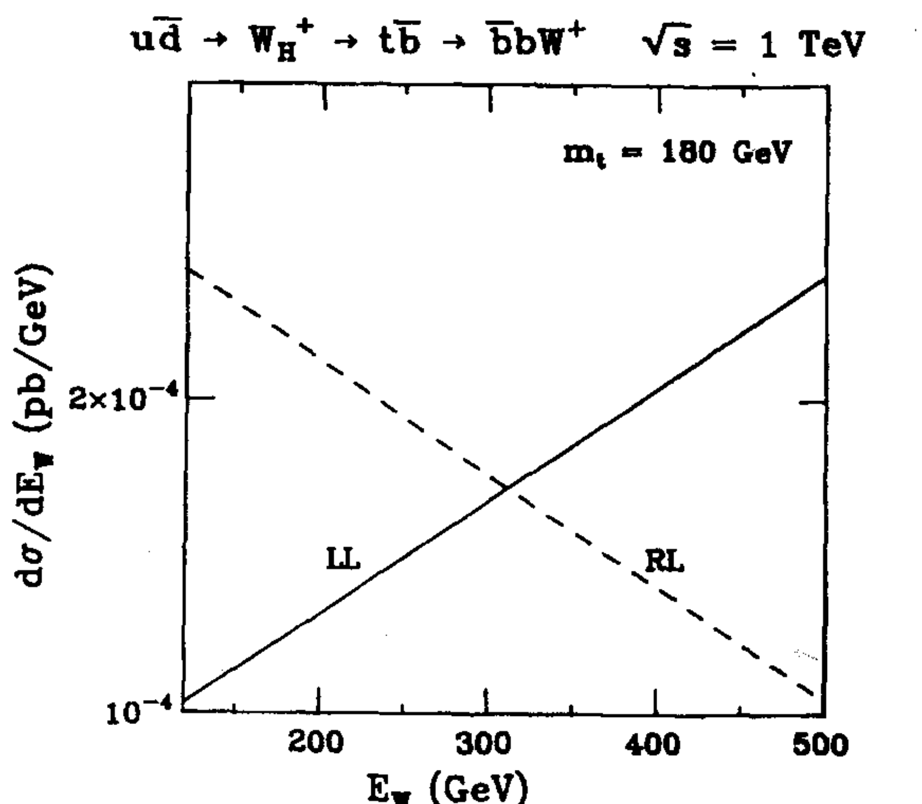
and a Ph.D. student*



*thanks to R. Frederix

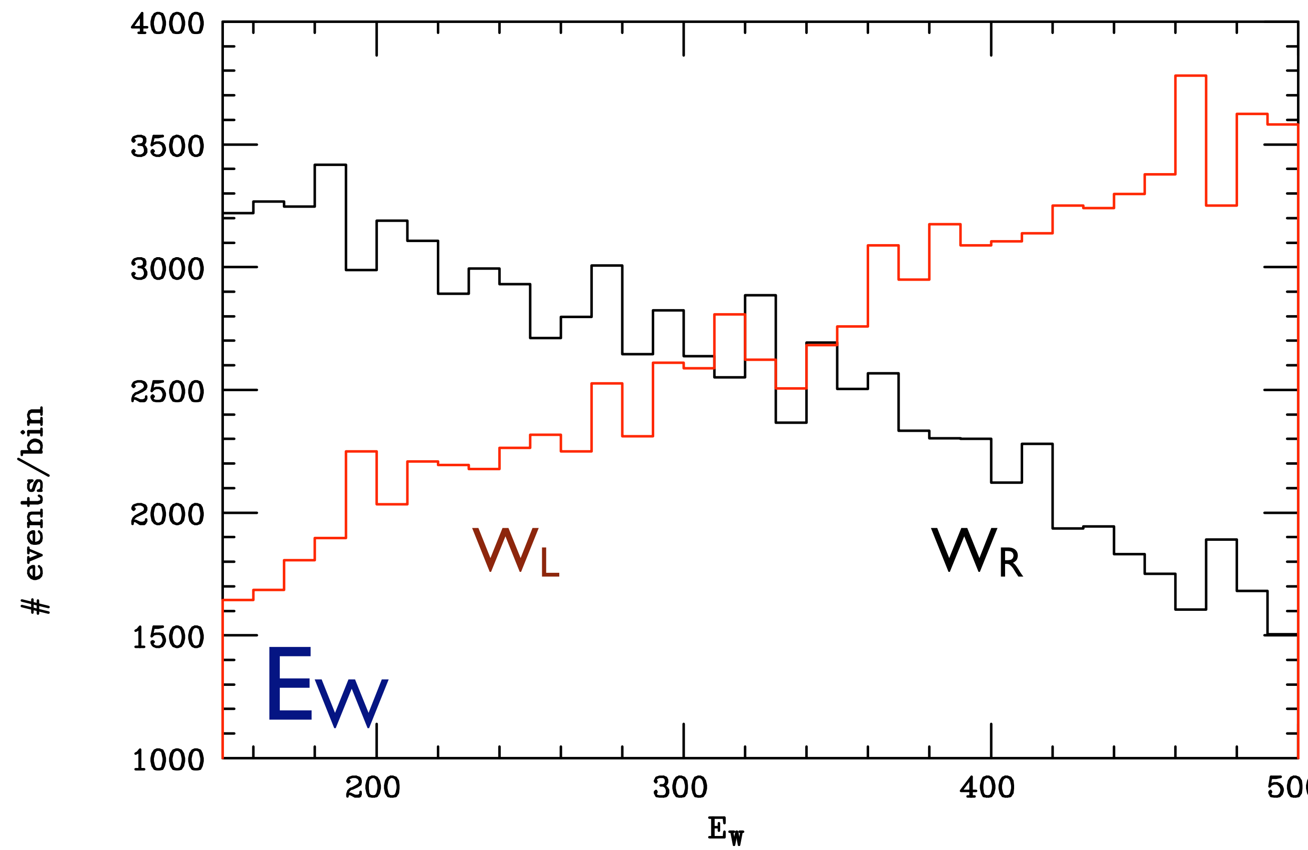
Example #1

1. Validation

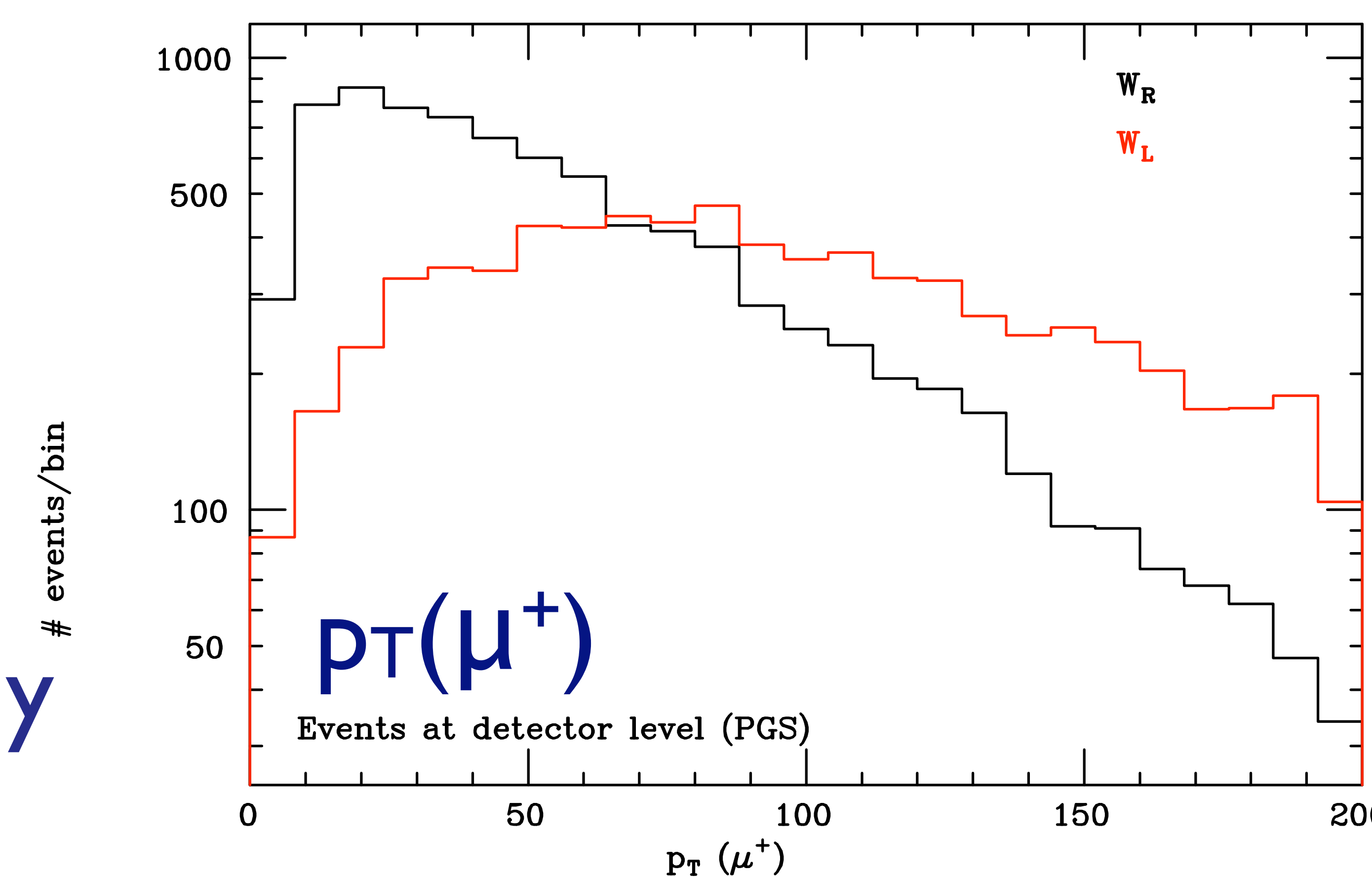


[Frere & Repko, 1991]

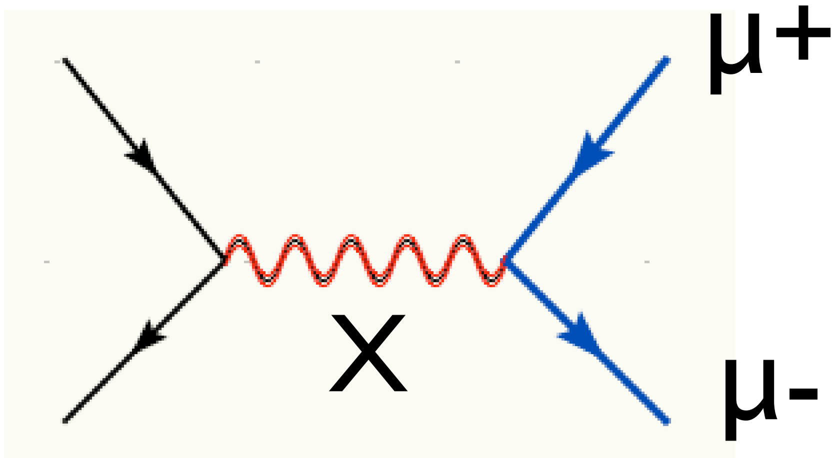
Fig. 1. The W energy distribution from t quark decay is shown for t production by the exchange of a heavy W_L (LL) and by the exchange of a heavy W_R(RL). The heavy W mass was taken to be 800 GeV.



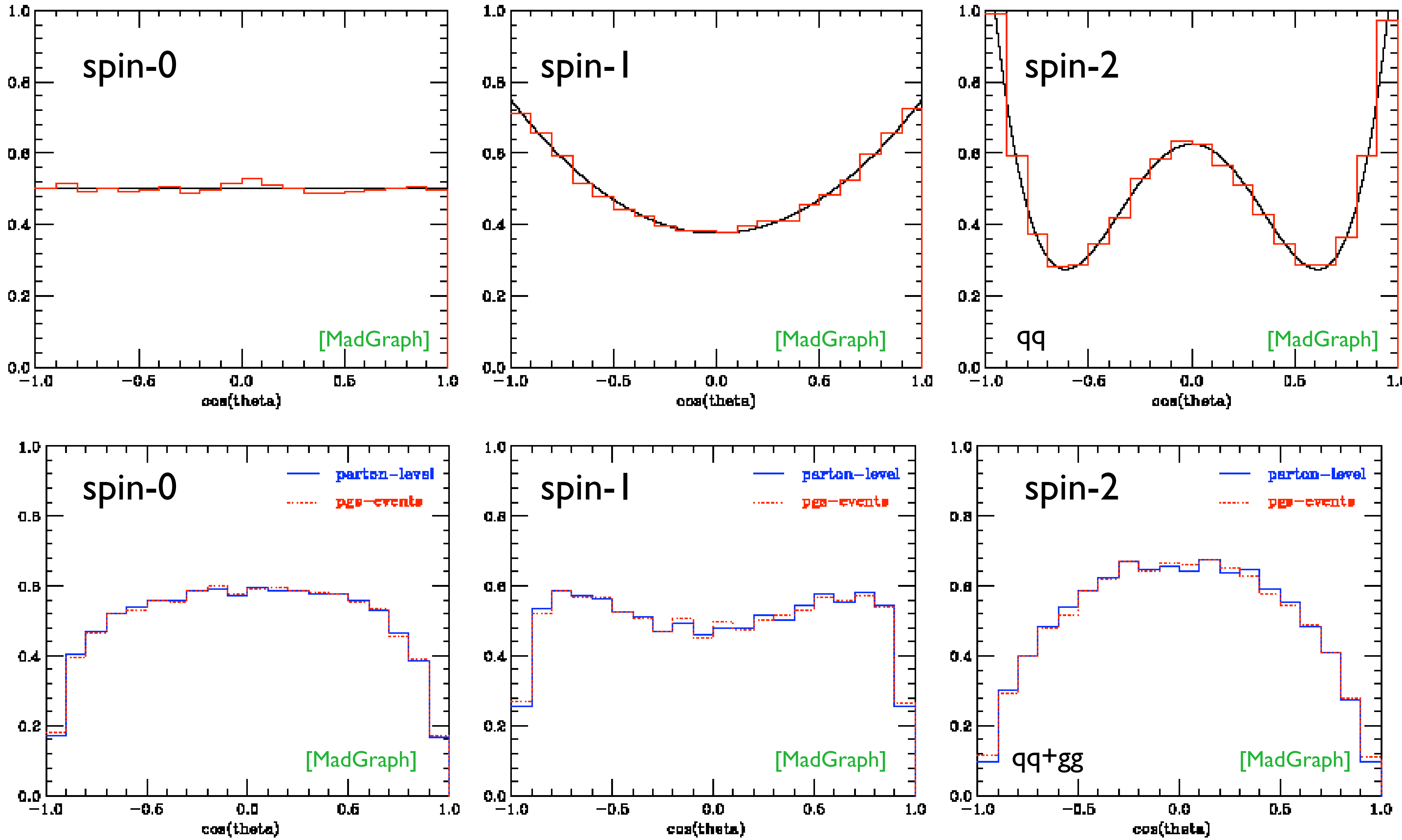
2. Pheno⇒Exp study



Example #2



[see ULB studies by B. Clerbaux et al.]



2HDM

"Natural expertise" on 2HDM in Belgium!

Very recent and on-going TH studies:

1. See-saw [X. Calmet and J.F. Oliver (ULB)]
2. Dark matter [L.Lopez Honorez, E. Nezri J.L.Oliver, M. Tytgat (ULB)]
3. Custodial symmetry [J.-M. Gerard and M. Herquet (UCL)]
4. Structure ...[Ivanov (ULg)]

On-going and future pheno/exp studies, for example in 1 and 3.

Need for a MC tool:

- Completely general 2HDM including CP violation
- Very accurately tested by comparaison with SM & MSSM

TwoHiggsCalc and 2HDM in MadGraph

[M. Herquest, S. de Visscher]

A parameter calculator for the general 2HDM

- Arbitrary choices for the input basis (Higgs/Standard)
- Full controll on SM parameters (2d generation masses, CKM matrix, ...)
- Samples including: decoupling limit (SM), MSSM scalar sector, type I, II and III, CP violation, ...
- User friendly web interface

TwoHiggsCalc and 2HDM in MadGraph

[M. Herquest, S. de Visscher]

Higgs Basis (more info)

$$
\begin{aligned}
V \;=\;& \mu_1 H_1^\dagger H_1 + \mu_2 H_2^\dagger H_2 - \left(\mu_3 H_1^\dagger H_2 + \text{h.c.}\right) \\
& \lambda_1 \left(H_1^\dagger H_1\right)^2 + \lambda_2 \left(H_2^\dagger H_2\right)^2 \\
& + \lambda_3 \left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + \lambda_4 \left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right) \\
& + \left[\left(\lambda_5 H_1^\dagger H_2 + \lambda_6 H_1^\dagger H_1 + \lambda_7 H_2^\dagger H_2\right)\left(H_1^\dagger H_2\right) + \text{h.c.}\right]
\end{aligned}
$$

lambda1	1
lambda2	1
lambda3	1
lambda4	0
lambda5	0
Norm of lambda6	0
Norm of lambda7	0
Phase of lambda6	0
Phase of lambda7	0
Mass of Charged Higgs (GeV)	300

Generic Basis (more info)

$$
\begin{aligned}
V \;=\;& \mu_1 \phi_1^\dagger \phi_1 + \mu_2 \phi_2^\dagger \phi_2 - \left(\mu_3 \phi_1^\dagger \phi_2 + \text{h.c.}\right) \\
& + \frac{1}{2}\lambda_1 \left(\phi_1^\dagger \phi_1\right)^2 + \frac{1}{2}\lambda_2 \left(\phi_2^\dagger \phi_2\right)^2 \\
& + \lambda_3 \left(\phi_1^\dagger \phi_1\right)\left(\phi_2^\dagger \phi_2\right) + \lambda_4 \left(\phi_1^\dagger \phi_2\right)\left(\phi_2^\dagger \phi_1\right) \\
& + \left[\left(\frac{1}{2}\lambda_5 \phi_1^\dagger \phi_2 + \lambda_6 \phi_1^\dagger \phi_1 + \lambda_7 \phi_2^\dagger \phi_2\right)\left(\phi_1^\dagger \phi_2\right) + \text{h.c.}\right]
\end{aligned}
$$

Tan(beta)=v2/v1	1
Phase of v2	0
Norm of mu3	0
lambda1	1
lambda2	1
lambda3	1
lambda4	0
Norm of lambda5	0
Norm of lambda6	0
Norm of lambda7	0
Phase of lambda5	0
Phase of lambda6	0
Phase of lambda7	0

Yukawa parameters

Higgs basis (more info)

$$
\begin{aligned}
\mathcal{L}_Y \;=\;& \frac{\overline{Q}_L \sqrt{2}}{v}\left[(M_d H_1 + Y_d H_2) d_R + (M_u \tilde{H}_1 + Y_u \tilde{H}_2) u_R\right] \\
& + \frac{\overline{E}_L \sqrt{2}}{v}\left[(M_e H_1 + Y_e H_2) e_R\right]
\end{aligned}
$$

Generic Basis (more info)

$$
\begin{aligned}
\mathcal{L}_Y \;=\;& \frac{\overline{Q}_L \sqrt{2}}{v}\left[(\Delta_d \phi_1 + \Gamma_d \phi_2) d_R + (\Delta_u \tilde{\phi}_1 + \Gamma_u \tilde{\phi}_2) u_R\right] \\
& + \frac{\overline{E}_L \sqrt{2}}{v}\left[(\Delta_e \phi_1 + \Gamma_e \phi_2) e_R\right]
\end{aligned}
$$

Yukawa couplings to the second Higgs doublet of the down type quarks (norm and phase)

Y1D/G1D	0	0	Y1S/G1S	0	0	Y1B/G1B	0	0
Y2D/G2D	0	0	Y2S/G2S	0	0	Y2B/G2B	0	0
Y3D/G3D	0	0	Y3S/G3S	0	0	Y3B/G3B	0	0

Top physics at LHC

Very active field in the CMS belgian community

[both at IIHE and UCL]

Why?

Strong Theory Motivation

Strong Exp Motivation

Top physics at LHC

Very active field in the CMS belgian community

[both at IIHE and UCL]

Theory Motivation:

In the SM, it is the only quark with a "natural mass":

$m_{top} = y_t\, v/\sqrt{2} \approx 174$ GeV $\Rightarrow y_t \approx 1$

It "strongly" interacts with the Higgs sector.

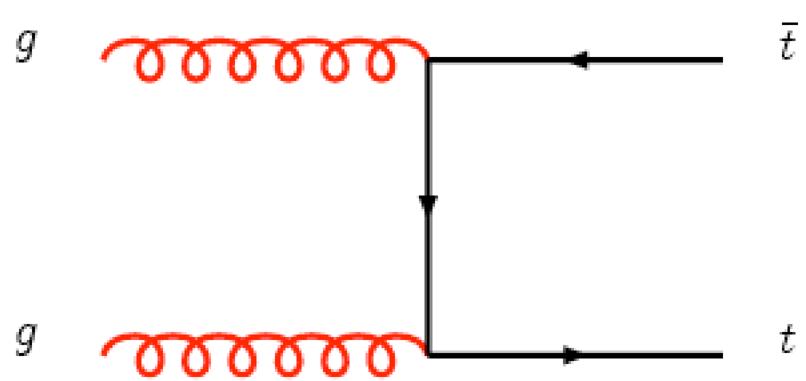
This also suggests that top might have special role in the mechanism of EWSB and/or fermion mass generation.

Top physics at LHC

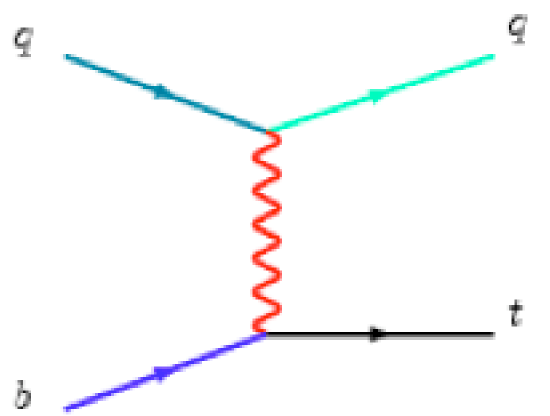
Very active field in the CMS belgian community

[both at IIHE and UCL]

Exp Motivation:



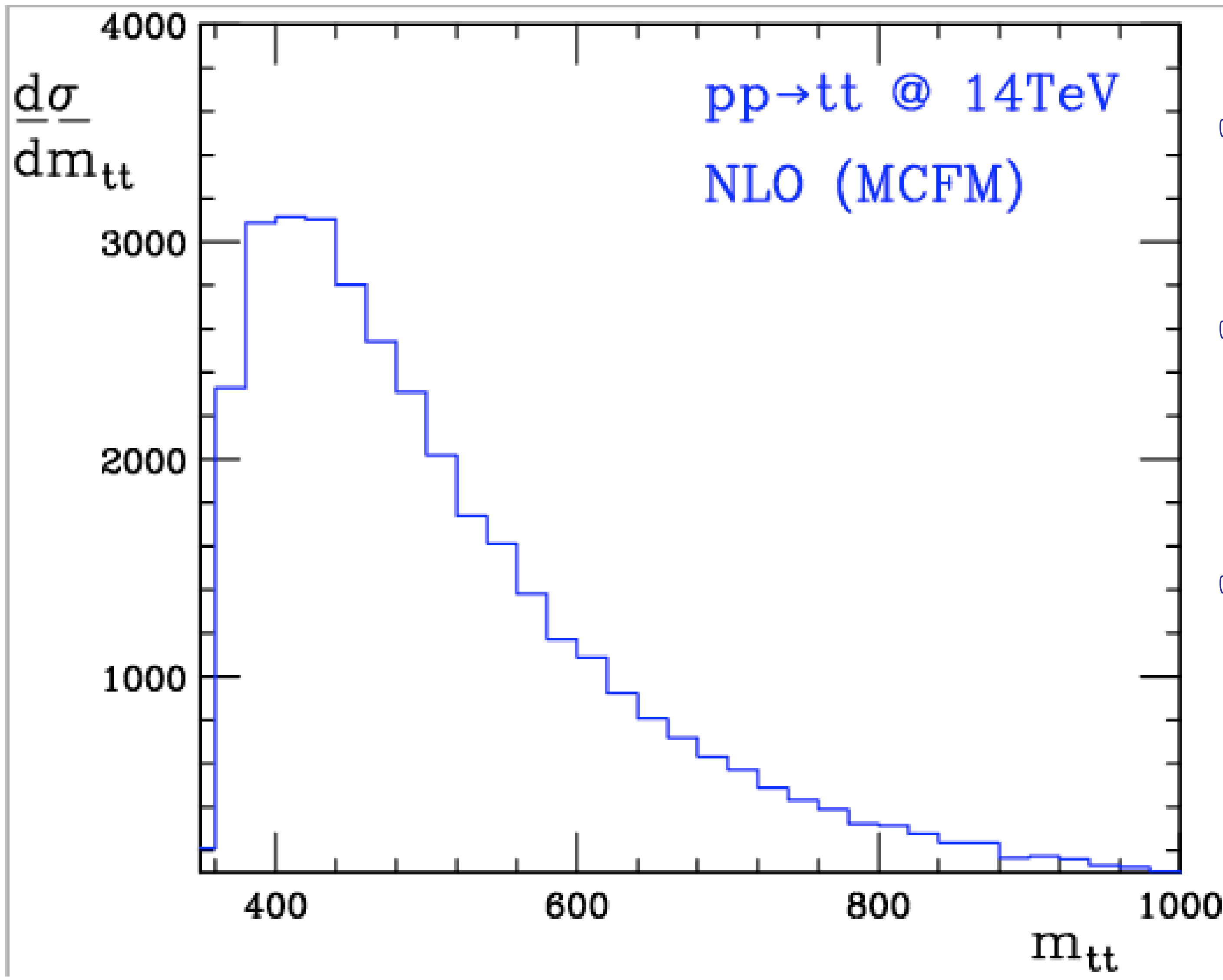
Strong ttbar production.
~800 pb, 1 tt pair per second
Events have typically many-jets (some bottom) and leptons. Very "easy" signature with a lot of events.



Electroweak single-top production. Three channels. Largest rate, (250 pb) ,from t-channel at the LHC, where 62% top, 38% anti-top.

$\sigma \propto |Vtb|^2$.

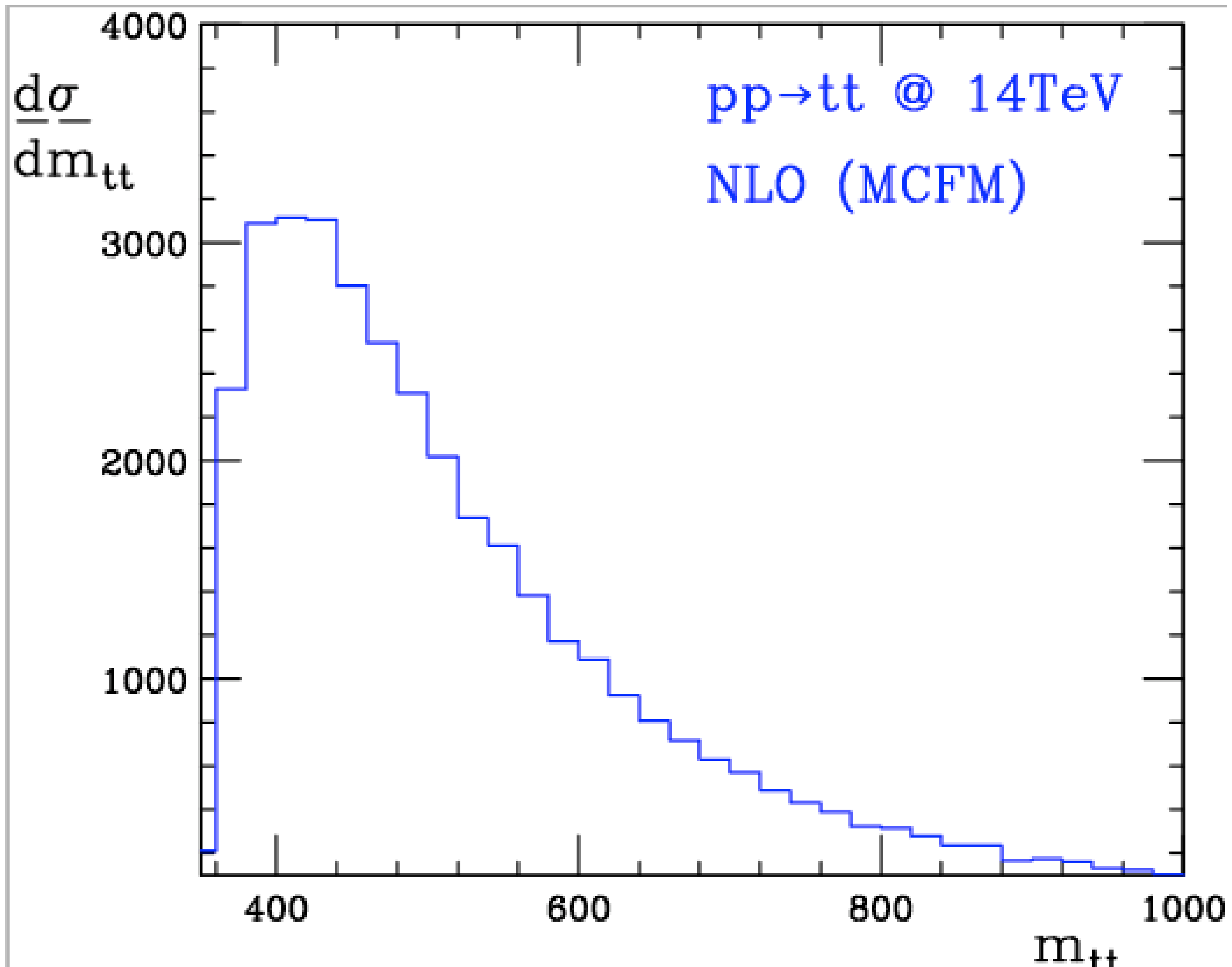
m_{tt} as a BSM physics observatory



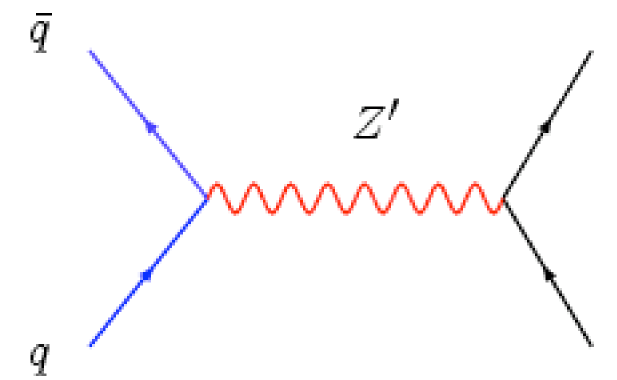
- Distribution known at NLO, including the matching with the shower (in MC@NLO).
- Very interesting SM study. The peak of the distribution is sensitive to the top mass. Possibility for a joint σ and m_t measurement.
- In the high mass-invariant tail, fully hadronic events look like two jet events: different systematics for m_t measurement.

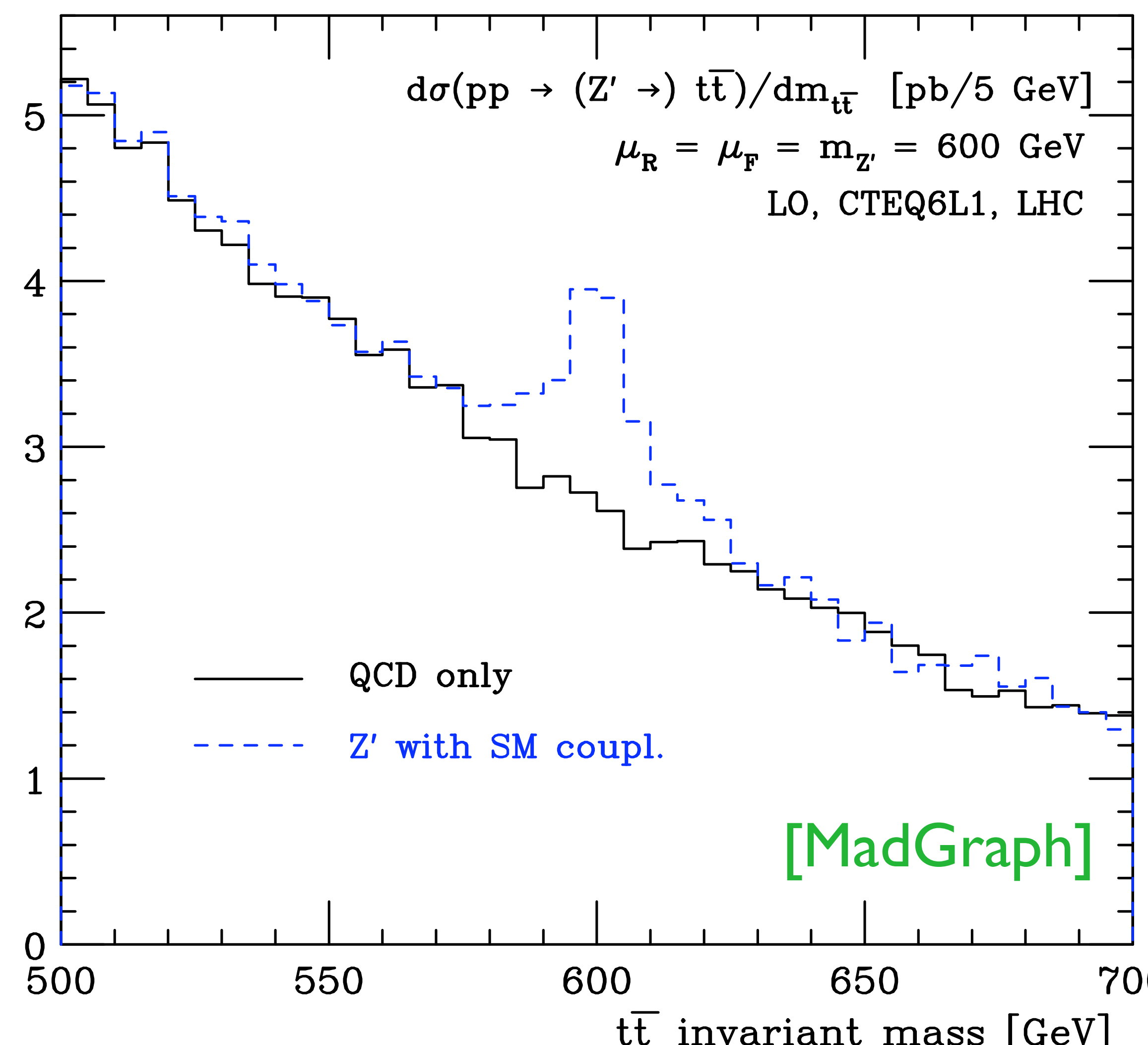
All work presented in section is in progress by
[Johan Alwall, Rikkert Frederix, and F.M.]

m_{tt} as a BSM physics observatory

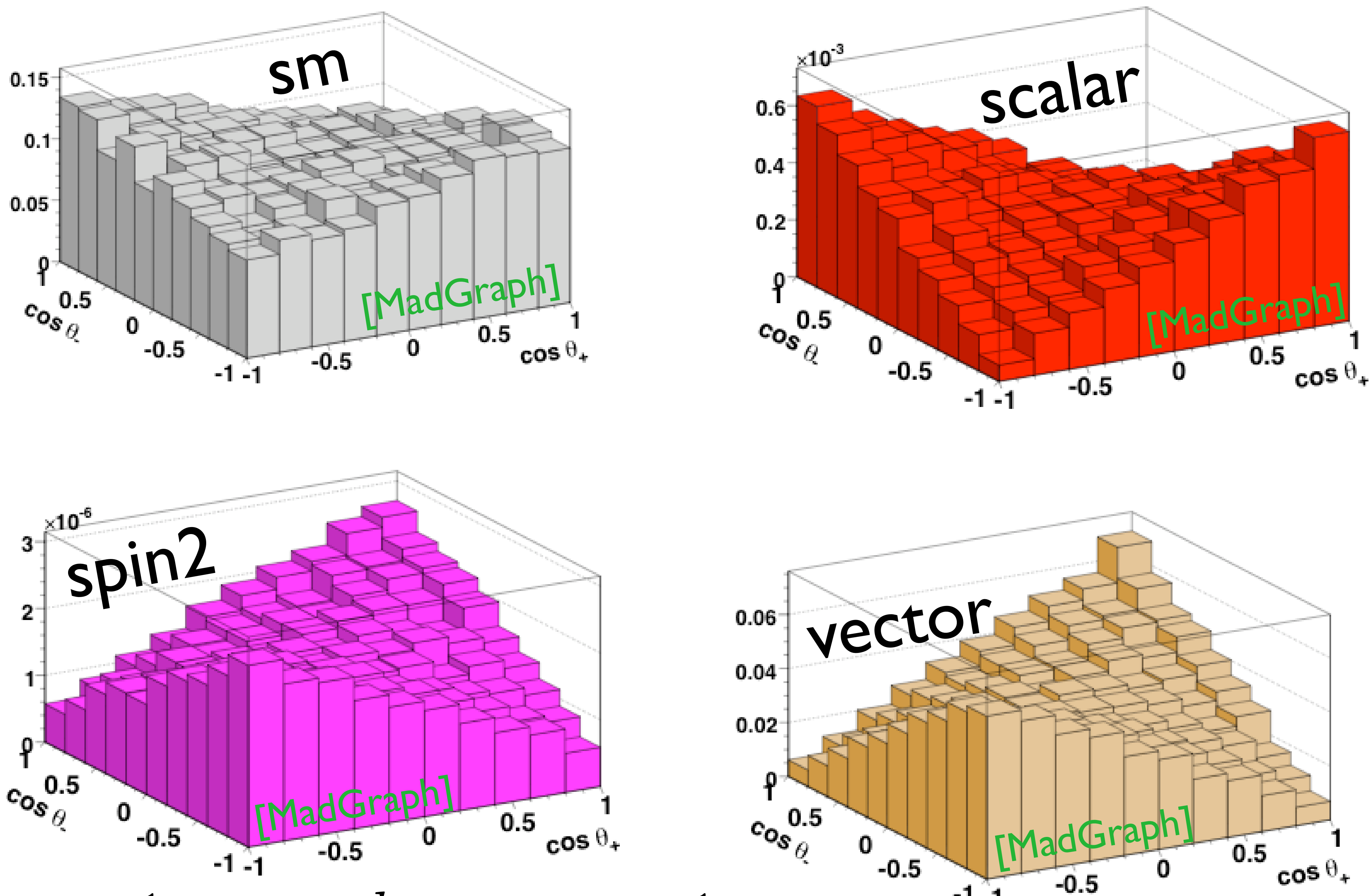


The best of all possible discoveries: a peak in the invariant mass distribution!
Similar results are obtained if a scalar or a spin2 particle is exchanged. How to distinguish them?



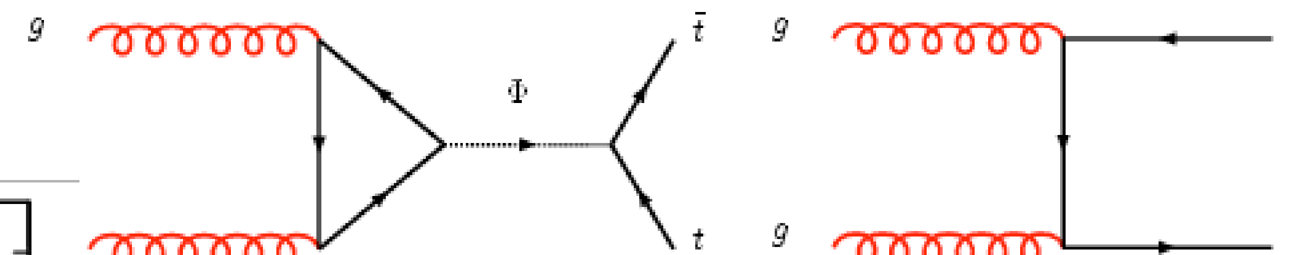


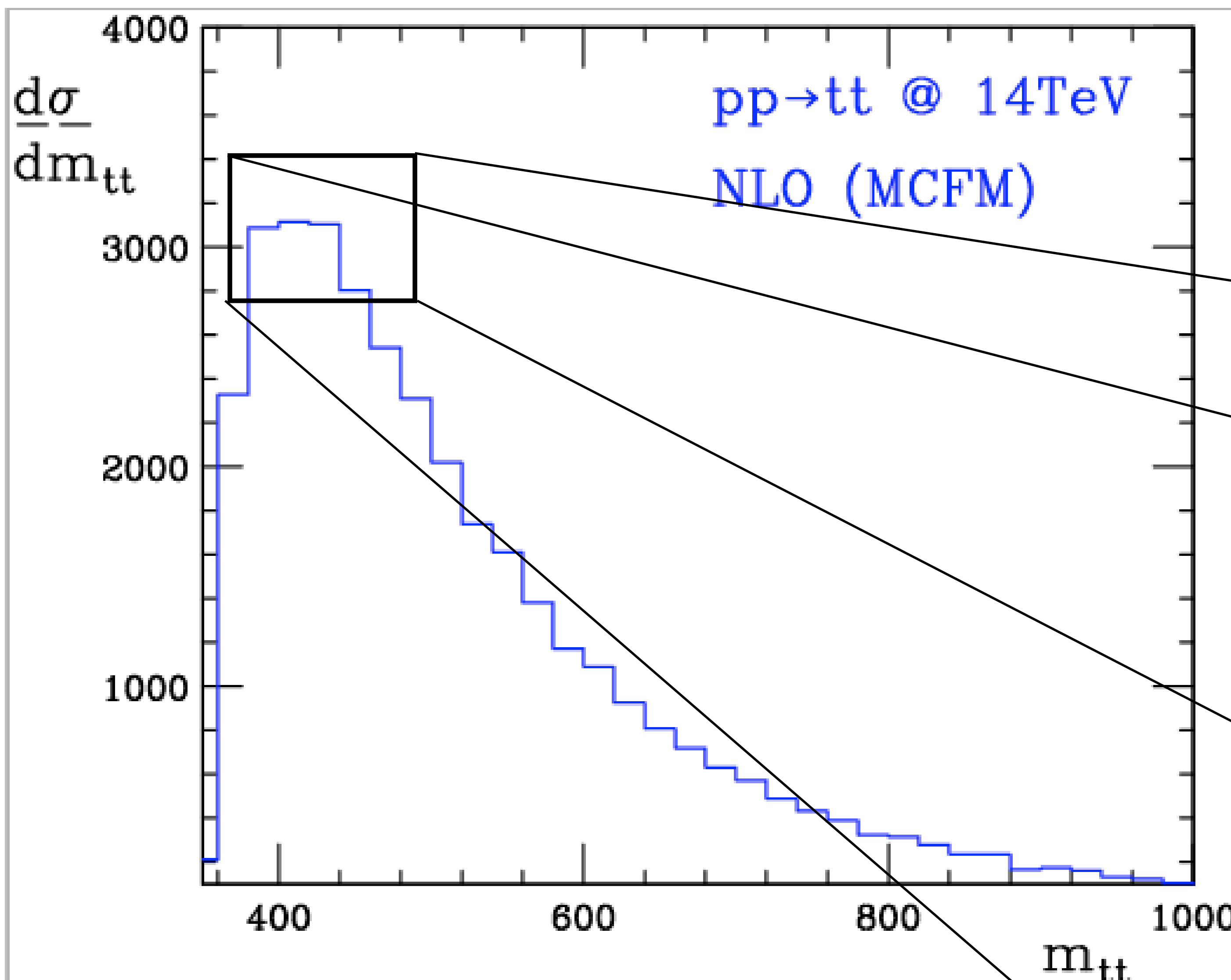
m_{tt} as a BSM physics observatory

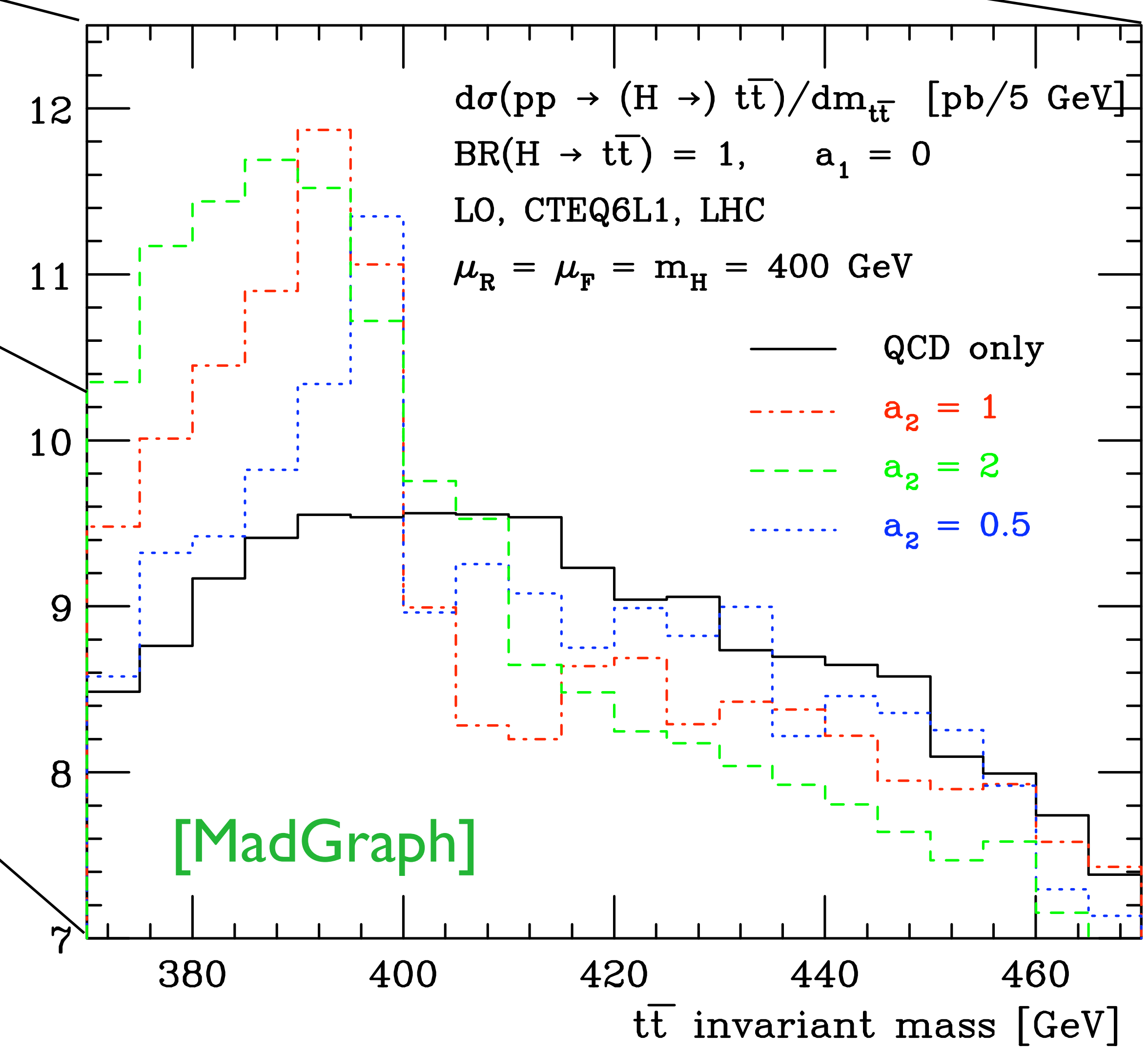


$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4}\left(1 + \kappa_t \kappa_{\bar{t}} D \cos\theta_- \cos\theta_+\right)$$

m_{tt} as a BSM physics observatory

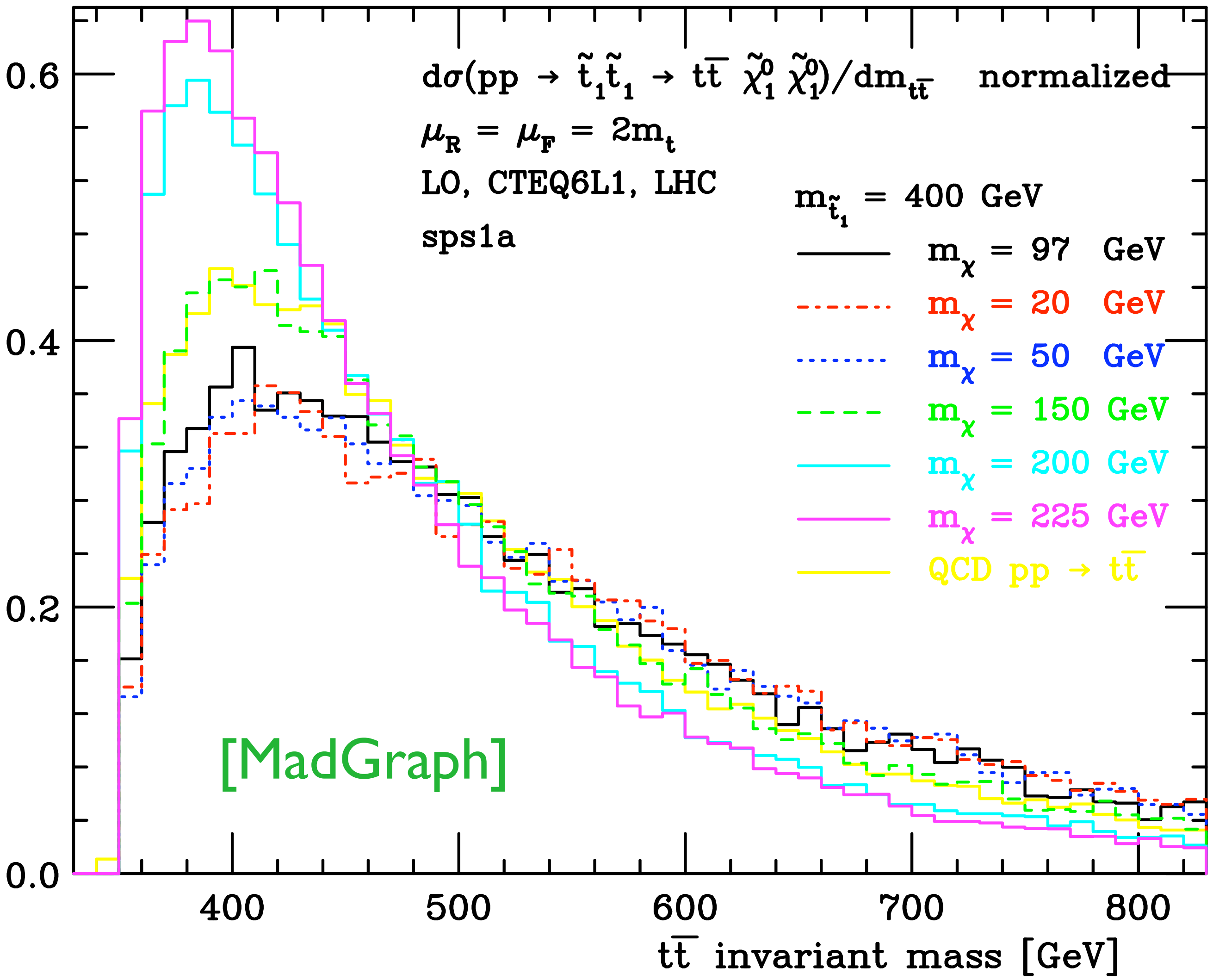


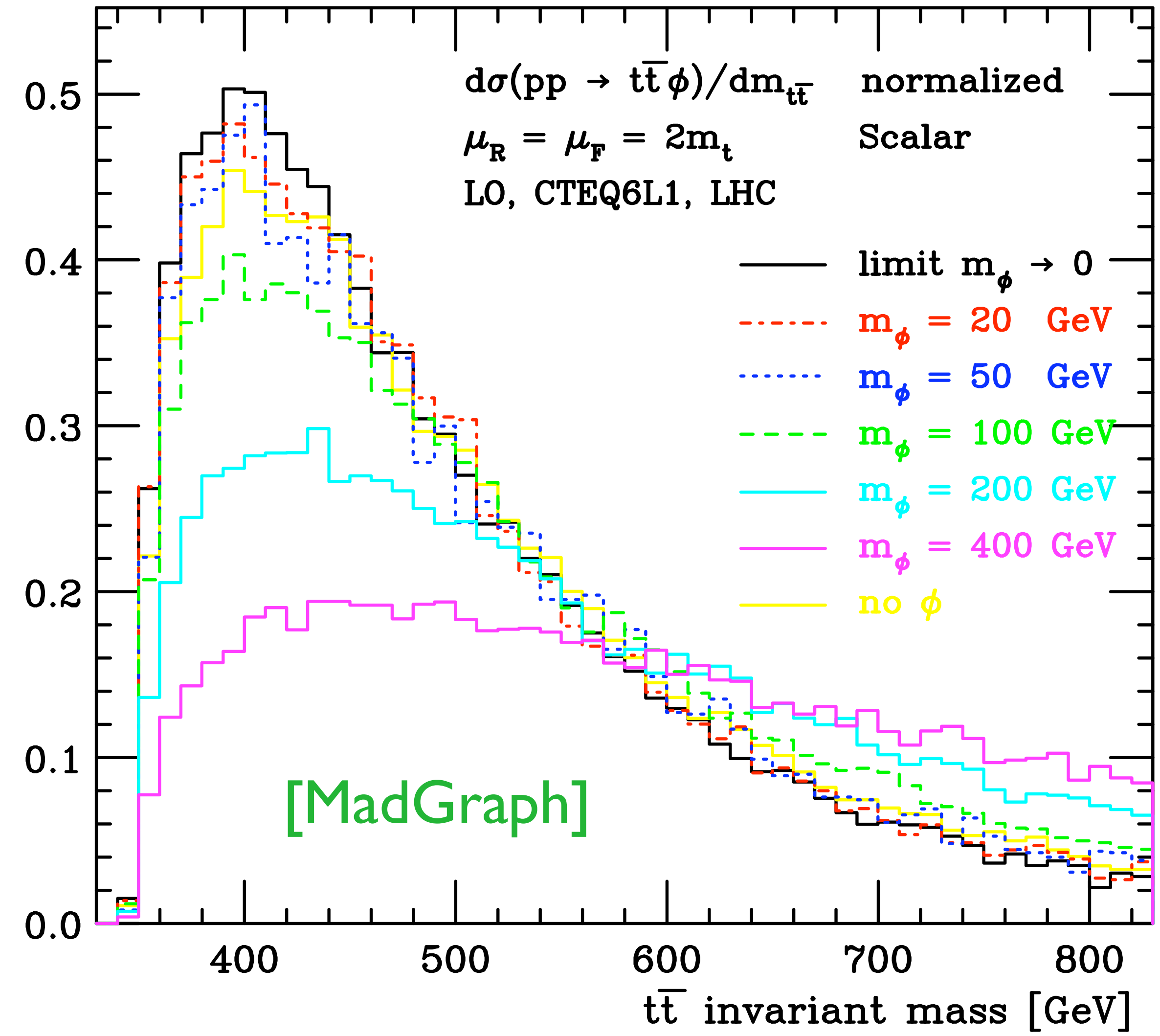


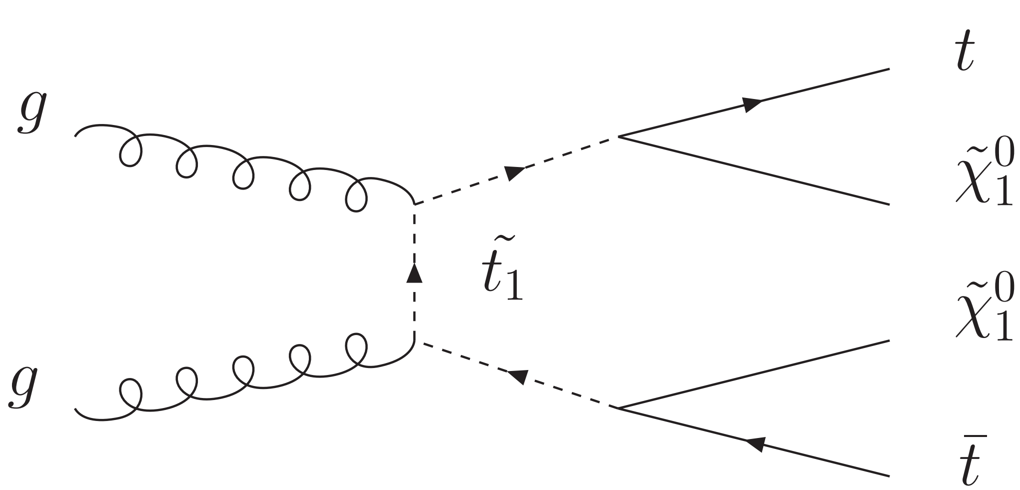


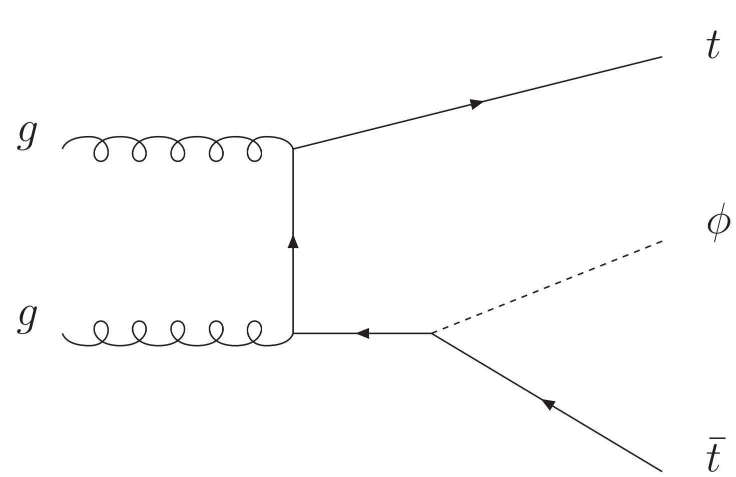
Non-trivial behavior (peak-dip) due to the interference between the signal and the background, only if top width dominated by $\Phi \to tt$.

m_{tt} as a BSM physics observatory

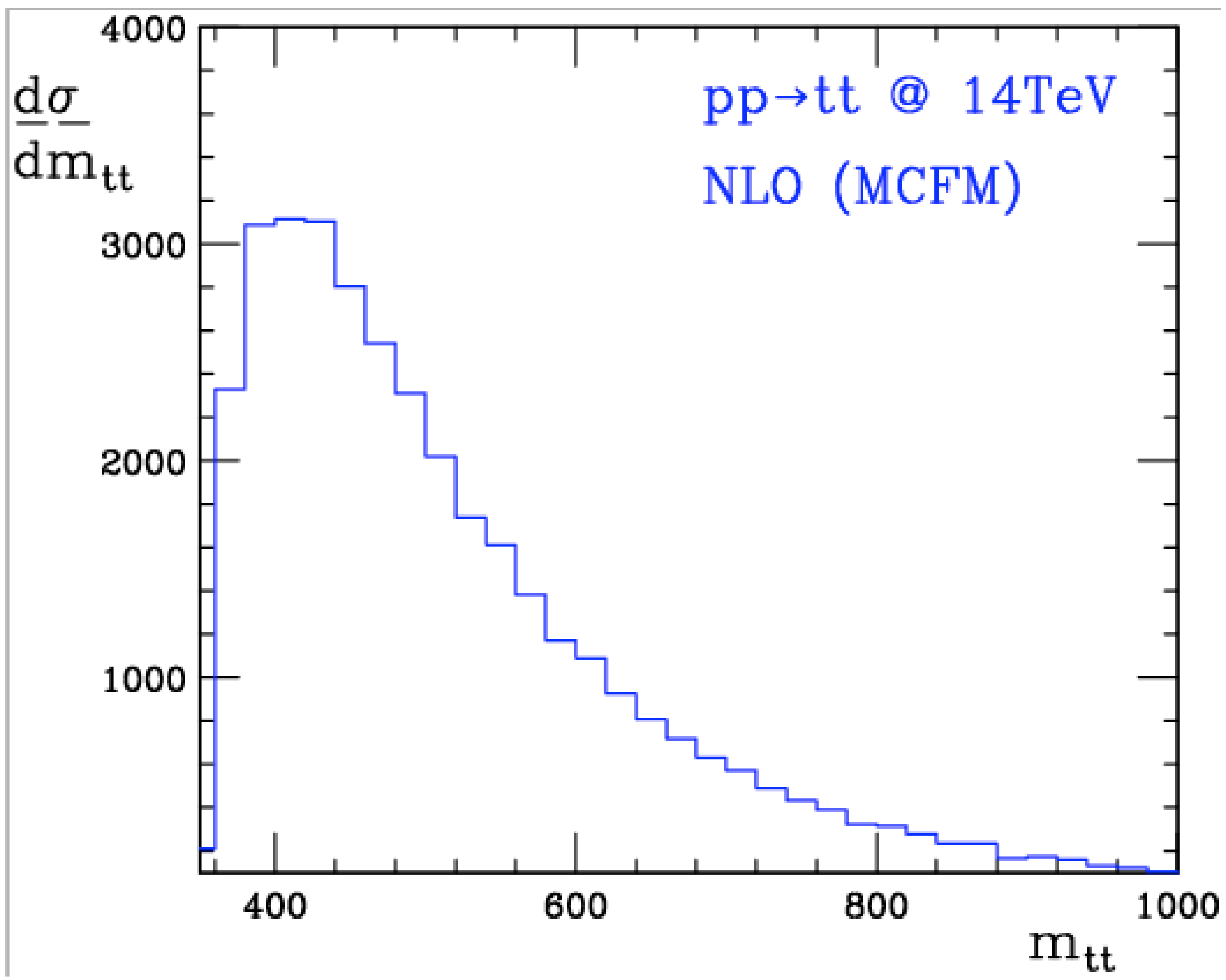


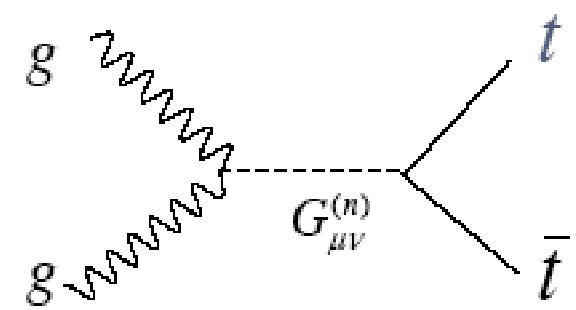


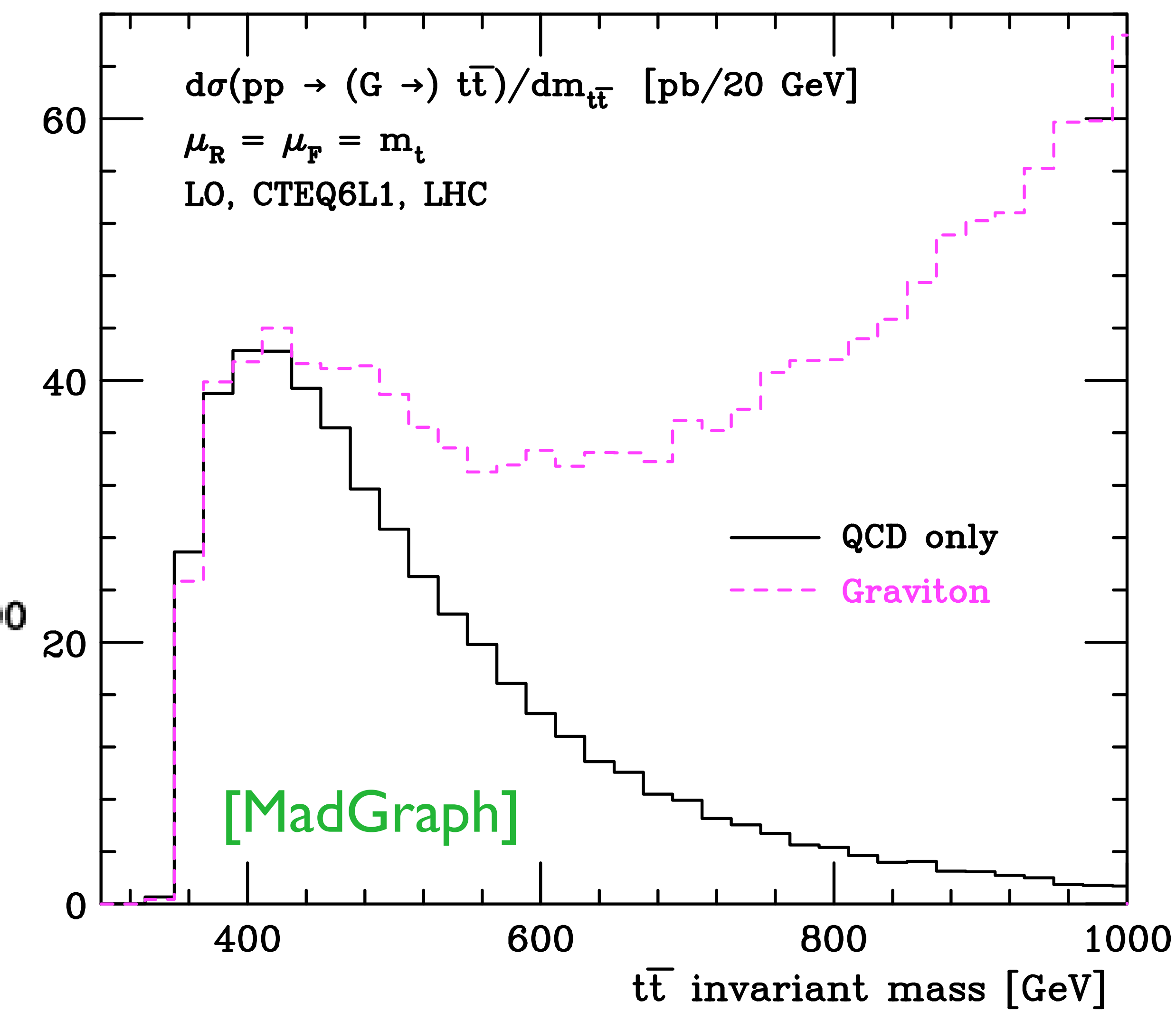




m_{tt} as a BSM physics observatory







In a UED scenario the cross section into tt may even start to violate unitarity due to the exchange of a KK graviton.

The MG/ME philosophy

- Fill the gap between theorists and experimentalists
  - Easy to implement new models
  - Easy to interface to hadronization/detector simulation
- Breath
  - Efficiently generate events for (basically) any process
  - Signal but also multiparticle backgrounds
- Web based event generation
  - Code runs in parallel on our farms
  - Centralized maintenance
  - Personal process database for each user

Conclusions

- Making discoveries at the LHC (most probably) won't be easy.
- SM backgrounds and in particular those coming from QCD multi-jet processes are large and their detailed understanding needed. [No QCD, No Party!]
- Remarkable progress in developing MC tools in the last 5 years. A new generation of codes to perform simulation has grown and it is now available.
- One of these projects, MadGraph/MadEvent MC is being actively pursued at UCL. Our approach is web-based, automatic and multi-purpose. Particular emphasis is currently given to physics models beyond the SM.
- One of our most important goals is to provide a easy-to-use and open framework for collaboration between theorists (both model builders and the MC/QCD community) and experimentalists!

LHC will start soon ... stay tuned!