Monte Carlo tools for quarkonia
part II

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Outline

- Introduction: Monte Carlo event generators
- Production in PYTHIA6
  - Hard process
  - Effects induced by showers, hadronization, etc
- Shower activity as handle to study the production mechanism?
- Associated charm production studies with MadOnia
- Issues for PYTHIA 8

Quarkonium event generators: overview

Before 2005: Monte Carlo generators based on LO singlet (or event generation flat in phasespace). However, for the preparation of LHC analyses, it's very useful to have more realistic MC event generators.

2005-2006: quarkonium event generation in PYTHIA6 improved

- NRQCD singlet and octet production included
- J/psi and Upsilon production tuned with cross section data
- But 2006: colour octet model seems to disagree with polarization data

2010: we agree that we need better Monte Carlo generators

- PYTHIA description needs to be improved, in PYTHIA8
- Use PYTHIA in combination with matrix elements from elsewhere
  - MadOnia: is it officially part of Madgraph??
  - Other generators for quarkonia for LHC??

This talk: - Outline difficulties and points to improve in MC generation modeling
- Show possible handles to understand the production mechanism (focus on prompt J/psi)

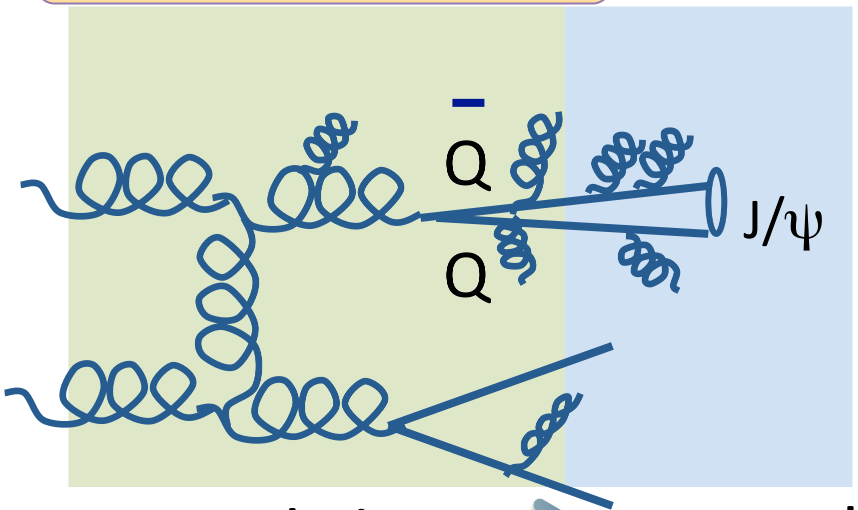
Quarkonium production in PYTHIA6

Let's start with the most widely used generator, PYTHIA6... (in PYTHIA 8, the production is along the same line)

➢**Leading order singlet and octet prompt production**

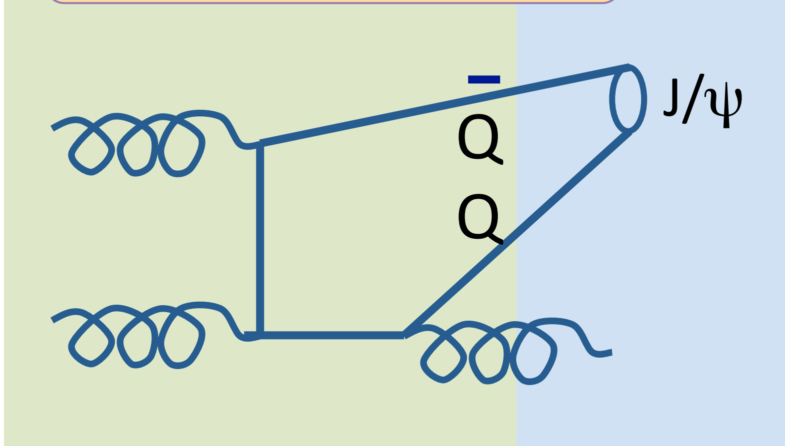
Generation of hard process → **Showers** → **Hadronization**

Octet production



perturbative → **non-perturbative**

Singlet production



perturbative → **non-perturbative**

Hard process: process switches

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

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

ccbar 2L+1 S=1 J=1 colour

$$\vec{J} = \vec{L} + \vec{S}$$

L=orbital angular momentum
S=spin [S means S=0,
P means S=1]
J=total angular momentum

- Each process has an NRQCD matrix-element.
  Certain processes share same matrix element,
  e.g. cc~[3P0(1)], cc~[3P1(1)] , cc~[3P2(1)]
- MSEL(61) generates direct J/ψ's and J/ψ's from χ's, but no J/ψ's from ψ(2S) (see slide 13)
  ➔Should be improved!
- The 2S states can be produced by changing NRQCD matrix elements, particle masses, BR (by hand)➔Should be improved!
- 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)]

NRQCD matrix elements

- Rates for all quarkonium processes given by NRQCD matrix elements
- The MEs are tuned to give agreement MC⇔TeVatron data: hep-ph/0003142,

  see table 13 and 14.
  - CSM values extracted from potential models (hep-ph/9503356)
  - COM values from CDF data
- Quark masses: m_c= 1.5 GeV, m_b = 4.88 GeV

[See M.Bargiotti, V. Vagnoni, CERN-LHCb-2007-042]

cc(1S)	PARP(141)	$\langle O^{J/\psi}[^3S_1^{(1)}]\rangle$	1.16
	PARP(142)	$\langle O^{J/\psi}[^3S_1^{(8)}]\rangle$	0.0119
	PARP(143)	$\langle O^{J/\psi}[^1S_0^{(8)}]\rangle$	0.01
	PARP(144)	$\langle O^{J/\psi}[^3P_0^{(8)}]\rangle / m_c^2$	0.01
	PARP(145)	$\langle O^{\chi_{c0}}[^3P_0^{(1)}]\rangle / m_c^2$	0.05
bb(1S)	PARP(146)	$\langle O^{\Upsilon}[^3S_1^{(1)}]\rangle$	9.28
	PARP(147)	$\langle O^{\Upsilon}[^3S_1^{(8)}]\rangle$	0.15
	PARP(148)	$\langle O^{\Upsilon}[^1S_0^{(8)}]\rangle$	0.02
	PARP(149)	$\langle O^{\Upsilon}[^3P_0^{(8)}]\rangle / m_b^2$	0.02
	PARP(150)	$\langle O^{\chi_{b0}}[^3P_0^{(1)}]\rangle / m_b^2$	0.085

Tuning is for 1S states, matrix elements for 2S states not included in PYTHIA

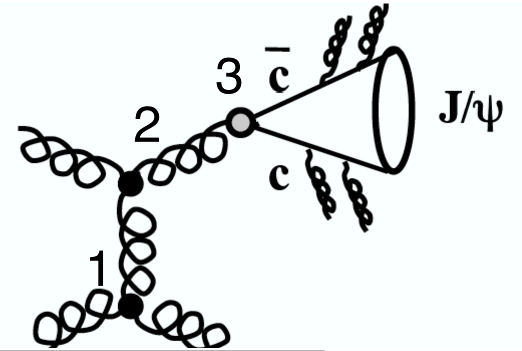
➔**Should be improved!**

Low p_T divergencies (1)

- Problem: even with octet, J/ψ cross section not right: too big at low p_T
- Solution: cross section dampened like gg→gg in underlying event formalism

T.Sjöstrand, M.v.Z, PRD36,2019, 1987

$$\frac{d\sigma}{dp_T} \propto \frac{[\alpha_S(p_T^2)]^2}{p_T^4} \Rightarrow \frac{[\alpha_S(p_{T_0}^2 + p_T^2)]^2}{(p_{T_0}^2 + p_T^2)^2}$$

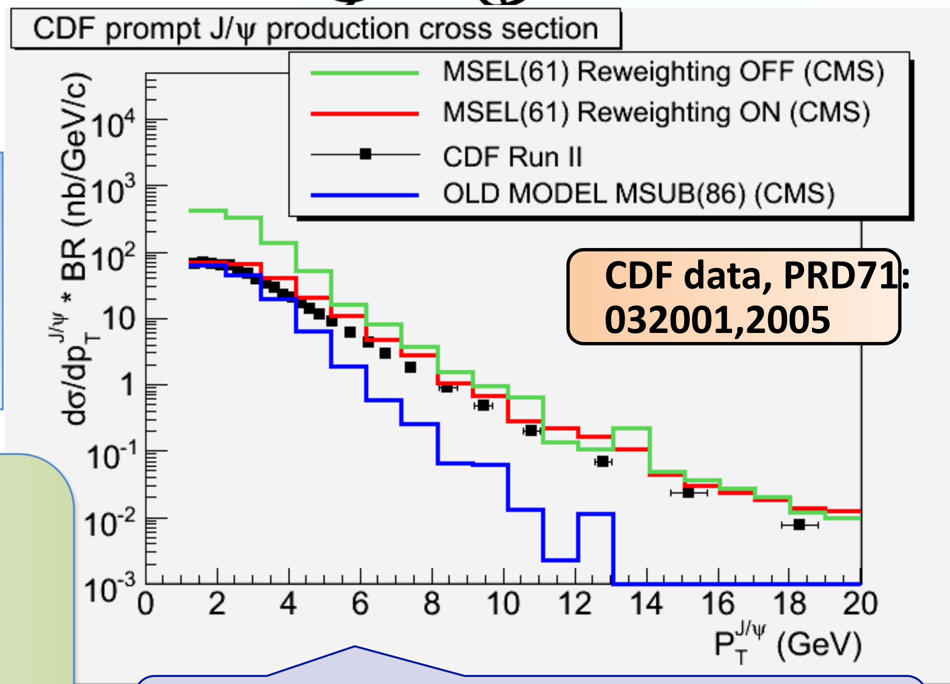


- Switch on with MSTP(142)=1
- Each event gets weight:

$$w_i = \left(\frac{\hat{p}_T^2}{p_{T_0}^2 + \hat{p}_T^2}\right)^2 \left(\frac{\alpha_S[p_{T_0}^2 + Q^2]}{\alpha_S[Q^2]}\right)^3$$

- p_{T0} ~ scale below which cannot resolve individual colours ⇒ α_s decreases ⇒ xs decreases
  CDF: p_{T0} ~2 GeV

Q ~ scale at which to evaluate coupling α_s
Default $Q = \hat{p}_T$

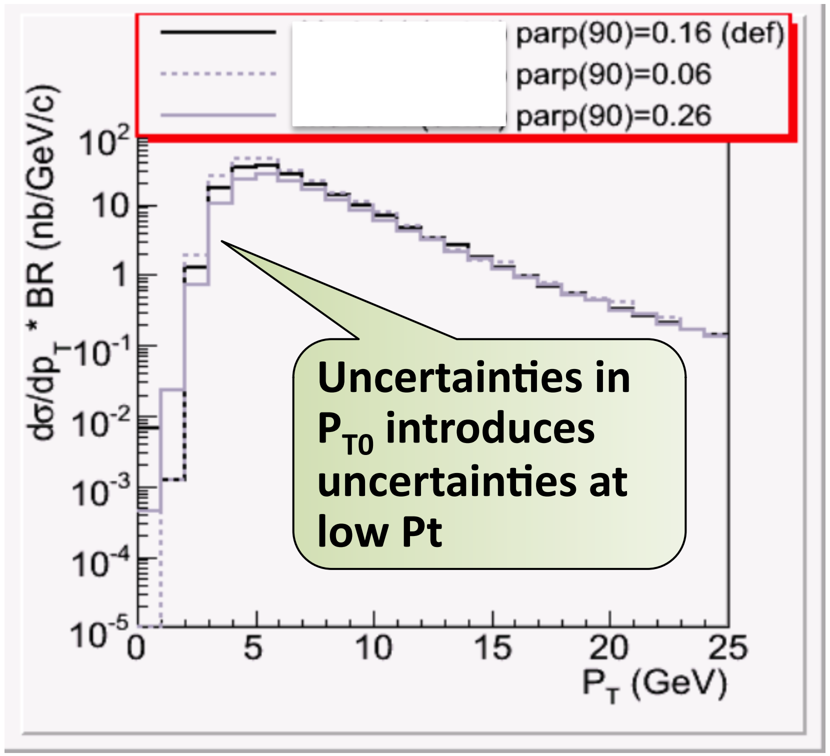


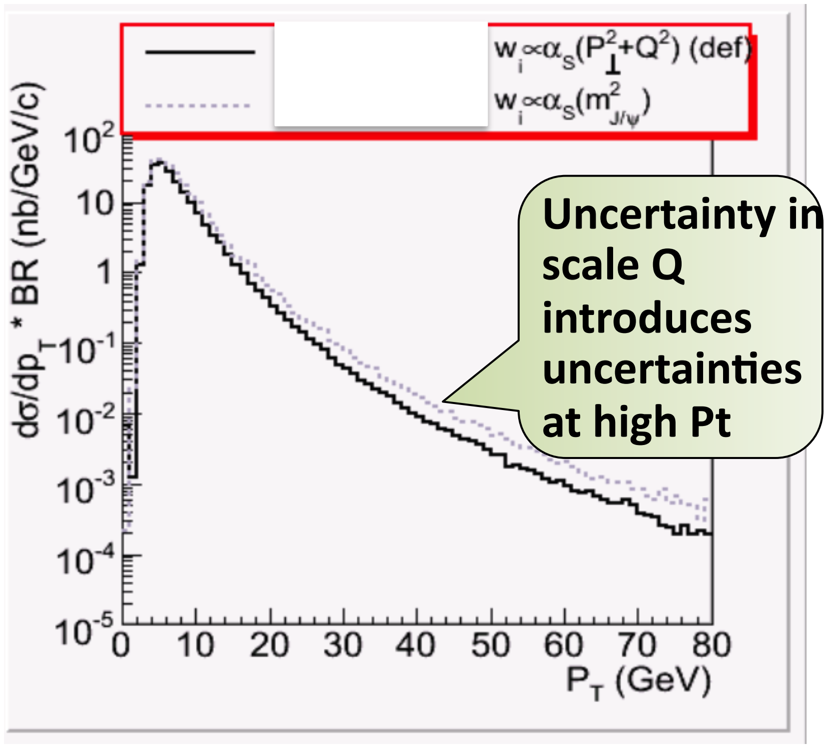
Now MC prediction of cross section of CDF not great but good enough...

Low p_T divergencies (2)

- **At CDF p_{T0}~2 GeV, but what would p_{T0} be at LHC energies??**
  We don't know! It is assumed to grow with √s [x smaller ➔ denser packing of gluons ➔ more screening
  CMS: $p_{T0} = 1.94(14\ \text{TeV}/1.96\ \text{TeV})^{0.16}$=2.66 GeV,
  change to 2.2 and 3.2 GeV

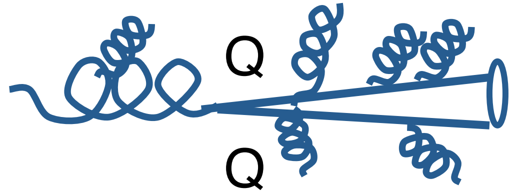
- **What is really the scale Q in α_S (Q)?**
  We don't know! Default: Q= pthat. Maybe smaller? Change to $m_{J/psi}$





Parton showers

Only relevant for octet (in singlet production QQ already colour neutral!)

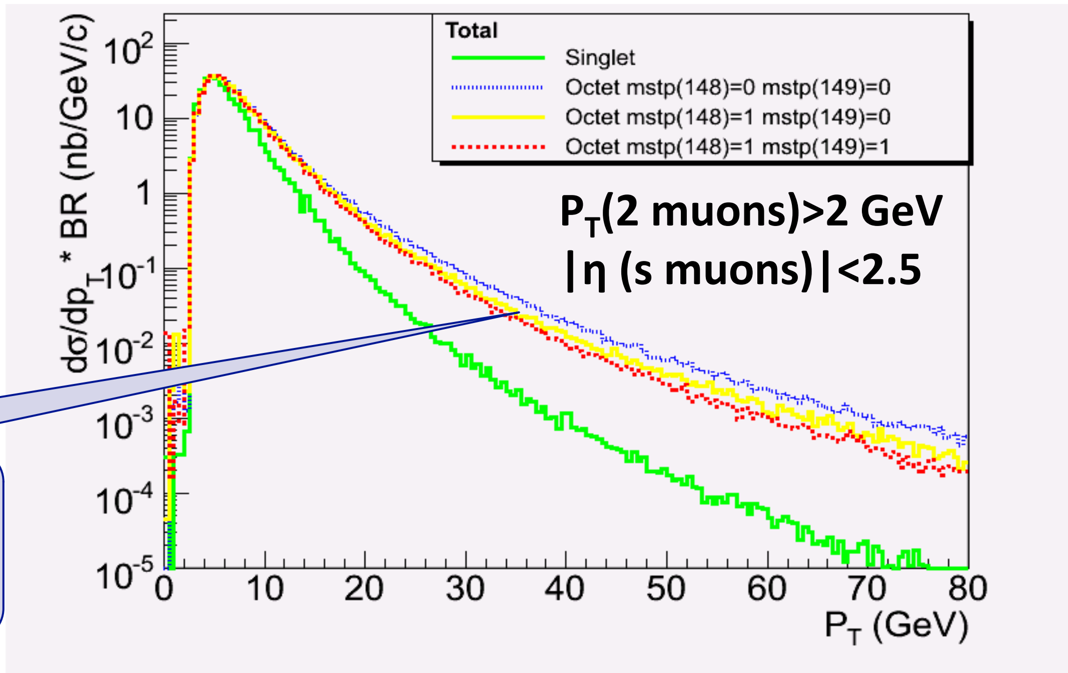


Several shower switches for QQ radiation:

- **MSTP(148)=0 (MSTP(149) doesn't matter)**
  Altarelli-Parisi splitting function: q→qg but corrected for presence of 2 quarks ⇒
  ⇒small amount of radiation
- **MSTP(148)=1, MSTP(149)=0**
  Altarelli-Parisi splitting function: g→gg, "follow" hardest gluon
  ⇒medium amount of radiation
- **MSTP(148)=1, MSTP(149)=1**
  Altarelli-Parisi splitting function: g→gg, symmetric
  ⇒large amount of radiation

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

Prompt J/psi production cross section at 14 TeV

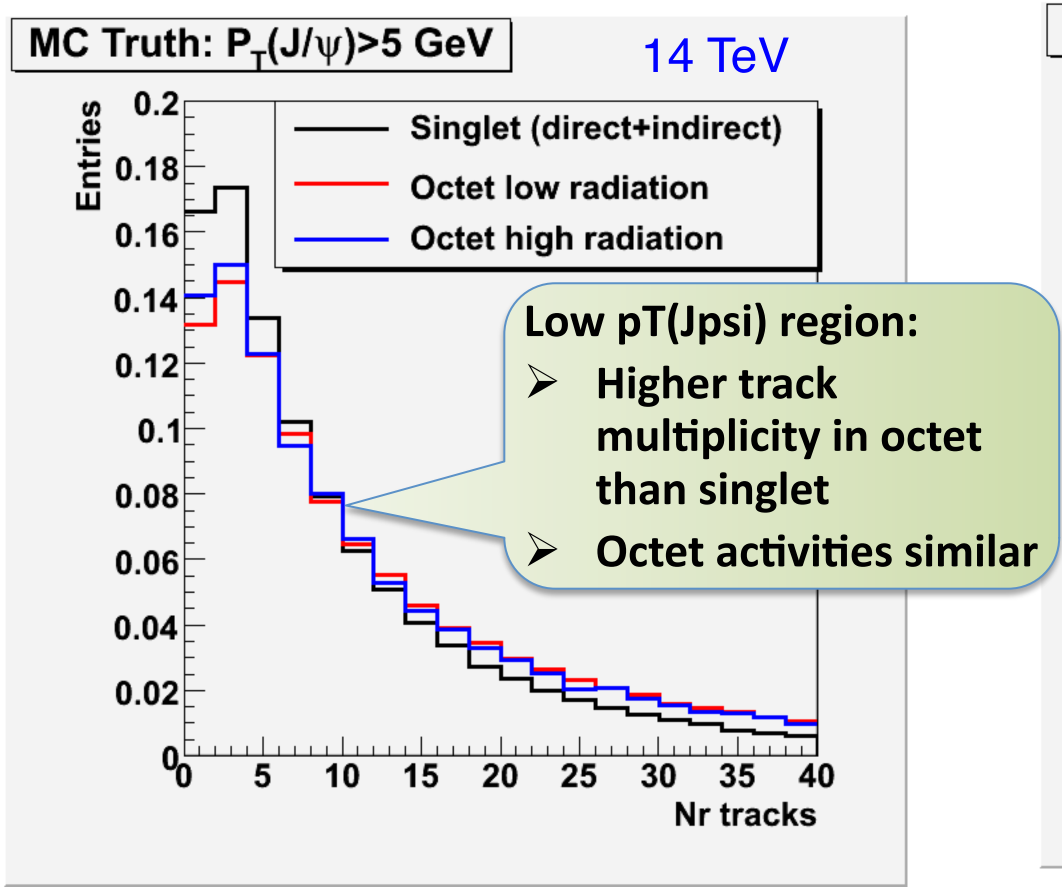


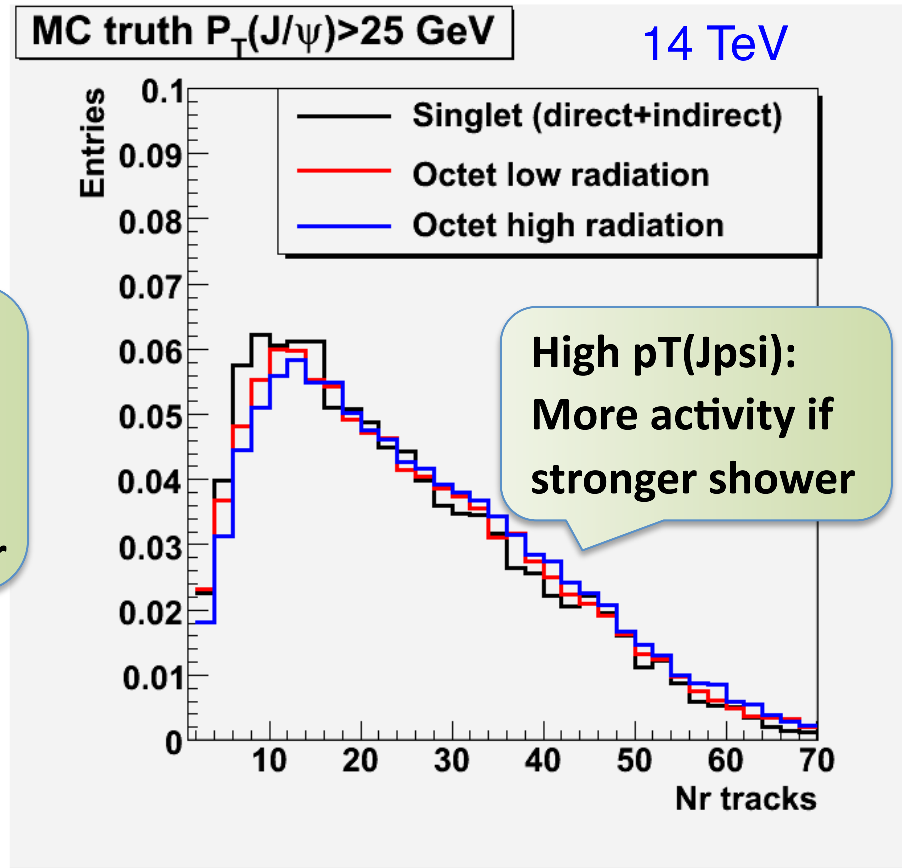
CDF (p_T<20) compatible with all scenario's

Particle multiplicity

Apart from the cross section, gluon emission and parton showers also influence the particle multiplicity of the event.

➔Look at TOTAL number of charged particles (Pt>0.9 GeV, muons excluded) in event (later on, we will concentrate on cone around J/ψ...)



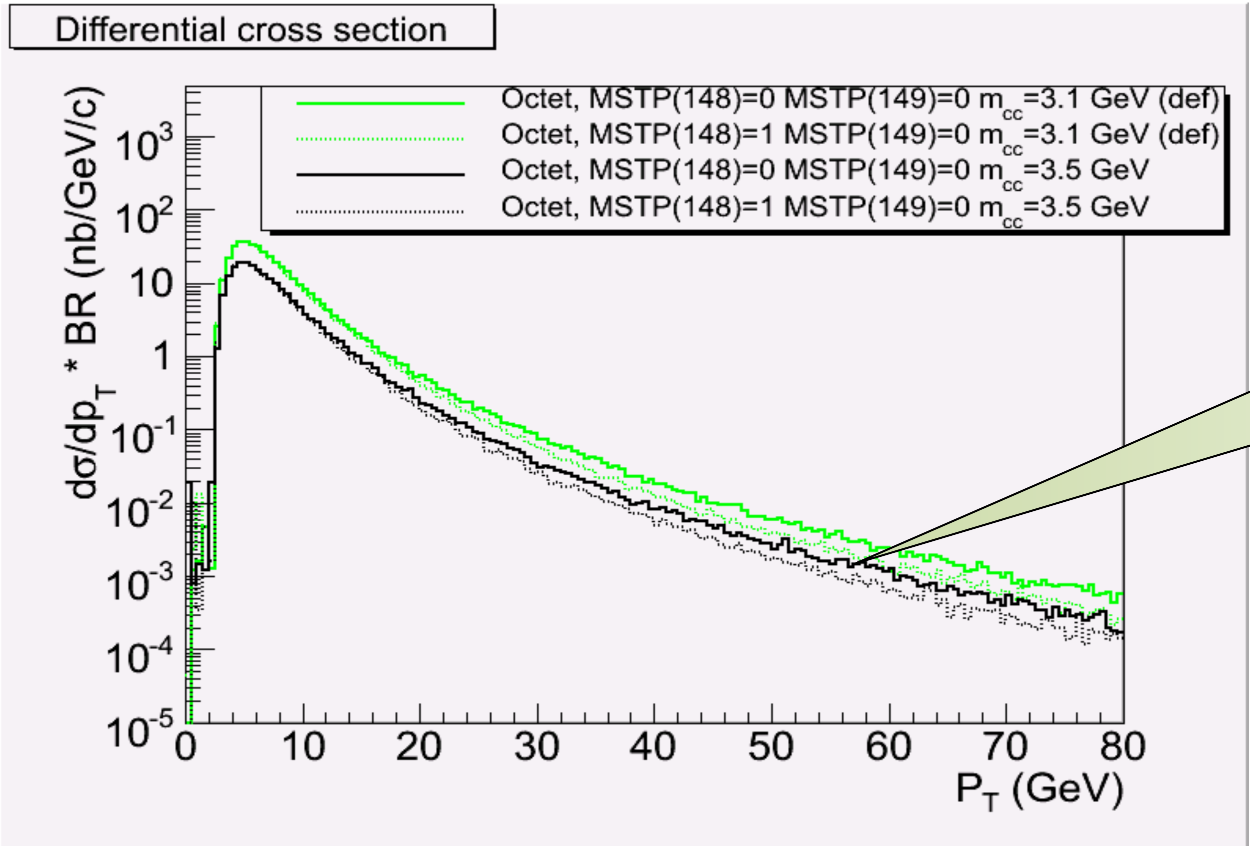


Uncertainty in octet model: mass of octet cc

- **In octet case, what is the mass value for the octet cc state??**

  We don't know! It's no physical state... But this mass value influences the differential cross section shape ➔Should be studied what best value is!

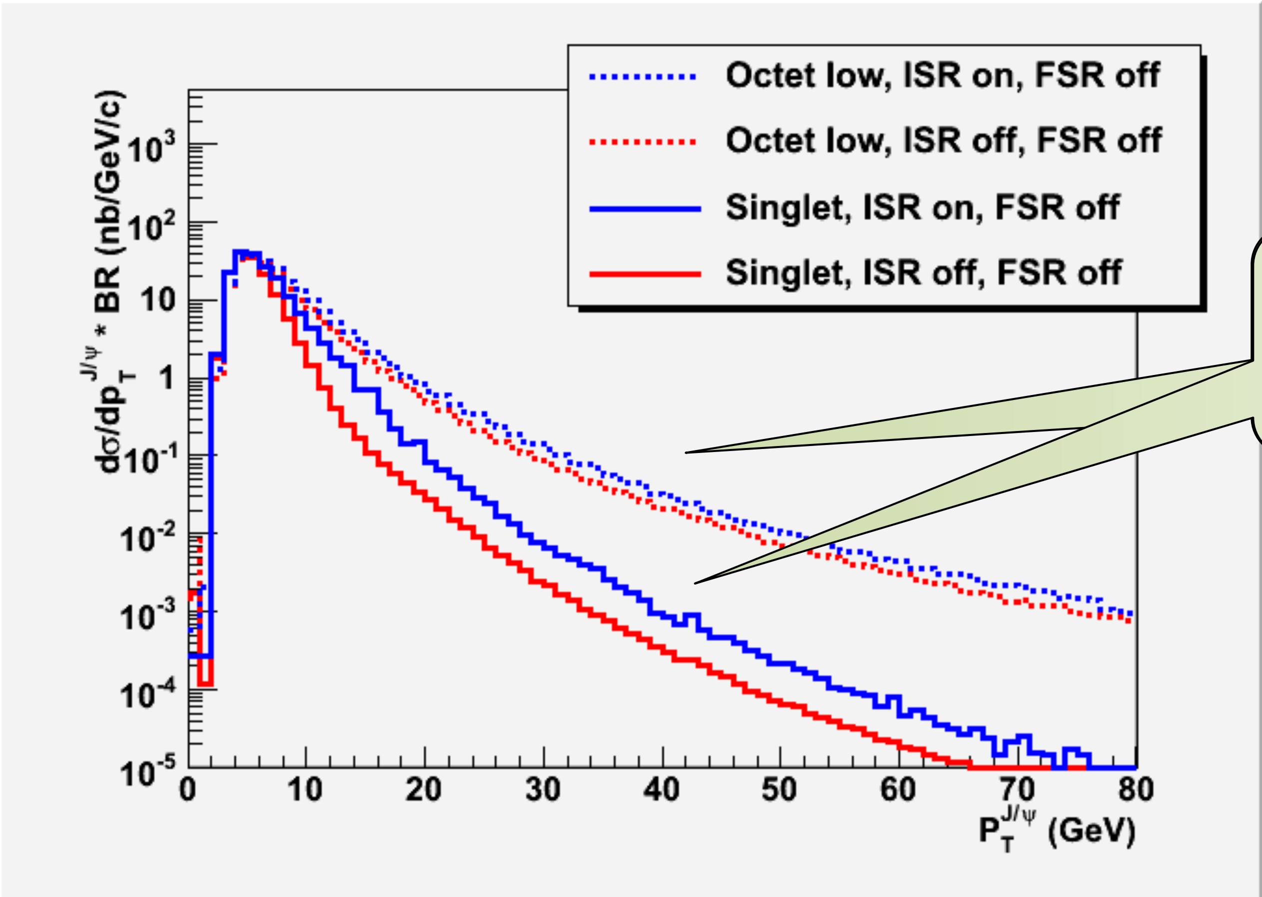
  Default is chosen to be M_{cc} : 3.1 ➔ change to 3.5 GeV



Higher mass ➔lower cross section and more showering

Influence of ISR

Also processed unrelated to hard quarkonium production process like ISR can influence the differential cross section shape...



When ISR=ON slight increase in p_T w.r.t. ISR=OFF

N.B. Unrelated... but mention anyway: multiple interactions do not influence differential cross section shape (i.e. on-off gives same)

Modeling of feeddown (prompt)

- Feeddown from ψ(2S): not included in NRQCD matrix elements (can be done by hand, but no ready-to-use option).
  Expectation ~ 10% of J/ ψ from ψ(2S)
  ➔Should be included!!

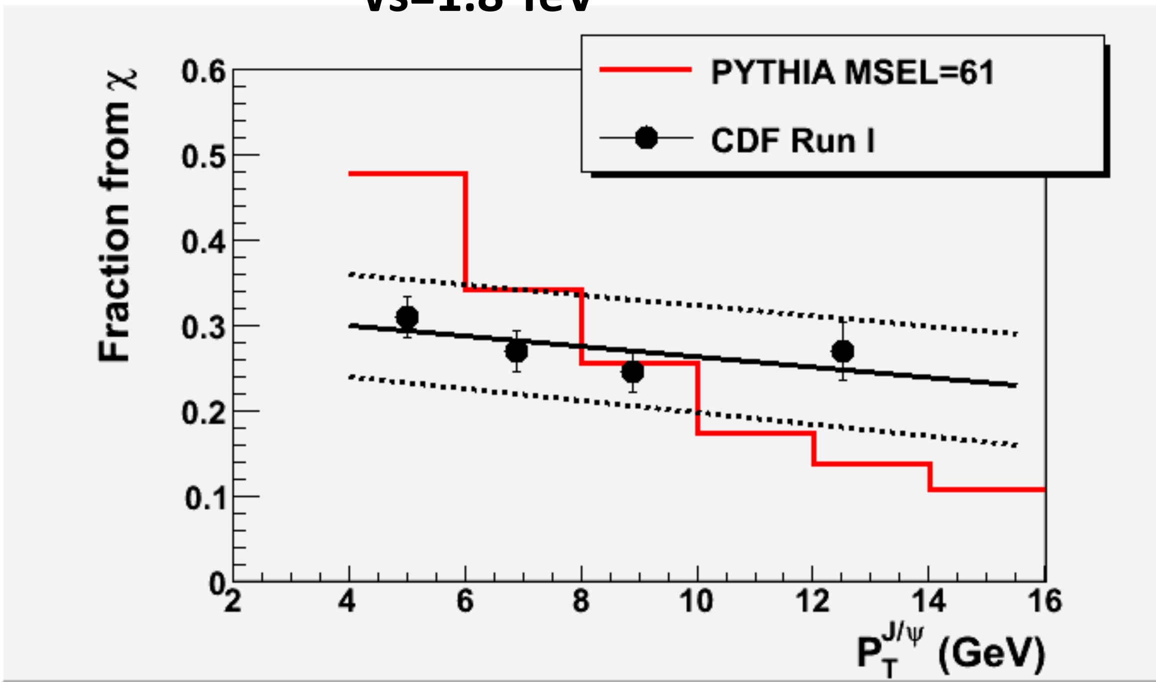
See e.g. CDF, PRL79:578-583,1997
Faccioli etal, JHEP 0810:004,2008

- Feeddown from χ's: Expectation ~ 30%
  – Only included in singlet production get χ's (strange ?)
  – Fraction does not agree well with data

➔Feeddown modeling should be improved!

N.B. CDF analysis assumes polarization of chi to be equal to that of J/psi. Could be different? (results in different acceptances)

√s=1.8 TeV



Outline

- Introduction: Monte Carlo event generators
- Production in PYTHIA6
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  - Non-trivial effects influencing the cross section
- Showeractivity as handle to study the production mechanism?
- Associated charm production with MadOnia
- Issues for PYTHIA 8

Understanding the production mechanism

➢A differential cross section measurement is going to give us important information, but won't tell us what the production mechanism really is.

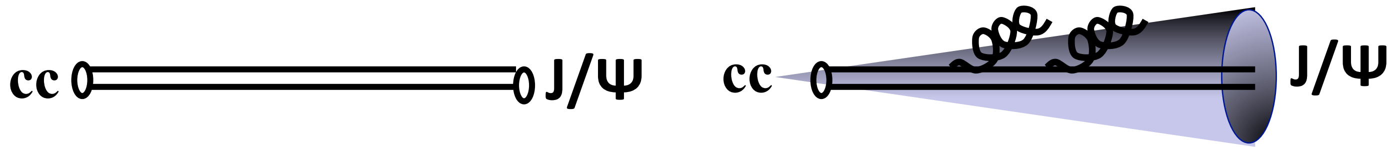
➢Other classical measurement: polarization

But what else can we do??

➢Study the dynamics of the particles around the J/ψ

– Sensitive to shower and gluon radiation in direct vicinity

– Differences visible between singlet and octet? (slides 16-20)



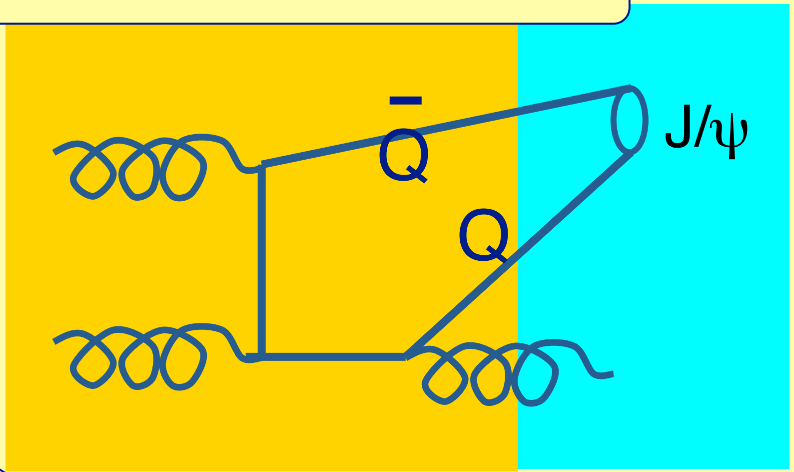
– Differences visible between directly and indirectly J/ψ's? (slides 21)

(Gluon emission in J/ψ, χ_{0c}, χ_{c1}, χ_{c2} is different due to quantum number conservation)

➢ Study production of associated particles like charm (slides 22-27)

Example 1: Strawman models used

Singlet production

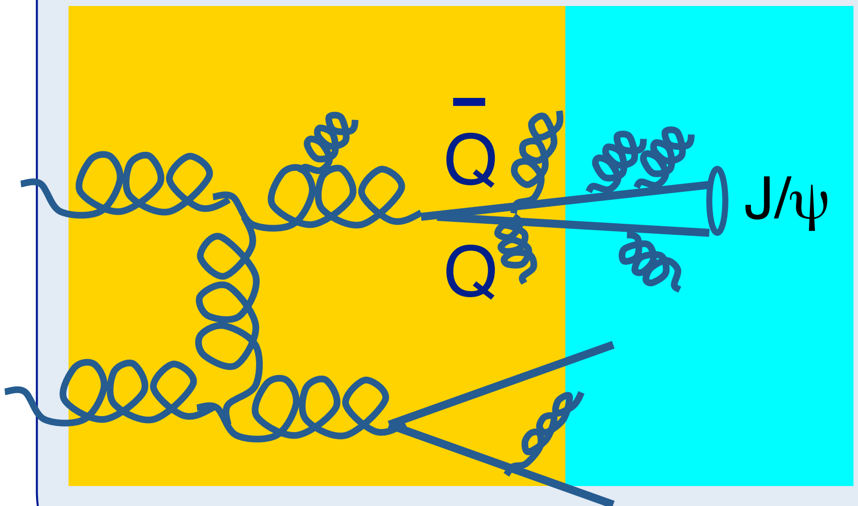


- QQ-state produced in colour singlet in hard interaction
- Based on tuned NRQCD matrix elements
- Color singlet➔less g-radiation

Model 1: no radiation around J/psi
(NB chi-feeddown included)

perturbative → non-perturbative

Octet production



- QQ-state produced in colour octet in hard interaction
- Based on tuned NRQCD matrix elements
- Color octet ➔ lots of g-radiation

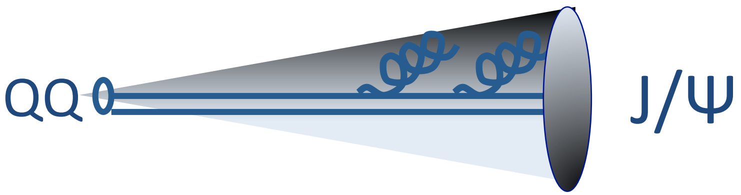
  ➡QQ produced in shower!
- Can regulate amount of radiation

Model 2: low radiation around J/psi
Model 3: high radiation around J/psi

Observable: activity around J/psi

- Shower activity of 3 models is different
  ➔ natural observable:

Nr charged particles (P_T>0.9, except μ's) around J/ψ in cone (here R=0.7)

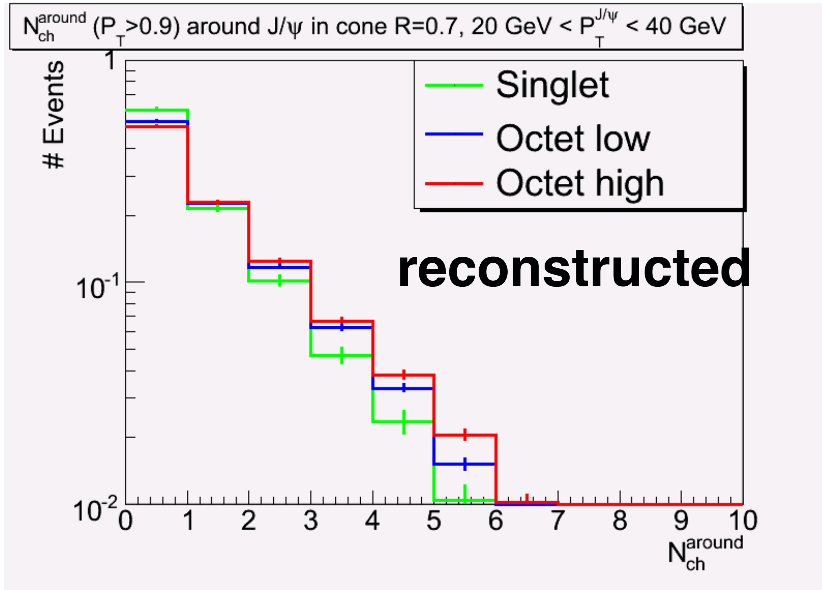


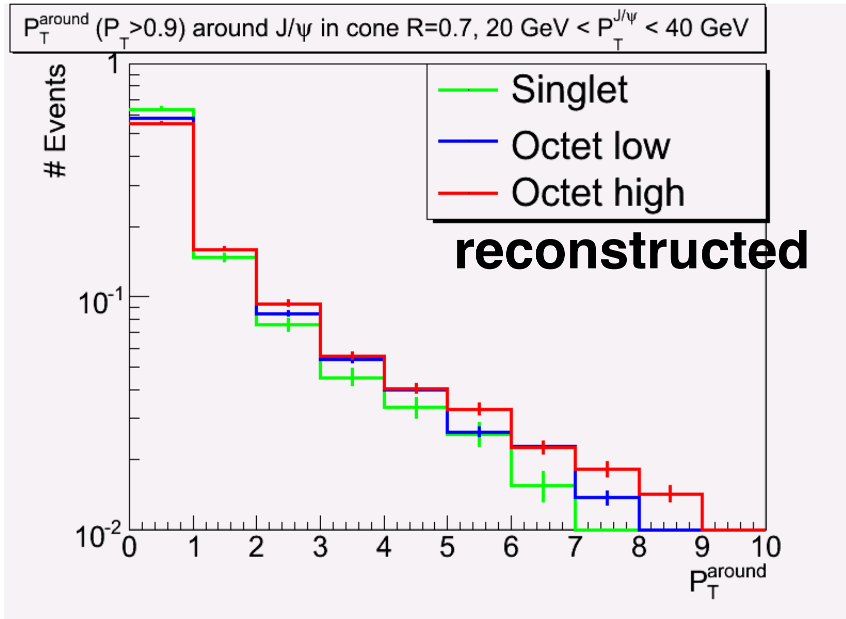
Scalar sum of P_T of charged particles around J/ψ in cone with R=0.7

✓The particles around the J/psi are generally low energetic (<1 GeV)!

✓The differences are at high P_T(J/ψ) (> 20 GeV/c)

✓The differences are subtile



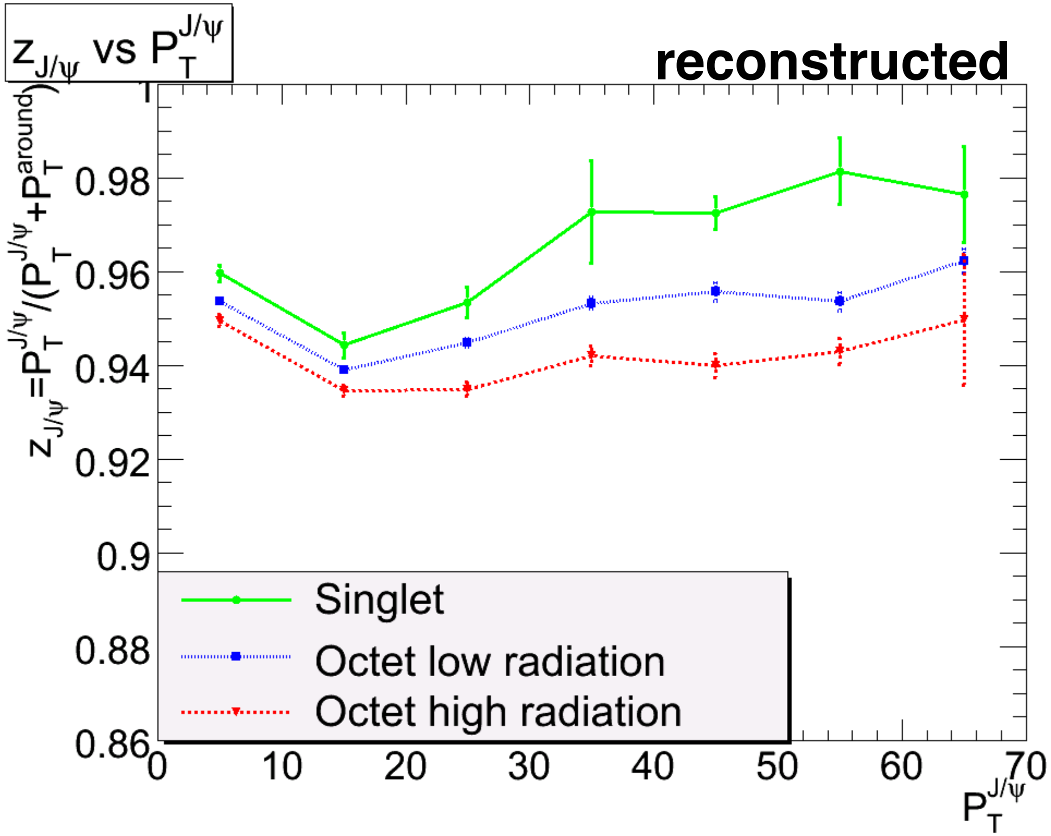


Possible observable: $z_{J/\psi}$

- Since for 4 models fragmentation function is different, try $z_{J/\psi}$ ~ theoretical fragmentation variable z

$$z = \frac{P_T^{J/psi\ itself}}{P_T^{J/psi} + P_T^{cone\ 0.7}}$$

- $Z_{J/psi}$ vs $P_T^{J/psi}$
- Interesting shape!
- Shape is influenced by multiple interactions (= collisions from partons of same protons) causing accidental hadronic activity

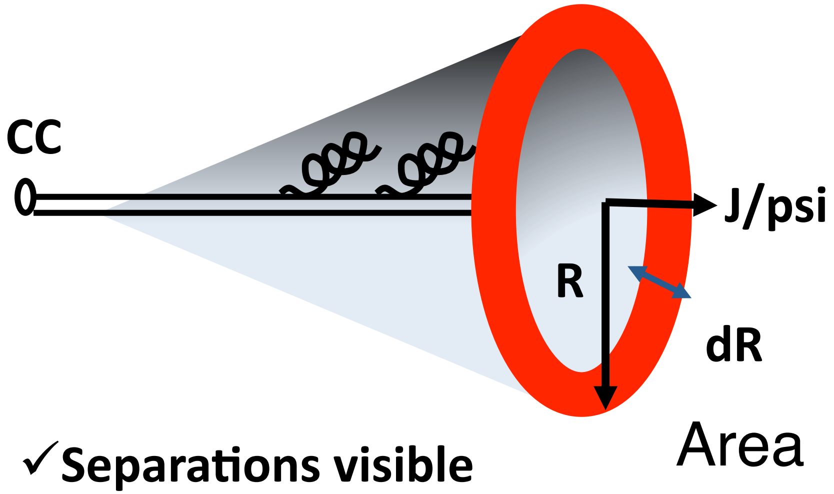


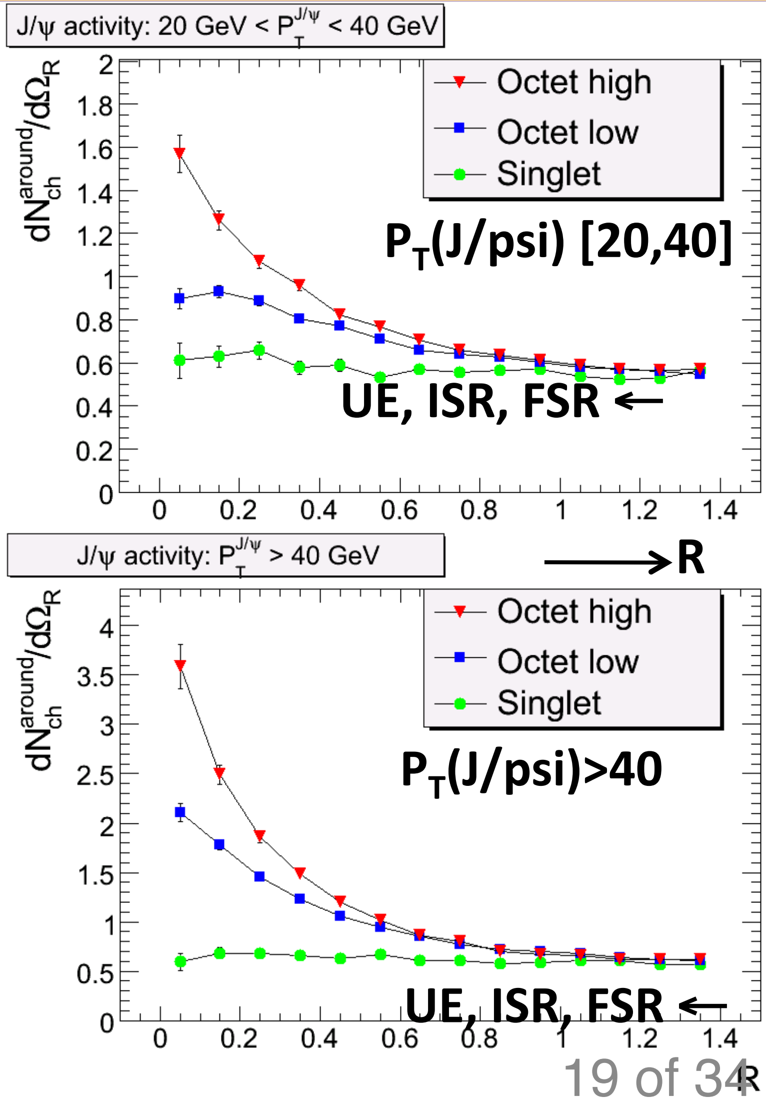
➔ $z_{J/\psi}$ interesting observable, but have to understand underlying event

Possible observable: track density vs. ΔR

- Instead of looking at 'average' activity, look at dN/dΩ vs ΔR between J/psi and surrounding 'tracks' (i.e. normalize with area)
- Higher energetic QQ has more collinear hadronization! I.o.w. highest energetic g's close to J/ψ

$$\frac{dN_{ch}^{around}(R)}{d\Omega_R} = \frac{N_{ch}^{around}(R+dR/2) - N_{ch}^{around}(R-dR/2)}{\pi[(R+dR/2)^2 - (R-dR/2)^2]}$$



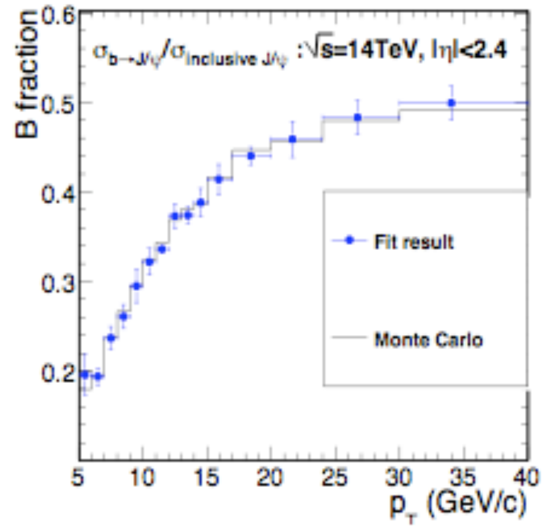


✓ Separations visible

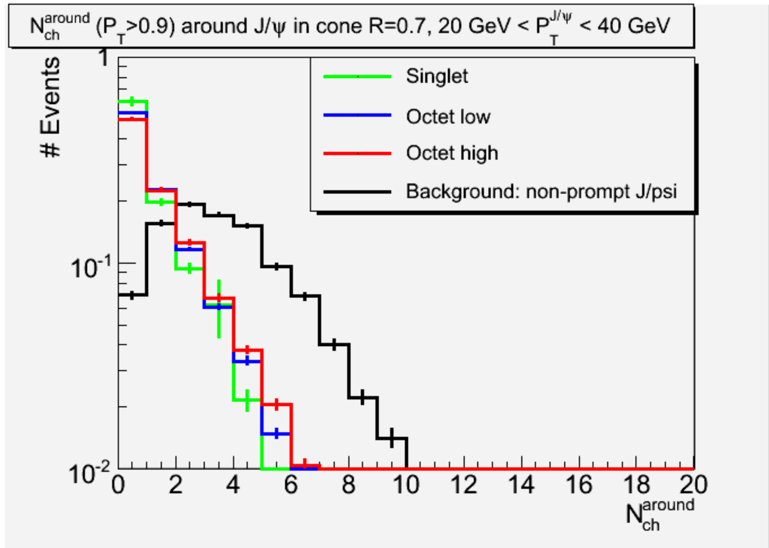
✓ Again underlying event activity present, but should be constant

Challenges

CMS-PAS-BPH-07-002

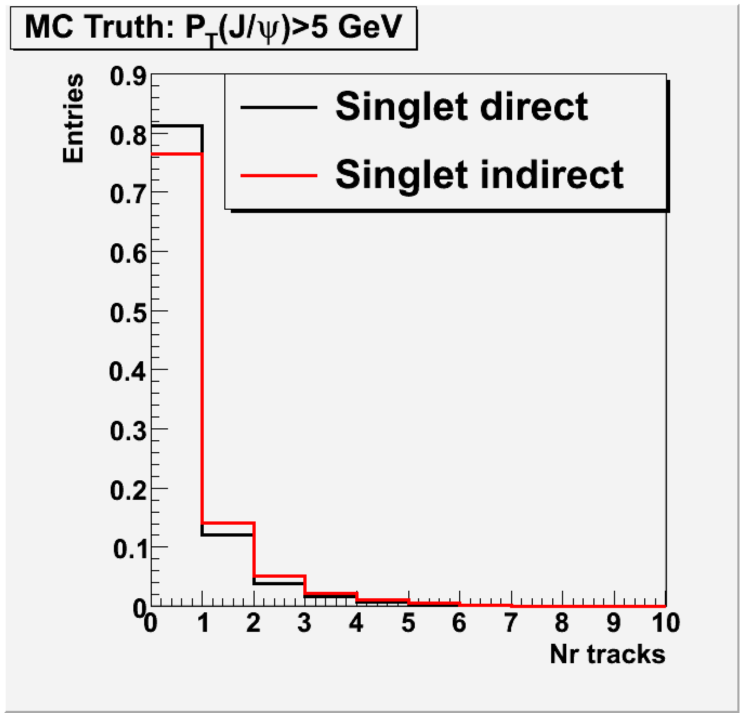


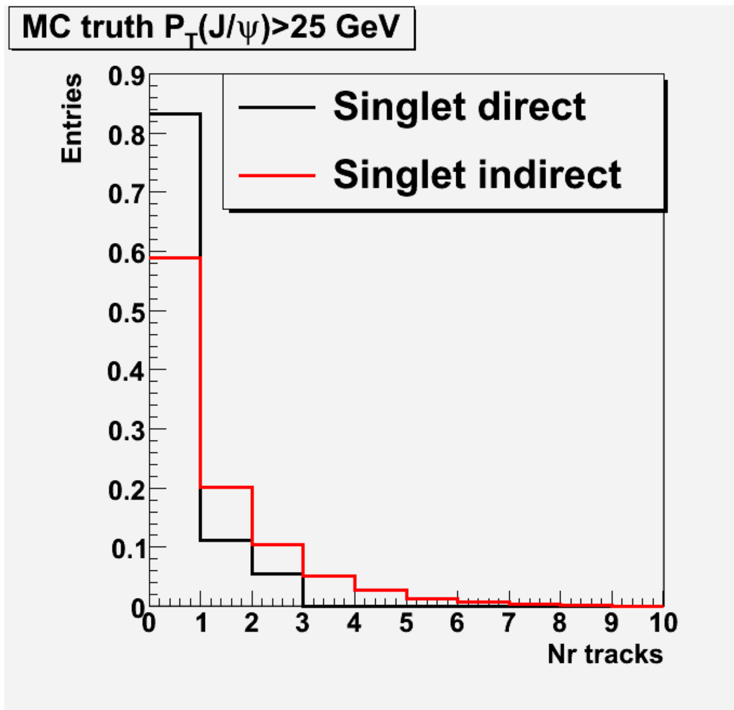
- Several experimental challenges in using these observables
  - Non-prompt J/ψ's:
    - There are a lot of non-prompt J/ψ's at high Pt!
    - These have a large activity around the J/ψ
    - Should cut very sharpy on lifetime to reduce it!!
    - But maybe easier to do for Upsilons...
      - No non-prompt Upsilons
      - But less gluon radiation
  - At high p_T(J/ψ) the muons are close in space. Detection of low energetic tracks very close to two high energetic muons with small opening angle may be difficult.



Direct versus indirect production

- Look at the difference between directly and indirectly produced J/ψ's
- Due to the conservation of quantum numbers, direct J/ψ, J/ψ via χ_{c0}, χ_{c1}, χ_{c2} have different gluon emission (nr of gluons differs, behaviour with Pt)
- Look at number of particles (p_T>0.9 GeV) in cone R=0.7
- Larger amount of activity in indirect case at low and high Pt... (??)
  - Not understood, needs to be investigated (Average Pt(J/ψ) value is not the reason)





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Example 2: associated charm production

with Jean-Philippe

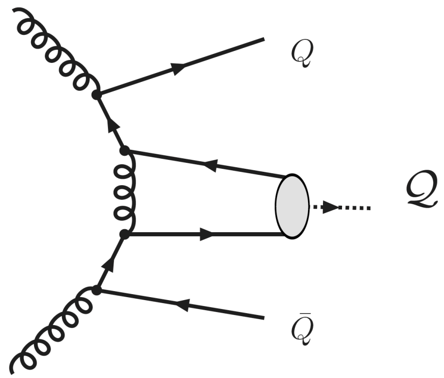
The CSM mechanism revived: add contributions to LO $gg \rightarrow J/\psi g$

1) Add NLO contribution to gg fusion:

$$gg \rightarrow J/\psi\ cc$$

Signature: charm quark pair in association with J/ψ

Artoisenet, Lansberg, Maltoni, PhysLettB653,60,2007
Baranov, PhysRevD73, 074021,2006

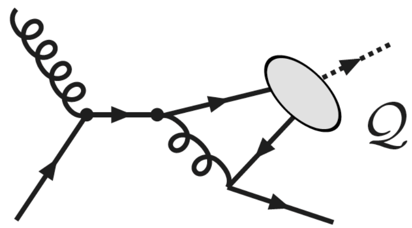


2) Add LO charm-gluon fusion contribution:

$$gc \rightarrow J/\psi c$$

Signature: charm quark opposite to J/ψ

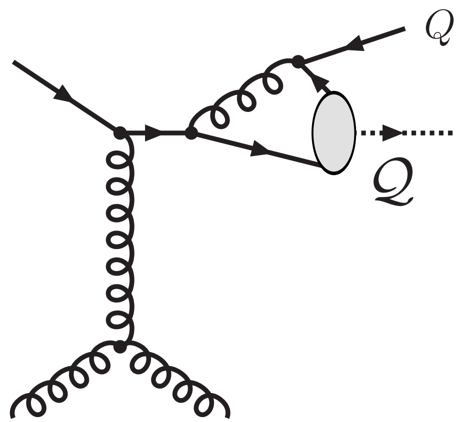
Brodsky&Lansberg, arXiv:0908.0754 [hep-ph].



3) Add NLO contribution of cg fusion:

$$gc \rightarrow J/\psi\ c\ g$$

Signature: charm quark close or opposite to J/ψ



Example 2: associated charm production

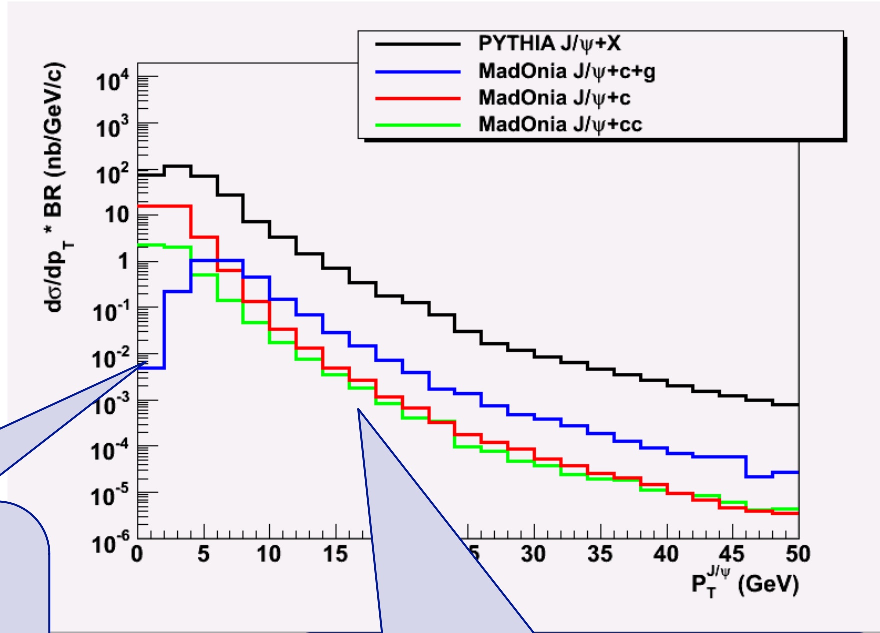
MadOnia events generated (JPL)

(gg➔J/ψcc, gc➔J/ψc, gc➔J/ψcg),

hadronized with PYTHIA6

Compared with default prompt J/ψ+X PYTHIA

[chi feeddown excluded here!]



Double muon filter applied:

both μ's η[-2.5,2.5]

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

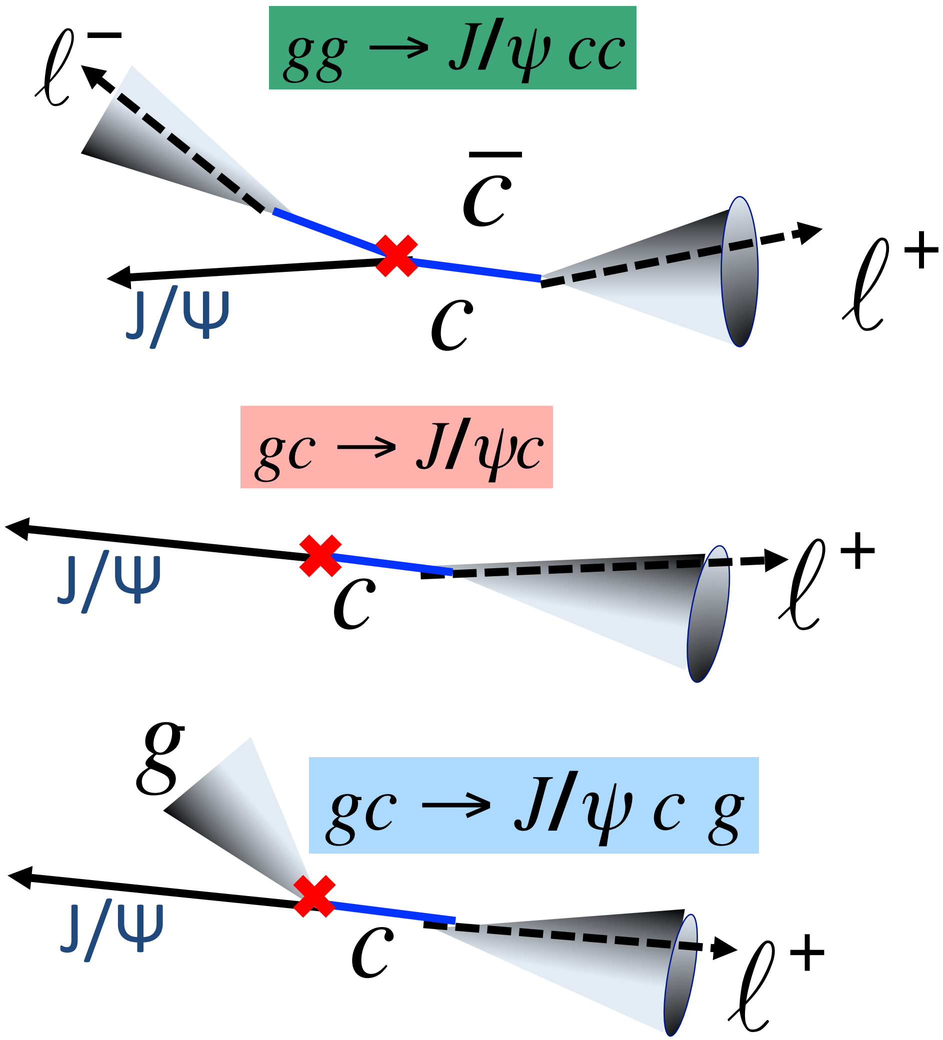
Contribution of charm about 10% of total!

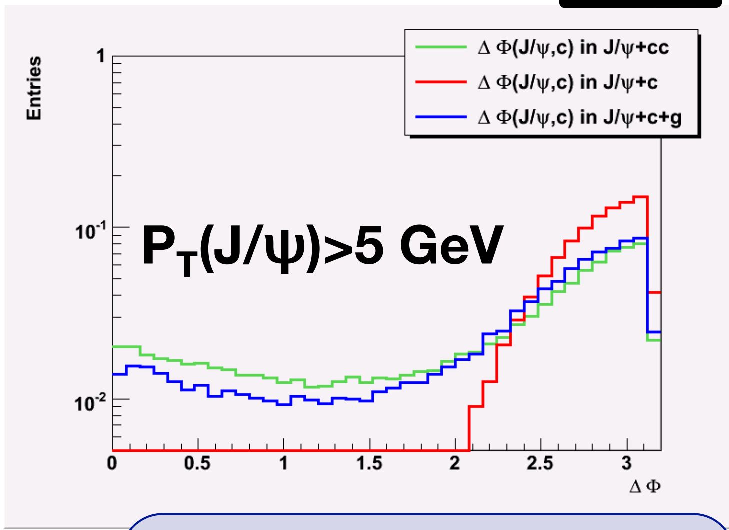
Charm jets could be detected by

- Using b/c-tagging algorithms
- Using leptons from the decay➔ here: look at events with 3 muons

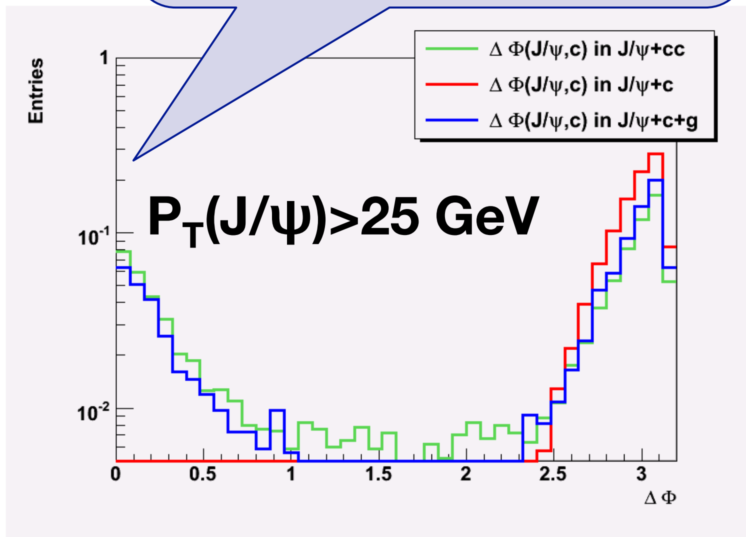
Example 2: associated charm production

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





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



Example 2: associated charm production

Look at MC events with 3 muons (BR(c➔μ X)~10%)

- Case 1: Low $P_T(J/\psi)$: - require P_T(any μ)>3 GeV, |η(any μ)|<2.5
  - $P_T(\mu\mu)$>5 GeV, $M_{inv}(\mu\mu)$[3.0,3.2] GeV
- Case 2: High $P_T(J/\psi)$: -require P_T(any μ)>5 GeV, |η(any μ)|<2.5
  -$P_T(\mu\,\mu)$>25 GeV, $M_{inv}(\mu\mu)$[3.0,3.2] GeV

Statistics for MC TRUTH muons

Sample	Case 1: Low $P_T(J/\psi)$ # events in 20 pb-1 with 3 μ's	Case 2: High $P_T(J/\psi)$ # events in 200 pb-1 with 3 μ's.
MadOnia J/ψcc	75	15
MadOnia J/ψc	95	10
MadOnia J/ψcg	575	90
PYTHIA prompt J/ψ X	520	221
PYTHIA Non-prompt J/ψ X	250	n.e.

Conclusion:
Low $P_T(J/\psi)$ region interesting (large excesss), but muons are difficult to reconstructg in CMS/ATLAS

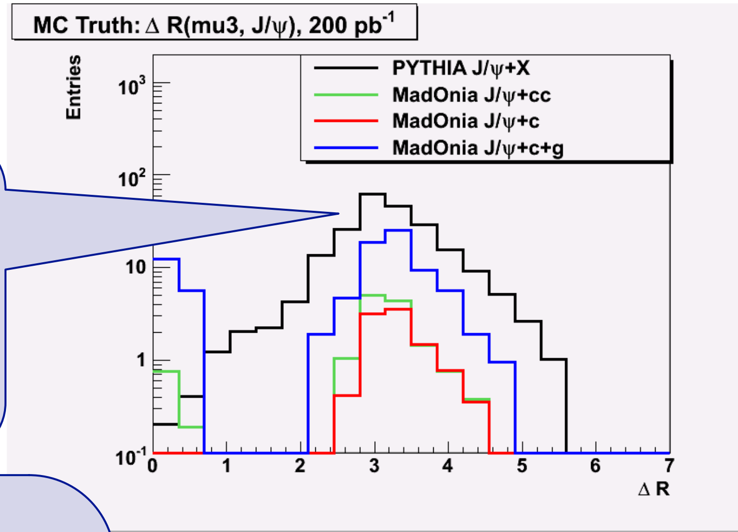
Concentrate now on high $P_T(J/\psi)$ region!

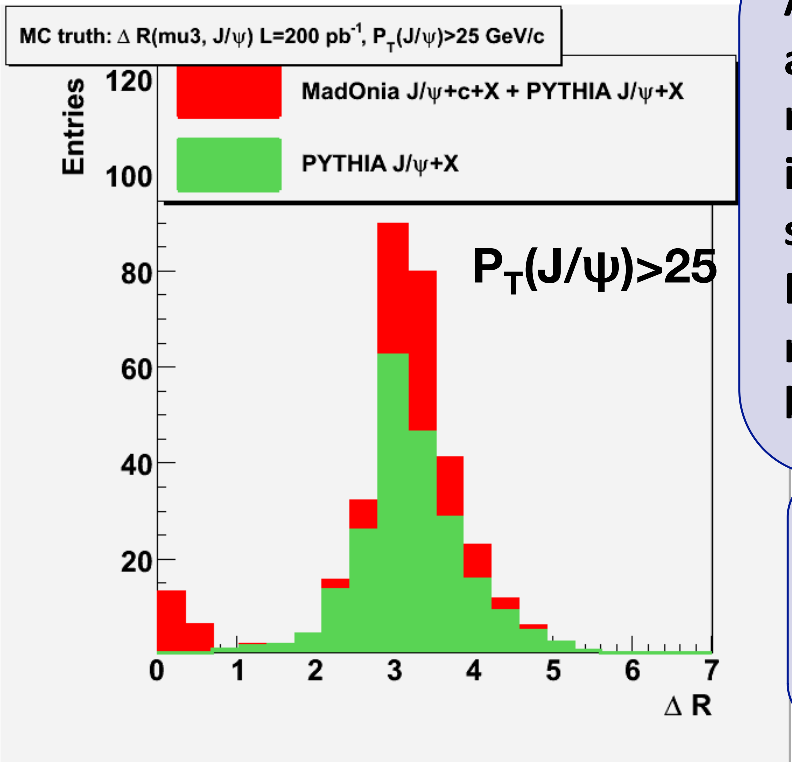
Example 2: associated charm production

Look at the angle between 3rd muon and J/ψ

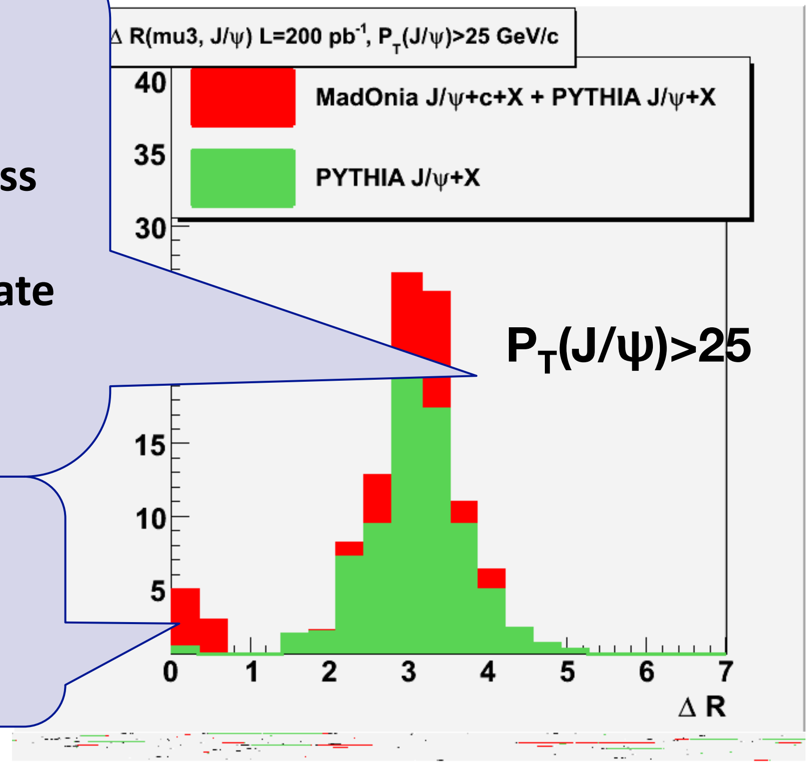
MC truth level: sum of all charm contributions

MC Truth: also PYTHIA prompt J/psi+X has leptons opposite to J/psi!





After taking into account reconstruction inefficiencies excess still visible.
But need to evaluate more carefully background!!



Challenging: detect 3 close muons!!!

Moving to PYTHIA 8

Main differences with PYTHIA 6:

- Two ways to generate quarkonia:
  - Explicitly request quarkonia production (prompt only)
  - As part of multiparton interaction framework, i.e. min bias events and the underlying event contain prompt and non-prompt J/psi;s!

- The OO structure of Pythia8 makes it simpler to extend/clone processes, so that e.g. Psi' production could be modeled as J/Psi.

- Torbjörn can do implementation, but:

  First experimentalists should formulate precisely what they want and contact relevant theory experts that can give input. These theory experts should contact Torbjörn and tell him what to use.

  Checks, validation and tuning work could be done by "less expertise" people.

Of course, PYTHIA 8 can also be used on external matrix elements like those coming from Madgraph!!

Conclusions

- **There is no satisfactory Monte Carlo event generator for quarkonia at this moment**
- **The generator mostly used is PYTHIA6**
- **If we want to base LHC studies on PYTHIA, a significant amount of improvements have to be done, in PYTHIA 8!!**
- **Only possible if quarkonium theory experts, event generator experts, and experimentalists do an effort**
- **Alternative ways to understand the j/psi production mechanism should be investigated. We probably won't solve the production mechanism puzzle just with cross section and polarization measurements!!!!**
- **Look for particles (shower tracks?, leptons?) very close to the J/psi?**
- **Look for leptons opposite to the J/psi?**