Monte Carlo Tools for Quarkonium

Part I

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Outline

Outline

- Progress on MC tools for the LHC

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- Progress on MC tools for the LHC
- Status of MC's for quarkonium

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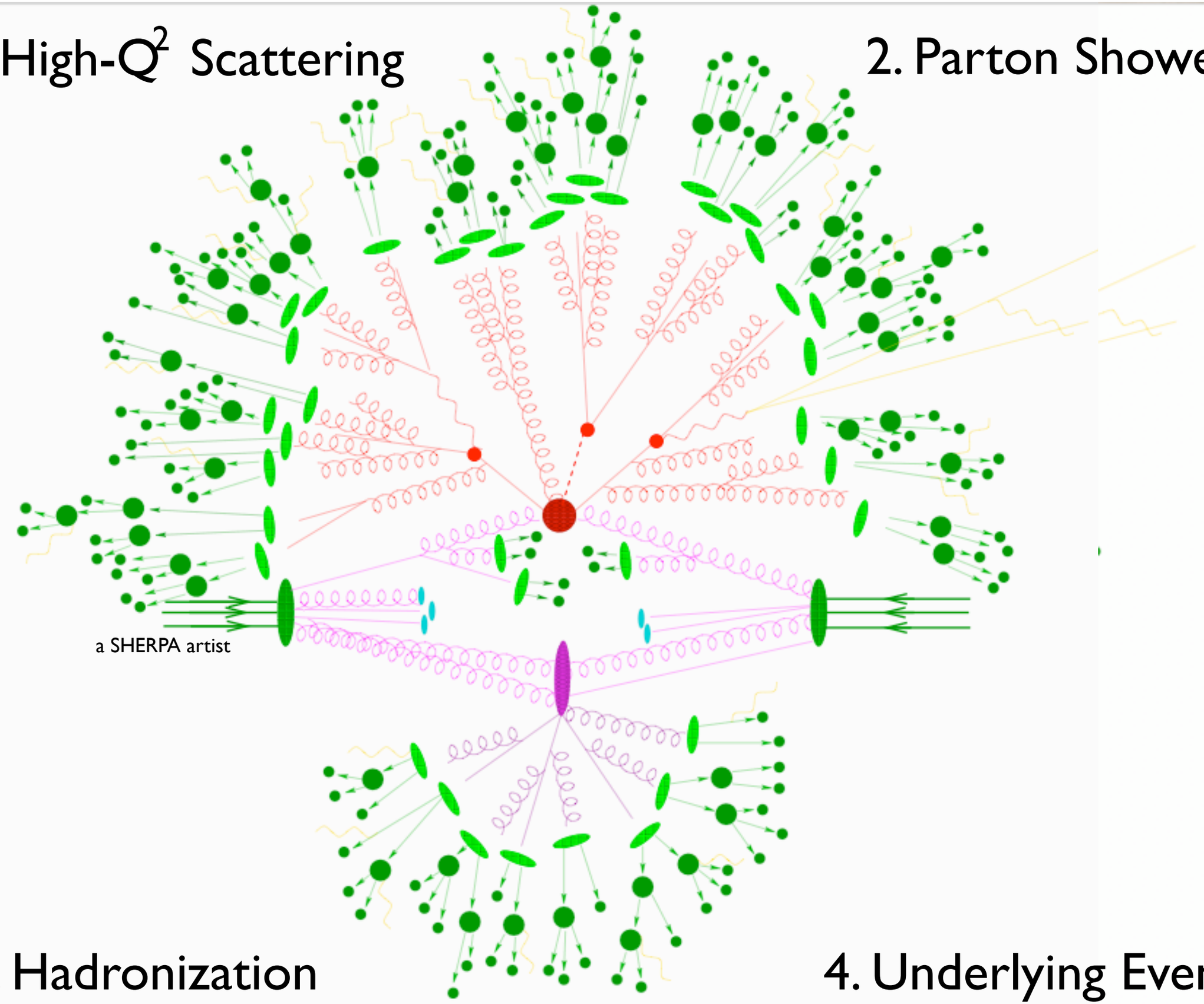
- Progress on MC tools for the LHC
- Status of MC's for quarkonium
- Outlook

1. High-Q^2 Scattering

2. Parton Shower

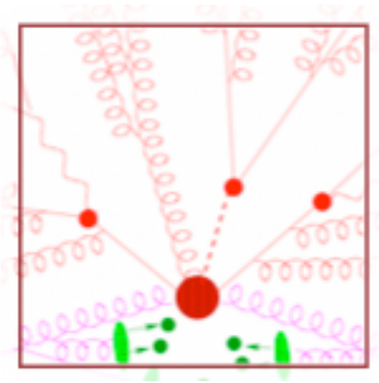


a SHERPA artist

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...)

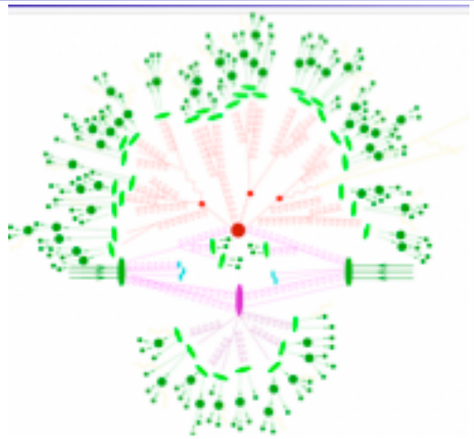
$$\Rightarrow \hat{\sigma}_{ab\to X} = \sigma_0 + \alpha_S \sigma_1 + \alpha_S^2 \sigma_2 + \dots$$

- 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 ⇒ cannot be directly employed in experimental studies

How experimentalists (used to) describe the data?



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 $2 \to 1$ or $2 \to 2$ procs, using a parton shower, and then an hadronization model

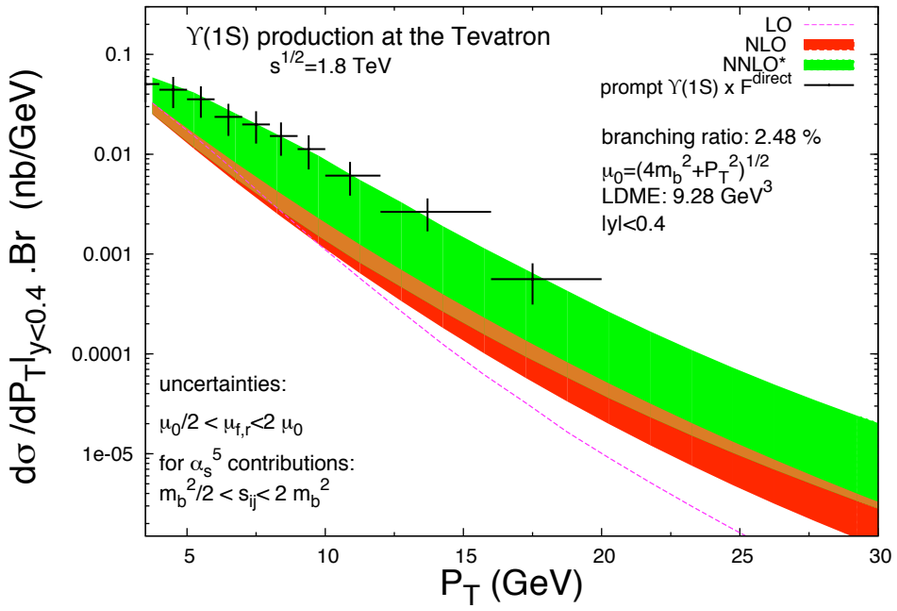
Comments:

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

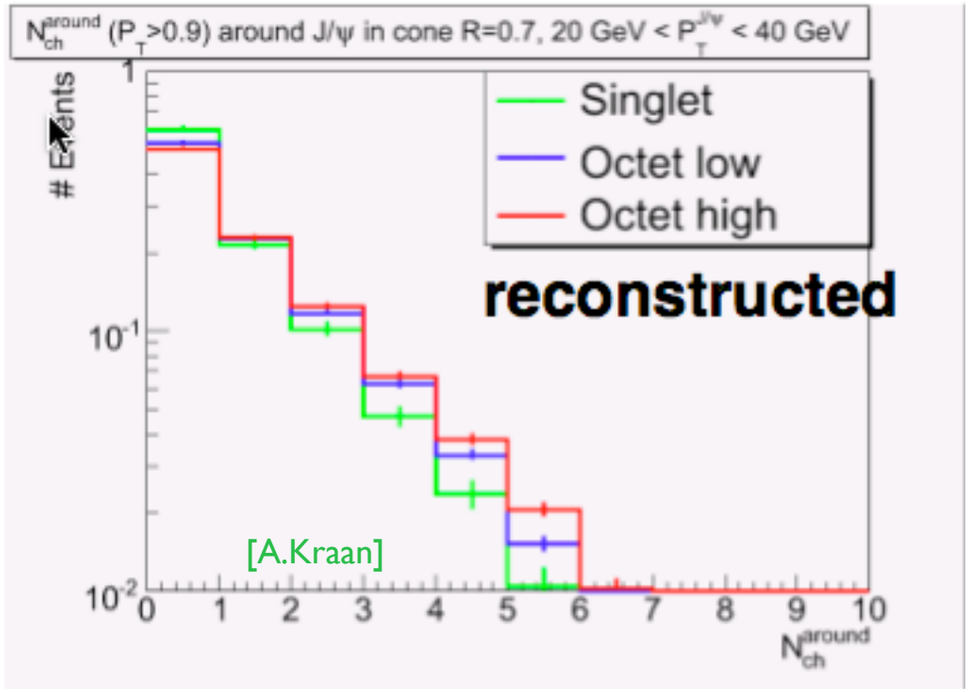
Two main types of tools

"Predictor"



Examples: MCFM, ALL current NLO codes

"Event Generator"



- Fully exclusive description
- In general not the TH predictions but tunable [descriptive]
- Results in terms of events

Examples: Pythia, MadOnia+Pythia,...

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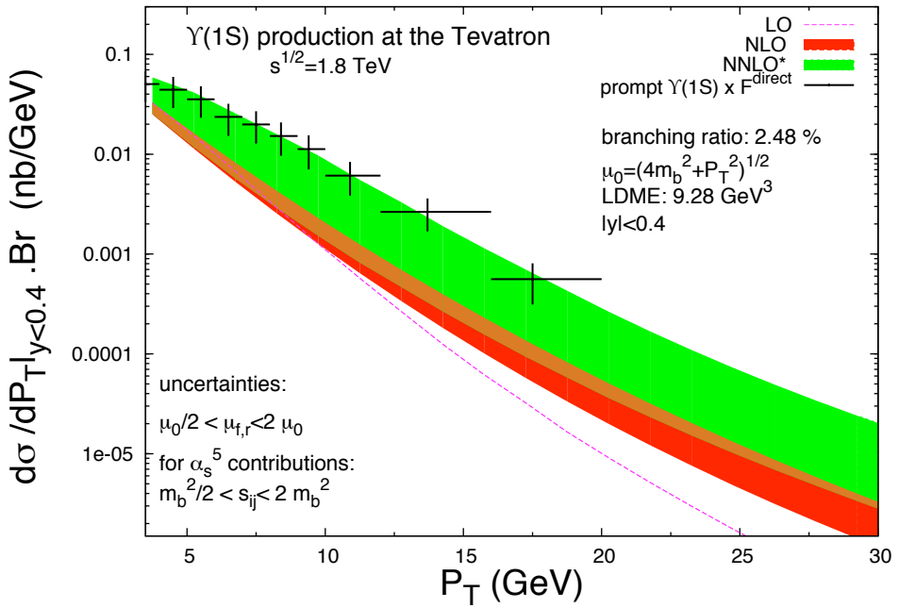

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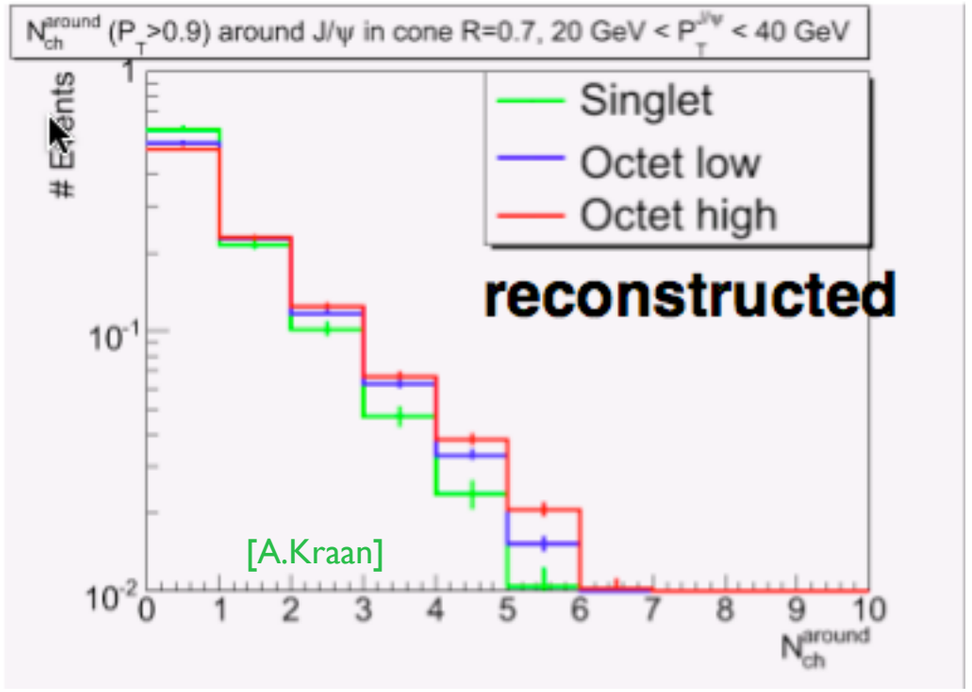

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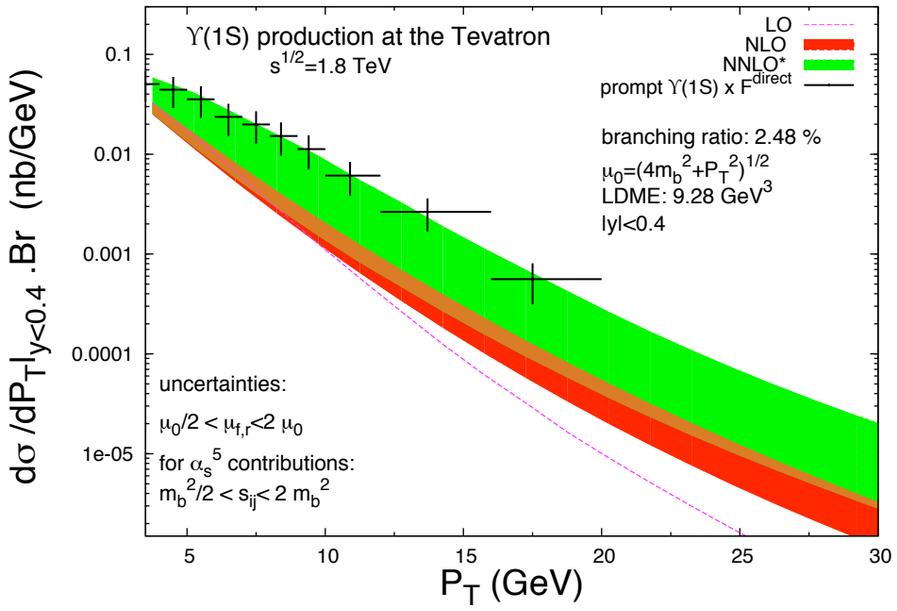

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- Represent the "BEST" th predicitons

Examples: MCFM, ALL current NLO codes

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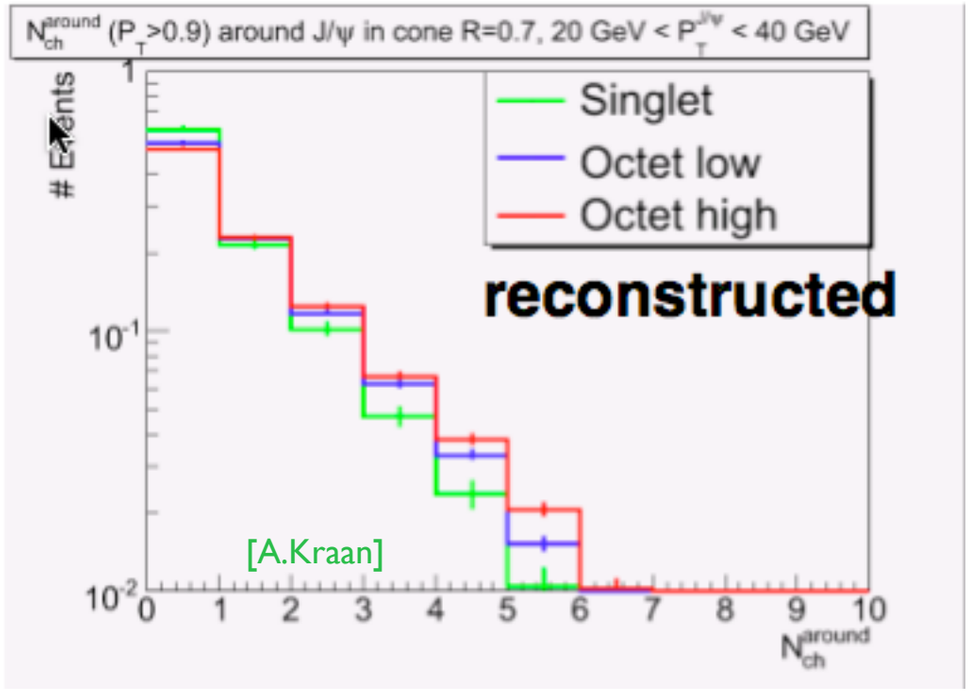

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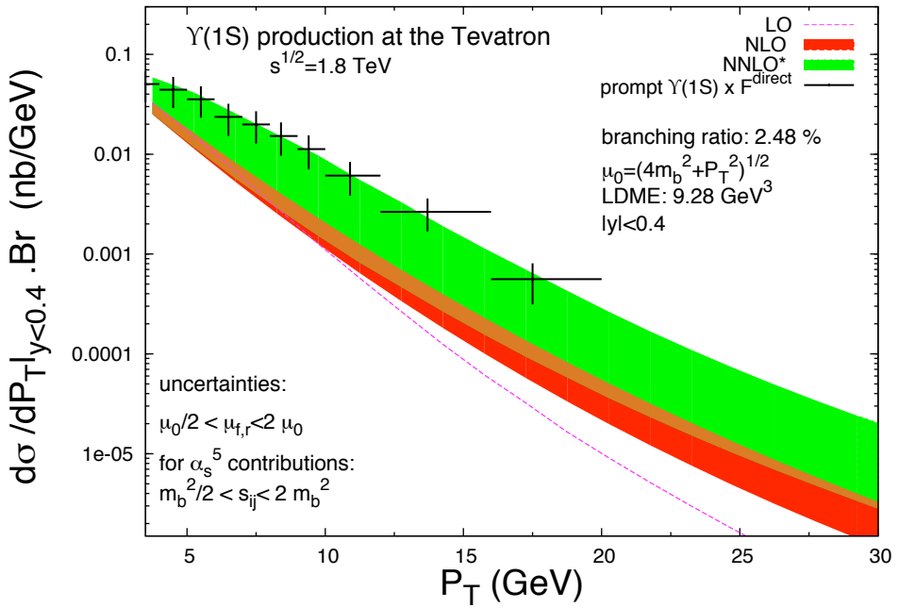
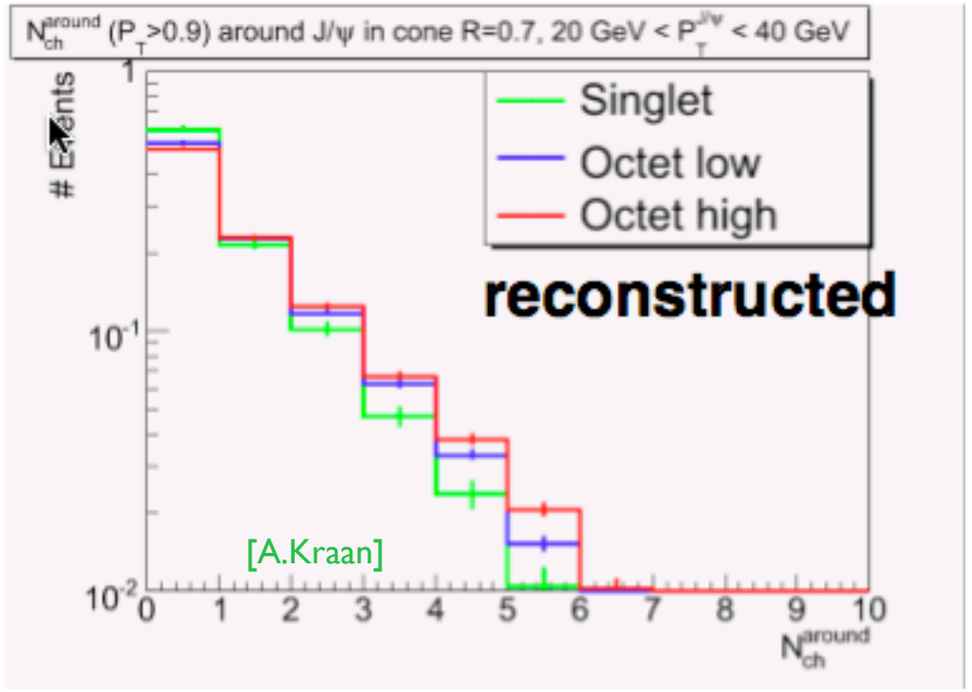


- "Theory" tools that can provide predictions for (more or less) inclusive observables.
- Represent the "BEST" th predicitons
- Results are given in terms of histograms

Examples: MCFM, ALL current NLO codes

"Event Generator"



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- In general not the TH predictions but tunable [descriptive]
- Results in terms of events

Examples: Pythia, MadOnia+Pythia,...

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

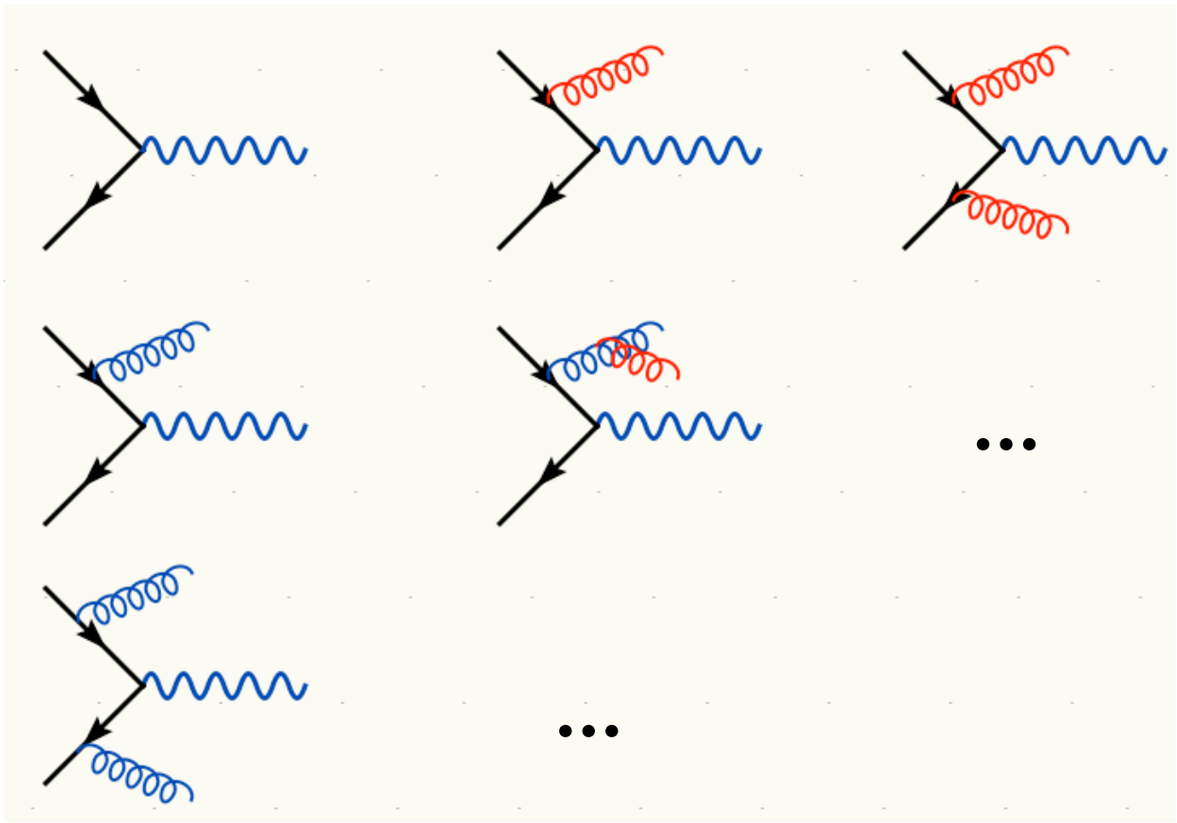
2. NLO with Parton Shower
Get fully exclusive description of events correct at NLO in the normalization and distributions. — NLOwPS

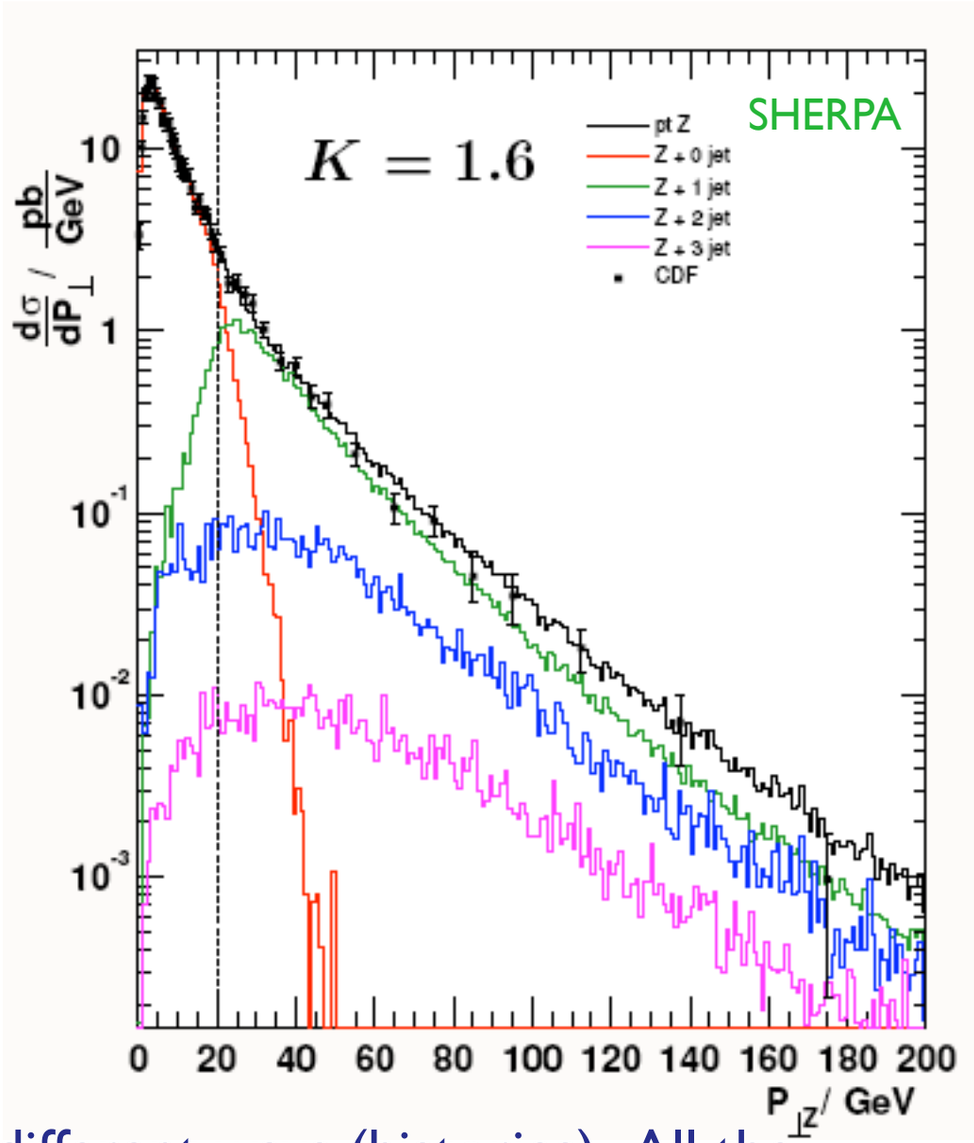
Merging fixed order with PS

[Mangano, 2003]
[Catani, Krauss, Kuhn, Webber,2003]

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 leading order.

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]
- Matches NLO to HERWIG angular-ordered PS.
- "Some" work to interface an NLO calculation to HERWIG.
  Uses only FKS subtraction scheme.
- Some events have negative weights.
- Sizable library of procs now.

POWHEG [Nason 2004; Frixione, Nason, Oleari, 2007]
- Is independent from the PS. It can be interfaced to PYTHIA or HERWIG.
- Can use existing NLO results.
- Generates only positive unit weights.

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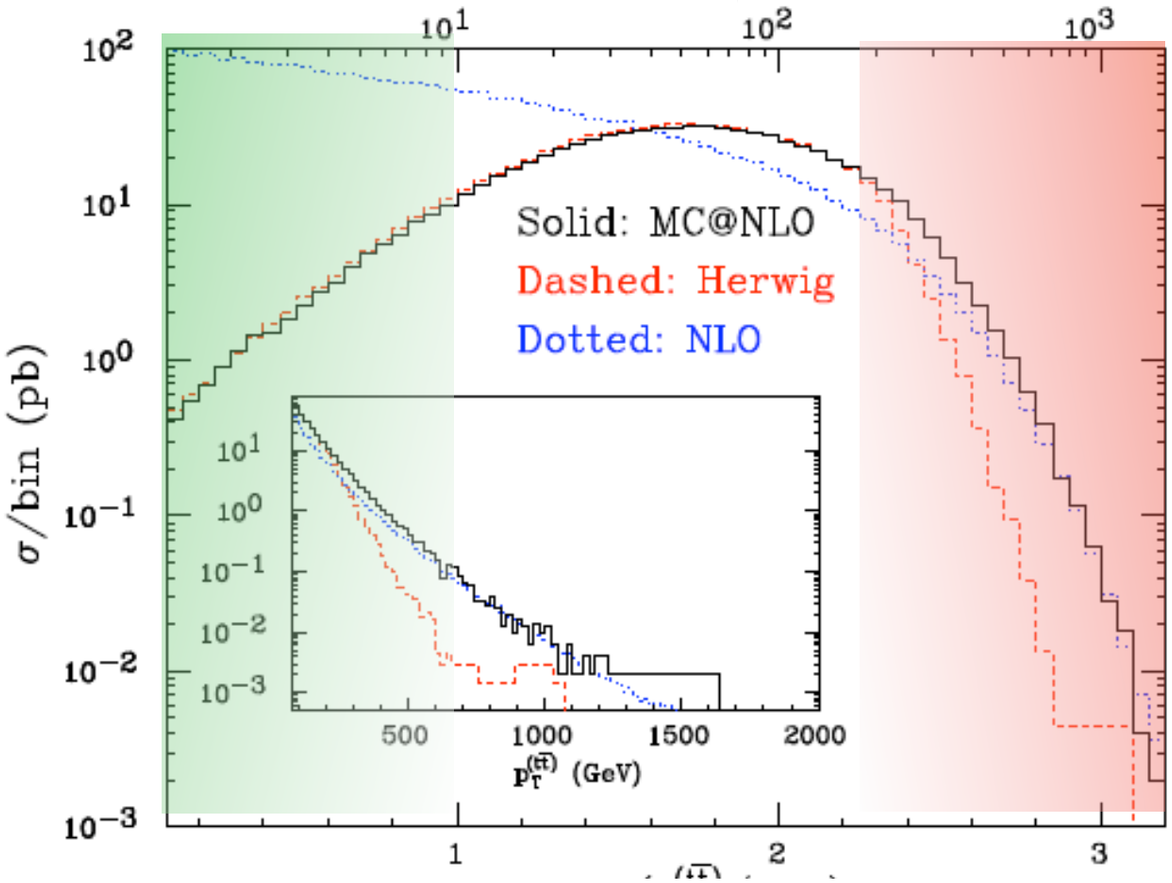
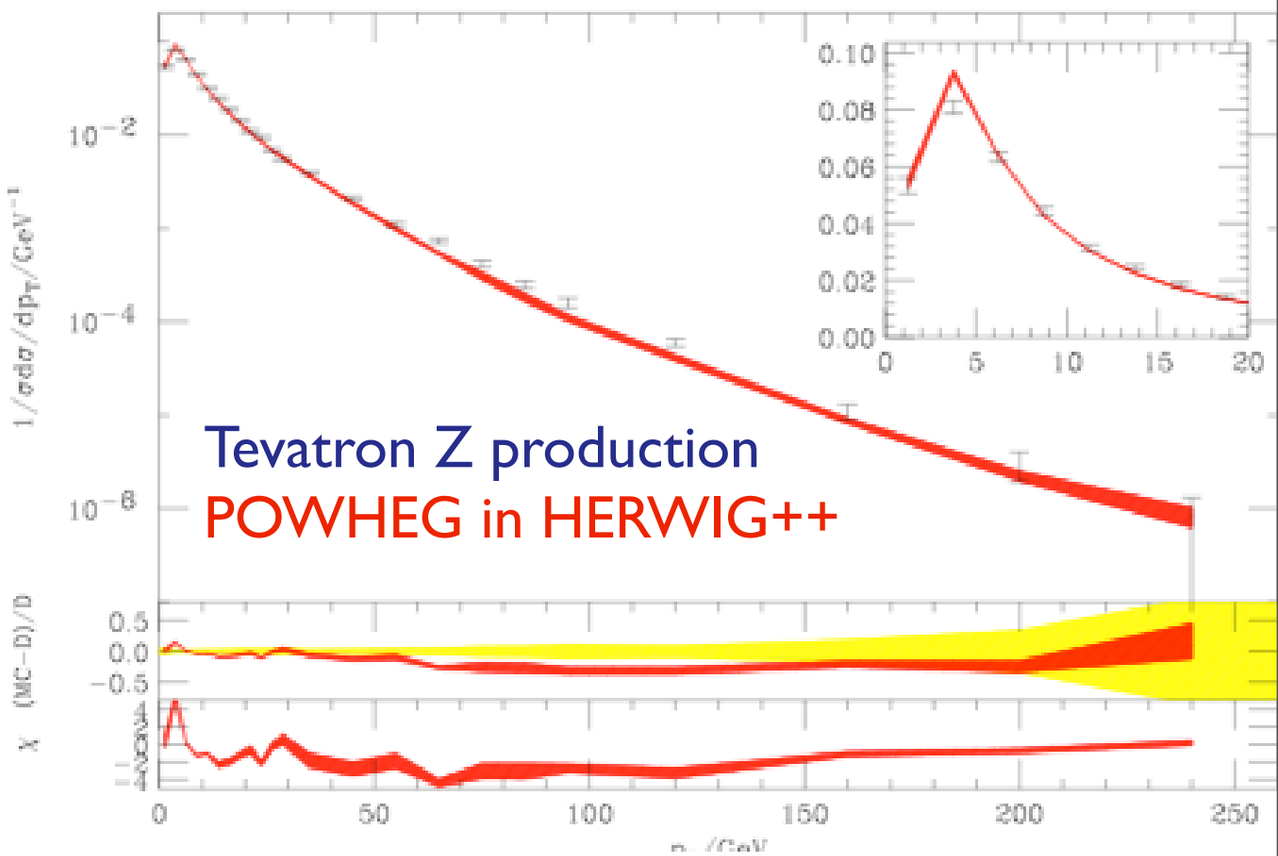




* Soft/Collinear resummation of the $p_T(t\bar{t}) \to 0$ region.

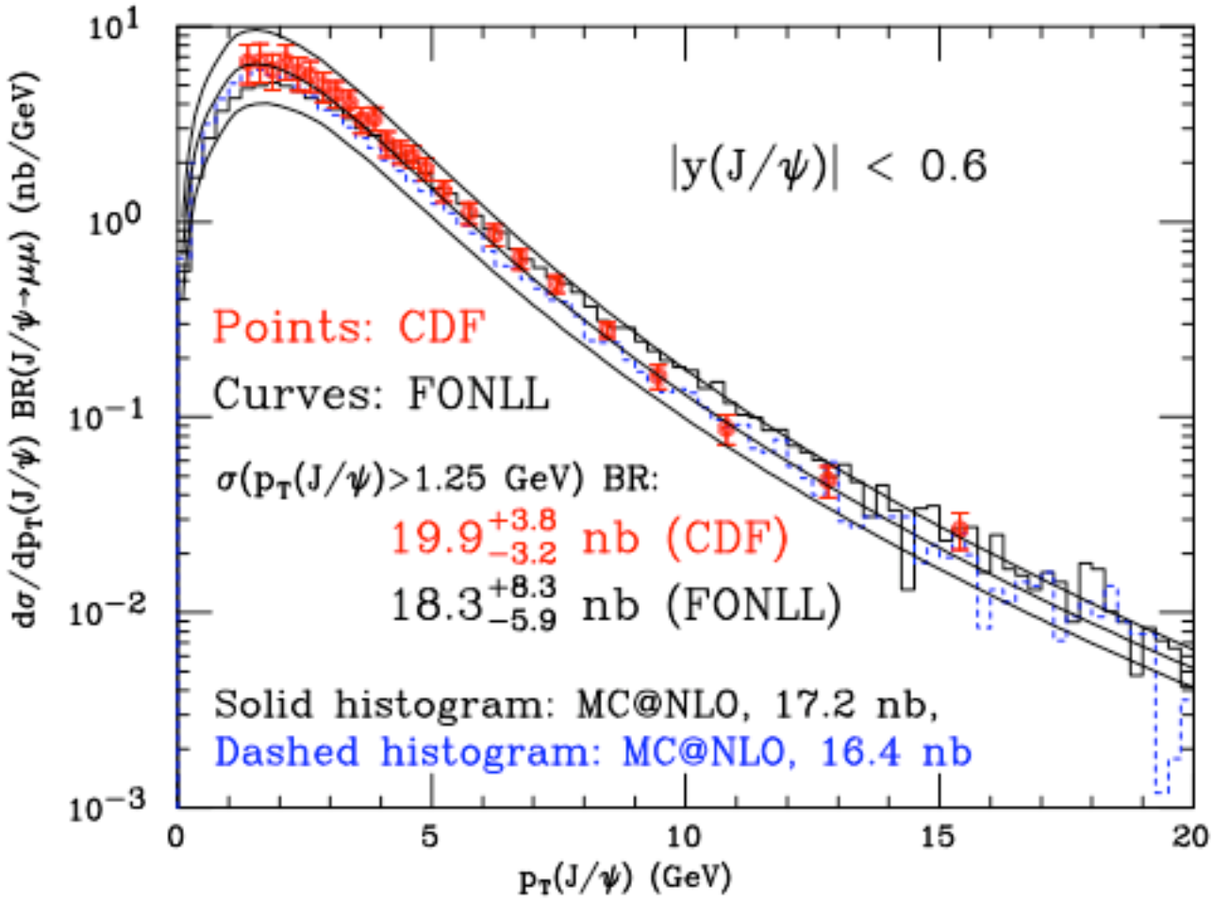
* At high $p_T(t\bar{t})$ it approaches the $t\bar{t}$+parton (tree-level) result.

* Normalization is FIXED and non trivial!!

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

The best of all (MC) worlds...

[Cacciari, Frixione, Mangano,Nason, Ridolfi]



J/psi production from B decays just shown by Pierre.

Best theoretical prediction is also available as a Event Generator code:

FONLL ⇔ MC@NLO

Exploits EXP information on energy spectrum of the J/psi as measured by B factories!

Descriptive & predictive

So where do we stand with quarkonium?

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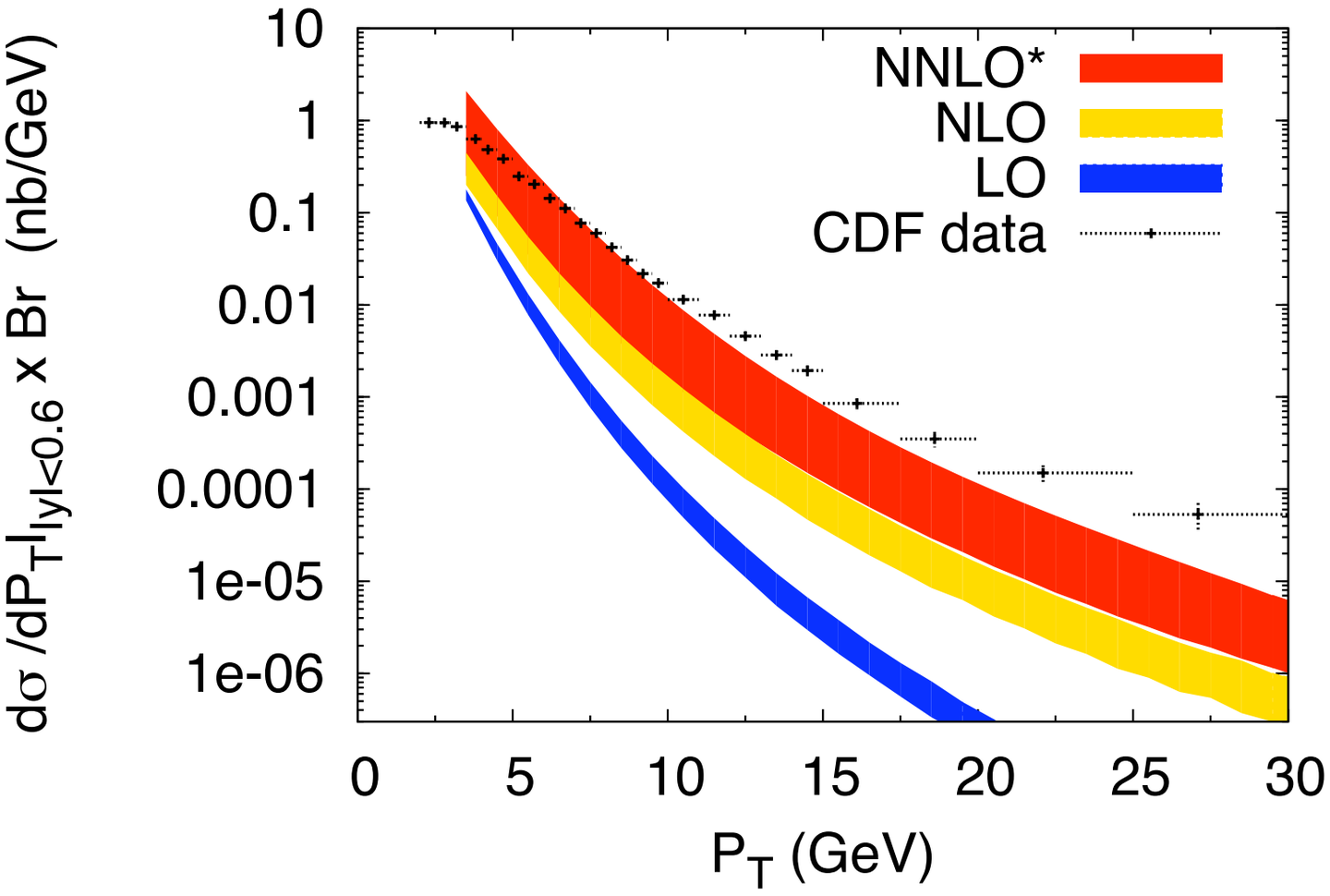
Well, not quite! The main reason is that we cannot yet claim that we understand all aspects of quarkonium production. However, we have made some progress....

Status for Predictors



Inclusive quarkonium production in NRQCD is available up to NLO in MCFM. However, this is not sufficient...

Other codes exist, none of which is public though.

Results within different approaches (K_T , for example) are available in the literature, but not in the form of codes...

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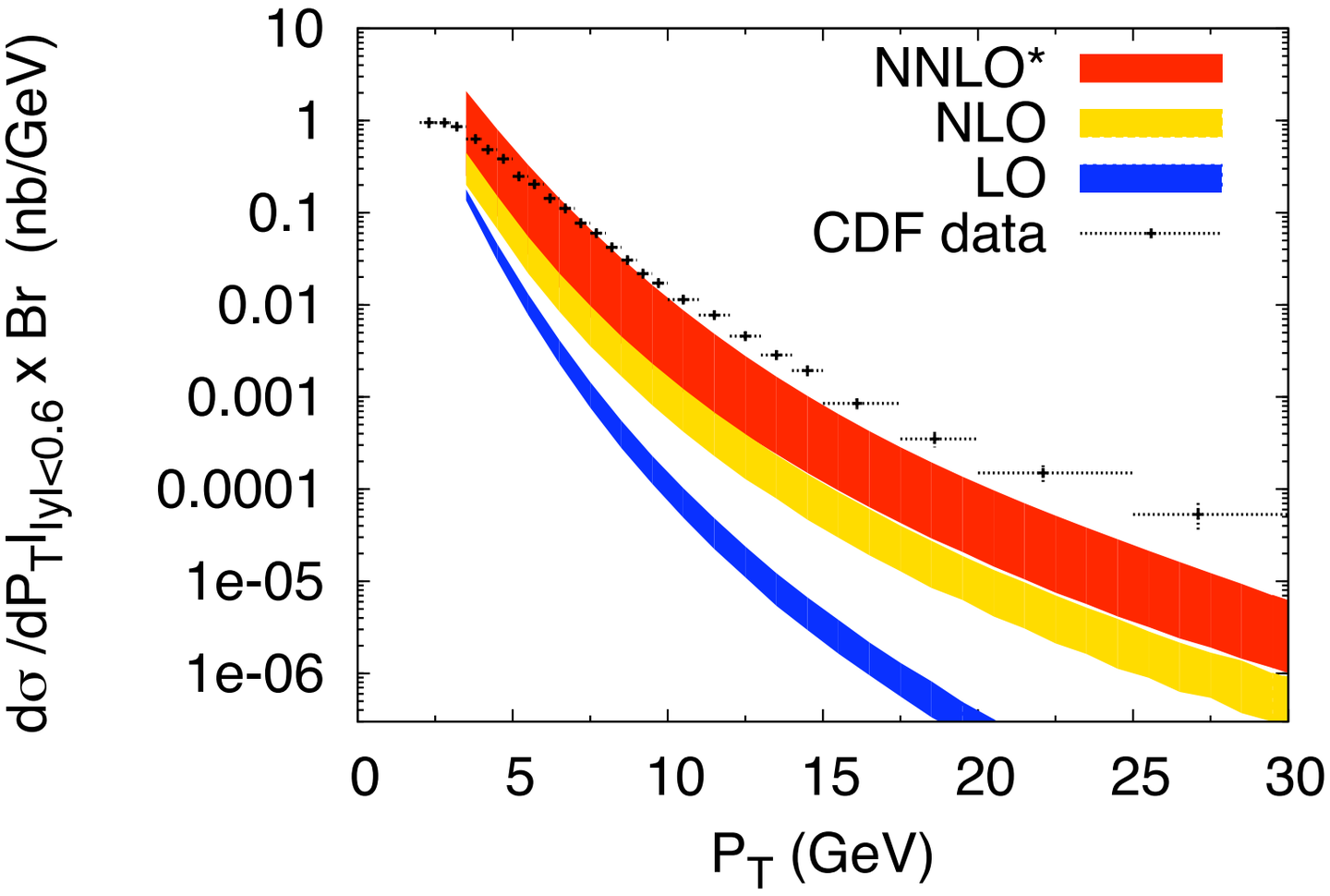

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Room for improvement !
Ex: code repository in QWG?

Event Generators

- The main tool is Pythia [see Aafke's presentation]
- Several 2→2 amplitudes implemented for both singlet and octet
- List of processes extendable through the LHEF interface to external matrix element generators*

*Working properly for singlets. Little work to be done for octets.

MadOnia

[P. Artoisent, F.M., T. Stelzer]

- Multipurpose matrix element generator for NRQCD amplitudes at tree-level.
- Based and integrated in MadGraph/MadEvent, available from the web.
- Works in three steps:

1. Generate the code for the requested process on the fly.
2. Run the code to calculate the cross section, distributions and unweighted parton-level events.
3. Pass the events to Pythia via the LHEF interface for showering and hadronization.

MadOnia

Example:

```
"
# Begin PROCESS # This is TAG. Do not modify this line

pp>jjbb~[3S11]*      # Y 3S1 singlet
QCD=99               # Max QCD couplings
end_coup             # End the couplings input

pp>bc~cb~[1S01]       # B_c 1S0 singlet
QCD=99               # Max QCD couplings
end_coup             # End the couplings input

done                 # this tells MG there are no more procs

# End PROCESS  # This is TAG. Do not modify this line
```

As manifest from the syntax Madonia starts from the amplitudes for open heavy quark production and then applies the desired NRQCD spin and color projections to obtain a given $^{2S+1}L_J$ [1,8] state.

NB: Polarization information encoded in the l+l- angular distributions for 3S1[1] states.

* input syntax slighly changed in the last version. Please check the manual for details http://cp3wks05.fynu.ucl.ac.be/twiki/bin/view/Main/IntroQuarkonium.

Example 1: testing new ideas

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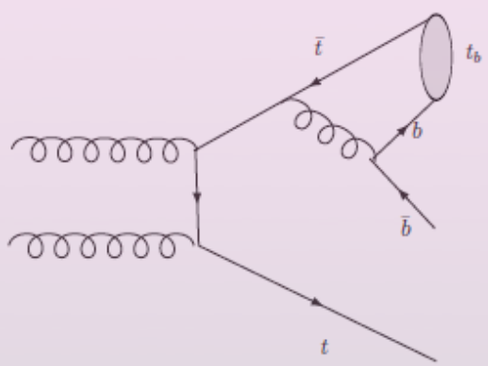
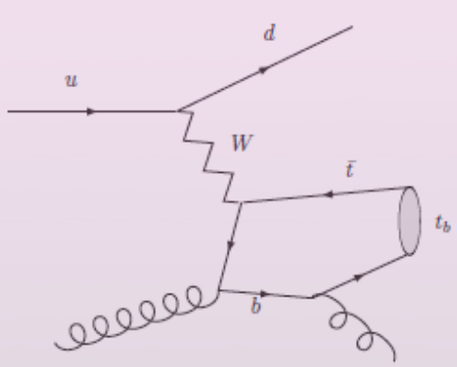
σ(Tb) meson at the LHC

$$V_{tb} = 0.3, \quad |R_{tb}|^2 = 8.13\,\text{GeV}^3$$



$\sigma = 9.95$ fb



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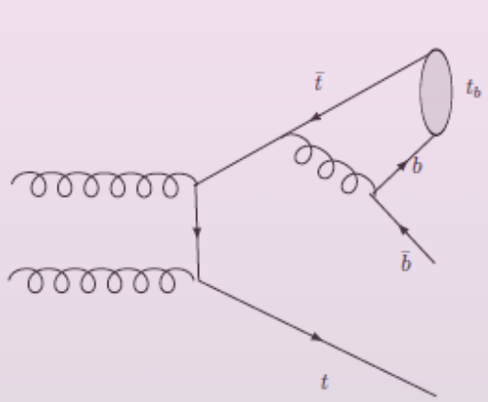

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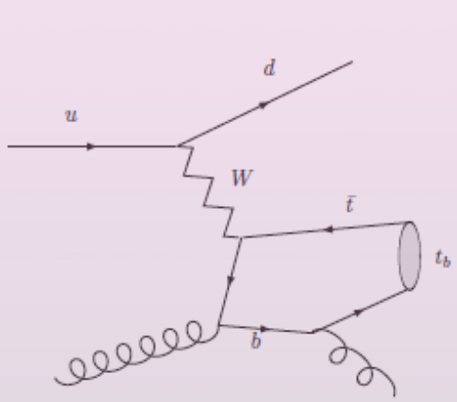

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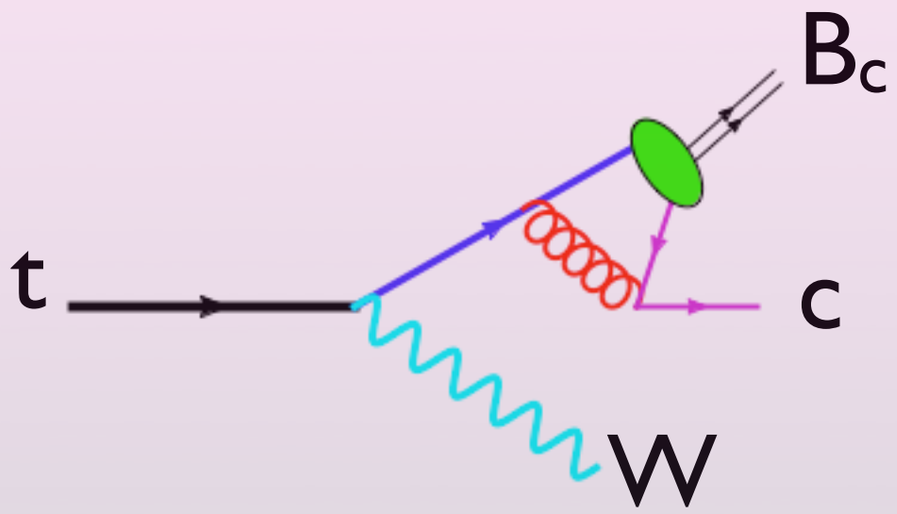
Br(t→B_c + X)



[Wu, arXiv:0805.4511]

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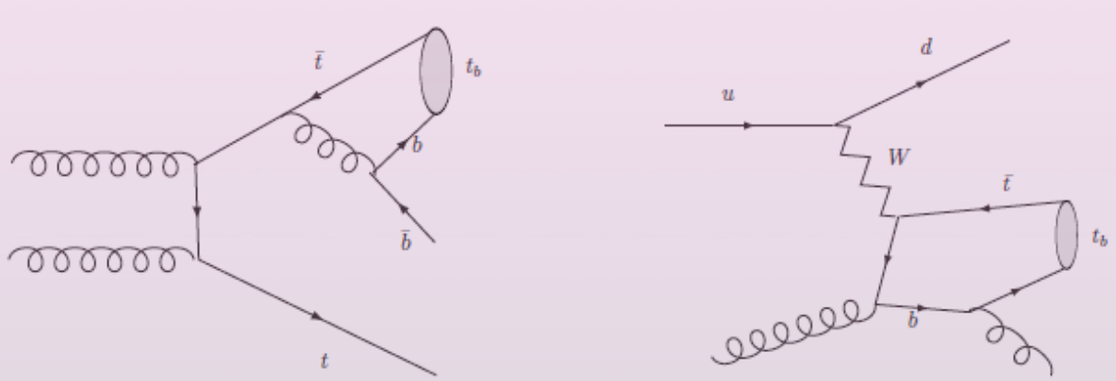

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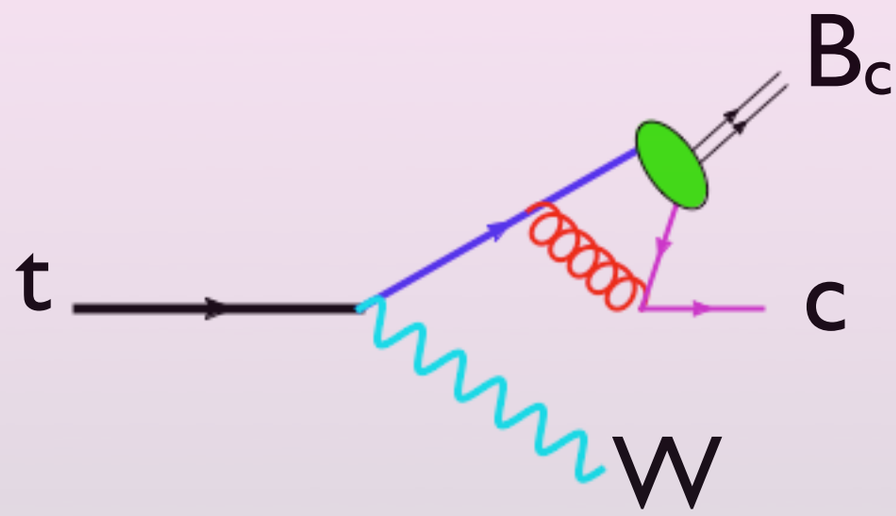
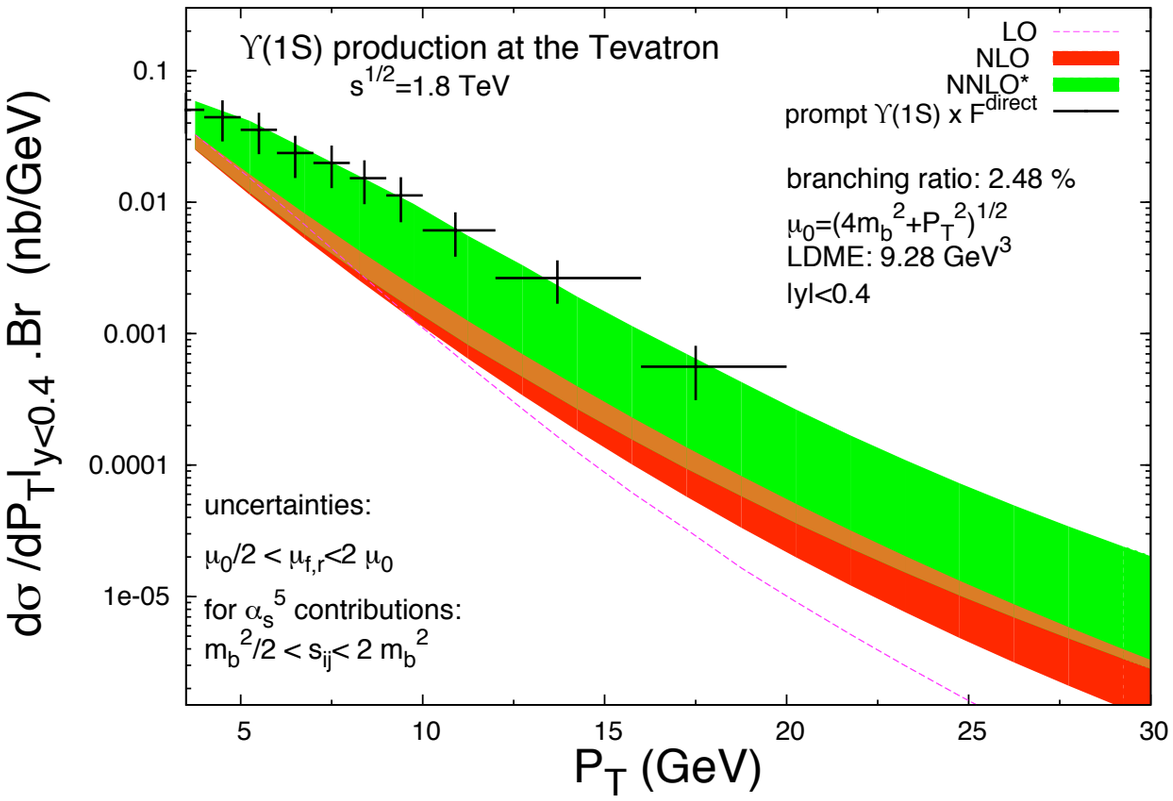


[Wu, arXiv:0805.4511]

And many others....

1. pp→O[n] Q Q' [Baranov,; P. Artoisent, et al.]
2. pp→O[n] + γ [Berger; Roy & Shridar; Kim & Song ; Rong Li, Wang, Lansberg]
3. pp→O[n] + (Z,W) [Braaten et al. ; Kniehl et al.]

Example II: improve on NLO predictions



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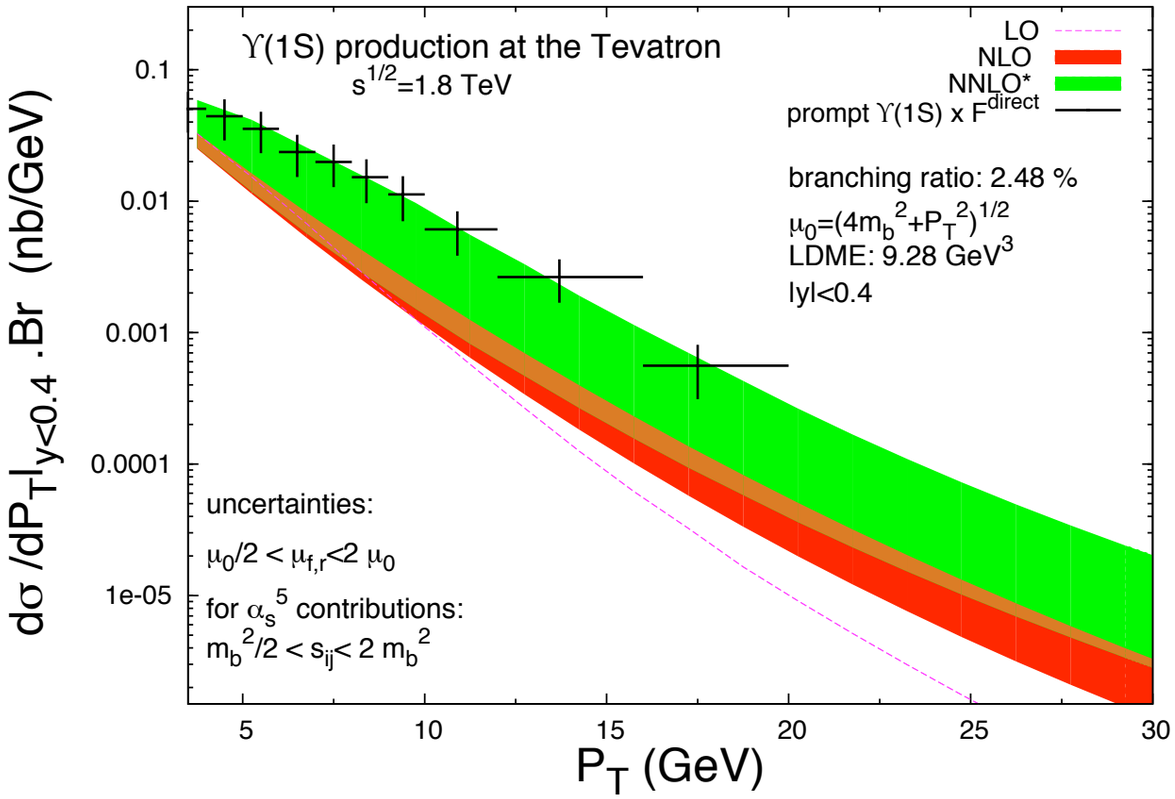

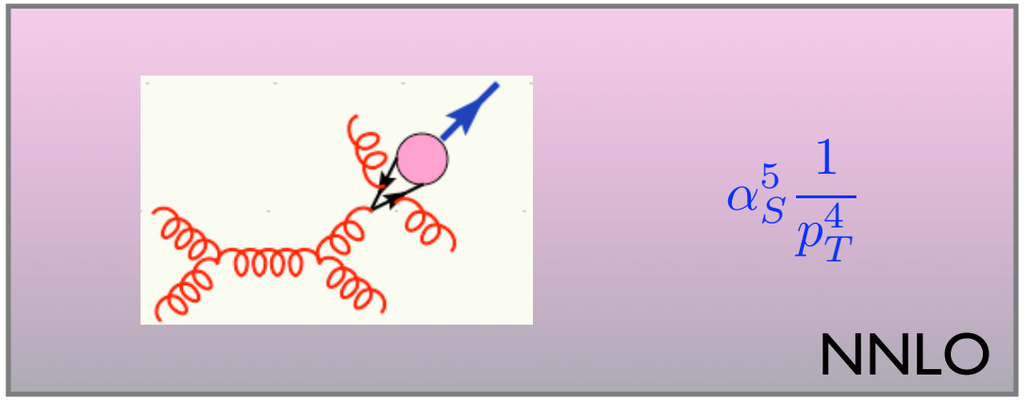

NLO predictions augmented by formally NNLO contributions.

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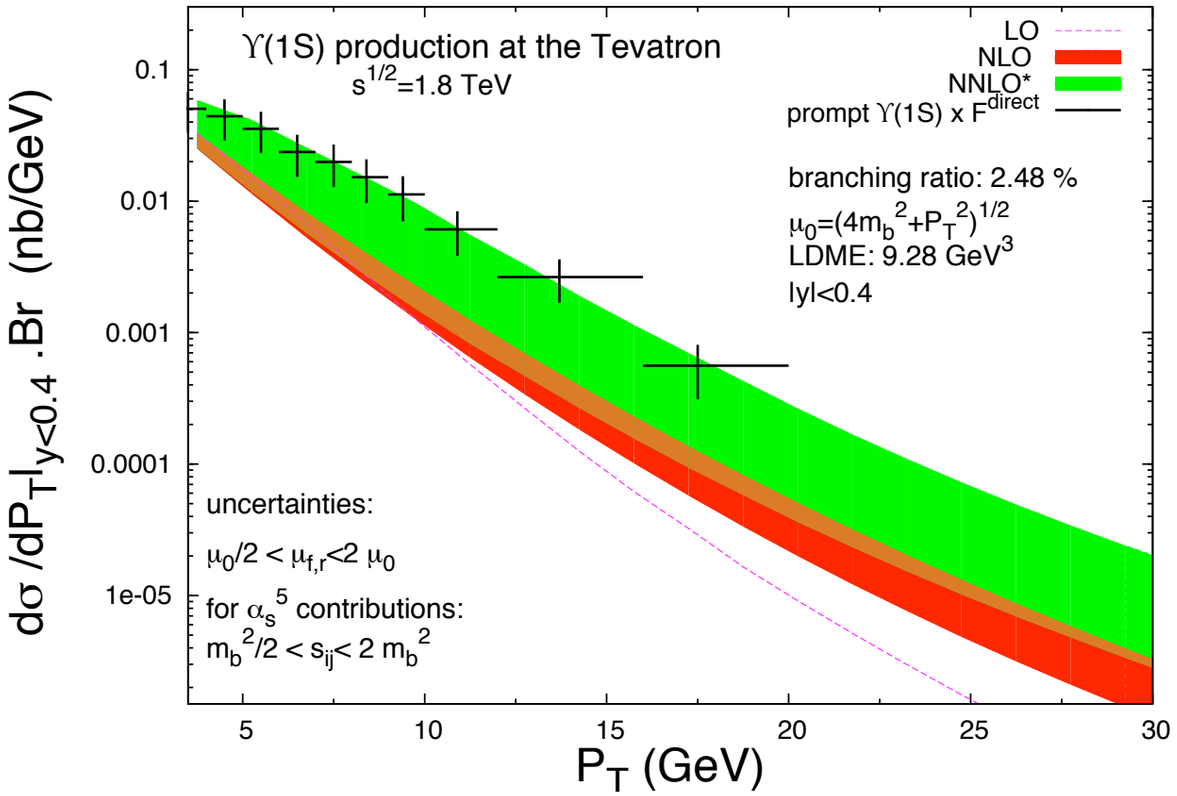

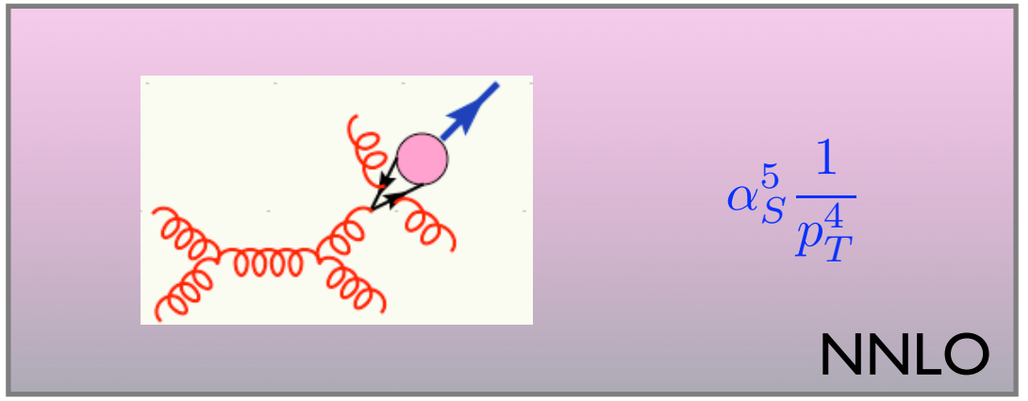

NLO predictions augmented by formally NNLO contributions.

Technically very challenging.

Υ + 3 jets production at the Tevatron

subprocesses:

dg_uuxdbbx3S11	gd_uuxdbbx3S11	gu_uuuxbbx3S11	ug_uddxbbx3S11	uux_uuxgbbx3S11
uxu_ddxgbbx3S11	du_udgbbx3S11	gdx_uuxdxbbx3S11	gux_uuxuxbbx3S11	ug_uggbbx3S11
uxd_uxdgbbx3S11	uxu_gggbbx3S11	dux_uxdgbbx3S11	gg_gggbbx3S11	gux_uxddxbbx3S11
ug_uuuxbbx3S11	uxdx_uxdxgbbx3S11	uxu_uuxgbbx3S11	dxg_duxdxbbx3S11	gg_uuxgbbx3S11
gux_uxggbbx3S11	uu_uugbbx3S11	uxg_uuxuxbbx3S11	uxux_uxuxgbbx3S11	dxu_udxgbbx3S11
gu_uddxbbx3S11	ud_udgbbx3S11	uux_ddxgbbx3S11	uxg_uxdcxbbx3S11	dxux_uxdxgbbx3S11
gu_uggbbx3S11	udx_udxgbbx3S11	uux_gggbbx3S11	uxg_uxggbbx3S11	

≈ 2000 Feynman diagrams (reduced by a factor $\frac{1}{4}$ after the colour and spin projections are applied)

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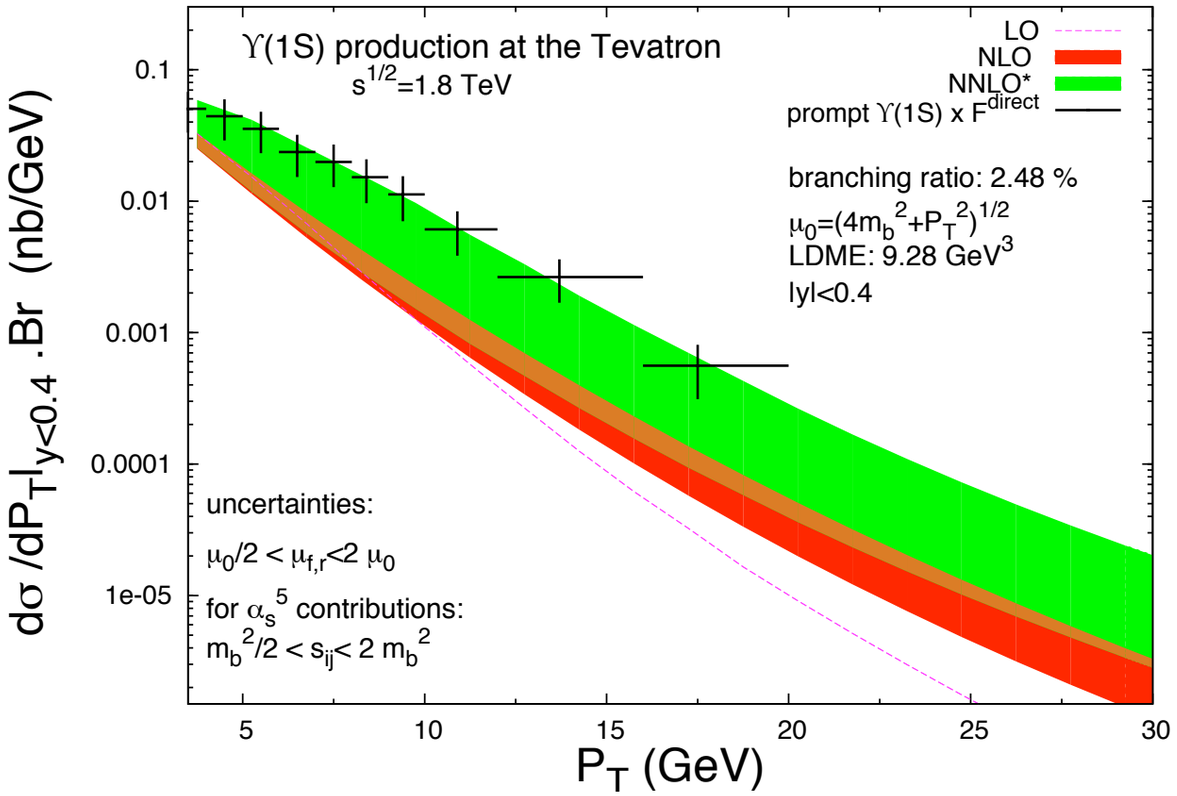
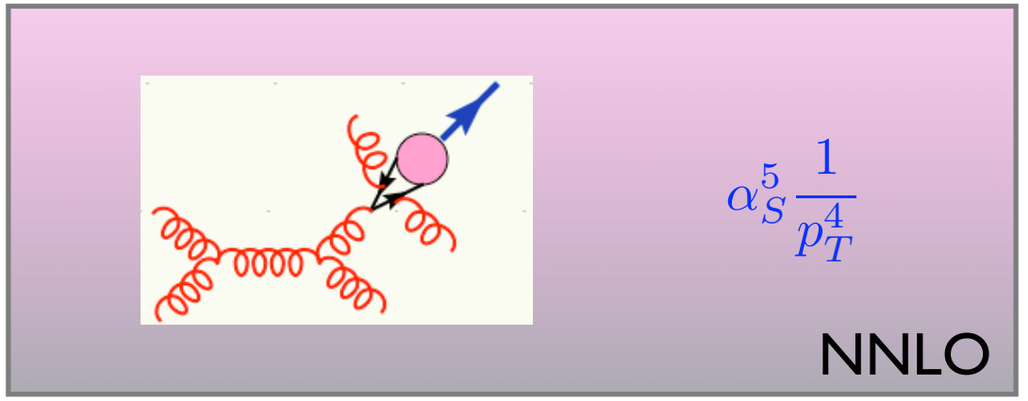




NLO predictions augmented by formally NNLO contributions.

Technically very challenging.

Results are cutoff dependent now, but matching could be employed to get rid of this dependence and produce accurate inclusive samples.
[Work in Progress]

Υ + 3 jets production at the Tevatron

subprocesses:

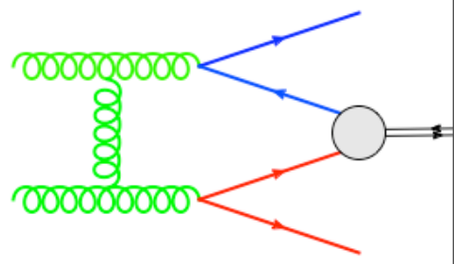
dg_uuxdbbx3S11	gd_uuxdbbx3S11	gu_uuuxbbx3S11	ug_uddxbbx3S11	uux_uuxgbbx3S11
uxu_ddxgbbx3S11	du_udgbbx3S11	gdx_uuxdxbbx3S11	gux_uuxuxbbx3S11	ug_uggbbx3S11
uxd_uxdgbbx3S11	uxu_gggbbx3S11	dux_uxdgbbx3S11	gg_gggbbx3S11	gux_uxddxbbx3S11
ug_uuuxbbx3S11	uxdx_uxdxgbbx3S11	uxu_uuxgbbx3S11	dxg_duxdxbbx3S11	gg_uuxgbbx3S11
gux_uxggbbx3S11	uu_uugbbx3S11	uxg_uuxuxbbx3S11	uxux_uxuxgbbx3S11	dxu_udxgbbx3S11
gu_uddxbbx3S11	ud_udgbbx3S11	uux_ddxgbbx3S11	uxg_uxdcxbbx3S11	dxux_uxdxgbbx3S11
gu_uggbbx3S11	udx_udxgbbx3S11	uux_gggbbx3S11	uxg_uxggbbx3S11	

≈ 2000 Feynman diagrams (reduced by a factor $\frac{1}{4}$ after the colour and spin projections are applied)

Other processes / tools

- X,Y states : nature and therefore production mechanism still under (heated) discussion [Braaten et al. vs. Polosa et al.]

- Bc : Best theoretical predictions still at LO = MC level. Only prompt production. Proven that the fragmentation approximation is not accurate.
  BCVEGPY [Chao-Hsi Chang, Jian-Xiong Wang, Xing-Gang Wu]
  Dedicated (matrix-element based) generator interfaced to Pythia. Well documented and currently used by several groups.



- Exclusive production : pp → O pp (via pomerons or photons)
  [Sizable community] : some tools exist. More info?

- More?

Outlook

Outlook

Outlook

- Room for improvement in Monte Carlo tools and techniques in quarkonium physics. Two main reasons:

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