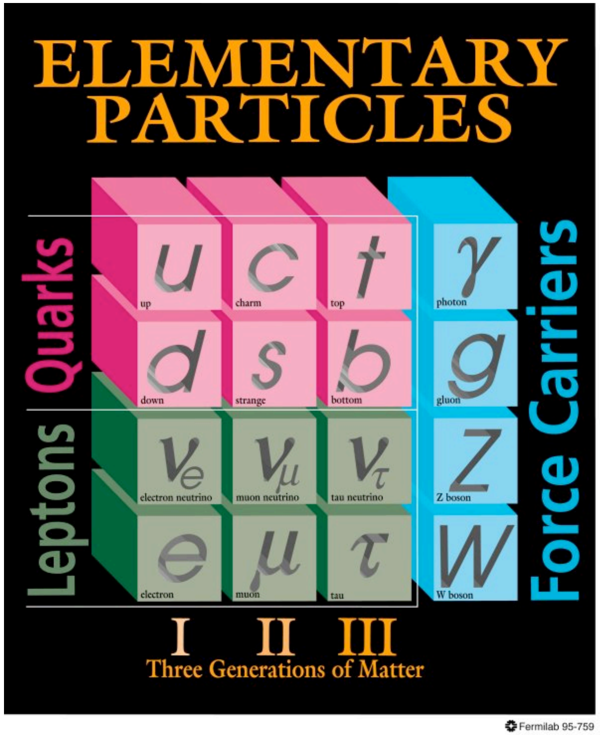
LHC上低质量多轻子末态
——从强相互作用到新物理的新机遇

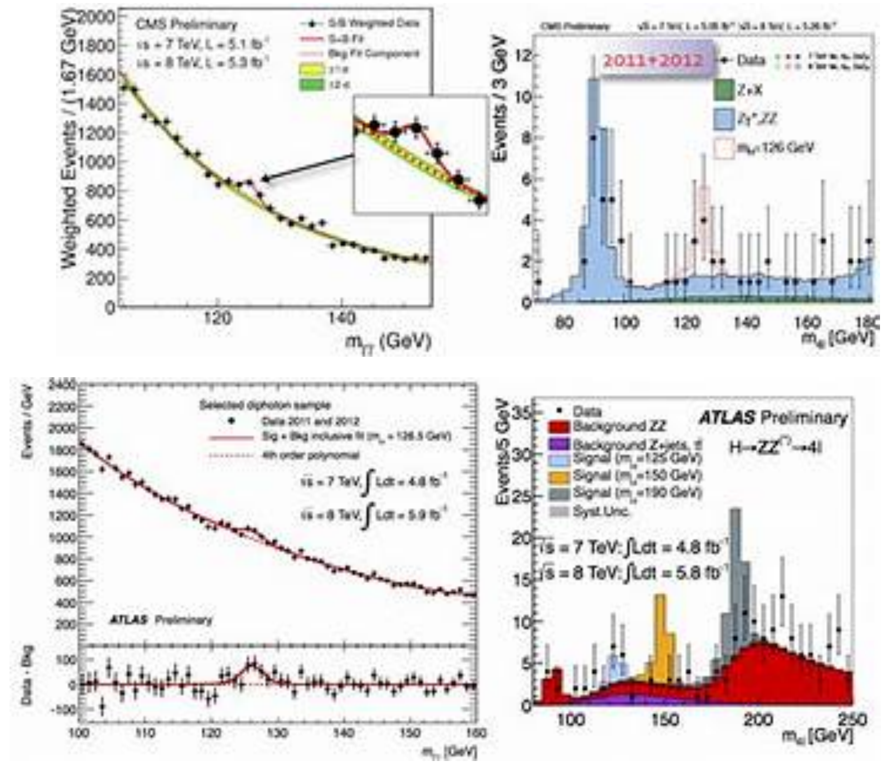
易凯——南京师范大学

中国CMS组参与单位：南师（易凯），
清华（胡震），复旦（沈成平）
(欢迎别的单位加入）

低质量多轻子末态研讨会南京，2020年6月20日

希格斯找到后找什么?





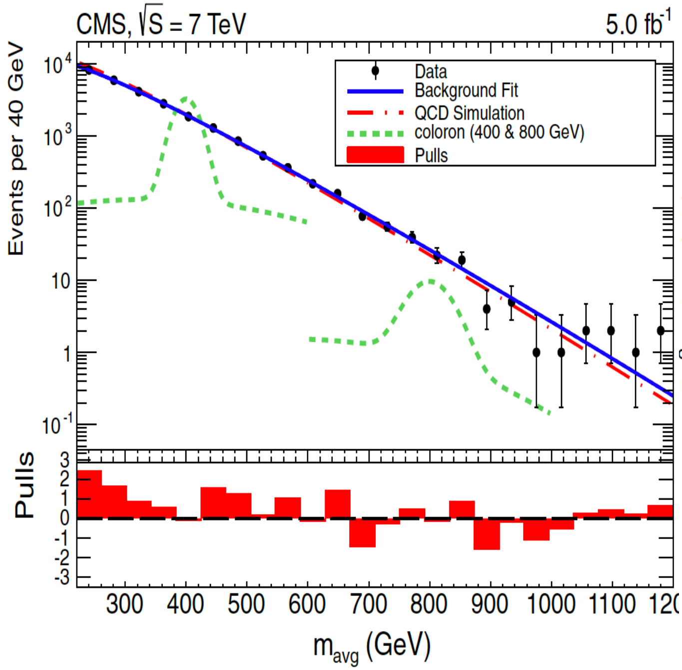
新的基本粒子? 新的作用力? 新的规律?

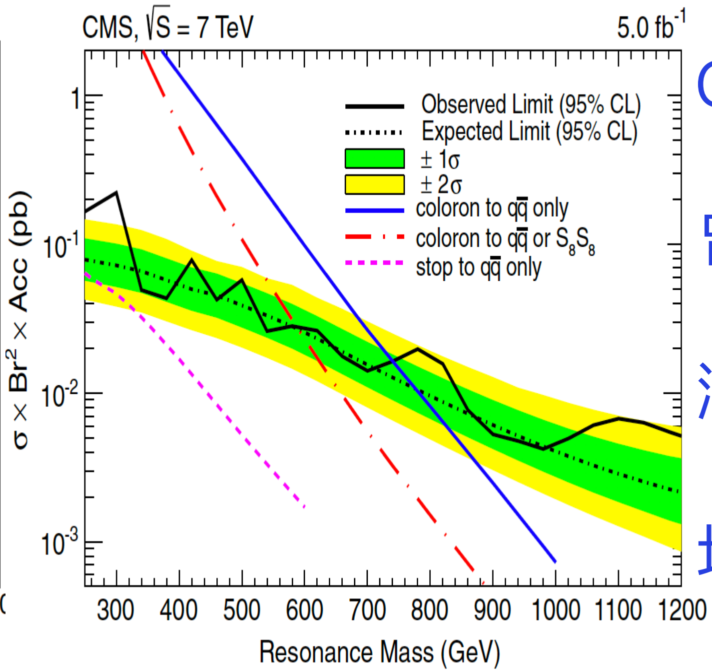
哪儿找: 高端质量区间，高端能量区间

“低端区间已经找过”

高端区间暂时没有

LHC开始时集中区间：高端喷注，轻子，光子，缺失能量等末态
目前暂时没有迹象：新粒子，新作用力，新规律
暗物质现在成为LHC的一个热点





CMS EXO-11-016

曾经“嗨”过（high）

涨落?

堆积本底?

回访低端：

缺少实验数据的低端区间

e⁺e⁻ 在不同能量区间的微分截面

http://arxiv.org/abs/hep-ph/0312114

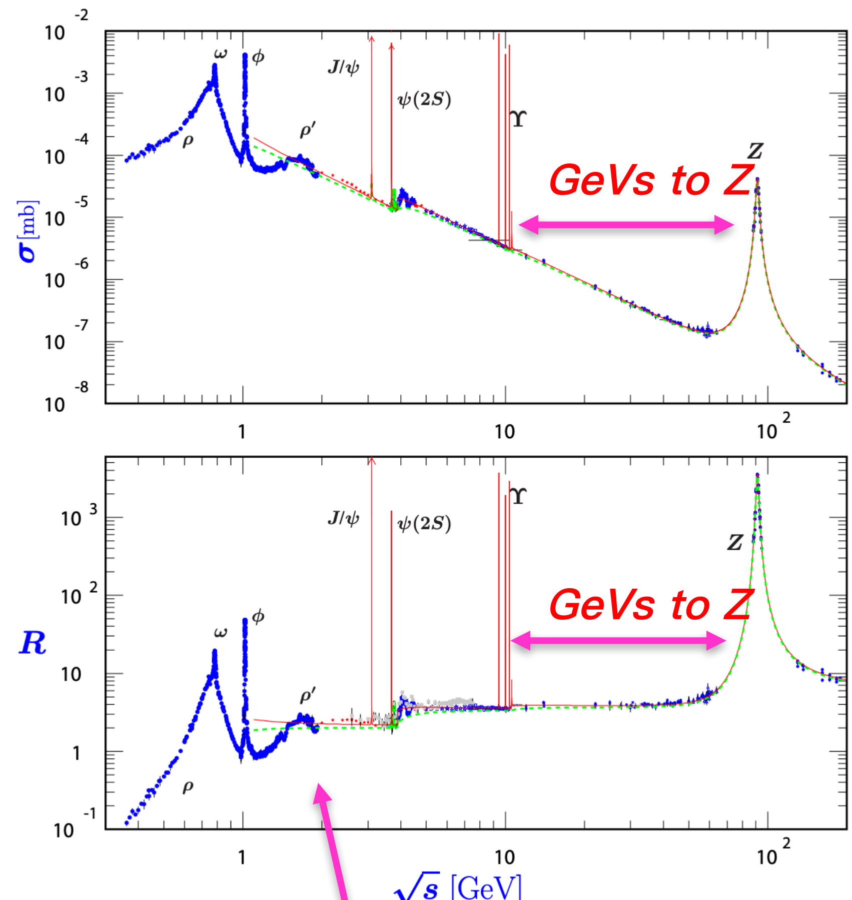


Figure 51.2: World data on the total cross section of $e^+e^- \to hadrons$ and the ratio $R(s) = \sigma(e^+e^- \to hadrons, s)/\sigma(e^+e^- \to \mu^+\mu^-, s)$. $\sigma(e^+e^- \to hadrons, s)$ is the experimental cross section corrected for initial state radiation and electron-positron vertex loops, $\sigma(e^+e^- \to \mu^+\mu^-, s) = 4\pi\alpha^2(s)/3s$. Data errors are total below 2 GeV and statistical above 2 GeV. The curves are an educative guide: the broken one (green) is a naive quark-parton model prediction, and the solid one (red) is 3-loop pQCD prediction (see "Quantum Chromodynamics" section of this *Review*, Eq. (9.7) or, for more details, K. G. Chetyrkin *et al.*, Nucl. Phys. **B586**, 56 (2000) (Erratum *ibid.* **B634**, 413 (2002)). Breit-Wigner

Experiment	E_{cm} [GeV]
* ADONE-MEA	2.23
BEPC-BES	2.0 - 4.8
BEPC-BES	2.6 - 5.0
* SPEAR-SMAG †	2.4 - 5.0
* SPEAR-SMAG+LGW	3.598 - 3.886
SPEAR-Crystal Ball	3.670 - 4.496
SPEAR-Crystal Ball	5.0 - 7.4
SLAC-MARK-II	3.670 - 3.872
DORIS-DASP	3.6025 - 5.1950
DORIS-II-LENA	7.440 - 9.415
* DORIS-II-ARGUS	9.360
DORIS-II-Crystal Ball	9.39 - 9.46
* DORIS-II-DHHM	9.45 - 10.04
DORIS-II-DASP	9.51
VEPP-4-MD1	7.30 - 10.29
CESR-CUSB	10.43 - 11.09
CESR-CLEO	10.49
CESR-CLEO ††	10.60 - 11.20
CESR-CLEO II	10.52
DORIS/PETRA-PLUTO	3.6 - 30.8
* PETRA-TASSO	12.0 - 41.4
* PETRA-TASSO	12.00 - 31.25
* PETRA-TASSO	14.03 - 43.70
PETRA-TASSO	41.45 - 44.20
PETRA-JADE	12.00 - 46.47
PETRA-MARK-J	12.00 - 46.47
* PETRA-MARK-J	31.57
* PETRA-MARK-J	34.85
PETRA-CELLO	14.0 - 46.6
PEP-MAC	29.0
* PEP-MARK-II	29.0
* TRISTAN-AMY	50.0 - 61.4
* TRISTAN-TOPAZ	50.0 - 61.4
* TRISTAN-TOPAZ	57.77
* TRISTAN-TOPAZ	57.37 - 59.84
* TRISTAN-VENUS	50.0 - 52.0
* TRISTAN-VENUS	63.6 - 64.0

A) 从几个GeV到Z质量(90 GeV)区间 缺少e⁺e⁻ 实验数据

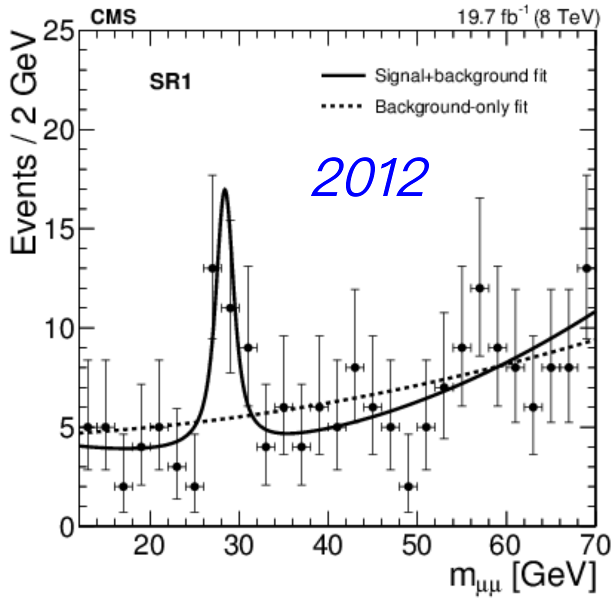
B) 此区间对各种物理模型的限制少

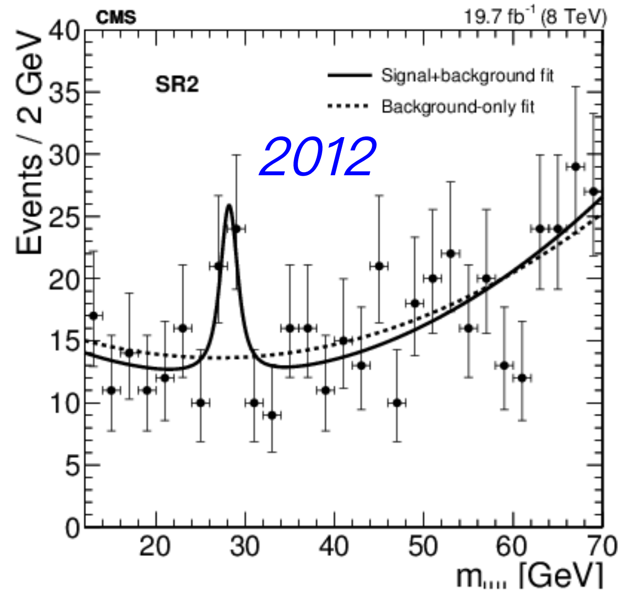
BES 合作组对此区间的贡献巨大

LHC给我们对未知世界的新窗口
(低端质量区间的多轻子末态)

可能的新物理迹象

arXiv:1808.01890 [hep-ex]
JHEP 11 (2018) 161

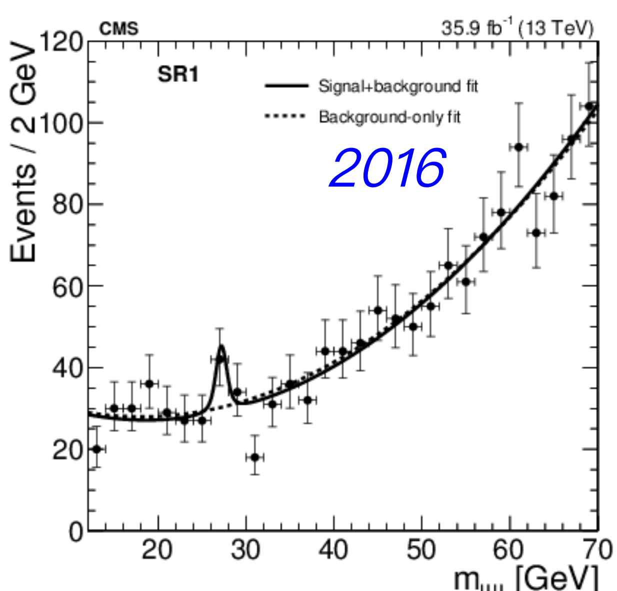


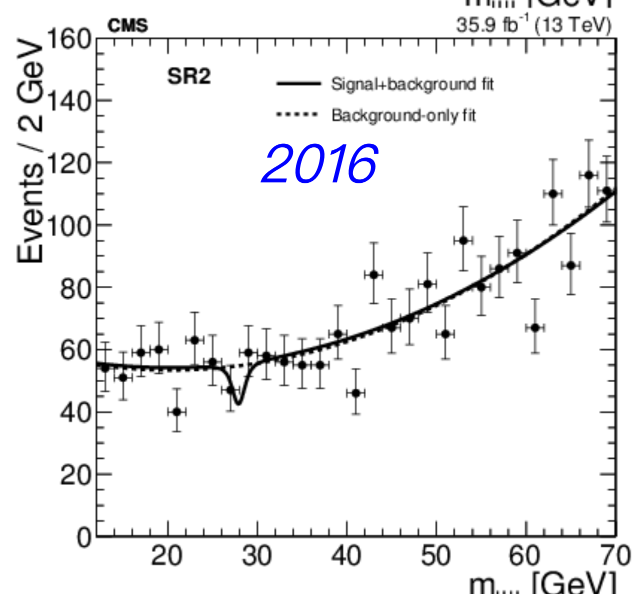


ATLAS 没看见
灵敏度一样?

2017数据 ?

2018数据?





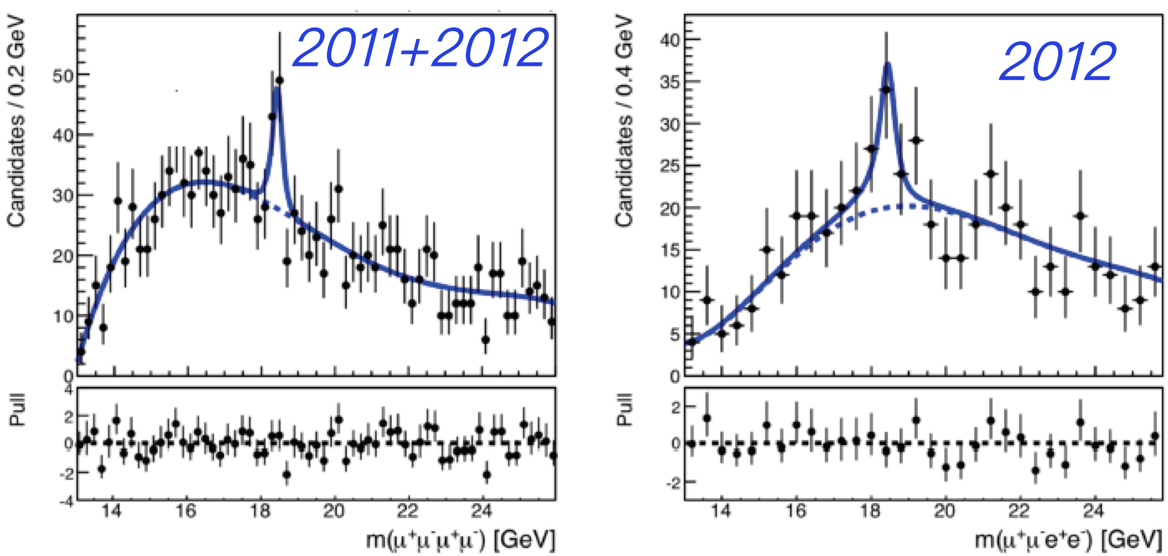
如果为真，指向新物理

对LHC低质量区间的一次探索

可能的强相互作用或新物理迹象

http://meetings.aps.org/Meeting/APR18/Session/U09.6

Combined Result



- Do a simultaneous fit to both channels, with fixed signal shapes but floating mass value.
- Best mass : 18.4 ± 0.1 (stat.) ± 0.2 (syst.) GeV
- Local Significance: 4.86σ ($p\_value = 5.8\times10^{-7}$)

- In order to calculate global significance, Look-Elsewhere-Effect must be taken into account. Lots of toy MC generations are required, not an efficient method.
- Global significance is calculated using Gross-Vitells method which is used in Higgs discovery.

Eur.Phys.J.C70:525-530,2010

12

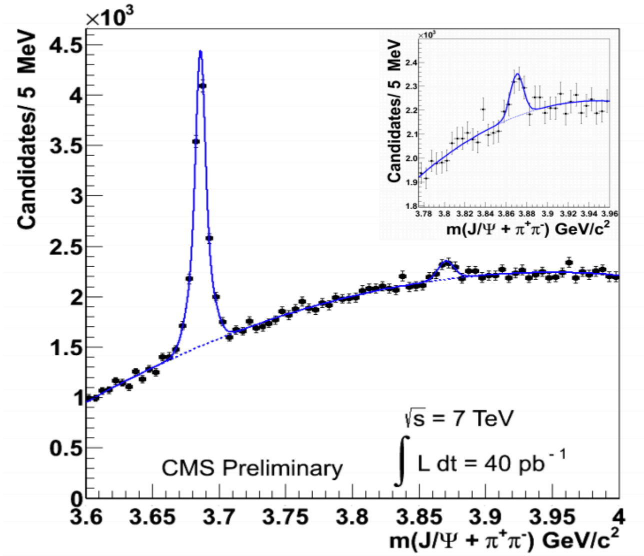
- The returned global significance was 3.6σ.

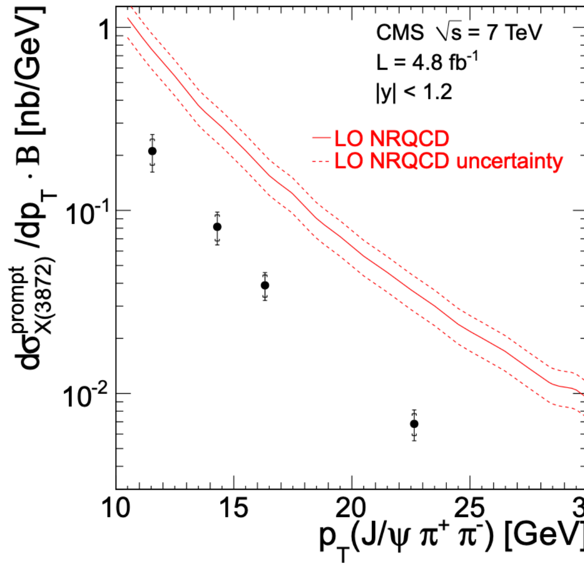
Run II(2016+2017+2018)数据?

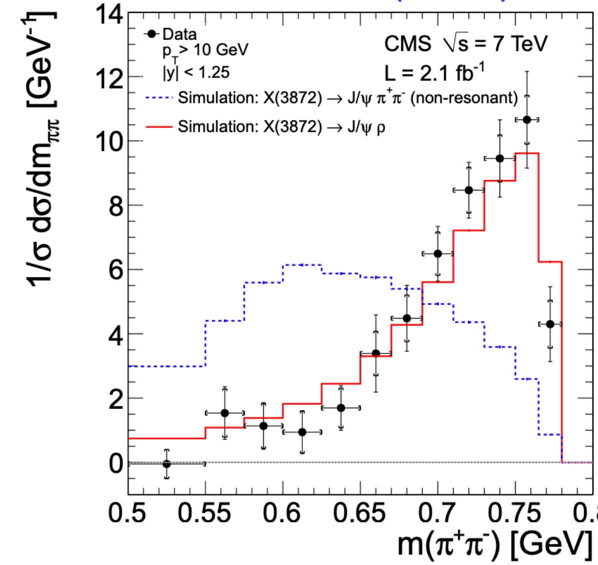
如果为真，可能是强相互作用的一个突破亮点，或者更有意思的东西

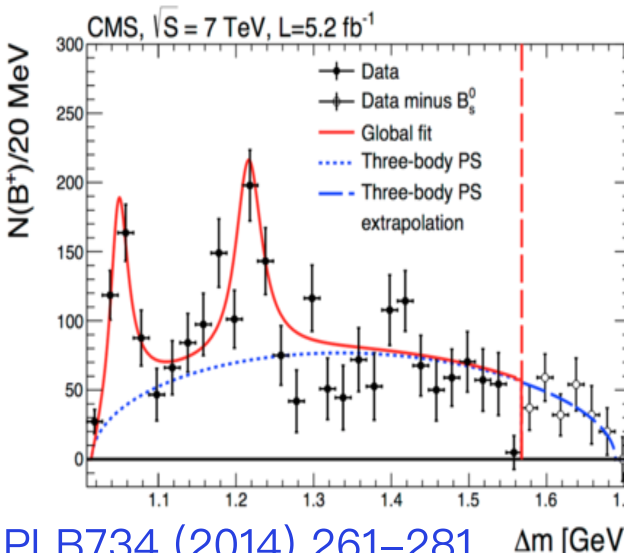
强相互作用的机遇—CMS对奇特强子已有的贡献

JHEP 04 (2013) 154

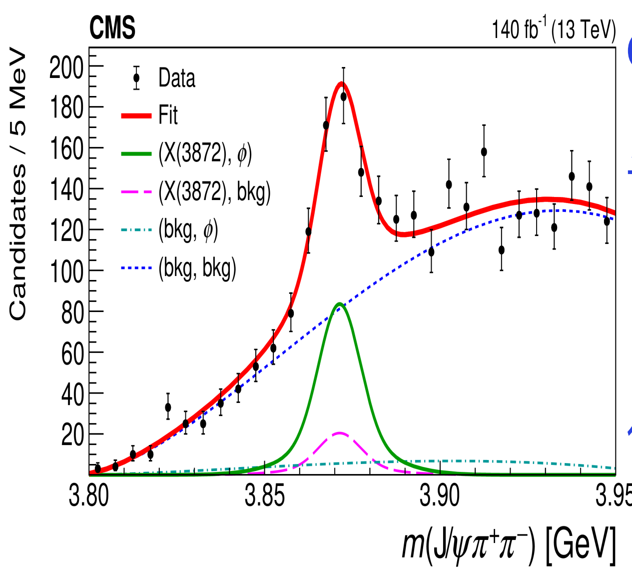








PLB734 (2014) 261–281



2005.04764 [hep-ex]

CMS探测器质量分辨率好

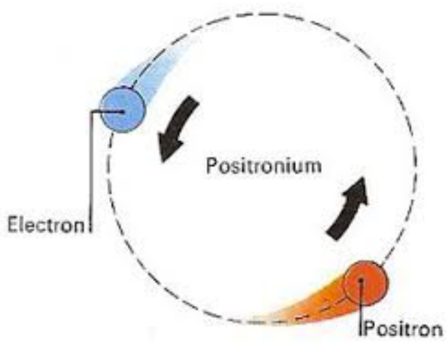
谬子鉴别力强

电磁量能器分辨率好

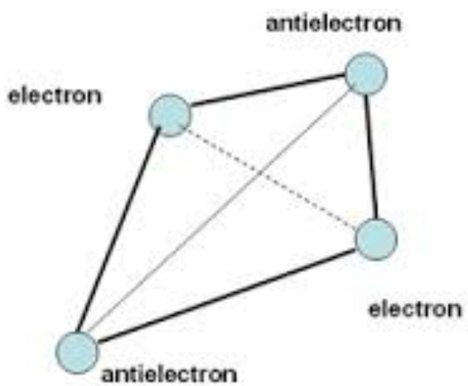
低能轻子优于ATLAS/LHCb

电子的“分子结构”

Positronium (1951)



positronium molecule (2007)



Vol 449 | 13 September 2007 | doi:10.1038/nature06094 nature

Nature letter LETTERS

The production of molecular positronium

D. B. Cassidy[1] & A. P. Mills Jr[1]

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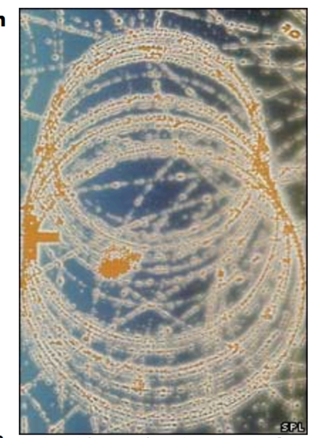
Mirror particles form new matter

By Jonathan Fildes
Science and technology reporter, BBC News

Fragile particles rarely seen in our Universe have been merged with ordinary electrons to make a new form of matter.

Di-positronium, as the new molecule is known, was predicted to exist in 1946 but has remained elusive to science.



Antiparticles are the mirror image of ordinary particles

Now, a US team has created thousands of the molecules by merging electrons with their antimatter equivalent: positrons.

The discovery, reported in the journal Nature, is a key step in the creation of ultra-powerful lasers known as gamma-ray annihilation lasers.

在夸克层次上有没有类似结构？（cccc），（bbbb）
一个可能在夸克层次上研究多体动力学的领域：束缚态，共振态

全重味奇特强子

- **较早的理论文章**

（cccc） *Phys. Rev. D 86, 034004 (2012)*

$0^{++\prime}$: $M = 5.966\,\text{GeV}$, $M - M_{\text{th}} = -228.\,\text{MeV}$,
$1^{+-\prime}$: $M = 6.051\,\text{GeV}$, $M - M_{\text{th}} = -142.\,\text{MeV}$,

Below double J/ψ threshold
*Search via J/ψμ⁺μ⁻, J/ψ**

2^{++} : $M = 6.223\,\text{GeV}$, $M - M_{\text{th}} = 29.5\,\text{MeV}$.

Above double J/ψ threshold
Search via J/ψJ/ψ

（bbcc）

$0^{++}a$: $M = 12.359\,\text{GeV}$, $M - M_{\text{th}} = -191.\,\text{MeV}$
$0^{++}b$: $M = 12.471\,\text{GeV}$, $M - M_{\text{th}} = -78.7\,\text{MeV}$,
$1^{+-}a$: $M = 12.424\,\text{GeV}$, $M - M_{\text{th}} = -126.\,\text{MeV}$
$1^{+-}b$: $M = 12.488\,\text{GeV}$, $M - M_{\text{th}} = -62.5\,\text{MeV}$,
1^{++} : $M = 12.485\,\text{GeV}$, $M - M_{\text{th}} = -64.9\,\text{MeV}$,

Below double B_c threshold
J/ψY(1S) threshold
? …

2^{++} : $M = 12.566\,\text{GeV}$, $M - M_{\text{th}} = 16.1\,\text{MeV}$.

Above double B_c threshold
J/ψY(1S) threshold
Search via the above two channels

（bbbb）

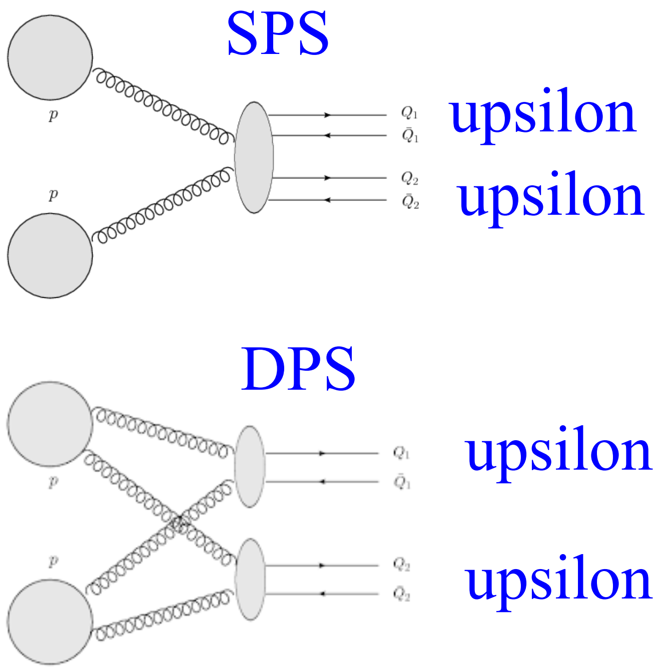
$0^{++\prime}$: $M = 18.754\,\text{GeV}$, $M - M_{\text{th}} = -544.\,\text{MeV}$,
$1^{+-\prime}$: $M = 18.808\,\text{GeV}$, $M - M_{\text{th}} = -490.\,\text{MeV}$,
2^{++} : $M = 18.916\,\text{GeV}$, $M - M_{\text{th}} = -382.\,\text{MeV}$.

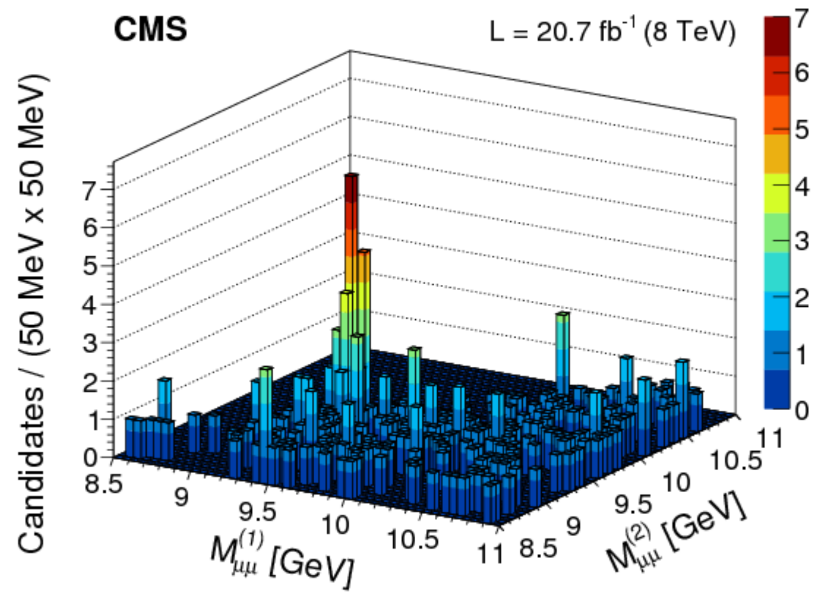
Below double Y(1S) threshold
Search via Y(1S)μ⁺μ⁻

如果能建立这样的态，就是一个突破，特别是束缚态。
全重味态是一个特别简单的系统，有利模型建立，检验，推广

Υ(1S)Υ(1S) 截面 @ 8 TeV—基准测量

JHEP 1705 (2017) 013





Υ(1S)Υ(1S) cross section at pp collision energy @8 TeV:

$$\sigma(pp \to \Upsilon\Upsilon) = 68.8 \pm 12.7(stat) \pm 7.4(syst) \pm 2.8(BR)pb$$

在CMS寻找全重味奇特强子的基准测量准备
对在此量级的奇特态有一定的灵敏度

强相互作用的机遇—全粲重味奇特强子机遇

PLB773 （2017） 247–251

J^{PC}	Currents	m_{X_c}(GeV)
0^{++}	J_1	6.44 ± 0.15
	J_2	6.59 ± 0.17
	J_3	6.47 ± 0.16
	J_4	6.46 ± 0.16
	J_5	6.82 ± 0.18

cccc--Kuang-Ta Chao

宽度：几十MeV

12 FERMILAB-Pub-80/70-THY

Table I(a). The quantum numbers and masses for the $(cc)_{\bar{3}}^{*} - (\overline{cc})_{3}$ states (without spin-dependent forces between two clusters)

L	S	J^{PC}	Mass (GeV)
1	0	1^{--}	6.55
	1	$0^{-+}, 1^{-+}, 2^{-+}$	
	2	$1^{--}, 2^{--}, 3^{--}$	
2	0	2^{++}	6.78
	1	$1^{+-}, 2^{+-}, 3^{+-}$	
	2	$0^{++}, 1^{++}, 2^{++}, 3^{++}, 4^{++}$	
3	0	3^{--}	6.98
	1	$2^{-+}, 3^{-+}, 4^{-+}$	
	2	$1^{--}, 2^{--}, 3^{-+}, 4^{--}, 5^{--}$	

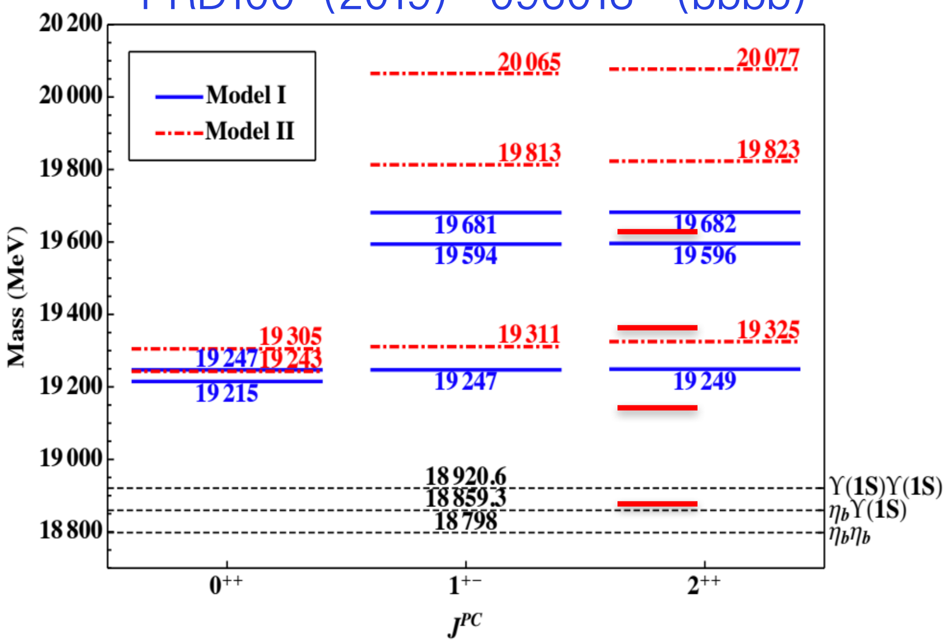
同样J^{PC}，理论预测好几个质量很接近的态

不同态之间干涉以及与本底的干涉
（最近有分波分析专家加入南师）

CMS寻找以及截面测量正在进行中

强相互作用的机遇—全美(beauty)重味奇特强子机遇

PRD100（2019） 096013 （bbbb）



共振态全在YY阈值之上

阈值之下无束缚态

Lattice QCD在阈值之下没有束缚态

美+美+美+美=美上加美！

上苍的礼物

同样J^{PC}，理论预测好几个质量很接近的态

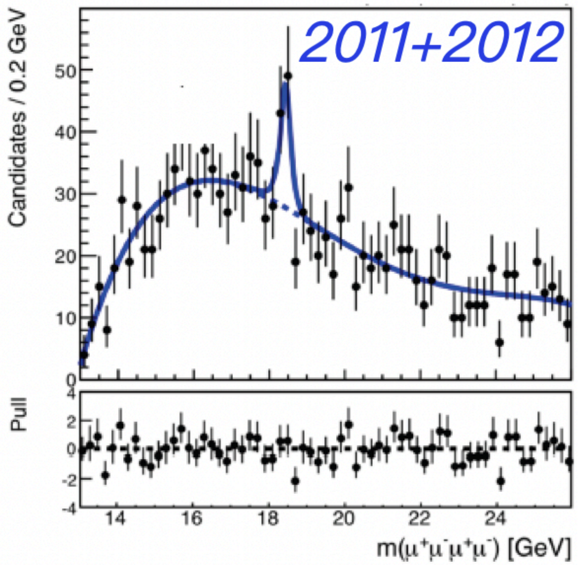
需要考虑不同态之间的干涉以及与本底的干涉（最近有分波分析专家加入南师）

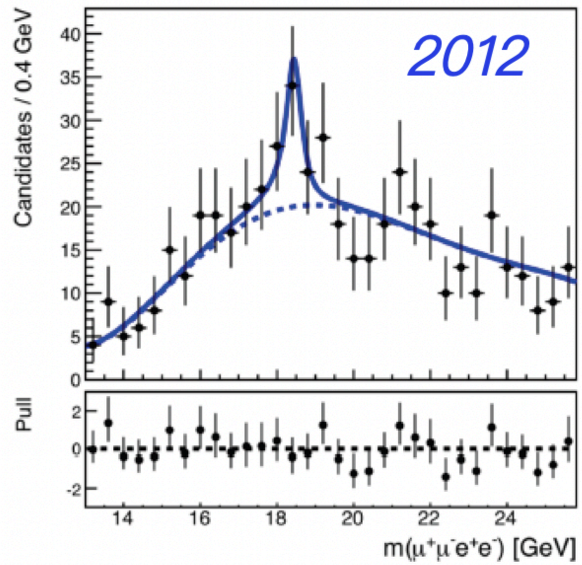
CMS寻找以及截面测量正在进行中

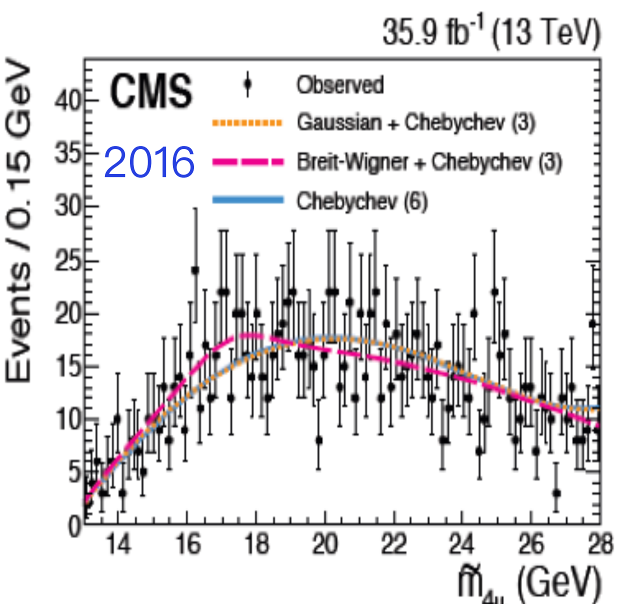
（bbcc）也可寻找（受触发影响）

新物理的机遇—18GeV超出是否存在

http://meetings.aps.org/Meeting/APR18/Session/U09.6





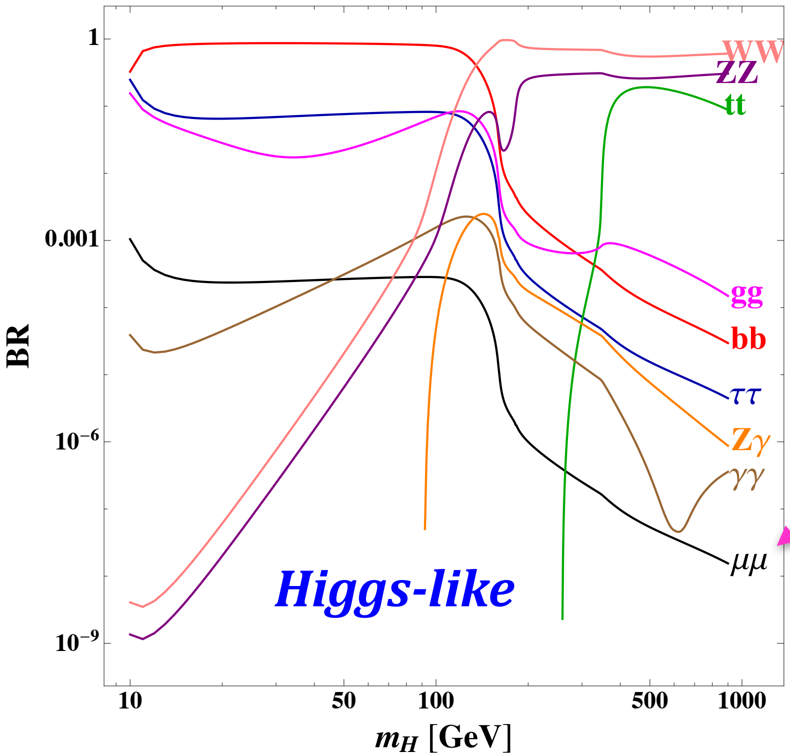


CMS (2016+2017+2018)数据分析进行中

是否存在需要数据说话

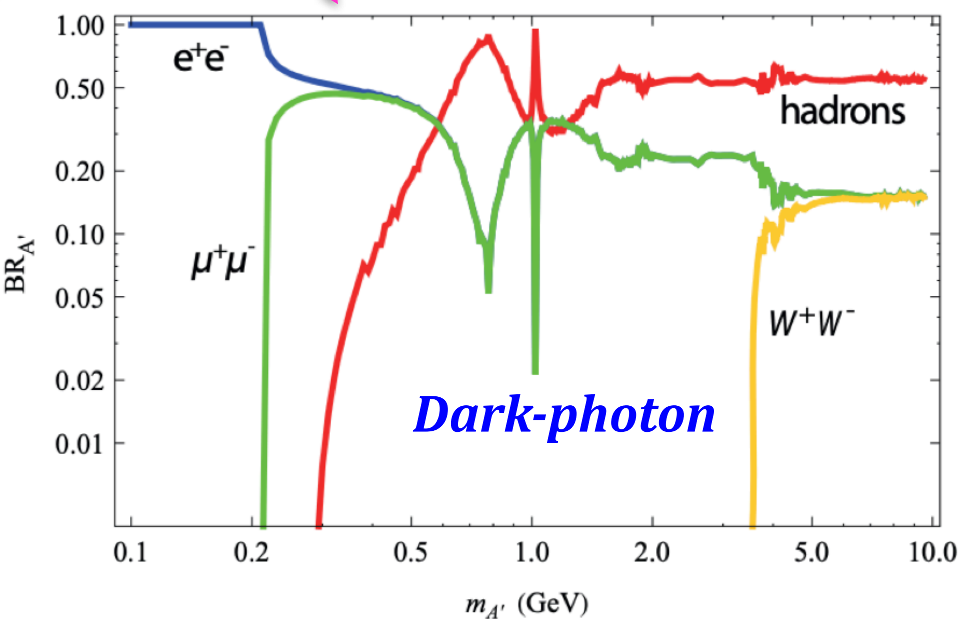
如果存在，尚不清楚为何物

新物理的机遇—还有什么?



这一区间有许多可能的模型

Leptonic decays can be significant signatures experimentally to identify



更高质量区间?

直接耦合到多轻子
（没有任何共振态在末态）

CEPC的反冲质量法

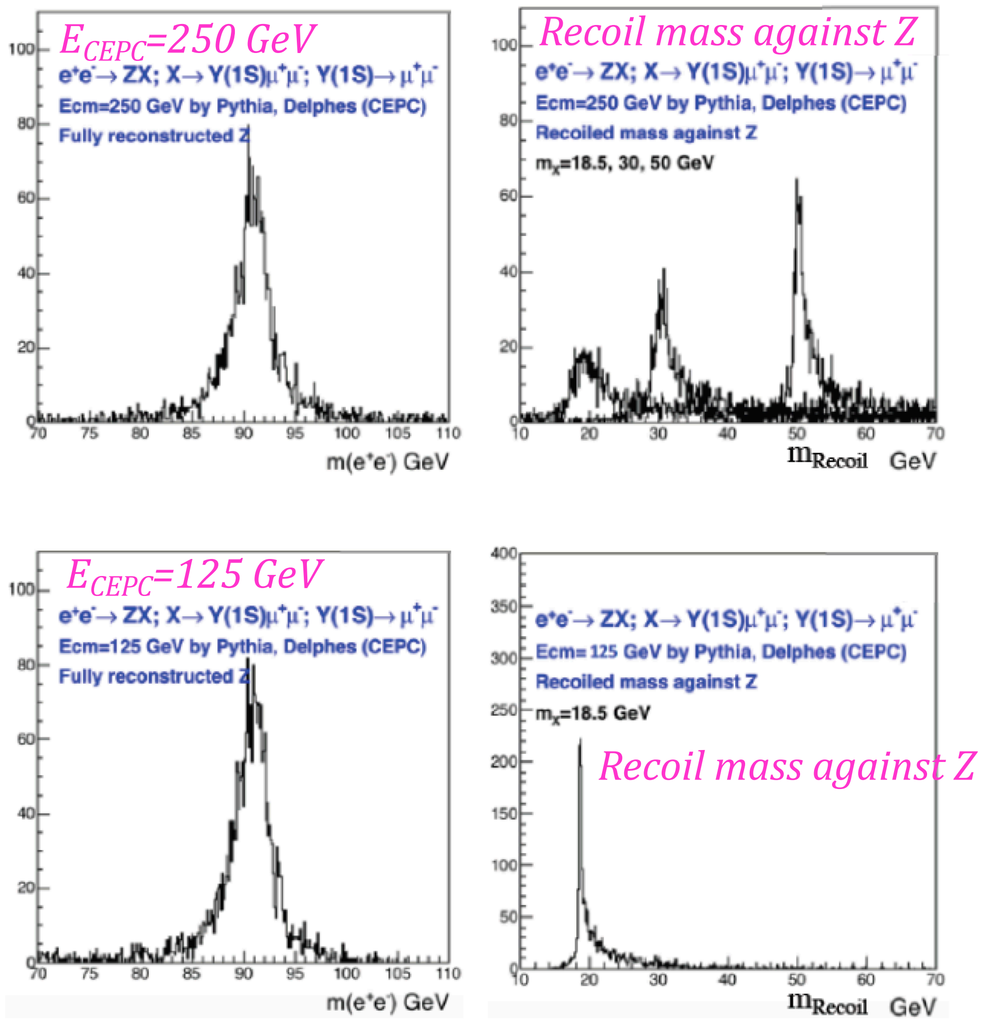


Fig. 2. The fully reconstructed Z mass and its recoiled mass against Z particle at the CEPC with different collision energy by assuming X particle mass as 18.5, 30 and 50 GeV produced in the process of $e^+e^- \to ZX$; $X \to \Upsilon(1S)\mu^+\mu^-$; $\Upsilon(1S) \to \mu^+\mu^-$. These events are simulated by Delphes with CEPC configuration.

IJMA, vol.33, 1850224

在不同对撞能量下
使用Delphes模拟CEPC

反冲质量法：
e^+e^- 对撞机独有的研究方法

包括所有末态

可用于测量分支比

CEPC上其他末态-- $\tau^+\tau^-$ 末态

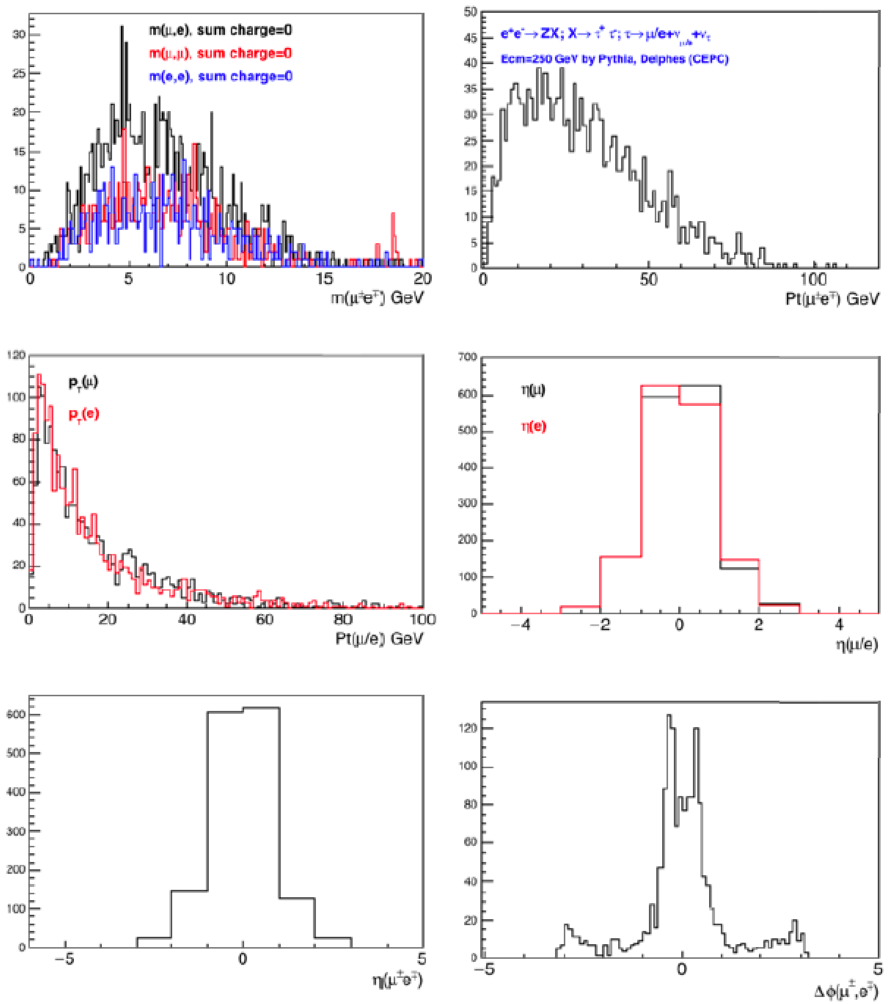


Fig. 7. The features of the $\mu^{\pm}e^{\mp}$ $(\tau^{\pm}\tau^{\mp})$ system in the $e^+e^- \to ZX$; $X \to \tau^{\pm}\tau^{\mp}$; $\tau^{\pm} \to \ell^{\pm}$ + anything-else, $\tau^{\mp} \to \ell^{\mp}$ + anything-else, where $\ell = \mu$, e process at the CEPC: (top left) the $\mu^{\pm}e^{\mp}/\mu^{\pm}\mu^{\mp}/e^{\pm}e^{\mp}$ mass distributions; (top right) the p_T distributions of $\mu^{\pm}e^{\mp}$; (middle left) the p_T distribution of muon and electron; (middle right) the η distribution of muon and electron; (bottom left) the η distribution of $\mu^{\pm}e^{\mp}$; (bottom right) the $\Delta\phi$ distribution between muon and electron. These events are simulated by Delphes with CEPC configuration.

IJMA, vol.33, 1850224

使用Delphes模拟CEPC

另一种研究$\tau^+\tau^-$末态的方案：CEPC上测量 μe 衰变道

CEPCE的优势

总结和讨论

- 低质量多轻子末态以前从未深入研究过

- LHC提供了前所未有的机遇
  --强相互作用
  --新物理

- CMS中国组目前处于前沿
  --近期可望在全粲/全美奇特强子首先取得结果
  --后期展望前景明亮，低动量轻子CMS有优势
  --触发至关重要，需要更多资源
  --期待更多理论指导

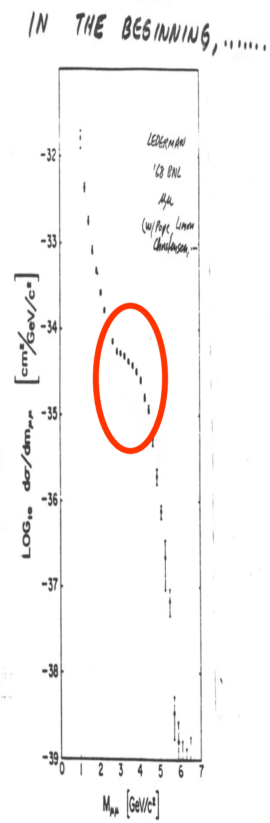
- 期待得到中国粒子物理界（理论和实验）的指导和支持！

谢谢！

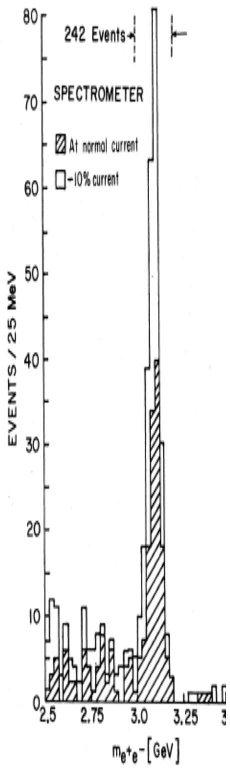
Backup

Milestones with leptonic decays

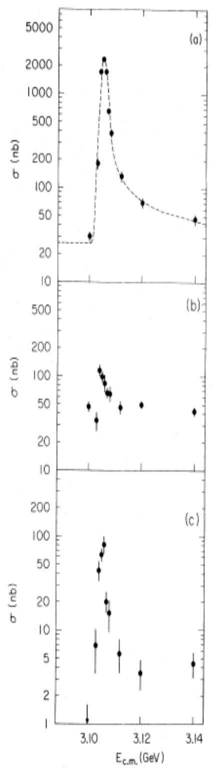
J/ψ (cc̄) ***ϒ (bb̄)*** ***Z*** ***Higgs***



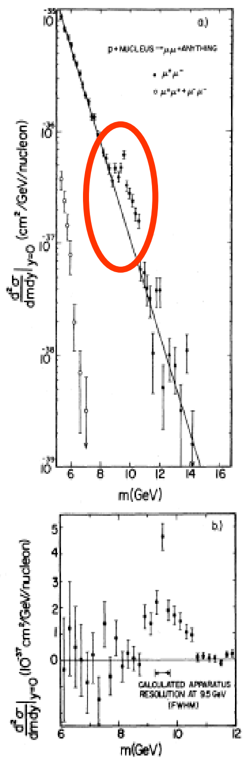
BNL-1968



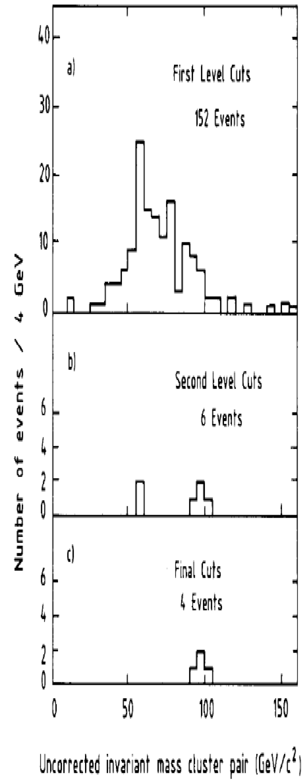
BNL-1974



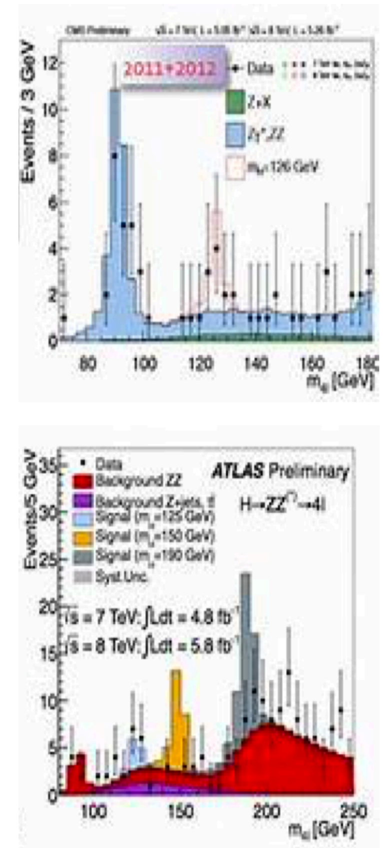
SLAC-1974



FNAL-1977



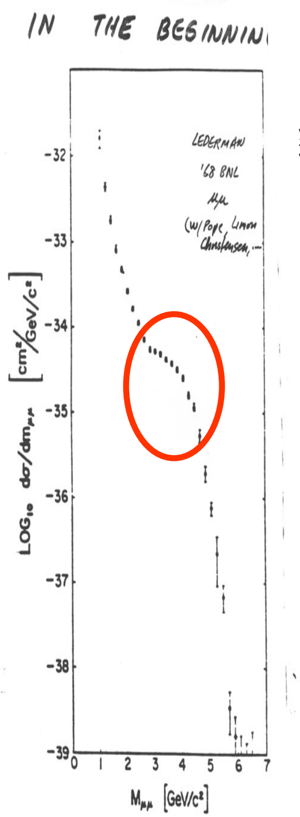
CERN-1983



CERN-2012

It is very beneficial for leptonic decays due to their clean signatures, however, anything can happen even so.

Oops-Leon



Volume 56B, number 5 PHYSICS LETTERS 26 May 1975

OBSERVATION OF HIGH MASS ELECTRON-POSITRON PAIRS PRODUCED IN PROTON-PROTON COLLISIONS AT THE CERN ISR

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Received 22 April 1975

In an experiment performed at the CERN Intersecting Storage Rings (ISR), 11 e^+e^- pairs of high invariant mass value (> 2.5 GeV/c²) have been observed. Of these events, 9 can be interpreted as arising from the reaction $p + p \to J(3.1) +$ anything. The cross-section for this reaction is estimated and compared with the result obtained at lower centre-of-mass energies.

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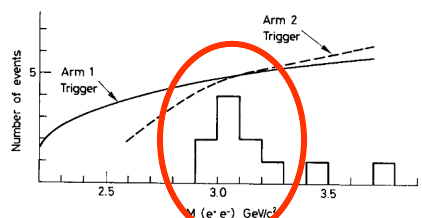


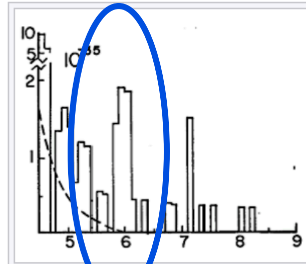
FIG. 2

Fig. 2. Invariant mass distribution for the observed e^+e^- pairs. The curves represent the shapes of the acceptance, as a function of the e^+e^- invariant mass value, for the Arm 1 and Arm 2 triggers, respectively.

cluded that the 11 e^+e^- pairs are genuine and correspond to the occurrence of reaction (1).

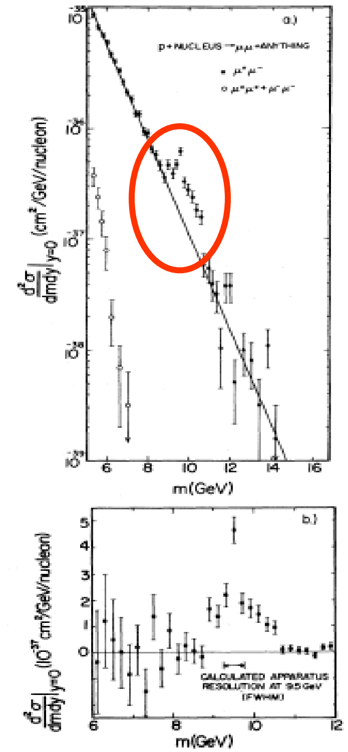
The invariant mass of each pair was calculated using the momenta of the particles as measured in the magnetic spectrometers. The distribution of invariant

Oops-Leon is the name given by particle physicists to what was thought to be a new subatomic particle "discovered" at Fermilab in 1976. The E288 experiment team, a group of physicists led by Leon Lederman who worked on the E288 particle detector, announced that a particle with a mass of about 6.0 GeV, which decayed into an electron and a positron, was being produced by the Fermilab particle accelerator.[1] The particle's initial name was the greek letter Upsilon (ϒ). After taking further data, the group discovered that this particle did not actually exist, and the "discovery" was named "Oops-Leon" as a pun on the original name and the first name of the E288 collaboration leader.[2]



A plot counting the rate of production of electron–positron pairs as a function of invariant mass (in GeV). The apparent peak around 6 GeV was initially identified as a new particle,[1] but named **Oops-Leon** when it turned out not to exist.

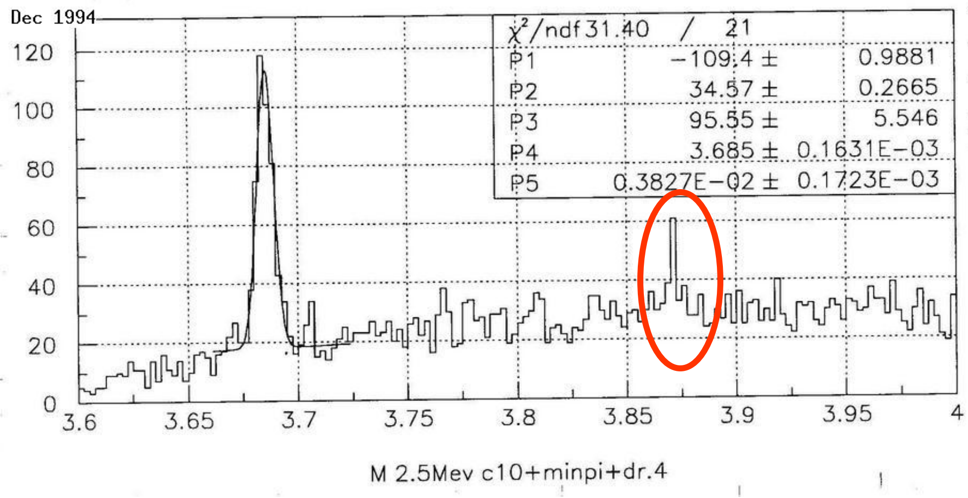
The original publication was based on an apparent peak (resonance) in a histogram of the invariant mass of electron-positron pairs produced by protons colliding with a stationary beryllium target, implying the existence of a particle with a mass of 6 GeV which was being produced and decaying into two leptons. An analysis showed that there was "less than one chance in fifty" that the apparent resonance was simply the result of a coincidence.[1] Subsequent data collected by the same experiment in 1977 revealed that the resonance had been such a coincidence after all.[2] However, a new resonance at 9.5 GeV was discovered using the same basic logic and greater statistical certainty,[3] and the name was reused (see Upsilon particle).



BNL-1968 *CERN ISR-1975* *FNAL-1976* *FNAL-1977*

Hints before the discovery of $X(3872) \to J/\psi\pi^+\pi^-$

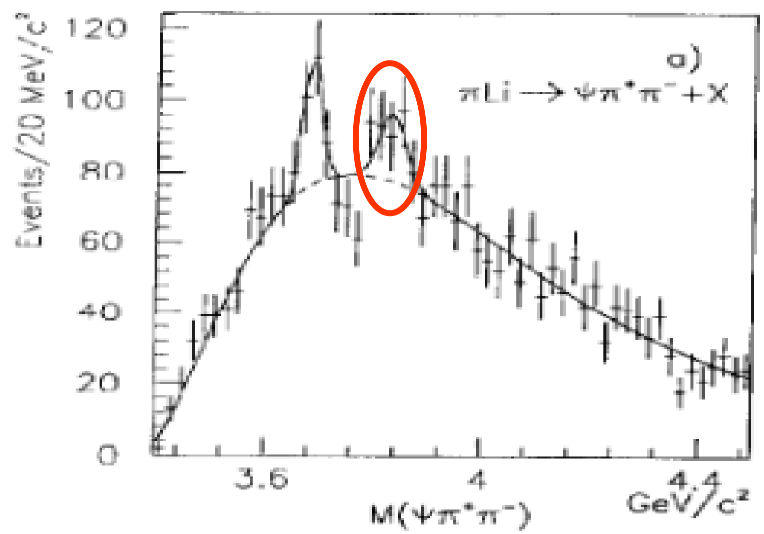
CDF internal, 1994



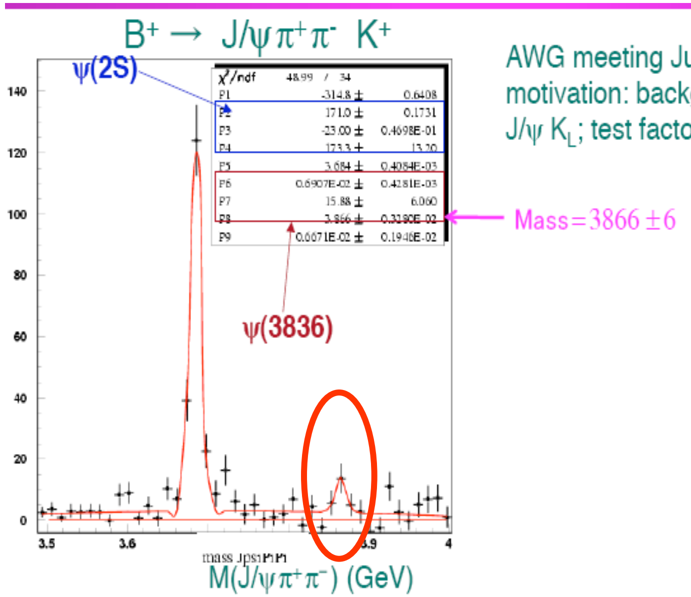
E705, PRD 50, 4258 (1994)

E705 saw $\psi(3836)$ (2^{--}) in 1994, 3.836±0.013 GeV

PRL 115 011803, PRL 111 032001



BaBar internal, 2003



AWG meeting June 2003
motivation: background to
$J/\psi K_L$; test factorization…

From BaBar B-Factory Symposium (C. Hearty)

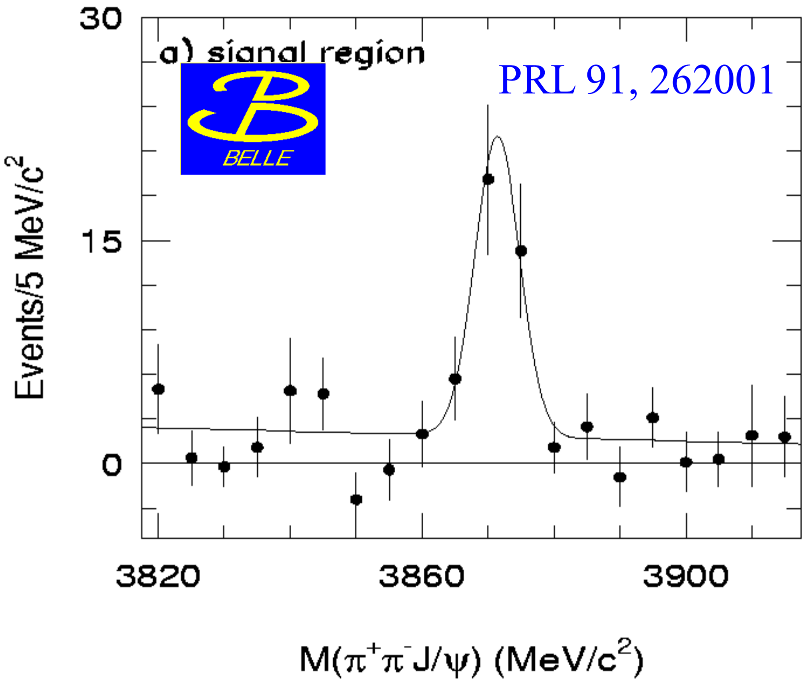
http://www-conf.slac.stanford.edu/b-factory-symposium/talks.asp

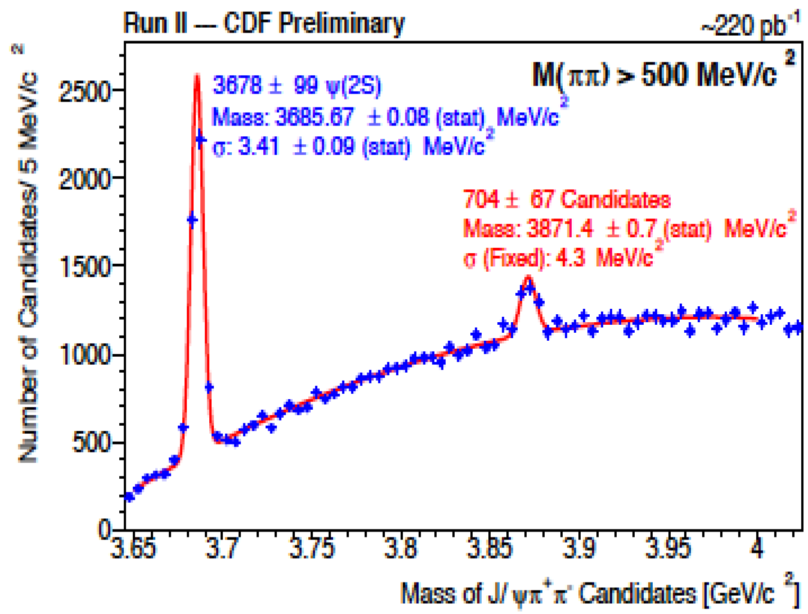
***CDF saw a hint in 1994**, unpublished*

BaBar saw a hint in 2003, unpublished

Both CDF and Babar spotted hints of X(3872) before its discovery!

X(3872) (Belle)--2003





2017 Laureates

"…The X(3872) was discovered by Dr. Sookyung Choi and Dr. Stephen Olsen with their colleagues in the Belle experiment among the final states of the decay of B mesons. The X(3872) was confirmed by seven other experimental groups thereafter and is the first example of a new type of XYZ meson and the most well-established state among them. …"

2017 Korean Ho-Am Science Prize