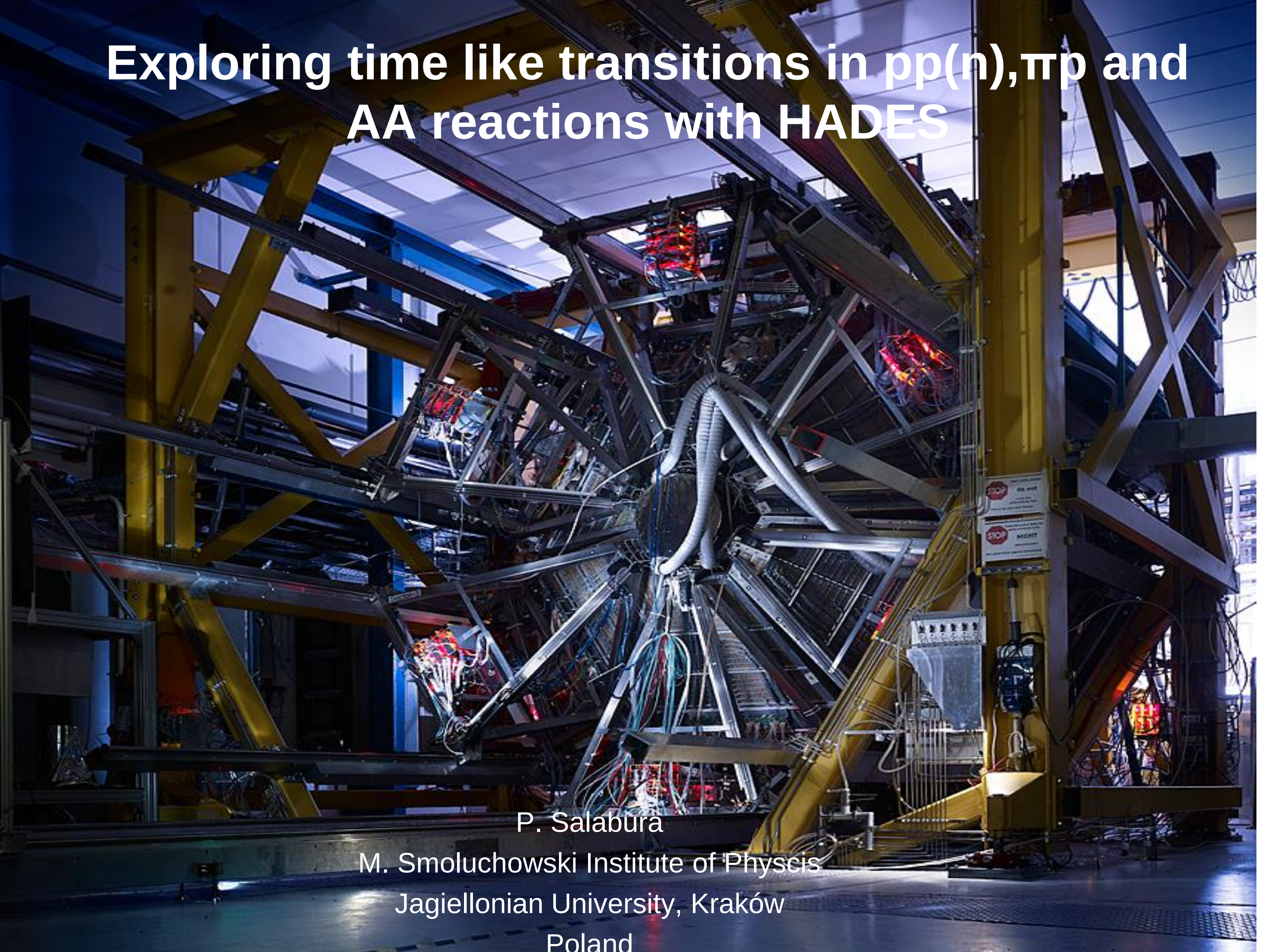
Exploring time like transitions in pp(n),πp and AA reactions with HADES



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Poland

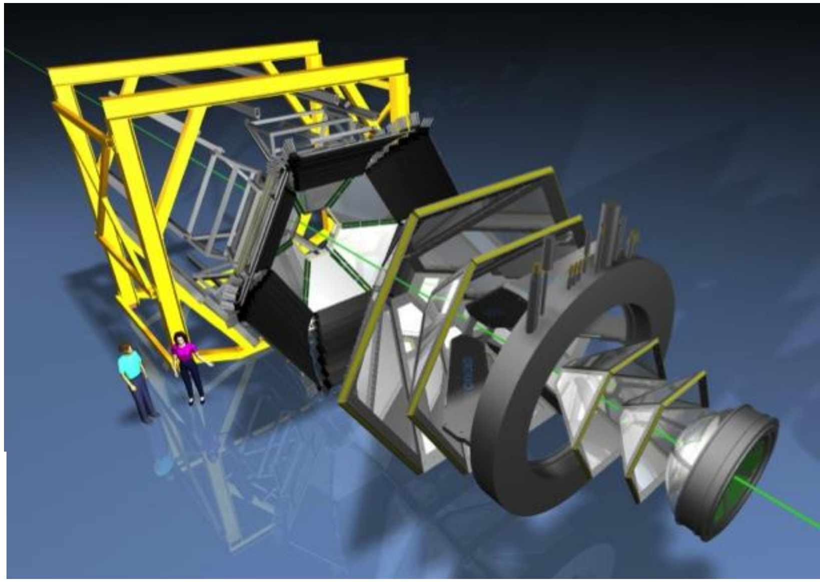
Content

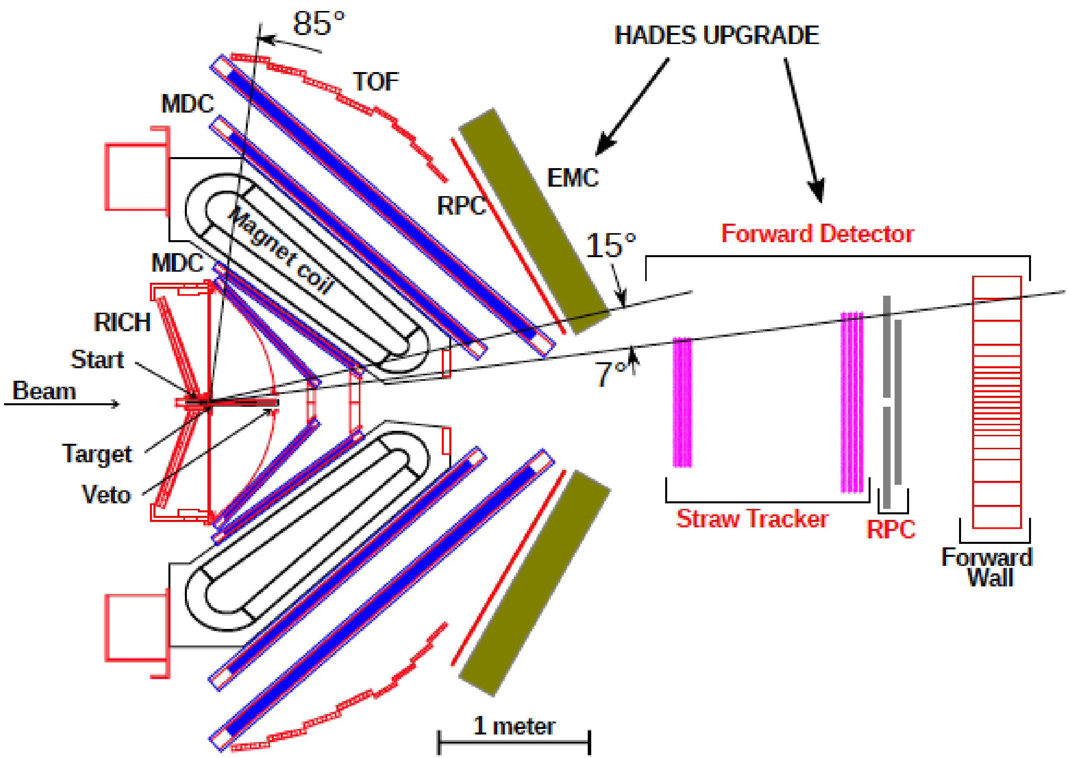
- ✓ Emissivity of QCD matter
- ✓ Low mass dileptons and from HIC , ρ in-medium spectral function (SF) → relations to chiral symmetry restoration
- ✓ Connections to time-like baryon em. transitions
- ✓ Measurements of baryon electromagnetic transitions in NN and πN reactions
- ✓ Summary & Outlook

High Acceptance Di-Electron Spectrometer

- ✓ Spectrometer with ΔM/M - 2% at ρ/ω @ GSI/FAIR
- ✓ electrons : RICH (hadron blind)
- ✓ hadrons: TOF & dE/dx vs p
- ✓ 2004-2014: HI (C+C, Ar+KCl, Au+Au √s~2.4-2.6 GeV)

p+p, d+p, p+N √s =2.4-3.0 GeV π+p √s= 1.5 GeV

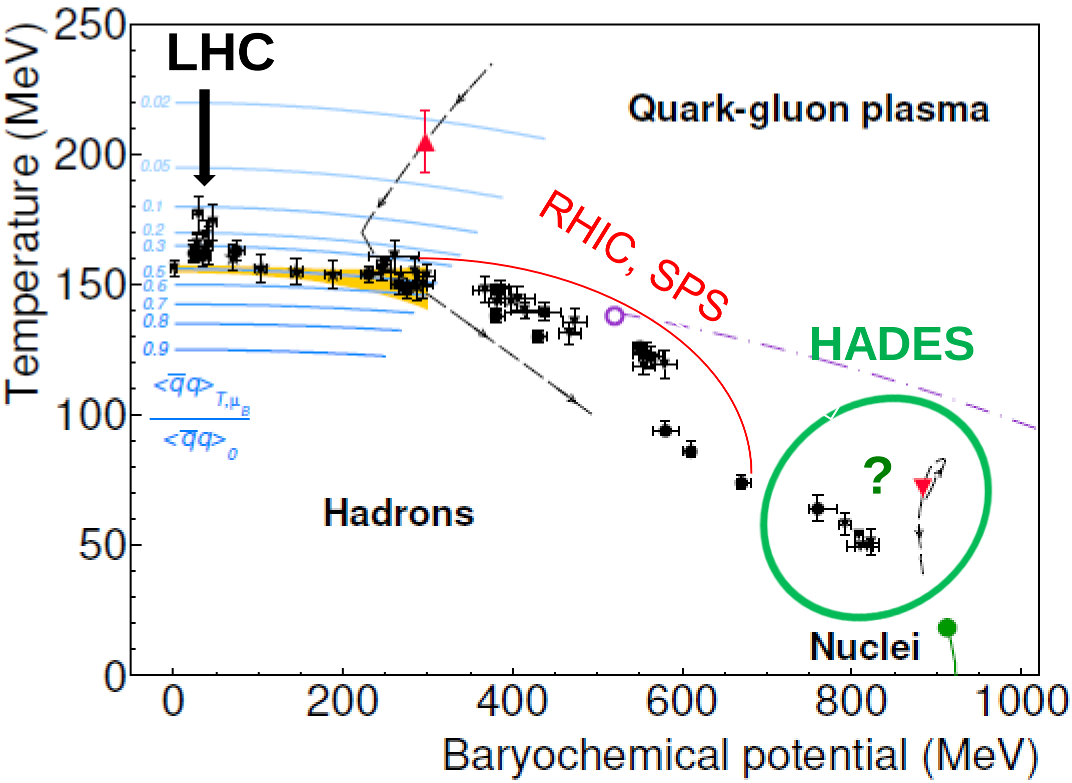




Upgrade 2018/2019

- New RICH photon det (HADES/CBM) – 2-3 ⊗ e_{eff}
- Forward tracking straws +RPC – Λ/Ξrec. in pp/pA (HADES/PANDA)
- el. Calorimiter (lead glass)- neutrals
- Planned: 200 kHz DAQ , 10⊗ count rate increase

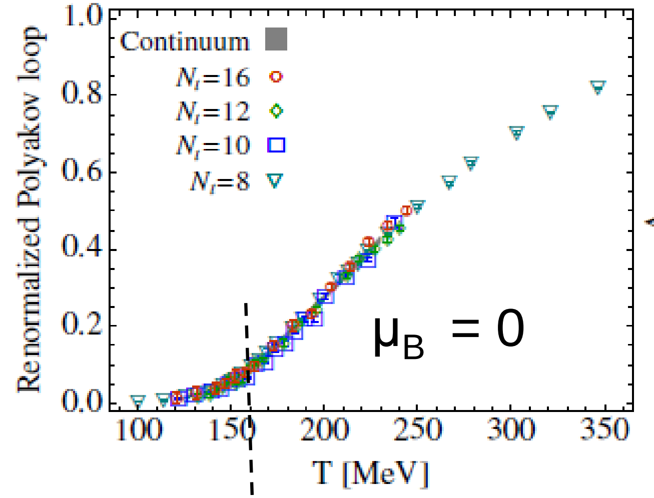
Various faces of QCD: phase diagram



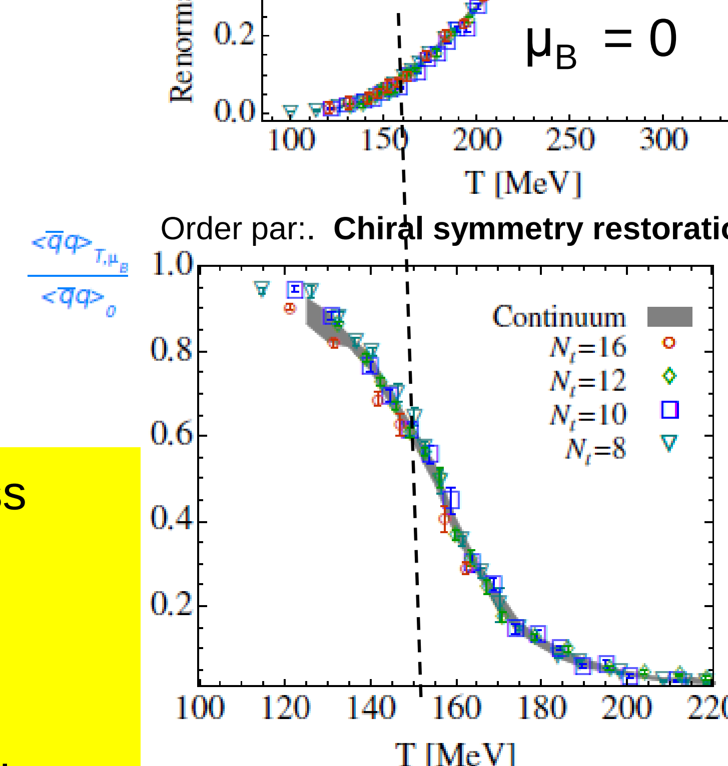
Lattice QCD

S. Borsnyi JHEP'2010

Order par:. **deconfinement**



Order par:. **Chiral symmetry restoration**



Substantial depletion od quark condensate close to T_c

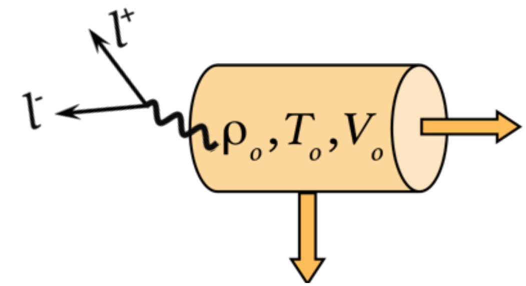
- ❑ Primary goal: (first!) measurement of Low Mass dileptons (e+e-) at high μ_B
- ❑ Complementary to studies with URHIC (LHC, RHIC, SPS) :

LM –→in-medium Vector Meson (ρ) spectral function

Emissivity of QCD matter with dileptons

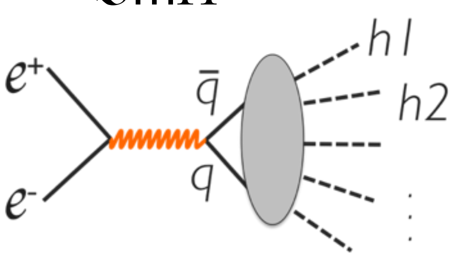
$$\frac{dN_{ll}}{d^4q\,d^4x} = -\frac{\alpha_{em}^2}{\pi^3}\frac{L(M^2)}{M^2} f^{BE}(q_0,T)\,\mathrm{Im}\Pi_{em}(M,q,T,\mu_B)$$

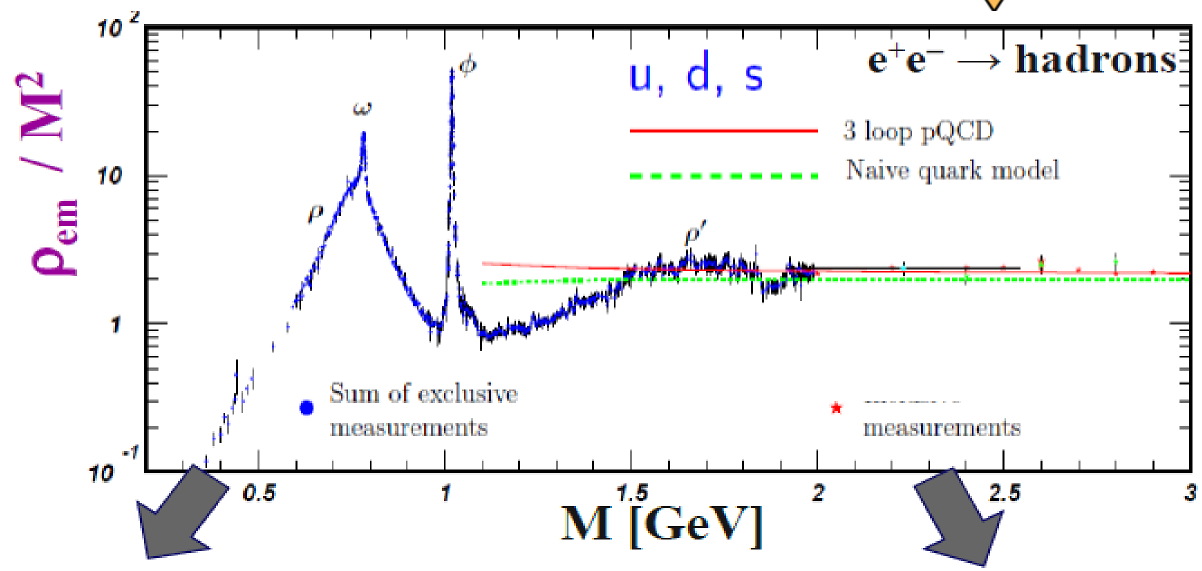
McLerran - Toimela formula, Phys. Rev. D 31 (1985) 545



In Vaccuum

$\Im m\Pi^{em}$





Low mass VectorMesons

• $q\bar{q}$ Continuum

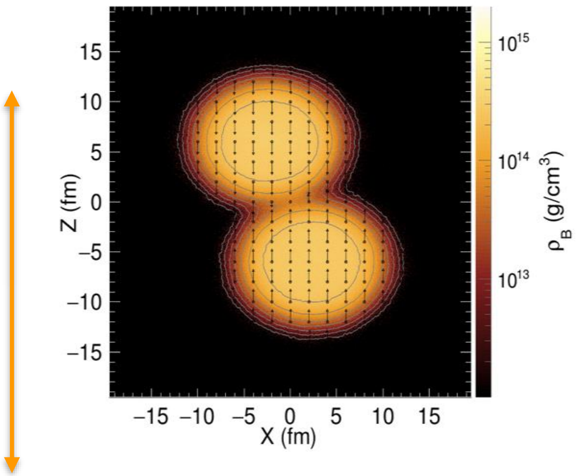
- ❑ Not disturbed by finite state interactions !
- ❑ Thermal distribution $f^{BE}(T)$ – *thermometer*

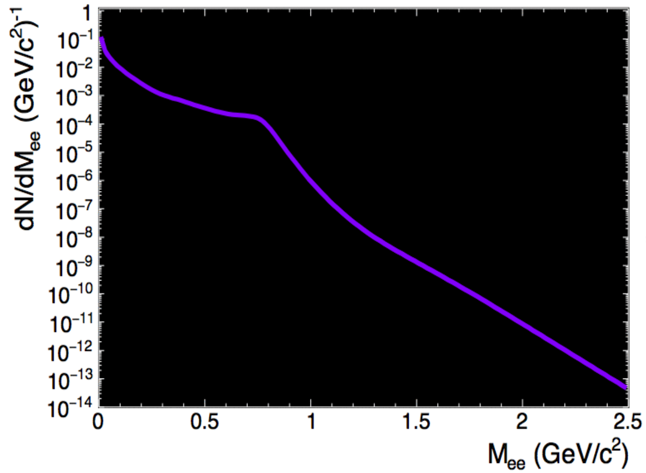
  $q^2 > 1.2$ GeV qq radiation pQCD ($\Im m\Pi_{em}$ flat) → T

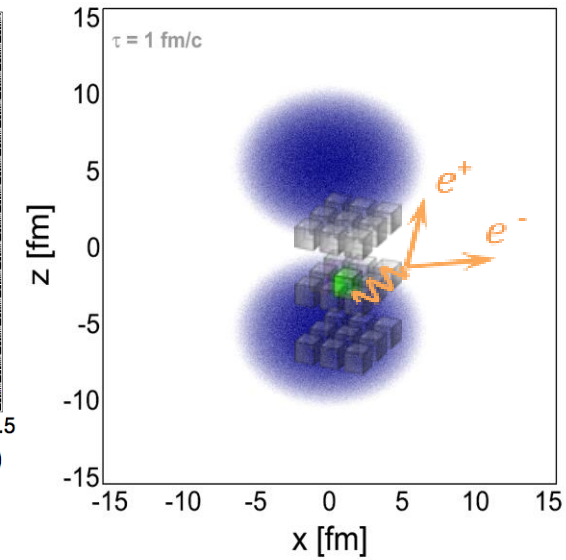
- ❑ $\Im m\, \Pi_{em}$: *$q^2 < 1$ GeV - in- medium VM (**ρ**) spectral functions*

Dielepton emission in HIC

HI collisions: total emission rate needs integration over full collision time (T,μ_B)







Compilation F. Seck and T. Galatyuk

„coarsed grained approach"

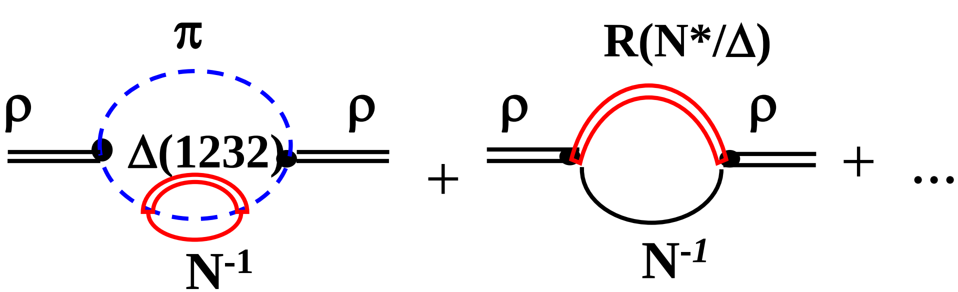
Huovinen et al., PRC 66 (2002) 014903
CG FRA Endres et al.: PRC 92 (2015) 014911
CG GSI-Texas A&M TG et al.: Eur.Phys.J.A52 (2016) no.5, 131

- ✓ energy (ε) and baryon densities (ρ_b) obtained in small cells ($\Delta x, \Delta t$ ~0.8fm,0.2 fm/c) in local rest frames with vanishing net baryon current
- ✓ EOS (hadron gas, QGP-lattice) used to relate ε with (T, ρ_B)
- ✓ Apply emissivity formula with in medium $\Im m \Pi_{em}$

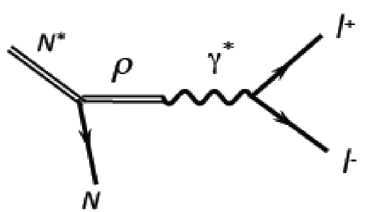
In medium ρ spectral function

$$A_\rho(M) = -\frac{2\,Im\Sigma_\rho(M)}{[M^2 - m_\rho^2 - \mathrm{Re}\Sigma_\rho(M)]^2 + [Im\Sigma_\rho(M)]^2}$$

In Medium:

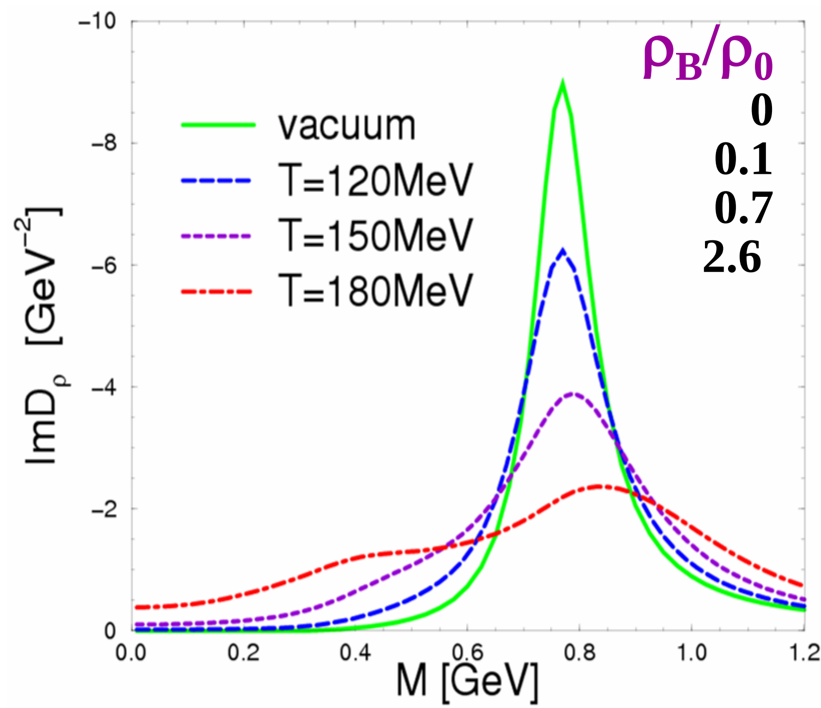


dominant role of ρ-R couplings –
Vector Meson Dominance
Strongly relies on input from elementary



R→**Ne+e- (Dalitz decays)**

Rapp, Wambach, Adv. Nucl. Phys. A25 (2000)1



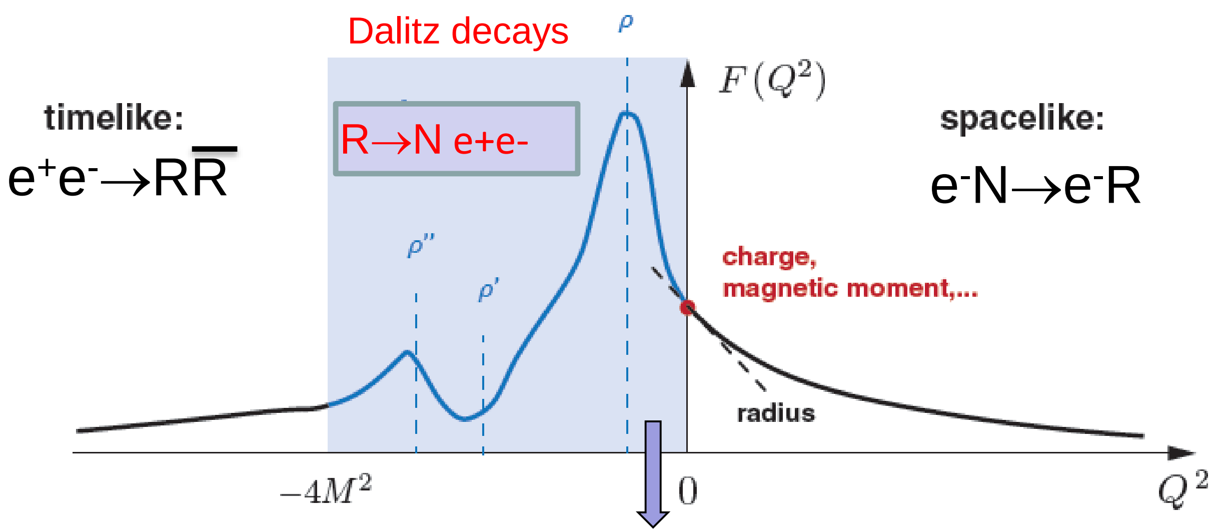
- connection to ChSR →
$\rho(760)/a_1(1260)$ become degenerate at $T \sim T_c$, $\mu_b = 0$

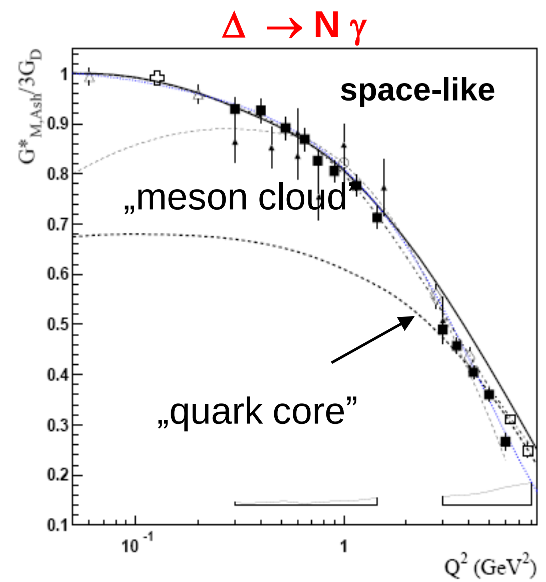
Weinberg QCD sum rules

$$\int ds\,(\rho_V - \rho_A) = -m_q \langle \bar{q} q \rangle$$

Hohler and Rapp Phys.Lett. B731 (2014)

Baryon electromagnetic transitions





I. G. Aznauryan and V. D. Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012)

- Dalitz decays : transition Form Factors (timelike)

(complementary to space-like region)

$$\frac{d\Gamma(\Delta \to N e^+ e^-)}{dq^2} = f\left(m_\Delta, q^2\right)\left(\left|G_M^2\left(q^2\right)\right| + 3\left|G_E^2\left(q^2\right)\right| + \frac{q^2}{2m_\Delta^2}\left|G_C^2\left(q^2\right)\right|\right)$$

Main players in HADES: Δ(1232), N*(1520), Δ(1600-1700),..

„QED"

Transitions of point-like particles

Form-Factors - models

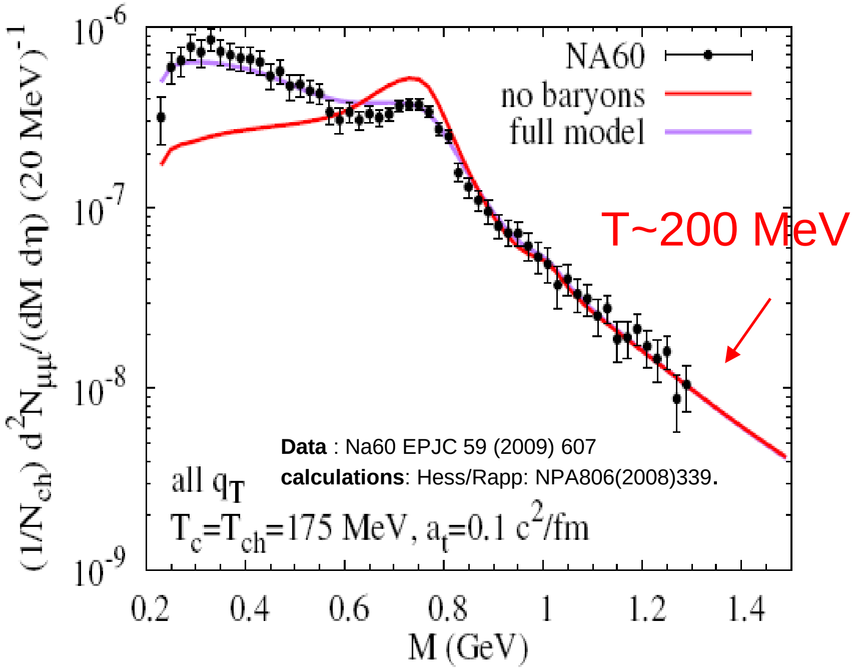
M. I. Krivoruchenko, et. al. An. Phys. 296, 299 (2002)
Q. Wan and F. Iachello, Int. J. Mod. Phys. A 20 (2005) 1846.
G. Ramalho and M.T. Peña, PRD 80 (2009) 013008
M. Zetenyi, Gy. Wolf, Heavy Ion Phys. 17, 27 (2003).

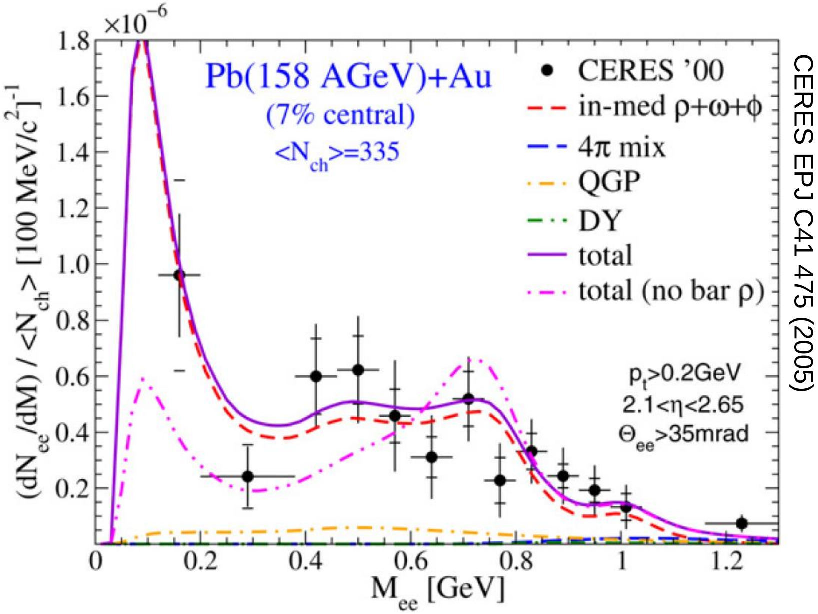
Results from HIC

Dielepton thermal rates from UrHIC SPS/RHIC

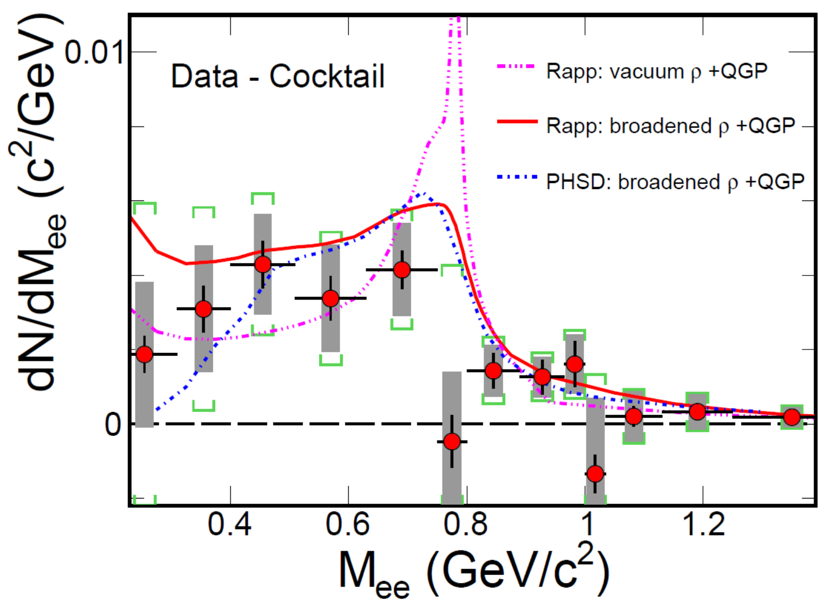
Na60 @ SPS In+In (μ+μ-)

√s=17.3 GeV





STAR √s=200 GeV PRC92 (2015)

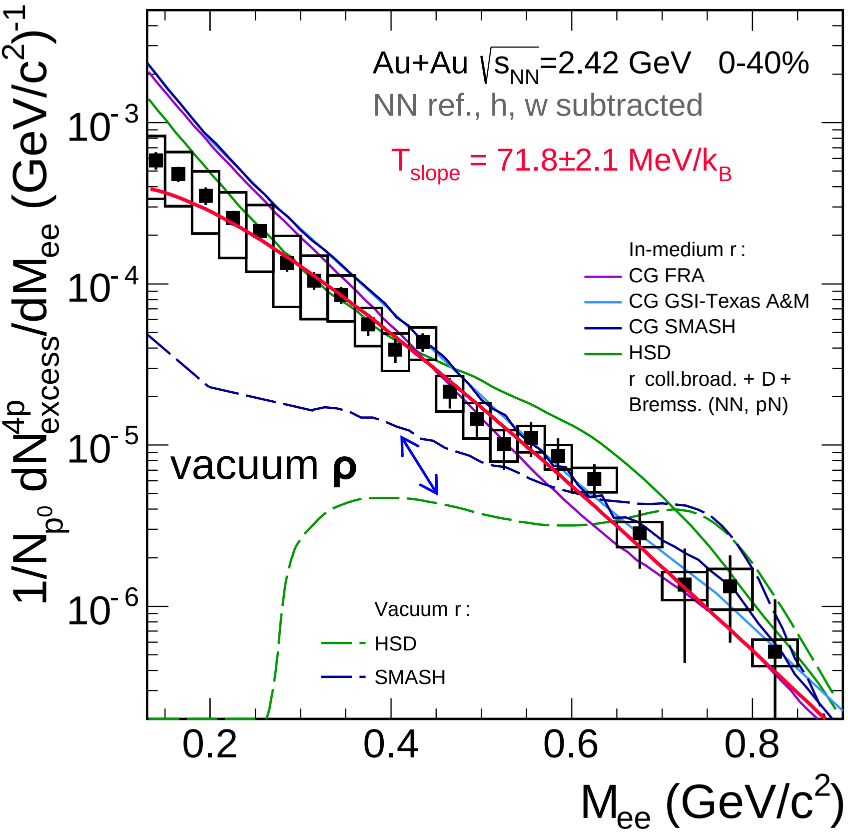


- LMR dominated by thermal radiation from ρ at $T \sim T_c$ (hadronic phase!)
- „Melting" of ρ : **baryon-ρ interactions**
- IMR: T~ 200 MeV - <T> of the early phase (QGP)

HADES Au+Au @ √s = 2.4 GeV

Excess yield fully corrected for acceptance

Accepted for pub. in Nature Phys. 2019



HADES Collab., submitted
CG FRA Endres et al.: PRC 92 (2015) 014911
CG GSI-Texas A&M TG et al.: Eur.Phys.J.A52 (2016) no.5, 131
CG SMASH: J. Staudenmaier et al., arXiv:1711.10297v1
HSD: Phys. Rev. C 87, 064907 (2013)

- Successful description with Coarse-Grained approach + emissivity formula

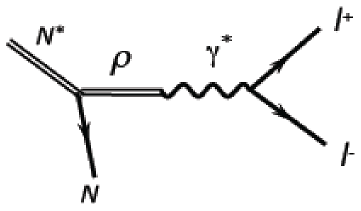
Dileptons as thermometer

- Mass spectrum falls exponentially → "Planck-like"
- Fit $\frac{dN}{dM} \sim M^{\frac{3}{2}} \times \exp\left(-\frac{M}{T}\right)$ in range M=0.2-0.8 GeV/c²
- $\langle T \rangle_{\text{emitting source}}$ = 72 ± 2 MeV/k_B

- Strong melting of ρ meson
- In agreement with microscopic model of Rapp & Wambach (interactions with baryons !)
- Same model describes also RHIC(STAR), SPS (CERES, Na60 data)

Robust understanding across QCD phase diagram

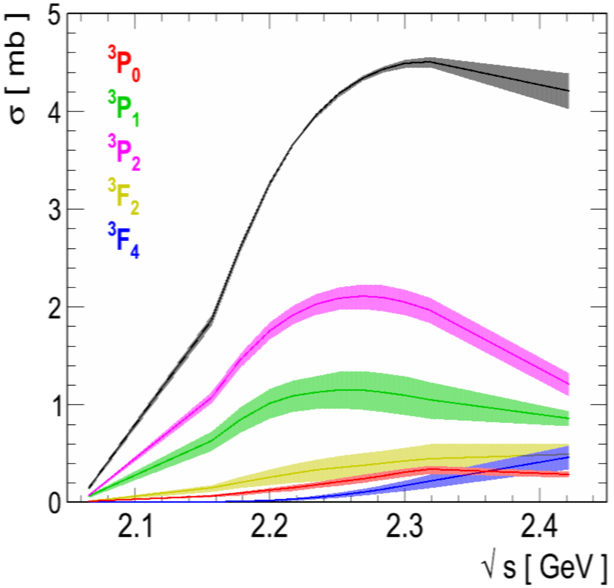
R $\rightarrow N\gamma^*$ transition and $NN \rightarrow NN\ \gamma^*$ bremsstrahlung in NN @ $\sqrt{\mathbf{s}}$**=** 2.42 GeV

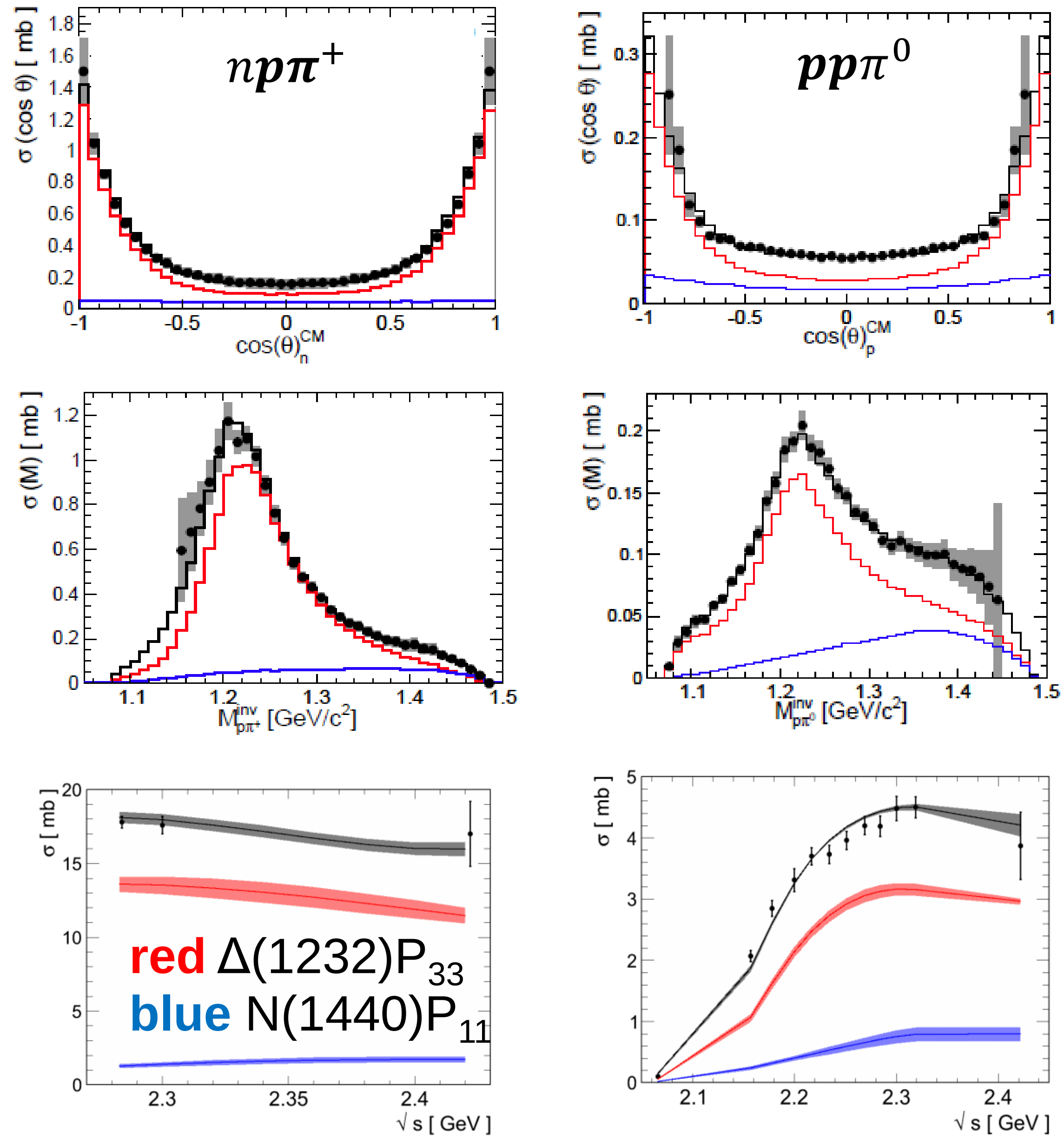


Δ ($p\pi^+$, $p\pi^0$) excitation in pp@ $\sqrt{s}$= 2.42 GeV

13 PNPI + 2 HADES data sets

BnGa PWA solutions





FINAL STATES:

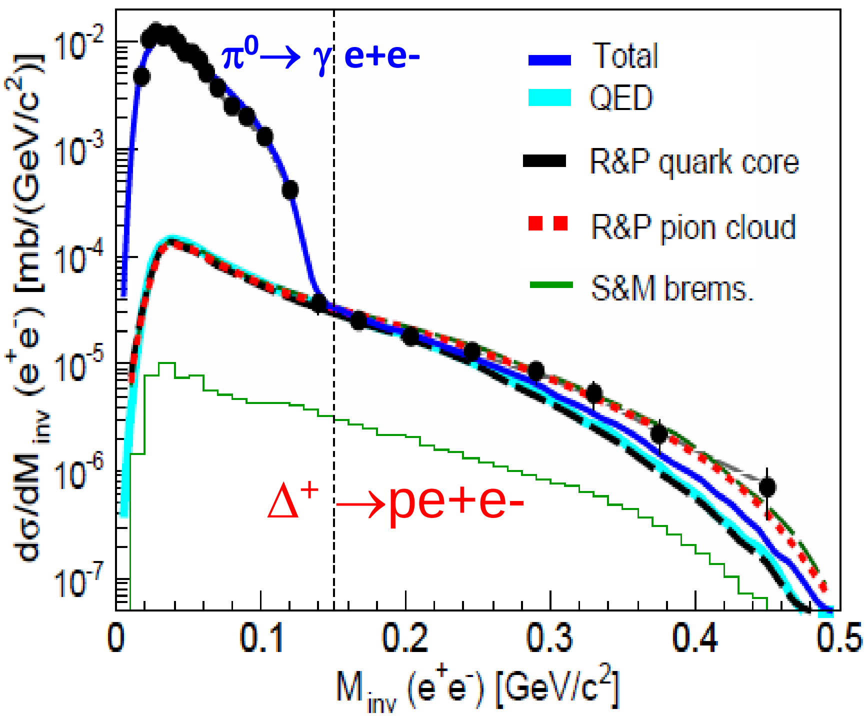
P_{33}(1232) and

P_{11}(1440) in πN state

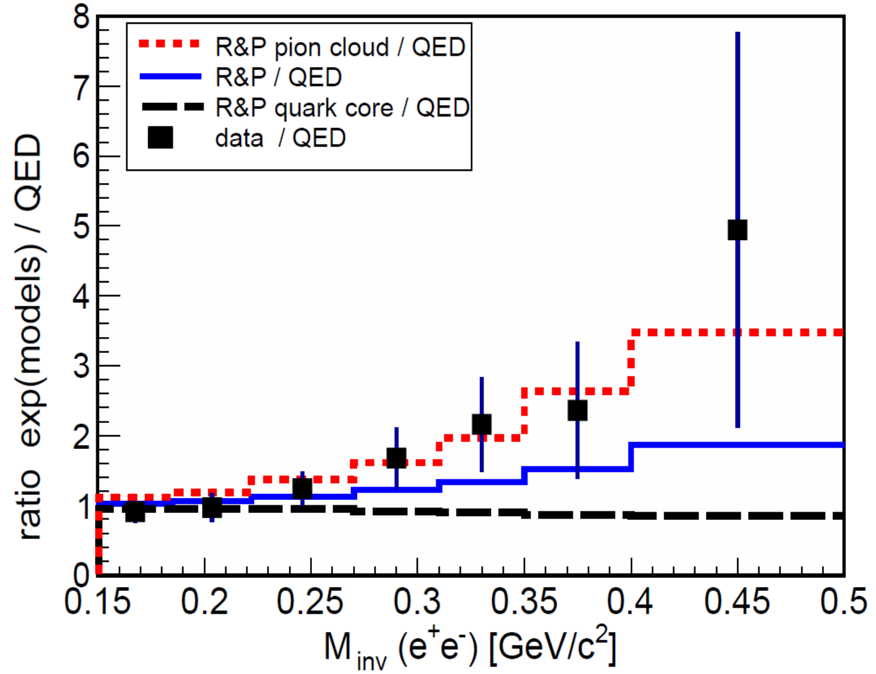
HADES :
Eur. Phys. J. A51 (2015) 137

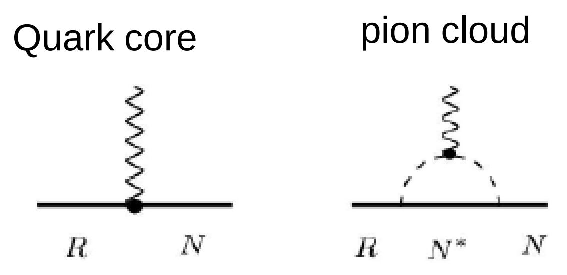
pp → ppe^+e^-

HADES Phys. Rev. C95 (2017) no.6, 065205)



$M_{e+e-} > M_{\pi}$

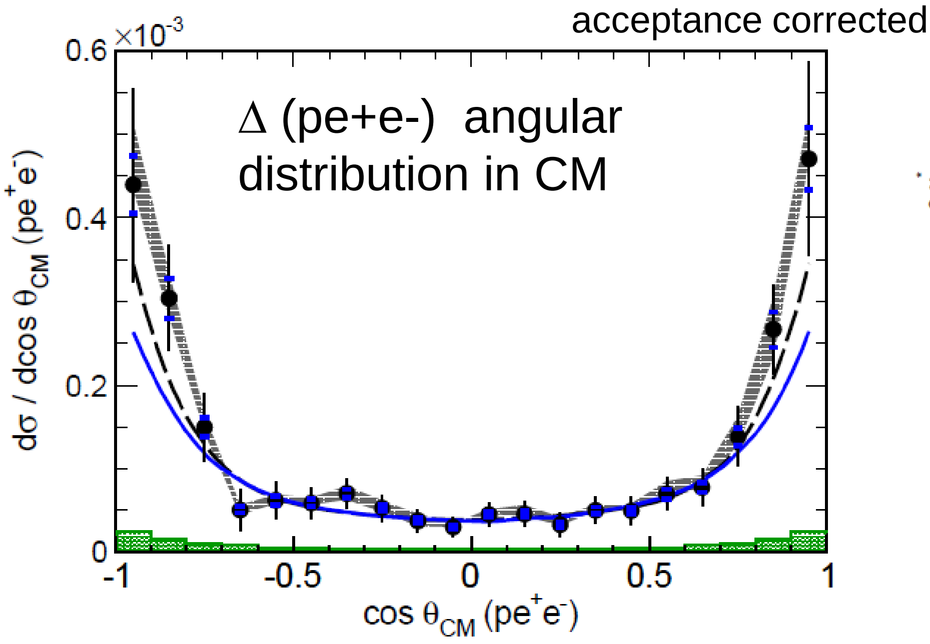


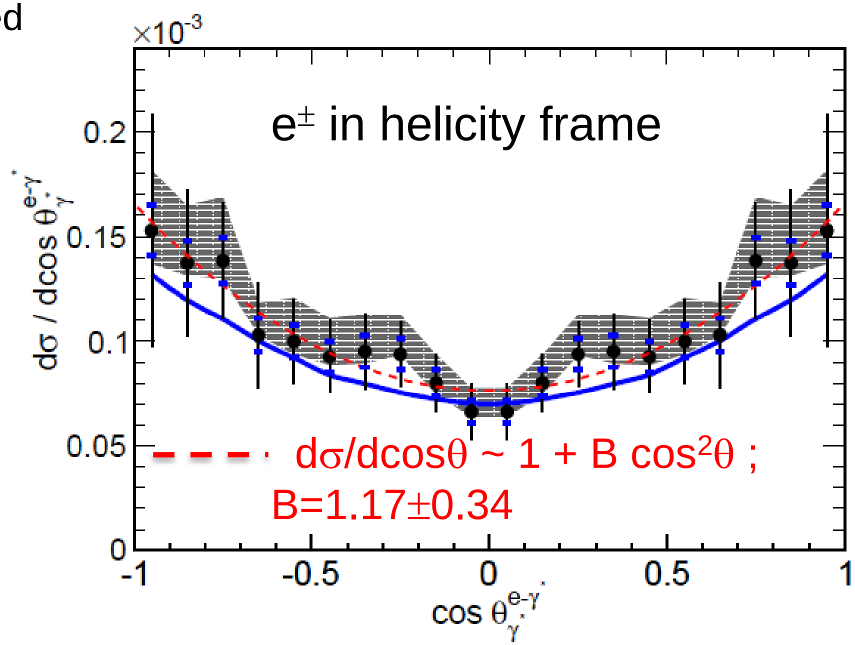


❑**BR (Δ→pe+e-)= 4.19 10^{-5} ± 0.62 (sys) ± 0.32(stat)**
(First measurement PDG entry)

❑ Good agreement with 2 component model of TFF Ramahlo & Pehna (R &P)
->Slight rise v.s Mass due to VM(ρ) - pion cloud effect

Angular distributions for Δ→pe+e- and leptons





PWA solution for pp →ΔN →pN π

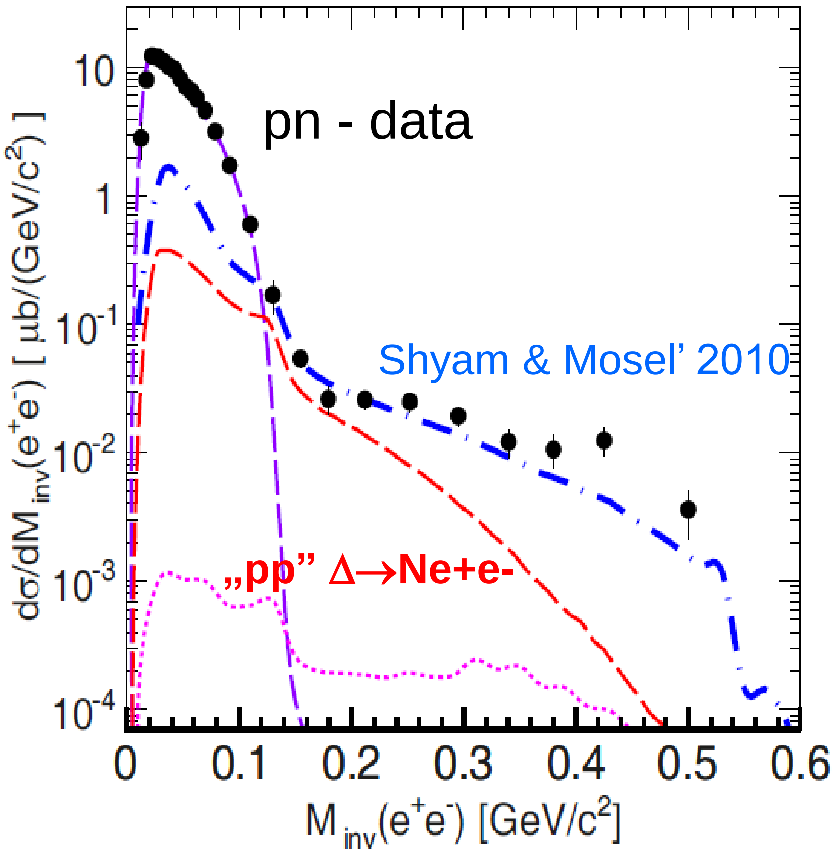
Δ^+ →pe+e- : PWA solution for Δ production and Ramahlo & Pena model for Dalitz decay

Δ^+ →pe+e- : calc. assuming dominance of G_M (transverse polarized γ*)

- ❑ Production and decay characteristics consistent with the expected for Δ^+ →pe+e-

pn→pnγ* →pne+e- (bremmstrahlung)

Many calculations (most recent only!):
R. Shyam/ U. Mosel *PRC 82:062201, 2010*
R. Shyam , U. Mosel *Phys. Rev. C 82:062201, 2010*
L.P. Kaptari, B. K¨ampfer, NPA 764 (2006) 338
Baskanov, Clement Eur. Phys. J. A 50, 107 (2014)
data**: **HADES PLB690 (2010)118 , *EPJA* 7, 149 (2017)



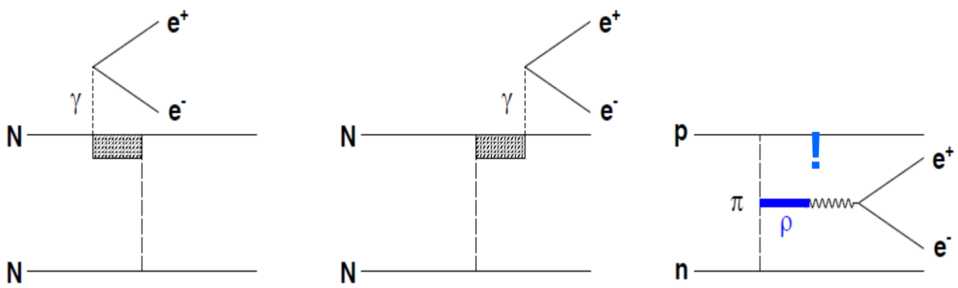
„quasi-elastic p-n bremsstrahlung"

difficult theoretical problem faced since 80'es

- off shell nucleon em. FF (in time-like region)
- nucleon-nucleon potential
- Conservation of gauge invariance in calculations

❑ Strong excess of p-n over p-p (p-p Δ pe+) !

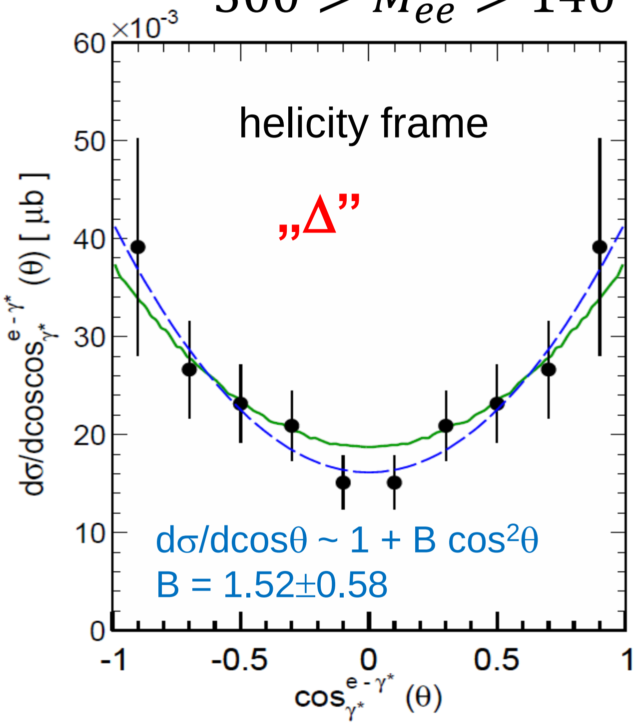
Explanations „ off shell ρ" production:
• emission from π exchange line Shyam & Mosel



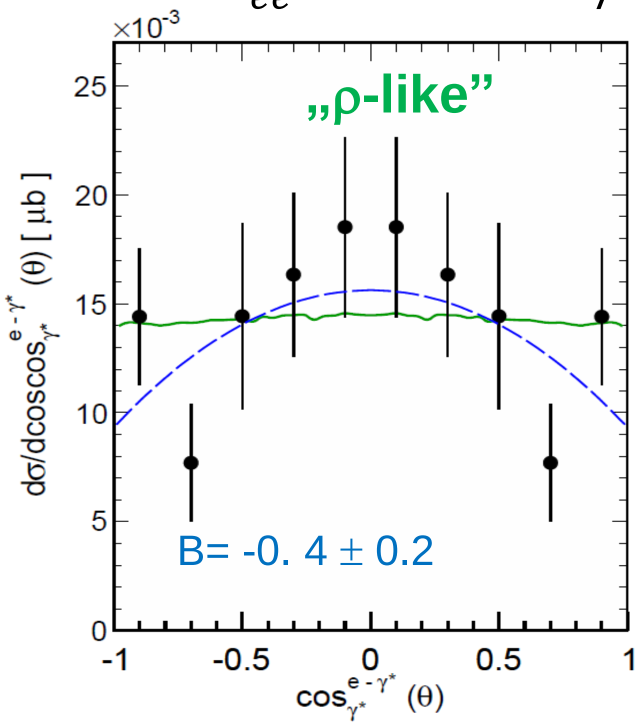
• **„ΔΔ"→pnρ →pne+e-** Bashkanov, Clement

electron distributions in γ* rest (helicity) frame

$300 > M_{ee} > 140$

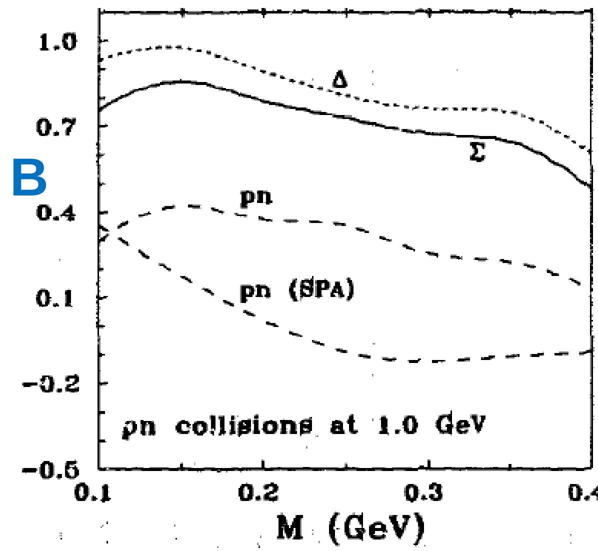


$M_{ee} > 300 \quad MeV/c^2$



OBE calculations

E. L. Bratkovskaya, at. al
Phys. Lett. B 348, 325 (1995).



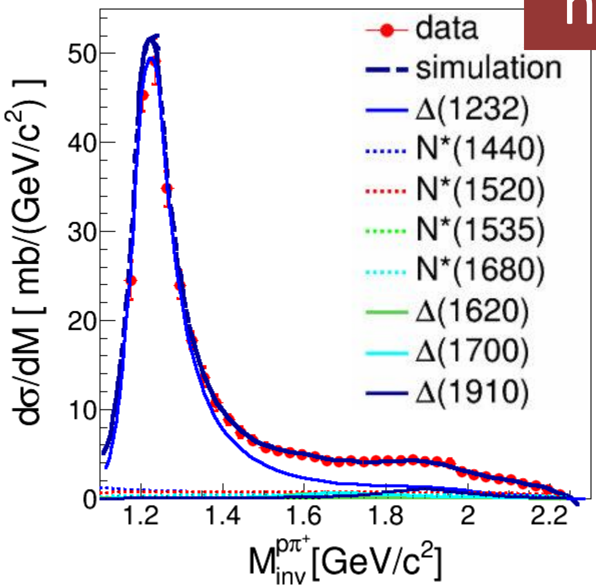
- ❑ as expected for Δ→pe+e-
- ❑ change of angular distribution

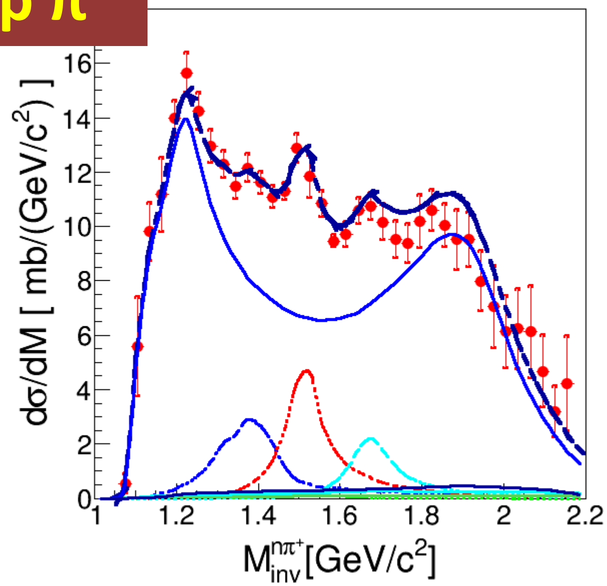
Expected for „p-n bremsstrahlung” (OBE models) with contribution from emission from charge pion exchange

Dalitz decays of Higher mass resonances in pp @ $\sqrt{s}$=3.1 GeV

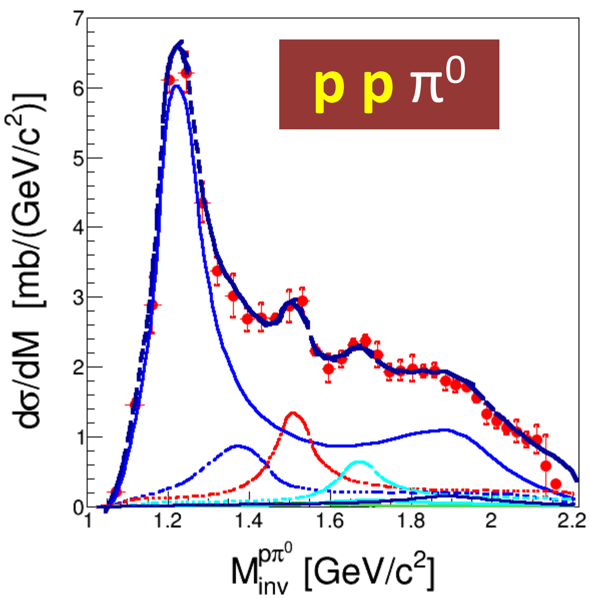
Resonance excition @ √s=3.1

n p π+

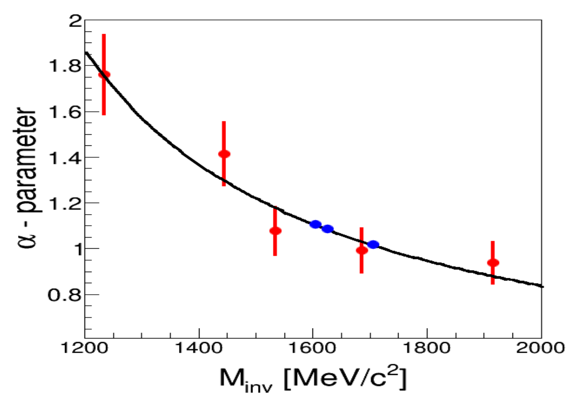




p p π0



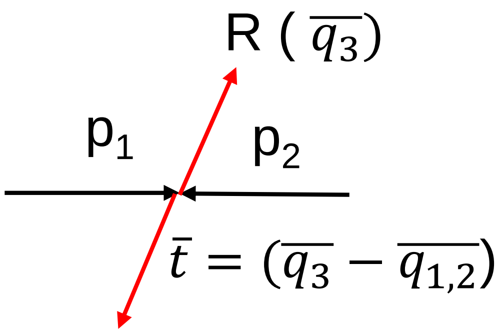
$$\frac{d\sigma}{dt}(M_R) \propto \frac{A}{t^{\alpha(M)}}$$



Resonance model:

Z. Teis et al., Z. Phys. A356 (1997) 421
J. Weil et al. (GiBUU) Eur. Phys. J. A48 (2012) 111
HADES : EPJA 50(2014) 42

Incoherent sum of
(Δ, N*) resonances



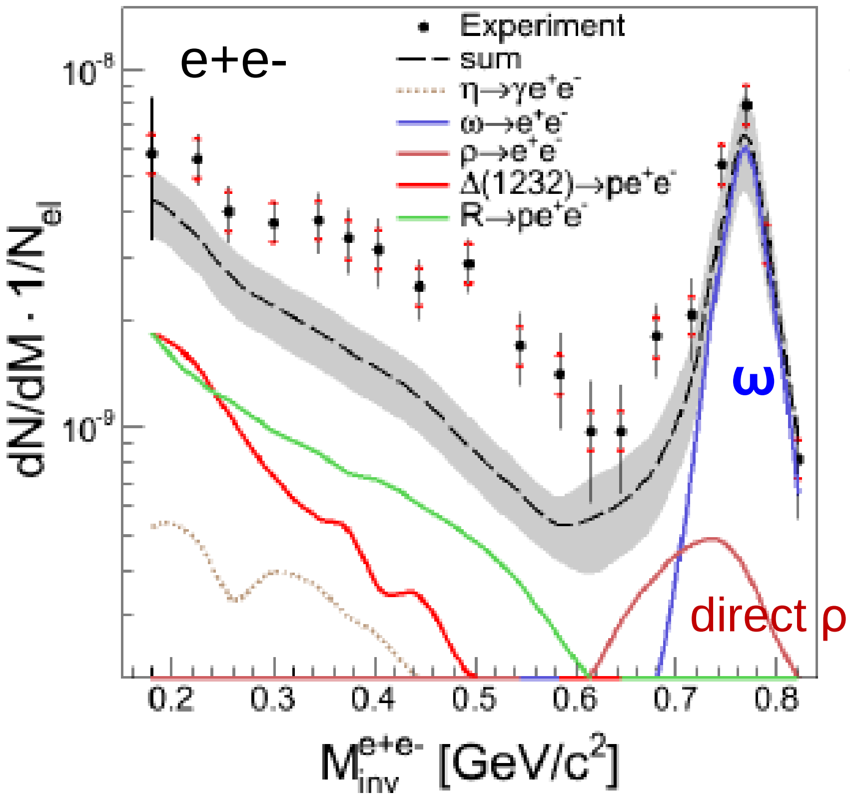
Empirical parametrisation of Resonance production as a function of
$\boldsymbol{t(M_R)}$
t- channel dominance

Recently confirmed also by π+π- channel
A. Belounnas talk

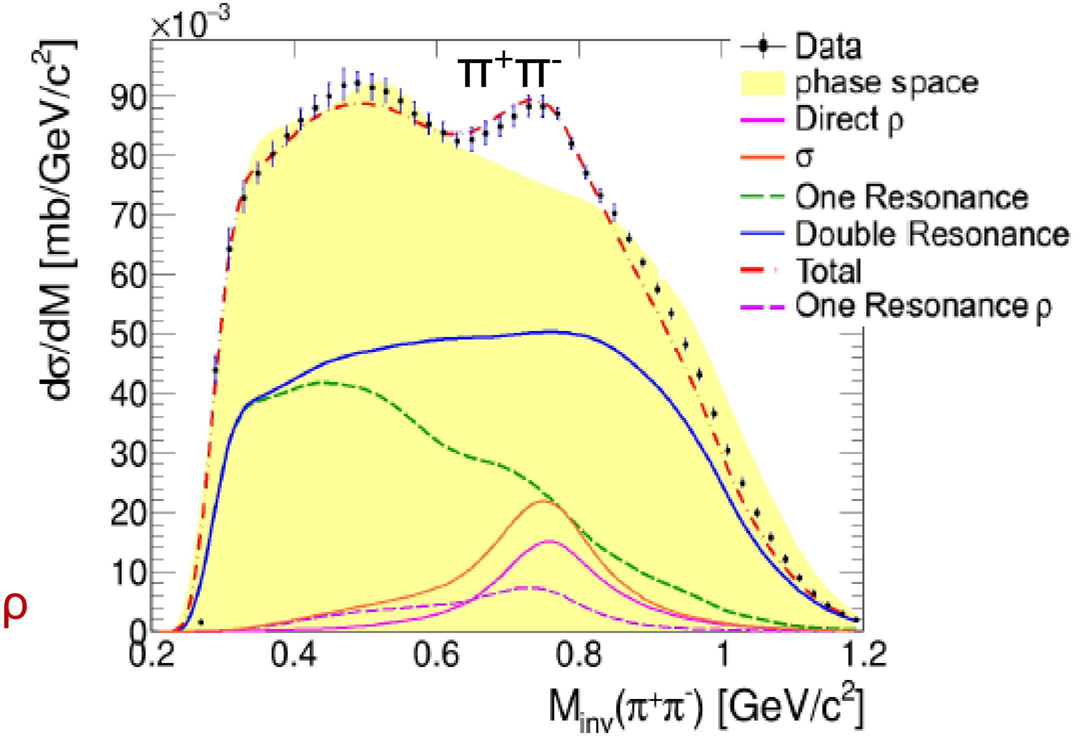
p+p→pp e⁺e⁻ (π⁺ π⁻)@ √s=3.1 GeV

(exclusive channels)

HADES coll. EPJA50(2014) 82



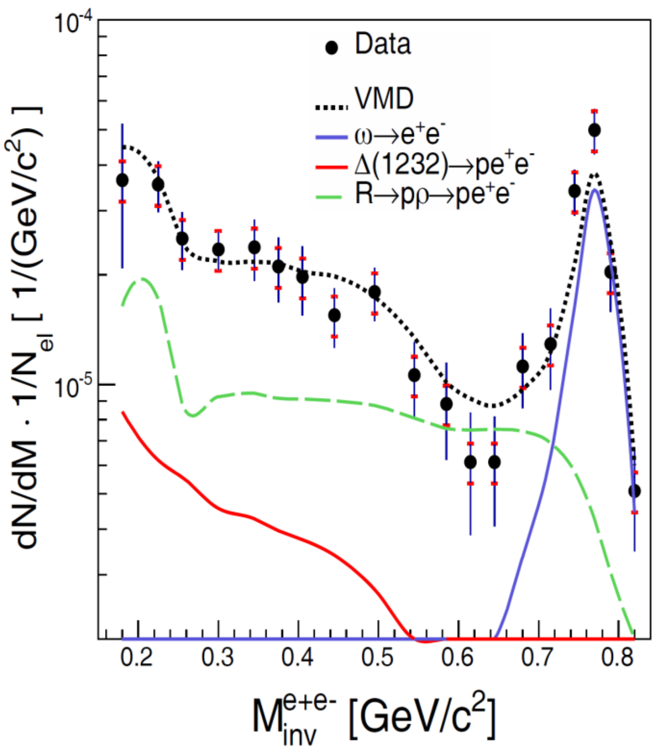
A. Belounnas (preliminary)



- ❑ Excess above QED cocktail due to for subthreshold coupling of R→Nρ→Ne+e- ?

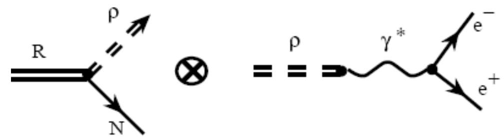
(direct ρ seen in 2 pion channel accounts only for small fraction of the e+e- yield !)

Comparison to models with strict VDM

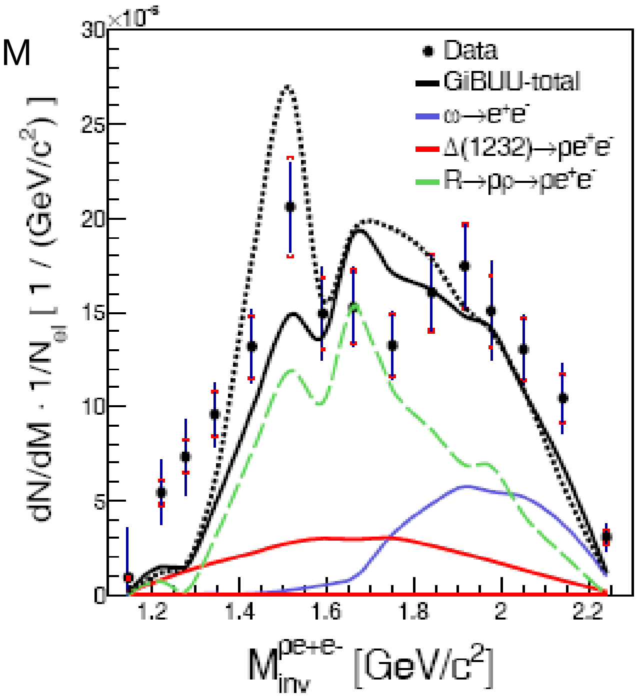


Resonance model + strict VDM

VDM



$$\frac{d\Gamma}{dM} = \frac{M_\rho}{M^3} \mathrm{BR}(M = M_\rho)$$



- Good description by „HADES resonance model" **but with BR for R→ Nρ** from BnGa (upper limits) (reduced as compared tp PDG' 2014)

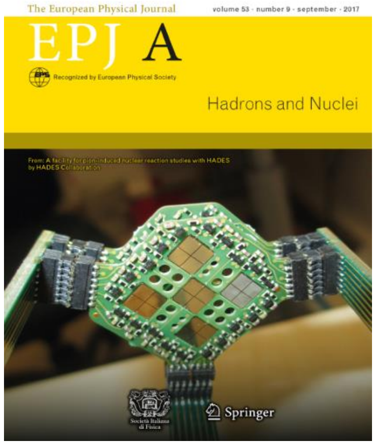
Needs pion beam !

Resonance -> Nρ Branching Ratios

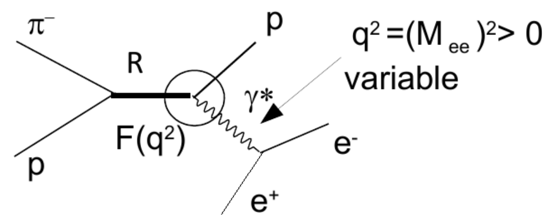
Contr. to e+e-	Resonances	GiBUU	UrQMD	KSU	BG	CLAS
38%	$N(1520)$	21	15	20.9(7)	10(3)	13(4)
15%	$\Delta(1620)$	29	5	26(2)	12(9)	16
22%	$N(1720)$	87	73	1.4(5)	10(13)	–
7%	$\Delta(1905)$	87	80	< 14	42(8)	–

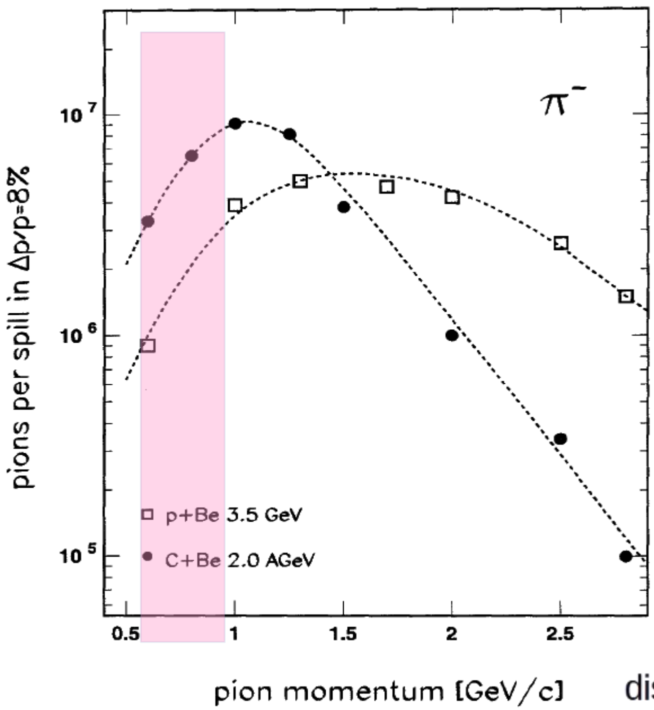
PDG Status 2014 !

Eur. Phys. J. A (2017) 53: 188

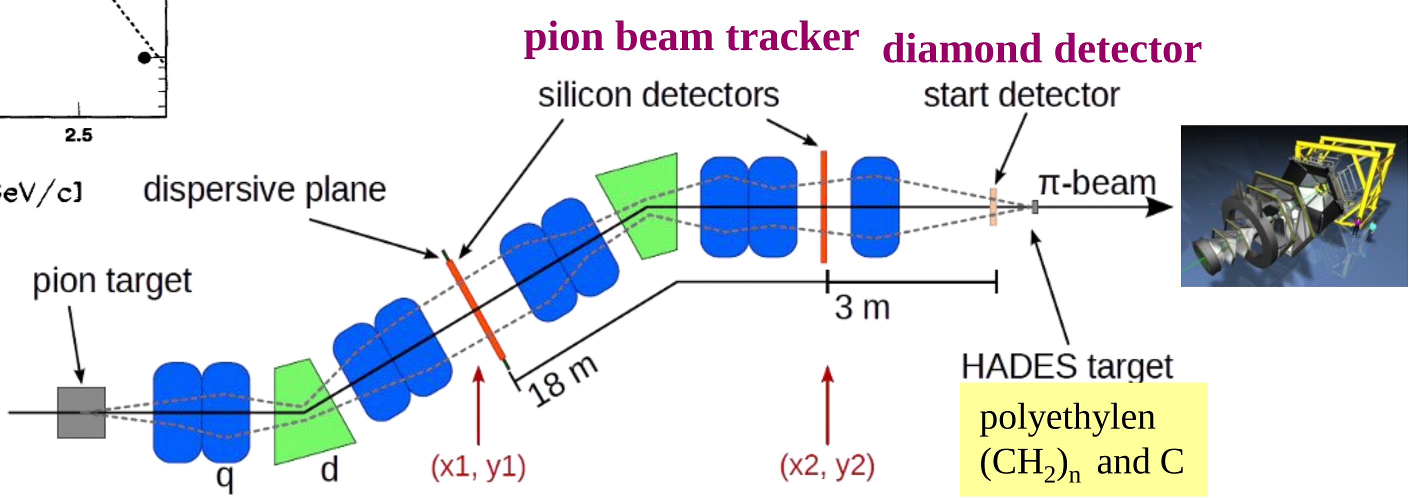


Pion Beam @ GSI





- reaction **N+Be**, 8-10*10^{10} N_2 ions/spill (4s)
- secondary **π^-** with **I ~ 2-3 10^5/s**
- **P = 654, 687, 737, 787 MeV/c ($\sqrt{s}$ ~1.5 GeV)**
- **PE $(CH_2)_n$** and **C** targets



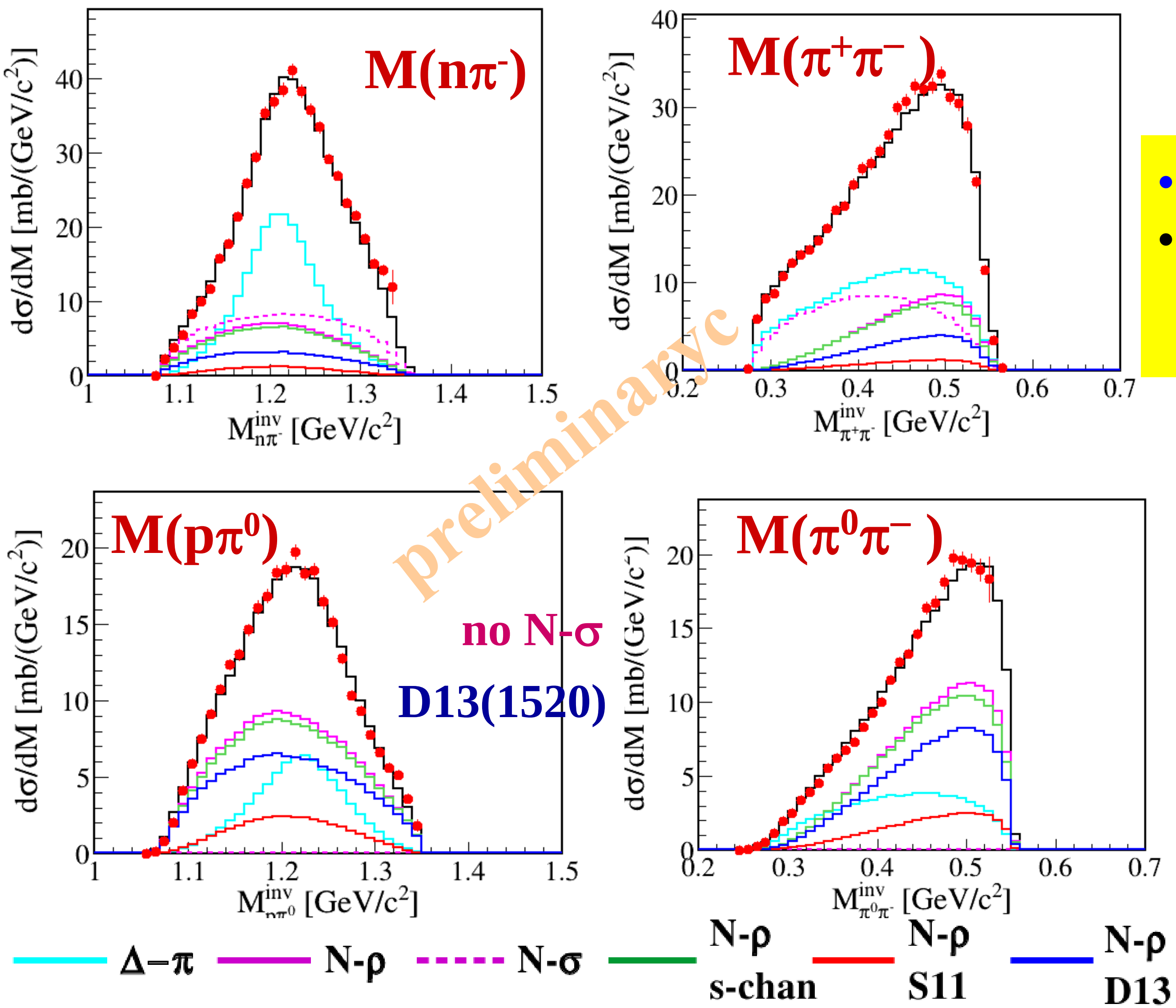
- pion momentum Δp/p =2.2% (σ)
- ~50% acceptance of pion beam line

Talks: I. Ciepal
B. Ramstein

2 pion production: PWA (BnGa) decomposition
Final States @ $\sqrt{s}$=1.49 GeV

acceptance corrected

„subthreshold" – no peak in $\rho \rightarrow \pi^{+} \pi^{-,0}$ mass distributions



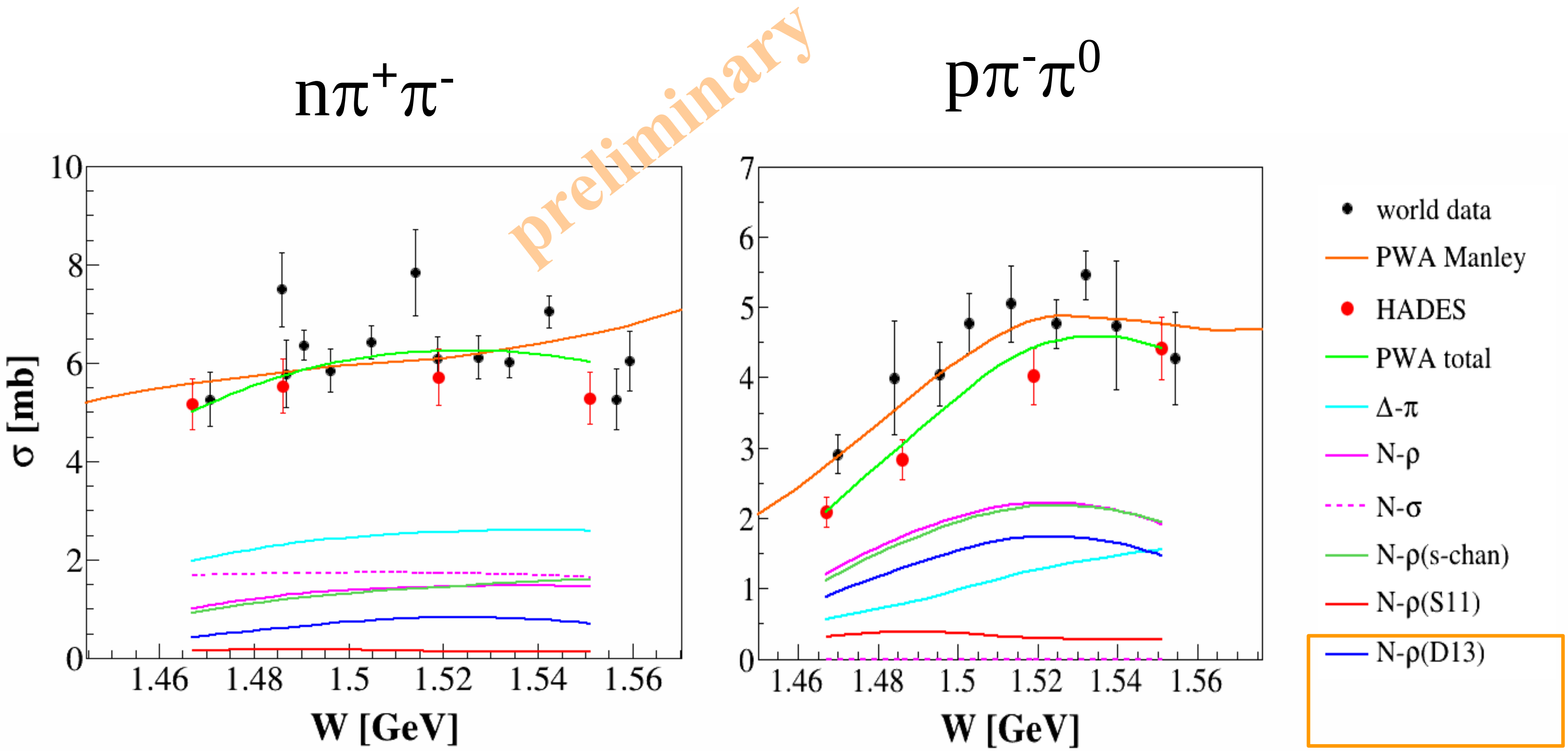
$n\pi^{+}\pi^{-}$

- **Δ-π** dominant,
- significant **N-ρ** dominat : s-channels I=1/2 (mainly D13)

$p\pi^{-}\pi^{0}$

- **Δ-π** smaller,
- **N-ρ** dominant (s-channels, D13)

Total Cross Sections

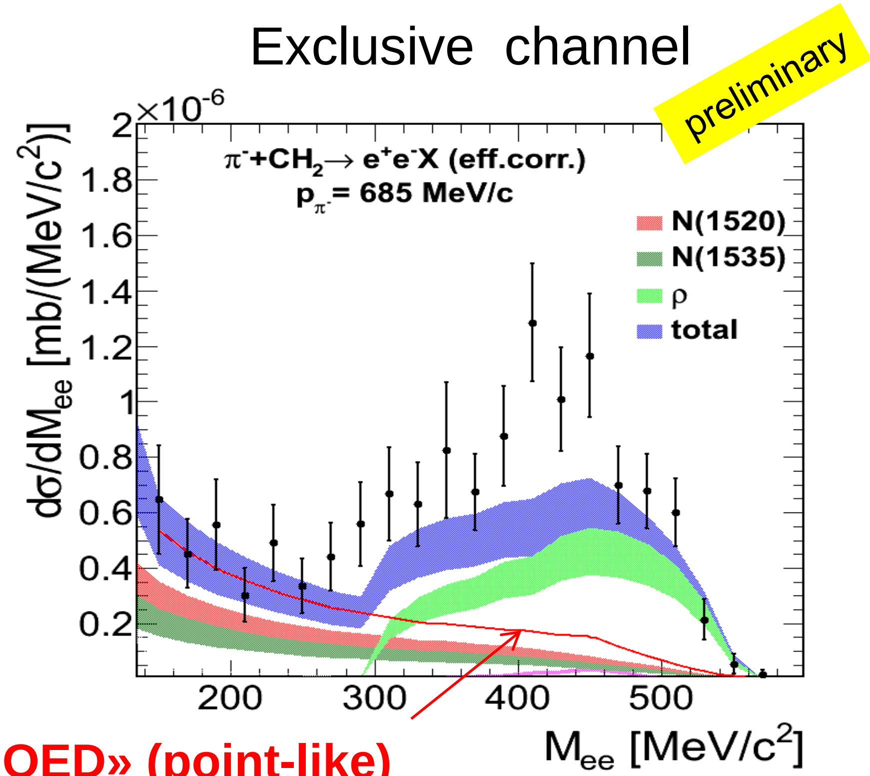


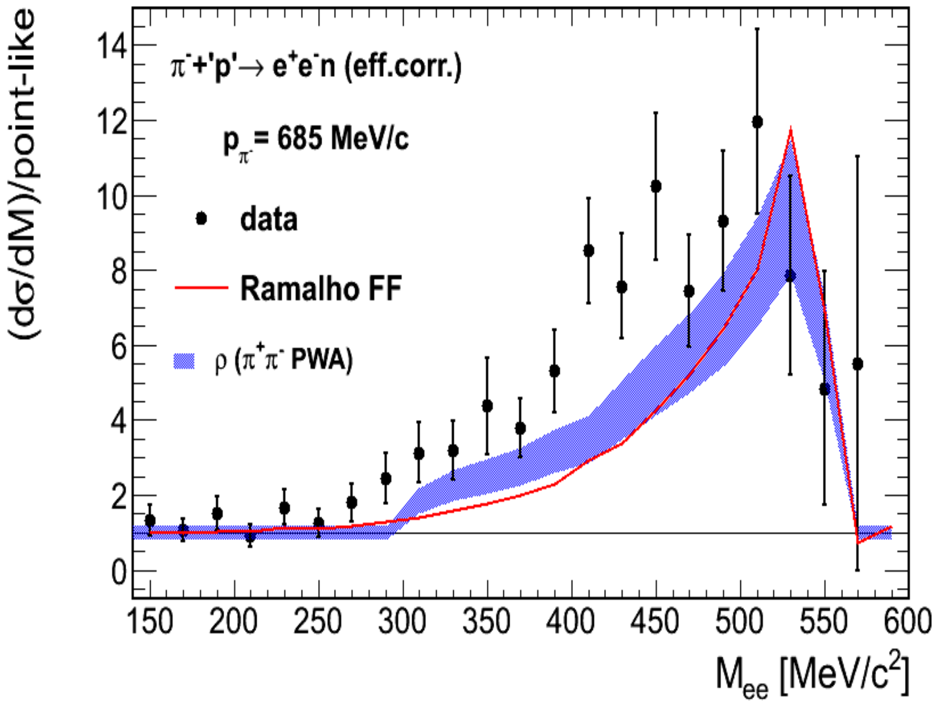
world data:
D. M. Manley *et al.*
Phys. Rev. D 30 (1984) 904

- ❑ consistent descripton of HADES data and ~ 130 other reactions with BnGa (A. Sarantsev)
- ❑ D_{13} (1520) dominant contribution to ρ production
  BR =12 +-2 %

$\pi^- p \rightarrow e+e-n$ @ $\sqrt{s}$=1.49 GeV

Exclusive channel





« QED» (point-like)
constrained by $\pi^- p \rightarrow n\gamma$
PWA BnGa

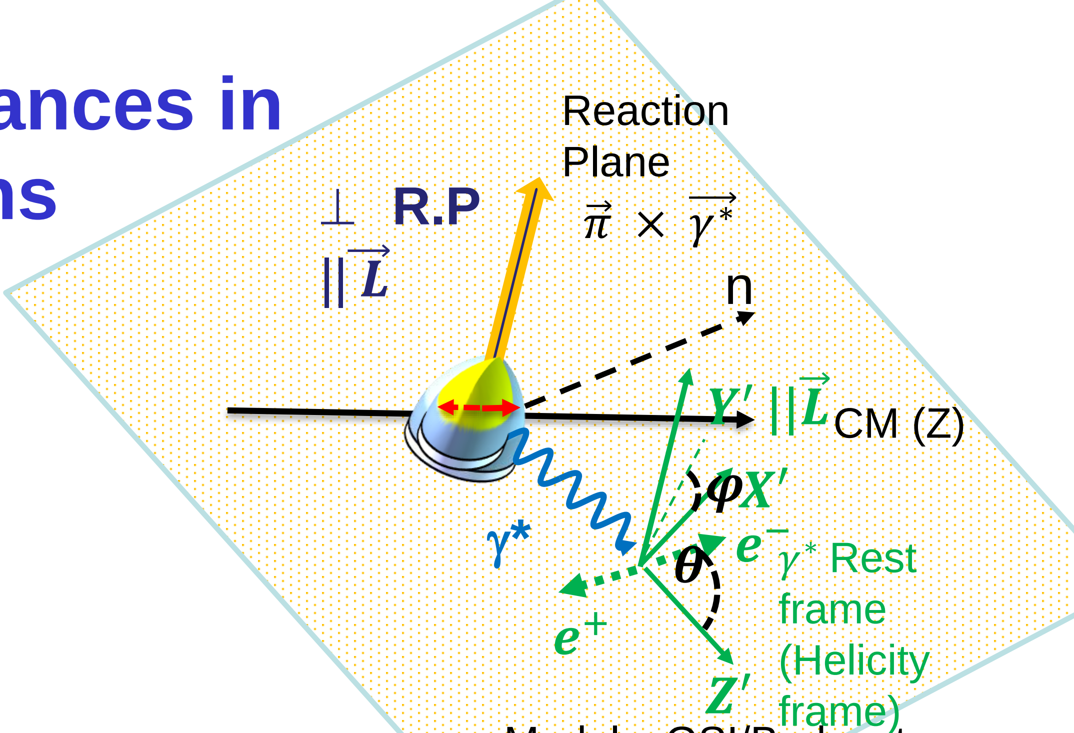
ρ→e+e- calculated as $\frac{d\sigma}{dM_{\pi+\pi-}}\frac{M_\varrho}{M^3}BR(\varrho \rightarrow e^+e^-)$

Strickt VDM

)

- ❑ Strong increase with mass – signature of VDM
- ❑ Yield consistent with ρ contribution expected from ππ (BnGa)
- ❑ Consistent with 2 component model of D13(1520) →ne+e- (Ramahlo & Pena)

Polarisation of resonances in pion induced reactions



Z- CMS quantization axis
$\vec{L} \perp$ R.P

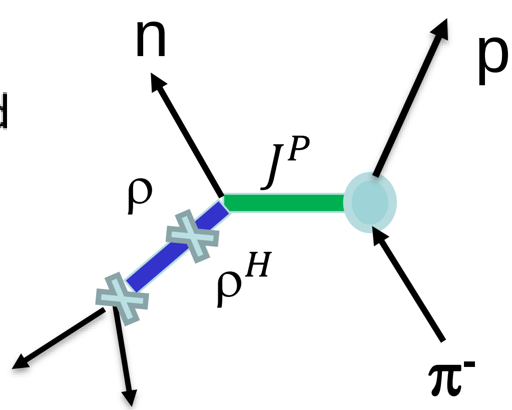
- π is spinless hence

$$J_Z^{N*} = S_Z^N = \pm\frac{1}{2}$$

- Polarization for $J^{N*} \geq \frac{3}{2}$ expected (only spin projections $\pm\frac{1}{2}$) allowed

Models: GSI/Budpest
E.Speranza et al.. PLB 764(2017)282

Talk by Denis Nitt
A. Sarantsev (priv. Comm)



$$|A|^2 = \sum_{\Lambda\Lambda'} \rho^{(H)}_{\Lambda\Lambda'} \rho^{(dec)}_{\Lambda\Lambda'}$$

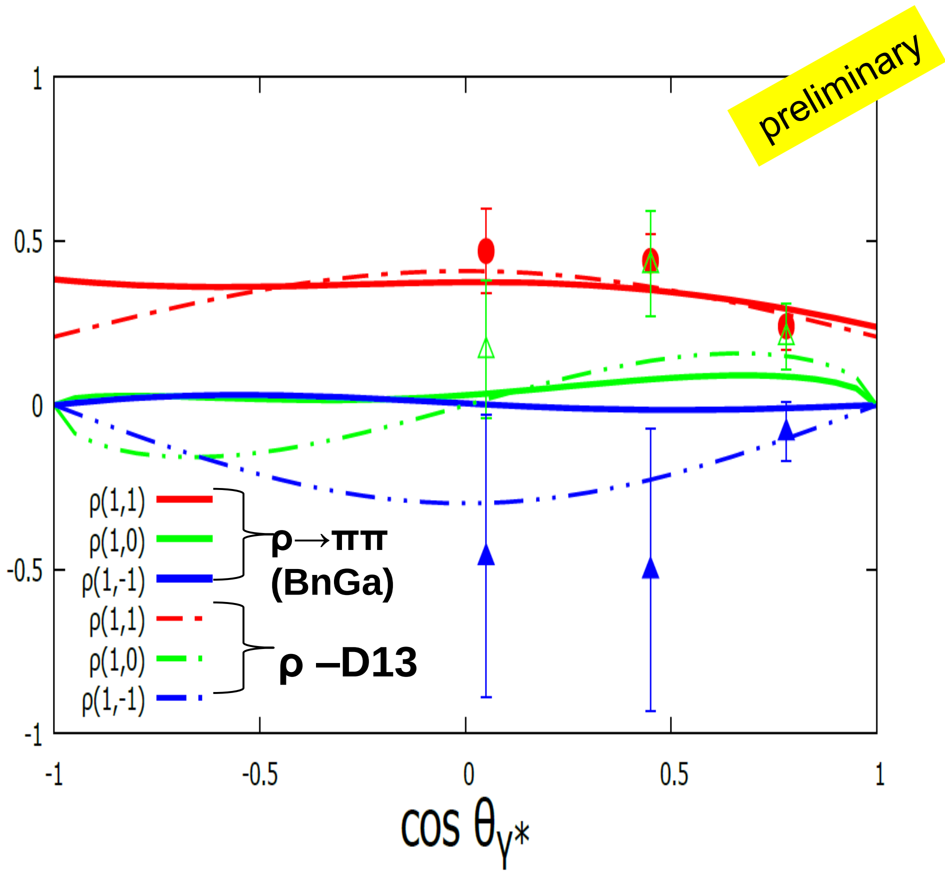
$\rho^{dec} \to \pi\pi$ or (e+e-)

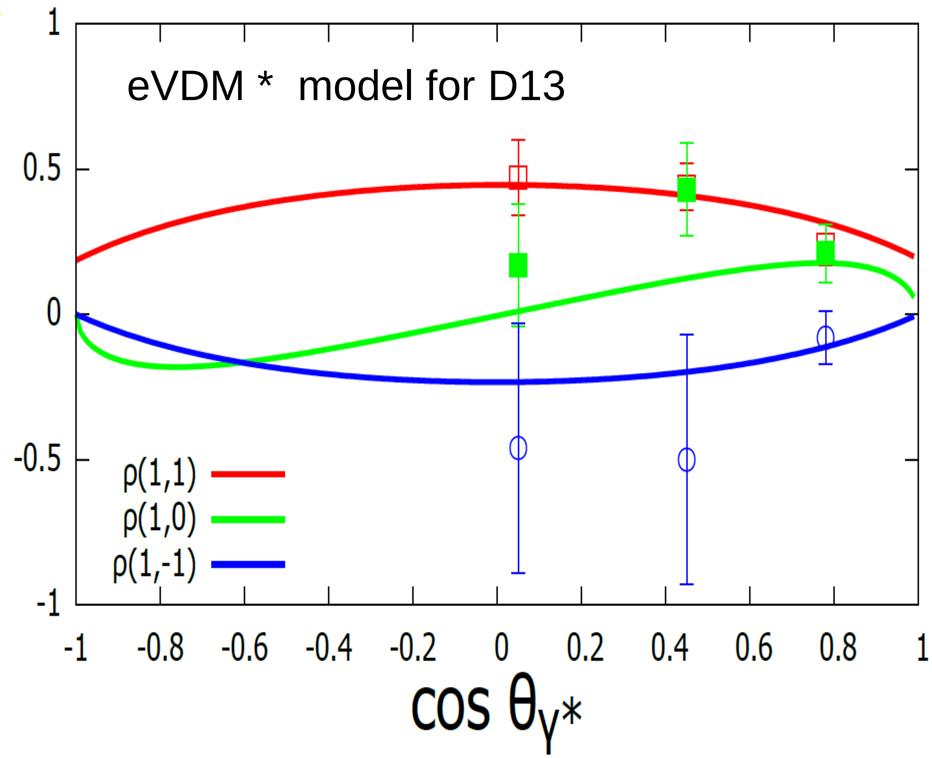
for e+e-

ρ^{dec} known, find ρ^H from data

$$|A|^2 = 8p_{\gamma*}^2 (1 - cos^2\theta_1 - \rho_{11}^H (3cos^2\theta_1 - 1) + \sqrt{2}\sin(2\theta)\, cos\varphi Re\rho_{10} + sin^2\theta\cos(2\varphi)\, Re\rho_{1-1}^H\,)$$

Results for ρ_{11} ρ_{10} ρ_{1-1} from e+e- and ππ





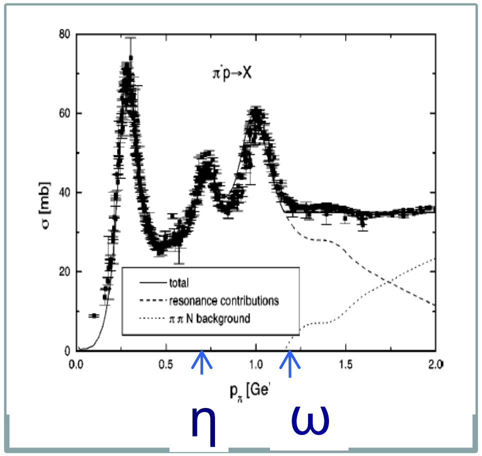
- ❑ consistent descripton of e+e- data with VDM * model (GSI/Budapest) for D13
- ❑ consistent description of e+e- data with ρ→ππ from BnGa
- ❑ dominance of D13

Summary

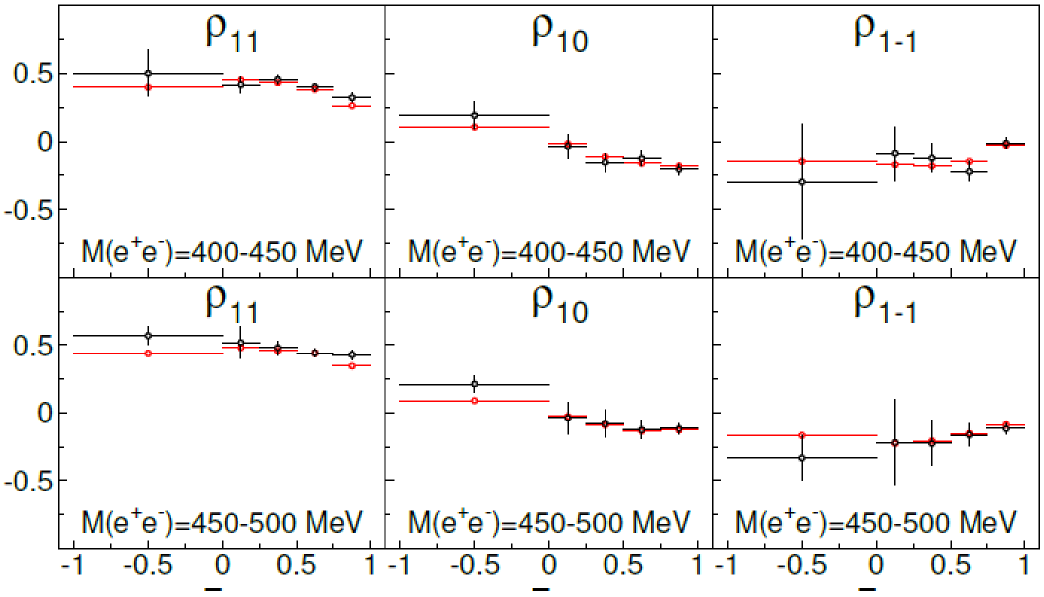
- Dilepton radiation (excess yield) in Low Mass Range in HIC can be described by emission form hot and dense phase using emissivity approach with strongly modified SF of ρ meson
- Modeling of SF requires detailed knowledge of elementary processes inolving baryon- meson interactions - $R \to N \gamma^*$ tranistions (em. Transition Form Factors) are directly related to hadronic loops in self. energy calculations
- Results of studies performed with NN and πN reactions demonstrate important role of intermediate ρ meson in em. transitions for Δ , D13 , along Vector Meson Dominance
- Angular distributions (triple differential cross sections) are important observable to discriminate between different contributions

Outlook

• Exp. proposals at GSI/SIS18 (FAIR0 phase 2019-2022)
explore the third resonance region ($\sqrt{s}$~1.7 GeV/c^2) with pion beams:
$\pi^- p \to n e^+ e^-$, $\pi^- p \to \pi\pi N$, ωn, ηn , $K^0\Lambda$, $K\Sigma$,….+photons (new electromagnetic calorimeter, Forward Detector (0-7), new Photon Detector RICH (better e+e- eff.)



Expected sensitivity



•Experiments with protons beams E=4.5 GeV at SIS18/FAIR to search for Hyperon dilepton transitions $Y^* \to \Lambda e^+e^-$ (common project with PANDA)

Hyperon decays

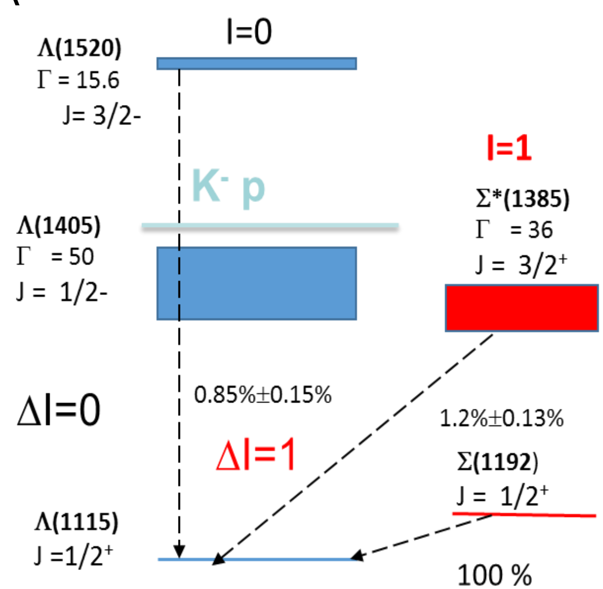
- Hyperons are narrow (Γ=15-40 MeV) : can be studied in pp, pA with HADES (and later p$\bar{p}$ with PANDA at FAIR).

Radiative decays of hyperons Y $\rightarrow \Lambda\gamma$

- Badly known
- High sensitivity to internal (quark,bag models,..)

Dalitz decays of hyperons Y $\rightarrow \Lambda$ e^+e^- (BR~10^{-5})

No measurement.



Relevance of Vector Dominance in the hyperon sector?

e.g. $\Sigma^*(1385)\rightarrow\Lambda\gamma^*$ is anologue of $\Delta(1232)\rightarrow N\gamma^*$ transition (measured by HADES)

calculations C. Granados et al. Eur. Phys. J.A54(2018)1.

ρ/a_1 -VM : connection to χSR

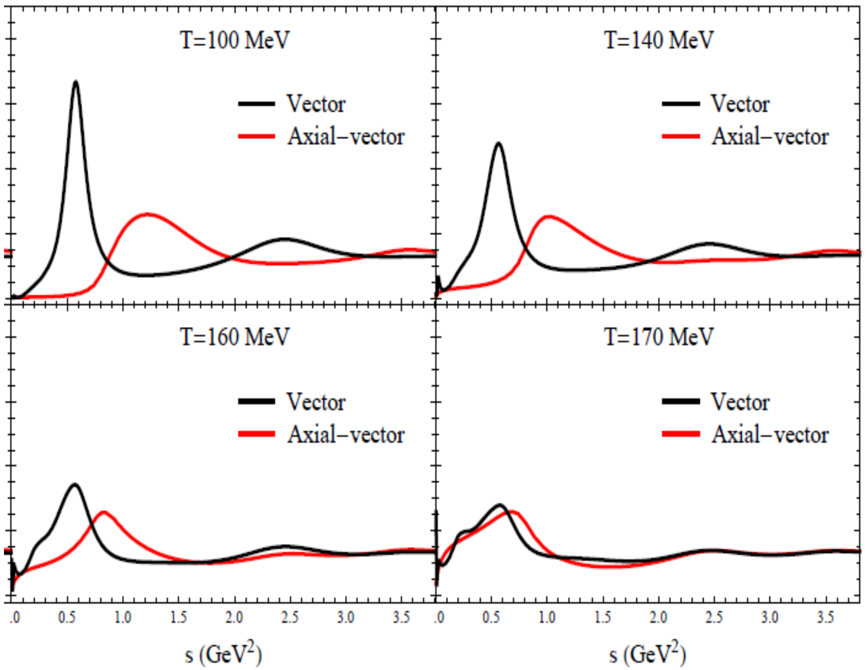
Weinberg Sum rules

[Weinberg '67, Das et al '67; Kapusta+Shuryak '94]

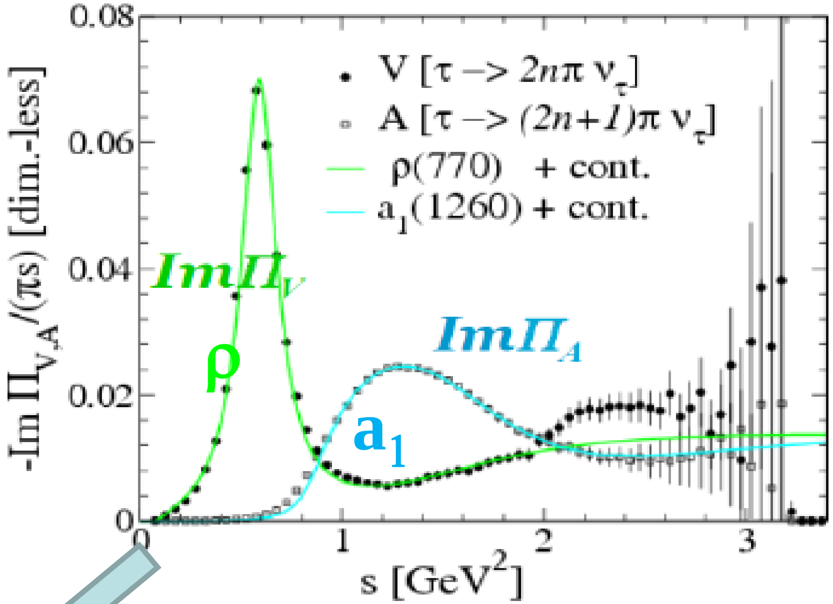
$$\int ds \, \frac{1}{s}(\rho_V - \rho_A) = f_\pi^2$$

$$\int ds \, (\rho_V - \rho_A) = -m_q \langle \bar{q}q \rangle$$

$$\int ds \, s \, (\rho_V - \rho_A) = c\alpha_s \langle (\bar{q}q)^2 \rangle$$



ρ/a_1 splitting in vaccuum



- ❑evolution of ρ SF from microscopic model Rapp& Wambach
- ❑ a_1 SF predicted from QCD constraints (sum rules) and lattice data

Merging of ρ/a_1 SF at T ~ T_c (calculations for μ_b =0)

Hohler and Rapp Phys.Lett. B731 (2014)