Strong Decays of: $\varphi_{(1s)}$, $\Upsilon_{(4s)}$ and $\Sigma^*_{(1385)}$ in Magnetic Field

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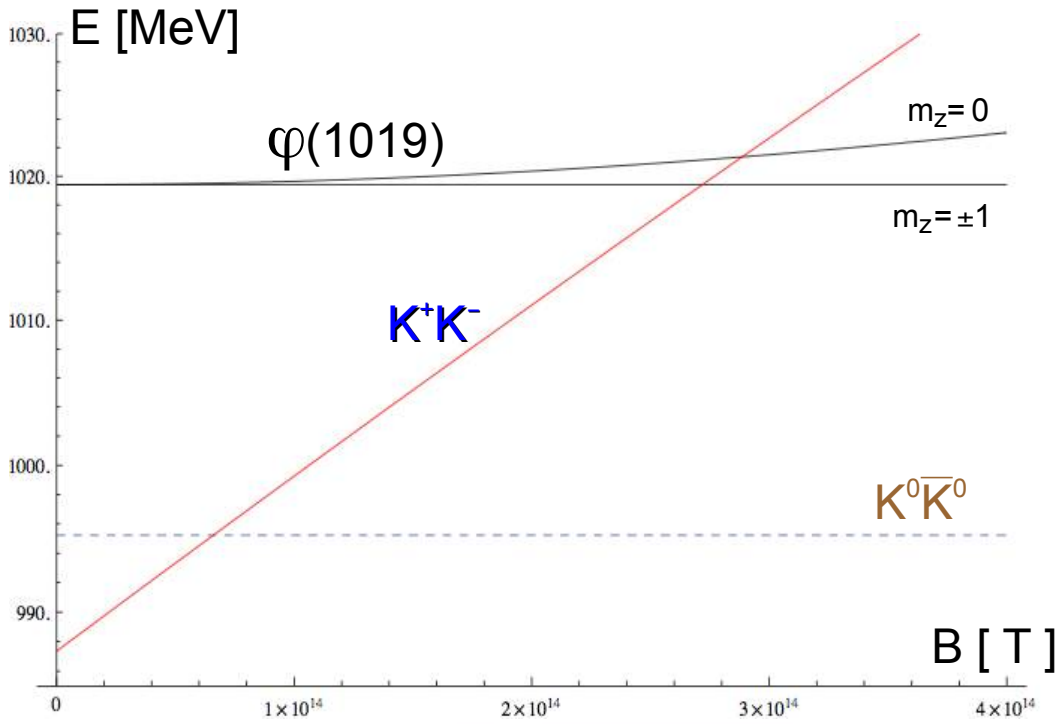
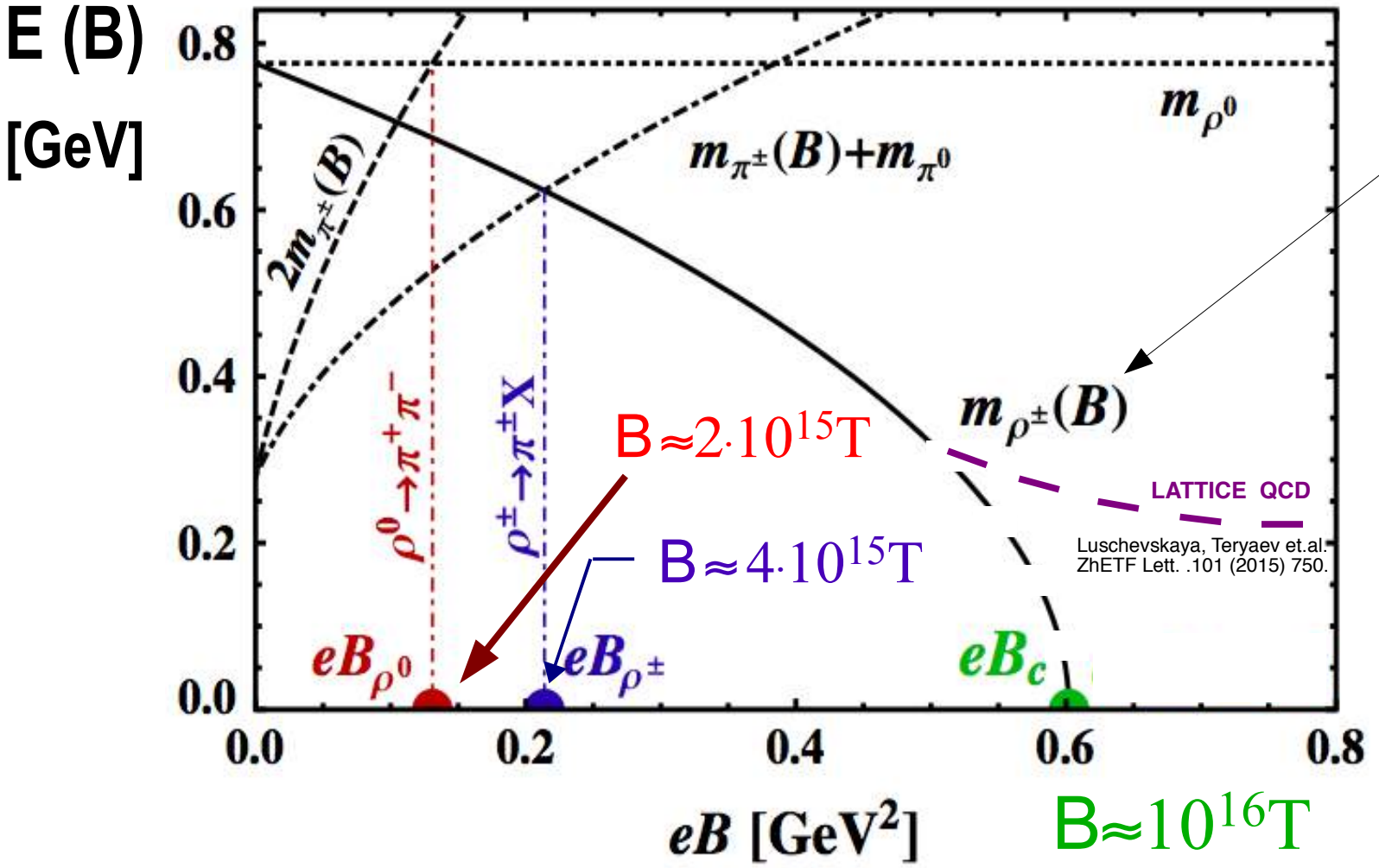
- origins: $\rho \rightarrow \pi^+\pi^-$ [B]
- $K^* \rightarrow K\pi$ decays [B]
- $\varphi \rightarrow KK$, $\Upsilon(4s) \rightarrow B^+B^-$
- $\Sigma^* \rightarrow \Lambda\pi, \Sigma\pi$ in [B]
- $D^* \rightarrow D\pi$ decays [B]
- Conclusions

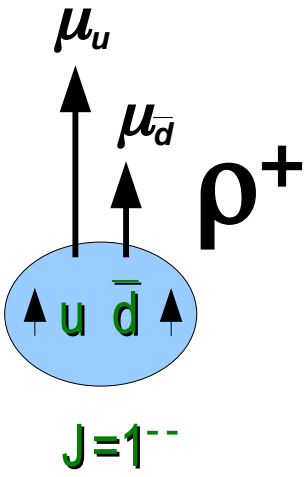


Origins of behavior: $\rho^{\pm 0}$ [B]

Chernodub: Physical Review D82 (2010) 085011

Fig. 1





E = - μ• B

energy in magnetic field [B]

- $\rho^{\pm,0}(770) \rightarrow \pi\pi$ decays **closed** in magnetic field: **B > 4·10^15T**

Energy of Charged Particles in [B] Field

(neglecting here: polarizability of hadrons)

Main idea: 1) $m^2_{\pi^\pm}(B_{\rm ext}) = m^2_{\pi^\pm} + eB_{\rm ext}$ J = 0

- Energy of n=0 Landau level of charged $\pi^\pm$:

Quantum Hall effect: Klitzing (1985)

$$\Delta E_L = eB/2m$$

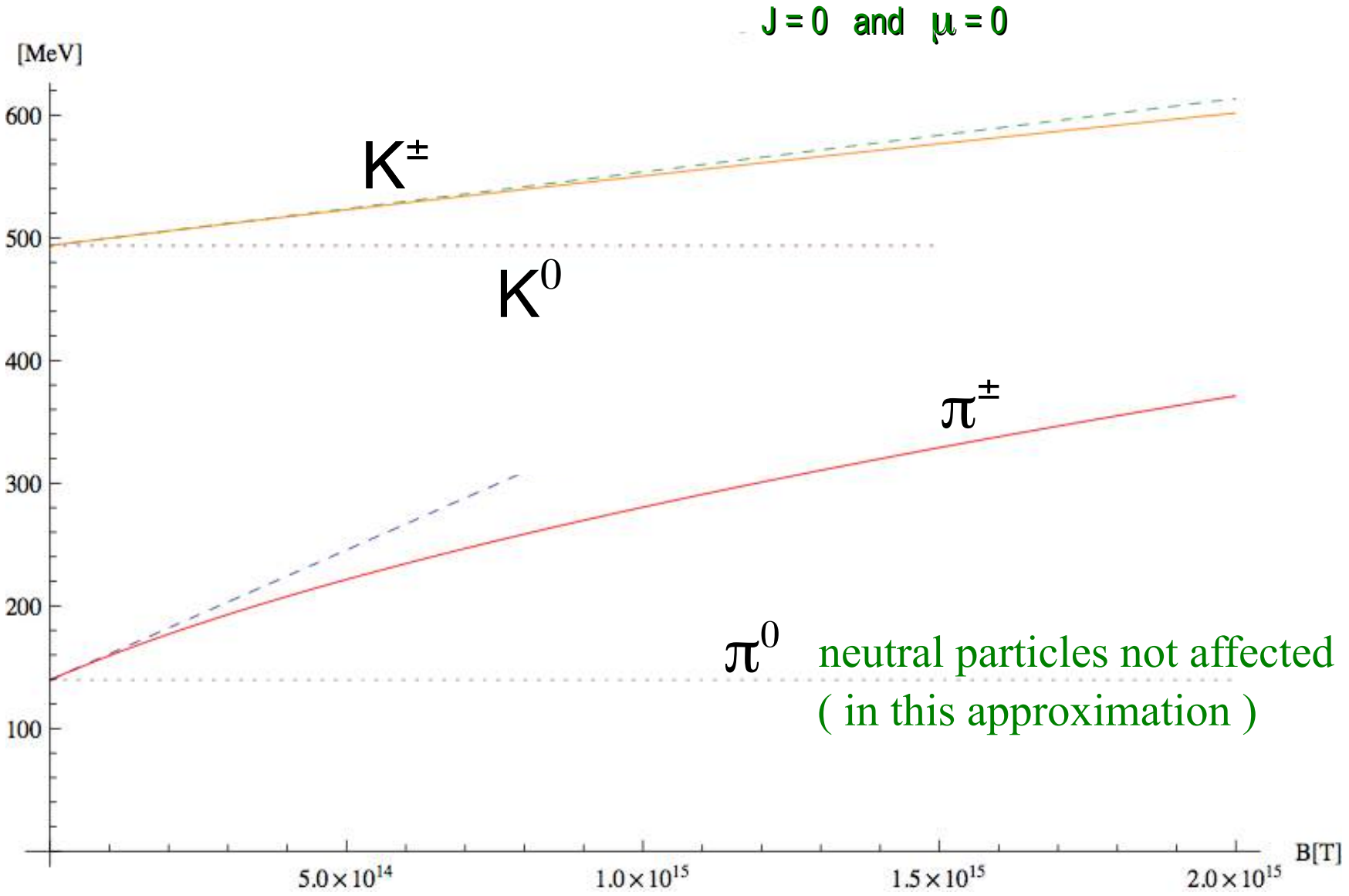
2) for **J > 0** particles: K*, Ξ*, ρ

$$E[B] = \sqrt{m^2 + p_z^2 + eB(1 - 2s_z)}$$

E = - μ · B

$$E[B] \approx m + (p_z^2 + eB)/2m - eBs_z/m$$

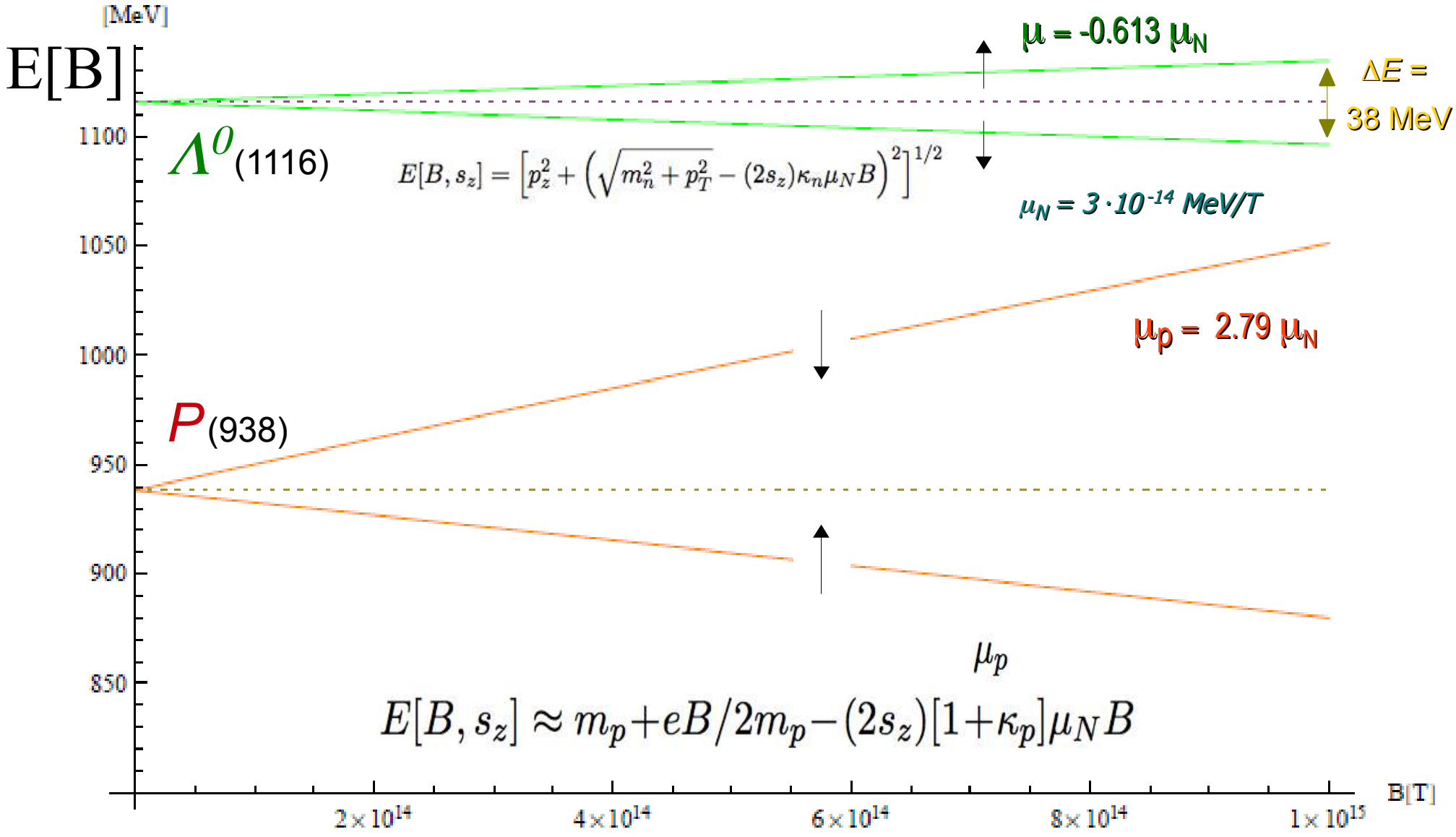
Landau energy of Kaon & Pion in [B]



- $K^{\pm}$ energy increase less than $\pi^{\pm}$ due to mass: $M_K > M_\pi$.

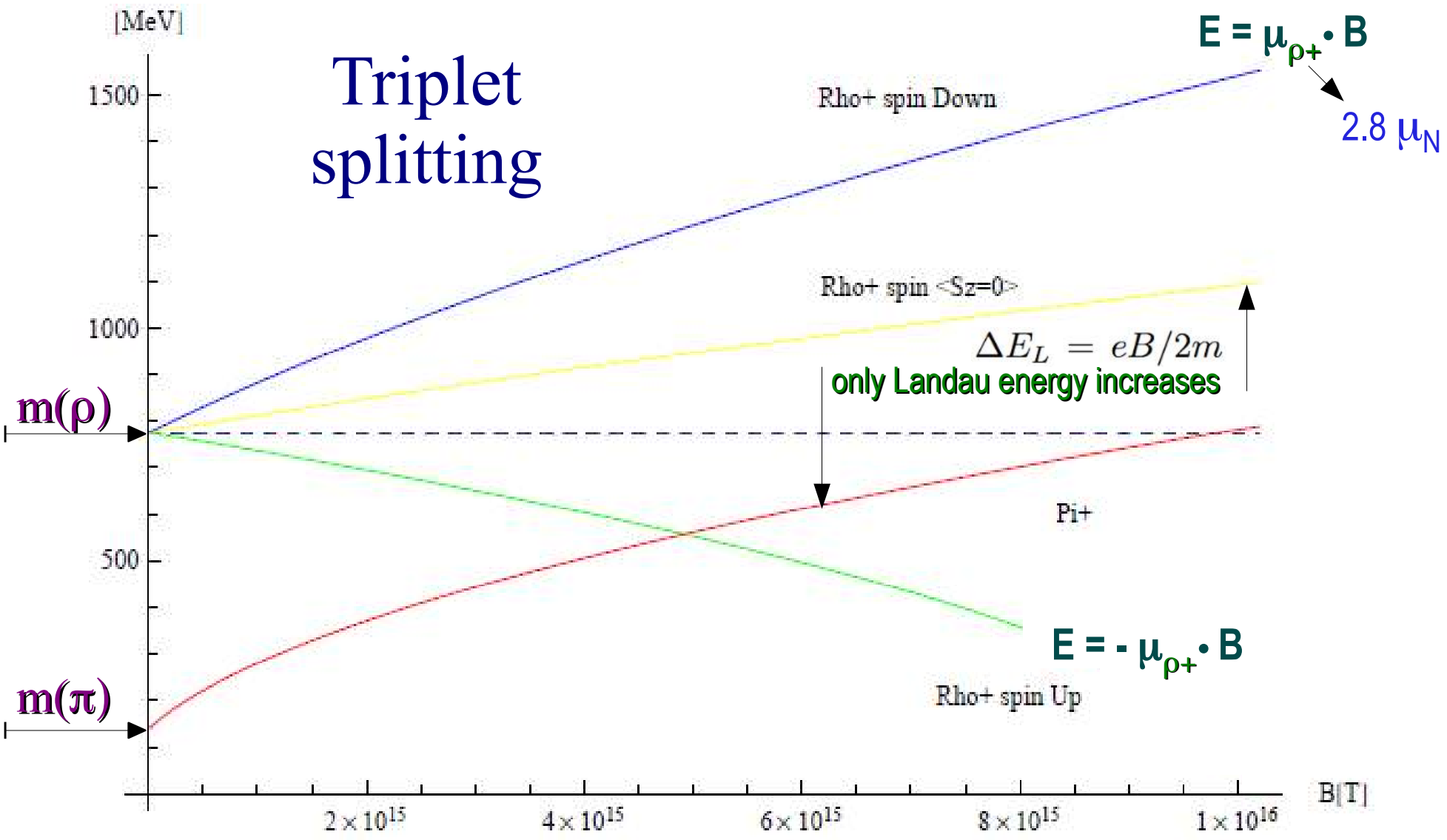
J = 1/2 J = 1/2

Energy of Proton and Lambda in [B]



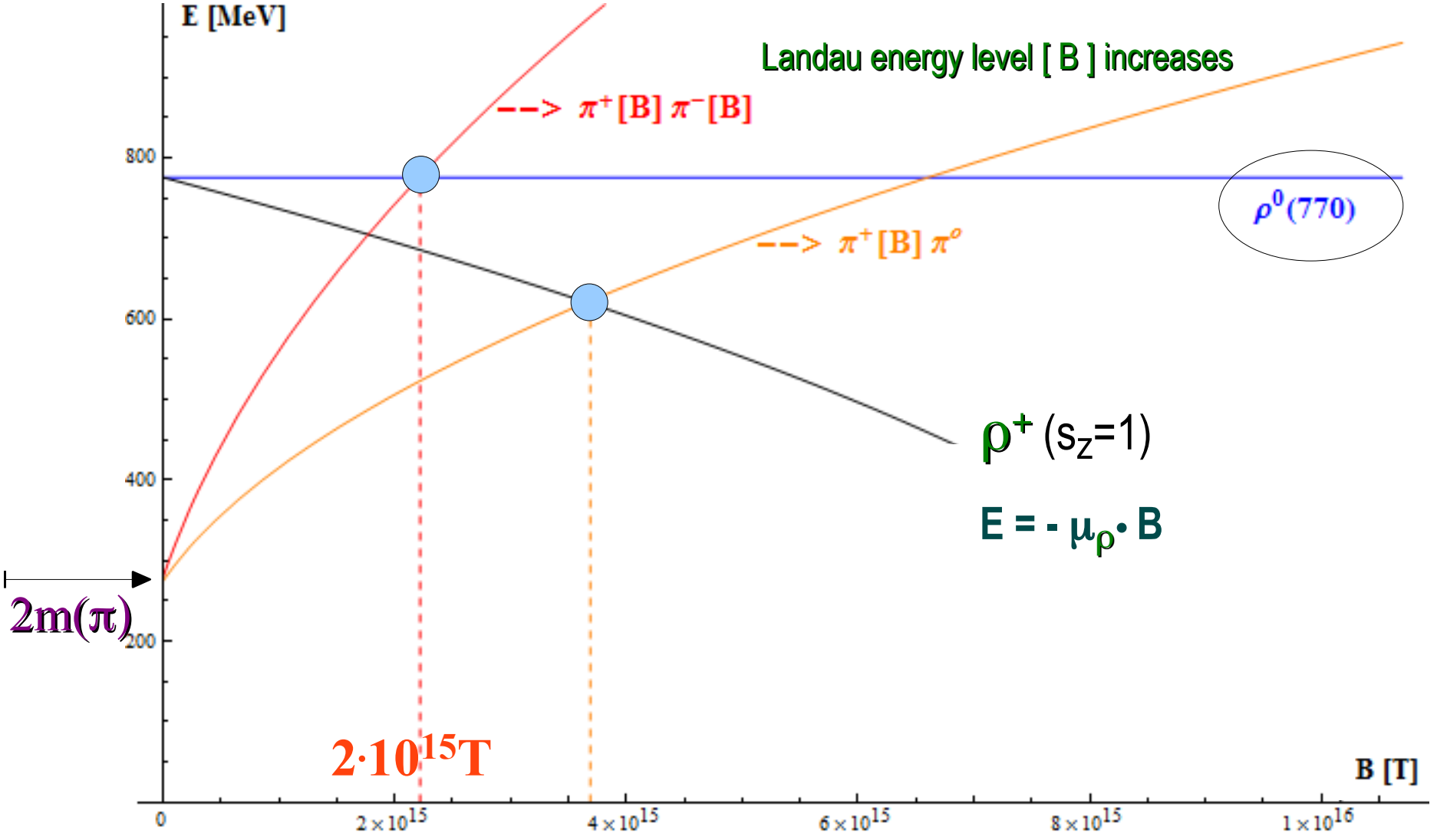
- Λ^0 energy $E = \pm \mu_\Lambda \cdot B$ Proton: $\pm \mu_P \cdot B$ + Landau ΔE

$\rho^{\pm}$ meson Energy levels ($s_z = +1,0,-1$) in [B]



- **Energy of $\rho^{\pm}(770)$ in [B] depends on spin projection +1, 0, -1**

ρ^0 and $\rho^{\pm}$ meson decays influenced by [B]



- **Energy of $\rho^{\pm}$(770) [B] , mass($\pi^{\pm}$)** modified: $\rho \rightarrow \pi\pi$ suppressed

Magnetic field effect on ρ^0 decay

$\rho(770)$ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	(MeV/c)
~~$\pi^+\pi^-$~~		~~~ 100 %~~		363
~~$\pi^0\pi^0$~~		→ 0 % • C – parity + isospin conservation		
		$\rho(770)^0$ decays		
$\pi^+\pi^-\gamma$		$(\ 9.9\ \pm 1.6\ ) \times 10^{-3}$		362
$\pi^0\gamma$		$(\ 6.0\ \pm 0.8\ ) \times 10^{-4}$		376
$\eta\gamma$		$(\ 3.00 \pm 0.21\ ) \times 10^{-4}$		194
$\pi^0\pi^0\gamma$		$(\ 4.5\ \pm 0.8\ ) \times 10^{-5}$		363
$\mu^+\mu^-$	[k]	$(\ 4.55 \pm 0.28\ ) \times 10^{-5}$		373
e^+e^-	[k]	$(\ 4.71 \pm 0.05\ ) \times 10^{-5}$		388
$\pi^+\pi^-\pi^0$		$(\ 1.01\ ^{+0.54}_{-0.36} \pm 0.34) \times 10^{-4}$		323
$\pi^+\pi^-\pi^+\pi^-$		$(\ 1.8\ \pm 0.9\ ) \times 10^{-5}$		251
$\pi^+\pi^-\pi^0\pi^0$		$< \ 4 \times 10^{-5}$	CL=90%	257

- $\rho^0 \Rightarrow \pi^+ + \pi^-$ phase space decreases → closed: $B > 2 * 10^{15}$T

Magnetic field effect on ρ^0 decays

$\rho(770)$ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	(MeV/c)
$\pi^+\pi^-$		$\sim$ 100 %		363
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$\mu^+\mu^-$	dileptons	[k] $(4.55 \pm 0.28) \times 10^{-5}$	? %	373
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$\pi^+\pi^-\pi^0$		$(1.01 \,^{+0.54}_{-0.36} \pm 0.34) \times 10^{-4}$		323
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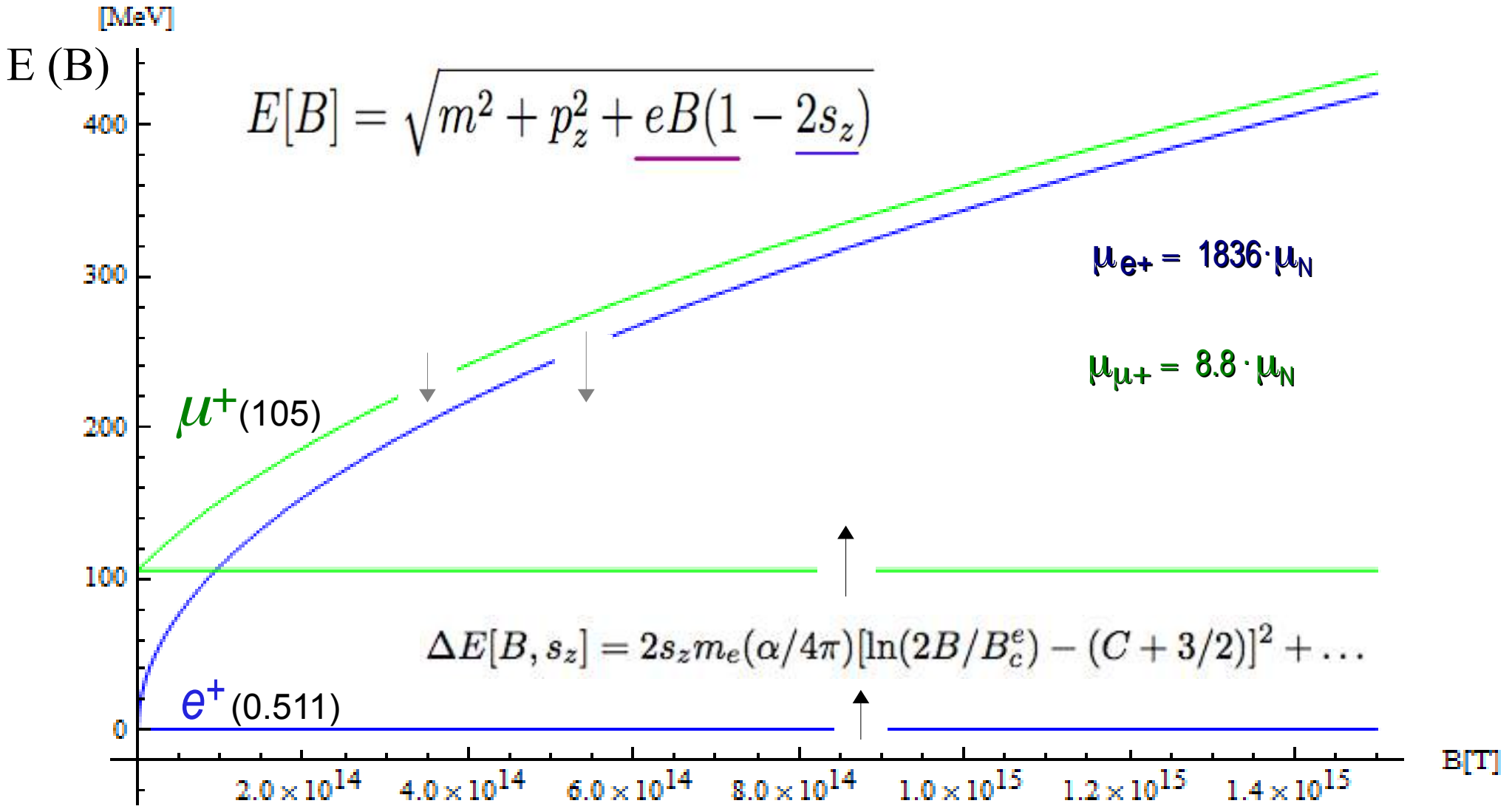
arXiv:1504.07008v1

- $\rho^0 \Rightarrow \pi^+ + \pi^-$ phase space decreases → closed: $B = 2 * 10^{15}$ T

J = 1/2 J = 1/2

Energy of Electron and Muon in [B]



- Exact energy dependence on spin projection [Schwinger (1948)]

OBSERVATION:

1) $\rho(770)$ decay is modified in B ~ 10^{15} T

- **Phys.Rev.D82: $\rho \rightarrow \pi\pi$ (closed) in $B = [2*10^{15}T]$**
  (2010) p.085011 $\tau = 1.2$ fm/c

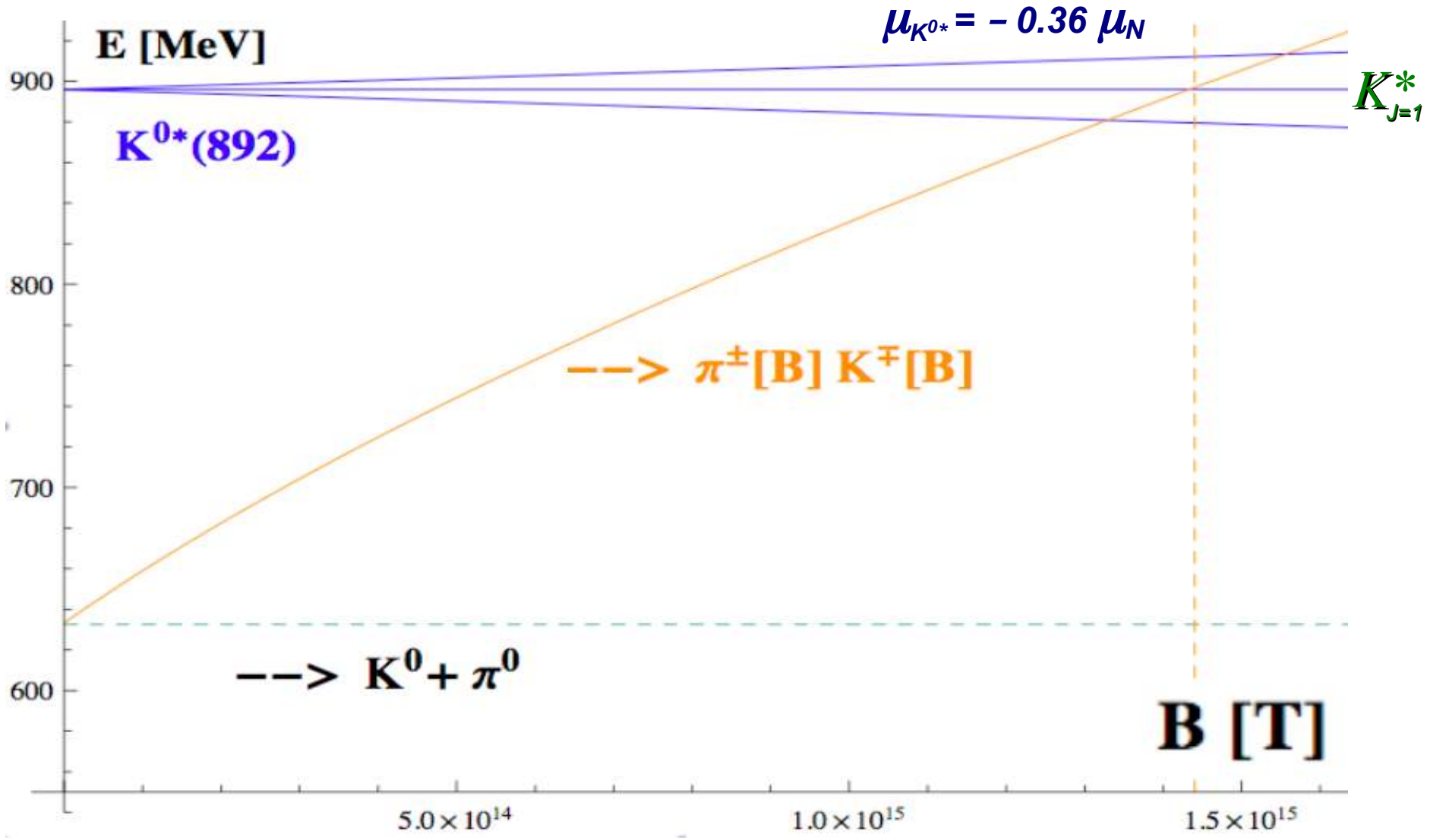
$\Rightarrow$ excess of photons and possibly dileptons may be generated:

if $\rho \rightarrow \pi^+\pi^-$ channel is suppressed for any reason

2) case of: $\varphi(1s)$, $\Upsilon(4s)$ and $\Sigma^*(1385)$

$\rightarrow$ first, let us have a look at: K^{+*}, K^{0*}

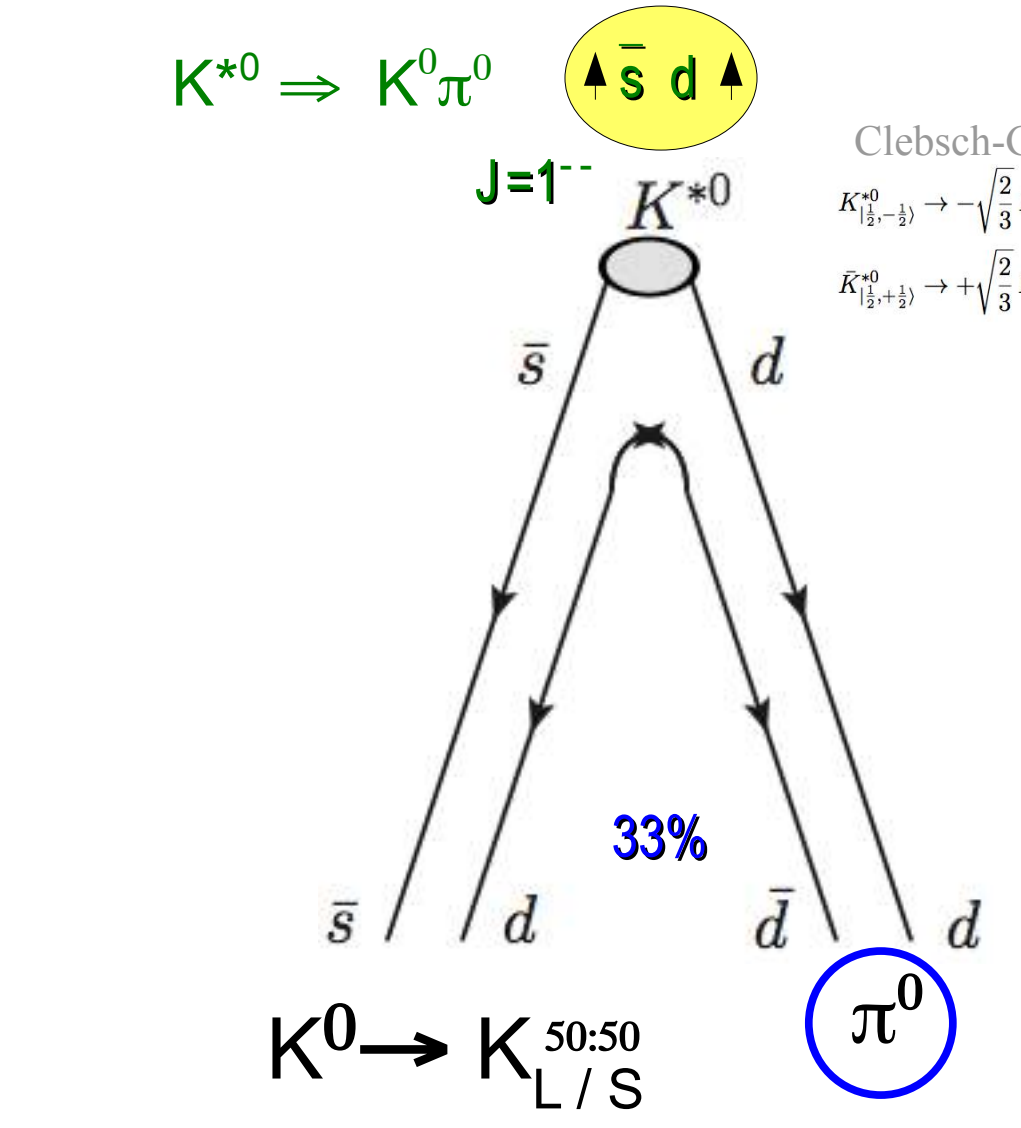
Magnetic field effect on K^{0*} decays



- $K^{0*} \Rightarrow \pi^{\pm}+K^{\pm}$ phase space decreas → closed: $B=1.5*10^{15}T$

Strong decays of neutral K^{0*}

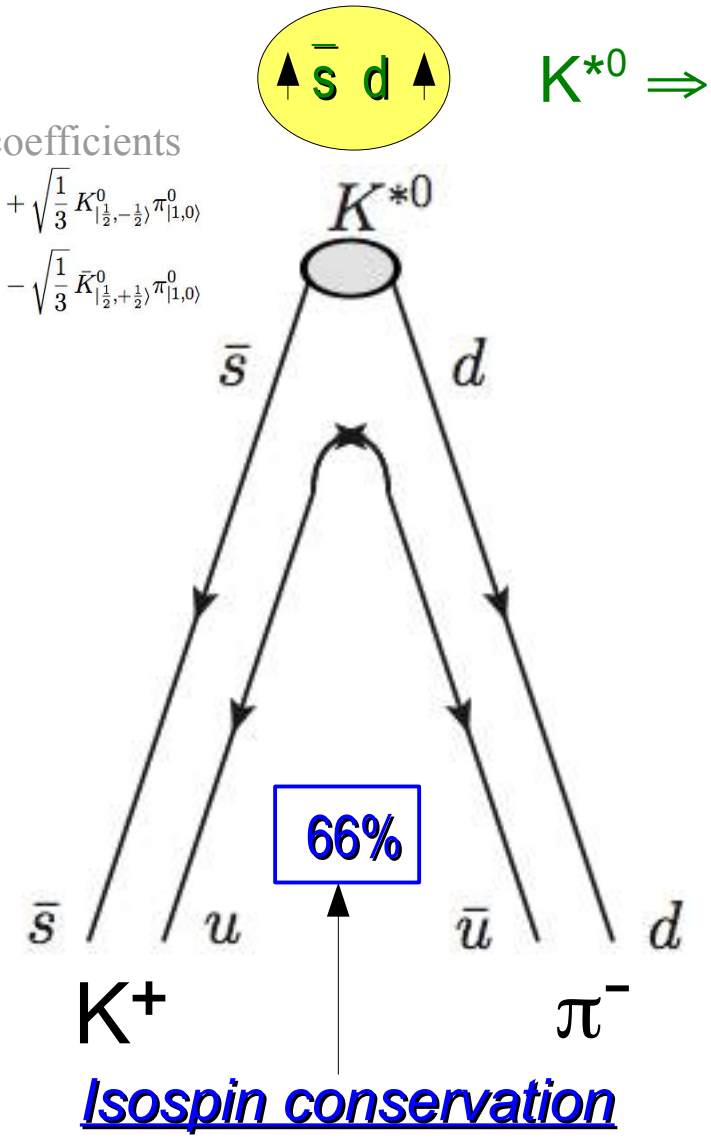
$K^{*0} \Rightarrow K^0\pi^0$ $\quad$ $K^{*0} \Rightarrow K^+\pi^-$



Clebsch-Gordan coefficients

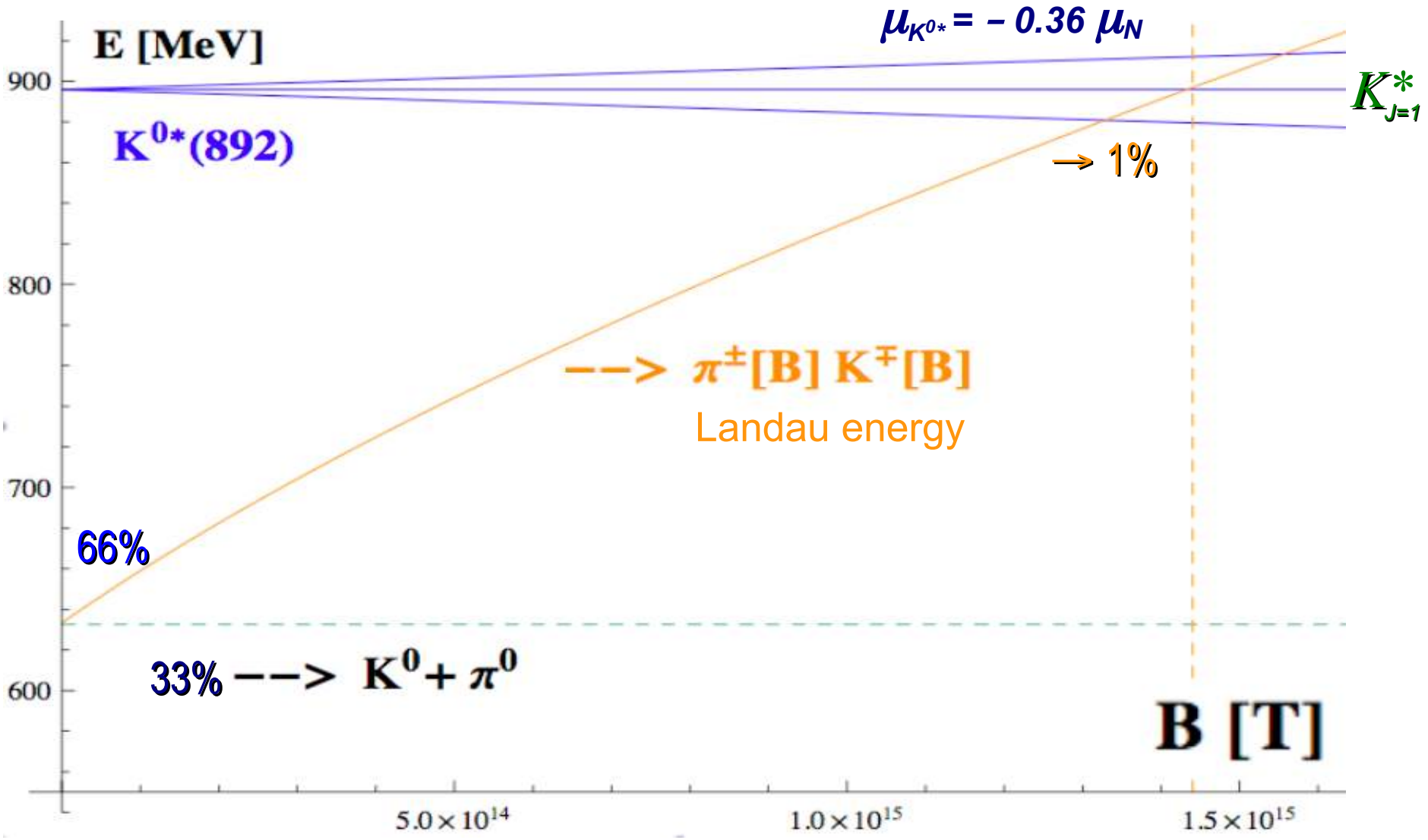
$$K^{*0}_{|\frac{1}{2},-\frac{1}{2}\rangle} \to -\sqrt{\frac{2}{3}}\,K^{+}_{|\frac{1}{2},+\frac{1}{2}\rangle}\pi^{-}_{|1,-1\rangle} + \sqrt{\frac{1}{3}}\,K^{0}_{|\frac{1}{2},-\frac{1}{2}\rangle}\pi^{0}_{|1,0\rangle}$$

$$\bar{K}^{*0}_{|\frac{1}{2},+\frac{1}{2}\rangle} \to +\sqrt{\frac{2}{3}}\,K^{-}_{|\frac{1}{2},-\frac{1}{2}\rangle}\pi^{+}_{|1,+1\rangle} - \sqrt{\frac{1}{3}}\,\bar{K}^{0}_{|\frac{1}{2},+\frac{1}{2}\rangle}\pi^{0}_{|1,0\rangle}$$



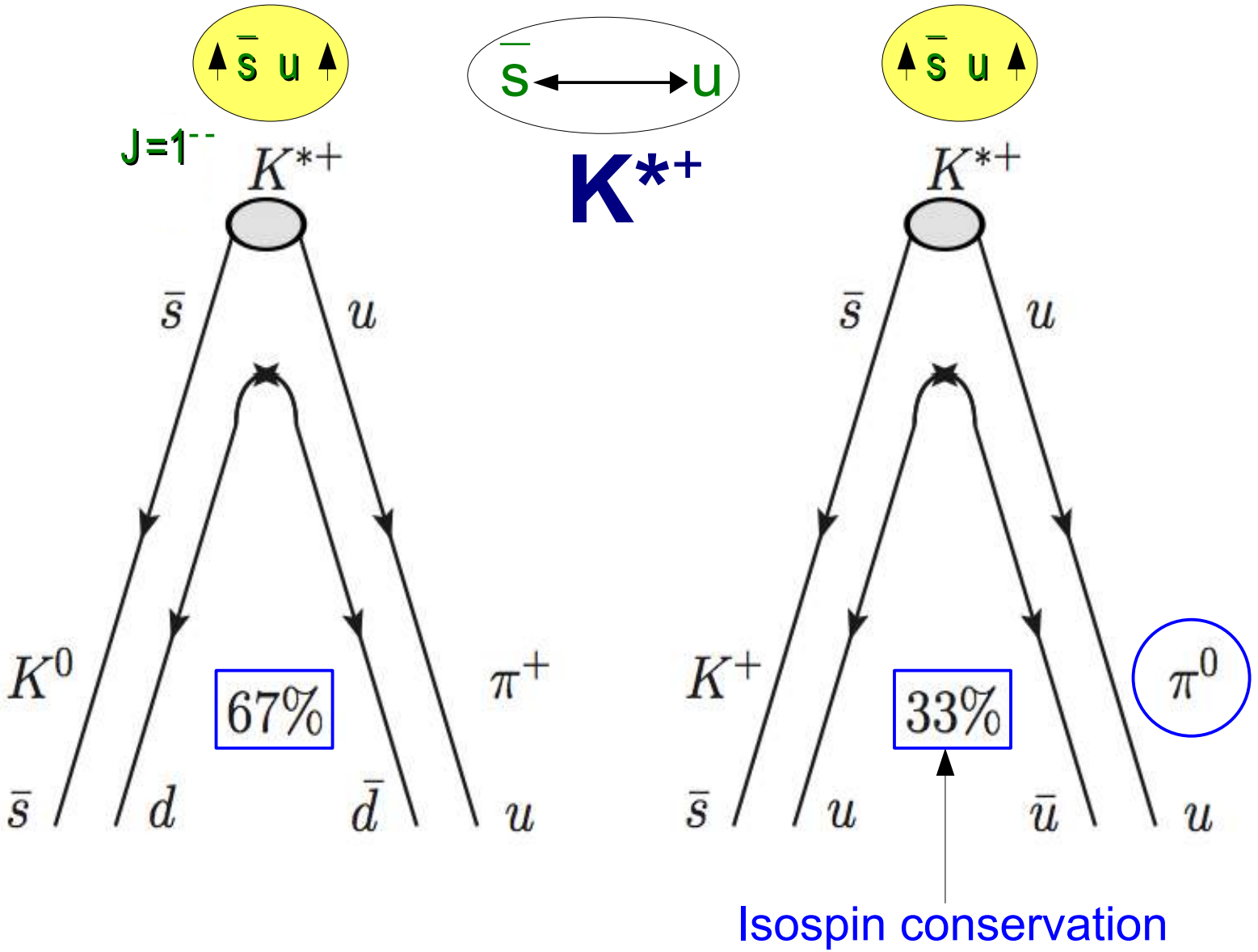
- Gluonic string breaking via $q\bar{q}$ (0^{++}) pair creation...

Magnetic field effect on K^{0*} decays



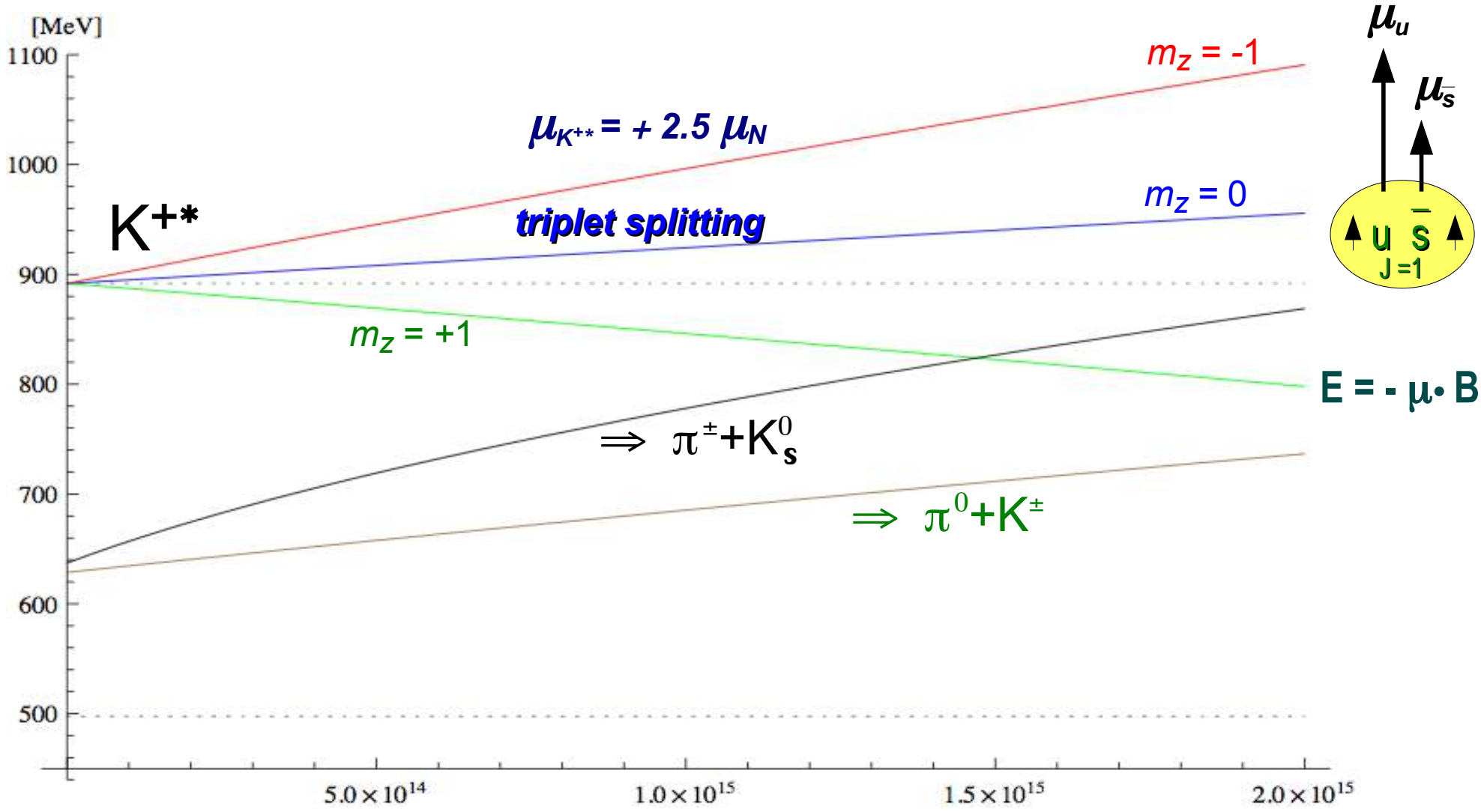
- $K^{0*} \Rightarrow \pi^{\pm}+K^{\pm}$ closed: $B=1.5 \cdot 10^{15}$T → Isospin violation

Strong decays of <u>charged</u> $K^{\pm *}$



- Gluonic string breaking via $q\bar{q}$ (0^{++}) pair creation...

K^{+*} in strong Magnetic Field



- $K^{\pm *} \Rightarrow \pi^{\pm}+K^0_s$ remains open @10^{15}T (becomes Tensor polarized)

Observation:

1) $K^{0*}(896)$ $\tau \approx 4$ fm/c → $\pi^- + K^+$ is sensitive to [B]

$\pi^0 + K^0$ unaffected

BR can be different than assumed (isospin rule violated)

2) $K^{+*}(892)$ $\tau \approx 4$ fm/c → $\pi^+ + K^0$ less sensitive [B]

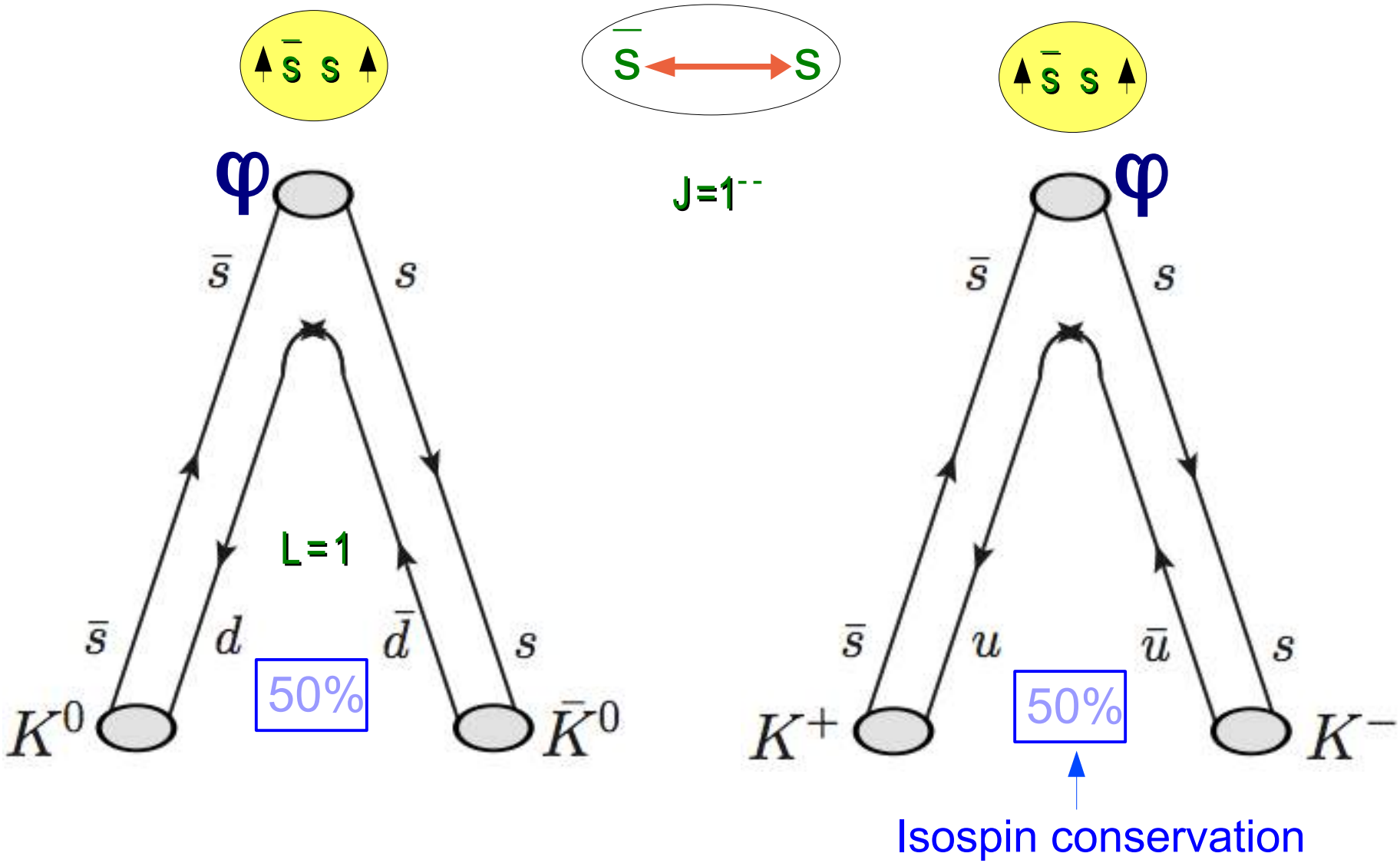
$\pi^0 + K^\pm$ usually not observed

⇒ **different response of K^{0*} ↔ $K^{\pm *}$ to B field.**

in HIC: different K^{0*}, $K^{\pm *}$ yield can be reconstructed

(if B field is still present during decay time)

Strong decay of $\varphi_{(1s)} \rightarrow KK$



- Gluonic string breaking via $q\bar{q}$ (0^{++}) pair creation...

$\phi(1020)$ decay in Vacuum

Mass $m = 1019.455 \pm 0.020$ MeV (S = 1.1)
Full width $\Gamma = 4.26 \pm 0.04$ MeV (S = 1.4)

$\phi(1020)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
K^+K^- ← More probable decay channel	(49.2 ±0.6) %	S=1.2	127
$K^0_L K^0_S$	(34.0 ±0.5) %	S=1.1	110

Angular momentum is conserved:

φ: $J^{PC} = 1^{--}$

J=1 ⇒ L=1 (KK pair) in P-wave

PHASE SPACE: $d\Omega \approx p^3$

K^+K^-

$\Delta M = (1019 - 2*493) = 32$ MeV

$\delta M = (1019 - 2*497) = 24$ MeV

K^0K^0

$$\frac{\Gamma(K^+K^-)}{\Gamma(K^0K^0)} = \frac{|A|^2 * p^3}{|A|^2 * p^3} = \frac{127^3}{110^3} = \frac{49\%}{34\%}$$

$\phi(1020)$ in magnetic field

Mass $m = 1019.455 \pm 0.020$ MeV $(S = 1.1)$
Full width $\Gamma = 4.26 \pm 0.04$ MeV $(S = 1.4)$

$\phi(1020)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
K^+K^- ← suppressed	(49.2 ±0.6) %	S=1.2	127
$K^0_L K^0_S$ → unaffected	(34.0 ±0.5) %	S=1.1	110

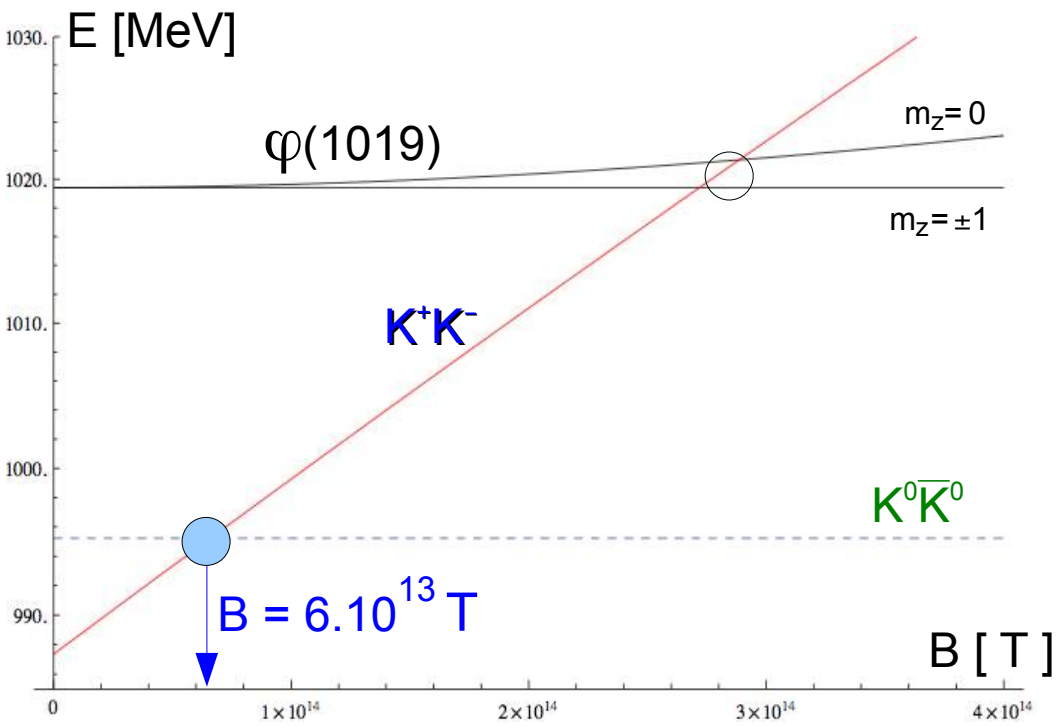
$\Delta M = (1019 - 2*497_{K^+K^-}) = 24$ MeV

$\delta M = (1019 - 2*497_{K^0K^0}) = 24$ MeV

P-wave: L=1

$B = 6.10^{13}$ T

$$\Gamma(K^+K^-) = |A|^2 * \frac{p^3}{p^3} = \frac{110^3}{110^3} = \frac{41\%}{41\%}$$
$$\Gamma(K^0K^0) = |A|^2 * p^3$$



$\phi(1020)$ in magnetic field

Mass $m = 1019.455 \pm 0.020$ MeV $(S = 1.1)$

Full width $\Gamma = 4.26 \pm 0.04$ MeV $(S = 1.4)$

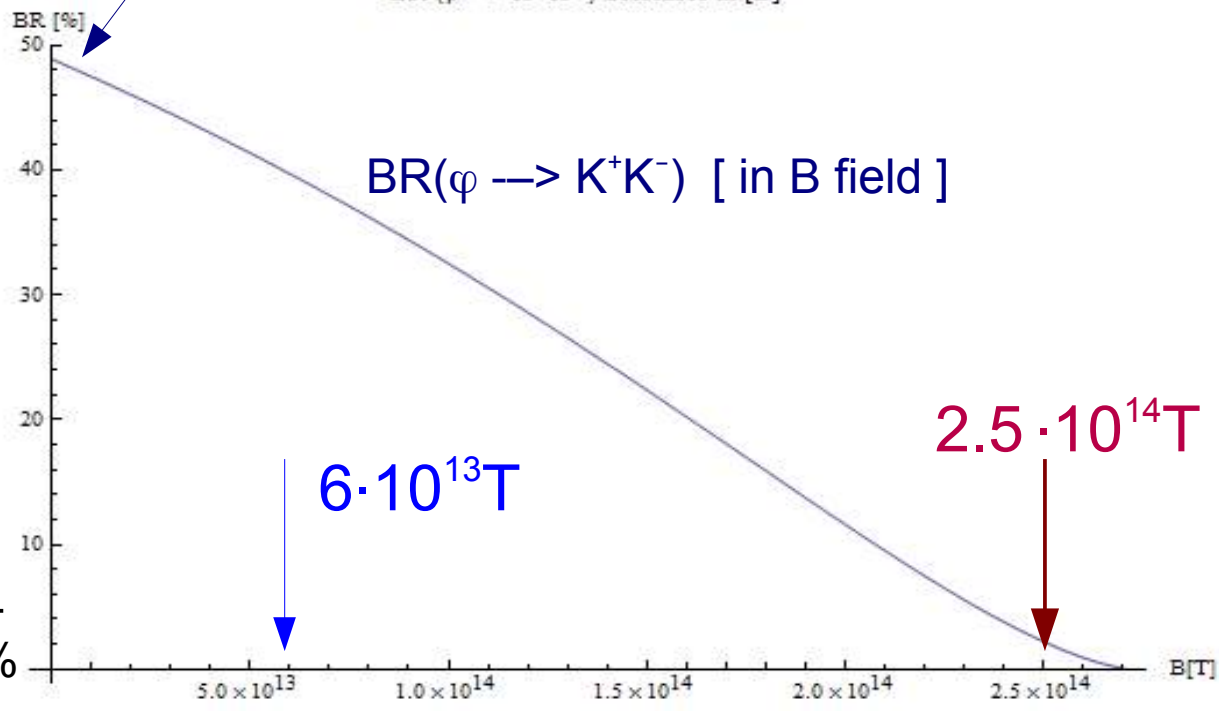
$\phi(1020)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
K^+K^- ← suppressed	(49.2 ±0.6) %	S=1.2	127
$K^0_L K^0_S$ → unaffected	(34.0 ±0.5) %	S=1.1	110

$\Delta M = (1019 - 2*493) = 32$ MeV (K^+K^-)

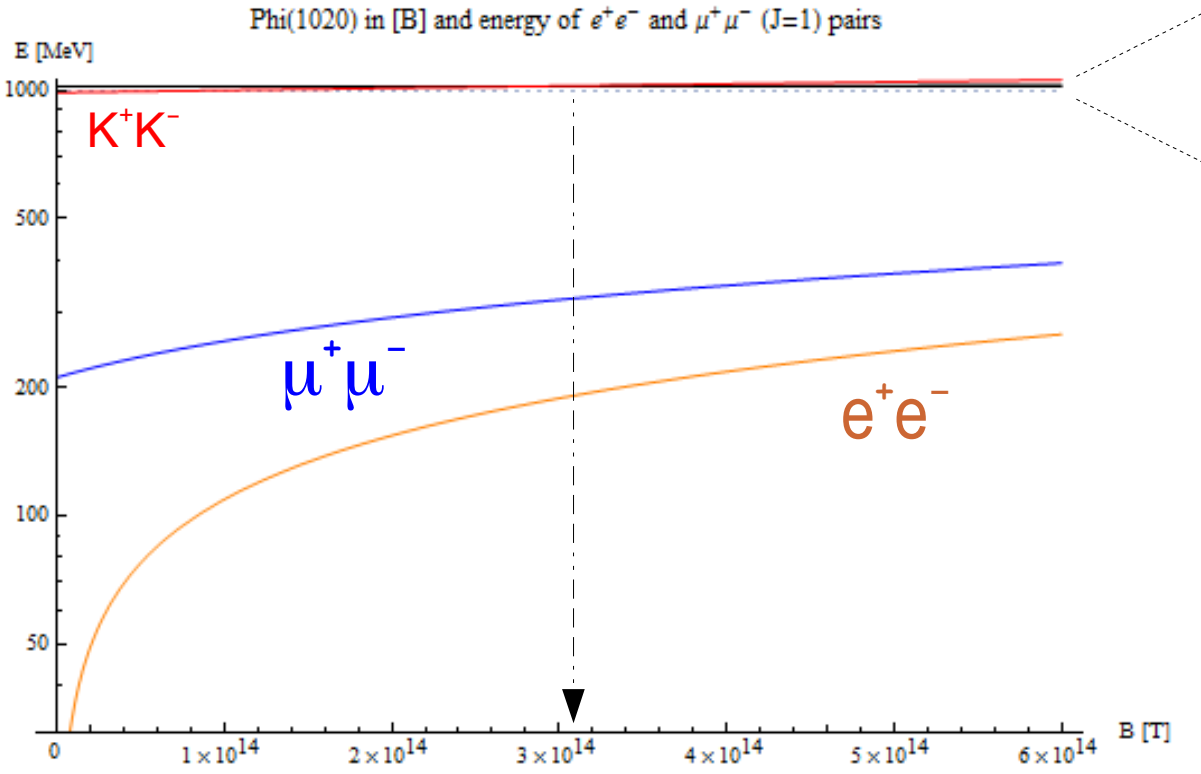
$\delta M = (1019 - 2*497) = 24$ MeV (K^0K^0)

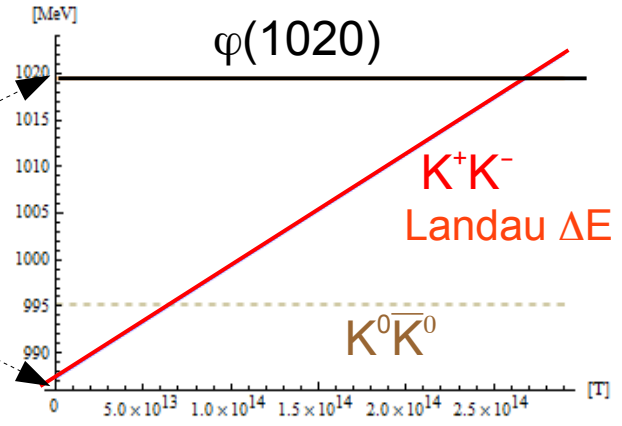
P-wave: J=1 --> 2x(s=0) + L=1

$$\Gamma(K^+K^-) = |A|^2 * \frac{p^3}{p^3} \approx \frac{1^3}{110^3} = \frac{2\%}{81\%} = \Gamma(K^0K^0) = |A|^2 * \frac{p^3}{p^3}$$



$\phi(1020)$ in magnetic field





- $\varphi \rightarrow K^0\overline{K}^0$ no change
  in our approximation
- $\varphi \rightarrow K^+K^-$ closed
- $\varphi \rightarrow e^+e^-$ affected ?
  (0.03%)

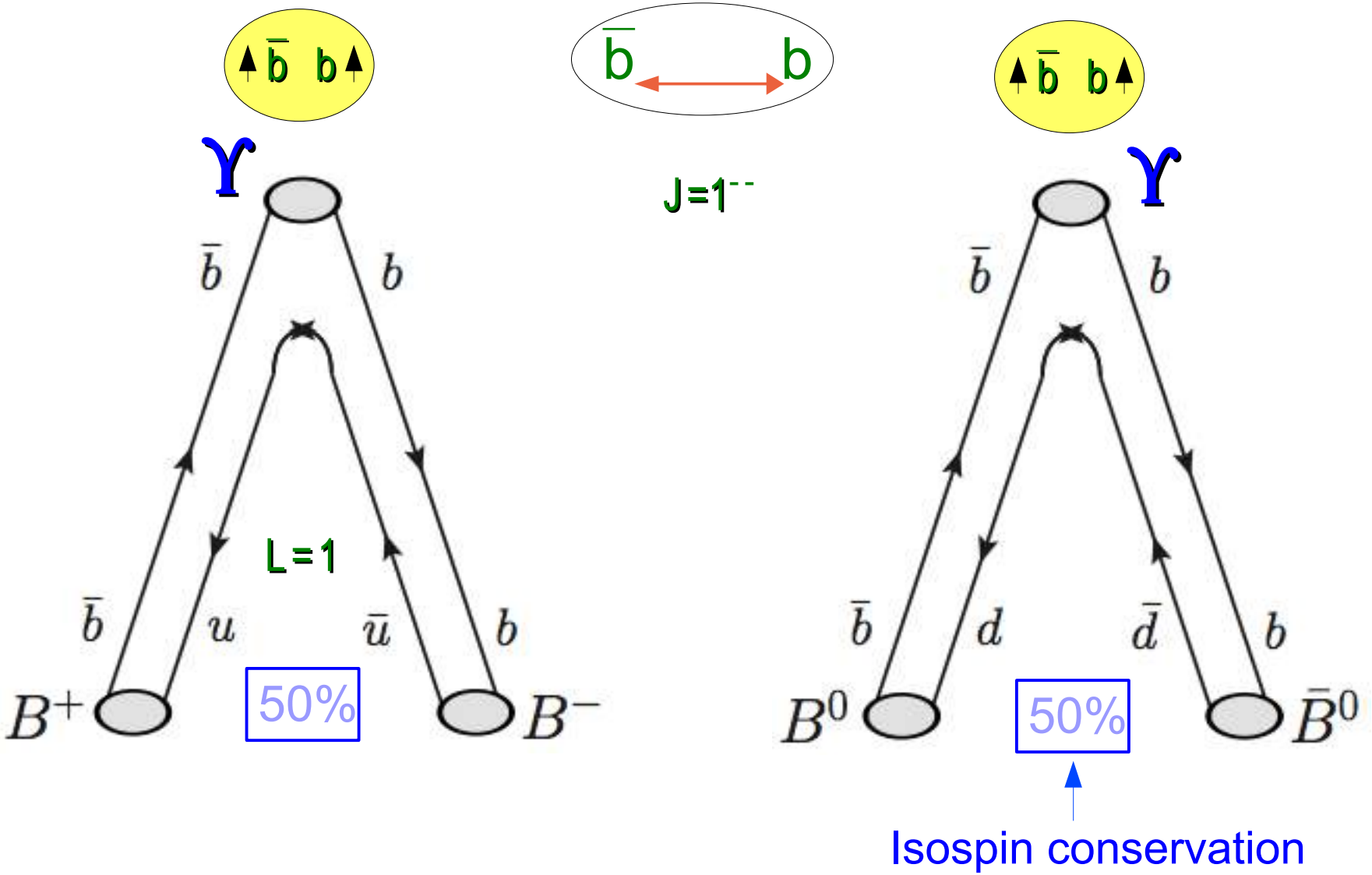
e^+e^-, $\mu^+\mu^-$ are still open, while K^+K^- is closed

COMPARISON
Lifetime vs Critical Field

	Width [MeV]	Lifetime [fm/c]	B critical [10^{14} T]	Channel
$\rho^{o}(770)$	150	1.3	20	$\pi^+ \pi^-$
$K^{o*}(896)$	50	4	15	$K^{\pm}\pi^{\pm}$
$K^{\pm *}(892)$	50	4	—	$K^{0}\pi^{\pm}$
φ (1019)	4 - 20	49 – 10	2	K^+K^-
Υ (4s)	20	10	18	B^+B^-

in dense medium: nucl-th: 0404069

Strong decay of $\Upsilon(4s) \rightarrow B\bar{B}$



- Gluonic string breaking via $q\bar{q}$ (0^{++}) pair creation...

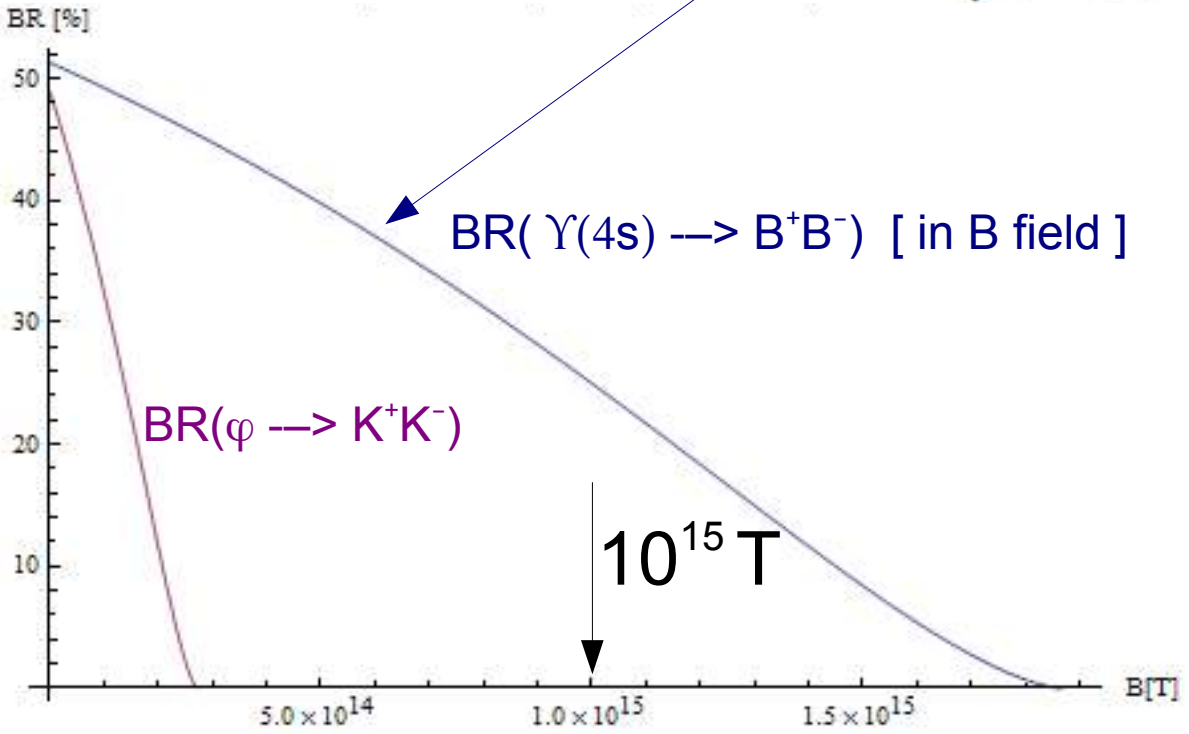
$\Upsilon(4S)$ or $\Upsilon(10580)$

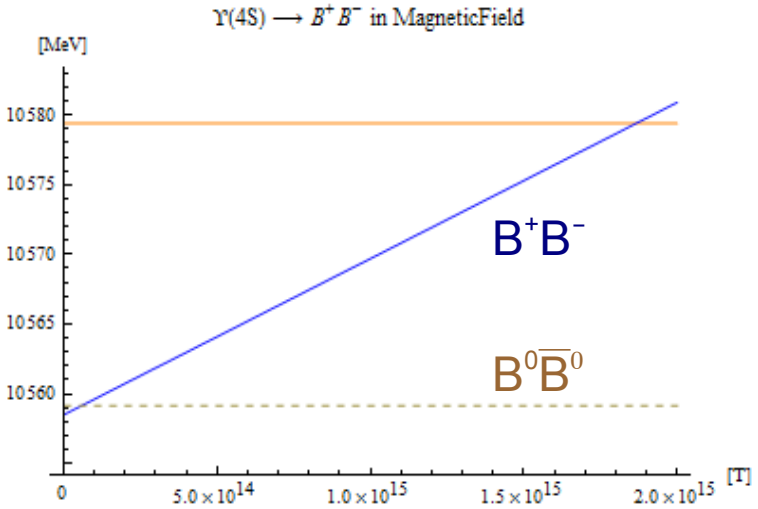
Mass $m = 10.5794 \pm 0.0012$ GeV

Full width $\Gamma = 20.5 \pm 2.5$ MeV

$\Upsilon(4S)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$B\overline{B}$		95%	
B^+B^-	(51.6 ±0.6) %		334^3
$B^0\overline{B}^0$	(48.4 ±0.6) %		328^3

$$\frac{(51.6 \pm 0.6)\,\%}{(48.4 \pm 0.6)\,\%} = 1.066 = \frac{334^3}{328^3}$$





Phase space (p^3) is reduced:
due to Landau Energy increase

BR [$\Upsilon \rightarrow B^+B^-$] gets smaller

COMPARISON
Lifetime vs Critical Field

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dense medium: nucl-th: 0404069

φ (1019)	4 - 20	49 – 10	2	K^+K^-
Υ (4s)	20	10	18	B^+B^-

$\Sigma^{\pm *}$

SUMMARY II:

$K^0+\overline{K}^0$ unaffected [B]

1) $\varphi(1019) \rightarrow$ K^-+K^+ is sensitive to [B]

$BR(K^+K^-)$ becomes smaller in [B]

2) $\varphi(1019) \rightarrow$ e^-+e^+ may be affected in [B]

$\rightarrow$ $\mu^-+\mu^+$ is less sensitive

φ yields in HIC may appear different in: K^+K^-, e^+e^-, $\mu^+\mu^-$

if B field remains present for considerable time

3) $\Upsilon_{(4s)} \rightarrow B^+B^-$ affected in 10^{15} T (LHC: Pb+X?)

COMPARISON
Lifetime vs Critical Field

	Width [MeV]	Lifetime [fm/c]	B critical [10^{14} T]	Channel
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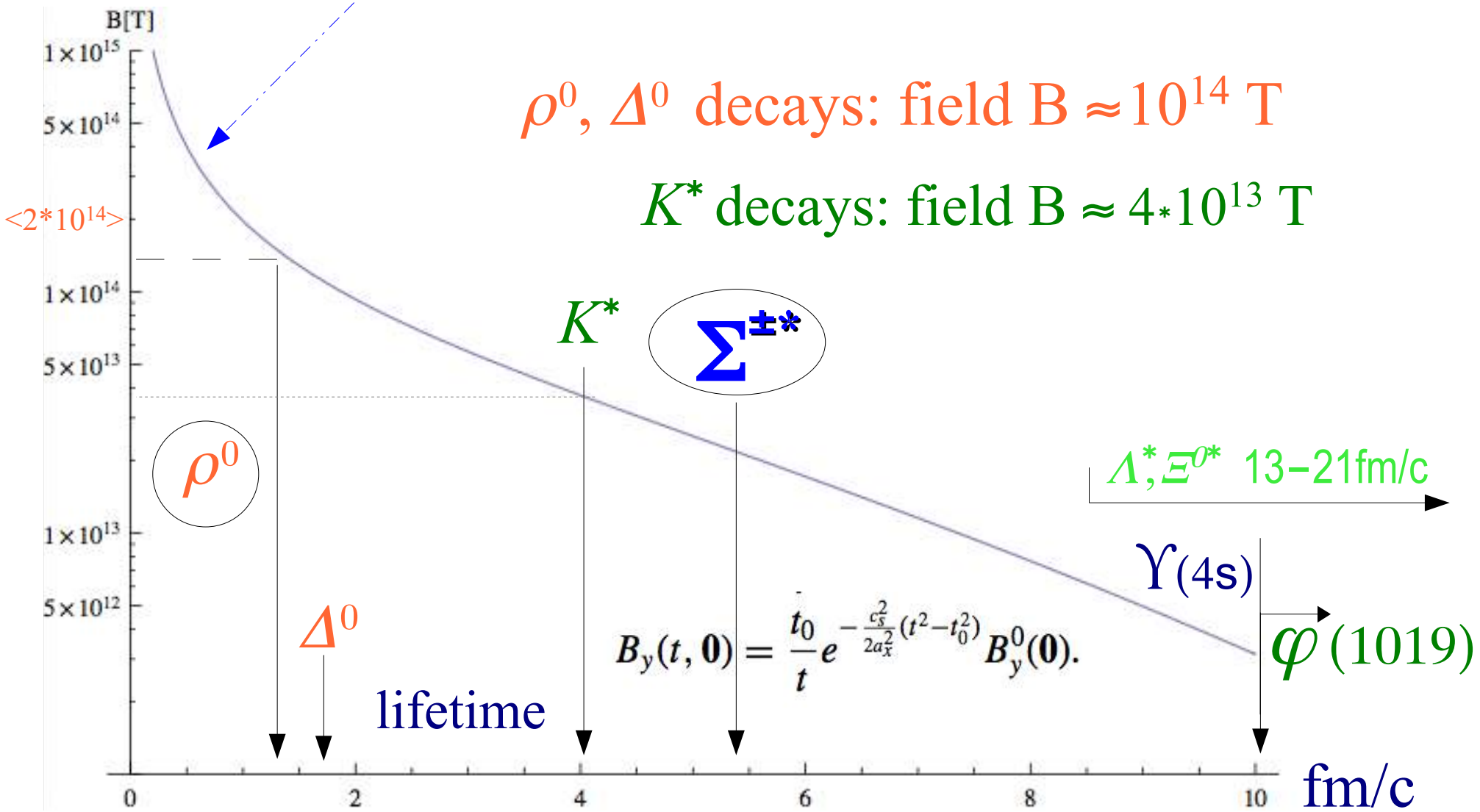
$K^{o*}(896)$	50	4	15	$K^{\pm}\pi^{\pm}$
$K^{\pm *}(892)$	50	4	—	$K^{0}\pi^{\pm}$

dense medium: nucl-th: 0404069

φ (1019)	4 - 20	49 – 10	2	K^+K^-
Υ (4s)	20	10	17	B^+B^-
$\Sigma^{\pm *}$	37	5	4	

B field evolution and ρ^0, Δ^0, K^*, Σ^* decays

PRC85 (2012) 044907, for Pb+Pb at **LHC**



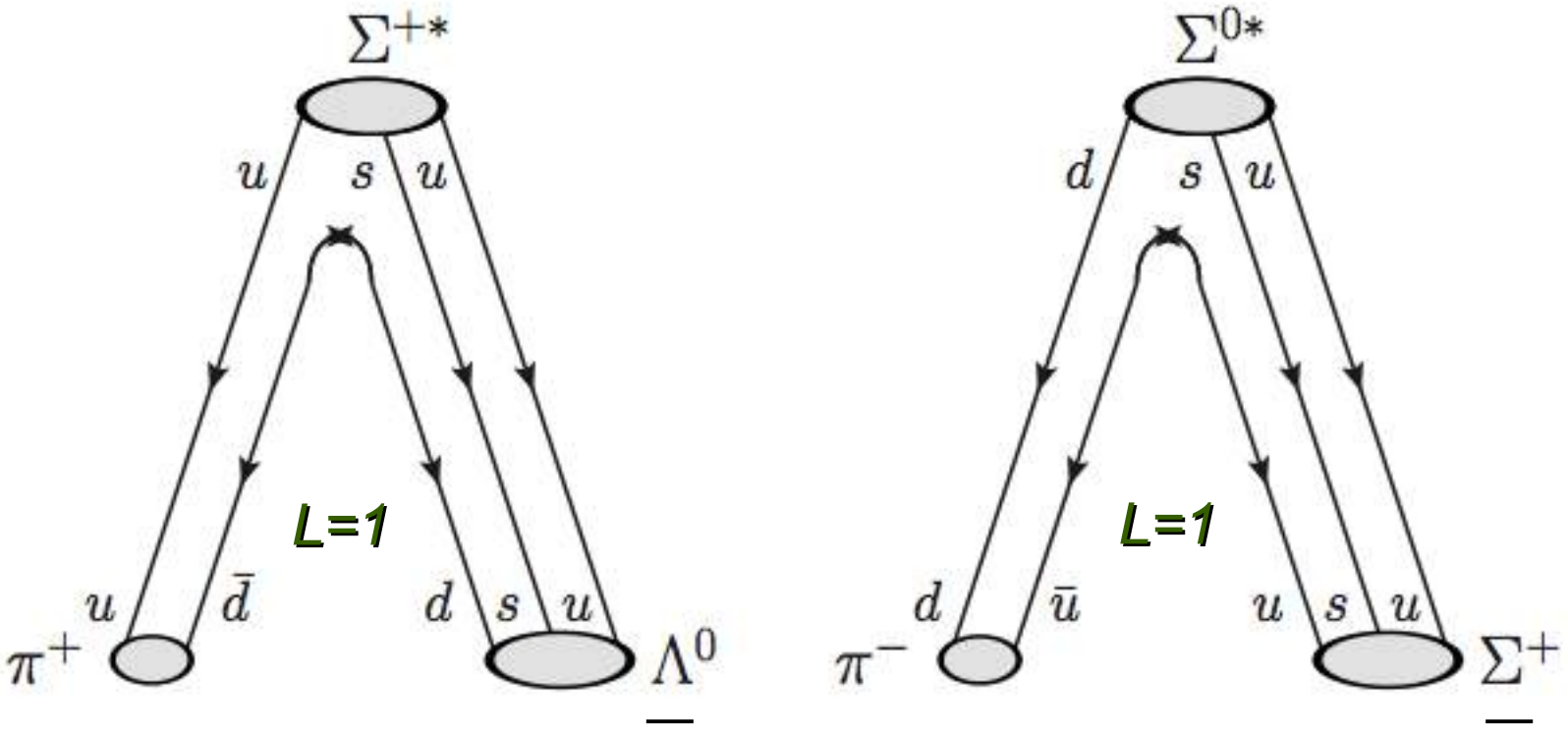
if QGP keeps B field long time & resonances created at t=0.

$\Sigma^{+*}_{3/2}$, $\Sigma^{0*}_{3/2}$ baryon ($u^{\uparrow}s^{\uparrow}u^{\uparrow}$) decays $d^{\uparrow}s^{\uparrow}u^{\uparrow}$

Radiative decay ~ 1.4%

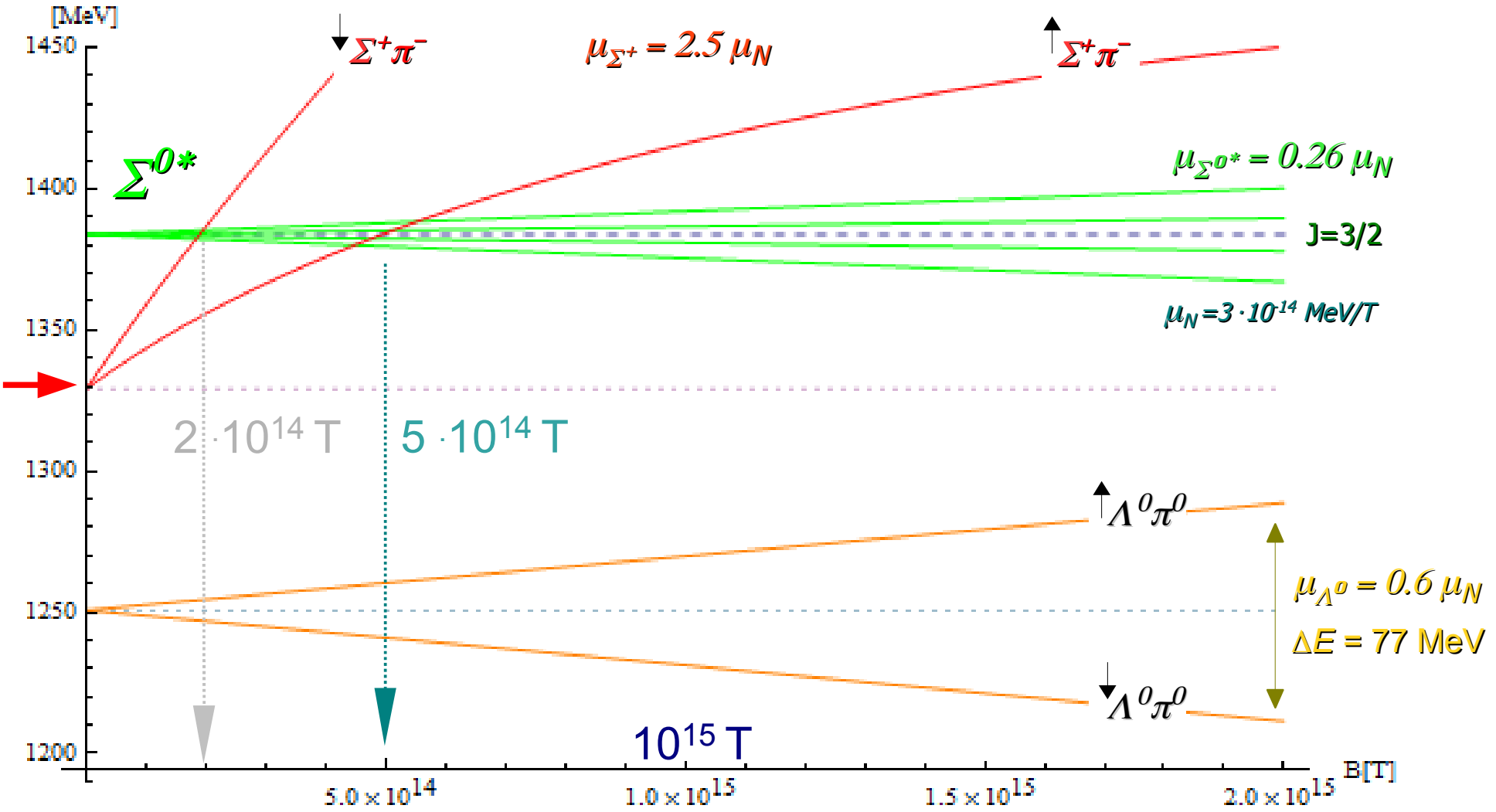
$\rightarrow \Lambda\pi$ (87.0 ± 1.5) %

$\rightarrow \Sigma\pi$ (11.7 ± 1.5) %



Strong decay process $(\bar{d}d),(u\bar{u})$ in mag. field: $B \approx 10^{14}$ T

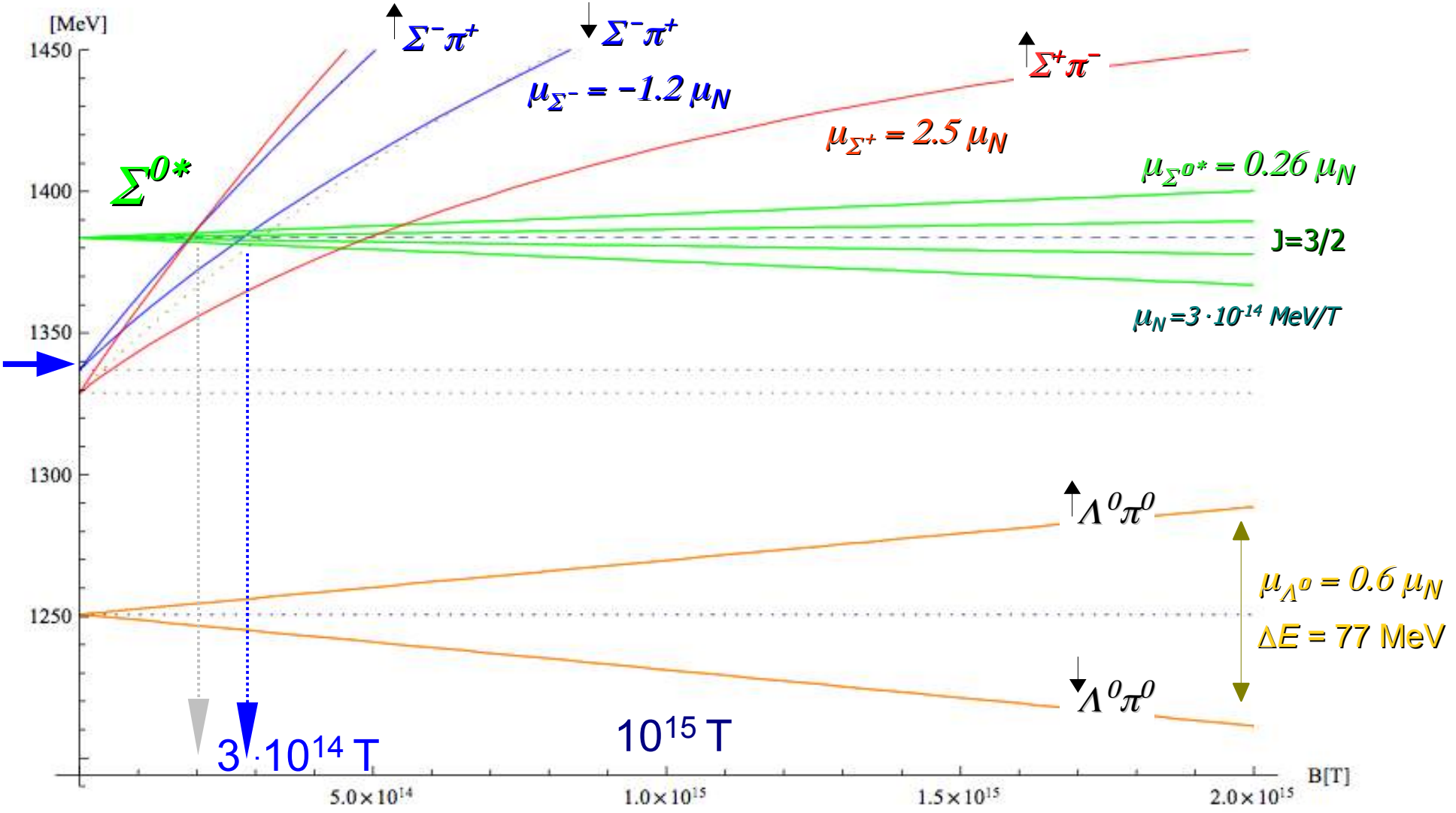
Σ^{0*} baryon in field B → 10^{15}T



$\Sigma^{0*} \rightarrow \Sigma^{\pm}\pi^{\pm}$ → 0 %

$\Sigma^{*} \rightarrow \Lambda^{0}\pi^{0}$ → 99%

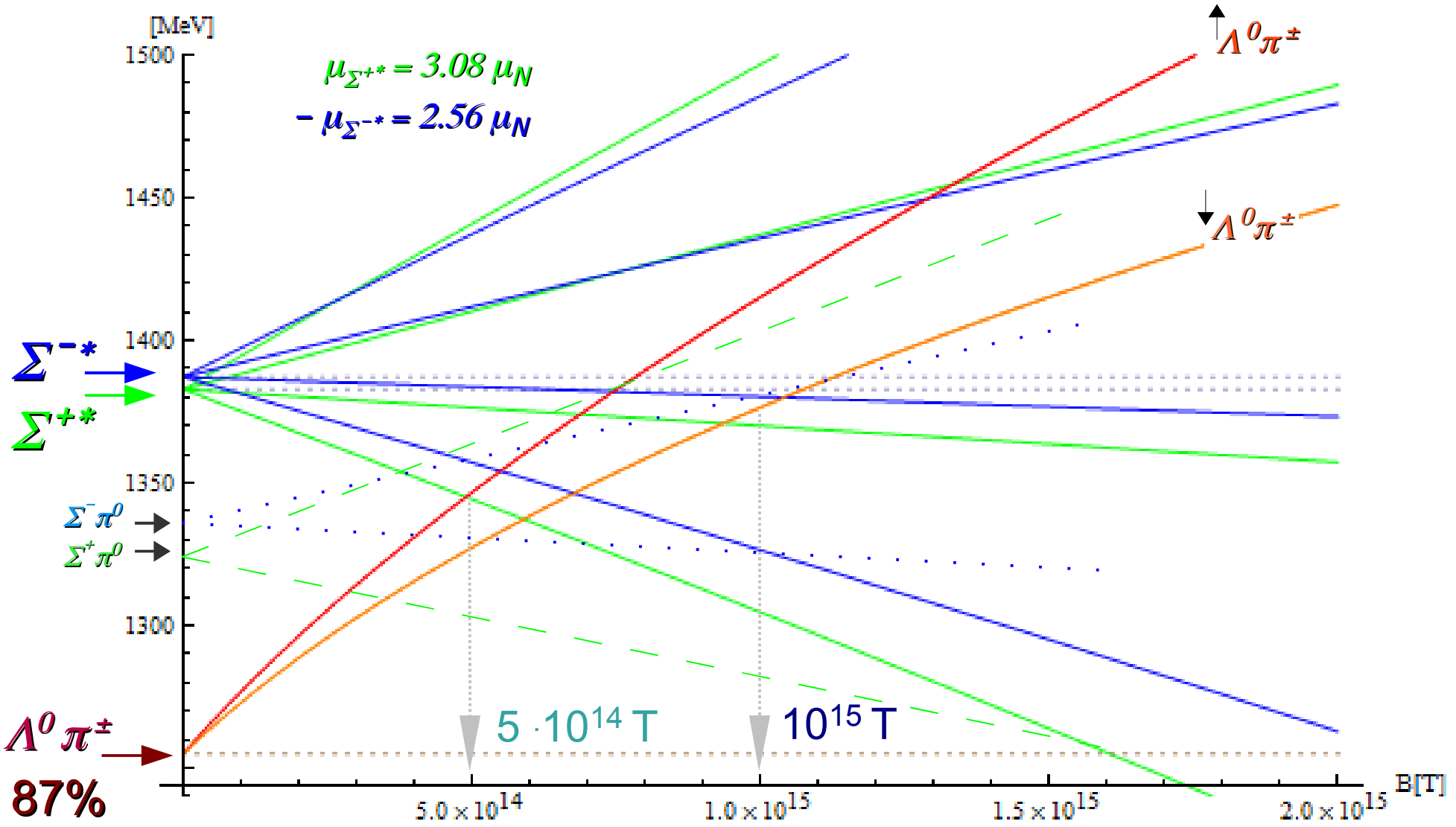
Σ^{0*} baryon in field B → 10^{15}T



$\Sigma^{0*} \rightarrow \Sigma^{\pm}\pi^{\pm}$ → 0 %

$\Sigma^{*} \rightarrow \Lambda^{0}\pi^{0}$ → 99%

$\Sigma^{\pm *}$ baryons in field B → 10^{15}T



$\Sigma^{\pm *} \rightarrow \Lambda^0\pi^\pm$: Polarization of $\Sigma^{\pm *}$ and BR change can appear

SUMMARY III:

$\Lambda^0 + \pi^0$ unaffected/enhanced

1) $\Sigma^{0*}(1385) \rightarrow \Sigma^{\pm} + \pi^{\pm}$ closed at [$B = 2\text{-}5 \cdot 10^{14}$ T]

this channel usually not observed

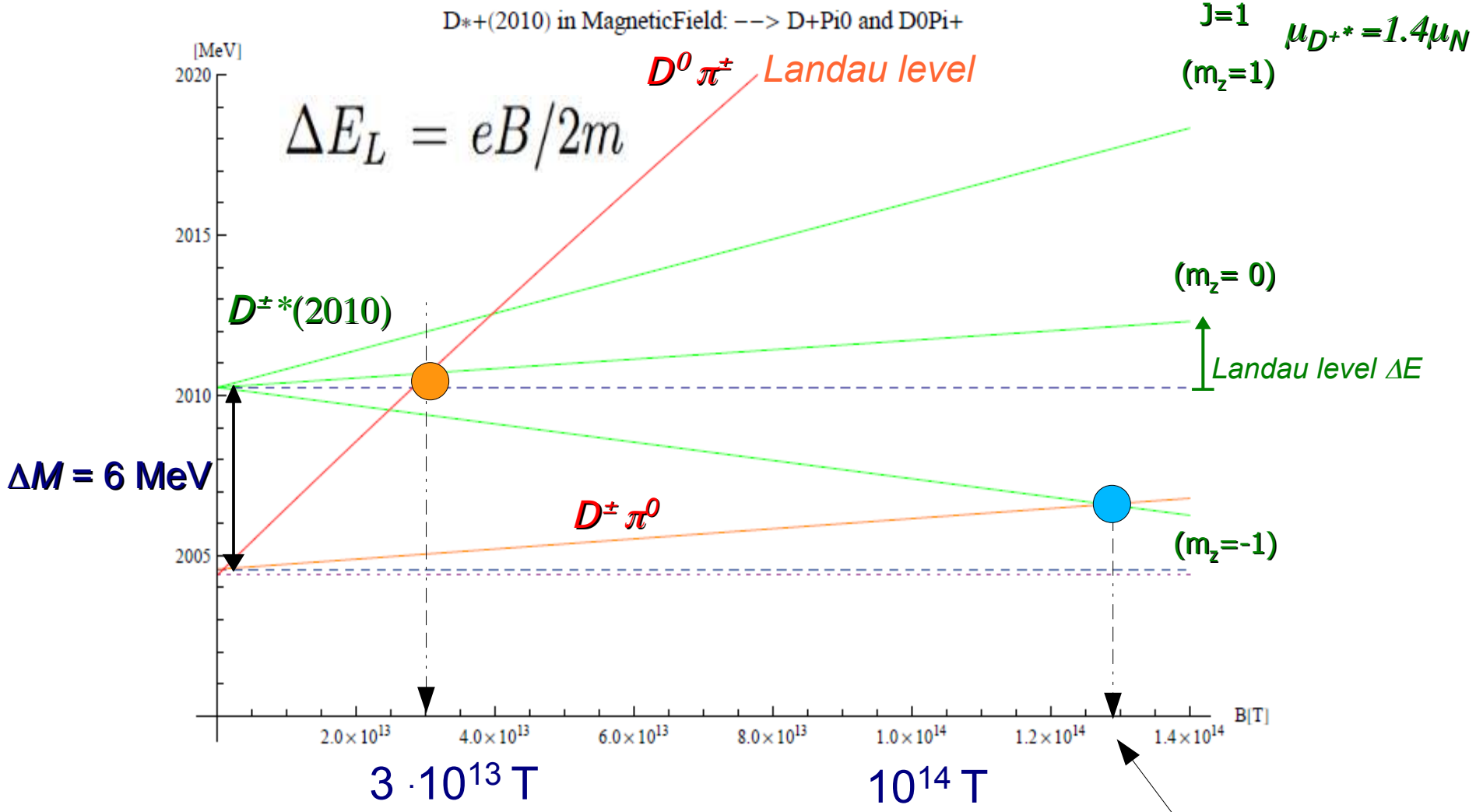
2) $\Sigma^{\pm *}(1385) \rightarrow \Lambda^0 + \pi^{\pm}$ affected in [$B \approx 5 \cdot 10^{14}$ T]

$\rightarrow \Sigma + \pi$ only 12%

$\Rightarrow$ Polarization of $\Sigma^{\pm *}$ in r-HIC may be observed

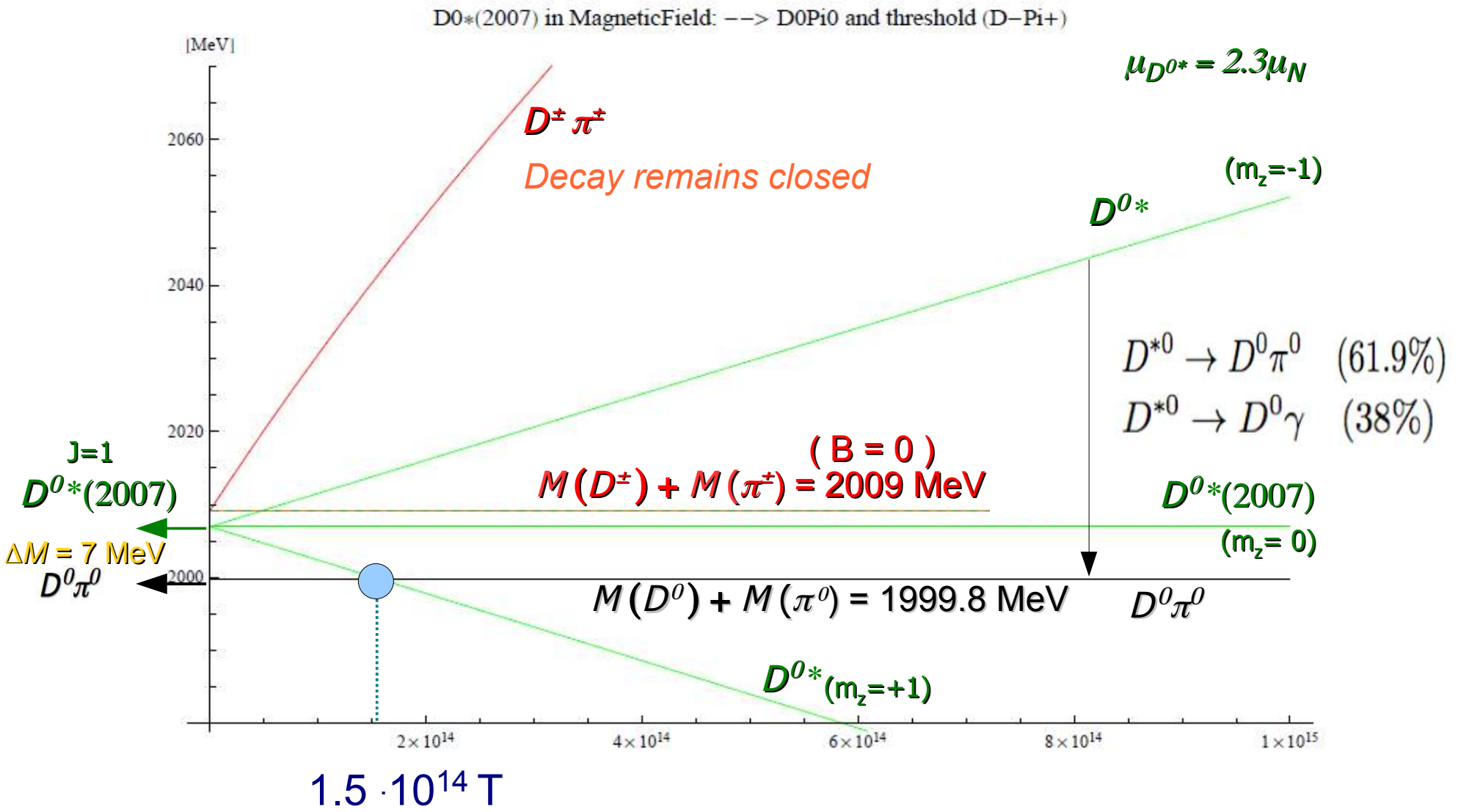
if B field remains present during decay time

$D^{\pm *}(2010)$ in field B=10^{14}T



$D^{\pm *} \to D^0\pi^\pm$ **closed** at B>3.10^{13}T, ($D^{\pm *} \to D^\pm\pi^0 \approx$ polarized)

$D^{0*}(2007)$ in field B → 10^{15}T



$1.5 \cdot 10^{14}$ T

30% of $D^{0*} \to D^0 + \pi^0$ decays become closed in B ≈ 10^{14} T

CONCLUSIONS.

1) if $B \approx 10^{14}$ T in R-HIC stays for a "long time" (kept by mixed phase) ($\tau > 5$fm/c)

→ anomalous yields / polarization / of $K^{\pm *}$, $\Sigma^{\pm *}$

→ difference in $\bar{K}^{0*}(s\bar{d})$ vs $K^{-*}(s\bar{u})$ yields

2) Modification of ρ^0, $\varphi(1s)$, $\Upsilon(4s)$ *decay* (BR) *in* B:

$\pi^+\pi^-$, K^+K^-, B^+B^- *suppressed*, e^+e^- *modified*, $\mu^+\mu^-$ *unchanged ?*

3) Lifetimes D^{0*}, $D^{\pm *}$ too long (≈2000fm/c)

THANK YOU

For ATTENTION

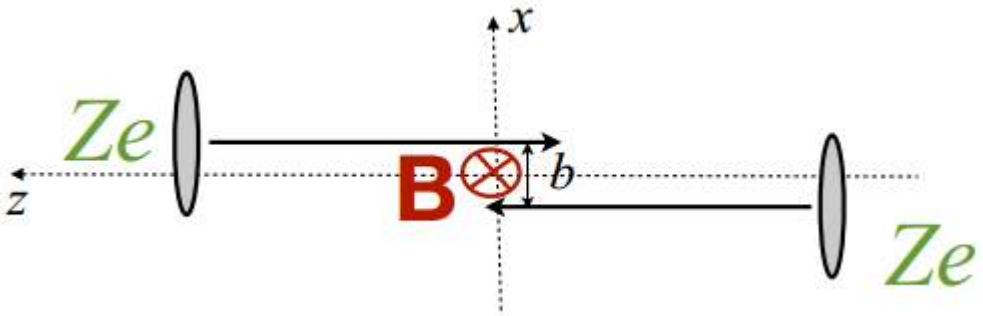
Magnetic Field in Heavy Ion Collisions

LHC: $B = 4.10^{15}T$

RHIC: $B = 3.10^{14}T$

Present for a very short time

PHYSICAL REVIEW C **85**, 044907 (2012)



PHYSICAL REVIEW C **83**, 054911 (2011)

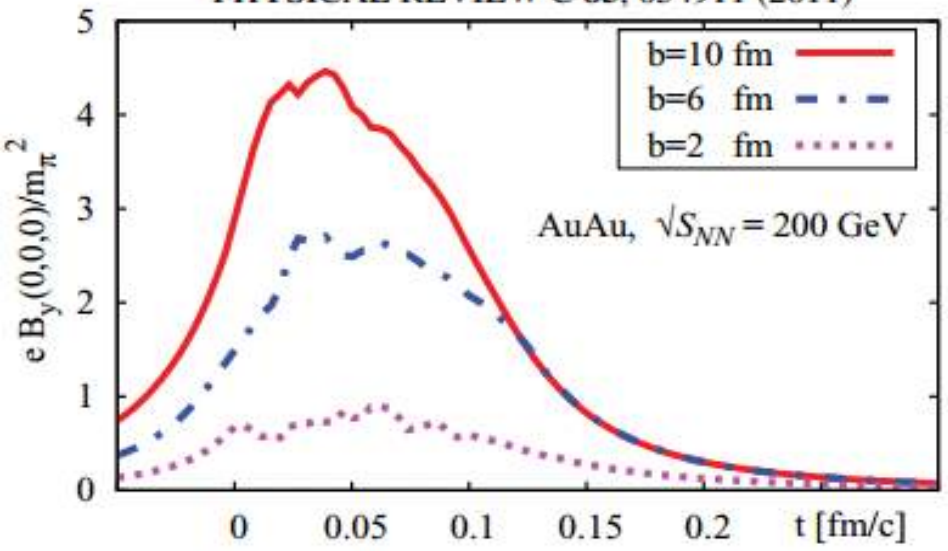
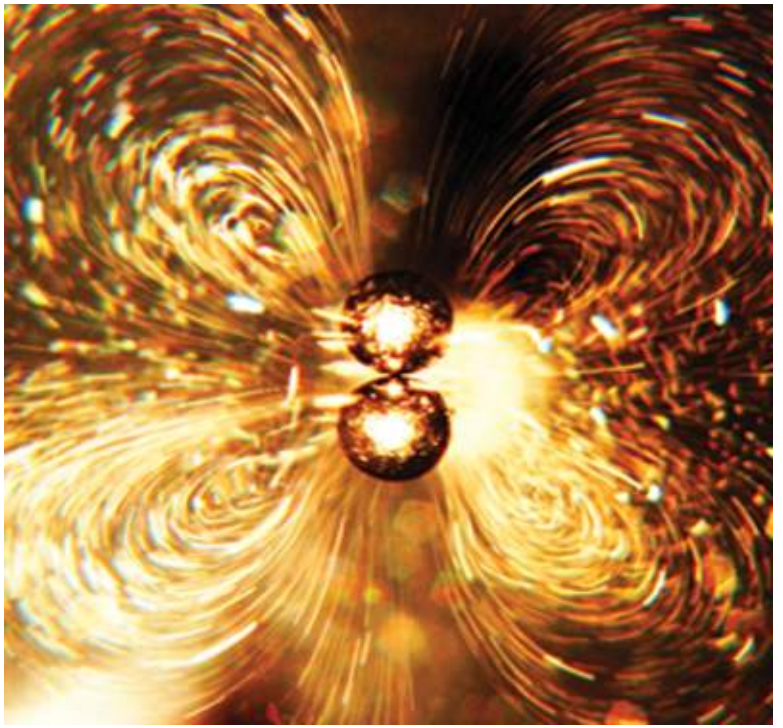


FIG. 13. Impact parameter dependence of the magnetic field Au + Au collisions $\sqrt{s_{NN}}$ = 200 GeV.



PHYSICAL REVIEW C **82**, 034904 (2010)

Kirill Tuchin

Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011, USA and

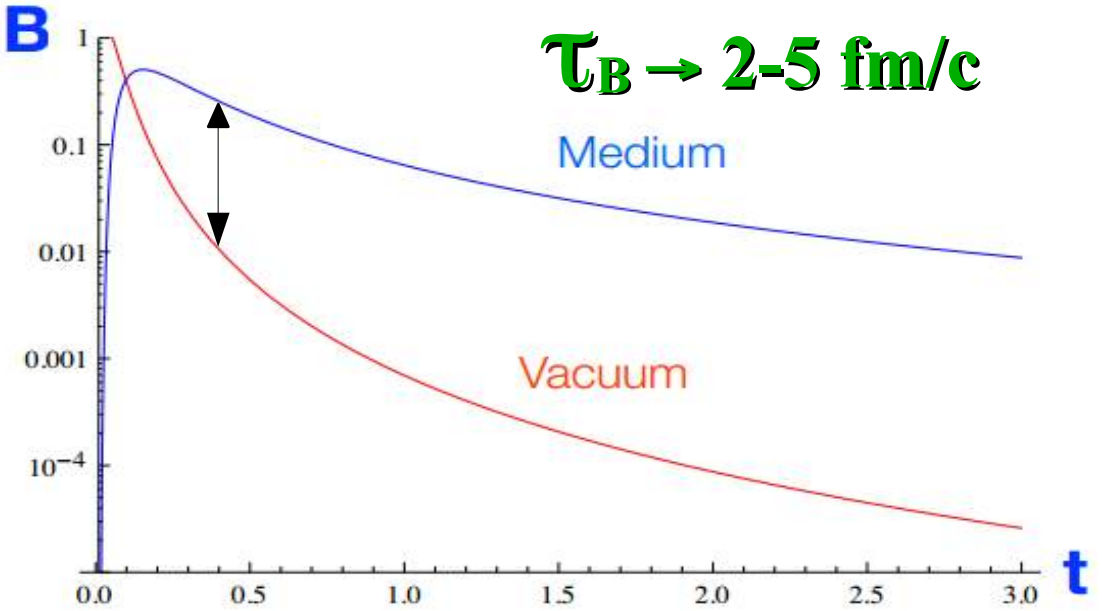
We study the synchrotron radiation of gluons by fast quarks in strong magnetic field produced by colliding relativistic heavy ions. We argue that due to high electric conductivity of plasma, the magnetic field is almost constant during the entire plasma lifetime. We calculate the energy loss due to synchrotron radiation of gluons by fast quarks. We find that the typical energy loss per unit length for a light quark at the Large Hadron Collider

Partonic gas ⇒ **"elmag"** Plasma ⇒ frozen B field

B field lifetime τ_B

can be enhanced

by factor 10x



$\tau_B \rightarrow$ 2-5 fm/c

PHYSICAL REVIEW C **85**, 044907 (2012)

Wei-Tian Deng[1,*] and Xu-Guang Huang[1]

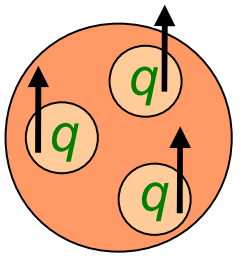
Event-by-event generation of electromagnetic fields in heavy-ion collisions

Magnetic moments for ***parallel spins***:

Observe: spin **3/2** baryons (L=0)

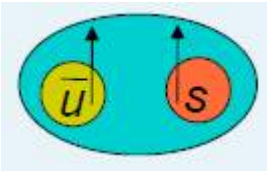
			μ_{exp}	δ_μ	μ
Ω^-	1672	sss	-2.02	9 %	-1.84
Δ^{++}	1232	uuu	6.14	(9%)	5.56
Δ^+	1232	uud	2.7	(1%)	2.73

$\mu^* = \sum \mu_q$



$\mu^* = \sum \mu_q$

Vector mesons: spin 1 (L=0)



K^{*-}

charged open-flavor $\mu^* = \sum \mu_q$

	ρ^-	K^{*+}	D^{*-}	D_s^{*-}	B^{*-}
m [MeV]	770	892	2010	2112	5325
$q\bar{q}$	$d\bar{u}$	$u\bar{s}$	$d\bar{c}$	$s\bar{c}$	$b\bar{u}$
μ [μ_N]	-2.82	2.46	-1.37	-1.02	-1.92

Agrees with L-QCD: Lee et al. PoS (LATTICE 2007) 151.

$\mu_q = \frac{\hbar Q}{2m^*}$

m^*_b=4730

m^*_c=1510

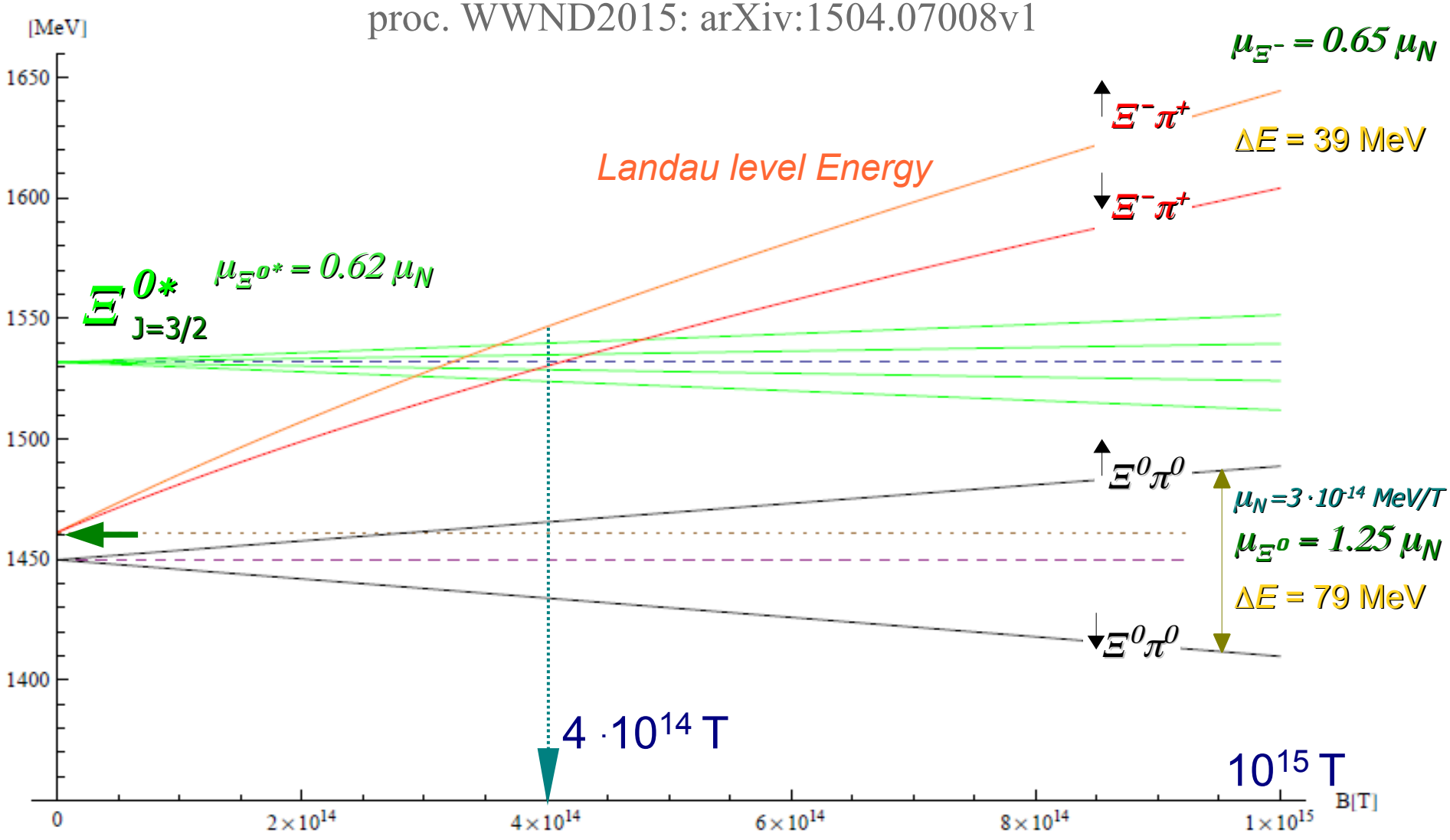
quark	Q	μ_q [μ_N]
u	2/3	1.852
d	-1/3	-0.972
s	-1/3	-0.613
c	2/3	0.404
b	-1/3	-0.066

-> $\mu_c = -2\mu_s / 3$

-> $\mu_b = \mu_s / 9$

Ξ^{0*} baryon in field B → 10^{15}T

proc. WWND2015: arXiv:1504.07008v1



$\Xi^{*0} \to \Xi^- \pi^+ \ (66\%)$ → 0 % 99% ← $\Xi^{*0} \to \Xi^0 \pi^0$