Production of b & c
and
Quarkonia Physics with CMS

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on behalf of the

CMS Collaboration

FPCP2011
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Summary

- LHC and CMS at Glance
- Heavy Flavour Physics
  Main Features and Reasons of Interest
- J/ψ and Y production
- B Physics Analyses:
  Features and Findings
- Challenges and Prospects for the Future
- Conclusions

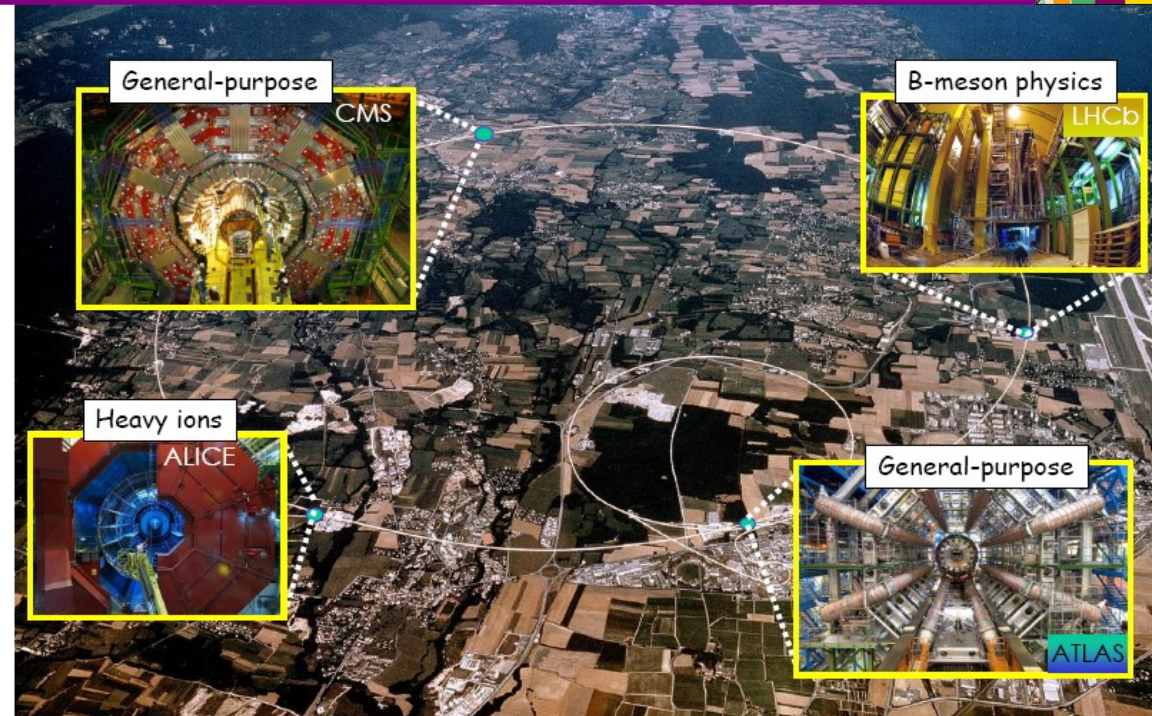
The LHC accelerator

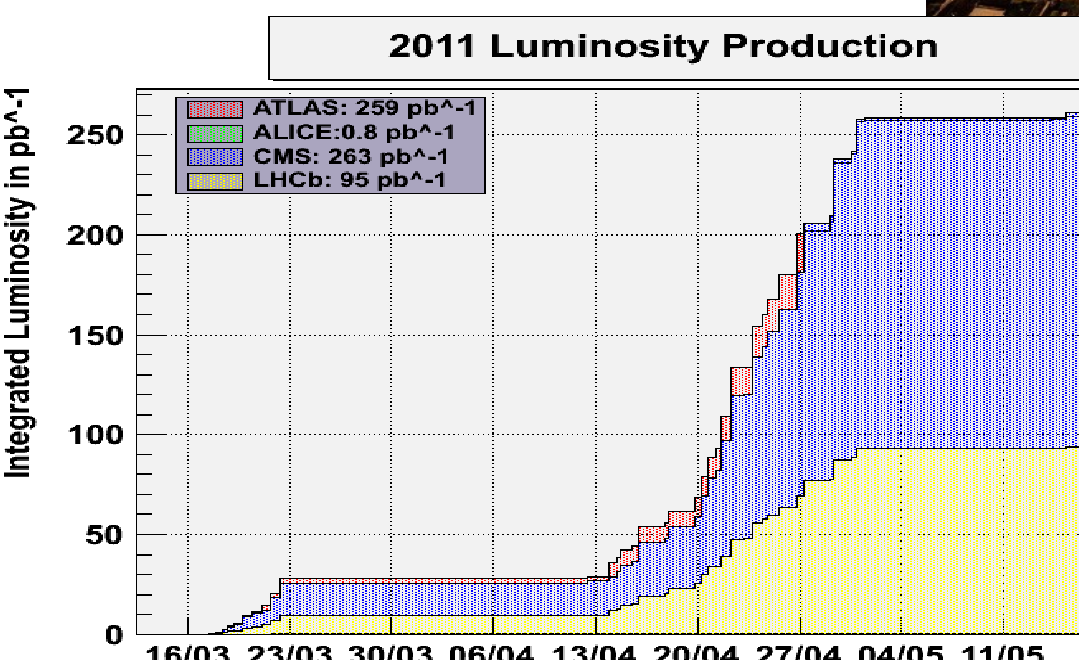
Excellent performances of the machine running smoothly @ 7 TeV since 2010

Instantaneous luminosity already reached 8.4 x 10^{32} $cm^{-2}s^{-1}$

Current records:

768 proton bunches circulating, with 1.7 $\cdot 10^{11}$ protons/bunch; time spacing 50 ns





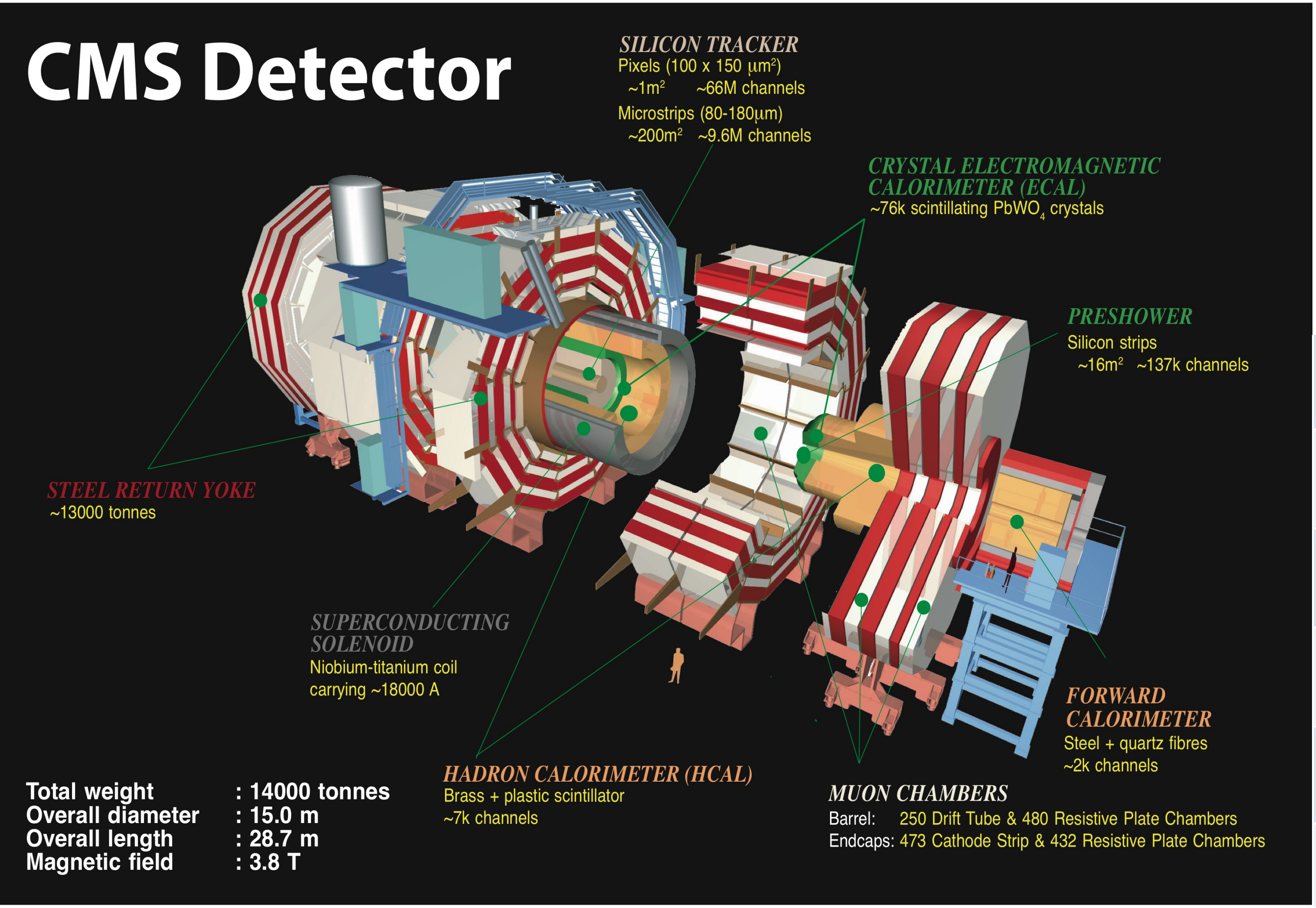
47 pb^{-1} delivered to CMS by the end of the 2010 pp run;

In 2011, ~250 pb^{-1} up to mid of May;

Overall CMS data taking efficiency > 90%;

The CMS Collaboration

3170 Physicist and engeneers, 169 institutes from 39 countries



- Highly redundant muon system, triggering and recording muons with p_T > 1-3 GeV and $|\eta|$ <2.4
- Tracking efficiency > 99% for central muons

4 T solenoid + return yoke
Si pixels, strips $\sigma/p_T \approx 1.5\times10^{-4} p_T + 0.005$
PbWO4 crystals $\sigma/E \approx 3\%/\sqrt{E} + 0.003$
Brass+scintillator (7 λ + catcher) $\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV
$\sigma/p_T \approx 1\%$ @ 50GeV to 10% @ 1TeV (DT/CSC+Tracker)
L1+HLT (L2 + L3)

All silicon inner tracker allowing good resolution on p_T and impact parameter measurements

B-hadron reconstruction mainly exploits:

- Muon detectors, for muon ID in semi-leptonic decays;
- Silicon Tracker detector, for b-tagging, lifetime measurements and inv. mass reconstruction.

HF Physics: topics and reasons of interest (I)

Open beauty Production

A testing bed for QCD;
calculations scale up to a new energy regime

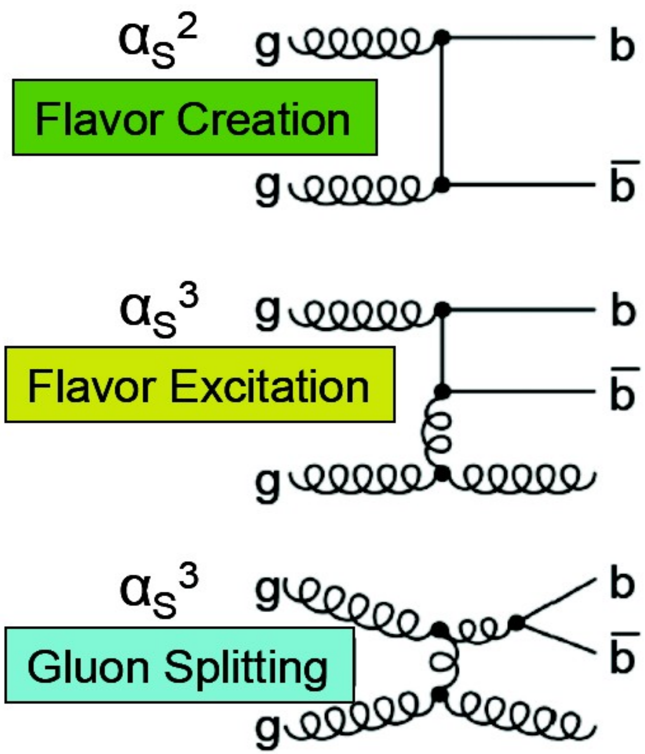
- NLO contributions essential at LHC;
- High energy scale makes perturbation calculations safe;
- Large uncertainties from factorization and renormalization scales.

b physics

- Very active research field, either experimentally and theoretically;
- Allows testing the CP and Flavour violation;
- Interesting challenge with B-factories in some topics.

b-jets

- Enclosing most of the radiation emitted by the b-quark → reliable messenger of the original parton, allowing purely perturbative predictions;
- High performance of tracking capabilities required, exploiting full detector potentialities;
- Measurements complementary to b-hadrons;
- Crucial role in many new physics studies.



Many results from CMS:

- J/ψ and Υ production
- Inclusive b production, bb angular correlations
- Exclusive B^+, B^0, B_s production

HF Physics: topics and reasons of interest (II)

Quarkonia Physics

Strong test for:

- non-relativistic QCD (NRQCD);
- models calculation methods describing the long-distance interaction and the bound state formation.

J/ψ 'troubles'

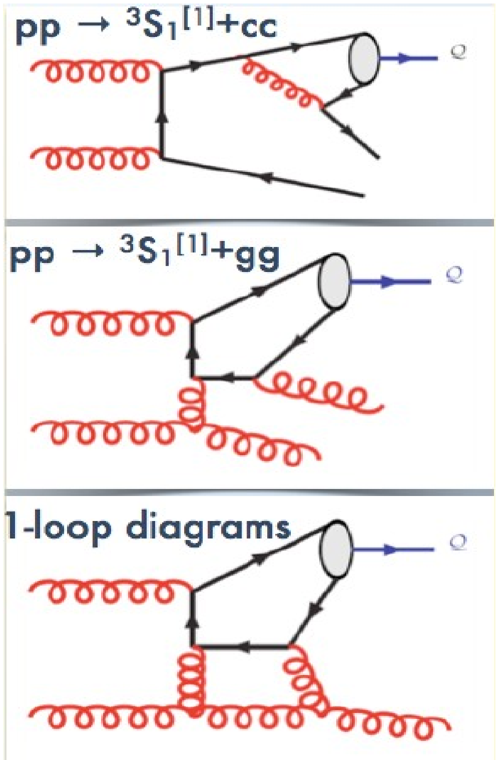
Production mechanisms:

- to be fully understood yet
- role for higher order vs color-octet contributions unclear

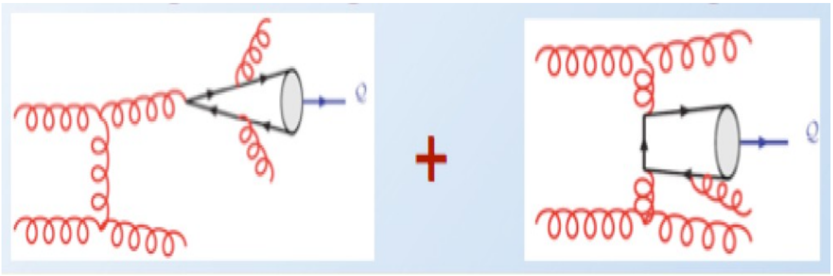
Polarization issues

- Predictions of some models for the J/ψ's polarization at large p_T not confirmed by HERA/Tevatron data;
- Apparent inconsistencies among experiments.

- Interesting to analyse the Υ polarization behaviour;
- Possibility to cross-check some measurements with b-jets (e.g. non-prompt J/ψ for bb cross sect.)



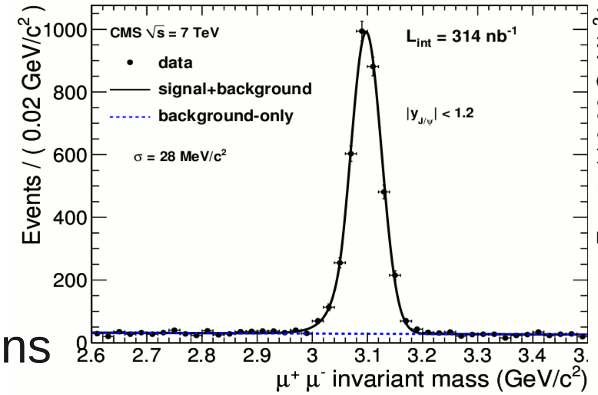
NLO Singlet contributions

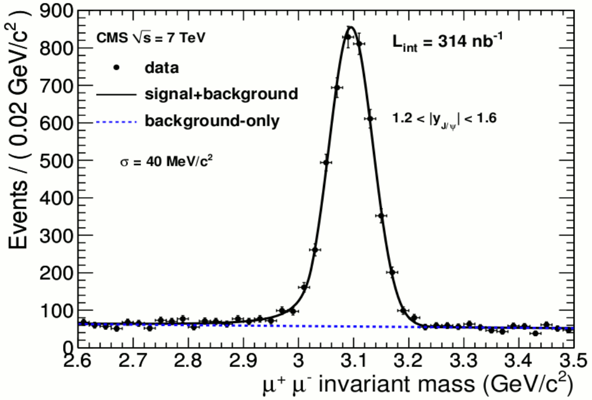


"NNLO" Singlet contributions

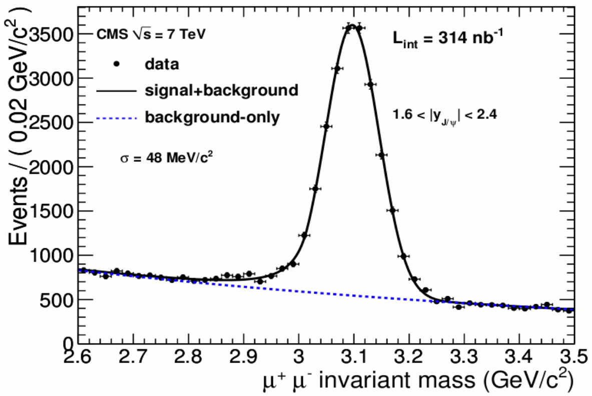
J/ψ production

Eur.Phys.J. C71 (2011) 1575



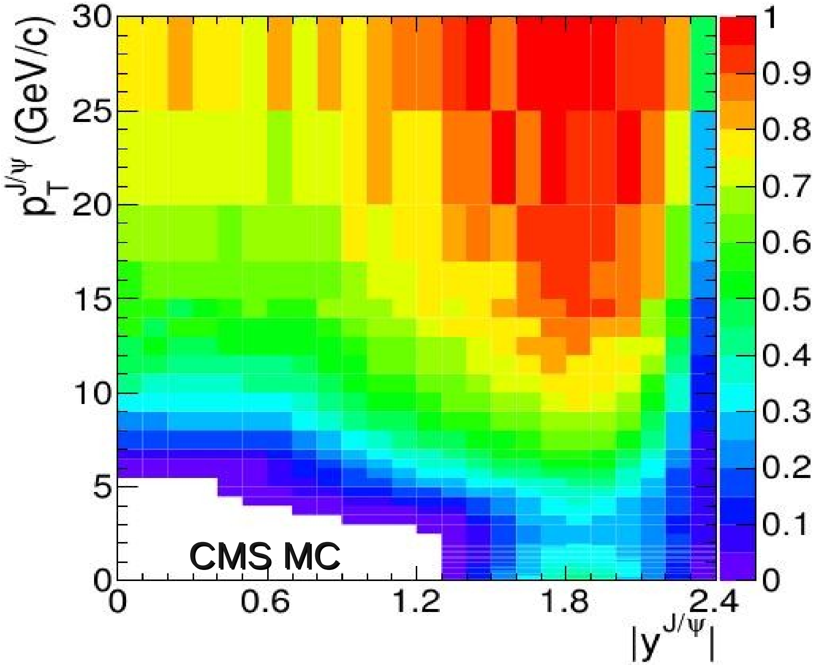


- Reconstructing J/ψ decaying in two muons
- Cross section determined in p_T and y intervals
- Muon momentum corrected for scale distortion through a fit on the invariant mass peak shape
- Yields corrected for **acceptance** and **efficiency**:



Acceptance calculated from MC; it depends on the assumed polarization scenario:

- isotropic (unpolrized);
- extreme values of λ_θ (= ±1) in the helicity frame (along the J/ψ momentum);
- extreme values of λ_θ (= ±1) in the Collins-Soper frame (along the collision axis);



Efficiency determined from data with the Tag & Probe method

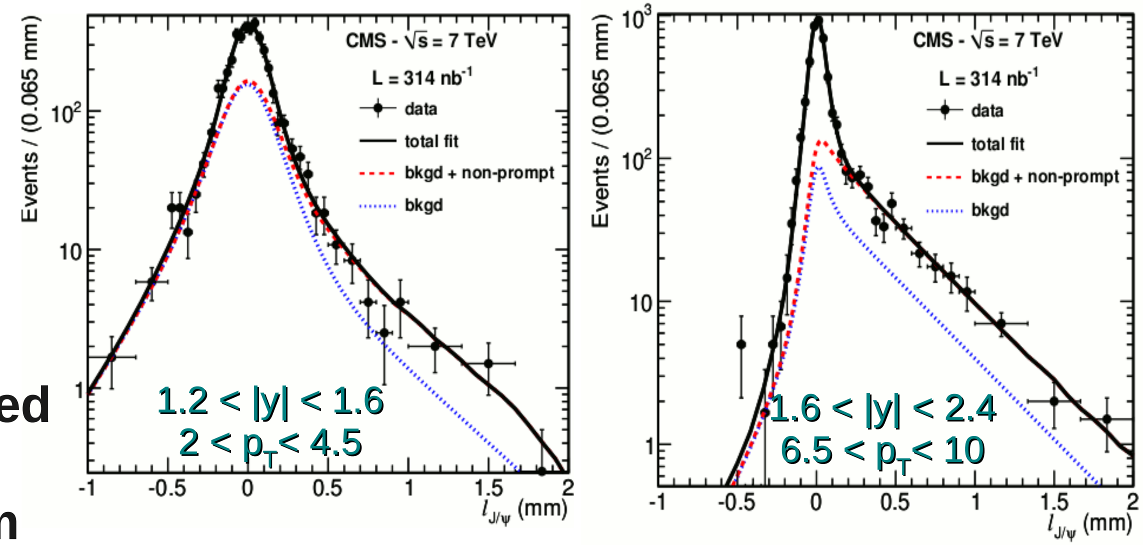
Main systematic uncertainties:

- kinematical distributions (< 3%)
- b-hadron fraction (< 3.1%)

J/ψ prompt and non-prompt components

Triggered with di-muon ;   Total yiels ~12000 ev

Fraction of J/ψ from b-hadron estimated by fitting the proper decay length together with di-muon mass spectrum



Prompt: $\sigma_{pp\to J/\psi X} \cdot Br(J/\psi \to \mu^+\mu^-) = (70.9 \pm 2.1\ (stat) \pm 3.0\ (sys) \pm 7.8\ (lumi))\ nb$

(assuming unpolarized production)

Non-prompt: $\sigma_{pp\to bX\to J/\psi X} \cdot Br(J/\psi_{|b} \to \mu^+\mu^-) = ((26.0 \pm 1.4\ (stat) \pm 1.6\ (syst) \pm 2.9\ (lumi))\ nb$

J/ψ and b-hadron pairs events simulated with PYTHIA; final-state bremsstr. implemented with PHOTOS;
b-hadrons decaying inclusively into J/ψ simulated with EvtGen package

In good agreement with measurements from ATLAS and LHCb

Different polarizations shift results as much as 20%

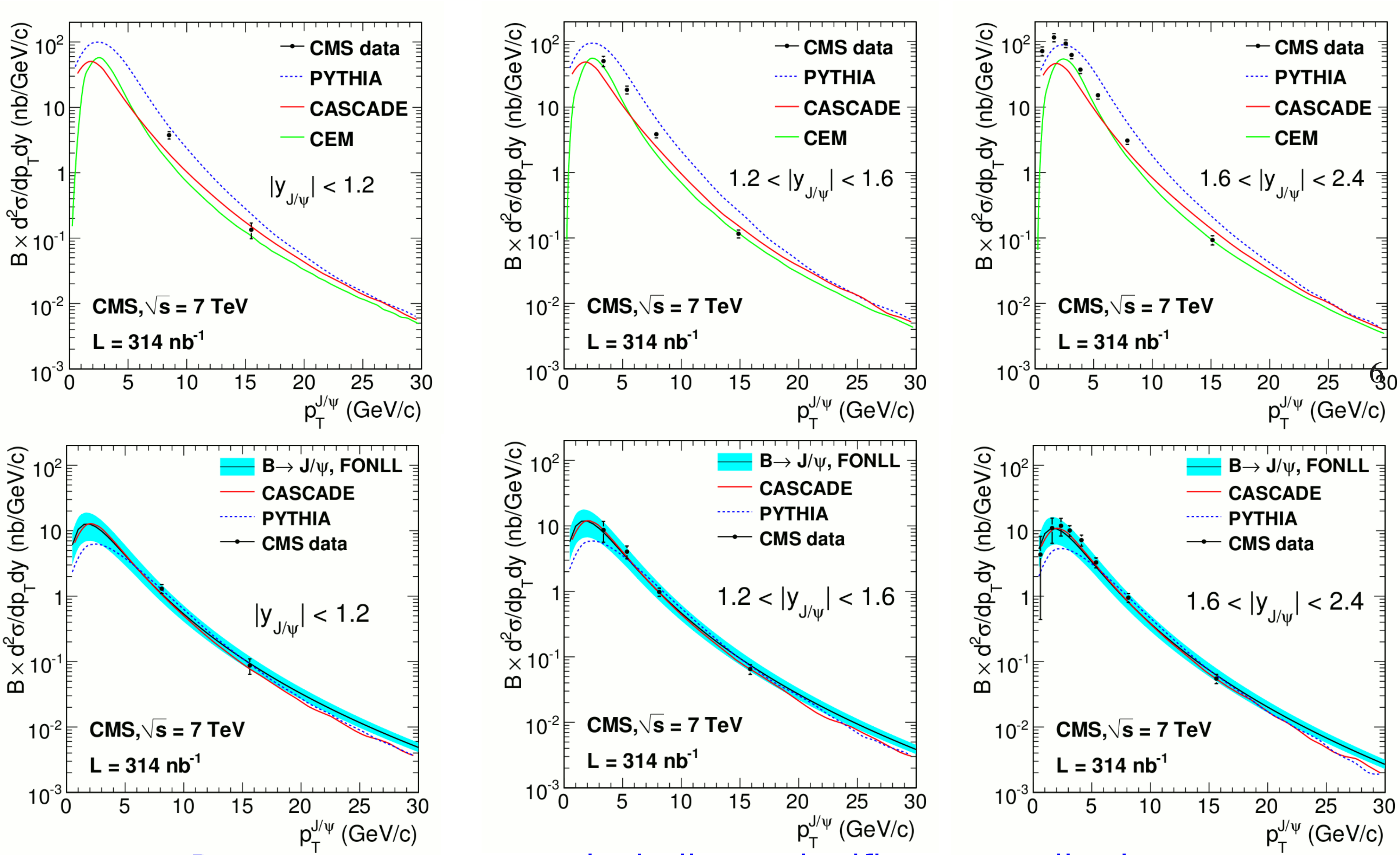
SYSTEMATICS:

- Primary vertex estimation
- Decay length resolution function
- Background fit
- Residual misalignments in the tracker
- b-hadron lifetime model
- Different prompt and non-prompt efficiencies

Comparison with models

Prompt

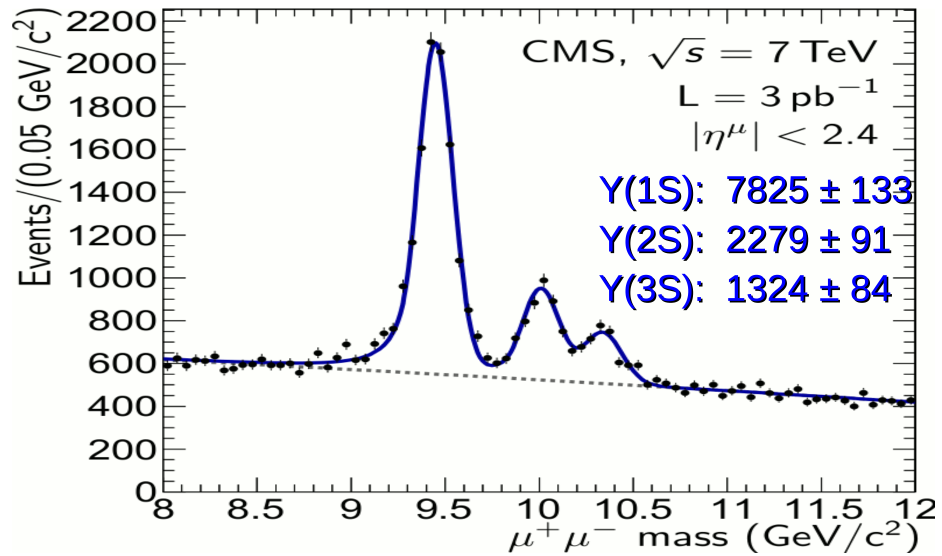
Non-prompt:



Prompt measurements including a significant contribution from feed-down decays (~30%)

Υ production

Submitted to Phys. Rev. D



Υ family reconstructed in di-muon final state; 1,2 and 3S states all evident above background

Mass resolution ~70 MeV for |η| < 1.0
yields extracted simultaneously with a maximum likelihood fits in p_T and y intervals

Double differential cross sections vs p_T and y

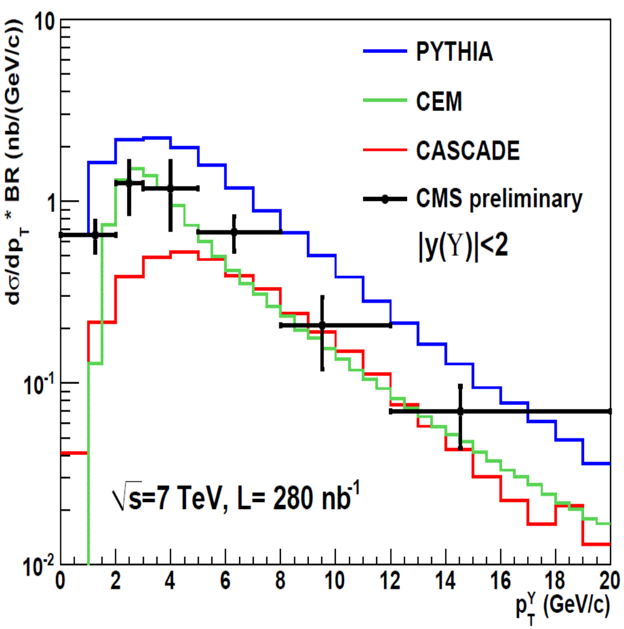
$$\sigma(pp\rightarrow \Upsilon(1S)X) \cdot Br(\Upsilon\rightarrow \mu^+\mu^-) = (7.37\ ^{+0.61}_{-0.42}\ (syst) \pm 0.13\ (stat) \pm 0.81\ (lumi)\ )\ nb$$

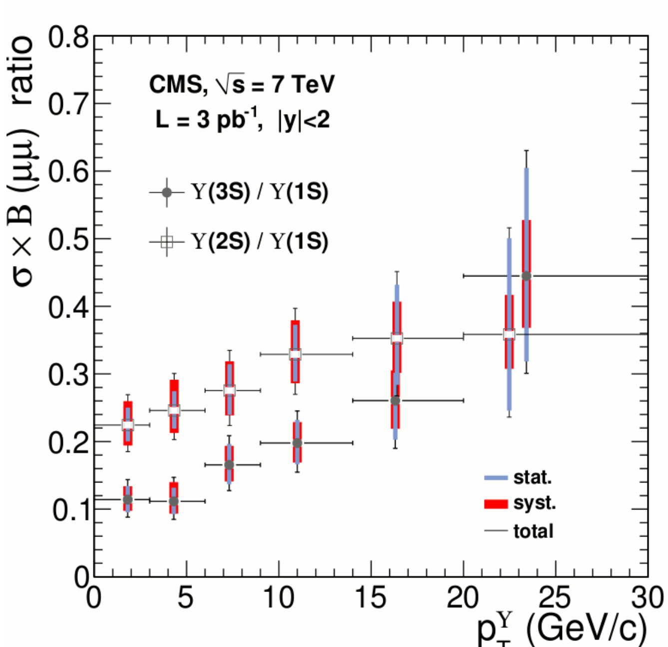
$$\sigma(pp\rightarrow \Upsilon(2S)X) \cdot Br(\Upsilon\rightarrow \mu^+\mu^-) = (1.90\ ^{+0.20}_{-0.14}\ (syst) \pm 0.09\ (stat) \pm 0.24\ (lumi)\ )\ nb$$

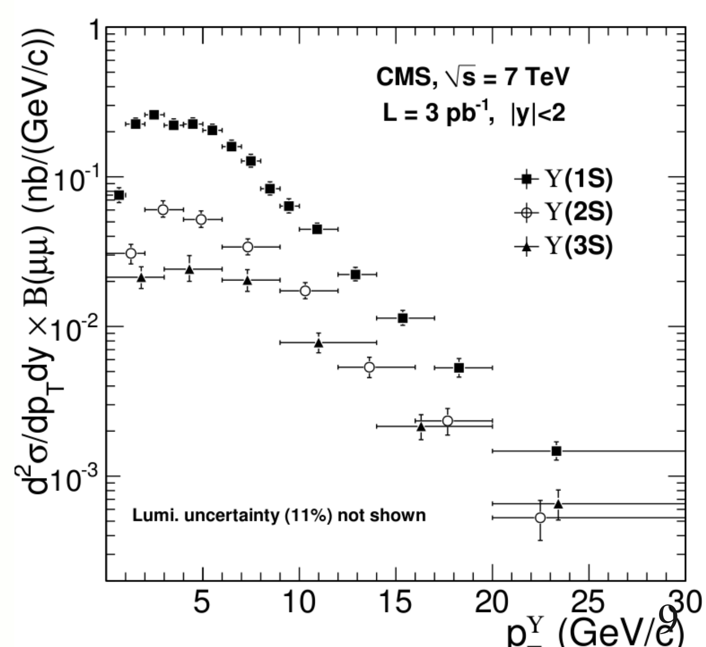
$$\sigma(pp\rightarrow \Upsilon(3S)X) \cdot Br(\Upsilon\rightarrow \mu^+\mu^-) = (1.02\ ^{+0.11}_{-0.08}\ (syst) \pm 0.07\ (stat) \pm 0.11\ (lumi)\ )\ nb$$

Good agreement with previous Tevatron measurements

Fraction of 2S and 3S increases with pT







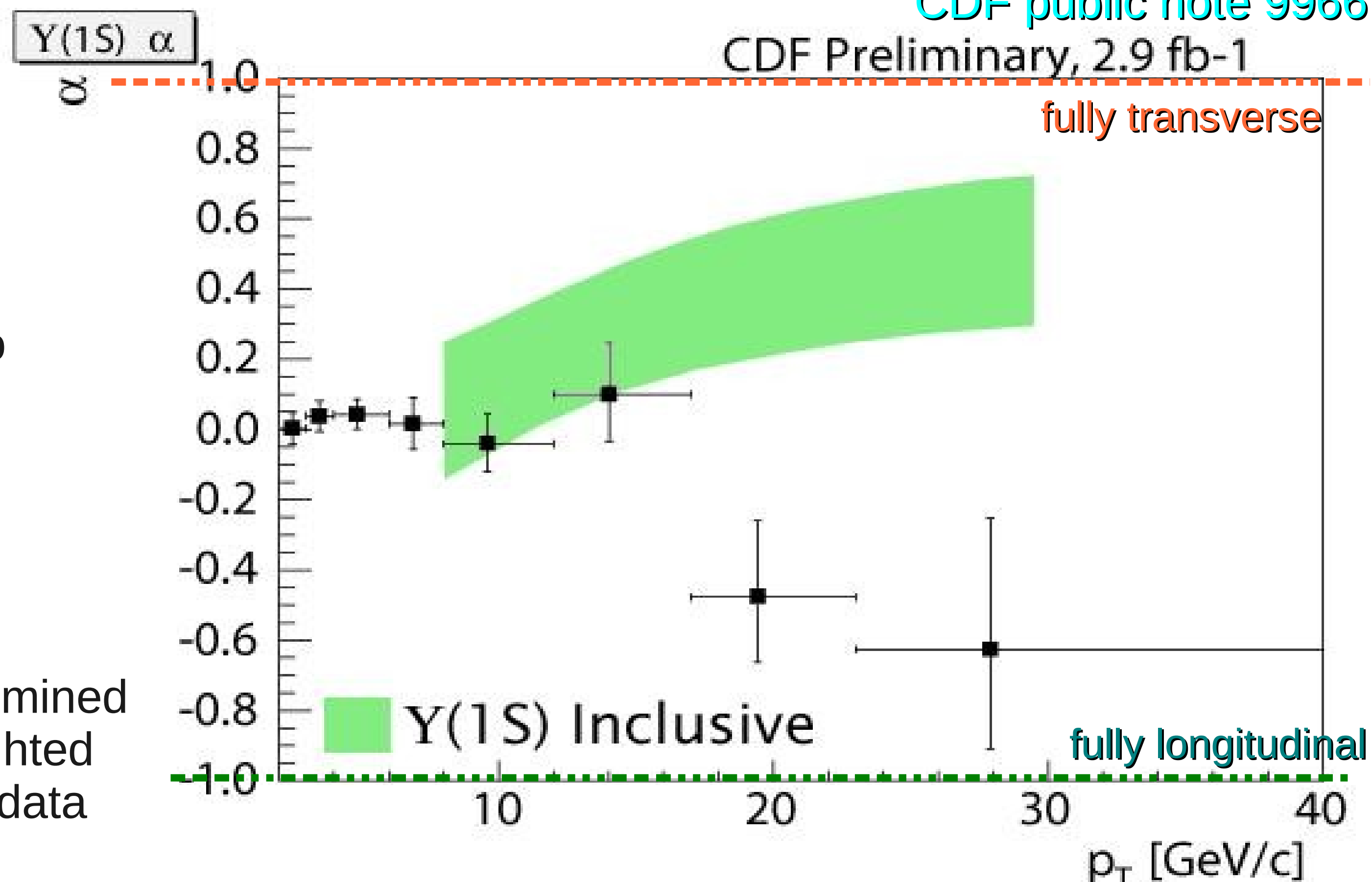
Latest results on Υ(1S) polarization from CDF

Fully transverse and fully longitudinal MC generated and subjected to detector acceptance and efficiency effects to form templates; MC iteratively re-weighted to match data p_T distributions.

Events selected using a mass fit, backgrounds from mass side-bands.

Polarization parameter determined matching a polarization-weighted combination of templates to data

CDF public note 9966



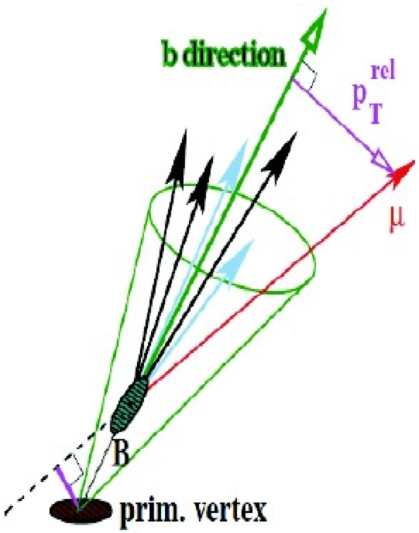
NRQCD predicts a transverse polarization at high p_T, whereas
Υ found to be unpolarized at low p_T before exhibiting marked polarization at high p_T!

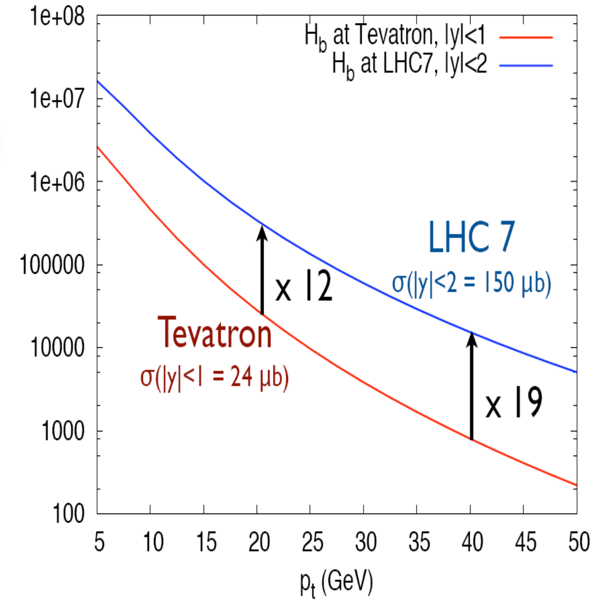
Consistent with CDF Run I [PRL 88, 161802 (02)], disagreement with D∅ run II [PRL 101, 182004 (08)]

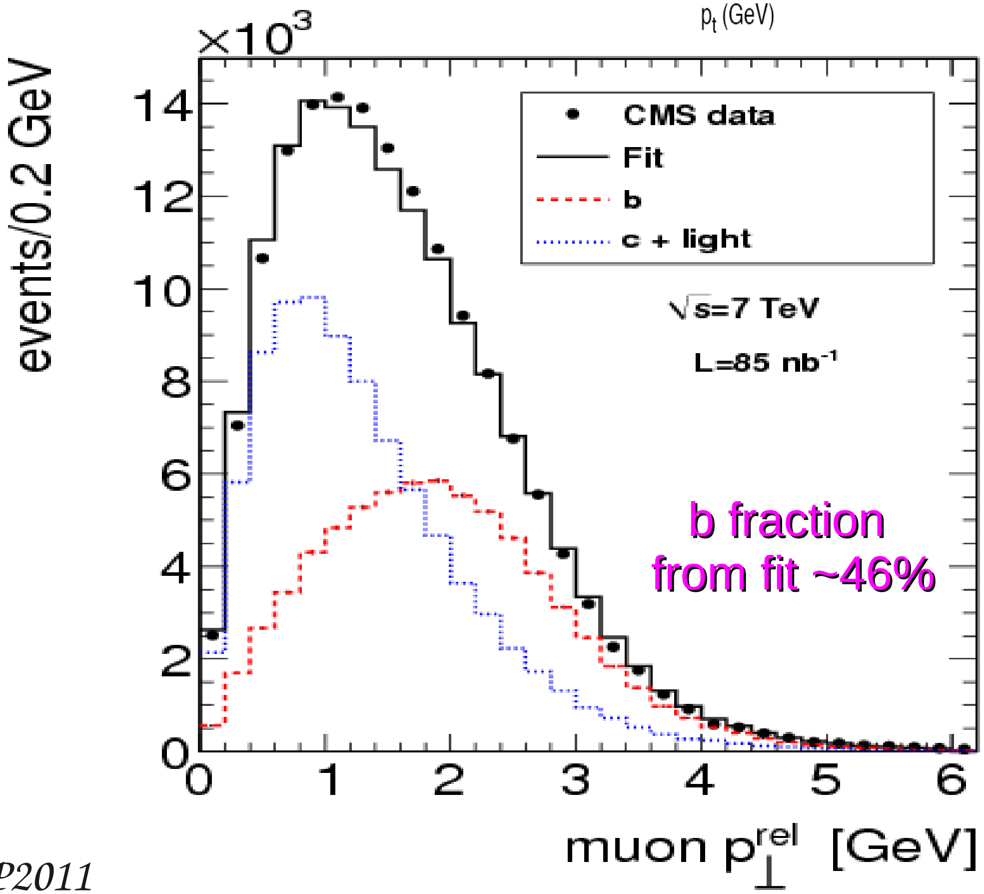
Inclusive beauty production

JHEP 1103 (2011) 090

- Use semi-leptonic decays to separate b-jets from udscg jets
- Triggering on muon (p_T > 3 GeV) and require p_T > 6 GeV, |η|< 2.1 offline
- Jets clustered with anti-k_T (R=0.5) from tracks with p_T > 300 MeV
- Muon from b decays discriminated with the distance from jet axis, on average larger than light quarks
- p_T-rel templates from MC (data) for b and c (udsg), with signal validated in b-enriched data
- Background templates combined in fit







Inclusive beauty cross section

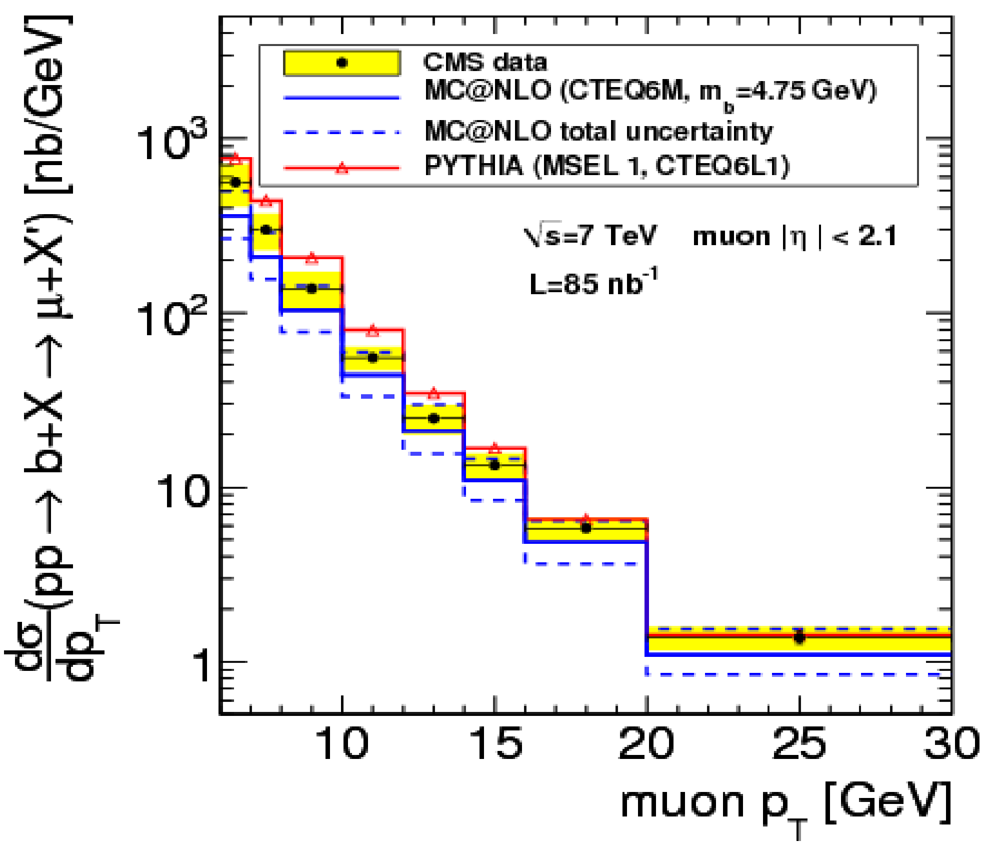
JHEP 1103 (2011) 090

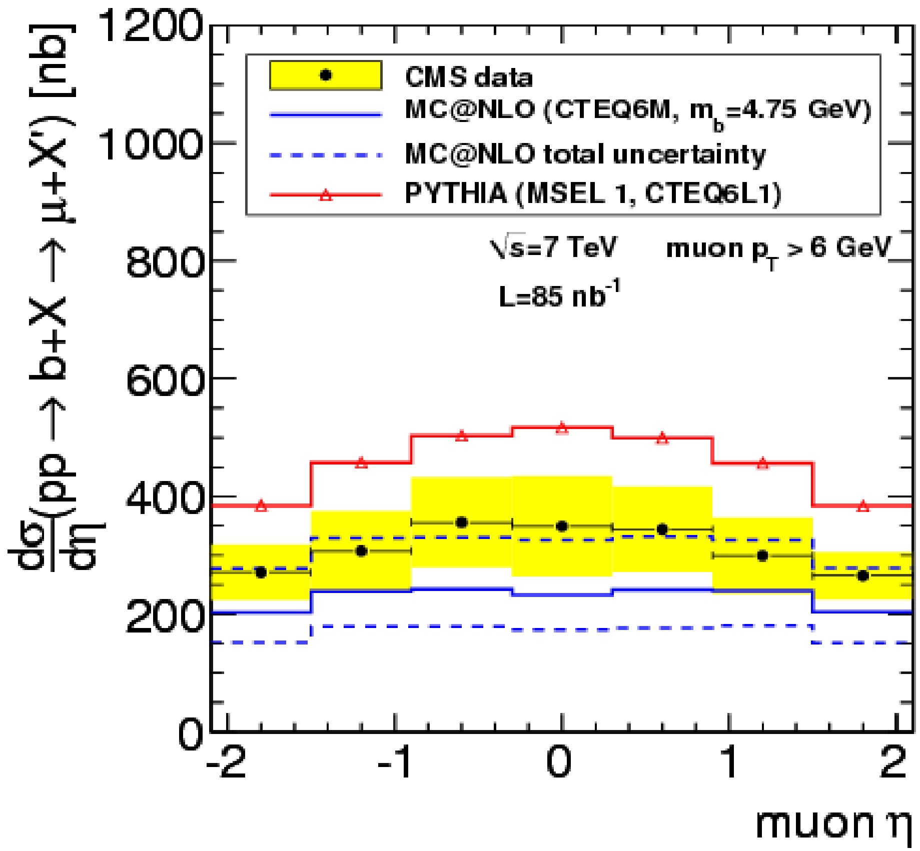
Measured visible cross section: muon p_T > 6 GeV, $|\eta|$ < 2.1;

$$\sigma(pp \to b\,X \to \mu\,X) = (1.32 \pm 0.01(stat.) \pm 0.30(syst.) \pm 0.15\,(lumi.)\,)\,\mu b$$

$\sigma_{MC@NLO} = (0.95_{-0.21}^{+0.42}\,(scale) \pm 0.09(m_b) \pm 0.05(pdf)\,)\,\mu b$; $\sigma_{PYTHIA} = 1.9\,\mu b$

uncertainty dominated by signal and background p_T rel shapes

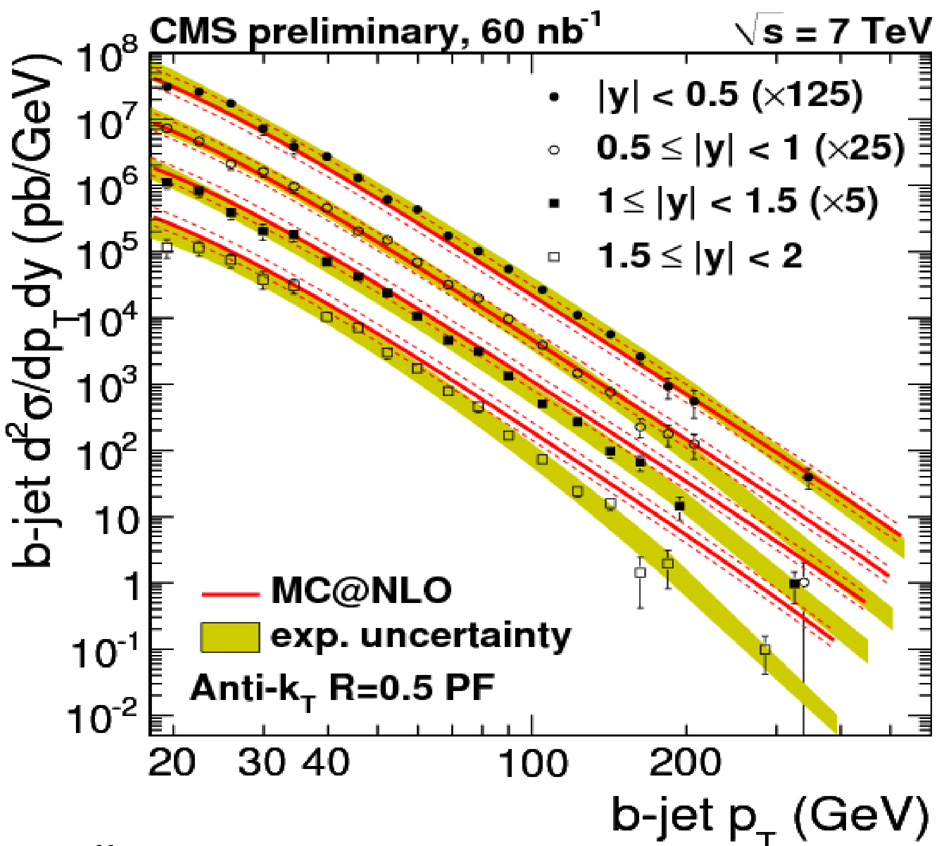


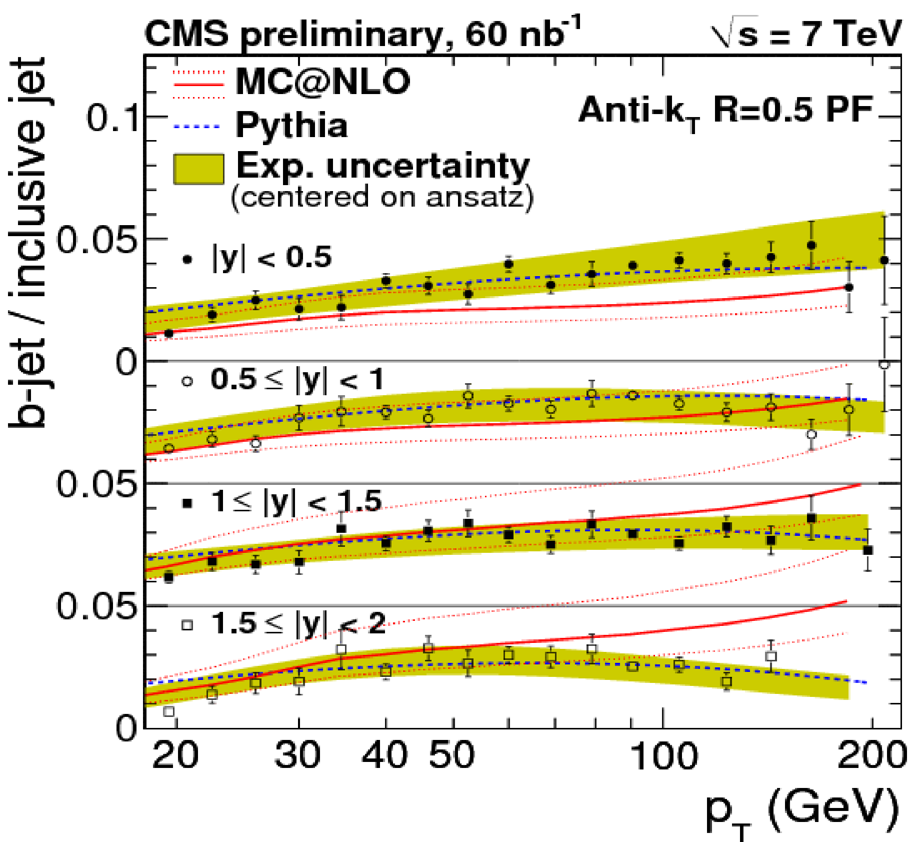


Inclusive b from jet tagging

Identification of b jets performed through the Secondary Vertex tagging

- Significantly extends the measurement in pT;
  tagging efficiency 50-60% for jet p_T = 100 GeV, with ~0.1% contamination
- Jets from anti-k_T algorithm using tracks and calorimeter information
- Displaced vertices selected with ≥ 3 tracks to identify b events
- Uncertainties dominated by b-tag efficiency and jet energy scale





$B\bar{B}$ correlations

JHEP 1103 (2011) 136

Use secondary vertex to study correlations between two B hadrons probed for the first time the region at small angular separation:

require exactly two secondary vertices, with ≥3 tracks, 3D flight length ≥ 5 σ

calculate $\Delta R = \sqrt{(\Delta\varphi^2+\Delta\eta^2)}$ of directions from primary vertex to each secondary

Measured momentum corrected through the 'true' B hadron momentum form MC

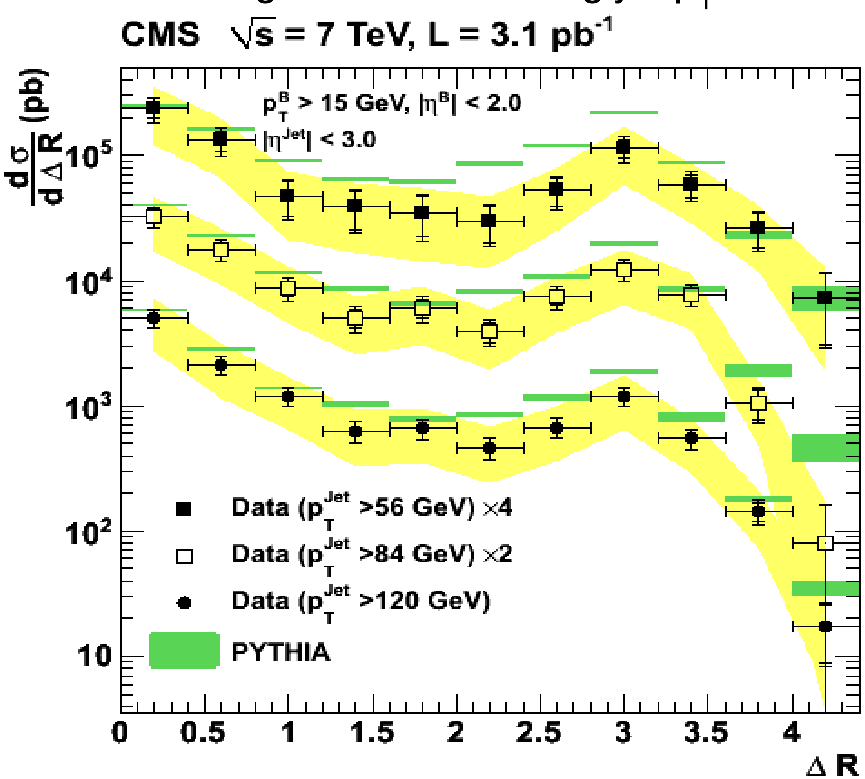
Results shown in different ranges for the leading jet p_T

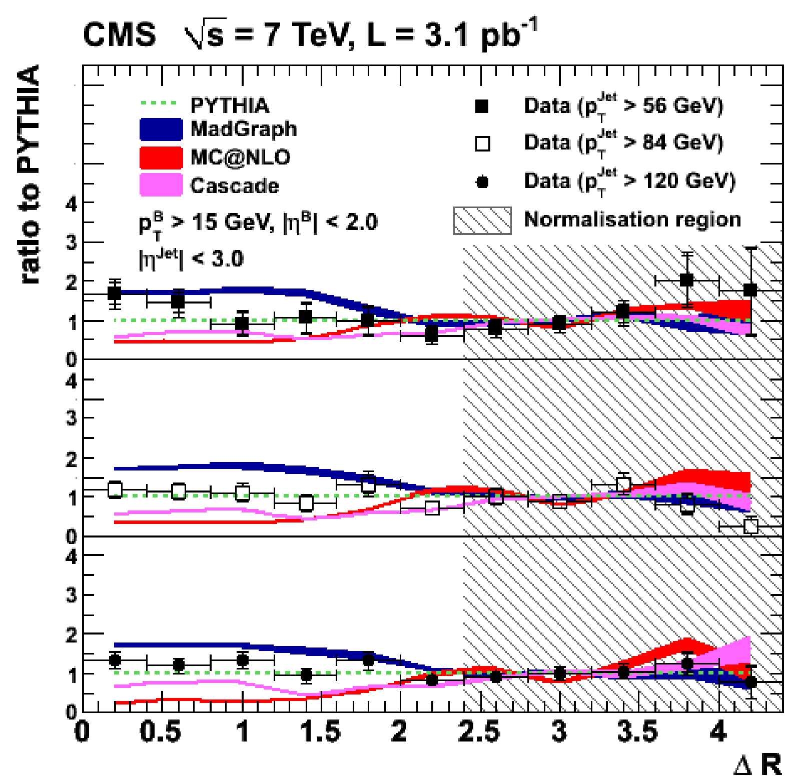
both B's in $|\eta|<2.0$, $p_T>15$ GeV

Flavour creation expected to dominate at high ΔR;

gluon splitting contributes more at low ΔR.

Data normalized to MC in high ΔR region.





The differential cross section shows that **a sizeable fraction of the BB pairs is produced with small opening angles**.

Exclusive beauty production

High bb cross section at the LHC already allows for measurements with early data

Reconstruct B hadrons in exclusive final states:

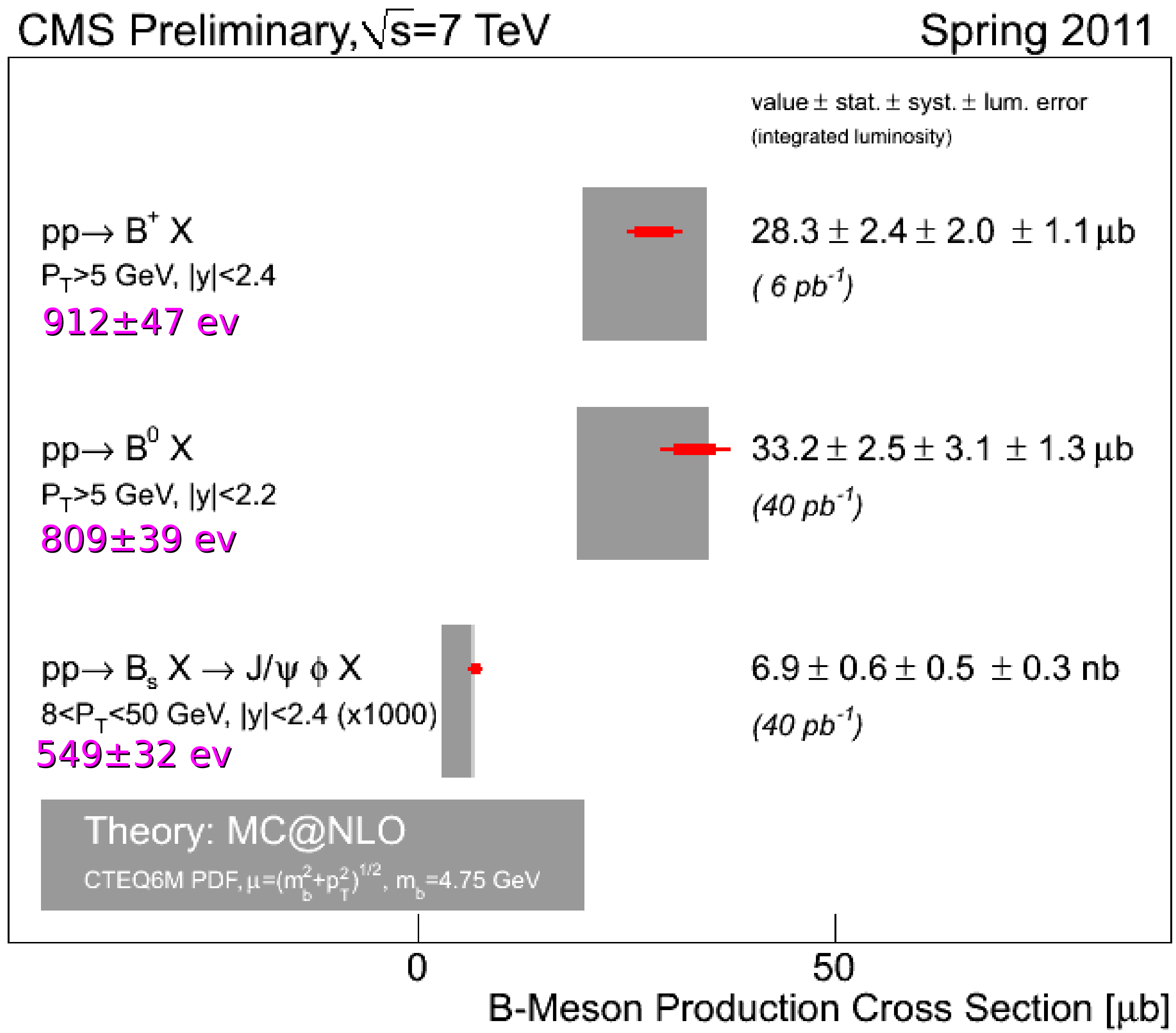
- $B^+ \rightarrow J/\psi K^+$
- $B^0 \rightarrow J/\psi K_s(\rightarrow \pi^+\pi^-)$
- $B_s \rightarrow J/\psi \Phi(\rightarrow K^+K^-)$

Always $J/\psi \rightarrow \mu^+\mu^-$

Triggering on di-muon from J/ψ

B^0 and B_s results obtained over the whole 2010 statistics (39.6 pb^{-1})

Small branching fractions ($2 - 6 \times 10^{-5}$, including product branching fractions)



Combined fit to the B meson mass and lifetime to reject the background
Measurement of cross sections differentially in p_T and η performed

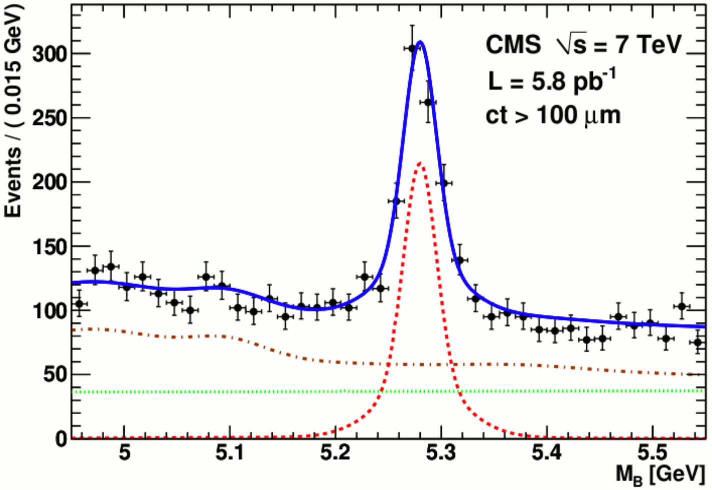
$B^+ \to J/\psi K^+$

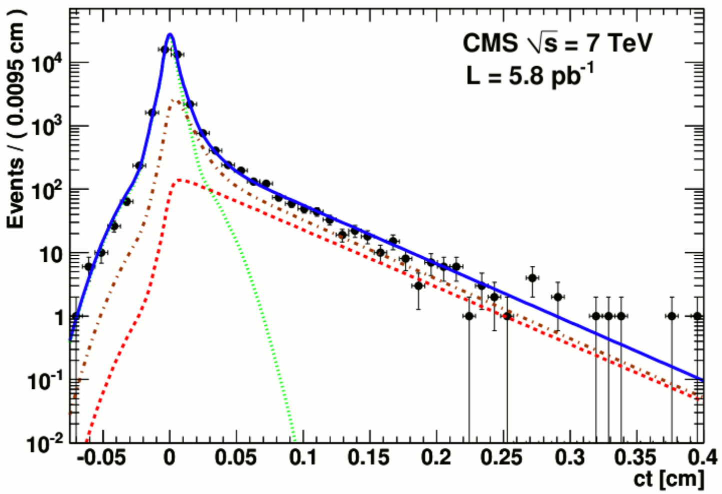
PRL 106, 112001 (2011)

pT (B^+) > 5 GeV

$|y(B^+)| < 2.4$

2D maximum likelihood fit to the B^+ mass and lifetime used to separate signal from background
Backgrounds from prompt J/ψ and mis-reconstructed b-hadron
Most fit shapes derived directly from data;
Peaking background and signal B mass from MC
Total yield = 912 ± 47
Efficiency of candidate reconstruction (1.5 - 33%) determined from data-driven techniques and MC

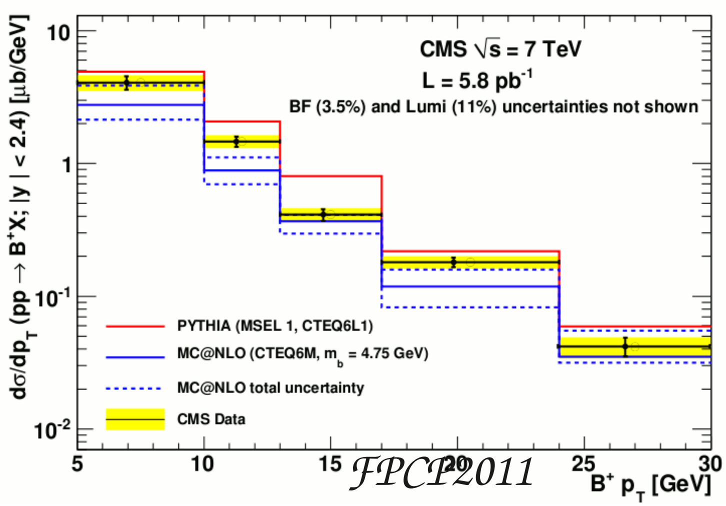


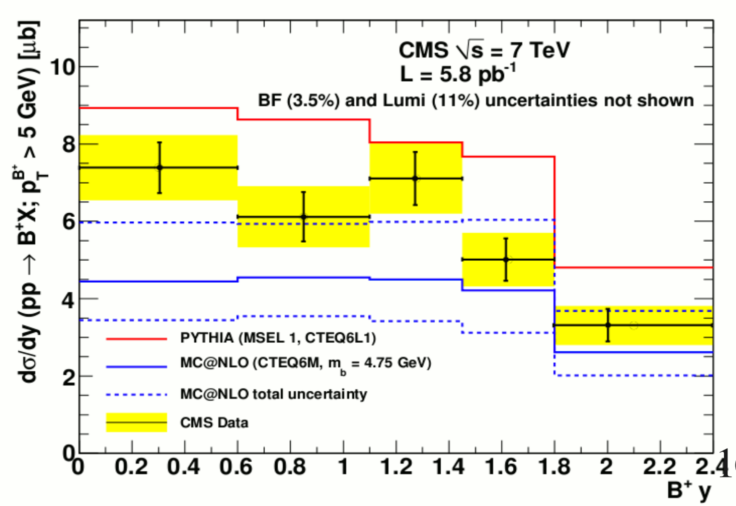


$$\sigma(pp \to B^+X) = (28.1 \pm 2.4(stat.) \pm 2.0(syst.) \pm 3.1\ (lumi))\ \mu b$$

$$\sigma_{MC@NLO} = 25.5_{-5.7}^{+9.2}\ \mu b; \qquad \sigma_{PYTHIA} = 48.1\ \mu b$$

Fits in bins of B^+'s p_T and y to measure B^+ differential cross section



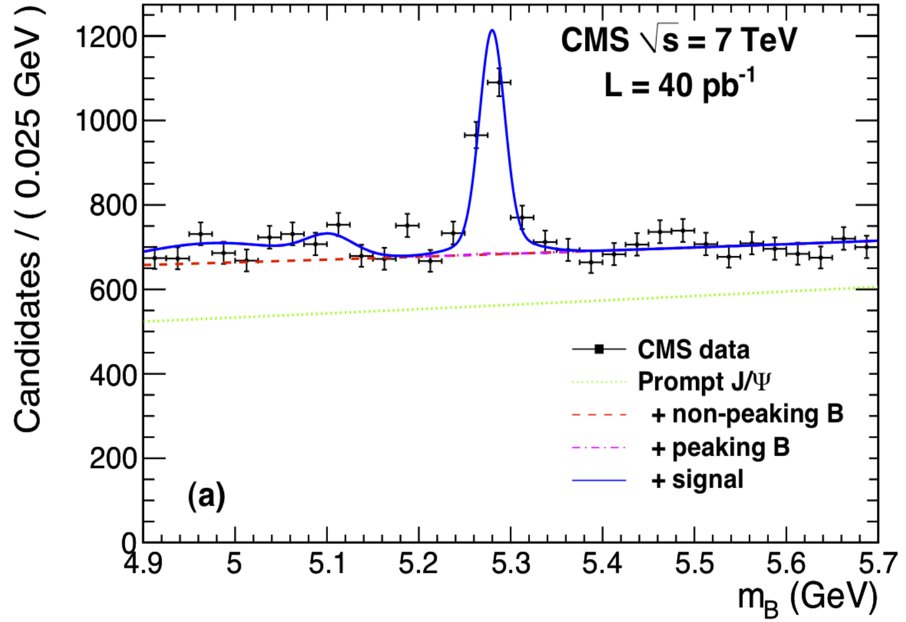


$B^0 \rightarrow J/\psi\ K_s$

Submitted to Phys.Rev.Lett.

$p_T(B^0) > 5$ GeV

$|y(B^0)| < 2.2$



$\sigma(pp \rightarrow B^0X) = (33.2 \pm 2.5\ (stat.) \pm 3.5\ (syst.))\ \mu b$

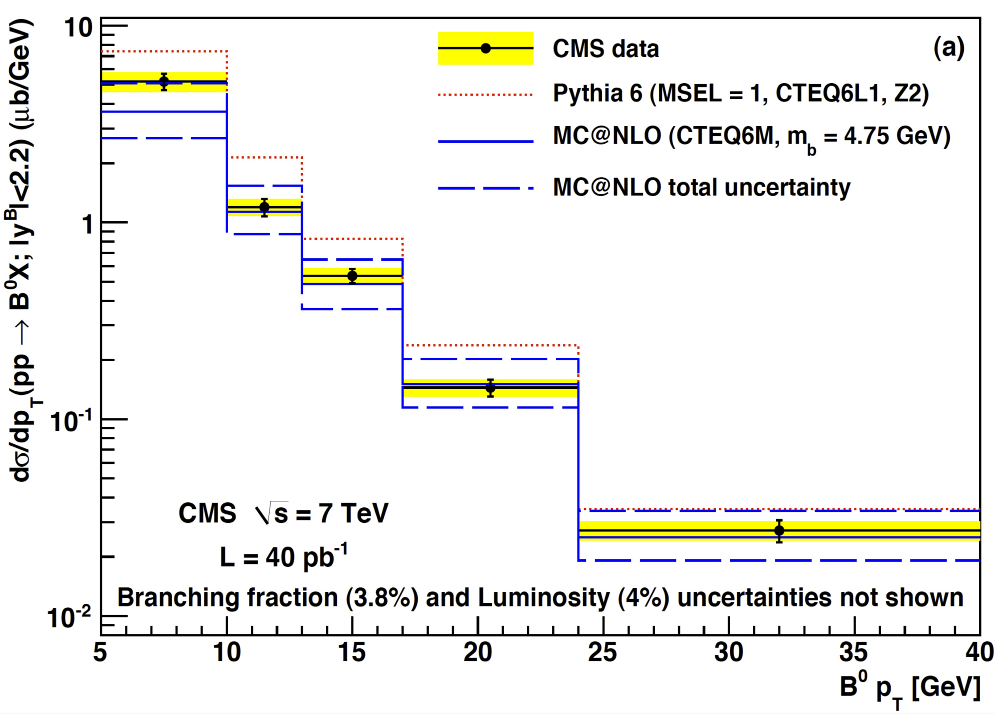
$\sigma_{MC@NLO} = 25.2^{+9.6}_{-6.2}\ \mu b$; $\sigma_{PYTHIA} = 49.1\ \mu b$

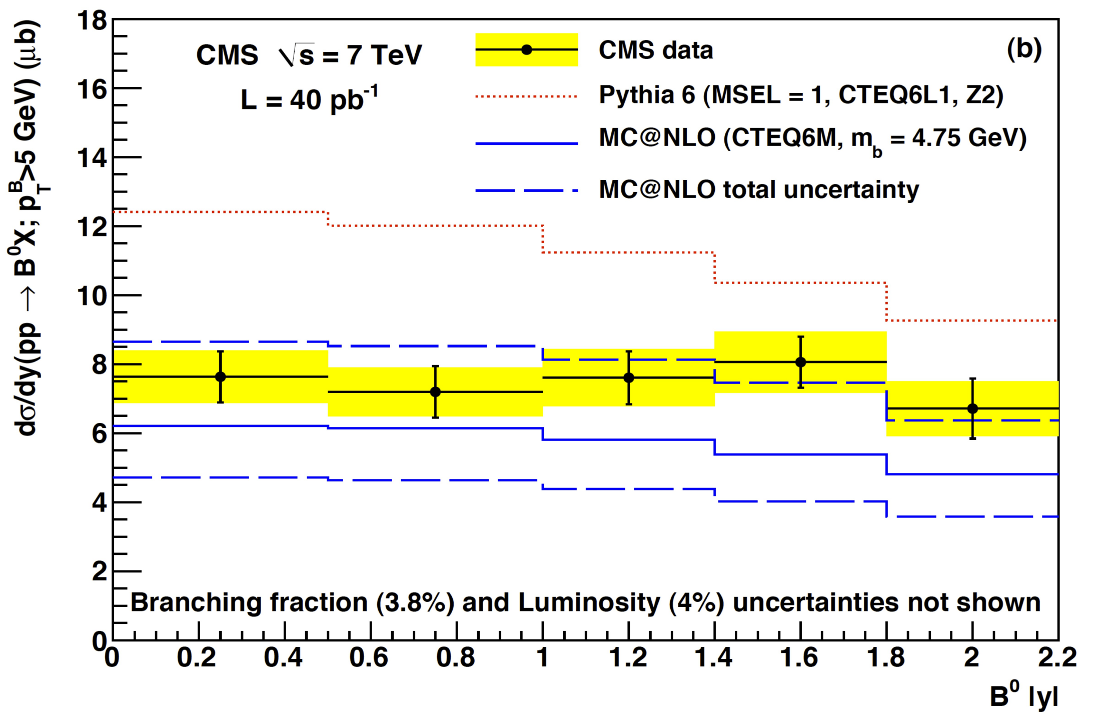
Resolutions:

~ 20 GeV for M_B, ~45 μm for cτ;

p_T shape in reasonable agreement with the models

Rapidity shape more flat than Pythia and MC@NLO

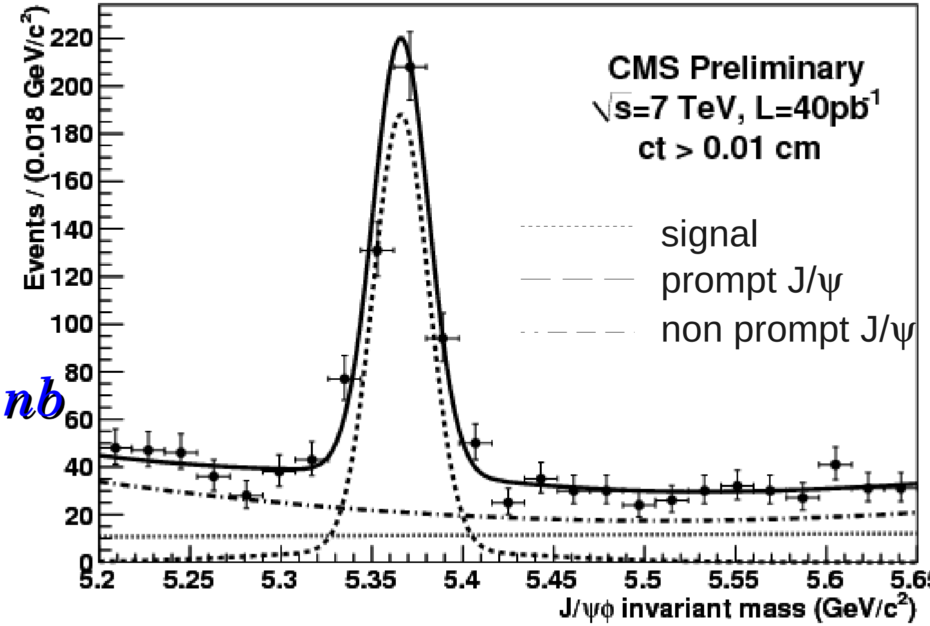




$B_s \rightarrow J/\psi\ \Phi$

$pT(B_s) > 8$ GeV

$|y(B_s)| < 2.4$



$$\sigma(pp \rightarrow B_s X) \cdot Br(pp\ \ B_s \rightarrow J/\psi) =$$

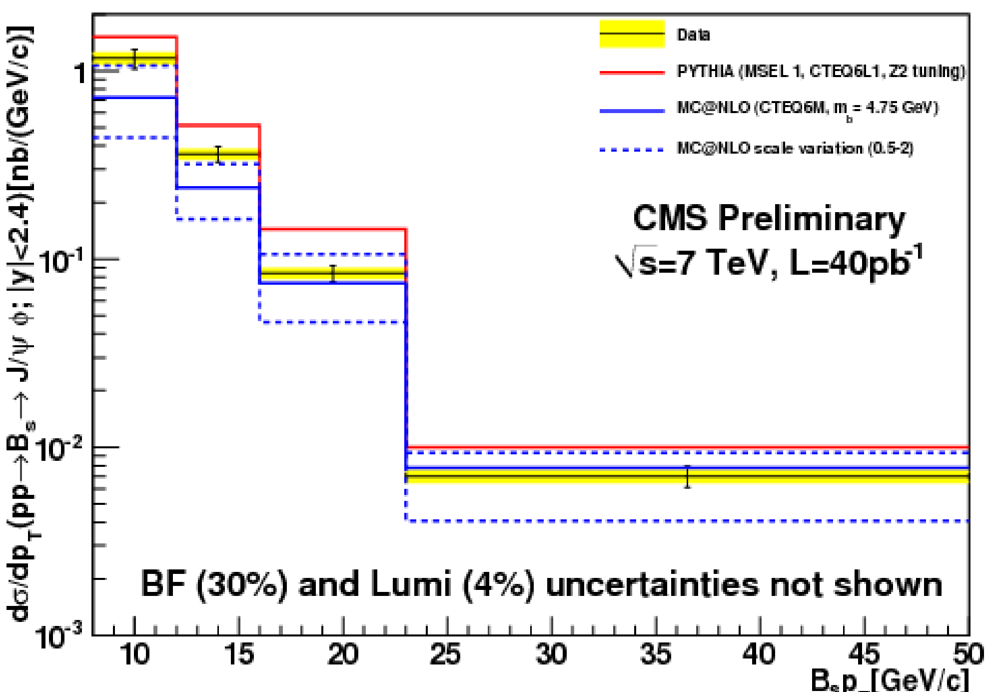
$$= (6.9 \pm 0.6\ (stat) \pm 0.5\ (syst) \pm 0.3\ (lumi)\ )\ nb$$

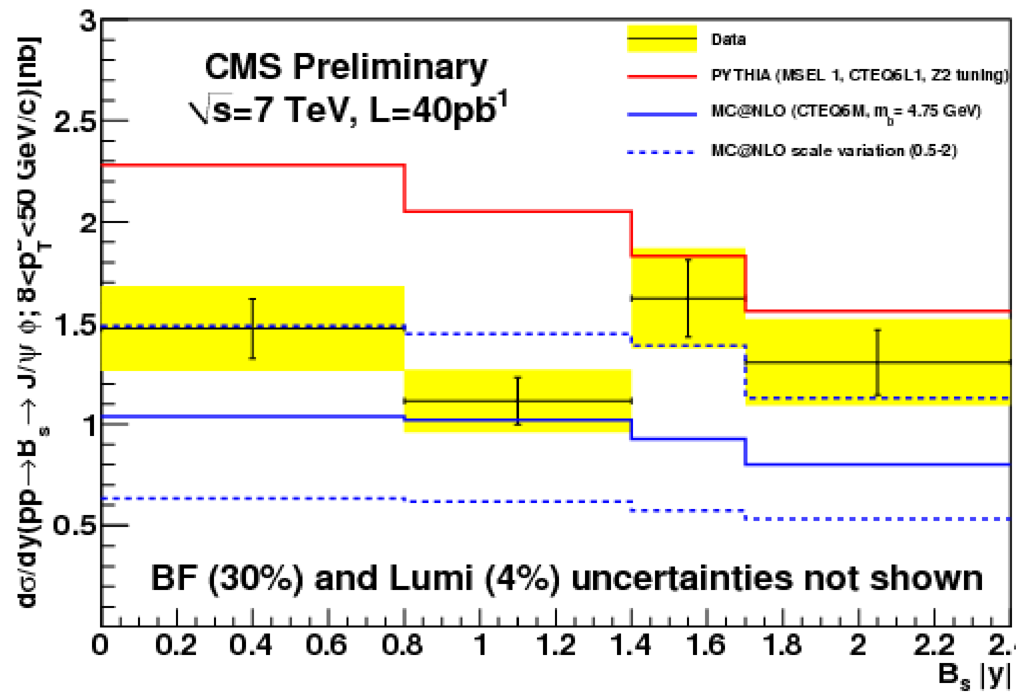
$\sigma_{MC@NLO} = (4.6_{-1.7}^{+1.9} \pm 1.4)$ nb;

$\sigma_{PYTHIA} = (9.4 \pm 2.8)$ nb [last errors from Br]

p_T shape in drops faster than MC@NLO

Rapidity distribution more flat than both the models

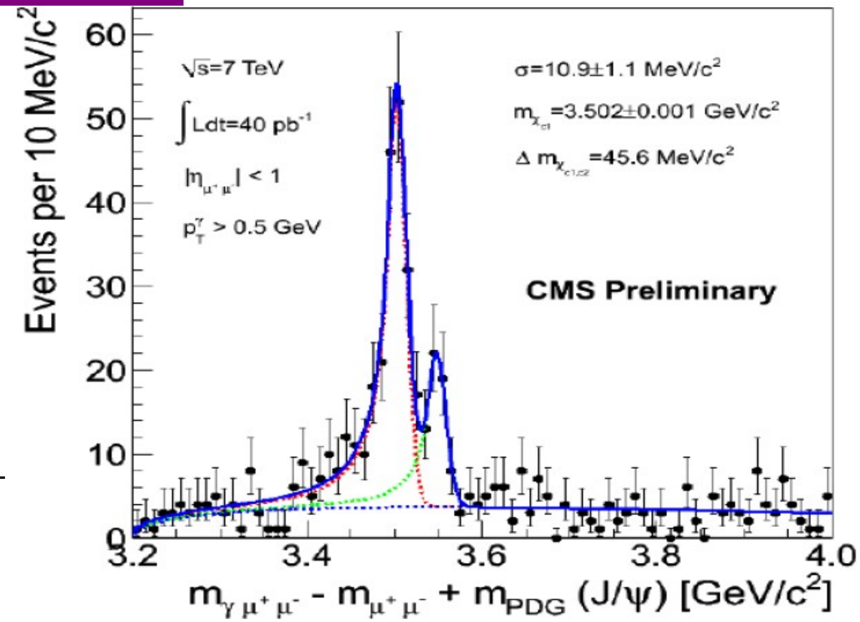




Observation of other heavy hadrons

$\chi_{c1,2}$

χ_{c1} and χ_{c1} seen in CMS in decay to $J/\psi\ \gamma$
high resolution needed (Δm = ~45 MeV);
CMS resolution very good (~11 MeV);
photon conversion rather challenging.

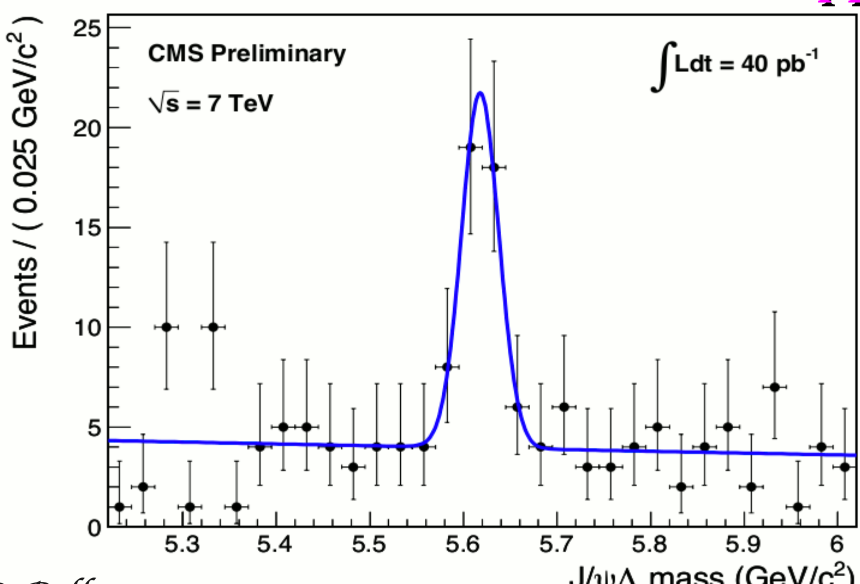


Λ_b observed in the decay channel $J/\psi\ \Lambda$
Yield and lifetime measured with early 2011 data

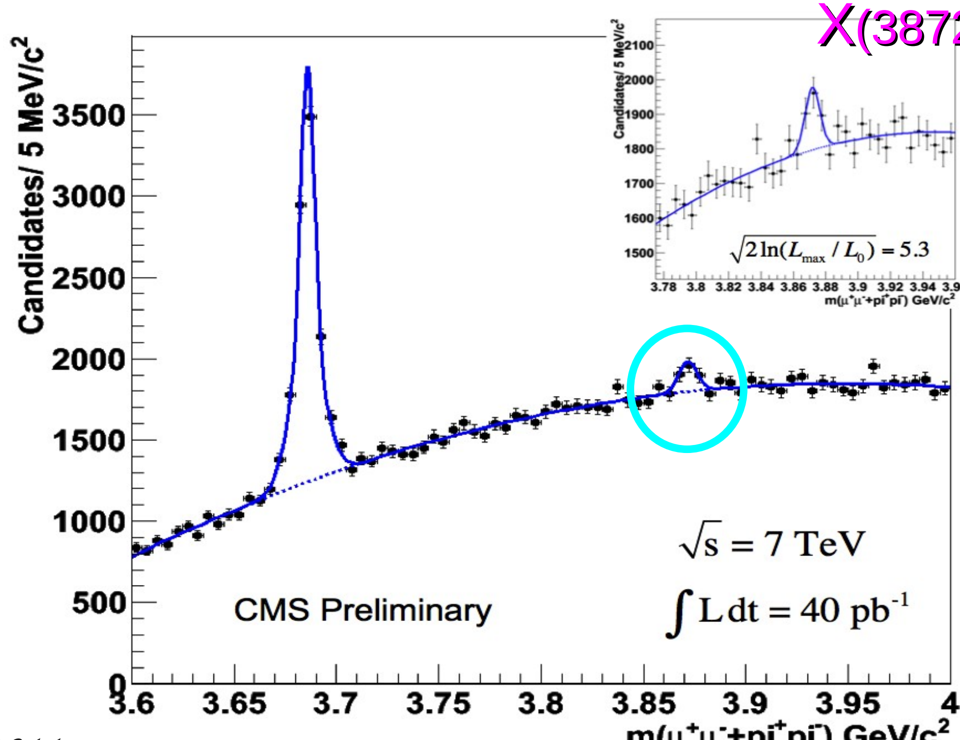
X(3872) status observed in the decay channel $J/\psi\ \pi^+\pi^-$ in 40 pb^{-1} with a significance of 5.3
Measured ratio of the cross section wrt Y(2S):

$R = 0.087 \pm 0.017(stat) \pm 0.009(syst)$

Λ_b



X(3872)



Conclusions and outlook

- Very successful B physics results with 2010 data
- More B physics papers from CMS than from other LHC experiments combined
- Heavy flavor production measurements performed with a wide variety of techniques
- Wealth of new data going to be used to refine theoretical models and improve MC simulation
- Many more interesting results to come (among others, efforts put on rare decays as $B_s \to \mu\mu$, $K^*\mu\mu$ and CP-violation in $B_s \to J/\psi\,\Phi$, ...)

Thanks for your attention!

BACK UP SPLIDES

References

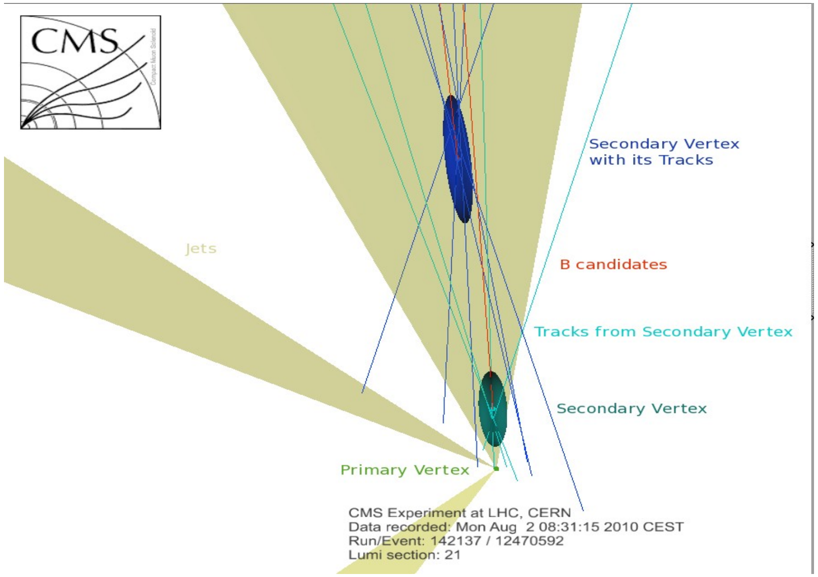
Topic	arXiv	Article	Luminosity (pb^{-1})
J/Ψ production	1011.4193	Eur.Phys.J. C71 (2011) 1575	0.314
Υ production	1012.5545	Accepted by PRD	3
B+ Production	1101.0131	PRL 106:112001,2011	5.8
Inclusive b-hadron production	1101.3512	JHEP 1103 (2011) 090	85
BB(bar) Angular Correlat. with SV	1102.3194	JHEP 1103 (2011) 136	3.1
B0_d Production	1104.2892	Submitted to PRL	40

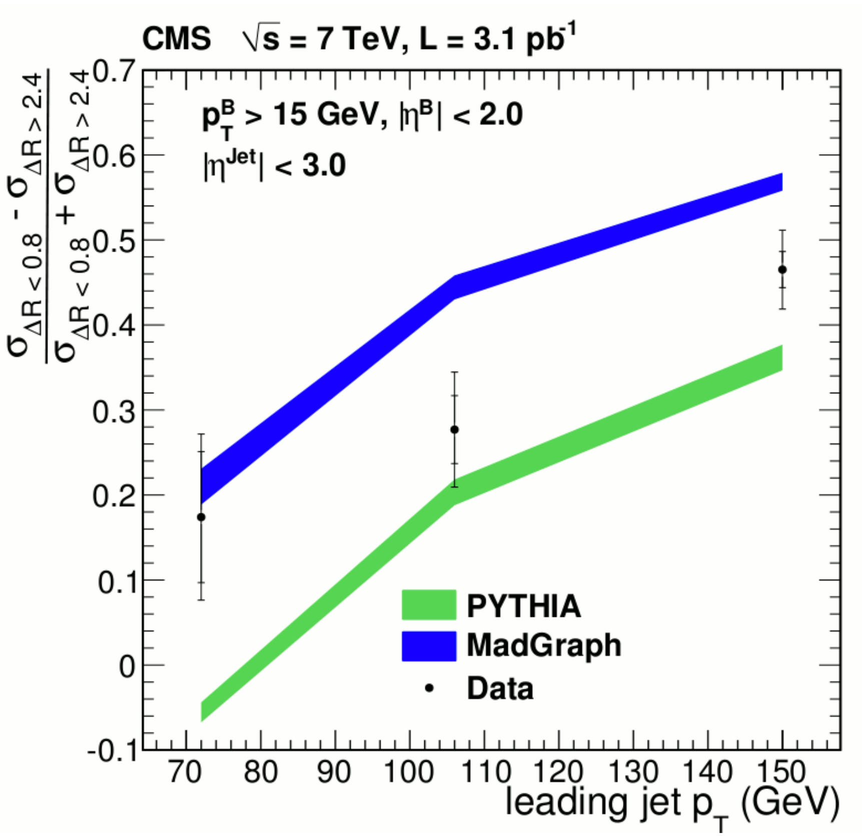
BB correlation and Secondary Vertices

None of the predictions describes the data very well, that lie between the MadGraph and Pythia

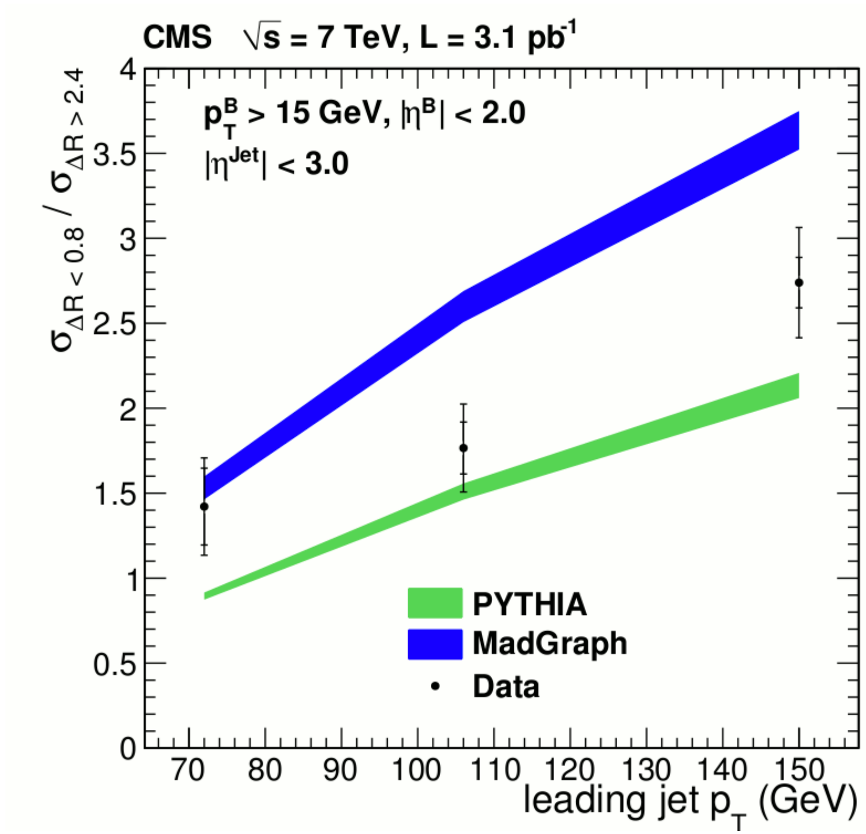
MC@NLO do not describe the shape of the ΔR, in particular @ small values.

Cascade predictions significantly below the data in all regions, both in the ΔR and $\Delta\phi$ distributions.





Asymmetry between BB production cross section in $\Delta R<0.8$ and $\Delta R>2.4$ as function of leading jet pT

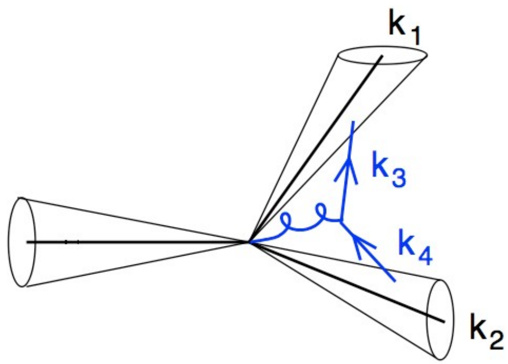


Ratio between BB production cross section in $\Delta R<0.8$ and $\Delta R>2.4$ as function of leading jet pT

b-jet cross section measurement

Higly non-trivial measurements

Sizable uncertainties from both th. and exp.



MEMO: standard jet definitions for flavoured jets are infrared-unsafe: soft gluons splitting into a qqbar pair can change the flavour of the jet

- **Theoretical Uncertainties (~ in order of importance):**
  - PDF Uncertainty
  - pQCD (Scale) Uncertainty
  - Non-perturbative Corrections
  - PDF Parameterization
  - Knowledge of $\alpha_s(M_Z)$
  - ...

Recall: Jet Algorithms used by CMS:
- Iterative Cone R = 0.5
- SISCone R = 0.5, 0.7
- k_T D = 0.4, 0.6

- **Experimental Uncertainties (~ in order of importance):**
  - Jet Energy Scale (JES)
    - Noise Treatment
    - Pile-Up Treatment
  - Luminosity
  - Jet Energy Resolution (JER)
  - Trigger Efficiencies
  - Resolution in Rapidity
  - Resolution in Azimuth
  - Non-Collision Background
  - ...

Main ingredients of the measurements

- Number of tagged jets N_{tagged}
- b-tagging efficiency f_b: fit from MC, data/MC scale with muon pTrel
- b-tag purity e_b: fit from MC, data/MC scale from SV mass templates

Master formula:

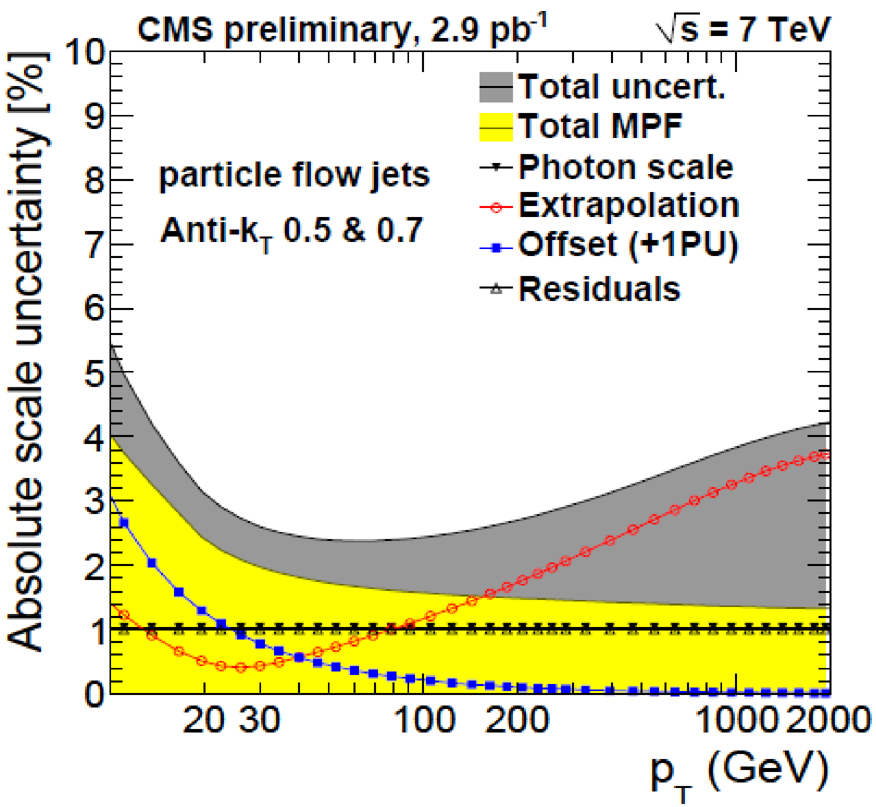
$$\frac{d^2\sigma_{\mathrm{b-jets}}(p_T, y)}{dp_T dy} = \frac{N_{\mathrm{tagged}}(p_T, y) f_b c_{\mathrm{smear}}}{\epsilon_b \Delta p_T \Delta y \mathcal{L} \epsilon_{\mathrm{jet}}}$$

Other corrections:

- Unfolding correction C_{smear}: need jet energy resolutions, ansatz fit
- b-jet JEC: same as inclusive jets (Pythia predicts residual difference <~1%)

Jets and b-tagging

- Most of jet analyses use particle-flow techniques to define the jet and anti-kT algorithm with DR<0.5
- Typical scale uncertainty for EWK measurements < 3%;
- Typical jet resolution 10-15%



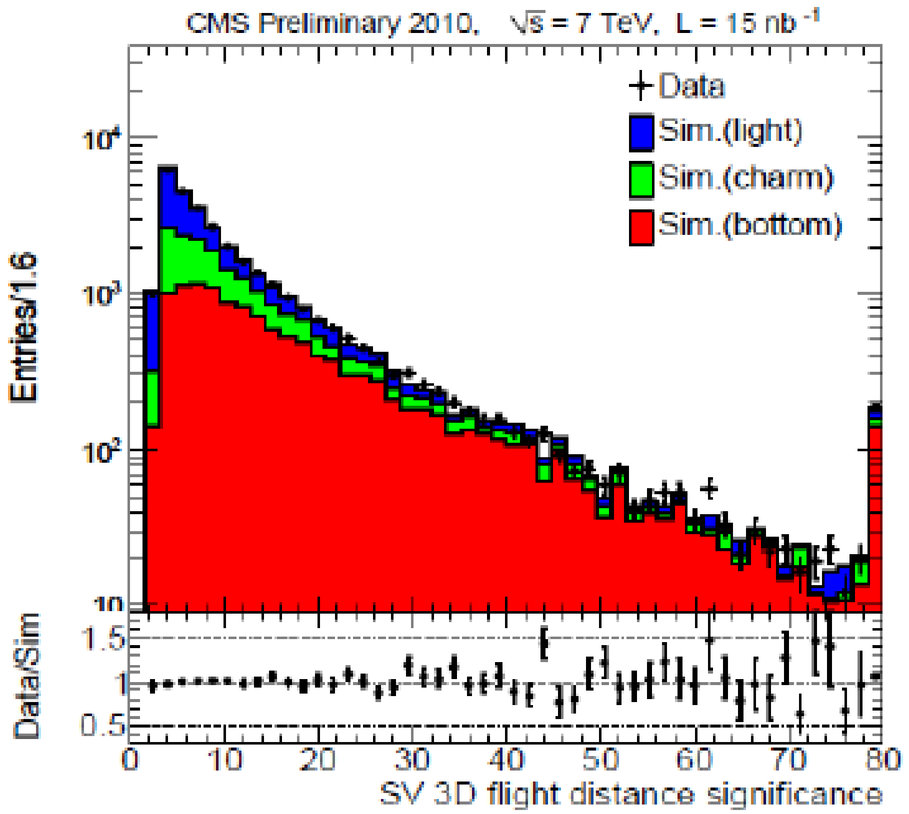
Good tracker performance and alignment → good b-tagging capabilities

Different algorithms:

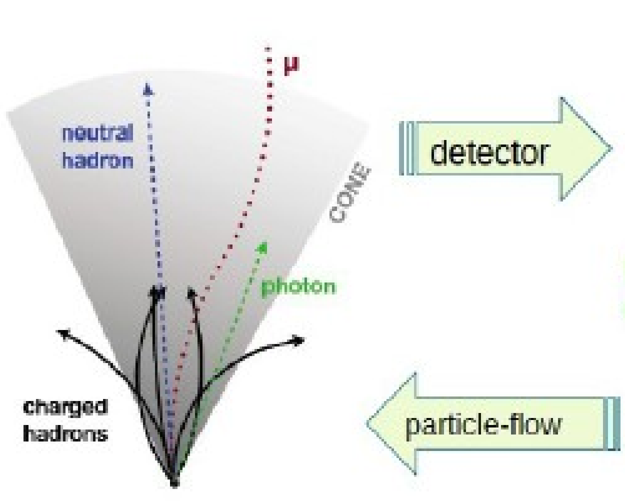
* Track counting (above some impact parameter significance threshold)

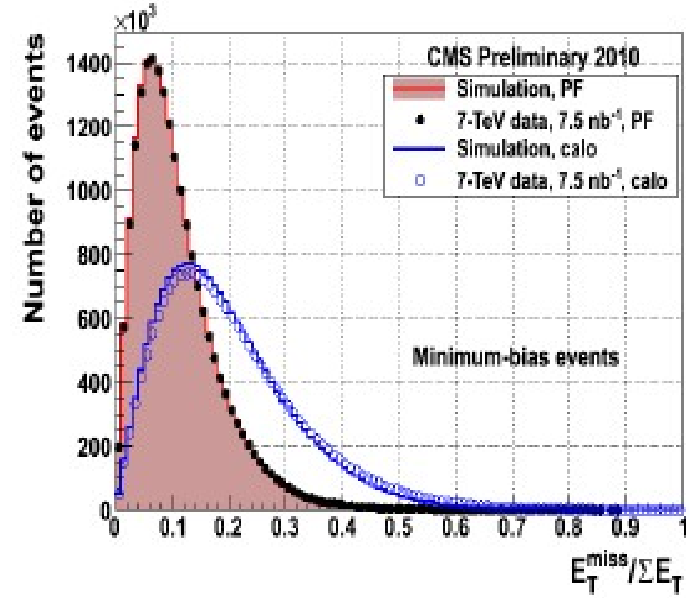
* Secondary vertex tagging (decay length significance)

* Combined



Particle Flow Technique in CMS



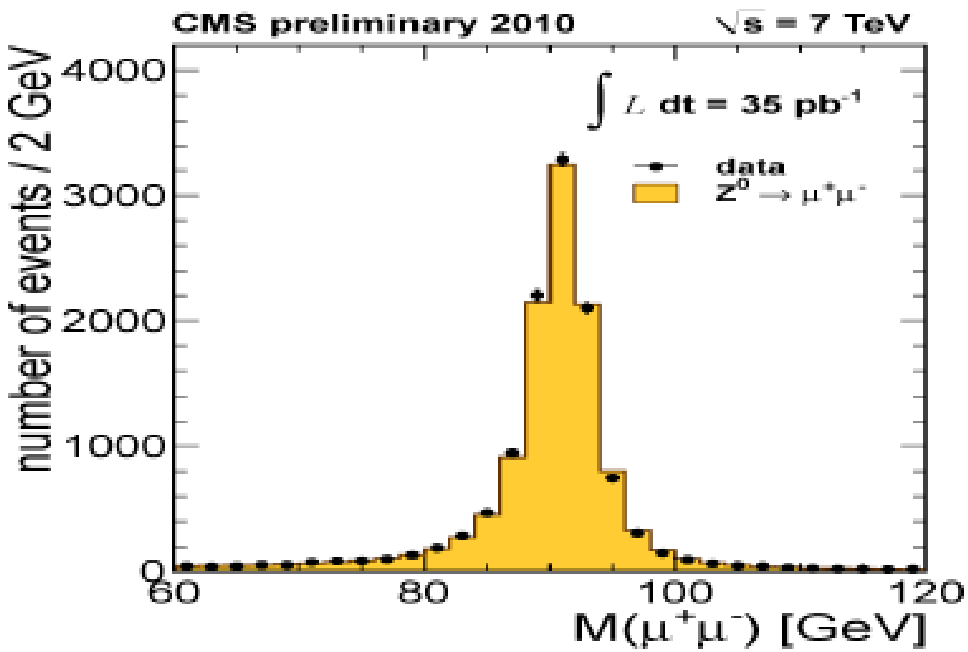


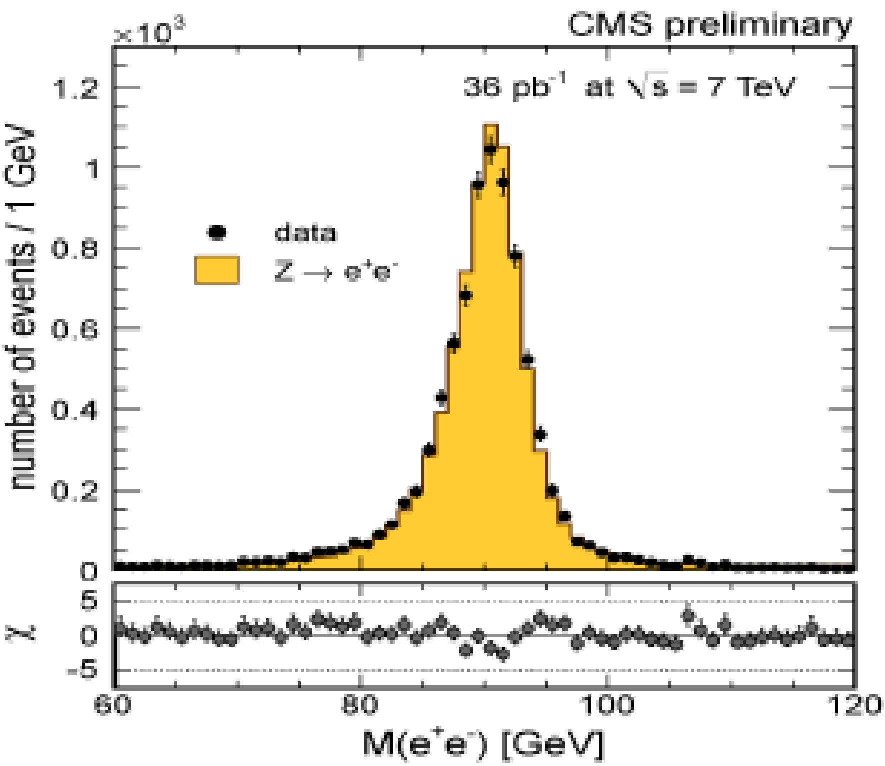
- In CMS, charged particles get well separated due to the huge tracker volume and the high magnetic field (3.8 T)
- CMS has an excellent tracking resolution, able to go to down to very low momenta (~few hundred MeV)
- CMS has also an excellent electromagnetic calorimeter with good granularity
- In multijet events, only 10% of energy corresponds to neutral (stable) hadrons

Big improvement in energy resolution and tau identification using particle-flow techniques

Muons and electrons

- Muon resolution dominated by inner tracking for up to p_T~200 GeV. Typical p_T resolution 1-2%
- Muon chambers: redundant trigger and coverage, muon identification
- Good identification capabilities: muons reconstructed both in inner tracker and muon spectrometer





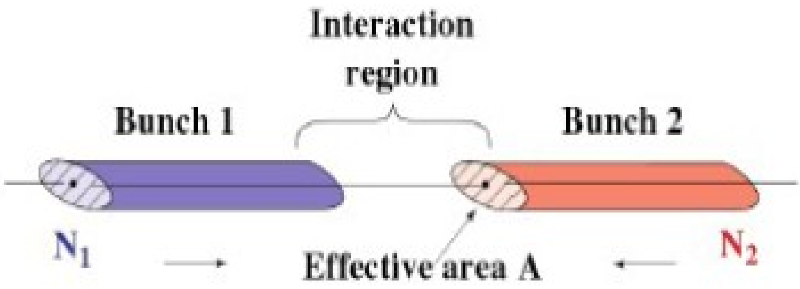
- Excellent energy resolution thanks to the precise $PbWO_4$ crystal calorimeter.
- Typical E_T resolution for EWK studies: 1%
- Good charge assignment and track matching, fitting techniques taking into account bremsstrahlung emissions
- Identification based on shower shape variables, tracking matching and HAD/EM. ratio (good agreement with the simulations)

Luminosity Measurements

$$\mathcal{L} = N_1 N_2 f n_b \int \rho_1(x,y)\rho_2(x,y)\,dxdy$$

$$\mathcal{L} = \frac{N_1 N_2 f n_b}{A_{eff}}$$

$$A_{eff} = 2\pi\sigma_x\sigma_y$$



- Intensities $N_{1,2}$ measured by LHC beam current transformers
- Shape and size of the interaction region, A_{eff}, measured via Van der Meer scans: relative variations or rate as a function of the transverse separation between beams
- Rates measured in CMS using fraction of zero counts of HF and vertexing

Systematic	Error (%)
Effective Area Determination	2.7
Beam Intensity	2.9
Sample Dependence	0.7
Total	**4.0**

Uncertainty: 4%

Luminosity correction wrt initial estimates: -0.7%

FONLL (Fixed Order plus Next-to-Leading Logarithms)

(M.Cacciari, M. Greco, S. Frixione, P. Nason) http://home.cern.ch/cacciari/FONLL

FONLL is a code for calculating double-differential, single inclusive heavy quark production cross sections in pp(bar) and (electro)photoproduction.

it merges the massive NLO calculation with the NLL resummation of terms of collinear origin, αSlog(pT/m), which become large when pT >> m

Two advantages of an FONLL-like framework:

1- the perturbative uncertainty does not increase when pT >> m

2- non-perturbative input describing the quark-to-meson hadronization can be extracted from e+e- data and included in predictions for hadronic collisions in a self-consistent way

Colour Evaporation Model (CEM)

based on the ’local hadron parton duality approach', Improved by including next to leading order processes. It predicts the J/Psi prod Xsec from that of the cc pair.

It assumes that color can be ”bleached” (evaporate) by multiple soft gluon interactions, implying a statistical treatment of color

(Because color is the source of hadrons, only the c.o. states yield asymptotically hadronic states)
CEM does not explain how the formation of the J/Psi proceeds. It assumes that the open cc pair transforms with a certain probability into a bound cc pair by soft gluon interactions.

Cascade

It incorporates off-shell ME for photon-gluon fusion @LO
with co, based on kT fact.
Initial state parton shower generated accordingly to the CCFM equation
j/psi produced in the CSM unintegrated gluon PDFs
Hadronizat. With Lund string model