HEAVY QUARKONIA SECTOR IN PYTHIA 6.3: TEST AND VALIDATION. PERSPECTIVES AT LHC AND LHCB

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OUTLINE

- Motivations for a reliable description of Heavy Quarkonia production in the Monte Carlo and relevance for LHC(b);
- New channels introduced in PYTHIA and NRQCD matrix element settings;
- Tests and validation: J/ψ and Y production;
- Comparison with Tevatron data and perspectives for LHC and LHCb;
- The LHCb detector and trigger and J/ψ yield.

MOTIVATIONS: HEAVY QUARKONIA PHYSICS CASE AT LHCb

- ☐ **LHCb is an experiment designed for measuring CP violation and rare decays in the beauty sector at the LHC**

- ☐ **Prompt J/ψ signals are important for this physics at LHCb, e.g.**
  - **they should be considered as potential backgrounds (in combination with other particles) for B→J/ψ X signals**
  - **they can be used for calibrating the proper time resolution**
- ☐ **Similar considerations hold for the general purpose detectors Atlas and CMS, which include in their physics programme B physics as well**

- ☐ **Of course, the measurement of heavy quarkonia production at the LHC is an interesting question itself, allowing to improve the knowledge of QCD and put some light on the production mechanisms (e.g. CSM, NRQCD, CEM)**

- ☐ **LHCb has a dedicated dimuon trigger for collecting large samples of ψ's and Y's decays and, as a forward spectrometer, is suitable for making precise studies in a low/moderate p_T range up to large values of pseudo-rapidity η~5**

MOTIVATIONS FOR THE INCLUSION OF NRQCD IN PYTHIA

- **Production of charm and beauty hidden flavor states in PYTHIA was incomplete:**
  - Only color singlet processes (Color Singlet Model);
  - CSM largely fails in shape and normalization;
- **Not too flexible**
  - Cannot allow simultaneous production of ψ’s and Y’s, nor Y(1S) and Y(2S), etc.
- **Following the discussion started at a LCG/GENSER meeting in March 2005, T. Sjostrand introduced NRQCD for heavy quarkonia production in PYTHIA 6.324.**
  - → Work done in the framework of LHCb and GENSER
    - For the GENSER side, precious collaboration with P. Bartalini
    - For the LHCb side, work done in collaboration with V. Vagnoni
    - Fundamental help from T. Sjostrand

NRQCD IN PYTHIA

Integration of the original code (developed by Stefan Wolf) made by T. Sjostrand in PYTHIA 6.324.

- This PYTHIA implementation for NRQCD already existed since a few years, but it was not validated and never included in official releases.
- PYTHIA 6.324 now relates **both to charmonia and bottomonia sector**
  - The code is now under validation;
  - Realistic settings (i.e. NRQCD MEs) have to be fixed.

→ OTHER VISIBLE IMPLICATIONS:

- **Possibility to produce simultaneously J/ψ and Υ (introduced as different processes)**
- **is still not possible to generate Υ' and ψ' simultaneously, but can be implemented in near future**

IMPLEMENTATION DETAILS: NEW CHANNELS (1)

- Originally **only the Color Singlet Model (CSM)** contributions to the quarkonia production were available **in PYTHIA 6.2**
- ….BUT Non-Relativistic Quantum Chromodynamics **(NRQCD)** predicts large contributions via the **color octet mechanism**

→ Introduction of new processes:

- **S-wave for $c\bar{c}$:**

ISUB	$g+g\rightarrow c\bar{c}[n]+g$	ISUB	$q+g\rightarrow q+c\bar{c}[n]$	ISUB	$q+\bar{q}\rightarrow g+c\bar{c}[n]$
421	$g+g\rightarrow c\bar{c}[{}^3S_1^{(1)}]+g$				
422	$g+g\rightarrow c\bar{c}[{}^3S_1^{(8)}]+g$	425	$q+g\rightarrow q+c\bar{c}[{}^3S_1^{(8)}]$	428	$q+\bar{q}\rightarrow g+c\bar{c}[{}^3S_1^{(8)}]$
423	$g+g\rightarrow c\bar{c}[{}^1S_0^{(8)}]+g$	426	$q+g\rightarrow q+c\bar{c}[{}^1S_0^{(8)}]$	429	$q+\bar{q}\rightarrow g+c\bar{c}[{}^1S_0^{(8)}]$
424	$g+g\rightarrow c\bar{c}[{}^3P_J^{(8)}]+g$	427	$q+g\rightarrow q+c\bar{c}[{}^3P_J^{(8)}]$	430	$q+\bar{q}\rightarrow g+c\bar{c}[{}^3P_J^{(8)}]$

… + many others, see backup slides

IMPLEMENTATION DETAILS: NEW CHANNELS (2)

…where e.g. the new CSM process g+g→J/ψg (ISUB = 421) is almost completely equivalent to the CSM process available before (ISUB = 86), except from the fact that the CSM factors out the wave function $|R(0)|^2$ at the origin, while NRQCD parametrizes the non-perturbative part with the ***NRQCD matrix elements***.

- For χ_c: in PYTHIA 6.2 were implemented only the gluon-gluon fusion mode: again new modes implemented (qg, $q\bar{q}$) with rearrenged constant as before.
- Altarelli – Parisi evolution equations: allows the final- state shower evolution both for $c\bar{c}[^3S_1^{(8)}]$ and for $b\bar{b}[^3S_1^{(8)}]$.
- Polarization implementation for quarkonia
- More implementation details in back-up slides of Appendix A: $c\bar{c}$ production in P wave and $b\bar{b}$ in S and P waves, Altarelli –Parisi evolution equations details and Polarization implementations.

The NRQCD matrix elements (1)

- As CSM, NRQCD parametrises the non-perturbative fragmentation of the $Q\overline{Q}$ pair into the quarkonium state…..**BUT**:
  - while CSM requires only two parameters ($|R(0)|^2$ and $|R'(0)|^2$) = wave function at the origin, and first derivative squared:

$$\langle O^{J/\psi}[{}^3S_1^{(1)}]\rangle = \frac{3N_C}{2\pi}|R(0)|^2 \, ,$$

$$\langle O^{\chi_c}[{}^3P_0^{(1)}]\rangle = \frac{3N_C}{2\pi}|R'(0)|^2 \, .$$

→ NRQCD requires **INDEPENDENT** matrix elements:

$$\langle O^H[{}^{2S+1}L_J^{(C)}]\rangle$$

to denote the probability that a $Q\overline{Q}$ pair in a state ${}^{2S+1}L_J^{(C)}$ build up the bound state H.

These matrix elements fullfils the relation due to heavy quark spin symmetry:

$$\langle O^{\chi_{cJ}}[{}^3P_J^{(8)}]\rangle = (2J+1)\langle O^{J/\psi}[{}^3P_0^{(8)}]\rangle,$$

$$\langle O^{\chi_{cJ}}[{}^3P_J^{(1)}]\rangle = (2J+1)\langle O^{\chi_{c0}}[{}^3P_0^{(1)}]\rangle.$$

THE NRQCD MATRIX ELEMENTS (2)

- The rates for these new processes are regulated by 10 NRQCD matrix elements values (their default values are set to one in the current release, and need tuning):
- NRQCD matrix elements inserted based on values extracted from: hep-ph/0003142
  - **CSM values extracted from Buchmuller-Tye (Eichten-Quigg) potential model (hep-ph/9503356)**
- 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

TEVATRON SIMULATION SETTINGS

- **MC data samples produced under the following Tevatron settings:**
  - $p\text{-}\bar{p}$ collisions;
  - Energy reference for Tevatron: 1960 GeV for J/ψ and 1800 GeV for Y;
  - processes on:
    - **all new processes: both for CSM and for COM**
    - **only J/ψ processes considered, both direct or produced from χ_c, excluding all B decays.**
    - **only Y(1S) processes considered, direct and from χ_b.**
    - **A-P evolution on;**
  - Rapidity region between **-0.6 ÷ 0.6** for J/ψ;
  - Rapidity region between **-0.4 ÷ 0.4** for Y;
  - **CTEQ6L** used as PDF set

DIVERGENCES FOR $p_T \rightarrow 0$: MIN. p_T CUT

- ☐ "Unfortunately", the cross sections of the CSM and COM processes considered are divergent at LO for p_T tending to zero
- ☐ QCD perturbation theory breaks down at low p_T values, confinement is not taken into account
  - ➢ From a phenomenological point of view, a way out is to allow for a screening related to the inverse color correlation lenght in protons
  - ➢ This is implemented in Pythia by the introduction of a p_T min. cut-off, that can be an abrupt one, or an appropriately smoothed cut-off defined by a reweight of the cross section:

$$W(p_T, p_{T0}) = \frac{p_T^4}{(p_{T0}^2 + p_T^2)^2}$$

T. Sjostrand *et al.*
Phys. Rev. D36:2019, 1987
JHEP 0403:053, 2004

together with a dampening of the strong coupling $\alpha_s(p_T^2) \rightarrow \alpha_s(p_{T0}^2 + p_T^2)$

- ☐ In this approach the cross section gets dampened at small p_T according to the value of the phenomenological parameter p_{T0}
  - ➨ for p_T>>p_{T0} the standard QCD perturbation theory is recovered
  - ➨ while at small p_T the cross section gets strongly dumped

RESULTS WITH CSM+COM

(ABRUPT 1 GEV P_T MIN CUT)

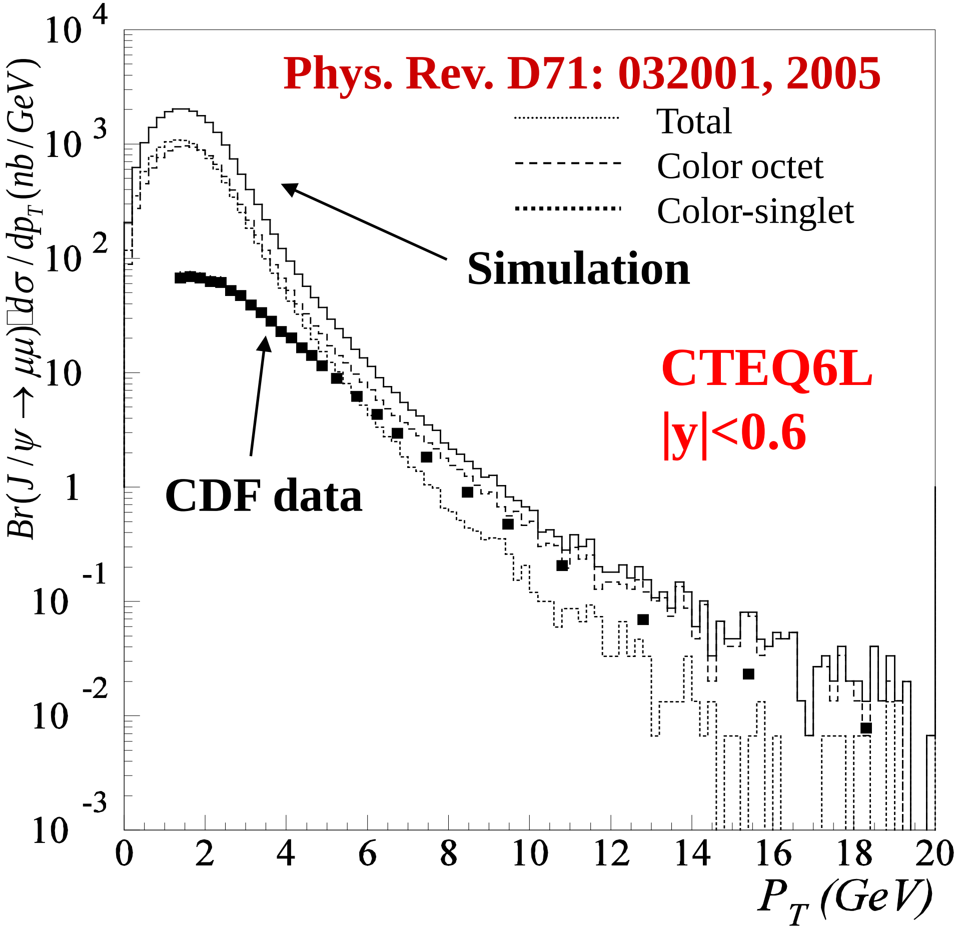
- CSM:
  - 10.0 million events produced with CSM model processes:
    - msub 421 active (S Wave):
      - $g+g\rightarrow c\bar{c}[^3S_1^{(1)}]+g$
    - msub 431- 439 (P Wave):
      - $g+g\rightarrow c\bar{c}[^3P_{0,1,2}^{(1)}]+g$
      - $g+q\rightarrow c\bar{c}[^3P_{0,1,2}^{(1)}]+q$
      - $q+\bar{q}\rightarrow c\bar{c}[^3P_{0,1,2}^{(1)}]+g$
    - all COM processes inactive
- COM:
  - 10.0 million events produced with COM model processes:
    - msub 422-430 active

$$g+g\rightarrow c\bar{c}[^{3,1}S_1^{(8)}]+g$$

$$g+g\rightarrow c\bar{c}[^3P_J^{(8)}]+g$$

+ qg and $q\bar{q}$ analogs

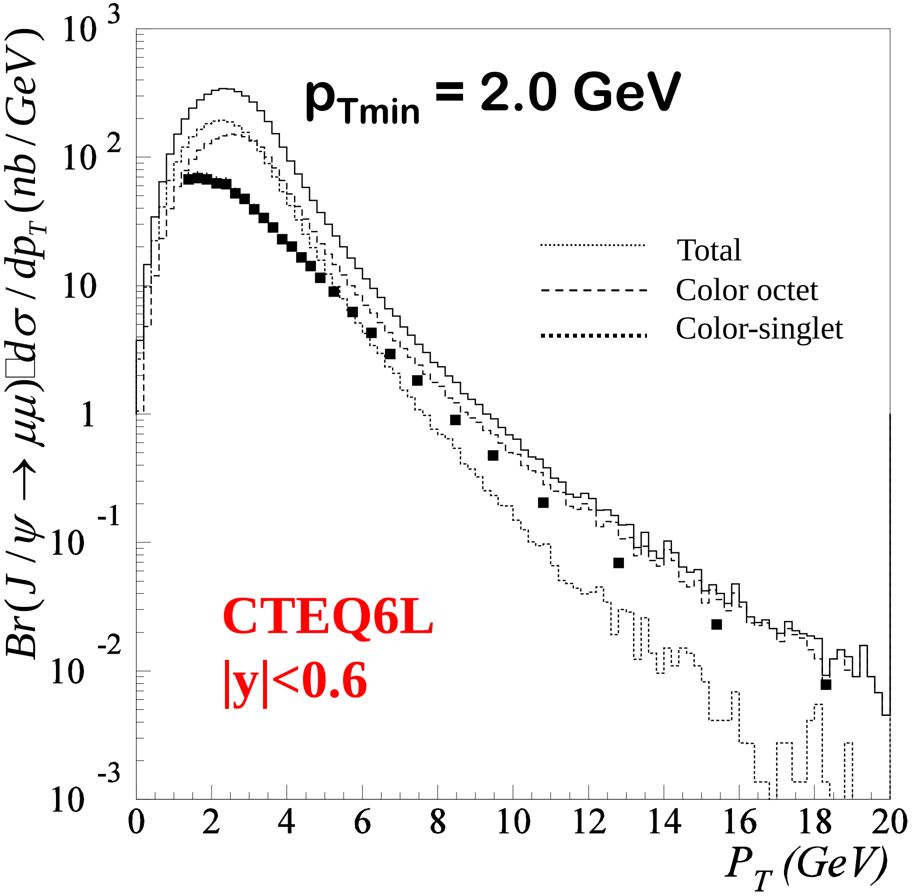
    - all CSM processes inactive

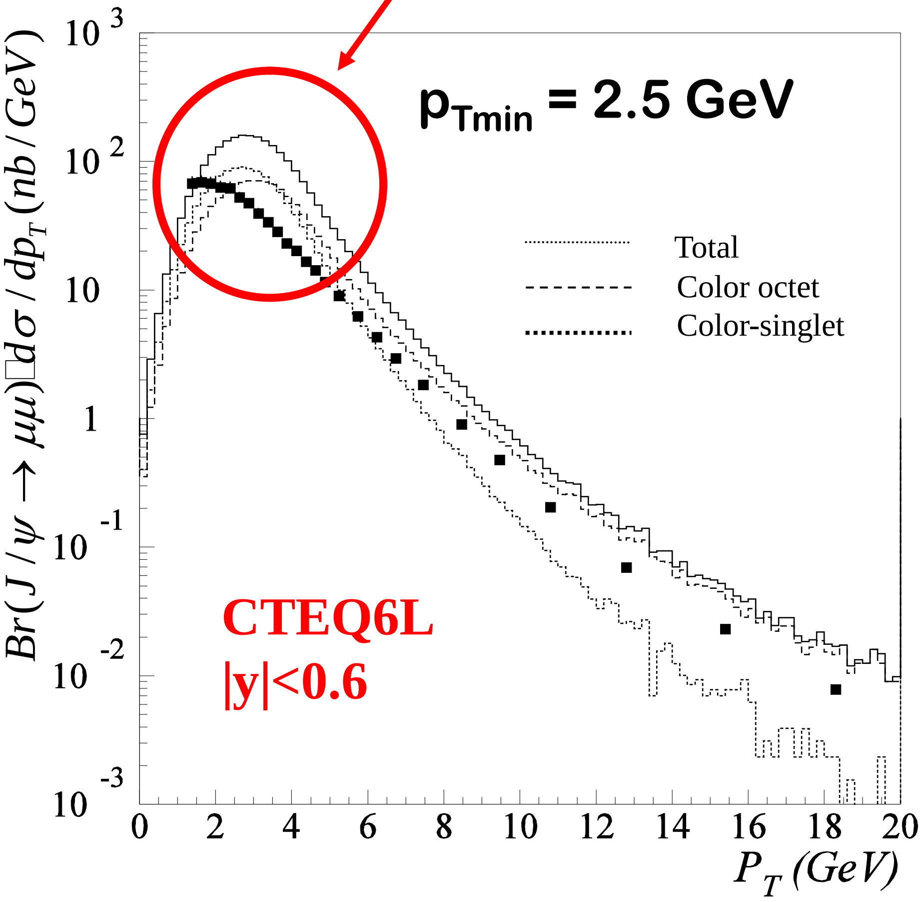


1 GEV P_T MIN CUT LARGELY INSUFFICIENT TO REPRODUCE DATA AT LOW P_T

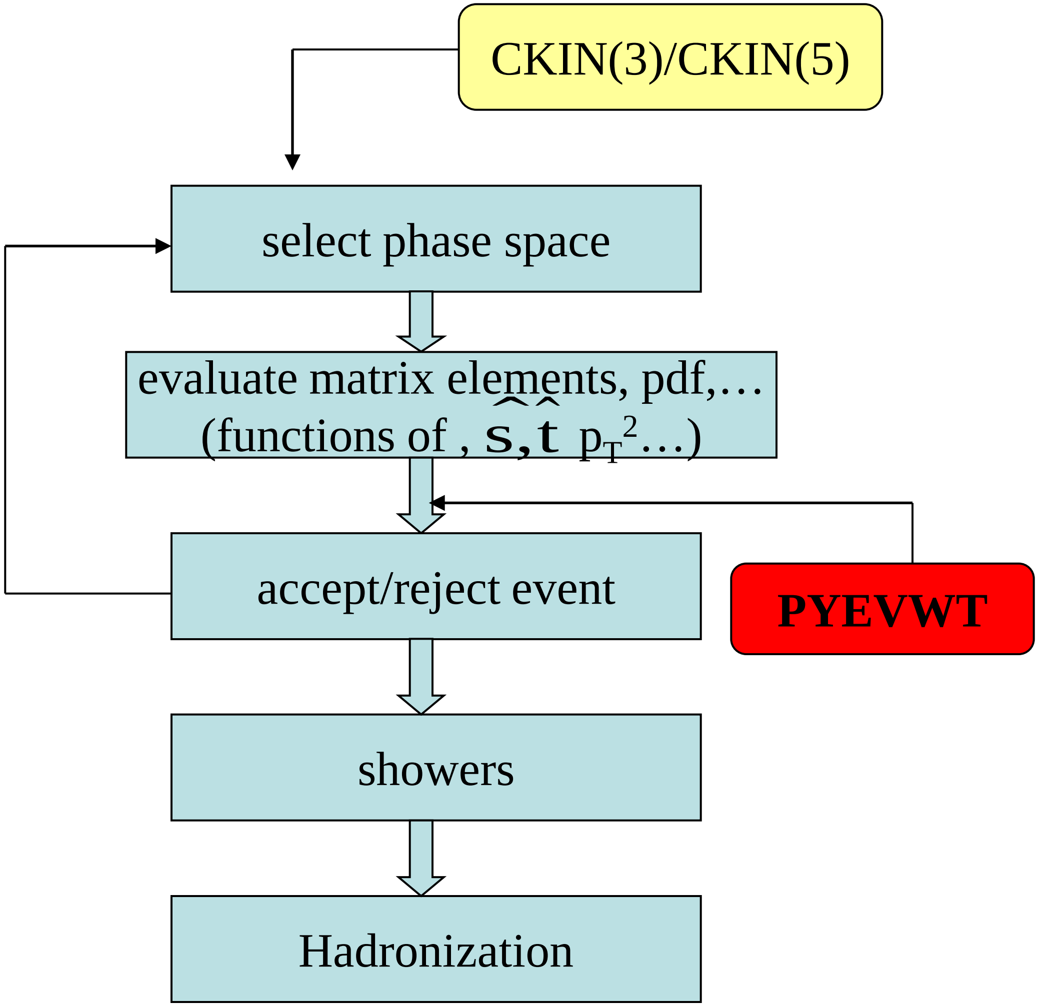
TRYING HARDER PT MIN CUTS

Still MC exceeds data, and wrong shape at p_T→0





CROSS SECTION SMOOTHED REWEIGHTING



CKIN(3)/CKIN(5)

select phase space

evaluate matrix elements, pdf,…
(functions of , $\hat{s},\hat{t}$ p_T^2…)

accept/reject event

PYEVWT

showers

Hadronization

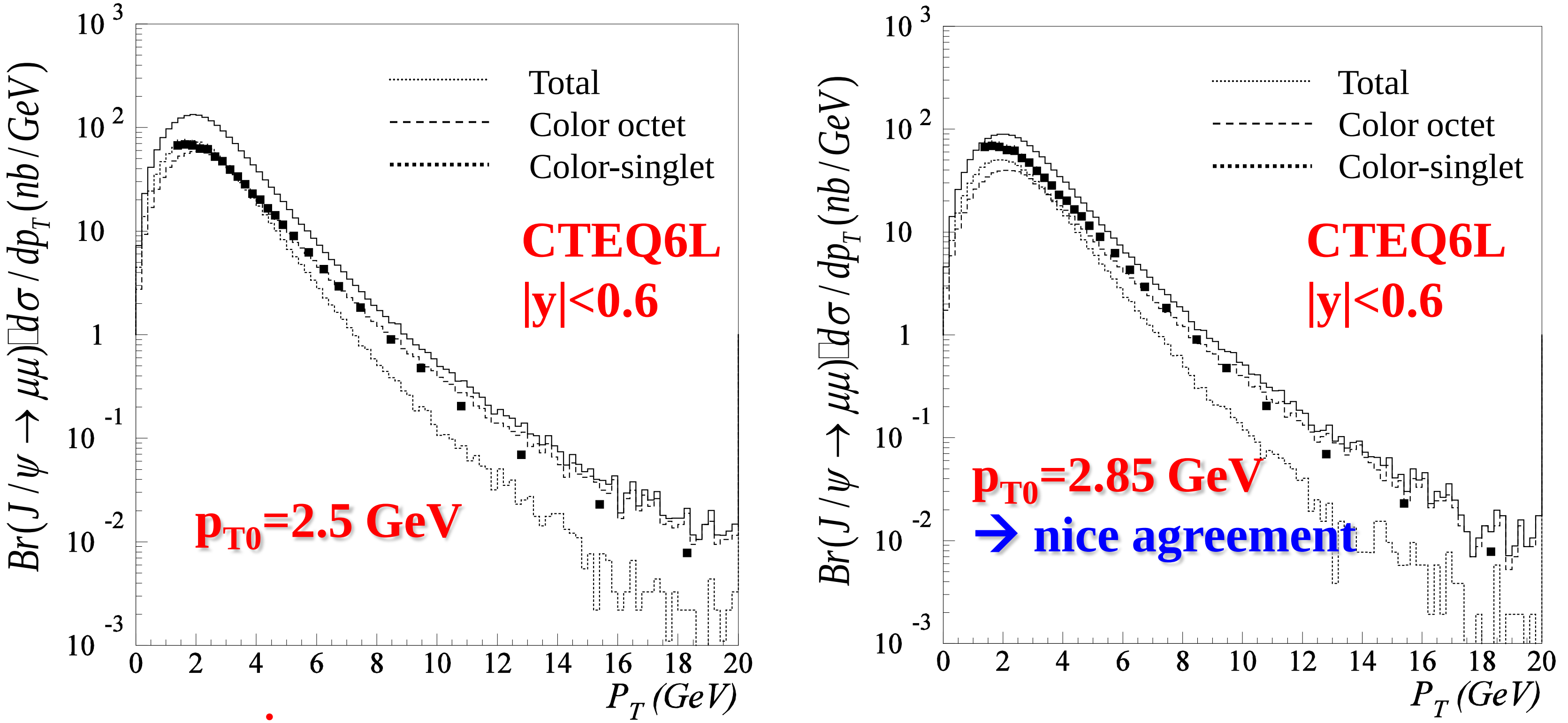
- The Pythia routine PYEVWT with MSTP(142)=2 allows to reweight event cross section by process type and kinematics of the hard scattering.
- unlike the abrupt cut-off governed by CKIN(5) that cuts from a certain p_T onward as a step function, we use the PYEVWT function to reweight the cross section, being the weight:

$$W(p_T, p_{T0}) = \frac{p_T^4}{(p_{T0}^2 + p_T^2)^2}$$

and dampening

$$\alpha_s(p_T^2) \rightarrow \alpha_s(p_{T0}^2 + p_T^2)$$

Results using event-by-event cross section reweighting



p_{T0}=2.5 GeV

p_{T0}=2.85 GeV

→ nice agreement

- **However, some issues:**

➢ Colour Singlet cross section at high p_T exceeds what one would expect, and this leads to a slight excess of the sum of the two contributions CSM+COM

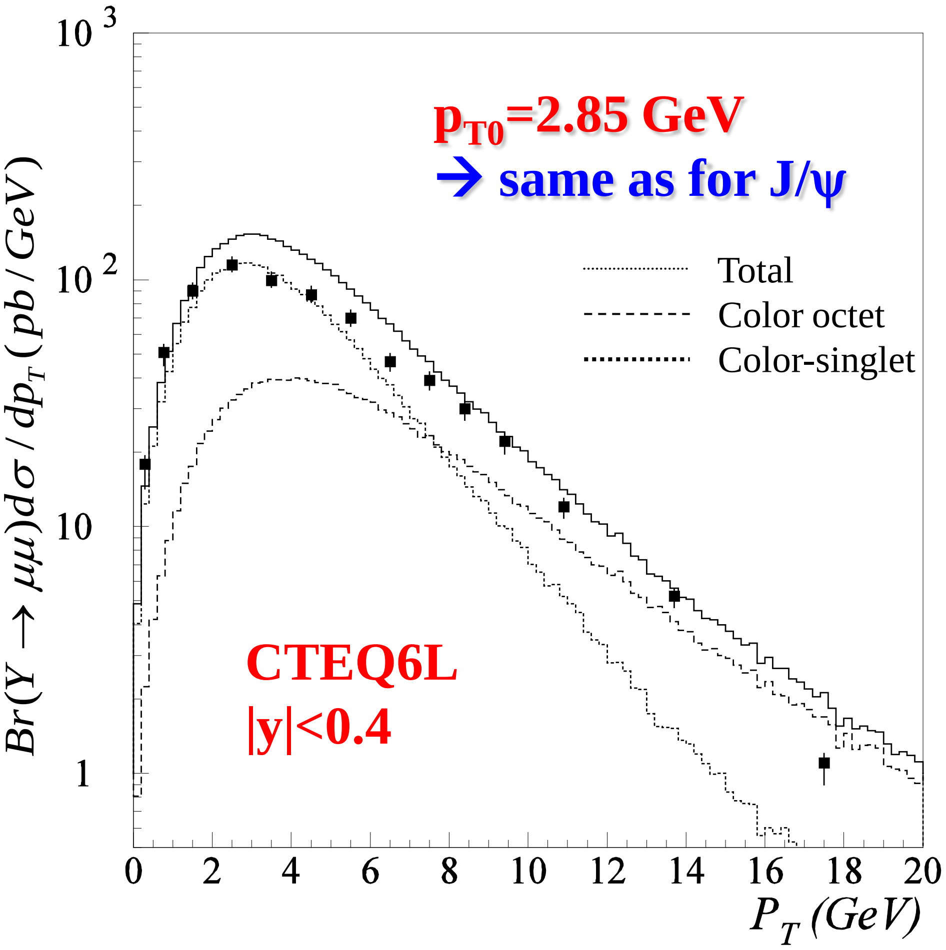
➢ p_{T0} value slightly on the large side, one would hope e.g. for 2-2.5 GeV similarly to the value used in the Multiple Parton Interaction scheme in Pythia, which adopts the same concept and mechanism for dampening the divergent cross sections at low p_T

Y PRODUCTION

Some studies have been performed also on Y(1S):

- CSM production: processes on 461 and 471 to 479 (P wave in bottomonia)
- COM production: processes on 462 to 470

- Results compared with the ones extracted from CDF publication: **Phys Rev. Lett. 88, 161802 (2002)**



p_{T0}=2.85 GeV

→ same as for J/ψ

CTEQ6L

|y|<0.4

PERSPECTIVES FOR LHC

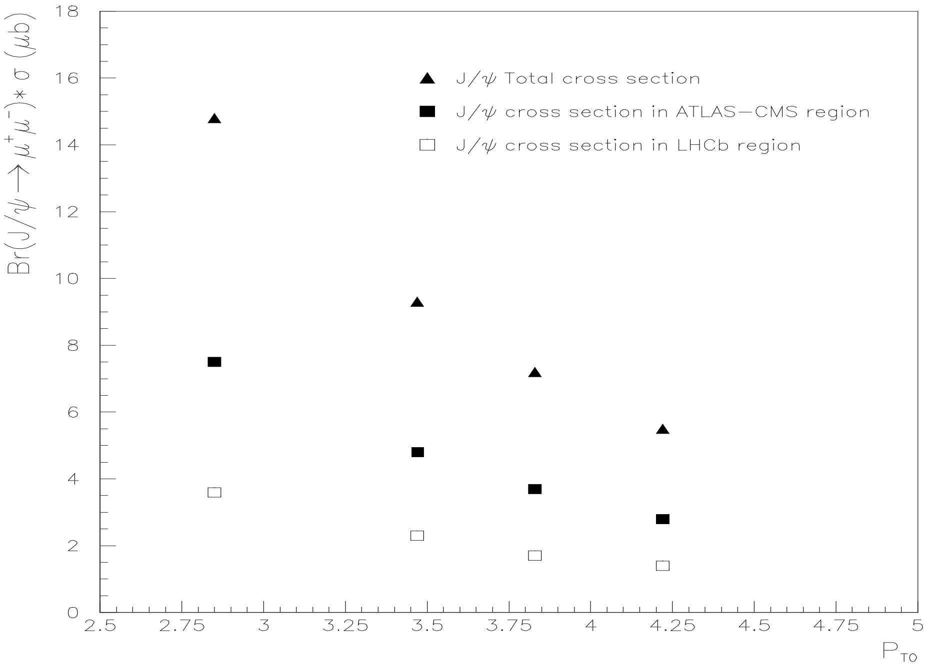
- We need to extrapolate the p_{T0} parameter at LHC energy:
  - p_{T0} should not be energy-independent, in principle
  - in strict analogy to the Pythia model of multiple parton-parton interactions that is applied by default for all the QCD 2→2 processes in Pythia, p_{T0} is assumed to exhibit a dependence on energy of the form (see **JHEP 0403:053, 2004** and **hep-ph/0003142, Sec. 8.2**)

$$p_{T0} \rightarrow p_{T0} \cdot \left(\frac{\sqrt{s}}{E_0} \right)^{\vartheta}$$

  - a reasonable value of ϑ, according to the tunings of the Pythia MPI model is expected to be around 0.16 (see e.g. **LHCb public note 99-028**)

- we assume here different scenarios depending on the value of ϑ**:**
  - **$\vartheta = 0$ → no dependence of p_{T0} on energy**
  - **$\vartheta = 0.1, 0.15, 0.2$ → dependence of p_{T0} on energy**

“PREDICTION” FOR J/ψ CROSS SECTION AT LHC

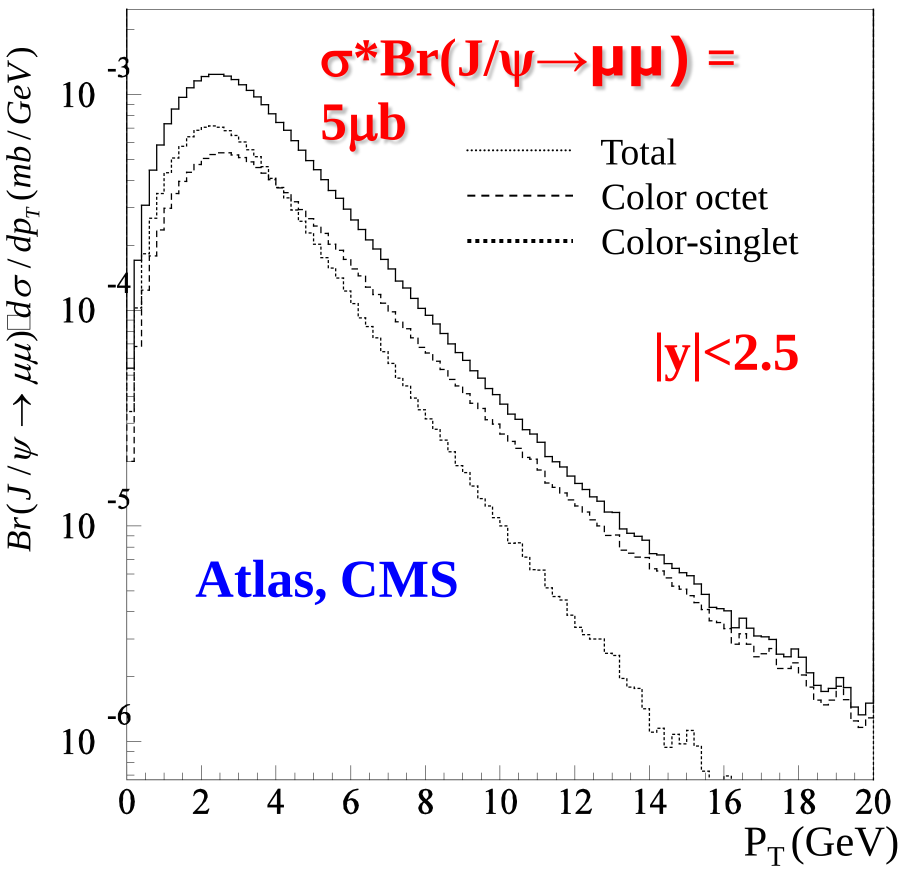


- **Two rapidity regions of interest at LHC:**
  - **-2.5 – 2.5 (ATLAS, CMS)**
  - **1.8 – 4.9 (LHCb)**
- **Total cross section ranging from 5.5 μb to 15 μb**

ϑ	p_{T0} [GeV]	$BR_{\mu\mu}\cdot\sigma_{tot}$ [μb]	$BR_{\mu\mu}\cdot\sigma_{Atlas,CMS}$ [μb]	$BR_{\mu\mu}\cdot\sigma_{LHCb}$ [μb]
0	**2.85**	**14.8**	**7.5**	**3.6**
0.1	**3.47**	**9.3**	**4.8**	**2.3**
0.15	**3.83**	**7.2**	**3.7**	**1.7**
0.2	**4.22**	**5.5**	**2.8**	**1.4**

PROMPT J/ψ CROSS SECTION AT LHC: DIFFERENTIAL SPECTRA

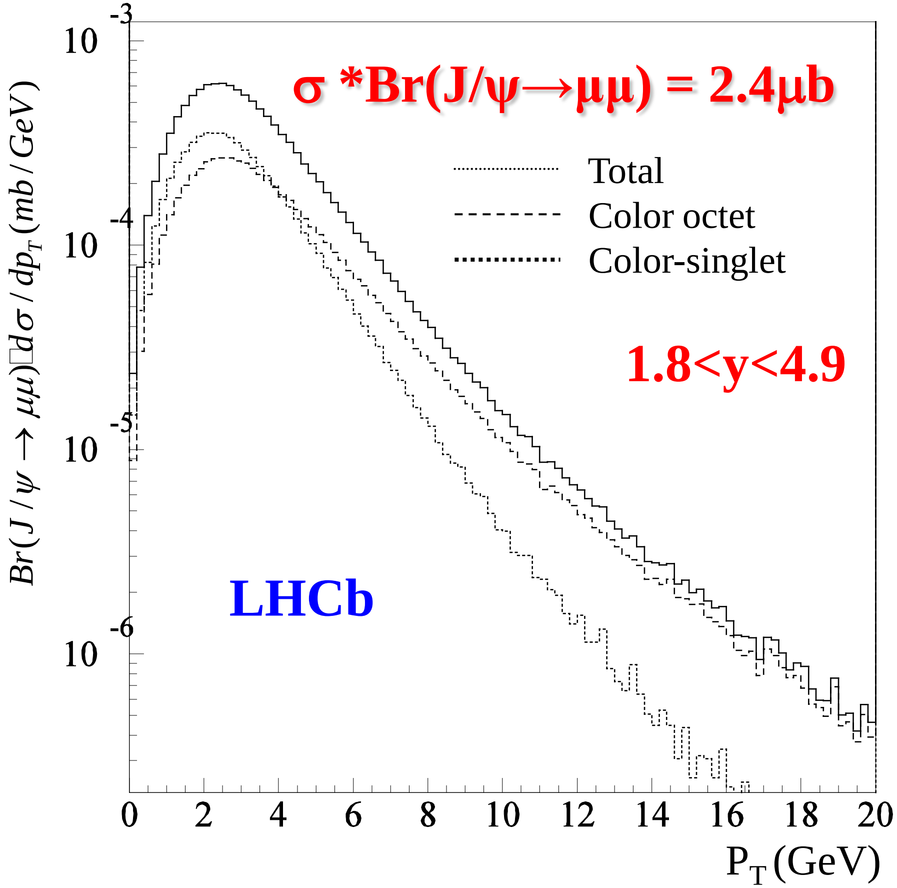
Plots obtained with p_{T0} = 3.42 GeV



σ*Br(J/ψ→μμ) = 5μb

|y|<2.5

Atlas, CMS



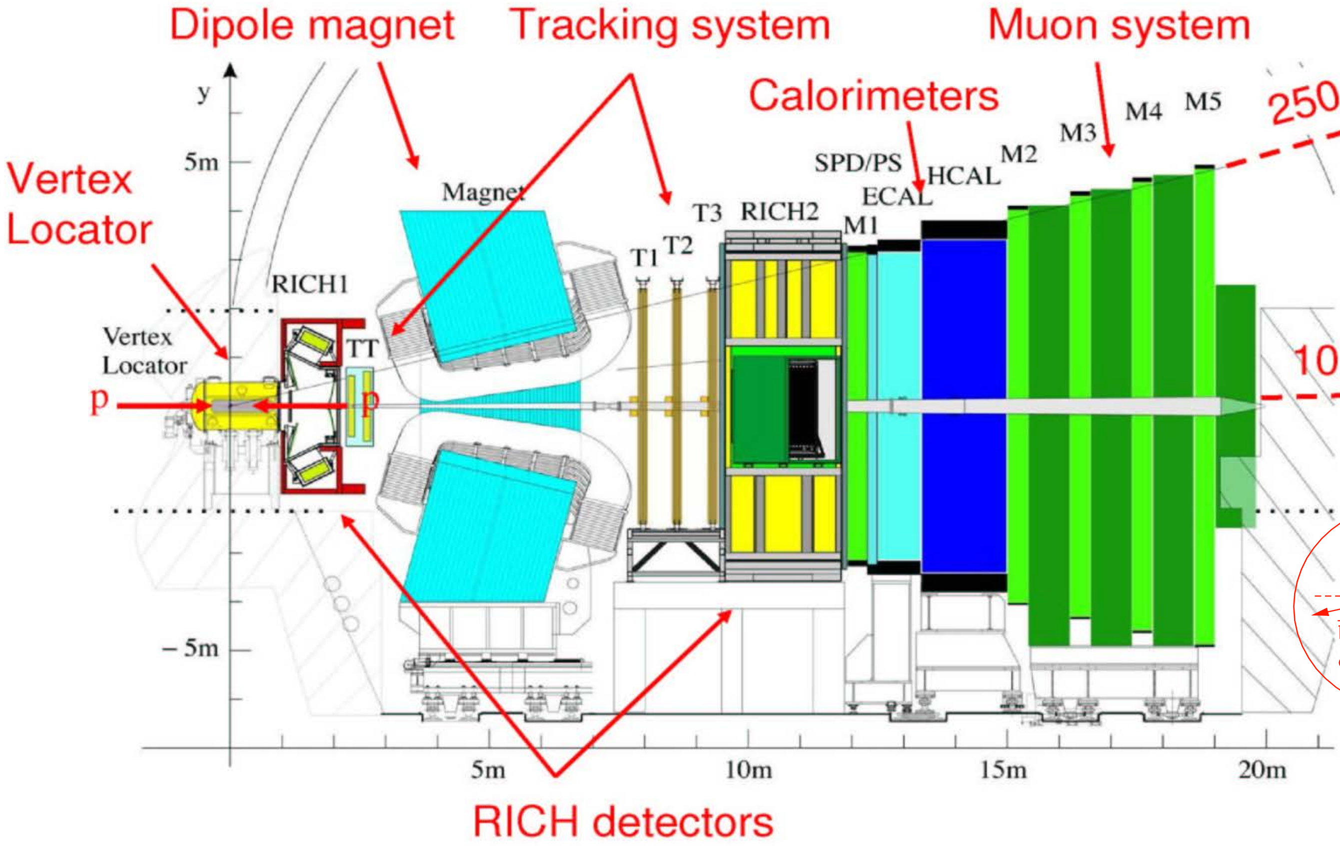
σ *Br(J/ψ→μμ) = 2.4μb

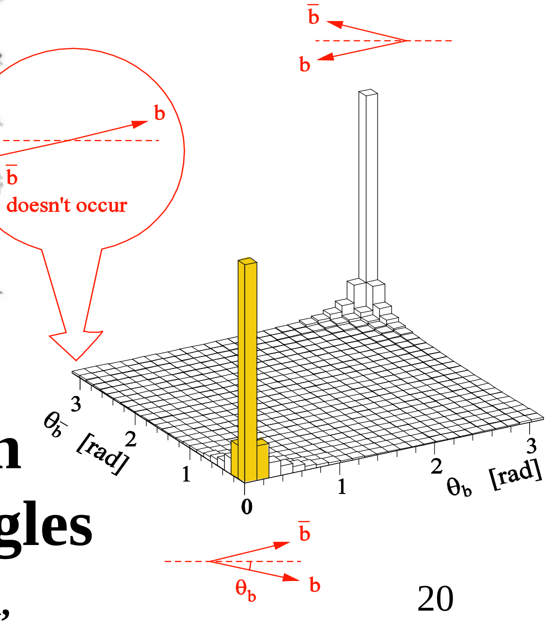
1.8<y<4.9

LHCb

σ_{tot} *Br(J/ψ→μμ) = 9.7μb

PERSPECTIVES FOR LHC*B*: DETECTOR





Detector optimized for reconstructing B meson decays, predominantly produced at low polar angles

LHC*b* TRIGGER

Two trigger levels:

- **L0**: Custom electronic boards
- **HLT**: Software trigger running on a CPU farm

- Reduce the rate from 40 Mhz to 1MHz (L0):
  - 40 MHz Bunch crossing
  - 10 MHz of crossing with visible interaction in LHCb at L=2x10^{32} cm^{-2} s^{-1}
  - Dedicated data from pile-up, calorimeters and muon detectors
  - Fixed latency at 4μs

- Reduced rate from 1MHz to 2KHz (HLT):
  - All detectors infos available
  - Average latency determined by the numbers of CPU: ~1800 boxes

HLT rate	Event type	Calibration	Physics
200 Hz	Exclusive B candidates	Tagging	B (core program)
600 Hz	High mass di-muons	Tracking	J/ψ, b→J/ψX (unbiased)
300 Hz	D* candidates	PID	Charm (mixing & CPV)
900 Hz	Inclusive b (e.g. b→μ)	Trigger	B (data mining)

Di-Muon Trigger: Muon Alley

L0μ Entry

Select the event triggered with L0μ

P res ~20%

200KHz

L0μ confirmation

Foreseen but empty at the moment

Muon PreTrigger

Partial reconstruction for muon track, factor ~ 10 rate reduction

P res ~5%

10-20KHz

Muon Trigger

Accurate reconstruction for muon track, factor ~10 rate reduction

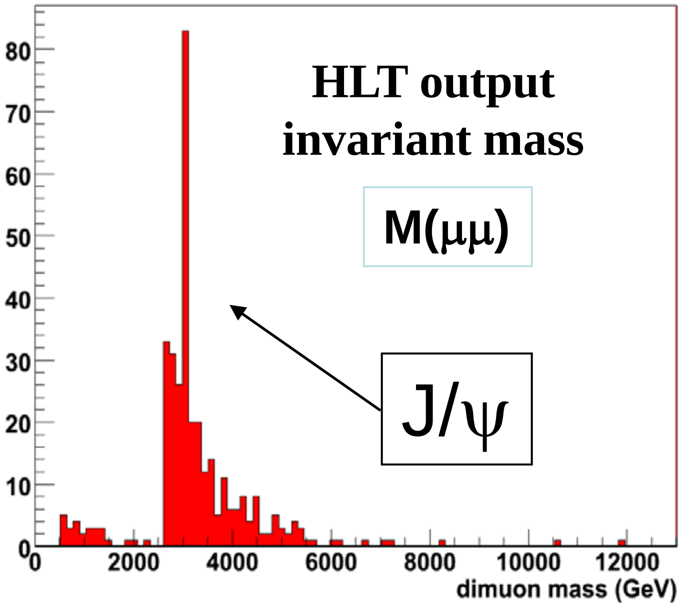
P res ~1%

~1-2KHz

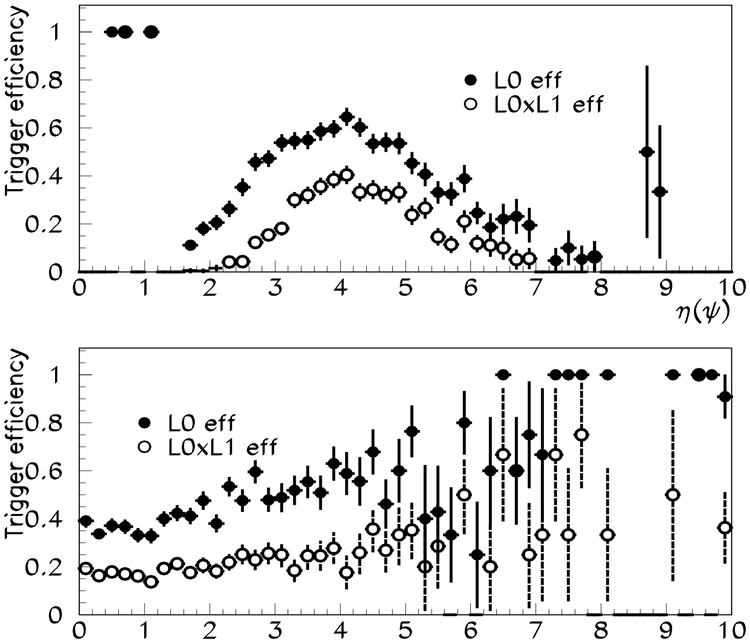
To tape

DI-MUON TRIGGER: REQUIREMENTS

- Simple cuts → minimize biases
  - **M(μμ)>2.5GeV OR (M(μμ)>0.5GeV && IP >100 μm)**
  - **Rate → order of 100- 200 Hz of J/ψ recorded to tape**
- **Order of 10^9 J/ψ's recorded on tape in one nominal year of data taking ($L=2fb^{-1}$) with a dimuon trigger!**



L0 and HLT trigger efficiencies as a function of η and p_T of the J/ψ



CONCLUSIONS

- Studies with Colour Octet contributions at different min. p_T cut-offs – used for regularizing the divergent cross section – give unsatisfactory results with abrupt p_T cut-off when comparing simulations with CDF data
- More promising results with event-by-event reweighting adopting the same weight used in the Pythia MPI model, both for J/ψ and Y production at Tevatron
  - ➡ However the contribution from CSM seems a bit excessive and needs to be understood
- Extrapolation of the reweighting parameter p_{T0} to the LHC energy made with different scenarios of energy dependence
  - ➡ Total cross section for Prompt J/ψ (times $BR_{\mu\mu}$) production predicted in the range 5.5-15 μb
- Copious production of Heavy Quarkonia states is expected at LHC
  - ➡ large sample of J/ψ - $O(10^9)$ - with an integrated luminosity of $L=2\ fb^{-1}$ (one nominal year of LHCb data taking) will be collected by LHCb allowing precise studies of quarkonium production at low/moderate p_T.

APPENDIX A:
NRQCD-PYTHIA DETAILS

P-wave $c\bar{c}$: χ_c implementations in PYTHIA 6.3: g-g, q-g, q-q channels

ISUB	$g+g\to c\bar{c}[^3P_J^{(1)}]+g$	ISUB	$q+g\to q+c\bar{c}[^3P_J^{(1)}]$	ISUB	$q+\bar{q}\to g+c\bar{c}[^3P_J^{(1)}$
431	$g+g\to c\bar{c}[^3P_0^{(1)}]+g$	434	$q+g\to q+c\bar{c}[^3P_0^{(1)}]$	437	$q+\bar{q}\to g+c\bar{c}[^3P_0^{(1)}$
432	$g+g\to c\bar{c}[^3P_1^{(1)}]+g$	435	$q+g\to q+c\bar{c}[^3P_1^{(1)}]$	438	$q+\bar{q}\to g+c\bar{c}[^3P_1^{(1)}$
433	$g+g\to c\bar{c}[^3P_2^{(1)}]+g$	436	$q+g\to q+c\bar{c}[^3P_2^{(1)}]$	439	$q+\bar{q}\to g+c\bar{c}[^3P_2^{(1)}$

Bottomonia implementation in PYTHIA 6.3

ISUB	$g+g\to b\bar{b}[n]+g$	ISUB	$q+g\to q+b\bar{b}[n]$	ISUB	$q+\bar{q}\to g+b\bar{b}[n]$
461	$g+g\to b\bar{b}[^3S_1^{(1)}]+g$				
462	$g+g\to b\bar{b}[^3S_1^{(8)}]+g$	465	$q+g\to q+b\bar{b}[^3S_1^{(8)}]$	468	$q+\bar{q}\to g+b\bar{b}[^3S_1^{(8)}]$
463	$g+g\to b\bar{b}[^1S_0^{(8)}]+g$	466	$q+g\to q+b\bar{b}[^1S_0^{(8)}]$	469	$q+\bar{q}\to g+b\bar{b}[^1S_0^{(8)}]$
464	$g+g\to b\bar{b}[^3P_J^{(8)}]+g$	467	$q+g\to q+b\bar{b}[^3P_J^{(8)}]$	470	$q+\bar{q}\to g+b\bar{b}[^3P_J^{(8)}]$

χ_b implementations in PYTHIA 6.3: g-g, q-g, q-q channels

ISUB	$g+g \rightarrow b\bar{b}[^3P_J^{(1)}]+g$	ISUB	$q+g \rightarrow q+b\bar{b}[^3P_J^{(1)}]$	ISUB	$q+\bar{q} \rightarrow g+b\bar{b}[^3P_J^{(1)}$
471	$g+g \rightarrow b\bar{b}[^3P_0^{(1)}]+g$	474	$q+g \rightarrow q+b\bar{b}[^3P_0^{(1)}]$	477	$q+\bar{q} \rightarrow g+b\bar{b}[^3P_0^{(1)}]$
472	$g+g \rightarrow b\bar{b}[^3P_1^{(1)}]+g$	475	$q+g \rightarrow q+b\bar{b}[^3P_1^{(1)}]$	478	$q+\bar{q} \rightarrow g+b\bar{b}[^3P_1^{(1)}]$
473	$g+g \rightarrow b\bar{b}[^3P_2^{(1)}]+g$	476	$q+g \rightarrow q+b\bar{b}[^3P_2^{(1)}]$	479	$q+\bar{q} \rightarrow g+b\bar{b}[^3P_2^{(1)}]$

Photoproduction channels implemented in PYTHIA 6.2 only: the tests of the proper implementation of these channels only include the expression of partonic amplitude squared (PYSIGH). Not tested yet

ISUB	$g+\gamma\to c\bar{c}[^{(2S+1)}L_J{}^{(C)}]+g$	ISUB	$g+\gamma\to q+c\bar{c}[^{(2S+1)}L_J{}^{(C)}]$
440	$g+\gamma\to c\bar{c}[^3S_1{}^{(1)}]+g$		
441	$g+\gamma\to c\bar{c}[^3S_1{}^{(8)}]+g$	444	$g+\gamma\to q+c\bar{c}[^3S_1{}^{(8)}]$
442	$g+\gamma\to c\bar{c}[^1S_0{}^{(8)}]+g$	445	$g+\gamma\to q+c\bar{c}[^1S_0{}^{(8)}]$
443	$g+\gamma\to c\bar{c}[^3P_J{}^{(8)}]+g$	446	$g+\gamma\to q+c\bar{c}[^3P_J{}^{(8)}]$

ALTARELLI-PARISI EVOLUTION (1)

- Contributions from $Q\overline{Q}[{}^3S_1^{(8)}]$ partly come from the fragmentation of a gluon → since the gluon could have splitted into 2 gluons before fragmentation, this effect have to be included:
  - 2 NEW switches: MSTP(148) to switch ON & OFF the splitting:

$$Q\overline{Q}[{}^3S_1^{(8)}] \rightarrow Q\overline{Q}[{}^3S_1^{(8)}] + g$$

and MSTP(149) to choose if it's ensured that the QQ pair always takes the larger fraction of the four-momentum. This evolution obeys the Altarelli-Parisi evolution for g→g+g

- Handling of the Altarelli-Parisi evolution of $Q\overline{Q}[{}^3S_1^{(8)}]$, done with the parameter MSTP(148) (defalt value 0), allows the final- state shower evolution both for $c\overline{c}[{}^3S_1^{(8)}]$ and for $b\overline{b}[{}^3S_1^{(8)}]$.

ALTARELLI-PARISI EVOLUTION (2)

- ATTENTION! **switching MSTP(148) ON may exaggerate shower effects, since not all** $QQ[^3S_1^{(8)}]$ **comes from the fragmentation component where radiation is expected!!!! :** Since the fragmentation contribution of $QQ[^3S_1^{(8)}]$ to production processes is the most important contribution, the higher the transverse momentum of the QQ pair is….. →**highly advisable to switch ON the Altarelli-Parisi evolution for events with large transverse momentum**

- →If the $Q\bar{Q}[^3S_1^{(8)}]$ states are allowed to radiate [MSTP(148) = 1], the parameter MSTP(149) determines the kinematic of the $Q\bar{Q}[^3S_1^{(8)}] \rightarrow Q\bar{Q}[^3S_1^{(8)}] + g$ branching:
    - MSTP(149) = 0, daughter $Q\bar{Q}[^3S_1^{(8)}]$ picks always the larger momentum fraction (z > 0.5);
    - MSTP(149) = 1, daughter $Q\bar{Q}[^3S_1^{(8)}]$ picks momentum fraction equally z < 0.5 and z > 0.5

POLARIZATION

- Possibility to swich ON & OFF the polarized generation of quarkonia through the parameter MSTP(145) [0=unpolarized, 1=polarized, with selection of helicity states or density matrix elements]

→**FOR EXPERTS ONLY:**

  - The selection of the different polarization reference is done through MSTP(146) whose possible states are:
    - **1: Recoil (recommended since it matches how PYTHIA defines particle directions);**
    - **2: Gottfried-Jackson;**
    - **3: Target;**
    - **4: Collins-Soper**
  - The selection of the different helicity states or density matrix is done through MSTP(147) (with MSTP(145)=1):

0: helicity 0;
1: helicity +-1;
2: helicity +-2;
3: density matrix element rho_{0,0};
4: density matrix element rho_{1,1};
5: density matrix element rho_{1,0};
6: density matrix element rho_{1,-1}.

APPENDIX B:
NRQCD QUICK THEORY SLIDES

COLOR SINGLET MODEL (CSM)

Quarkonia inclusive decay rates and cross section were calculated at LO (*Leading Order*), with assumption of factorization:

→ short distance part, describing the annihilation (or creation) of the heavy quark pair in a COLOR SINGLET state;

→ non perturbative long distance factor, accounting for the soft part of the process.

The $c\bar{c}$ pair **is created in a color neutral state** with **the same quantum numbers as the final charmonium state**:

→CSM (Color Singlet Model)

✓For charmonia S-wave, NO infrared divergences of CSM for one-loop corrections;

✓ BUT in P-wave decays in light hadrons, appearance of infrared singularities in short distance coefficients → PROBLEM !

EXPERIMENTAL TESTS OF CSM

In fact: during the last 10 years, found orders of magnitude of disagreement between CSM prediction and new measurements of J/ψ and ψ’ production at several collider facilities.

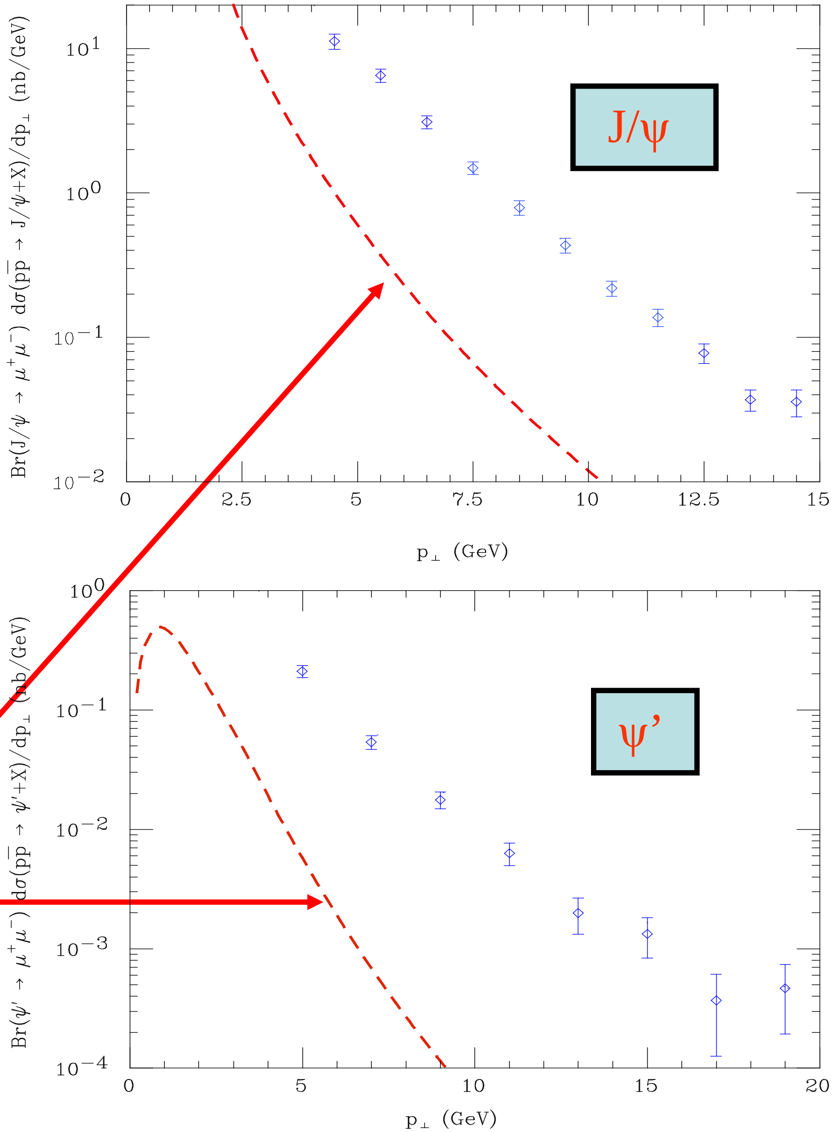
An example is the striking observation by CDF of large p_T J/ψ and ψ’ states

→ more than 1 order of magnitude larger than the theoretical predictions by CSM !

Tevatron transverse momentum differential cross sections:

Color Singlet predictions

both for J/ψ and ψ’ production



NRQCD

- Possible solution? → Effective field theory introduced → **Non-Relativistic QCD (NRQCD).**
  - quarkonium production and decay take place via intermediate $q\bar{q}$ states with different quantum numbers than the physical quarkonium state, that is producing or decaying.
  - a transition probability $\langle O_{1,8}^{H}(n)\rangle$ describes the transition of $c\bar{c}$ pair (color octet + color singlet) into the final $q\bar{q}$ state;
  - The NRQCD factorization formula for the production cross section of state H is:

$$\sigma^{H} = \sum_{n} \sigma_{1,8}^{c\bar{c}}(n)\langle O_{1,8}^{H}(n)\rangle$$

  - $\sigma_{1,8}^{c\bar{c}}(n)$: short-distance production of a $q\bar{q}$ pair in color, spin and angular momentum state *n* ($^{2S+1}L_J^{[1,8]}$);
  - $\langle O_{1,8}^{H}(n)\rangle$: describes the hadronization of the pair into the observable state H.

NRQCD predictions

→With the addiction of color octet contributions, the Tevatron transverse momentum cross sections AGREE well with the NRQCD predictions

for both of charmonium states.