Progress in Monte Carlo tools for quarkonia

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Quarkonium Working Group Meeting

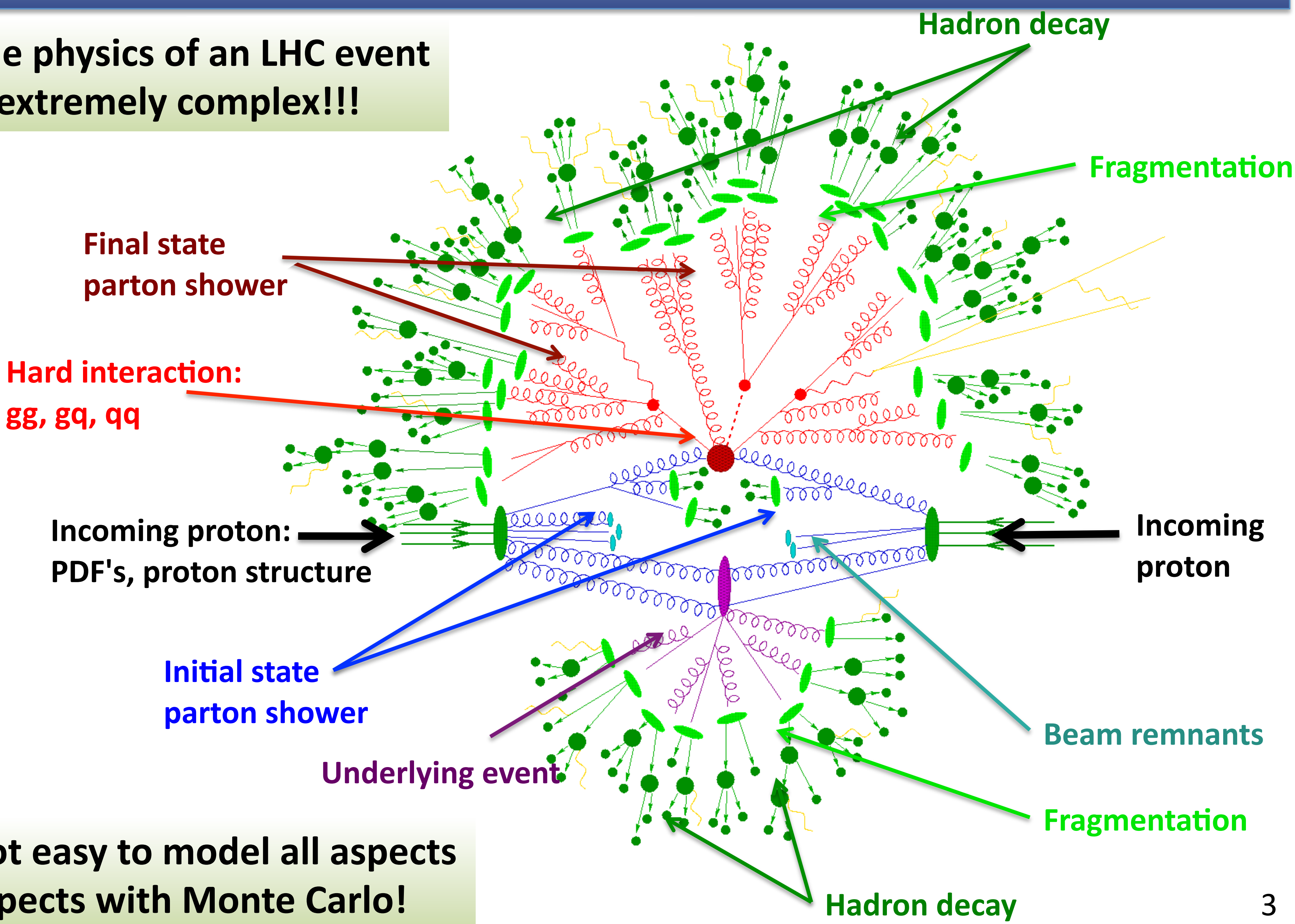
Fermilab, 18-21 May 2010

Outline

- **Introduction**
- **Available event generators for quarkonia:**
  - **PYTHIA6**
  - **PYTHIA8**
  - **MadOnia**
  - **CASCADE**
  - **Non-prompt J/psi generators and other generators**
- **Wishlist from experimentalists to Monte Carlo experts**
- **Conclusion**

Introduction: a typical LHC event

The physics of an LHC event is extremely complex!!!



Not easy to model all aspects aspects with Monte Carlo!

Introduction

- **Reliable Monte Carlo tools are very important for data analysis at the LHC!**
  - **For preparation before running on real data**
  - **How many events can we expect at a certain pT/Eta**
  - **...**
- **Februari 2010: overview was given of quarkonia MC tools (Maltoni, A. K.)**
  ➔Conclusion: only few Monte Carlo tools on the market, and do not describe existing data very well
- **Why?? The underlying production mechanism is not understood. So making Monte Carlo tools is not an easy task...**

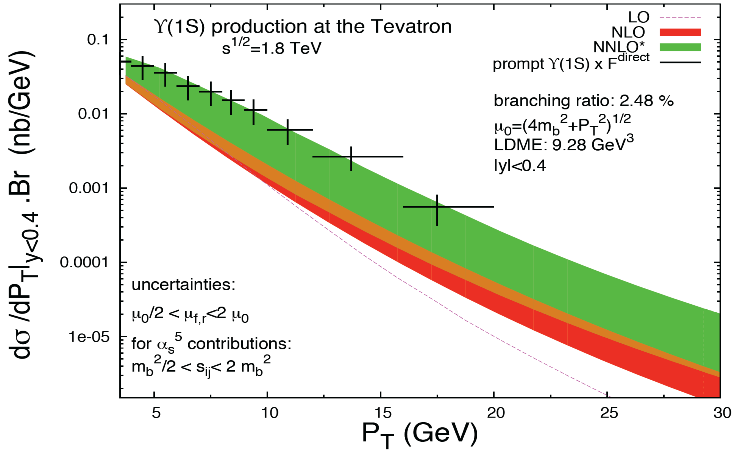
This talk:

- **Monte Carlo tools from experimental point of view.**
- **Concentrate on MC tools for quarkonia production in pp collisions at LHC.**
- **For each Monte Carlo tool: general description, what is relevant/special for quarkonia, some practical info.**

Slide from Fabio Maltoni, 19 February 2010

Two main types of Monte Carlo tools

"Predictor"

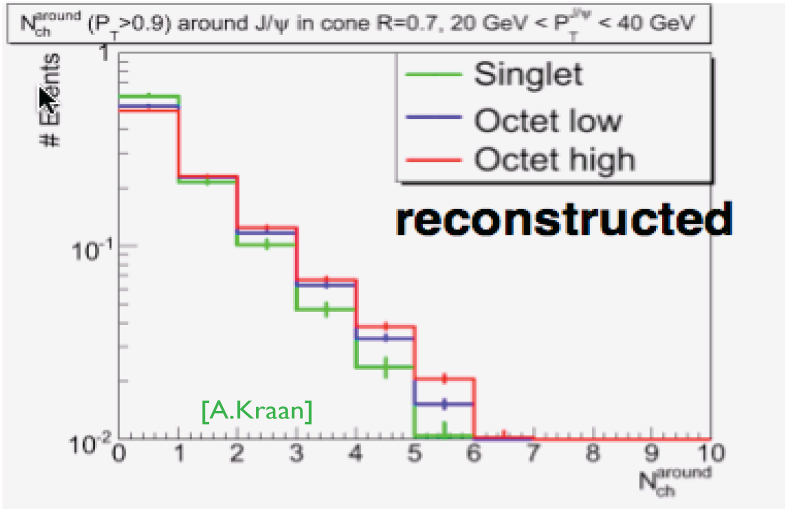


- "Theory" tools that can provide predictions for (more or less) inclusive observables.
- Represent the "BEST" th predicitons

Examples: MCFM, ALL current NLO codes

See talk F. Maltoni at 1-day quarkonium workshop CERN 19/02/10

"Event Generator"



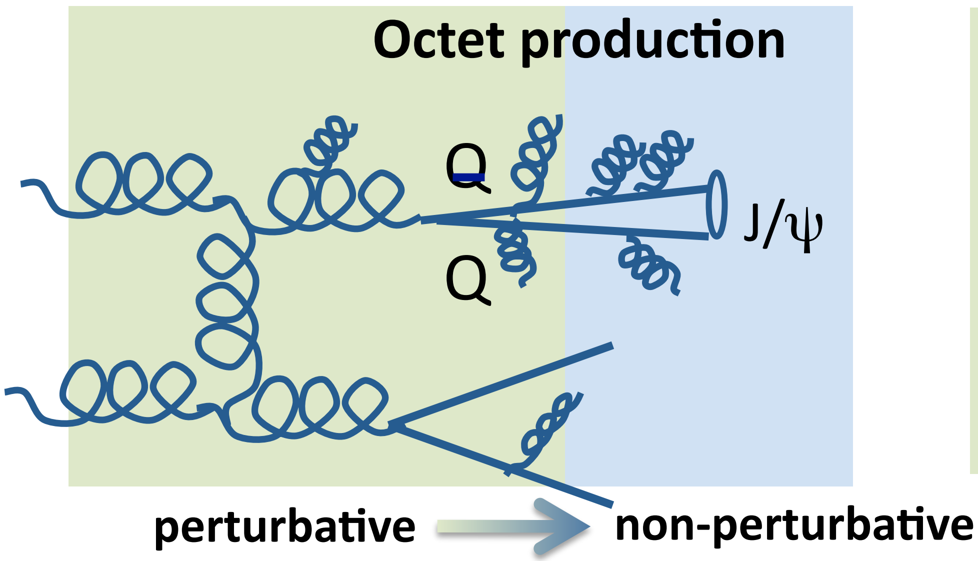
- Fully exclusive description
- In general not the TH predictions but tunable [descriptive]
- Results in terms of events

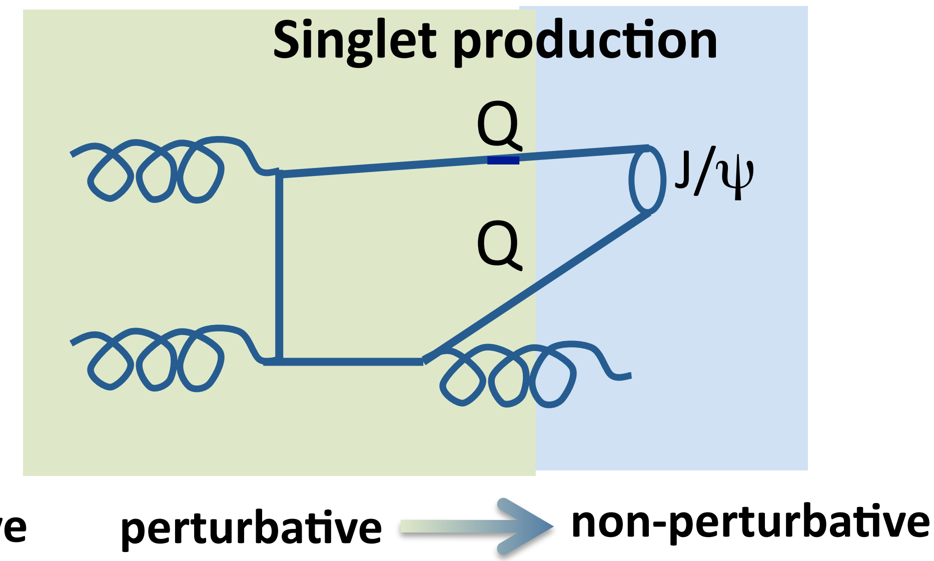
Examples: Pythia, MadOnia+Pythia,...

Focus here on event generators, i.e. tools that give something that can be processed through a detector simulation.

Prompt quarkonia with PYTHIA 6

- **LO singlet and octet production is possible with PYTHIA 6**
- **Even though we know now that significant octet production is disfavoured by experimental data, for many purposes is sufficient to have a predictive and tunable program**
- **Via LHEF (Les Houches interface) can be linked with external ME programs**
- **Main flow:** Generation of hard process → Showers → Hadronization



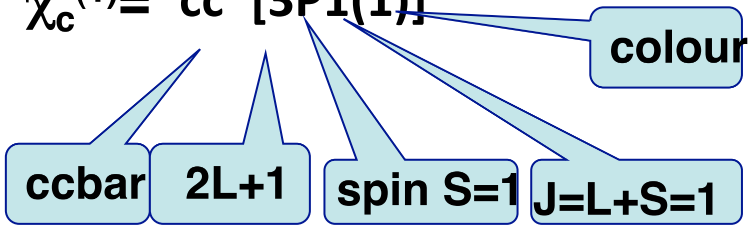


See: http://home.thep.lu.se/~torbjorn/Pythia.html

PYTHIA: hard process

- Prompt J/ψ production with MSEL=61
- Turns on several sub-process (MSUB) producing colour singlet and octet states. For example:

$\chi_c^{(1)}$= cc~[3P1(1)]



- Each process has an NRQCD matrix-element.
  - Tuned to fit Tevatron data, see CERN-LHCb-2007-042
- The 2S states can be produced by changing NRQCD matrix elements, particle masses, BR (by hand)
- J/ψ feeddown not modelled well:
  - Feeddown from χ's disagrees with data.
  - Feeddown from ψ(2S) not included.
- Production of Y's along same line, with MSEL=62

PROCESSES:

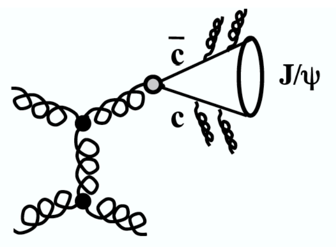
421 g + g -> cc~[3S1(1)] + g
422 g + g -> cc~[3S1(8)] + g
423 g + g -> cc~[1S0(8)] + g
424 g + g -> cc~[3PJ(8)] + g
425 g + q -> q + cc~[3S1(8)]
426 g + q -> q + cc~[1S0(8)]
427 g + q -> q + cc~[3PJ(8)]
428 q + q~ -> g + cc~[3S1(8)]
429 q + q~ -> g + cc~[1S0(8)]
430 q + q~ -> g + cc~[3PJ(8)]
431 g + g -> cc~[3P0(1)] + g
432 g + g -> cc~[3P1(1)] + g
433 g + g -> cc~[3P2(1)] + g
434 q + g -> q + cc~[3P0(1)]
435 q + g -> q + cc~[3P1(1)]
436 q + g -> q + cc~[3P2(1)]
437 q + q~ -> g + cc~[3P0(1)]
438 q + q~ -> g + cc~[3P1(1)]
439 q + q~ -> g + cc~[3P2(1)]

PYTHIA: low p_T divergencies

- **But even with octet, prompt J/ψ cross section not right: too big at low p_T**
- **Solution: cross section dampened (MSTP(142) similar to what is done in PYTHIA for gg→gg in underlying event formalism:**

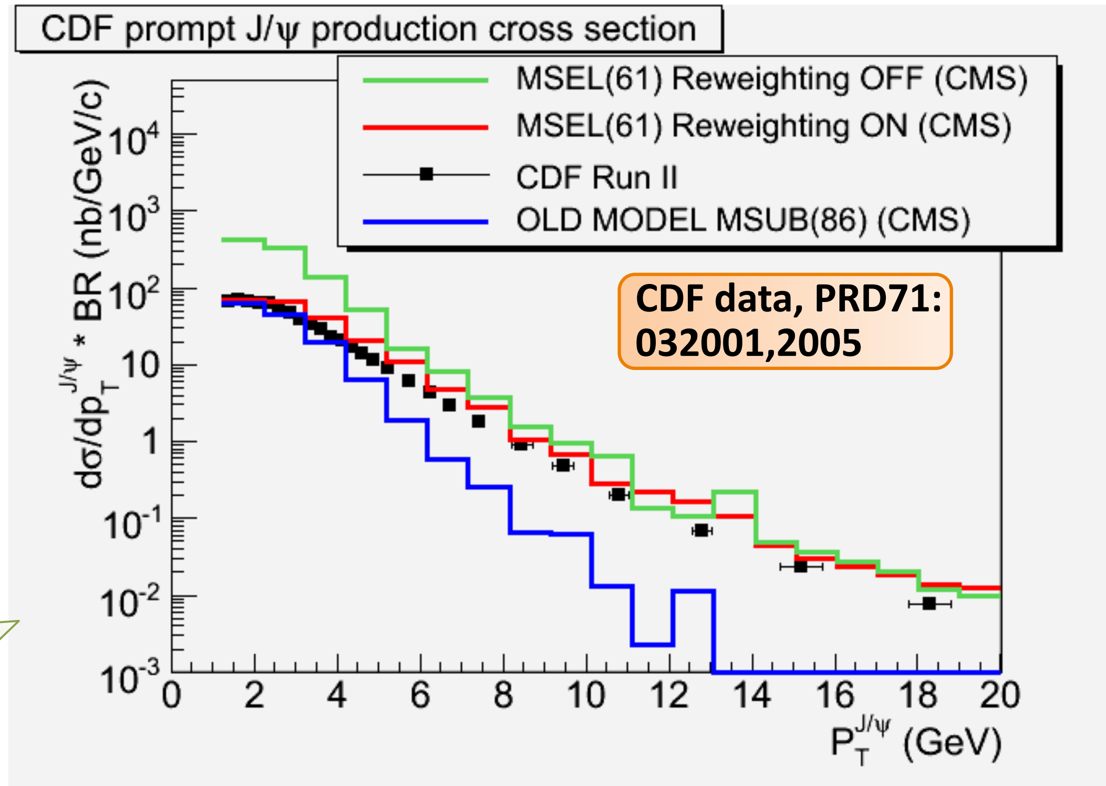
  Below a certain pT scale the individual colours in the proton cannot be resolved ⇒ cross section decreases

T.Sjöstrand, M.v.Z, PRD36,2019, 1987



Several uncertainties/ free parameters here.

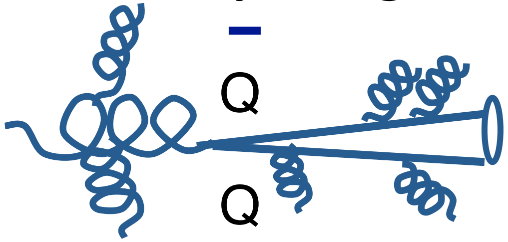
Now MC prediction of p$\bar{p}$ cross section at 1.96 TeV (CDF) reasonable.



PYTHIA: parton showers and hadronization

Only relevant for octet production!

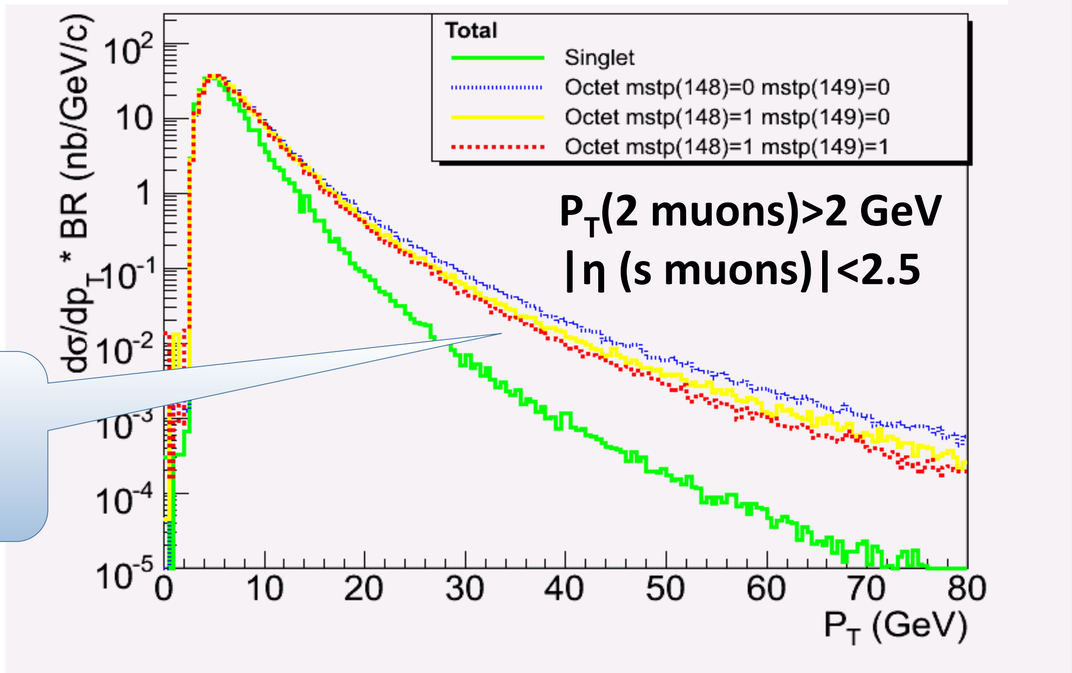
QQ octet fragmentation: different options for Altarelli-Parisi splitting function:



- **AP splitting function of q→qg, but corrected for presence of 2 quarks**
  ⇒small amount of radiation (MSTP(148=0)
- **AP splitting function of g→gg, "follow" hardest gluon**
  ⇒medium amount of radiation (MSTP(149)=1, MSTP(148)=0
- **AP splitting function: g→gg, symmetric (DEFAULT!)**
  ⇒large amount of radiation (MSTP(148)=1, MSTP(149)=1

Shower details influence octet cross section shape: more showering➔ fall steeper

Prompt J/psi production cross section at 14 TeV



➡ **Uncertainties: mass of octet, amount of radiation**

CDF (p_T<20) compatible with all shower scenario's

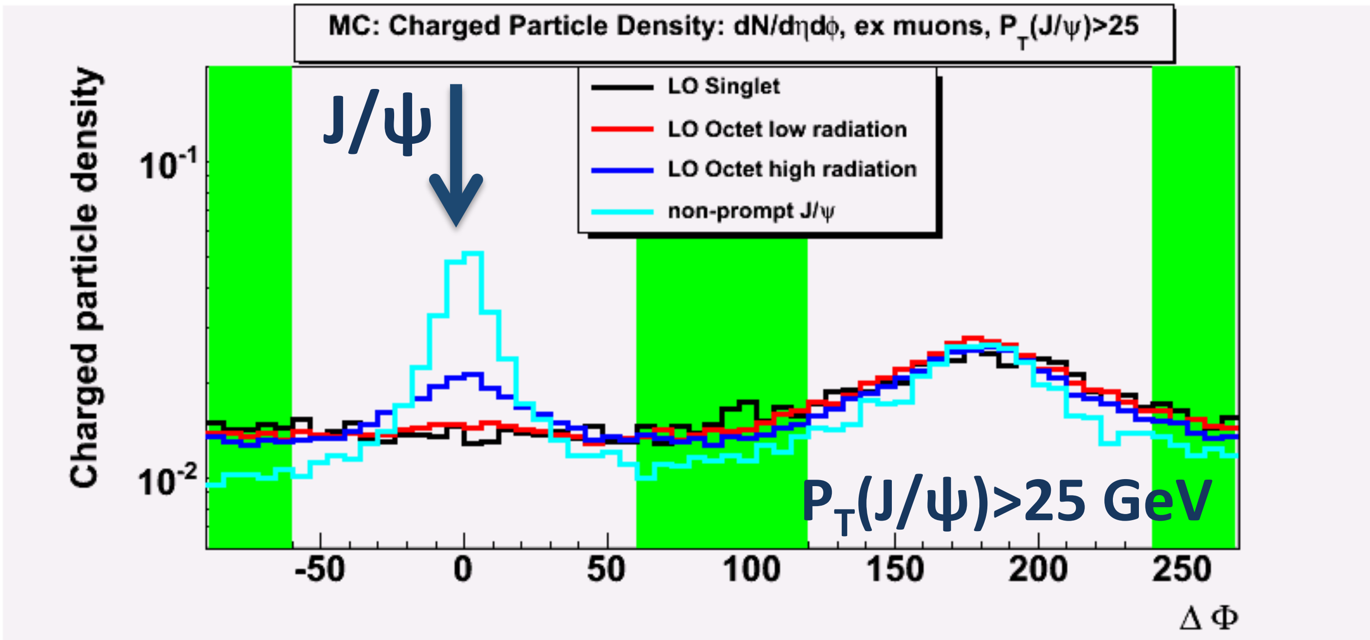
PYTHIA: particle multiplicity dN/dη

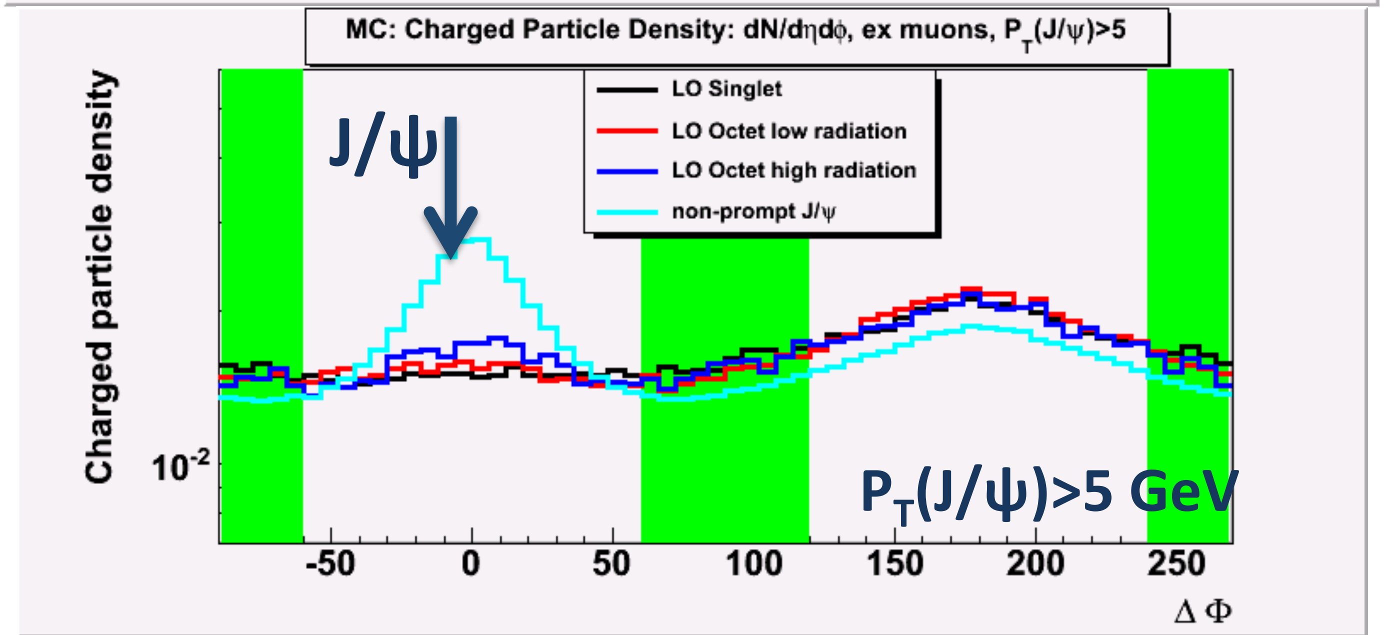
Production model and shower details influence charged particle multiplicity

J/ψ➔μμ production:
Study Δϕ between J/ψ and other charged particle (pT>0.5 GeV)

- Octet has more particles close to J/psi than singlet

- Obviously, non-prompt J/ψ has real jet





Quarkonia with PYTHIA 8

- Basic physics is the same as in PYTHIA6, some technical differences:

➢ Two ways to generate prompt quarkonia: 1) explicitly and 2) as part of multiparton interaction framework [PYTHIA6: only 1)]

➢ The OO structure of Pythia8 makes it simpler to extend/clone processes, so that e.g. Psi' production could be modeled as J/Psi (but input needed).

	PYTHIA 6	PYTHIA 8
main process switches	MSEL=61 MSEL=62	Charmonium:all Bottomonium:all
sub process	MSEL=0, MSUB(421)=1, ...	Charmonium:gg2QQbar[3S1(1)]g, ...
low Pt treatment	PYEVWT.f	SuppressSmallPT (UserHooks)
decay mode	MDME(858,1)=0, ... MDME(859,1) = 1	443:onMode = off 443:onIfAny = 13
NRQCD ME's	PARP(141)=..., ...	Charmonium:OJpsi3S11=... , ...
shower parameters	MSTP(148)=0,1 MSTP(149)=0,1	TimeShower:octetOniumFraction (0→1) TimeShower:octetOniumColFac (0→4)

Small translation table

Program and tutorials see: http://home.thep.lu.se/~torbjorn/Pythia.html

MadOnia

A multipurpose automatic matrix element generator for NRQCD amplitudes at treelevel, which is integrated in MadGraph/MadEvent

3 Steps:

1) Generate code for requested process → **2) run code to calculate cross sections, distributions and unweighted parton-level events** → LHEF → **3) PYTHIA (or HERWIG) for showers and hadronization**

- **Automatic evaluation of any tree-level matrix element involving a heavy-quark pair in a definite spin and color $^{2S+1}L_J$[1,8] state**
- **Process syntax: e.g.** gg>gbb~[3S11to553], gg>ggbb~[3S11to553], gg>gggcc~[3S11to443], pp>cccc~[3S11to443]...
- **Polarization information conserved for the 3S1[1]**
- **Only tree-level, no loop corrections**

See: http://cp3wks05.fynu.ucl.ac.be/twiki/bin/view/Main/IntroQuarkonium
http://cp3wks05.fynu.ucl.ac.be/twiki/bin/view/Software/MadOniaManual

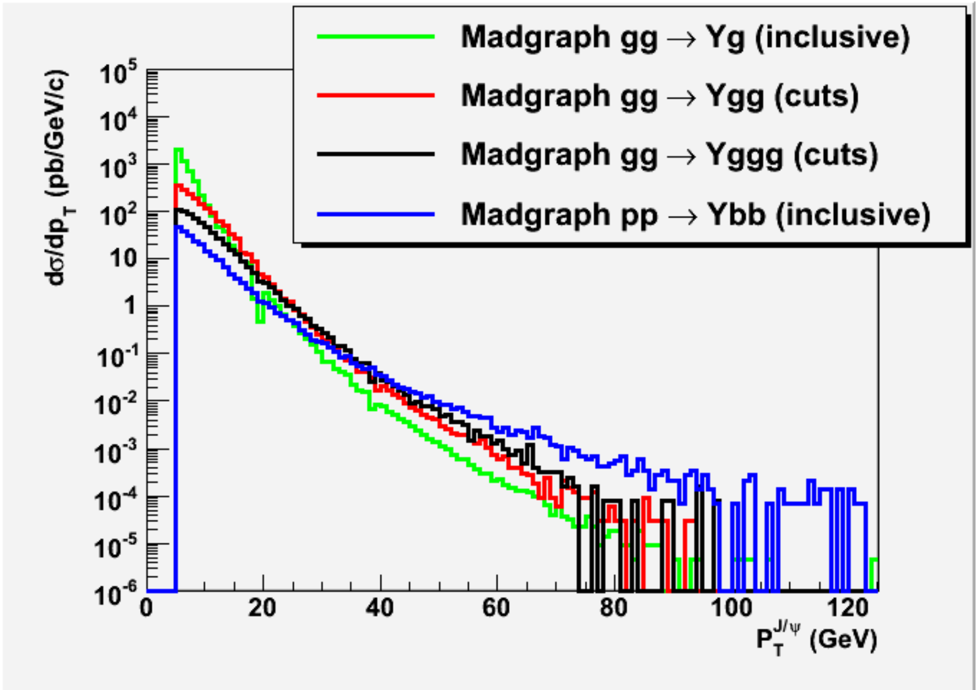
What can be done for quarkonia with default Madgraph

See: http://madgraph.hep.uiuc.edu/

Examplea of studies that can be done with the current default Madgraph that is found online:

- **Inclusive quarkonium production at LO:**
  gg➔ϒ+g, gg➔J/ψ+g (~α_s^3)
- **Higher jet multiplicities in quarkonium production**
  ϒ+n jets, J/ψ+n jets(~α_s^{n+2})
  each jet has to be resolved (minimum cut on jet pT and ΔR)
- **Associated cc/bb production (~α_s^4):**
  pp➔ϒ+bb, pp➔J/ψ+cc (see next!)

➢ All distributions of events produced by Madgraph are leading-order ➔large uncertainties in the normalization... Attempts to go beyond LO made (not yet integrated) see:



Maltoni etal, Phys.Rev.Lett.101:152001,2008,
Artoisenet etal, JHEP 0802:102,2008,
Lansberg, Eur.Phys.J.C61:693-703,2009

MadOnia example: associated charm production

With JP Lansberg

Several contributions involving c-quarks are expected to contribute to inclusive J/ψ production

Maltoni etal, PhysLettB653,60,2007,
Baranov, PhysRevD73, 074021,2006,
Lansberg, PhysRevD81:0501501, 2010

1) Add NLO contribution to gg fusion: $gg \to J/\psi\, cc$
   Signature: charm quark pair in association with J/ψ

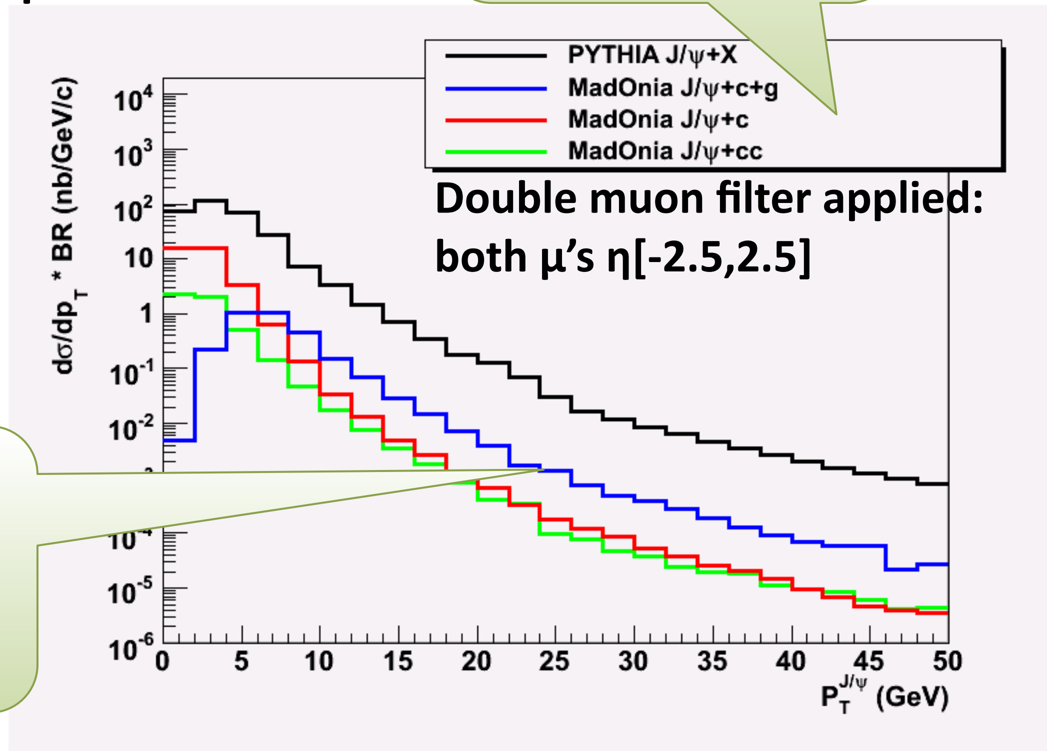
2) Add LO charm-gluon fusion contribution: $gc \to J/\psi c$
   Signature: charm quark opposite to J/ψ

3) Add NLO contribution of cg fusion:

$$gc \to J/\psi\; c\; g$$

Signature: charm quark close or opposite to J/ψ

Differential cross section for PROMPT J/ψ➔μμ at 14 TeV: (|y|<0.5)



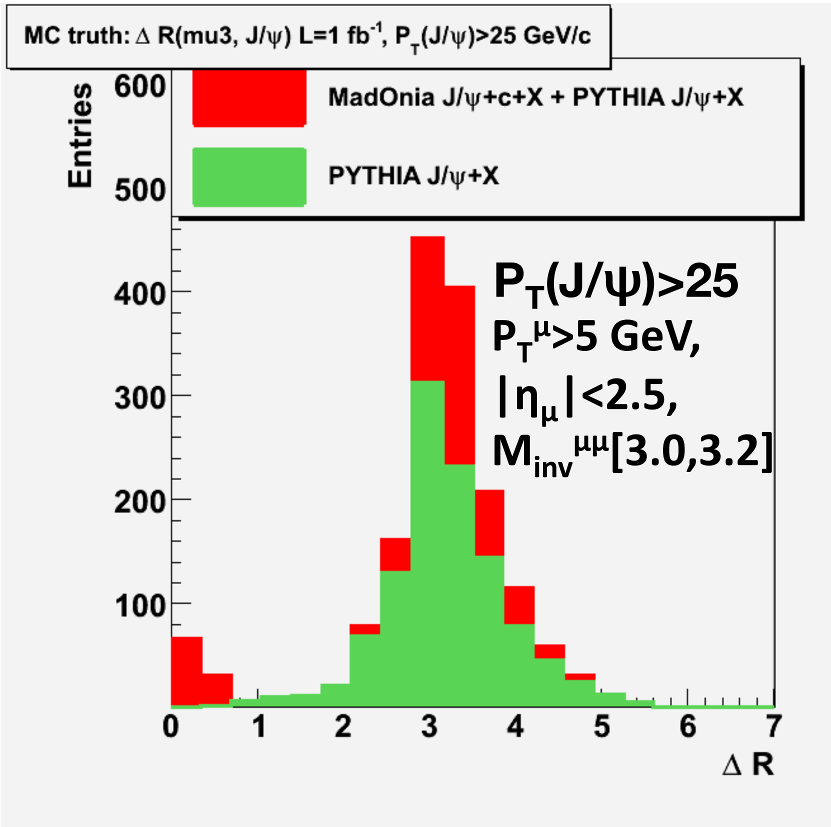
Contribution of charm at high pT could be 10% of total prompt production, low pT even more! (but some uncertainty)

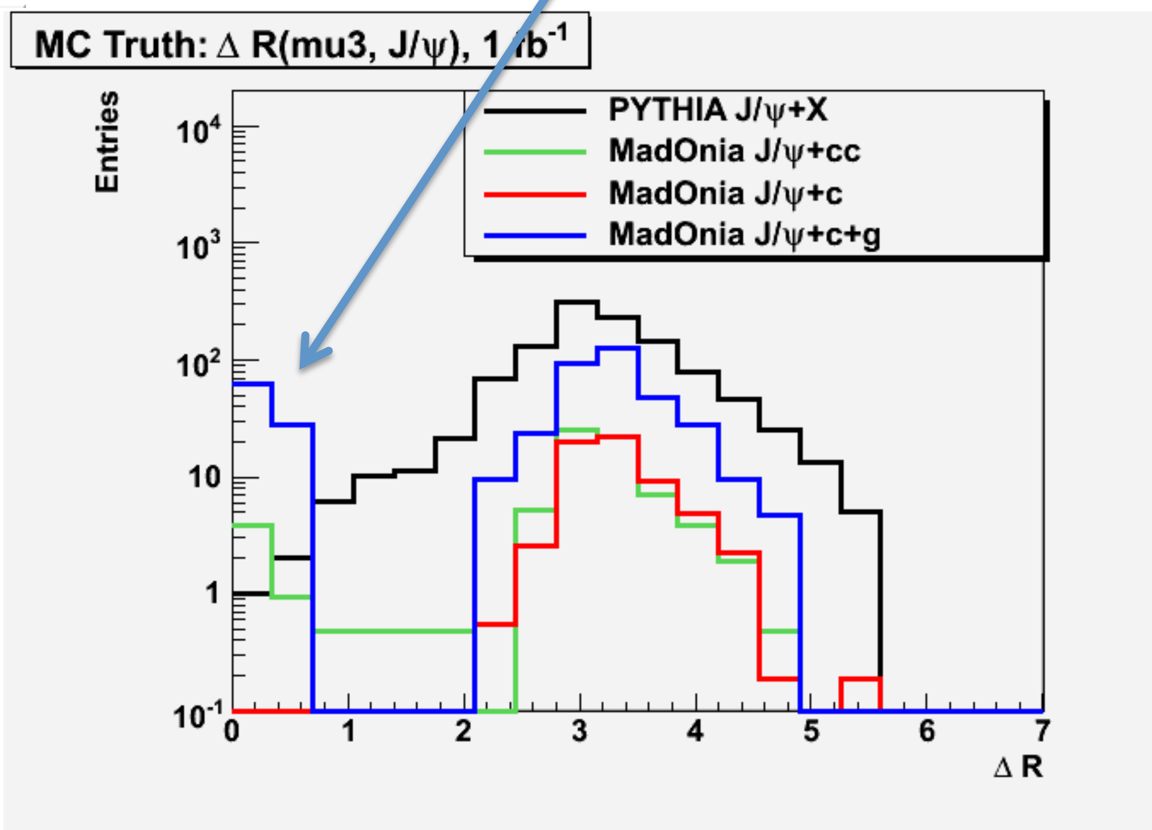
MadOnia example: Associated charm production

Quick look at J/ψ events with 3 muons (BR(c➔μ X)~10%): 2 from J/ψ, 1 from c

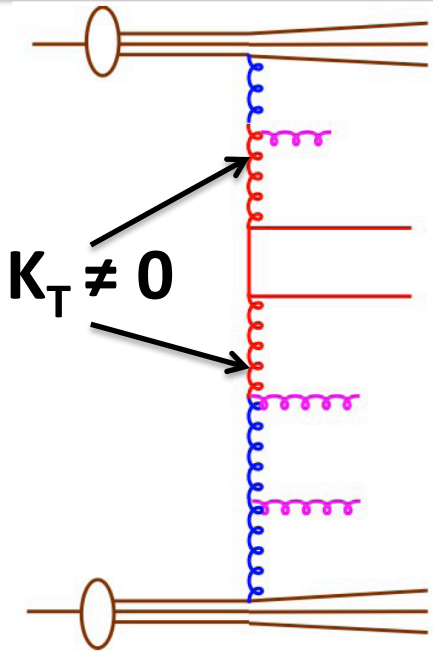
- **Significant excess of 3-muon events in <u>prompt</u> production expected**
- **At high P_T(J/ψ), characteristic signature from J/psi+c+g with 3rd lepton closeby J/ψ! ... but challenging to detect 3 very close high pT muons!**

Could be useful to look at these kind of things in real data!





The CASCADE event generator



Different approach for initial shower evolution developed for small-x (quarkonia!) and forward physics (H.Jung etal)

Basic elements:

- Generation of hard process: off-shell matrix elements
  - tested at HERA and Tevatron
- PDF's: k_T unintegrated PDF's:

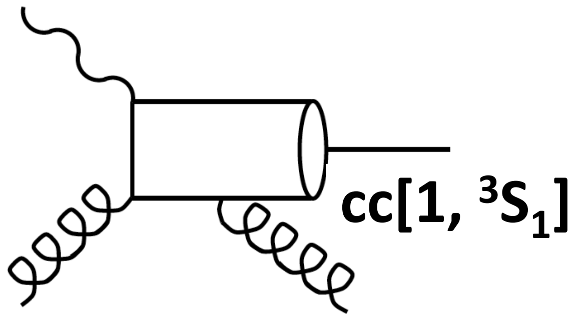
$$\sigma(pp \to q\bar{q}X) = \int \frac{dx_{g1}}{x_{g1}} \frac{dx_{g2}}{x_{g2}} \int d^2k_{t1} d^2k_{t2} \hat{\sigma}(\hat{s}, k_t, \bar{q}) x_{g1} A(x_{g1}, k_{t1}, \bar{q}) x_{g2} A(x_{g2}, k_{t2}, \bar{q})$$

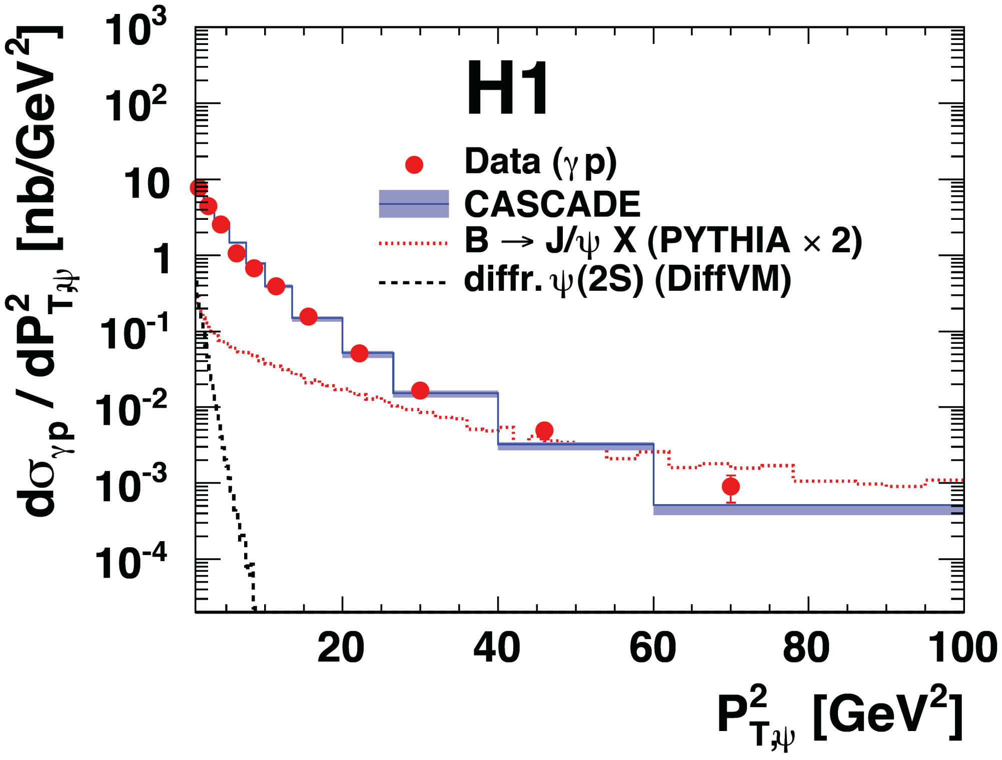
- Initial state parton shower: evolution based on angular ordering (CCFM)
  - At small x-values, pT of emissions can go up and down with evolution of the shower (PYTHIA initial state shower pT ordered: DGLAP)
  - Contains NLO components
- Proton remnants, final state parton shower, hadronization: PYTHIA

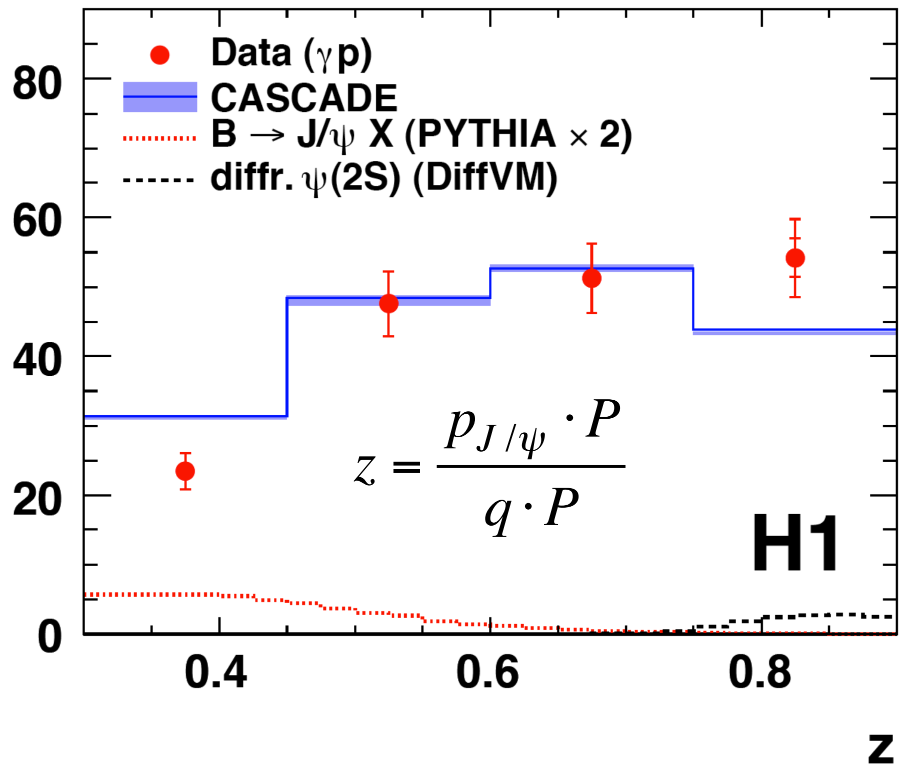
Code: see http://projects.hepforge.org/cascade/

CASCADE at HERA

- Quarkonia implementation: Color Singlet Model (NRQCD matrix elements) with K_T factorization
- γp collision data (pT, z): description of shape and normalization ok, no need for octet!



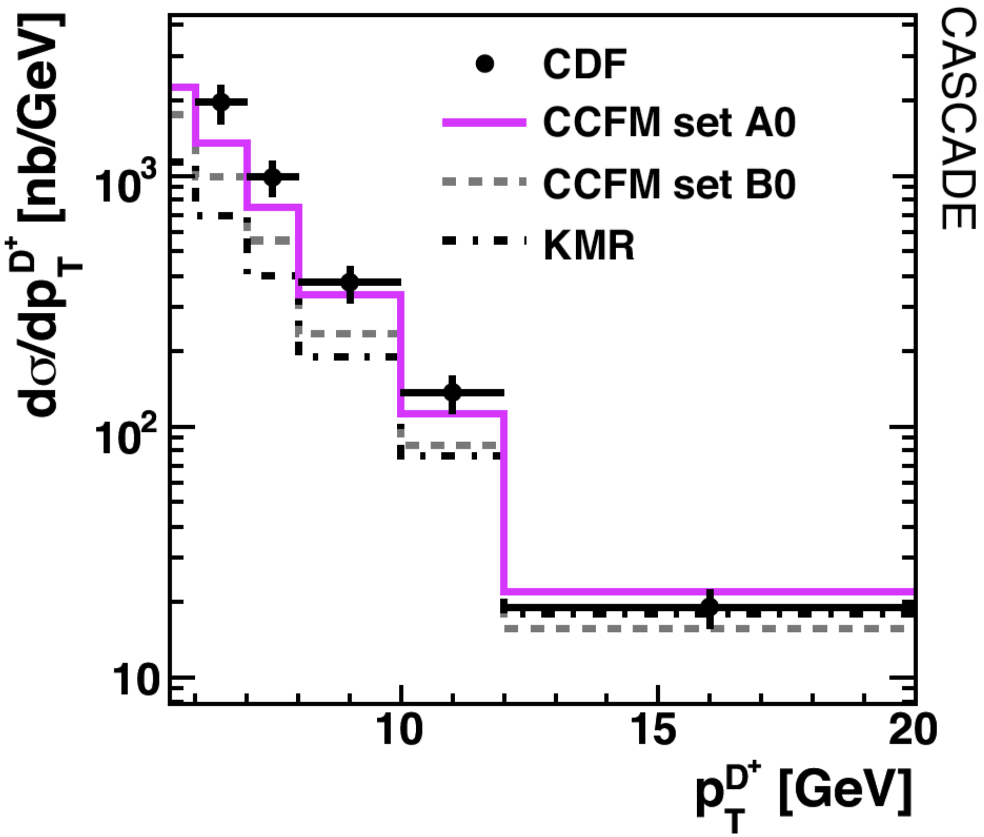


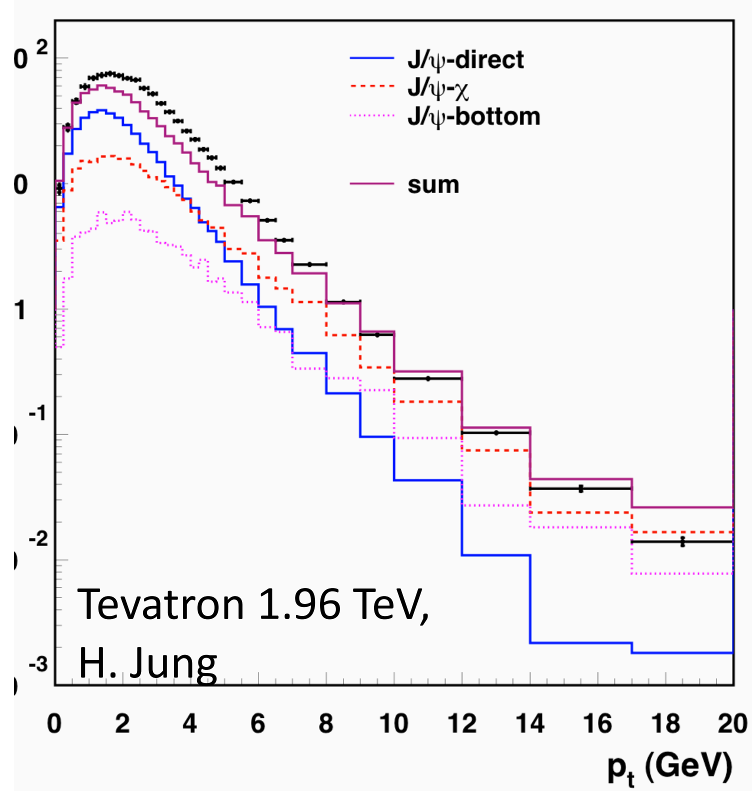


CASCADE at the Tevatron

new!

- **Using quarkonia ME from S. Baranov etal [Phys.Rev.D66, 114003, 2002]**
- **Recently lots of progress in description of heavy flavour production at Tevatron, see also talk by M. Krämer DIS2010!**
- **J/ψ inclusive cross section at Tevatron: shape and normalization not too bad**

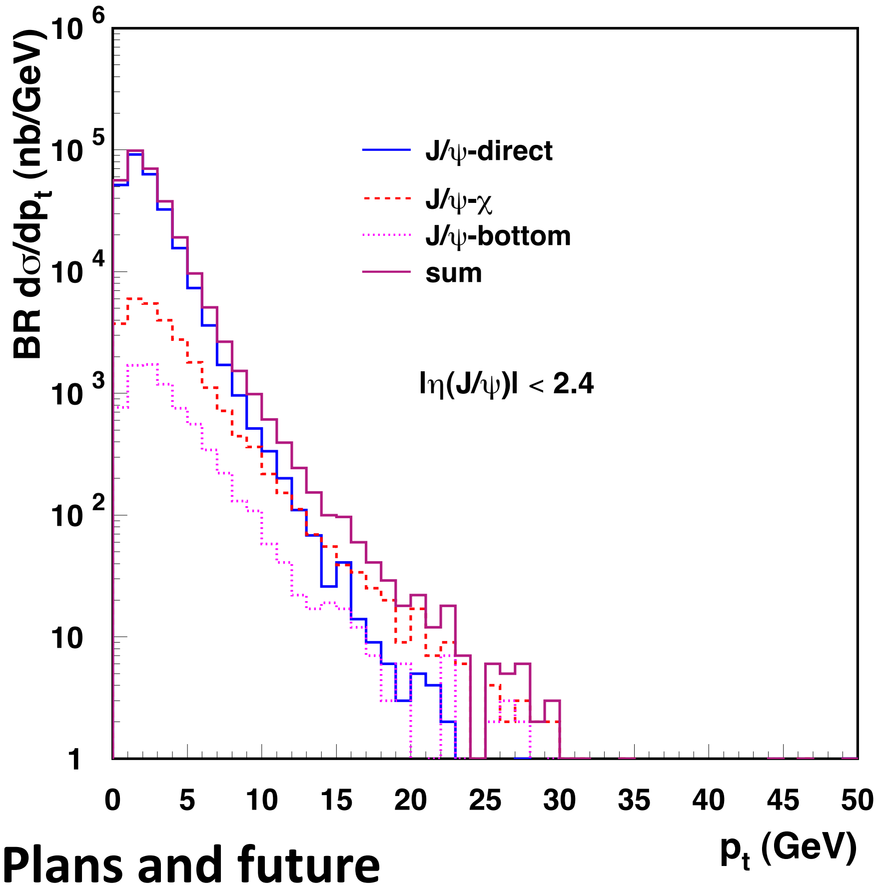


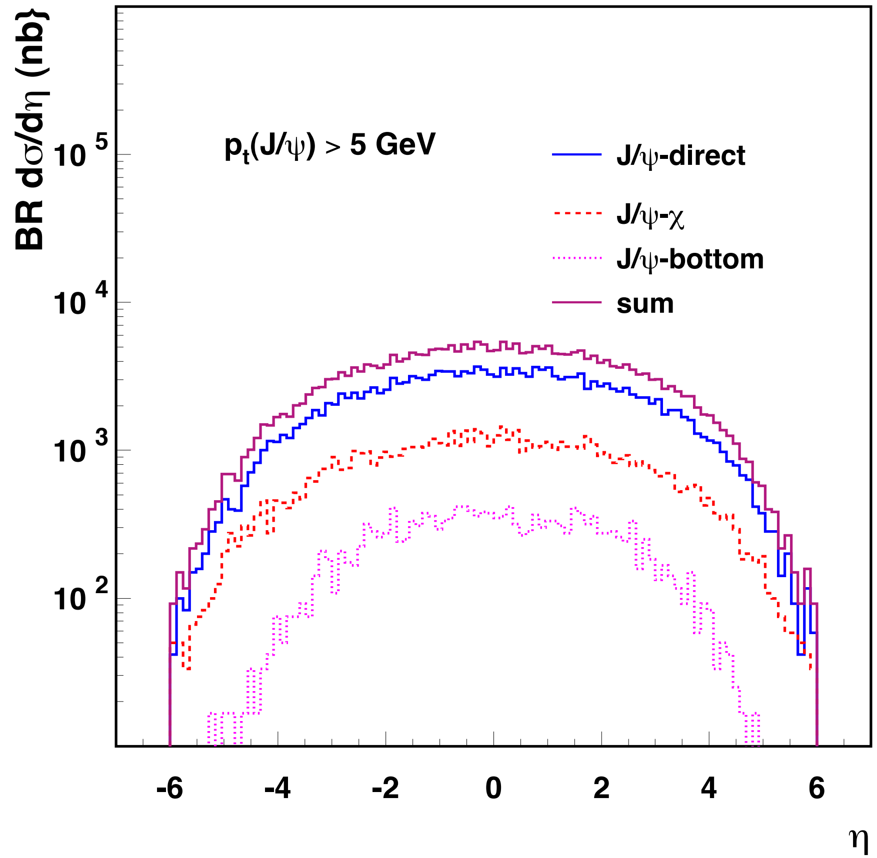


CASCADE at the LHC

new!

Very recently CASCADE has been tested for J/psi at LHC!!





Plans and future

- Extension to Upsilon sector (easy)
- Extension to 2S and 3S states, but requires more work
- Interface to ATLAS ready, CMS almost ready, LHCb getting started

Other generators

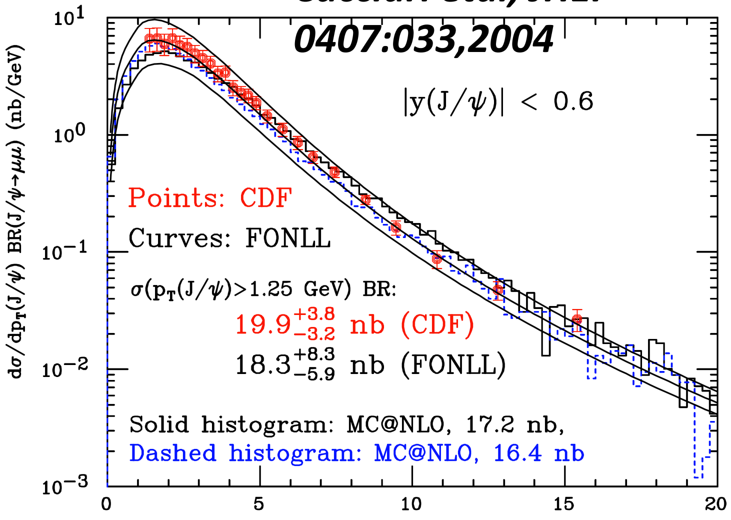
Non-promt J/psi generators:

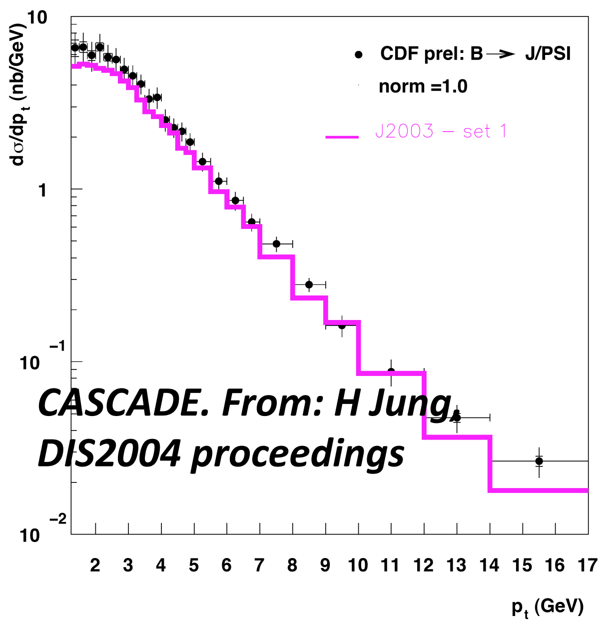
- **MC@NLO: matching NLO QCD calculations with parton shower simulations.**
  - **Total rates are NLO!**
  - **Smooth transition between soft and hard**
  - **region**
- **CASCADE: similar results as MC@NLO**
- **PYTHIA: : minimum bias mode (CPU intensive)**

Other generators on the market:

- **BCVEGPY0.2 (B_c meson)**
- **LEPTO (DIS)**
- **...?**

MC@NLO. From: Cacciari etal, JHEP 0407:033,2004



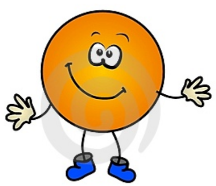


CASCADE. From: H Jung, DIS2004 proceedings

Wishlist

Wishlist from experimentalists to Monte Carlo theory experts:

- **Everything needs to be in an official release of the generator code**
  We highly prefer not to touch MC source code
- **We understand less than you think... Provide example programs, input cards, explanations, which parameters can be tuned and which not to touch, etc.**
- **Output in the Les Houches standard format**
- **User friendly**
- **User support**
- **We cannot complain! The collaboration between experimentalists and Monte Carlo theory experts is already working quite well!**



Conclusion

- Experimentalists need Monte Carlo event generators to prepare and do analyses.
- Currently available event generators: PYTHIA6, PYTHIA8, MadOnia+PYTHIA, CASCADE, MC@NLO, ...
  - PYTHIA: easy to use, tunable, but not all production aspects modelled well
  - MadOnia+PYTHIA: provides interesting possibilities, tools for full phase space predictions under development.
  - CASCADE: new on the market for LHC experiments!
  - MC@NLO: non-prompt J/psi
- None of the prompt production generators includes exact NLO calculations.
  - New directions (merging LO matrix elements with PS, NLO with PS) that are being explored for other physics processes like ttbar, W, Z are not yet available for quarkonia.
  - But work in this direction is ongoing.

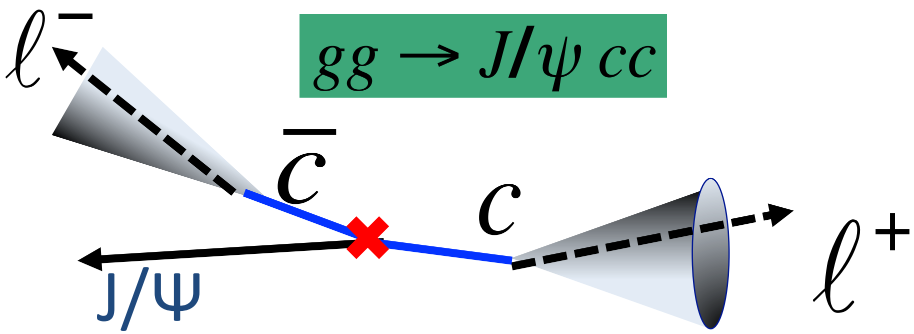
Thanks to Pierre, Jean-Philippe, Fabio Maltoni, Hannes Jung and the organizers of this workshop!

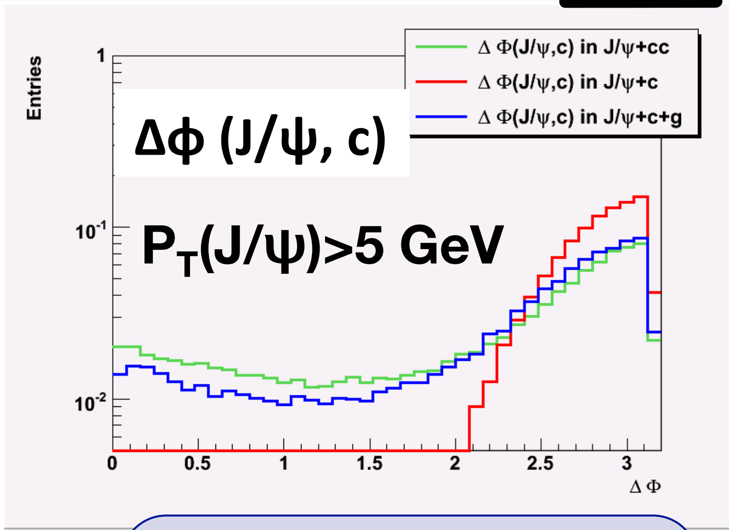
backup

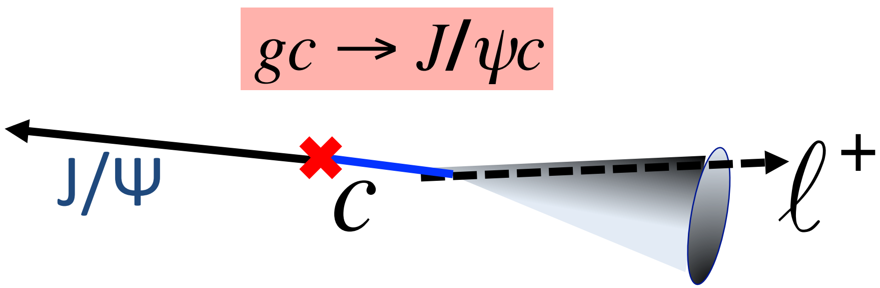
MadOnia example: Associated charm production

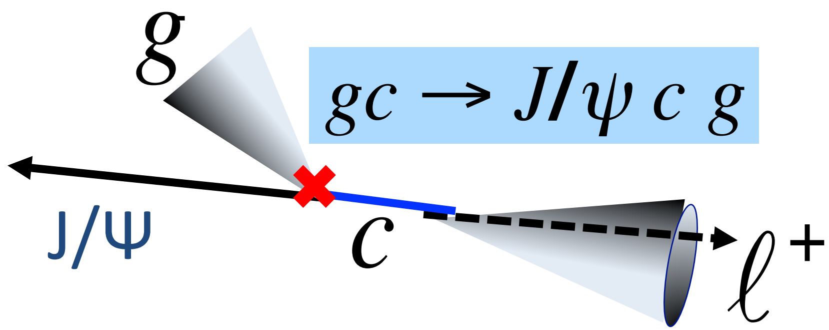
Charm jets could be detected with b/c-tagging algorithm or using leptons from the decay

Where is the c-quark with respect to the J/ψ??









At high $P_T(J/\psi)$ contribution at Δϕ➔0 becomes more important!