Theoretical modeling of SM processes in hadronic collisions

The path towards discoveries

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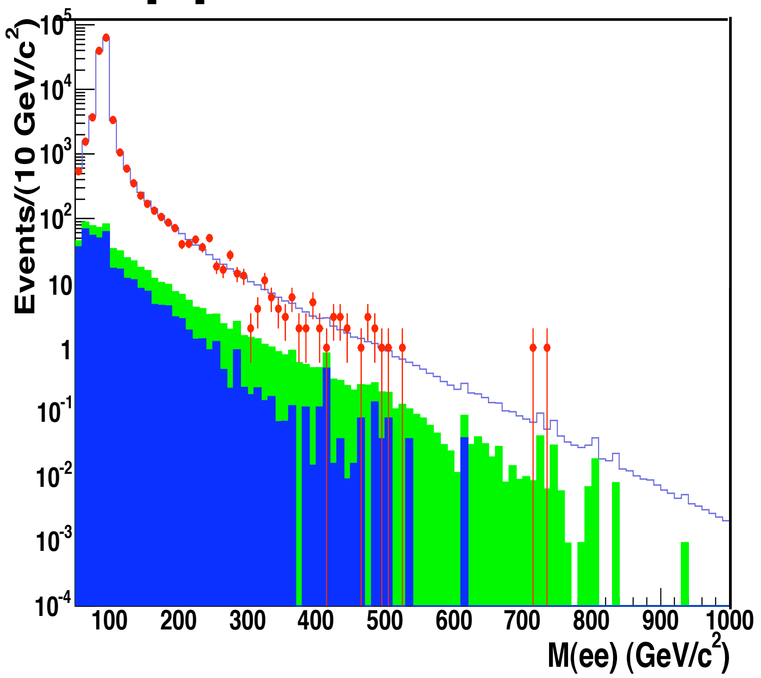
Central Question

Do we understand and are we able to predict SM physics (QCD+EW) well enough to make discoveries at the LHC?

Discoveries at hadron colliders

peak

$pp \to Z' \to e^+e^-$

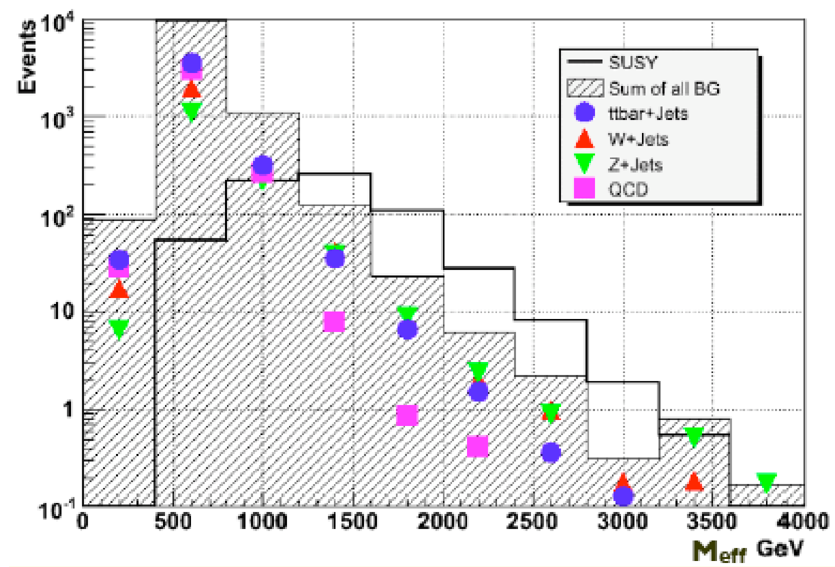


"easy"

Background directly measured from data. TH needed only for parameter extraction (Normalization, acceptance,...)

shape

$pp \to \tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q} \to jets + \not{E}_T$

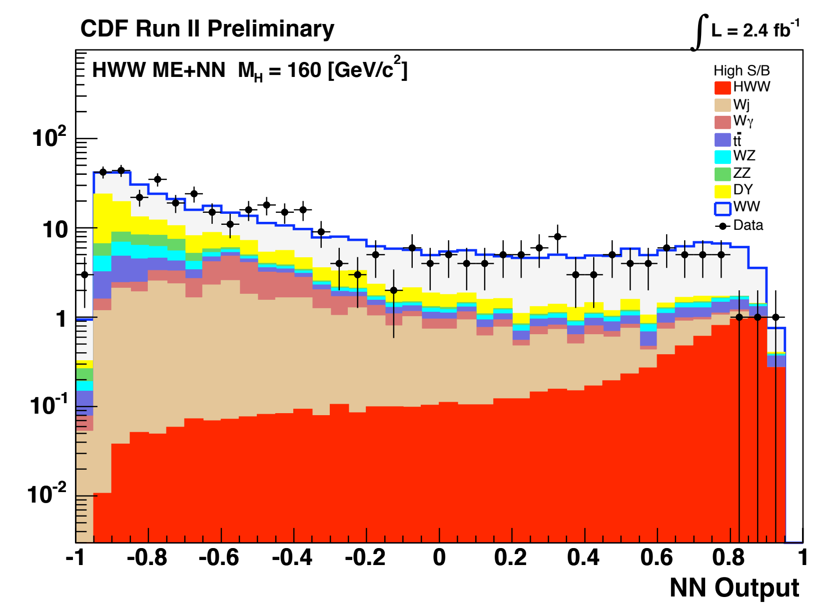


hard

Background shapes needed. Flexible MC for both signal and backgroud tuned and validated with data.

rate

$pp \to H \to W^+W^-$

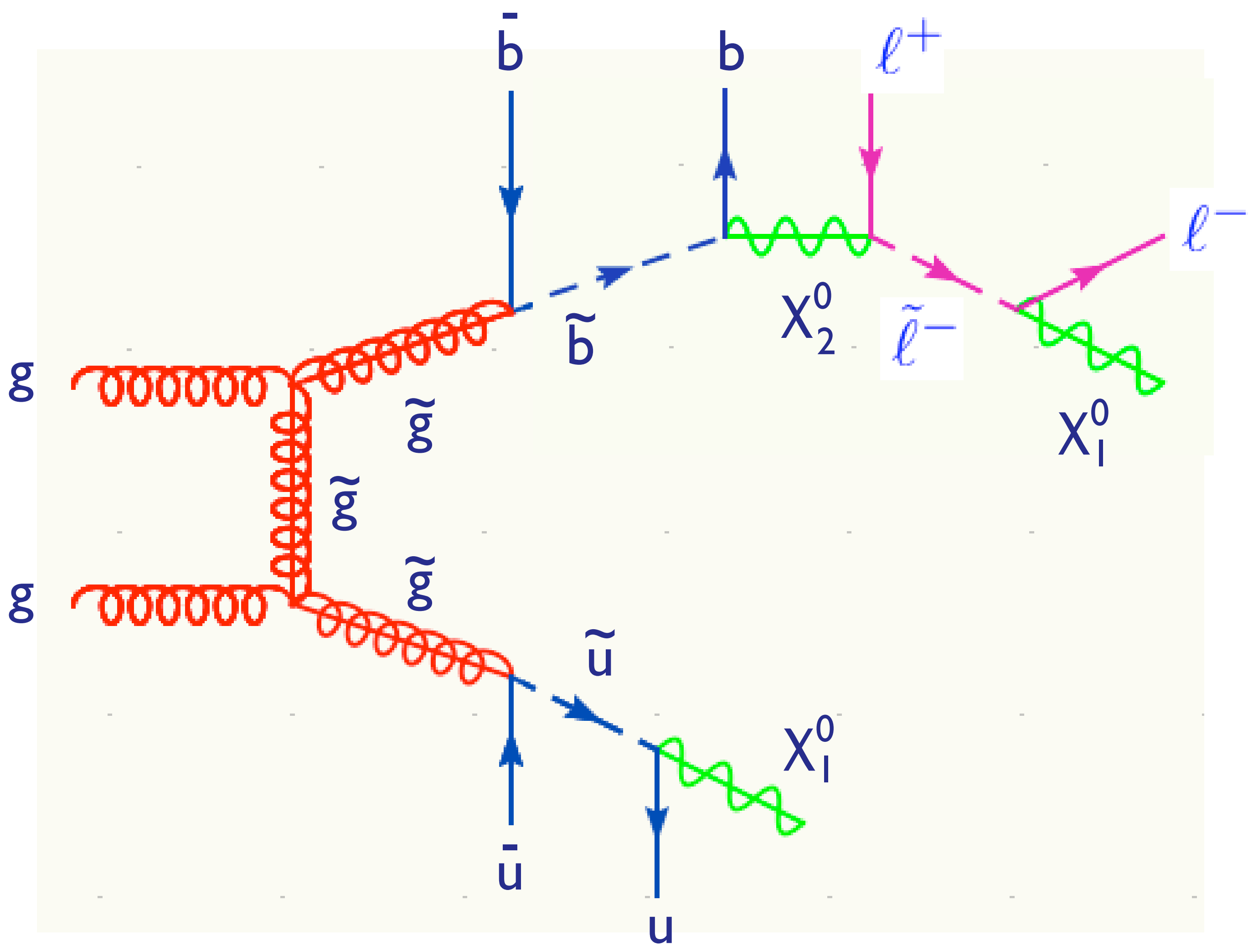


very hard

Background normalization and shapes known very well. Interplay with the best theoretical predictions (via MC) and data.

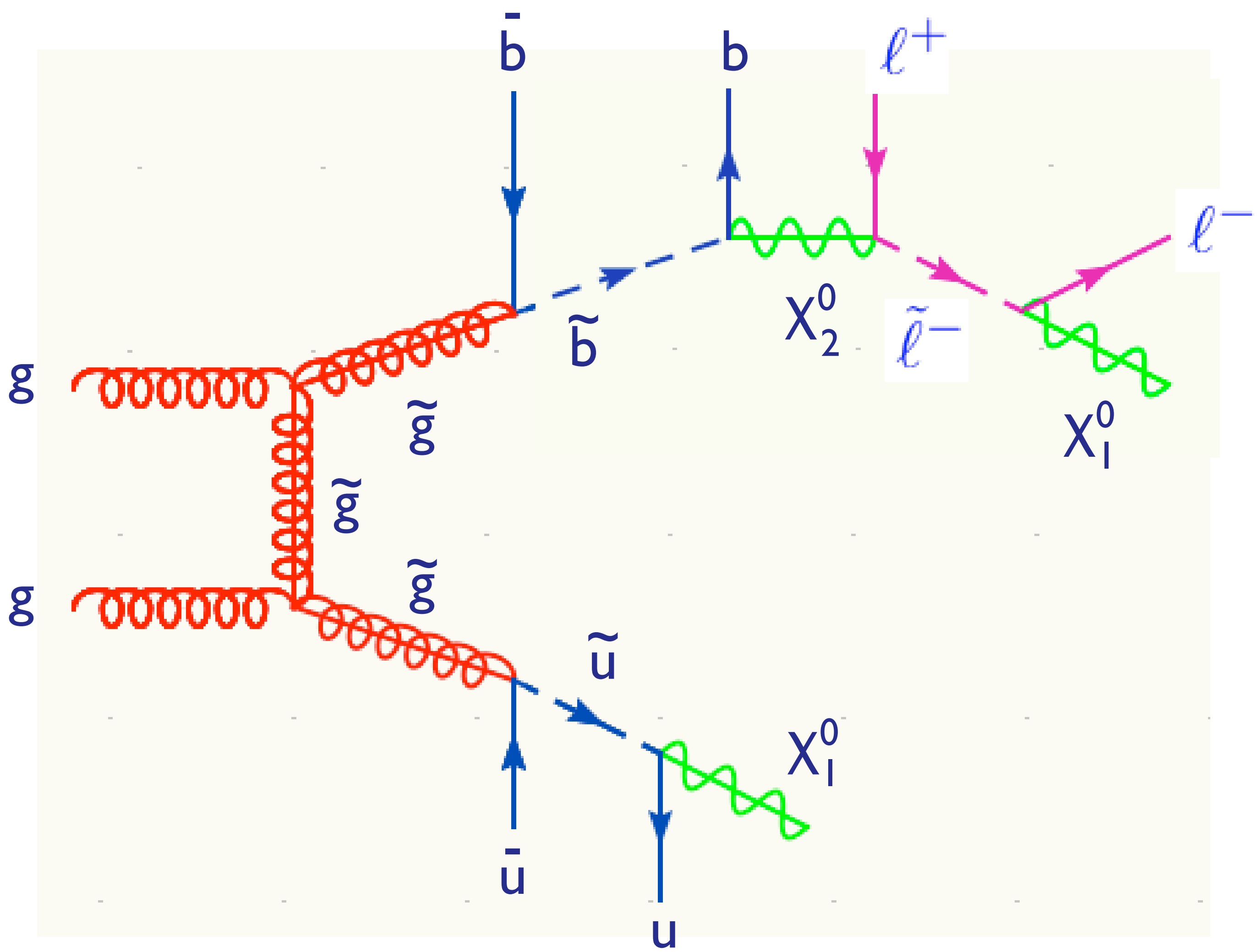
A new challenge

Consider SUSY-like inclusive searches: heavy colored states decaying through a chain into jets, leptons and missing E_T...

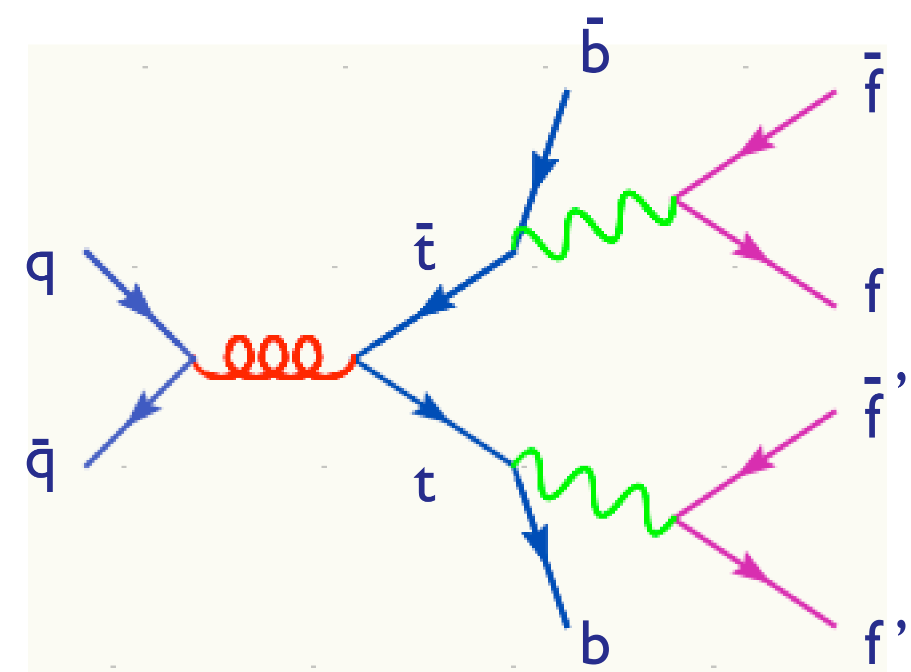


A new challenge

Consider SUSY-like inclusive searches: heavy colored states decaying through a chain into jets, leptons and missing E_T... We have already a very good example of a similar discovery!



VS



Follow the same approach of CDF in 1995 to establish first evidence of an excess wrt to SM-top and then consistency with SM top production [mt=174, t→blv, σ(tt)] , works for the SM Higgs, but in general beware that...

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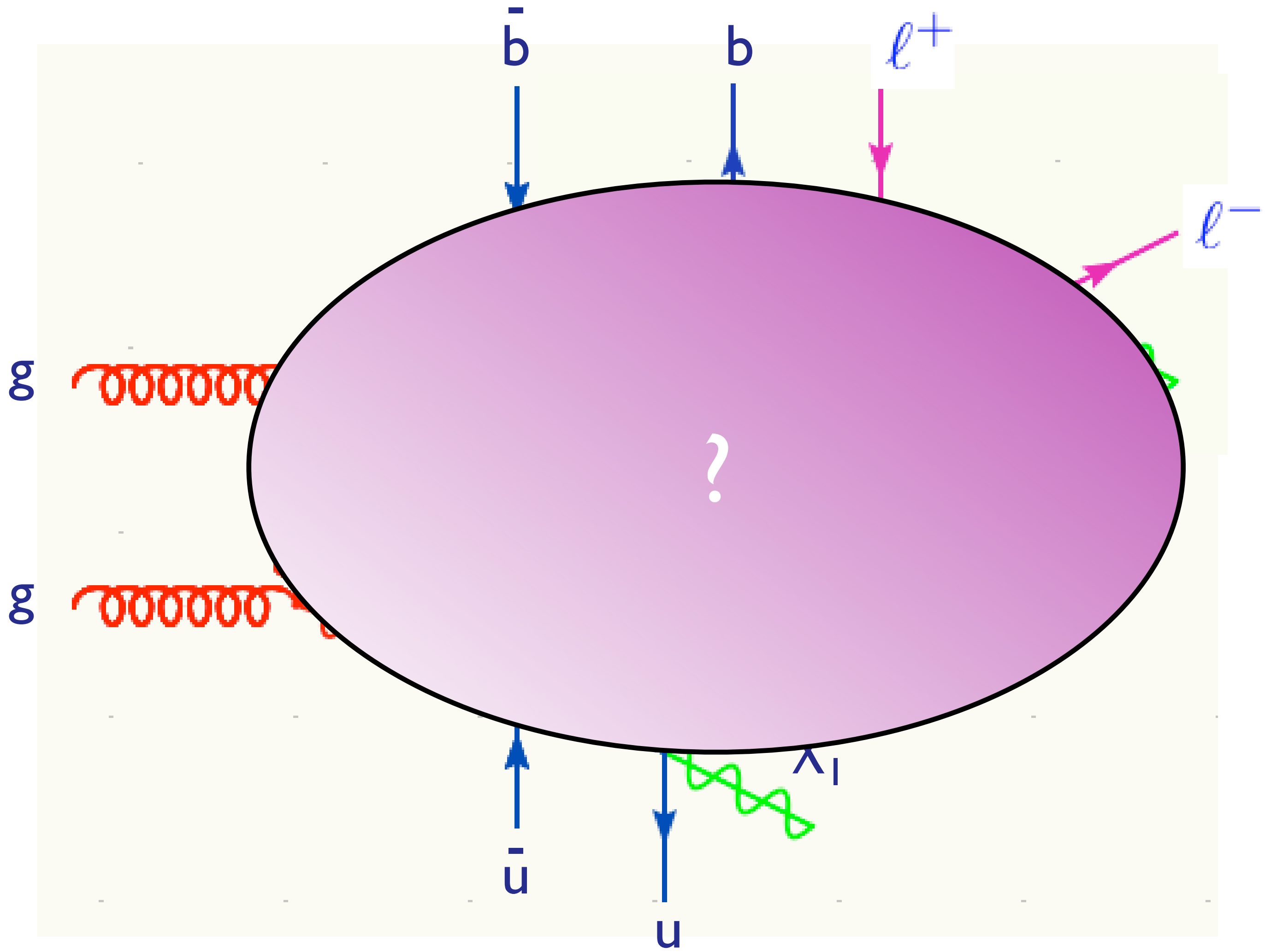
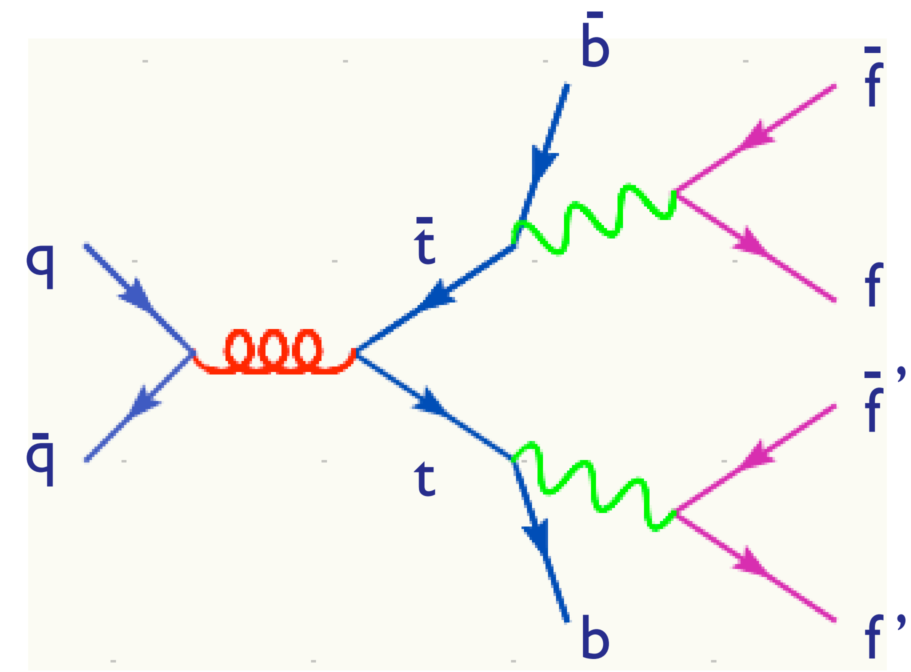


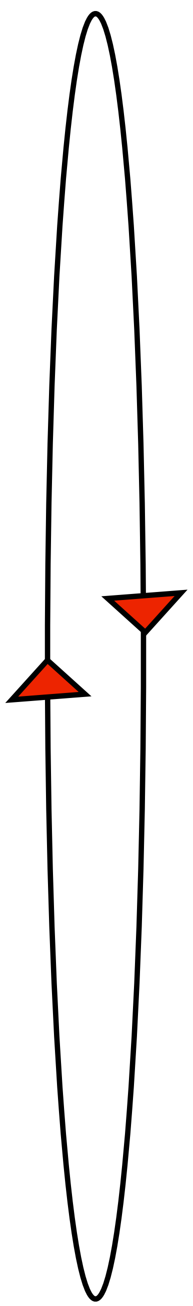
VS



Follow the same approach of CDF in 1995 to establish first evidence of an excess wrt to SM-top and then consistency with SM top production [mt=174, t→blν, σ(tt)] , works for the SM Higgs, but in general beware that... we don't know what to expect! [see G.Burdman's talk]

The path towards discoveries

LHC physics = QCD + ϵ



1. Rediscover the known SM at the LHC (top's, W's, Z's) + jets.

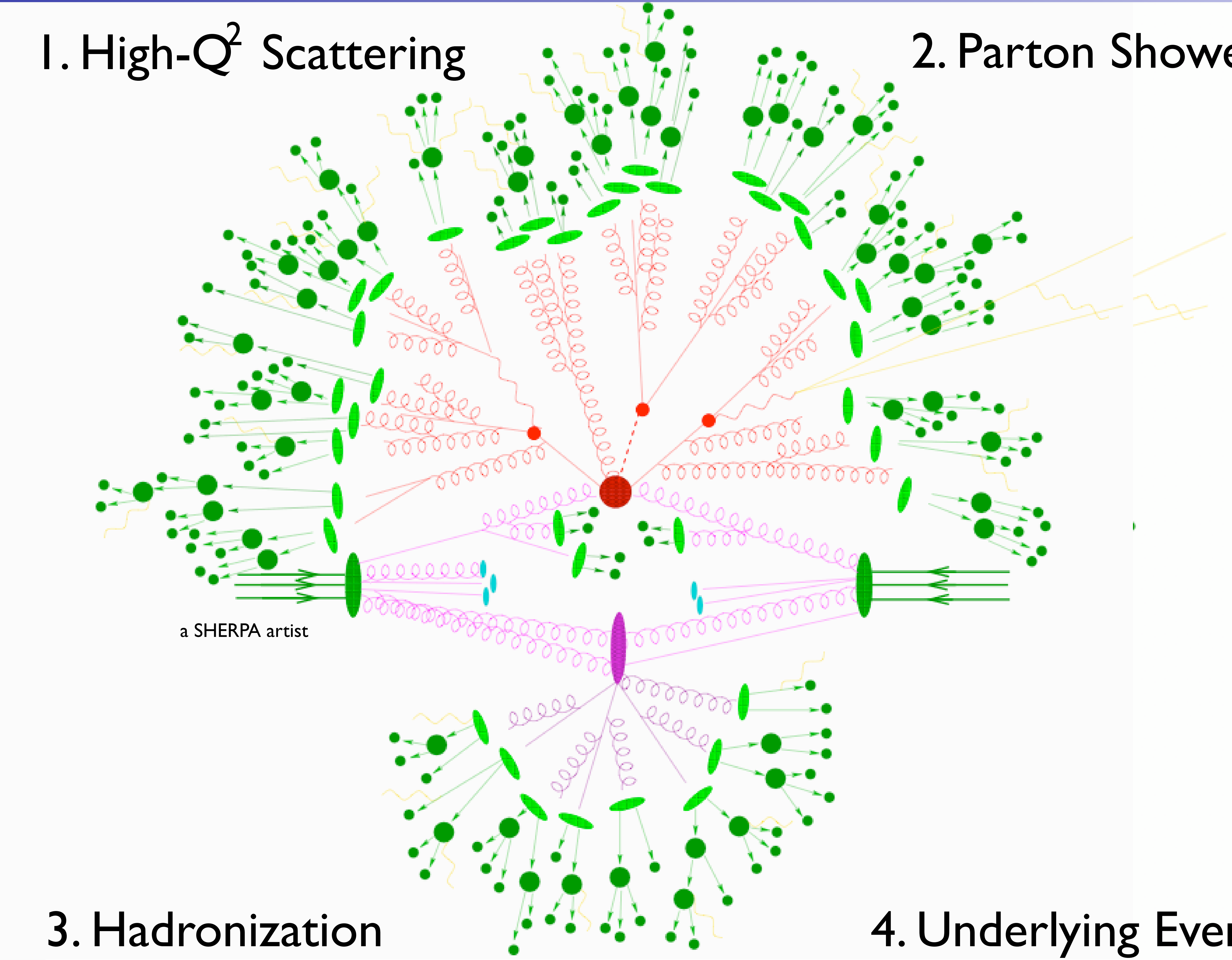
New regime for QCD. Exclusive description for rich and energetic final states with flexible MC to be validated and tuned to control samples. Shapes for multi-jet final states and normalization for key process important. Accurate predictions (NLO,NNLO) needed only for standard candle cross sections.

2. Identify excess(es) over SM

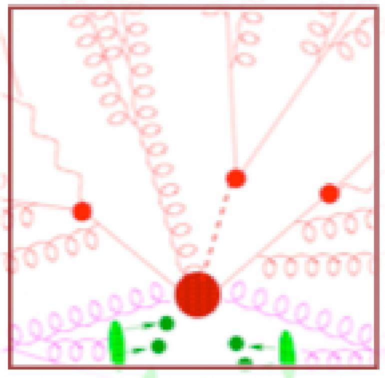
Importance of a good theoretical description depends on the nature of the physics discovered: from none (resonances) to fundamental (inclusive SUSY).

3. Identify the nature of BSM: from coarse information to measurements of mass spectrum, quantum numbers, couplings.

Not fully worked out strategy. Several approaches proposed (MARMOSET, VISTA,...). Only in the final phase accurate QCD predictions and MC tools for SM as well as for the BSM signals will be needed.


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

How theorists (used to) make predictions?



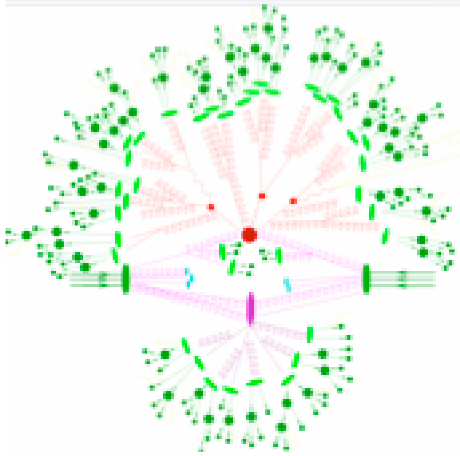
Evolution is unitary and universal: ignore it!
Focus on the high Q^2:

- For low parton multiplicity include higher order terms in our fixed-order calculations (LO→NLO→NNLO...)
  $\Rightarrow \hat{\sigma}_{ab\to X} = \sigma_0 + \alpha_S \sigma_1 + \alpha_S^2 \sigma_2 + \ldots$
- For high parton multiplicity use the tree-level results

Comments:

1. The theoretical errors systematically decrease
2. A lot of new techniques and universal algorithms are developed
3. Final description only in terms of partons and calculation of IR safe observables $\Rightarrow$ cannot be directly employed in experimental studies

How experimentalists (used to) make predictions?



Fully exclusive final state description for detector simulations more important ⇒ give up on the high Q^2 complexity.

- Describe final states with high multiplicities starting from 2 →1 or 2 →2 procs, using a parton shower, and then an hadronization model

Comments:

1. Very flexible and tunable tools. Good description of the data possible
2. Catches the bulk (log-enhanced) part of the cross section
3. Predictive power for normalization and kinematic distributions for high-pt multi-parton final states very limited

most known and used: PYTHIA, HERWIG, SHERPA*

Matrix element vs Parton Shower

Matrix element	Shower MC
1. valid when partons are hard and well separated	1. based on subsequent soft/collinear splittings
2. fixed order calculation	2. resums large logs
3. only few partons	3. high multiplicities

New trend

Common Principle:

Avoid the weakest link! Balance the accuracy over the steps in the simulation chain. Improve not only the single steps but also their merging.

Two directions:

1. Matrix Elements + Parton Showers
Get fully exclusive description of many parton events correct at LO (LL) in all the phase space

ME+PS

2. NLO with Parton Shower
Get fully exclusive description of events correct at NLO in the normalization and distributions.

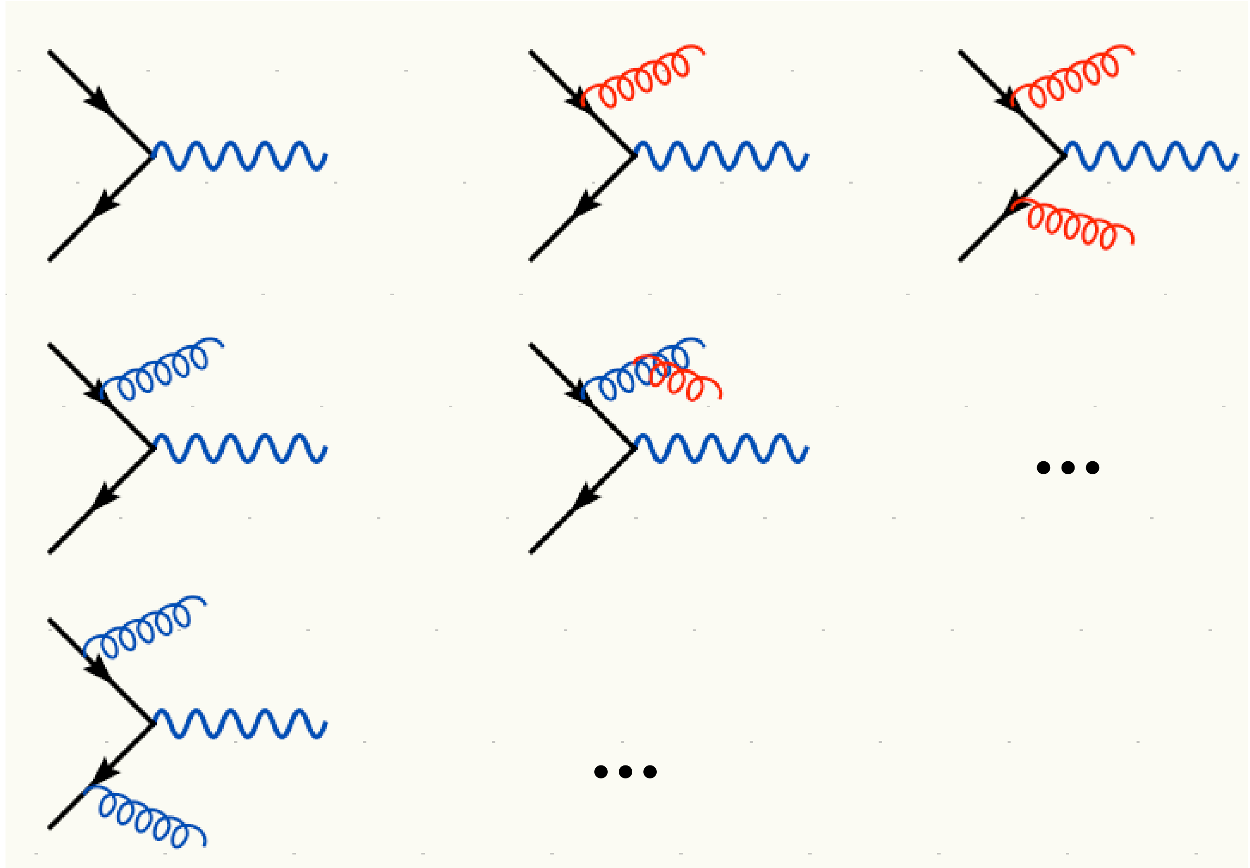
NLOwPS

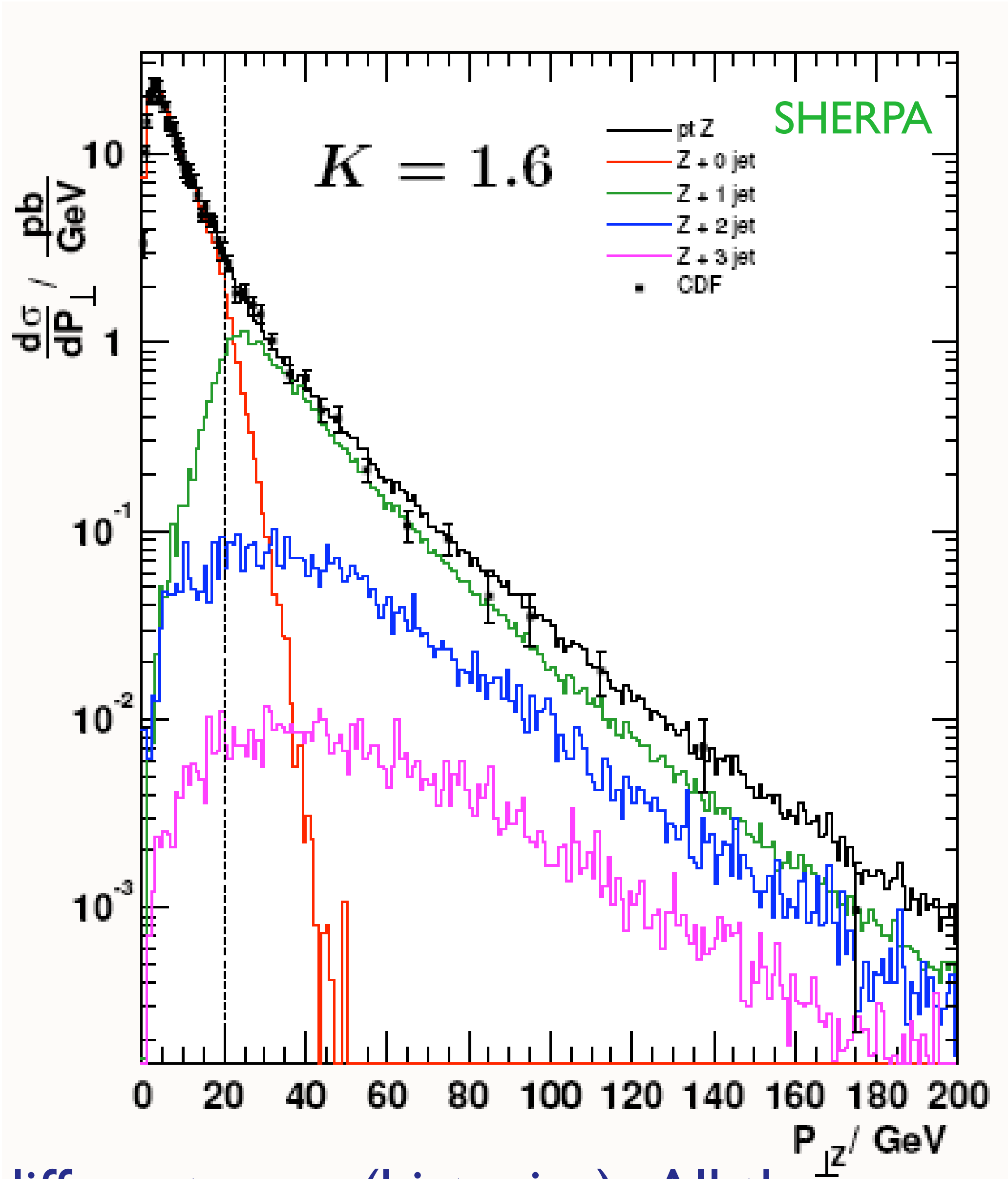
Merging fixed order with PS

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

PS →

ME ↓

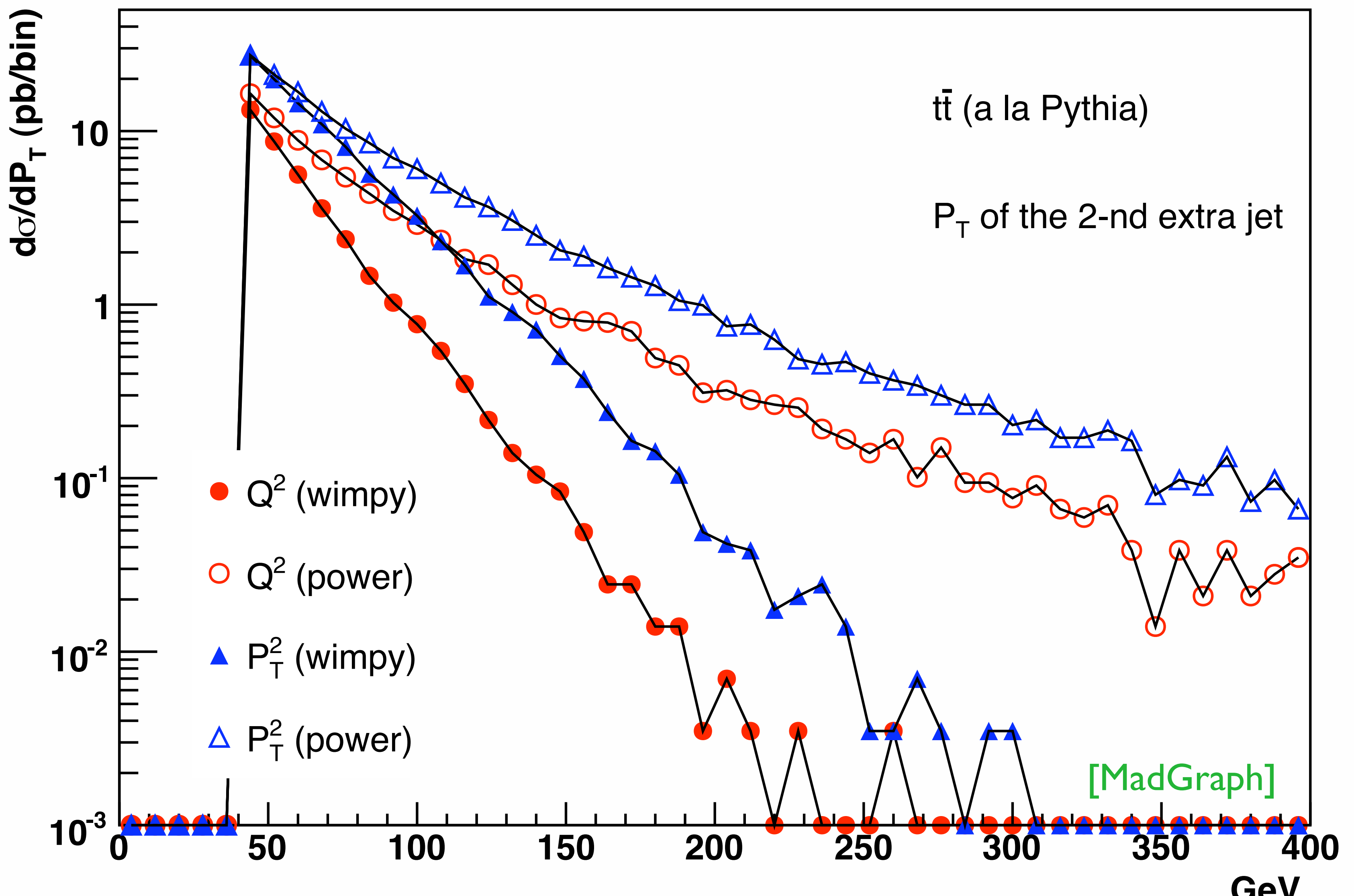




Double counting of configurations that can be obtained in different ways (histories). All the matching algorithms (CKKW, MLM,...) apply criteria to select only one possibility based on the hardness of the partons. As the result events are exclusive and can be added together into an inclusive sample. Distributions are accurate but overall normalization still "arbitrary".

PS alone vs matched samples

A MC shower produces inclusive samples covering all phase space. However, there are regions of the phase space (ex. high pt tails) which cannot be described well by the log enhanced (shower) terms in the QCD expansion and lead to ambiguities. Consider for instance the high-pt distribution of the second jet in ttbar events:



Changing some choices/parameters leads to huge differences ⇒ self diagnosis. Trying to tune the log terms to make up for it not a good idea ⇒ problems in other regions/shapes, proc dependence.

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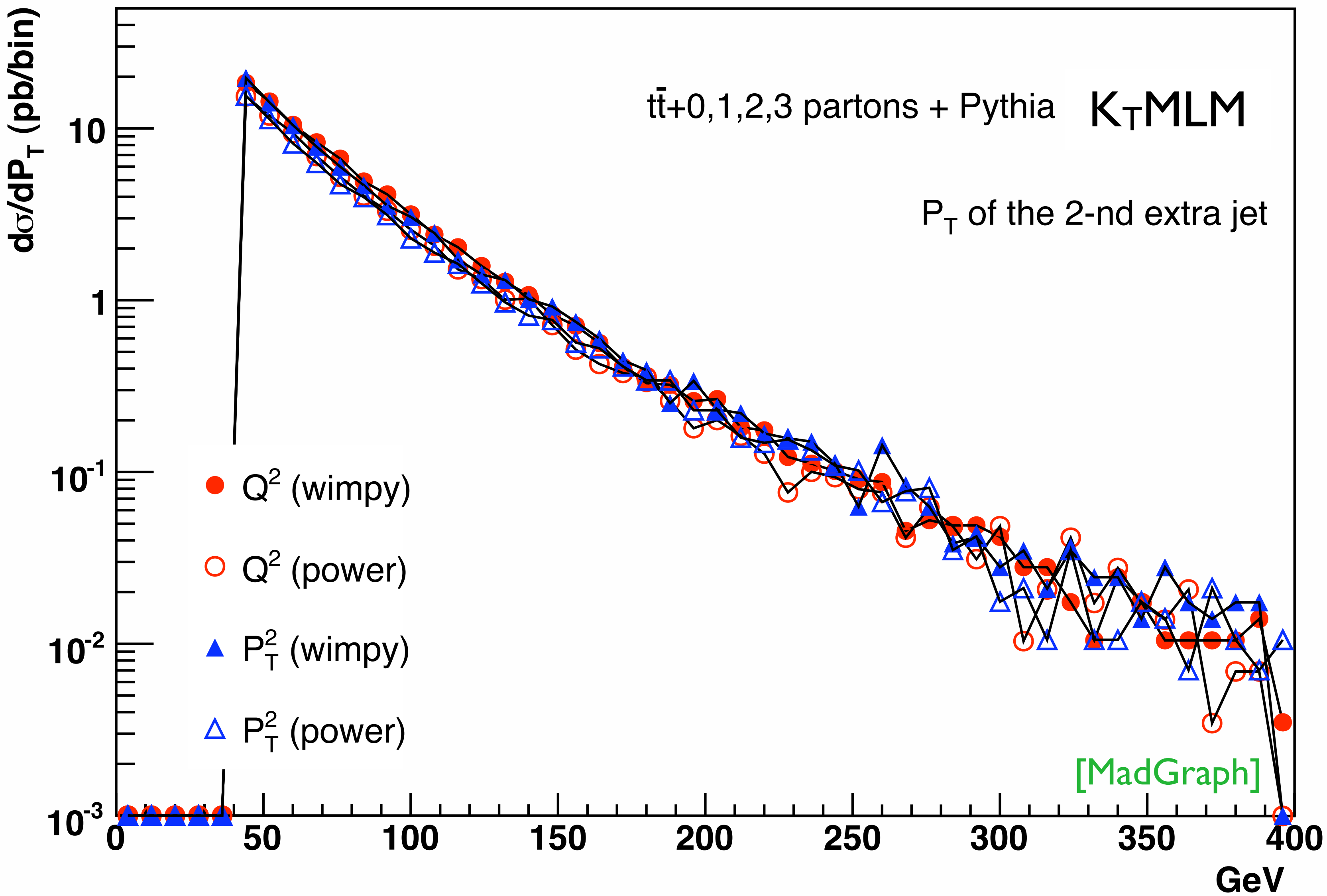
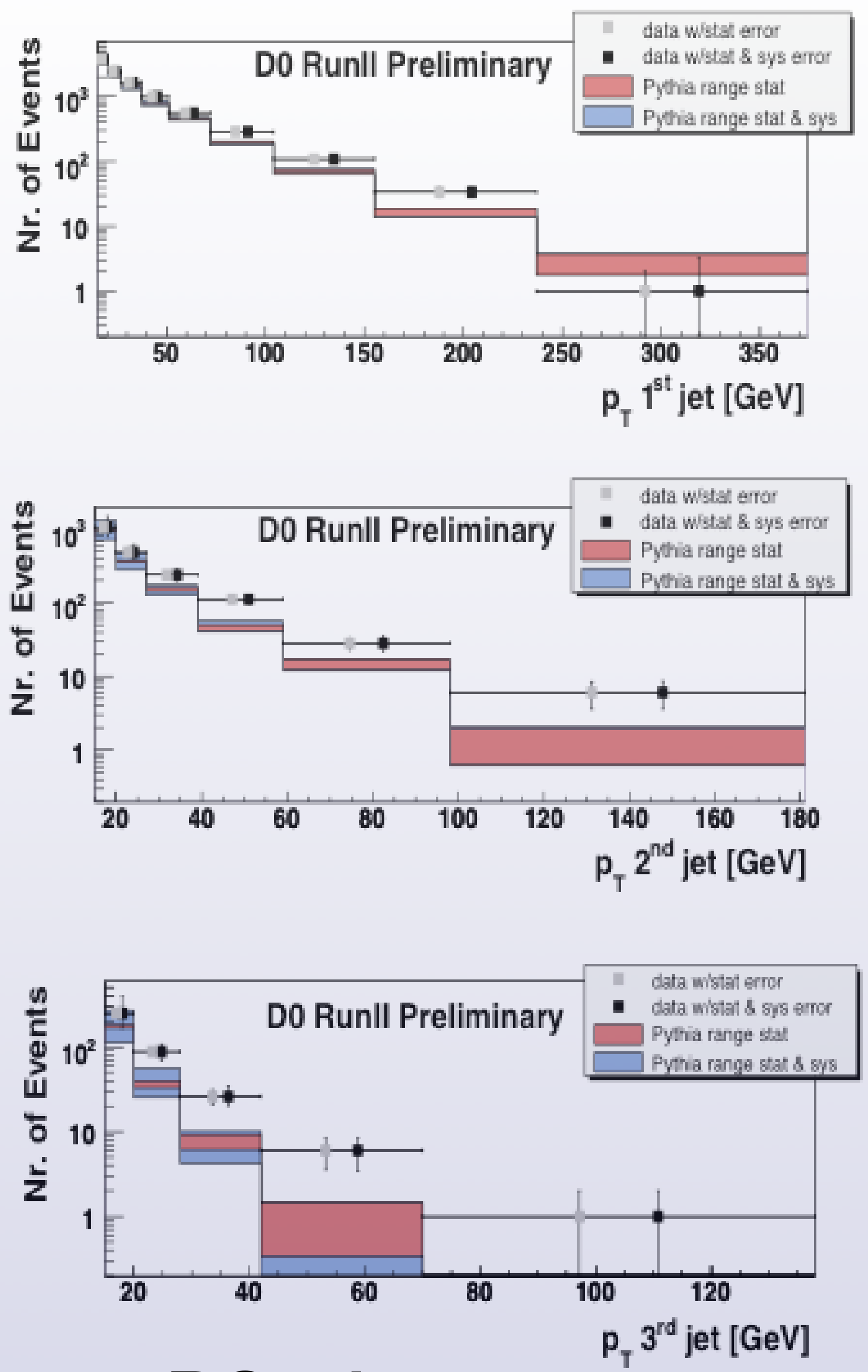
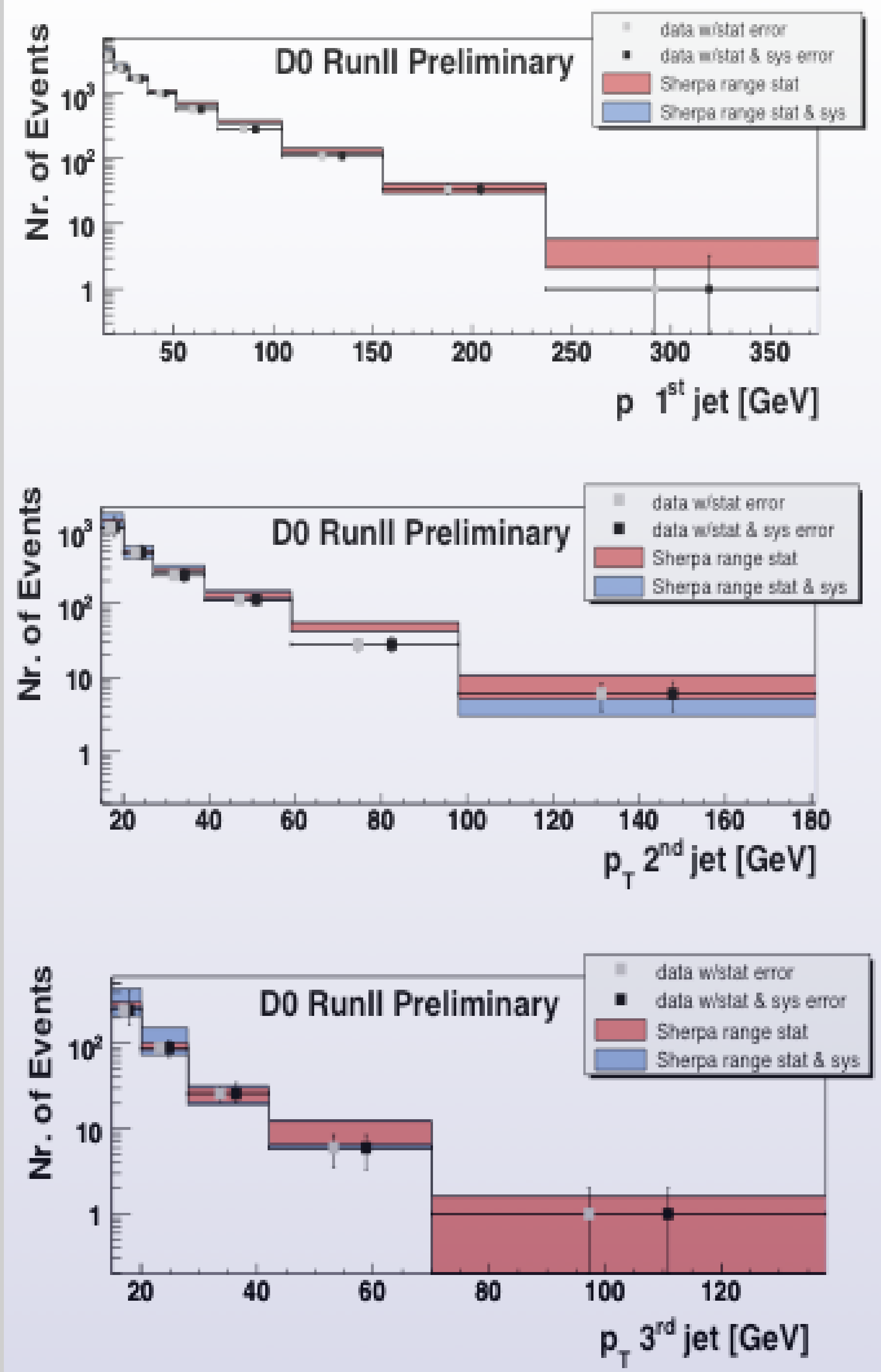


In a matched sample these differences are irrelevant since the behaviour at high pt is dominated by the matrix element. LO+LL is more reliable. (Matching uncertaintes not shown.)

PS alone vs matched samples : Z+jets at D0

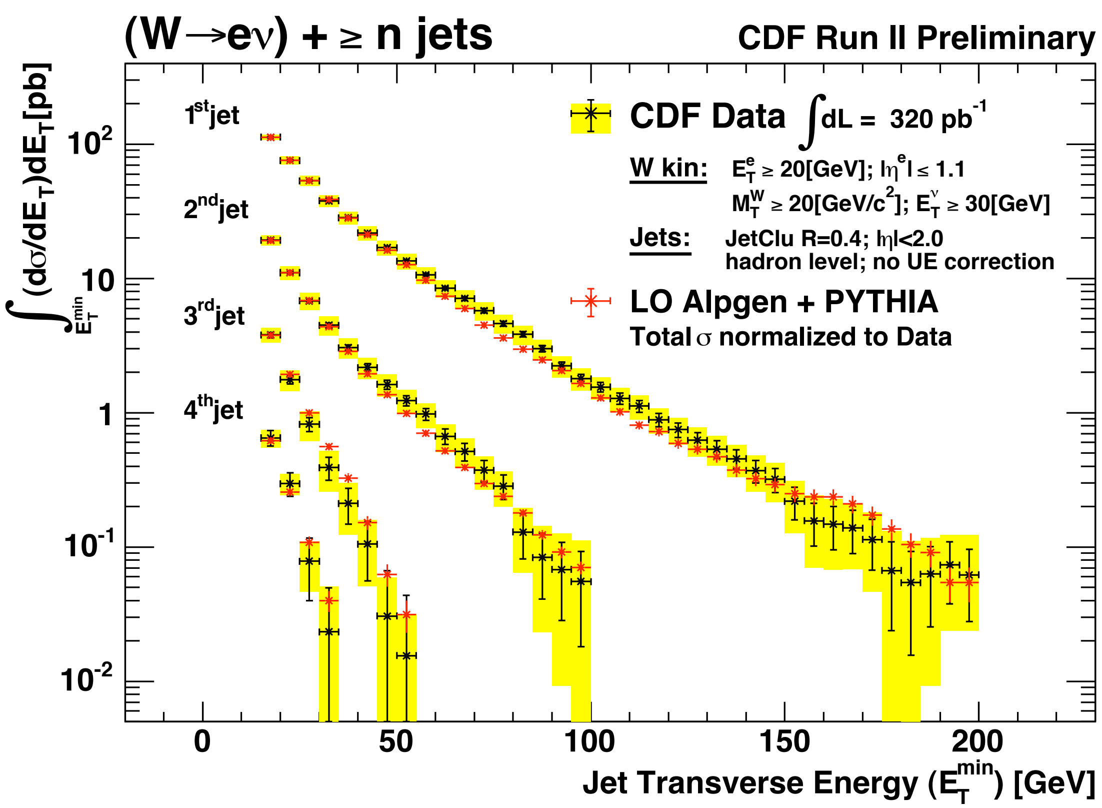


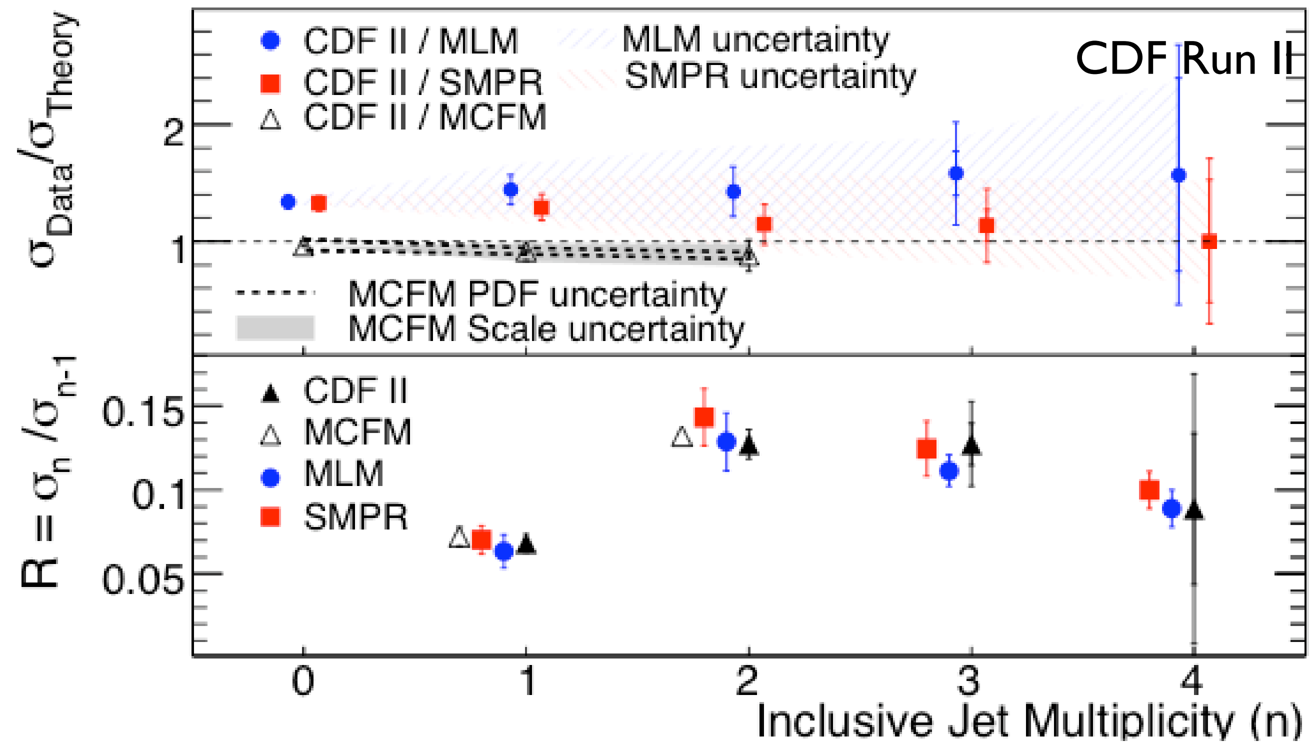
PS alone (Pythia)



ME+PS (SHERPA)

W+jets at CDF





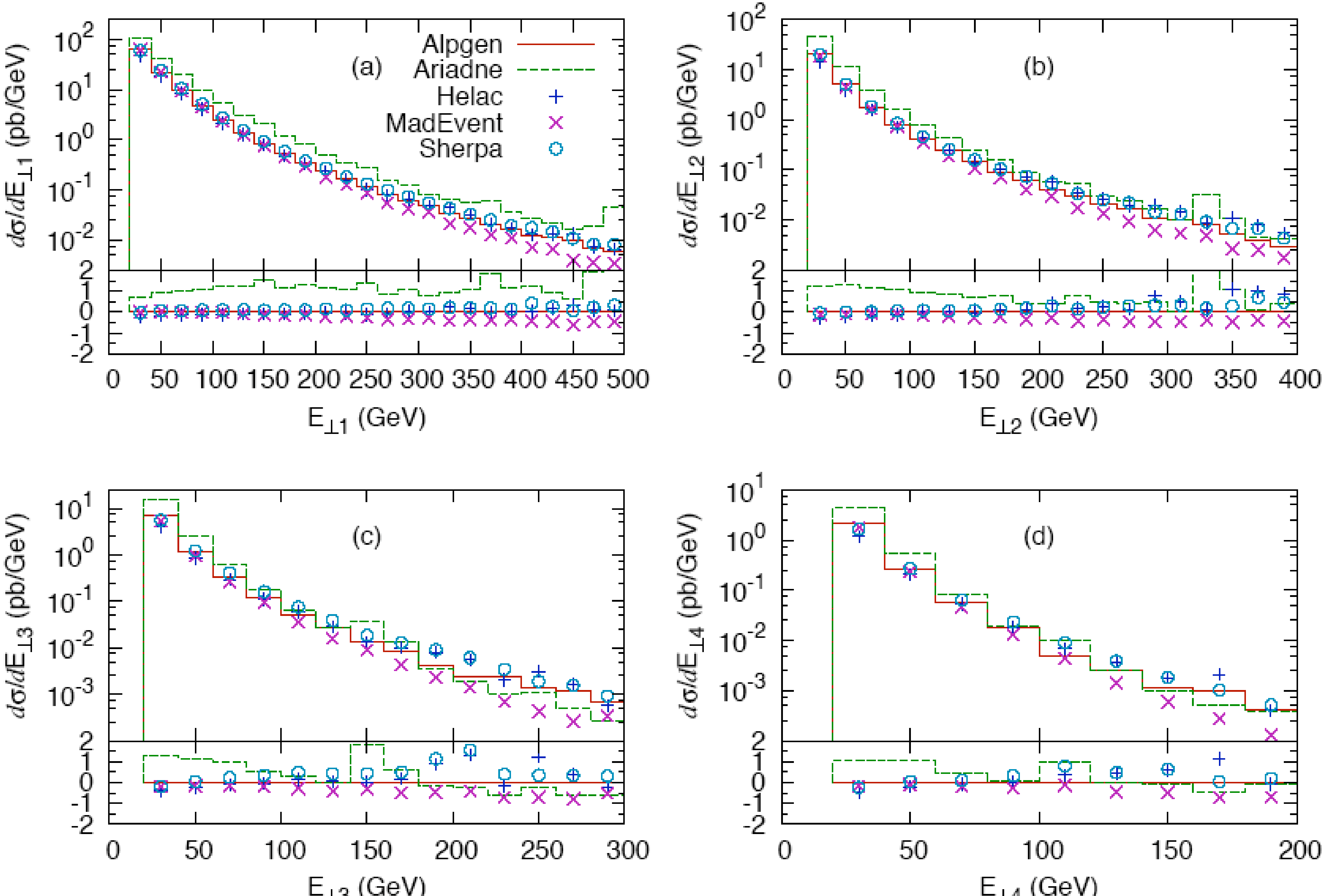
*Very good agreement in shapes (left) and in relative normalization (right).

* NLO rates in outstanding agreement with data.

* Matched samples obtained via different matching schemes (MLM and CKKW) consistent within the expected uncertaintes. Differences might arise in more exclusive quantities.

W+ jets @ LHC : MC comparison

[J. Alwall et al.,2007]

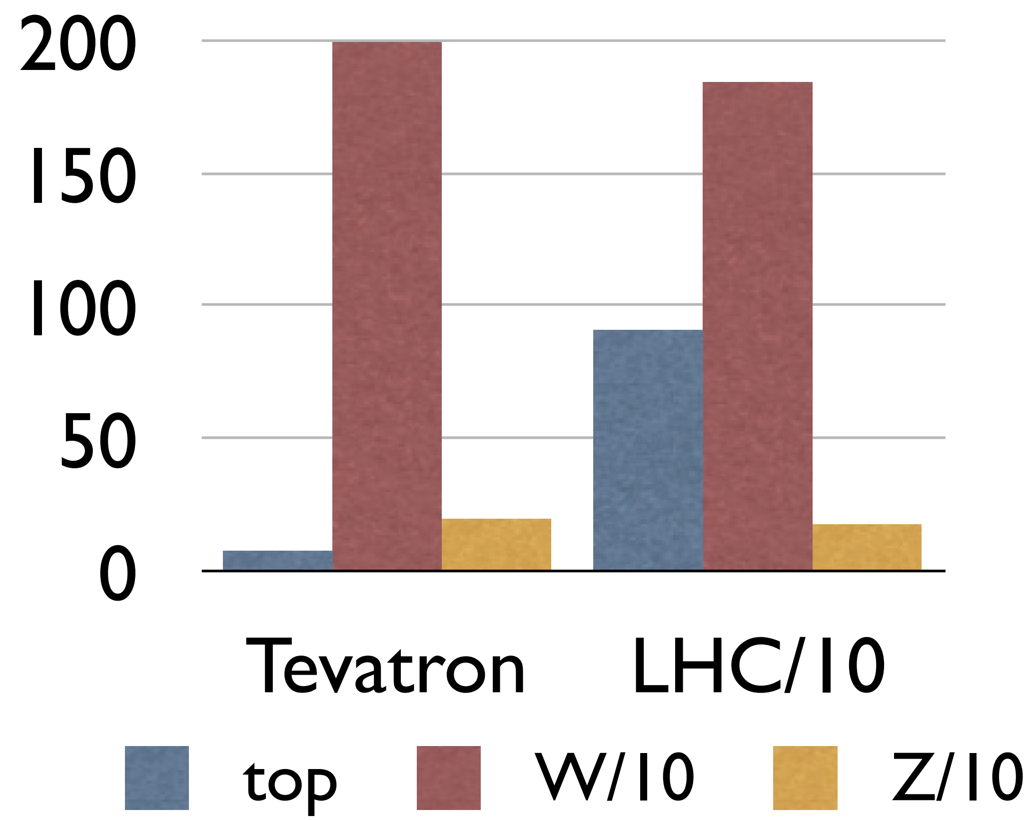


Cross sections : from Tevatron to the LHC

Total cross section for ttbar increases by a factor of 100, while Drell-Yan only by a factor of 10.

Top will be one of the major background to any new physics!

However, extra hard radiation is much easier at the LHC than at the Tevatron!



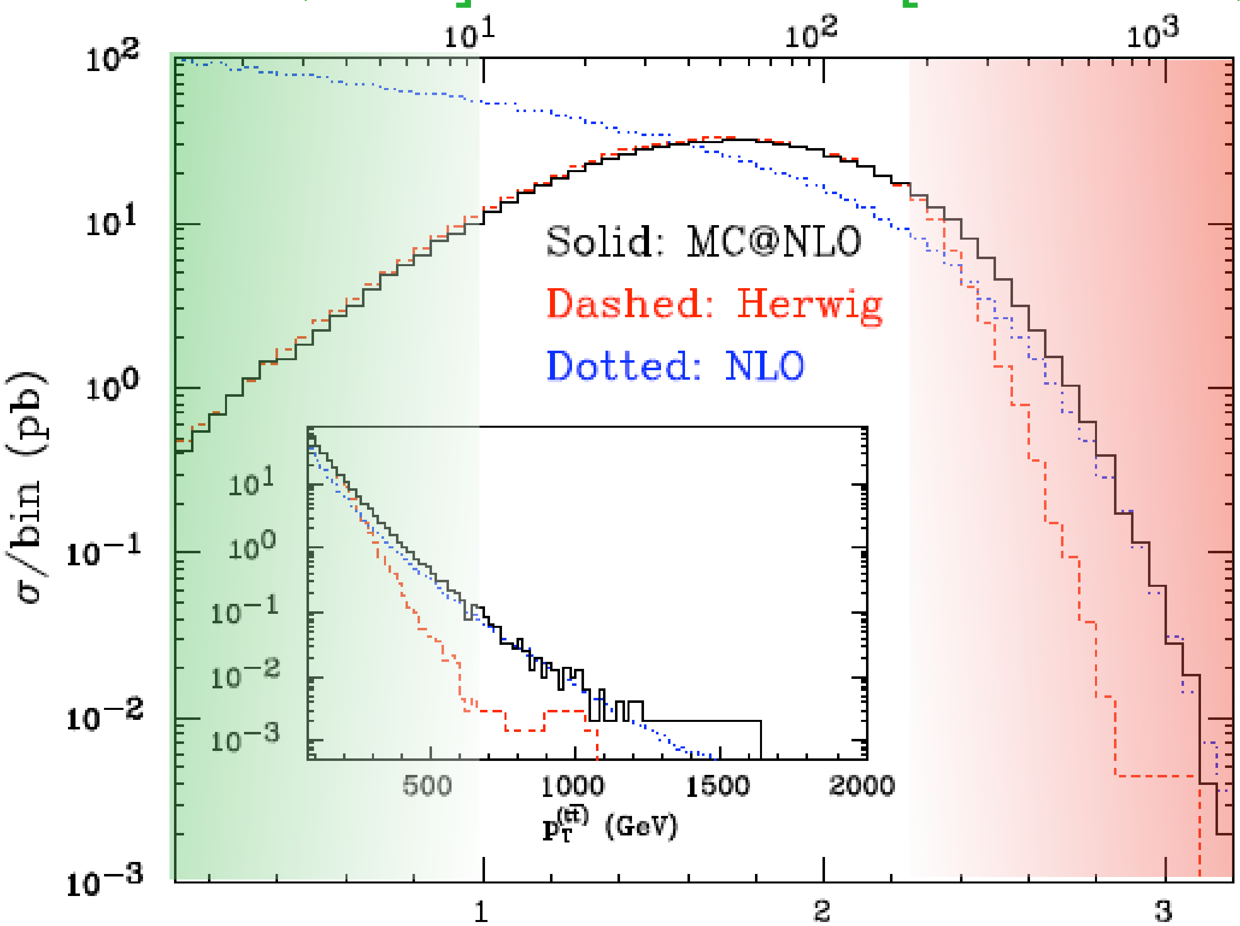
pb	tt	$W^{+-} \to e^{+-} \nu_e$ inclusive	$Z \to e^+ e^-$ inclusive	$W \to e^{+-} \nu_e$ + 4jets		$Z \to e^+ e^-$ + 4jets	
TeV	7.6	2000	200	0.98		0.096	
LHC	910	18500	1800	220	(20)	21	(2.1)
Gain	120	9	9	220	(21)	220	(22)

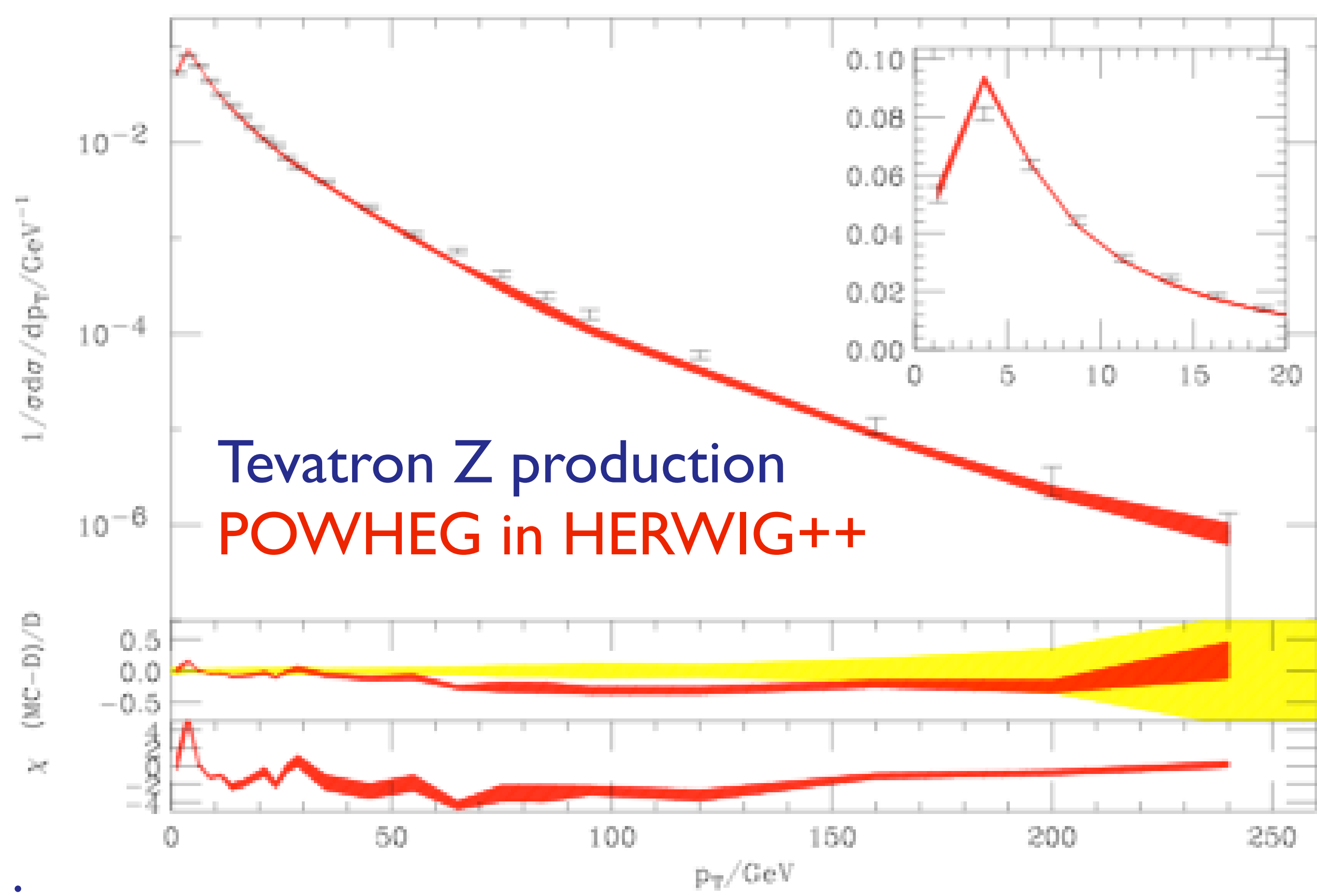
pt(j)>20 (50) GeV , |eta(j)|<3, DeltaR(jj)>0.7

NLOwPS

Problem of double counting becomes even more severe at NLO
* Real emission from NLO and PS has to be counted once
* Virtual contributions in the NLO and Sudakov should not overlap

Current available (and working) solutions: MC@NLO [Frixione, Webber, 2003; Frixione, Nason, Webber, 2003] and POWHEG [Nason 2004; Frixione, Nason, Oleari, 2007]





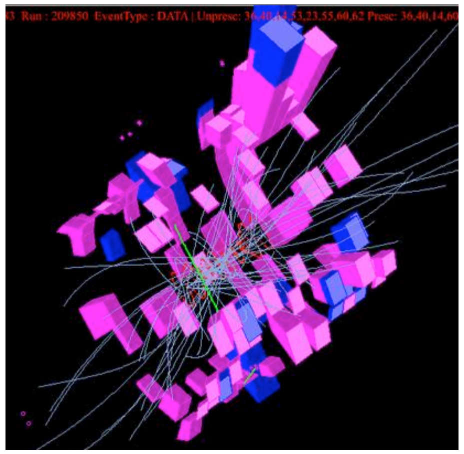
* Soft/Collinear resummation of the $p_T(tt) \to 0$ region.
* At high $p_T(tt)$ it approaches the tt+parton (tree-level) result.
* Normalization is FIXED and non trivial!!

[Hamilton, Richardson, Tully, 2008; Alioli, Nason, Oleari, Re, 2008]

Outlook

$$\mathcal{L}_{QCD} = -\frac{1}{4}\mathcal{F}_a{}^{\mu\nu}\mathcal{F}^a{}_{\mu\nu} + \bar{\psi}_j(i\gamma^\mu D_\mu - m)^j{}_i\psi^i$$

→ Feynman rules → matrix element → phase space integration → cross-section & parton-level events → showering & merging → UE, hadronization & decays → detector simulation →



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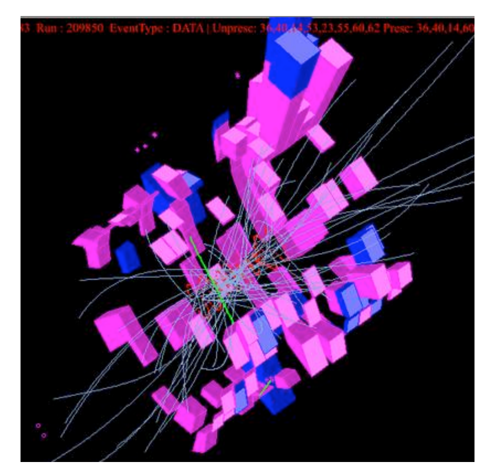
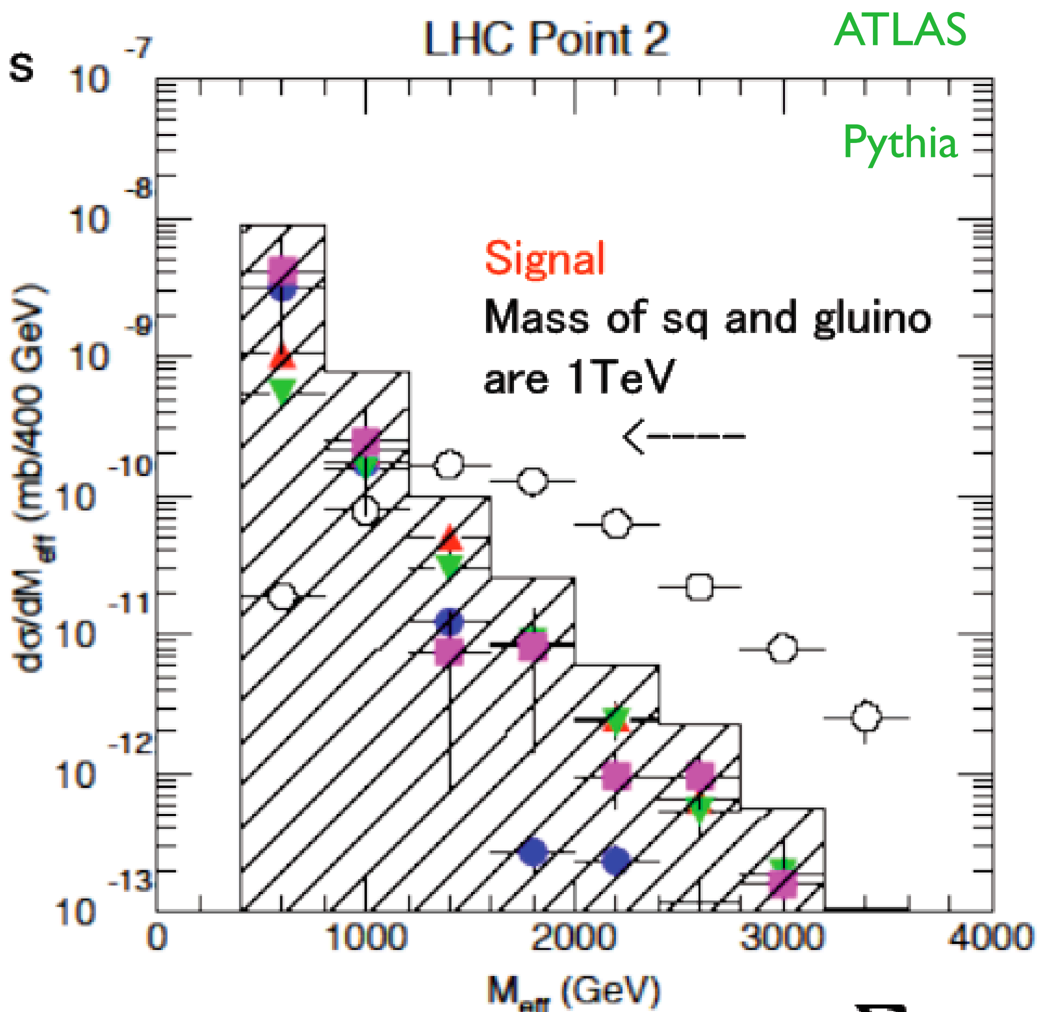
Complete automatization for tree-level based calculations available, including merging with the parton shower in multi-jet final states, for SM as well as for BSM physics.

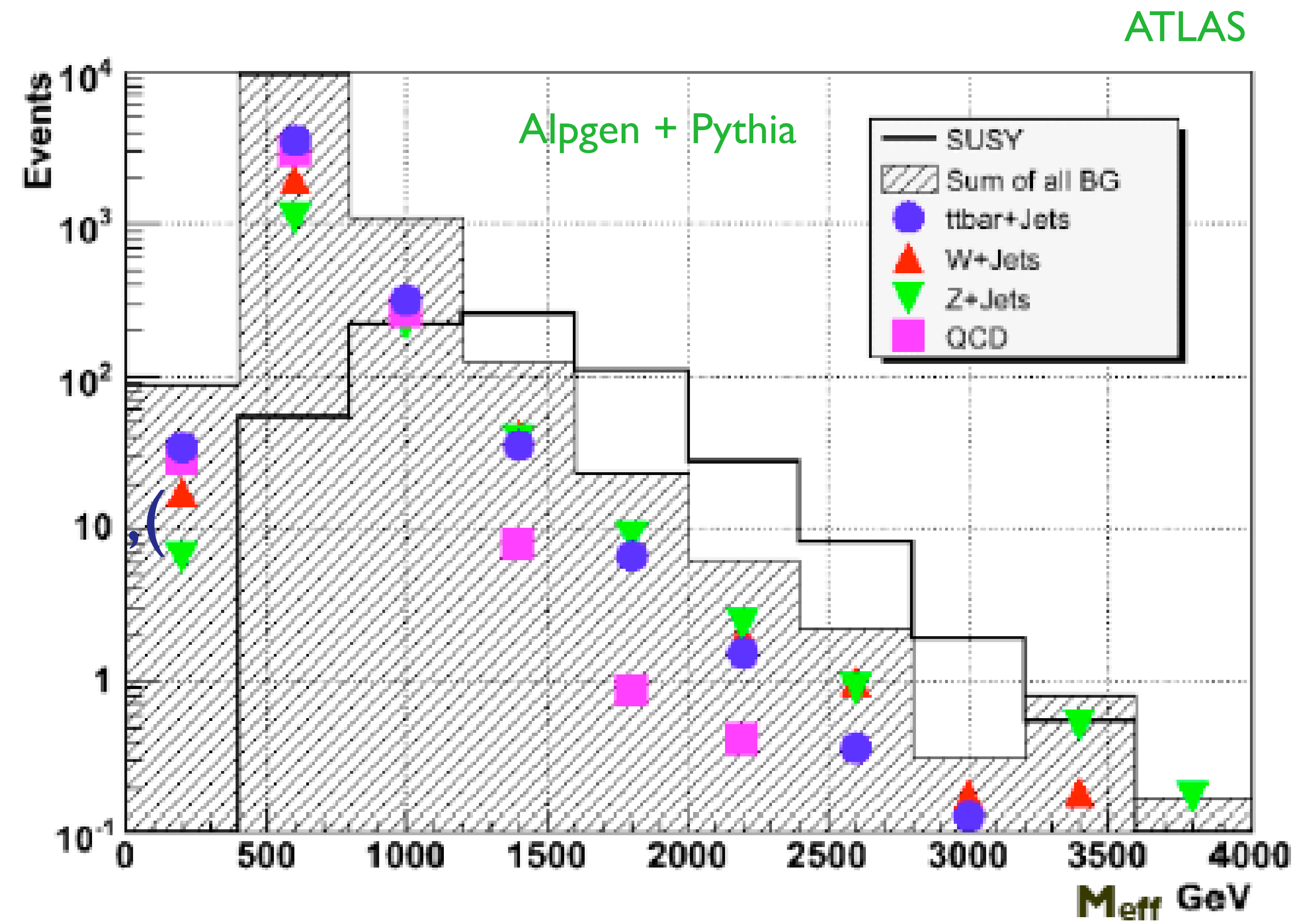
Automatization for pure NLO calculations not available yet [see G. Zanderighi's talk] but in sight now. General framework for merging with the shower available in principle.



BSM @ LHC : past and present



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



Signal: SUSY inclusive. Background: t tbar+jets,(Z,W)+jets, QCD jets.

With more realistic simulations life's harder! MC's help in indentifying and understanding the possible sources of backgrounds and eventually model the data better. Need for validation, control samples and robust extrapolations.

Conclusions

- The need for better description and more reliable predictions for SM processes for the LHC has motivated a significant increase of theoretical and phenomenological activity in the last years, leading to several important achievements.
- A new generation of tools and techniques has been developed. Among the most useful is the matching between fixed-order and parton-shower both at tree-level (Matrix element + PS) and NLO (MC@NLO and POWHEG).
- Shift in paradigm: useful TH predictions in the form of tools that can be used by EXP's. Communication and collaboration between THs & EXPs easier $\Rightarrow$ emergence of an integrated LHC community.

Credits

Thanks:

to all the MC interested community
for continuous, lively and fruitful collaborations.

References:

M.L. Mangano, arxiv:0802.0026