Experimental aspects of heavy quarkonium production at the LHC

Aafke Kraan
INFN Pisa

Three Days of Strong Interactions and Astrophysics HLPW 2008

Joint Meeting Heidelberg-Liège-Paris-Wroclaw

Outline

- Introduction
- Quarkonium production in PYTHIA 6.409
- J/psi production studies
- Upsilon production studies
- Quarkonia measurements planned at LHC
- Plans and conclusions

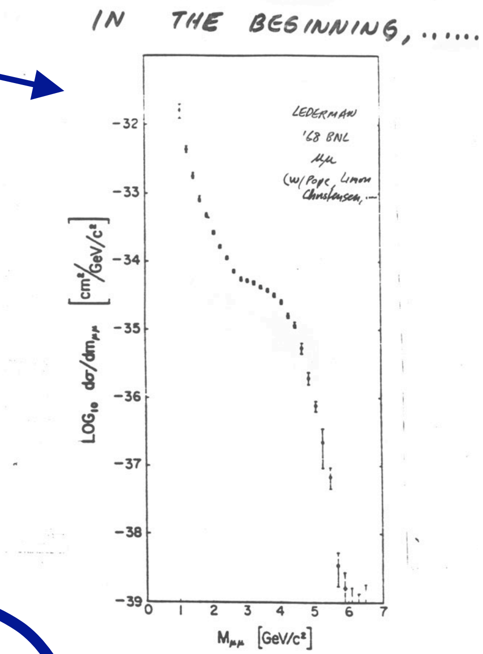
Motivations

The J/psi has been discovered more than 30 years ago... and has since then been studied by many experiments like Tevatron, HERA, ...

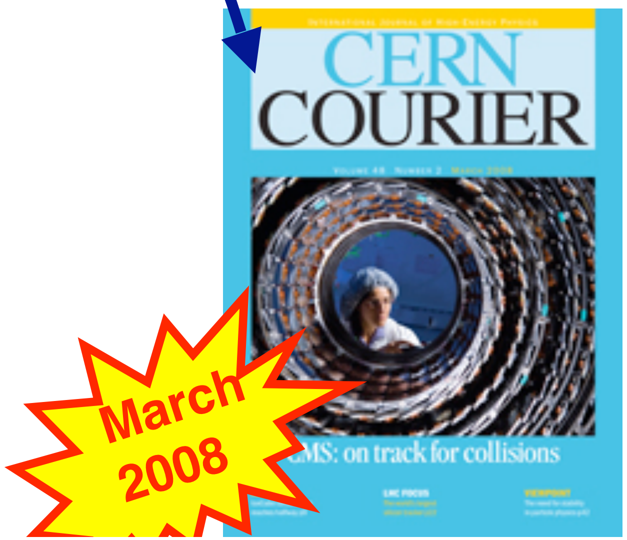
$Q\bar{Q}=c\bar{c},\ b\bar{b}$

Why still study quarkonia at the LHC?

- Still today quarkonium production not understood!
  - Experimental data not understood!
- Theoretically recently lots of progress made, calculations should be compared with LHC data
- The LHC allows for new studies: higher P_T &luminosity!
- Quarkonia crucial to understand detectors (alignment, calibration)



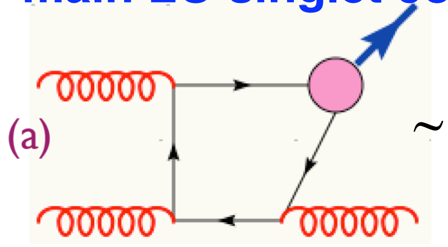
Still lots of interest for quarkonia studies at LHC!



Quarkonium production models

Before CDF Run 1: J/psi's thought to be produced via singlet mechanism.
CDF data factor 50 above theory

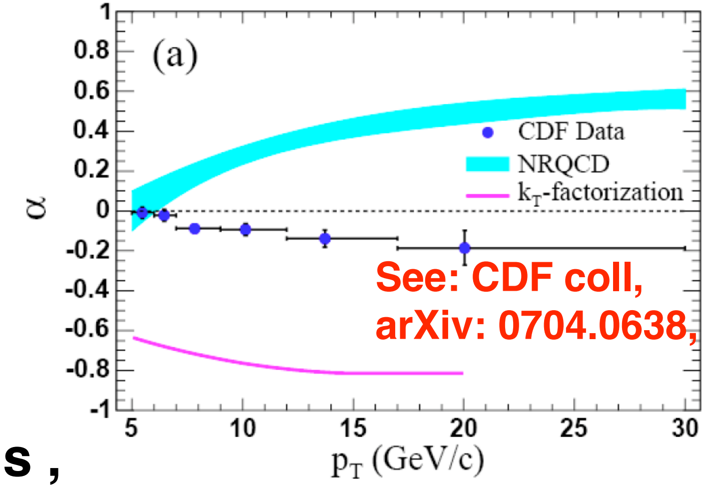
main LO singlet contribution



$$\sim \alpha_S^3 \frac{(2m_c)^4}{P_T^8}$$

➡ **New approaches developed!**

- **Non-Relativistic QCD-formalism**
  - **Quarkonium state written as expansion in v in Fock-space:**
    (v = velocity of Q in bound state in CM) ➡ **singlet&octet mechanism**
  - **Octet contribution could explain P_T spectrum at Tevatron, but not polarization!**
- **NNLO singlet calculations** ➔ **no need for octet??** new
- **K_T factorization approach**
- **Older models: soft-colour-Interaction models , colour-evap. models, ..**



See: CDF coll, arXiv: 0704.0638,

Overview see J.-P.Lansberg, Int.J.Mod.Phys.A21:3857-3916,2006

Quarkonium production at LHC

There are several ways to study (prompt) quarkonium production

- **Diff. cross section** measurements➔ Will be done in first months

  Important, but cross section sensitive to many factors (slide 10+24)...

- **Polarization** measurements ➔ Will be done in first months

  Gives important information on production mechanism

- **Hadronic activity** around J/psi ➔ Possible? Not yet clear!

  Might gives complementary information on production mechanism (idea with Torbjörn Sjöstrand) ➨ today

  How? Compare models with different shower activity and try to investigate sensitivity of typical LHC detector (ATLAS or CMS).

These three measurements together should allow the quarkonium production puzzle to get solved at LHC!

NB1: For quarkonium measurement, so far concentrate on muon decays! BR ($J/\psi \rightarrow \mu\mu$)=5.98% BR ($\Upsilon \rightarrow \mu\mu$)=2.48%

NB2: Prompt production! But do not distinguish between direct&indirect.

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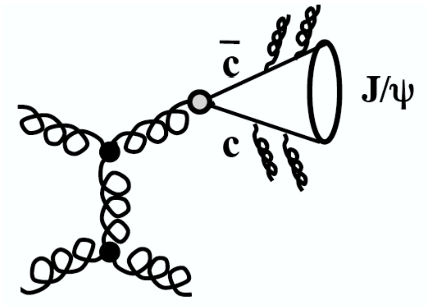
Quarkonium event generation: Pythia 6.409

Original implementation by S. Wolf (2002, never in official release)

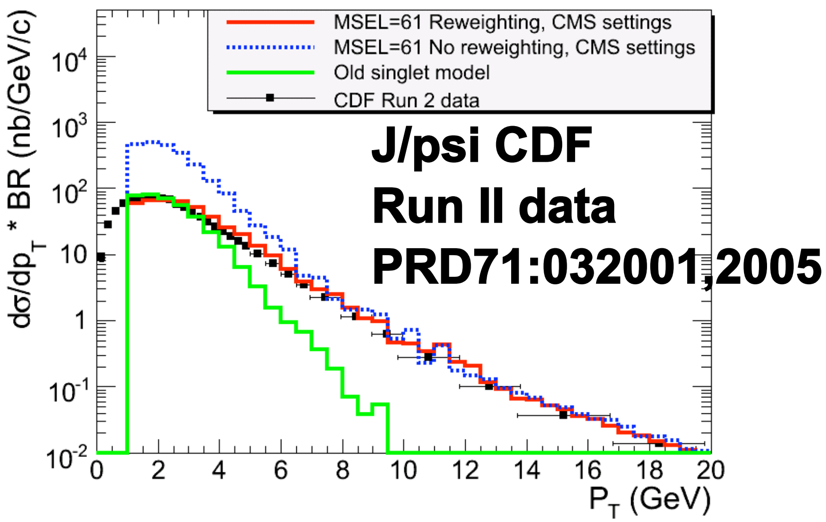
- Based on NRQCD- approach
- Singlet and octet $Q\bar{Q}$ produced perturbatively, followed by shower
- Parton showers for radiation off octet $Q\bar{Q}$: switches: MSTP(148),MSTP(149)

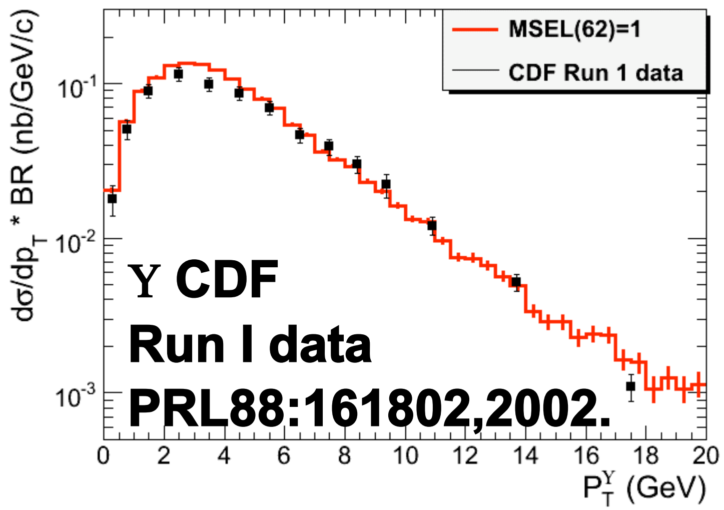
Recent (2006,2007) progress:



- Code integrated (Sjöstrand): PYTHIA ≥6.324
- Possibility to dampen cross section at small P_T like for gg→gg in underlying event (PYEVWT)
- NRQCD matrix elements tuned [See Bargiotti, CERN-LHCb-2007-042.

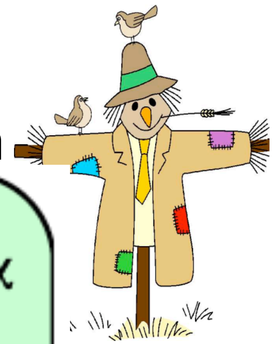
For our generation: parameters checked by generating CDF events





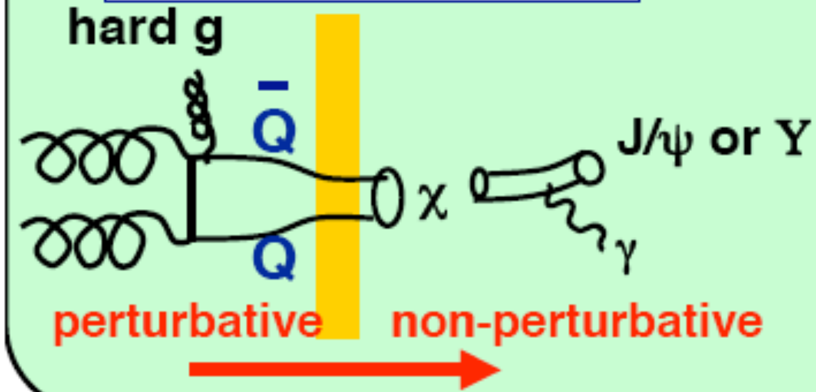
Spa, 6-8

We will compare 4 strawman models



- MC truth + LHC-like detector (CMS, ATLAS) with fast simulation

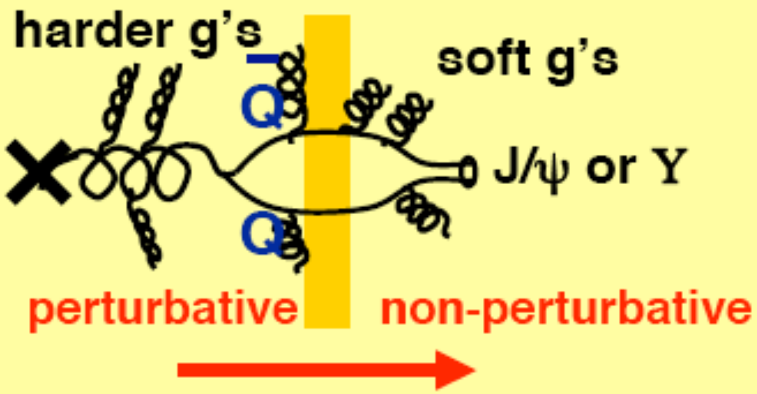
Singlet production



- Quarkonium produced direct or via χ
- QQ-state produced in colour singlet in hard interaction
- Color singlet→ no g-radiation
- J/psi produced in isolation!

MODEL 1: NO RADIATION

Octet production



- Quarkonium produced direct of via χ
- Physics-wise: shower expected from
  1) gg→ggg→gggg...
  2) g→$QQ^{(8)}$
  3) $QQ^{(8)}$→J/psi or Υ
- Technically: cc-octetin hard interaction
- Switches MSTP(148), MSTP(149)
- J/psi produced in shower!

MODEL 2: LOW RADIATION
MODEL 3: MEDIUM RADIATION
MODEL 4: HIGH RADIATION

- NB Model (1+2), (1+3), (1+4) all fit CDF data!

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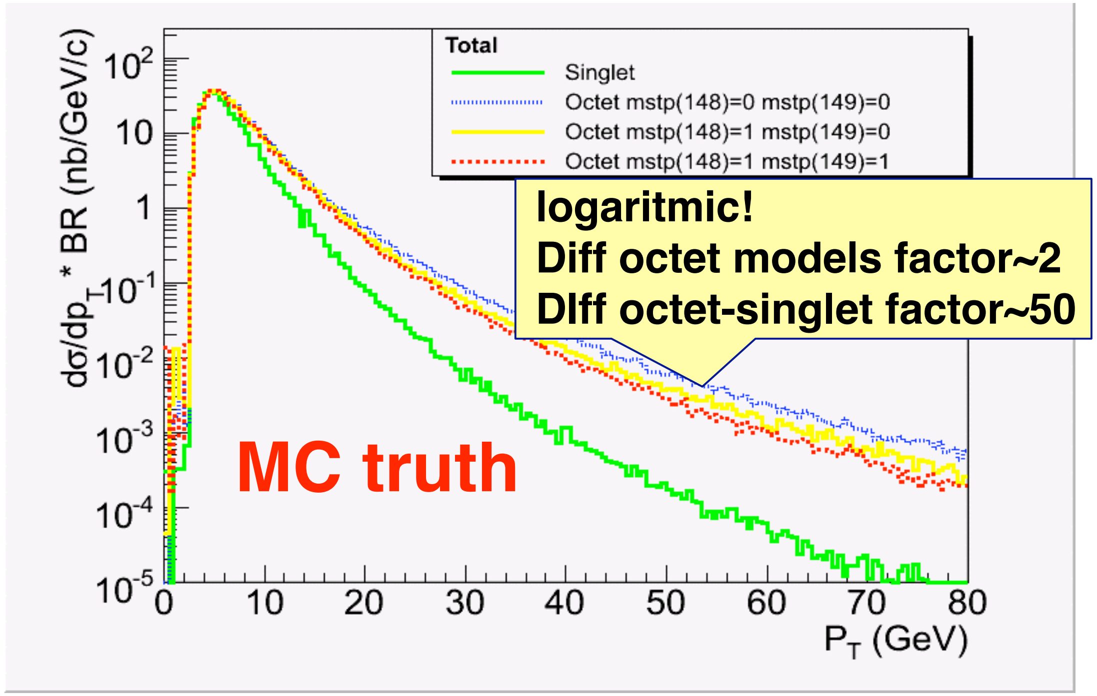
Prompt J/psi differential cross section

Prompt J/psi production cross section at LHC



The cross section is excellent observable for understanding J/psi production!!

However many parameters influence cross section shape...

- ISR & FSR
- Mass of cc-octet
- Cross section dampening at small P_T: free parameters!

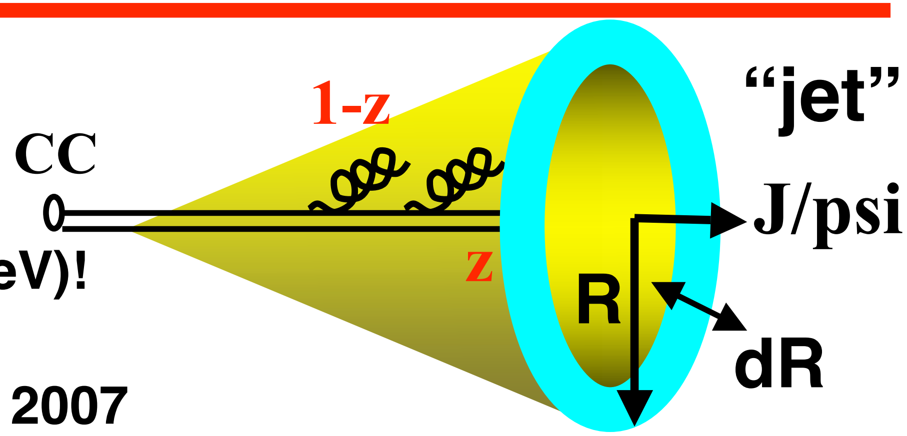
➡ Need more observables!!

- In 100 pb-1 (Pythia prompt J/psi singlet+octet): $|\eta(mu)|<2.5$ $P_T(mu)>2.5$

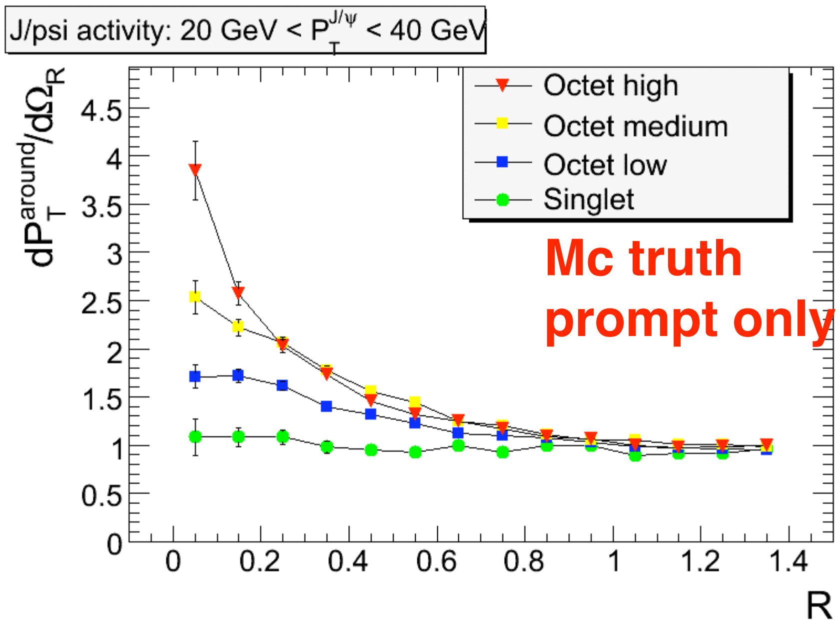
P_T (J/ψ)>	Produced	Reconstructed
5 GeV	~2*10^7	O(10^6)
20 GeV	~3*10^5	O(10^5)
50 GeV	~5*10^3	O(10^3)

Prompt J/psi: associated hadronic activity

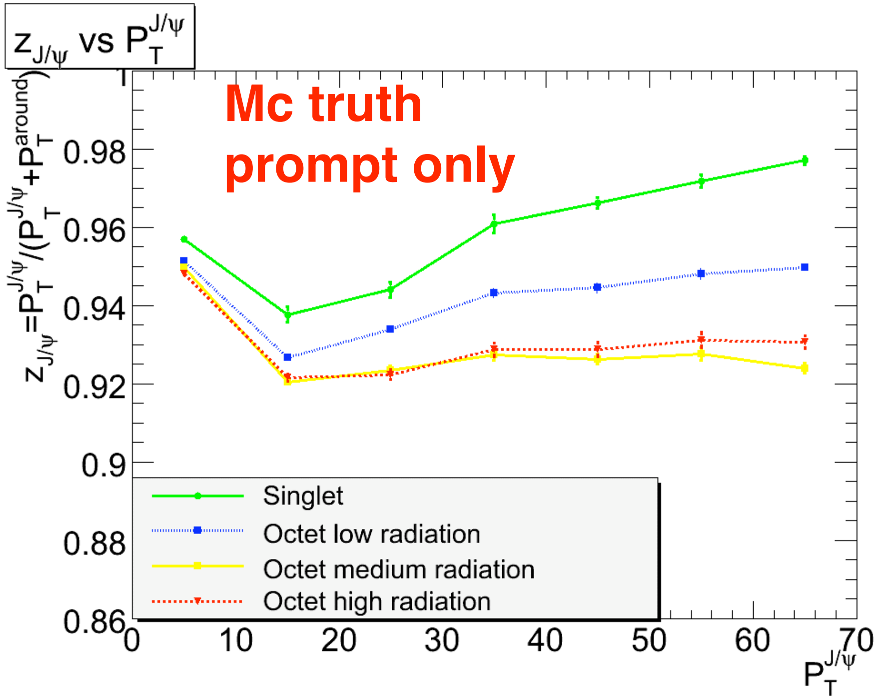
- Shower activity of 4 models is different ➡ investigate activity around J/psi in cone R
- Differences at higher P_T(jpsi)>20 GeV)! [low P_T: little shower]
- More info: see Quark.WG Hamburg 2007
- Example: "Pt-density" around J/psi



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



- Or fragmentation var. z:



Prompt J/psi trigger & reconstruction

Triggers at LHC: at low luminosity 10^{32} cm^{2} s^{-1}: typically a double muon trigger (with some threshold, e.g. P_T>3 GeV in CMS)

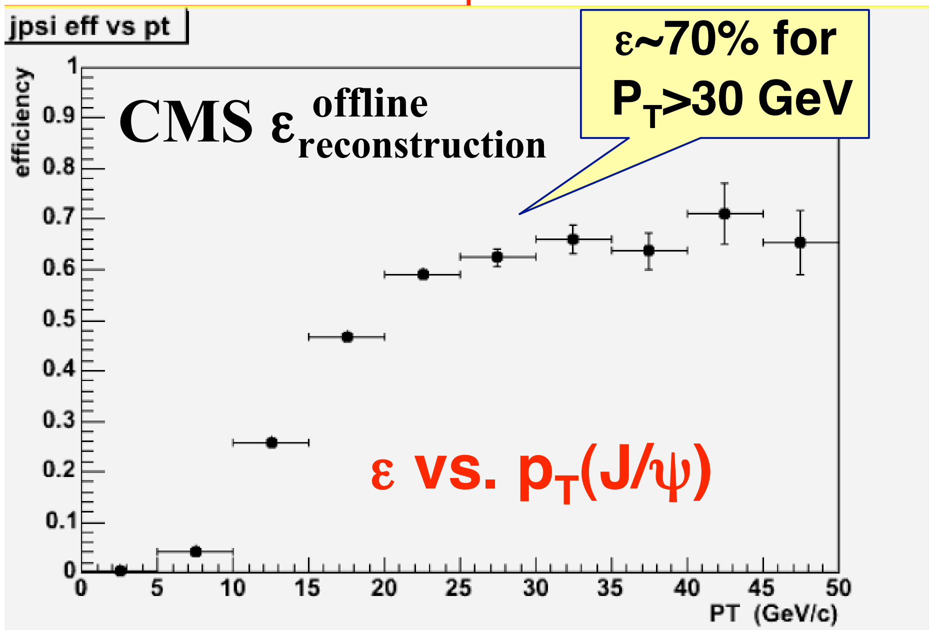
Offline reconstruction: Use tracker&muon chambers.

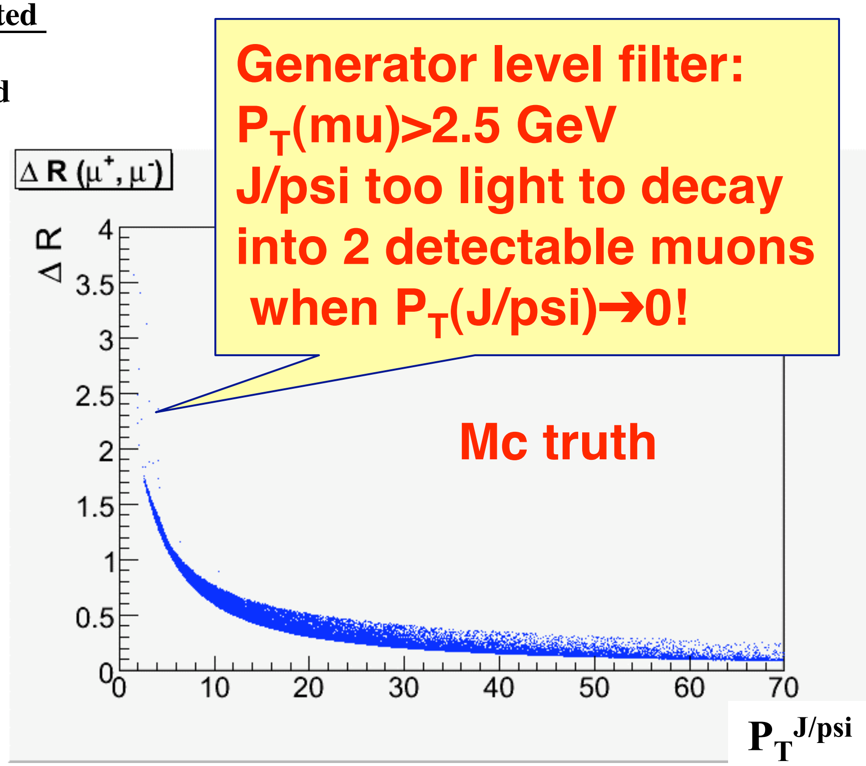
NB efficiency drops to 0 at P_T(J/psi)→0

NB efficiency independent of hadronic activity

Z. Yang and S. Qian,
CMS-note 2006/094
CMS-note-2007/017

$$\varepsilon_{reconstruction} = \frac{N_{reconstructed}}{N_{generated}}$$



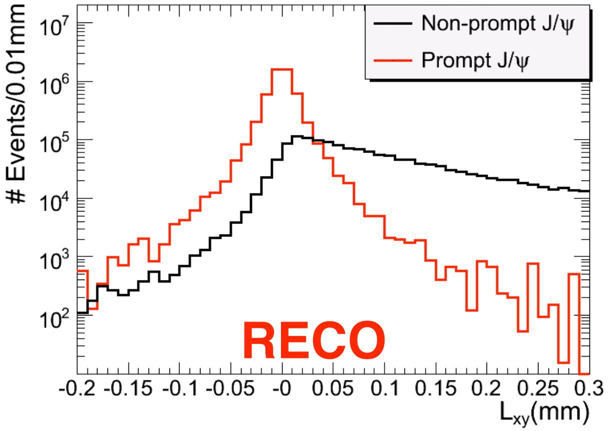


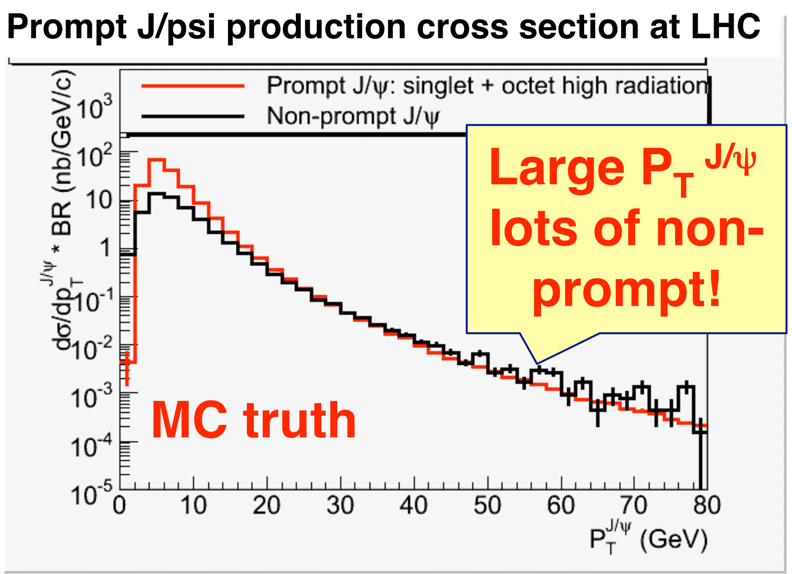
Prompt J/psi measurements: challenges

Background: is important for any measurement of prompt J/psi's!

- **Non-prompt J/psi's (b➔J/psi X)**

Well-known behaviour of impact parameter ➡ Evaluate amount of prompt and non-prompt background





- **General QCD processes (pp➔MuX)**

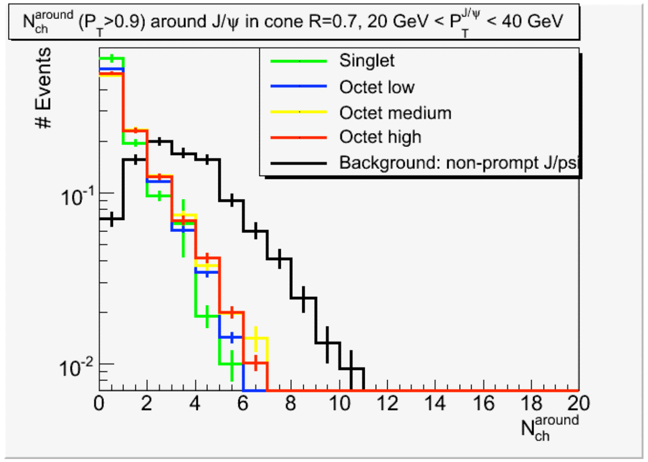
Lots of it… amount reconstructed "fake" J/psi's with mass [3.0-3.2] ~ amount prompt J/psi's. But well-known behaviour of invariant mass: subtract backgr. with techniques such as side-band-subtraction

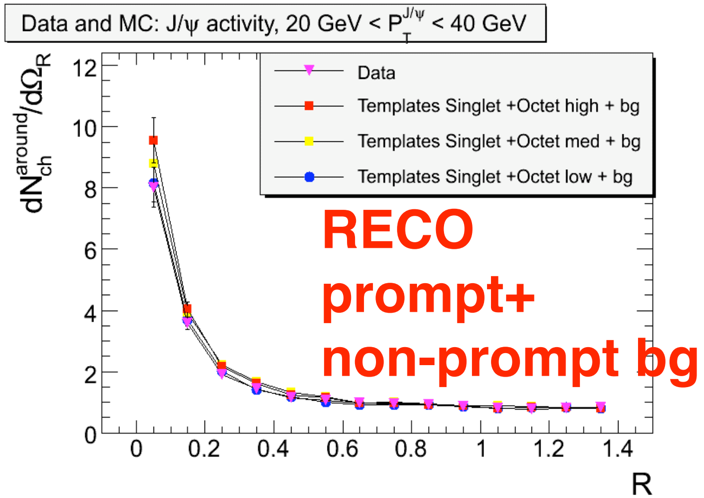
NB: it's not trivial to collect background (and signal) MC statistics…

Hadronic activity study: challenges

Unlike for cross section measurement, backgrounds is harder to deal with when studying hadronic activity!

Background studied so far: Non-prompt J/psi





Several challenges (making it probably not an analysis to do with first data):

- **Non-prompt J/ψ's have large amount of activity [high P_T many of them]!**
- **Wrong estimation of background could lead to totally wrong conclusion**
- **Improvements possible! (even sharper cuts on lifetime, MC statistics, separation prompt-non-prompt, use more variables together), but maybe easier for ϒ's? (no non-prompt ϒ's!)**

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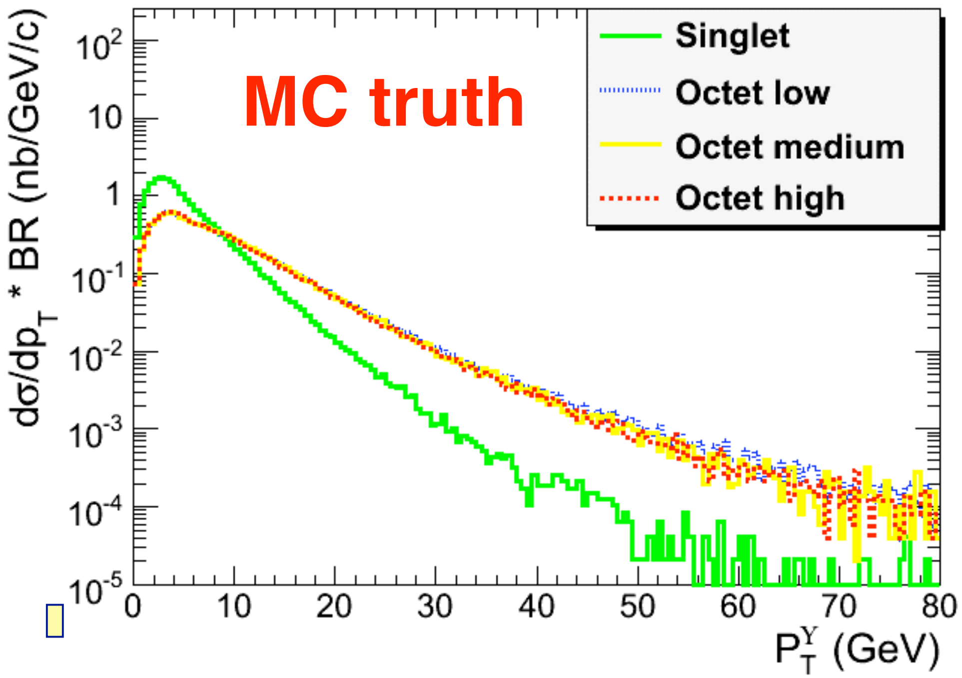
Upsilon (1S) differential cross section

Prompt Upsilon (1S) production cross section at LHC



- **In 100 pb-1 (Pythia singlet+octet): η(mu)<2.5 P_T(mu)>2.5 GeV**

P_T (Υ)>	Produced	Reconstructed
5 GeV	~6*10^5	O(10^5)
20 GeV	~2*10^4	O(10^4)
50 GeV	~5*10^2	O(10^2)

Same 4 models as J/psi generated (sl 8), and same generator cuts:
|η(mu)|<2.5 P_T(mu)>2.5 GeV

Compare Upsilon/Jpsi:

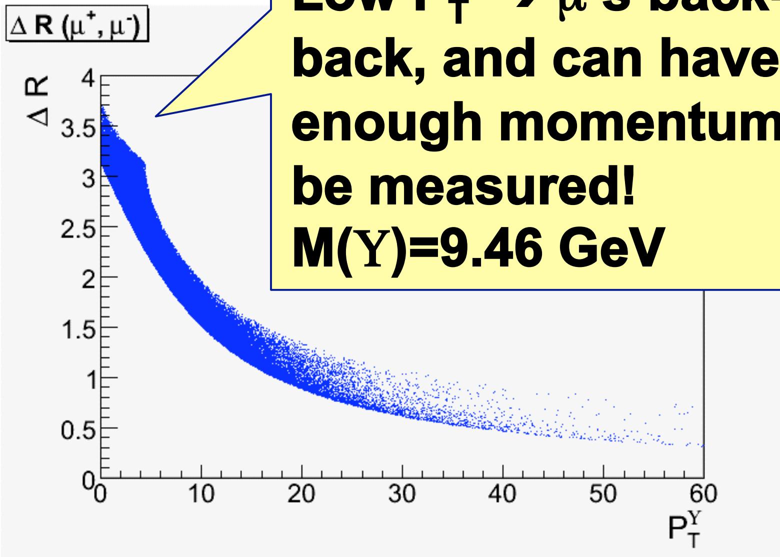
- **Smaller cross section so 100 pb-1 easy to generate**
- **Upsilon cross section falling less rapidly**
- **Differences in radiation less pronounced: the heavier the colored object, the less it radiates!**

Upsilon trigger&offline reconstruction

Upsilon trigger: as J/psi (2Mu P_T>3), but with different mass window cut

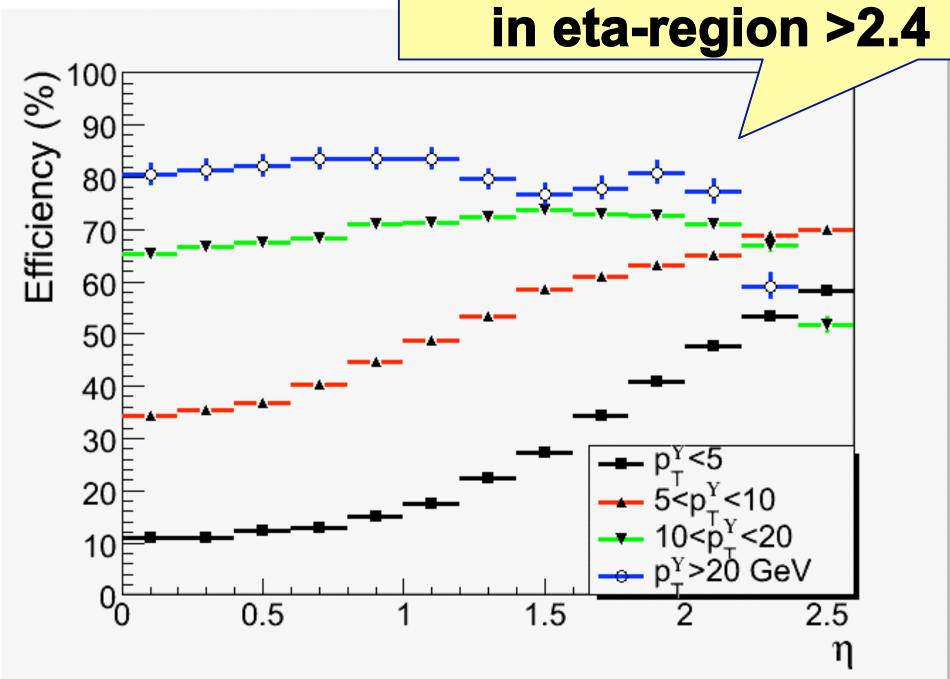
Offline reconstruction: can do measurements down to zero!

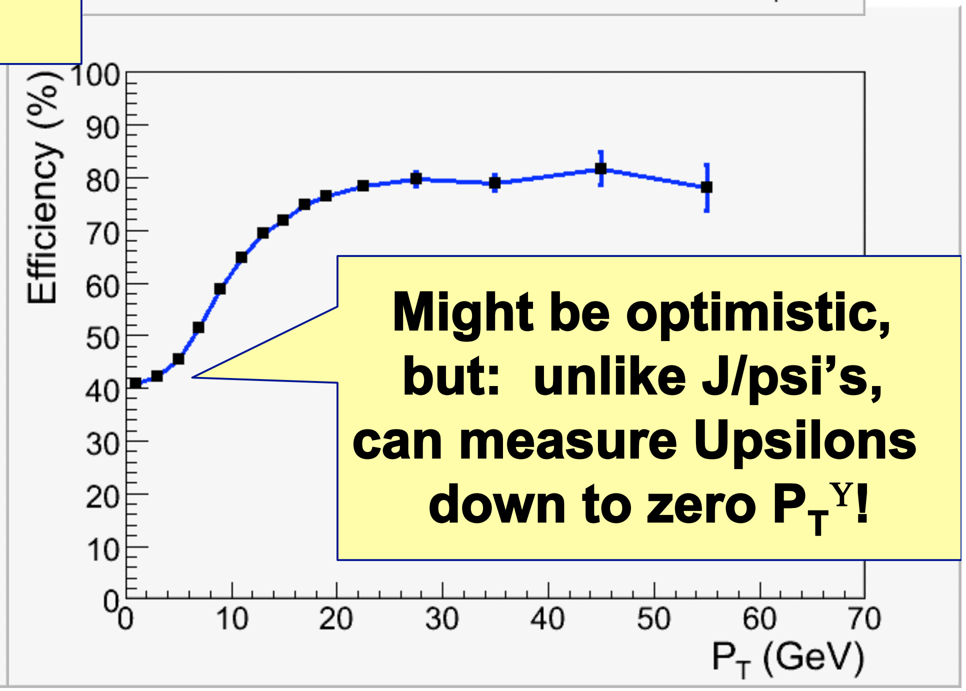
(nice for studying low P_T dampening)



Low P_T^{Υ}➔ μ's back-to back, and can have enough momentum to be measured! M(Υ)=9.46 GeV

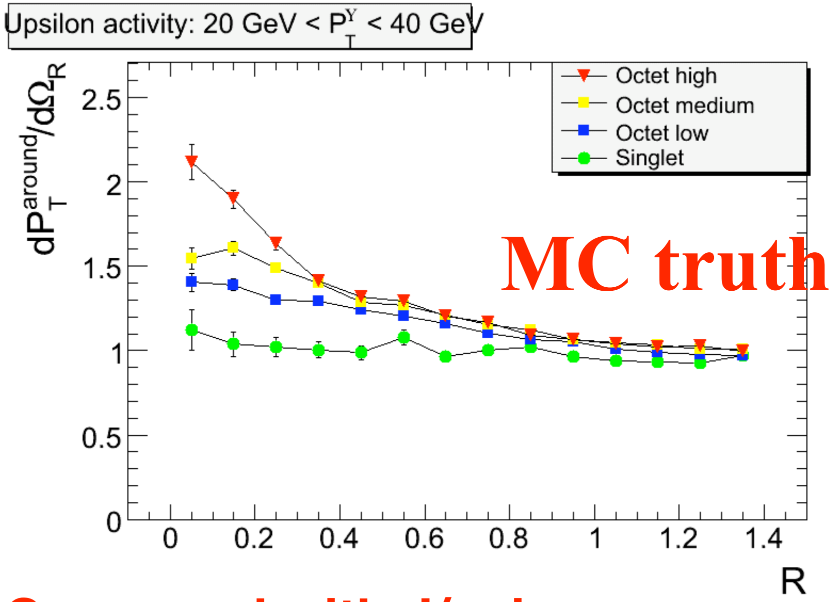
High Pt: eff decreases at large eta! muons go in eta-region >2.4





Might be optimistic, but: unlike J/psi's, can measure Upsilons down to zero P_T^{Υ}!

Upsilon hadronic activity

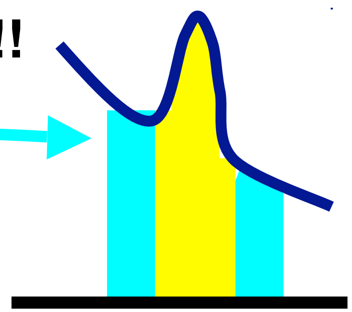


amount of radiation smaller than for J/psi

Compared with J/psi:

- ++ Background: no non-prompt Υ's, only QCD processes (pp➔MuX)
- - - Amount of radiation off bb-state is smaller than for cc-state.
- As J/psi, for background the activity around misidentified Υ's is high (e.g. events with b➔mu + b➔mu)
- Not talked about: sensitive to underlying event and pile-up!!

- Current limitation: background statistics...
- Real data: measuring activity in sidebands of Υ inv. mass should allow for a proper subtraction of the background!



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Quarkonium measurements at LHC

CMS & ATLAS & LHCb are planning :

- Differential cross section measurement: J/ψ, ψ(2S), Υ(1S), (2S)...
- Polarization measurements
- Hadronization measurement (ATLAS, CMS?)
- Measurements of χ_b and χ_c
- LHCb in addition investigating ψ(3770) --> DD.

NB All experiments focus on muon decay channels

More details in discussion session!

Conclusions

- Recent theory progress makes it even more exciting to compare real LHC data with theory predictions!
- For quarkonium studies at LHC: PYTHIA commonly used [easy in use]
- Cross section &polarization measurement are first observables to understand underlying quarkonium production mechanism.
- However, cross section is sensitive to several factors ➡ would be good with more observables!
- Examples of observables shown, taking into account dynamics of particles around the J/psi.
- Based on 4 "strawman" models in PYTHIA, clear separations visible, at larger values of P_T(J/psi) (>30 GeV)
- J/psi: non-prompt background forms problem
- Upsilon: less radiation, but less background: work in progress...
- CMS, ATLAS, LHCb are all planning quarkonium measurements based on muon decay channels

Thanks!

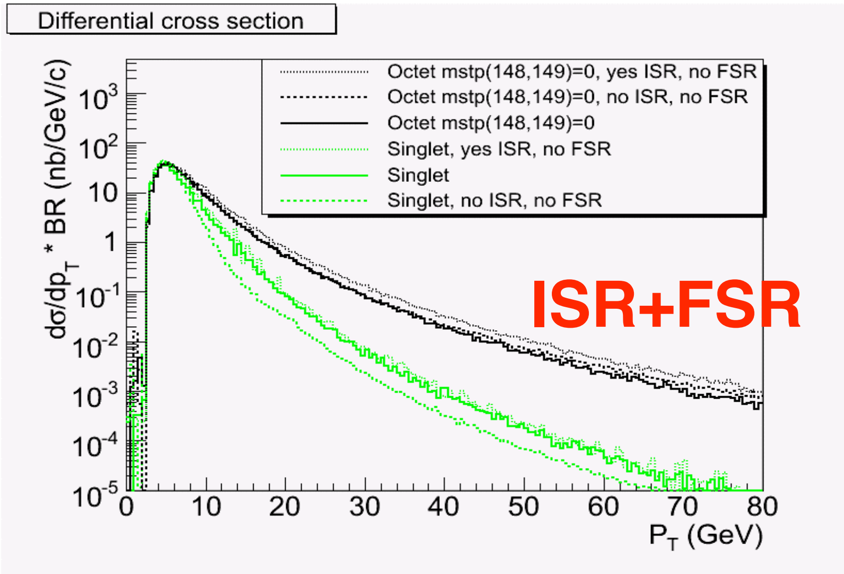
- **Thanks to: Torbjörn Sjöstrand, Zongchang Yang, Fabrizio Palla, Urs Langenegger, Carlos Lourenco for help & discussions, and thanks to Jean-Philippe and the organization of this conference!**

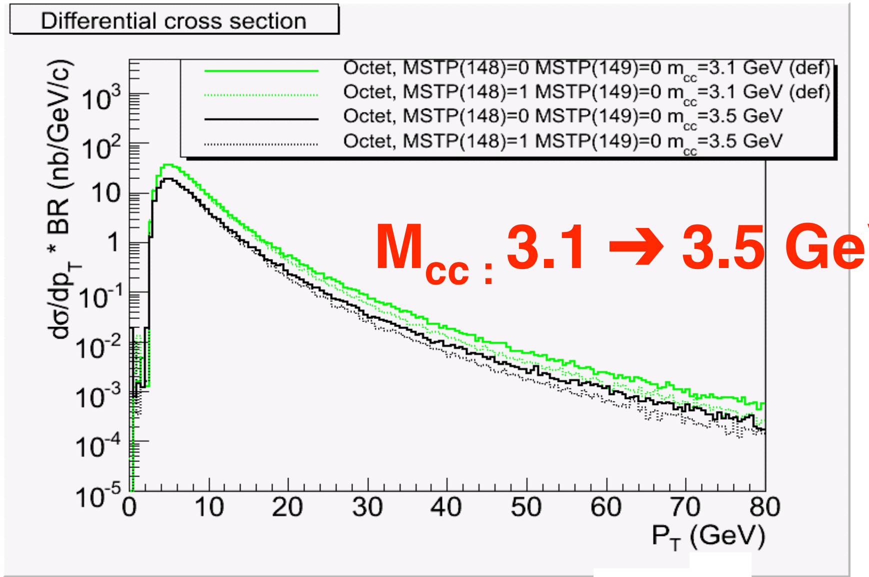


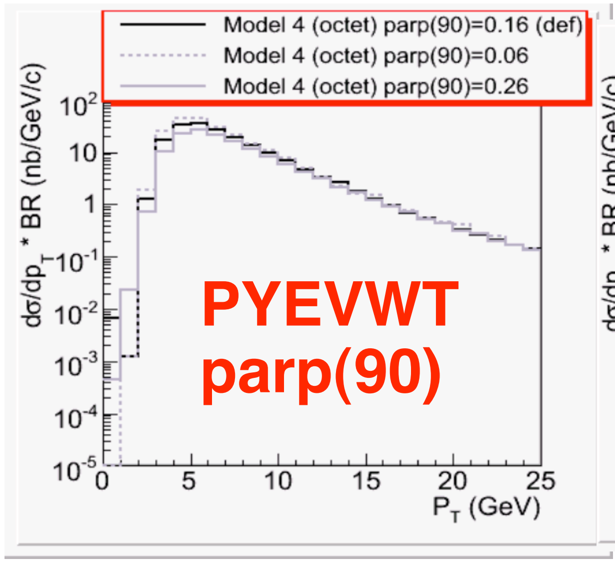

EXTRA SLIDES

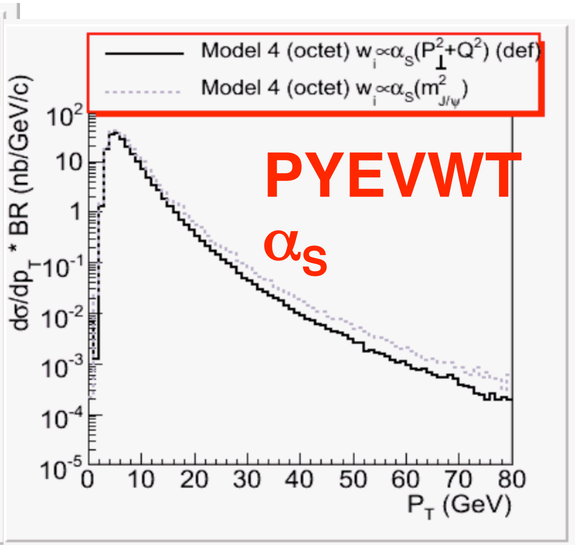
Prompt J/psi differential cross section

Examples of changes in the differential cross section:









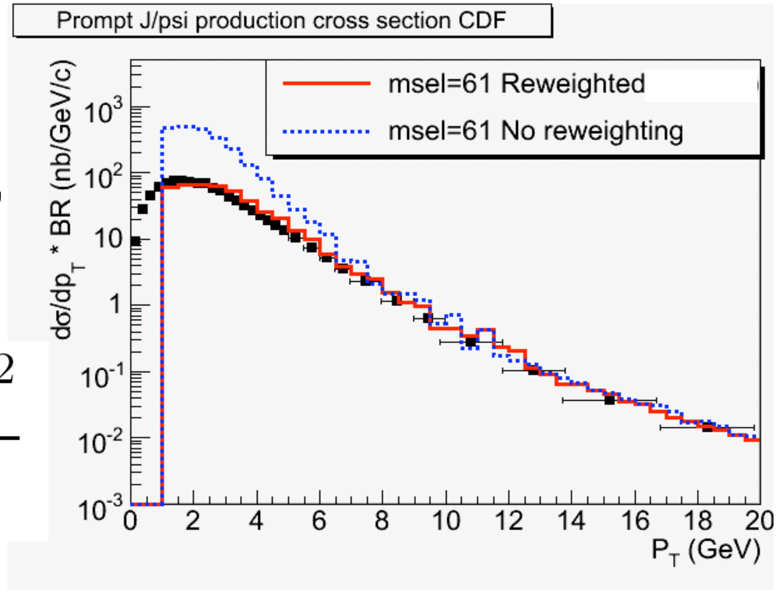
Conclusion:

- **Diff. xs can change significantly!**
- **Even is we can measure the spectrum, doesn't mean we understand the production...**

J/psi production in PYTHIA: PYEVWT.f

- **Problem:** even with octet, quarkonium cross section not right shape (too big at low Pt)
- **Solution:** PYEVWT.f: cross section dampened, like gg→gg in underlying event formalism

T. Sjöstrand and M.v.Z, PRD 1987

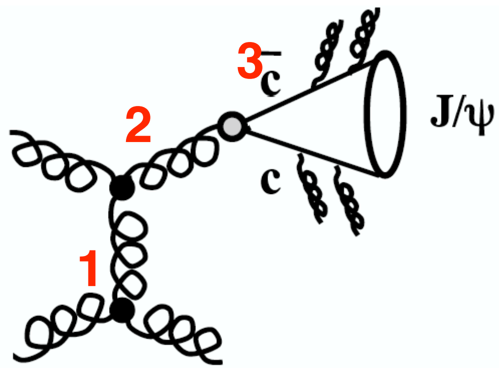


$$\frac{d\sigma}{dp_T^2} \propto \frac{[\alpha_S(p_T^2)]^2}{p_T^4} \implies \frac{[\alpha_S(p_{T_0}^2 + p_T^2)]^2}{(p_{T_0}^2 + p_T^2)^2}$$

- **Applies naturally here too!**

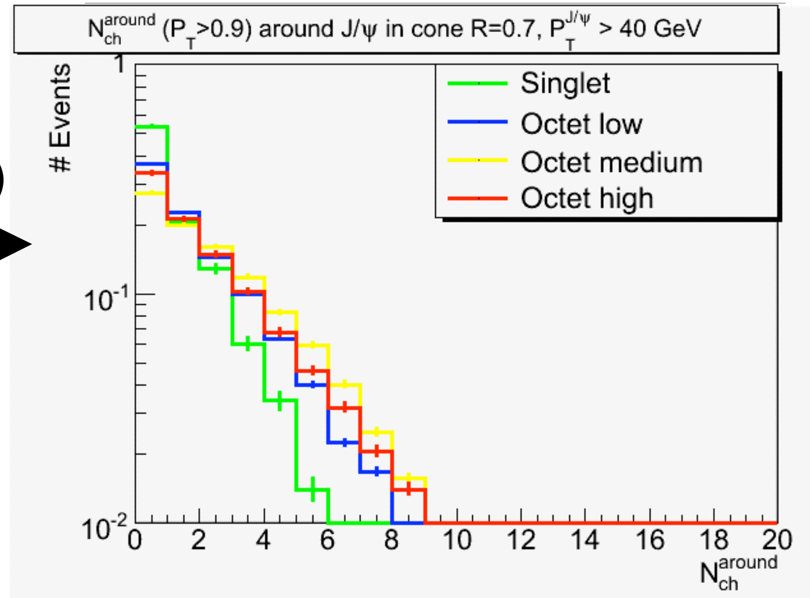
$$w_i = \frac{\sigma_{reweighted}}{\sigma_{not\ reweighted}} = \left(\frac{\hat{p}_T^2}{p_{T_0}^2 + \hat{p}_T^2}\right)^2 \left(\frac{\alpha_S(p_{T_0}^2 + Q^2)}{\alpha_S(Q^2)}\right)^3$$

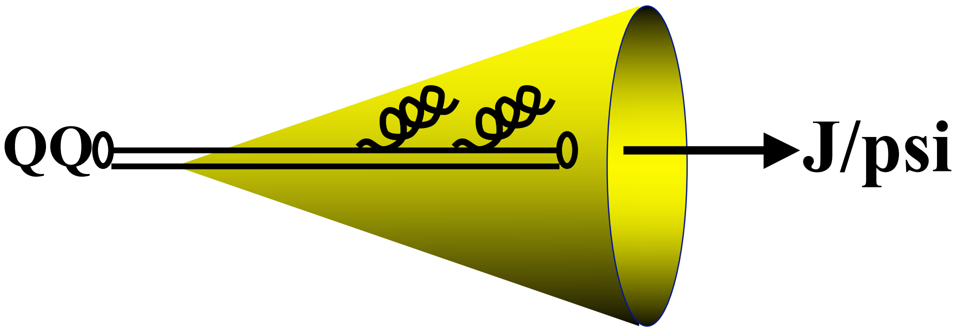
- p_{T0} ~ scale below which g cannot resolve colours ⇒ coupling decreases ⇒ xs decreases!
- p_{T0} ~ 2 GeV at CDF, is assumed to grow with √ s
  [x smaller ➔ denser packing of gluons ➔ more screening
  LHC: p_{T0} = 1.94(14 TeV/1.96 TeV)$^{0.16}$=2.66 GeV



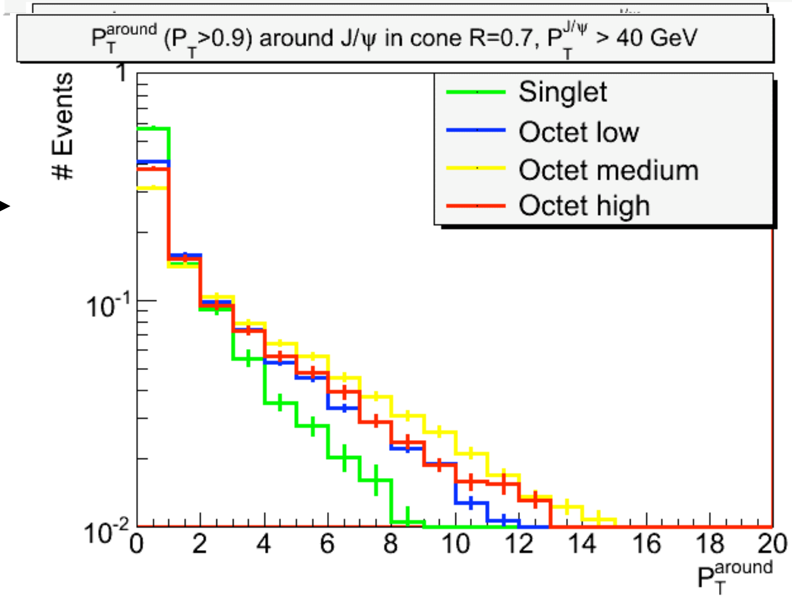
Activity around J/psi

- ➢ **Shower activity of 4 models is different (see slide 7) ➔ natural observable: Nr charged particles (P_T>0.9, except μ's) around J/ψ in cone with R=0.7** →





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



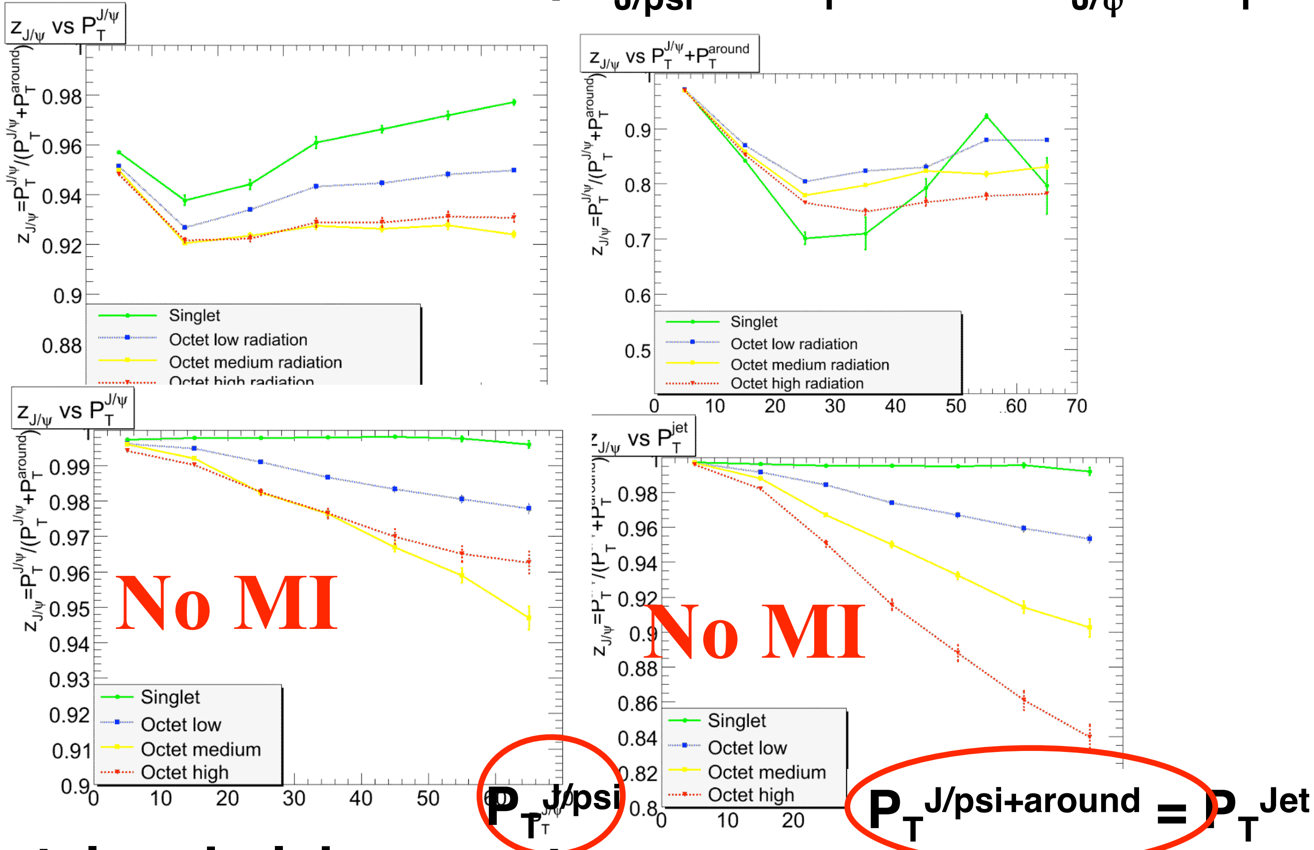
✓ **The particles around the J/psi are generally low energetic!**

✓ **The differences are at high P_T(J/psi)**

$$z = \frac{P_T^{J/psi\ itself}}{P_T^{jet}}$$

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

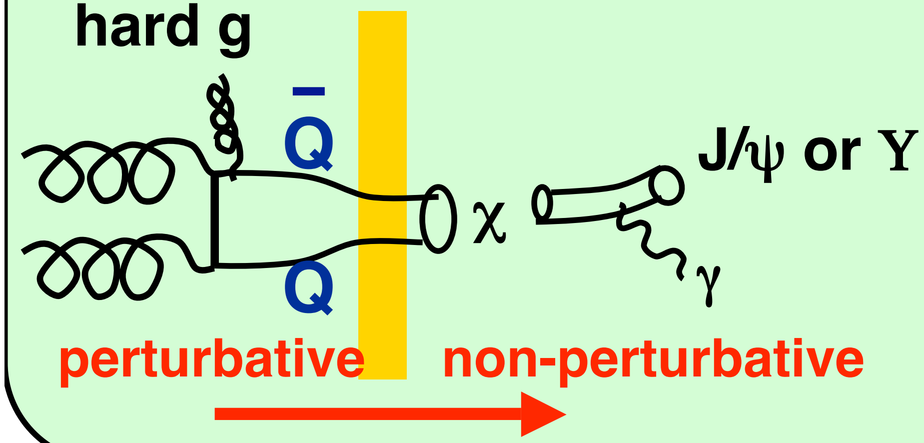
- Since for 4 models fragmentation function is different, try $z_{J/\psi}$ ~ theoretical fragmentation variable z ⇨Try $z_{J/psi}$ vs $P_T^{J/psi}$ and $z_{J/\psi}$ vs P_T^{Jet}
- Interesting shape!
- Investigate effect multiple interactions,
- 2M new events



- **Conclusion**: accidental underlying event activity around J/psi can be important
- $z_{J/\psi}$ possible observable, but have to understand underlying event

Parton showers

Singlet production



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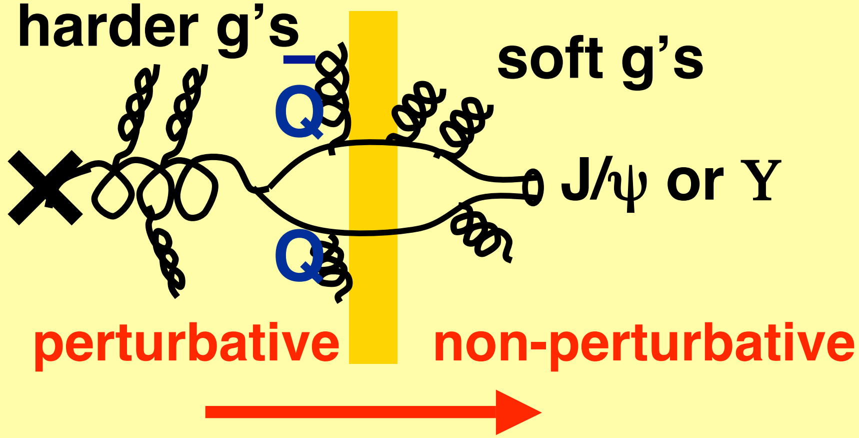
MODEL 1: NO RADIATION

Octet production



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MODEL 4: HIGH RADIATION

NRQCD matrix elements

- Rates for all quarkonium processes given by NRQCD matrix elements

See also talk by M.Bargiotti at HERA-LHC workshop 2006

- Motivation of tuning: agreement MC⇔data

- NRQCD matrix elements from: hep-ph/0003142
  - 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

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
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