Heavy Quarks in CMS

Gerd J. Kunde

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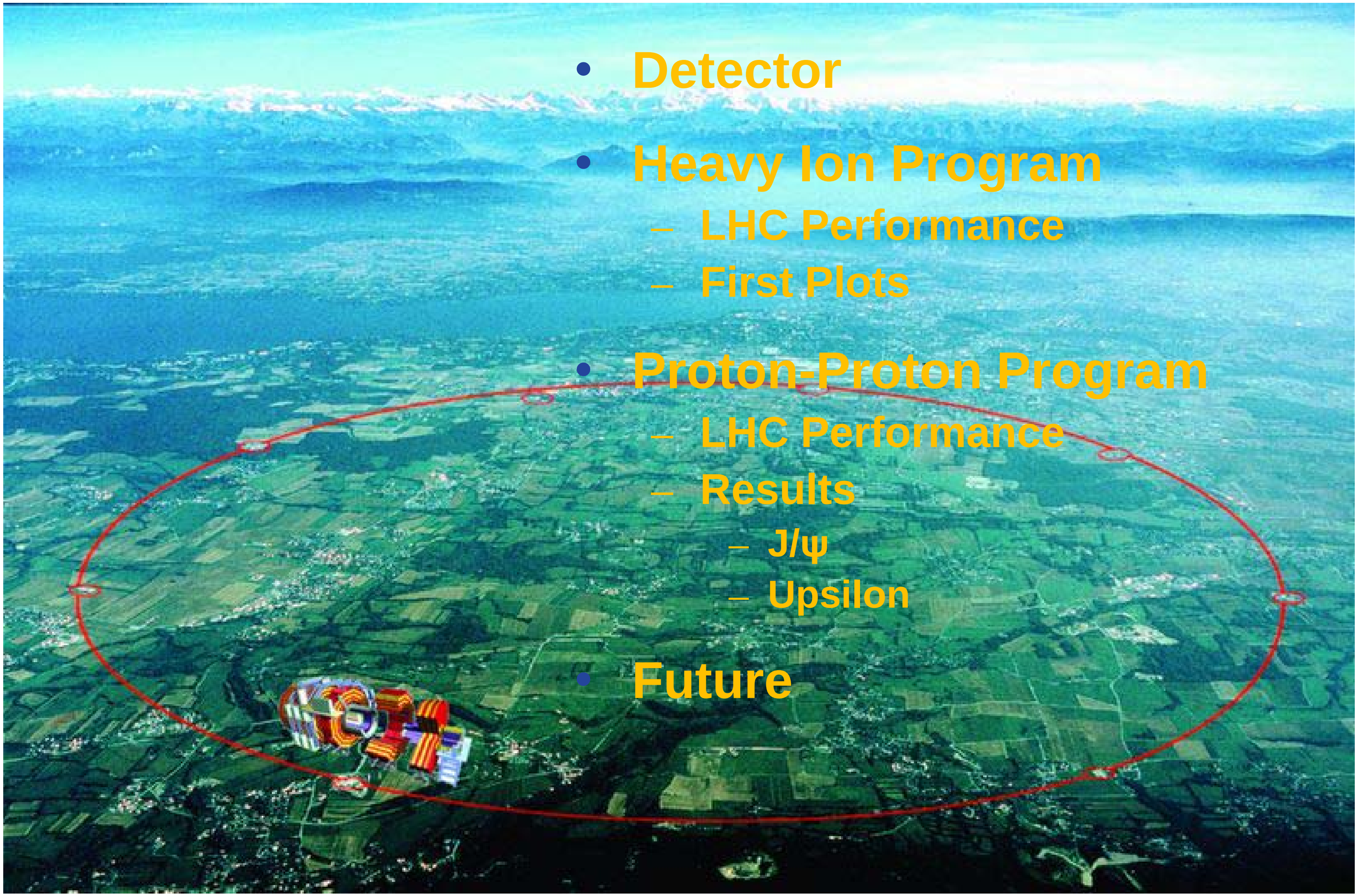
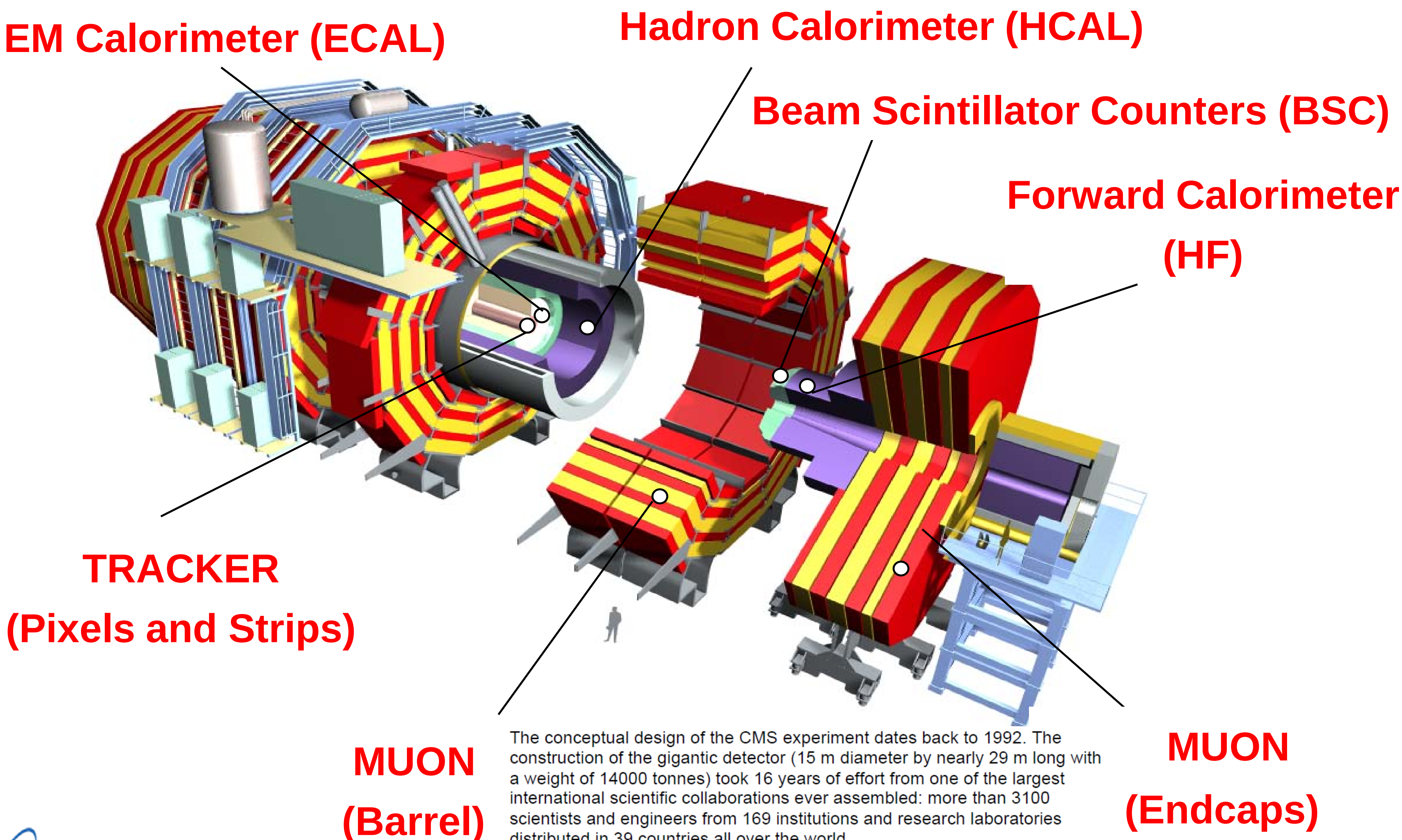


- Detector
- Heavy Ion Program
  - LHC Performance
  - First Plots
- Proton-Proton Program
  - LHC Performance
  - Results
    - J/ψ
    - Upsilon
- Future

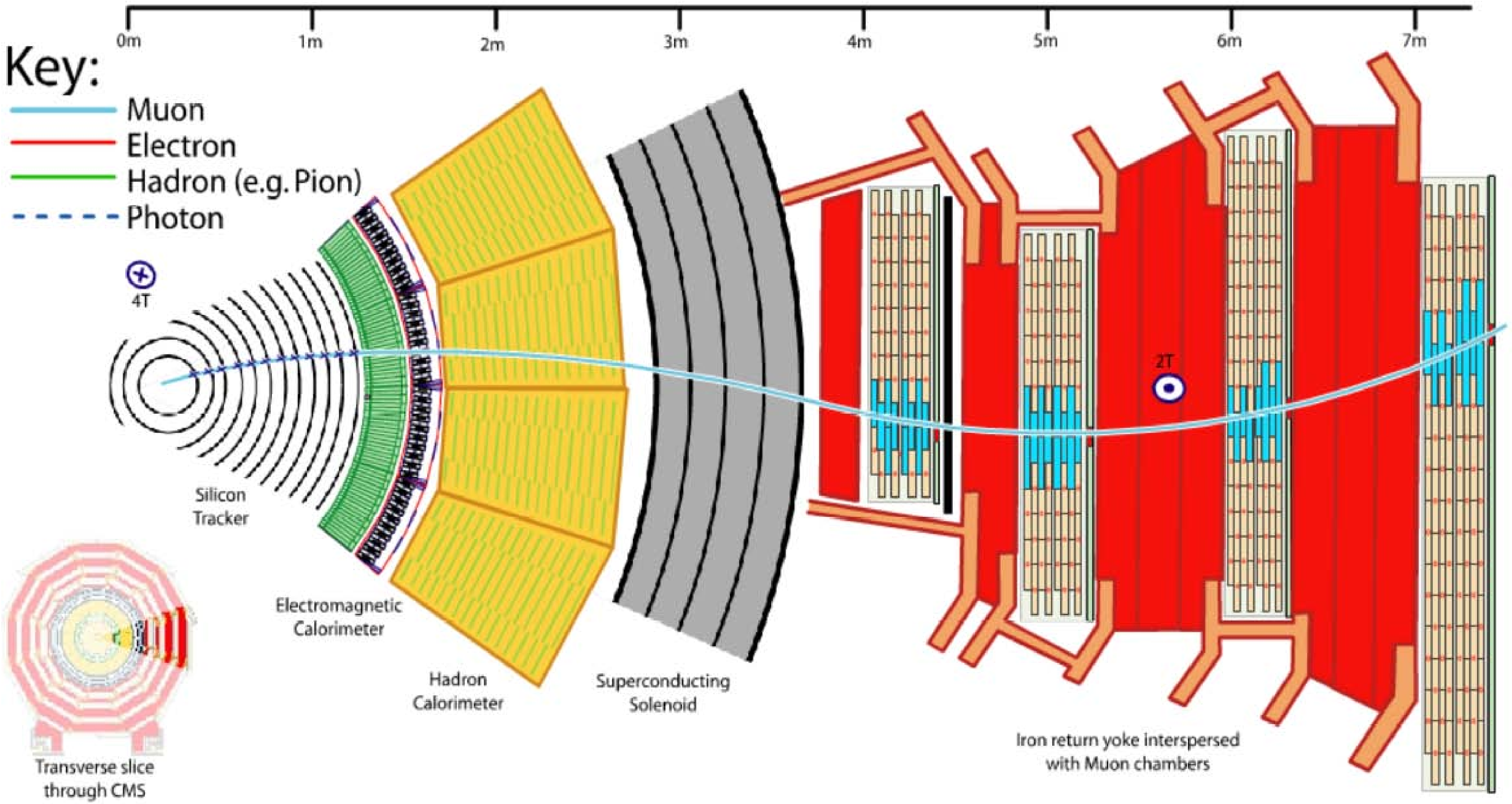
g.j.kunde@lanl.gov

The Compact Muon Solenoid Detector



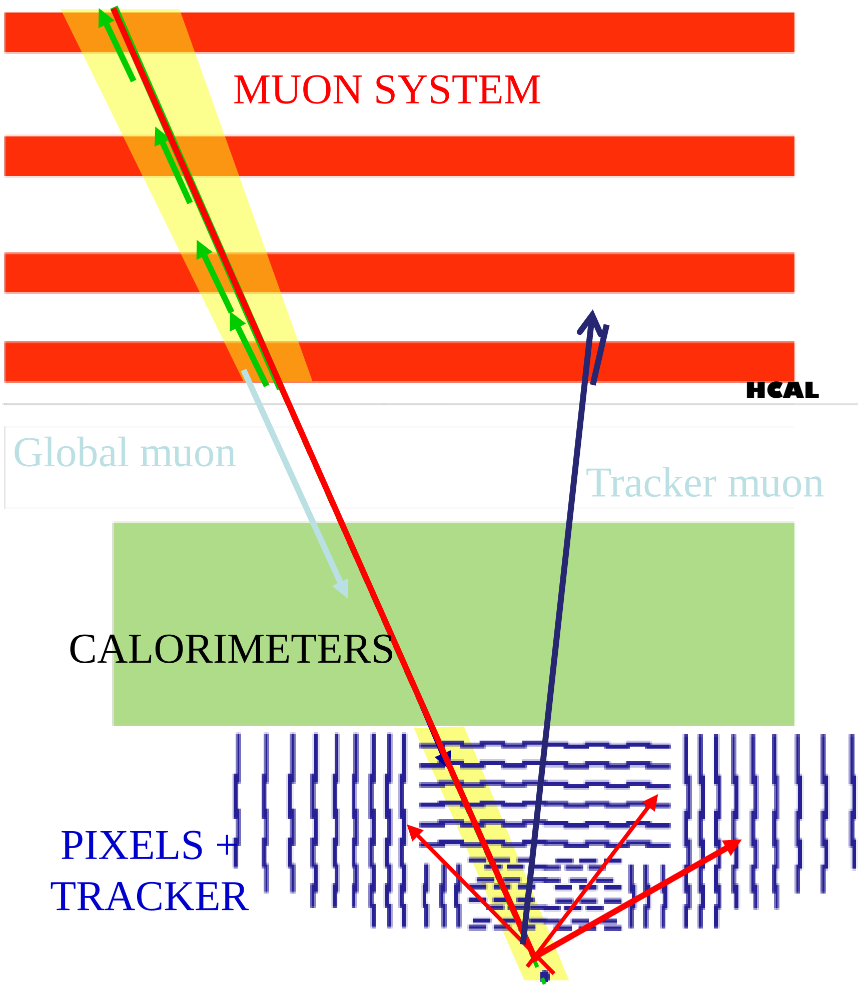
The conceptual design of the CMS experiment dates back to 1992. The construction of the gigantic detector (15 m diameter by nearly 29 m long with a weight of 14000 tonnes) took 16 years of effort from one of the largest international scientific collaborations ever assembled: more than 3100 scientists and engineers from 169 institutions and research laboratories distributed in 39 countries all over the world.

Muon Reconstruction



Muon Detection: Drift Tubes – Cathode Strips – Resistive Plate Chambers

Muon Reconstruction cont.

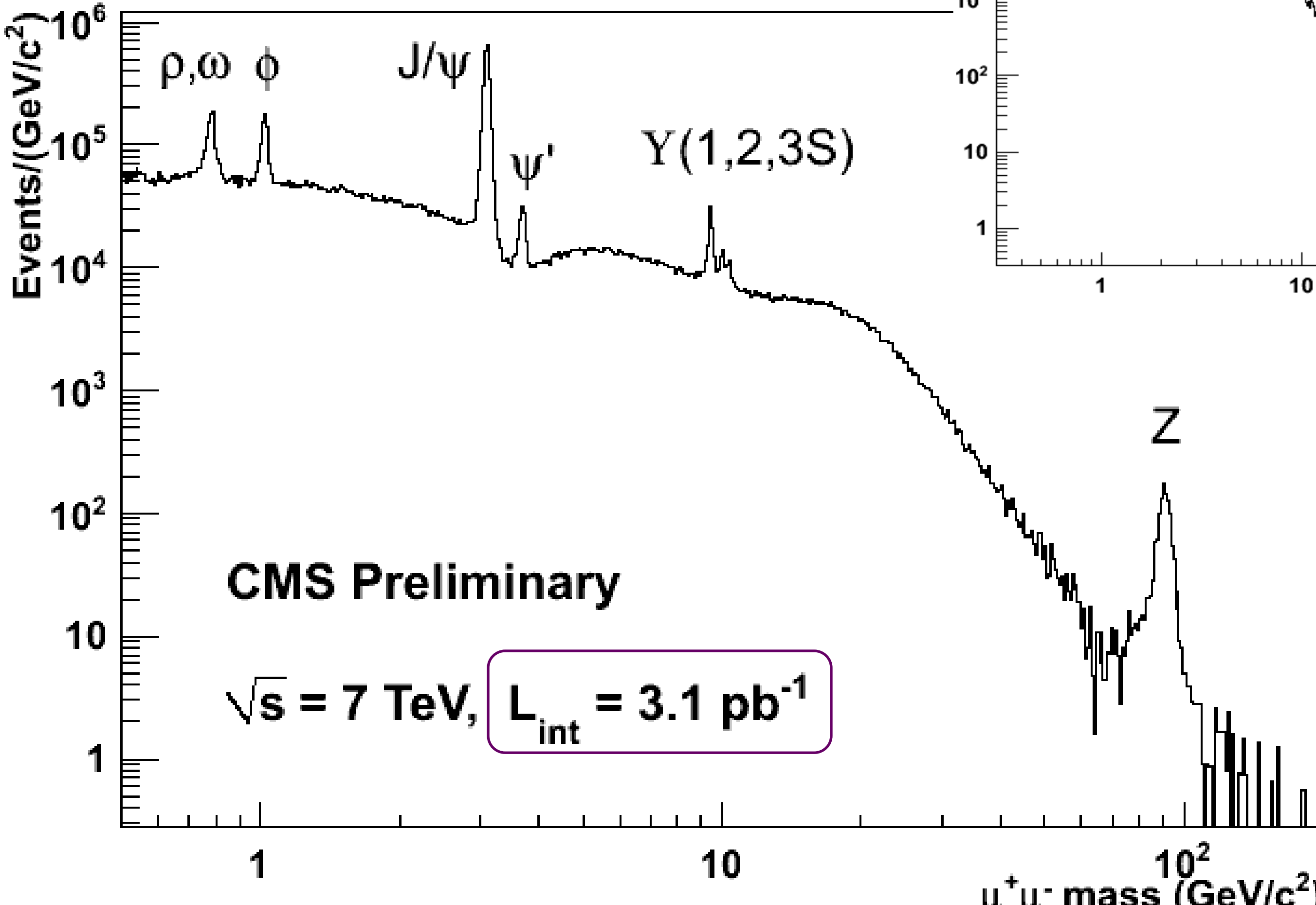


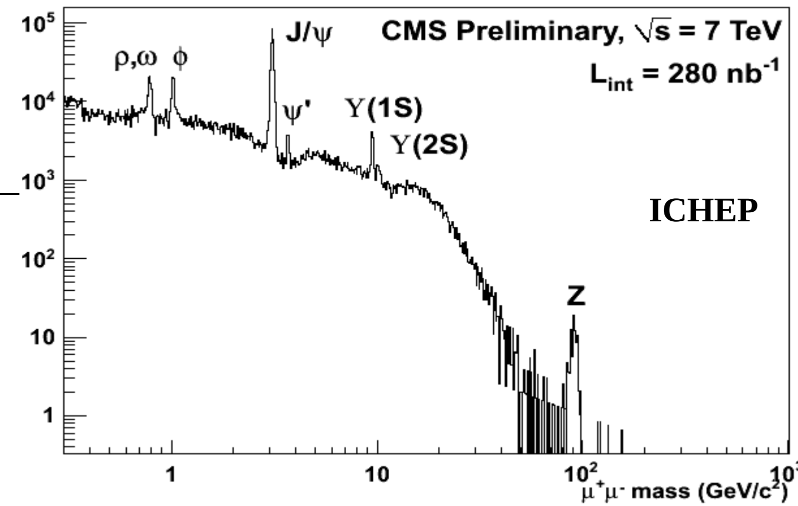
- Large rapidity coverage:
  - $|\eta| < 2.4$
- Excellent muon momentum resolution:
  - matching between μ-chambers and in the silicon tracker (only using the latter for momentum determination at low p_T)
  - strong magnetic field (3.8 T)

Two muon identifications:

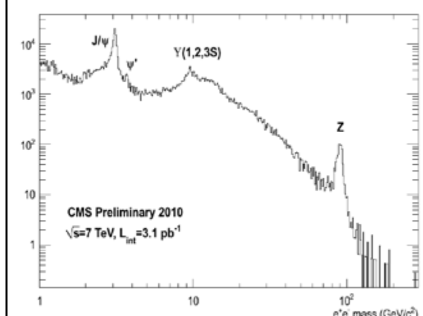
- Global muon (outside-in):
  - *High purity*
  - *Low efficiency for low momentum muon*
- Tracker muon (inside-out):
  - *Fake muon level high*
  - *Higher efficiency low momentum muon*

Proton-Proton Dimuon Spectra

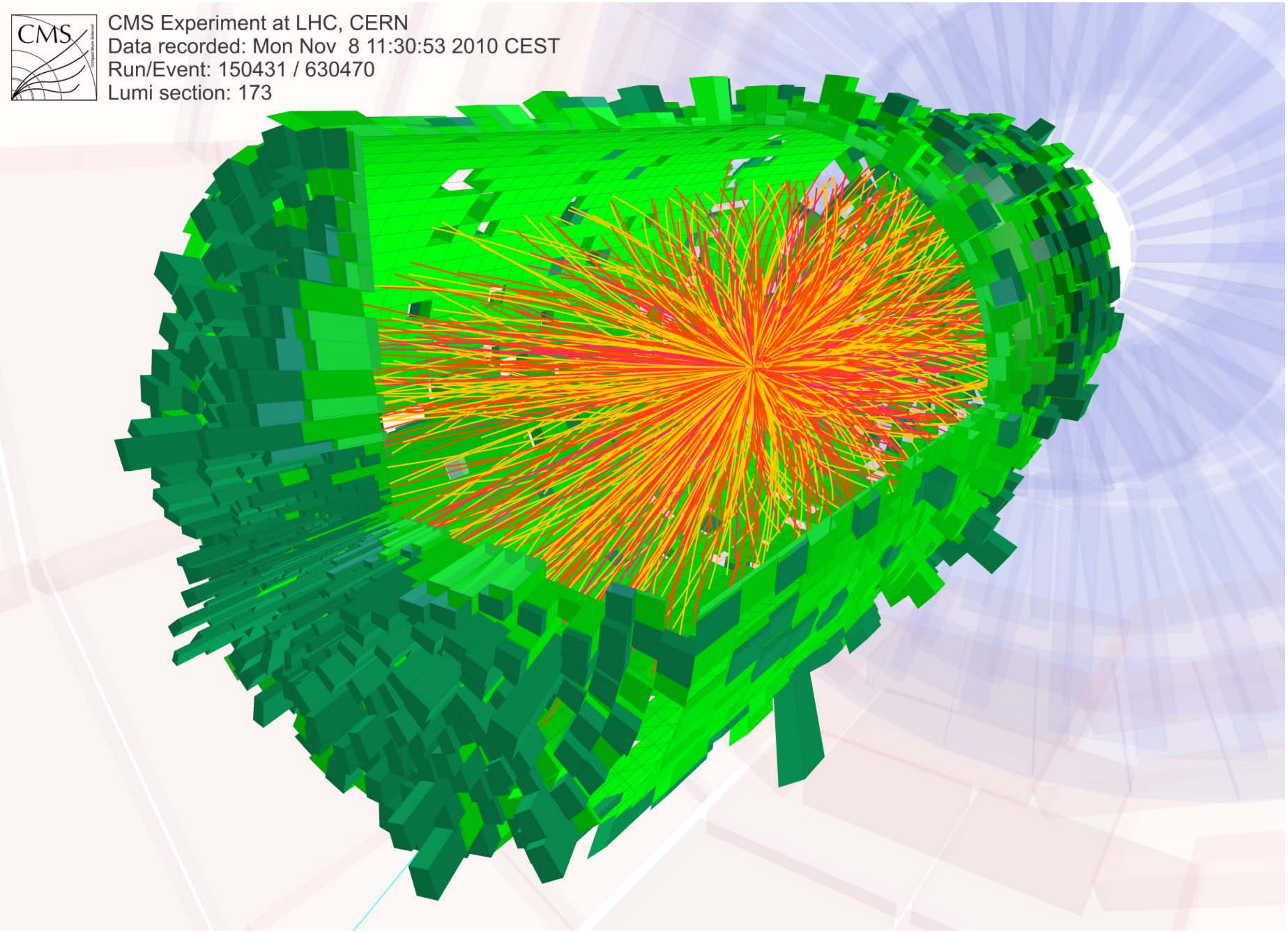




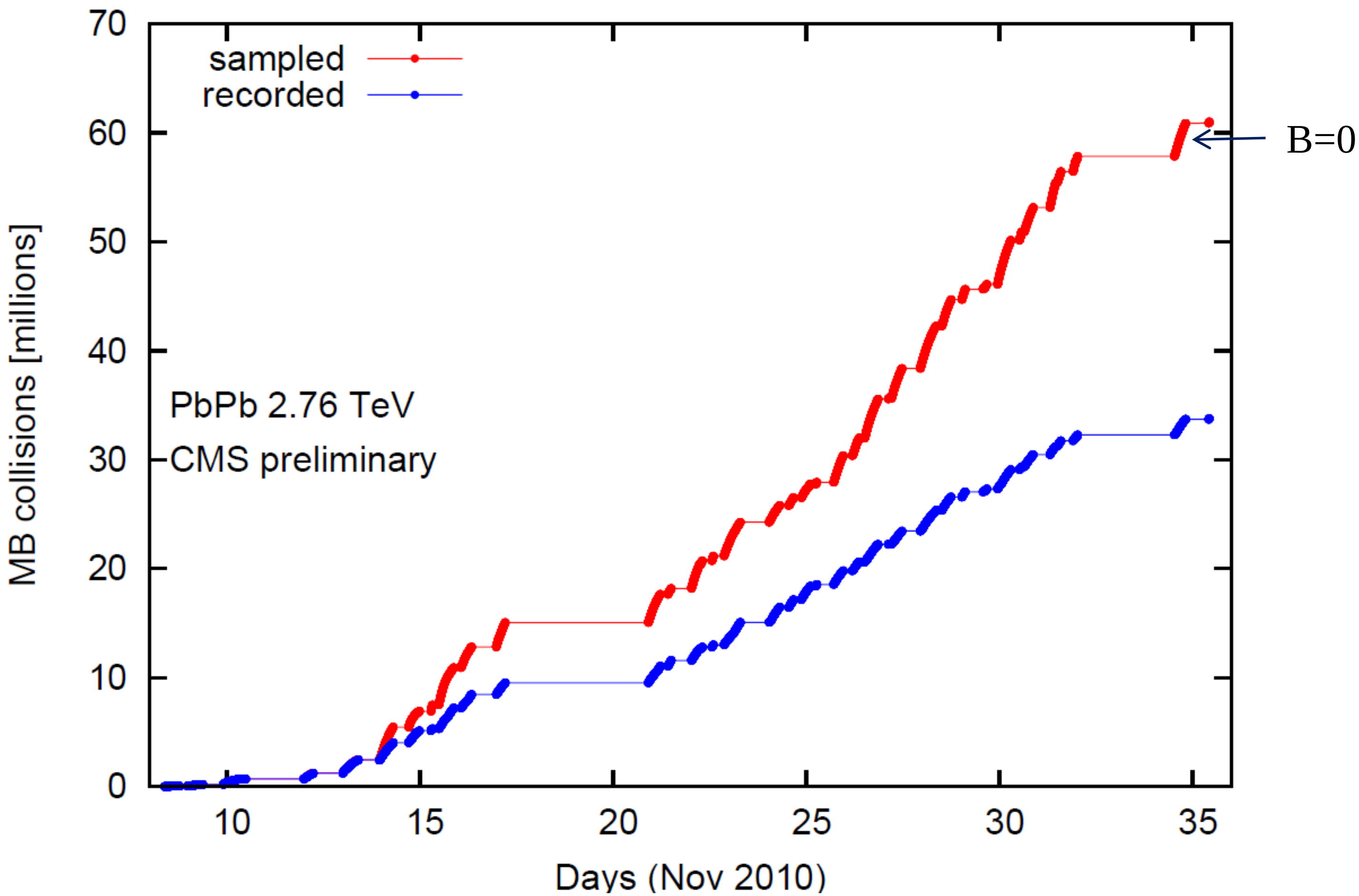
electrons !



The Heavy Ion Run



Heavy Ion Data Taking with CMS



GREAT thanks to LHC Team

$7.36\ \mu b^{-1} = 56.3\ M$

g.j.kunde@lanl.gov

Heavy Ion Triggering on Collisions

- Maximize efficiency for high p_T probes
  - Muons
  - Jets
  - Photons/Electrons
- Record large Minimum Bias sample
- Additional triggers
  - Ultra Peripheral Collisions
  - Background monitoring
- Minimize backgrounds

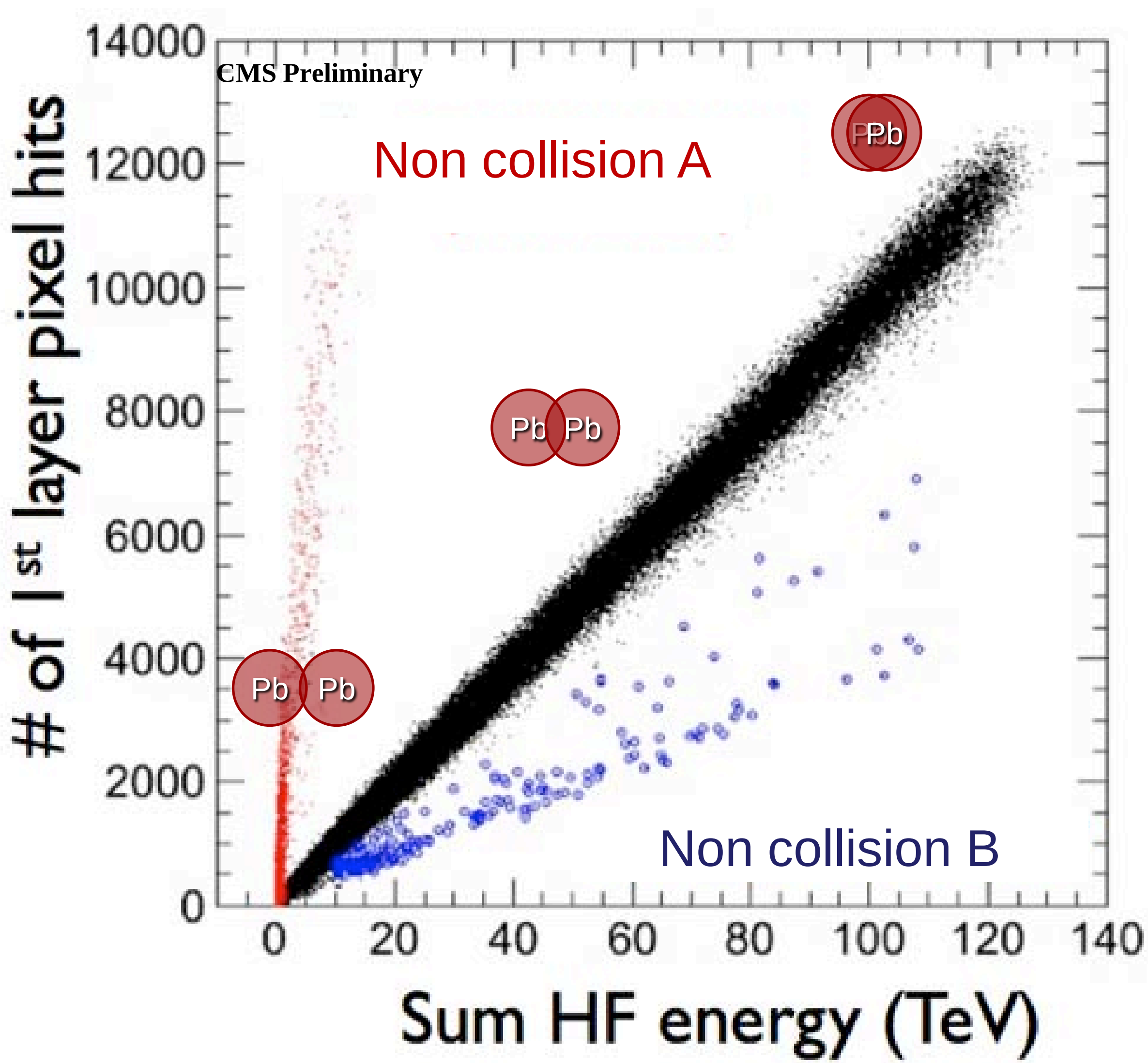
g.j.kunde@lanl.gov

HI Event Selection

- Level 1 trigger
  - Coincidence of two scintillator counters OR
  - Coincidence of two HF towers
  - Muons
- High Level Trigger
  - Jets
  - Muons
  - Photons
- Offline
  - Veto on scintillator beam halo
  - At least 3 HF towers on each side above threshold ($E > 3$ GeV)
  - Reconstructed pixel vertex with two or more tracks
  - Beam-scraping removal with pixel cluster vertex compatibility

g.j.kunde@lanl.gov

HI Minimum Bias Event Sample



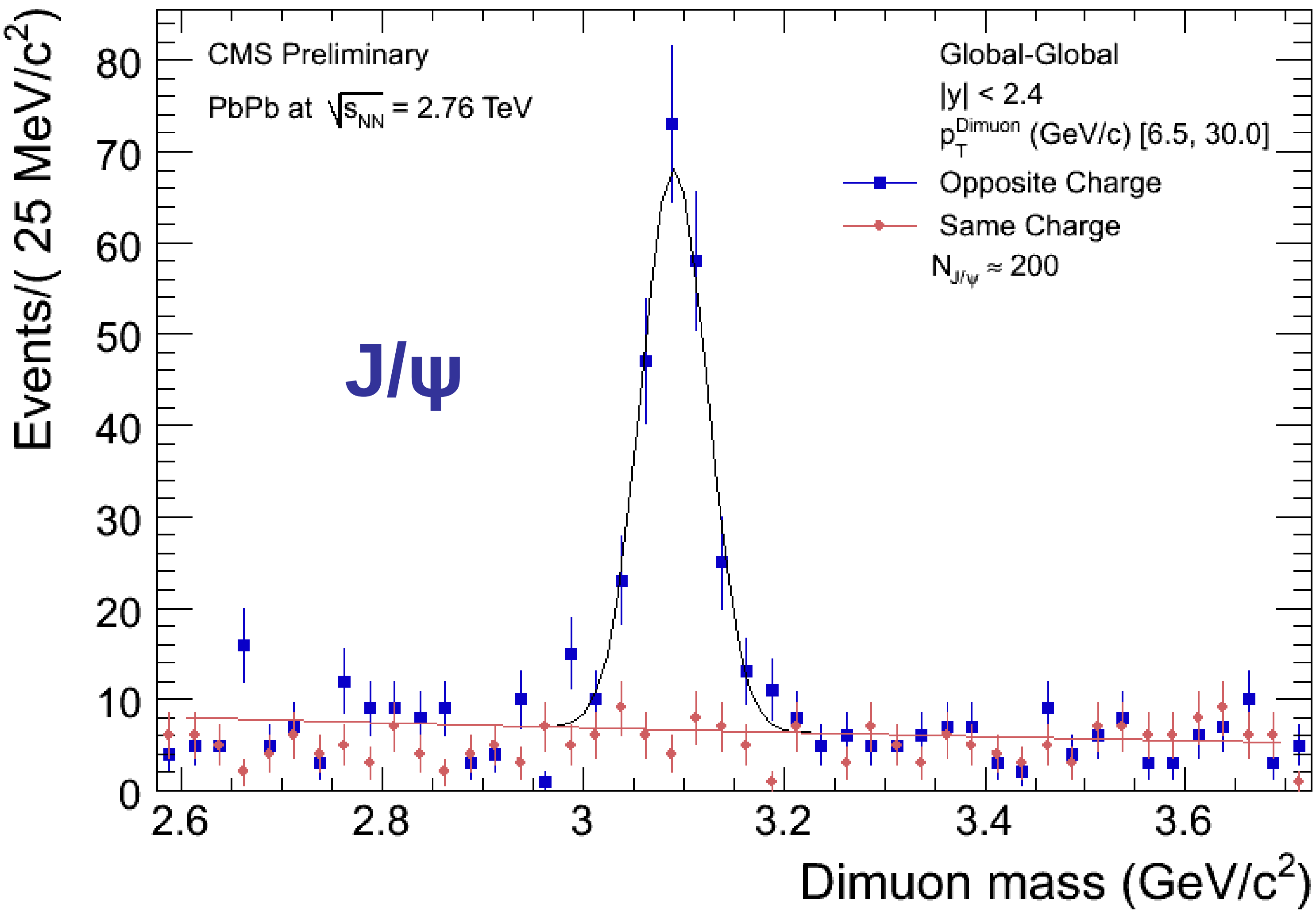
HI Dileptons: Past and Future

Quarkonia should melt in the Quark Gluon Plasma...

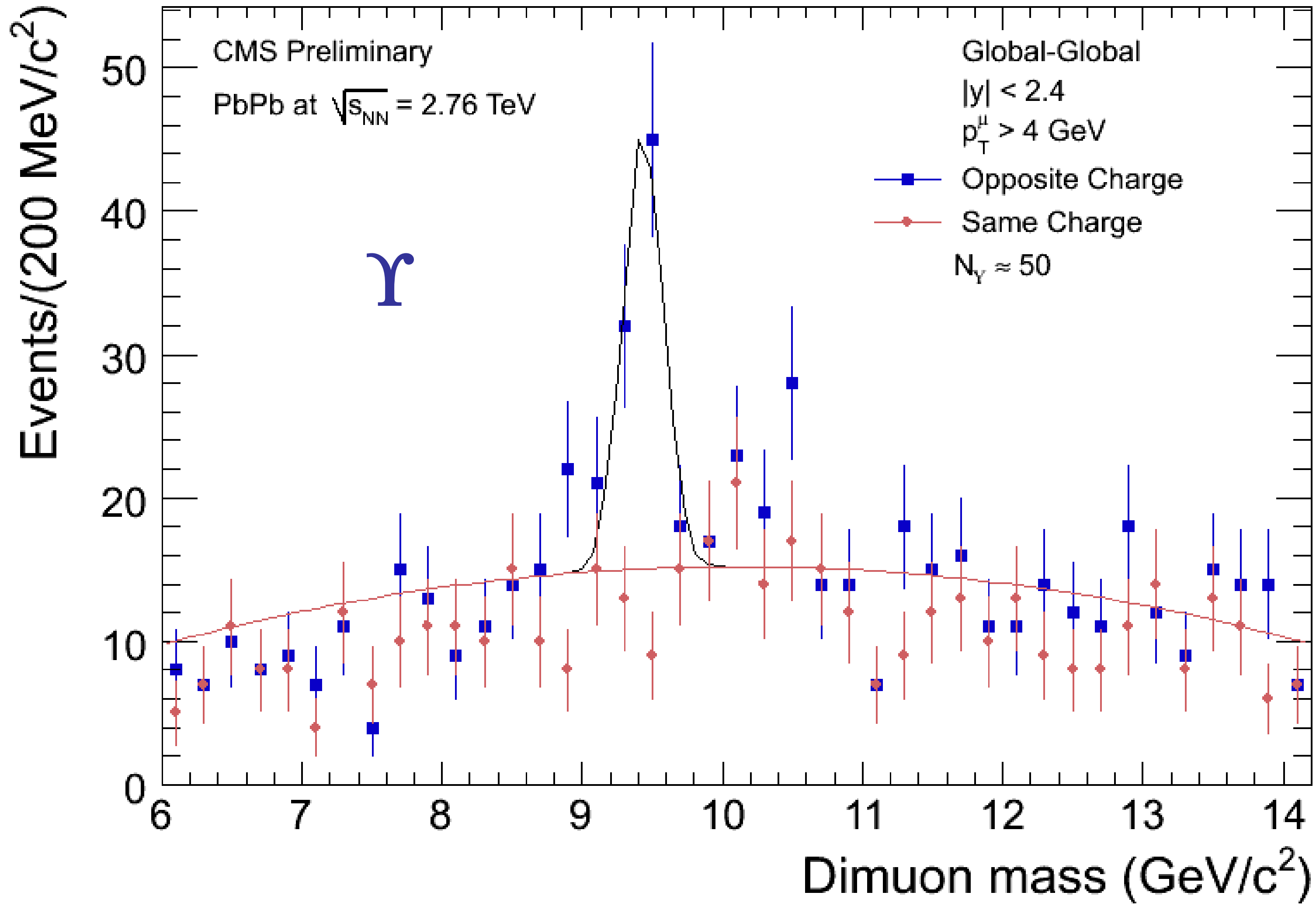
- J/ψ suppression has been seen at SPS and RHIC
  - Details are not completly understood , interplay of cold and hot effects
  - Regeneration of J/ψ from the (large) number of uncorrelated cc pairs would be a golden probe at LHC
- Only order 100 Upsilons seen at RHIC
  - Successive melting of the three bound states could act as a thermometer
- Weak bosons have not been observed at RHIC
  - Test of nuclear PDFs
  - Standard candle for other processes
  - Future Z-tagging (high luminosity)
- CMS will be able to study all of the above in detail

g.j.kunde@lanl.gov

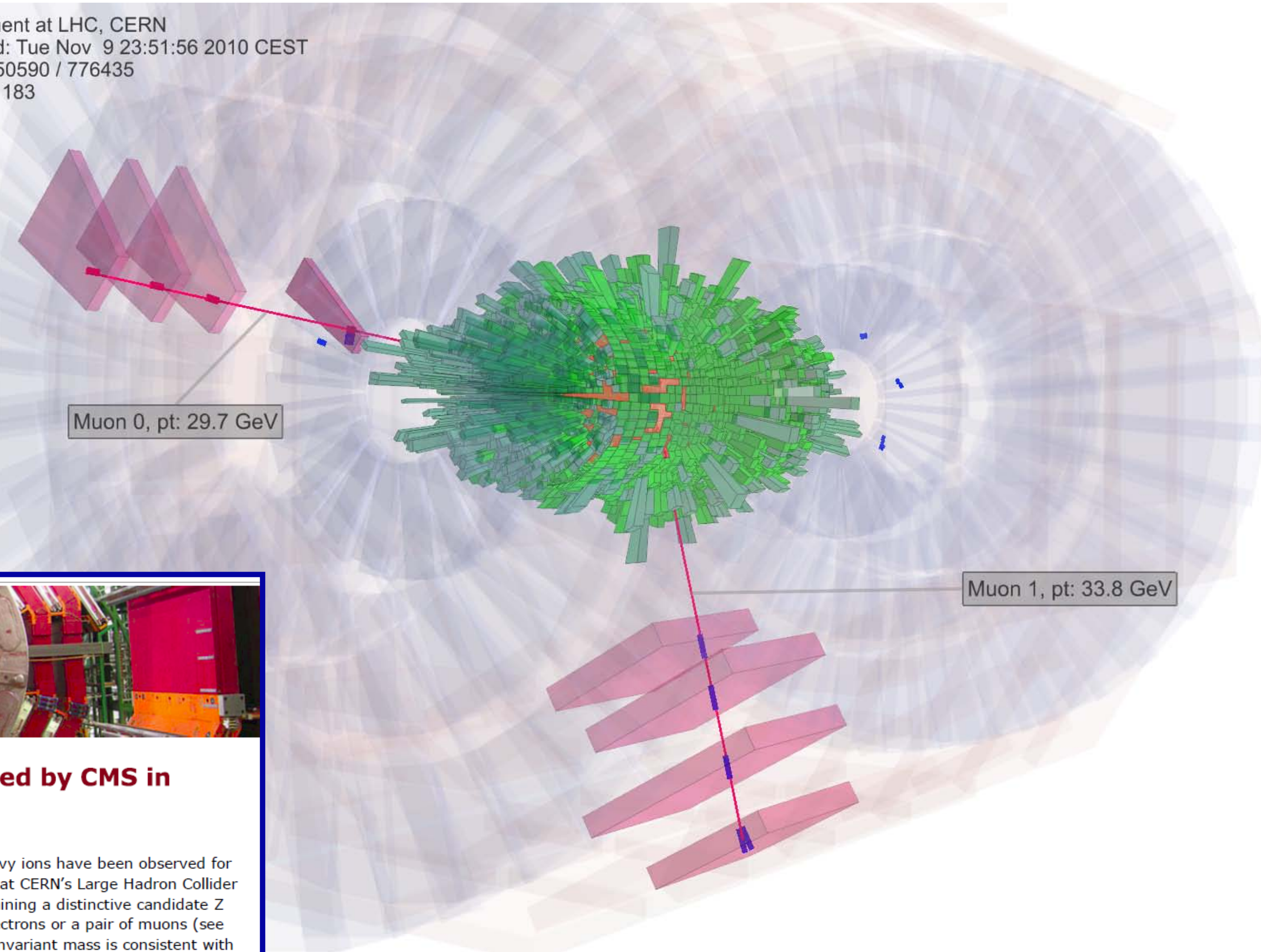
HI: High p_T J/ψ→$\mu^+\mu^-$

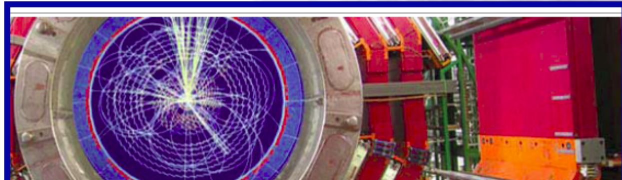


HI: High p_T $\Upsilon \rightarrow \mu^+\mu^-$



HI: First $Z^0 \rightarrow \mu^+\mu^-$ Candidate



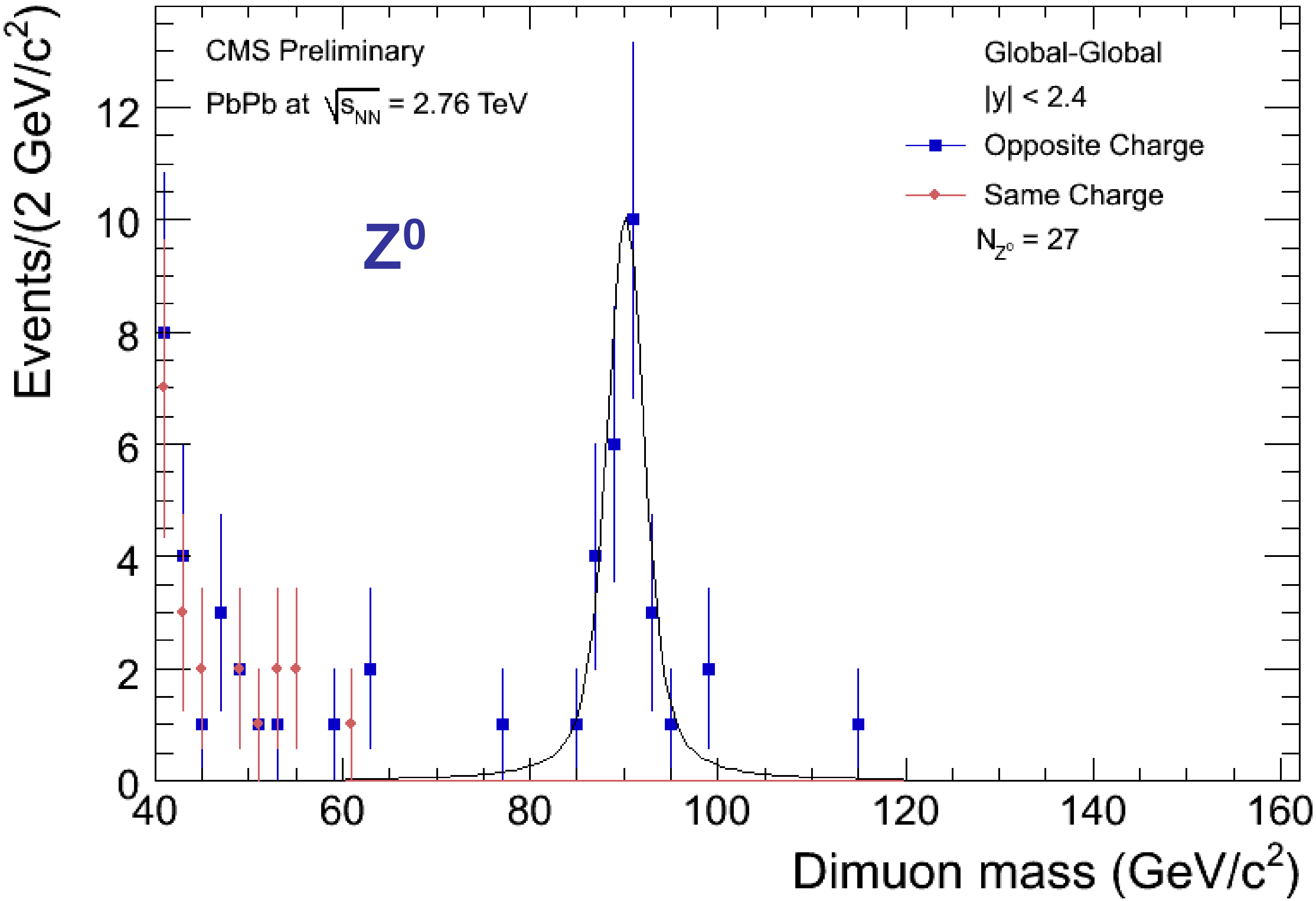


First Z bosons detected by CMS in heavy-ion collisions

November 18th 2010

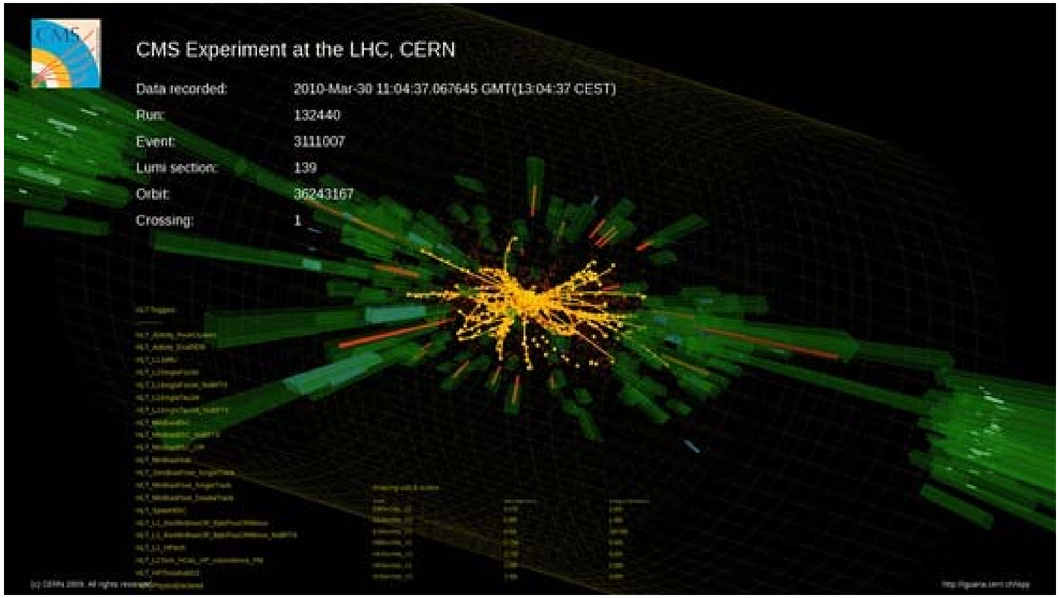
Z bosons produced in collisions of heavy ions have been observed for the first time by the CMS experiment at CERN's Large Hadron Collider (LHC). CMS observed 10 events containing a distinctive candidate Z boson reconstructed from a pair of electrons or a pair of muons (see figures 1 and 2 respectively), whose invariant mass is consistent with the Z boson mass.

HI: $Z^0 \rightarrow \mu^+\mu^-$

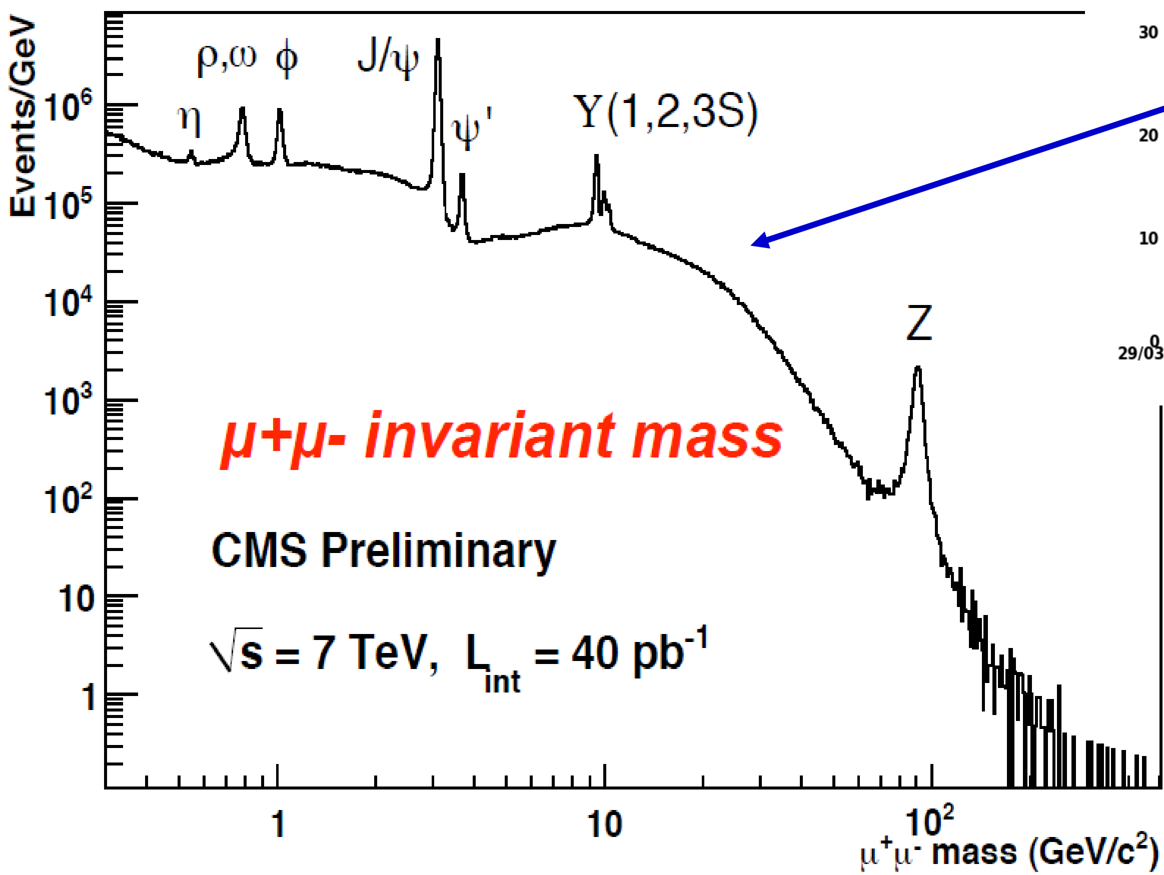


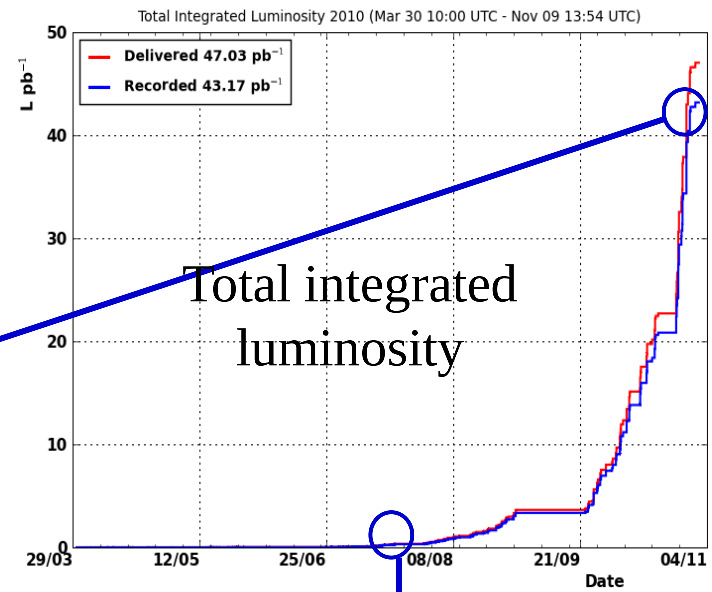
Proton-Proton Results

- LHC performance and mass spectrum
- J/ψ
  - Trigger selection
  - Efficiency, acceptance
  - Cross-sections
  - Non-prompt
- Upsilon
  - Data sample
  - Efficency, acceptance
  - Cross-sections



p-p Dimuon Mass Spectrum





Total integrated luminosity

Used for the analyses shown here:
Submitted to EPJC
arXiv:1011.4193
Analysis with full 2010 statistics in progress.

p-p Muon triggers

- Two trigger levels

L1: hardware
muon system and calorimeters only

↓

HLT: software
Matching of different sub-detectors.
Fast local track reconstruction for muons

Trigger requirements changing with increasing luminosity:

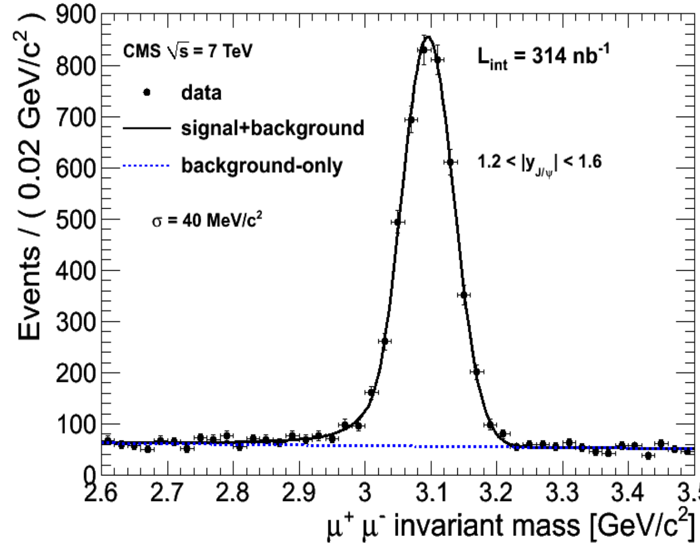
- Single muons:
  $p_T > 3$ GeV threshold at the startup
  Gradually increasing ($p_T > 7$ GeV at L ~ 10^{31} Hz cm^{-2})
- Double muons:
  L1 requirements only at the startup, no p_T threshold

allows to go down to zero quarkonium p_T in the forward region

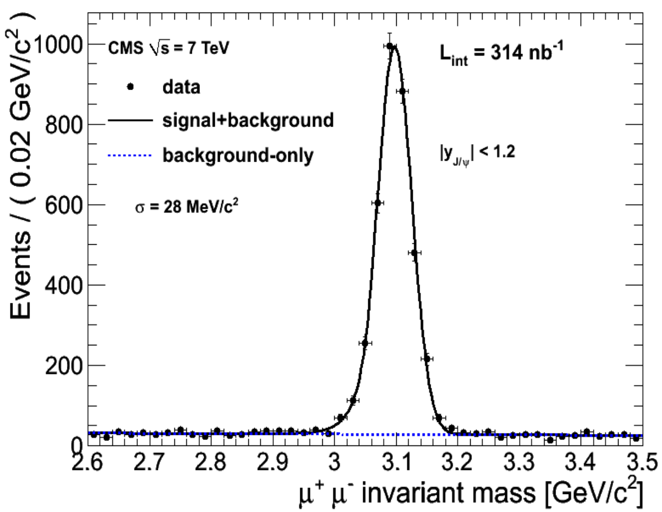
At L ~ 10^{31} Hz cm^{-2} new strategies adopted for quarkonia (combination of L1 and HLT muons, or HLT muon and track in specific invariant mass regions… etc.)

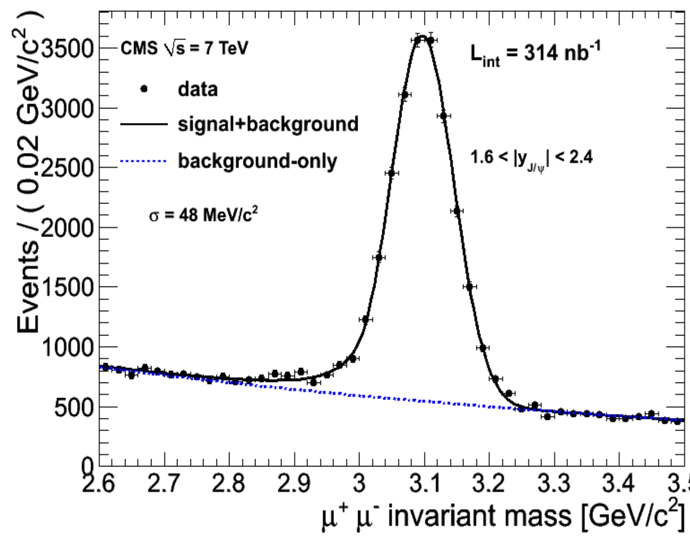
p-p J/ψ Selection and Yields

- Selections:
  - Muons in acceptance window
  - Track quality (n_{hits}, n_{hits} in pixels, χ^2, $|d_{xy}|$, $|d_z|$)
  - Muon quality (global fit χ^2, track-muon segment angular matching)
  - Di-muon vertex probability

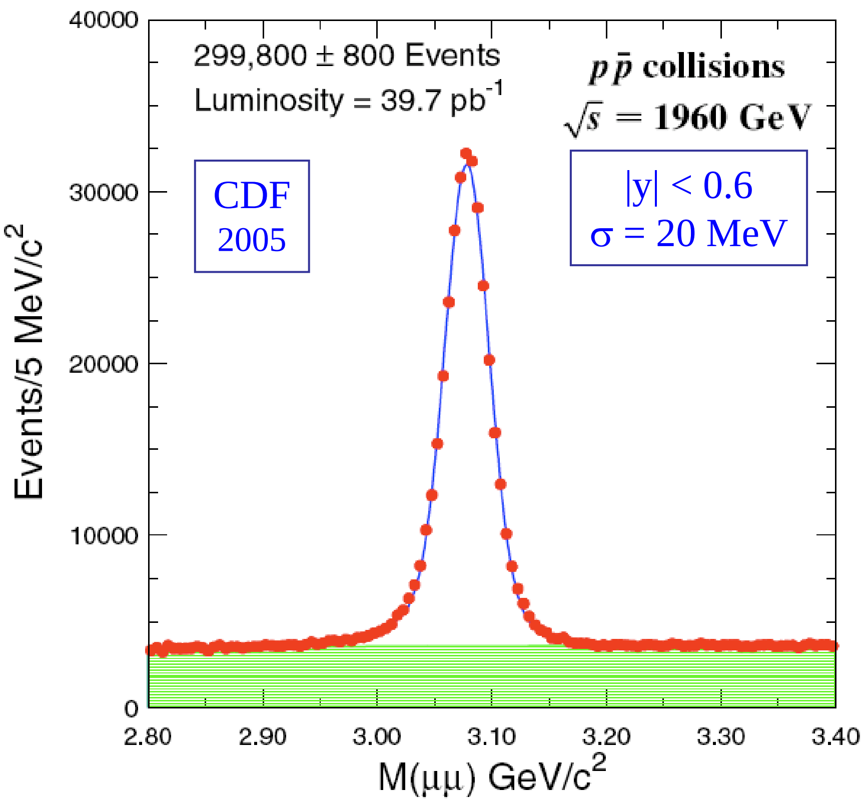


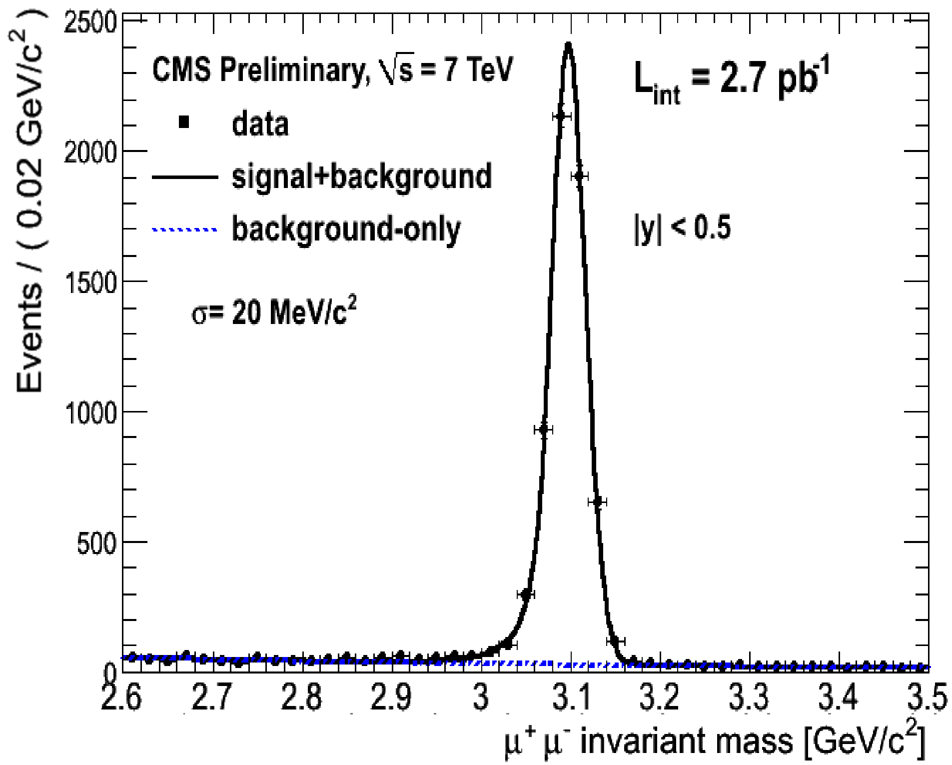
- ~27000 events selected





p-p J/ψ Resolution





- CMS already reached a similar quality after 6 *months* of data taking and "debugging"
- In a couple of weeks, with ~40 pb^{-1} on tape, CMS will be able to do the physics analyses with around **2.5 million** J/ψ dimuons, *after* offline quality selection cuts

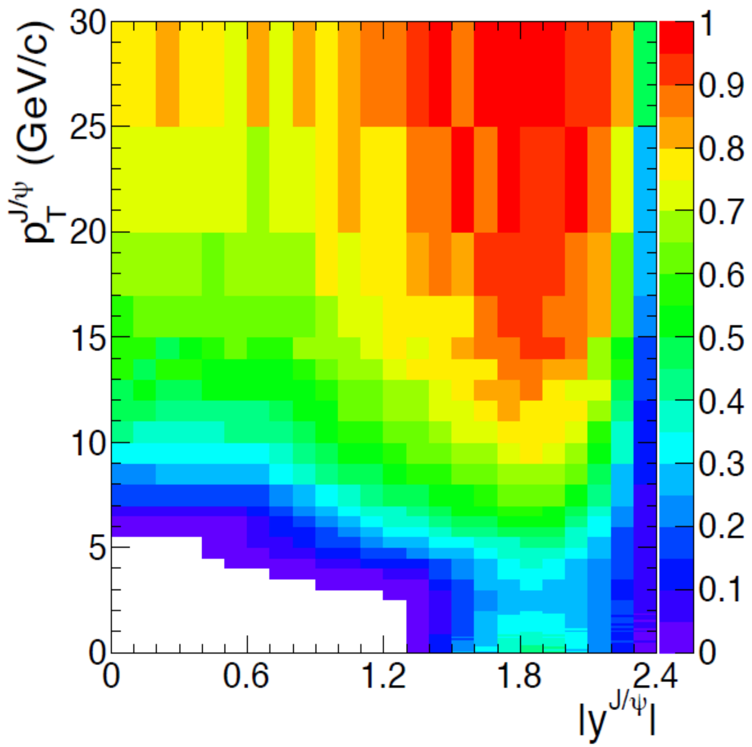
p-p J/ψ Acceptance

- Acceptance is determined from MC:

$$A(p_T, y, \lambda_\theta) = \frac{N_{det}(p_T, y, \lambda_\theta)}{N_{gen}(p_T, y, \lambda_\theta)}$$

  - Strongly dependent on polarization assumptions for the prompt component (polarization not well known)
  - Agreement to give result in 5 scenarios:
    - Isotropic
    - Extreme values of λ_θ (= ±1) in the helicity frame (along the QQ momentum)
    - Extreme values of λ_θ (= ±1) in the Collins-Soper frame (along the collision axis)

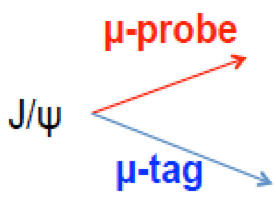
J/ψ acceptance in isotropic scenario

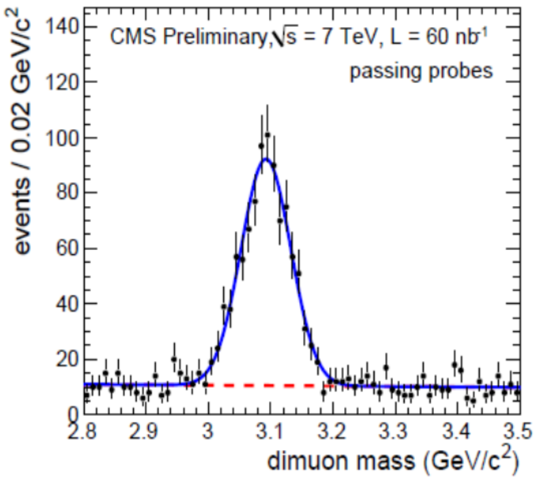


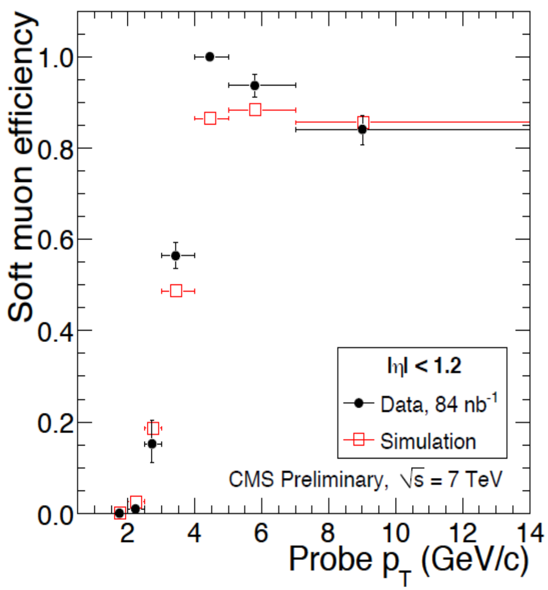
- Main systematic uncertainties coming from:
  - p_T smearing and calibration
  - uncertainty on final state radiation spectrum

p-p Muon Tag&Probe

- Muon efficiency from data: the "tag-and-probe" method:
  - Require one well-identified muon in the event ("tag")
  - Another candidate muon, with looser criteria, is paired to it ("probe")
  - Compare resonance yields for all tag-probe pairs and for pairs where the probes pass a given selection.





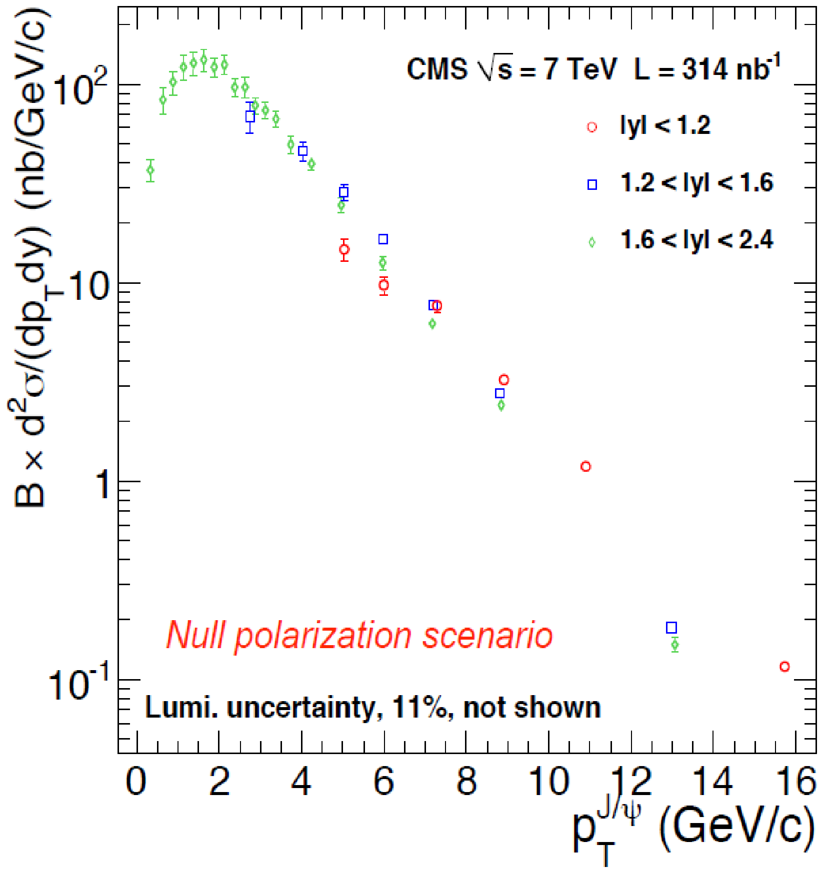


p-p Inclusive J/ψ Cross-section

$$\frac{d^2\sigma}{dp_T dy} \times B(J/\psi \to \mu\mu) = \frac{N_{fit}\left\langle \frac{1}{A \cdot \varepsilon} \right\rangle}{\int L dt \cdot \Delta p_T \cdot \Delta y}$$

$\langle A \cdot \varepsilon \rangle$ = average signal acceptance/efficiency in bin

Acceptance: from MC simulation
Efficiency: determined with tag and probe method from J/ψ events



Systematic uncertainties

Source	Relative error (%)		
	$\lvert y\rvert < 1.2$	$1.2 < \lvert y\rvert < 1.6$	$1.6 < \lvert y\rvert < 2.4$
FSR	0.8 – 2.5	0.3 – 1.6	0.0 – 0.9
p_T calibration and resolution	1.0 – 2.5	0.8 – 1.2	0.1 – 1.0
Kinematical distributions	0.3 – 0.8	0.6 – 2.6	0.9 – 3.1
b-hadron fraction and polarization	1.9 – 3.1	0.5 – 1.2	0.2 – 3.0
Muon efficiency	1.9 – 5.1	2.3 – 12.2	2.7 – 9.2
ρ factor	0.5 – 0.9	0.6 – 8.1	0.2 – 7.1
Fit function	0.6 – 1.1	0.4 – 5.3	0.3 – 8.8

$$\boxed{\sigma(pp \to J/\psi + X) \cdot BR(J/\psi \to \mu^+\mu^-) = 97.5 \pm 1.5(\text{stat}) \pm 3.4(\text{syst}) \pm 10.7(\text{luminosity})\ \text{nb}}$$

p-p Non-prompt J/ψ Fraction

Measurement of prompt/non-prompt component with a 2D fit to mass and "pseudo"-proper decay length

$$\ell_{xy} = \frac{L_{xy}^{J/\psi} \cdot M^{J/\psi}}{P_T^{J/\psi}} \qquad L_{xy} = \frac{\mathbf{u}^T \sigma^{-1} \mathbf{x}}{\mathbf{u}^T \sigma^{-1} \mathbf{u}^T}$$

μ^+

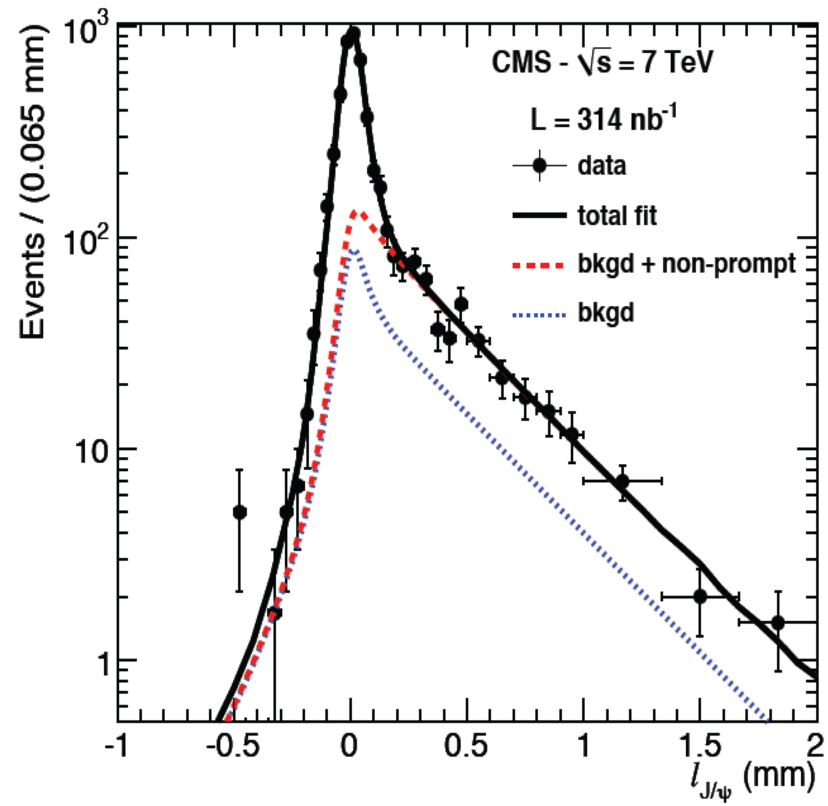
J/ψ

$L_{xy}^{J/\psi}$ is the transverse component of most probable decay length in lab system

Decay length parameterization:

- For prompt events, δ-function
- For non-prompt events, MC templates
- For background events a generic superposition of different contributions (symmetric + asymmetric with effective lifetimes)

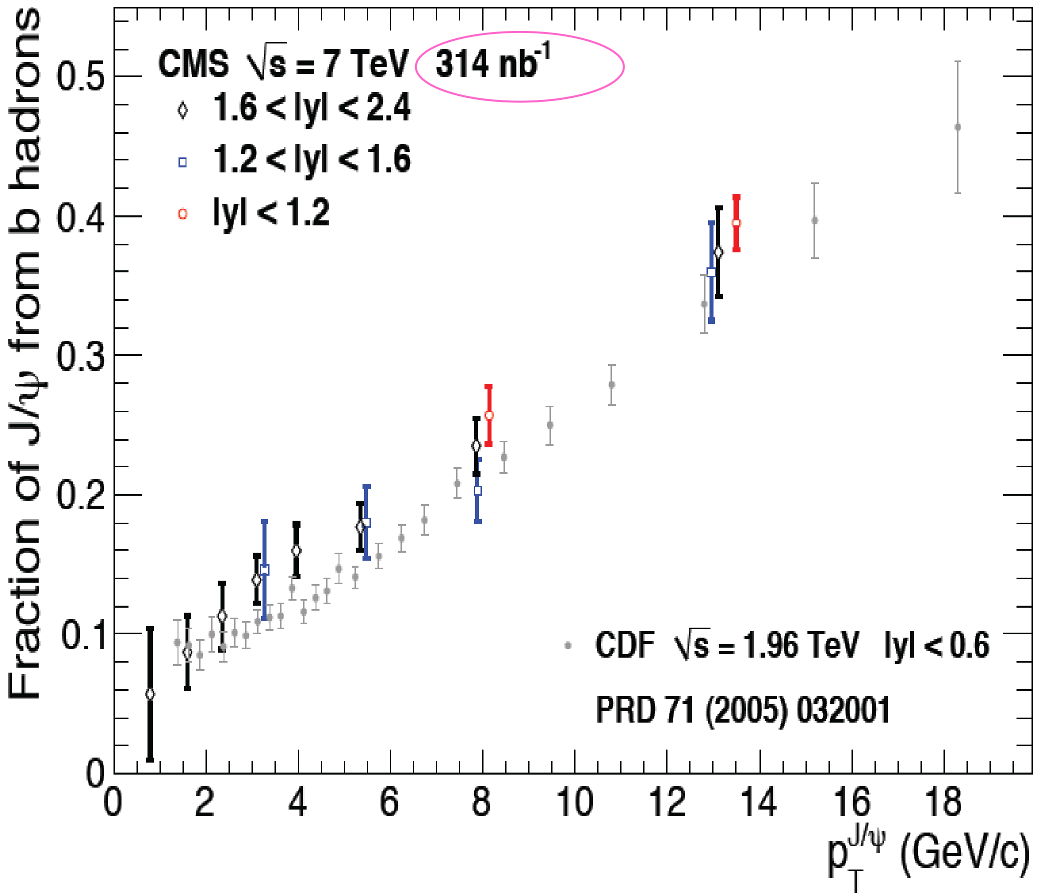
all convoluted with 3-Gaussian resolution



6.5<p$_T$<10 GeV/c, 1.6<|y|<2.4

Cross check with fit with the mean B-hadron lifetime left as a free parameter and found it to be $t_B = 1.32 \pm 0.07$ *ps*, where the error is statistical only, consistent with the world average

p-p Non-prompt J/ψ Fraction cont.

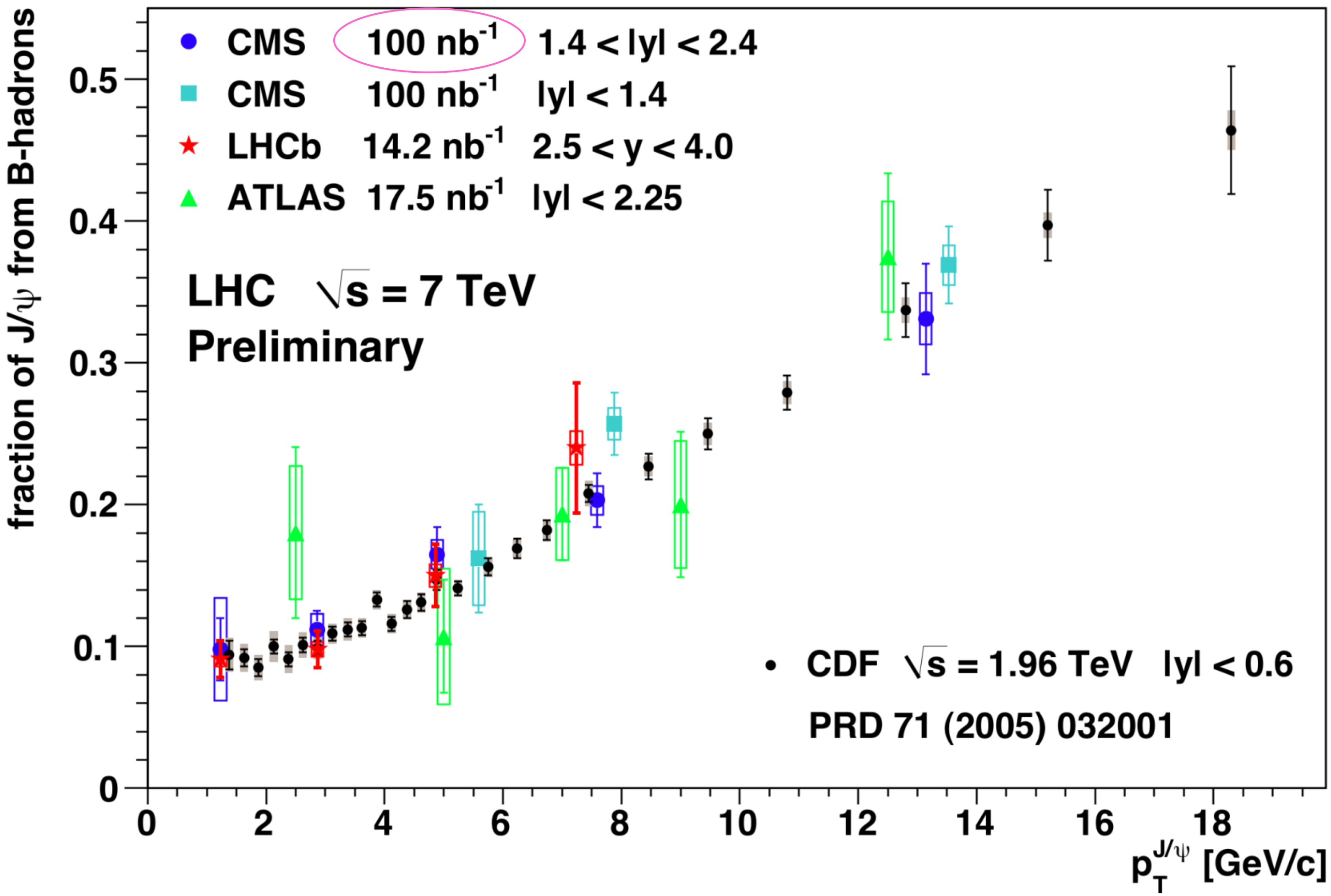


Systematics of the non-prompt fraction:

	$\|y\| < 1.2$	$1.2 < \|y\| < 1.6$	$1.6 < \|y\| < 2.4$
Tracker misalignment	0.5 – 0.7	0.9 – 4.6	0.7 – 9.1
b-lifetime model	0.0 – 0.1	0.5 – 4.8	0.5 – 11.2
Vertex estimation	0.3	1.0 – 12.3	0.9 – 65.8
Background fit	0.1 – 4.7	0.5 – 9.5	0.2 – 14.8
Resolution model	0.8 – 2.8	1.3 – 13.0	0.4 – 30.2
Efficiency	0.1 – 1.1	0.3 – 1.3	0.2 – 2.4

Very little sensitivity to rapidity and energy (>2 TeV)

p-p Non-prompt J/ψ Fraction cont.



No sensitivity to rapidity nor energy (>2 TeV)

g.j.kunde@lanl.gov

p-p J/ψ Theory Comparison

- Only with models that include feed-down decays

  - PYTHIA

    "PYTHIA 6.4 Physics and Manual", *JHEP* (2006) 05 026.

  - FONLL Cascade

    H. Jung *Comp.Phys.Commun.* 143 (2002) 100.

  - Color Evaporation Model

F. Halzen, "Cvc for Gluons and Hadroproduction of Quark Flavors", *Phys. Lett.* B69 (1977) 105. doi:10.1016/0370-2693(77)90144-7.

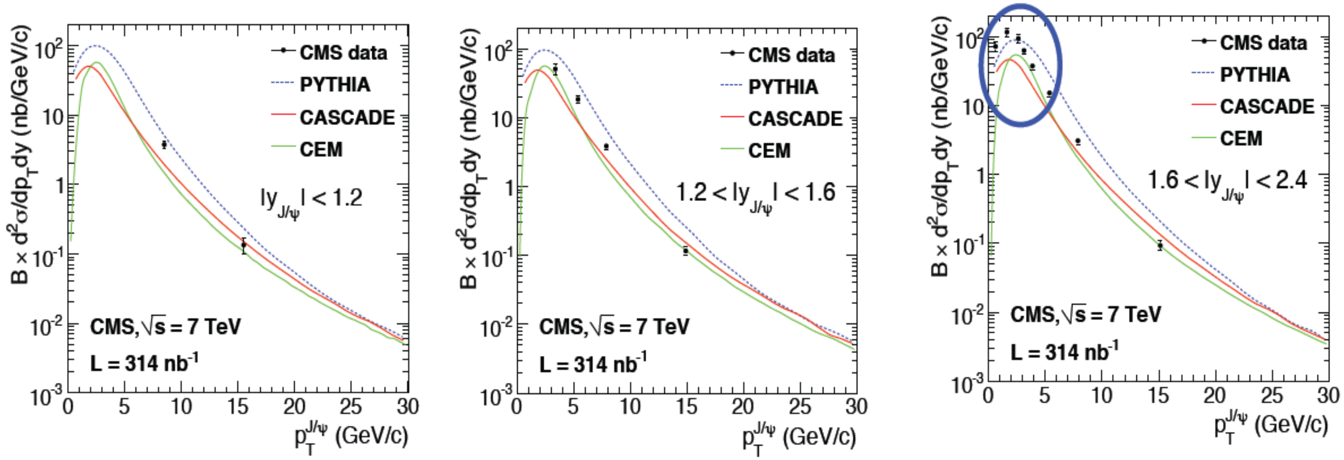
H. Fritzsch, "Producing Heavy Quark Flavors in Hadronic Collisions: A Test of Quantum Chromodynamics", *Phys. Lett.* B67 (1977) 217. doi:10.1016/0370-2693(77)90108-3.

M. Gluck, J. F. Owens, and E. Reya, "Gluon Contribution to Hadronic J/psi Production", *Phys. Rev.* D17 (1978) 2324. doi:10.1103/PhysRevD.17.2324.

V. D. Barger, W.-Y. Keung, and R. J. N. Phillips, "On psi and Upsilon Production via Gluons", *Phys. Lett.* B91 (1980) 253. doi:10.1016/0370-2693(80)90444-X.

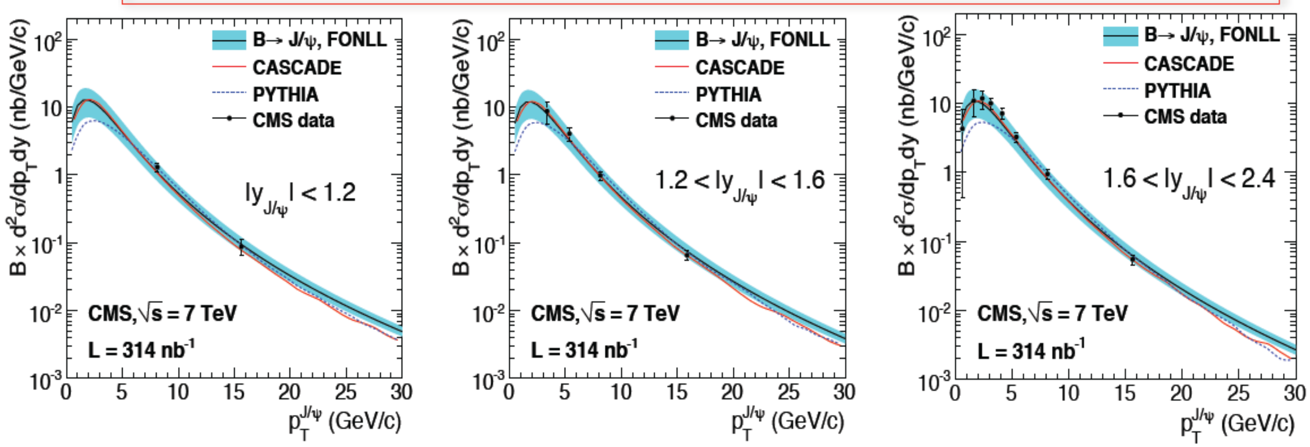
p-p J/ψ Theory Comparison cont.

prompt



$$\sigma(pp \to J/\psi + X) \cdot BR(J/\psi \to \mu^+\mu^-) = 70.9 \pm 2.1(\mathrm{stat}) \pm 3.0(\mathrm{syst}) \pm 7.8(\mathrm{luminosity})\ \mathrm{nb}$$

non-prompt



$$\sigma(pp \to bX \to J/\psi X) \cdot BR(J/\psi \to \mu^+\mu^-) = 26.0 \pm 1.4\ (\mathrm{stat}) \pm 1.6\ (\mathrm{syst}) \pm 2.9\ (\mathrm{luminosity})\ \mathrm{nb}$$

Comparison only with models that include feed down from higher states

p-p Upsilon Data Sample

Apr-Sep run: $\mathcal{L}=10^{31}\,cm^{-2}s^{-1},\ \int \mathcal{L}\,dt = 3.1 \pm 0.3\ pb^{-1}$

Trigger : 2 muons at Hardware level, no p_T cut

Offline muon identification:

- track extrapolation matches hits in at least one μ-chamber
- track momentum : $p_T^{\mu} > 3.5$ GeV if $|\eta| < 1.6$, $p_T^{\mu} > 2.5$ GeV if $1.6 < |\eta| < 2.4$
- track quality : $n_{\mathrm{hits}} \geq 12, n_{\mathrm{pixel}} \geq 1, \chi^2 < 5 \cdot \mathrm{Ndf}, d_{xy} < 0.2\,cm, d_Z < 25\,cm$

U selection

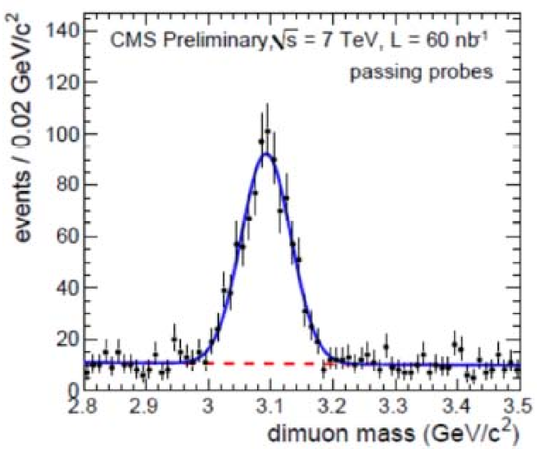
- two opposite-charge muons with $8 \leq M_{\mu\mu} < 12\,\mathrm{GeV}$
- probability of common vertex > 0.1%
- distance along Z < 2 cm
- rapidity $|y_{\mu\mu}| < 2$

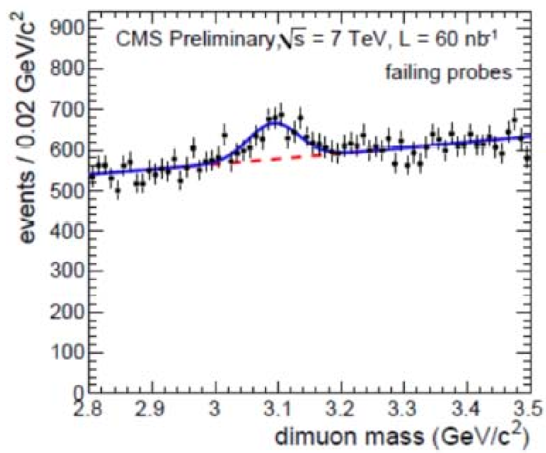
p-p Upsilon Efficiency Correction

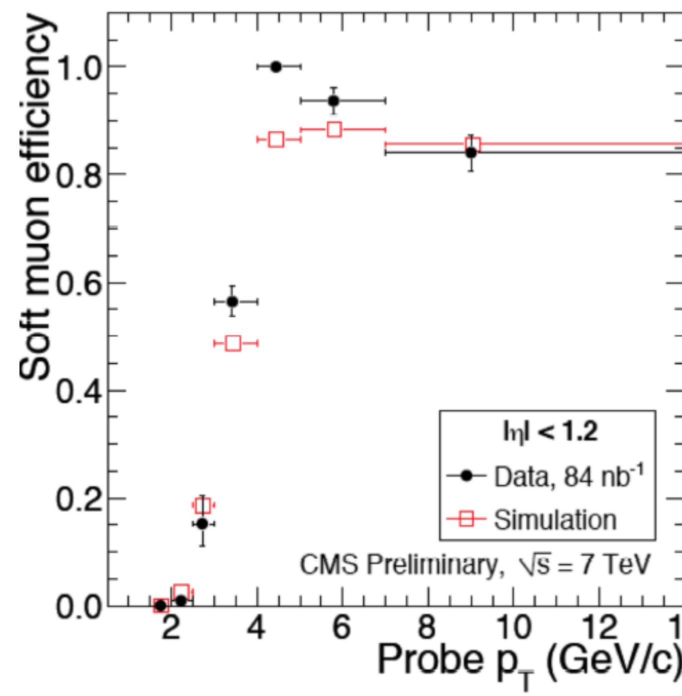
- Trigger Efficiency * Tracking Efficiency * Muon Identification

$$\varepsilon(\text{total}) = \varepsilon(\text{trig}|\text{id}) \times \varepsilon(\text{id}|\text{track}) \times \varepsilon(\text{track}|\text{accepted}) \equiv \varepsilon_{\text{trig}} \times \varepsilon_{\text{id}} \times \varepsilon_{\text{track}}$$

- Tag&Probe and embedding for J/psi sample (statistics)

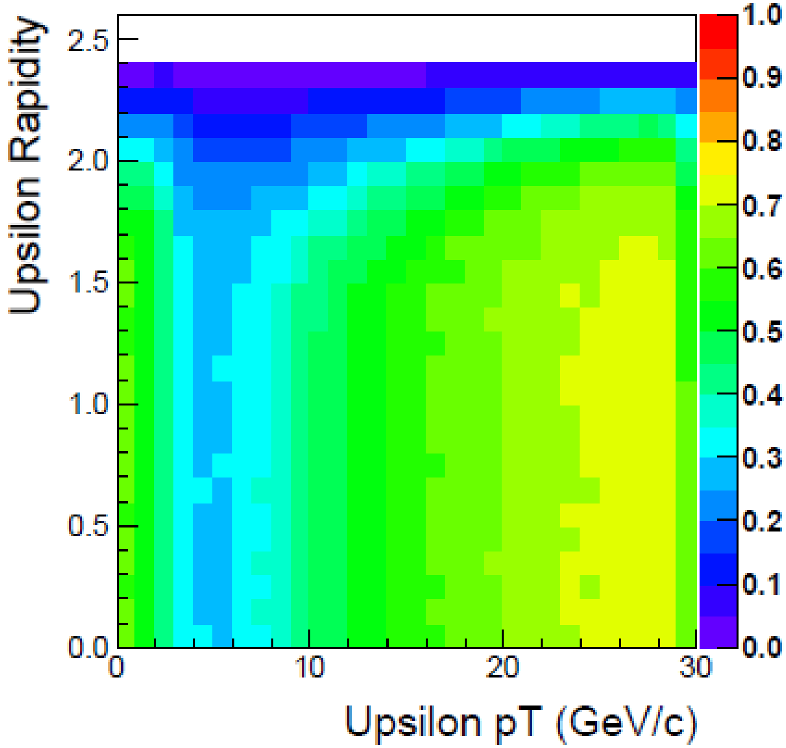


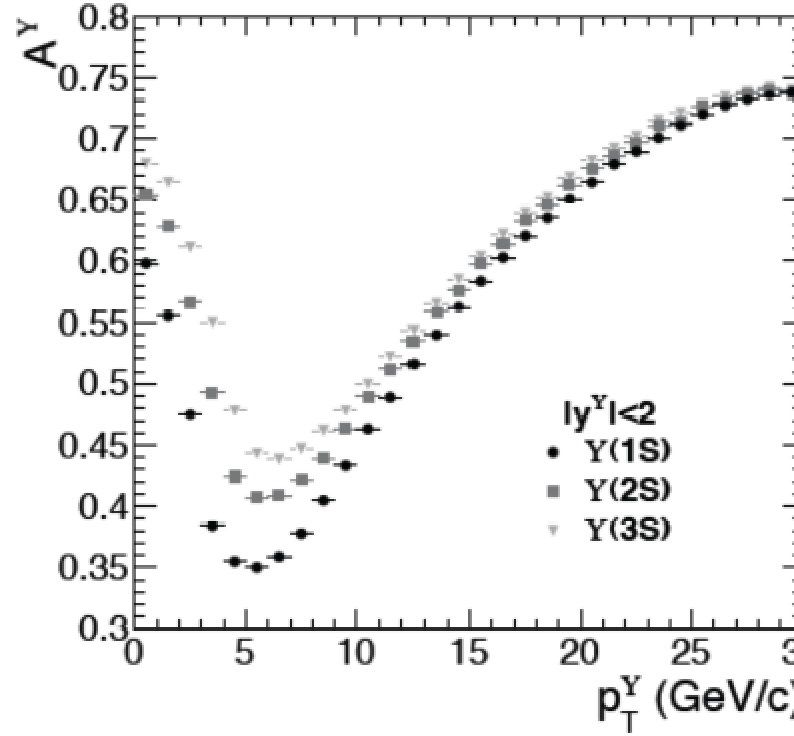




p-p Upsilon Acceptance Correction

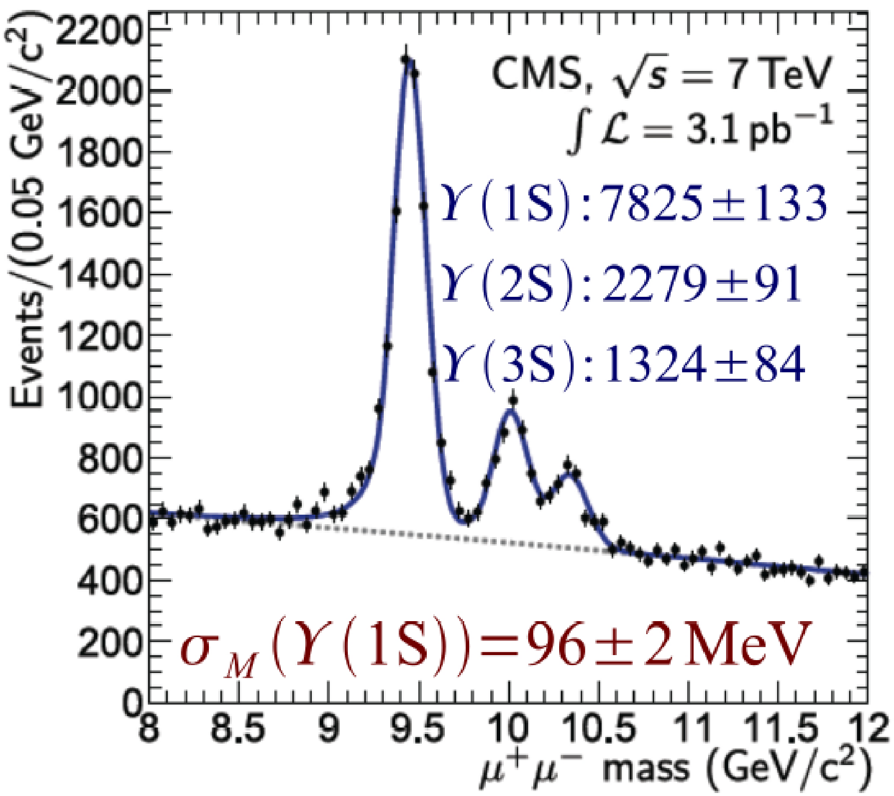
- Via Geant4 simulation of the CMS detector using \the upsilon “particle gun”

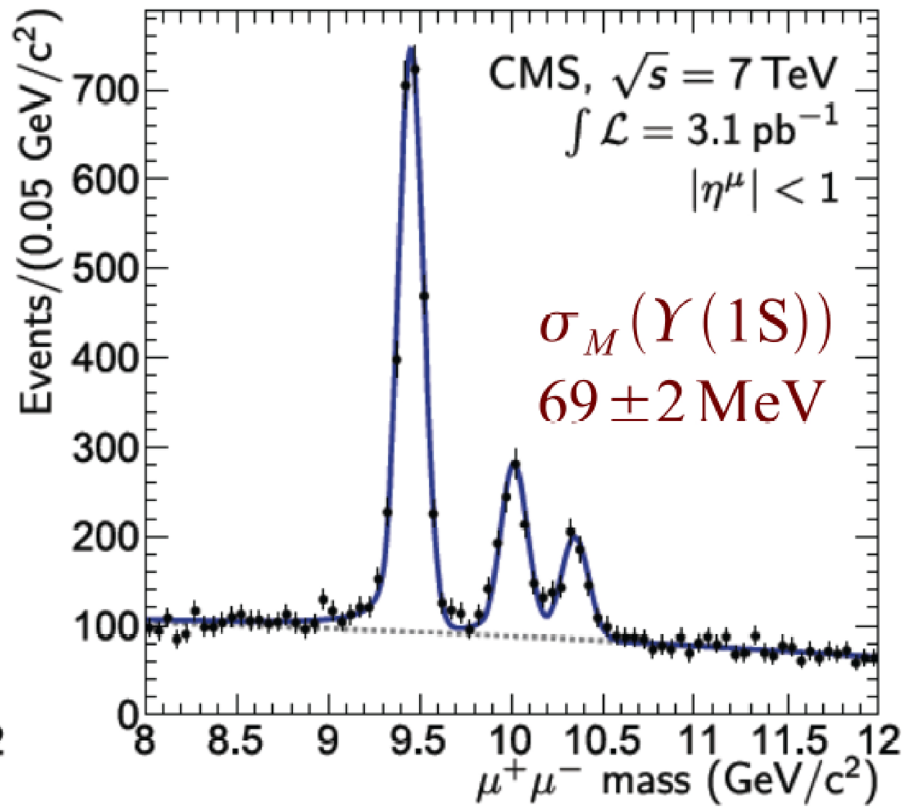




- Very good acceptance even at low pt

p-p Upsilon Event Yield





- Fit epsilon/A corrected spectra in pt/eta bins
- Float yields, background shape parameters width and position of 1S peak
- Fix relative (1S) (2S,3S) mass difference to PDG

p-p Upsilon Cross-section Results

$$\left.\frac{d\sigma\,(pp \to \Upsilon(\mathrm{nS}))}{dp_{\mathrm{T}}}\right|_{|y|<2} \mathcal{B}\,(\Upsilon(\mathrm{nS}) \to \mu^+\mu^-) = \frac{N^{\mathrm{fit}}_{\Upsilon(\mathrm{nS})}(p_{\mathrm{T}}; \mathcal{A}, \varepsilon_{\mathrm{track}}, \varepsilon_{\mathrm{id}}, \varepsilon_{\mathrm{trig}})}{\mathcal{L}\cdot \Delta p_{\mathrm{T}}}$$

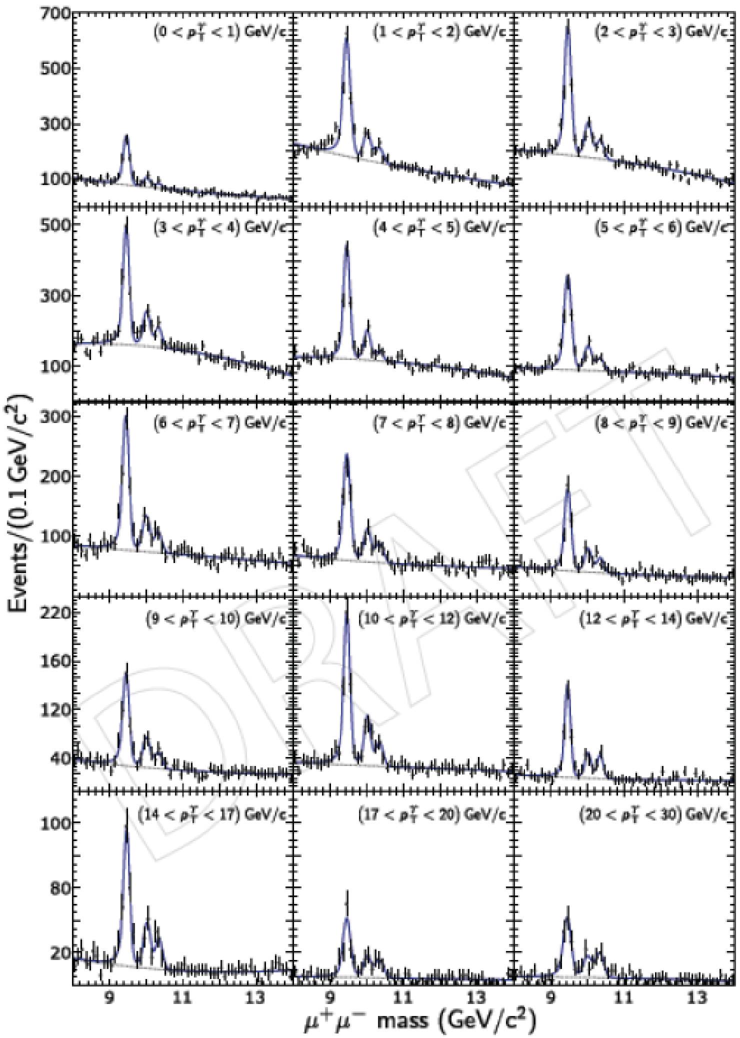
$$\sigma(pp \to \Upsilon(1S)X)\cdot \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-) = (7.49 \pm 0.13(\mathrm{stat.})^{+0.67}_{-0.49}(\mathrm{syst.}) \pm 0.82(\mathrm{lumi.}))\ \mathrm{nb}\,,$$

$$\sigma(pp \to \Upsilon(2S)X)\cdot \mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-) = (1.93 \pm 0.08(\mathrm{stat.})^{+0.19}_{-0.14}(\mathrm{syst.}) \pm 0.21(\mathrm{lumi.}))\ \mathrm{nb}\,,$$

$$\sigma(pp \to \Upsilon(3S)X)\cdot \mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-) = (1.04 \pm 0.07(\mathrm{stat.})^{+0.12}_{-0.09}(\mathrm{syst.}) \pm 0.11(\mathrm{lumi.}))\ \mathrm{nb}\,.$$

- Included Uncertainties
  - Detector effects
  - Statistics of the tag&probe sample
  - Luminosity (dominating)
- NOT Included
  - Polarization effects: +-20 % effect

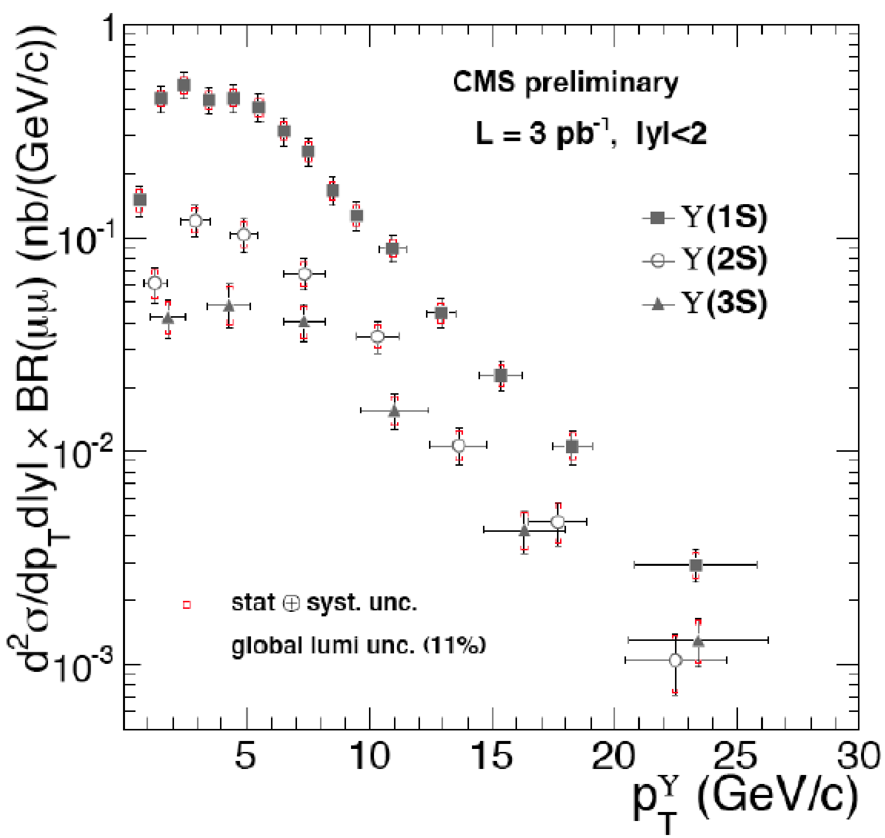
p-p Upsilon p_t-dependent Cross-section

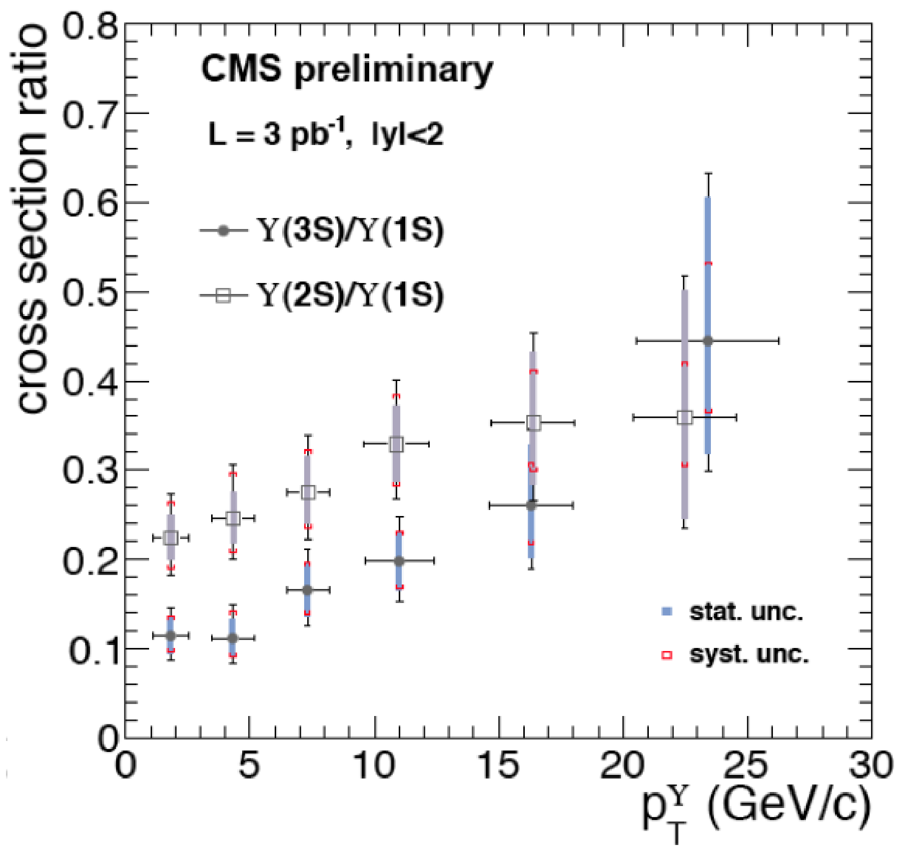


Polarization Models

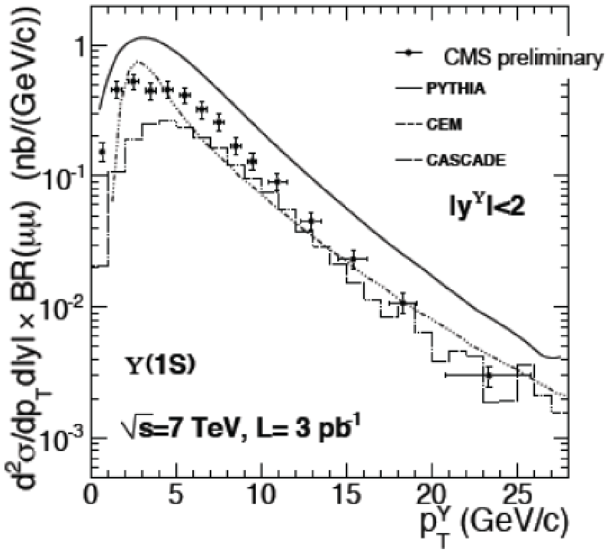
p_T (GeV/c)	σ	stat./σ	$\sum_{syst.}/\sigma$	$\Delta\sigma/\sigma$	HX T	HX L	CS T	CS L
	Υ(1S)					($\lvert y\rvert < 2$)		
0 – 30	7.49	1.8	9 (7)	14 (13)	+16	-22	+13	-16
0 – 1	0.31	8	10 (8)	17 (16)	+16	-22	+17	-23
1 – 2	0.91	5	9 (7)	15 (14)	+16	-20	+19	-24
2 – 3	1.05	5	9 (7)	15 (14)	+15	-20	+19	-24
3 – 4	0.90	6	10 (8)	16 (15)	+18	-23	+18	-23
4 – 5	0.91	6	9 (7)	15 (14)	+18	-23	+16	-21
5 – 6	0.83	6	9 (6)	15 (14)	+17	-23	+13	-19
6 – 7	0.65	7	9 (6)	16 (14)	+17	-22	+11	-16
7 – 8	0.52	7	9 (7)	16 (15)	+16	-22	+7	-10
8 – 9	0.34	8	9 (6)	16 (15)	+16	-22	+4	-5
9 – 10	0.26	8	9 (6)	17 (15)	+15	-21	+2	-1
10 – 12	0.36	6	9 (6)	15 (14)	+15	-21	-1	+3
12 – 14	0.18	8	9 (6)	16 (15)	+15	-20	-3	+7
14 – 17	0.14	9	10 (6)	17 (15)	+14	-19	-4	+9
17 – 20	0.06	12	10 (7)	19 (18)	+12	-18	-4	+9
20 – 30	0.06	12	10 (6)	19 (17)	+12	-17	-4	+10
	Υ(2S)							
0 – 30	1.93	4.2	10 (7)	15 (14)	+14	-19	+12	-15
0 – 2	0.25	12	12 (10)	20 (19)	+14	-19	+17	-22
2 – 4	0.49	8	13 (12)	19 (18)	+12	-17	+18	-23
4 – 6	0.42	10	11 (9)	18 (17)	+16	-22	+15	-20
6 – 9	0.41	9	10 (7)	18 (16)	+15	-21	+9	-13
9 – 12	0.21	10	10 (6)	18 (16)	+14	-20	+1	-0
12 – 16	0.09	13	10 (7)	20 (19)	+14	-19	-2	+6
16 – 20	0.04	18	11 (8)	24 (23)	+12	-18	-4	+9
20 – 30	0.02	23	20 (18)	33 (32)	+12	-17	-4	+11
	Υ(3S)							
0 – 30	1.04	6.7	12 (9)	17 (16)	+14	-19	+10	-13
0 – 3	0.26	14	11 (9)	21 (20)	+13	-18	+16	-22
3 – 6	0.29	14	19 (18)	26 (25)	+13	-18	+16	-21
6 – 9	0.25	14	11 (9)	21 (20)	+15	-20	+10	-13
9 – 14	0.16	12	10 (8)	19 (18)	+14	-20	-1	+2
14 – 20	0.05	17	11 (9)	23 (22)	+13	-18	-4	+9
20 – 30	0.03	20	13 (10)	26 (25)	+11	-16	-4	+9

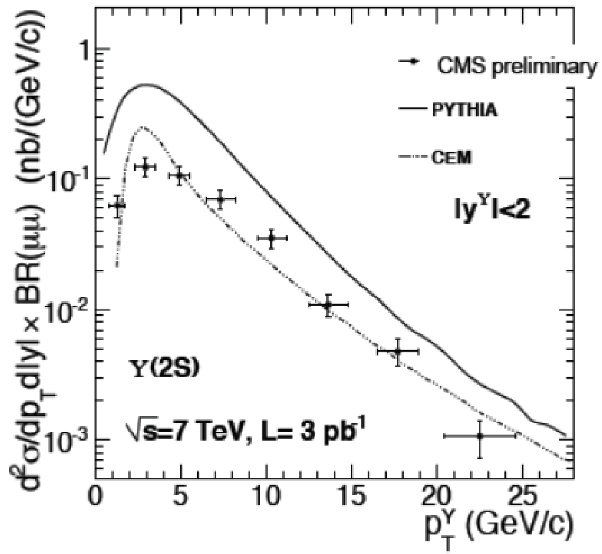
p-p Upsilon Cross-section cont.

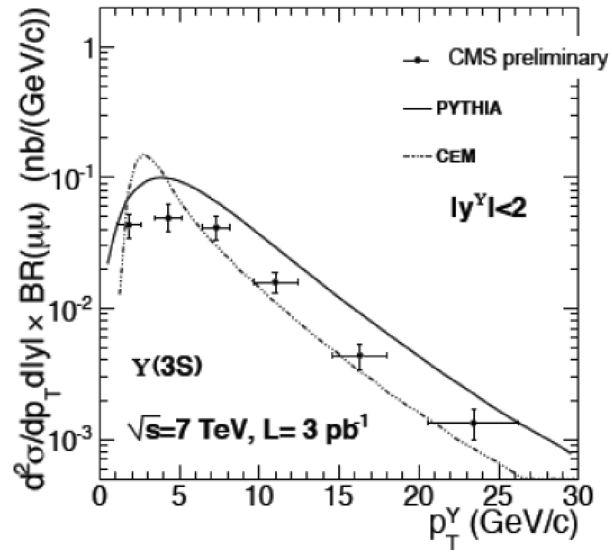




p-p Upsilon Theory Comparisons







- PYTHIA – FONLL Cascade - Color Evaporation Model

H. Jung *Comp.Phys.Commun.* **143** (2002) 100.

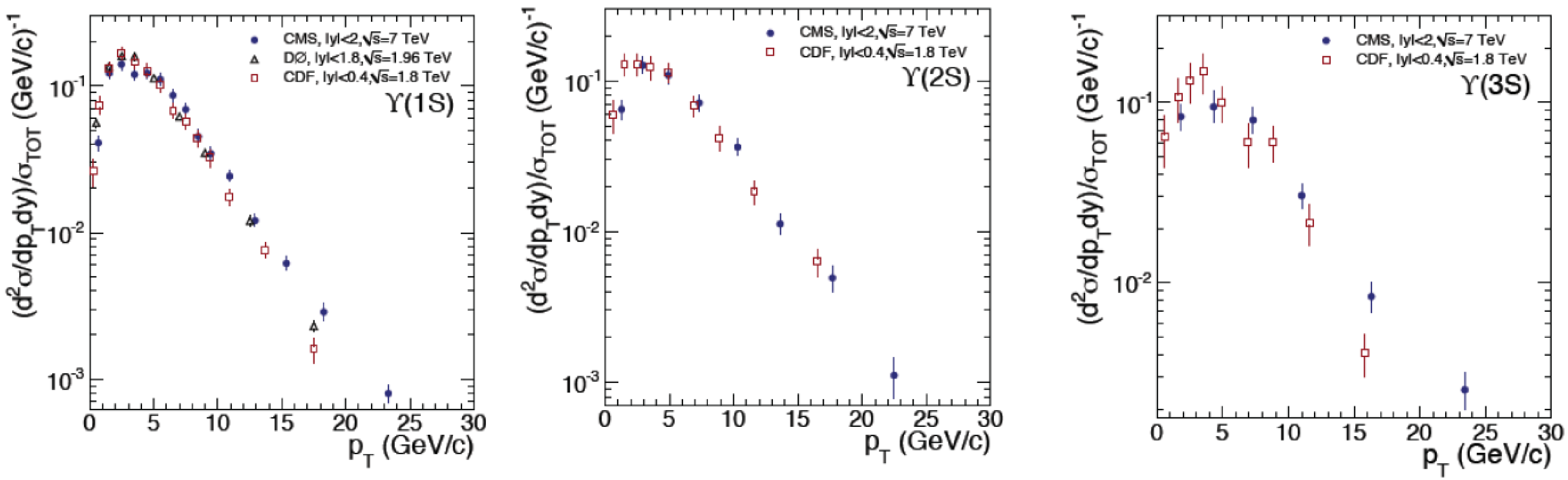
F. Halzen, "CVC for Gluons and Hadroproduction of Quark Flavors", *Phys. Lett.* **B69** (1977) 105. doi:10.1016/0370-2693(77)90144-7.

H. Fritzsch, "Producing Heavy Quark Flavors in Hadronic Collisions: A Test of Quantum Chromodynamics", *Phys. Lett.* **B67** (1977) 217. doi:10.1016/0370-2693(77)90108-3.

M. Gluck, J. F. Owens, and E. Reya, "Gluon Contribution to Hadronic J/psi Production", *Phys. Rev.* **D17** (1978) 2324. doi:10.1103/PhysRevD.17.2324.

V. D. Barger, W.-Y. Keung, and R. J. N. Phillips, "On psi and Upsilon Production via Gluons", *Phys. Lett.* **B91** (1980) 253. doi:10.1016/0370-2693(80)90444-X.

p-p Upsilon Tevatron Comparisons



Little sensitivity of p_t spectra to center of mass energy

Future

- For 7 TeV p-p collisions CMS collected a quarkonium event sample of around 2.5 M J/ψ and 100 000 Υ(1S) (only counting dimuons)
  - J/ψ and Upsilon polarization, in several p_T and y intervals, over a broad phase space
  - χ_c over J/ψ cross section ratio, using calorimeter-seeded photons
  - χ_{c1} over χ_{c2} cross section ratio, using tracker-seeded photon conversions
- For 2.76 TeV Pb-Pb collisions analyses of J/ψ and Upsilon are in progress and the first Z^0 paper is being written … plus there is a great future at higher luminosities