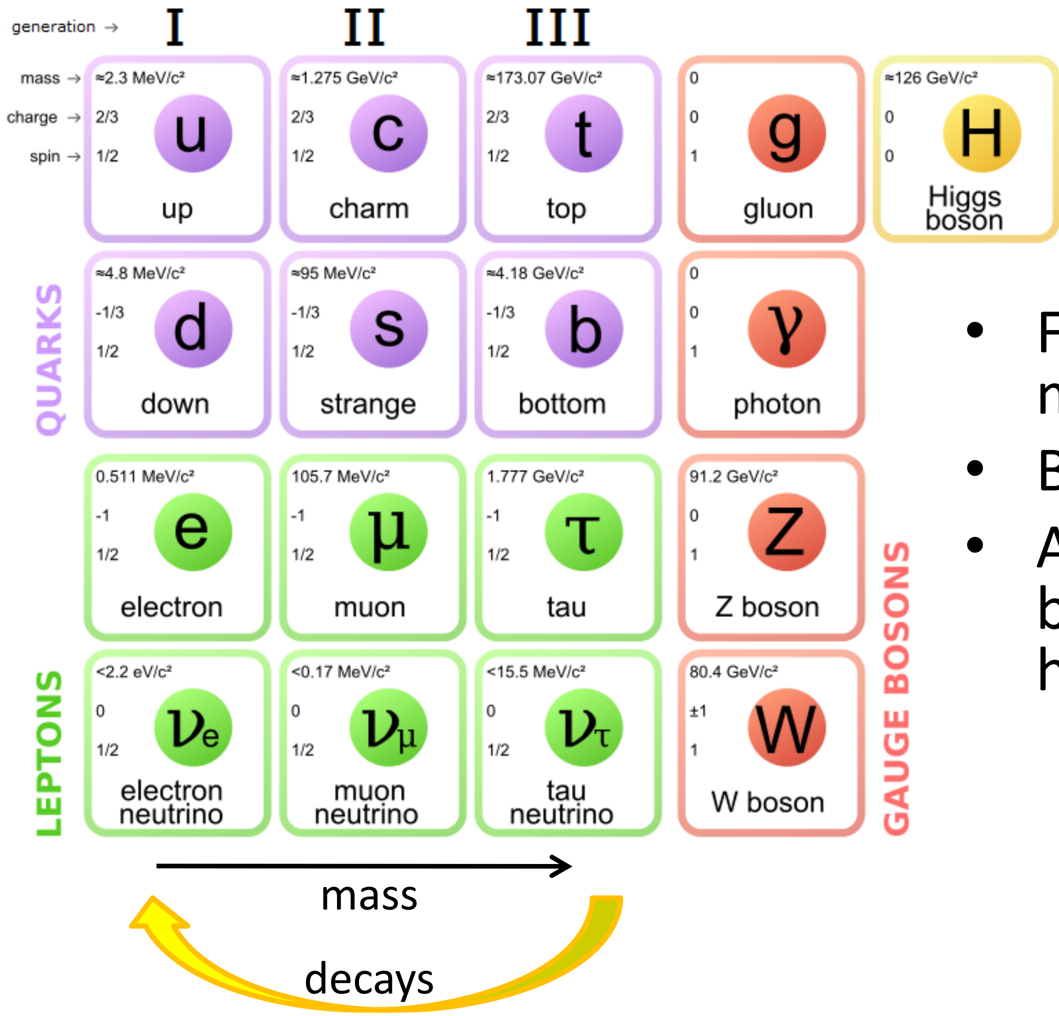
Search for new particles at LHC

Charmonium Renaissance

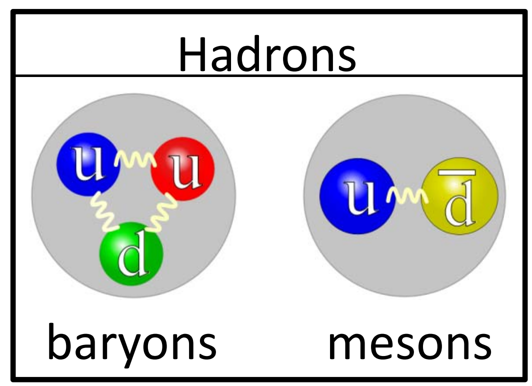
Stefan Spanier
University of Tennessee

• Standard Model

Generation



- Fermions: basic constituents of matter
- Bosons: force mediators
- Anti-particles: opposite charge, baryon/lepton number, and helicity, same mass

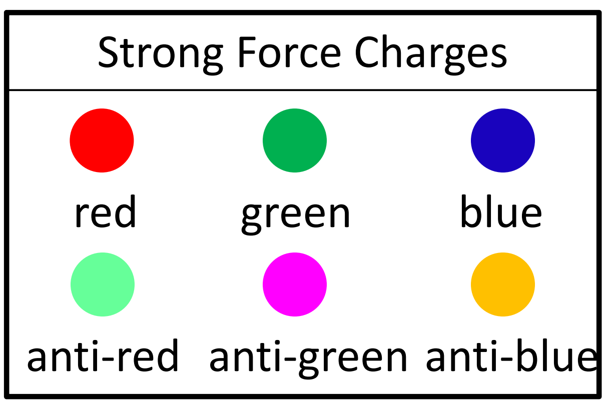


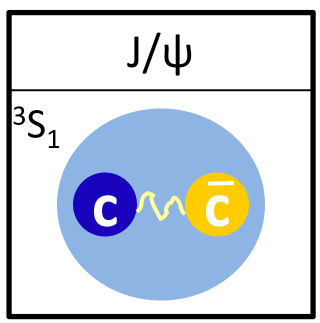
..maybe more, but not clear

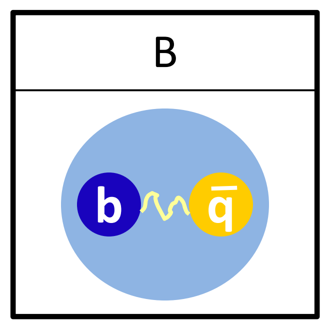
- Standard Model Interactions

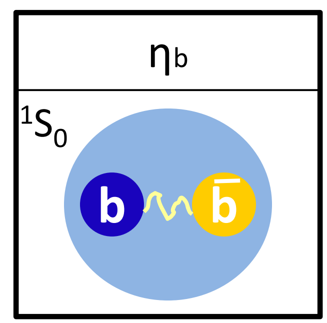
Interaction	Mediator	Range	In Nature	
Strong	gluon	10^{-15}m	Binds quarks into hadrons	QCD
Electromagnetic	photon	$\infty\ \frac{1}{r^2}$	Binds together atoms and molecules	Glashow
Weak	W, Z boson	$< 10^{-18}$m	Enables beta decay of neutron	

- SM is a Quantum Field Theory: describes all interactions as exchange of particles, and all particles as excited states of quantum field
  - Gauge Invariant: force laws applicable at all places and times (global) + local !
  - Renormalizable: predicted interaction rates scale based on energy/distance



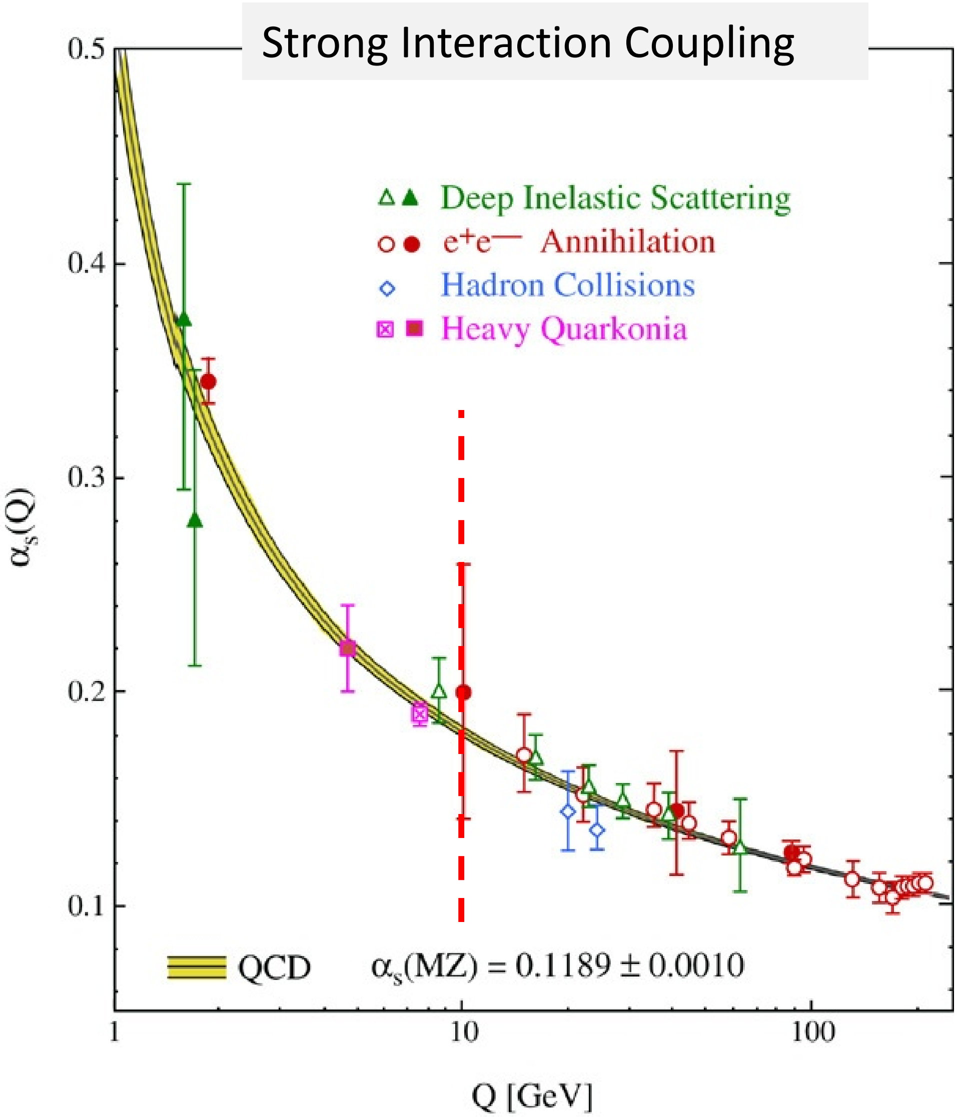






- QCD Running Coupling Constant

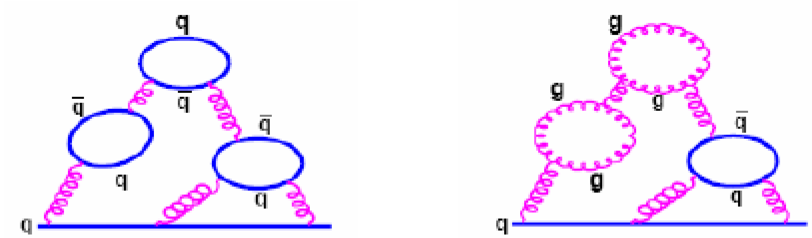
Nuclear physics



[Experimental Tests of Asymptotic Freedom, arXiv:hep-ex/0606035]

Gross, Politzer, Wilczek
Noble Price 2004

Quantum Fluctuations (anti) screen color charge

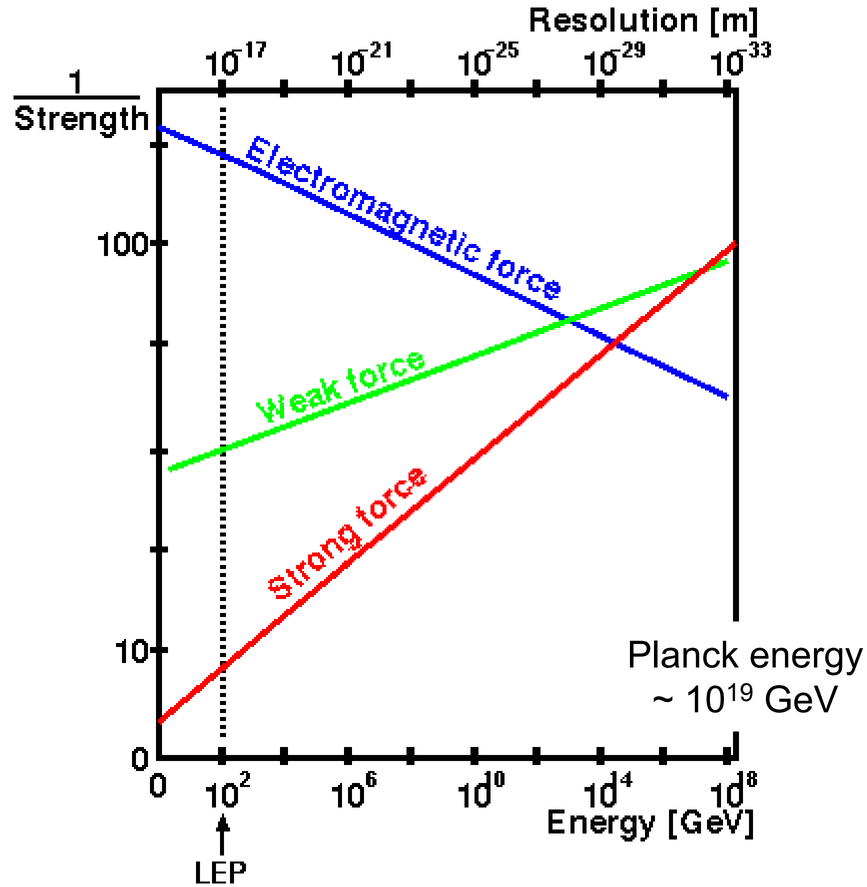


dominates at large distance (low energy) → confinement

$$\lambda \propto 1/E$$

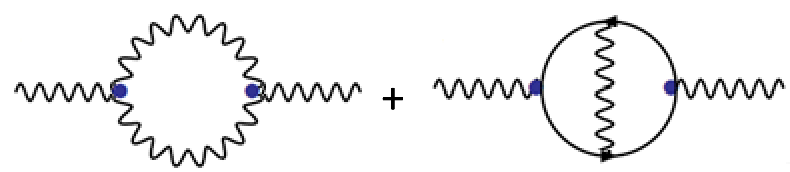
→ Perturbation Theory fails use Potential Models, Symmetries ..

- Shortcomings
  - Standard Model unsatisfactory for several reasons, e.g.
    - 19 ad-hoc free parameters
      –> no prediction beyond EW scale
    - Forces do not converge
    - Gravity (DM) not included
  - Additional particles/interactions?



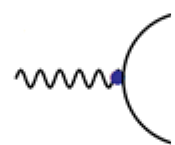
Search

indirectly (rare decays)



SM New?

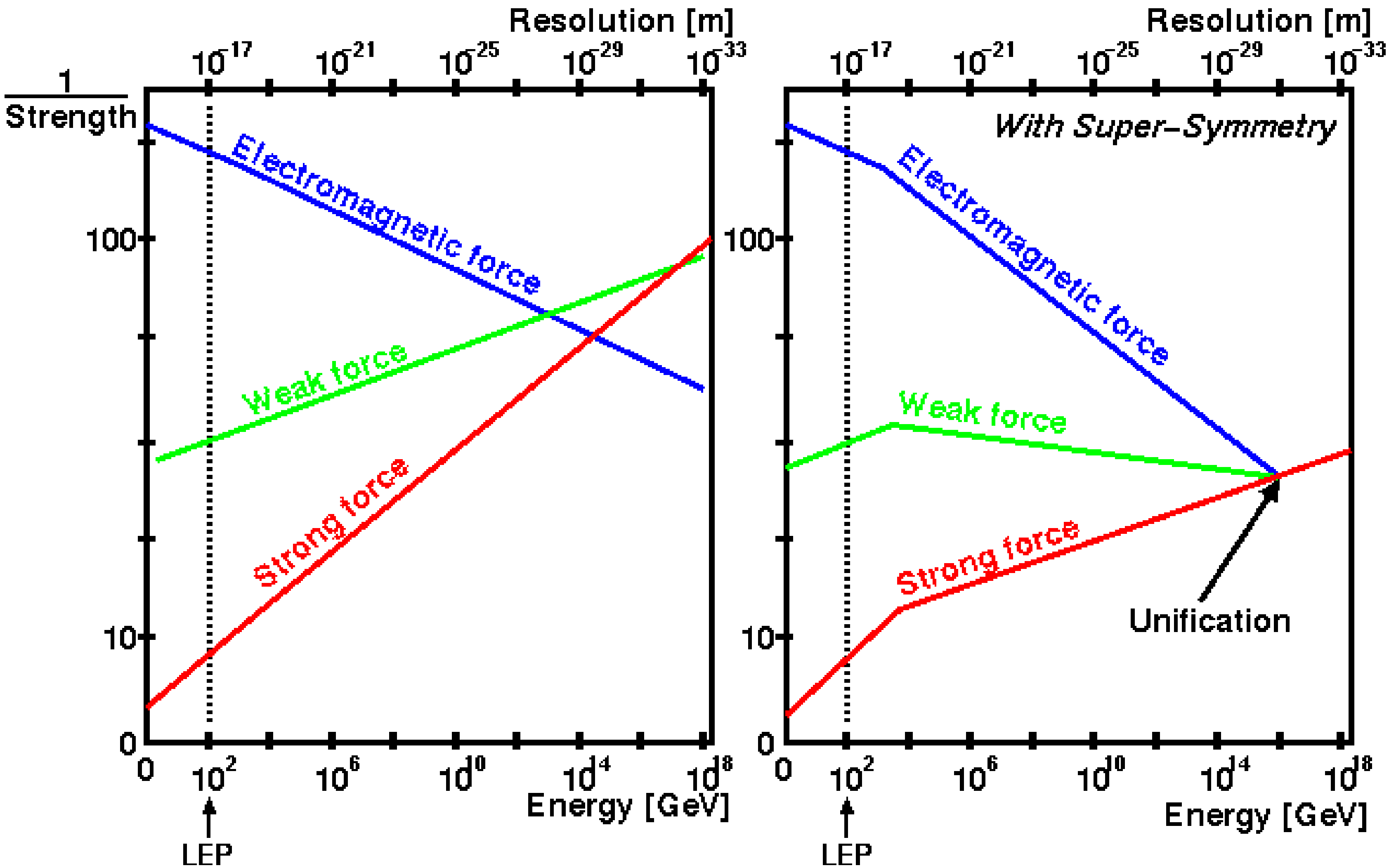
directly (new peaks in spectra)



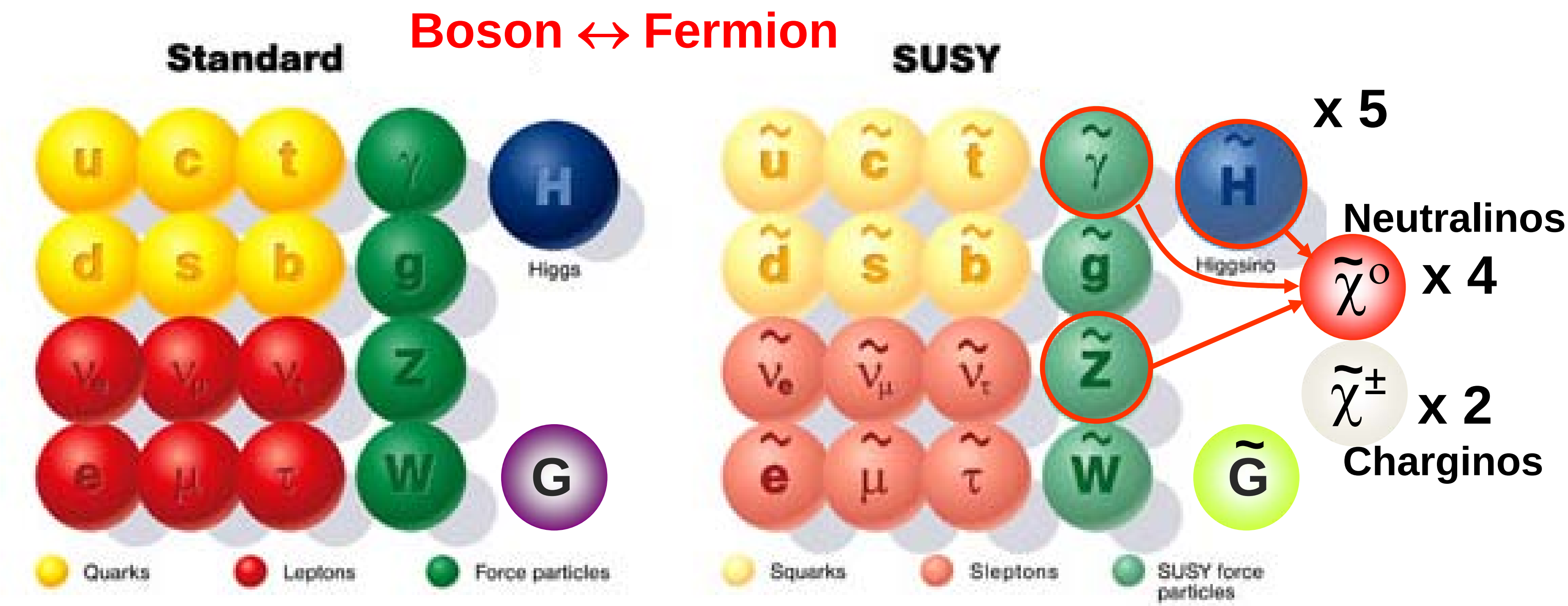
New?

- Grand Unification Theory

Minimal Supersymmetric SM



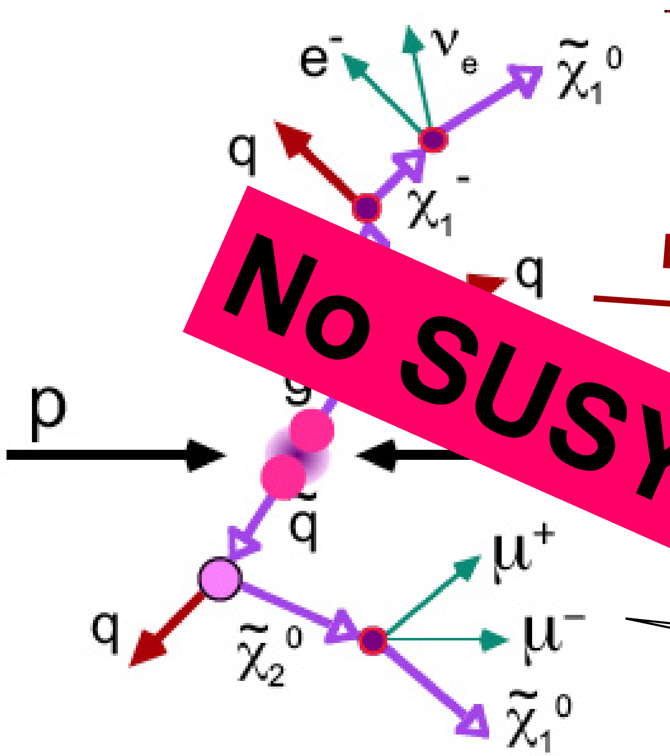
• SUSY - MSSM

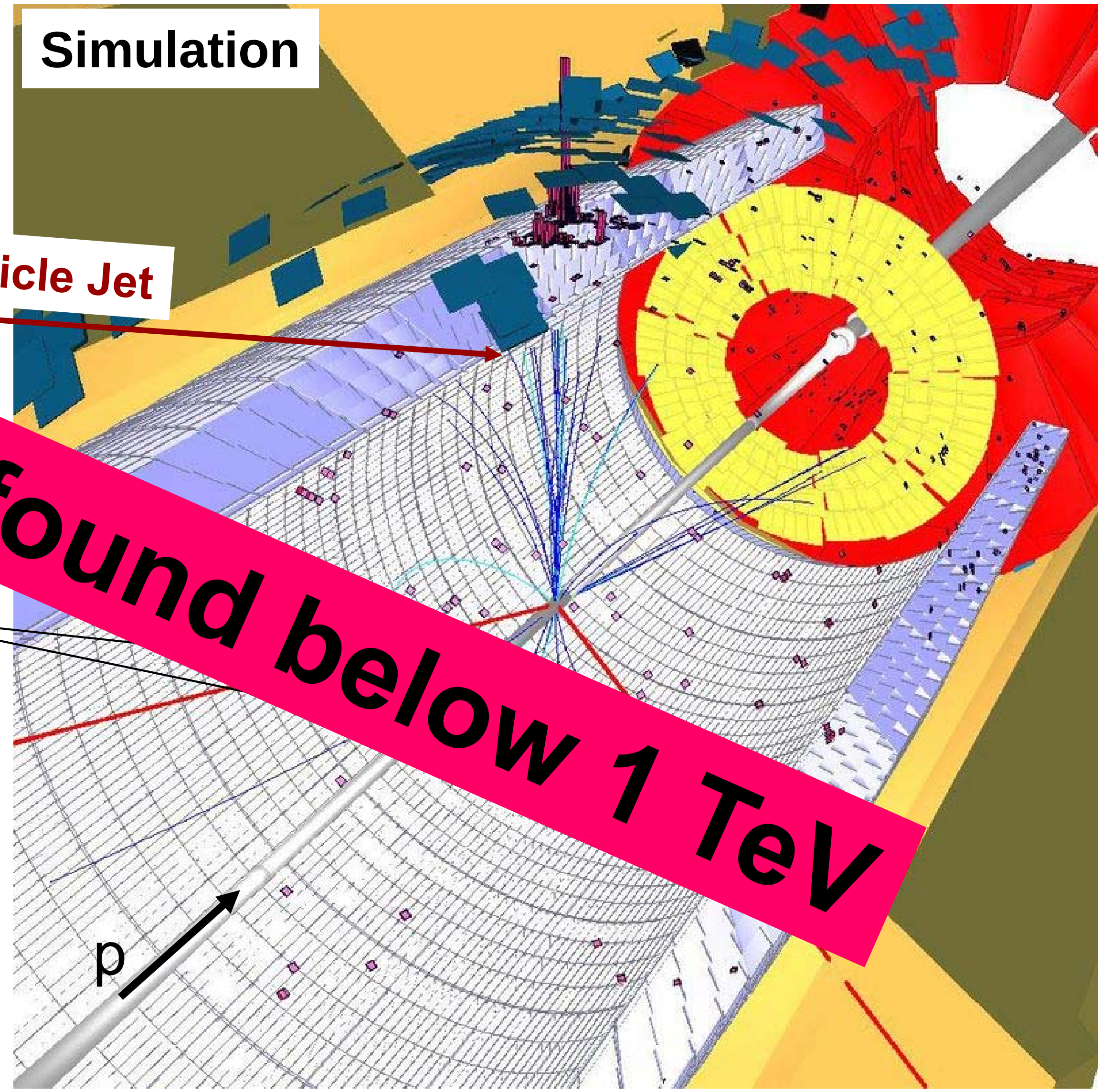


Mass: 100 GeV .. 1 TeV

- The SUSY extension is a small perturbation consistent with electroweak precision data (CP violation in B Decays)
- The lightest SUSY neutralino is stable and massive →
- Lightest SUSY-Higgs mass well below 100 GeV (?) and is pseudo-scalar

- **SUSY**

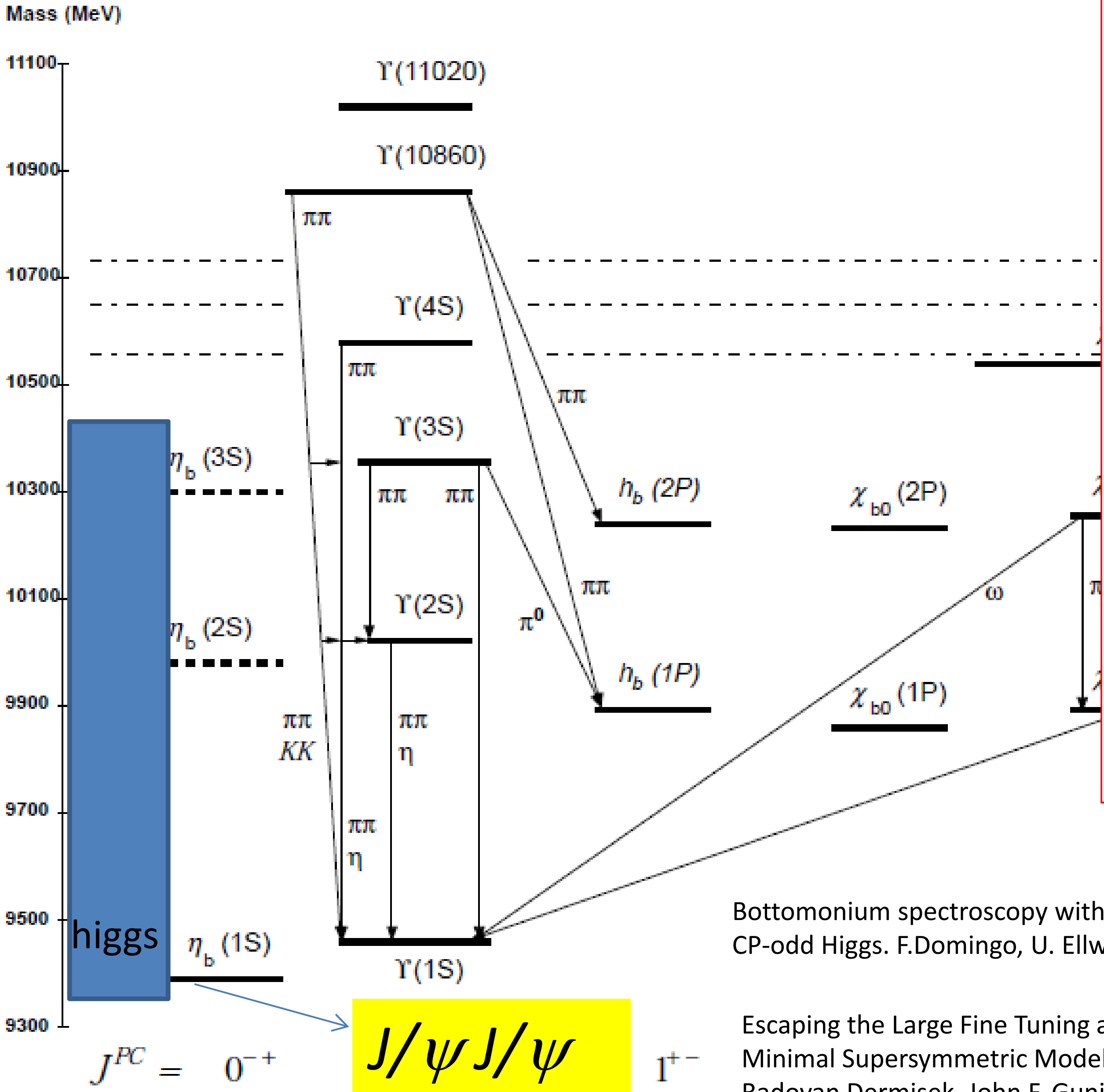


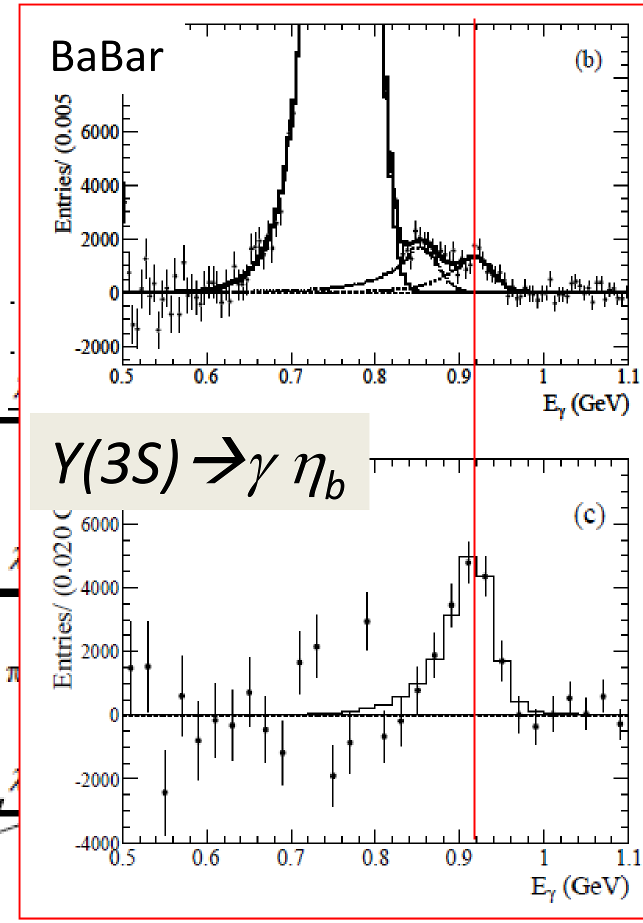


<u>Signature</u>

- Transverse energy, momentum (mass) unbalanced
- Same-sign leptons

• Bottonium Spectrum Hides MSSM Higgs ?





Phys.Rev.Lett.101:071801,2008

Bottomonium spectroscopy with mixing of eta_b states and a light CP-odd Higgs. F.Domingo, U. Ellwanger, M-A Sanchis-Lozano

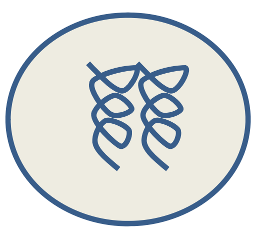
Phys.Rev.Lett.103:111802,2009

Escaping the Large Fine Tuning and Little Hierarchy Problems in the Next to Minimal Supersymmetric Model and h-> aa Decays
Radovan Dermisek, John F. Gunion Phys.Rev.Lett. 95 (2005) 041801

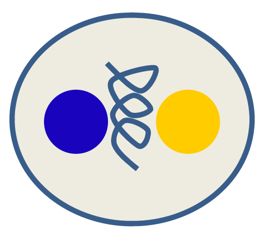
- Summary

    - Standard Model is unsatisfactory and probably a low energy limit of a more general theory
      → Where are the new (non-SM) particles?

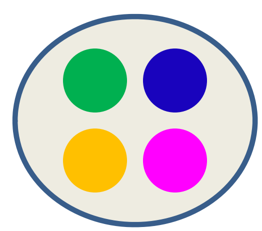
    - Details within the SM, particularly QCD require effort to be able to distinguish new from old
      → Where are objetcs made of gluons and quarks other than mesons and hadrons that are predicted by QCD but haven’t been found



Glueballs



Hybrids

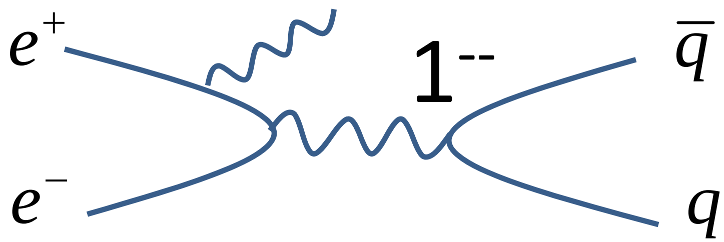


Tetra-quark states …

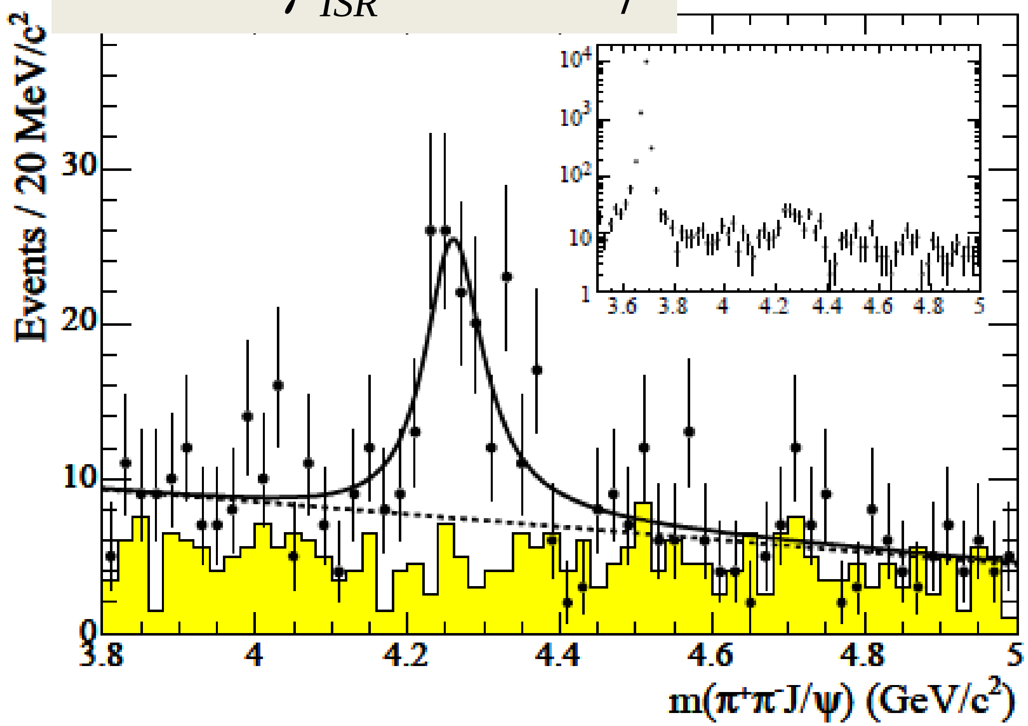
- Onia States

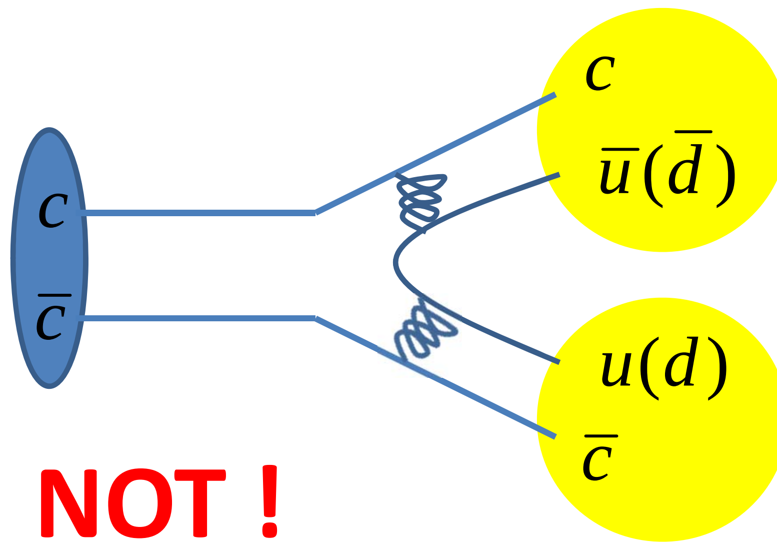
In 2005 BaBar experiment discovers charmonium like state in initial state radiation among whole series of discovery of new, unexpected states

→ Even though above D$\bar{D}$ threshold does not decay this way



$$e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^- J/\psi$$





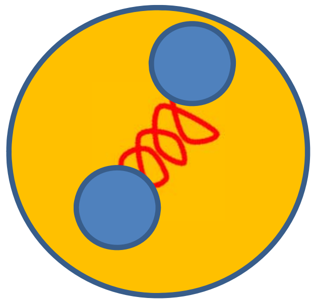
NOT !

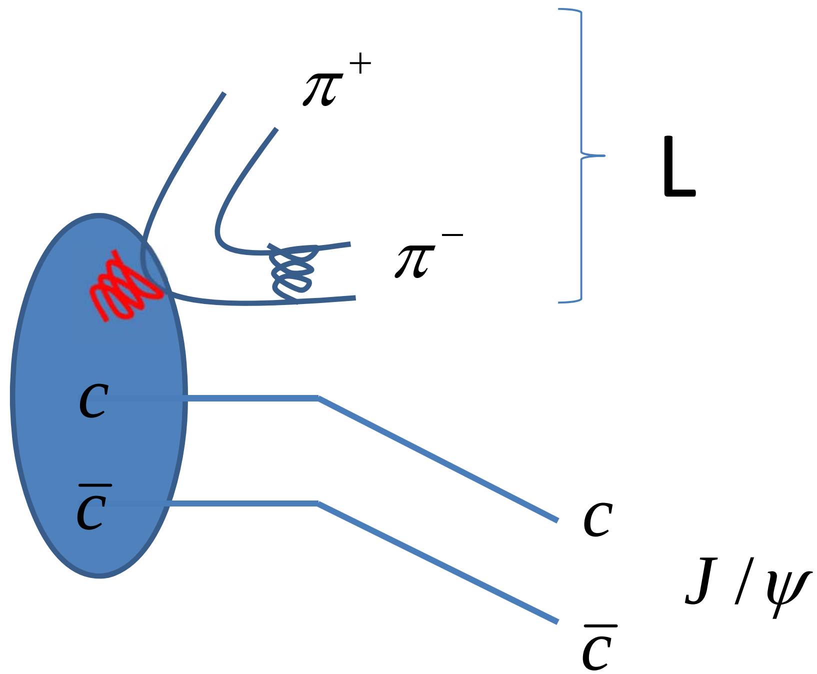
D^+D^- or $D^0\overline{D}^0$

m(D) ~ 1.87 GeV

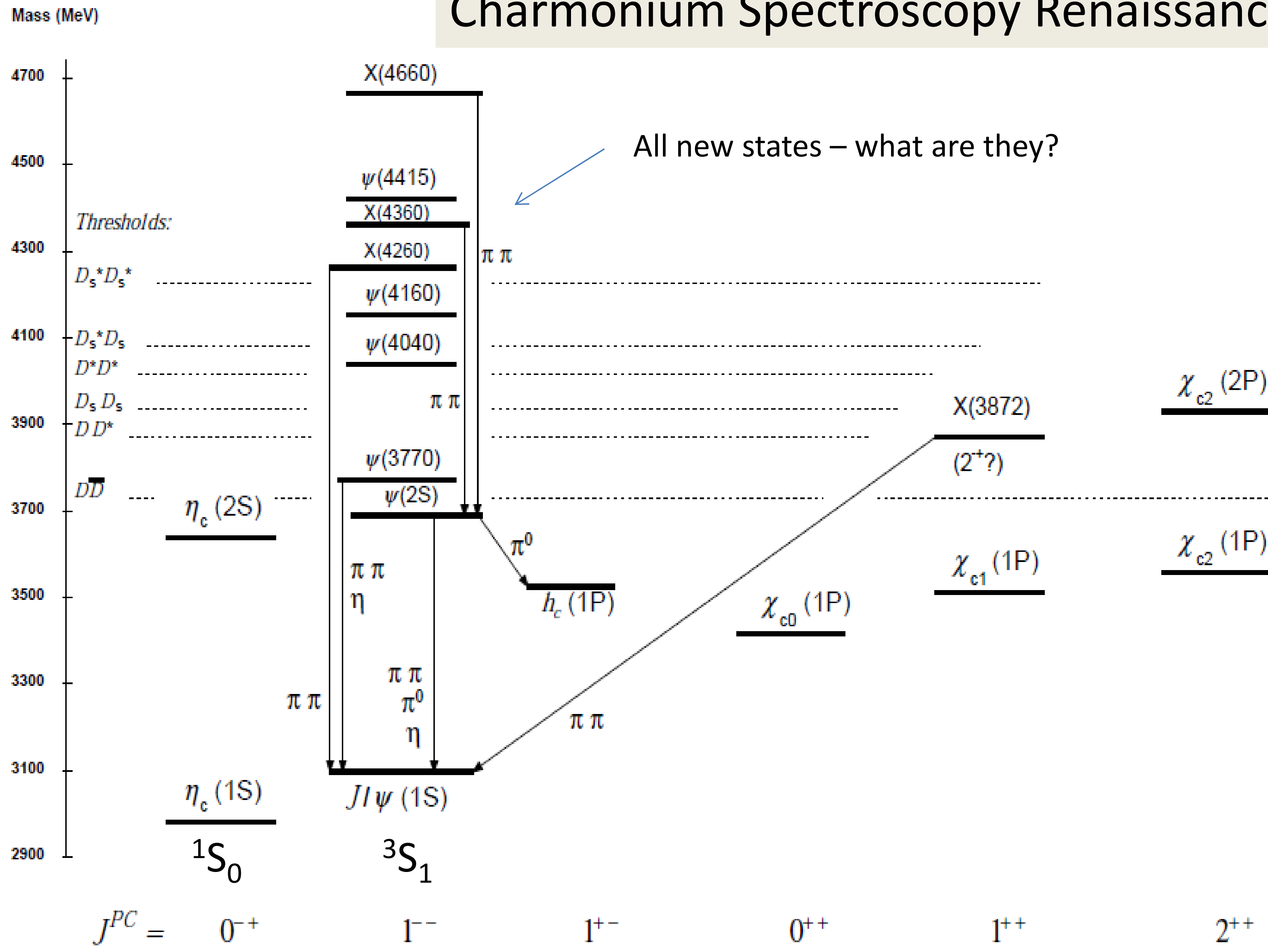
- Onia States

MAYBE



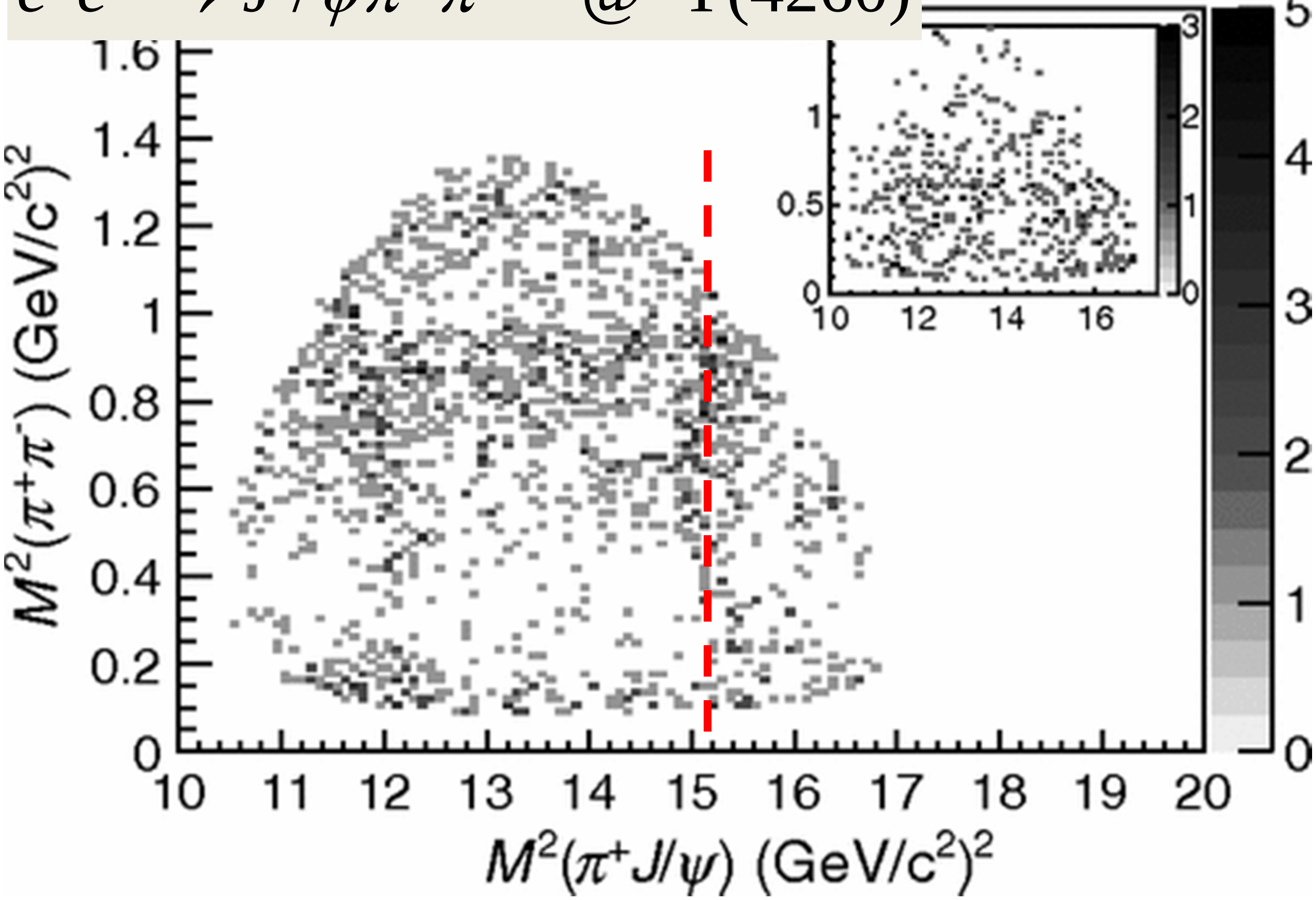


Charmonium Spectroscopy Renaissance



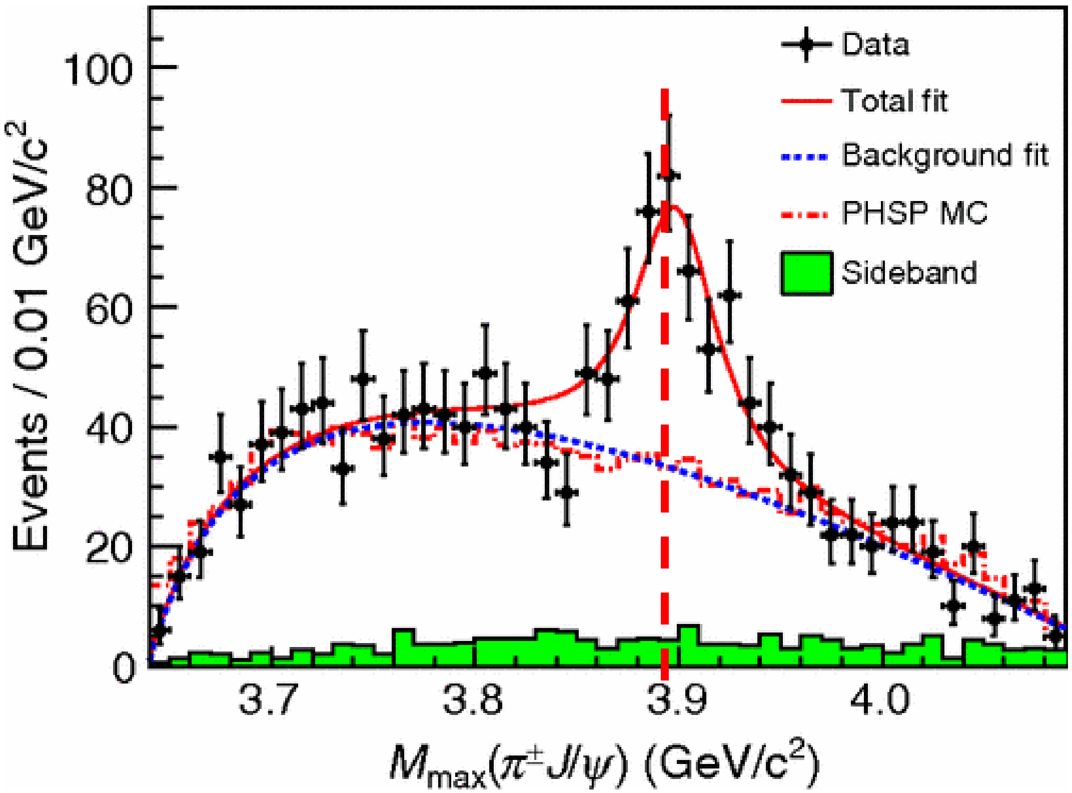
- More States in Sub-Decays

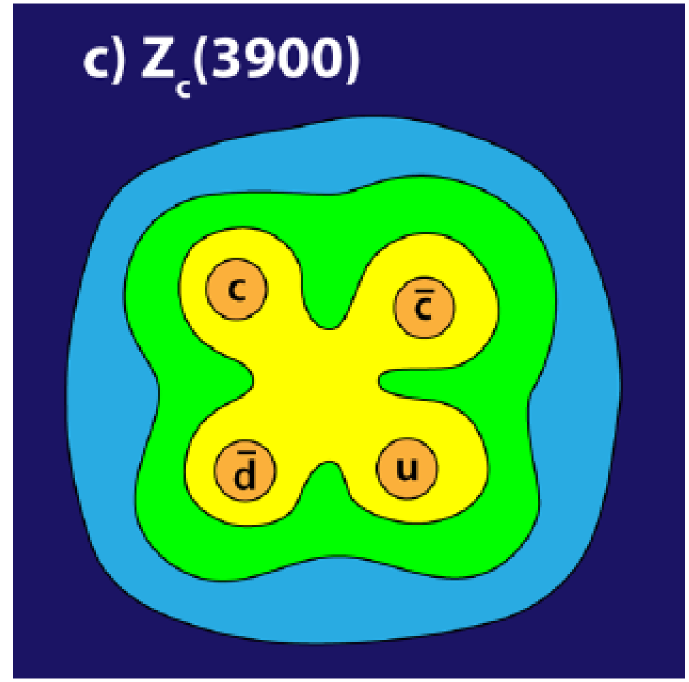
$e^+e^- \to J/\psi\pi^+\pi^- \quad @ \ \Upsilon(4260)$



[1] M. Ablikim *et al.* (BESIII Collaboration), "Observation of a Charged Charmoniumlike Structure in $e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s} = 4.26$ GeV," *Phys. Rev. Lett.* **110**, 252001 (2013).
[2] Z. Q. Liu *et al.* (Belle Collaboration), "Study of $e^+e^- \to \pi^+\pi^- J/\psi$ and Observation of a Charged Charmoniumlike State at Belle," *Phys. Rev. Lett.* **110**, 252002 (2013).

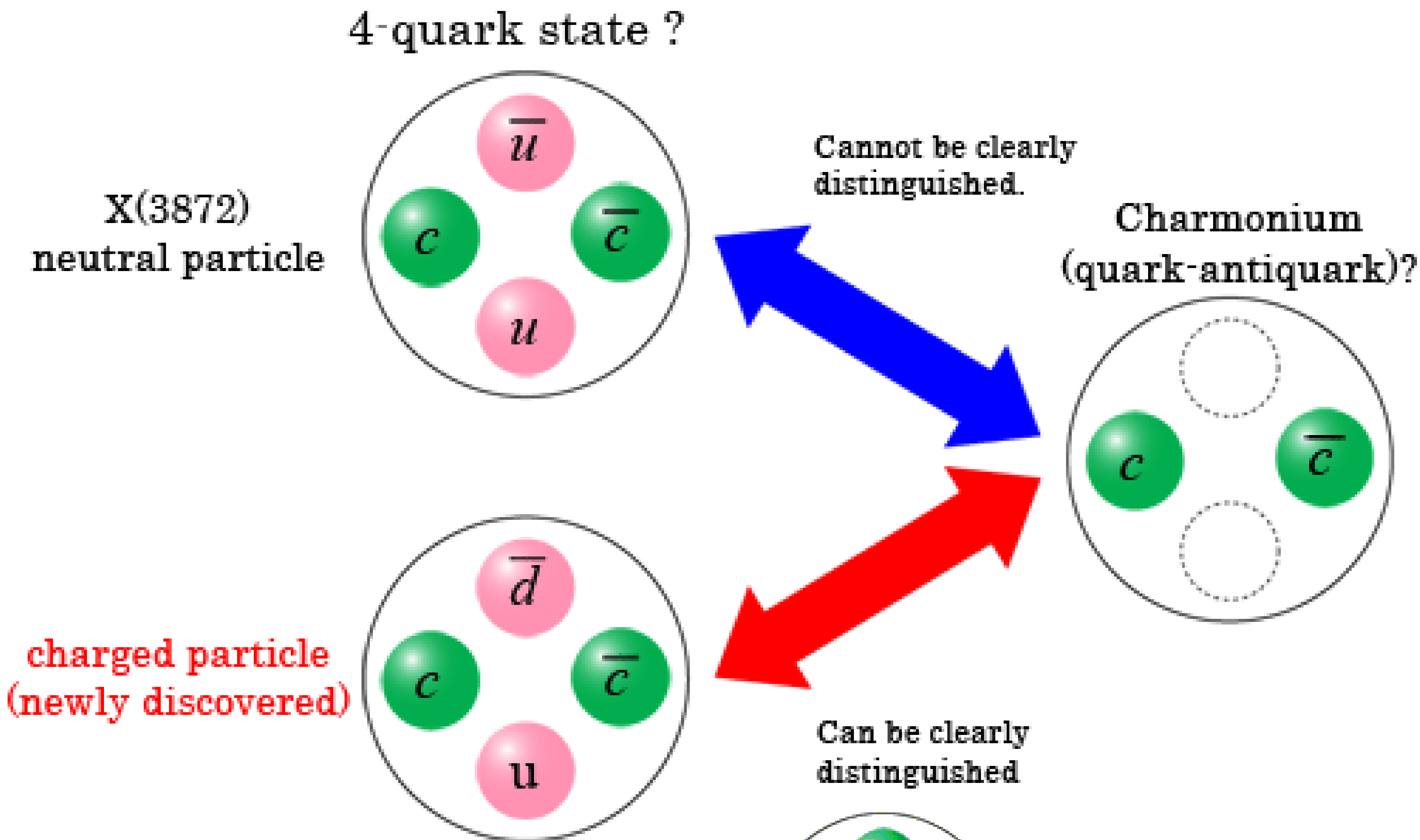
- Exotic States

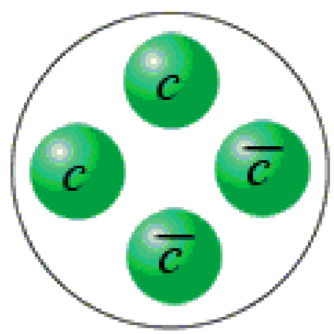




- Large mass, decay into J/ψ implies $c\bar{c}$ content; $c\bar{c}$-bar is electrically neutral
- Charged pion carries charge of the Z_C state
  → implies additional (light) quarks ($u\bar{d}$ or $\bar{u}d$) participate in state

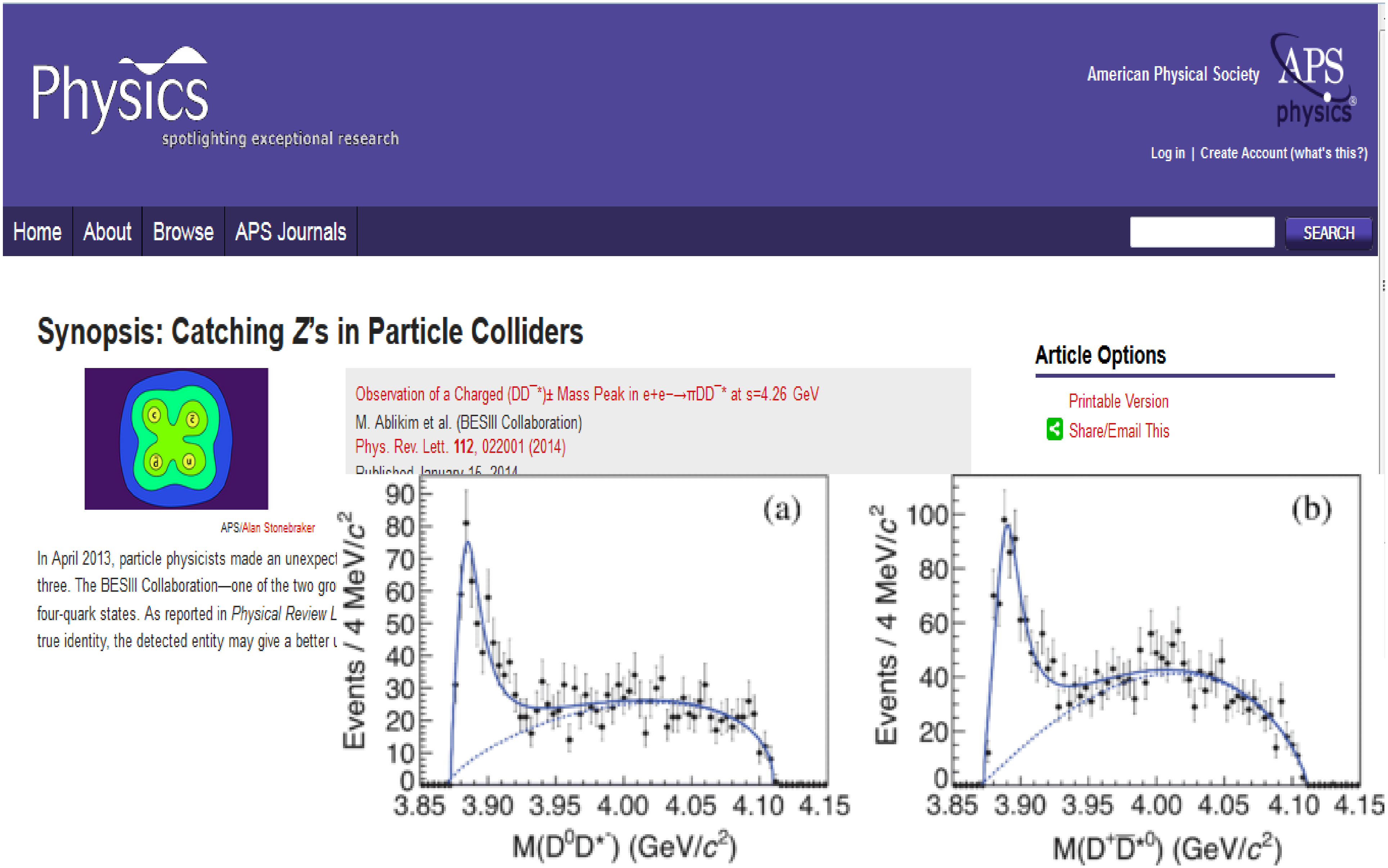
➔ 4-Quark States never been observed before !?



Furthermore, states such as 

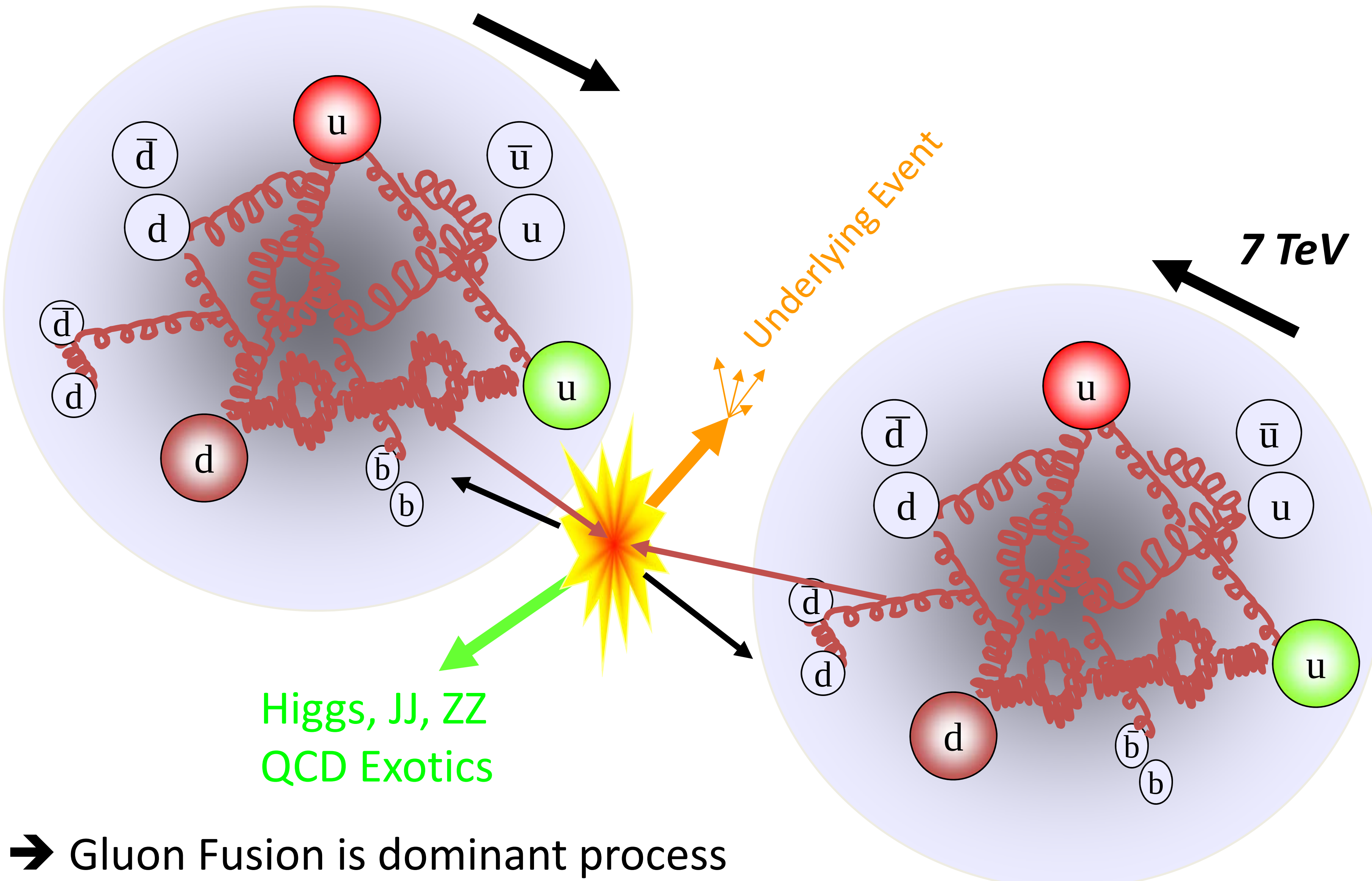
predicted

- 4 Quark States



.. or could it be a DD molecule ?

- Particle Production in Proton-Proton Collisions at LHC

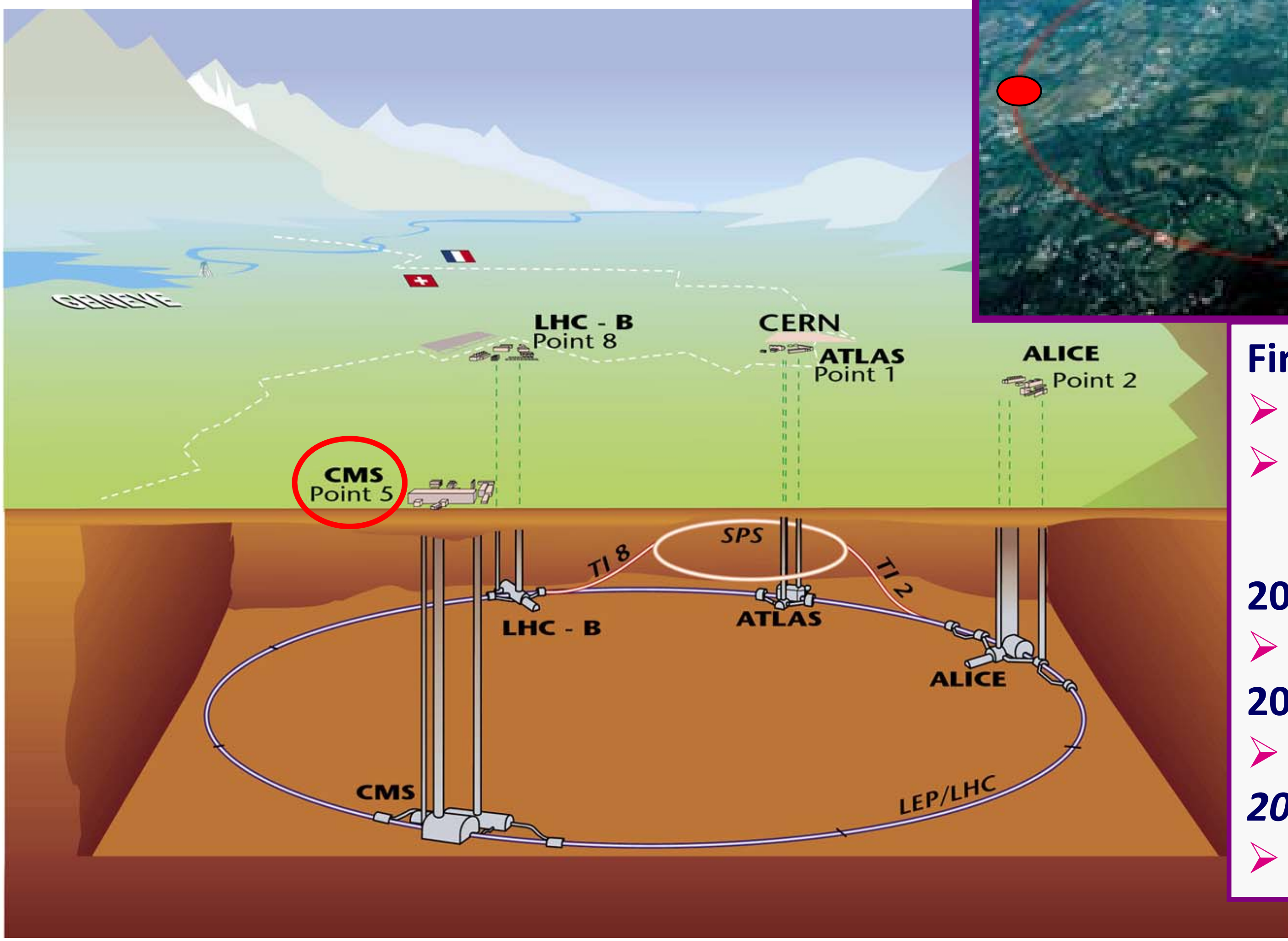


➔ Gluon Fusion is dominant process

➔ Soft-scattering has higher cross section but mostly along beam

- The Large Hadron Collider (LHC)

Proton-proton collider (up to E_{CM}=14 TeV)
27 km in circumference, 50-175m deep
between Jura mountains (France) and
Lake Geneva (Switzerland)



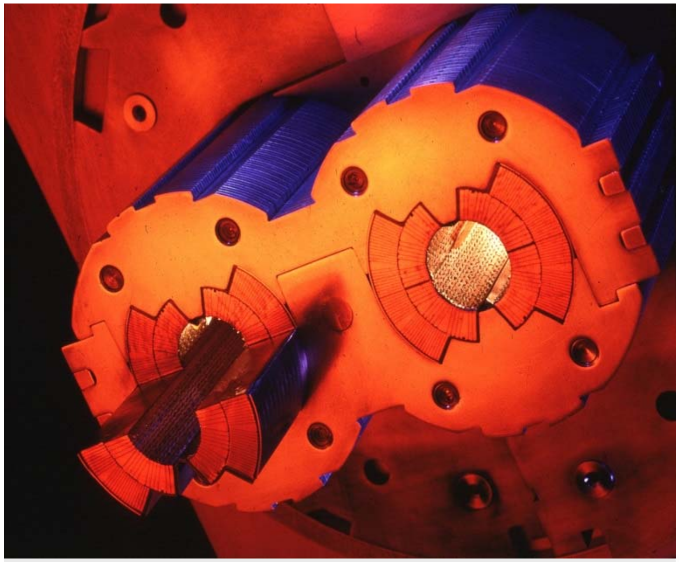
First year running:
- ***Startup Nov. 2009***
- ***Several months calibration runs***

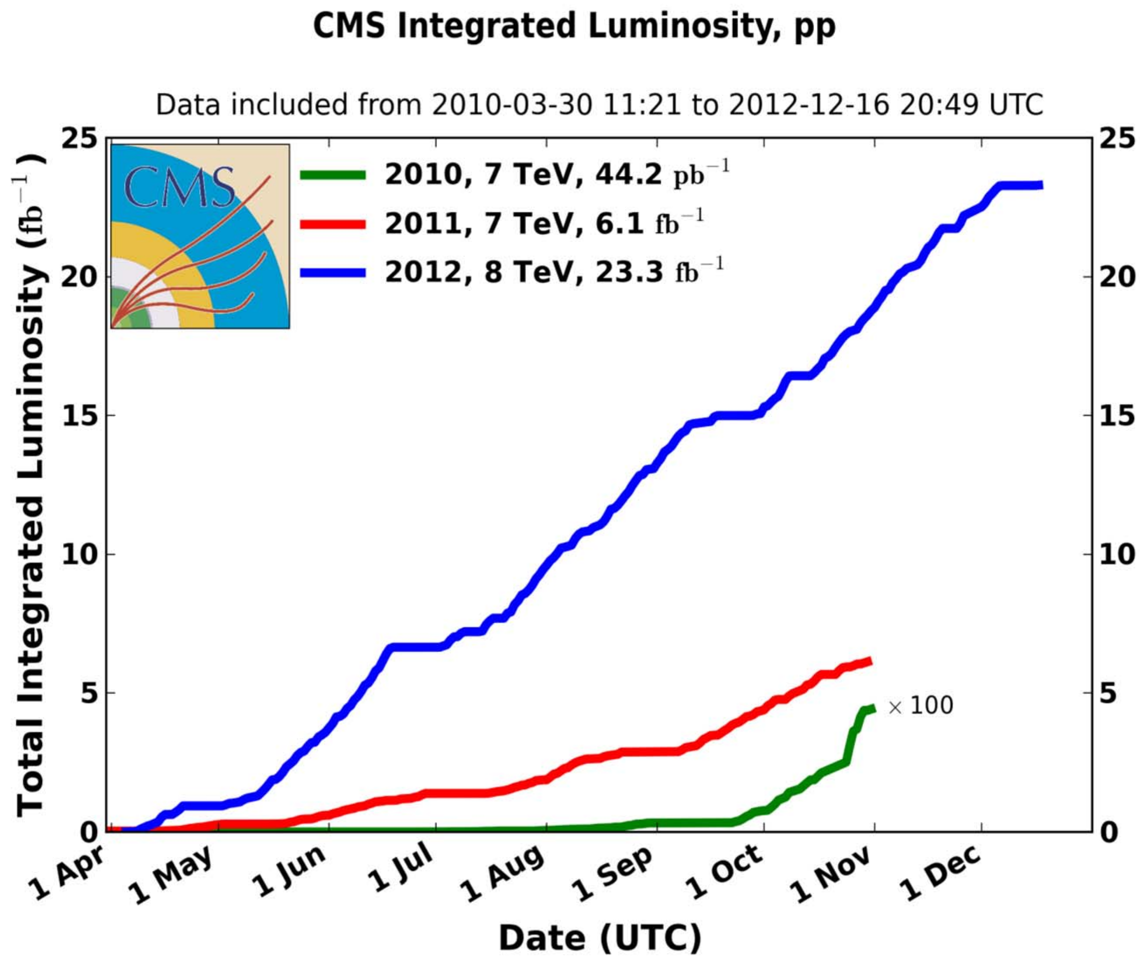
2011 running:
- ***7 TeV p-p runs***

2012 running
- ***8 TeV p-p runs***

2015 resume running
- ***13 TeV p-p***

- LHC



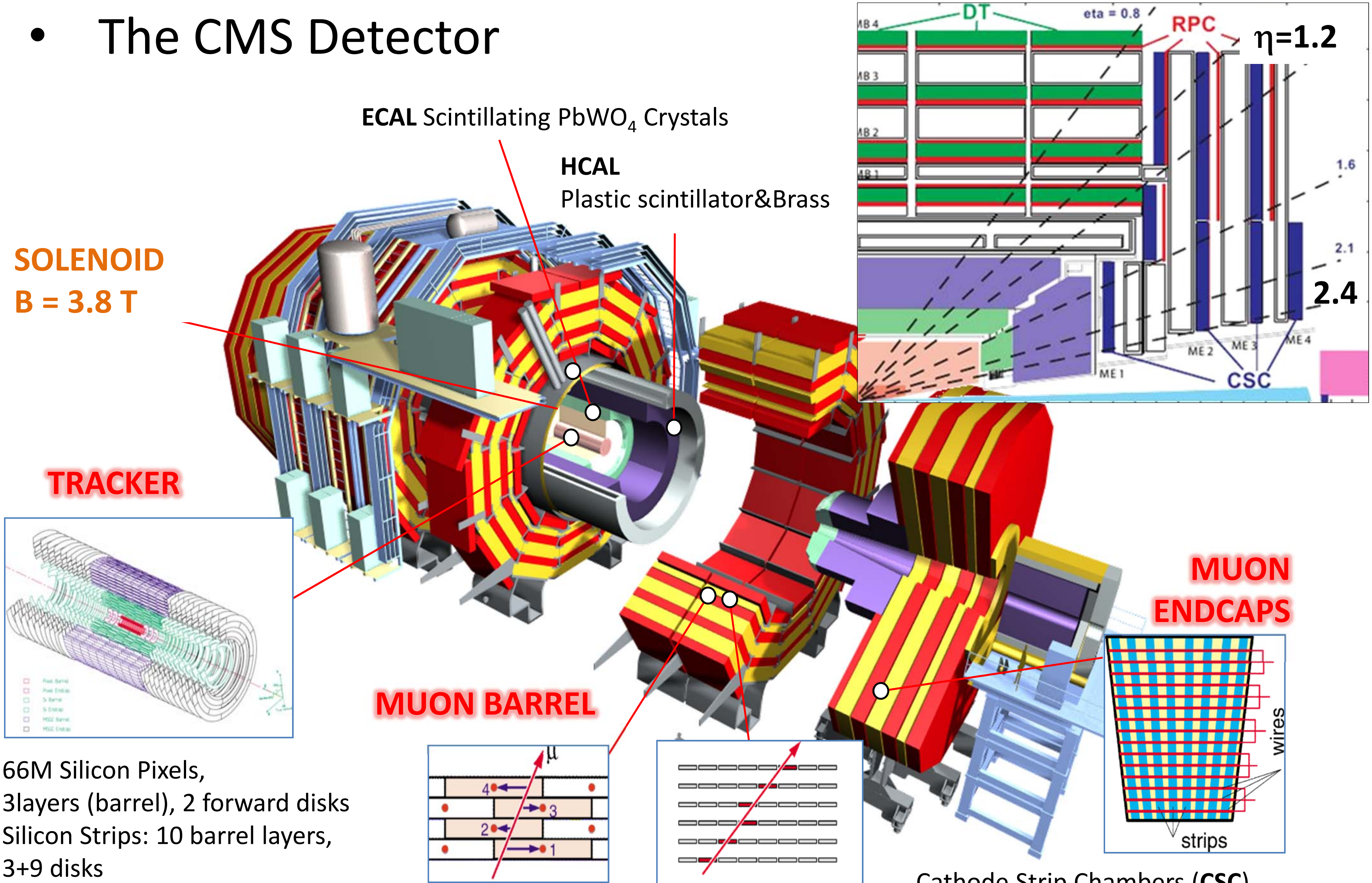


Each beam

- 2808 bunches of protons
- ~10^{11} protons/bunch
- Circulation time: 89 μs
- Current: ~ 0.6 Ampere
- Time between collisions: 25 ns

- Fill time (450 GeV): 7.5 min
- Acceleration time : 20 min
- Beam lifetime : ~15 hours

- The CMS Detector



66M Silicon Pixels,
3layers (barrel), 2 forward disks
Silicon Strips: 10 barrel layers,
3+9 disks

Drift Tubes (**DT**)
→ position

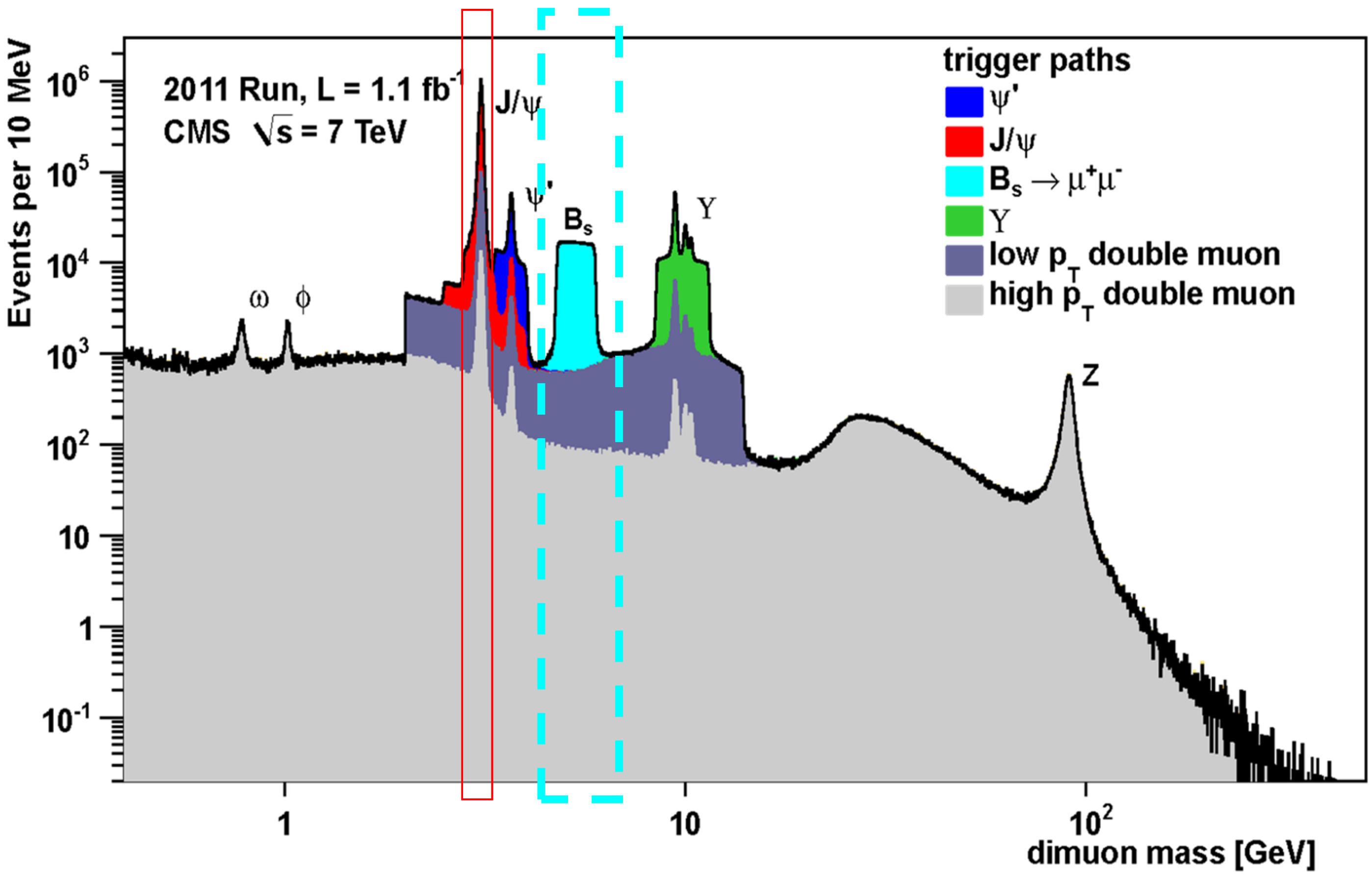
Resistive Plate
Chambers (**RPC**)
→ timing

Cathode Strip Chambers (**CSC**)
→ position
Resistive Plate Chambers (**RPC**)
→ time

- Muon Trigger
  - L1 hardware trigger (~1μs)
  - High-level trigger: tracking/vertexing

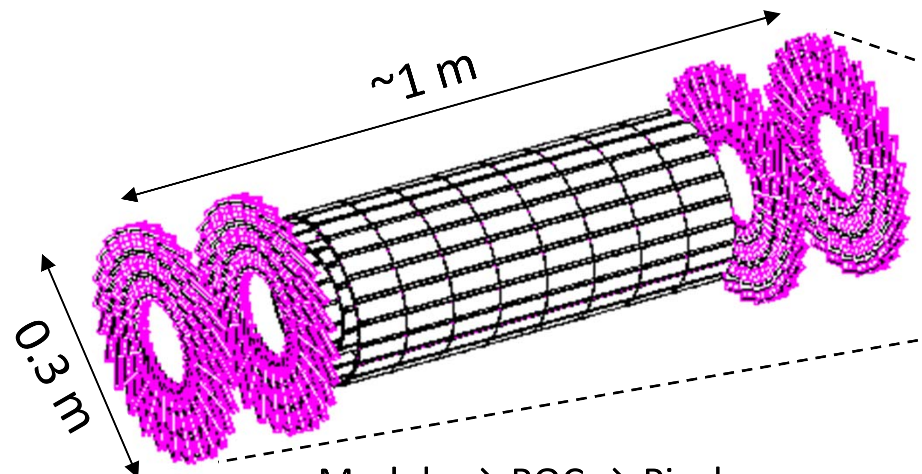
invariant $\mu^+\mu^-$ mass combinations

$J/\psi \rightarrow \mu^+\mu^-$ displaced (Δm=200 MeV)/prompt (250 MeV)

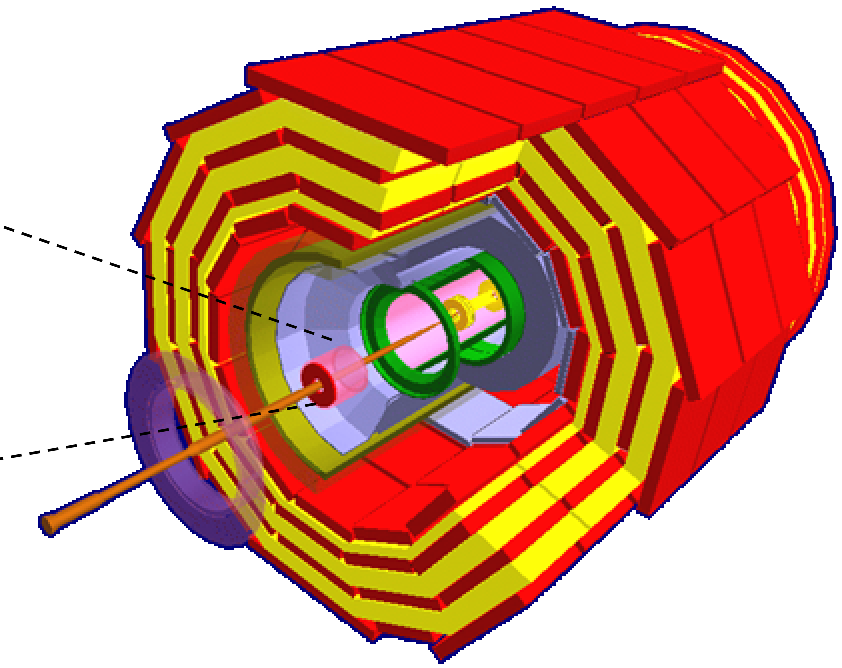


More restrictive with higher luminosity

- Silicon Pixel Detector



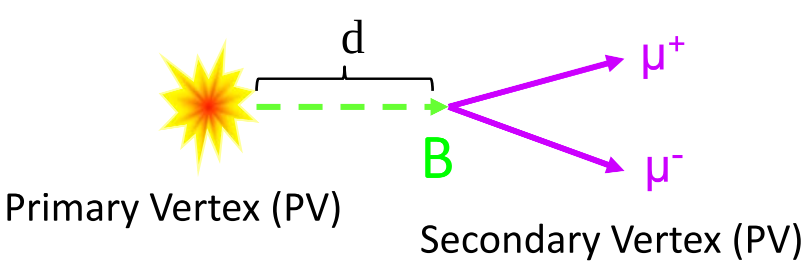
Module → ROC → Pixel



Requirements:

High resolution (~15 μm), granular tracker
Hermetic

Operate 5 years in high radiation field
Important for vertex finding

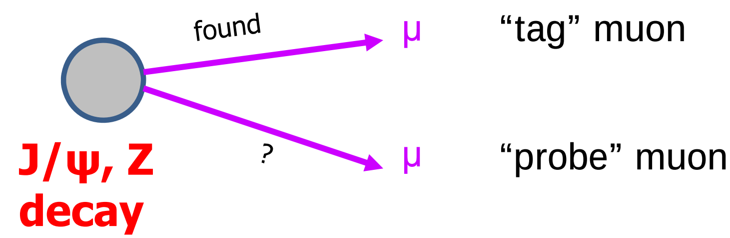


- Barrel Pixel Detector (BPix)
  - 3 layers at radii 4.3, 7.2, and 11.0 cm
  - ~48 million pixels
- Forward Pixel Detector (FPix)
  - 2 disks at Z = 34.5 and 46.5 cm
  - ~18 million pixels

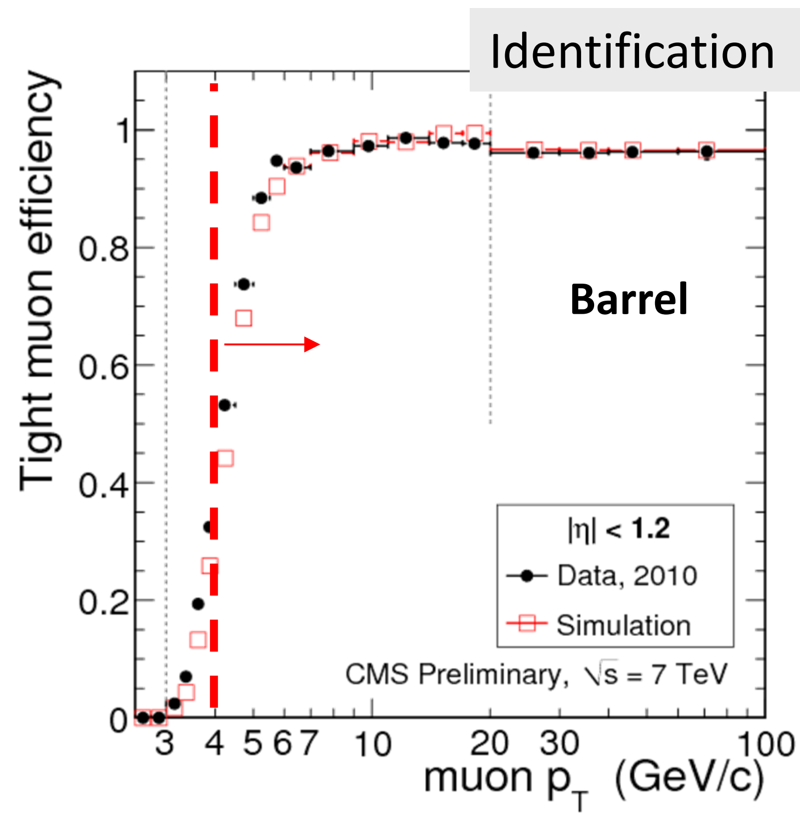
- Muon Efficiency

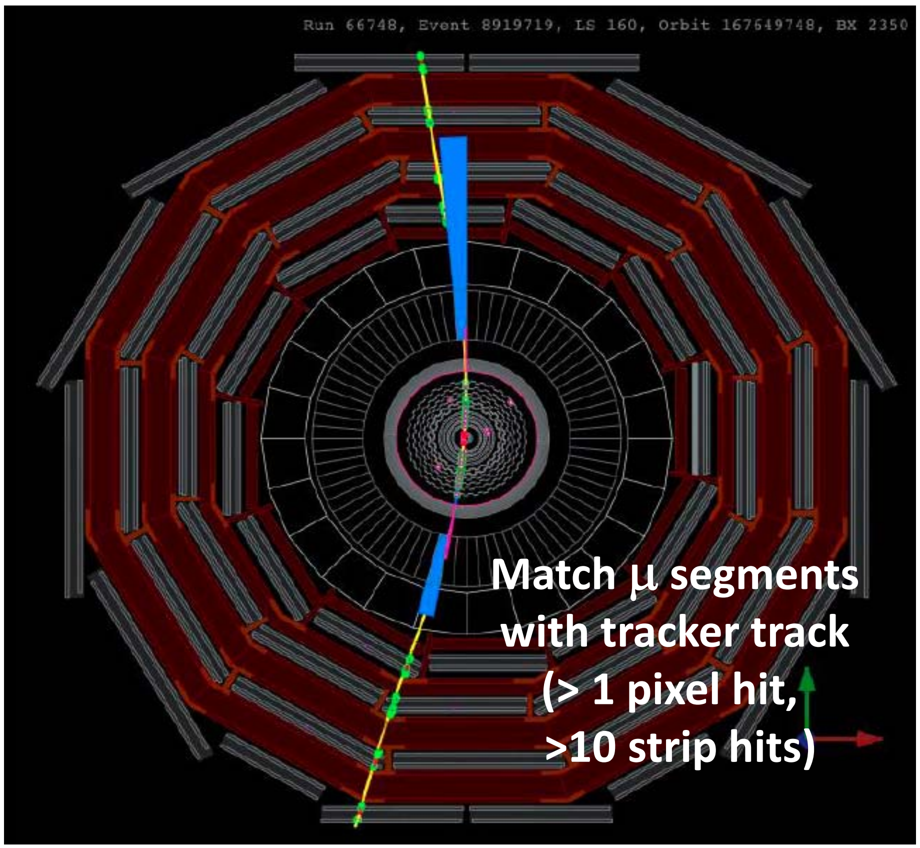
- Muon tracking
  - excellent σ_{p_T}/p_T ~ 1%
  - efficiency > 99% for central μ
  - excellent vertex reconstruction
    impact parameter σ ~15um

- Muon Efficiency
  - "tag and probe" in data



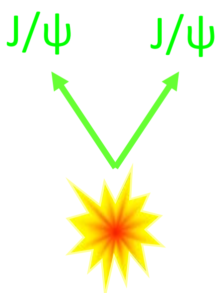
- Monte Carlo *(compatible with data)*





- # Search for Double J/ψ

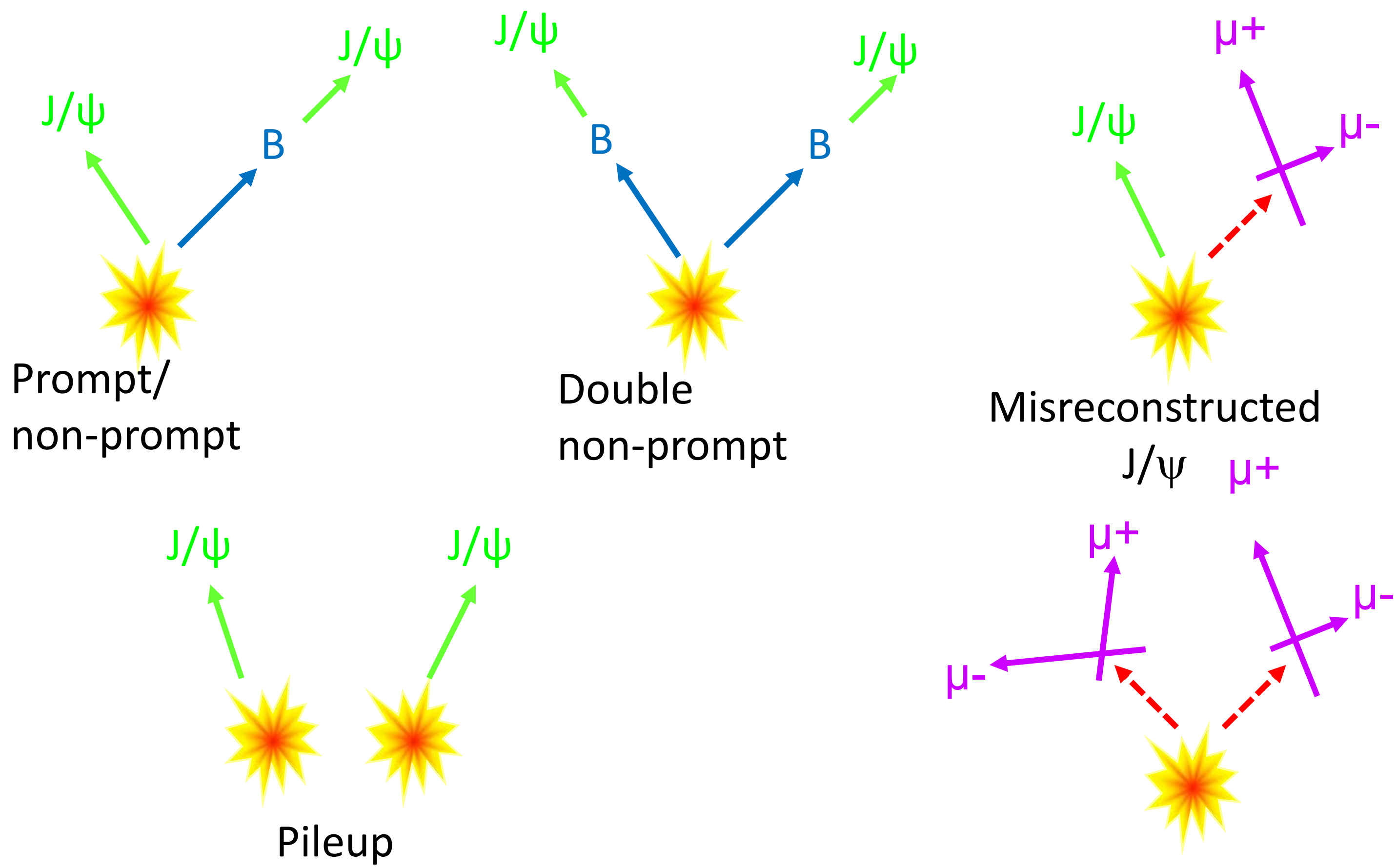
Signal:



Prompt double J/ψ

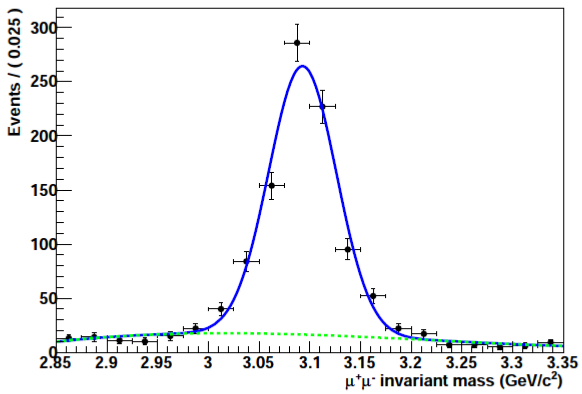
clean 4 muon topology

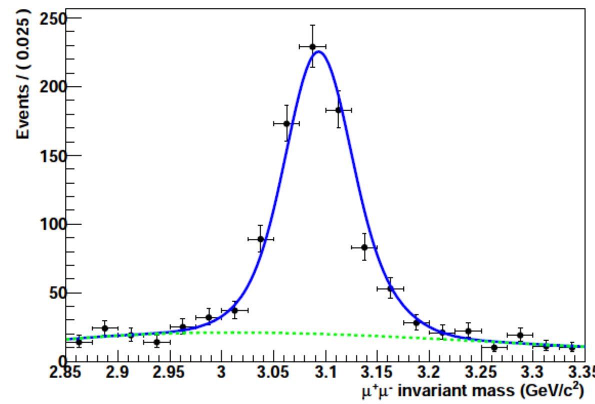
Background:



• Search for Double J/ψ - Discriminating Variables

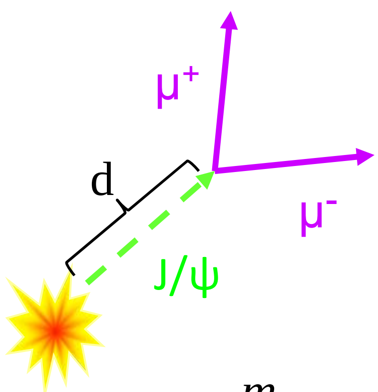
ψ1 Mass	ψ2 Mass



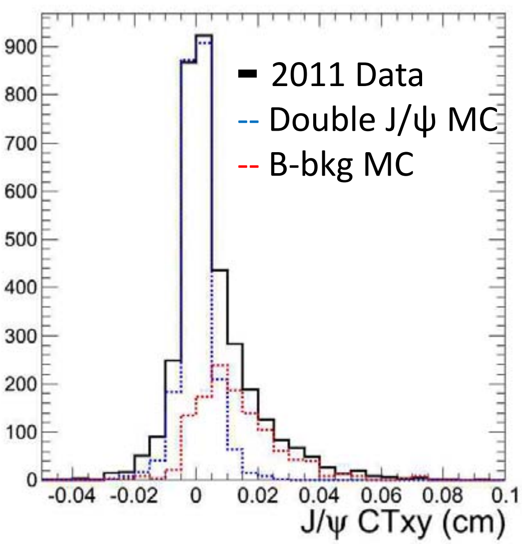


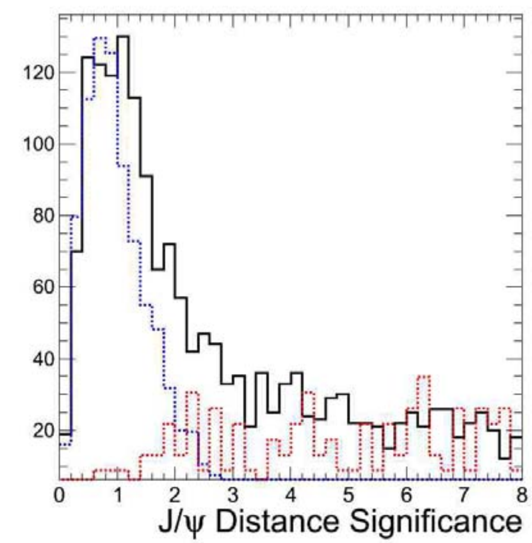
ψ1 refers to higher-pT J/ψ

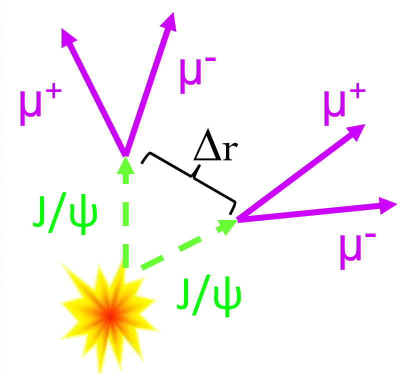
ψ1 Proper Decay Length, CTxy	Significance of Distance between J/ψ, $d^{J/\psi}$



$$c\tau = \frac{m}{|p|} d$$







$$d^{J/\psi} = \Delta\vec{r} / \sigma_{\Delta\vec{r}}$$

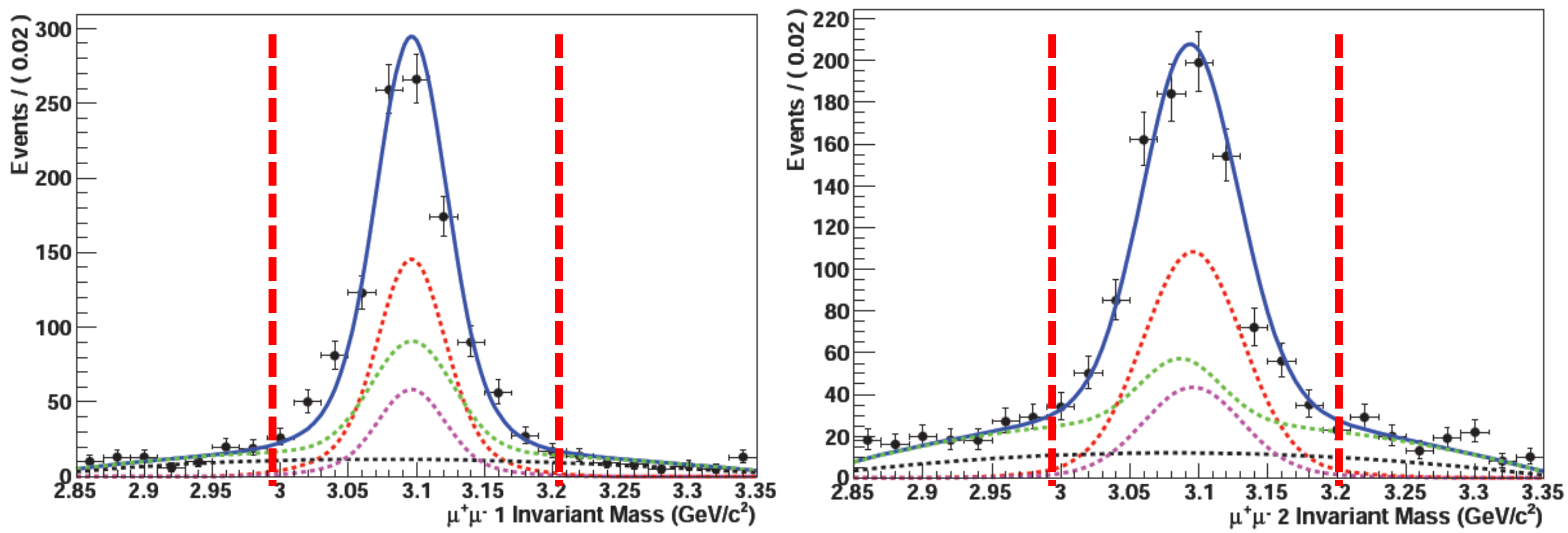
- # Maximum Likelihood Fit

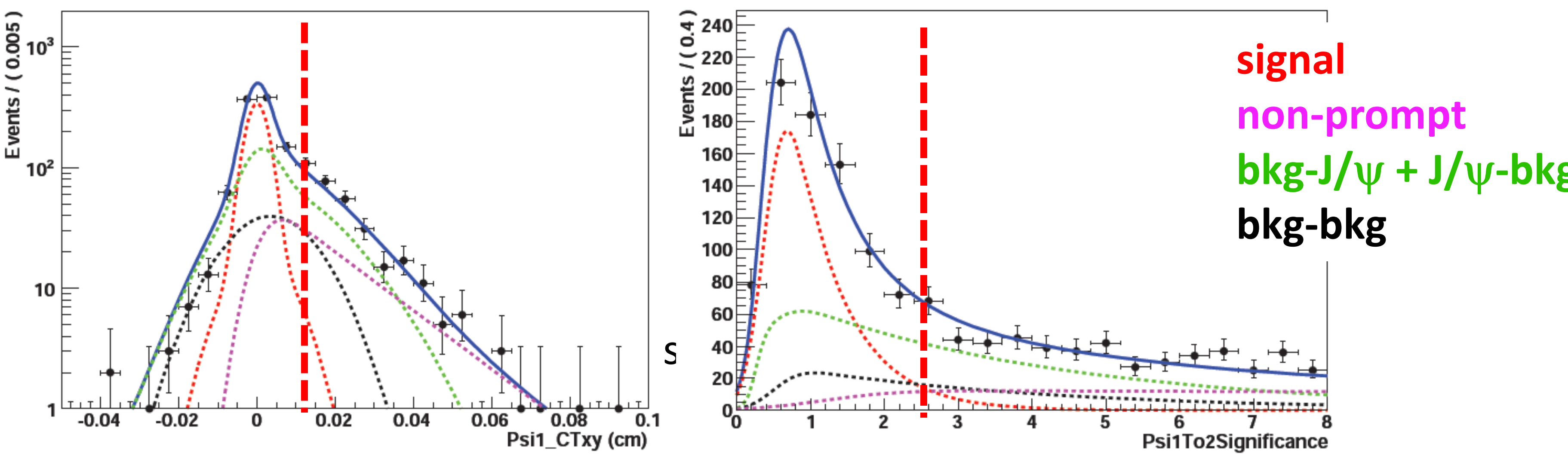
2011 Data

Fit validated with simulated events.

Significant observation of double-J/ψ production

Signal	446 ± 23
Non-prompt	182 ± 18
J/ψ-bkg/bkg-J/ψ	321 ± 28
bkg-bkg	94 ± 16





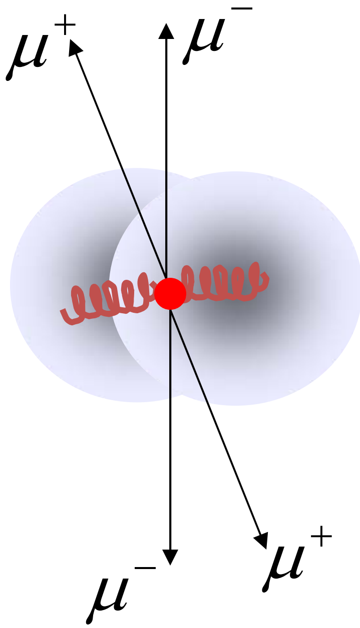
- Search for Double J/ψ Cut and Count

With somewhat restricted kinematic range
And requirements as indicated in event variable distributions

?

- Production of Double J/ψ - Background % Opportunity

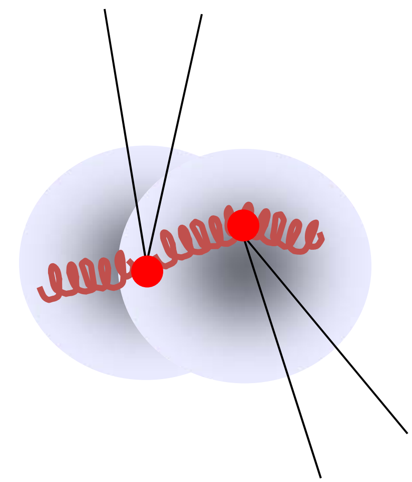
Single Parton Scattering (SPS) – 2 particle production



Production of particles such as Higgs or others due to this process – only?

Double-parton scattering (DPS) present ?

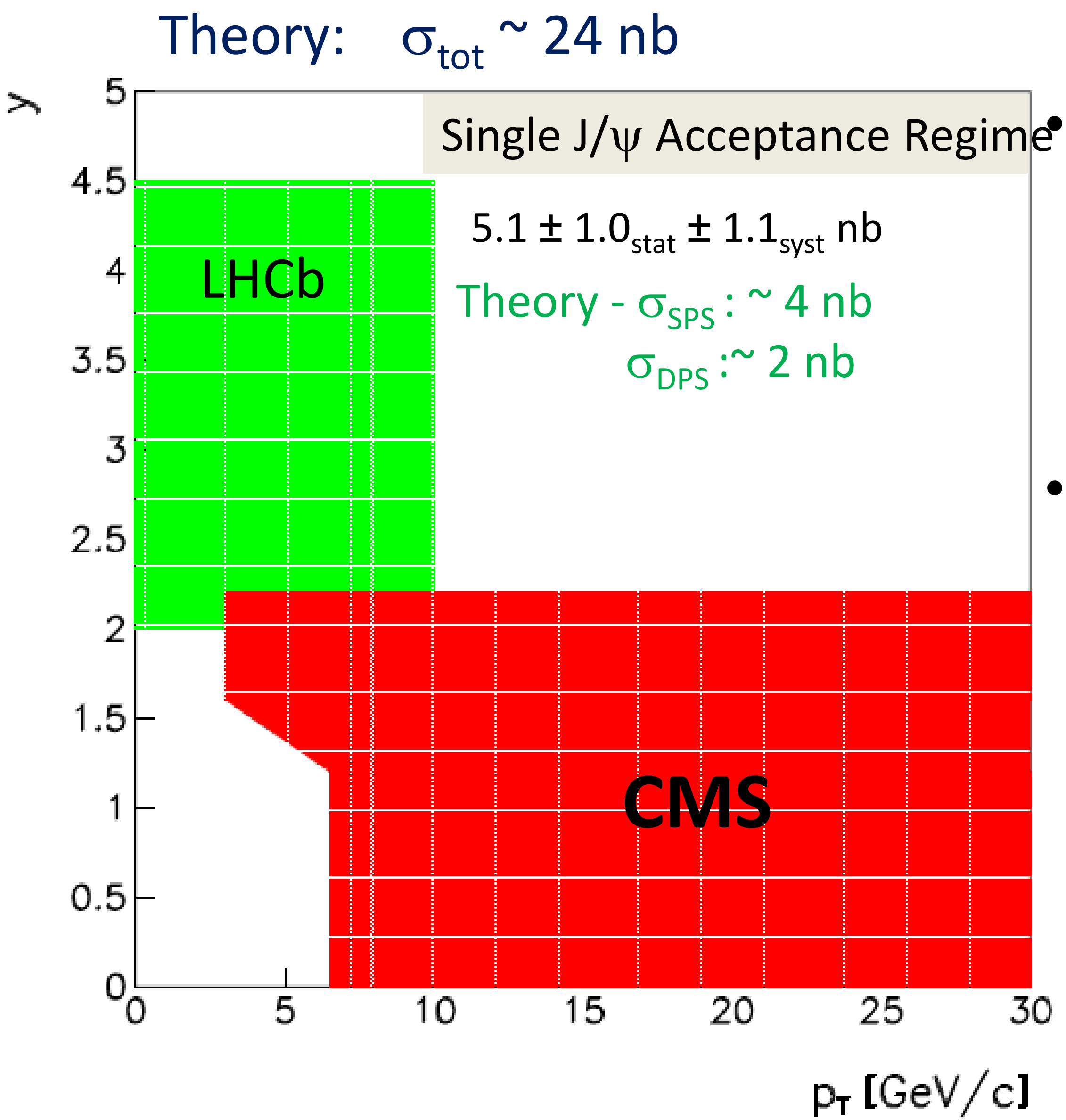
If present changes predictions of production rate (indirect searches) and background predictions (direct ~)
➔ Sensitivity in search for new particles limited by knowledge about DPS % SPS



Theory does not make predictions for the kinematic regime of CMS !!

Each double J produced still needs to be combined with rest of the event
➔ Complex hadronic production models

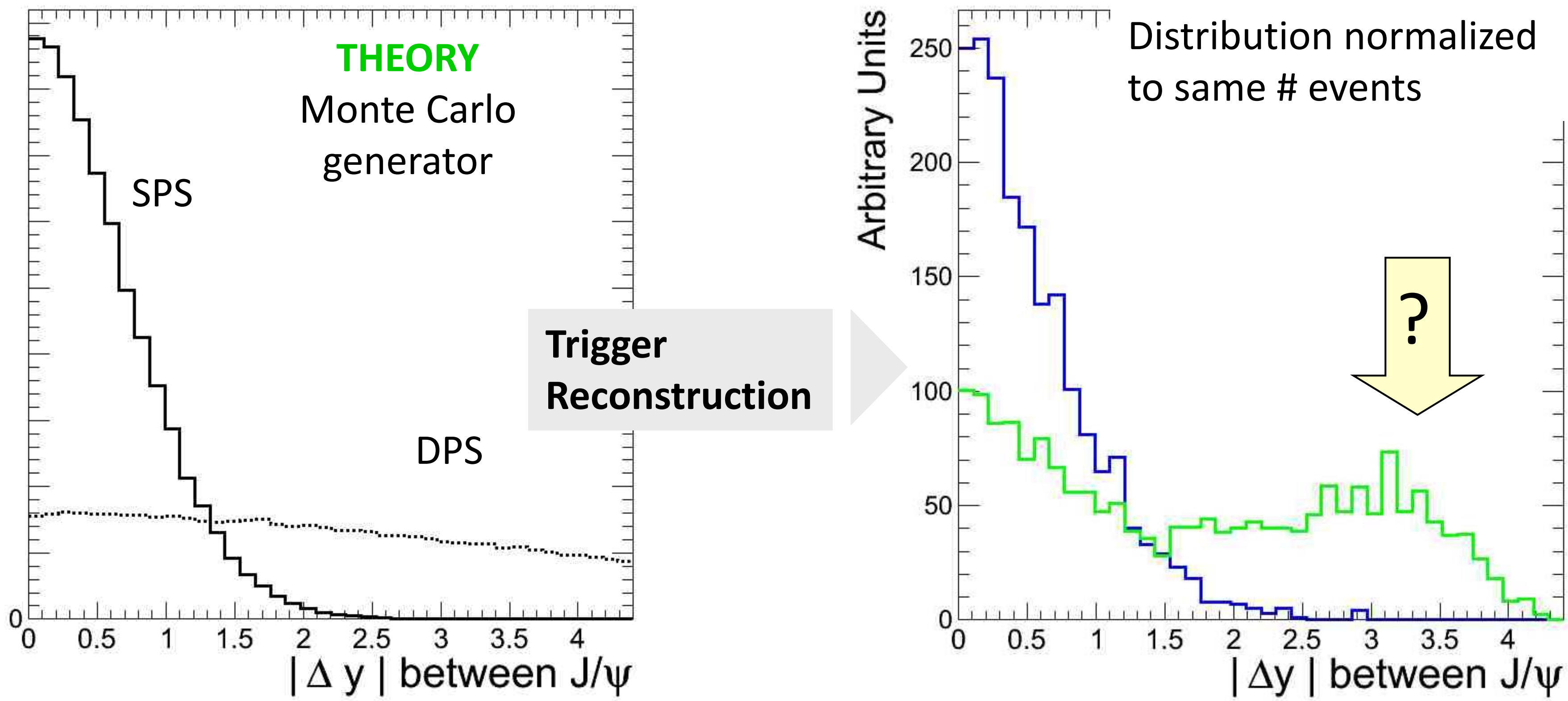
- Measurement of Double J/ψ



- Models not developed for CMS acceptance
  - Assumes dominance of SPS, CS production, e.g.

  [Novoselov, arXiv:1106.2184v1]
- Expect distinct differences between different models
  - SPS/DPS in $|\Delta y|$
  - CS/CO in p_T

- Measurement of Double J/ψ



Reverse engineer the cross section from data

→ model independent!

CMS is in kinematic regime complementary to LHCb

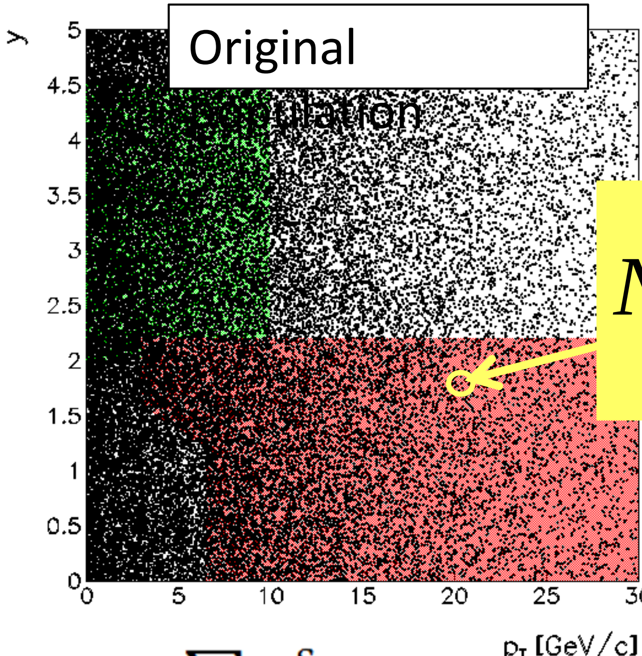
- # Event-by-event Correction of Signal Yield

Least Model Dependence

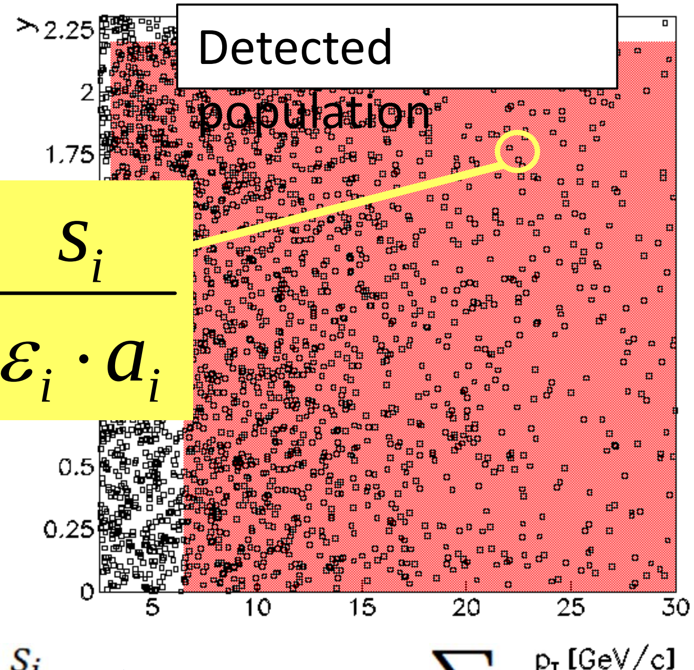
Observed event = event probability
that it was produced within J/ψ window

- muons fall within CMS detector a_i
- muons were triggered&detected ε_i
- is signal s_i

Original population



Detected population



$$N_i = \frac{s_i}{\varepsilon_i \cdot a_i}$$

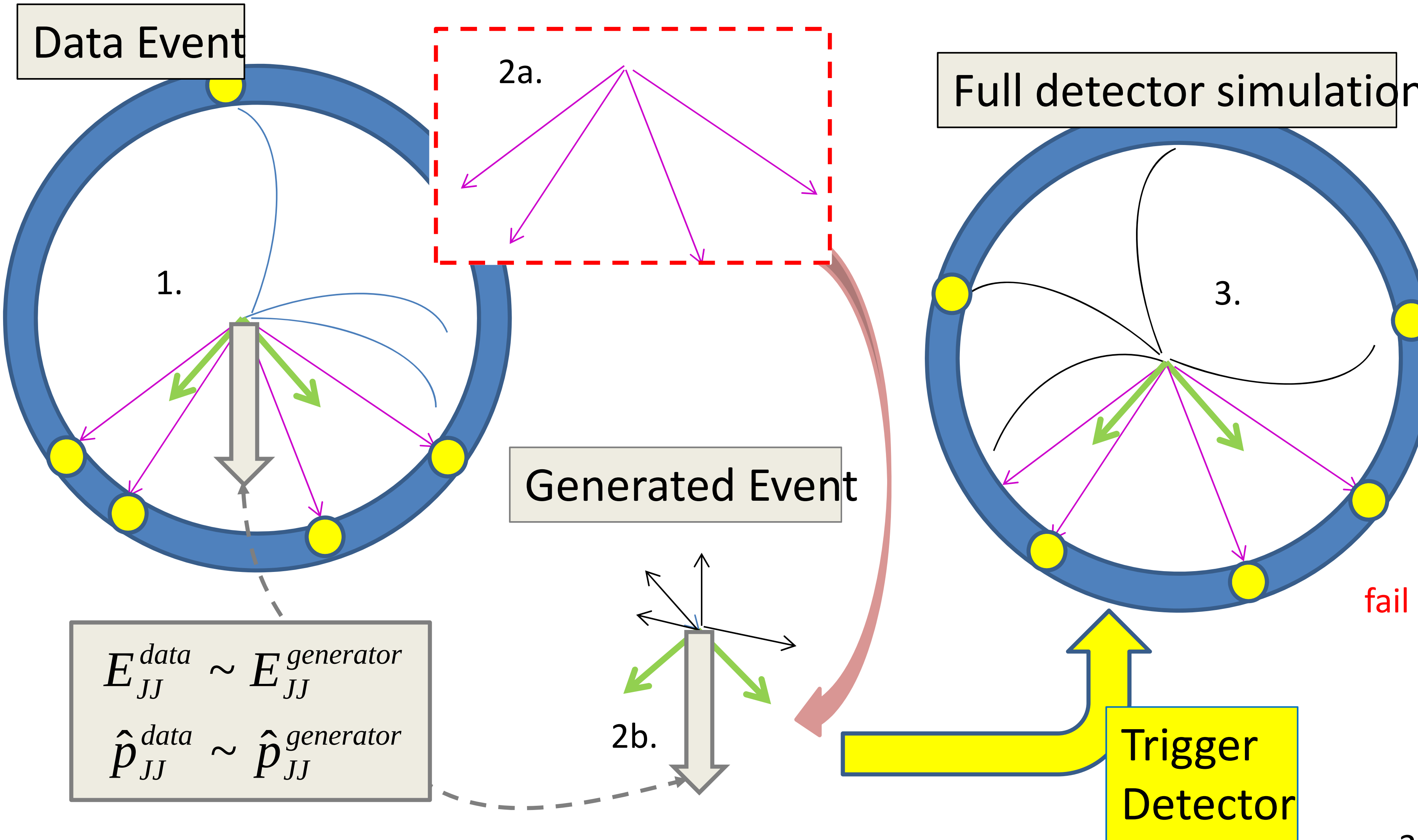
$$\sum_i \frac{s_i}{\epsilon_i \cdot a_i} \leftarrow \sum_i \frac{s_i}{\epsilon_i} \leftarrow \sum_i s_i$$

Signal population within J/ψ acceptance region	Signal population within J/ψ and muon acceptance region	Detected signal population

- Efficiency ε_i - Muon Substitution Method

Place the measured muon 4-momenta in a simulated event

Ensure energy and momentum conservation in approximation



$$E_{JJ}^{data} \sim E_{JJ}^{generator}$$
$$\hat{p}_{JJ}^{data} \sim \hat{p}_{JJ}^{generator}$$

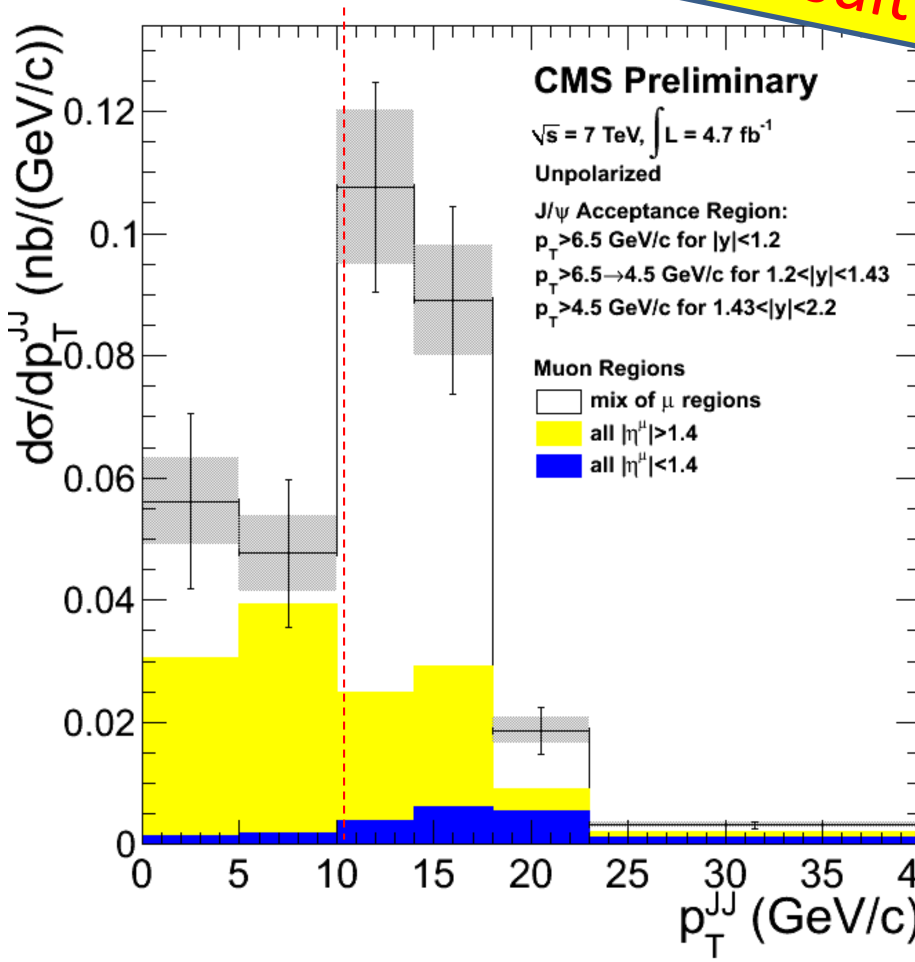
- Differential Cross Section

New Result

nb/(GeV/c)

p_T [GeV/c]	$d\sigma/dp_T$	Stat. Err.	Syst. Err.
0-5	0.056	0.007	0.012
5-10	0.048	0.006	0.010
10-14	0.108	0.013	0.012
14-18	0.089	0.009	0.012
18-23	0.019	0.002	0.003
23-40	0.003	0.0004	0.0004

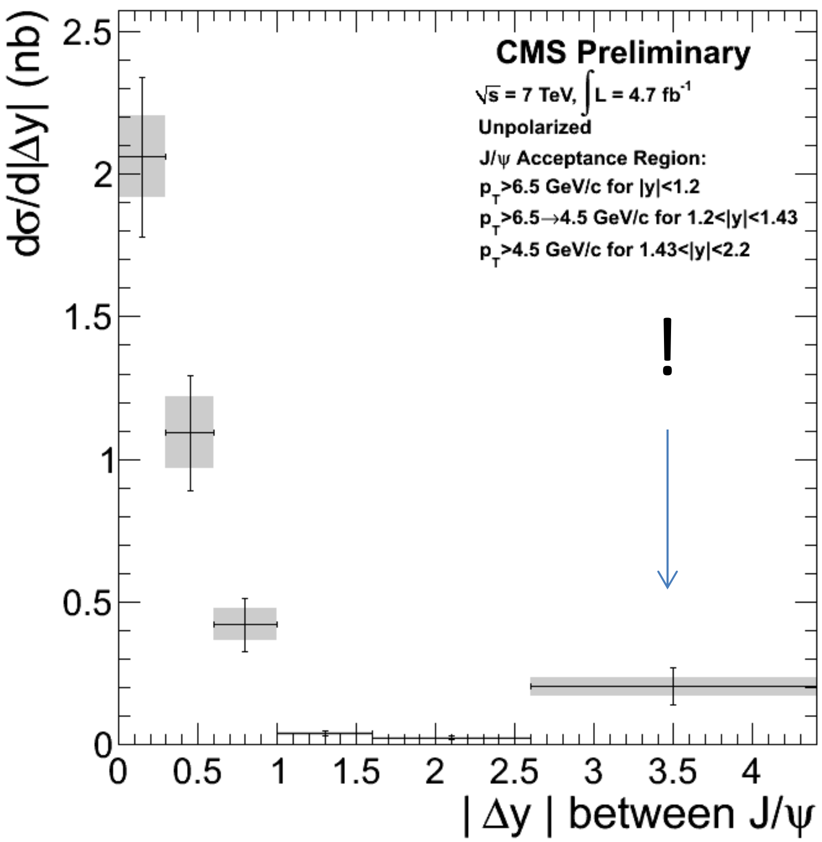
$\|y\| < 1.2$	pT > 6.5 GeV/c
$1.2 < \|y\| < 1.43$	pT > 6.5→4.5 GeV/c
$1.43 < \|y\| < 2.2$	pT > 4.5 GeV/c

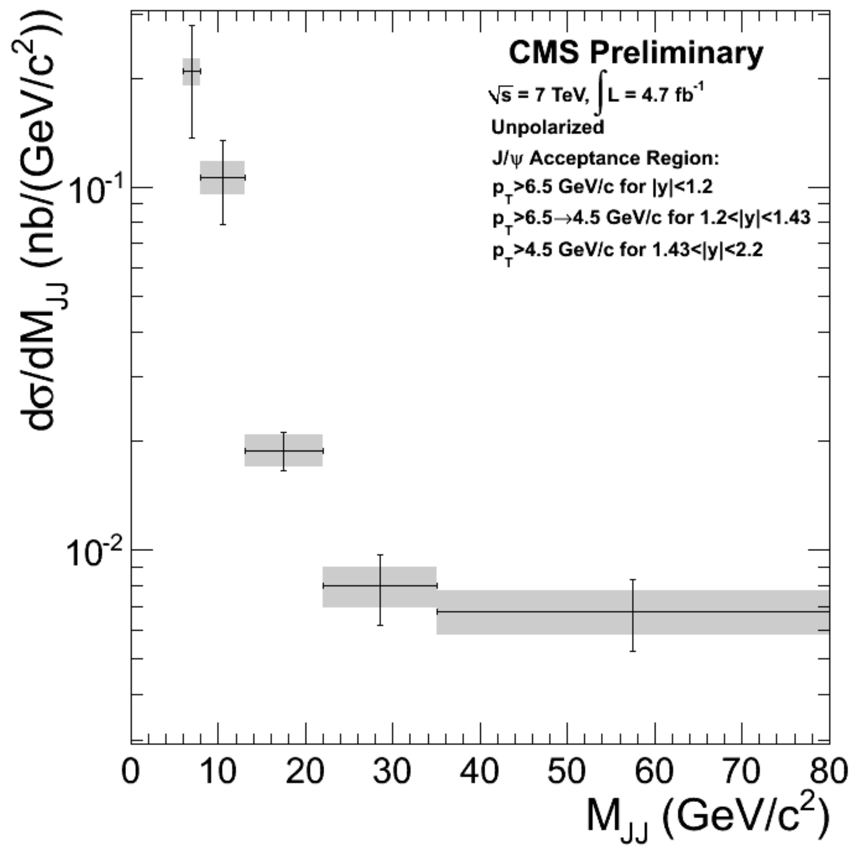


$$\frac{d\sigma(pp \to 2J/\psi + X)}{dp_T} = \sum_i \frac{N_i}{L \cdot BF(J/\psi \to \mu^+\mu^-)^2 \cdot \Delta p_T}$$

Andrew York, Thesis UTK

- Differential Cross Section





→ Published to provide input for model builders

→ Use improved generator and subject to full detector simulation

- What do others see?

Observation of J/ψ pair production in pp collisions at $\sqrt{s} = 7$ TeV

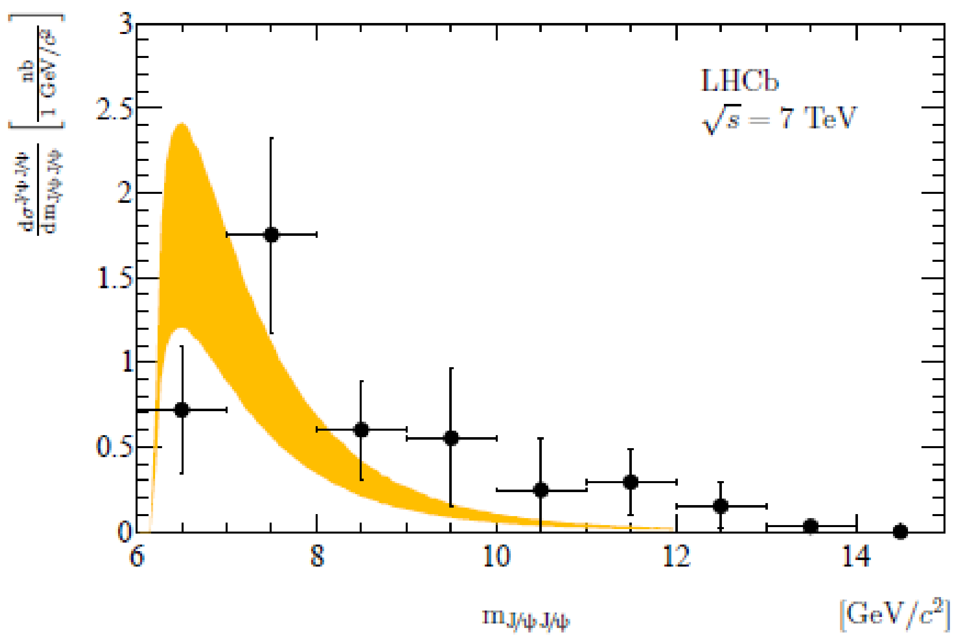
The LHCb Collaboration [1]

Abstract

The production of J/ψ pairs in proton-proton collisions at a centre-of-mass energy of 7 TeV has been observed using an integrated luminosity of 37.5 pb^{-1} collected with the LHCb detector. The production cross-section for pairs with both J/ψ in the rapidity range $2 < y^{J/\psi} < 4.5$ and transverse momentum $p_T^{J/\psi} < 10$ GeV/c is

$$\sigma^{J/\psi\, J/\psi} = 5.1 \pm 1.0 \pm 1.1 \text{ nb},$$

where the first uncertainty is statistical and the second systematic.



- What do others see?

EVIDENCE FOR ψψ PRODUCTION IN π^- INTERACTIONS AT 150 AND 280 GeV/c

NA3 Collaboration [Phys Lett B 114B (1982) 457]

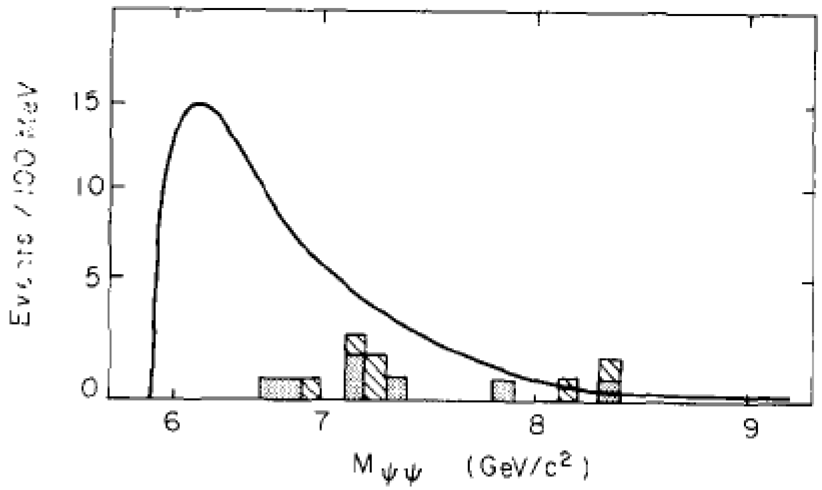
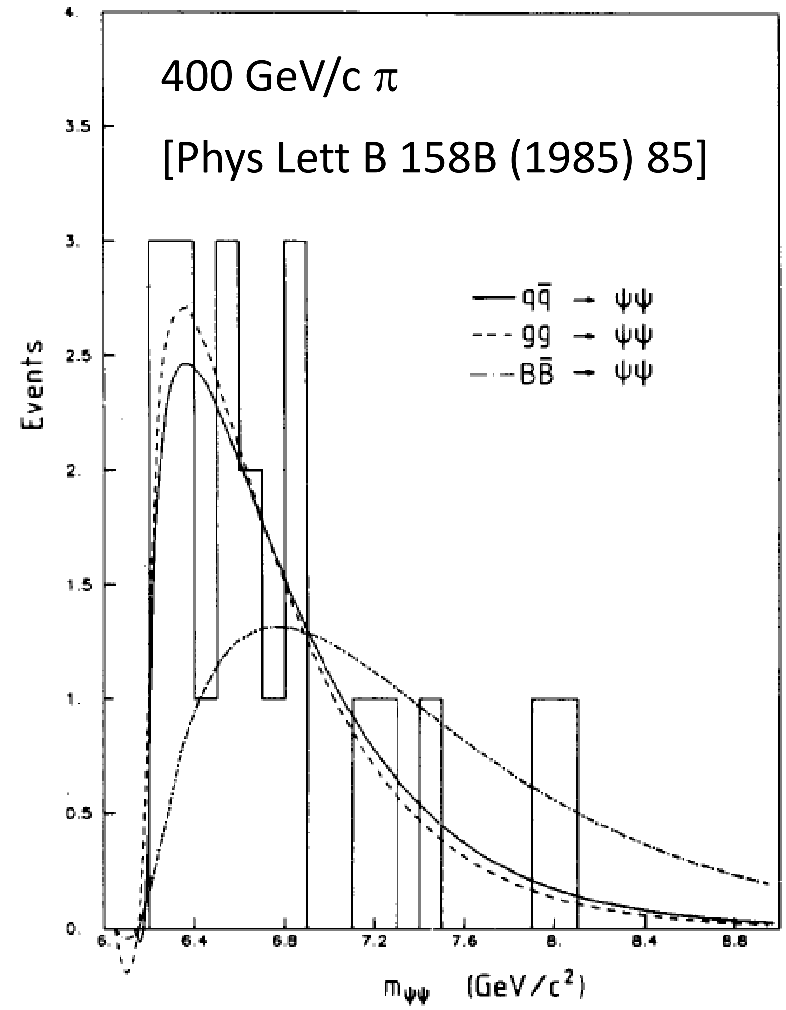


Fig. 3. ψψ invariant mass spectrum. Dashed squares: 150 GeV/c data. Dotted: 280 GeV/c data. The curve is the computed mass spectrum of uncorrelated ψψ pairs generated by Monte Carlo and accepted by the apparatus (arbitrary normalisation).



- Summary

LHC is successfully continuing particle production described by SM and beyond SM

The proton-proton collision program will continue in 2015 with the chance to turn many 3 sigma evidences into observations or nothing

We opened a new box for new particle searches that has been not accessed before

If confirmed, signals may continue the onia renaissance or even turn out to be beyond SM signals