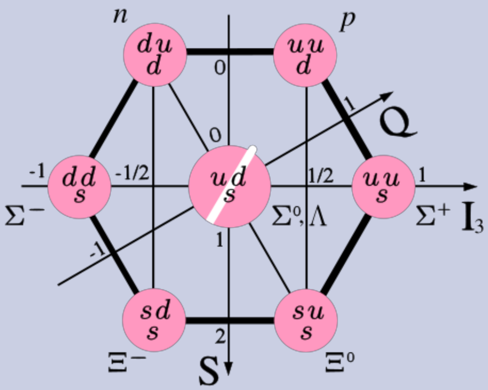
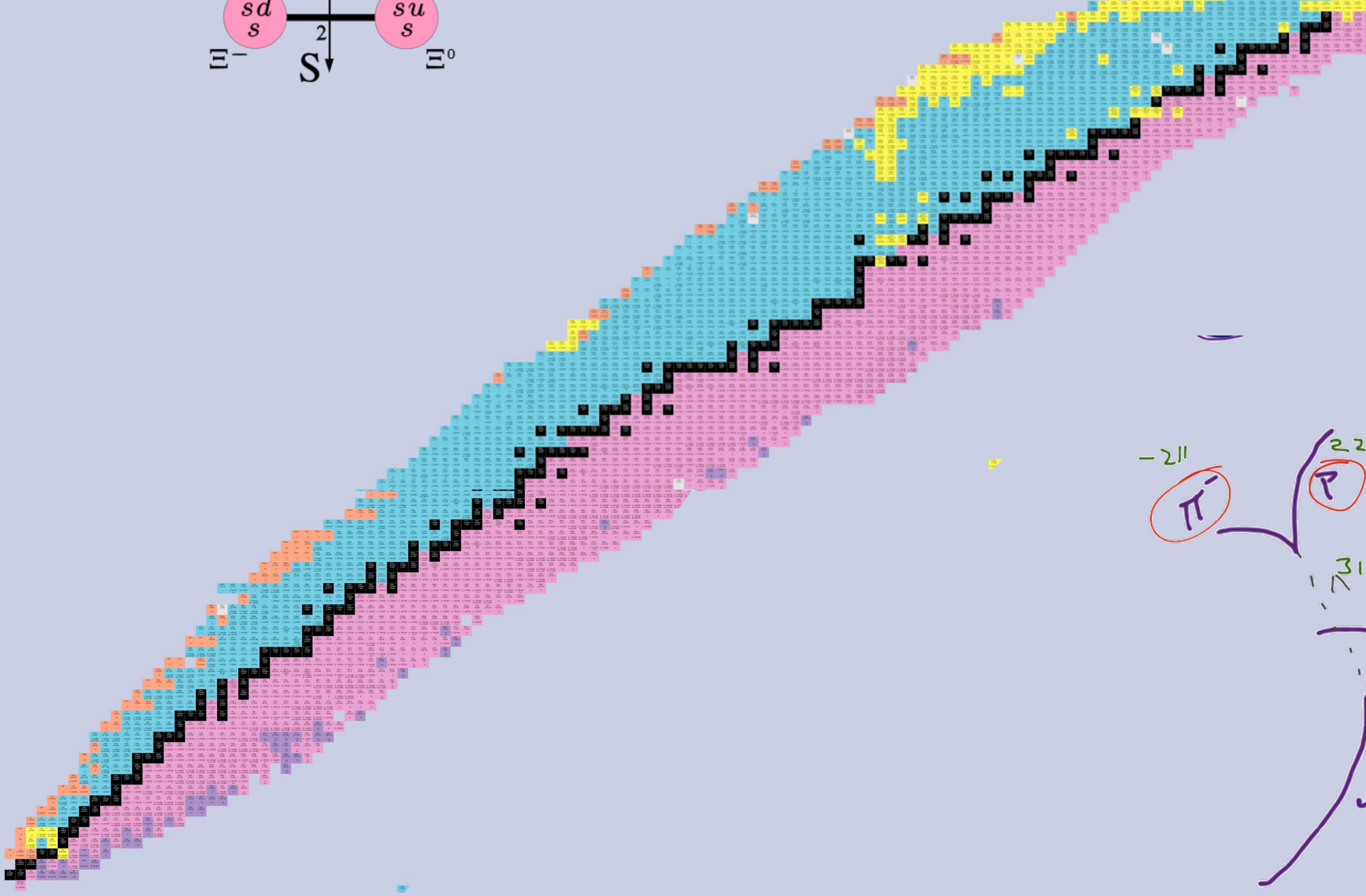
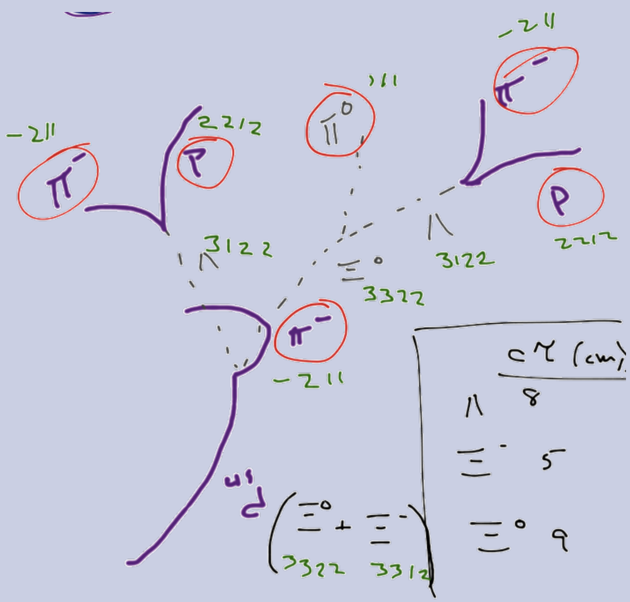
^{4S}d: the "other" di-baryon state
Searching in STAR

Alex Schmah and Mike Lisa

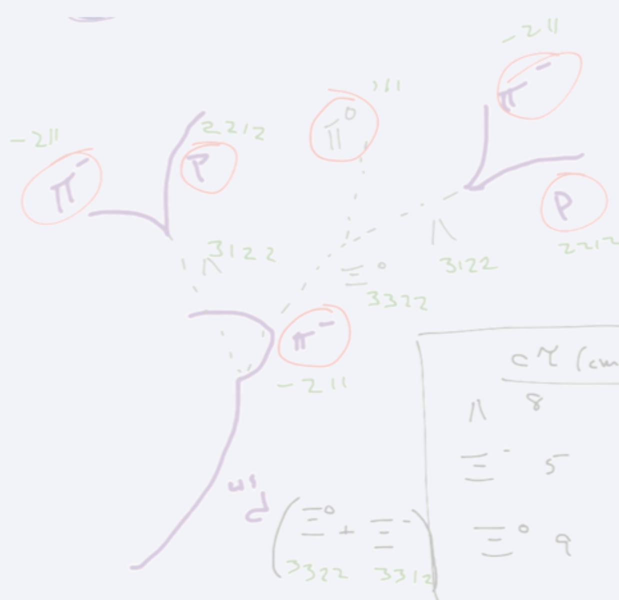






Outline

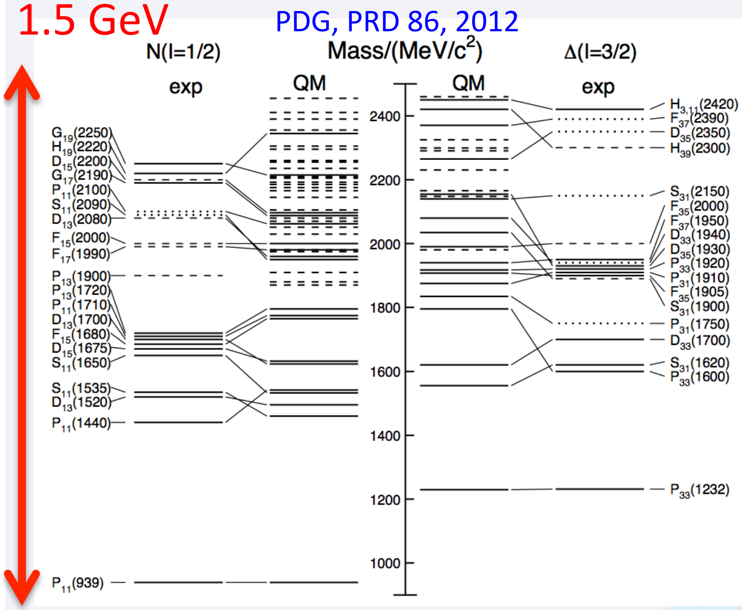
- Motivation & possibility of a new state
- Mass, decay mode, lifetime estimates
- Best energy for a search?
- expected yields
- searching in STAR



QCD and "nuclear" physics – light sector

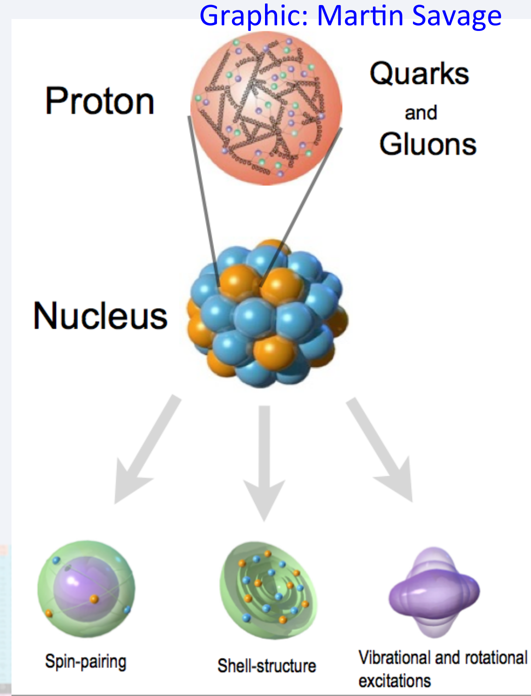
1.5 GeV

PDG, PRD 86, 2012



N and Δ -- $\ell\ell\ell$

Graphic: Martin Savage

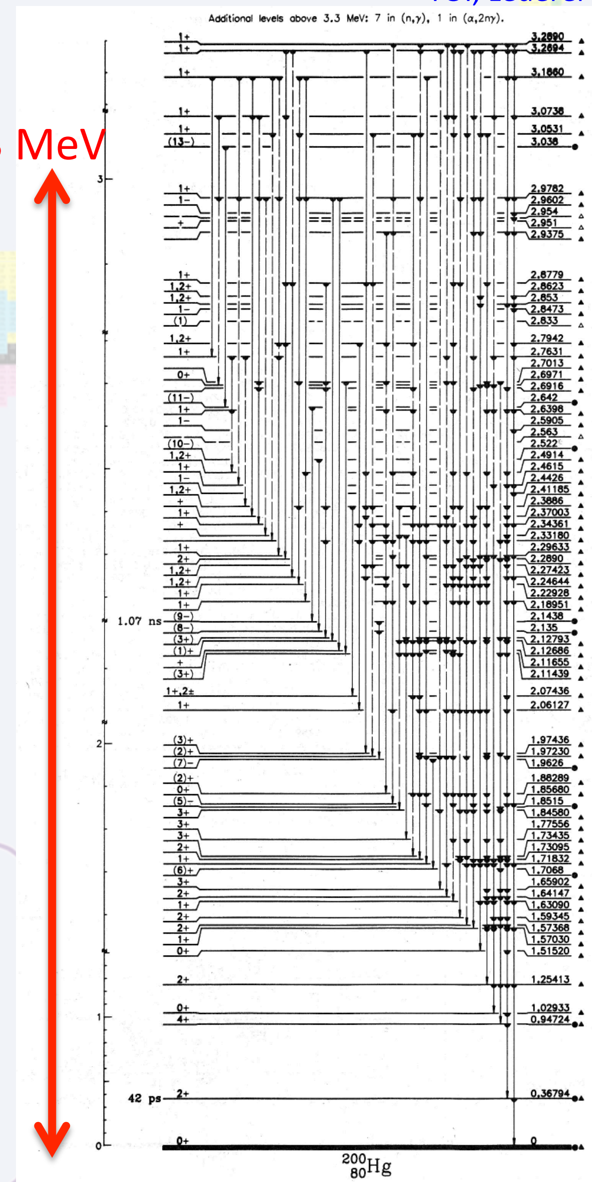


Hadronic structure from fundamental interaction ~ GeV

Nuclear structure from residual interaction ~ MeV

TOI, Lederer

3 MeV



^{200}Hg -- 80 protons & 120 neutrons

QCD and "nuclear" physics – light sector

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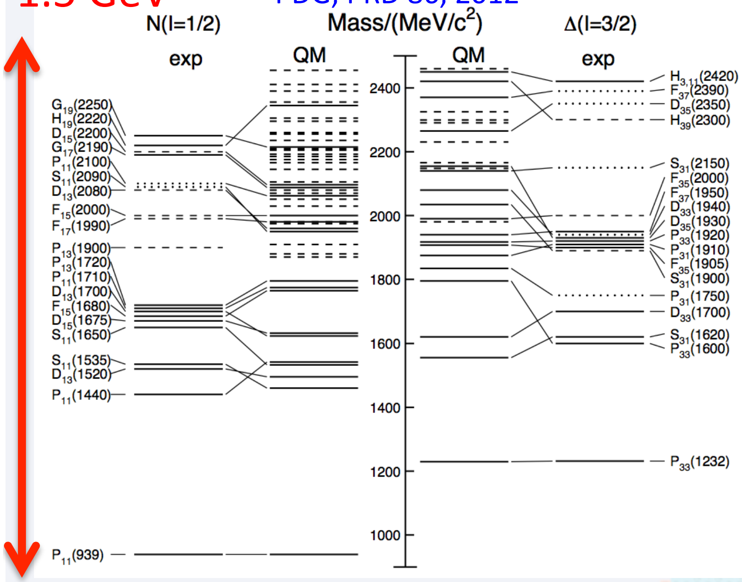

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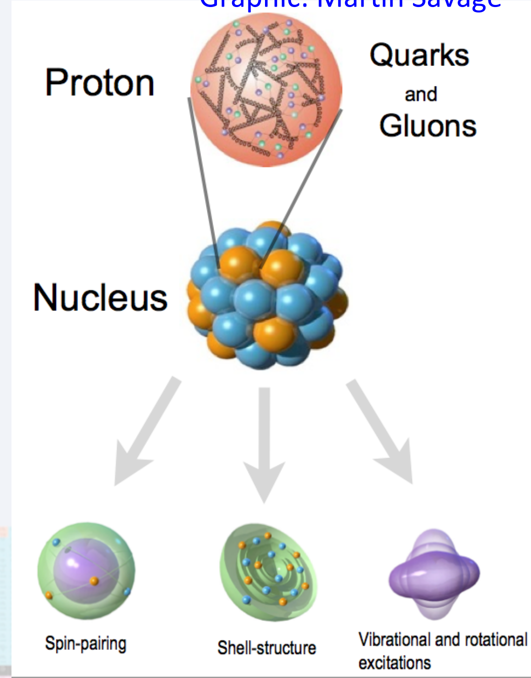

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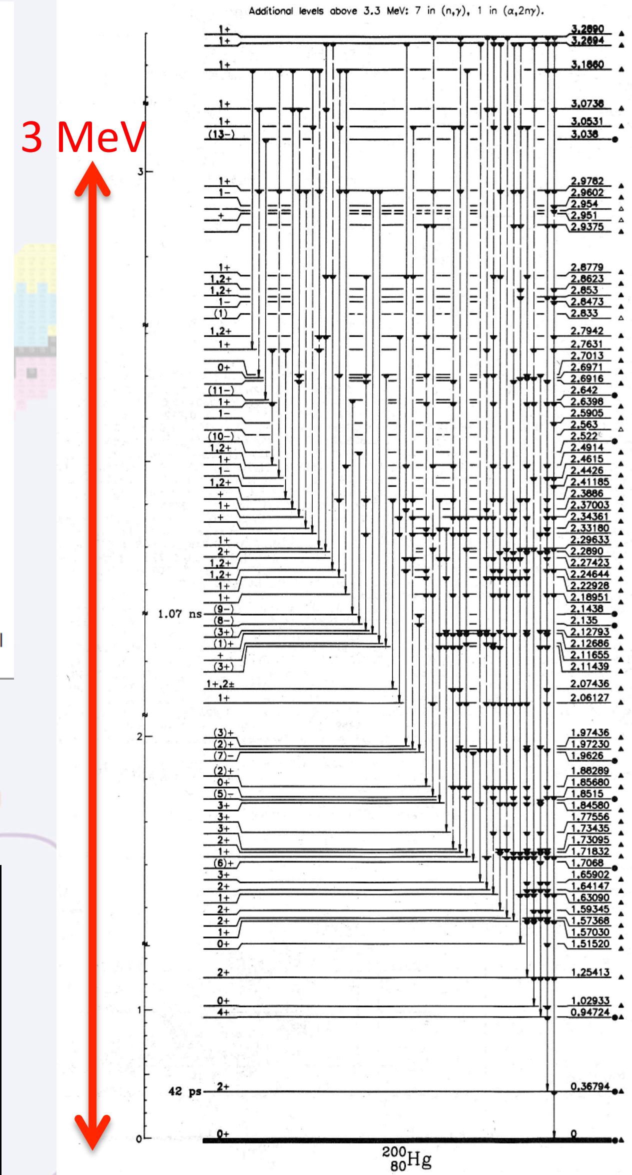


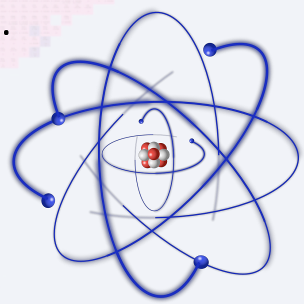
^{200}Hg -- 80 protons & 120 neutrons

Hadronic structure from fundamental interaction ~ GeV

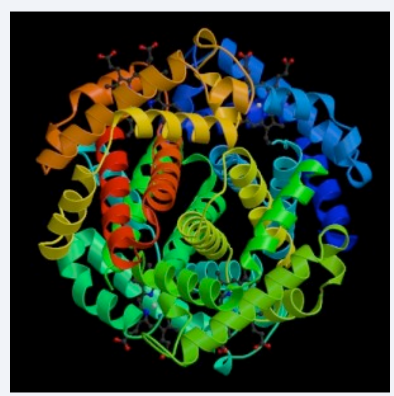
Nuclear structure from residual interaction ~ MeV

major cancellation →

- 1000x smaller forces.
- complexity



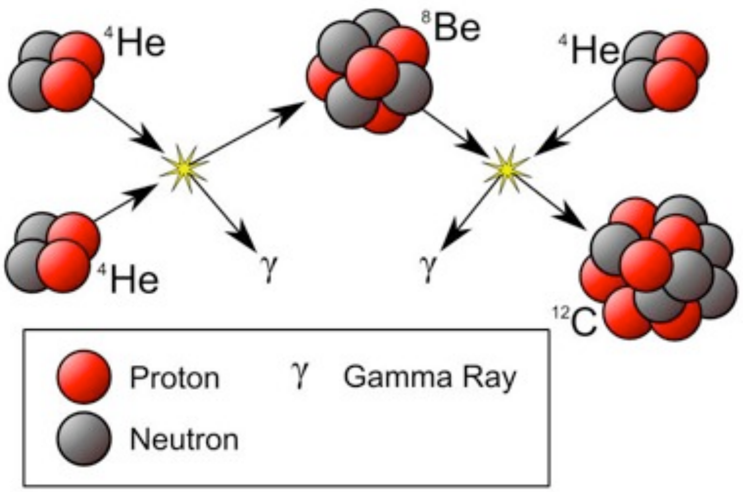
~ eV



1-10 meV

Details matter!

Fine-tuned nuclear physics



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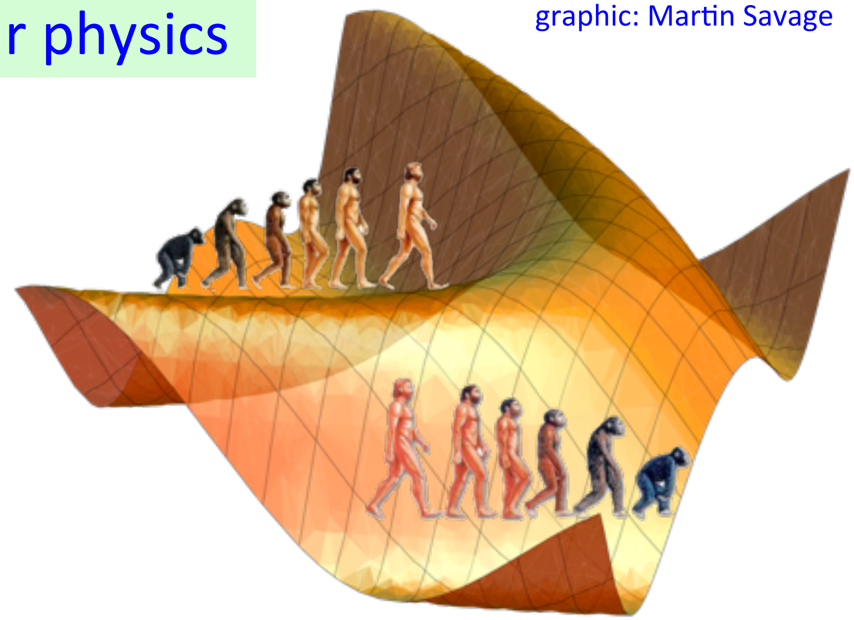
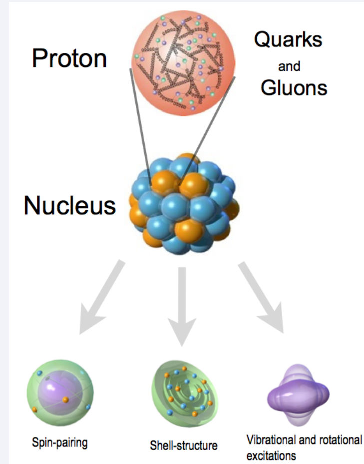


Hadronic structure from fundamental interaction ~ GeV
Nuclear structure from residual interaction ~ MeV
major cancellation →

- 1000x smaller forces.
- complexity

- Nuclear forces "maximally complex:" space, spin, flavor (isospin), tensor, & momentum components
  - "first-principles" no-core shell calculations (*based on forces*): ~ oxygen on supercomputer.
  - calculations *of those forces* on Lattice extremely challenging
- Only one known bound di-baryon state: the deuteron.
  - so fragile (BE ~ 2.2 MeV) that it has not a single bound state

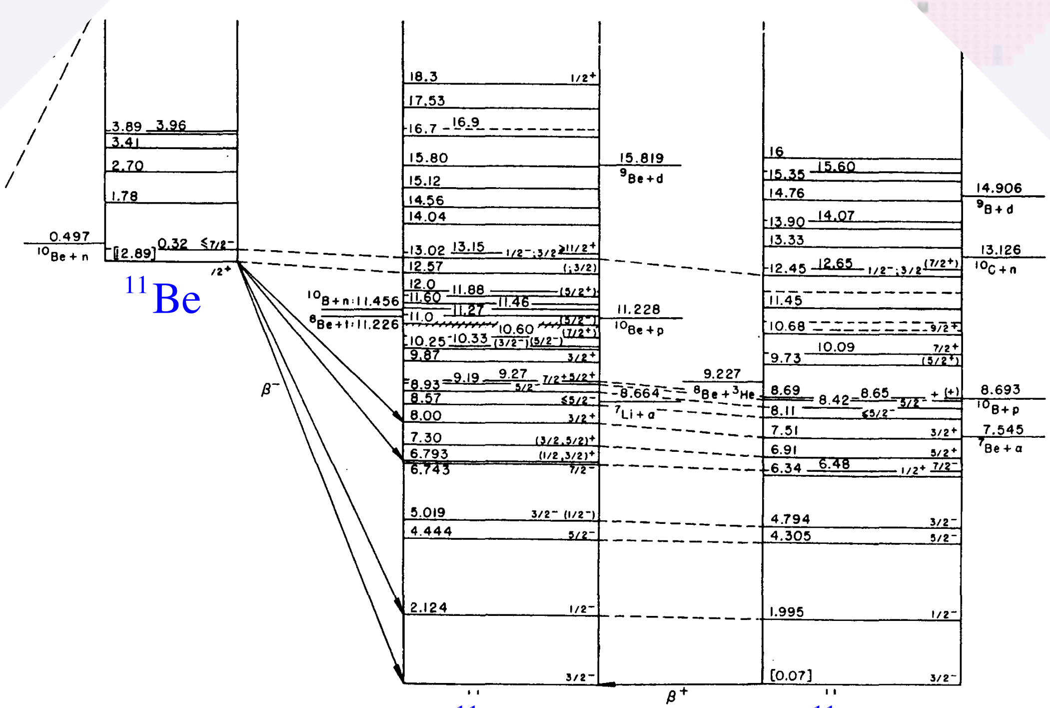
Isospin symmetry at partonic and nuclear level

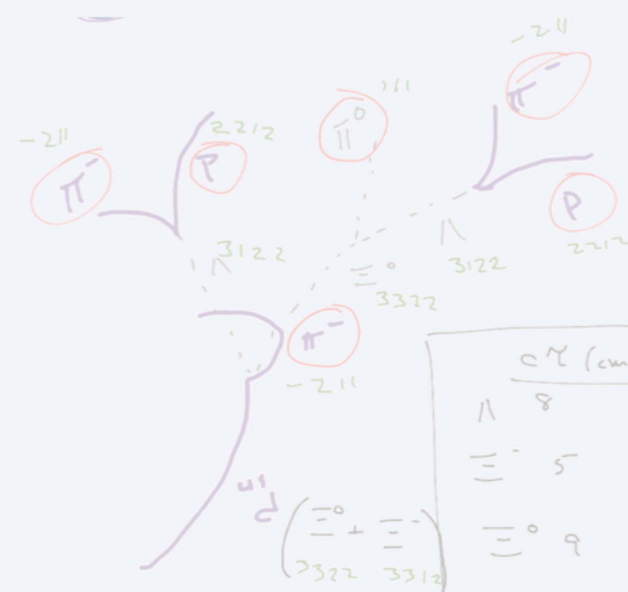


Motivated by discovery of the neutron and its properties symmetry, Heisenberg conceptualized isospin

- approximate symmetry of “nuclear” force
- useful in categorizing nuclear states

isobaric states: $\Delta E \approx 5 \div 100$ keV





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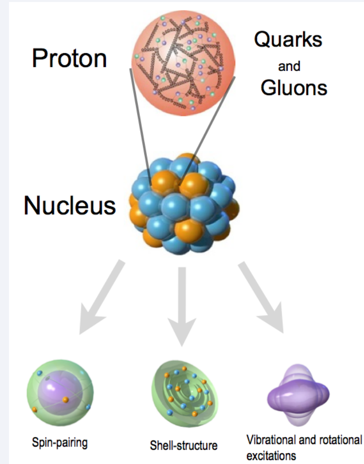
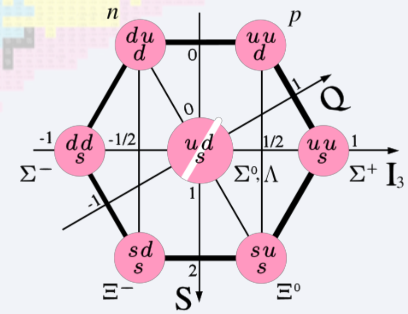
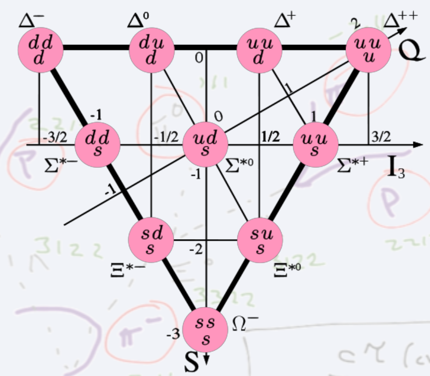


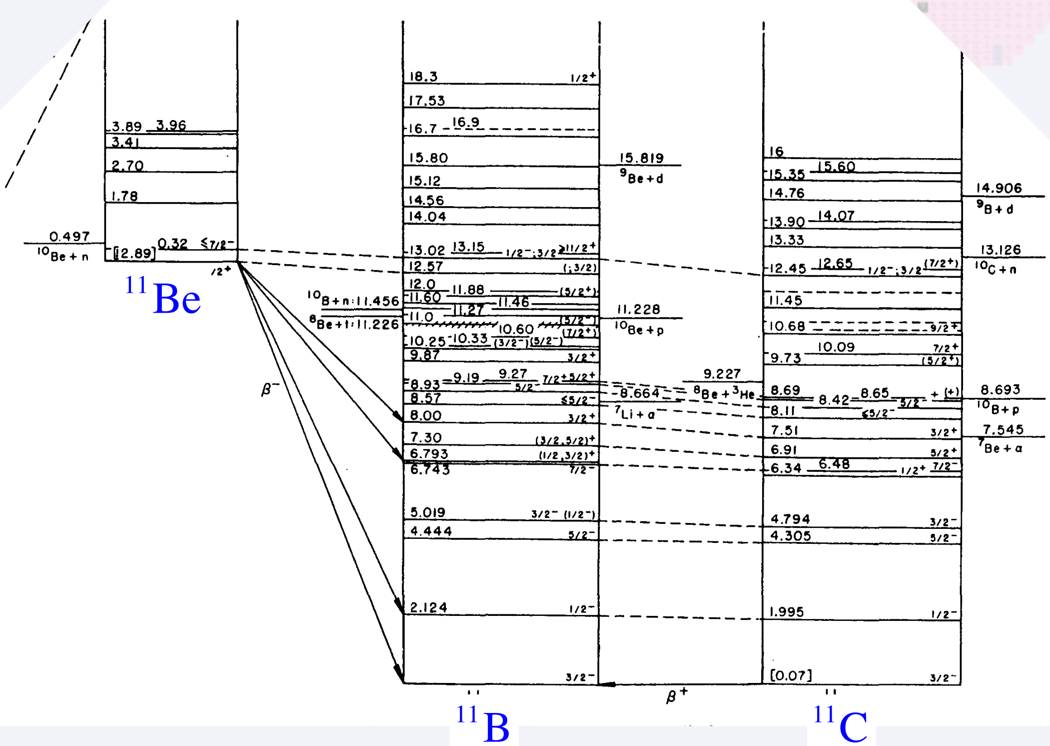
In a sense, even *better* at hadronic level

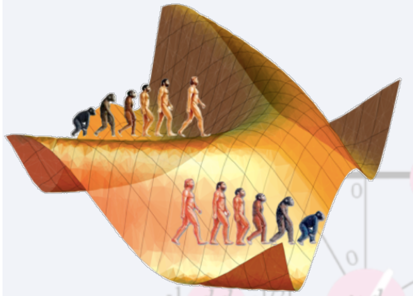




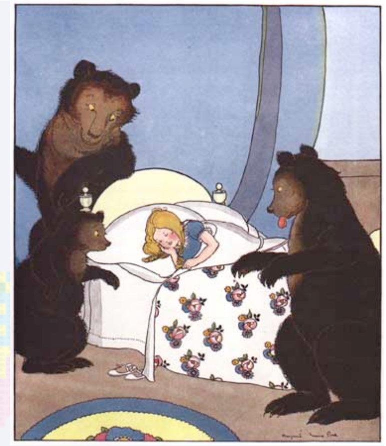
$$m_n[udd] - m_p[uud] = 1.3 \text{ MeV}$$

$$m_{\Delta^0}[udd] - m_{\Delta^{++}}[uuu] = 2.5 \text{ MeV}$$

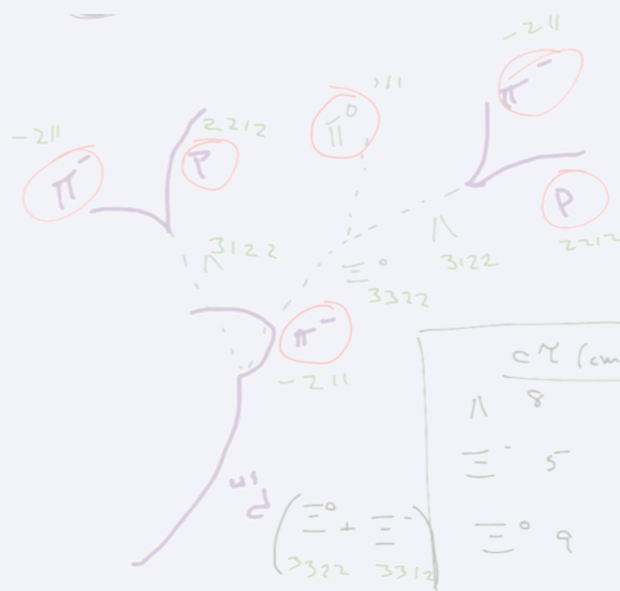




Why is deuteron "just right?"



- So far as we know, all baryon-baryon potentials are attractive...
  - "HBT" correlations: p+p, n+n, Lambda+p
  - calculations/prelim-HBT: Lambda+Lambda
  - hypernuclei: Lambda+groups of nucleons
  - Lattice calculations: Sigma+Sigma, Cascade+Cascade, Sigma-N



PHYSICAL REVIEW D **85,** 054511 (2012)

Deuteron and exotic two-body bound states from lattice QCD

S. R. Beane,[1] E. Chang,[2] W. Detmold,[3,4] H. W. Lin,[5] T. C. Luu,[6] K. Orginos,[3,4] A. Parreño,[2] M. J. Savage,[5] A. Torok,[7] and A. Walker-Loud[8]

(NPLQCD Collaboration)

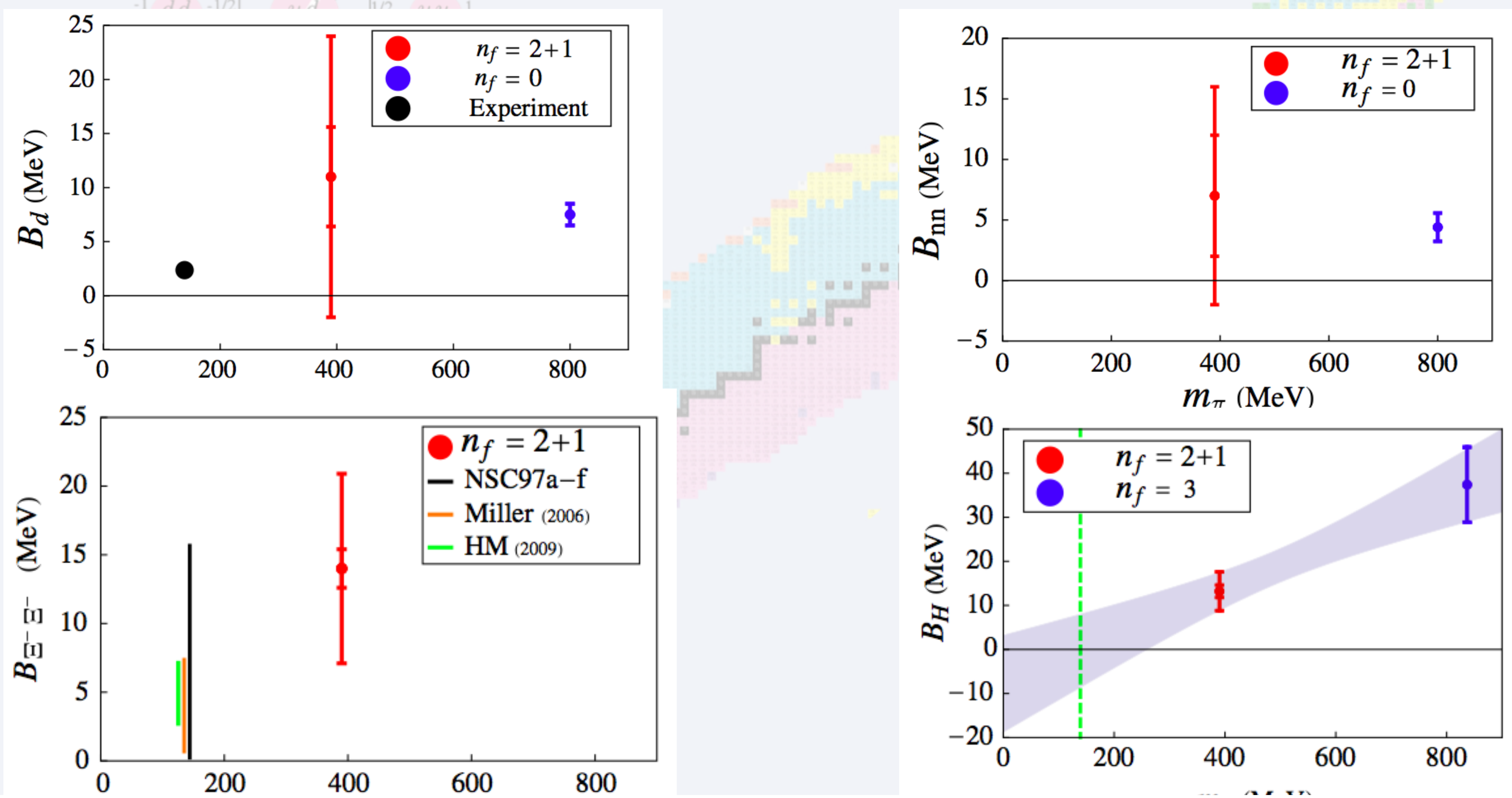
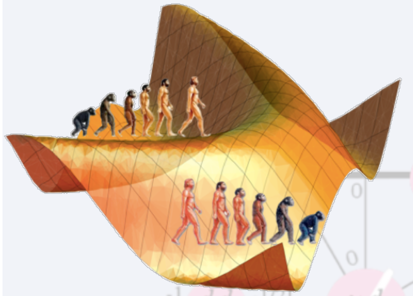


TABLE III. A summary of the two-body binding energies determined in this work.

	Deuteron	Dineutron	H-dibaryon	$\Xi^-\Xi^-$
Binding energy (MeV)	11(05)(12)	7.1(5.2)(7.3)	13.2(1.8)(4.0)	14.0(1.4)(6.7)



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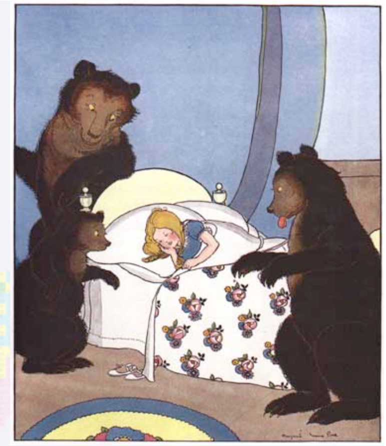
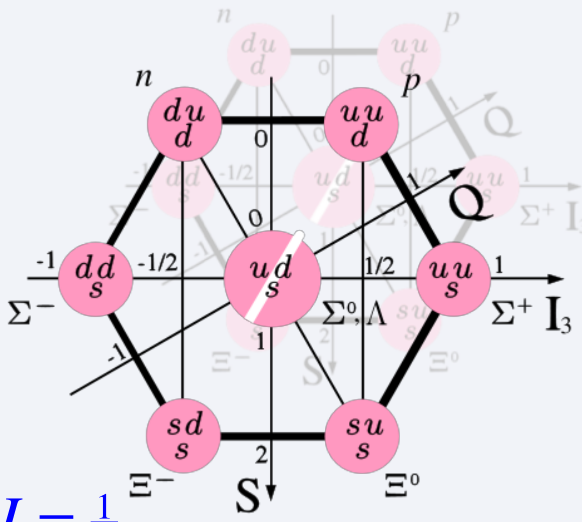


- So far as we know, all baryon-baryon potentials are attractive...
  - "HBT" correlations: p+p, n+n, Lambda+p
  - calculations/prelim-HBT: Lambda+Lambda
  - hypernuclei: Lambda+groups of nucleons
  - Lattice calculations: Sigma+Sigma, Cascade+Cascade, Sigma-N
- Lattice: most baryon-baryon states are barely or very nearly bound.
- Existence of deuteron when n+n is unbound ➔ isocoupling is the crucial "nudge"
  - only the antisymmetric isoscalar coupling of two isospinors gives sufficiently attractive potential to be bound. Isovector coupling (T=1) is attractive but not bound
  - Can we better understand this crucial symmetry of the strong (and "nuclear" force) and expand the number of known baryon-baryon bound states from one to two?

The deuteron's strange cousin?

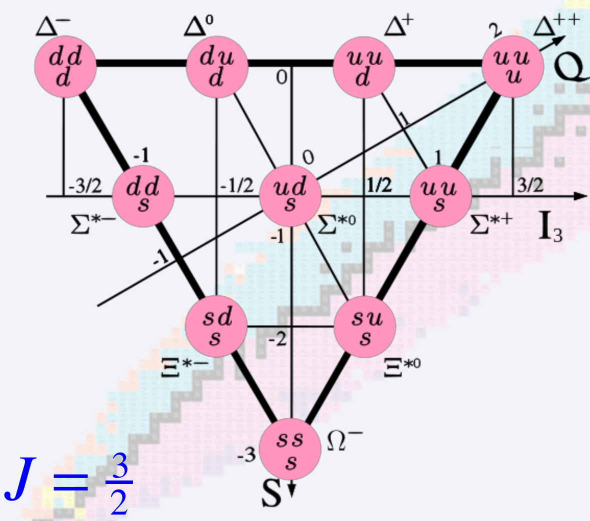


$J = \frac{1}{2}$

$T = \frac{1}{2}$

$T = 0,1$

$T = \frac{1}{2}$



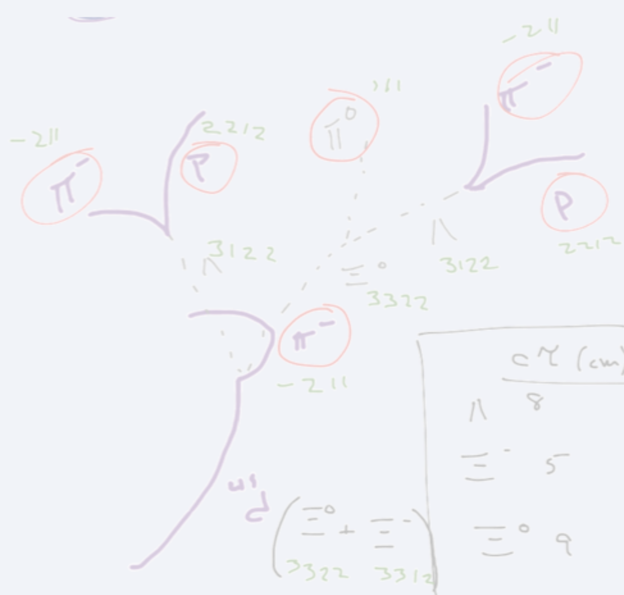
$J = \frac{3}{2}$

$T = \frac{3}{2}$

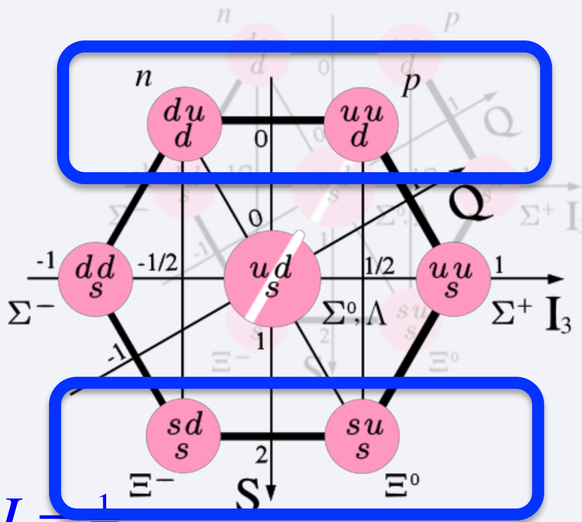
$T = 1$

$T = \frac{1}{2}$

$T = 0$



The deuteron's strange cousin?



$T = \frac{1}{2}$

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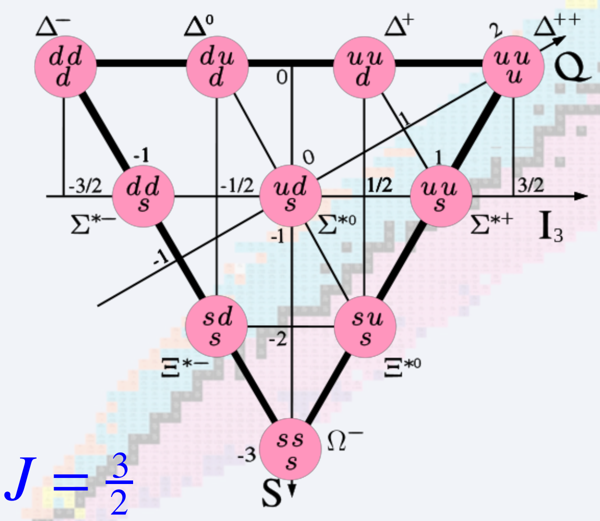


$T = \frac{3}{2}$

$T = 1$

$T = \frac{1}{2}$

$T = 0$

$J = \frac{3}{2}$

$$\left|J, T, T_3, Y, B\right\rangle$$

$$\underbrace{\left|\tfrac{1}{2}, \tfrac{1}{2}, \tfrac{1}{2}, 0, 1\right\rangle}_{p} \otimes \underbrace{\left|\tfrac{1}{2}, \tfrac{1}{2}, -\tfrac{1}{2}, 0, 1\right\rangle}_{n} = \underbrace{\left|1, 0, 0, 0, 2\right\rangle}_{d}$$

$$\underbrace{\left|\tfrac{1}{2}, \tfrac{1}{2}, \tfrac{1}{2}, -2, 1\right\rangle}_{\Xi} \otimes \underbrace{\left|\tfrac{1}{2}, \tfrac{1}{2}, -\tfrac{1}{2}, -2, 1\right\rangle}_{\Xi^-} = \underbrace{\left|1, 0, 0, -4, 2\right\rangle}_{^{4S}d}$$

presumably loosely (not "weakly") bound system of two "almost free" baryons

→ optimal formation is via coalescence of co-moving cascade baryons

→ THE place to look is the aftermath of R.H.I.C.

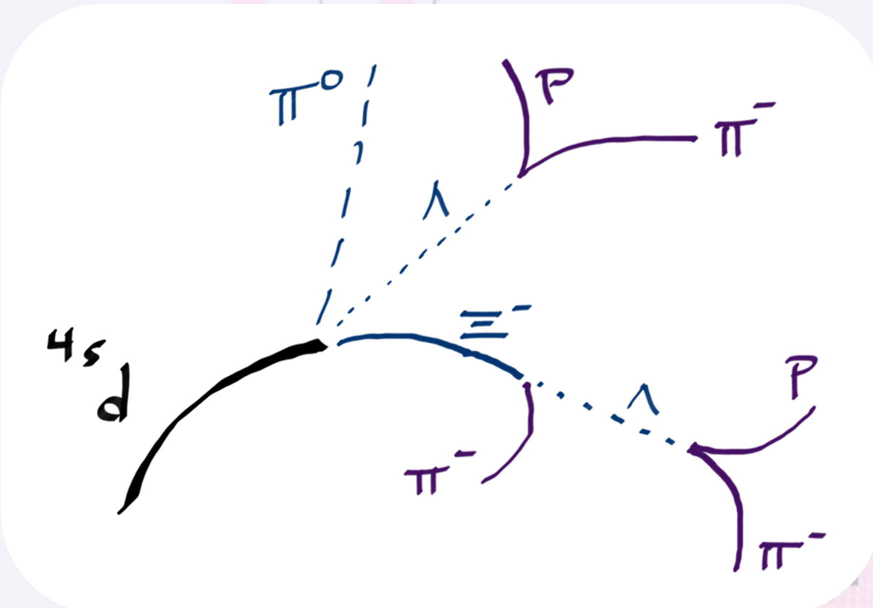
Motivation behind authors' focus on $\Xi^- - \Xi^-$ system, cousin to dineutron, is unclear to me.

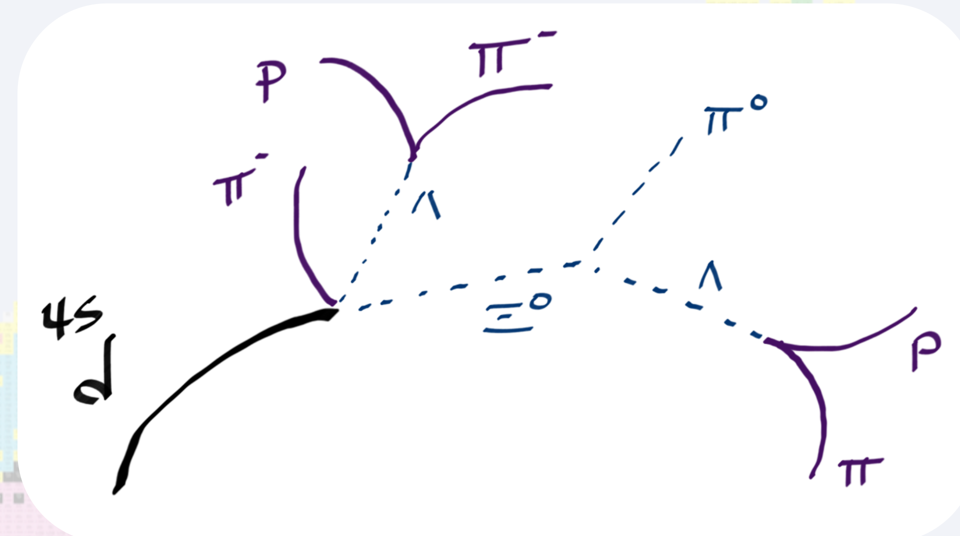
naive expectations of a strange cousin

- strongly bound but weakly unstable: 2.57 < mass < 2.64 GeV/c^2
- loosely bound baryons behave “almost” free: decay weakly “in situ”
  - but more slowly! n in deuteron lives “forever”; in triton, for years
    - even the slightest binding energy has huge effects
    - c*tau >~ 5 cmm – maybe we see this (charged) thing in the TPC!

$$\underbrace{{}^{4S}d \to \Xi^- + \underbrace{\left(\pi^0 + \Lambda\right)}_{\text{off-shell } \Xi^0}}_{\text{"0 first mode"}} \qquad \underbrace{{}^{4S}d \to \Xi^0 + \underbrace{\left(\pi^- + \Lambda\right)}_{\text{off-shell } \Xi^-}}_{\text{"- first mode"}}$$

Decay modes



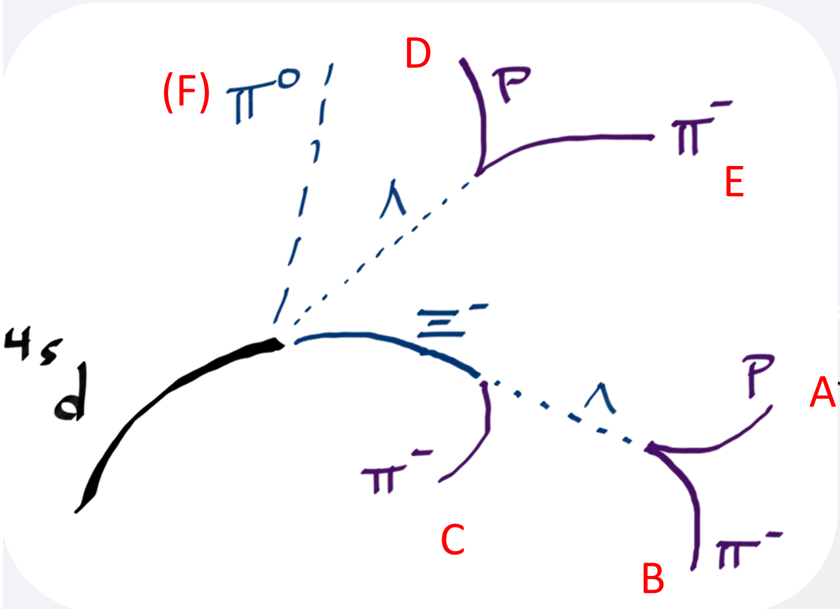


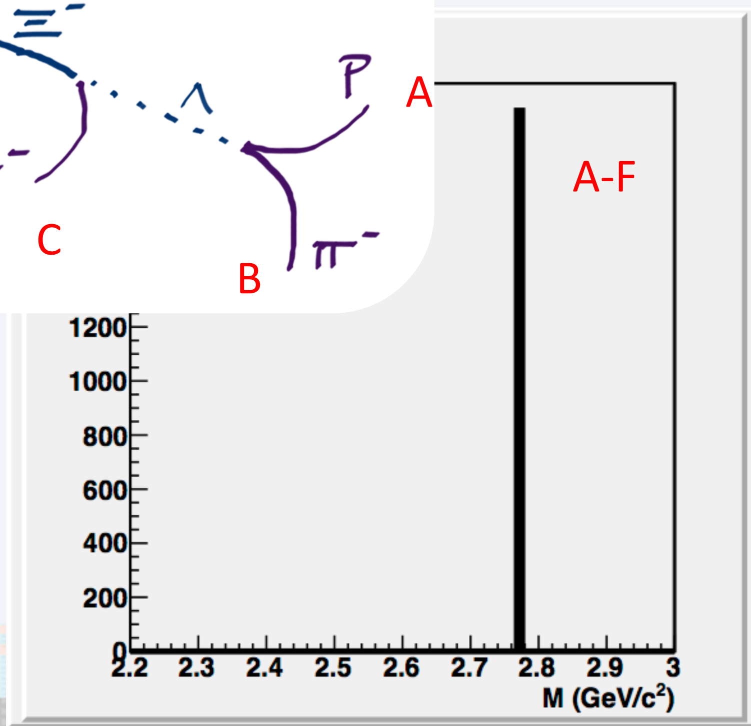
$$^{4S}d \rightarrow \underbrace{\Xi^- + \underbrace{\left(\pi^0 + \Lambda\right)}_{\text{off-shell } \Xi^0}}_{\text{"0 first mode"}}$$

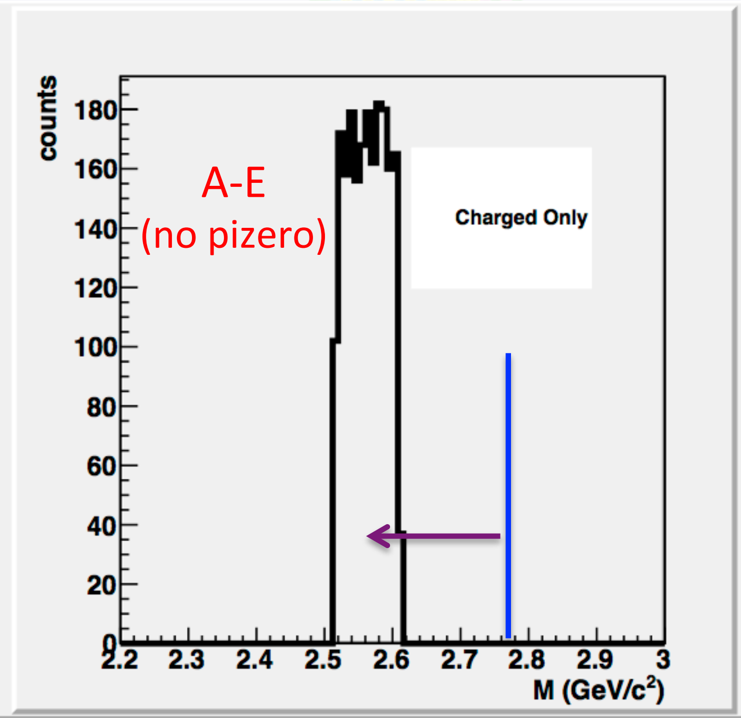
$$^{4S}d \rightarrow \underbrace{\Xi^0 + \underbrace{\left(\pi^- + \Lambda\right)}_{\text{off-shell } \Xi^-}}_{\text{"- first mode"}}$$

- 6-hadron final state.
- Actually, 2-hadron final state: Xi0 & Xi-
- missing the pi-zero→ 2-hadron final state: Xi- & Lambda
  - “0-first mode” : Lambda and Xi- are “on-shell” and point back to d4s decay point

Invariant mass distribution quick calculation/simulation





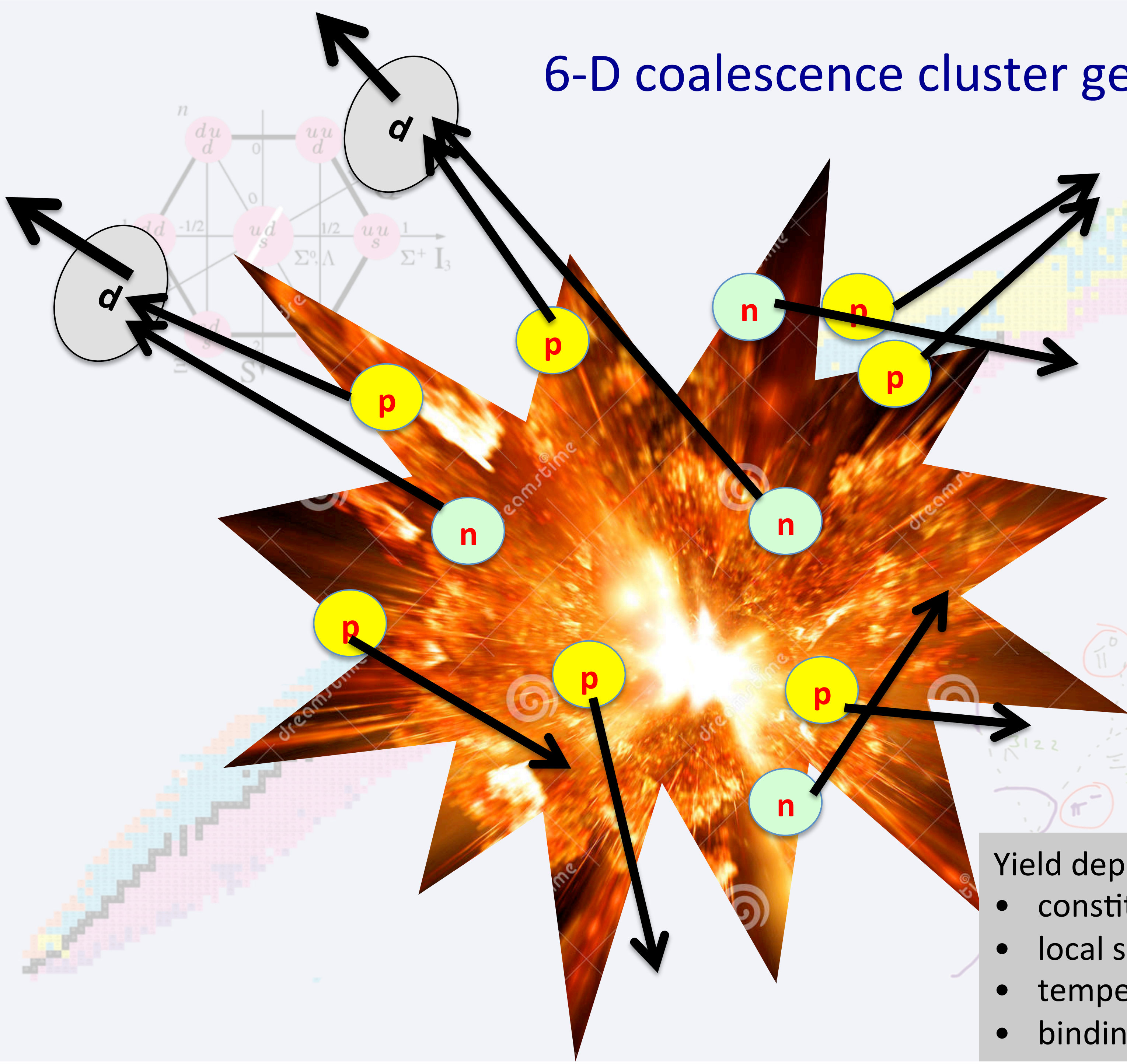


Using charged particles only:
shift: ~200 MeV
broadening: ~ 100 MeV

Naively expect peak at:

$$\underbrace{1321\ \text{MeV}}_{m_{\Xi^-}} + \underbrace{1315\ \text{MeV}}_{m_{\Xi^0}} - \underbrace{5\ \text{MeV}}_{B.E.} + \underbrace{50\ \text{MeV}}_{Q(?)} - \underbrace{200\ \text{MeV}}_{\text{shift}} \approx 2480\ \text{MeV}$$

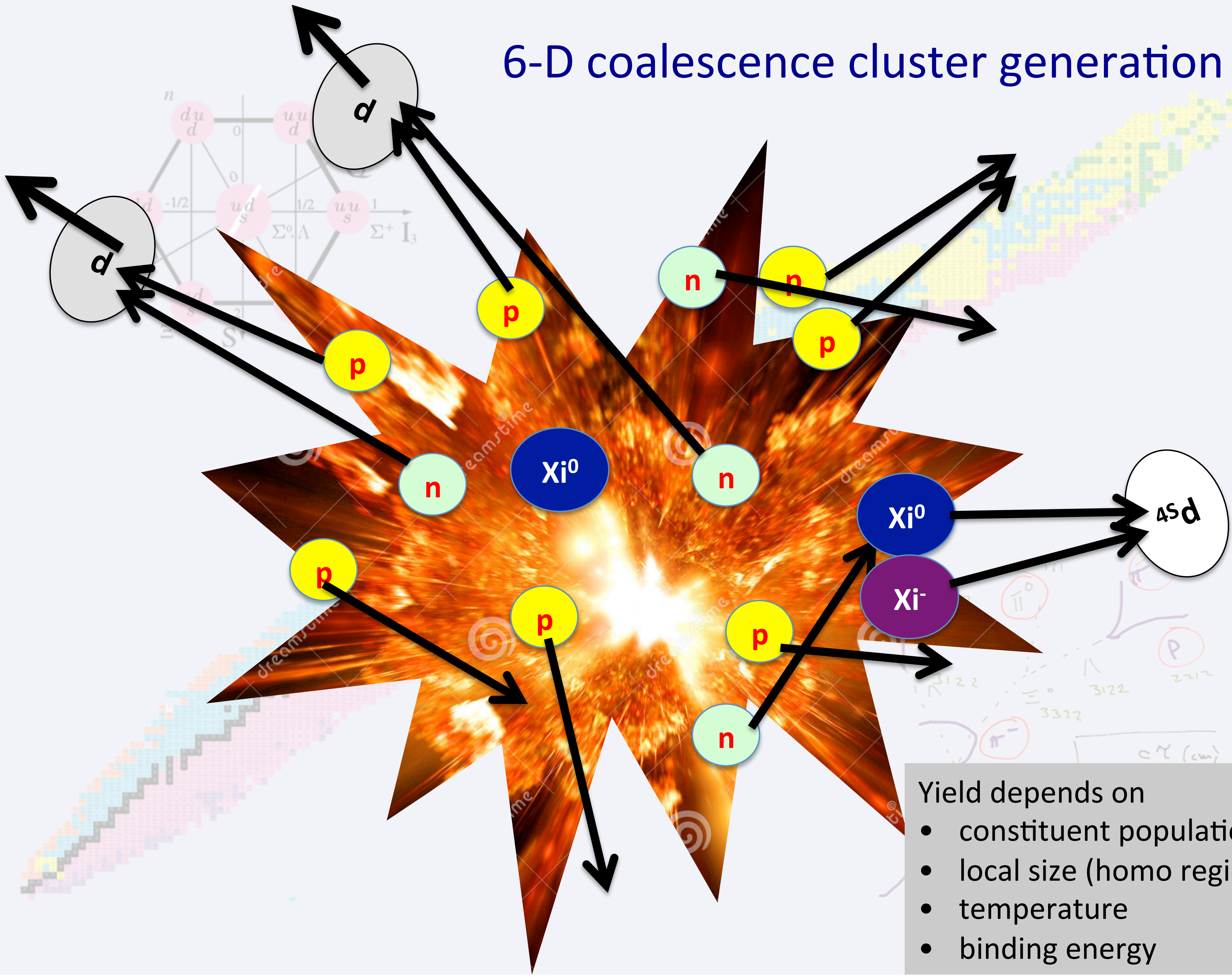
6-D coalescence cluster generation



Yield depends on

- constituent population
- local size (homo regions)
- temperature
- binding energy

6-D coalescence cluster generation



Yield depends on

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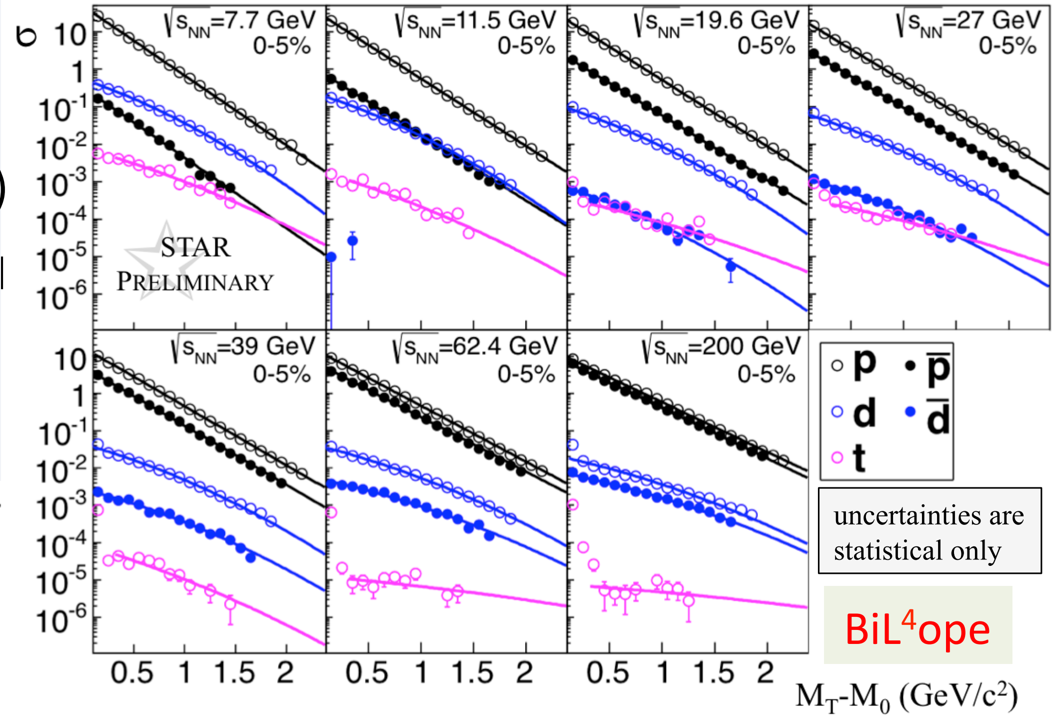
What to expect

deuteron yield per event decreases (mildly) with root(s), due to higher temperature (larger phasespace) and decreased proton population upon which to draw

BiL[4]ope



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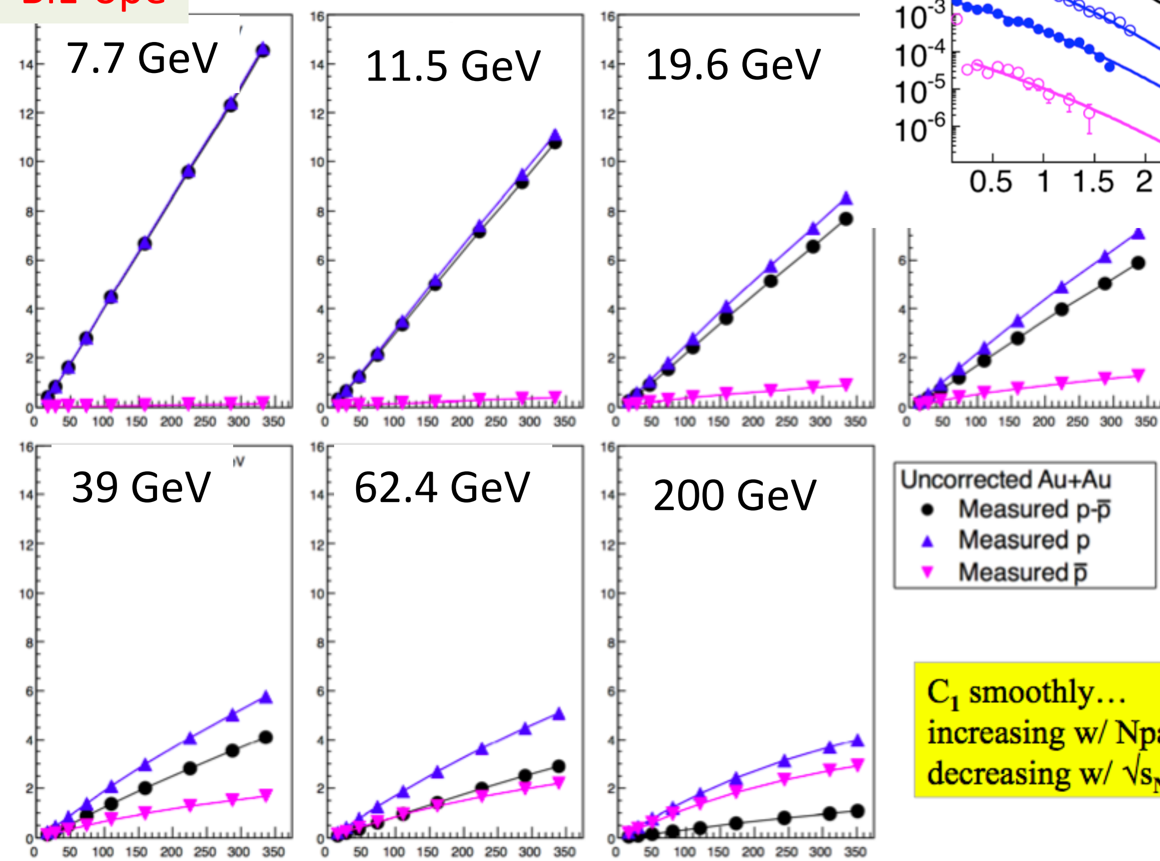


C_1 smoothly…
increasing w/ Npar
decreasing w/ $\sqrt{s_{NN}}$

underlying population for d4s production (i.e. Xi) requires higher root(s), at least partially compensating for this.

Any "sweet spot" is likely to be a broad zone.

Make an estimate of statistics, and look under the lamppost.

What is expected yield of d4s?

If same formation mechanism (coalescence) and similar binding energy,

we can guestimate:

$$\frac{N_{4S_d}}{N_{\Xi}^2} \approx \frac{N_d}{N_p^2} \rightarrow N_{4S_d} \approx \left(\frac{N_{\Xi}}{N_p}\right)^2 \times N_d = \overbrace{\underbrace{\left(\frac{6.4}{18.4}\right)^2}_{STAR\ nucl-ex/0607033\ and\ PRC77\ 044908\ (2008)}}^{0.12} \times \underbrace{0.07}_{PHENIX\ PRL94\ 122302\ (2005)} = 0.008$$

So, 0.008 d4s's per central Au+Au event!! Wow! That's a lot!

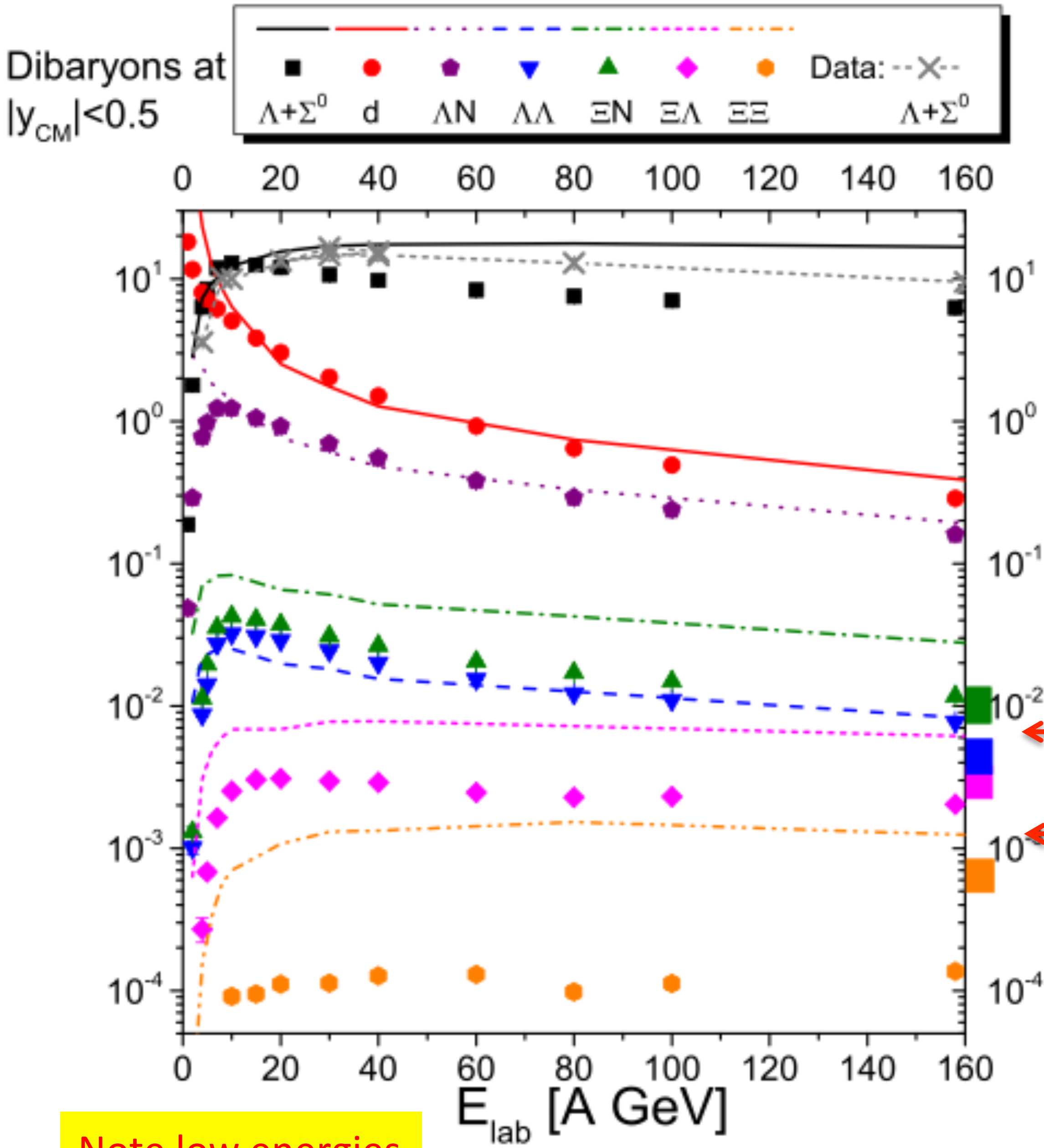
That's a d4s produced every 120 central events!!

note that there are 0.12 d4s for every "normal" deuteron!

say 1% d4s detection efficiency, → detection every 12,500 (central) events!
That's 80 per million events

→ STAR should be able to see this thing.

Somewhat lower estimate from more sophisticated UrQMD study



J. Steinheimer et al
arxiv:1203.2547

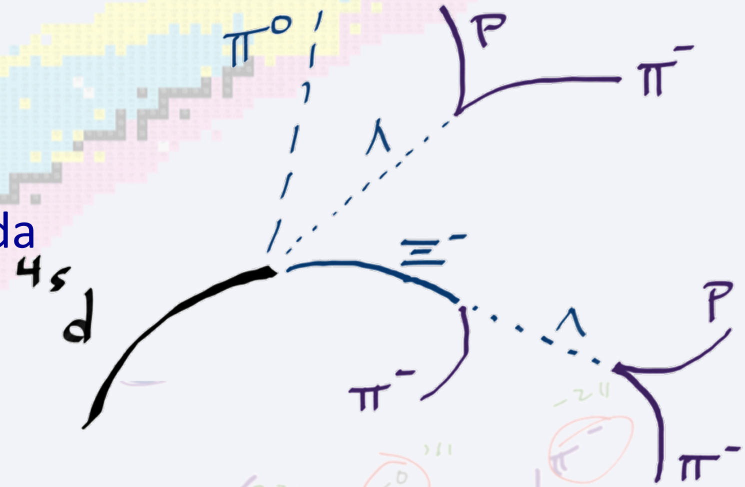
0.008 / event @ 200 GeV
(prev page)

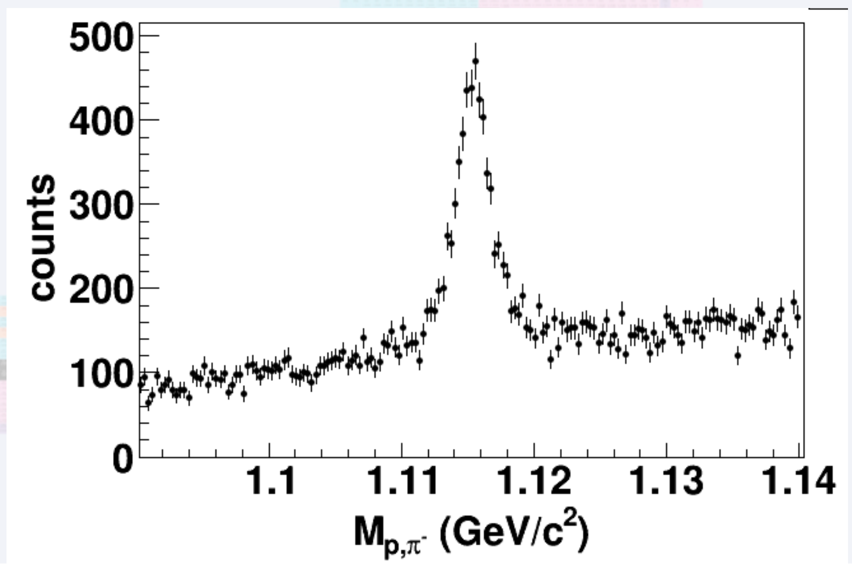
0.001 / event @ 20 GeV
(UrQMD)

Note low energies

Ongoing search in Xi-Lambda channel (d4s)

- 130M collisions at 39 GeV processed in full.
  - partial studies exist and underway at 27 and 62.4 GeV; 200 GeV planned
  - might hope for ~1% x 130M x 0.001 = 1300
- TPC and TOF PID selections for p, pi
- Topological cuts for Xi and "orphan" Lambda
  - build on work for BES v2 paper
  - tweaks: hyperons trace back to d4s decay point rather than primary vertex





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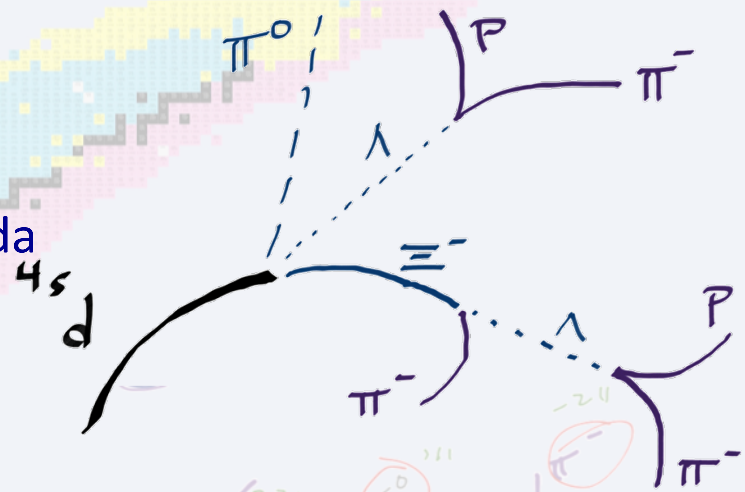
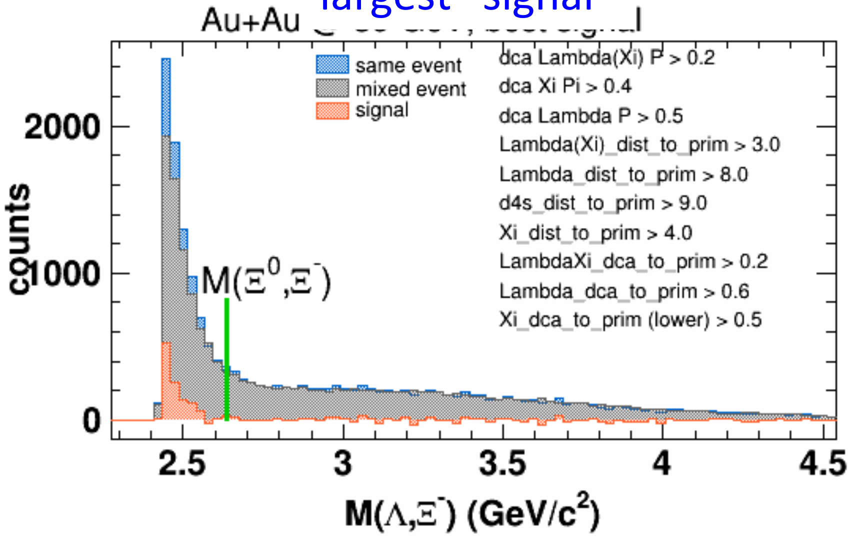


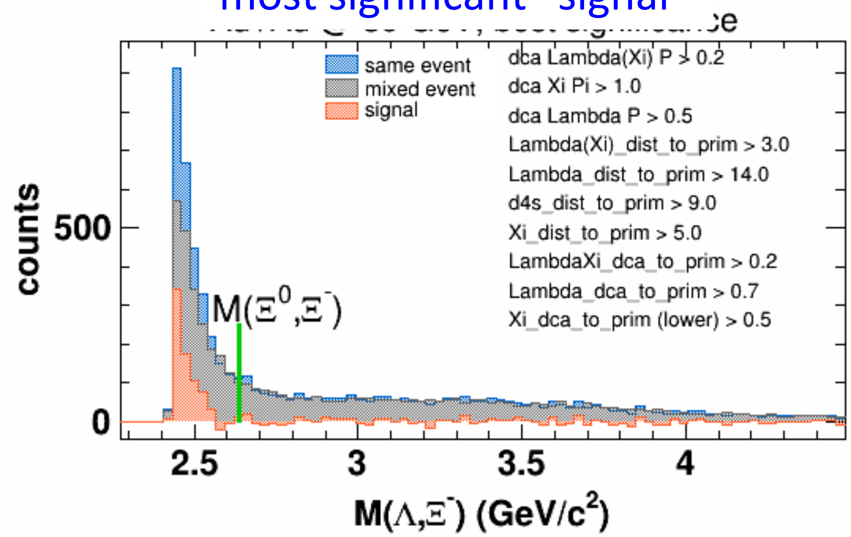
- Careful to avoid "Lambda incest," Xi-Lambda M_{inv} distribution formed
- Shifting primary vertices, applying same cuts, etc, "mixed-pair" distribution also made
- Subtraction after normalization in a "control" region (not sensitive to choice)
- 59k cut combinations scanned. Results still being digested

4 of 59k topological cut combinations scanned

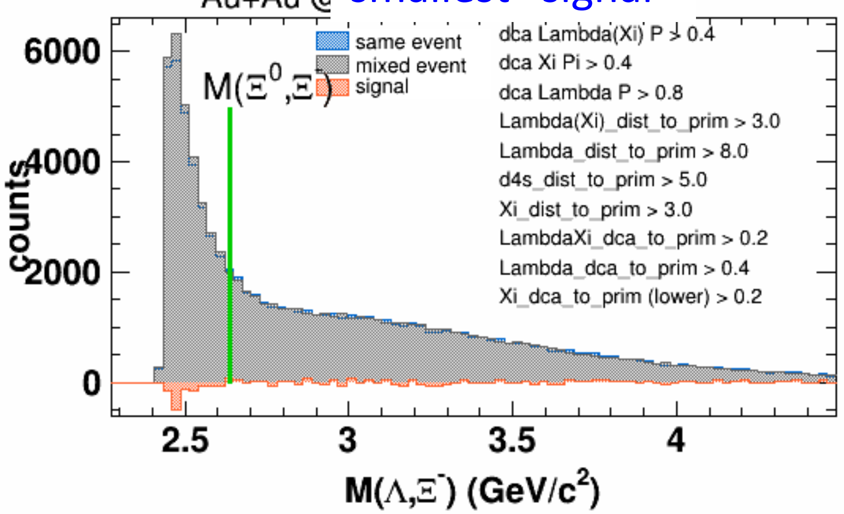
largest “signal”



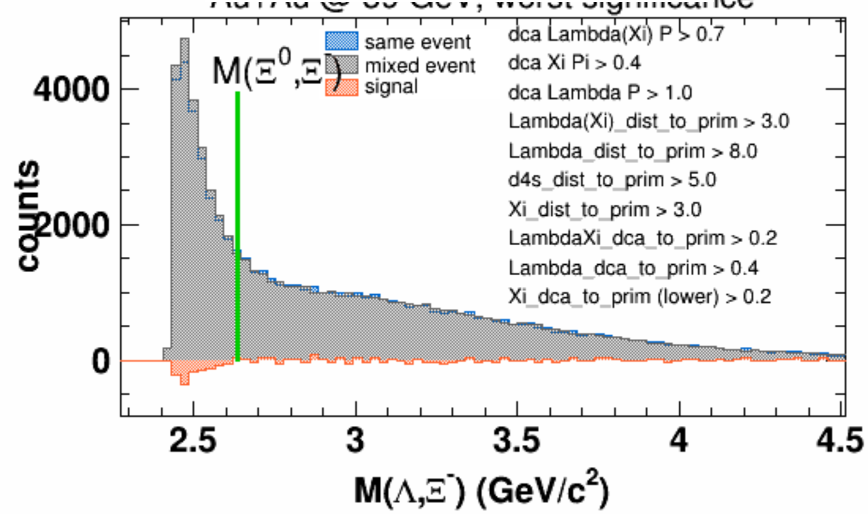
most significant “signal”



smallest “signal”



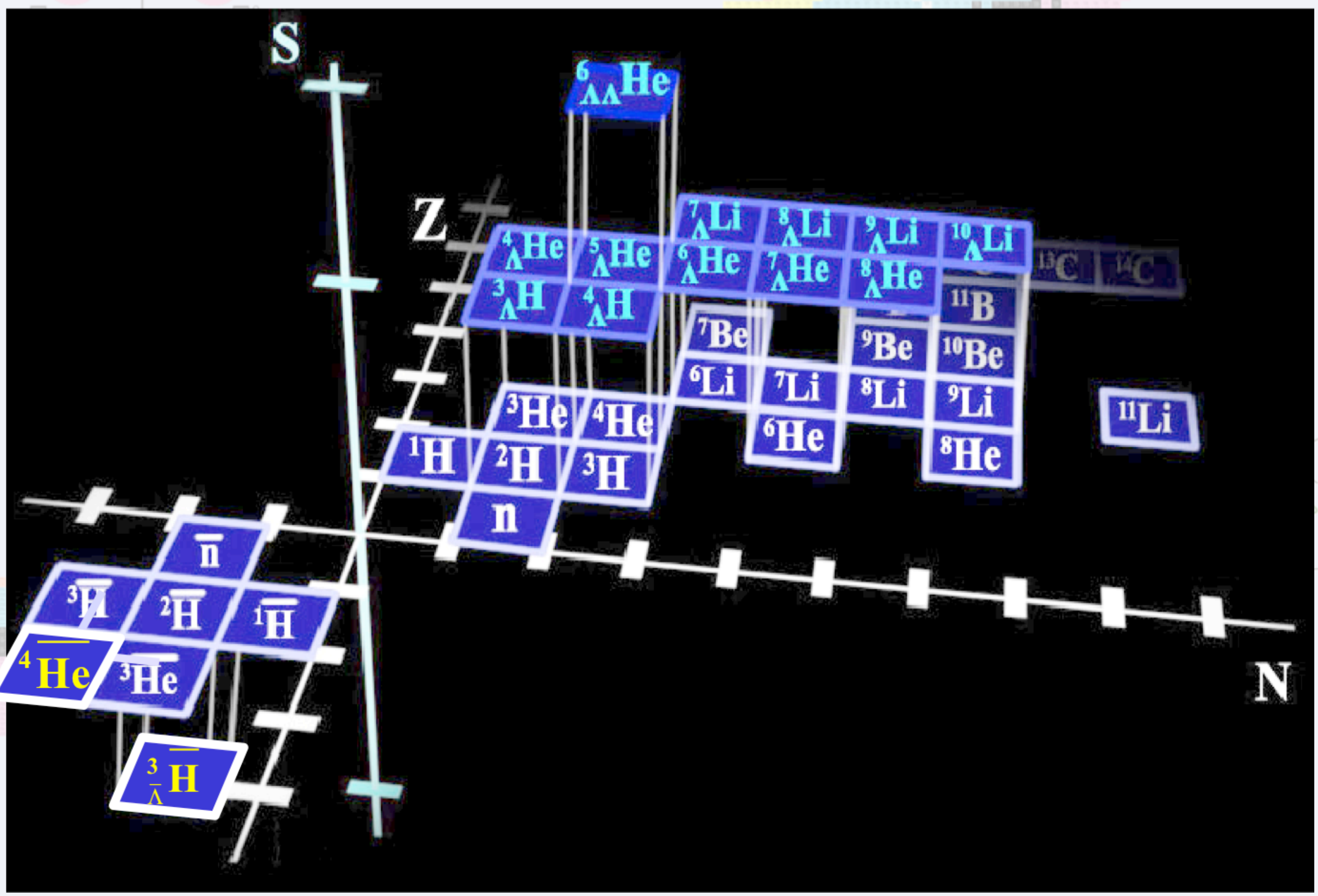
least significant “signal”



peak (?) is at “right” location and has “right” width and not too far below “right” area.
But its location at the edge of phasespace is unfortunate. We must be careful.

Summary and outlook

- Observation of an isoscalar di-cascade (d4s) would be groundbreaking
  - continuing STAR's multi-dimensional expansion of "nuclear" physics and shedding new and much needed light on "simplest" and crucially-tuned symmetry of dibaryon system



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- substantial machinery in place. 39 GeV results partially digested.
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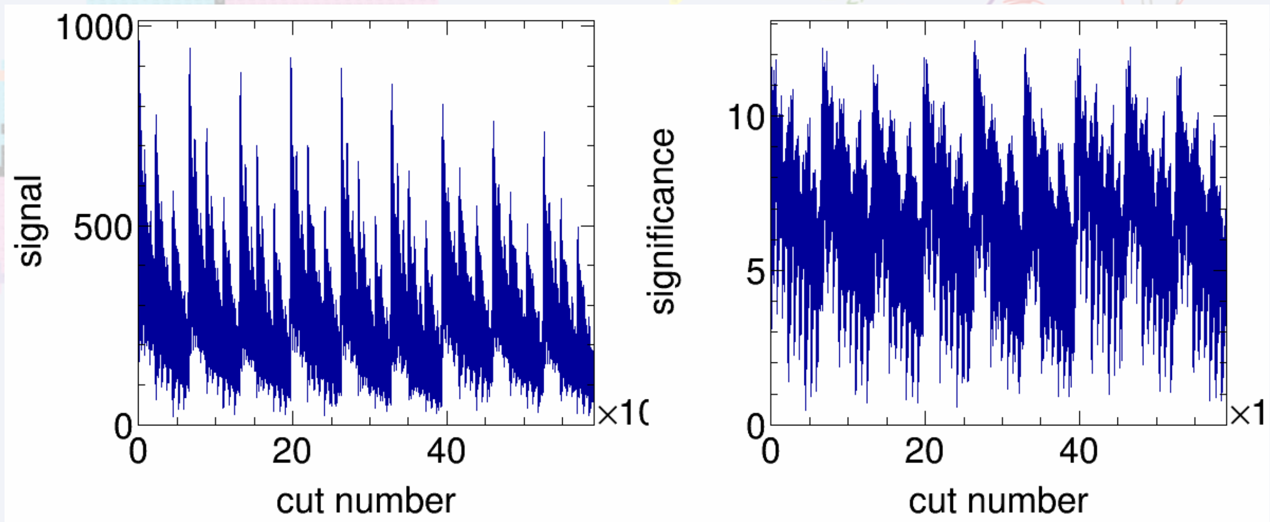

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  - systematics being analyzed
- Next steps
  - compare 29 and 200 GeV
  - antiparticle distributions at higher energies
  - decay length distributions, etc.
  - also search for strange cousin of di-neutron?
  - suggestions??