# Charmonium production at SPD

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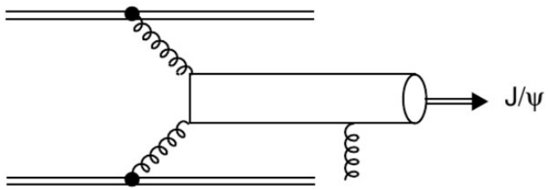
# Motivation

I. Extraction of TMD PDFs from DY is very complicated due to large background mostly from pion decays.

II. J/ψ production




a) is sensitive to quark and gluon pdf,

b) has large cross-section and have very distinct signal in the dimuon mode,

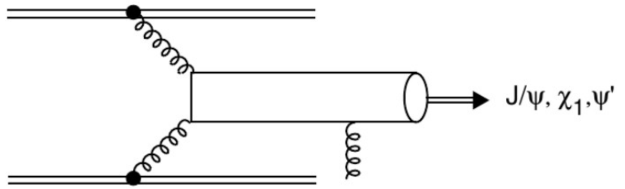
c) is theoretically ambiguous,

d) is a sum of direct and feed-down processes.

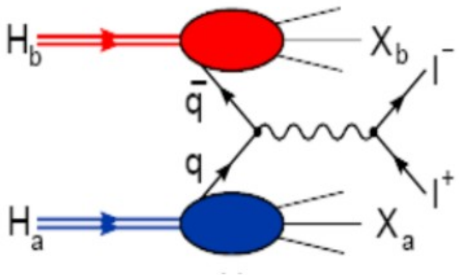
III. J/ψ production is complimentary to the DY and prompt photons studies.

IV. Study and verification of J/ψ production mechanisms would be crucial for extraction of gluon pdf in AMBER at similar c.m.s. energies.

# J/ψ Vs. DY




For e.c.m. 24-26 GeV




- Cross-section of 150-200 nb
- Expected statistics is 20M per year
- Clean dimuon mode  (9-12 nb in dimuon mode)
- Sensitive to gluon and quark pdf
- Suggested to measure Sivers effect for gluons. Might be possible to study quark asymmetries.

**Feed-down contributions:**
30-40% of J/ψ are produced in $\chi_{c1}$, $\chi_{c2}$, and ψ(2S) decays, thus complicating the analysis kinematic distributions.

ψ(2S) is free from feed-down contributions, but statistics in dimuon mode is suppressed by aprox. 60.

$M_{l+l-}$ > 4 GeV:

- Cross-section 0.06-0.07 nb
- Expected statistics ~100K

# Theretical models

- Color evaporation models (CEM)
  - collinear factorization (old)
  - Improved CEM: $k_T$-factorization similar to PRA (e.g. Phys. Rev. D 98, 114029 (2018))
- NRQCD
  - collinear factorization (old)
  - **PRA and TMD factorization**

# NRQCD in collinear factorization

Phys.Rev.D54:2005,1996

For the process $A+B \to H+X$ in the collinear factorization:

$$\sigma_H = \sum_{i,j} \int_0^1 dx_1 dx_2 f_{i/A}(x_1) f_{i/B}(x_2) \hat{\sigma}(ij \to H).$$

1. **Conjecture** of the cross-section factorization to short-distance ($x \approx 1/m_c$) and long-distance parts:

$$\hat{\sigma}(ij \to H) = \sum_n C^{ij}_{Q\bar{Q}[n]} \langle O^H_n \rangle.$$

   $C^{ij}_{Q\bar{Q}[n]}$ (SDC) describe heavy quark pair production, $\langle O^H_n \rangle$ long distance matrix elements (LDME) describe its hadronization to quarkonium $H$ and $n = {}^{2S+1}L_J^{(1,8)}$. **Proven only for sufficiently large $p_T$.**

2. **Hierarchy** of LDME $\langle O^H_n \rangle$ with respect to $v$ ($v^2 \approx 0.2 - 0.3$ for charmonium).

Expression for cross-section is a **double** series in $\alpha_s$ and $v$. There are indications that the series is well-converged.

# NRQCD in collinear factorization

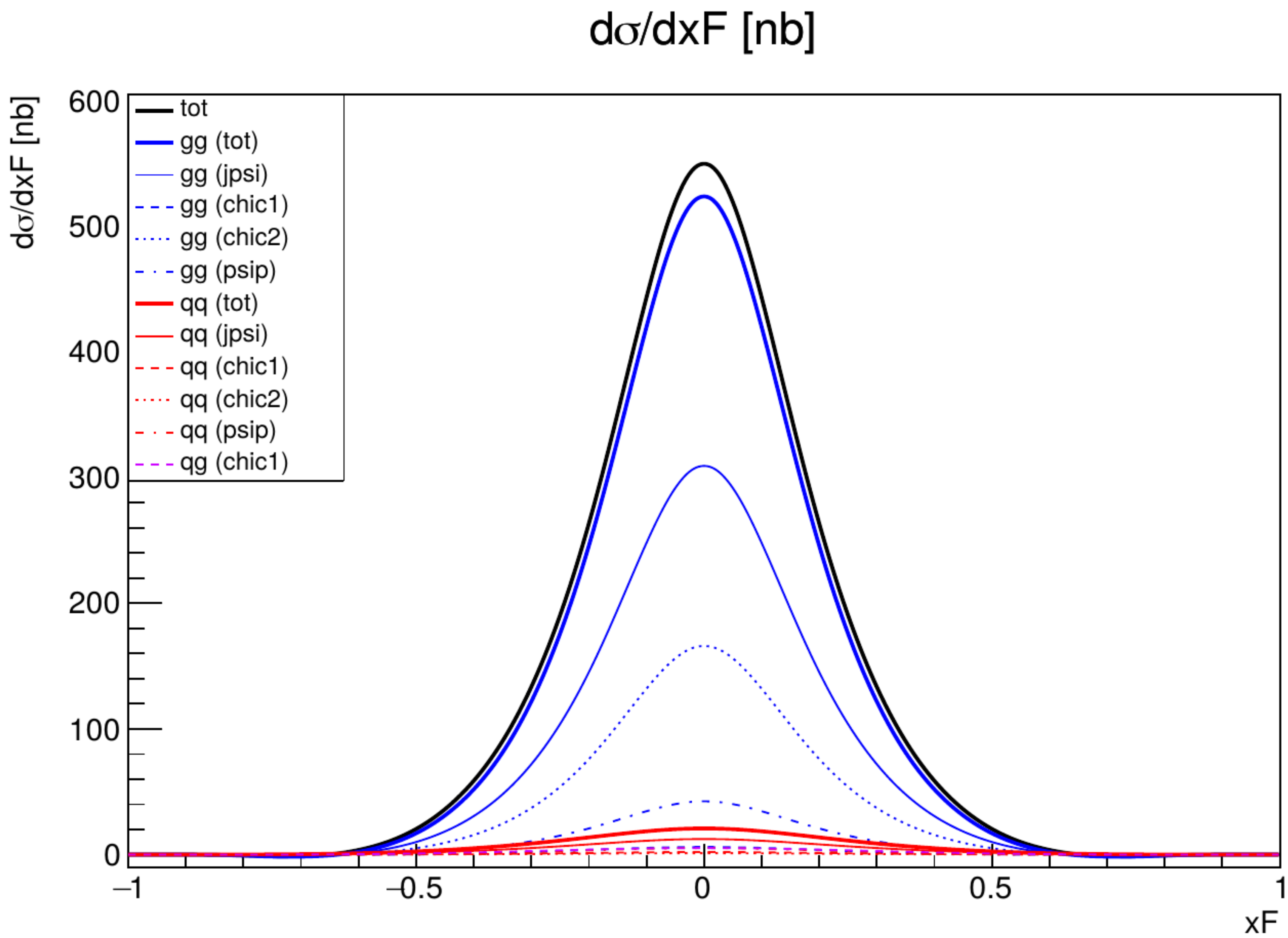
**Ingredients:**

- **SDC** are determined from NRQCD.
- The **singlet LDME** are determined from charmonium decays or charmonium wave function in potential models ($O(v^2)$).
- The **octet LDME** are determined from the fits to experimental data.
- The are **lattice** calculations only for $\langle O_1^{\chi_{cJ}}(^3P_J)\rangle$ and $\langle O_8^{\chi_{cJ}}(^3S_1)\rangle$ (Phys.Rev.Lett.77(1996)2376). They are reasonably consistent with global fits (Braaten, Lectures on NRQCD factorization).

**Predictions:**

- $x_F$, separate contributions from quark-antiquark annihilation and gluon-gluon fusion;
- $p_T$ in for $p_T > 2m_c$ for collinear factorization (not at SPD energies);
- charmonia polarization;
- $\sqrt{s}$ dependence.

# $x_F$: contributions of subprocesses

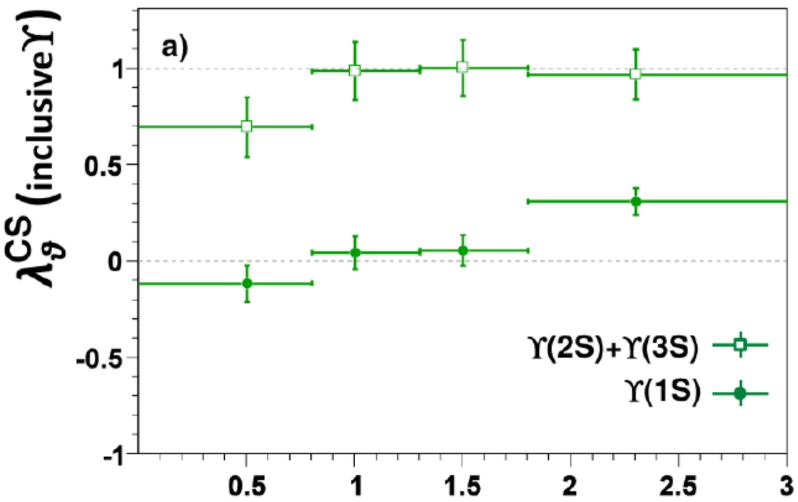



- Formulas and LDME from Phys.Rev.D54:2005,1996
- PDF: NNPDF23 NLO

# J/ψ polarization

- $d\sigma/d\cos\theta \sim 1 + \alpha$
  - $\alpha = 1$ – transverse
  - $\alpha = -1$ – longitudinal
- The J/ψ polarization is sensitive to elementary J/ψ production process and is a nontrivial test to the NRQCD.
- Polarization of $\chi_{cJ}$ states has not been measured yet.
- Previous measurements from fixed-target experiments are not precise and may suffer from 1D efficiency corrections (Faccioli, Mod. Phys. Lett. A 27. 1230022(2012))

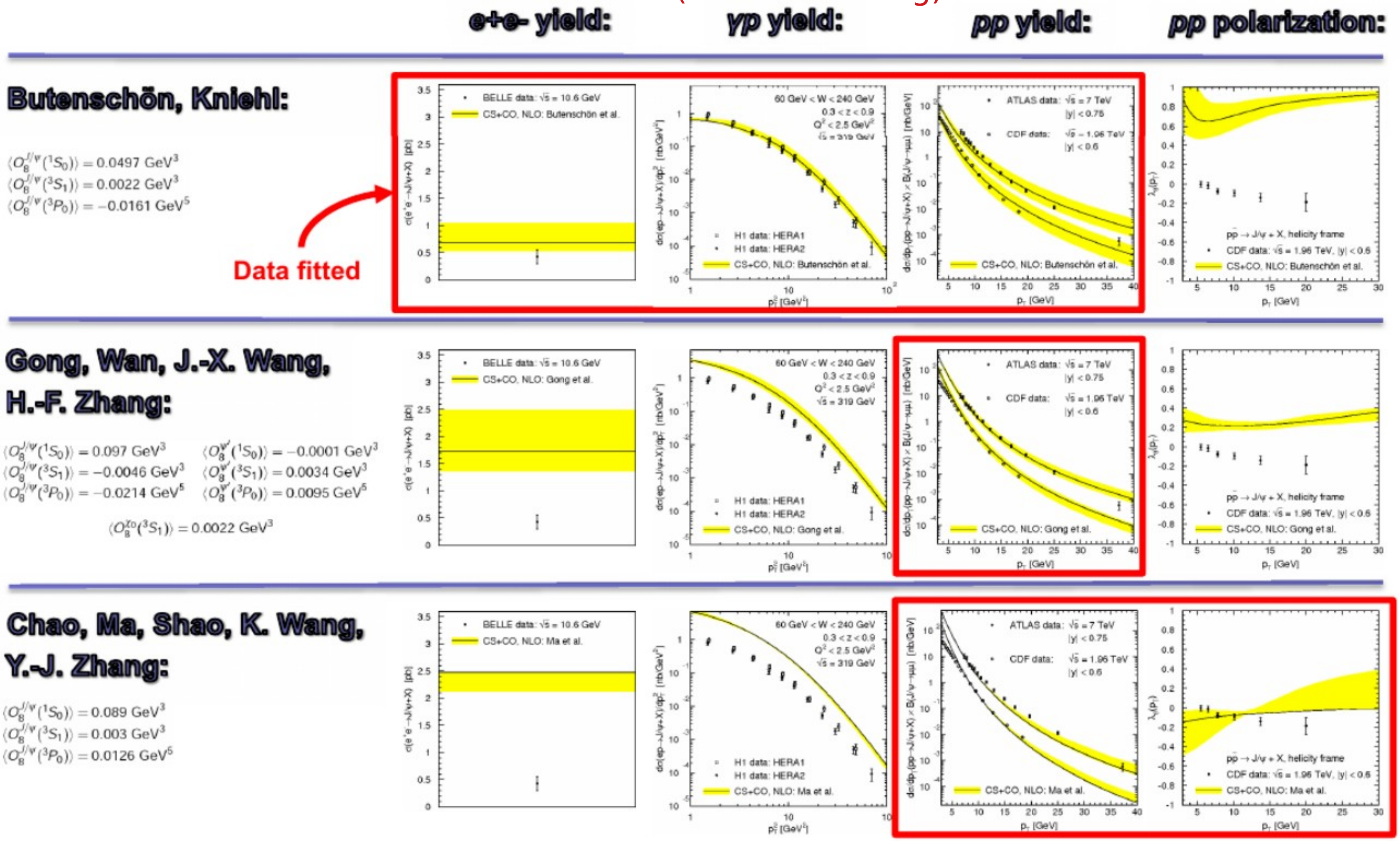
Feed-down contribution may play significant role in the polarization puzzle!




E866 data on Υ polarization. Figure from Mod.Phys.Lett. A27 (2012) 1230022

# LDME

Slide borrowed from M. Butenschoen DIS 2016 (DESY Hamburg)




Details in Mod.Phys.Lett.A,Vol.28,No.9(2013) 1350027.

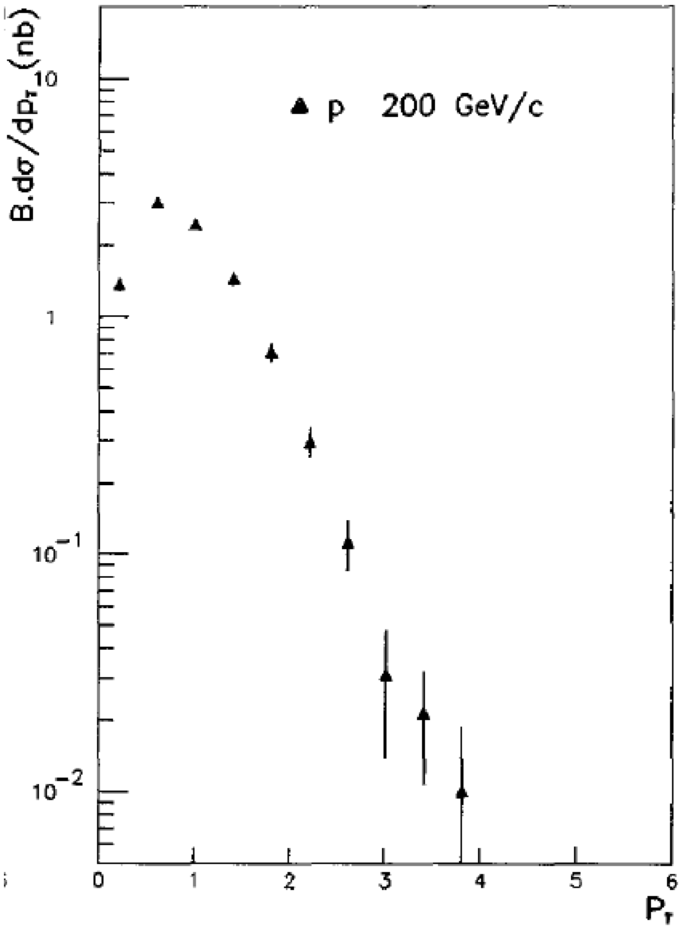
No SDML set can described all $e^+e^-$, $\gamma p$, $pp$ and $pp$ polarization data.

# Theoretical aproaches for SPD

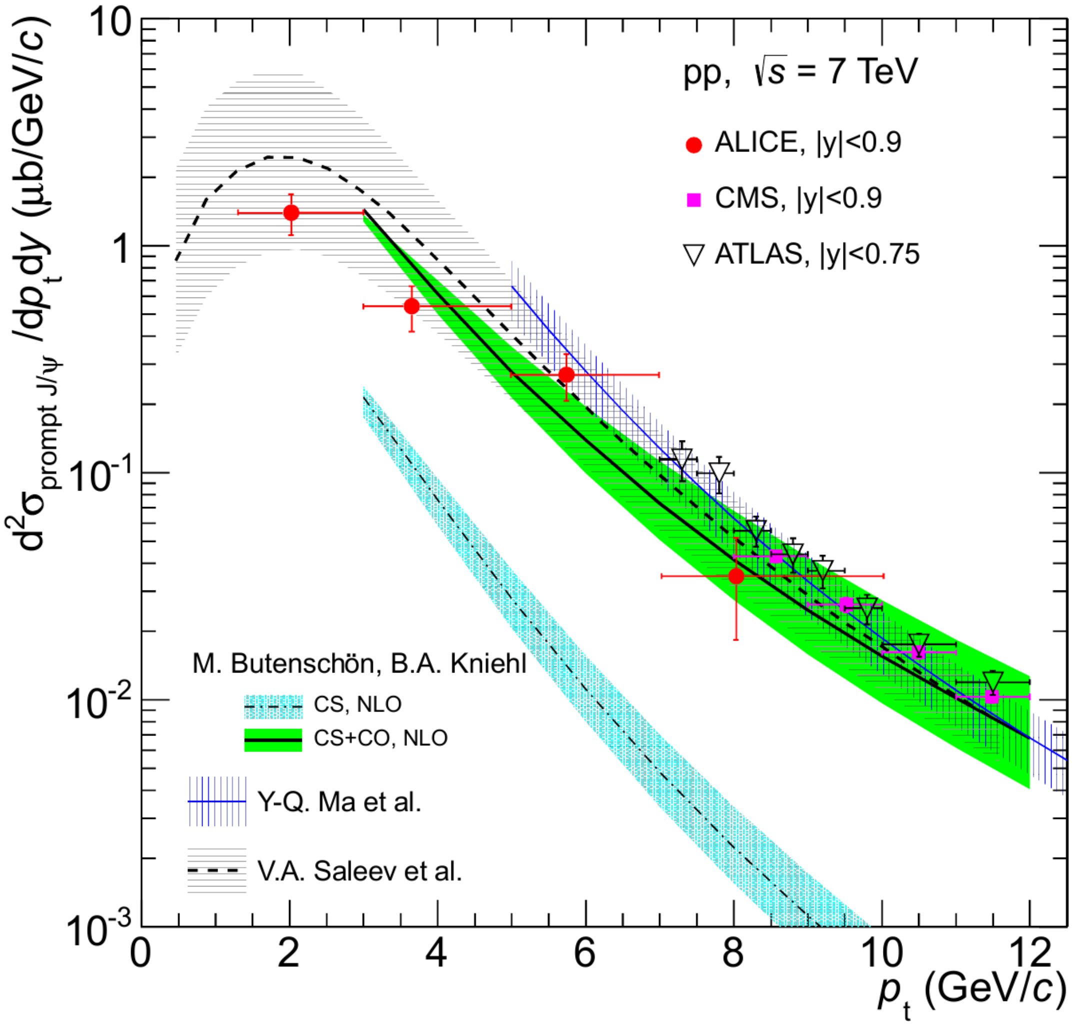
NA3
sqrt(s) = 19.4 GeV

The SPD $p_T$ range below 3-4 GeV is very complicated for the analysis:

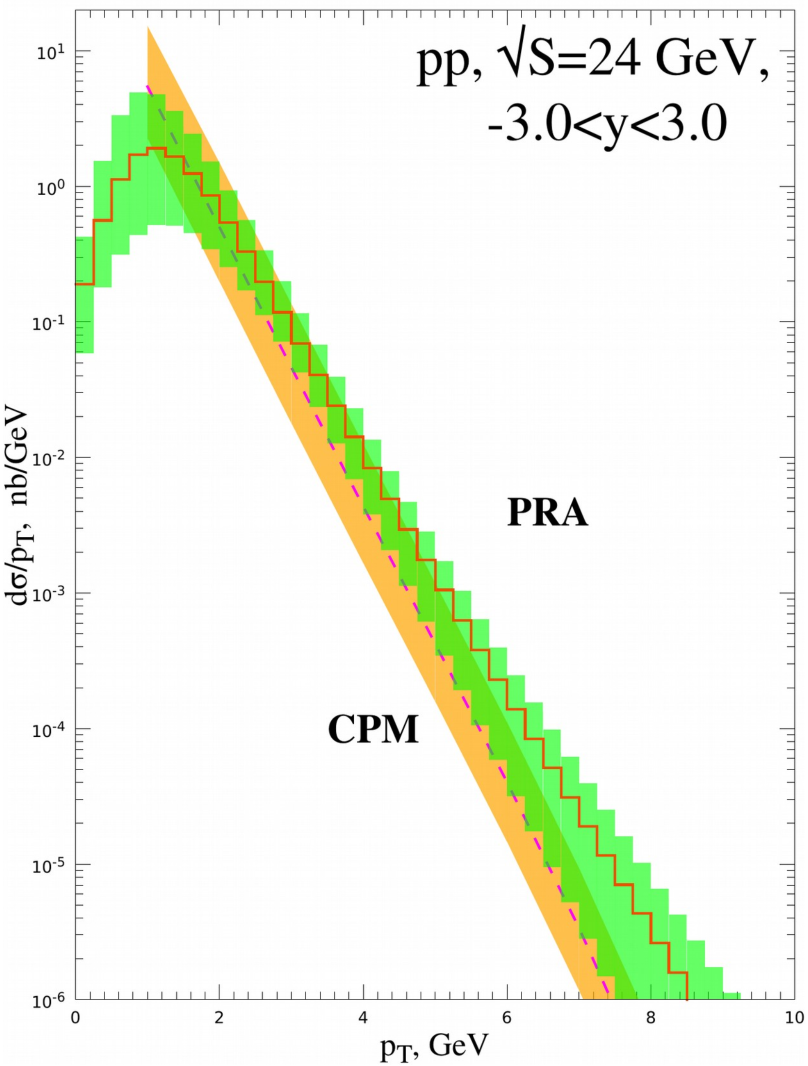
- collinear factorization is not applicable below 4 GeV (or even higher values) and the $p_T$ spectrum diverges for $p_T \to 0$,
- TMD factorization is valid for $p_T << M_{J/\psi}$,
- Parton Reggeization Approach (PRA) is expected to be valid in the whole expected $p_T$ range.



# PRA approach




ALICE Collaboration, JHEP 1211 (2012) 065




**CPM** is NLO CPM calculation by B.A. Kniehl, and M. Butenschoen.
**PRA** is LO Parton Reggeization Approache by M.Nefedov and V. Saleev.

# J/ψ polarization in PRA

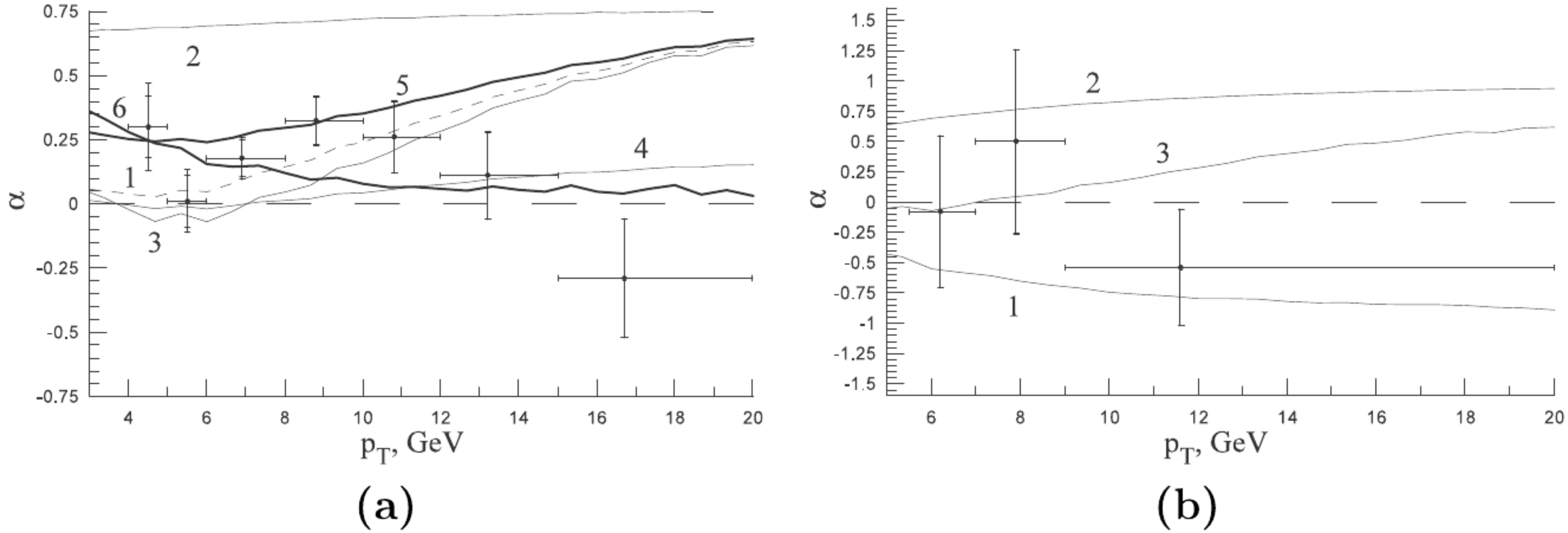
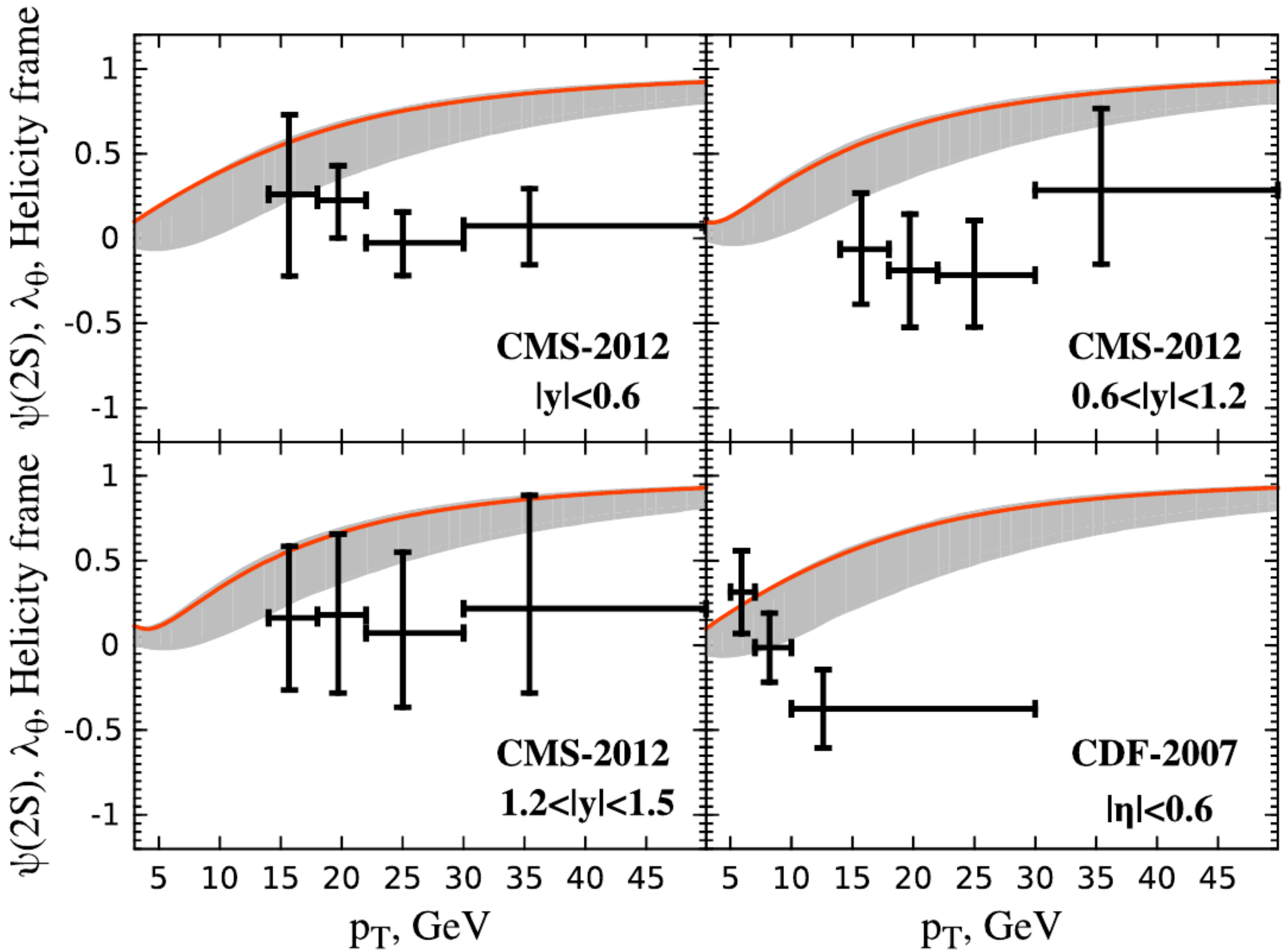
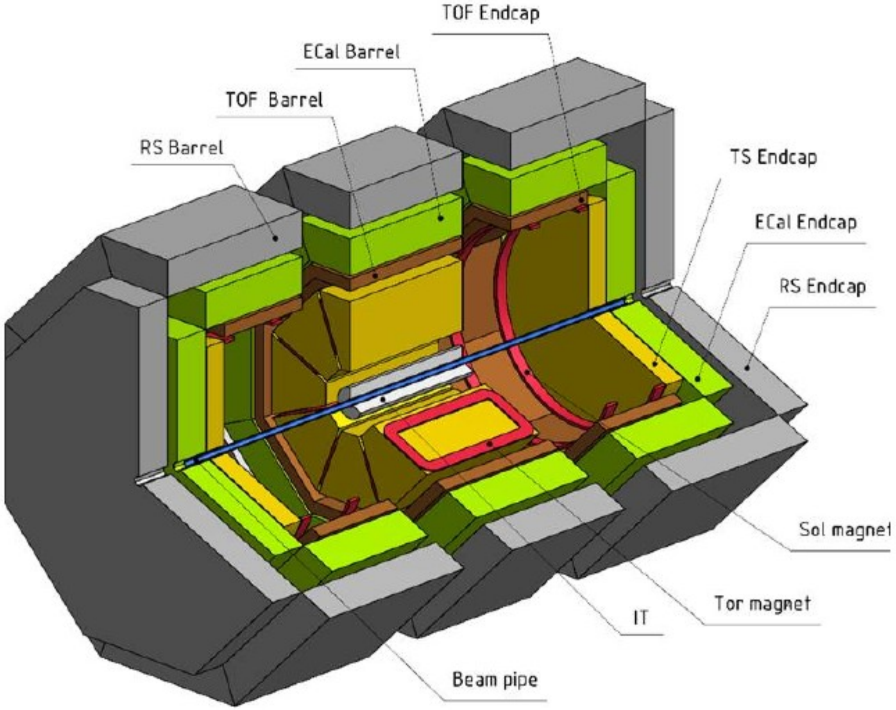



**Figure 1a.** Polarization parameter $\alpha(p_T)$ for prompt $J/\psi$ production. Curve 1 — the direct production channel, 2 — $J/\psi$ from $\chi_c \to J/\Psi\gamma$ decays, 3 — $J/\psi$ from $\psi' \to J/\psi$ decays, 4 — $J/\psi$ from $\psi' \to \chi_c \to J/\psi$ decays, 5 — the sum of (1)-(4) terms , 6 — the CSM prediction.
**Figure 1b.** Polarization parameter $\alpha(p_T)$ for direct $\psi'$ meson production. Curve 1 — the CSM prediction, 2 — the color-octet mechanism prediction, 3 — the direct production channel.

# ψ(2S) polarization in PRA



# Detector simulation status




## Detector is mostly available as material maps.

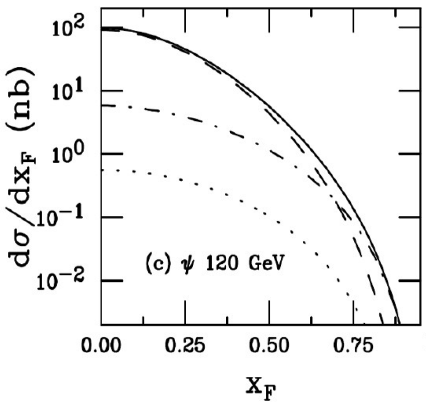
- **magnetic system and field:** available
- **vertex detector**: preliminary set-up
- **tof**: not implemented
- **tracking system**: very preliminary set-up, material map
- **electromagnetic calorimeter:** material map (detailed description is available, but it is not default)
- **range system**: material map, detailed description is expected soon

**Tracking performance is uncertain!**

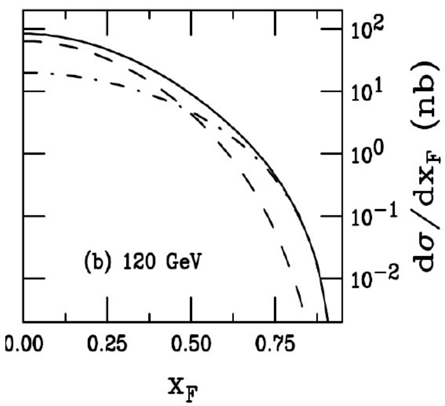
# Barrel/Endcap distribution of muons

Phys.Rev.C61:035203,2000

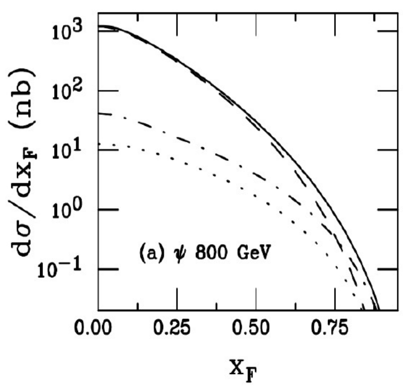
NRQCD sqrt(s)=15 GeV



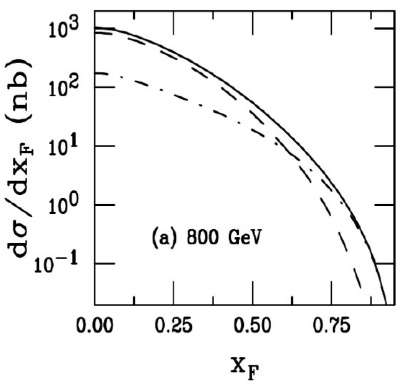

CEM sqrt(s)=15 GeV



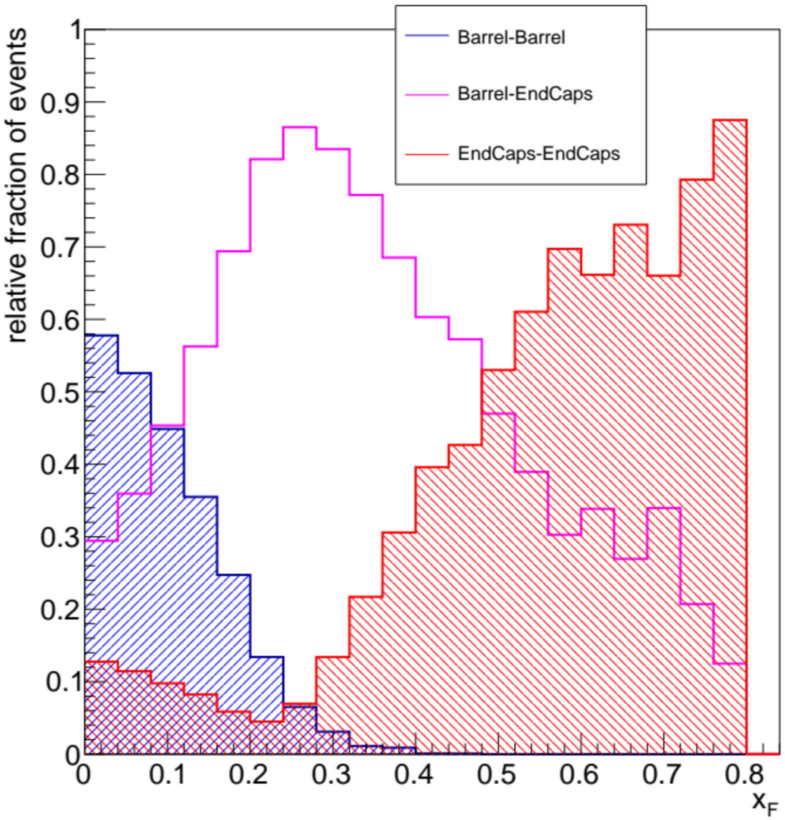

NRQCD sqrt(s)=39 GeV




CEM sqrt(s)=39 GeV

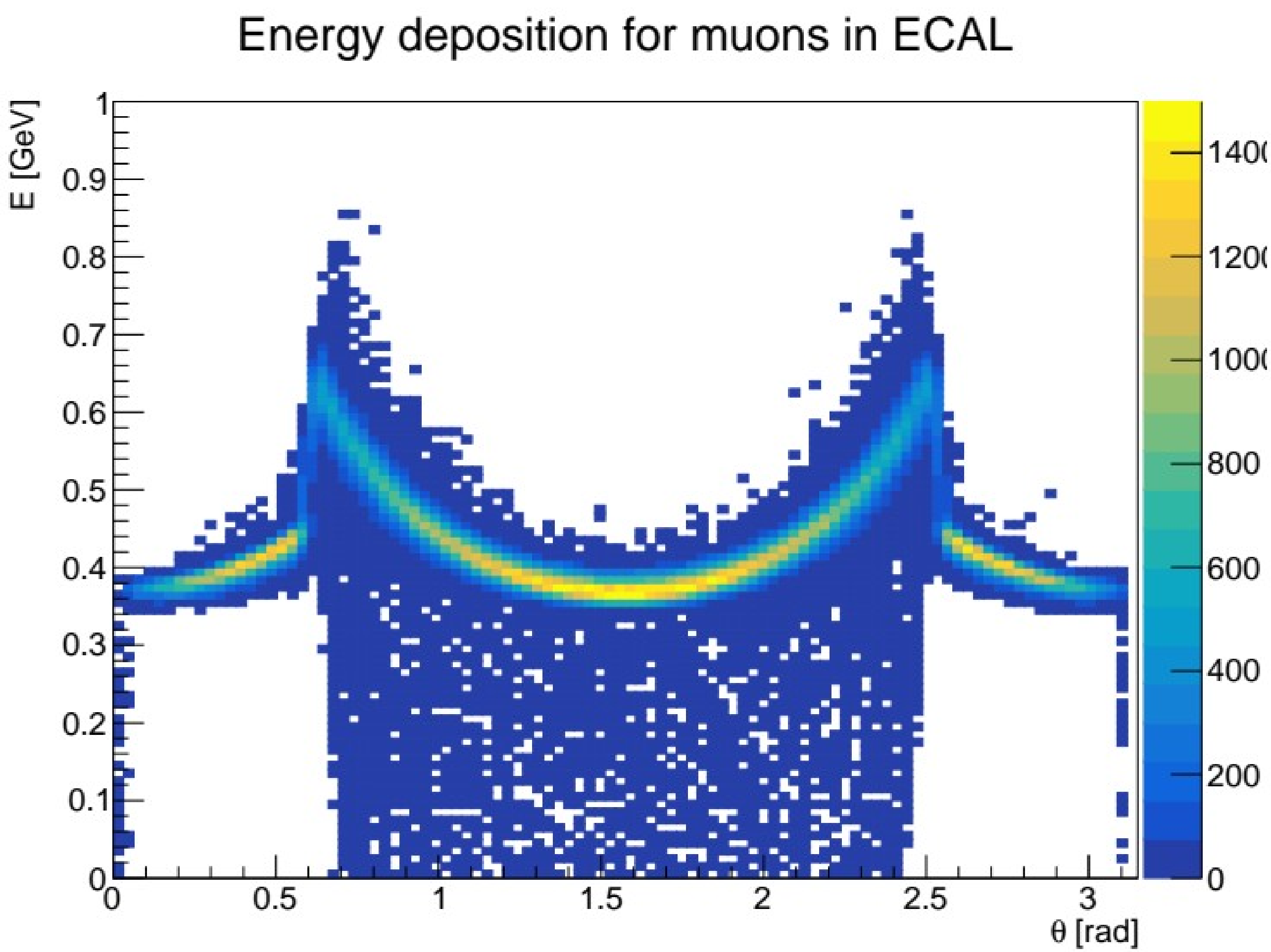



Pythia6 gg → J/ψ X



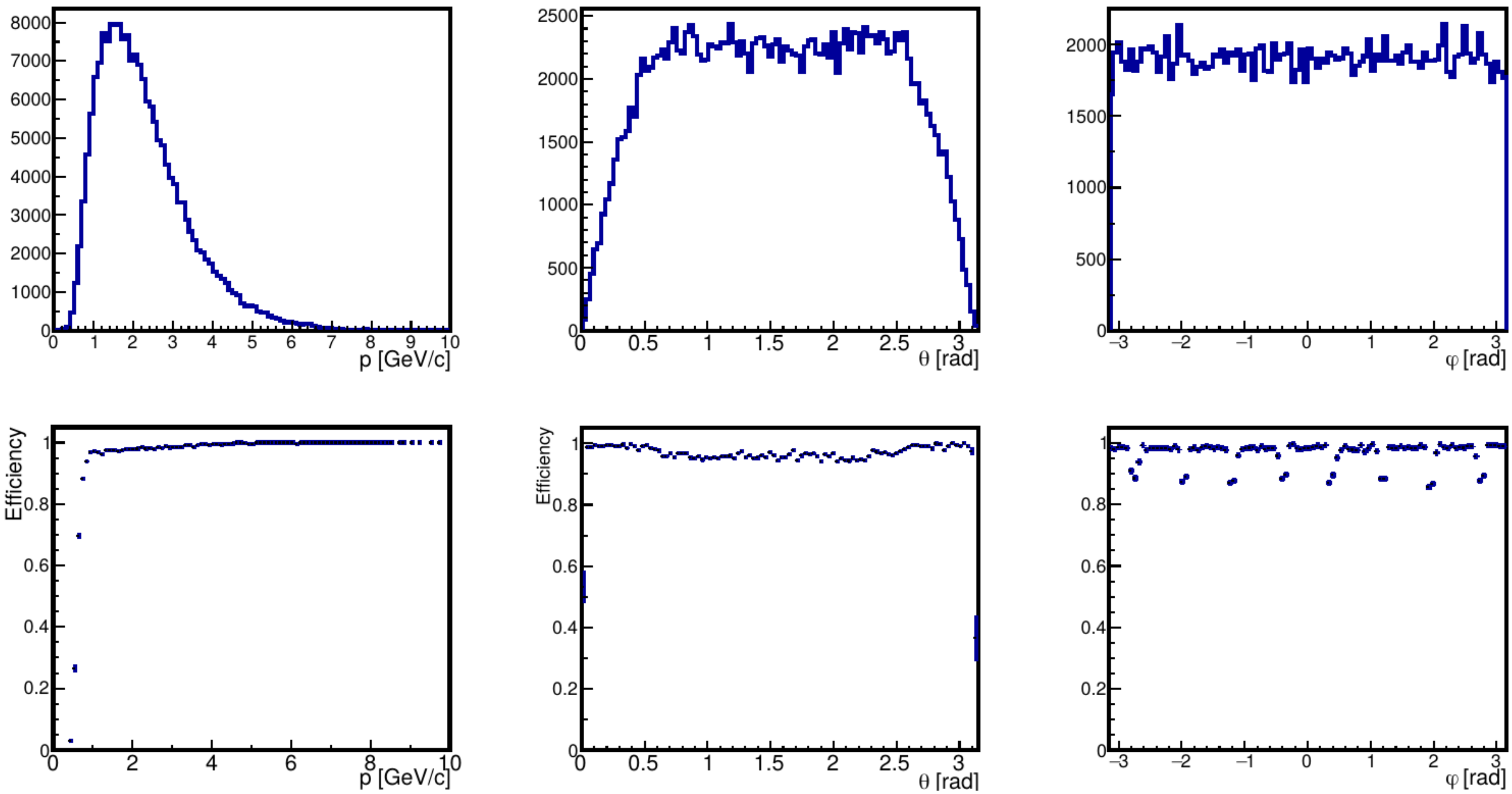

High performance of endcaps is essential for medium and high $x_F$ values, where relative contribution from $q\bar{q}$ annihilation may become significant.

# Energy loss for mouns



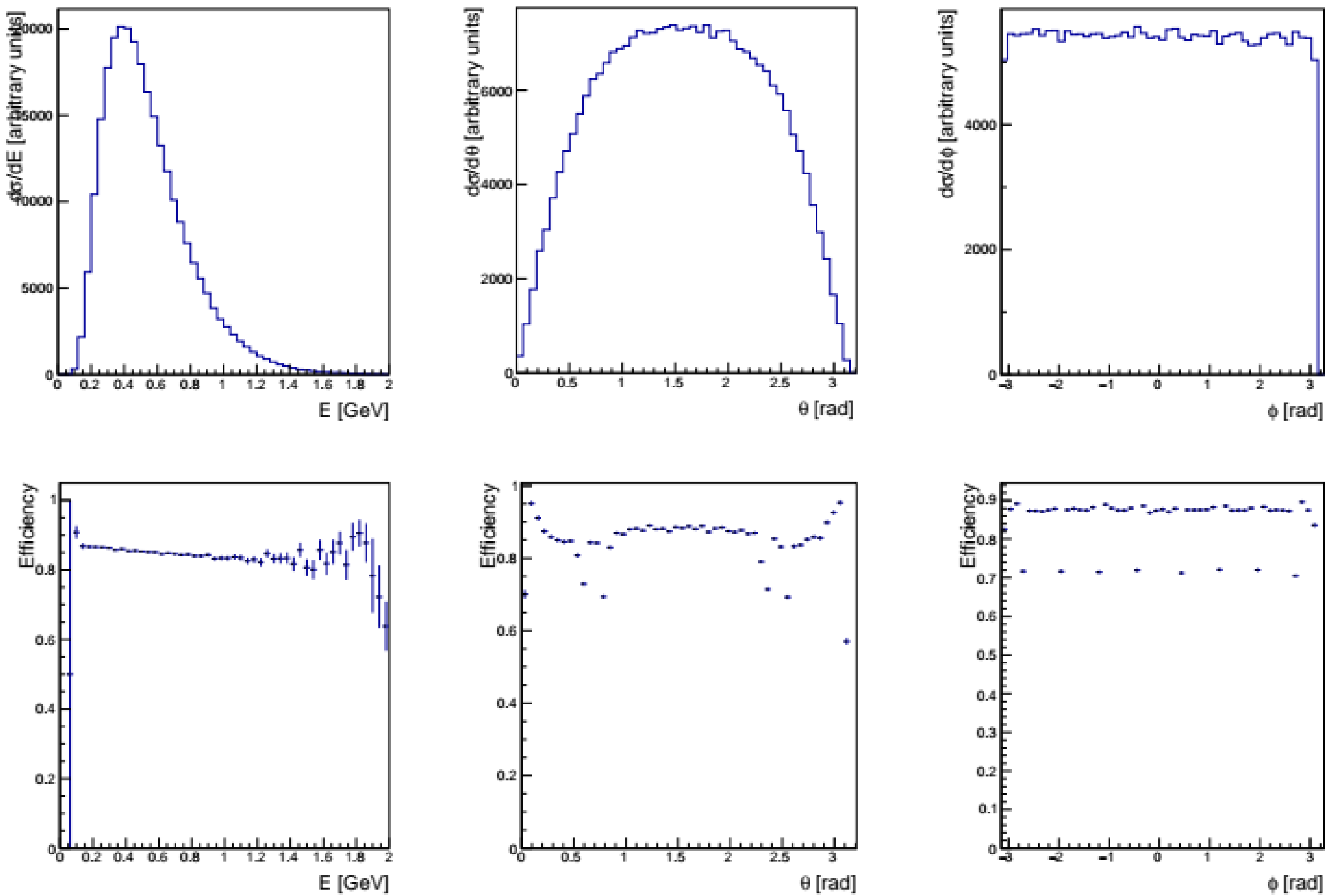

- Most of the energy muons lose in ECAL.
- The energy deposition agree with expectations.

# Acceptance for mouns




- Process: Pythia6 gg → J/ψ X
- 93% of muons rich the range system

# Acceptance for photons from $\chi_{c1} \to \gamma J/\psi$




Kinematic distributions for photon from the $gg \to \chi_{c1}X$, $\chi_{c1} \to \gamma J/\psi$ process (Pythia 6). The total acceptance (muons reach RS and photon reaches ECAL) for $\chi_{cJ} \to \gamma J/\psi$ is approximately 80%.

# On resolution

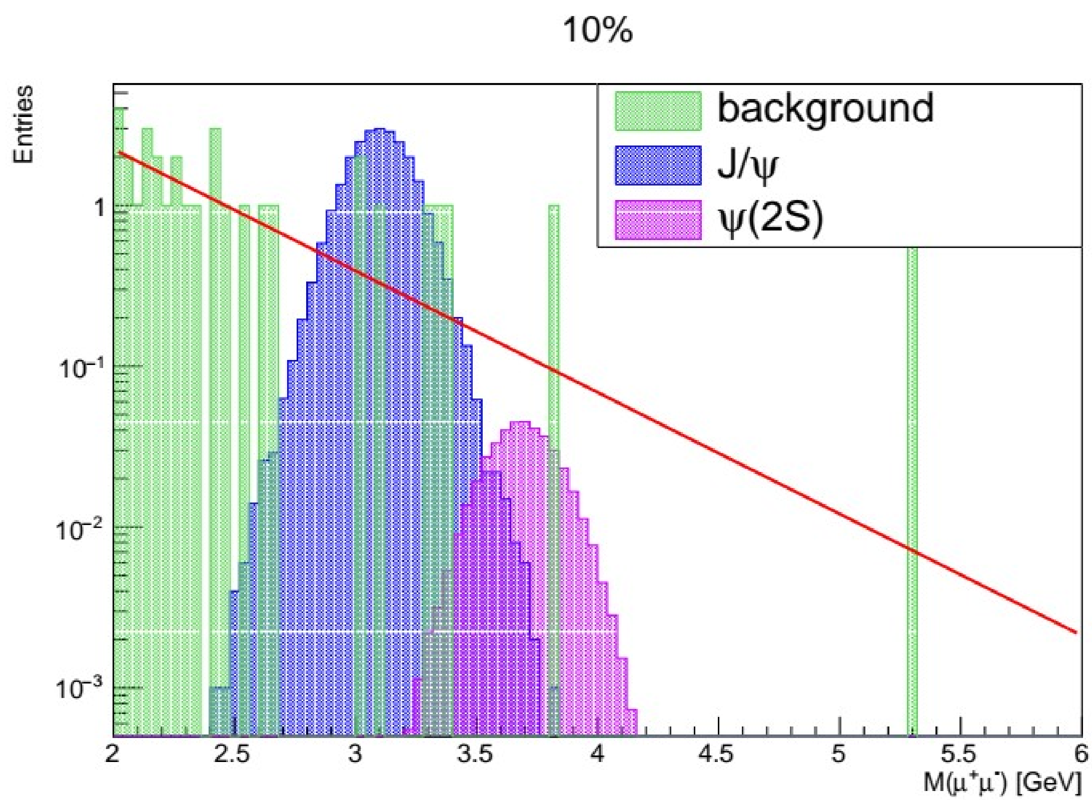
**Generator-level simulation:**

- 100 millions minimum bias events (Pythia6)
- J/ψ cross-section 200 nb
- ψ(2S) cross-section 1/60 of J/ψ cross-section
- Muons produced within
  - r<750 cm
  - |z| < 1000 cm

**Base cuts:**

- distance to the beam axis < 2 mm
- distance between muon tracks < 1 cm
- |cosθ| < 0.9 for muons

Momentum resolution:



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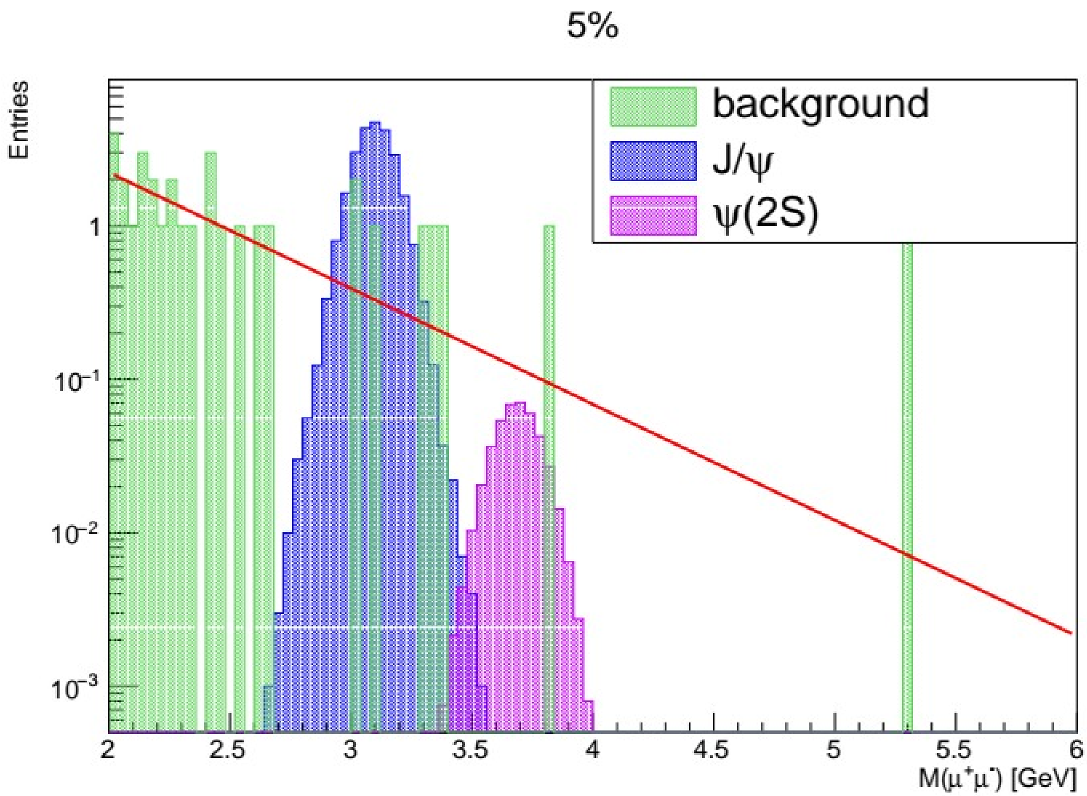

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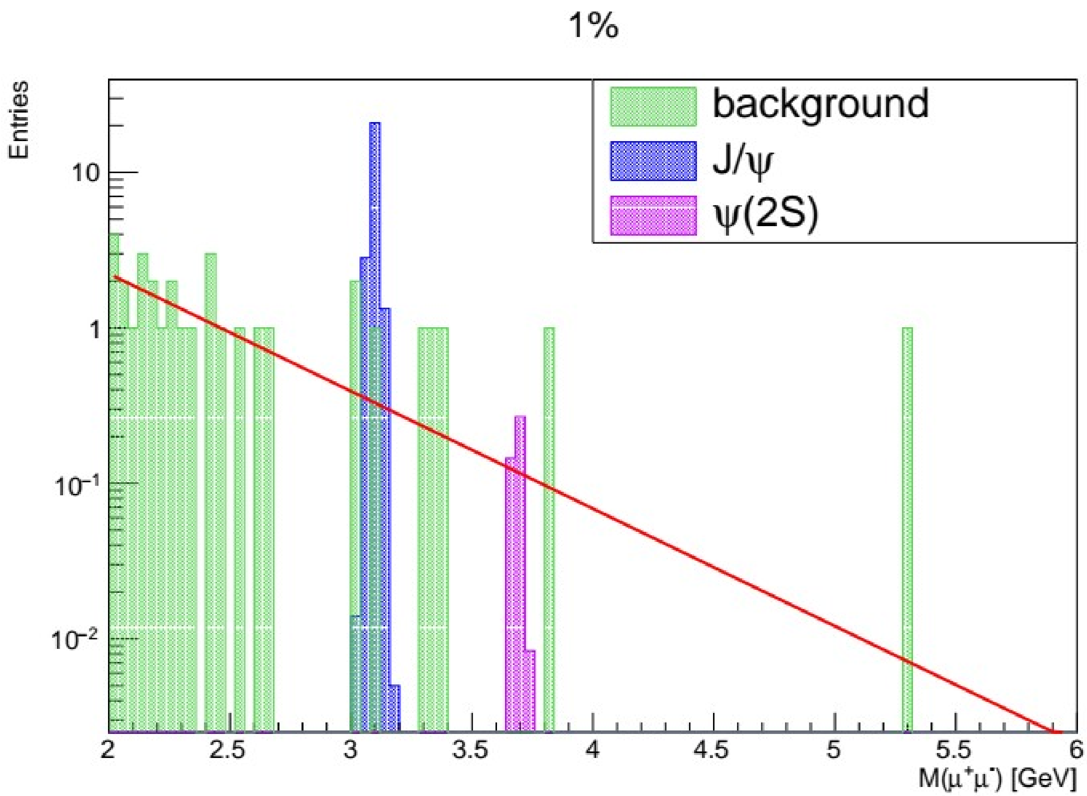


# Charmonium group

**Charmonium group:**

- Alexey Guskov
- Igor Denisenko
- Jose Rubiera (all plots in this talk obtained with SPDROOT)
- Dario Zaldivar

# Summary

- Charmonia production is a powerful tool to probe parton distributions. It is complimentary to DY and prompt photons.
- We have a group, but in the absence of tracking and detailed description of detector subsystems and their performance we can do only very basic simulation of physical processes.
- Good momentum resolution is essential for charmonium program: values of the order of 10% would reduce SPD experimental capabilities to ones of the previous fixed-target experiments.
- We work with V. Saleev to get predictions from the up-to-date theoretical approaches.
- For the moment exclusive charmonia production has not been considered, but may be also interesting.

# Backup

# $J/\psi$ hadroproduction: from high to low energies

V.A. Saleev*

in collaboration with M.A. Nefedov*, A.V. Karpishkov* and A.V. Shipilova*,
B.A. Kniehl**, and M. Butenschoen**

Samara National Research University(*), and Hamburg University(**)

06.05.2015
SPD-NICA, JINR, Dubna

# NICA:

1. $\sqrt{S} = 24$ GeV
2. $|y| < 3$
3. $0 < p_T < 6$ GeV
4. Prompt production = direct + from decays $\psi', \chi_c$

# Theoretical approaches which can be used

1. CPM + NLO QCD, only for $p_T > 3$ GeV
2. TMD-factorization (Collins-Soper-Sterman), only for $p_T << M_\psi \sim 3$ GeV.
3. Parton Reggeization Approach can be used for all $p_T$.

# Prompt $J/\psi$ production at high energies in LO PRA and NLO CPM

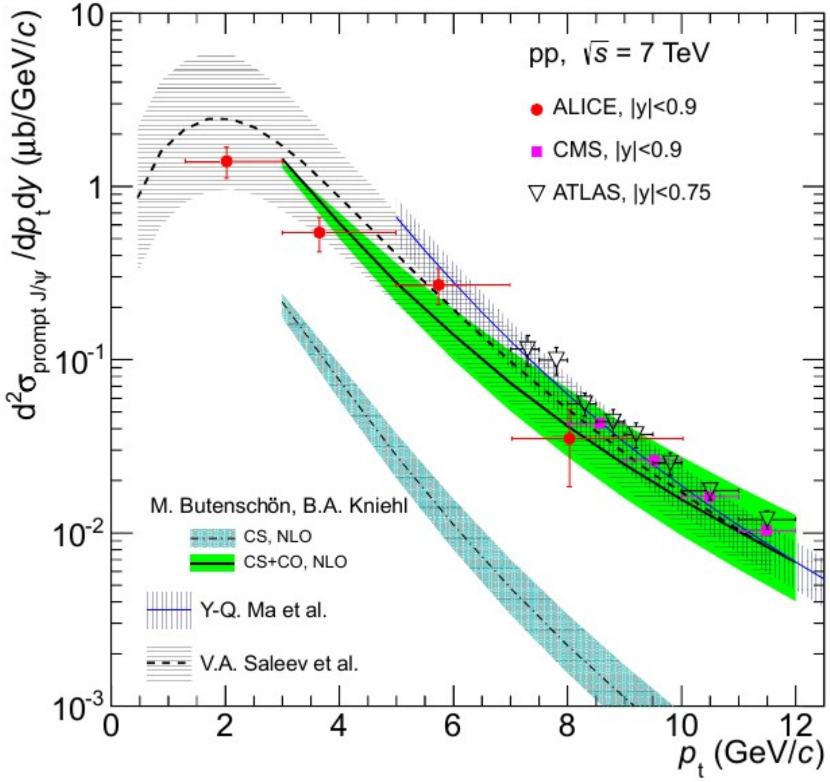



**Fig. 4:** $\frac{d\sigma_{\text{prompt } J/\psi}}{dp_t dy}$ as a function of $p_t$ compared to results from ATLAS [16] and CMS [18] at mid-rapidity and to theoretical calculations [19–21]. The error bars represent the quadratic sum of the statistical and systematic uncertainties.

# Prompt $J/\psi$ production at high energies in PRA

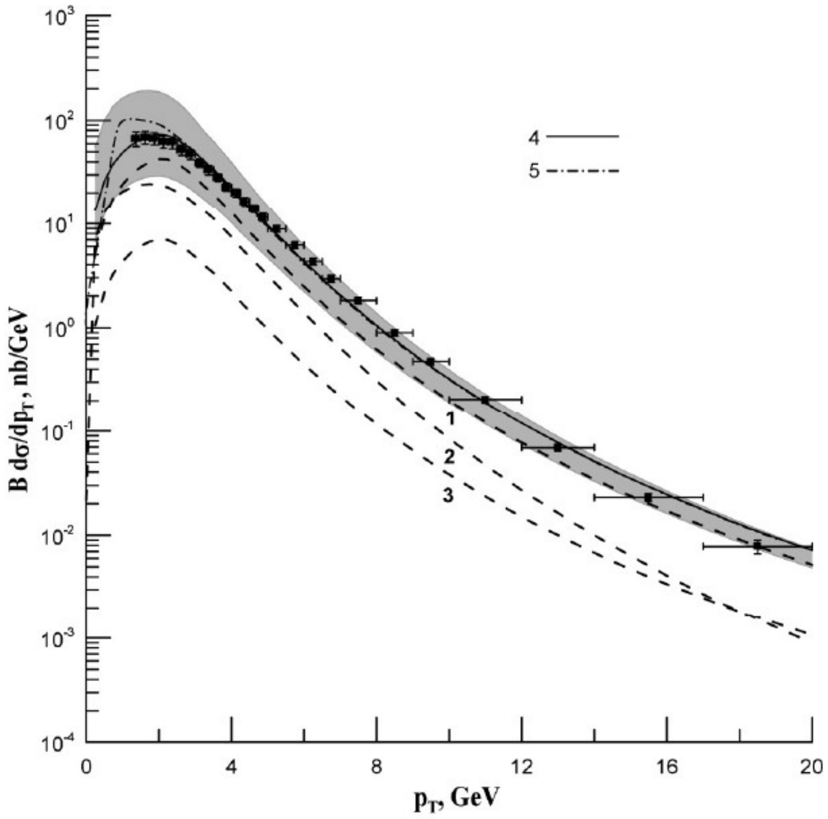
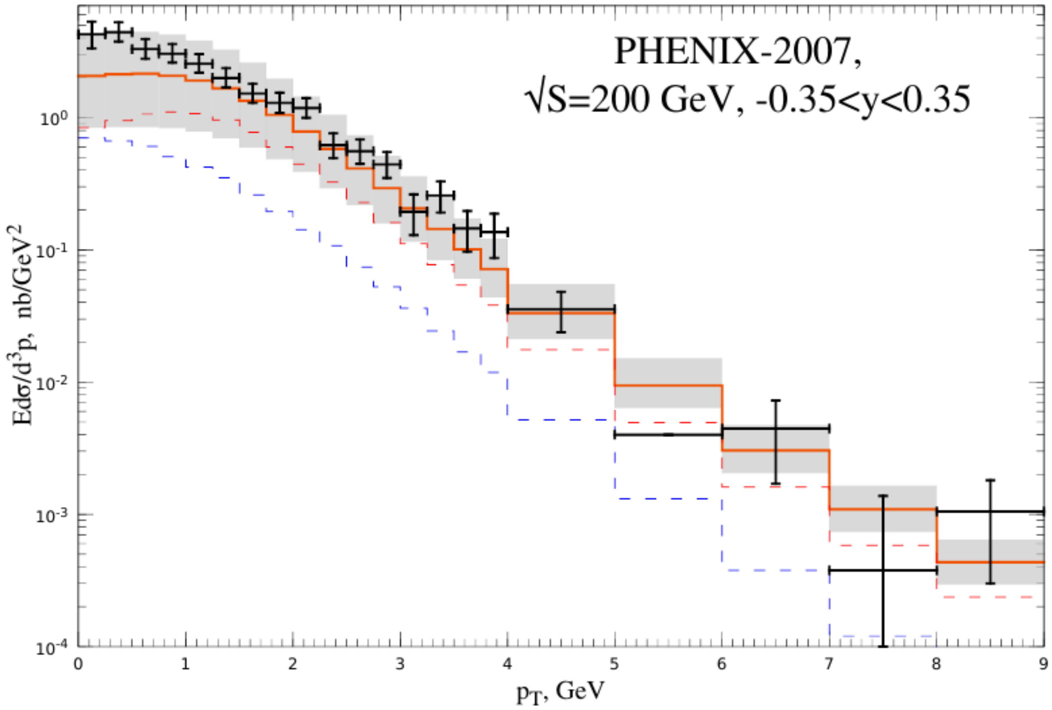


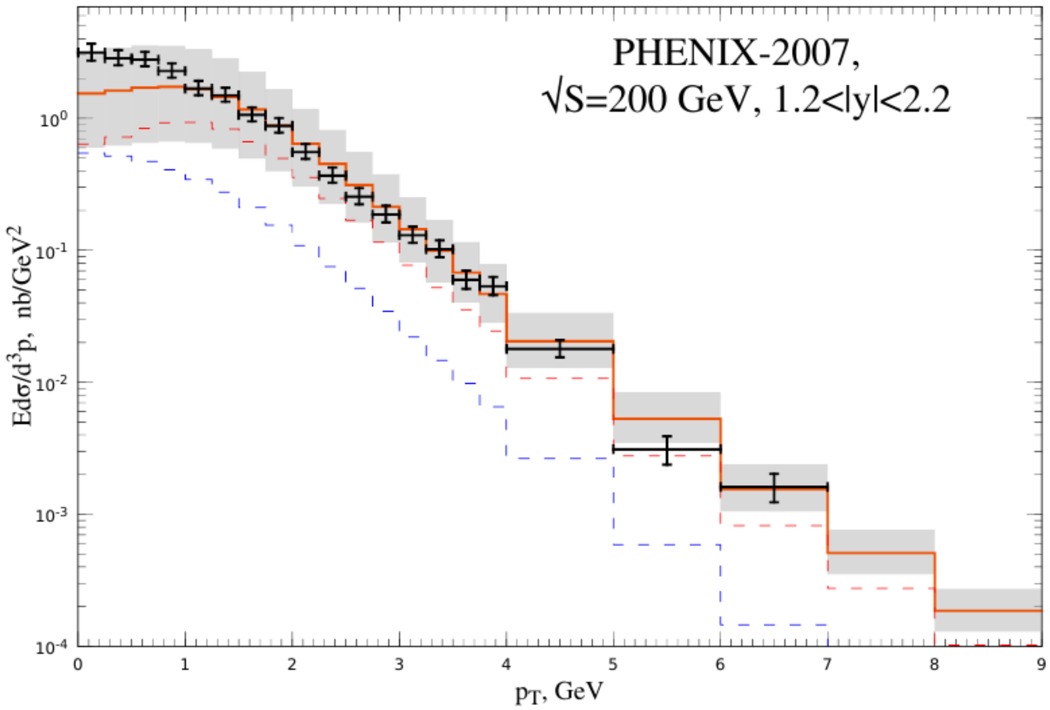

FIG. 4. Prompt $J/\psi$ transverse-momentum spectrum from CDF Collaboration [28], $\sqrt{S} = 1.96$ TeV, $|y| < 0.6$, (1) is the direct production, (2) from $\chi_{cJ}$ decays, (3) from $\psi'$ decays, (4) sum of all contributions (KMR unPDF), (5) sum of all contributions (Blümlein unPDF).

# Prompt $J/\psi$ production at high energies in PRA




Blue dashed curve is color-singlet contribution, red dashed curve is color-octet contribution, red solid curve is their sum. The gray band for the solid red curve shows scale-uncertainty of our prediction.

# Prompt $J/\psi$ production at high energies in PRA

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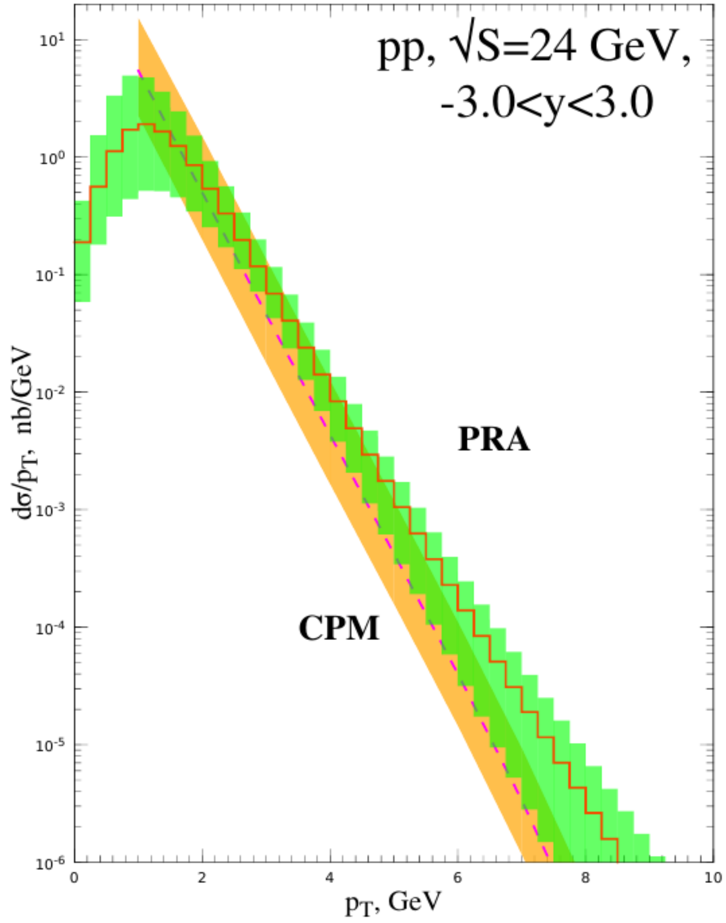
# Prompt $J/\psi$ production at high energies

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