Glennys Farrar, NYU

A winding journey

Sexaquark as possible stable hadron & dark matter ➜

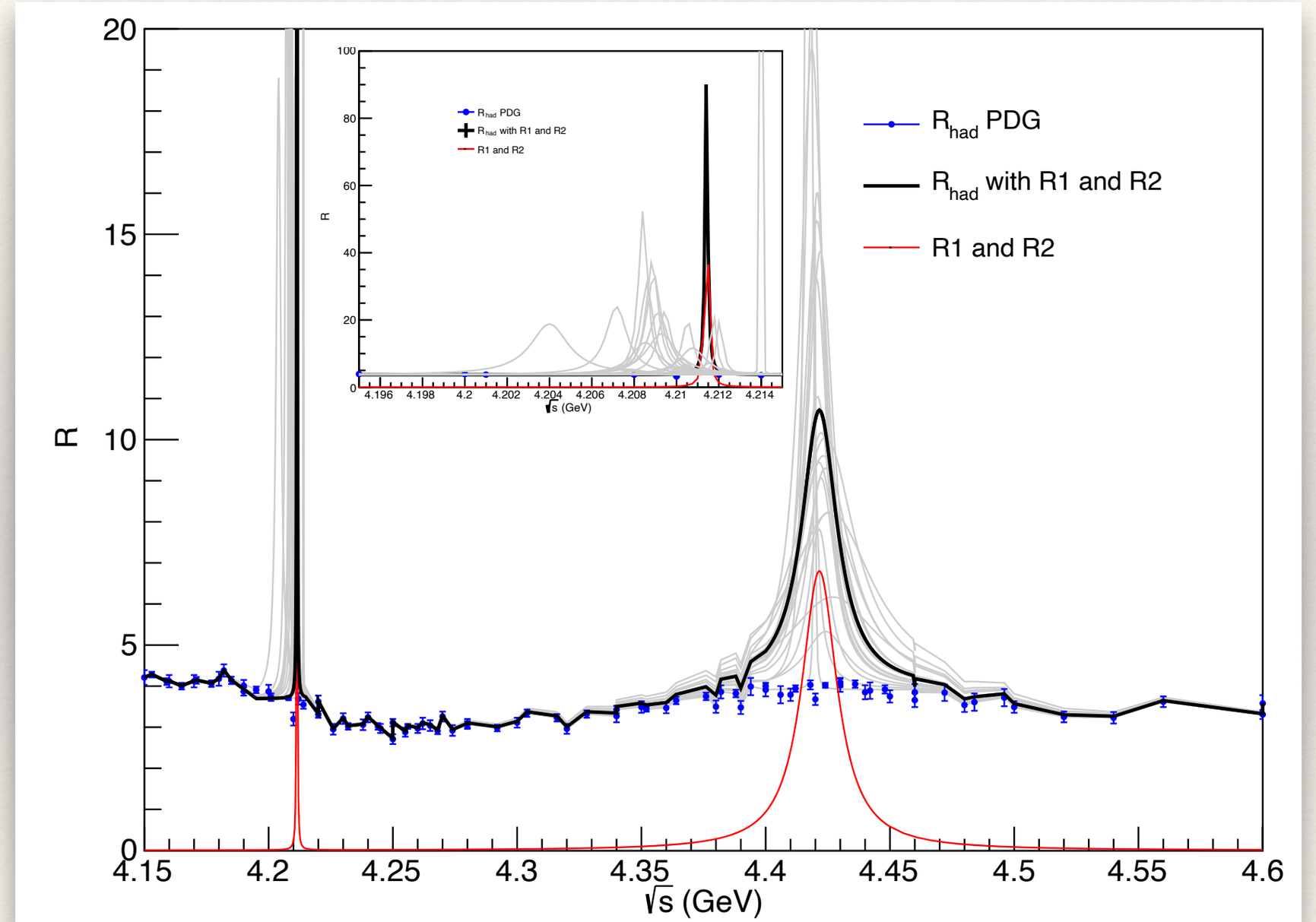
"invisible" final states in e^+e^- annihilation (preliminary)

Dedicated to the memory of Valery Rubakov

Journey

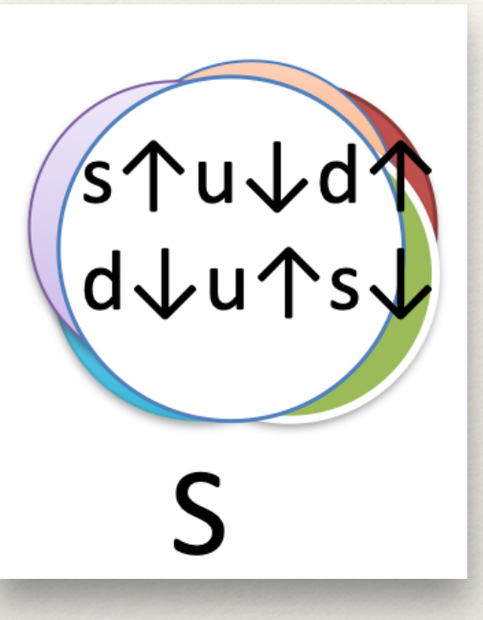
- **Deeply bound uuddss state (?)**
- **Dark matter & interactions with baryons**
- **Search in accelerators**
- **Invisible states via precision $e^+e^- \rightarrow \mu^+\mu^-$**

Destination: R true vs detected (prelimary)

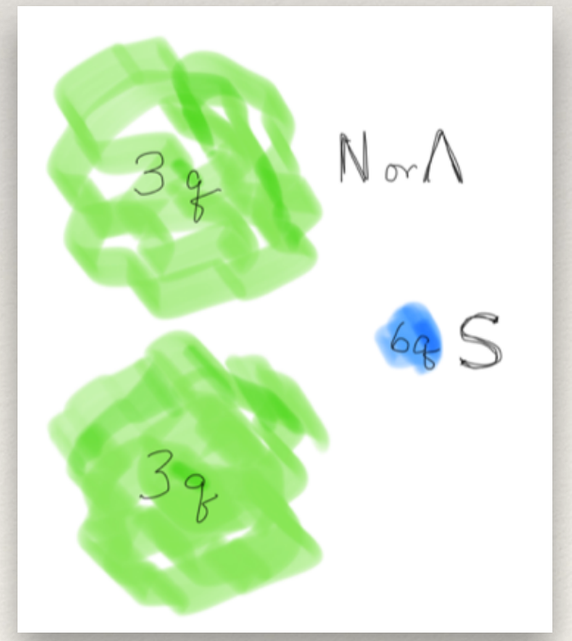


In collaboration with Changzheng Yuan and Qiming Li

Starting Point: deeply bound uuddss state (?)

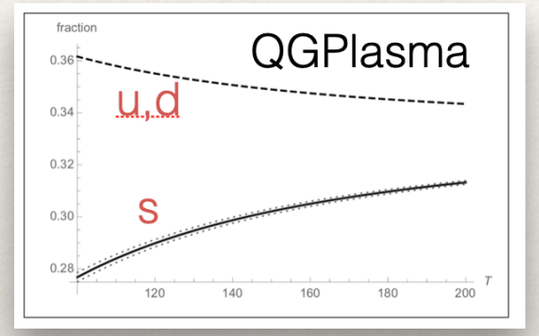


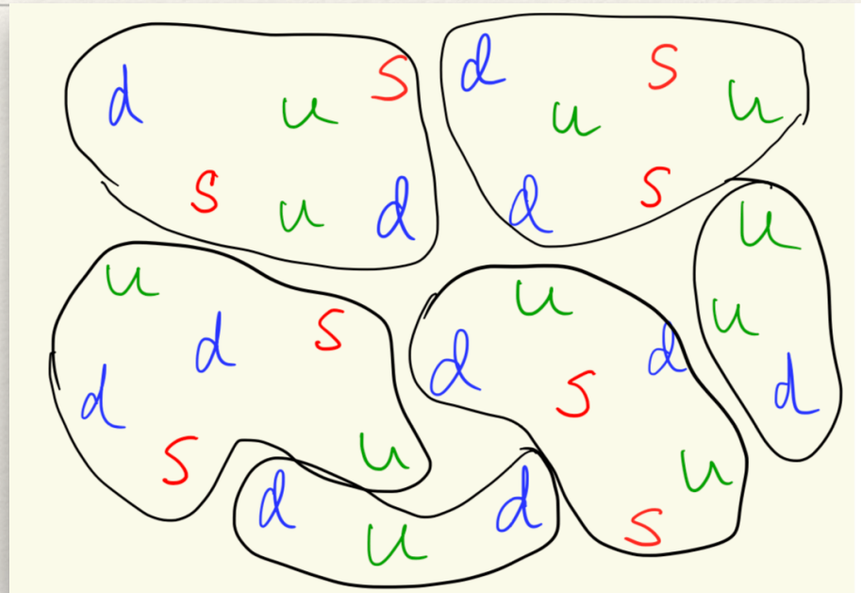
- Arkady-fest 2002!
- Deeply bound state ≡ **S** to distinguish from H-dibaryon
  - Ξ-nucleus decay (Nagara event) ⇒ $m_H > 2227$ MeV
  - ➜ H di-baryon is molecule or unbound (also lattice QCD)
- S is long-lived if $m_S < 2054$ MeV (threshold for S ➜ n Λ)
  - Naturally compact & hard to break-up
  - τ_S >> age of Universe
  - m_S >~ 1880 MeV (deuteron stability)
  - could be dark matter (GRF 1805.03723)



Relic Dark Matter Abundance

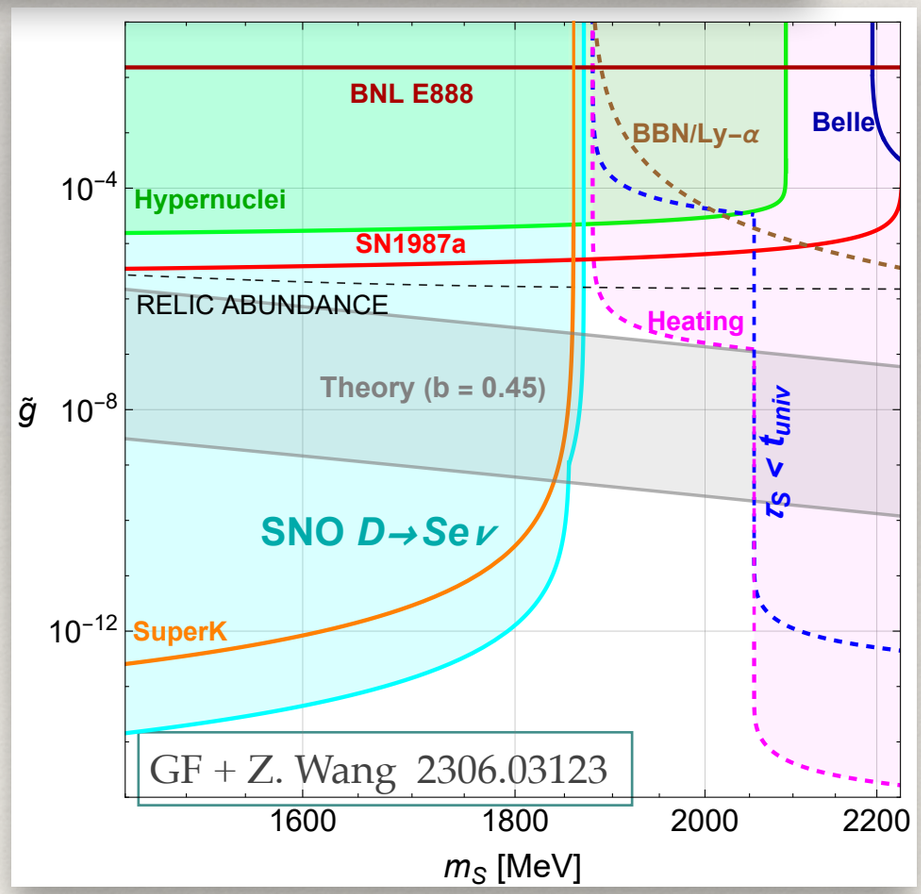
- Baryons are the leftovers!





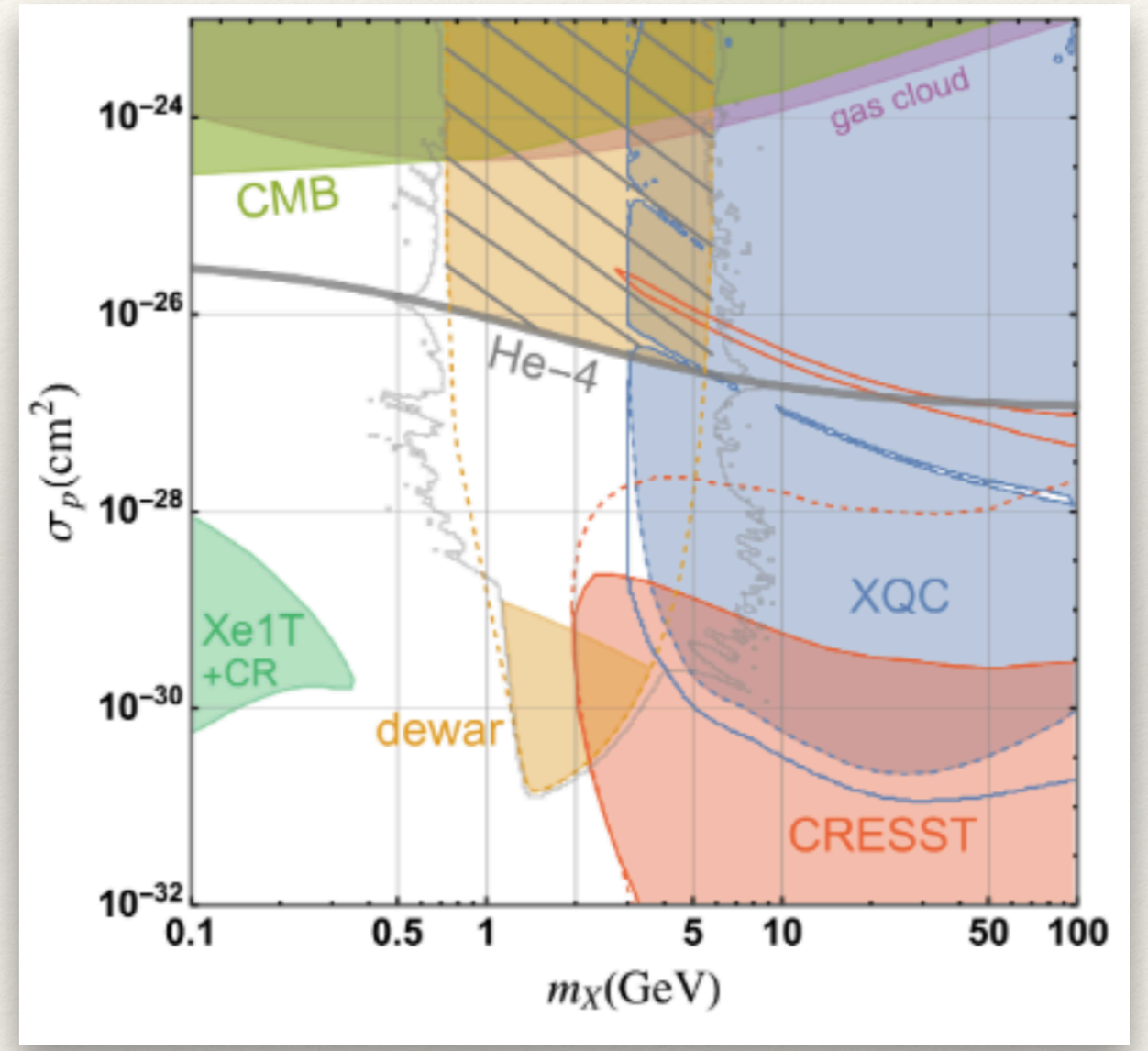
- Relic abundance estimated from Boltzmann is right order of magnitude GF 1805.03723

- Small $\tilde{g}$ ensures S survives hot hadronic phase



Dark Matter Baryon Interactions

- Expect hadronic scattering cross section O(mb)
- Consistent with direct and indirect detection constraints
  X. Xu + GRF, 2112.00707 & PRD 2023
- May be good for cosmology

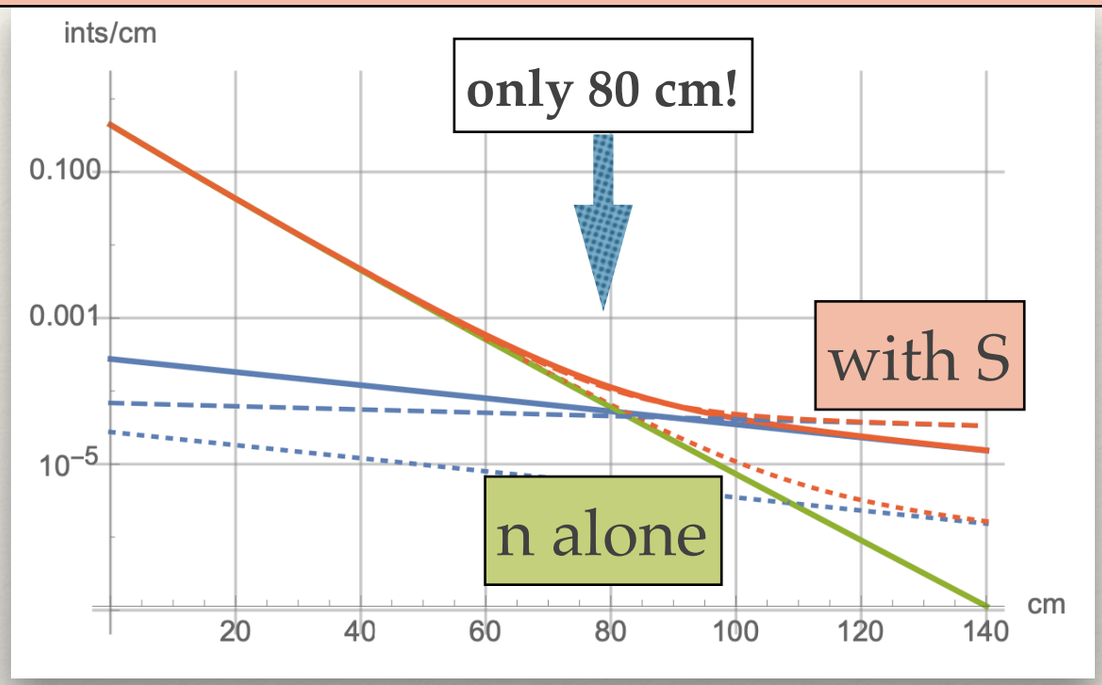


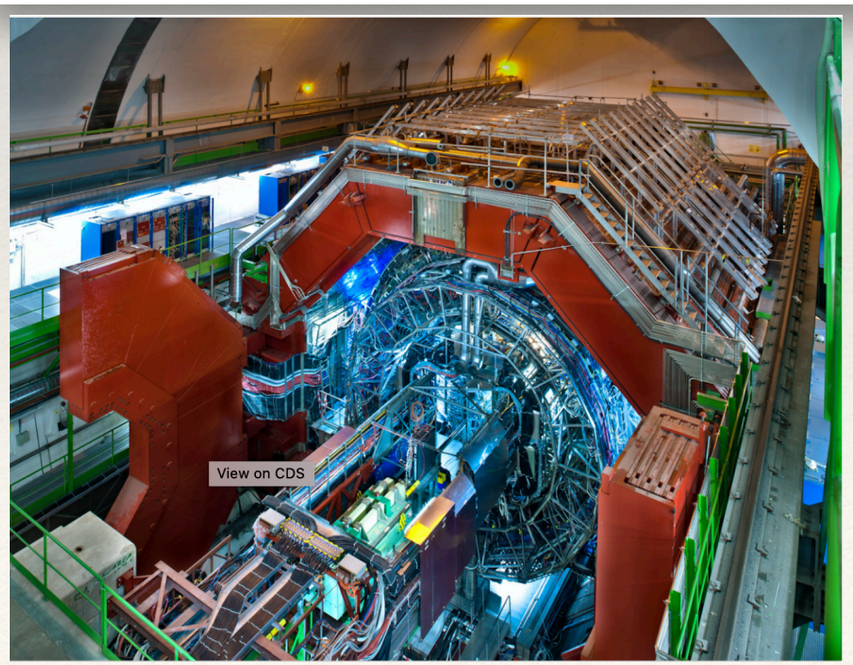
Search for S in particle experiment

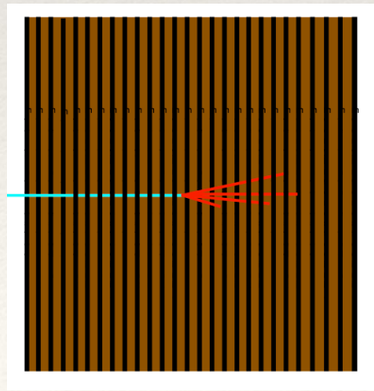
Elusive: $m_S \approx m_n$ & $n_n \approx 10^{3\text{-}5}\, n_S$

- **Belle-KEK** (Japan) e+e- 10 GeV
  - Inclusive production: est. br. fraction ~ 10^{-7}
    - **Υ -> Λ Λ [$\bar{S}$]** (+ pions) $M_S^2 = (p_\Upsilon - p_{\Lambda 1} - p_{\Lambda 2} - \Sigma p_{\pi i})^2$
  - Apparent lack of B and S conservation:
    - correlated missing B = ± 2 + missing S = ∓ 2
- HE Hadron beam or collider **(CERN)**
  - **Long Interaction Length Neutral Particle Detector**
    - second exponential in interaction length
- Hi intensity (10^{12}) γ p ➜ S $\bar{\Lambda}$ K^+ (**J-lab**)
  - Quantum numbers & missing mass

Long-interaction-length-neutral detector





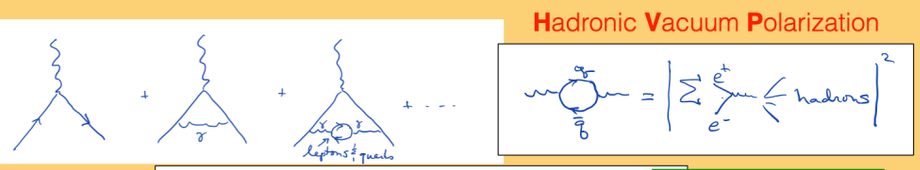


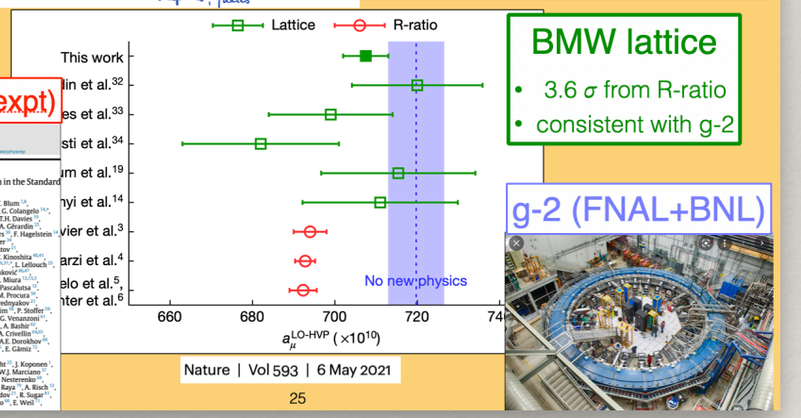
Muon g-2 SM deficit: "Invisible" final states in e^+e^-?

GRF 2206.13460: missed contribution to R_{had} due to $S\bar{S}$ production (neutral, don't decay)

Muon g-2 & Hadronic Vacuum Polarization from lattice QCD vs R-ratio

Hadronic Vacuum Polarization





BMW lattice
- 3.6 σ from R-ratio
- consistent with g-2

R-ratio (e^+e^- expt)


Physics Reports

The anomalous magnetic moment of the muon in the Standard Model

Nature | Vol 593 | 6 May 2021

g-2 (FNAL+BNL)

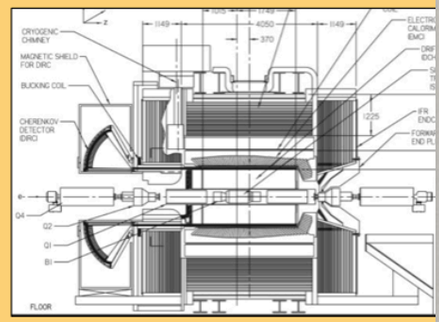
25

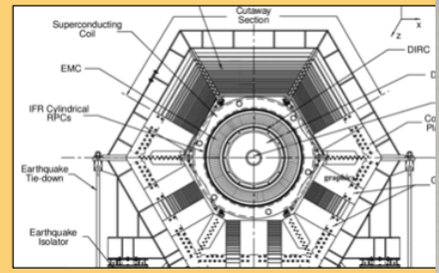
Could an S S̄ final state have been missed?

YES!!!!

GRF arXiv:2206.134

- Backgrounds to suppress (e.g.BABAR)
  - `physics' ($\mu^+\mu^-$, $\tau^+\tau^-$, q qbar) 65 Hz
  - Bhabha ($e^+e^- \rightarrow e^+e^-$) 500 Hz
  - beam backgrounds 20,000 Hz





- Suppress bkg with triggers.

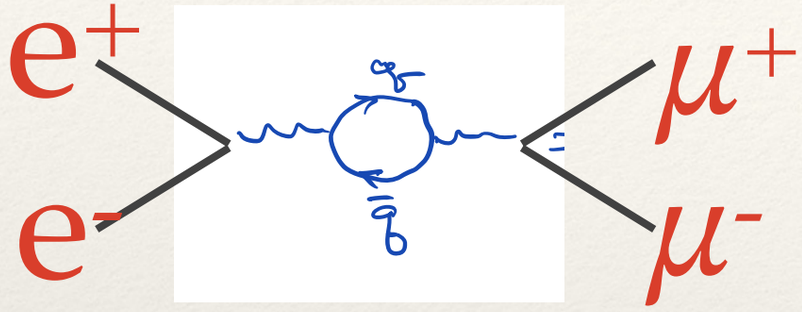
I. ("classic") Require:

- 2 charged particles from collision point or
- 2 photons consistent with π^0 from collision point …

- $S\bar{S}$ are neutral, back-to-back in CM. Only interact — if at all - far from the collision point. **$S\bar{S}$ events don't get recorded!**

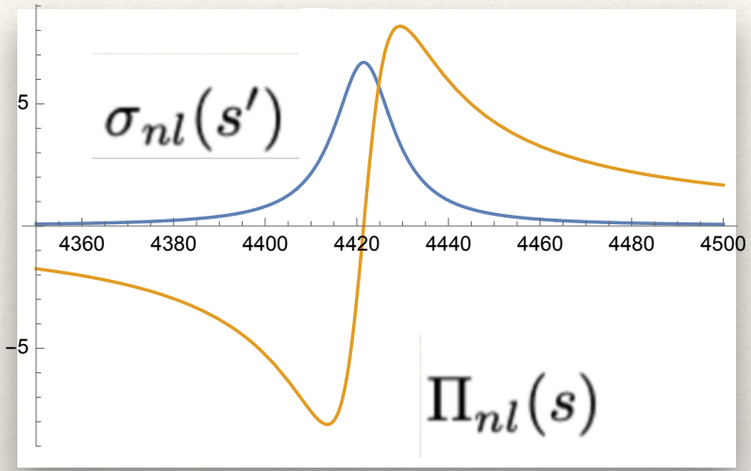
Search in $e^+e^- \to \mu^+\mu^-$

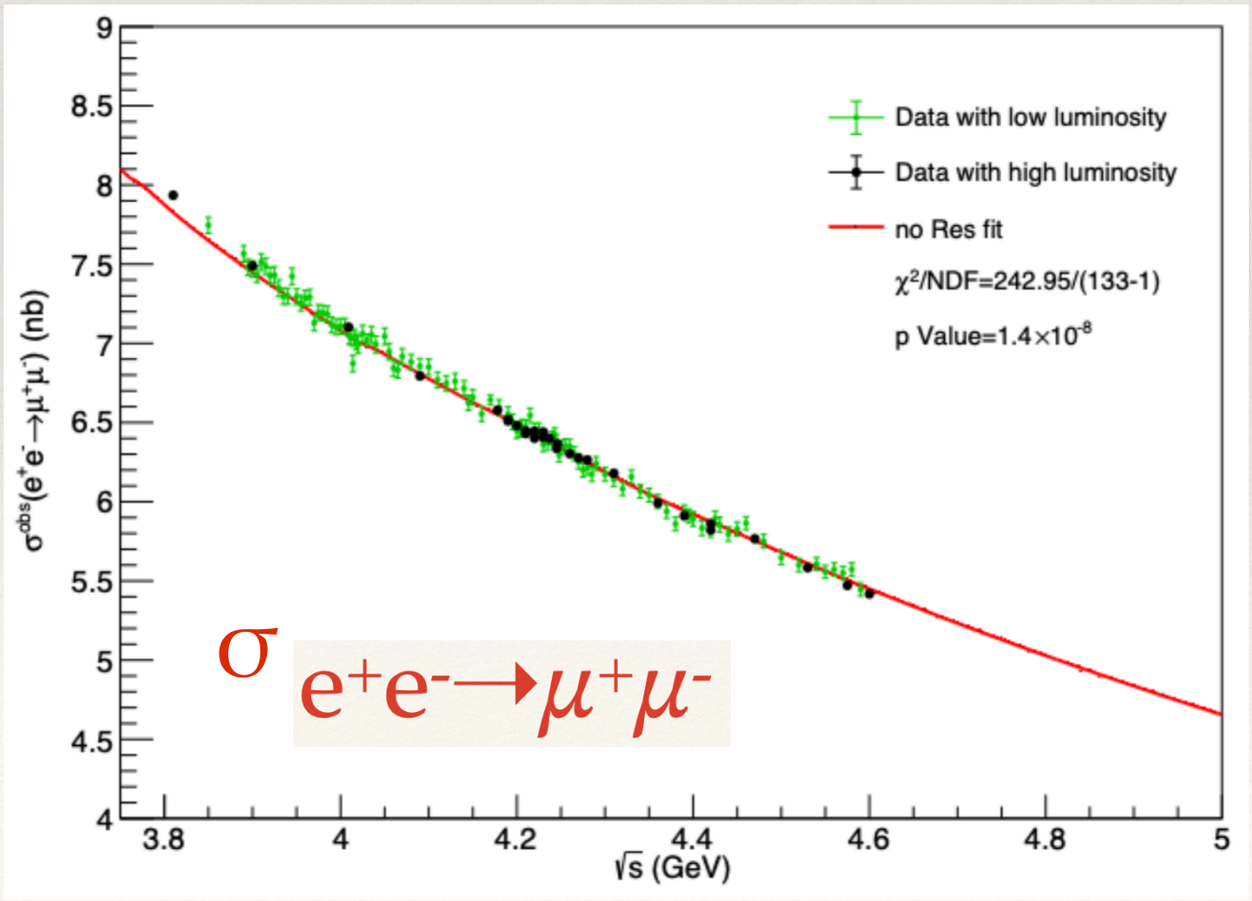
Analysis of published BES data in collaboration with Changzheng Yuan and Qiming Li

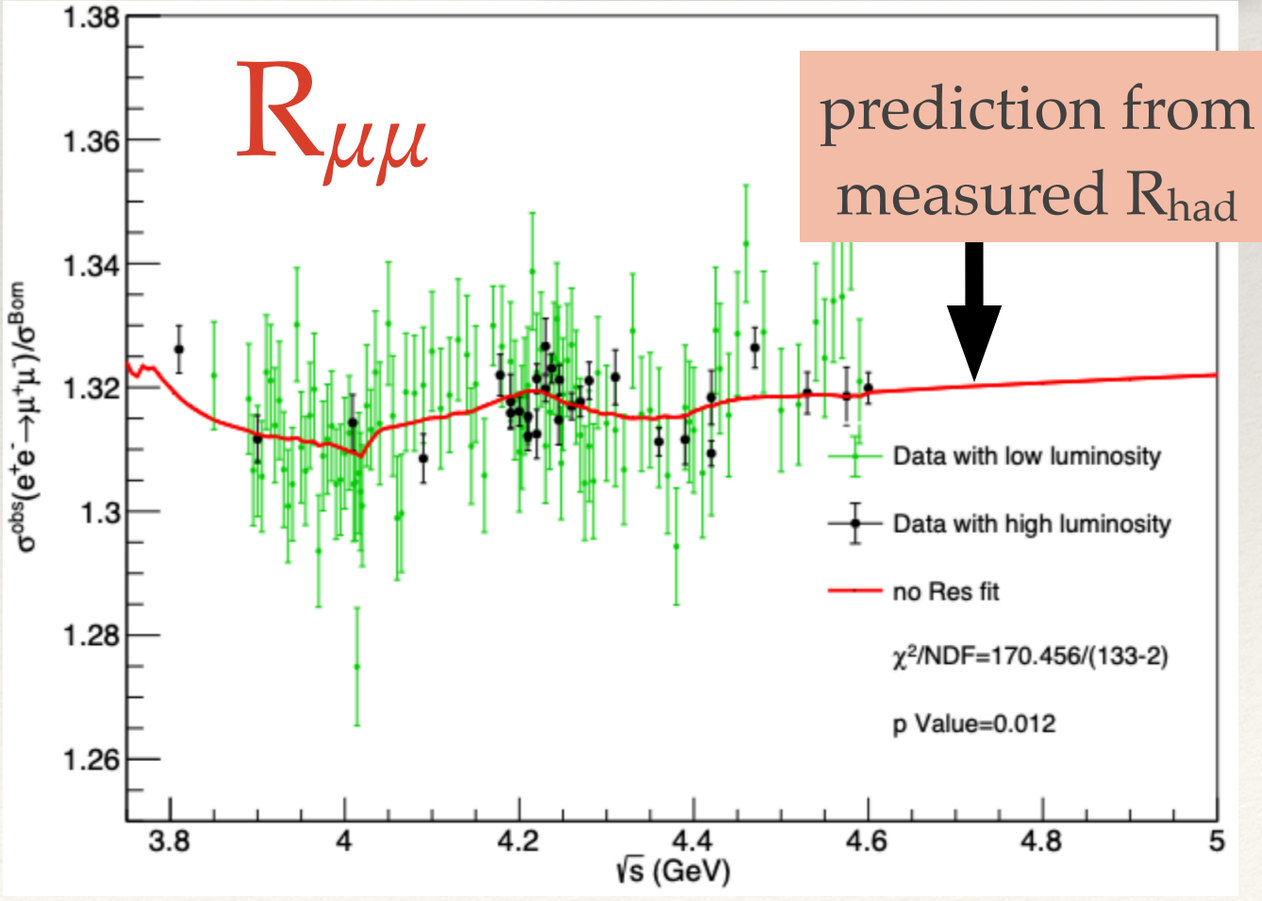


$$\sigma_{\mu^+\mu^-}(s) = \frac{\sigma^{\mathrm{B}}_{\mu^+\mu^-}(s)}{|1-\Pi(s)|^2}$$

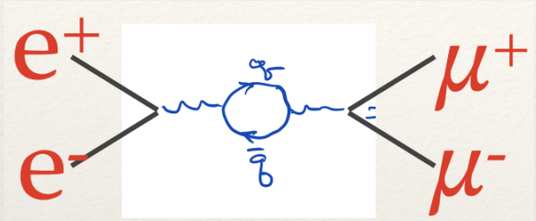
$$\Pi_{nl}(s) = \frac{s}{4\pi^2\alpha}\int_{4m_\pi^2}^{\infty}\frac{\sigma_{nl}(s')}{s-s'+i\epsilon}ds'$$

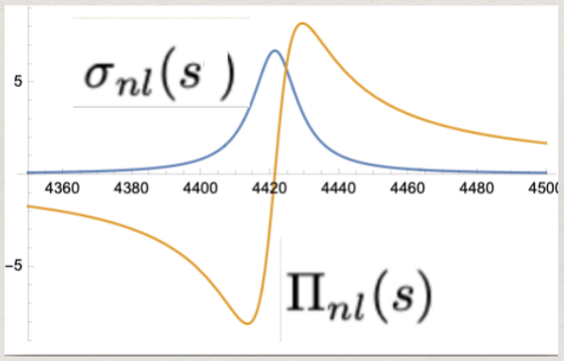


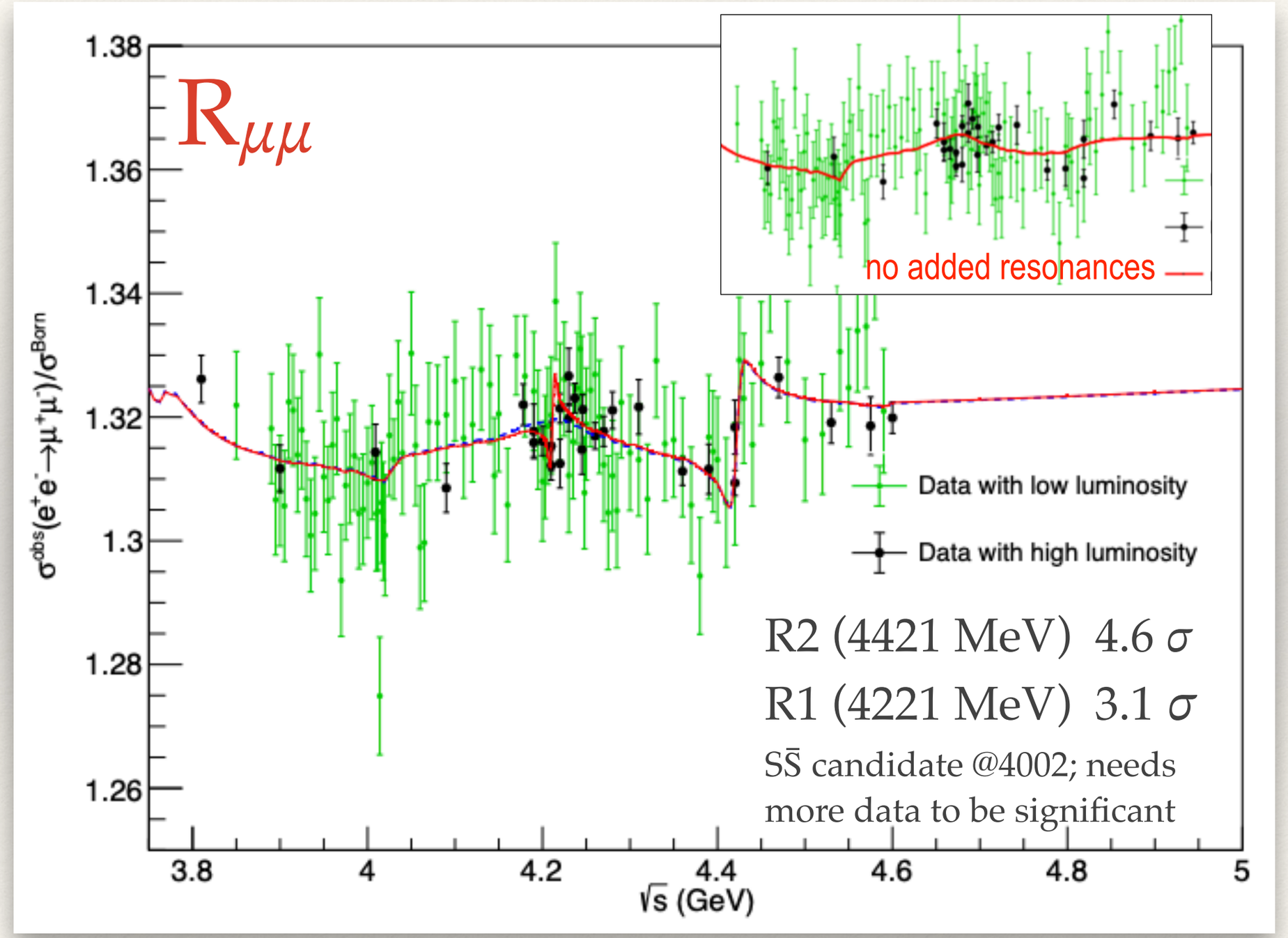




Dramatically better fit with R1,R2







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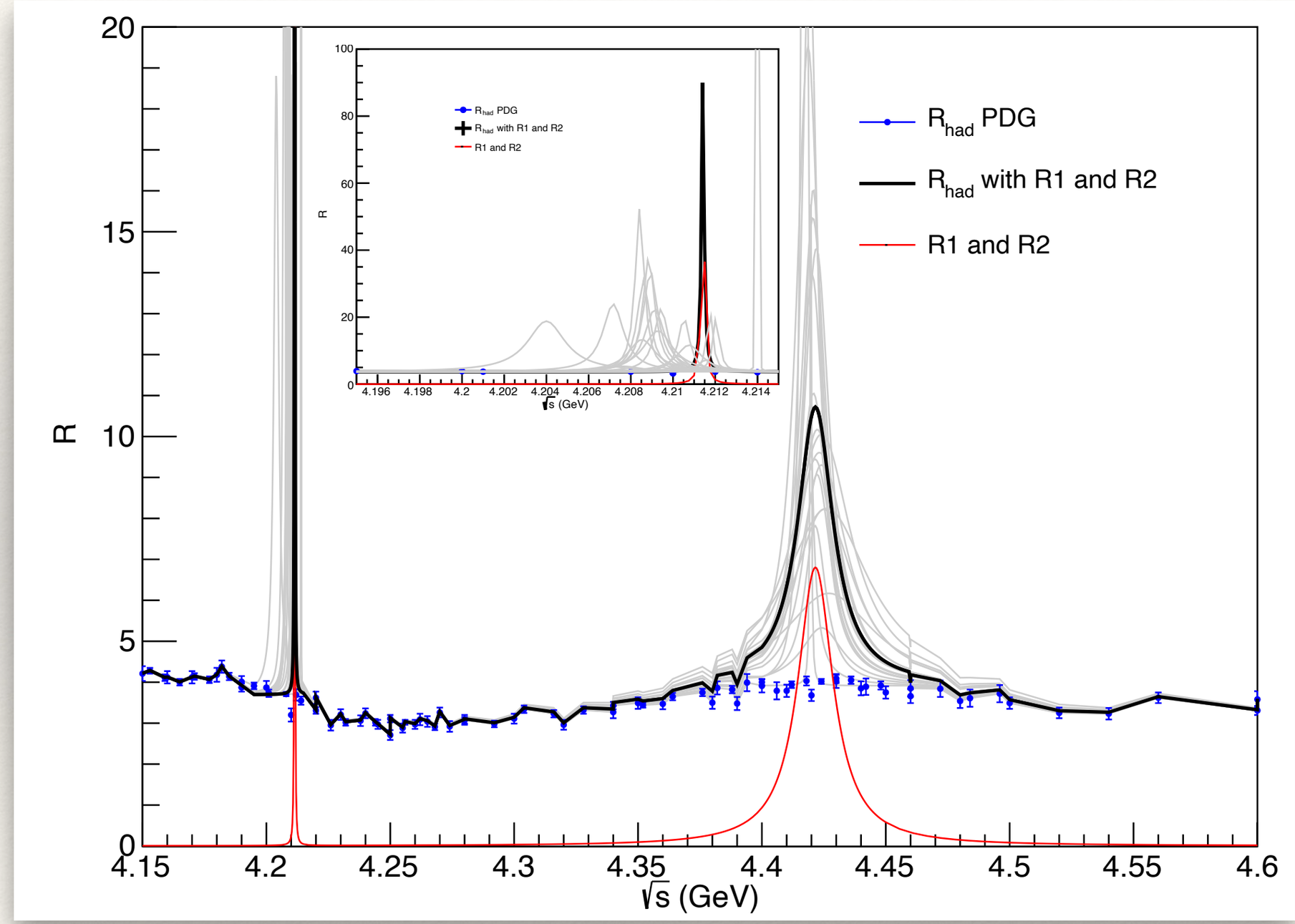
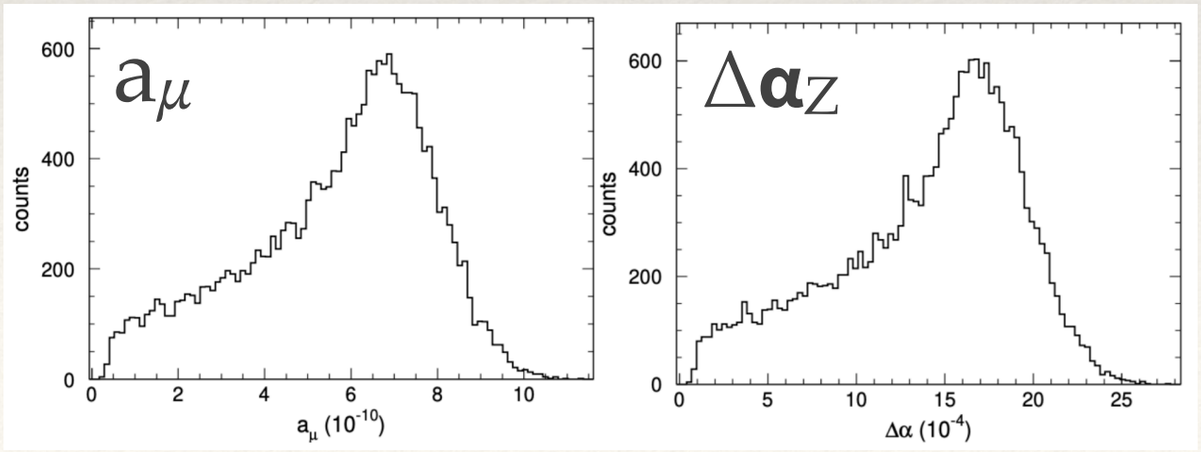
Best fit to $e^+e^- \to \mu^+\mu^-$: R_{true} (prelimary)

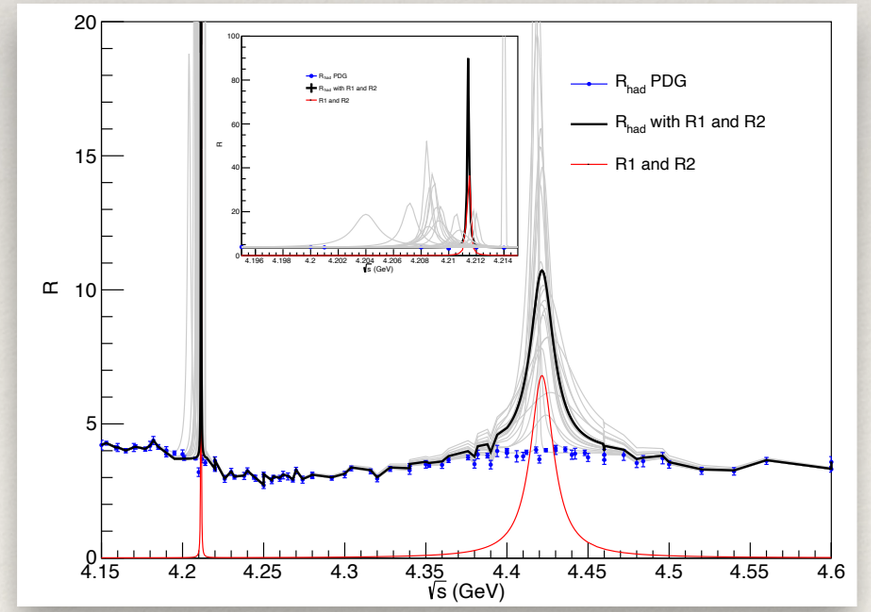


In collaboration with Changzheng Yuan and Qiming Li

Conclusions & Interpretation

- Precision $e^+ e^- \rightarrow \mu^+ \mu^-$ is valuable tool for hadron spectrum
- Missed final states in R_{had}:
  - Reduces discrepancy in g-2. What could their origin be?
- Sexaquark is a posible undiscovered stable hadron





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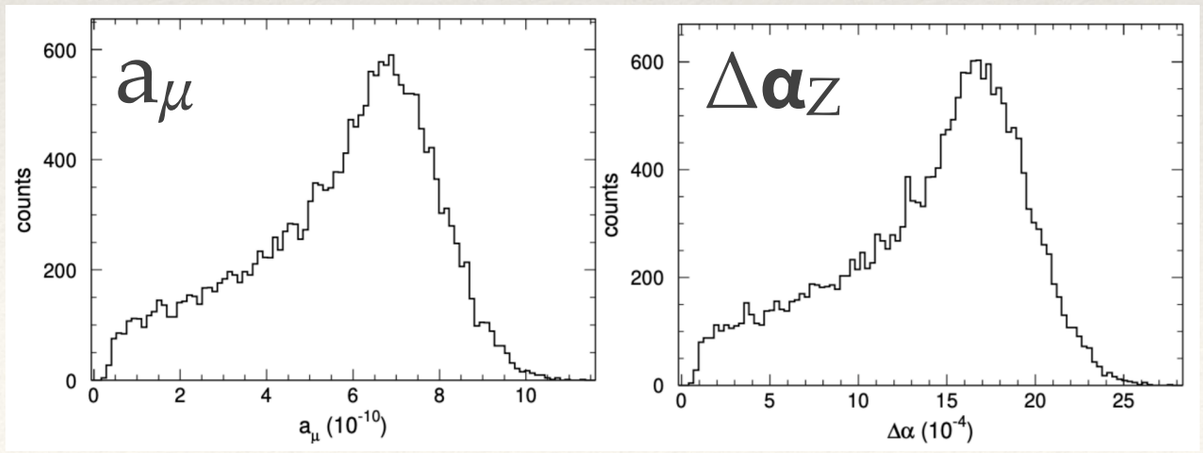
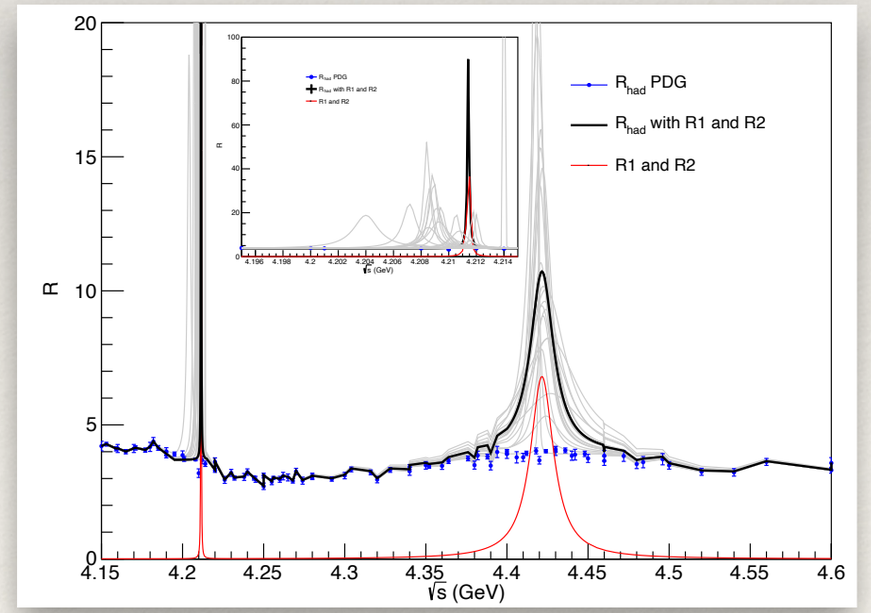
Thanks!





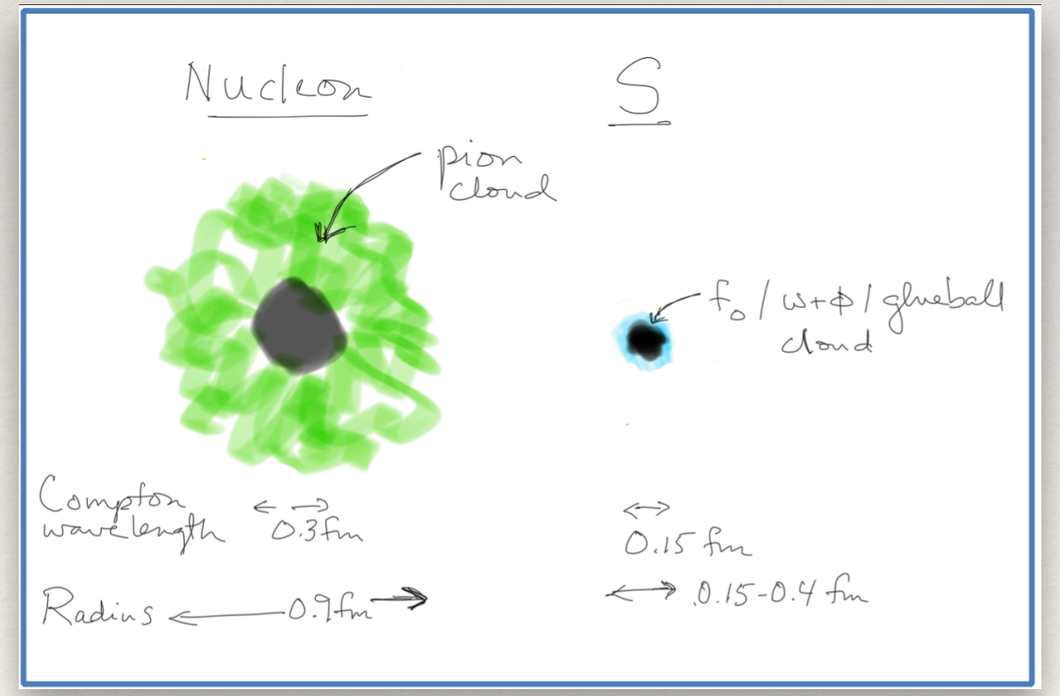
References

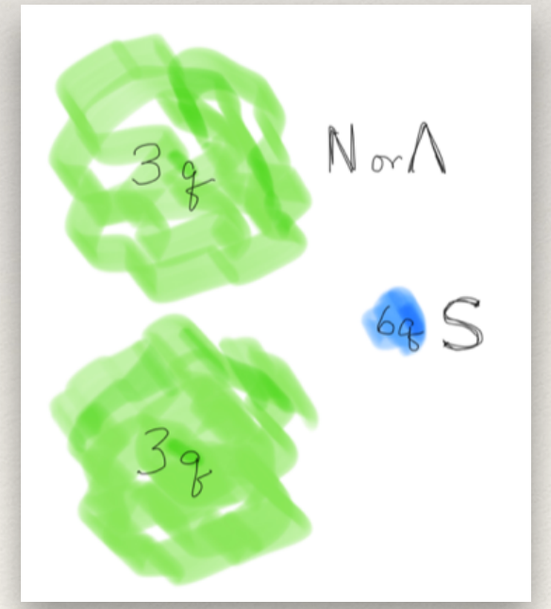
- Long lifetime if compact: GF+G. Zaharijas PRD2003
- Compact, long-lived = consistent with expt: GF 1708.08951
- Relic Abundance from QCD phase transition: GF 1805.03723
- Stable S: Overview & Detection Strategies GF 2201.01334
- g-2 deficit maybe due to missed final states in R_{had} GF 2206.13460
- Dark Matter Detection & constraints on $\tilde{g}$: GF+{Z. Wang, X.Xu} 2007.10378, 2101.00142, 2112.00707, 2306.03123
- Invisible states from precision $e^+e^- \rightarrow \mu^+\mu^-$: GF, Q. Li, C. Yuan in prep

Backup Slides

How sexaquarks interact

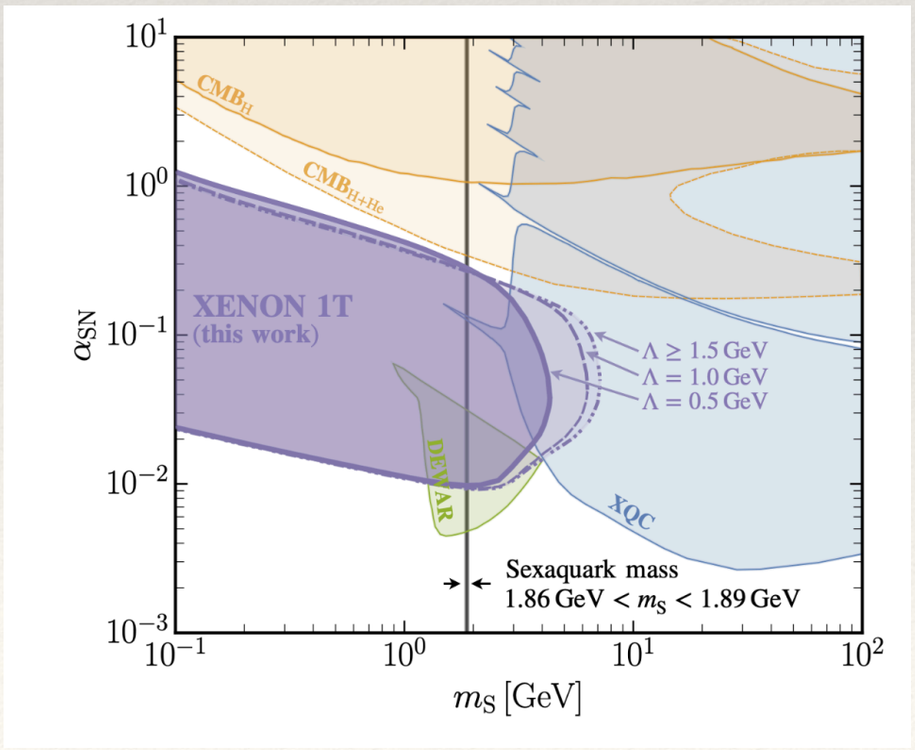
- **No EM interactions** (Q=0, no dipole moment)
- QCD flavor singlet.
  - **No coupling to pion** (⇒ reduced xcn)
  - **Hard to break up/create** due to small overlap & energy barrier

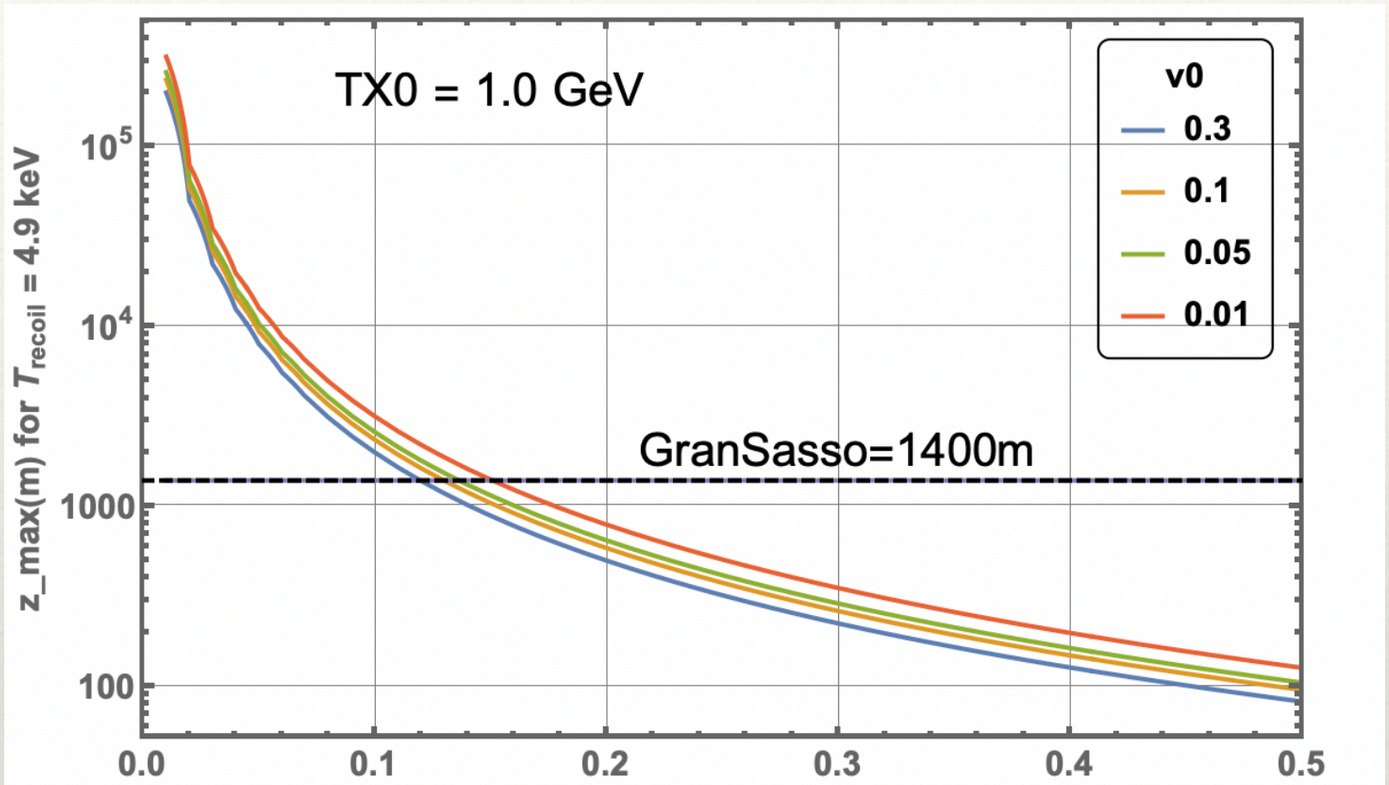




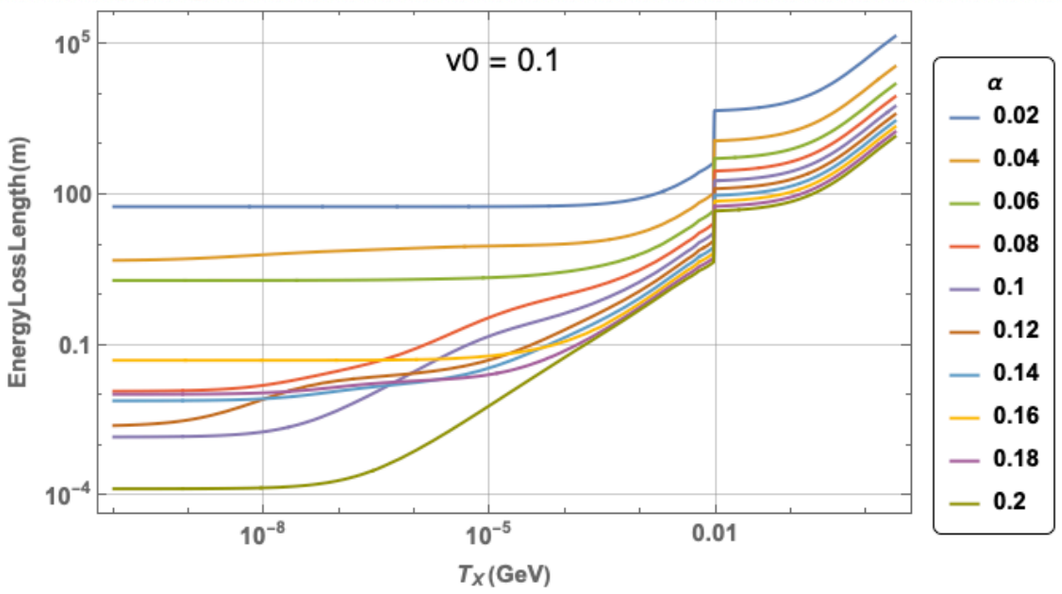
Cosmic Ray Dark Matter

Avery, Bringmann, Kolosova limits too strong (didn't consider non-pert E-loss)

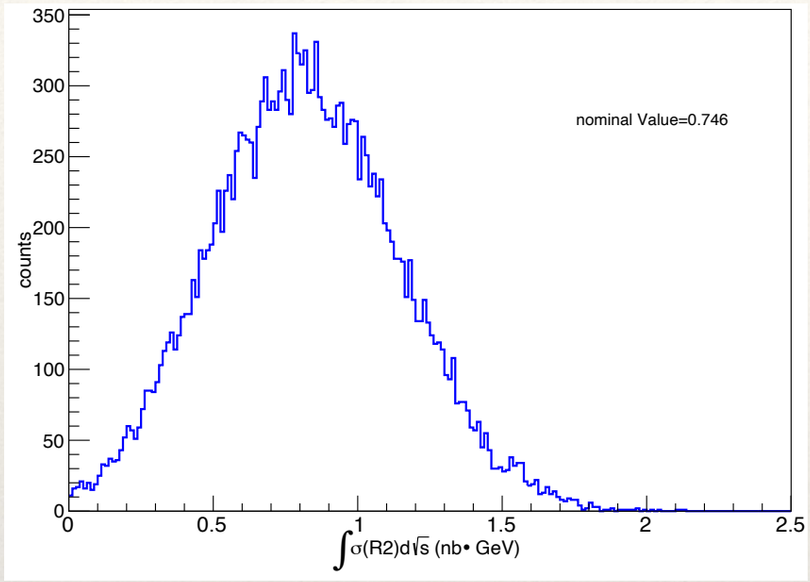


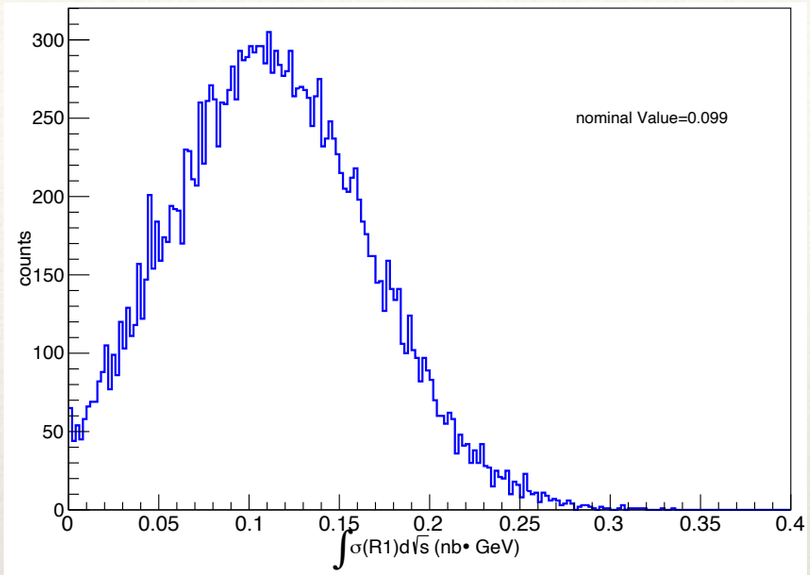


Xu & GRF



$\int \sigma_{had}\, dE_{cm}$ (nb GeV)





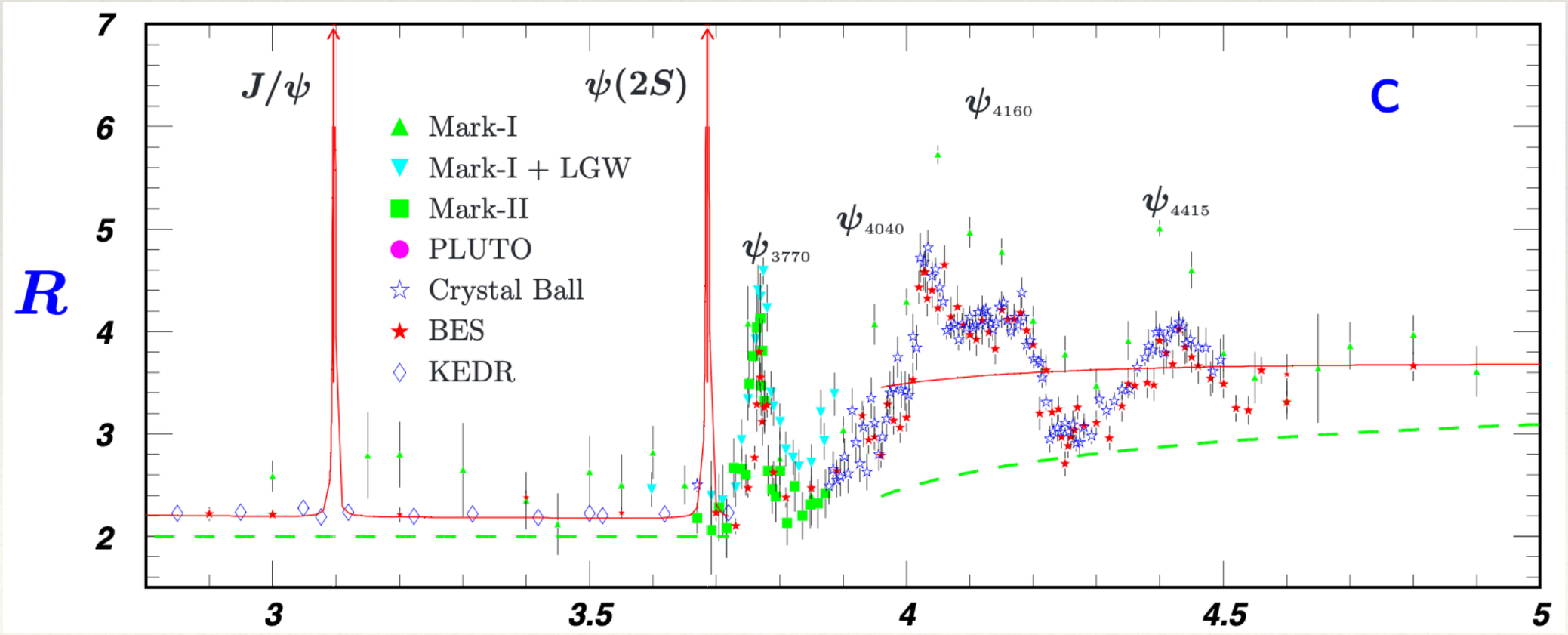
J/Ψ: 0.52

Ψ2S: 0.41

Ψ3770: 0.42

R1: 0.1

R2: 0.75



sim to

Ψ(4230)

Ψ(4415)

Parameters Missing Resonance Fit

(preliminary)

R2 (4421.5±3.5 MeV) 4.6 σ $\Gamma 2 = 15.9 \pm 15.4$ MeV $\Gamma 2_{ee} = 0.63 \pm 0.31$ keV

R1 (4211.4±2.1MeV) 3.1 σ $\Gamma 1 = 0.15 \pm 1.32$ MeV $\Gamma 1_{ee} = 0.077 \pm 0.044$ keV

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