Collider probes of SUSY

Where do we go now with SUSY searches?

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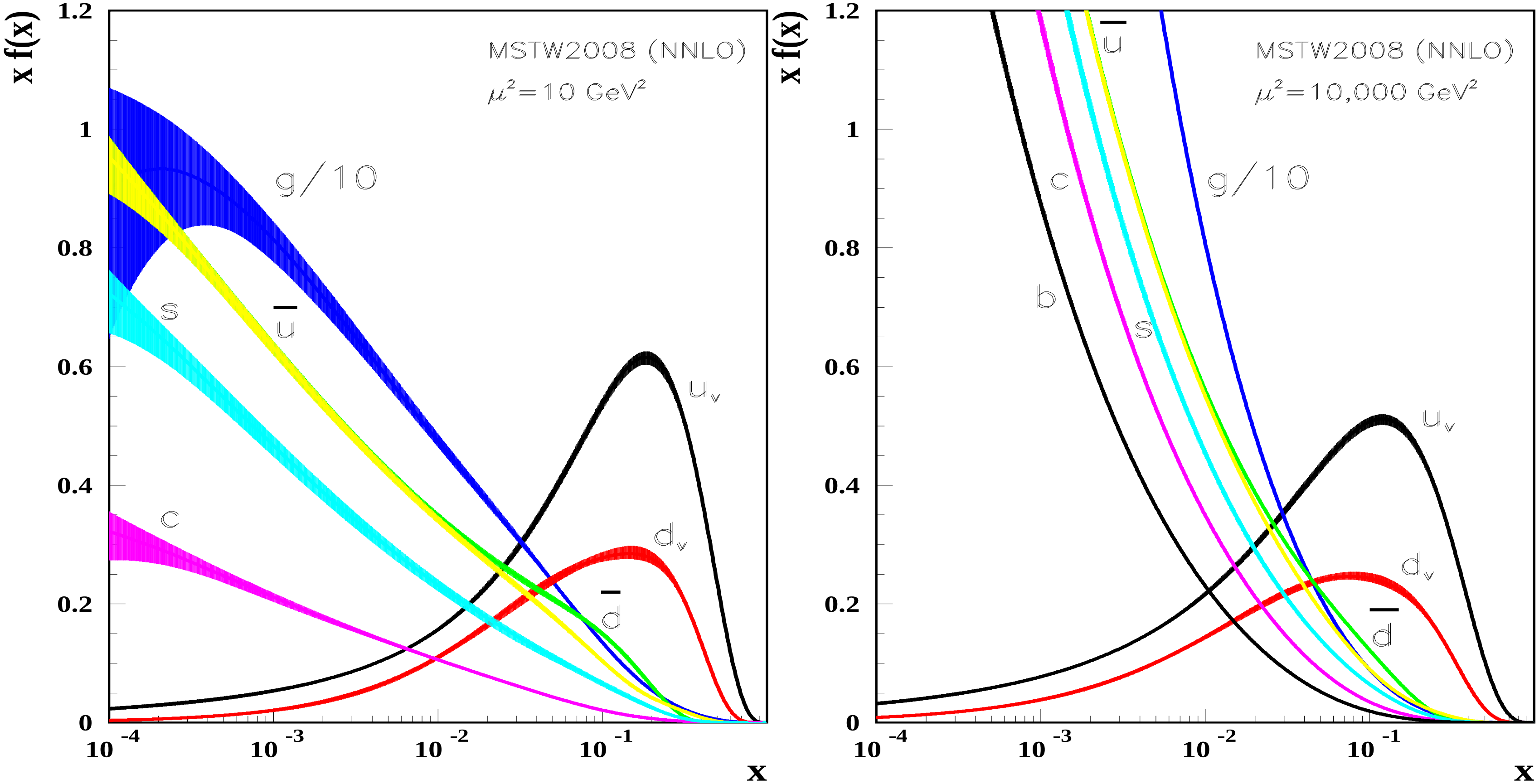
Happening at the Pre SUSY school at SUSY 2014, Manchester.

A few comments about PDF's.

Recall to produce a particular final state of invariant mass M^2 one needs to sample $f_{x_i}, i = 1, 2$ at x_1, x_2 such that

$$M^2 = \hat{s} = Sx_1x_2$$

$$\sigma(M^2, S) = \sum_{1,2,3,4} \int dx_1 dx_2 \delta(M^2 - Sx_1x_2)\hat{\sigma}(P_1 + P_2 \to P_3P_4)$$


x f(x)
MSTW2008 (NNLO)
μ²=10 GeV²
g/10
s
ū
c
u_v
d_v
d̄
x
MSTW2008 (NNLO)
μ²=10,000 GeV²
c
b
s
ū
g/10
u_v
d_v
d̄
x

1)The luminosity drops off as a function of M^2 as the parton densities fall off at large x. Reach in $\sqrt{\hat{s}} \sim 0.2\sqrt{S}$.

2) Gluon fluxes dominate for low invariant mass final states.

3)As the energy of the collider increases, the reach for high mass states which can be produced by gluons increases rapidly.

For $t\bar{t}$ the cross-section increases by an order of magnitude, as one goes from Tevatron to LHC, mainly because gluon fluxes become large, $\hat{\sigma}$ for gg induced production of $t\bar{t}$ dominates over $q\bar{q}$ induced one.

4)In general subprocess cross-sections drop off a $1/M^2$, unless there are some t–channel enhancements.

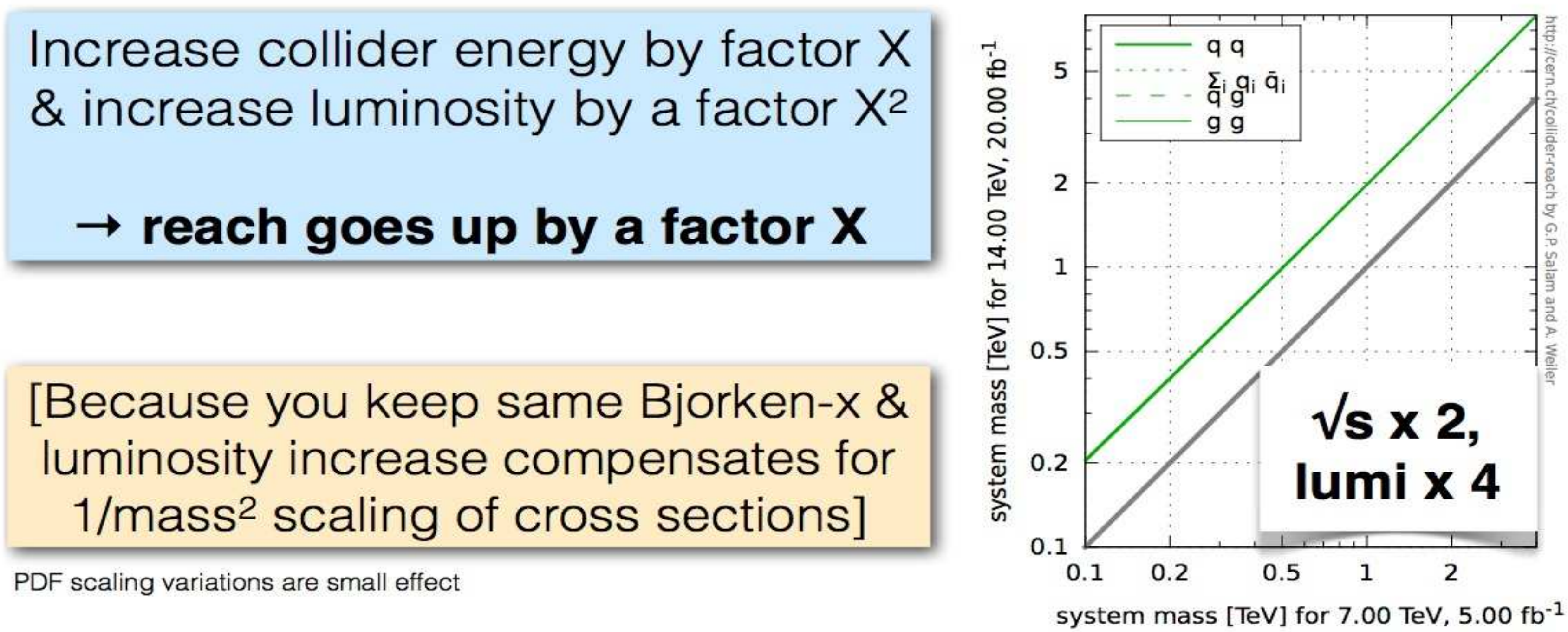
5)There are almost no differences between q and $\bar{q}$ fluxes at higher energies as the relevant values of x are low where these two not differ. (That is why we did not need to build the much more difficult $p\bar{p}$)

6)The q fluxes rather similar in all PDF's, it is the gluon which is different. But at larger x mostly similar. At large invariant mass rather PDF uncertainties rather small. On the other hand for Higgs coupling determination, at high luminosity PDF uncertainties will dominate the error.

7)The b quark is almost massless..this has implications on how to compute processes which involve a b in the initial state! Relevant for SUSY. Charged Higgs production or the pseudo-scalar Higgs production as b couplings can be enhanced for these in SUSY.

Natural question that will arise: As the collider energy increases what about the reach in mass for producing new particles particles which have colour charge. Today address only the cross-section issue.

(from a slide by G. Salam.)



LHC requires from QCD theory:

- Precise inputs
  - α_s
  - Parton Density Functions (PDF's)
- Accurate calculations of subprocess cross-sections
  - NLO, NNLO calculations of cross-sections.
  - Resummation of large logarithms.

- New physics → large masses → long decay chains Discussions of SUSY signals → Multijet final states → high order tree level matrix elements

- PT-NonPT interface

  - parton-hadron transistion fragmentation functions
  - underlying event.
  - multiple hard scattering.
  - low p_T interactions(minimum bias interactions).

Do I need to know this if all I want to do is look for exotic physics (SUSY!)?

Answer is yes..We have to have an understanding of the picture to evaluate and understand the results that are being presented to us and also calculate new/unusual signals that one may want to propose to be studied!

Because SUSY signals seem to be really hiding (if they exist) an appreciation of good calculations of shapes of distribution etc. becomes important!

Traditional theorist's way!

Cross-sections in QCD Calculated by truncating perturbative expansion to a fixed order (FO).

$$
\begin{aligned}
\hat{\sigma}(p_1,p_2;Q,\{Q_1,\ldots\};\mu_F^2) = \alpha_s^k(\mu_R^2)\Big\{ & \hat{\sigma}^{(LO)}(p_1,p_2;Q,\{Q_1,\ldots\}) \\
& + \alpha_s(\mu_R^2)\,\hat{\sigma}^{(NLO)}(p_1,p_2;Q,\{Q_1,\ldots\};\mu_R^2;\mu_F^2) \\
& + \alpha_s^2(\mu_R^2)\,\hat{\sigma}^{(NNLO)}(p_1,p_2;Q,\{Q_1,\ldots\};\mu_R^2;\mu_F^2) \\
& + \ldots\Big\}
\end{aligned}
$$

The LO (tree level) calculation has a strong dependence on the choice of scale Q^2. The scale dependence is reduced by going to NLO. To get a reliable estimate of error on theoretical calculation, a NLLO calculation is necessary.

Using an actual NLO or NNLO calculation in experimental analysis was a complicated story.

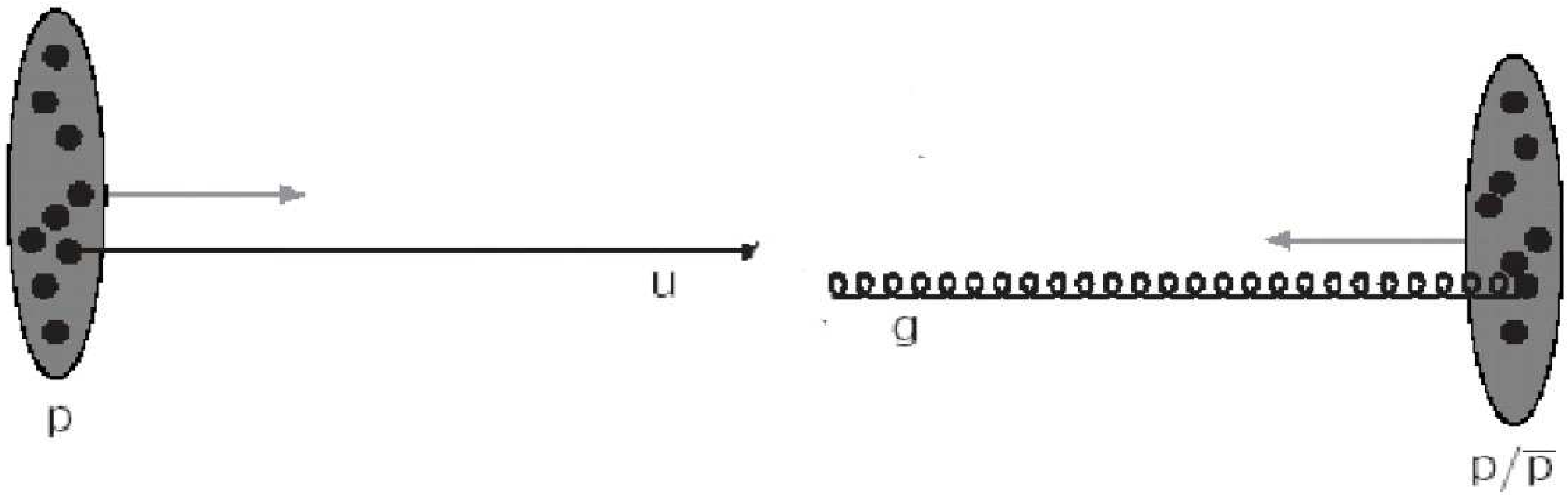
But

1)For precision SM physics.

AND

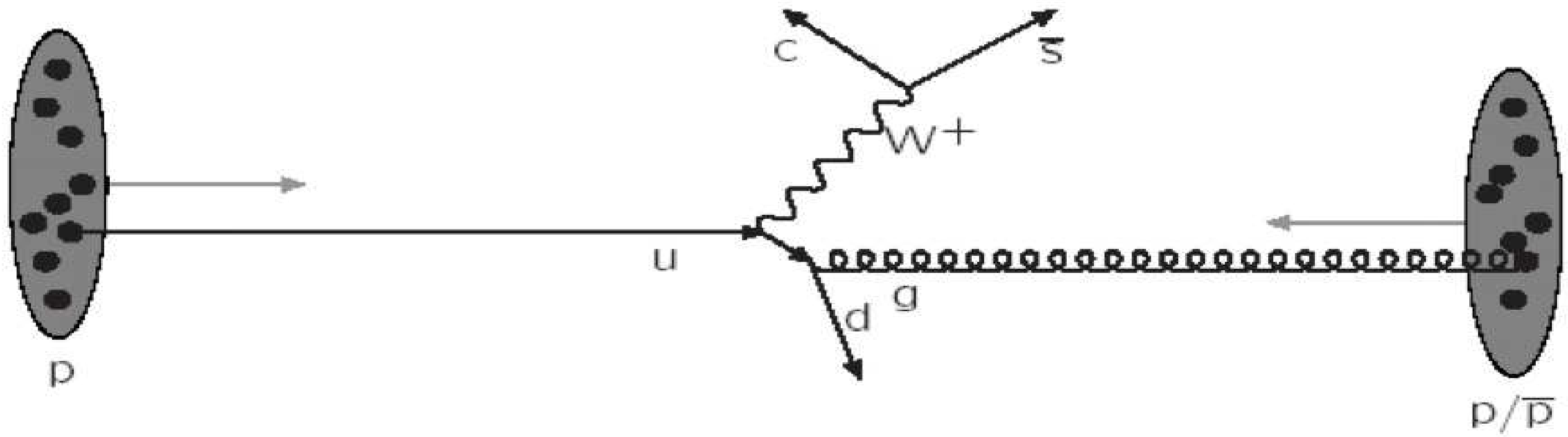
2) Efficient search for BSM physics.

Inclusion of these in the analyses experimentalists perform are a must!
If it can be automated all the better!



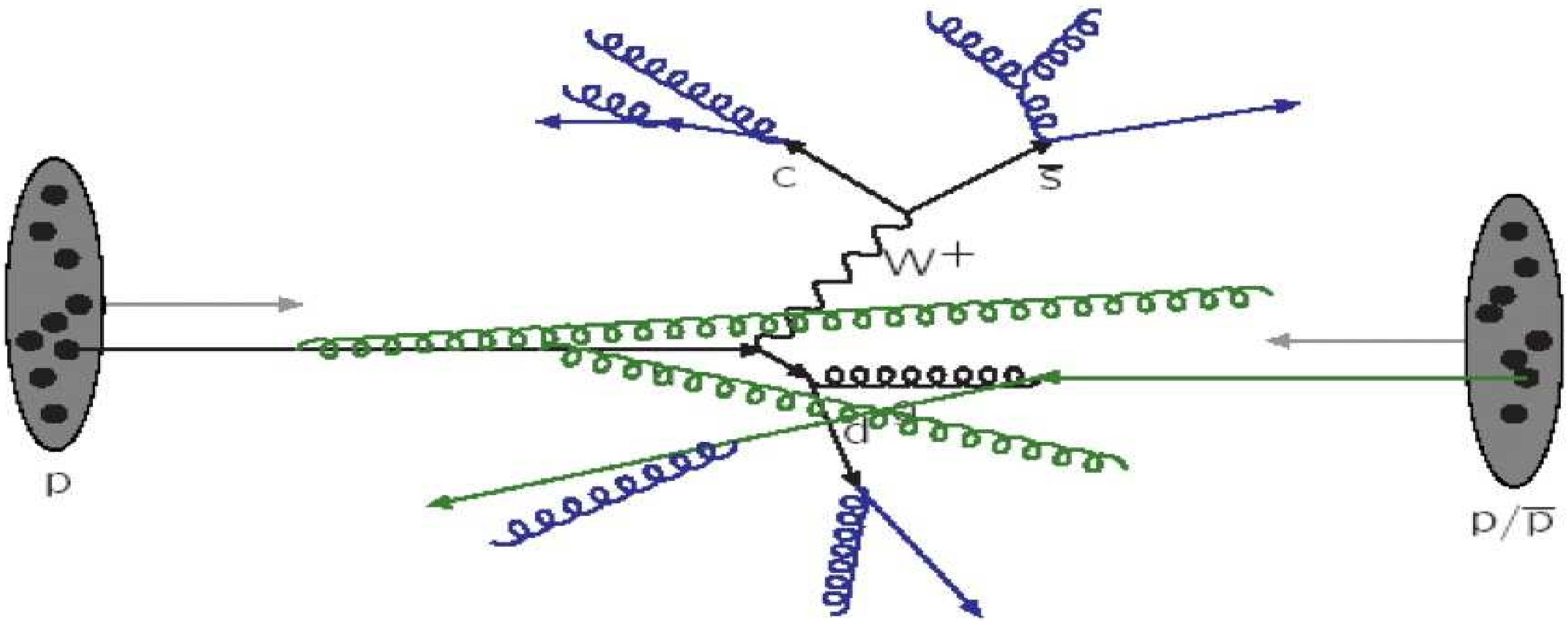
0. Pull out one parton from each of the incoming hadrons (use PDFs to choose flavour and x)

(Frixione + T. Sjostrand)



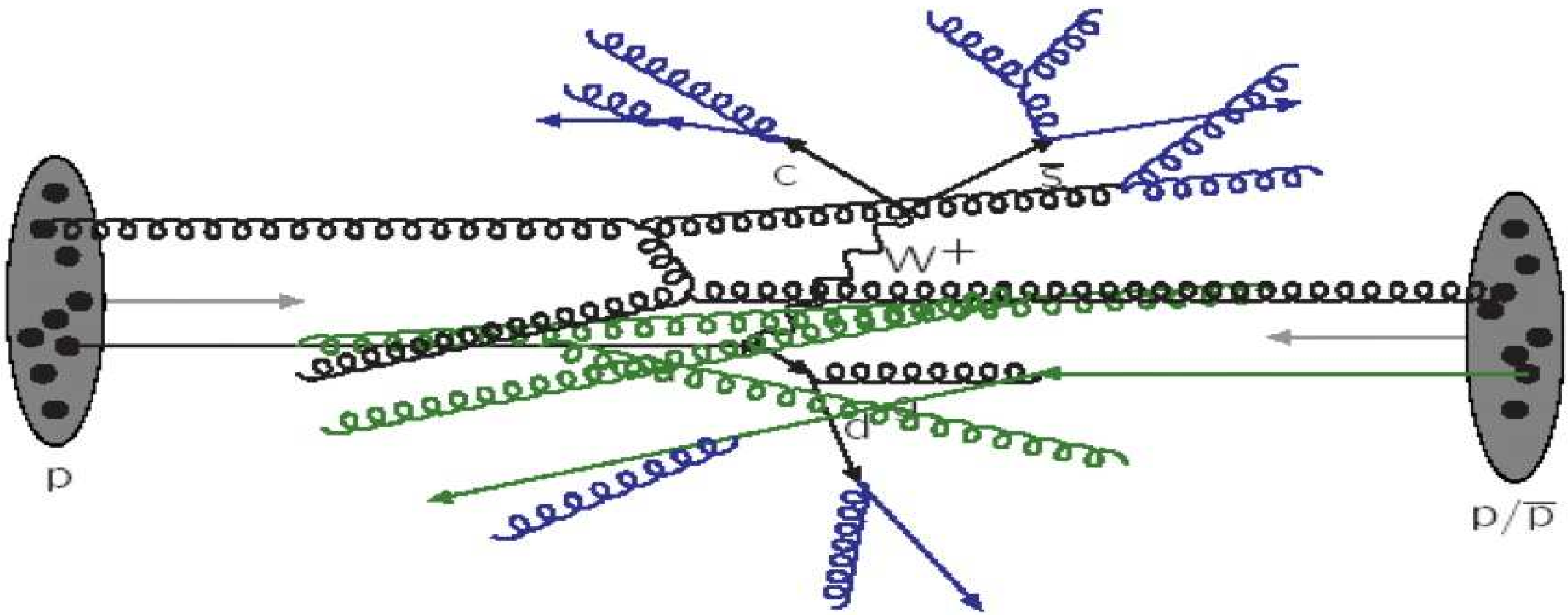
1. Make them collide and produce *large-p_T stuff* (Hard Subprocess)

(Frixione + T. Sjostrand)



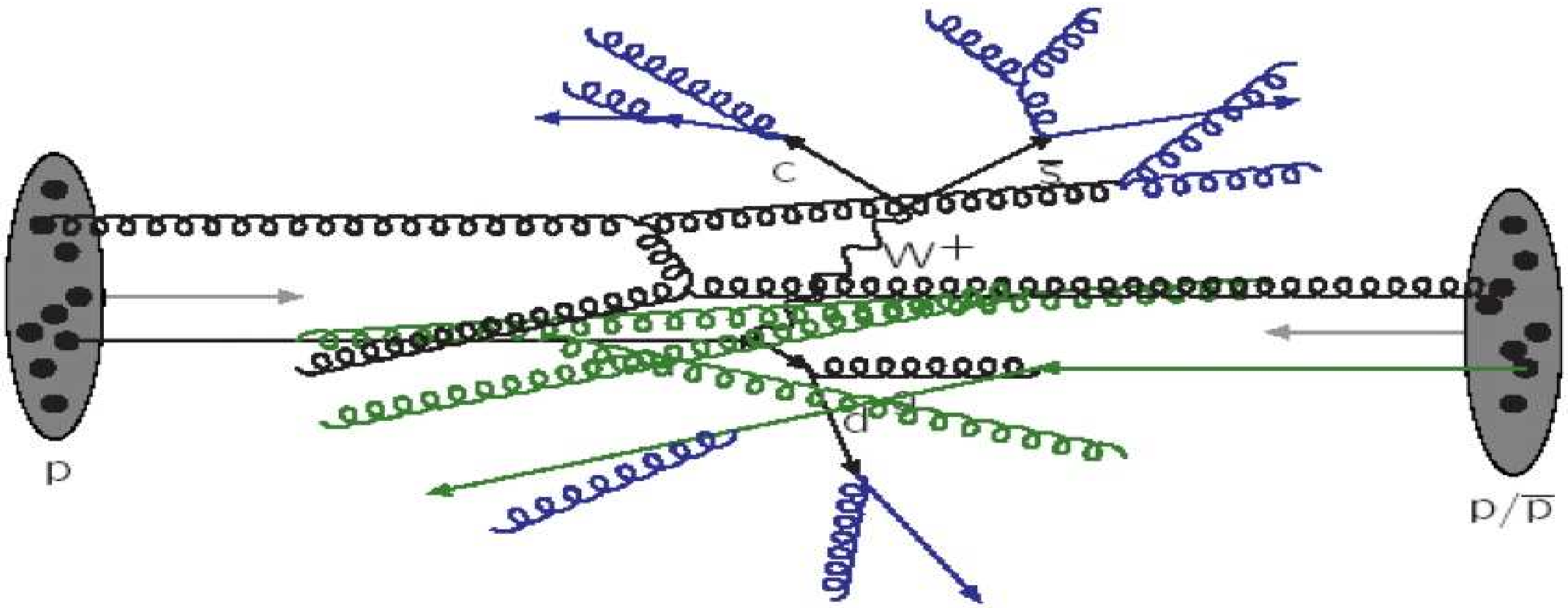
2. Let quarks and gluons emit other quarks and gluons
(Parton Shower)

(Frixione + T. Sjostrand)



3. Other partons may undergo the same fate *at smaller* p_T*'s* (MPI + beam remnants ≡ Underlying Event)

(Frixione + T. Sjostrand)



4. Convert quarks and gluons into physical hadrons (Hadronization)

(Frixione + T. Sjostrand)

Parton Shower:

The hard process calculated to a certain order in perturbation theory and parton emission is added.

On top of this add: Multiple parton scattering + beam remnants : Underlying event!

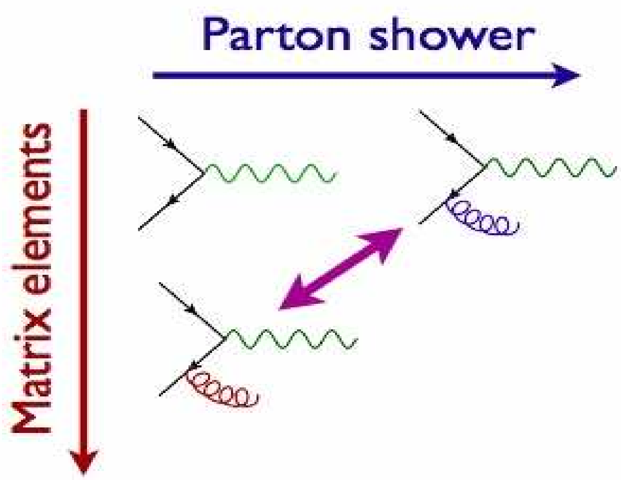
Hadronisation: How do the patrons convert themselves into hadrons!

For a real description of the data collected in the detectors this is what is needed!

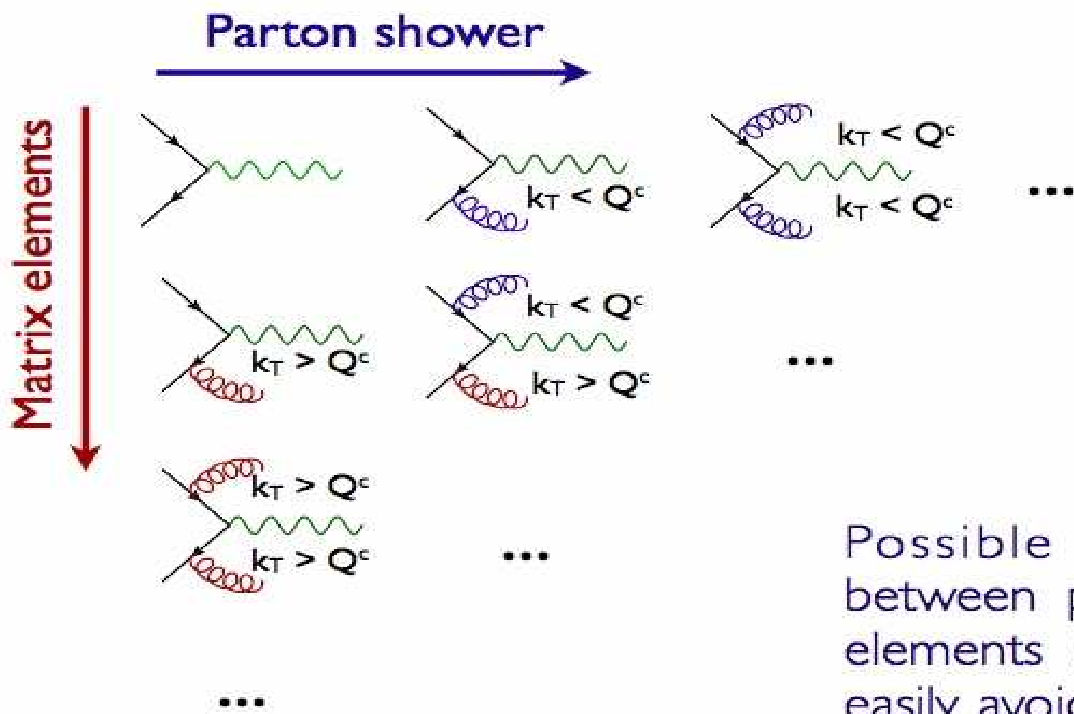
How to make contact with high precision, higher order calculations being done by theorists?

Local expertise!

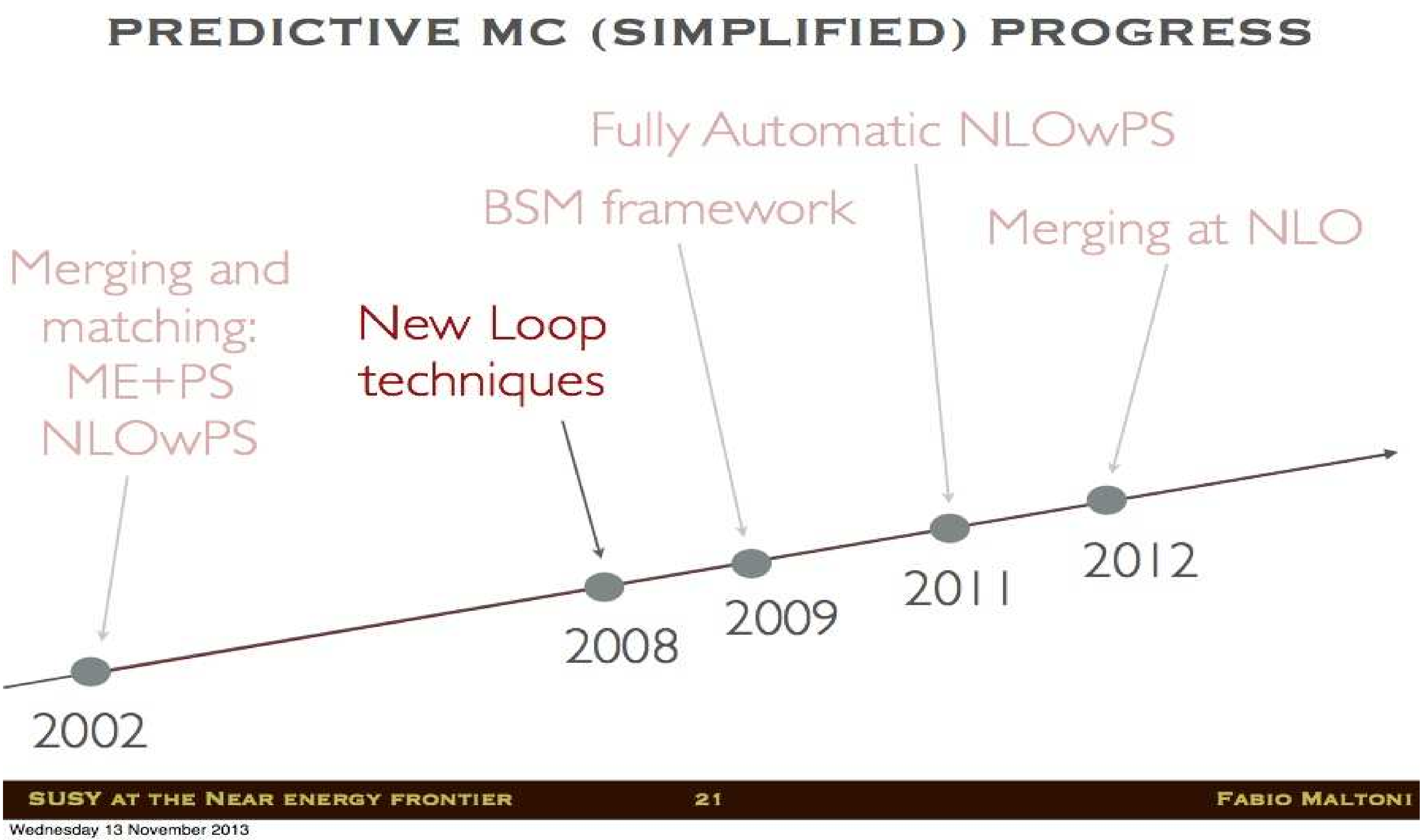
Merging fixed order with PS



Merging fixed order with PS



Possible double counting between partons from matrix elements and parton shower easily avoided by applying a cut in phase space


PREDICTIVE MC (SIMPLIFIED) PROGRESS
Fully Automatic NLOwPS
BSM framework
Merging at NLO
Merging and matching: ME+PS NLOwPS
New Loop techniques
2002
2008
2009
2011
2012
SUSY AT THE NEAR ENERGY FRONTIER
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1)MC @NLO : Frixione and collaborators

2)POWHEG: Oleari and collaborators

3)Automation of MC at higher order: AMC@NLO Fabio Maltoni and collaborators, for BSM.

Probing BSM at colliders:

1)Explore the region in parameter space of the your favorite BSM model and find the region where all the current constraints are satisfied. The most difficult ones used to be LEP EW constraints. Now it is the Higgs mass, Higgs signal strengths! Since mostly these are virtual effects of the new particles on the $Zb\bar{b}$ coupling, Higgs couplings, Higgs cross-section, flavor changing neutral currents... etc.

2)In the remaining parameter space identify the mass, spin of the new particles (if any) predicted in the BSM. Every version of BSM has some particles accessible to the LHC. At least we all try to build models which do.

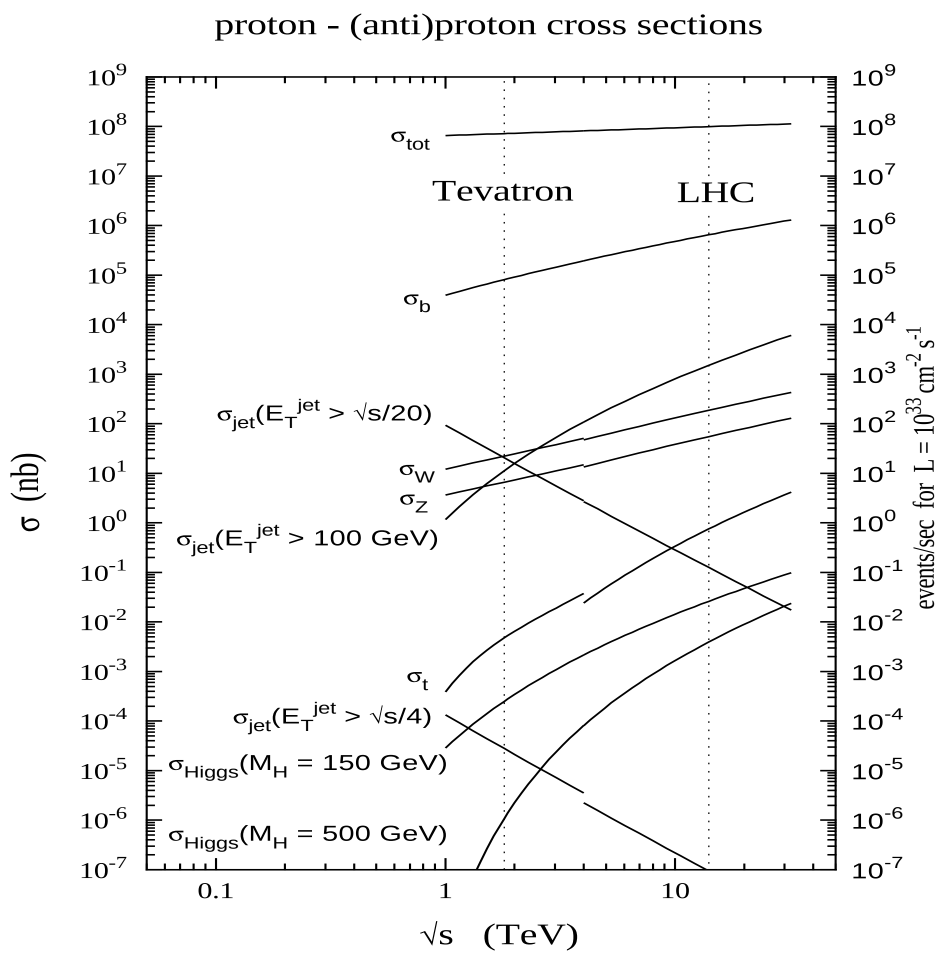
3)Identify production and decay modes of these new particles. Two possibilities:

- They are produced 'on shell'. Study possible signals at colliders due to 'direct' production.

- They contribute virtually. Get information 'indirectly' through virtual effects on collider processes: say jet production, l^+l^- production....

4)Most of the time signal size way smaller than background.

5)Now comes the fun and magic part of phenomenology. Conjure up observables such that making cuts in that observable will kill the background without affecting the signal unduly. **Needs calculation of distributions in kinematic variables for signal and background**



proton - (anti)proton cross sections
σ (nb)
√s (TeV)
events/sec for L = 10^33 cm^-2 s^-1
Tevatron
LHC
σtot
σb
σjet(ET jet > √s/20)
σW
σZ
σjet(ET jet > 100 GeV)
σt
σjet(ET jet > √s/4)
σHiggs(MH = 150 GeV)
σHiggs(MH = 500 GeV)
0.1
1
10

So how to find this needle in haystack?

Paint it **red and bright**!!

How to do that?

Use information from Kinematics

This is 'fun' part !

Use the Monte Carlos

This is the difficult part, made easy by the Monte Carlo developers!

No. of events $= \mathcal{L} \times \sigma, \mathcal{L} = 10^{33} cm^{-2} sec{-1} \rightarrow 10 fb^{-1}/yr$

We expect to measure signals which have cross-section of ~ 1 **pb or so, giving 1000 events/yr. Cross section for Higgs production for** 125 **GeV mass is about 20 pb.** Luminosity now is $\sim 30 fb^{-1}$.

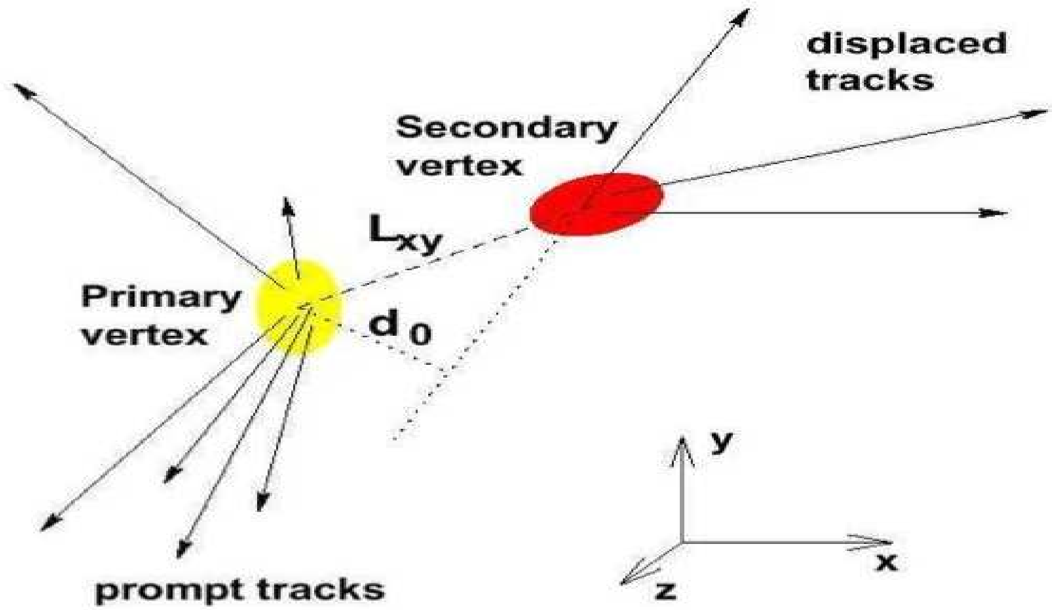
Process	$\sigma(nb) \equiv$ # of events/sec	events so far
Total cross-sections	10^8	3×10^{15}
$W^{\pm} \rightarrow e\nu$	20	6×10^8
$Z \rightarrow e^+e^-$	2	6×10^7
$t\bar{t}$	0.8	2.5×10^7
$b\bar{b}$	5×10^5	1.5×10^{13}
central jets ($P_T > 100 GeV$)	10^3	3×10^{10}
Higgs (125 GeV)	**0.02**	$\mathbf{3 \times 10^4}$

Rules of thumb: obviously apply only to things simple. Three things can happen.

- Particles which do not decay in the detector and are neutral. 'missing energy'

- Particles which decay 'instantaneously' and produce decay products at the interaction vertex itself which will be detected: through the energy deposition in the detectors or as charged particle tracks.

- Particles which decay with a life time $\sim 10^{-12}$ sec. and produce a secondary vertex.



The B-mesons, D-mesons have life times of this order!

What is the significance of this? Using silicon detectors the experimentalists can see the presence of the b-flavoured hadrons.

First discuss particles which decay in the detector:

1)Look at regions of low rapidity: central region. One is free of the remnant activity. If majority of your signal sits there you are in good shape!

2)Choose final states with $\gamma, e^-, \mu^-, \tau^-$. Backgrounds are usually smaller because production rates are controlled by electroweak coupling. One pays the price smaller branching ratio into leptonic channels with smaller rates.

3)Choose final states with properties very distinctive to the signal and bkgd can not mimic it.

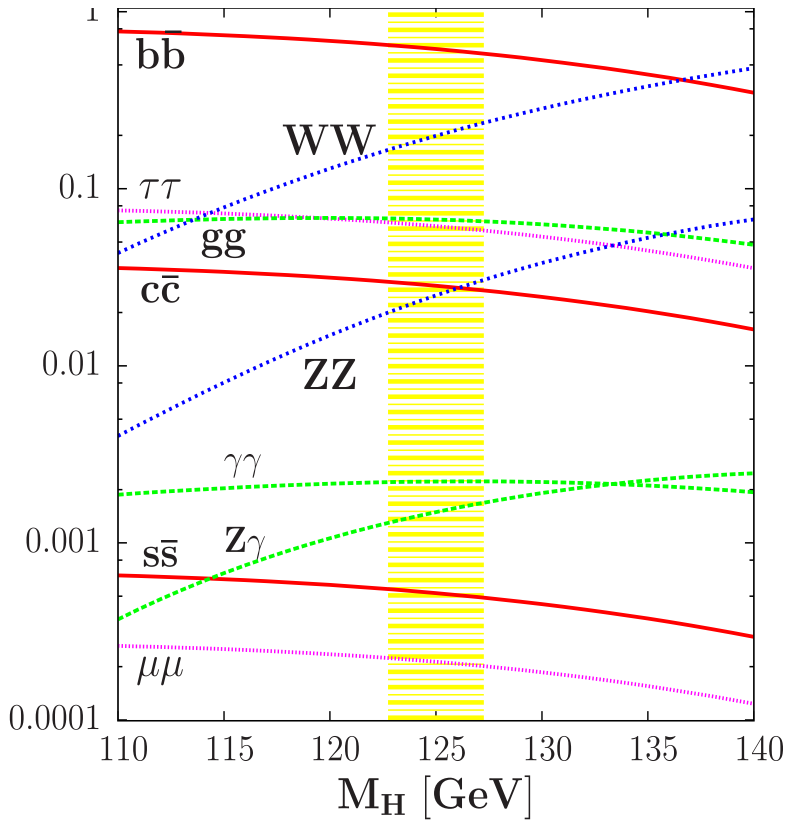


Fig: courtesy A. Djouadi.

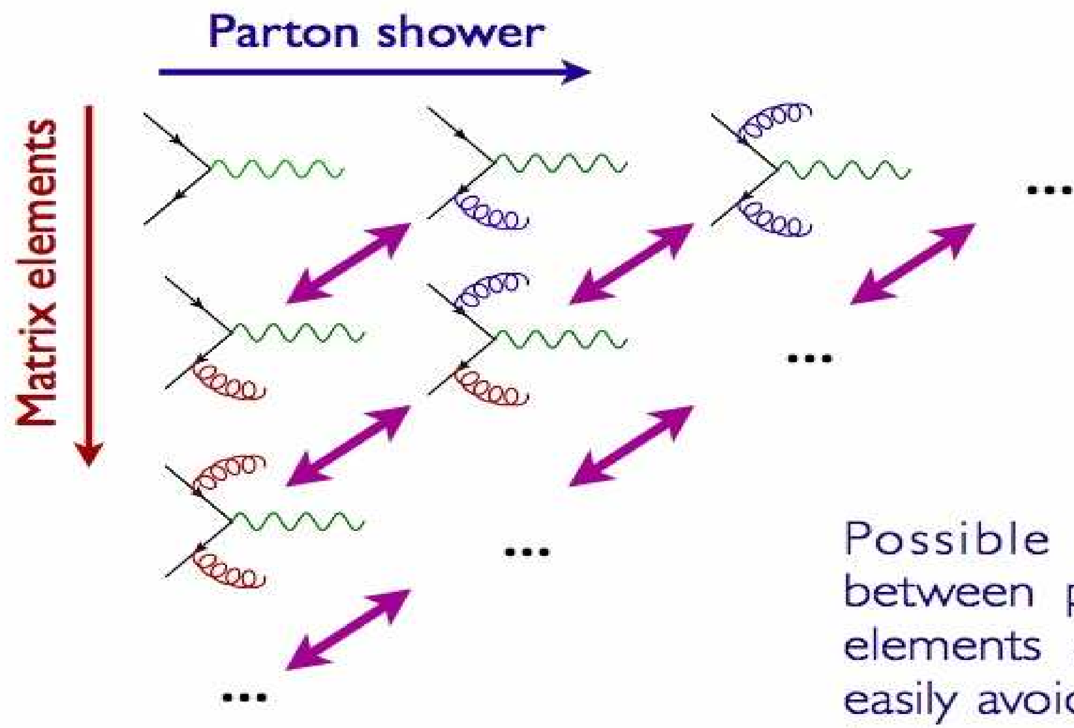
The choice of $\gamma\gamma$ final states ideal for the Higgs in spite of the small branching ratio ~ 0.002 because of the much smaller SM background which will come from processes like $q\bar{q} \to \gamma\gamma, gg \to \gamma\gamma$ etc.

The ZZ final state is better than the WW final state in spite of the fact that ZZ branching ratio is 10 times smaller. The four leptons in the final state make it much more efficient than the WW final state which contains two νs.

The most difficult final state was $b\bar{b}$ final state which has the largest QCD background and hence was one of the last ones to see the 5σ signal!

BACKUP

MERGING FIXED ORDER WITH PS



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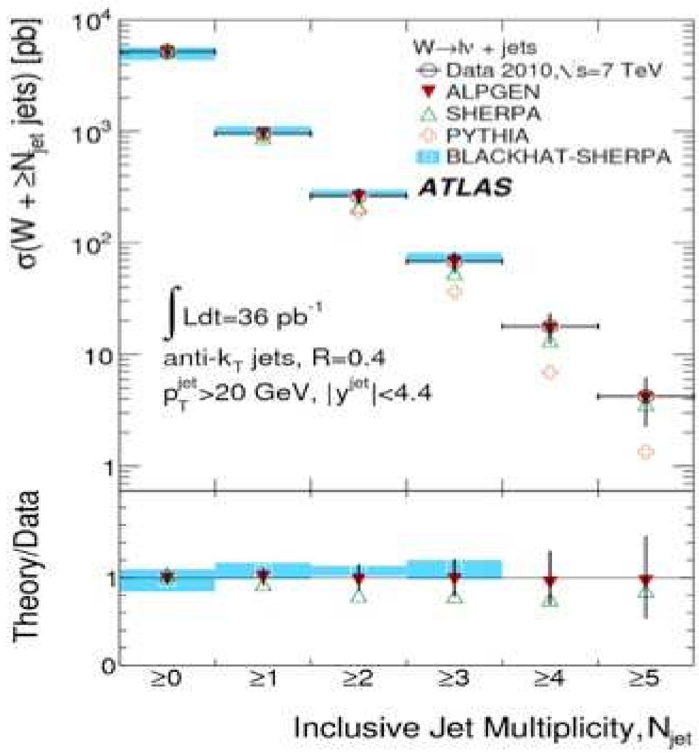
V+JETS AT THE LHC



Working amazingly well!

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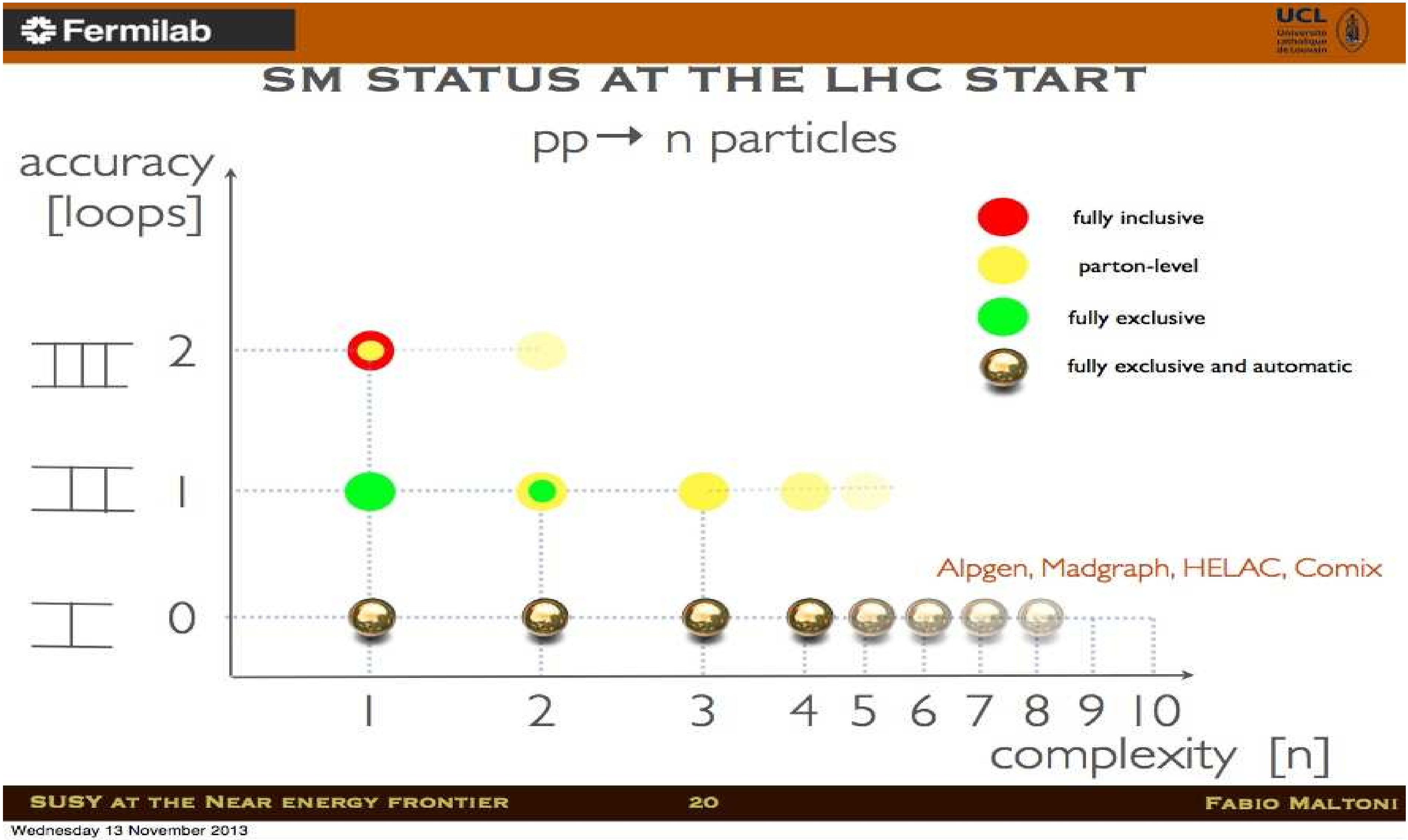
Fermilab
UCL
SM STATUS AT THE LHC START
pp→ n particles
accuracy [loops]
2
1
0
fully inclusive
parton-level
fully exclusive
fully exclusive and automatic
Alpgen, Madgraph, HELAC, Comix
1 2 3 4 5 6 7 8 9 10
complexity [n]
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