Experimental Opportunities in Hadron Physics

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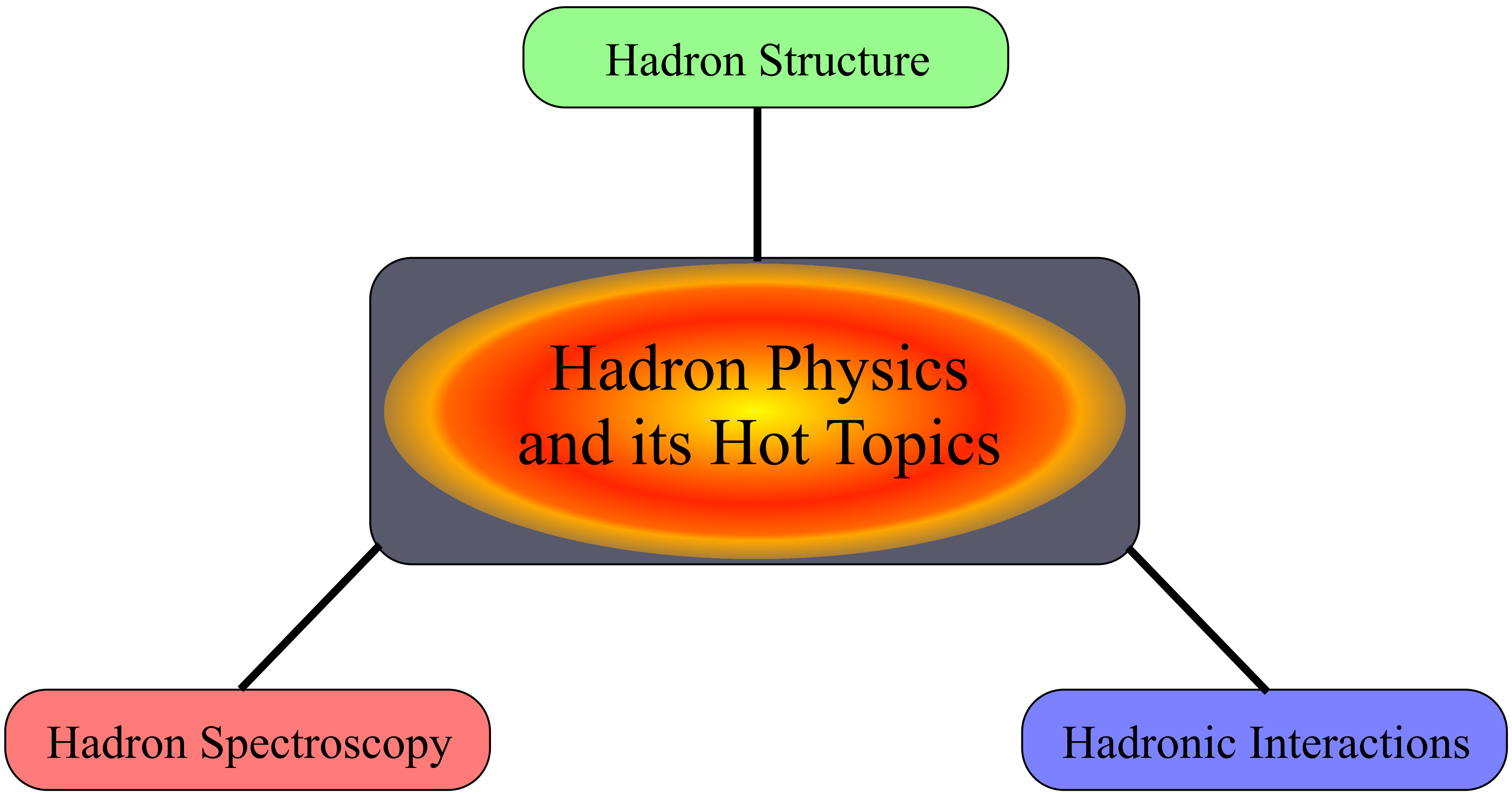
Ruhr-University Bochum (Germany)

XV Hadron Physics Workshop, ITA, 26. Feb. 2019

The areas of hadron physics



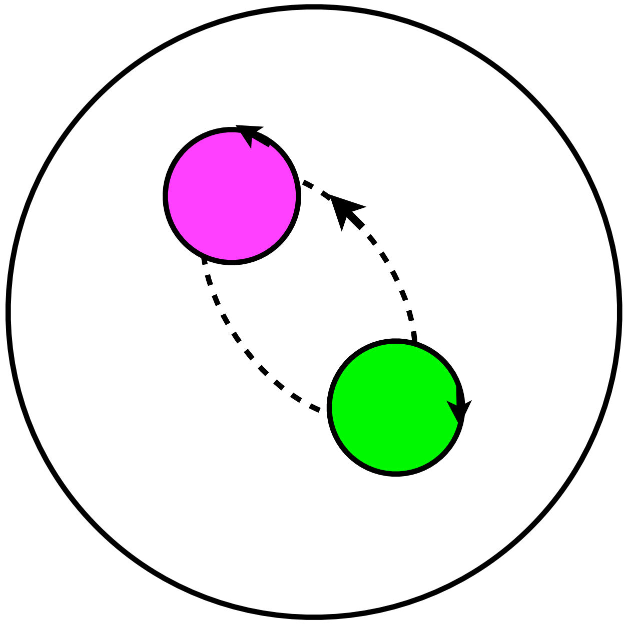
How to study hadrons?

All hadrons except the proton are unstable and have to be produced

- *Build them together in a controlled manner*
  - ✧ e^+e^- collider can produce vector mesons (other particles in decays)
  - ✧ hadron beams have high production cross sections but little control (except for antiprotons)
- *Observe them in a spectroscopic way*
  - ✧ study their properties (mass, spin, lifetime, ...)
  - ✧ study their decay patterns
  - ✧ study their production modes
- *Explore their structure and interactions*

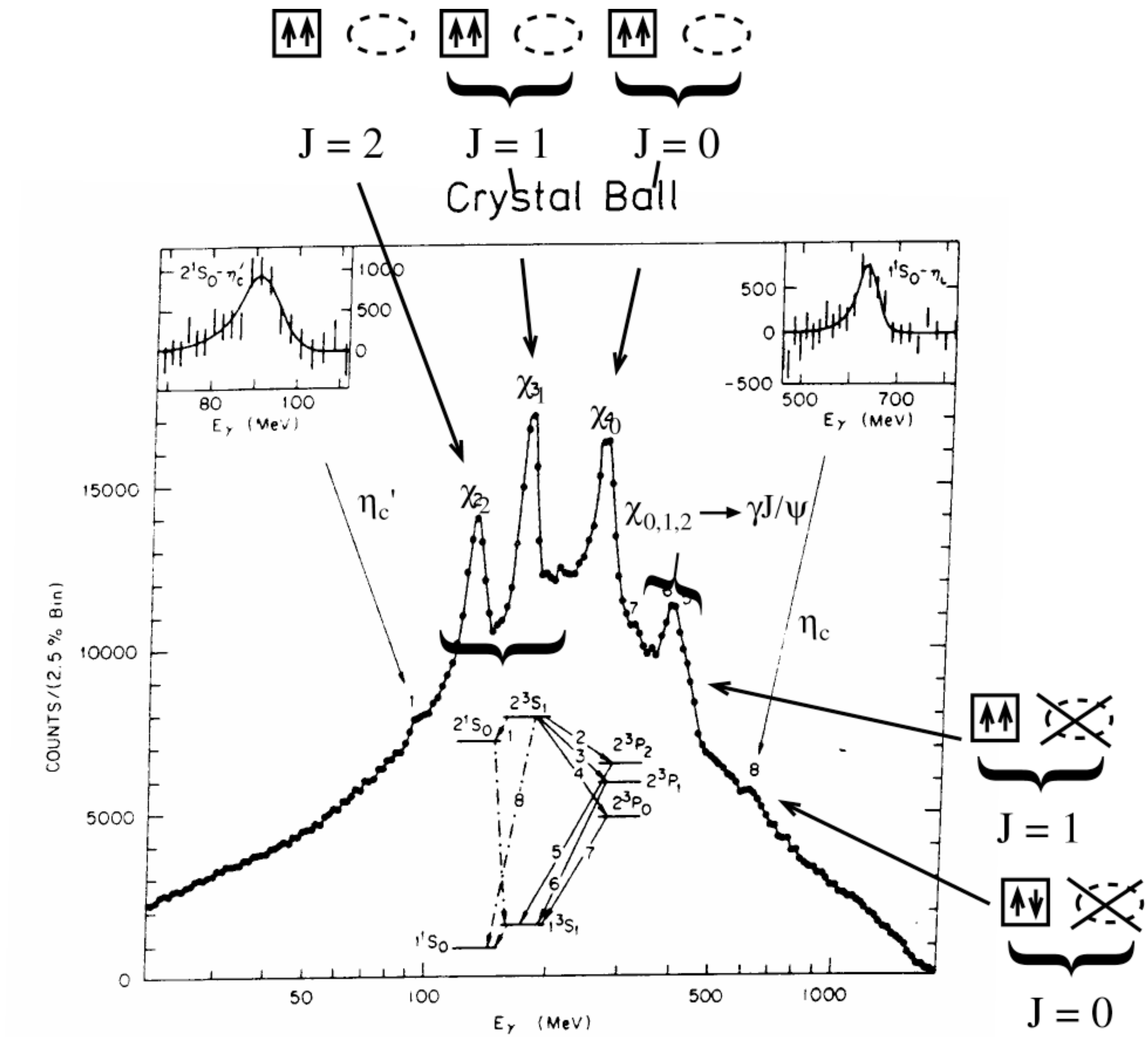
There are certain rules for building hadrons:

- Even though quarks and gluons carry color, hadrons are colorless
- The total angular momentum J = S(spin) + L(angular momentum)



- There are rules for parity and C parity

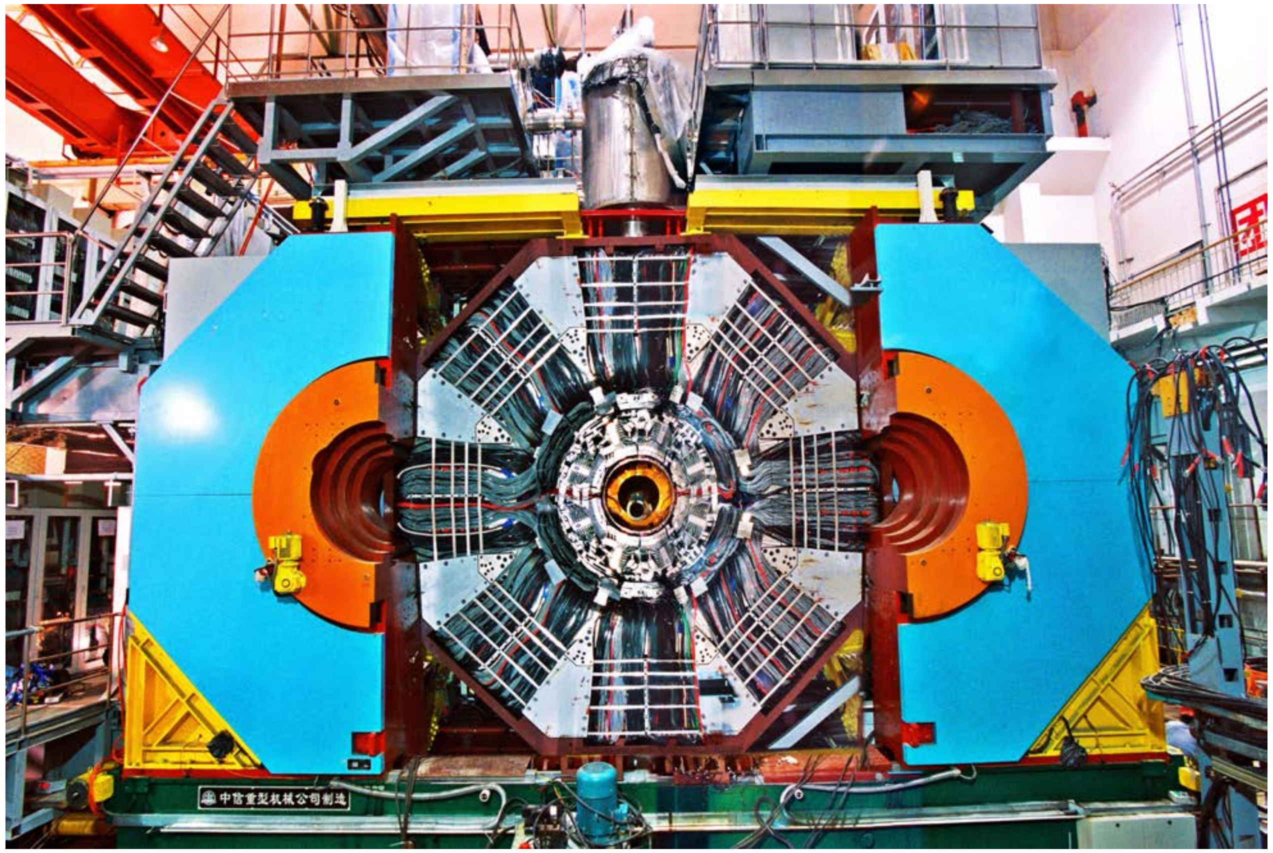
Striking evidence for quarks: The Charmonium Spectrum



A typical hadron physics experiment nowadays

BESIII has produced beautiful new results and delivers many important papers.

(336 in high-ranking refereed journals from 2010 – now)



BESIII

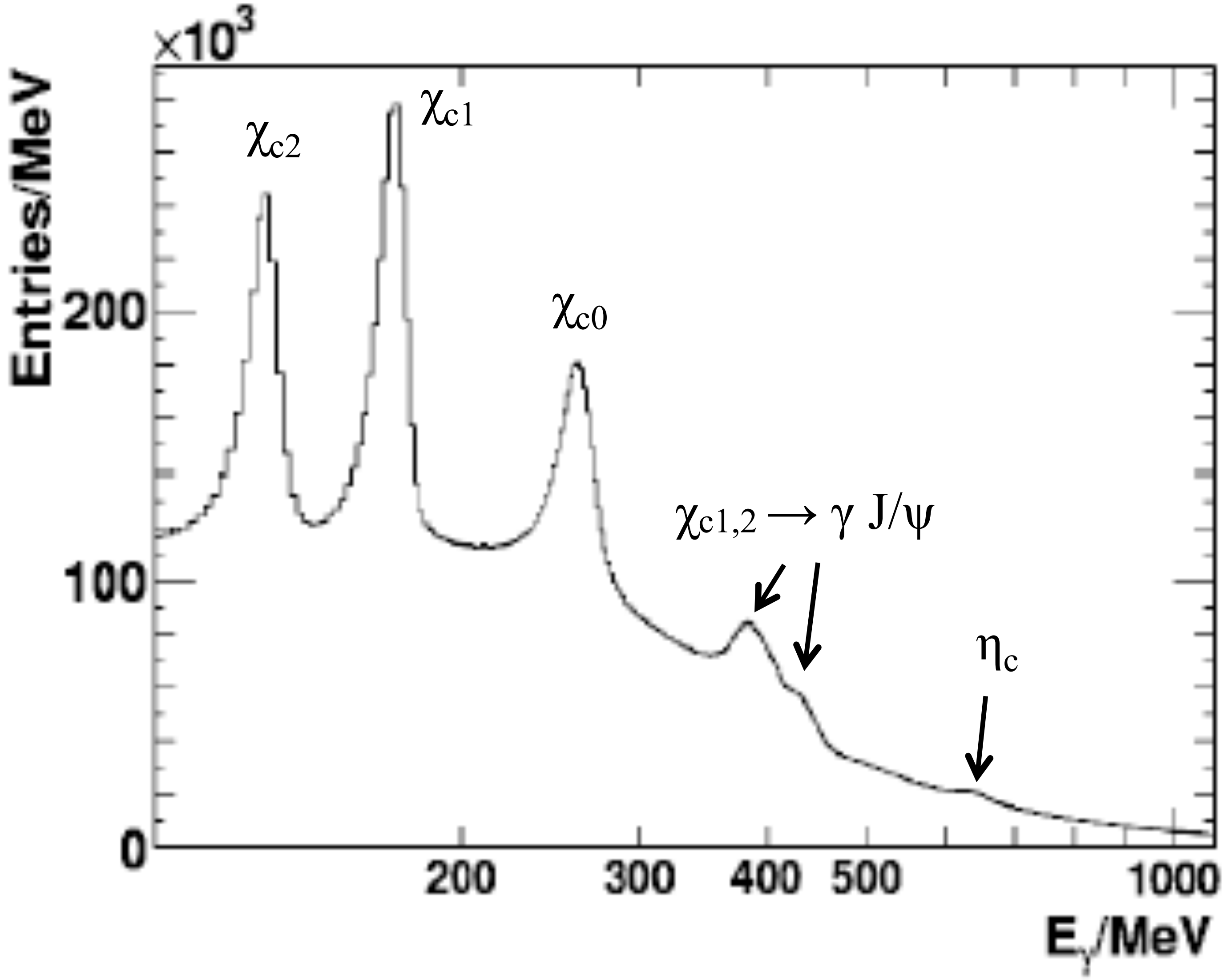
One lesson from the past:

To determine nature of states: different production mechanisms and decay pattern necessary

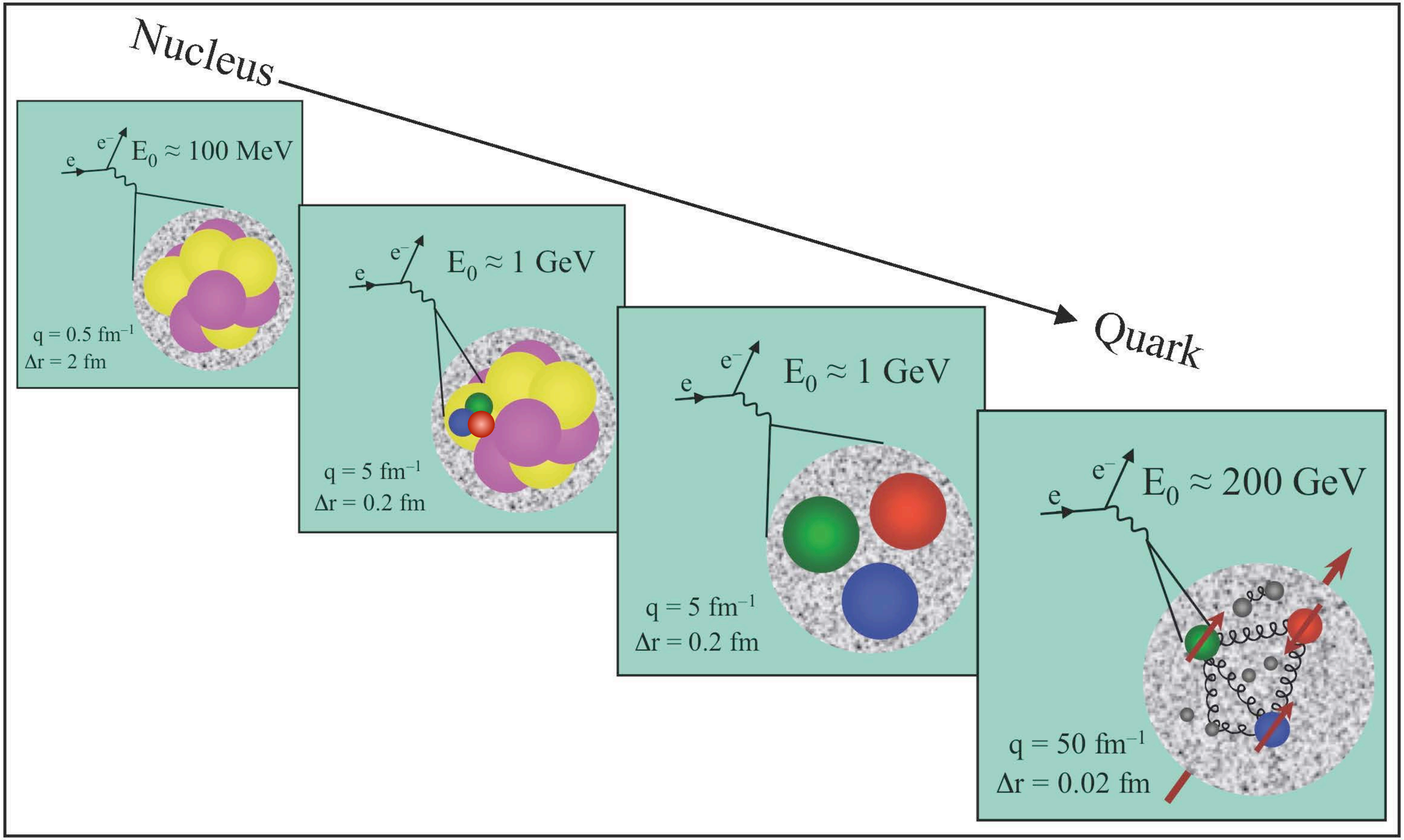
⇒ combine results from as many as possible sources

BESIII data quality

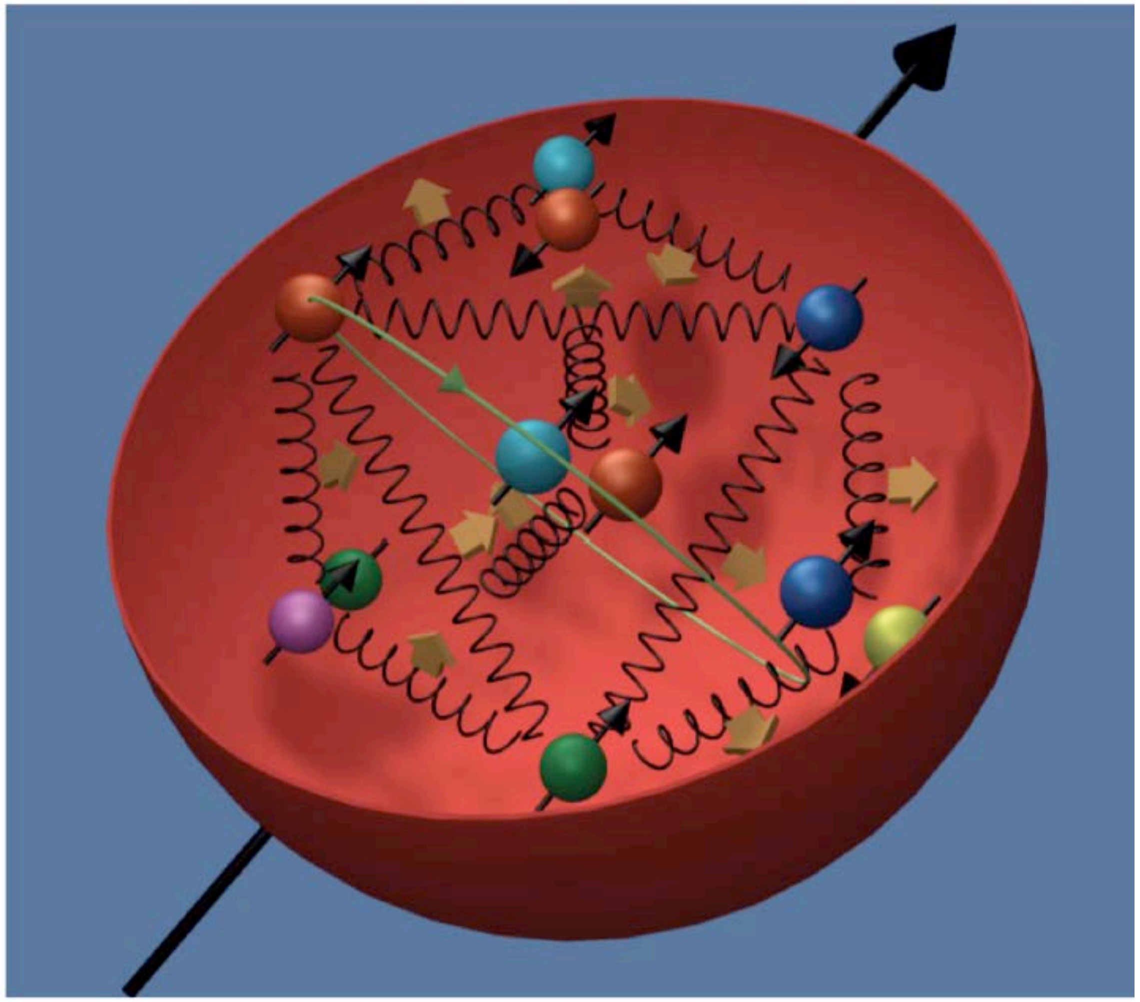
$\psi' \to \gamma X$



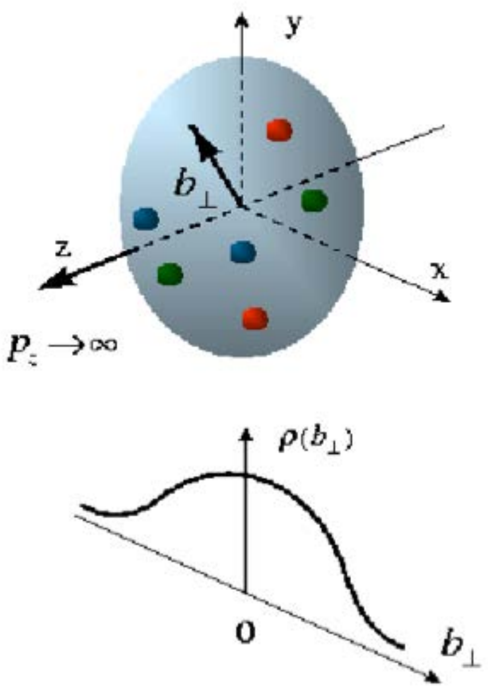
Hadronic Structure



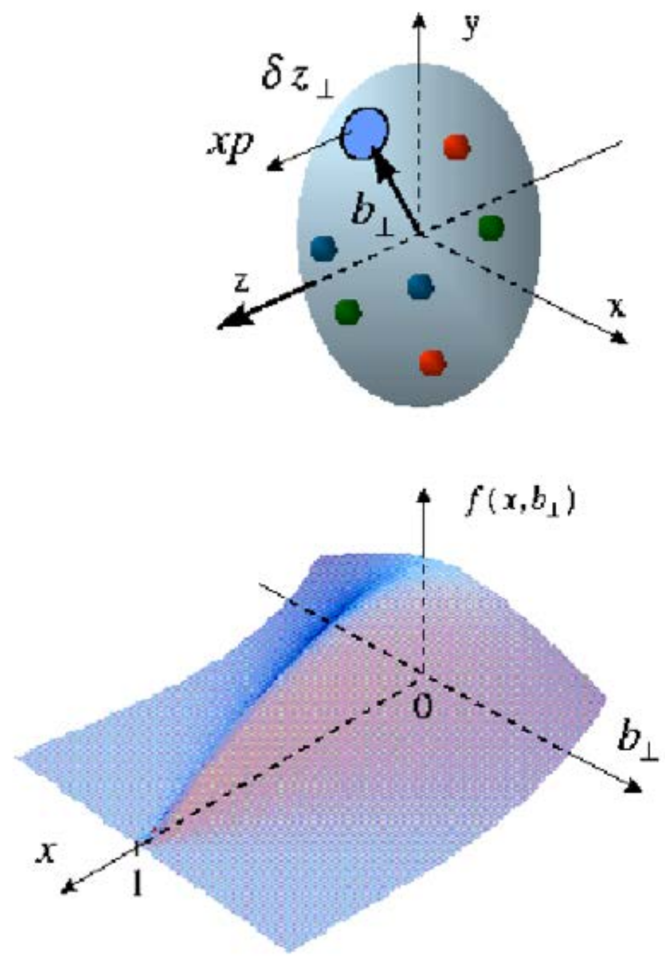
The Nucleon (as composed by fundamental particles)



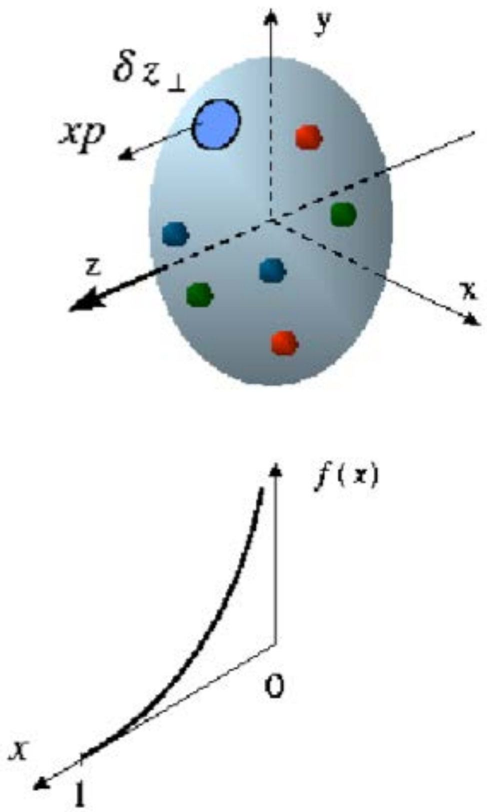
More than form factors and quark distributions
⇒ Generalized Parton Distributions (GPDs)



Elastic scattering reveals
form factors:
transverse charge and
current densities



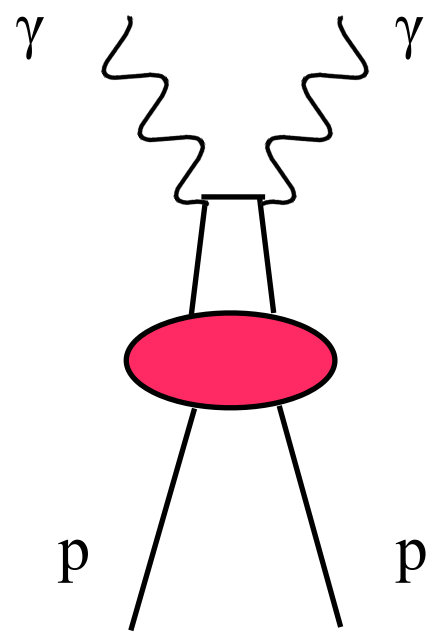
Common description:
GPDs are *correlated* quark momentum
and helicity distributions in
transverse space (tomography)



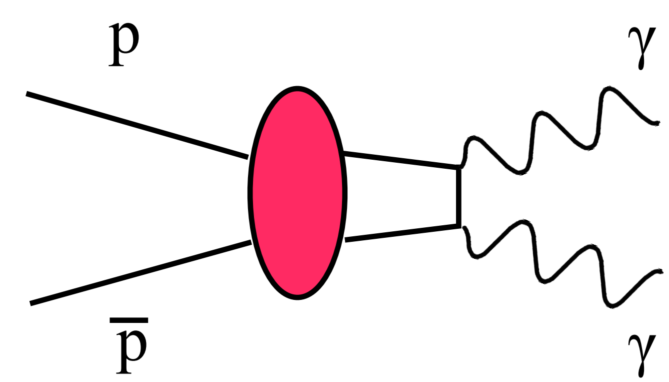
Deep inelastic scattering:
Structure functions:
quark *longitudinal*
momentum & helicity
distributions

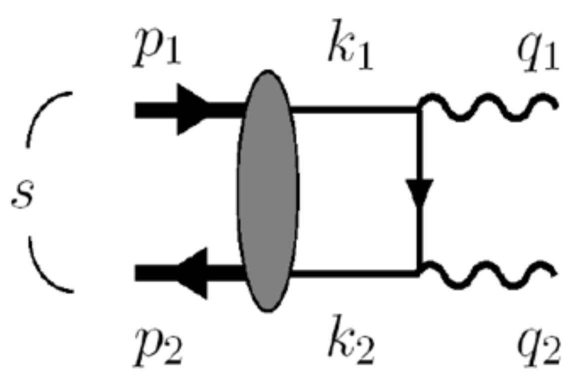
Extending longitudinal quark momentum & helicity distributions
⇒ transverse momentum distributions (TMDs).

Electromagnetic Processes: $\bar{p}p \rightarrow \gamma\gamma$



crossed-channel
Compton scattering





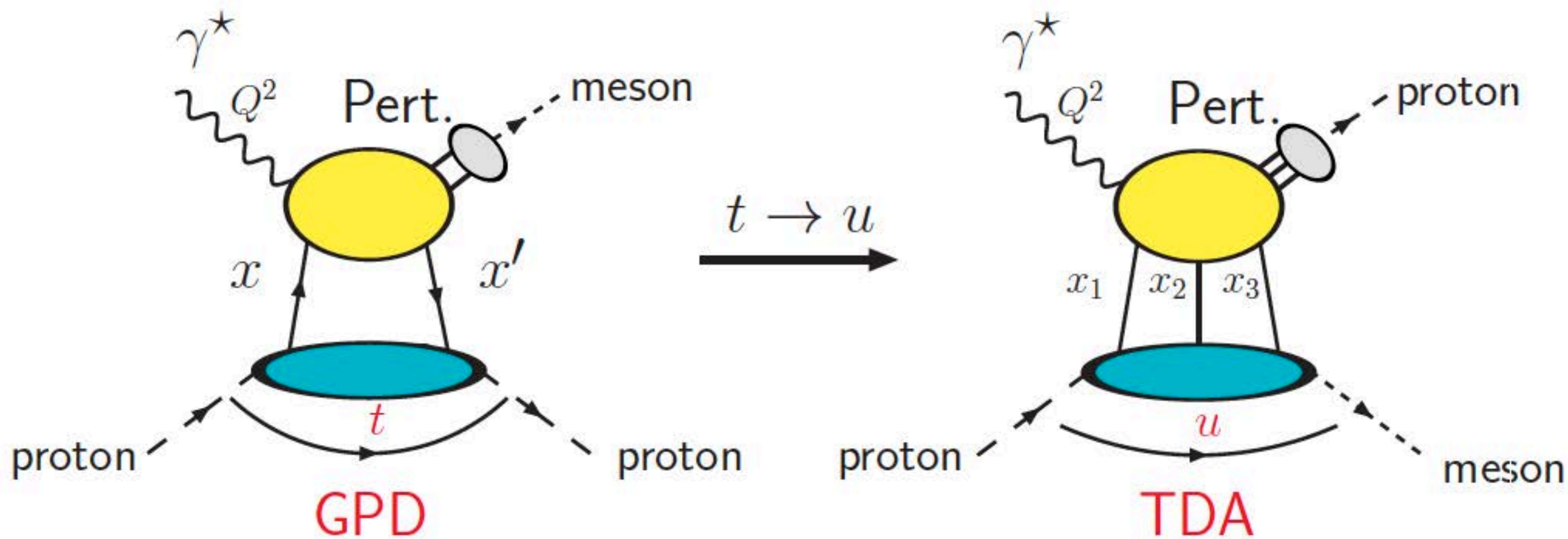
Handbag diagram separates a soft part described by GPDs from a hard $\bar{q}q$ annihilation process

Predicted rates*: several thousand / month or above

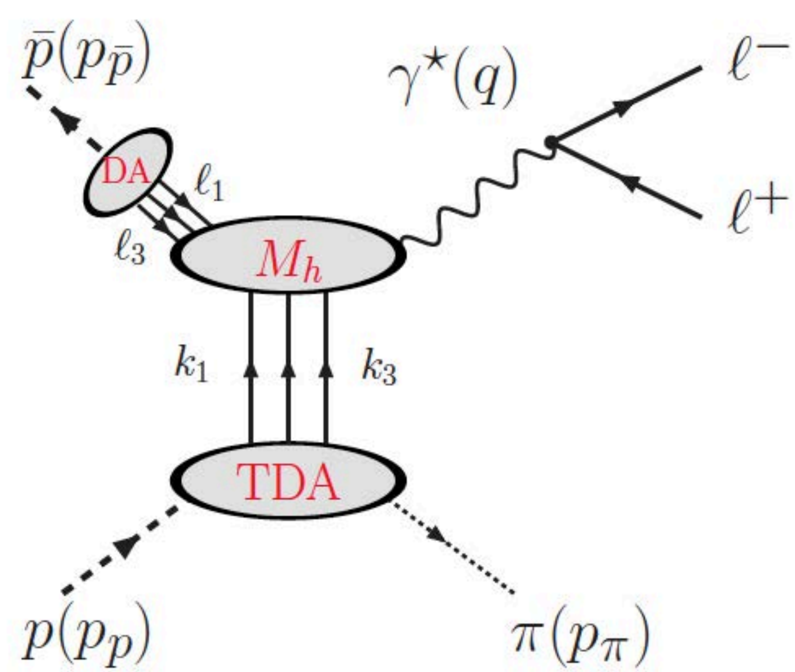
Exp. problem: Background channels like $\pi^0\gamma$ or $\pi^0\pi^0$ 5× - 100× stronger.

*A. Freund, A. Radyushkin, A. Schäfer, and C. Weiss, Phys. Rev. Lett. 90, 092001 (2003).

From GPDs to TDAs



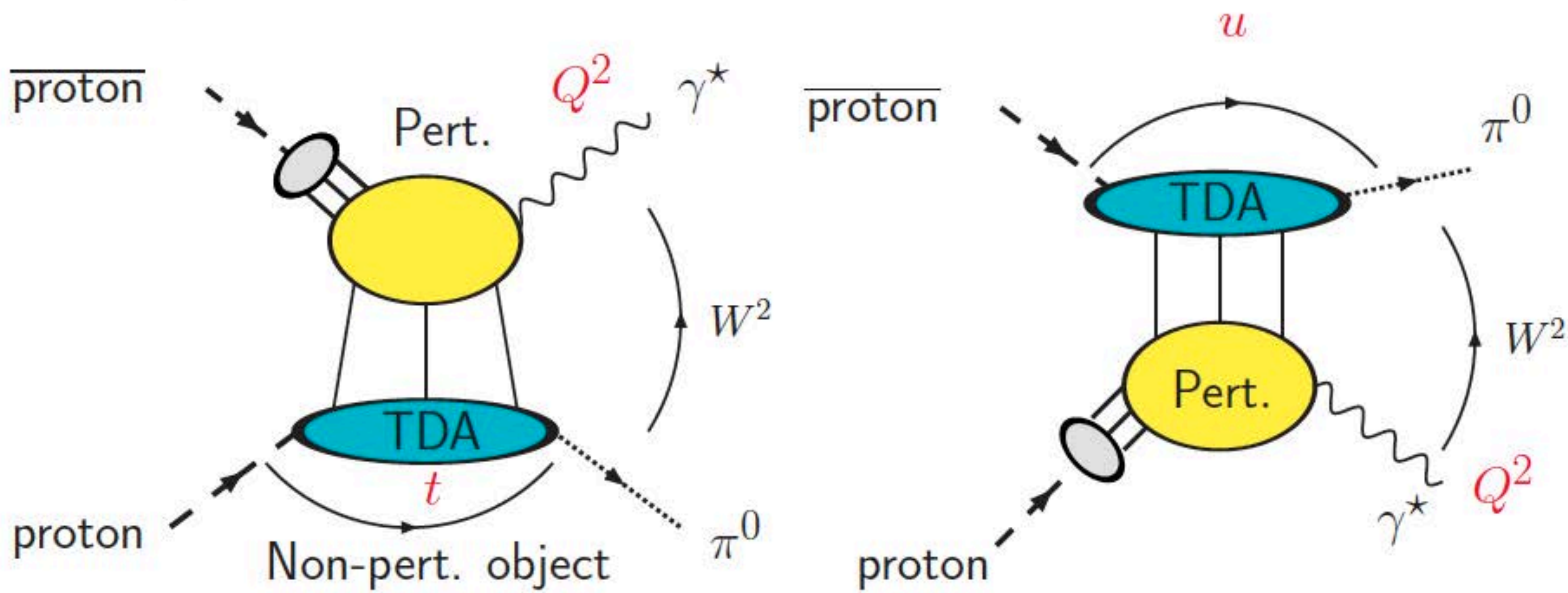
PANDA:



J.P. Lansberg, B. Pire, L. Szymanowski, Phys. Rev. D 76 (2007) 111502(R).

J.P. Lansberg, Workshop PANDA Orsay, France 2011

The π^0 could come from the p or the $\bar{p}$

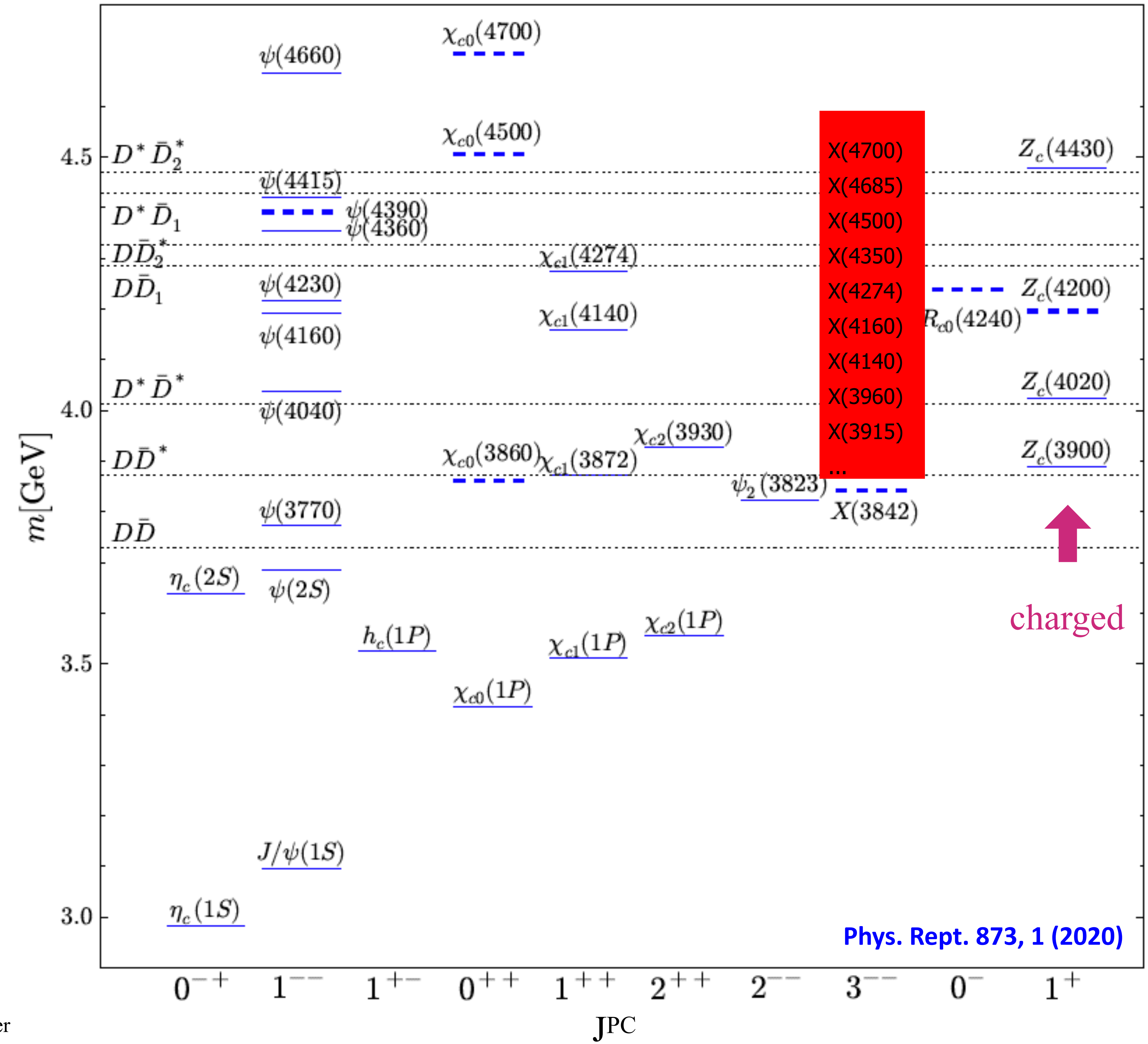


Unique test of matter-antimatter symmetry only possible in PANDA

J.P. Lansberg, B. Pire, L. Szymanowski, Phys. Rev. D 76 (2007) 111502(R).

J.P. Lansberg, Workshop PANDA Orsay, France 2011

Spectroscopy in the Charmonium regime



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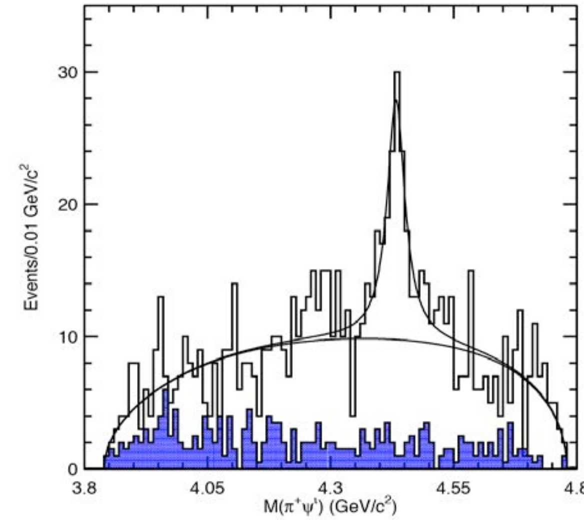
Even more exotic: $Z^{\pm}$

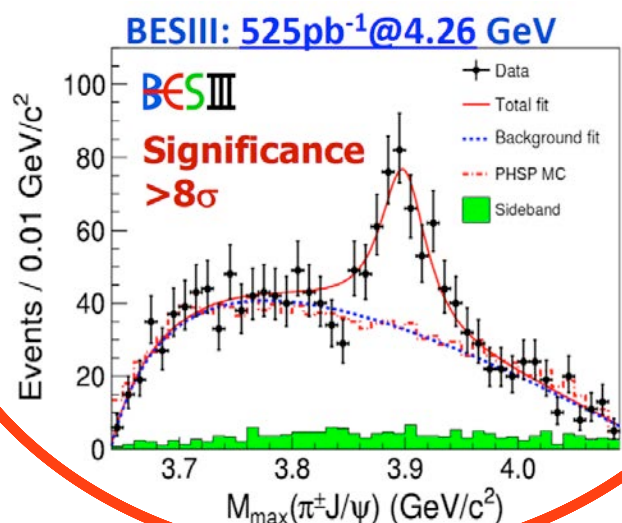
The first one: $Z^+ (4430) \rightarrow \pi^+\psi'$



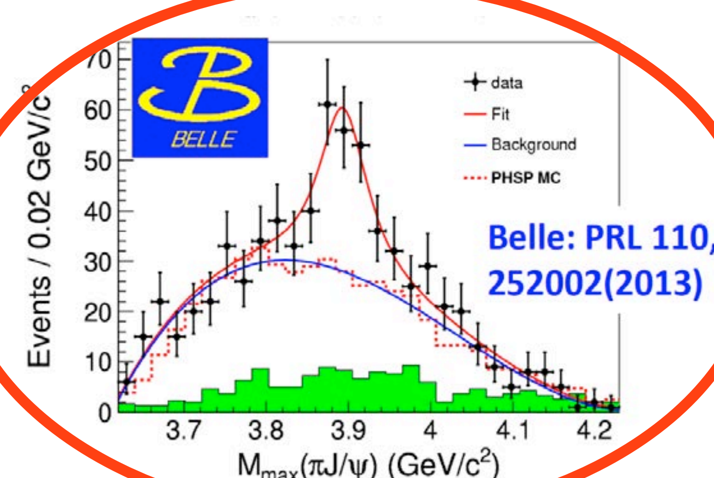
PRL 100, 142001 (2008)
arXiv:0708.1790 [hep-ex]

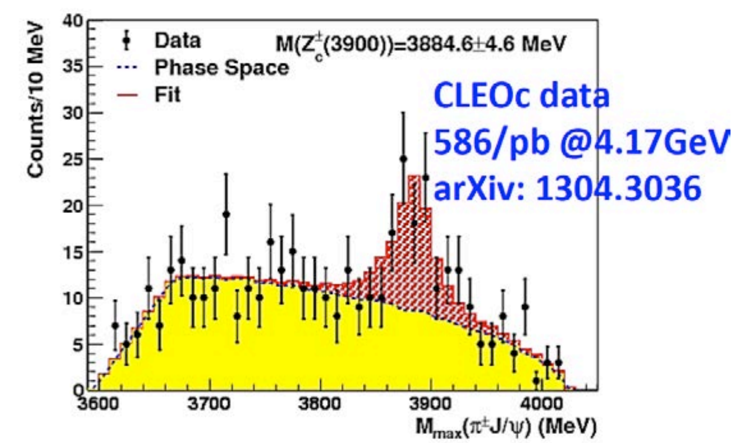
~ 1 month data

$Z_c(3900)$ at BESIII



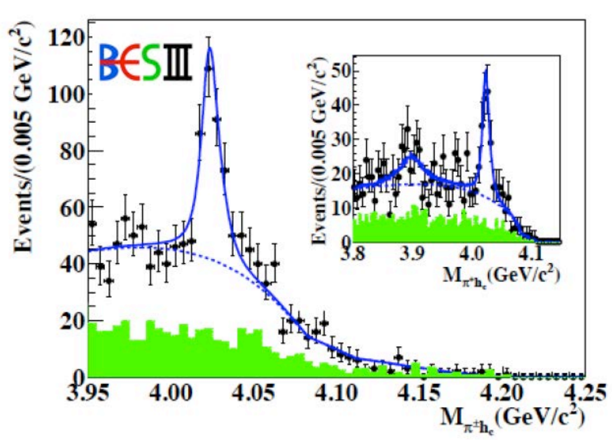
... quickly confirmed



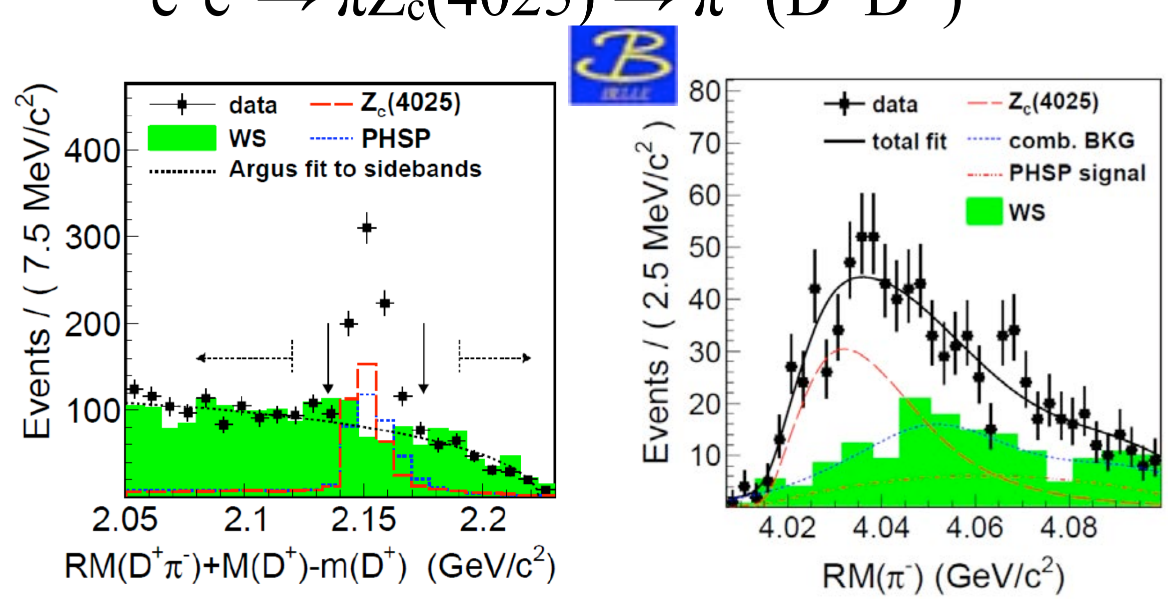


~ 10 years data

$e^+e^- \rightarrow \pi Z_c(4020) \rightarrow \pi^+\pi^- h_c$



$e^+e^- \rightarrow \pi Z_c(4025) \rightarrow \pi^- (D^*\overline{D^*})^+$



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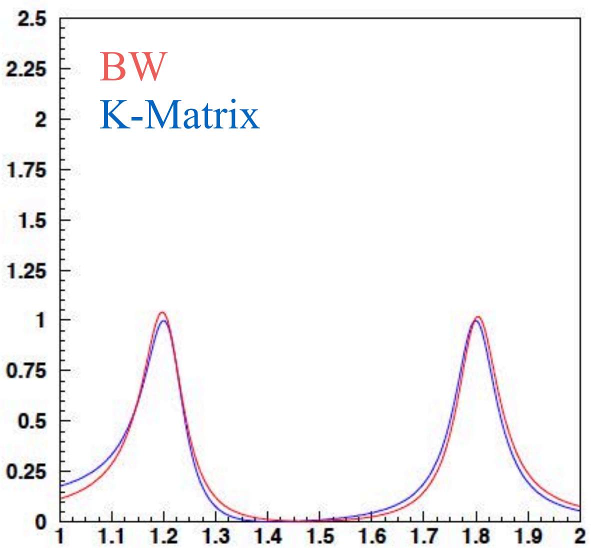
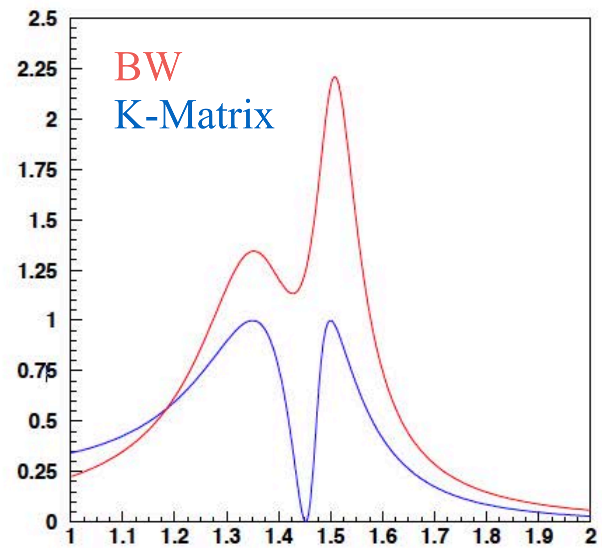
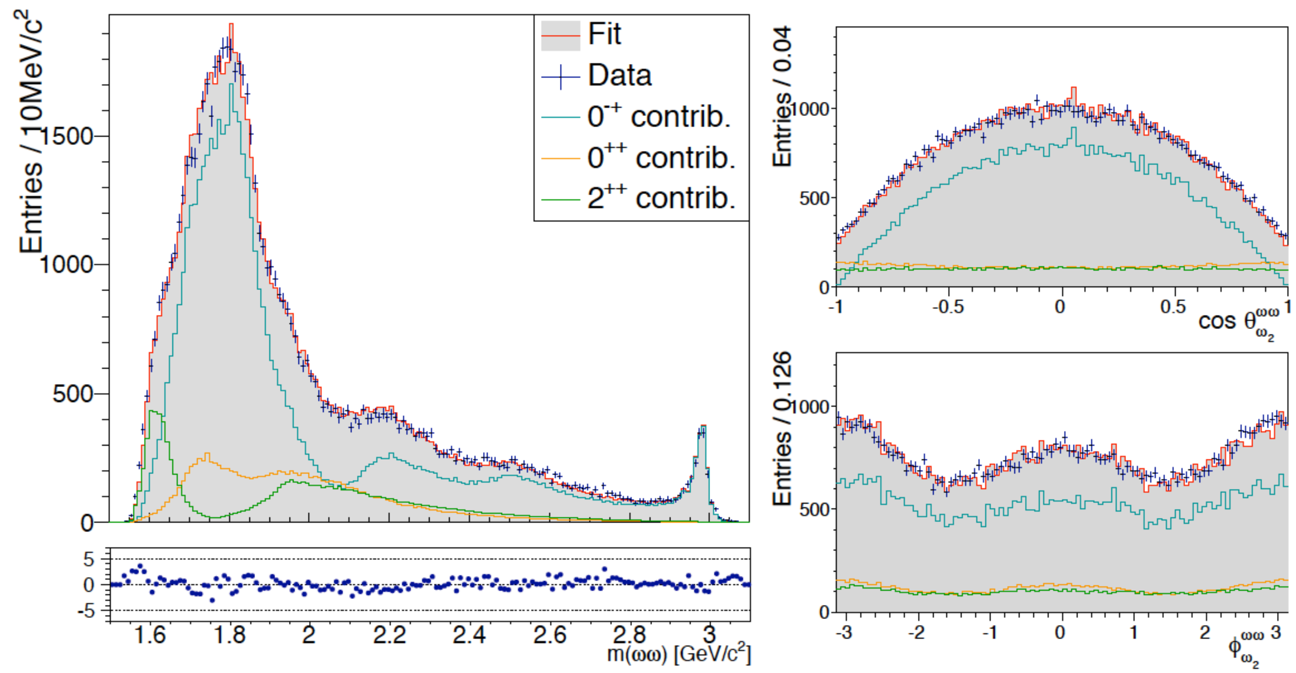
Amplitude analysis (PWA): Breit-Wigner and K-Matrix formalism

Breit-Wigner fitting might not be sufficient:

J/ψ → γωω PAWIAN K-Matrix (Malte Albrecht)







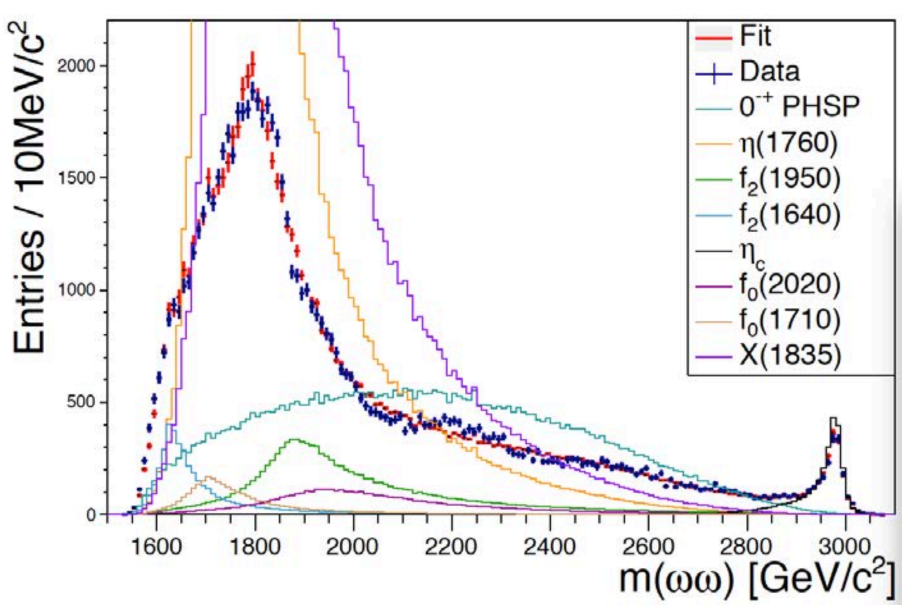
$f_0(1200)$, $\Gamma = 100$
$f_0(1800)$, $\Gamma = 100$

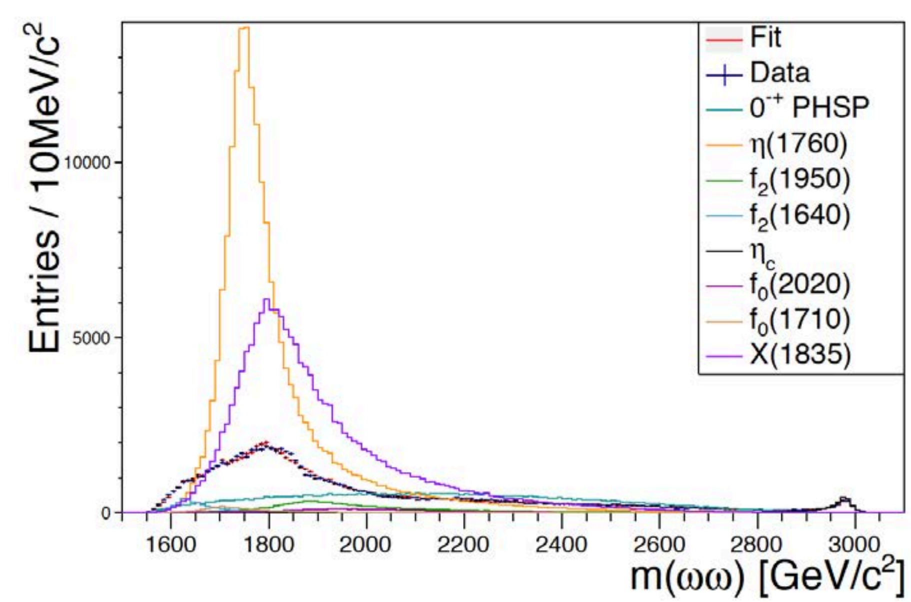
Plots: Curtis Meyer

$f_0(1350)$, $\Gamma = 300$
$f_0(1500)$, $\Gamma = 100$

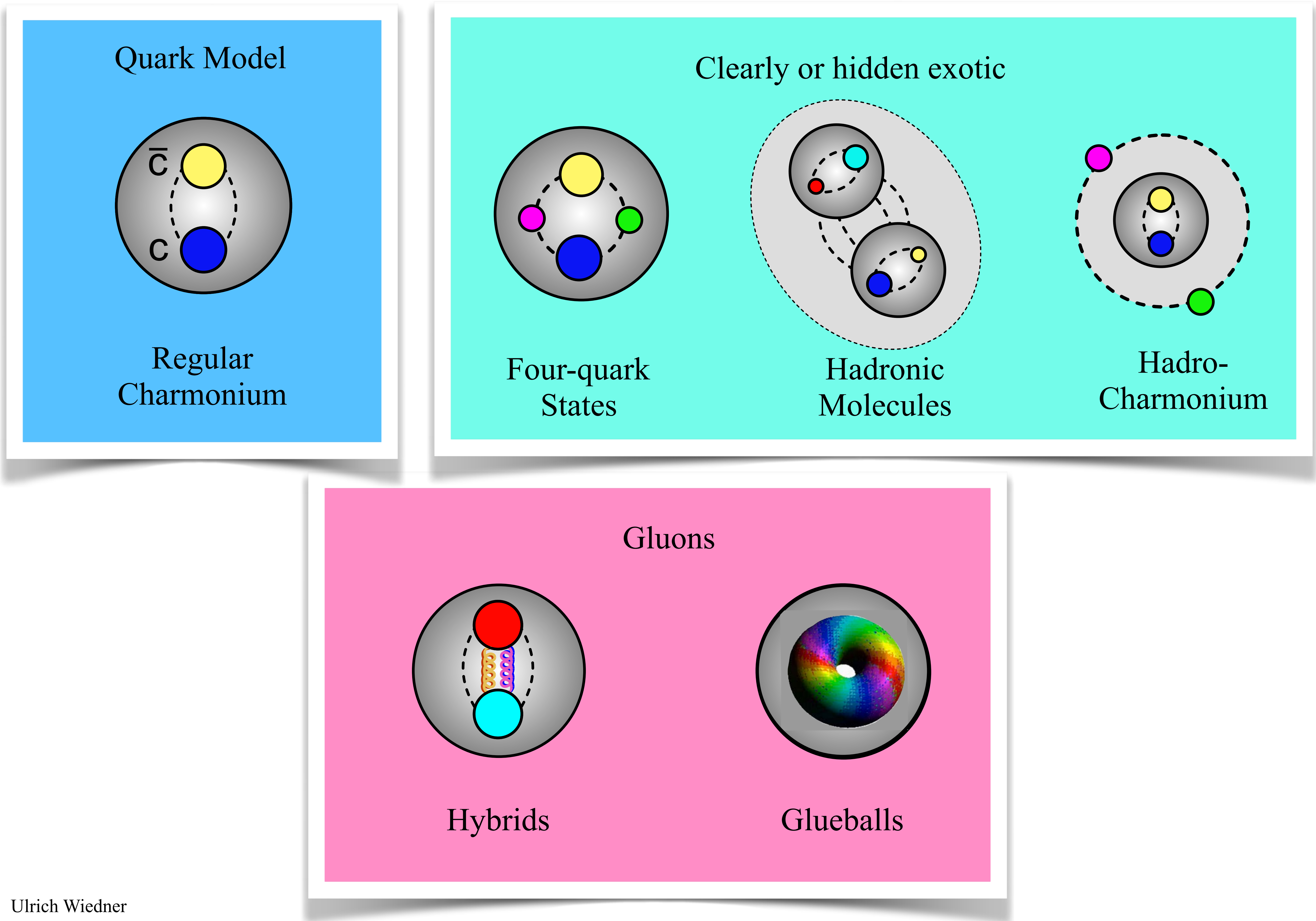
but still might give an equally good description:

… unfortunately unphysical:





The burning question: *What is what?*



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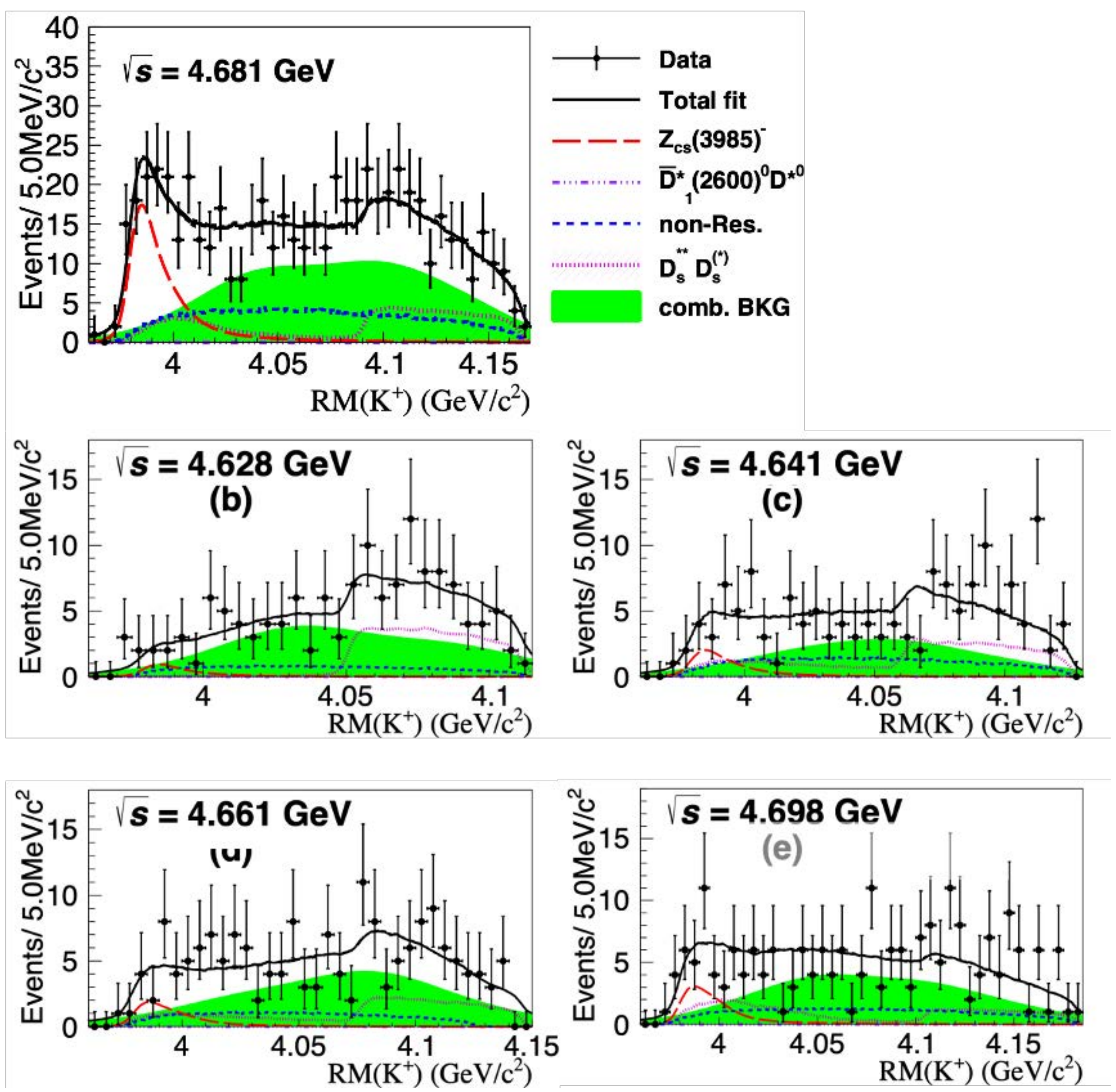
Z_{CS} (3985) from e^+e^- annihilations

$$e^+e^- \rightarrow K^+(D^-D^{*0} + D^{*-}D^0)$$

PRL 126, 102001 (2021)

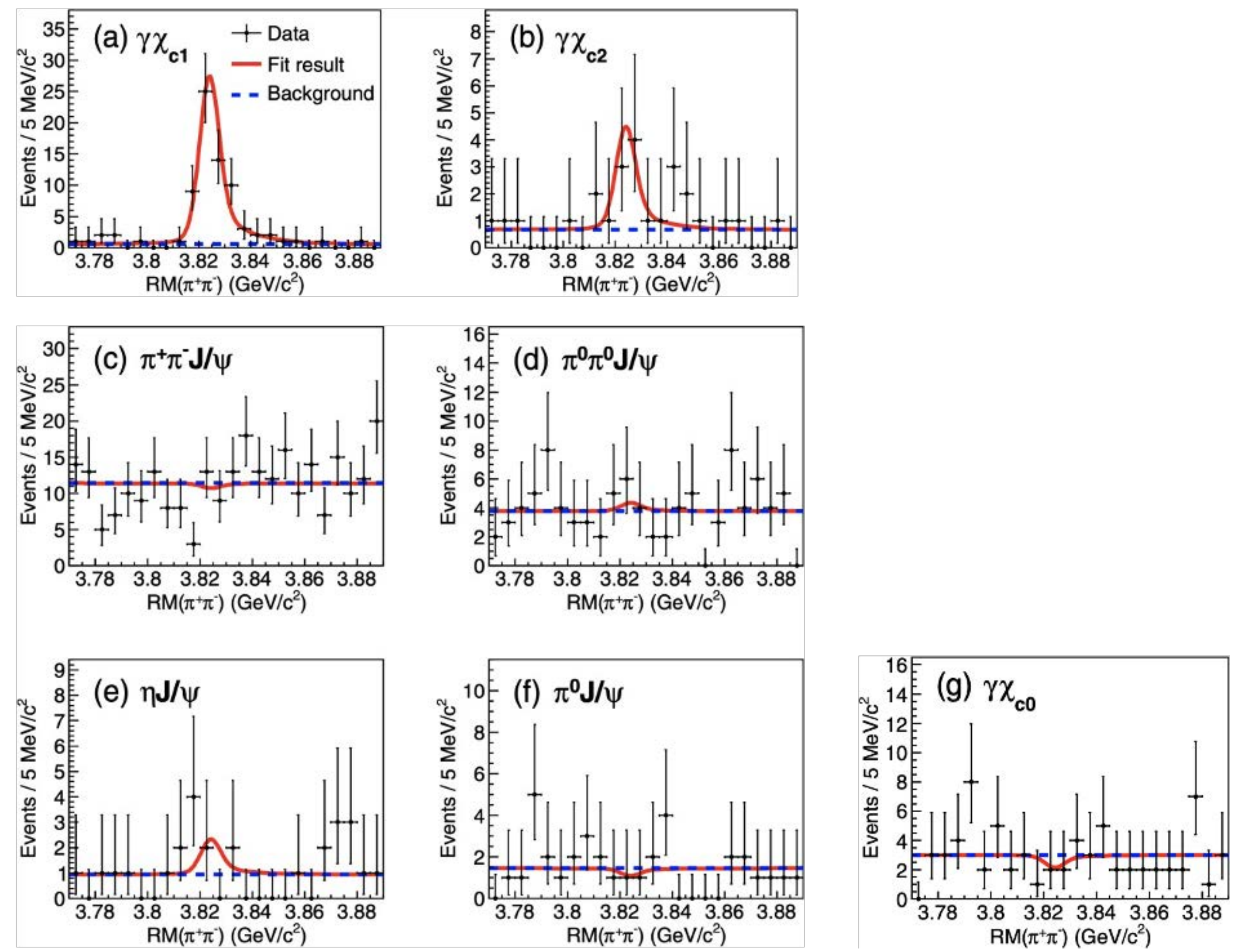


$\psi_2(3823)$ decay modes

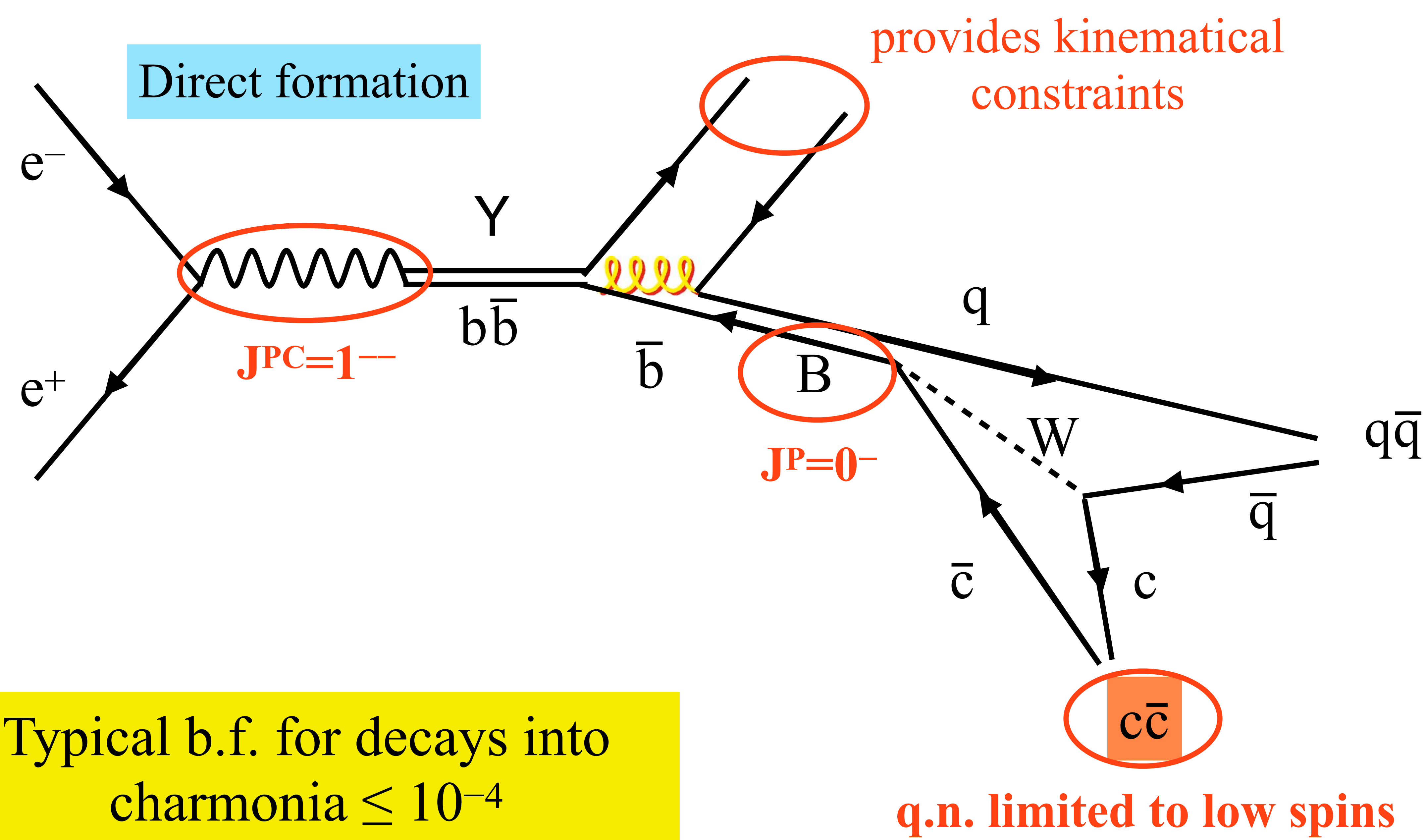
$$e^+e^- \rightarrow \pi^+\pi^-\psi_2(3823)$$

$$\psi_2(3823) \rightarrow \gamma\chi_{c0,1,2}\ ,\ \pi\pi J/\psi\ ,\ \eta J/\psi\ ,\ \pi^0 J/\psi$$

PRD 103, L091102(2021)



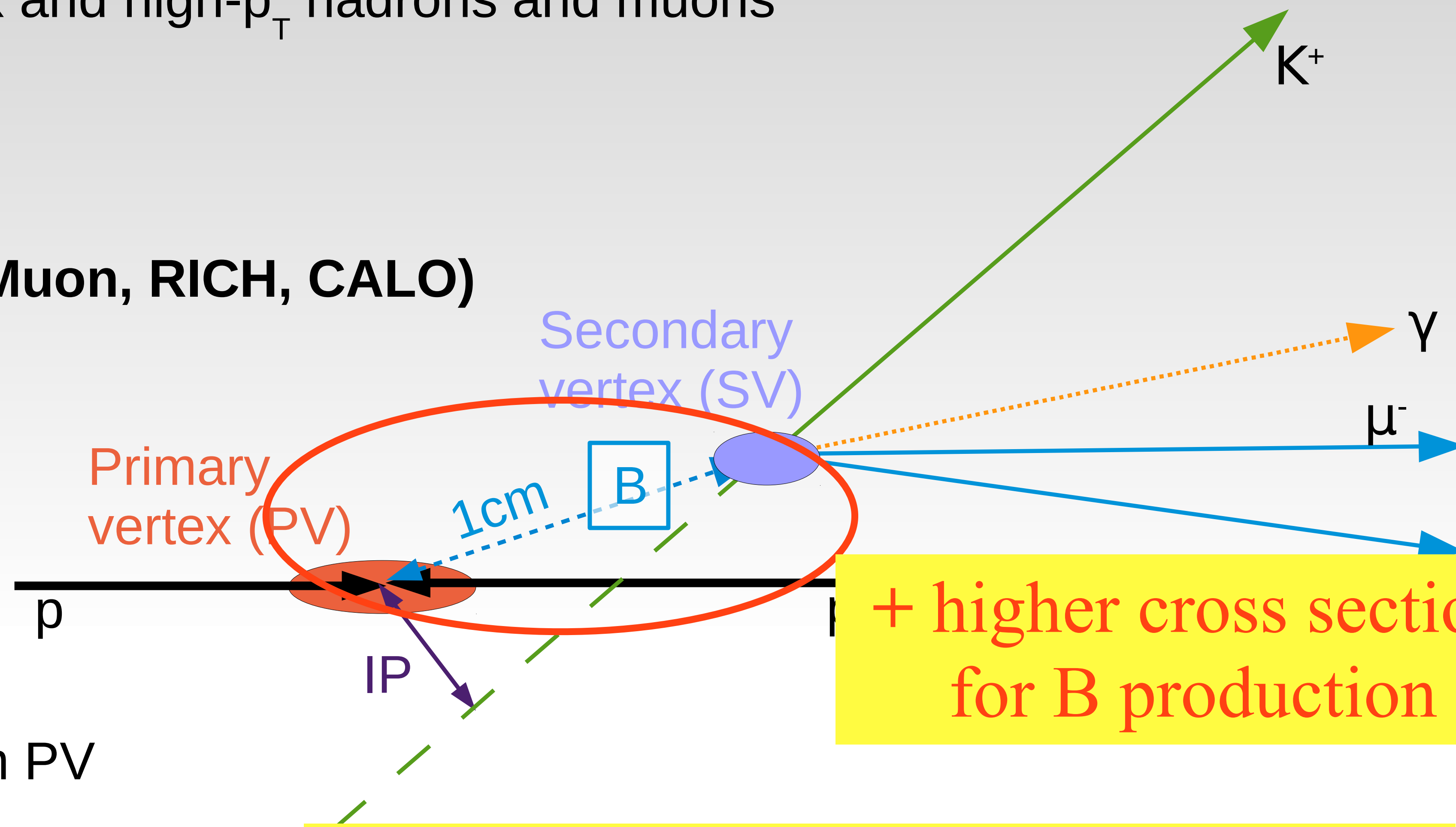
Charmonium production in e^+e^- at B-factories (BELLE)



Typical b.f. for decays into charmonia $\leq 10^{-4}$

Selection

- Trigger on detached vertex and high-p_T hadrons and muons
- Good quality tracks
- **μ, K, π, γ identification (Muon, RICH, CALO)**
- **Vertex quality**
- **PV and SV separation**



+ higher cross section for B production

- Daughter particles not from PV
- B-candidate from the PV
- Decay structure consistent

– missing kinematical constraints lead to reduced resolution

- Rectangular cuts or Boosted Decision Trees (BDT)

Efficiencies:

- Efficiencies from simulation
- when possible from data – for PID, trigger

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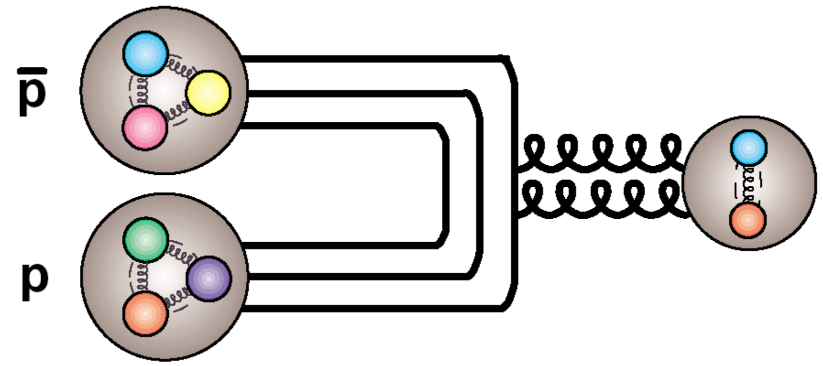
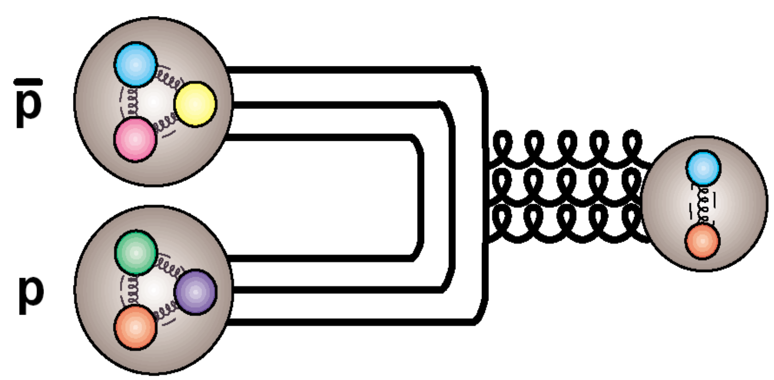
The advantage of antiproton annihilations:

- gluon-rich
- high-spin states possible without limitations on q.n.

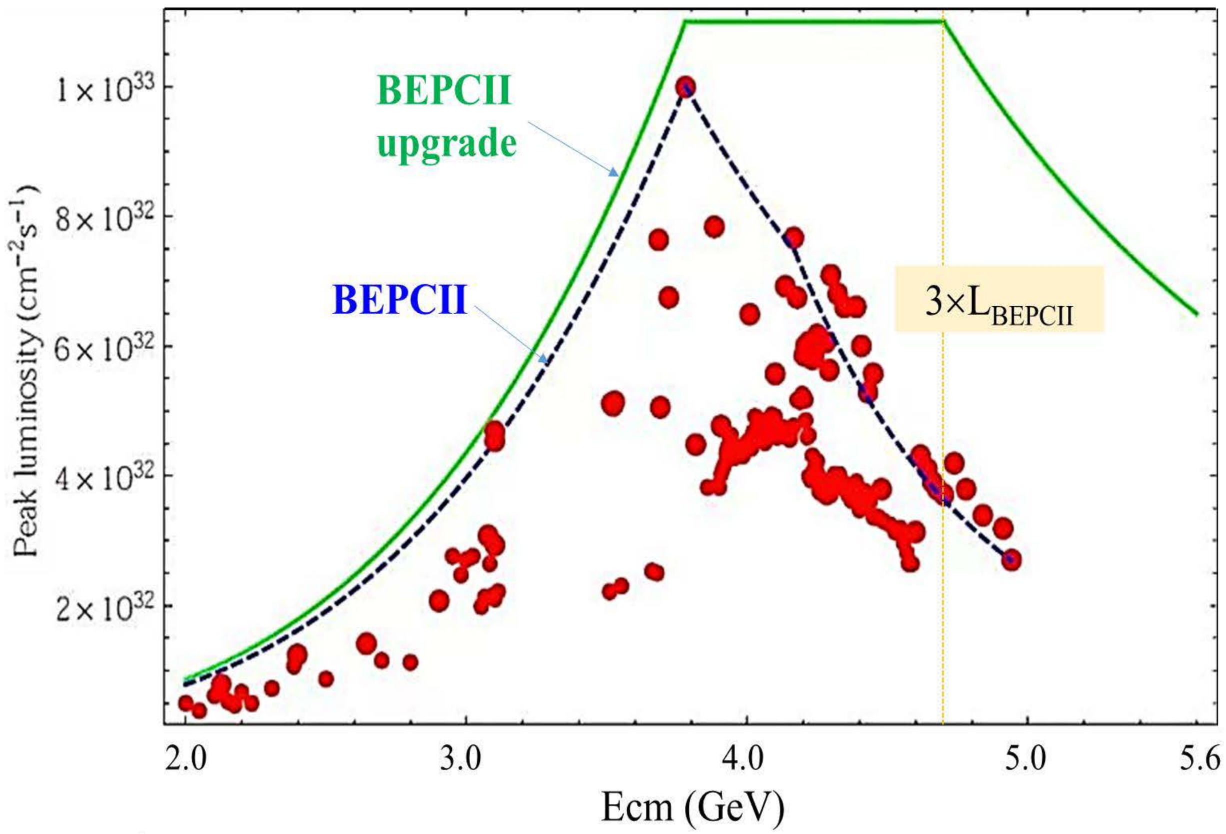


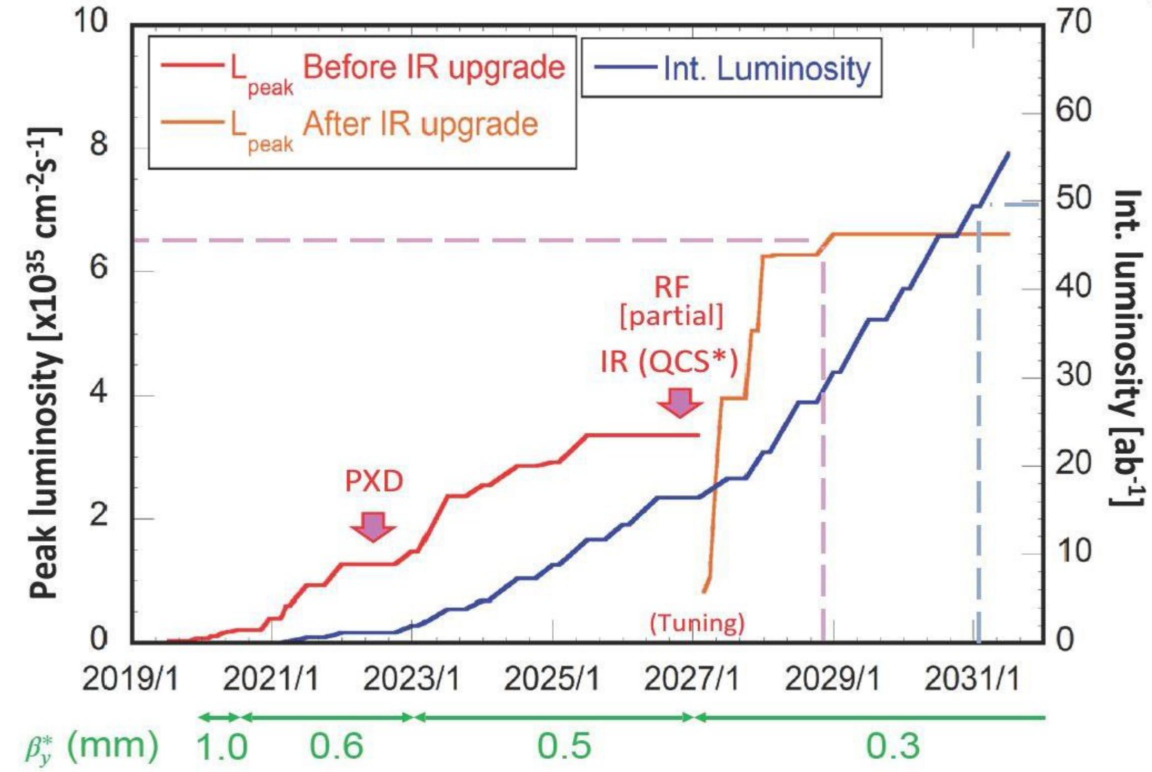
J = 0, 2, ...
C = +



J = 1
C = –

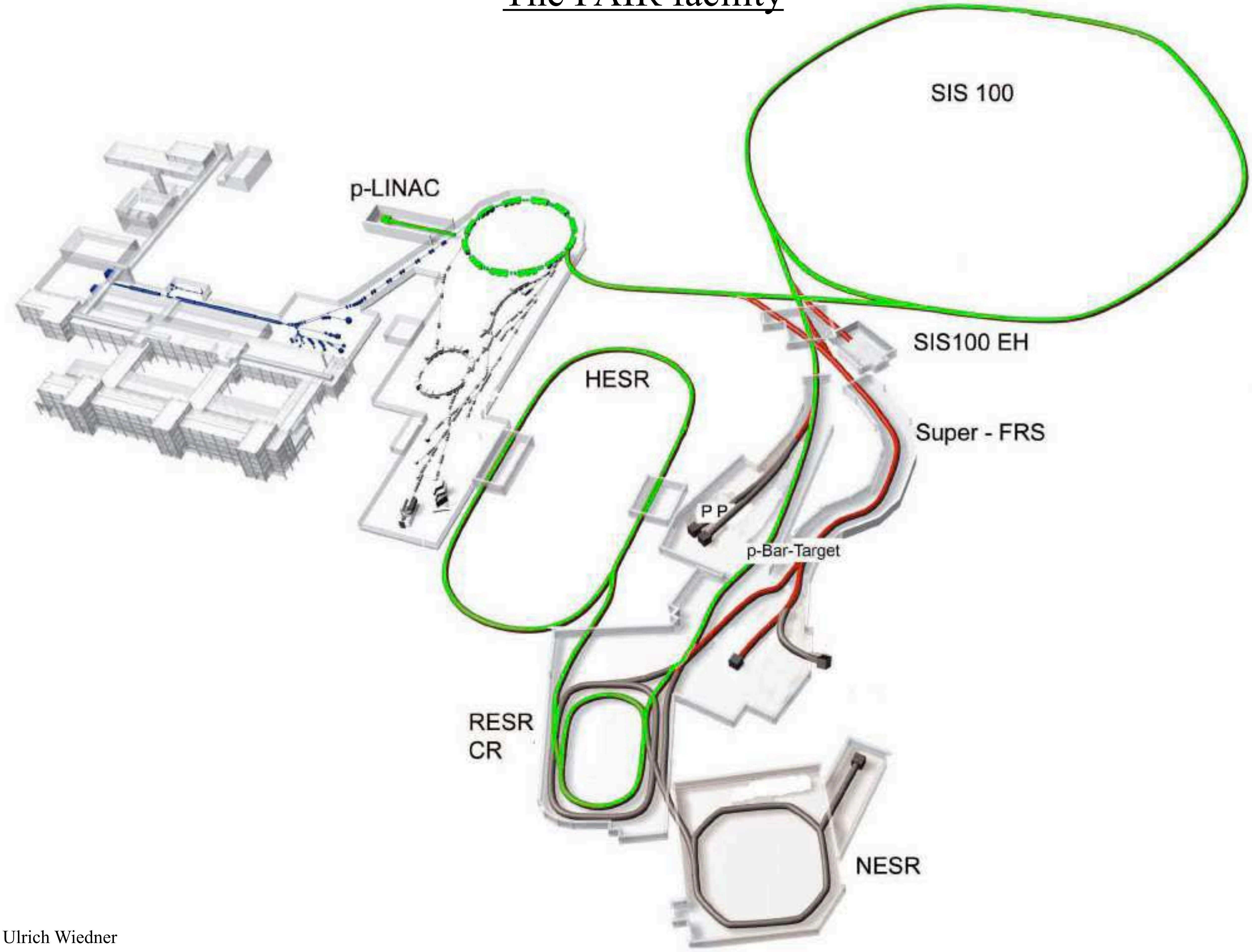
Future



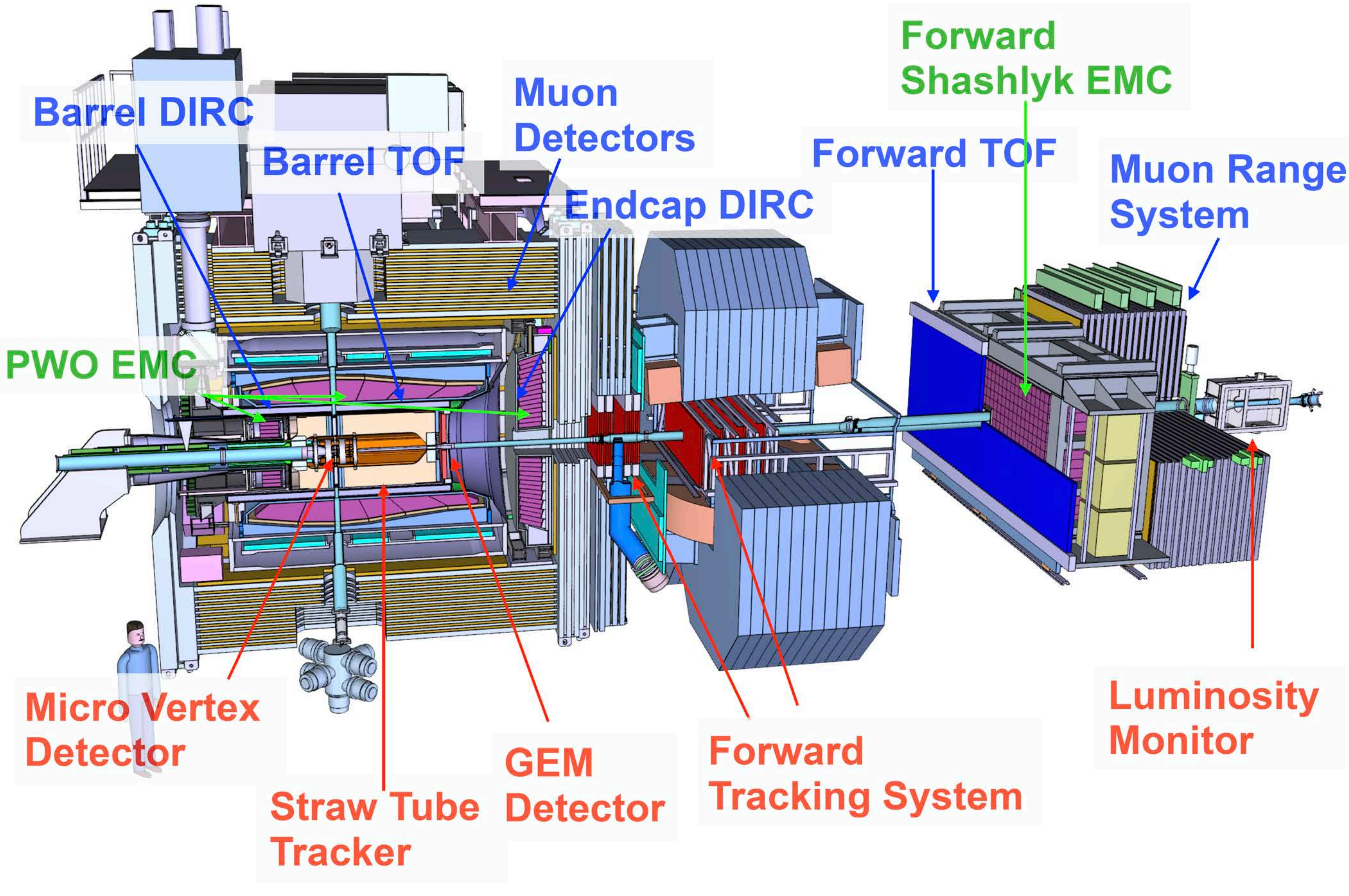


2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	203+
		Run III						Run IV					Run V	
LS2						LS3					LS4			
LHCb 40 MHz UPGRADE I			$L = 2 \times 10^{33}$		LHCb Consolidate: UPGRADE Ib				$L = 2 \times 10^{33}$ 50 fb^{-1}		LHCb UPGRADE II		$L=1\text{-}2 \times 10^{34}$ 300 fb^{-1}	
ATLAS Phase I Upgr			$L = 2 \times 10^{34}$		ATLAS Phase II UPGRADE				HL-LHC $L = 5 \times 10^{34}$				HL-LHC $L = 5 \times 10^{34}$	
CMS Phase I Upgr			300 fb^{-1}		CMS Phase II UPGRADE								3000 fb^{-1}	

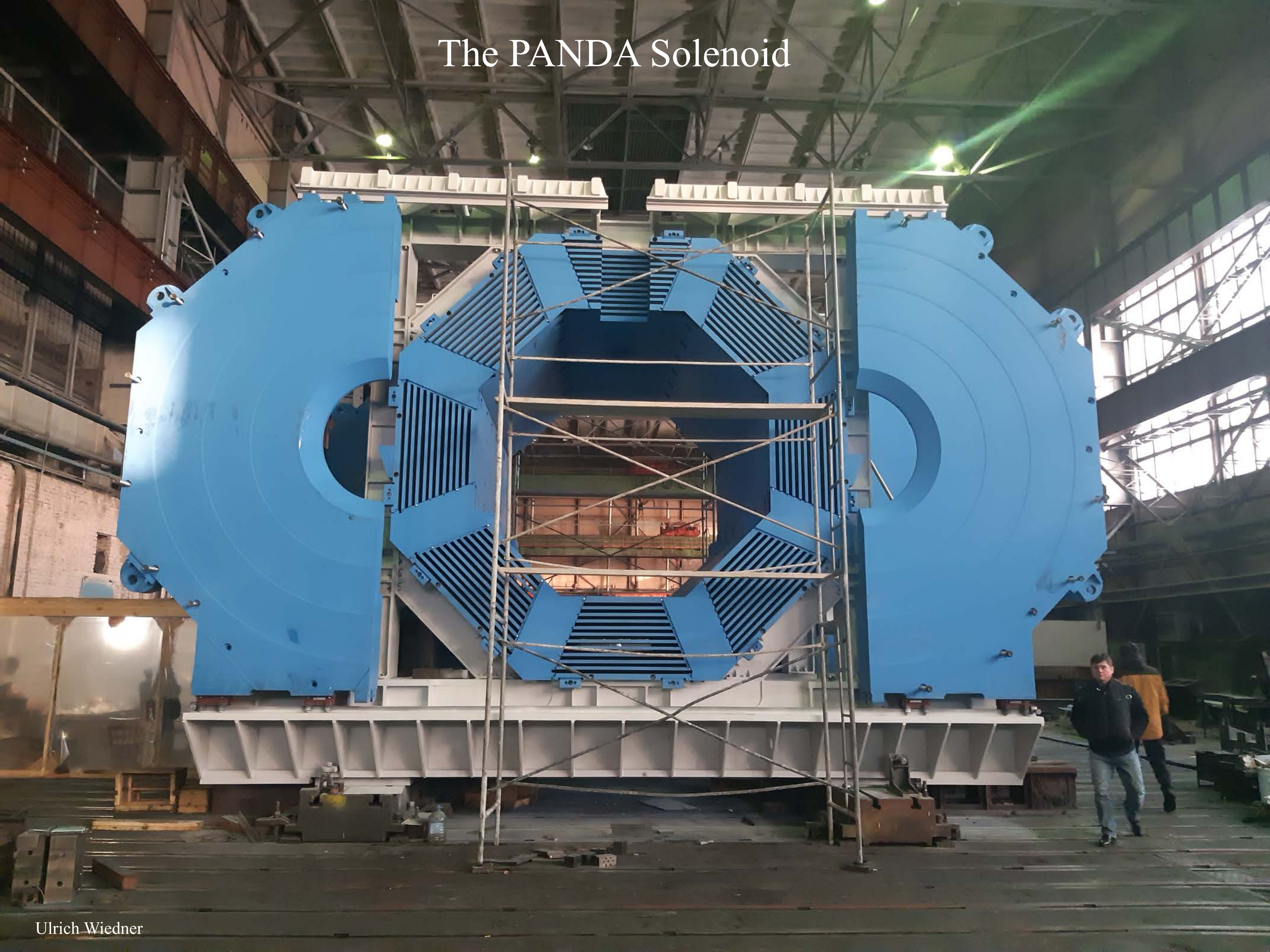
The FAIR facility



The PANDA detector



The PANDA Solenoid



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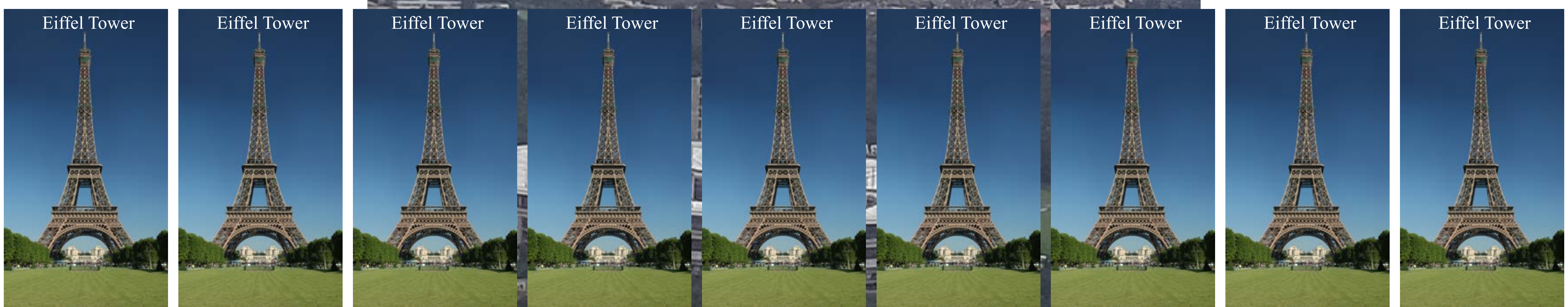
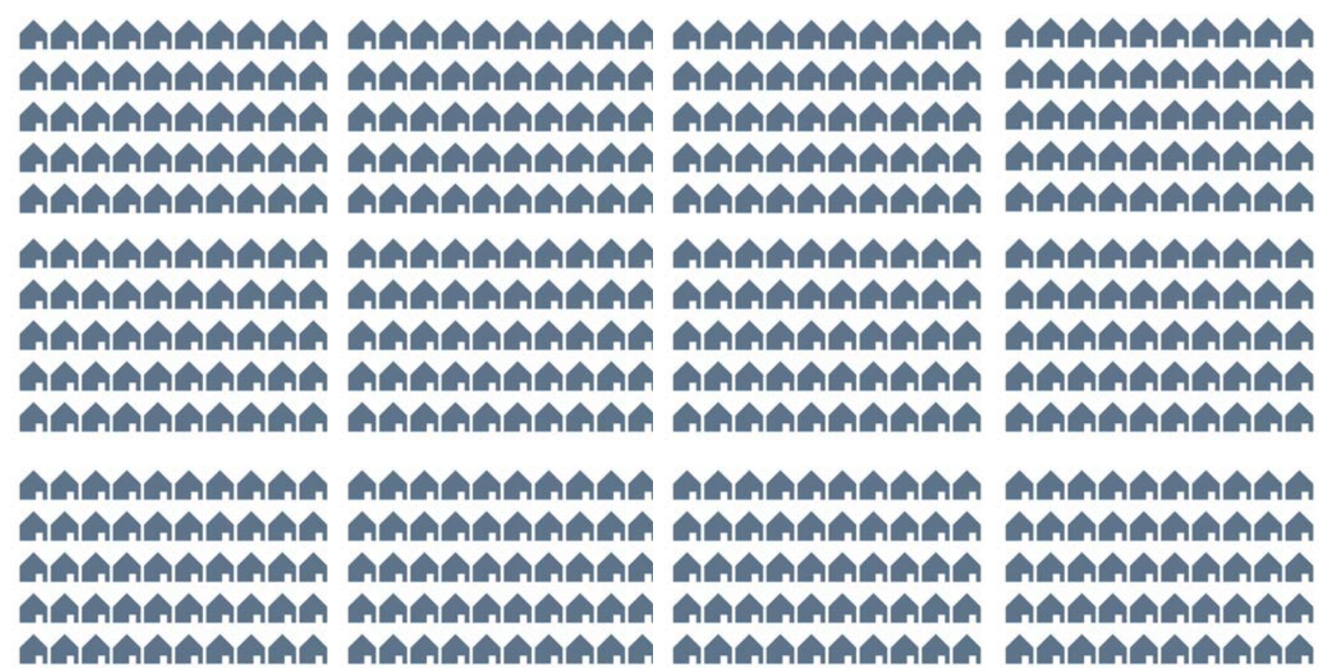
600,000 m³ of concrete: 8 soccer stadiums



65,000 tons of steel: 9 Eiffel towers

2,000,000 m³ of earth excavated:
5,000 single-family homes



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June 2019

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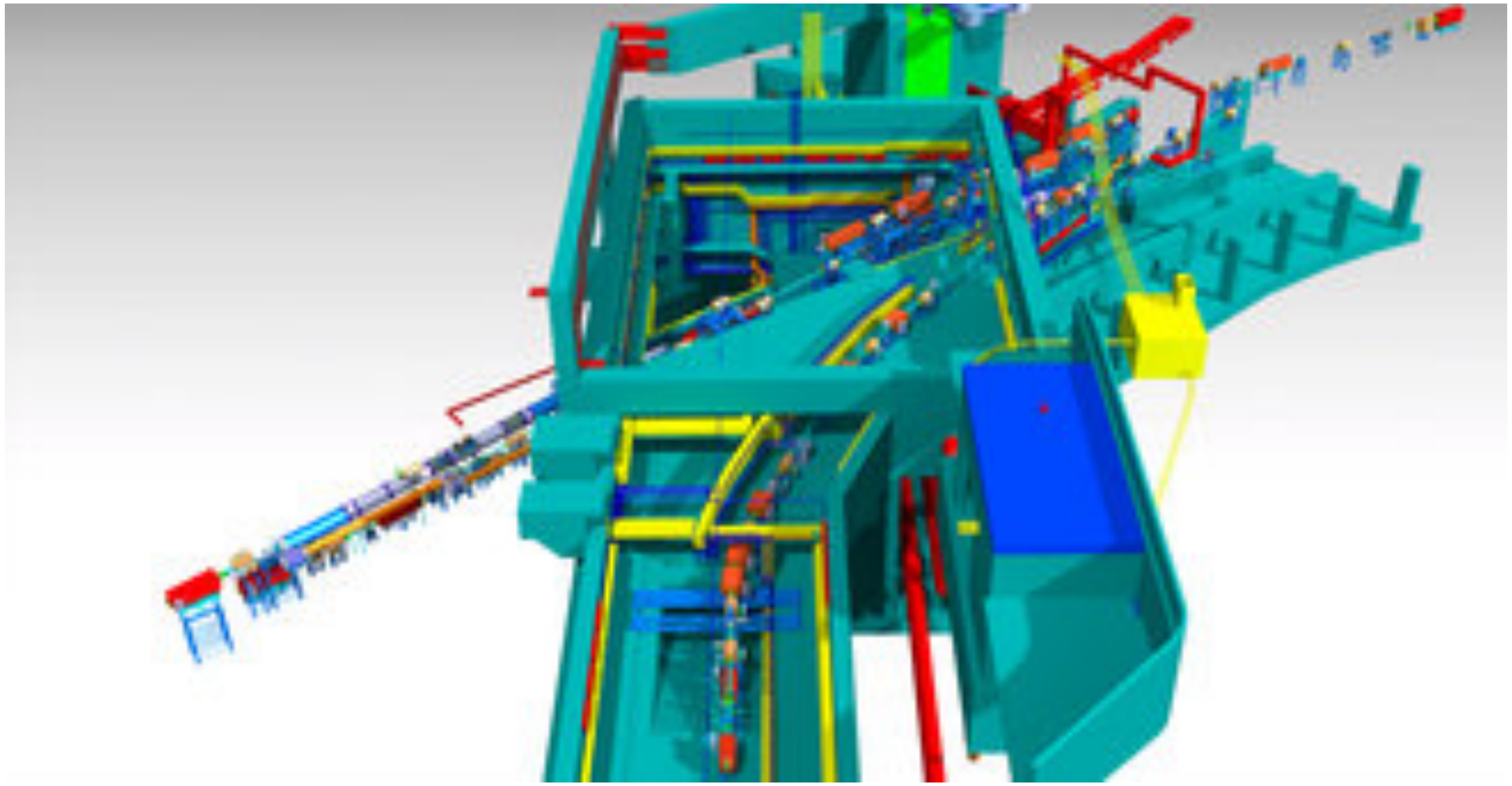
Very complex buildings with several beam lines crossing



I hope I could show you that the investigation of hadrons can tell us a lot of fundamental results about nature.

Thank you!