Directions in hadron physics: theory

EINN 2023
15th European Research Conference
on Electromagnetic Interactions with Nucleons and Nuclei
Paphos, 31 Oct. - 4 Nov. 2023

M. Vanderhaeghen

JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U

Genesis of hadron physics

1932-33: measurement of the g-factor of proton

Nobel Prize
Physics 1943:
Otto Stern

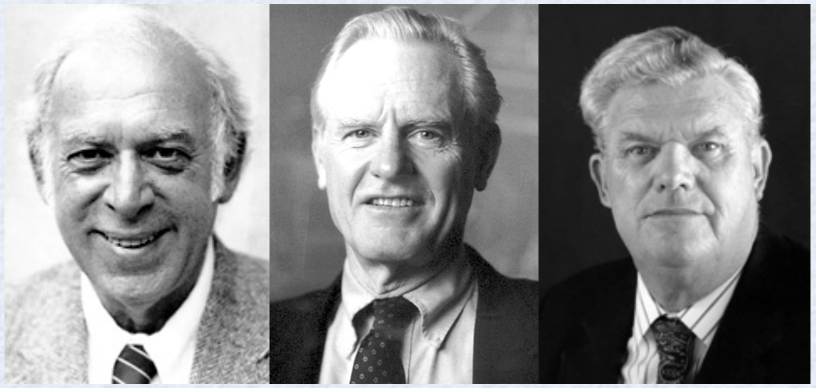
"for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton"

1955-56: elastic e-p scattering

Nobel Prize
Physics 1961:
Robert Hofstadter

"for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons"

1969: deep-inelastic e-p scattering



Nobel Prize
Physics 1990:
J.I. Friedman,
H.W. Kendall,
R.E. Taylor

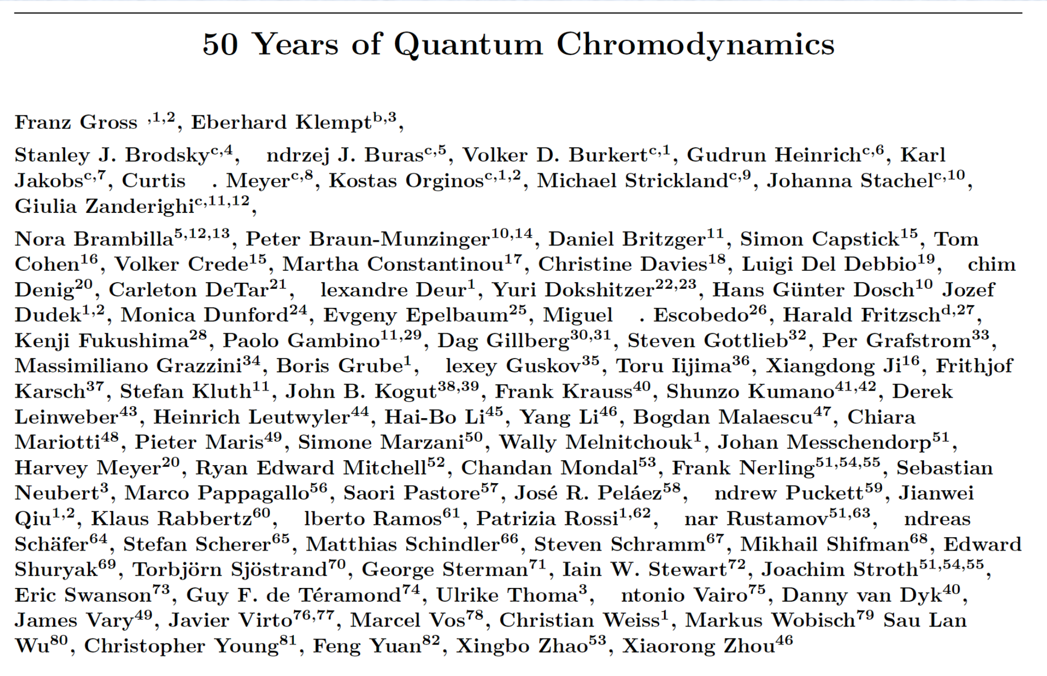
"for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics"

1974: QCD asymptotic freedom

Nobel Prize
Physics 2004:
D.J. Gross,
H.D. Politzer,
F.Wilczek

"for the discovery of asymptotic freedom in the theory of the strong interaction"

Quo vadis?



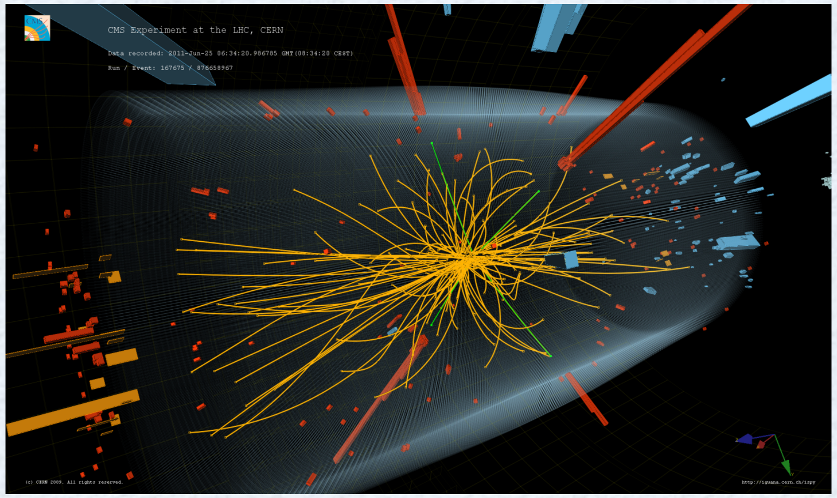
50 Years of Quantum Chromodynamics

Franz Gross [,1,2], Eberhard Klempt[b,3],

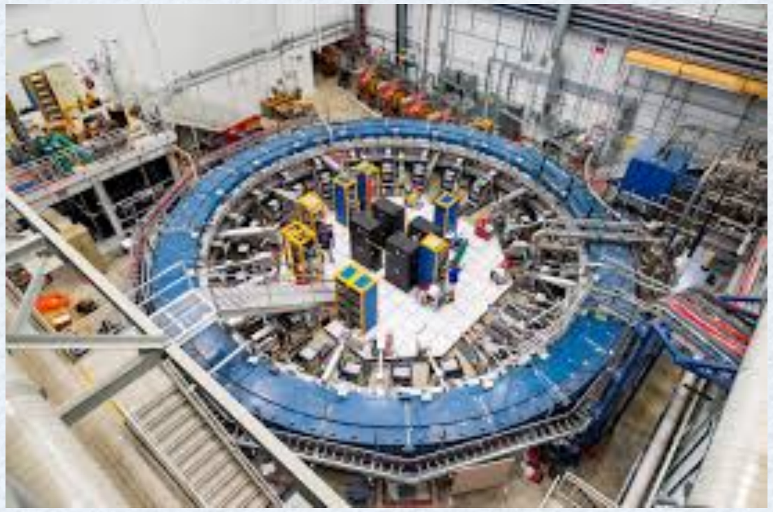
Stanley J. Brodsky[c,4], ndrzej J. Buras[c,5], Volker D. Burkert[c,1], Gudrun Heinrich[c,6], Karl Jakobs[c,7], Curtis . Meyer[c,8], Kostas Orginos[c,1,2], Michael Strickland[c,9], Johanna Stachel[c,10], Giulia Zanderighi[c,11,12],

Nora Brambilla[5,12,13], Peter Braun-Munzinger[10,14], Daniel Britzger[11], Simon Capstick[15], Tom Cohen[16], Volker Crede[15], Martha Constantinou[17], Christine Davies[18], Luigi Del Debbio[19], chim Denig[20], Carleton DeTar[21], lexandre Deur[1], Yuri Dokshitzer[22,23], Hans Günter Dosch[10] Jozef Dudek[1,2], Monica Dunford[24], Evgeny Epelbaum[25], Miguel . Escobedo[26], Harald Fritzsch[d,27], Kenji Fukushima[28], Paolo Gambino[11,29], Dag Gillberg[30,31], Steven Gottlieb[32], Per Grafstrom[33], Massimiliano Grazzini[34], Boris Grube[1], lexey Guskov[35], Toru Iijima[36], Xiangdong Ji[16], Frithjof Karsch[37], Stefan Kluth[11], John B. Kogut[38,39], Frank Krauss[40], Shunzo Kumano[41,42], Derek Leinweber[43], Heinrich Leutwyler[44], Hai-Bo Li[45], Yang Li[46], Bogdan Malaescu[47], Chiara Mariotti[48], Pieter Maris[49], Simone Marzani[50], Wally Melnitchouk[1], Johan Messchendorp[51], Harvey Meyer[20], Ryan Edward Mitchell[52], Chandan Mondal[53], Frank Nerling[51,54,55], Sebastian Neubert[3], Marco Pappagallo[56], Saori Pastore[57], José R. Peláez[58], ndrew Puckett[59], Jianwei Qiu[1,2], Klaus Rabbertz[60], lberto Ramos[61], Patrizia Rossi[1,62], nar Rustamov[51,63], ndreas Schäfer[64], Stefan Scherer[65], Matthias Schindler[66], Steven Schramm[67], Mikhail Shifman[68], Edward Shuryak[69], Torbjörn Sjöstrand[70], George Sterman[71], Iain W. Stewart[72], Joachim Stroth[51,54,55], Eric Swanson[73], Guy F. de Téramond[74], Ulrike Thoma[3], ntonio Vairo[75], Danny van Dyk[40], James Vary[49], Javier Virto[76,77], Marcel Vos[78], Christian Weiss[1], Markus Wobisch[79] Sau Lan Wu[80], Christopher Young[81], Feng Yuan[82], Xingbo Zhao[53], Xiaorong Zhou[46]

`arXiv 2212.11107 [hep-ph]`

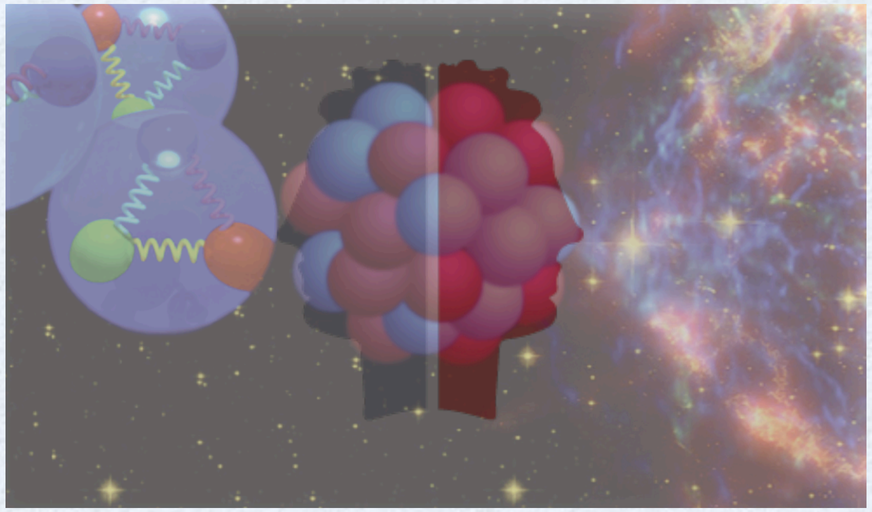


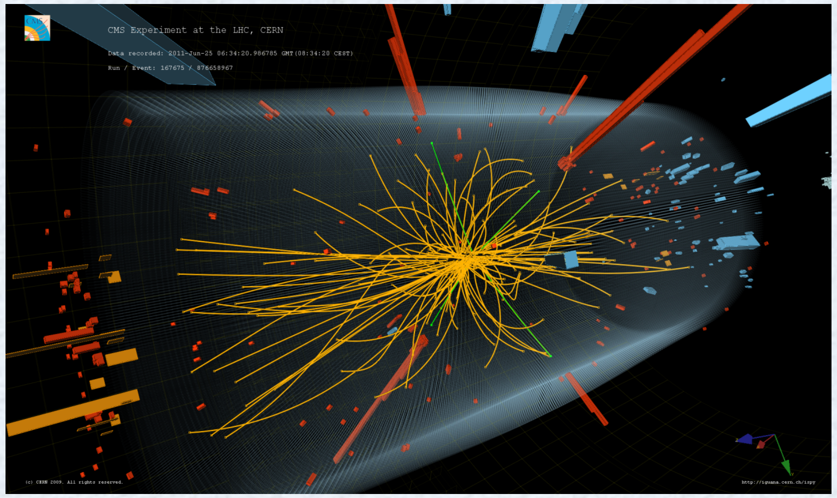
High-energy frontier



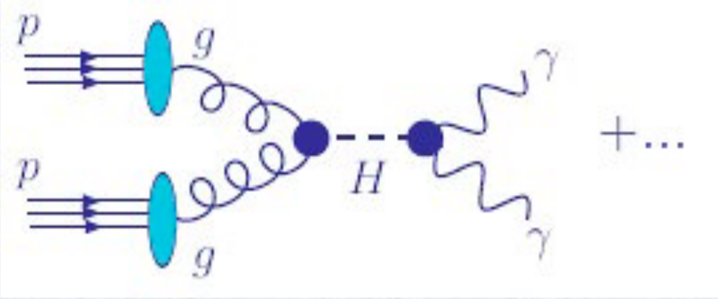
Precision frontier

Low-energy frontier





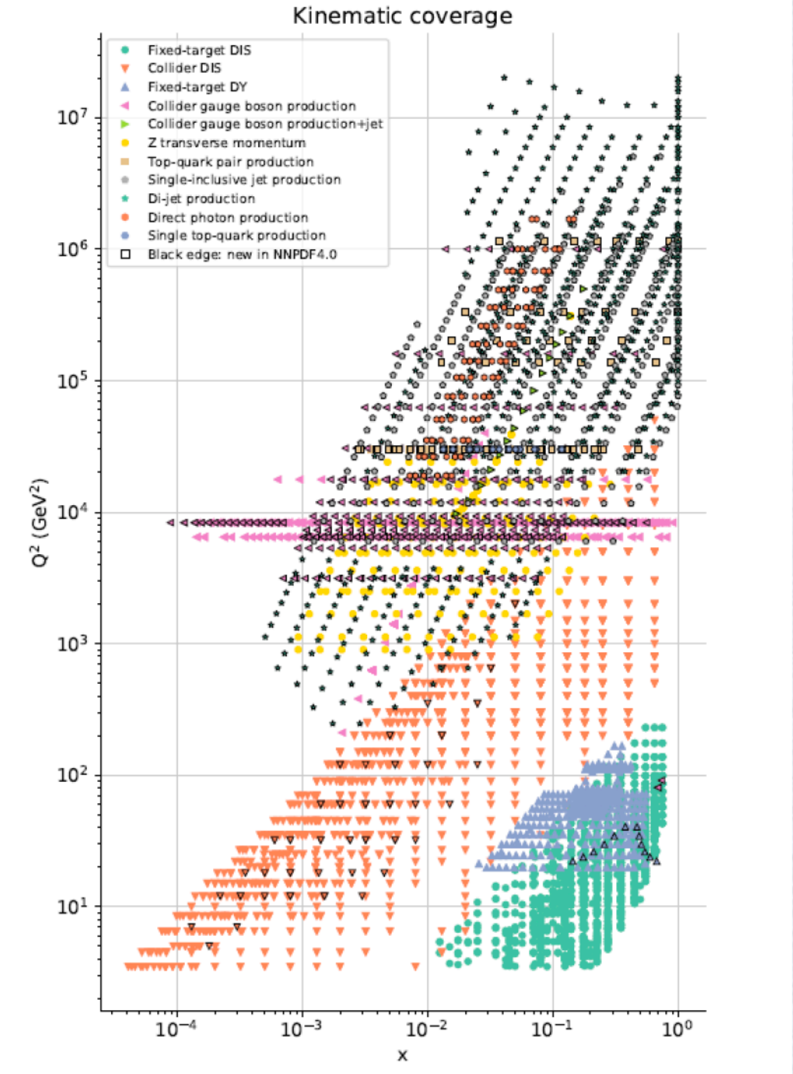
High-energy frontier



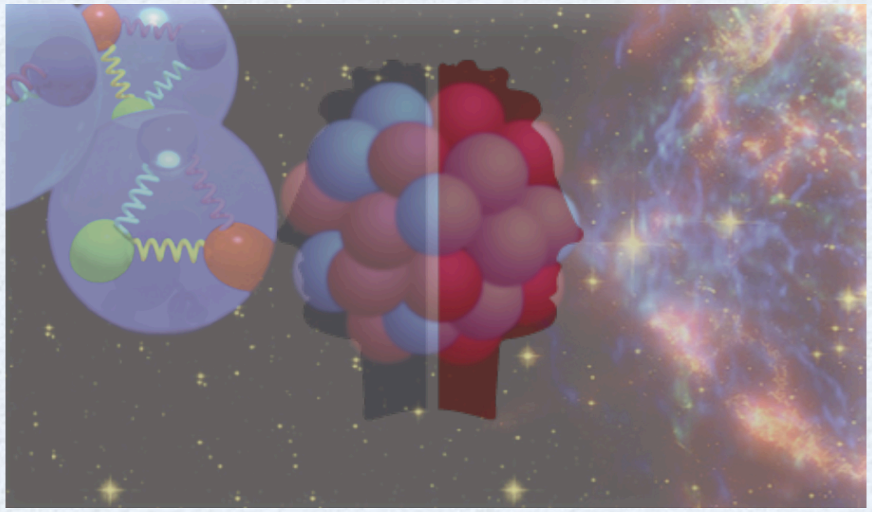
talk: Nadolsky

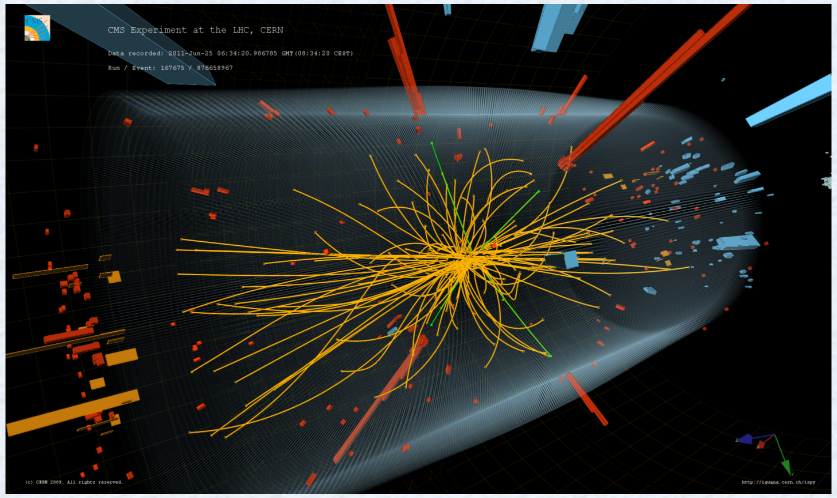
QCD precision analysis: Coordinated community strategy to adopt the **replicability** mindset

Data in the NNPDF4.0



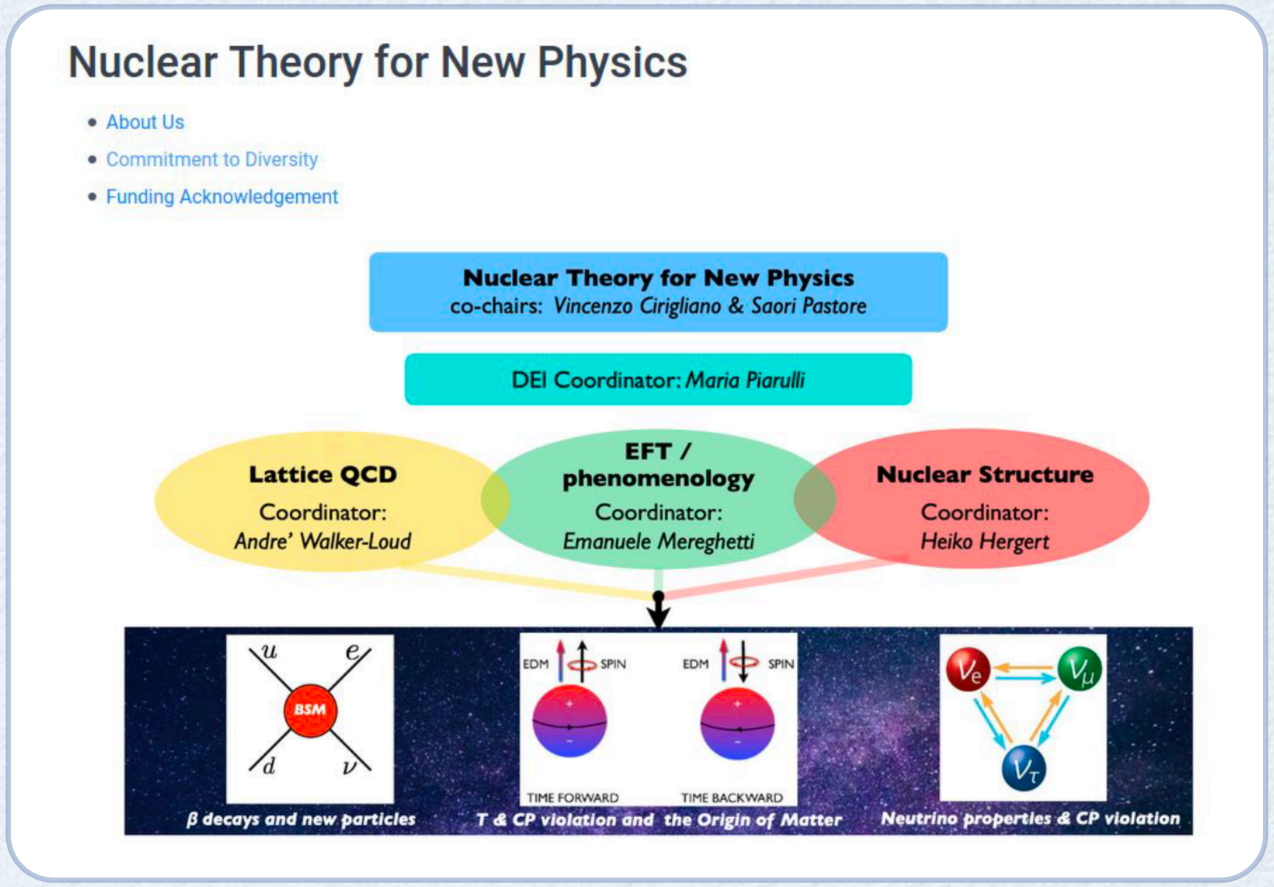
Low-energy frontier





High-energy frontier

talk: Pastore



Nuclear Theory for New Physics

- About Us
- Commitment to Diversity
- Funding Acknowledgement

Nuclear Theory for New Physics
co-chairs: *Vincenzo Cirigliano & Saori Pastore*

DEI Coordinator: *Maria Piarulli*

Lattice QCD
Coordinator:
Andre' Walker-Loud

EFT / phenomenology
Coordinator:
Emanuele Mereghetti

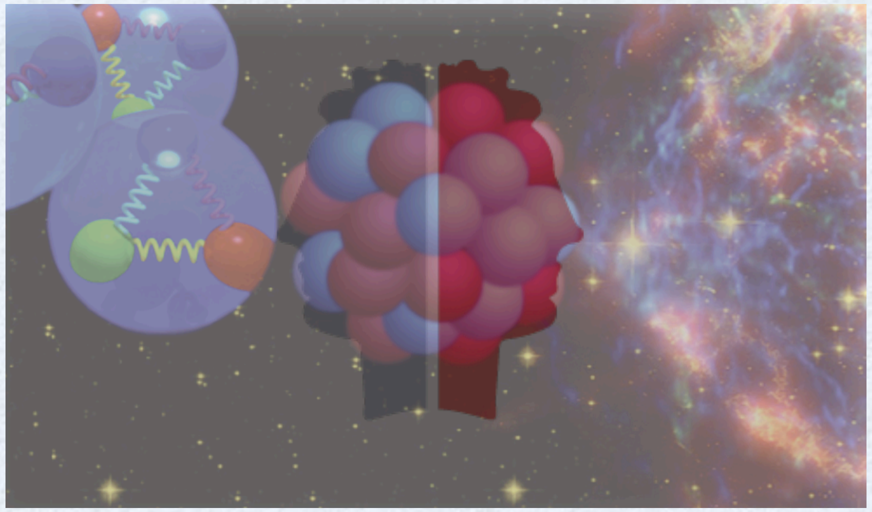
Nuclear Structure
Coordinator:
Heiko Hergert

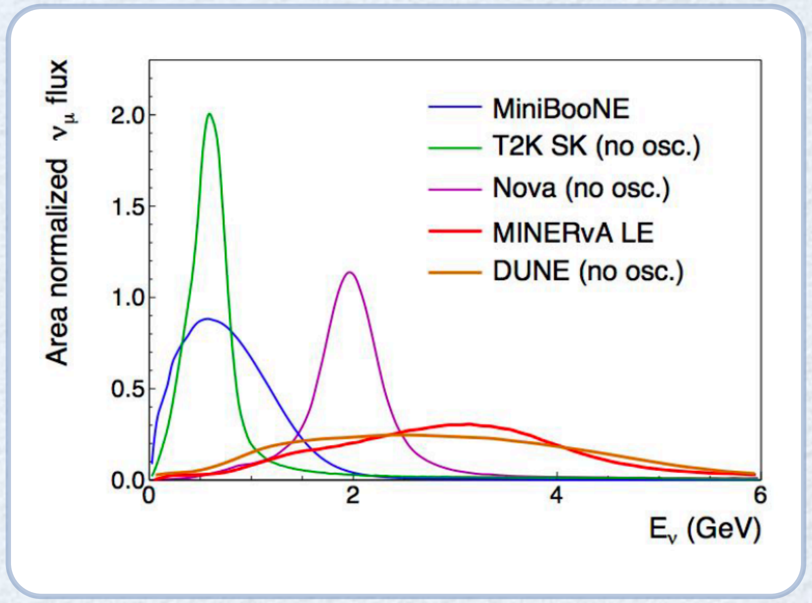
β decays and new particles

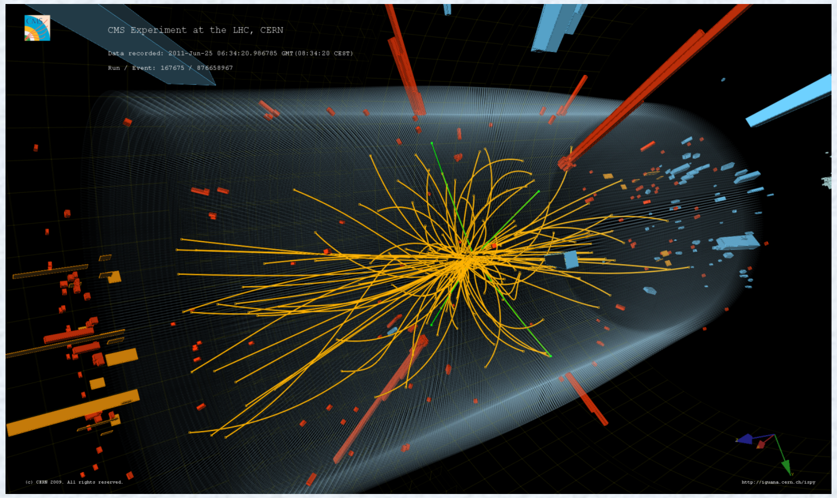
T & CP violation and the Origin of Matter

Neutrino properties & CP violation

Low-energy frontier

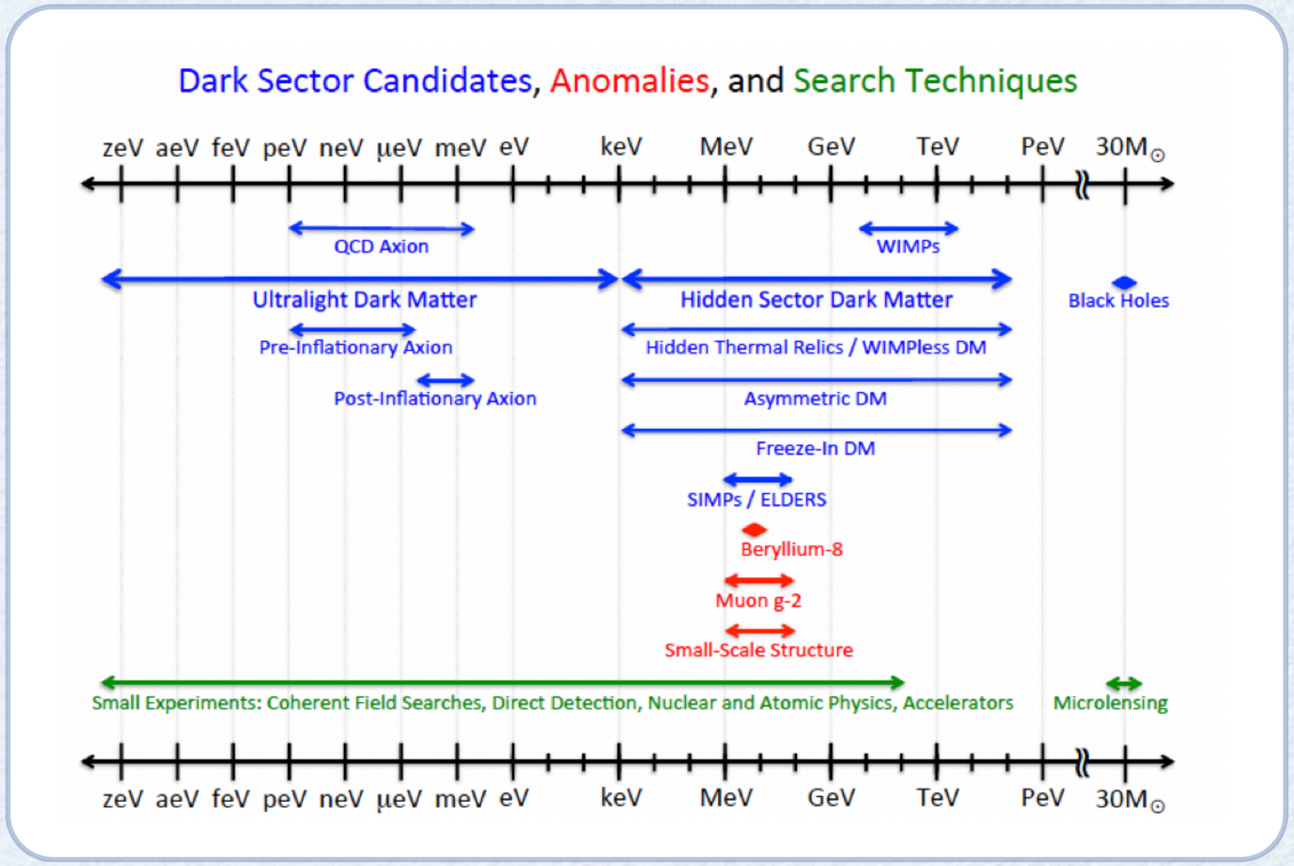






High-energy frontier

talks: Gianotti, Denig

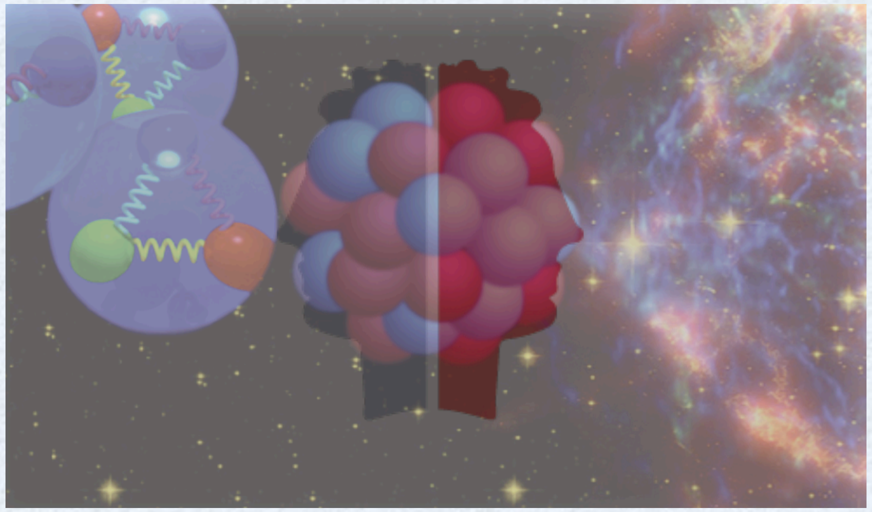


Dark matter could be lighter than previously thought, **MeV - GeV mass range**: ALPs, dark photon, X17, …

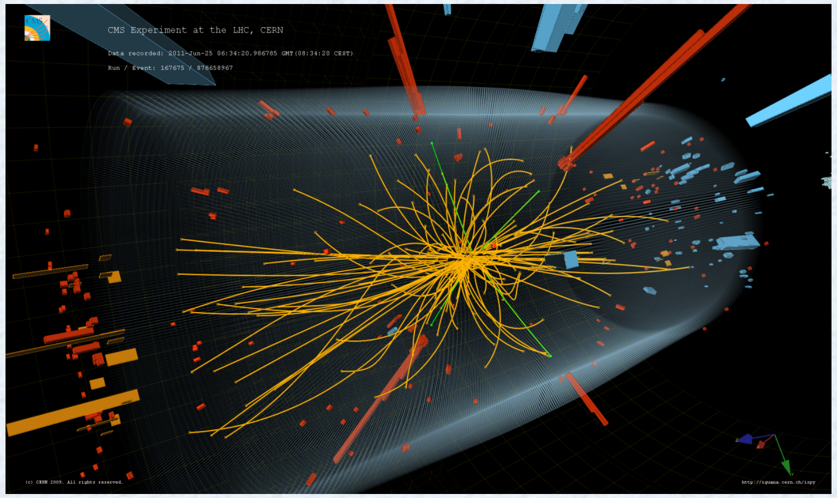
CERN Physics Beyond Colliders

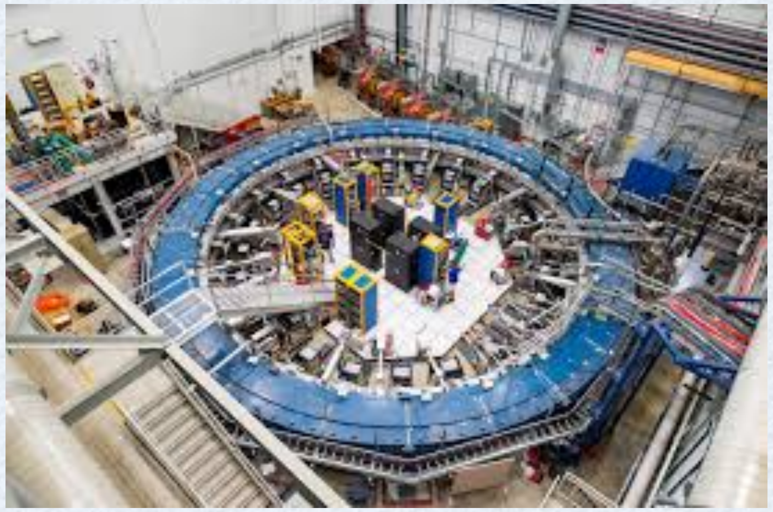
arXiv:1901.09966

Low-energy frontier



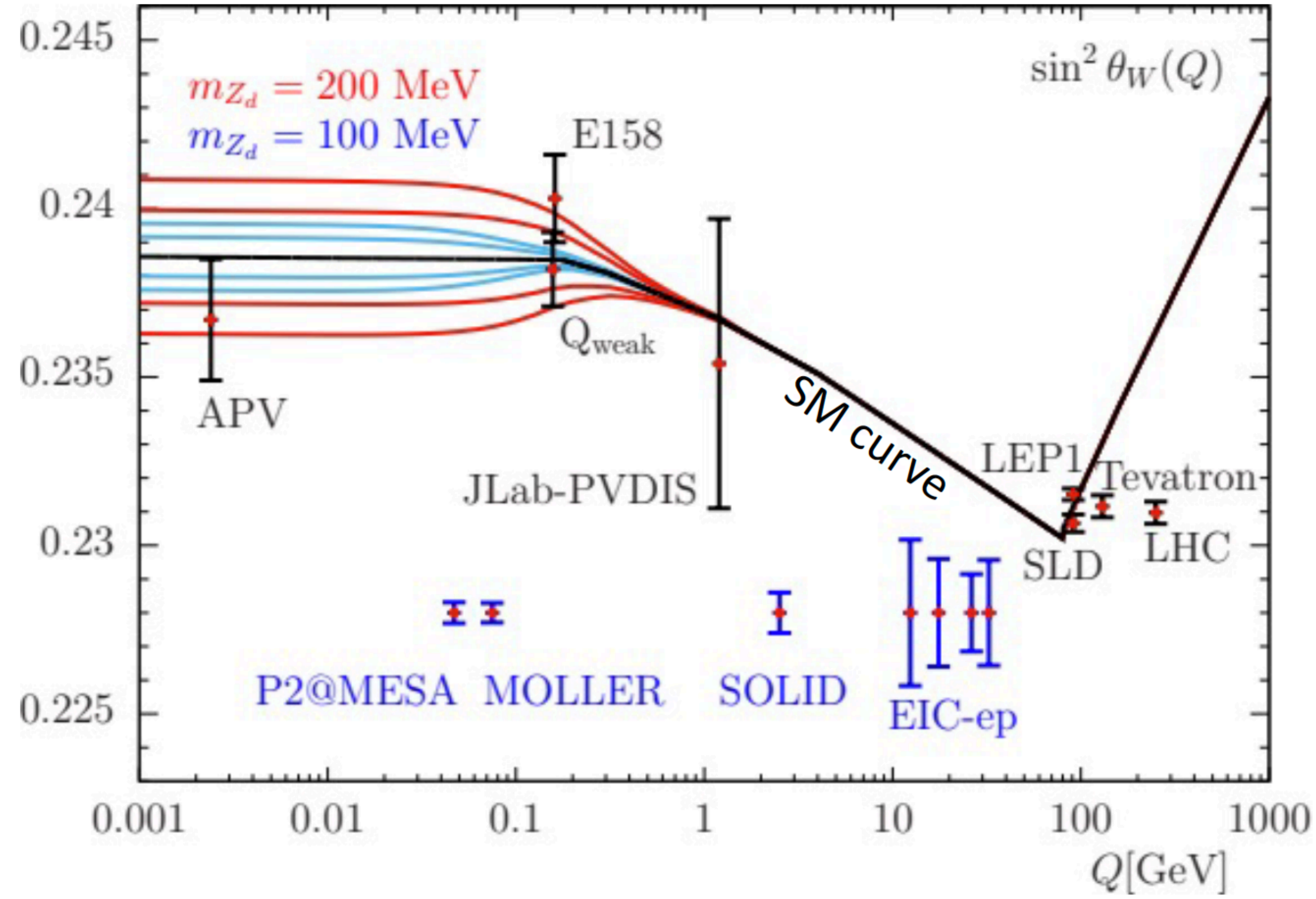
New opportunities:
PADME, Belle II, …
MESA, BDX@JLab, …





High-energy frontier ⟷ **Precision frontier**

Running of $\sin^2 \theta_W$

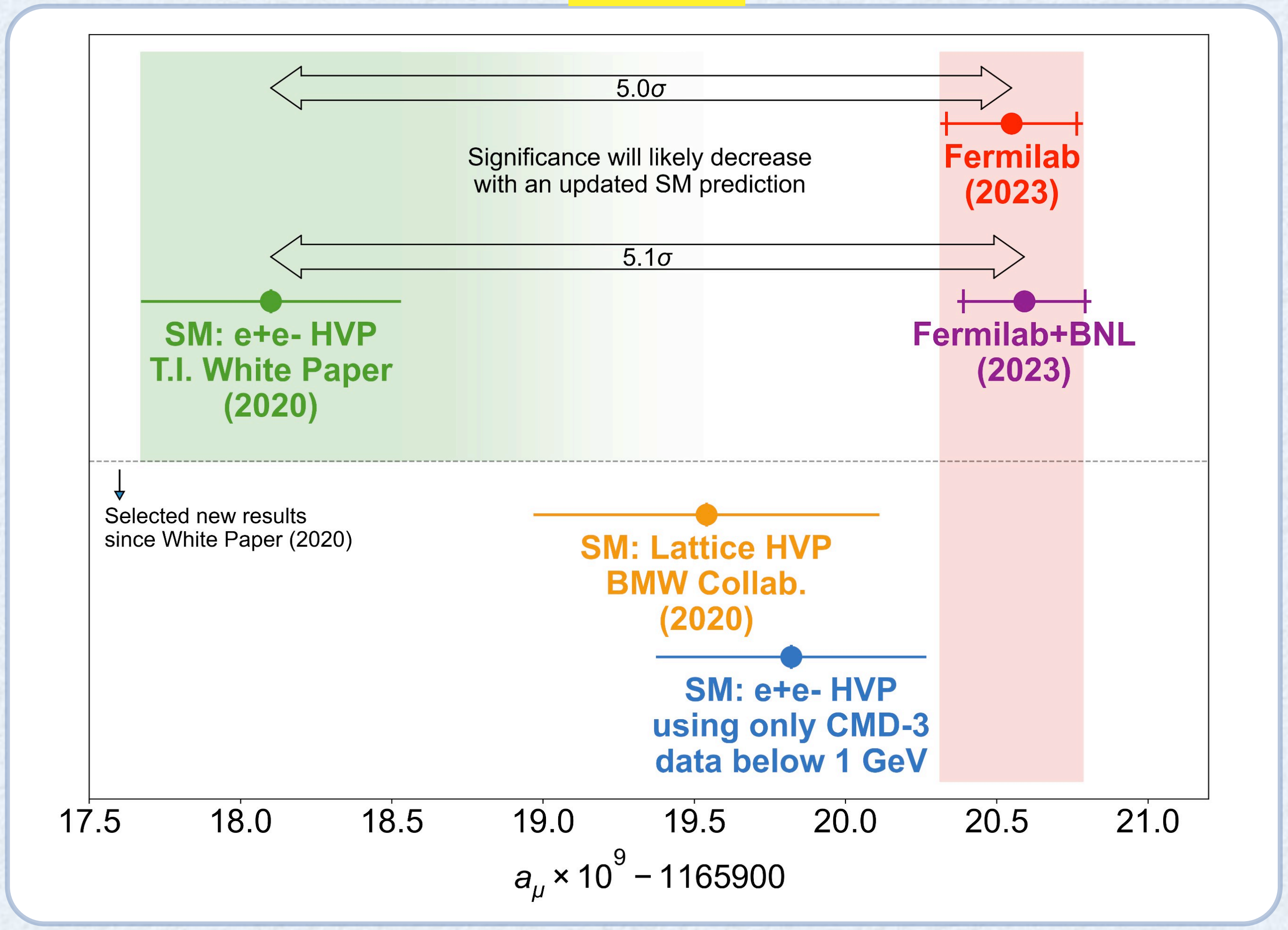


talks: Denig, Ramsey-Musolf

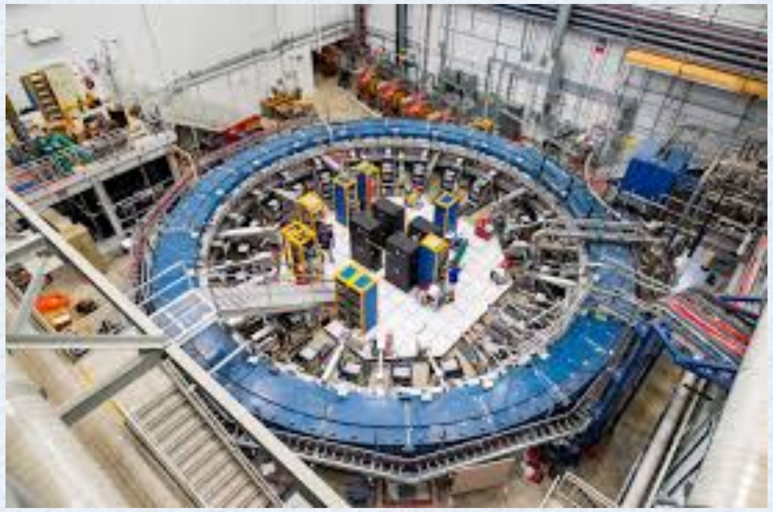
Precision low Q^2 expt.

-> P2@MESA: 0.16% error
-> Controlled hadronic physics corrections
-> reaches new physics scale of ~50 TeV !

$(g\text{-}2)_\mu$

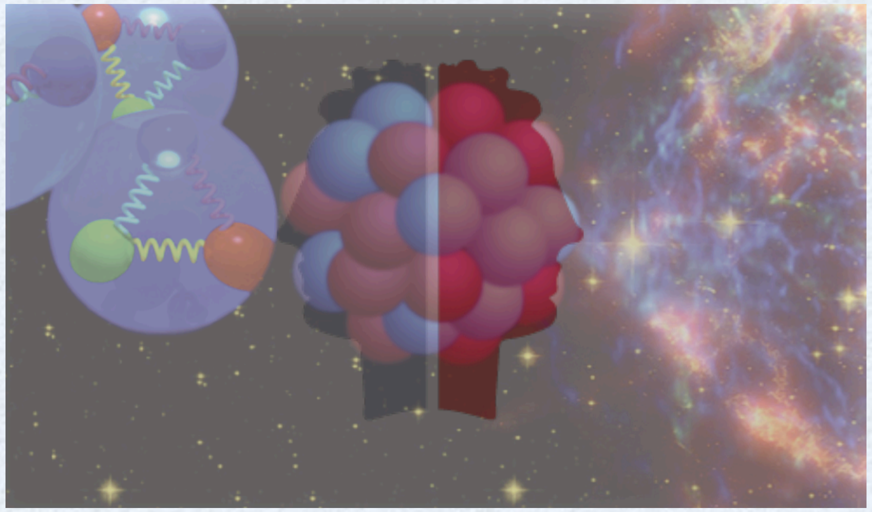


talks: Bottalico, Fodor

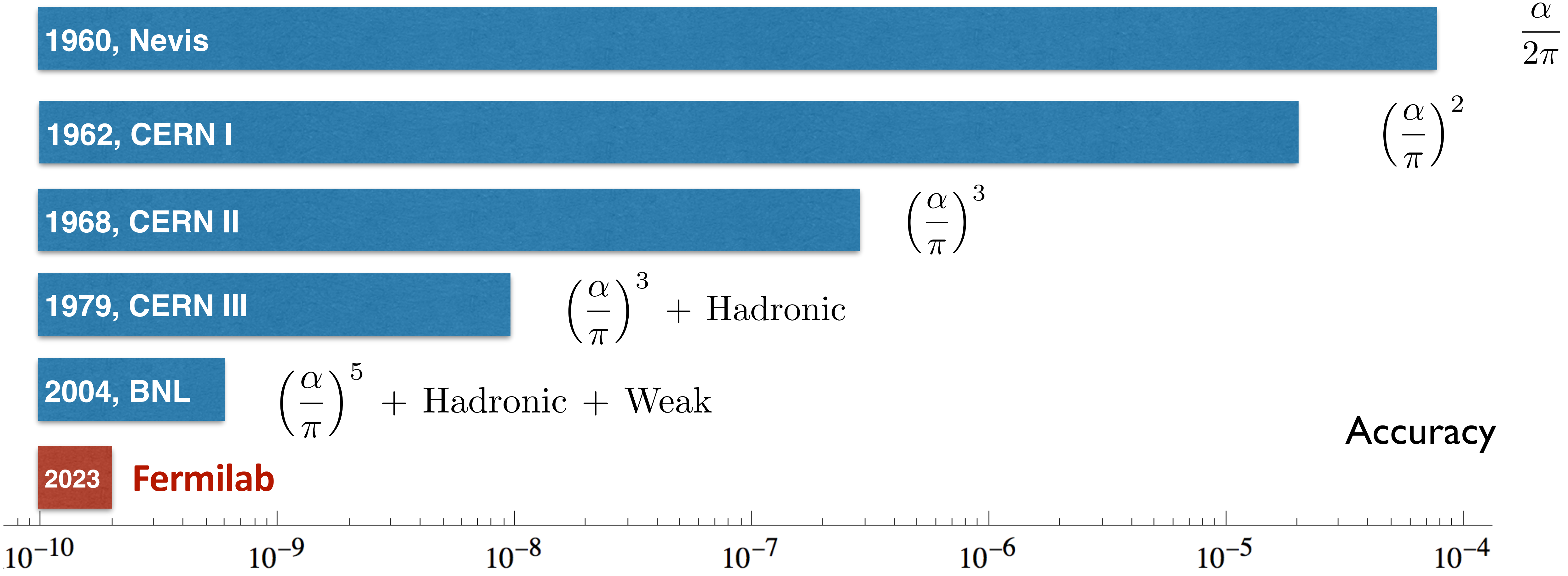


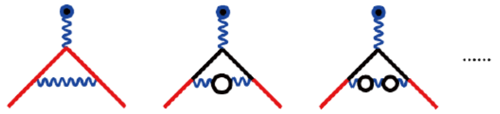
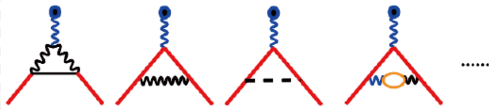
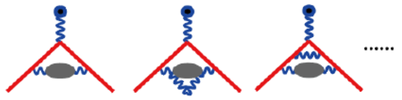
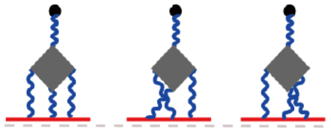
Precision frontier

Low-energy frontier



$(g\text{-}2)_\mu$: history of achieved accuracy



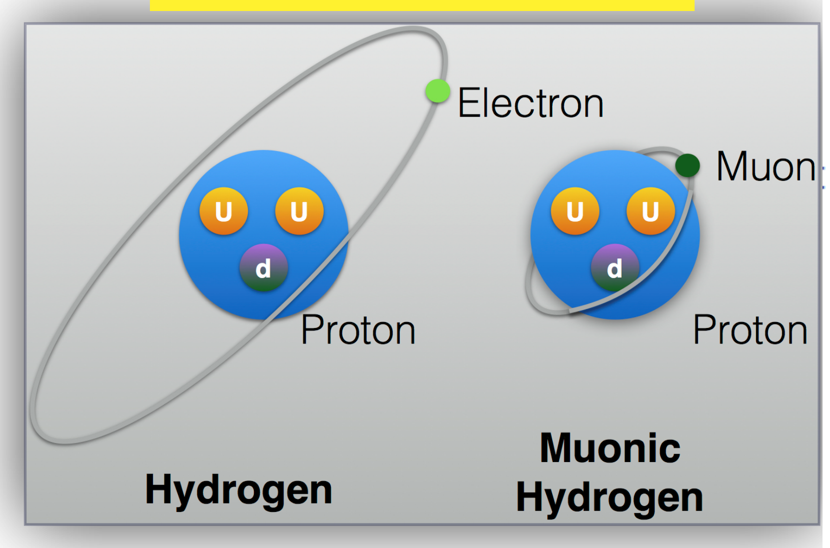
QED *fully perturbative*	$\left(\frac{\alpha}{\pi}\right)^1 + \left(\frac{\alpha}{\pi}\right)^2 + \left(\frac{\alpha}{\pi}\right)^3 + \left(\frac{\alpha}{\pi}\right)^4 + \left(\frac{\alpha}{\pi}\right)^5$		116584718.931 ± 0.104
EW *perturbative* + *(small) non-pert.*	1-loop + 2-loop		153.6 ± 1.0
Had *fully non-perturbative*	$\left(\frac{\alpha}{\pi}\right)^2 + \left(\frac{\alpha}{\pi}\right)^3 + \left(\frac{\alpha}{\pi}\right)^4$	**Hadronic vacuum polarization (HVP)** 	6845 ± 40
	Hadronic Light-by-Light (HLbL) $\left(\frac{\alpha}{\pi}\right)^3$	**Hadronic Light-by-Light (HLbL)** 	92 ± 18

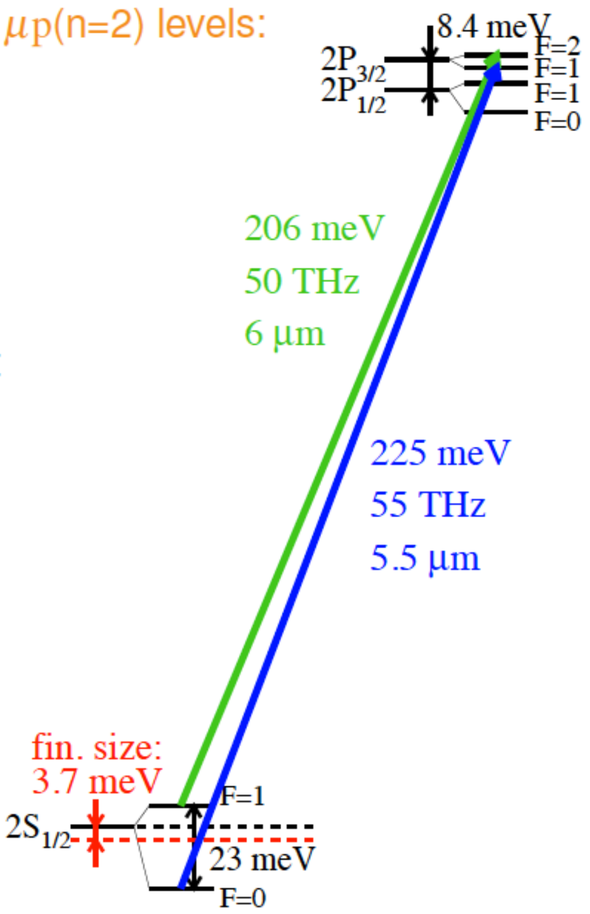
x 10^{-11}

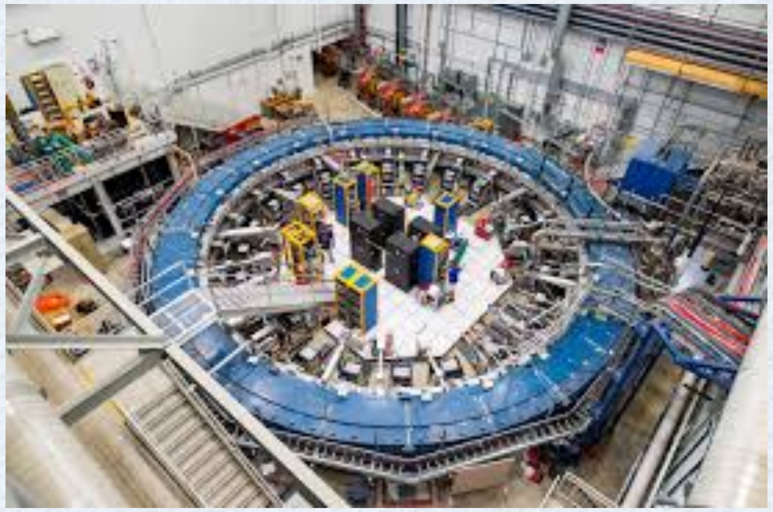
$(g\text{-}2)_\mu$ theory initiative

`Phys.Rept.887 (2020)`

Precision atomic spectroscopy

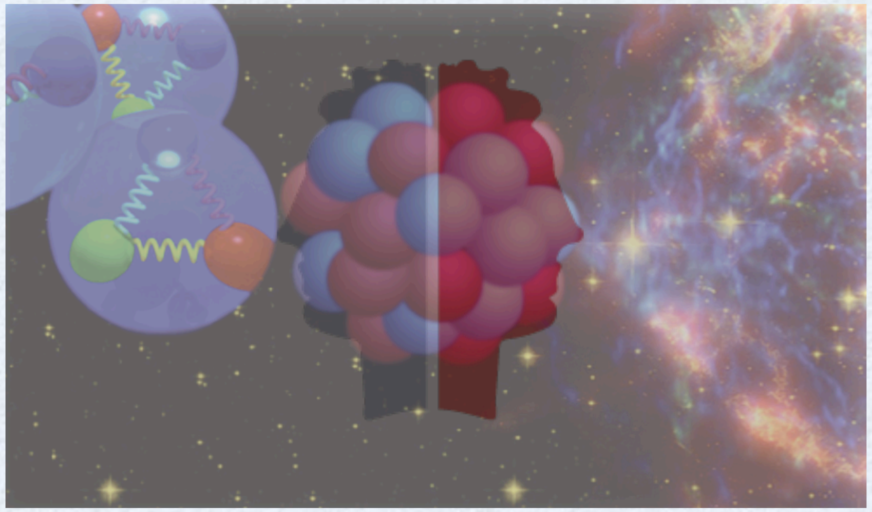




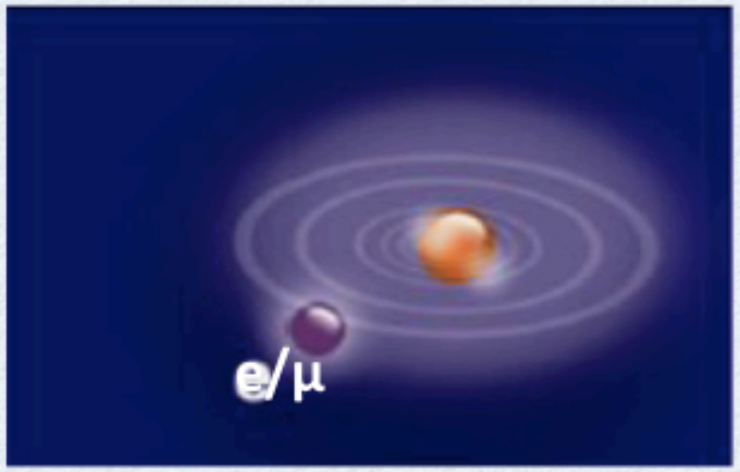


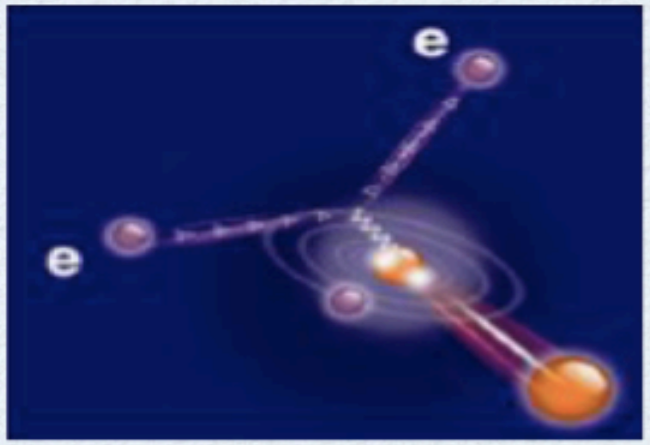
Precision frontier

Low-energy frontier



Proton size
and
electromagnetic structure





Proton radius puzzle

$$\Delta E_{LS} = 206.0336\,(15) \;-\; 5.2275\,(10)\; R_E^2 \;+\; \Delta E_{TPE} \qquad \text{meV}$$

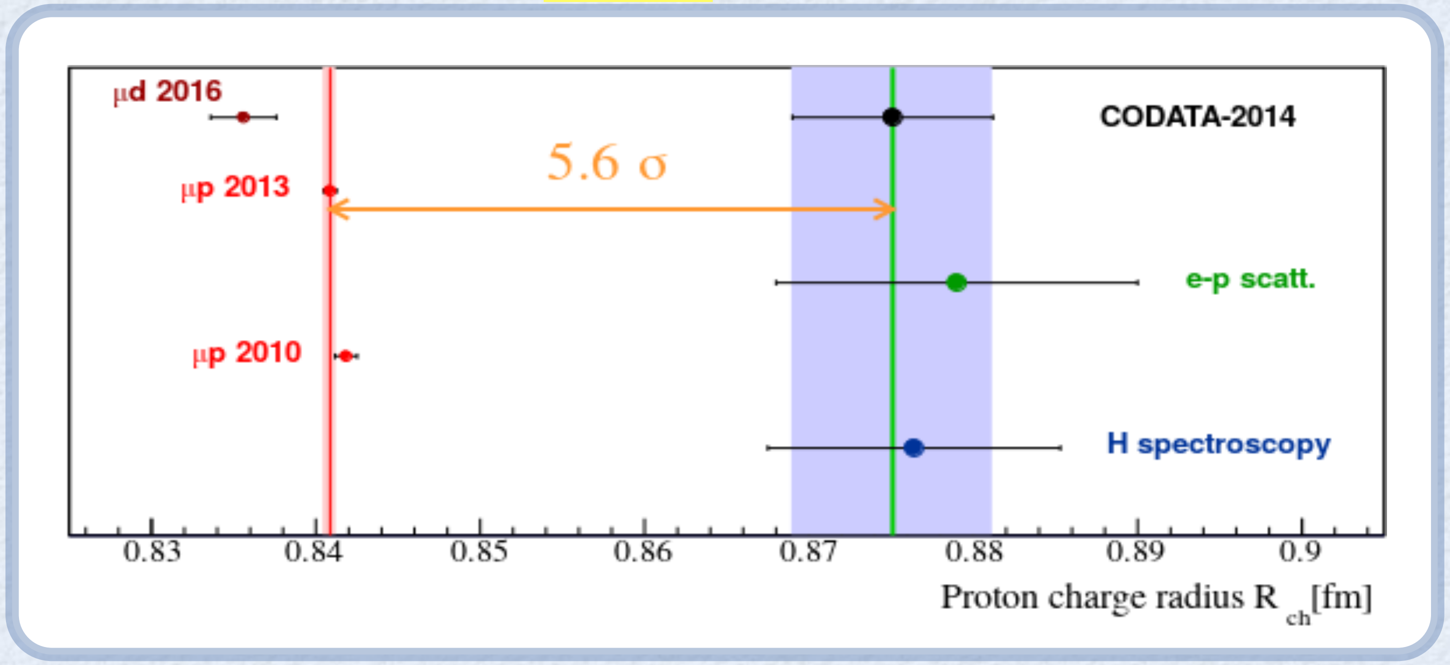
Antognini et al. (2013)

3.70 meV

O(α^5) correction

0.0332 (20) meV

2016



μH data: $R_E = 0.8409 \pm 0.0004$ fm

Pohl et al. (2010)

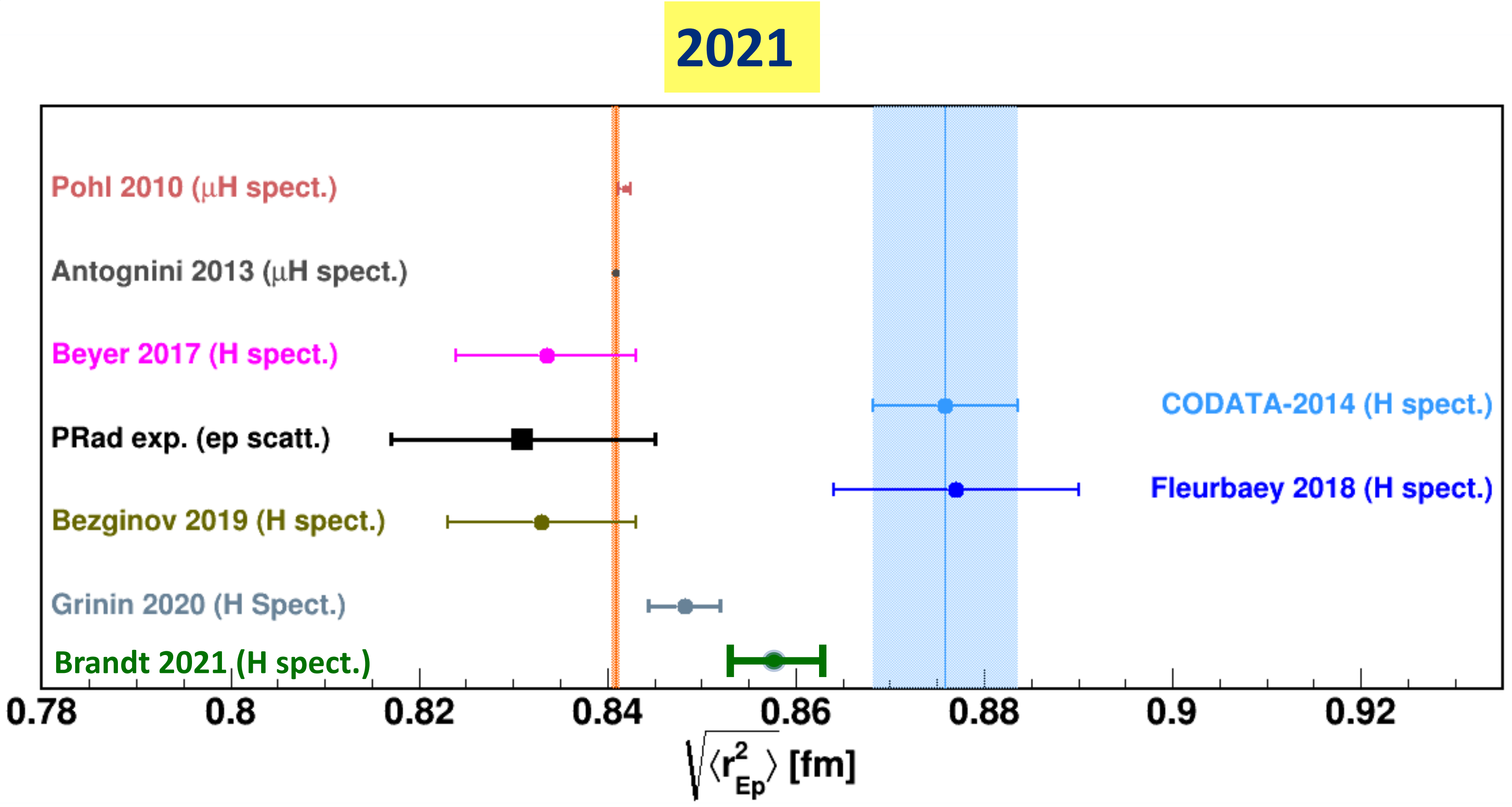
Antognini et al. (2013)

5.6 σ difference

ep data: $R_E = 0.8775 \pm 0.0051$ fm

CODATA (2014)

Proton charge radius: present experimental status



Hydrogen 2S-4P

Hydrogen 2S-2P

Hydrogen 1S-3S

Hydrogen 2S-8D

Hydrogen 1S-3S

from recent compilation **Rev. Mod. Phys. 94 (2022) 015002** `H.Gao, M.Vdh`

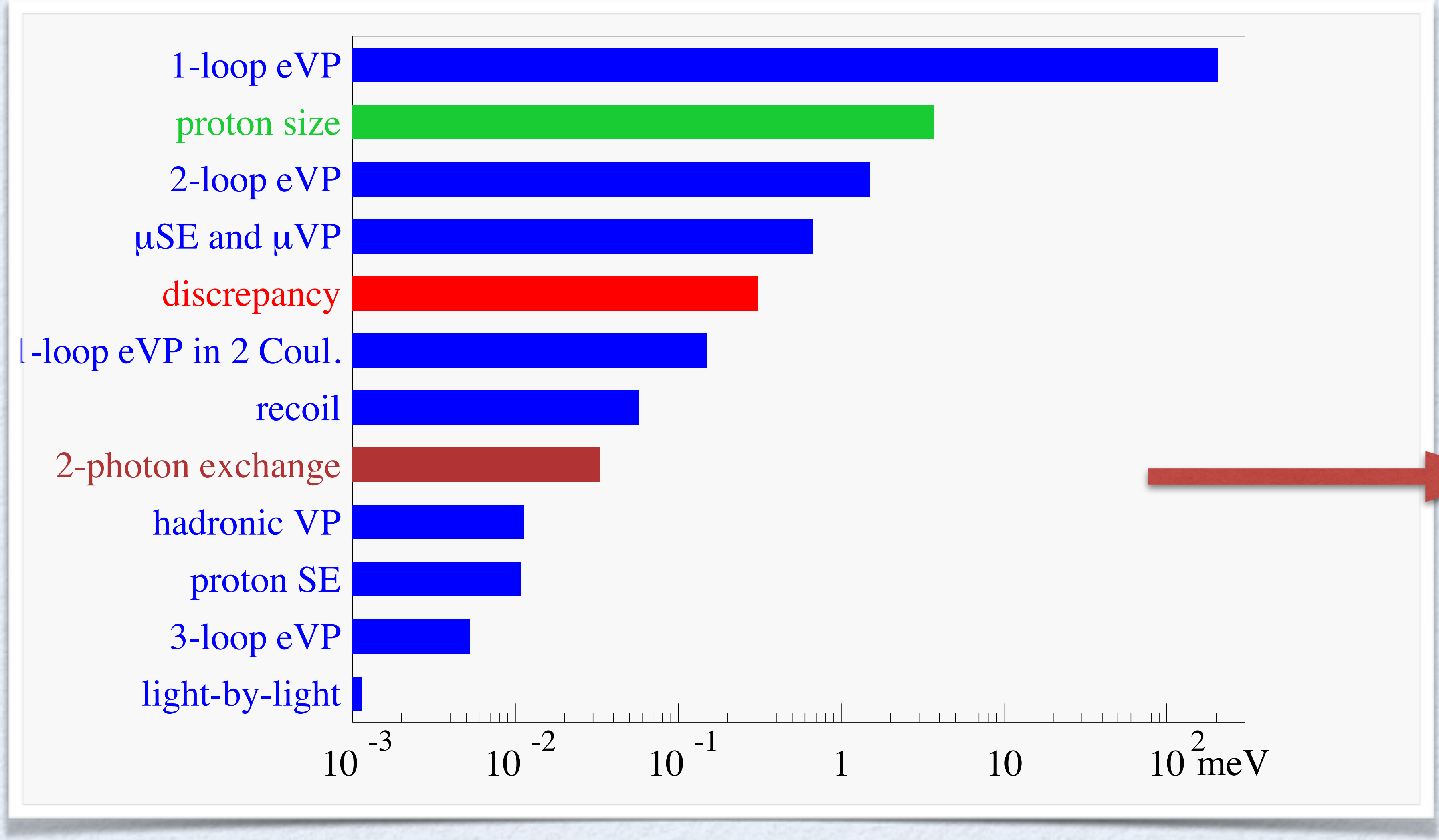
- 3 out of 6 new results are fully consistent with muonic hydrogen result
- inconsistency between Fleurbaey et al. (Paris) and Grinin et al. (Garching) results for 1S-3S H : Grinin et al.: factor 2 more precise, ~2σ smaller than Fleurbaey et al., ~2σ larger than μH result
- Brandt et al. (Colorado) result is ~3σ larger than CODATA 2018 / muonic atom spect.

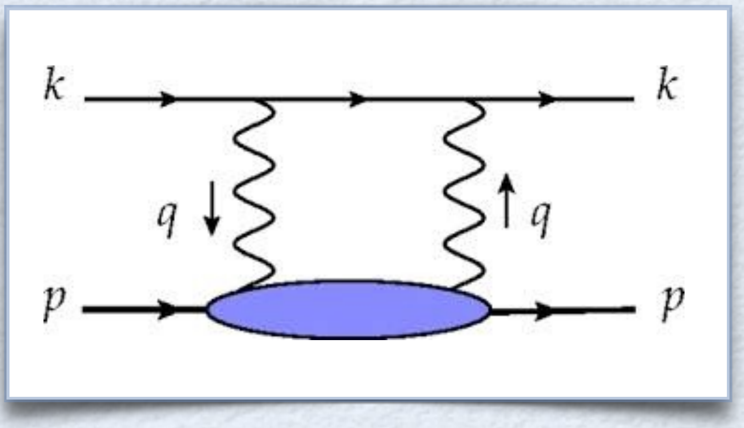
vigorous ongoing program in electron/muon scattering

talks: Denig, Quintans, Gao

Lamb shift: status of theory

μH Lamb shift: summary of corrections





largest theoretical uncertainty

total hadronic correction on Lamb shift

- elastic contribution on 2S level: ΔE_{2S} = -23 μeV
- inelastic contribution: `Carlson, Vdh (2011) + Birse, McGovern (2012)`

ΔE_{TPE} (2P-2S) = (33 ± 2) μeV

For H: present accuracy comparable with experimental precision δ_{exp} (ΔE_{LS}) = 2.3 μeV

Muonic atom spectroscopy needs nucleon/nuclear input

2S-2P
Lamb Shift:

THEORY **EXPERIMENT**

	$\Delta E_{TPE} \pm \delta_{theo}\ (\Delta E_{TPE})$	Ref.	$\delta_{exp}(\Delta_{LS})$	Ref.
μH	33 μeV $\pm$ 2 μeV	Antognini et al. (2013)	2.3 μeV	Antognini et al. (2013)
μD	1710 μeV $\pm$ 15 μeV	Krauth et al. (2015)	3.4 μeV	Pohl et al. (2016)
μ^3He$^+$	15.30 meV $\pm$ 0.52 meV	Franke et al. (2017)	0.05 meV	
μ^4He$^+$	9.34 meV $\pm$ 0.25 meV -0.15 meV $\pm$ 0.15 meV (3PE)	Diepold et al. (2018) Pachucki et al. (2018)	0.05 meV	Krauth et al. (2020)

μH:

present accuracy comparable with experimental precision

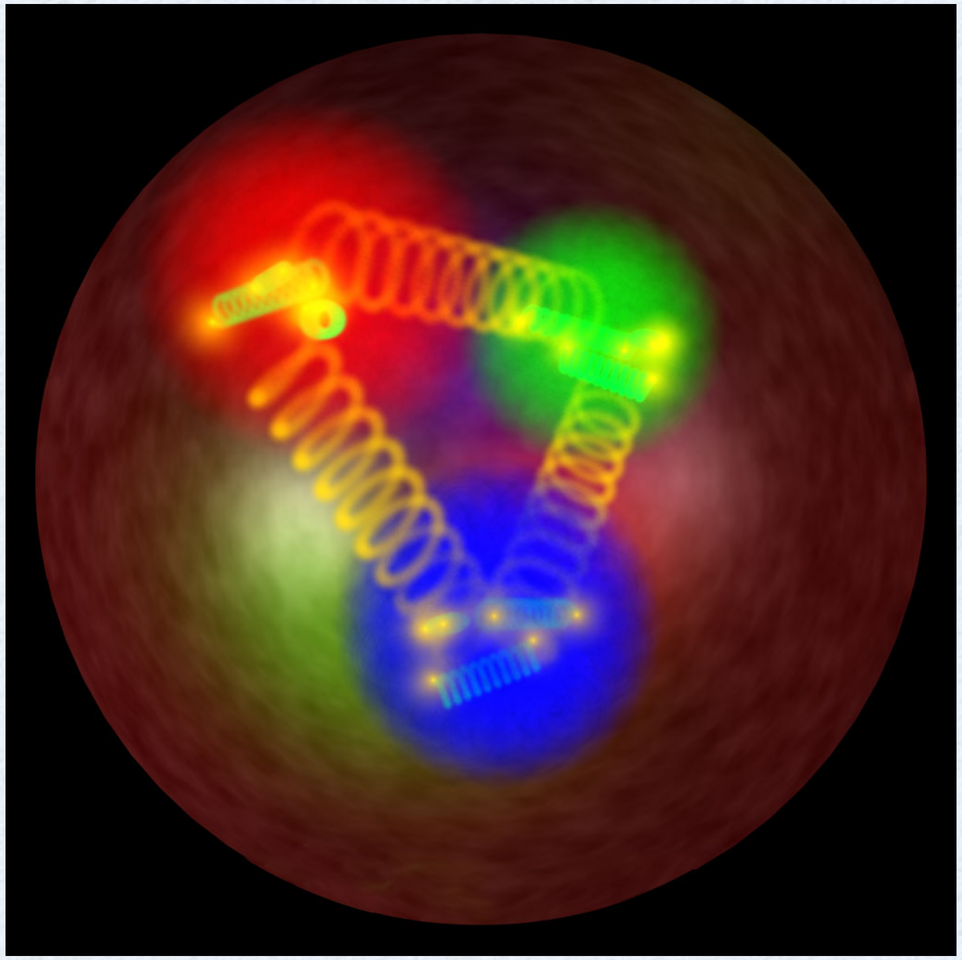
Future: factor 5 improvement on Lamb shift planned @PSI

CREMA, FAMU, J-PARC: 1S hyperfine splitting in μH to 1ppm

μD, μ^{3}He$^+$, μ^{4}He$^+$:

present accuracy factor 5-10 worse than experimental precision

Imaging of partons in hadrons



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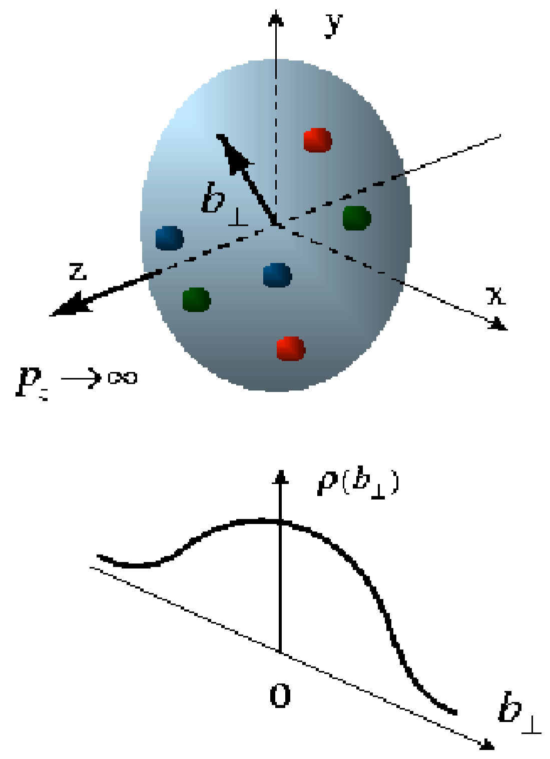
APS physics

Volume 100, Number 3

Quark transverse charge densities in nucleon in IMF

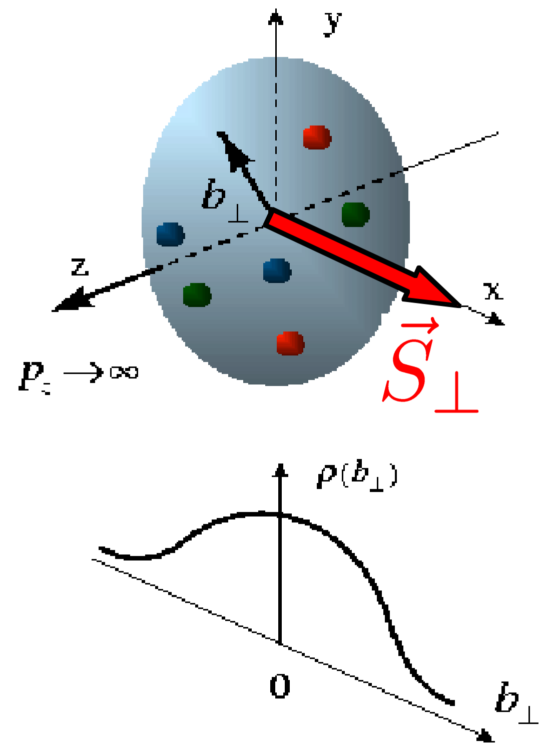
transverse c.m. can be fixed in a light-front frame



- longitudinally polarized nucleon

$$\rho_0^N(\vec{b}) \equiv \int \frac{d^2\vec{q}_\perp}{(2\pi)^2}\, e^{-i\vec{q}_\perp\cdot\vec{b}}\, \frac{1}{2P^+} \langle P^+, \frac{\vec{q}_\perp}{2}, \lambda | J^+(0) | P^+, -\frac{\vec{q}_\perp}{2}, \lambda \rangle$$
$$= \int_0^\infty \frac{dQ}{2\pi}\, Q J_0(bQ) F_1(Q^2)$$

Soper (1997) Burkardt (2000) Miller (2007)



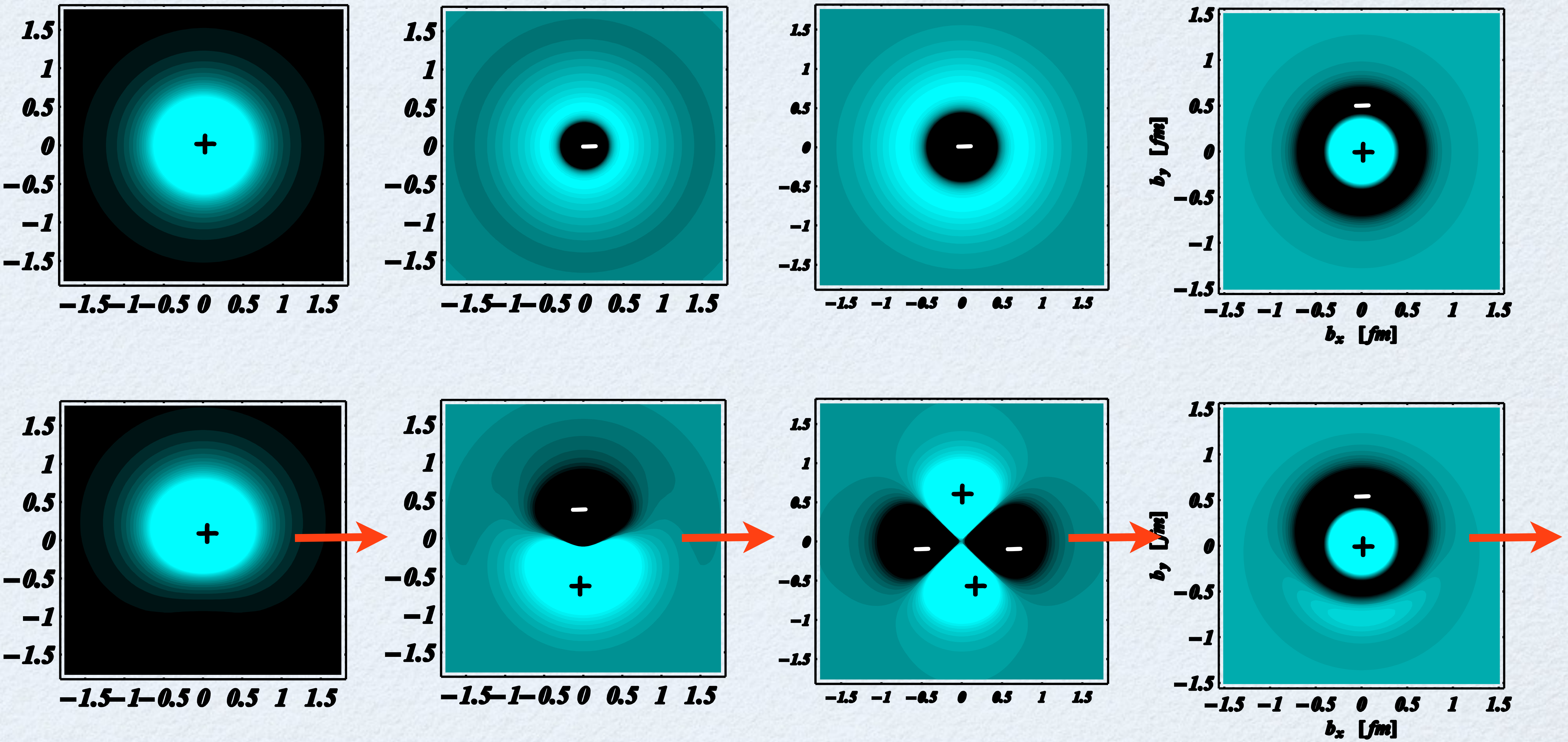
- transversely polarized nucleon

$$\rho_T^N(\vec{b}) \equiv \int \frac{d^2\vec{q}_\perp}{(2\pi)^2}\, e^{-i\vec{q}_\perp\cdot\vec{b}}\, \frac{1}{2P^+} \langle P^+, \frac{\vec{q}_\perp}{2}, s_\perp = +\frac{1}{2} | J^+(0) | P^+, -\frac{\vec{q}_\perp}{2}, s_\perp = +\frac{1}{2} \rangle$$
$$= \rho_0^N(b) + \sin(\phi_b - \phi_S) \int_0^\infty \frac{dQ}{2\pi}\, \frac{Q^2}{2M}\, J_1(bQ) F_2(Q^2)$$

dipole field pattern

Carlson, Vdh (2007)

Spatial imaging of hadrons



proton

neutron

p -> Δ^+

p -> $N(1440)1/2^+$

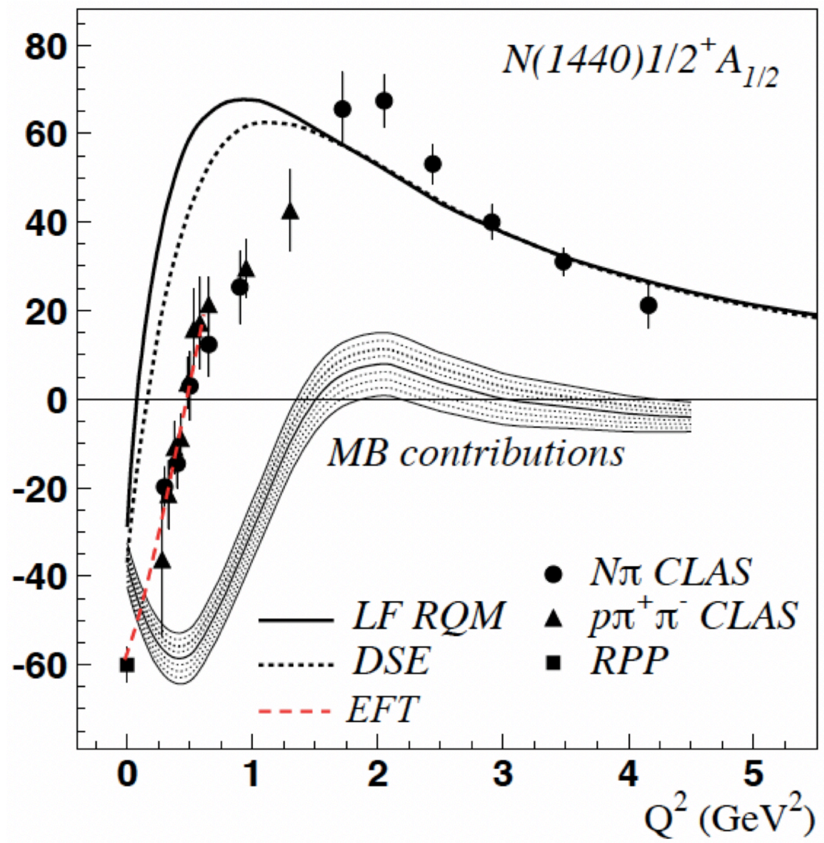
Miller(2007)

Carlson, Vdh(2007)

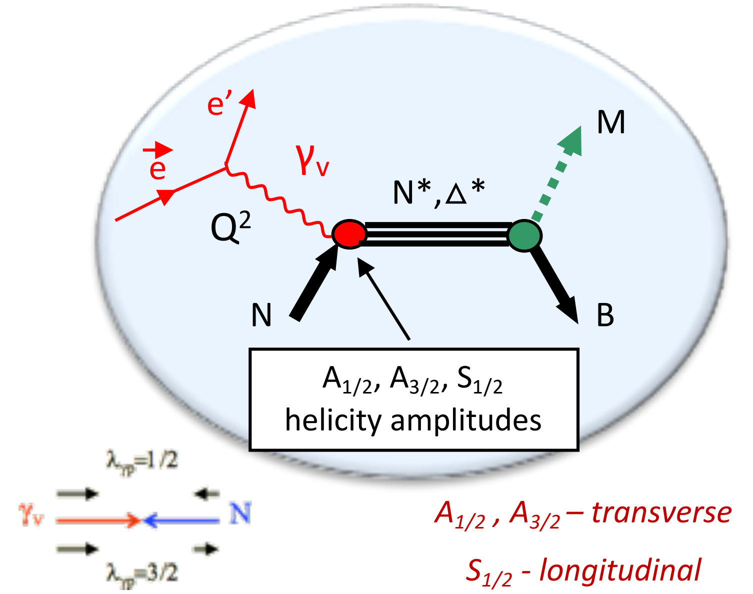
Tiator, Vdh(2007)

$N \rightarrow N(1440)1/2^+$ transition densities

talk: D'Angelo

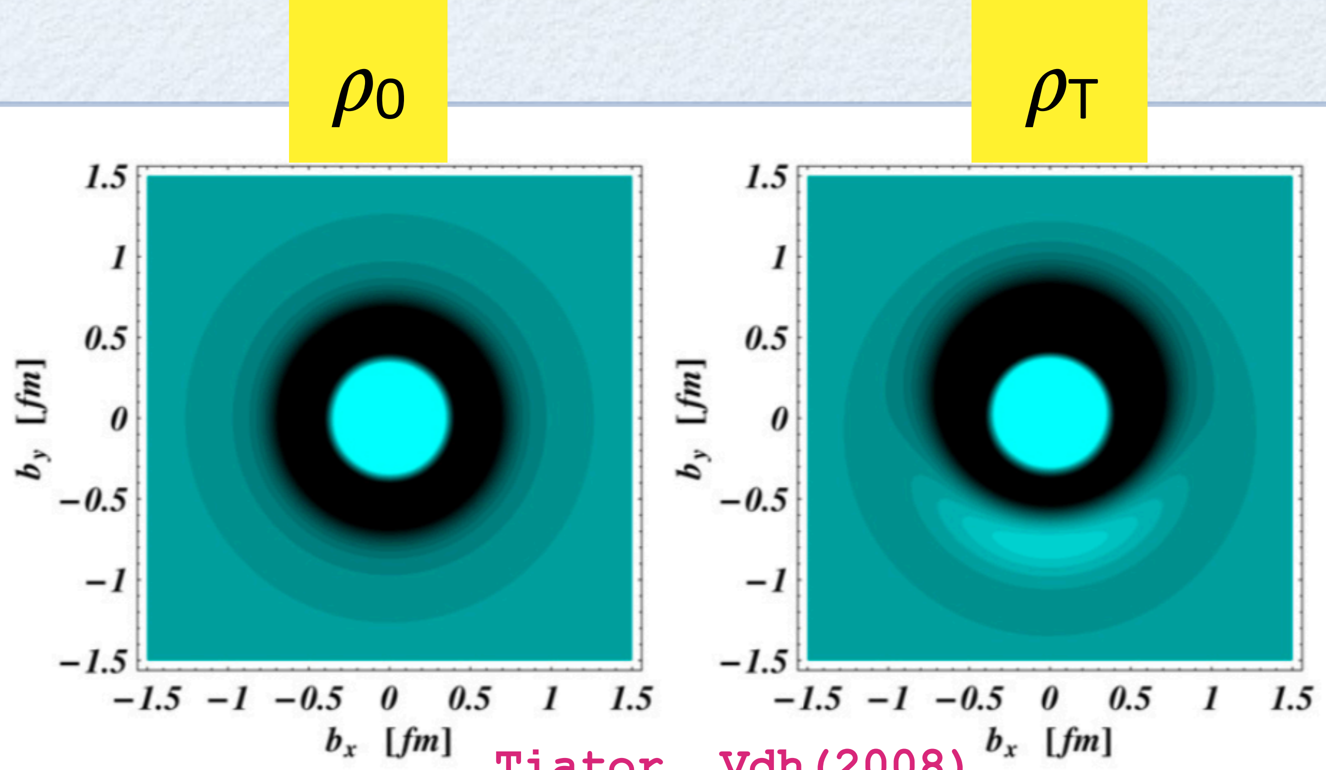


`Burkert, Roberts(2019)`



$A_{1/2}$, $A_{3/2}$ – transverse

$S_{1/2}$ - longitudinal

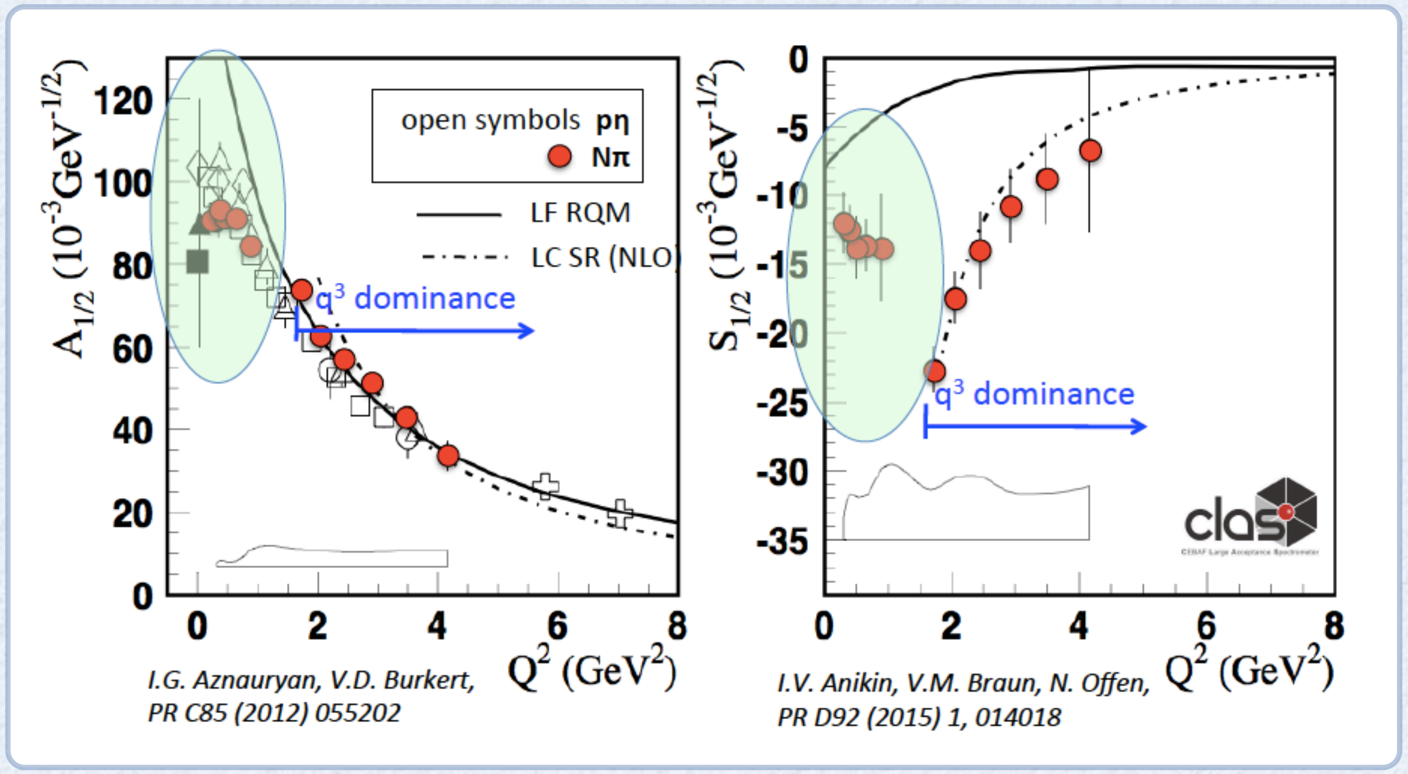


`Tiator, Vdh(2008)`

Nature of 1st radial excitation of nucleon:

consistent with u-quark core screened by mesonic tail

N → N*, Δ* transition form factors / densities



I.G. Aznauryan, V.D. Burkert, PR C85 (2012) 055202

I.V. Anikin, V.M. Braun, N. Offen, PR D92 (2015) 1, 014018

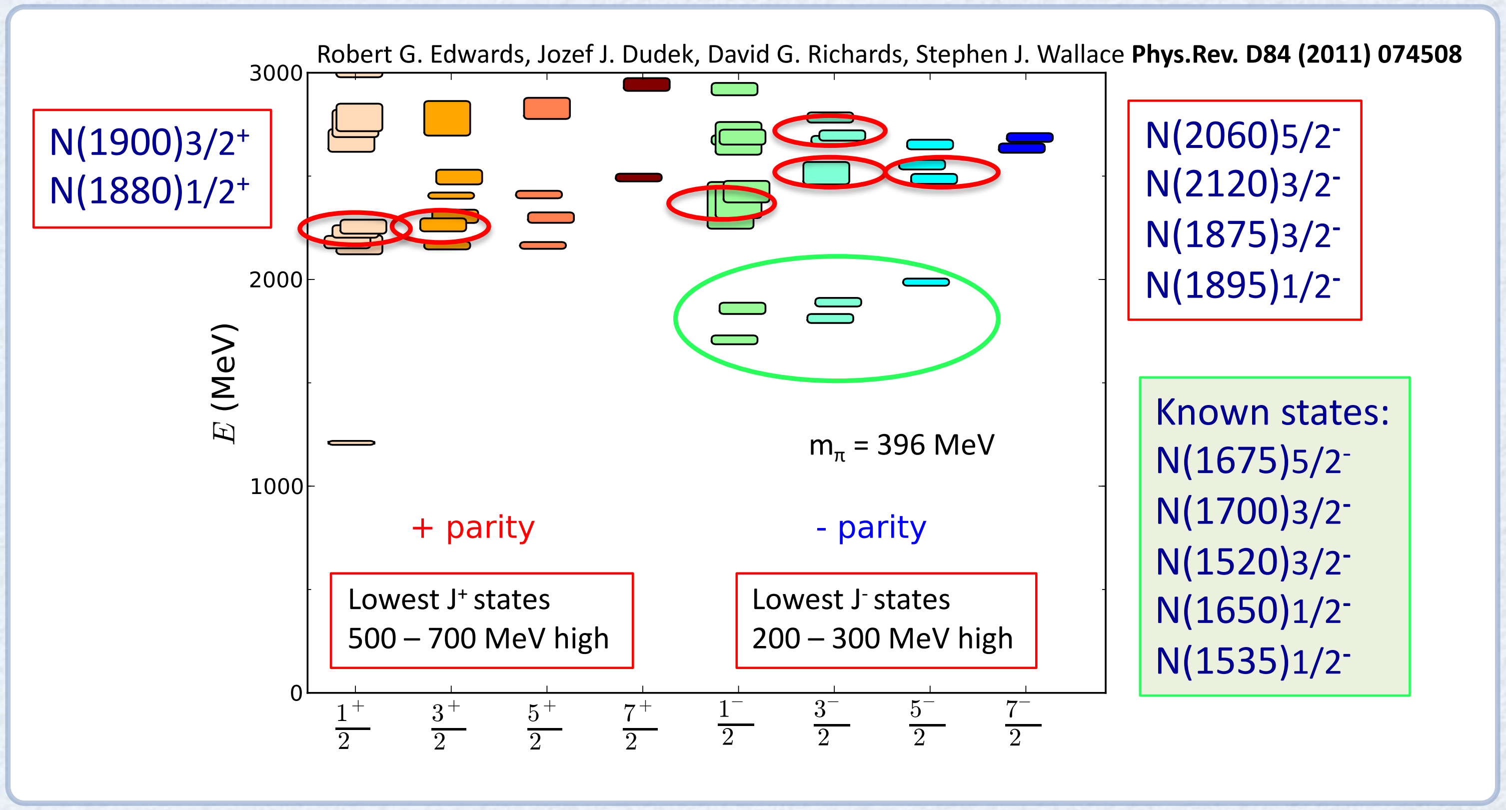
N → N(1535)$1/2^-$

Interpretation consistent with first orbital excitation of nucleon

talk: D'Angelo

State N(mass)J^P	PDG pre 2010	PDG 2012	PDG 2021
N(1710)$1/2^+$	***	***	****
N(1880)$1/2^+$		**	***
N(1895)$1/2^-$		**	****
N(1900)$3/2^+$	**	***	****
N(1875)$3/2^-$		***	***
N(2120)$3/2^-$		**	***
N(2000)$5/2^+$	*		**
N(2060)$5/2^-$		**	***

Challenge for lattice QCD



Robert G. Edwards, Jozef J. Dudek, David G. Richards, Stephen J. Wallace **Phys.Rev. D84 (2011) 074508**

N(1900)$3/2^+$
N(1880)$1/2^+$

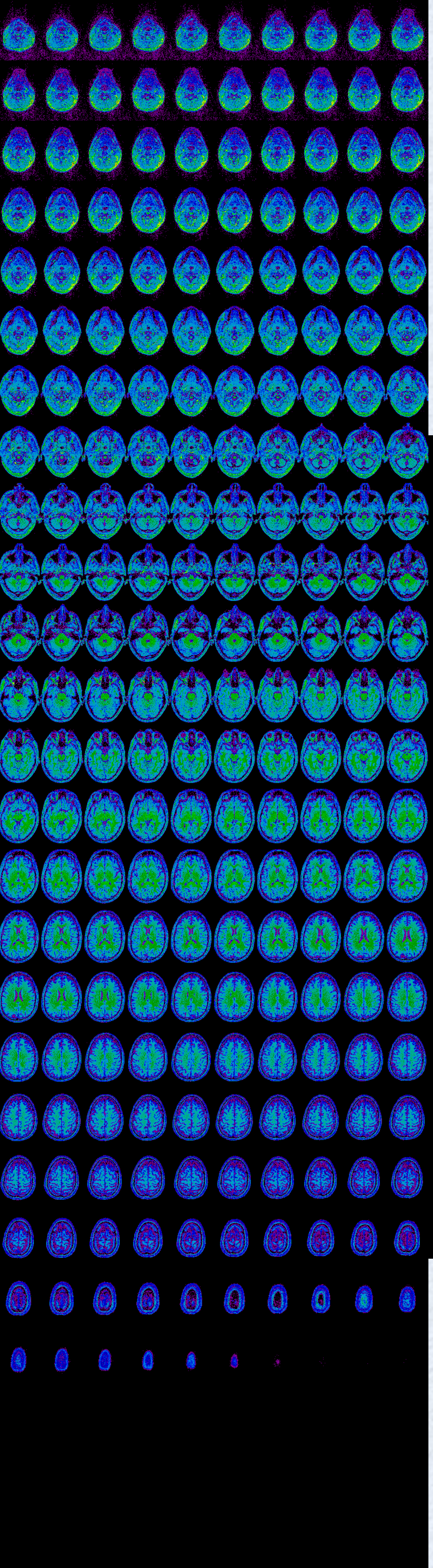
Lowest J^+ states
500 – 700 MeV high

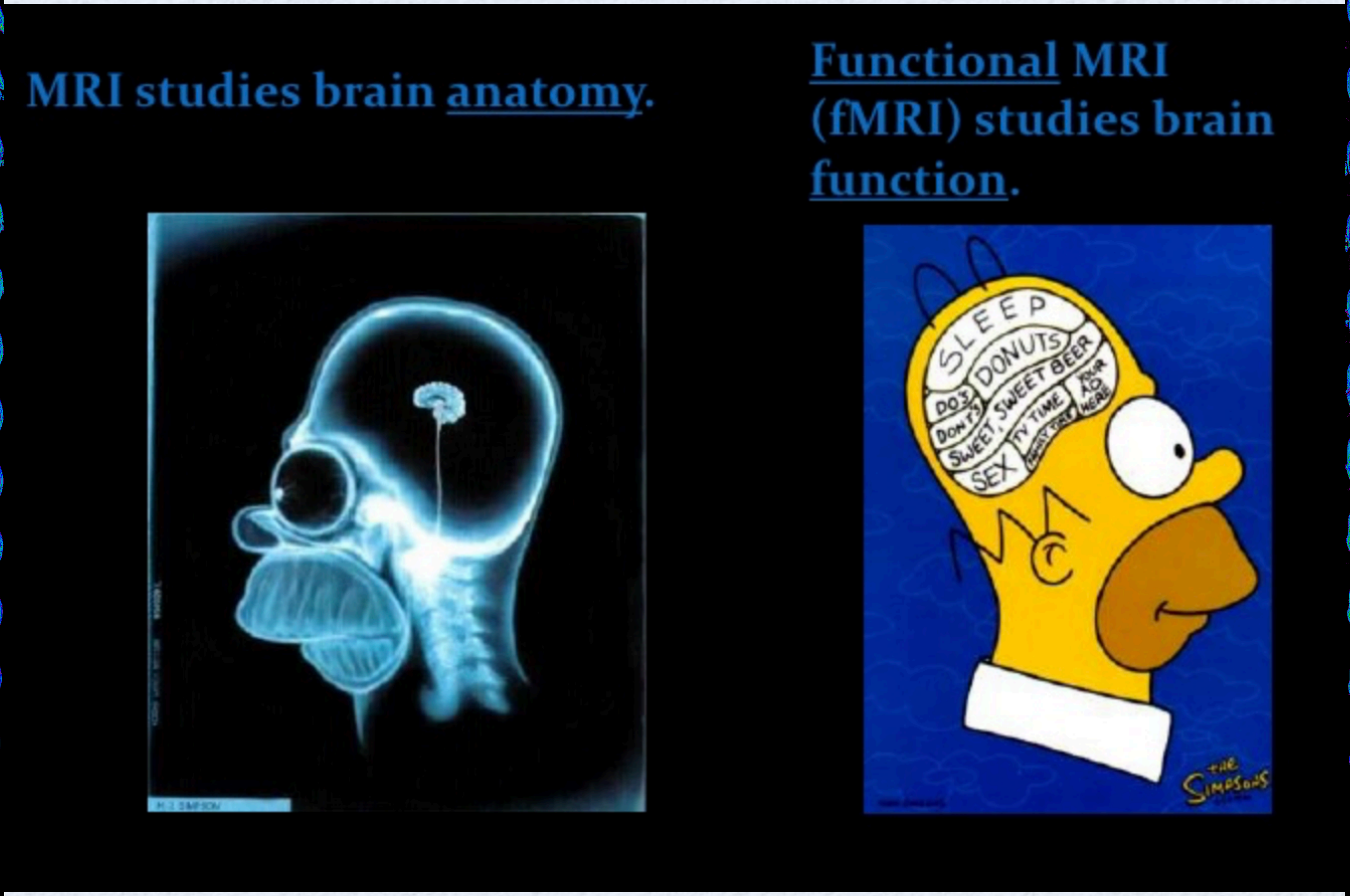
Lowest J^- states
200 – 300 MeV high

N(2060)$5/2^-$
N(2120)$3/2^-$
N(1875)$3/2^-$
N(1895)$1/2^-$

Known states:
N(1675)$5/2^-$
N(1700)$3/2^-$
N(1520)$3/2^-$
N(1650)$1/2^-$
N(1535)$1/2^-$

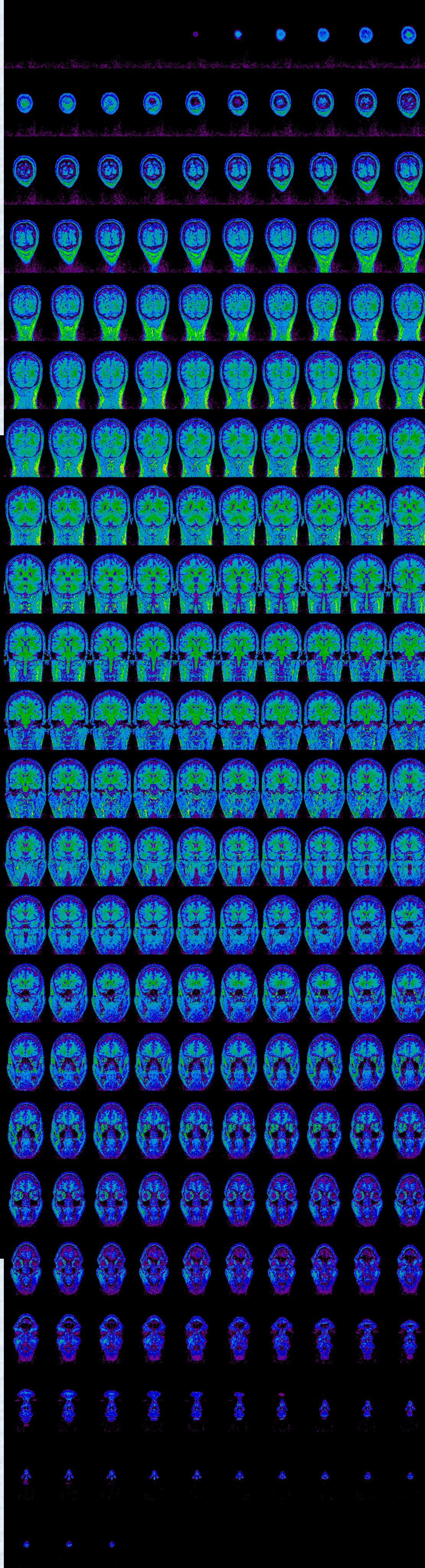
Structure vs dynamics: Quark spatial vs momentum distributions





MRI studies brain anatomy.

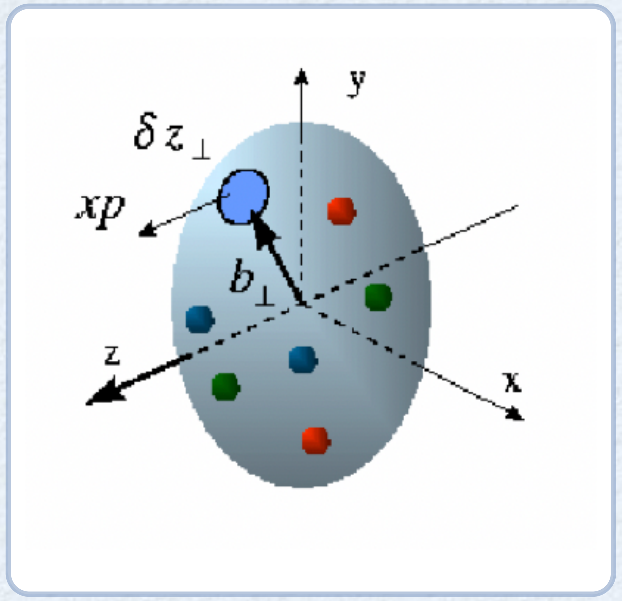
Functional MRI (fMRI) studies brain function.



Correlations in transverse position/longitudinal momentum

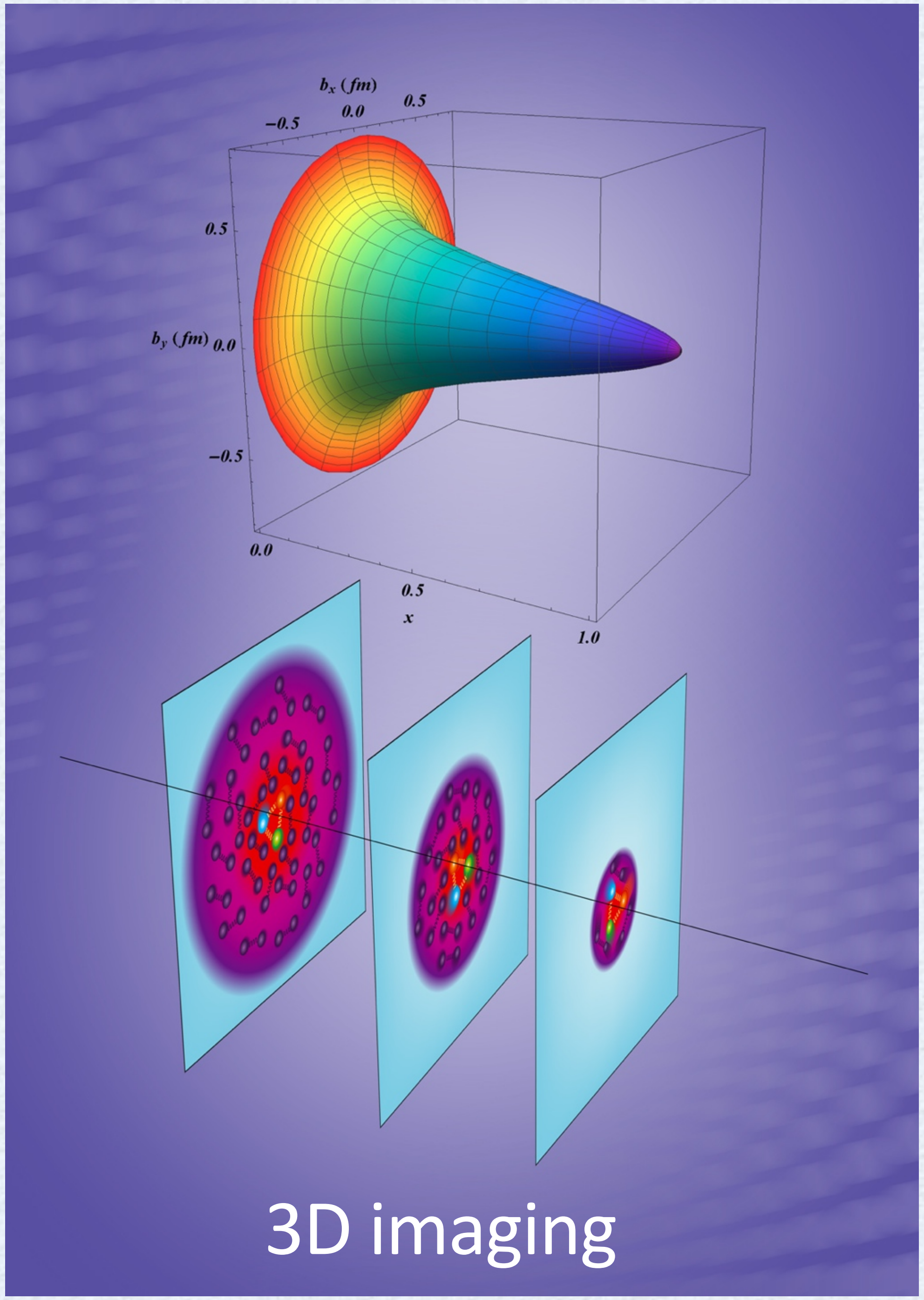
elastic scattering → **GPDs** ← **DIS**

quark distributions in **transverse position space**



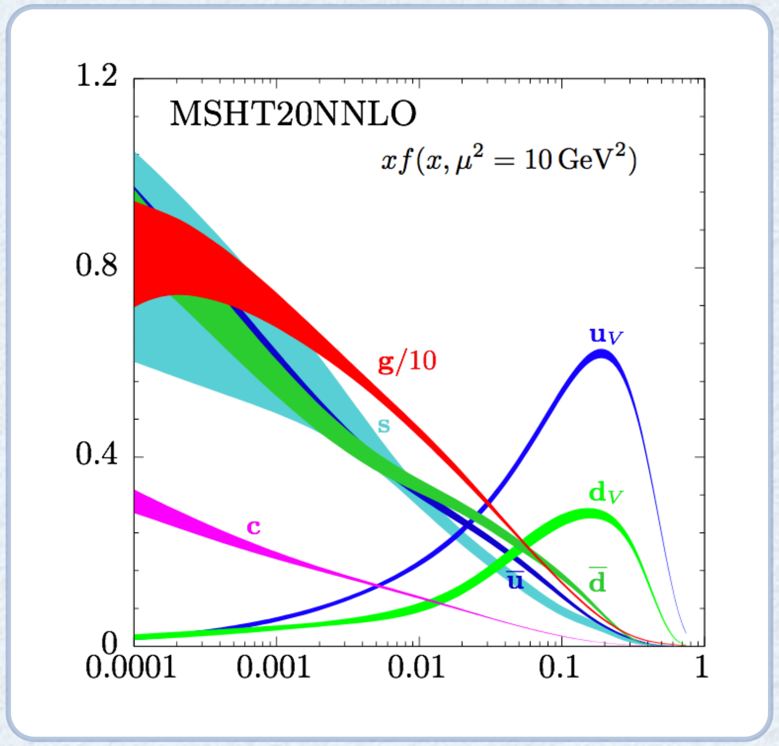
Burkardt(2000, 2003)

Belitsky, Ji, Yuan (2004)



3D imaging

quark distributions in **longitudinal momentum**



Broader picture of nucleon structure:
Generalized Transverse Momentum Distributions

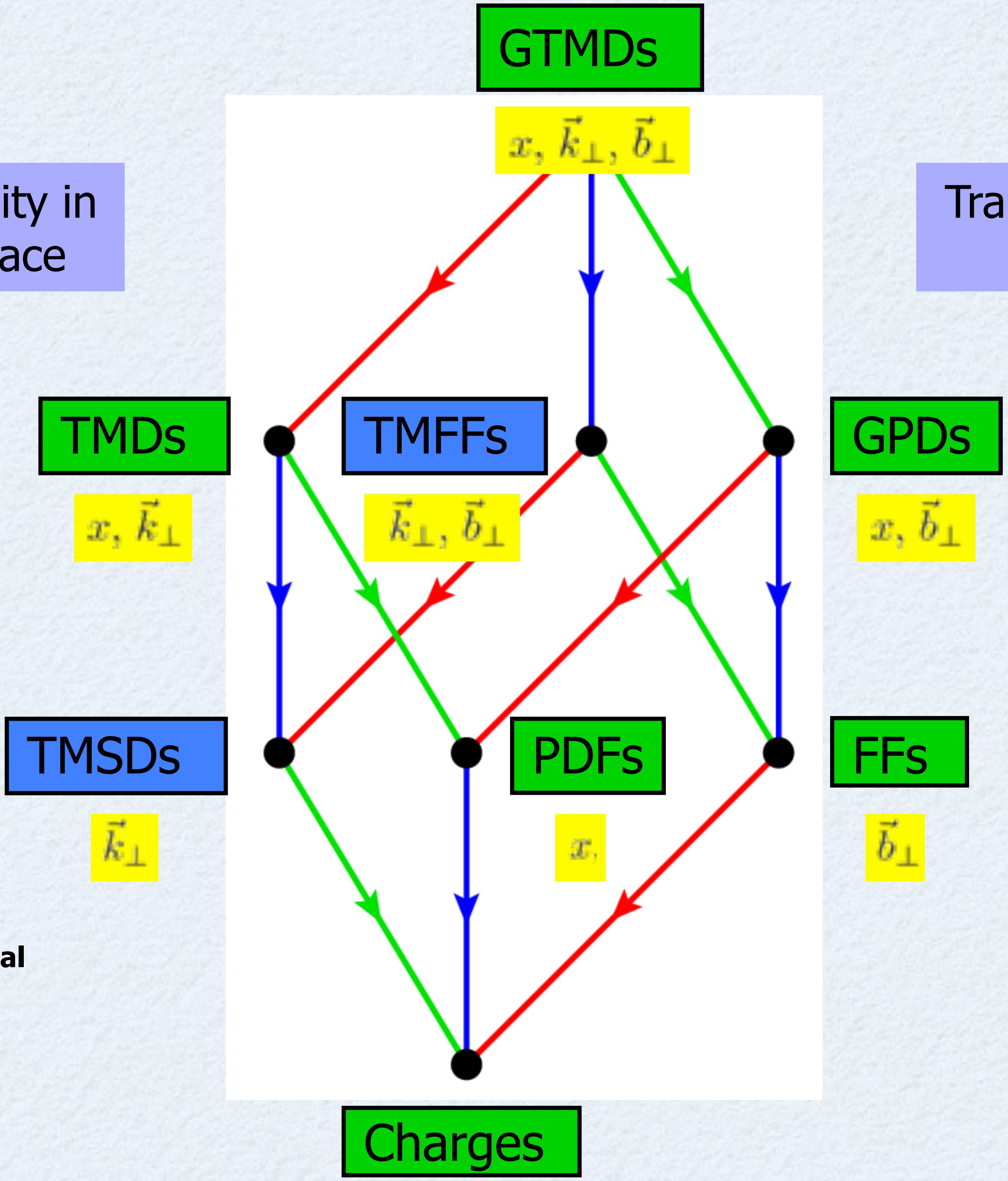
Plenary talks: Meziani, Diehl, Riedl, Nadolsky, Metz, Seidl, Karpie, Voutier
+ talks at dedicated parallel workshop 2

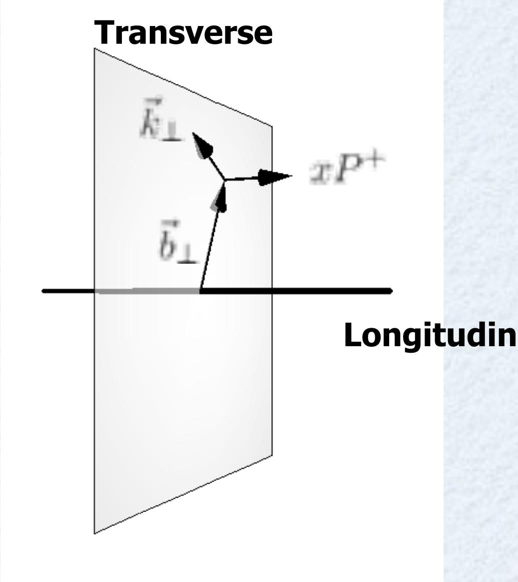
Momentum space	$\vec{k}_\perp \leftrightarrow \vec{z}_\perp$ $\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$	**Position space**

Transverse density in momentum space

Transverse density in position space

Lorcé (2011)





🟥 $\int \mathrm{d}^2 b_\perp$

🟦 $\int \mathrm{d}x$

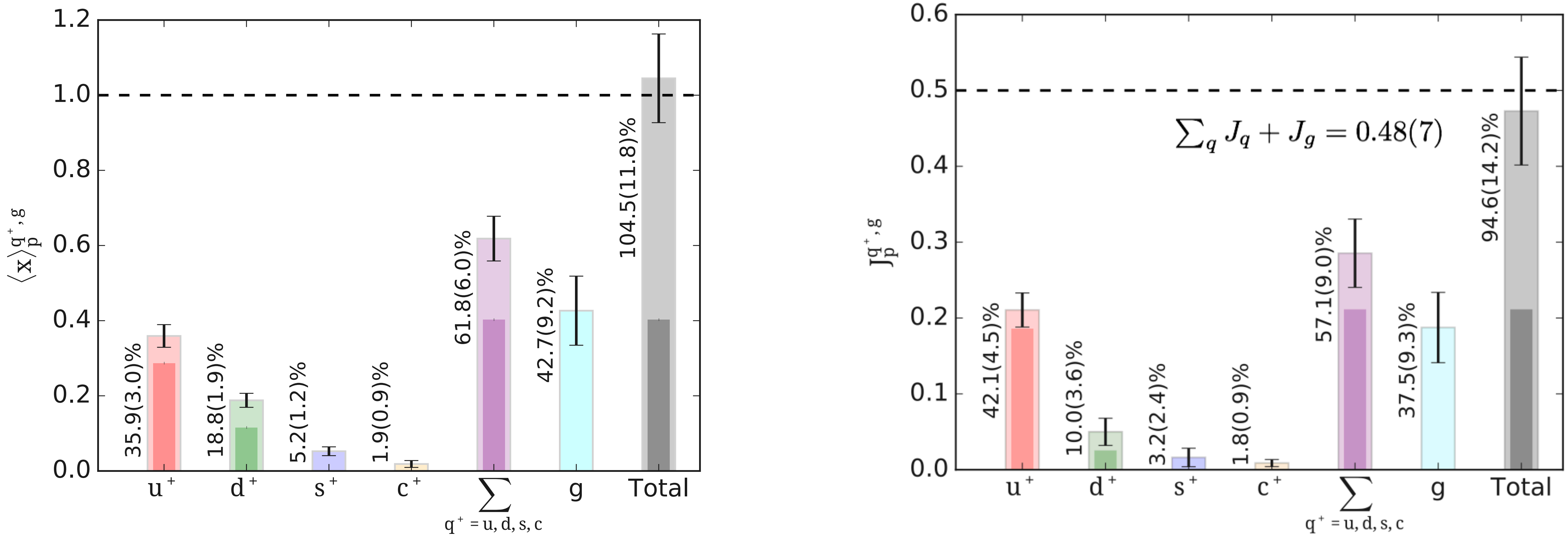
🟩 $\int \mathrm{d}^2 k_\perp$

Nucleon momentum and angular momentum

$$\int_{-1}^{+1} dx\,x\,\{H^q(x,\xi,0) + E^q(x,\xi,0)\} = A(0) + B(0) = 2J^q$$

lattice QCD calculations at the physical point ($\overline{\text{MS}}$ at 2 GeV)

Alexandrou et al. (ETMC) (2020)



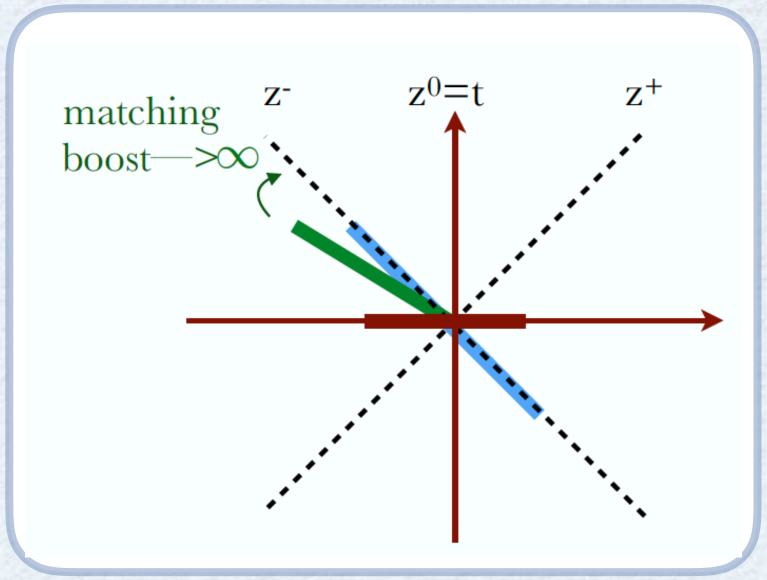
Sharing of momentum and total angular momentum between quarks and gluons nearly identical in proton ! approximately for each parton separately

$$B_{q,g}(0) \approx 0$$

Nucleon quasi/pseudo-PDFs/GPDs from lattice QCD

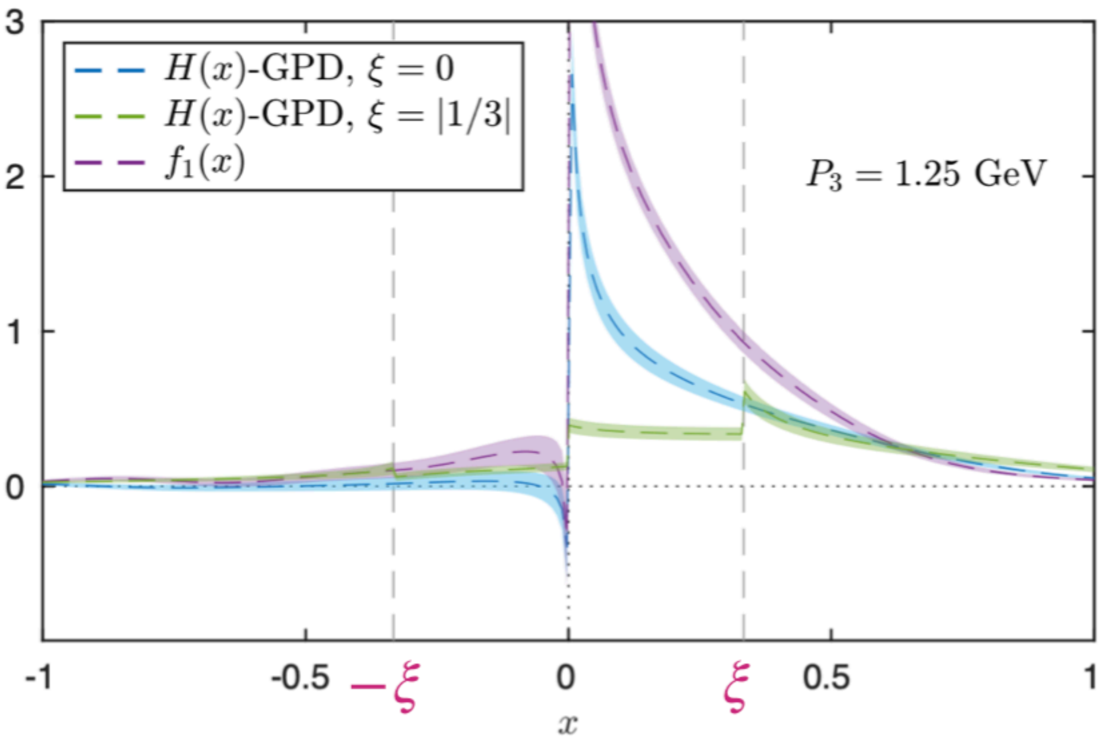
Talks: Karpie, Constantinou

Define spatial correlators (e.g. along z^3)
and boost nucleon state to large momentum

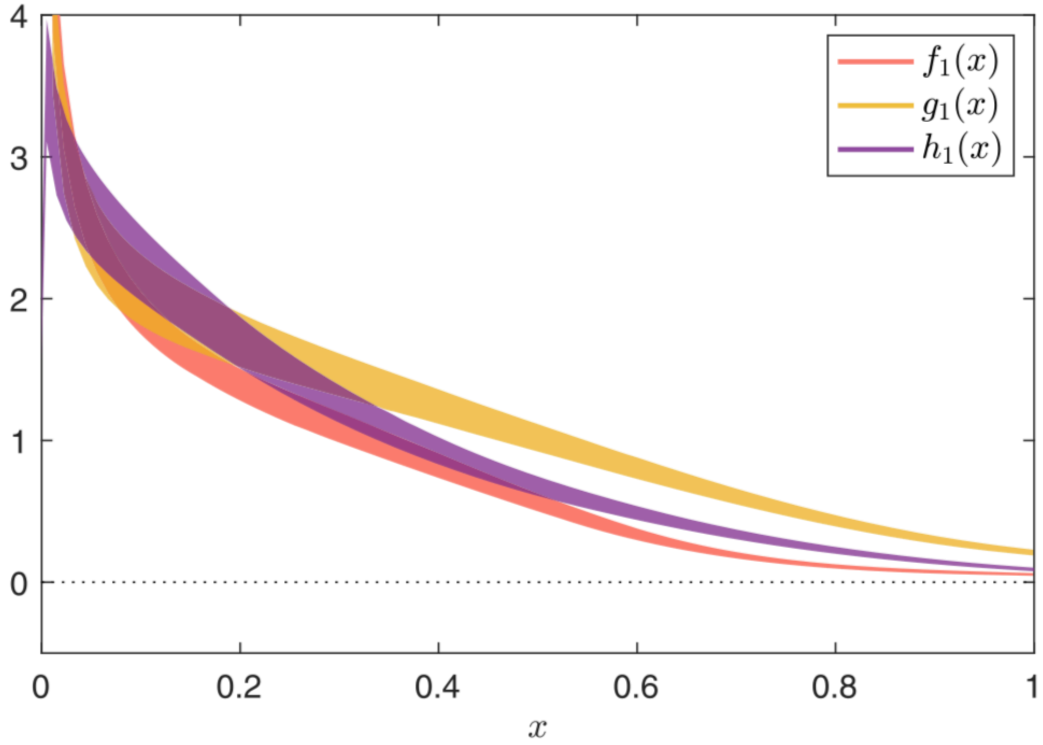


Alexandrou et al.(ETMC) (2020)

m_π= 260 MeV

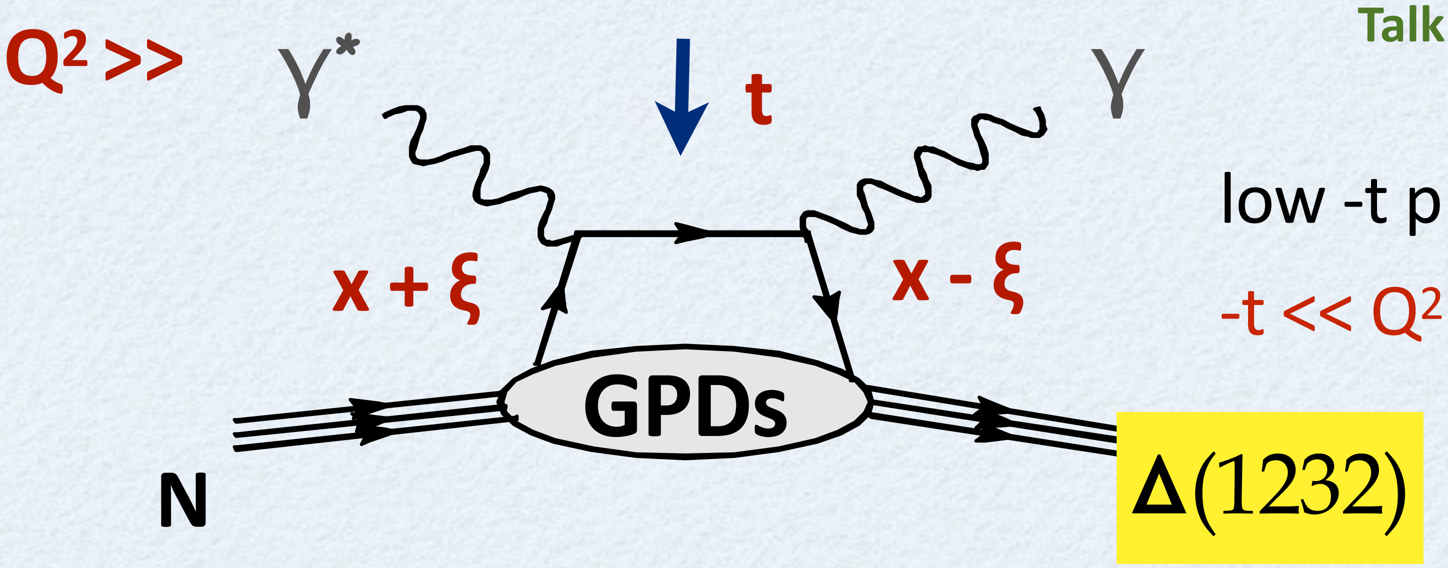


Alexandrou et al.(ETMC) (2022)



Future calculations have the potential to transform the field of GPDs

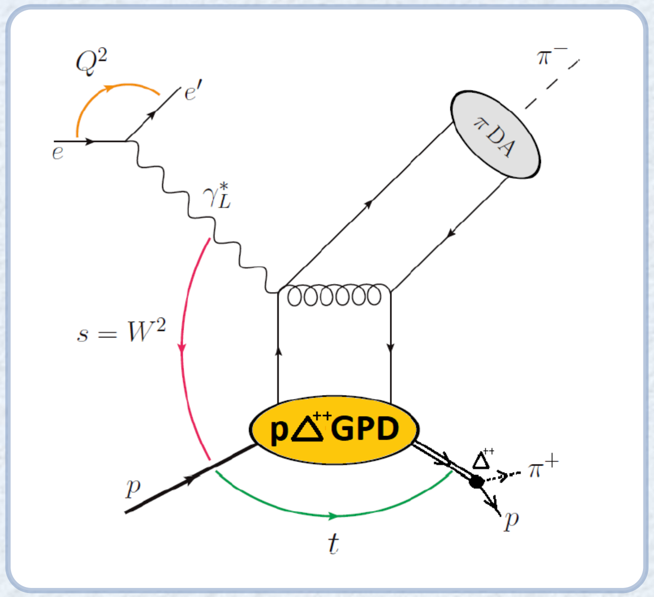
N → Δ(1232) DVCS / DVMP and GPDs



Talk: Voutier

low -t process:

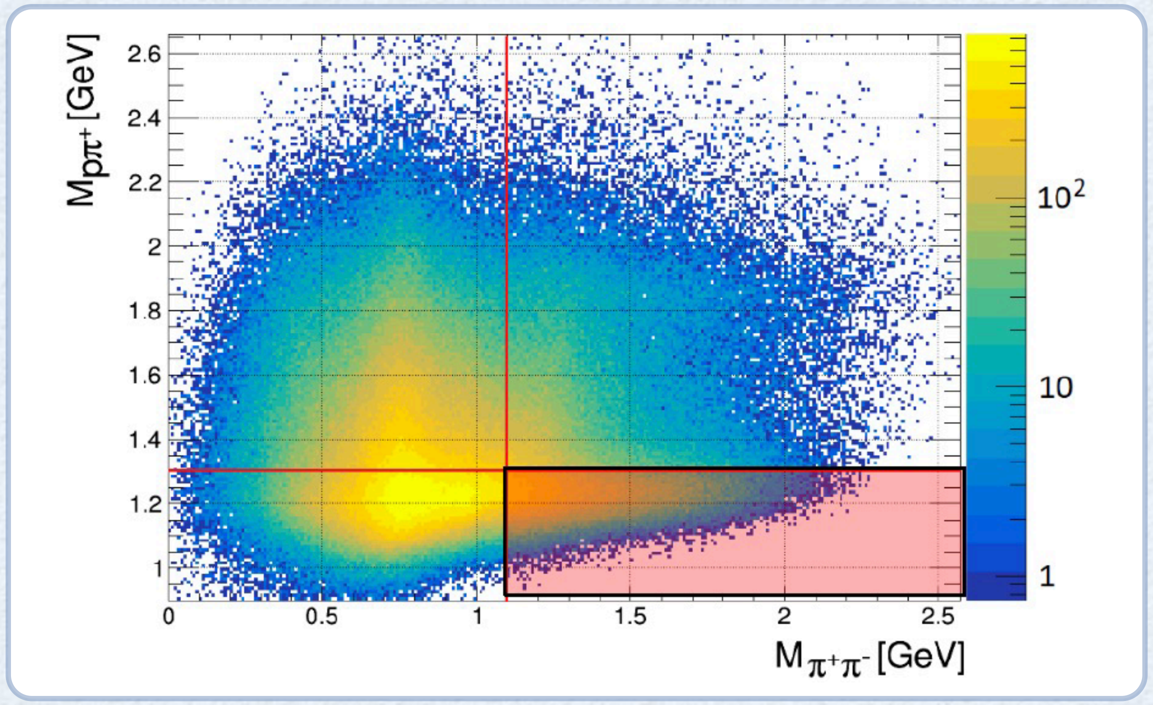
$-t << Q^2$



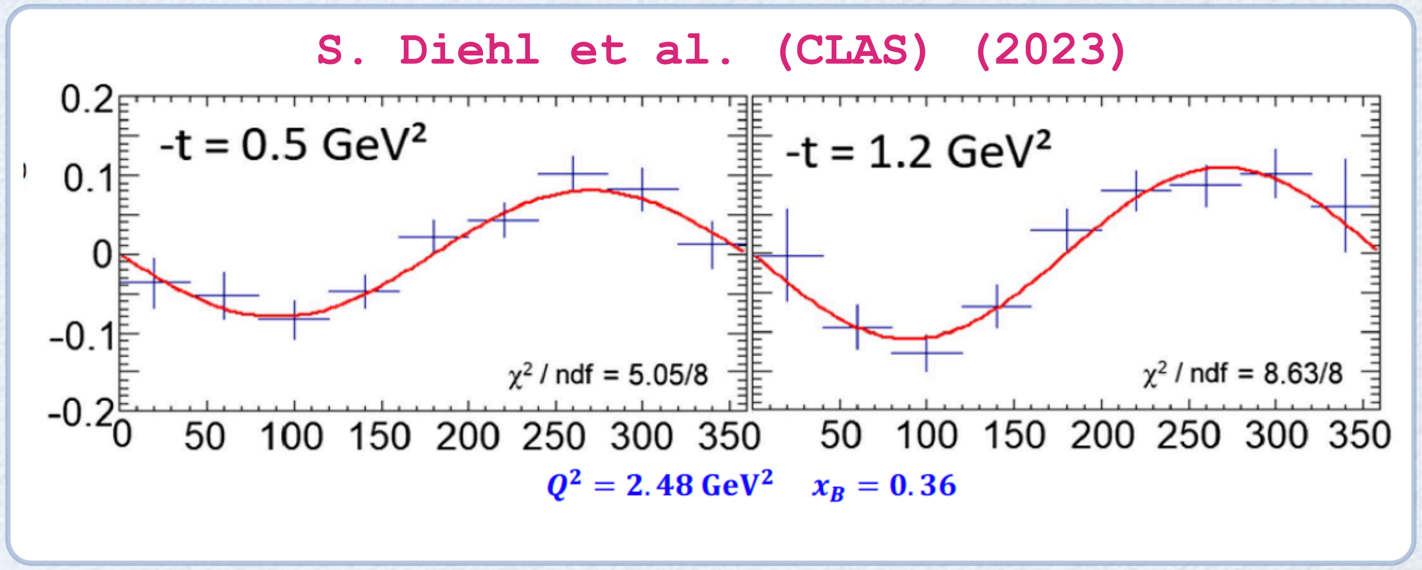
8 helicity conserving and 8 helicity flip **N** → **Δ GPDs(x, ξ, t)**

Recent works: `Kroll, Passek-Kumerički (2023); Semenov-Tian-Shansky, Vdh(2023)`

large N_c relations to N GPDs `Frankfurt,Polyakov, Strikman, Vdh(2000)`



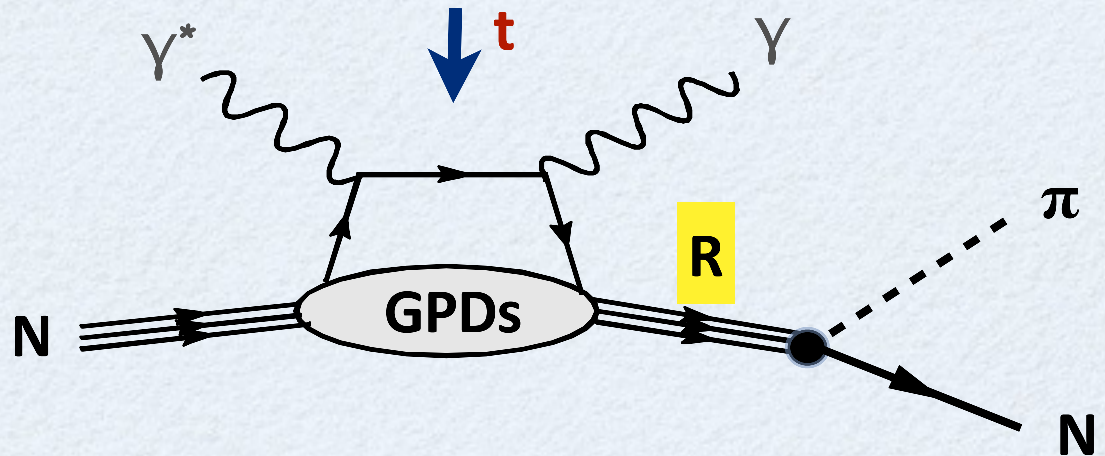
$e^- p \to e^- \pi^- \Delta^{++}(1232)$: BSA

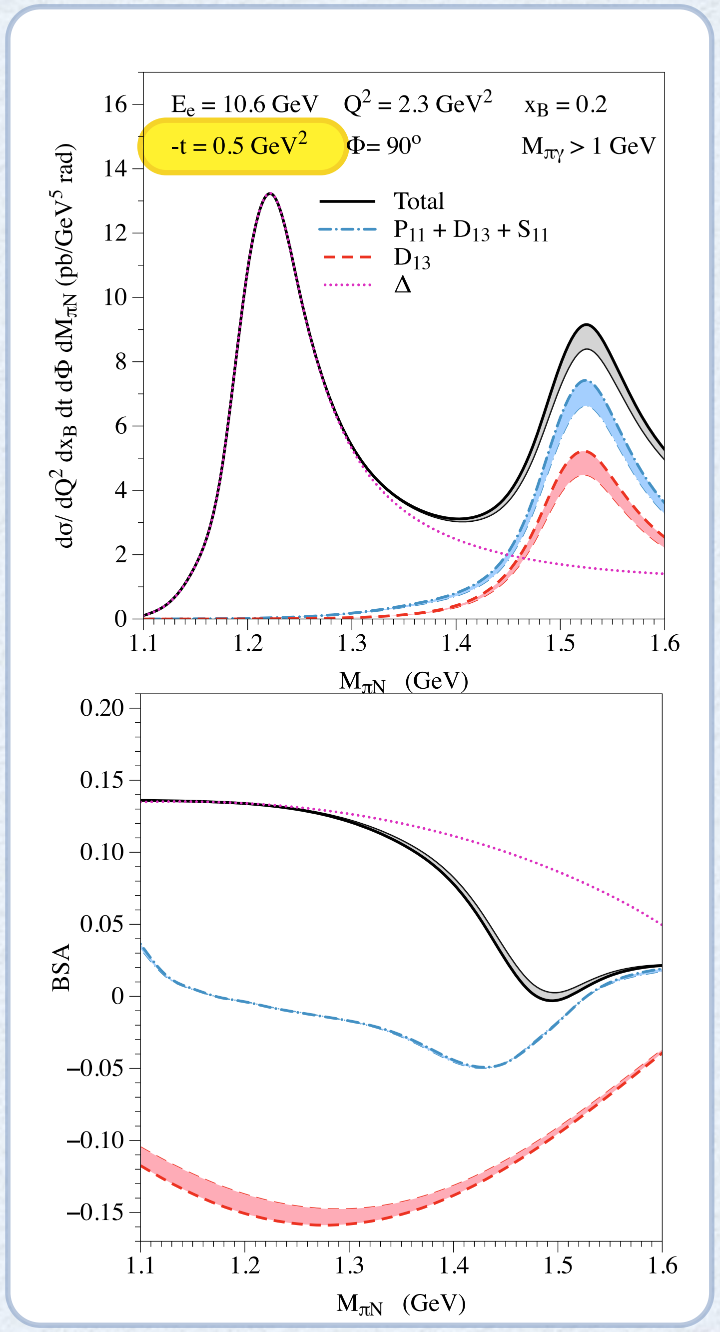


S. Diehl et al. (CLAS) (2023)

$Q^2 = 2.48$ GeV² $x_B = 0.36$

$e^- p \rightarrow e^- \gamma N^* \rightarrow e^- \gamma \pi^+ n$: cross section and BSA





Semenov-Tian-Shansky, Vdh(2023)

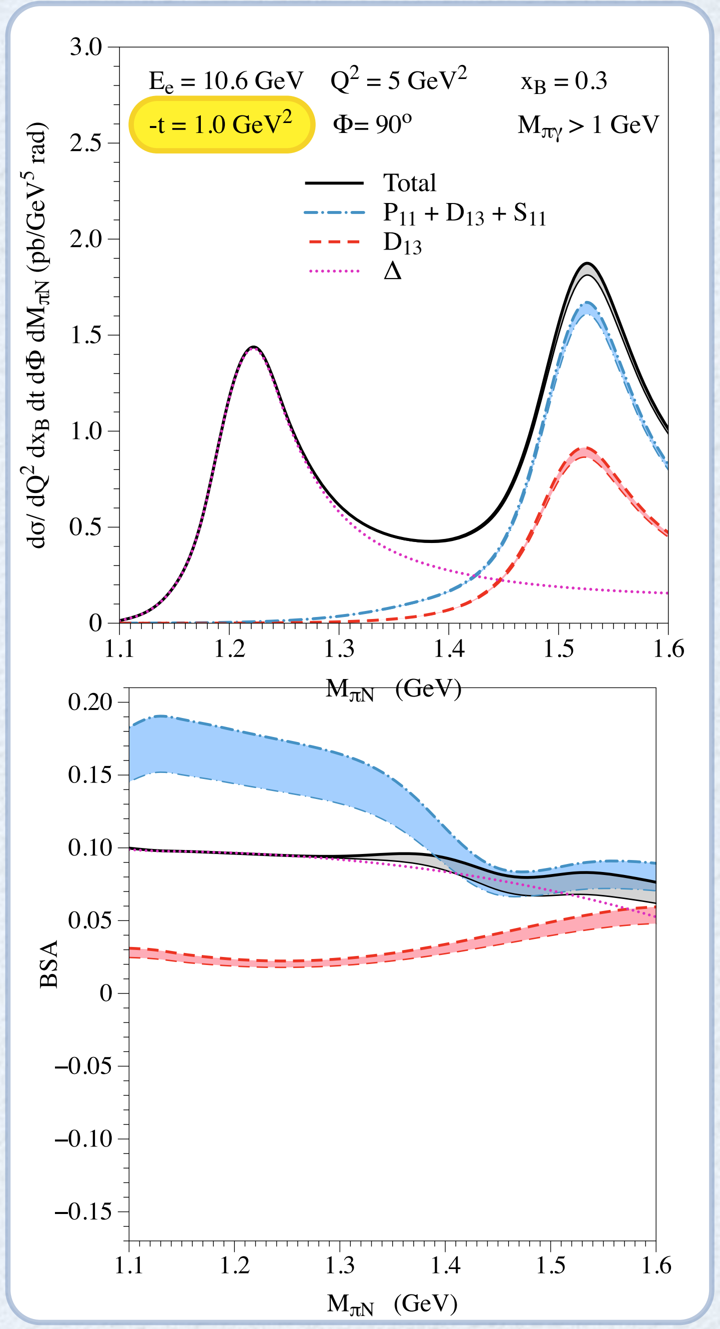
BH + DVCS

with **increasing -t**:

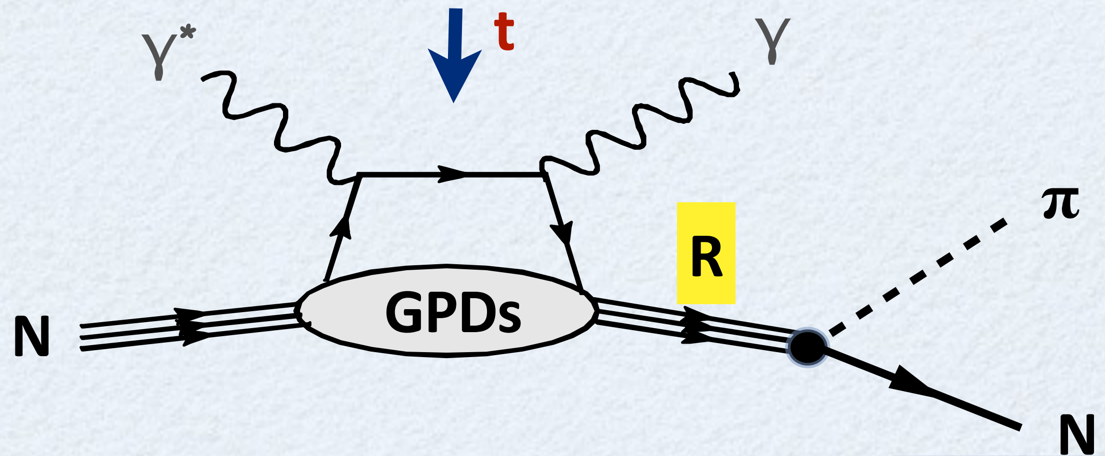
2nd resonance region

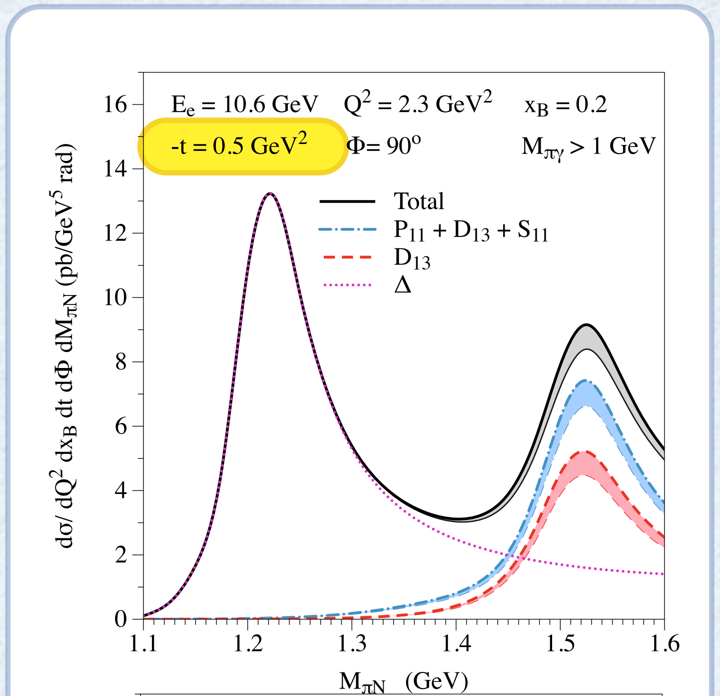
becomes **more**

pronounced



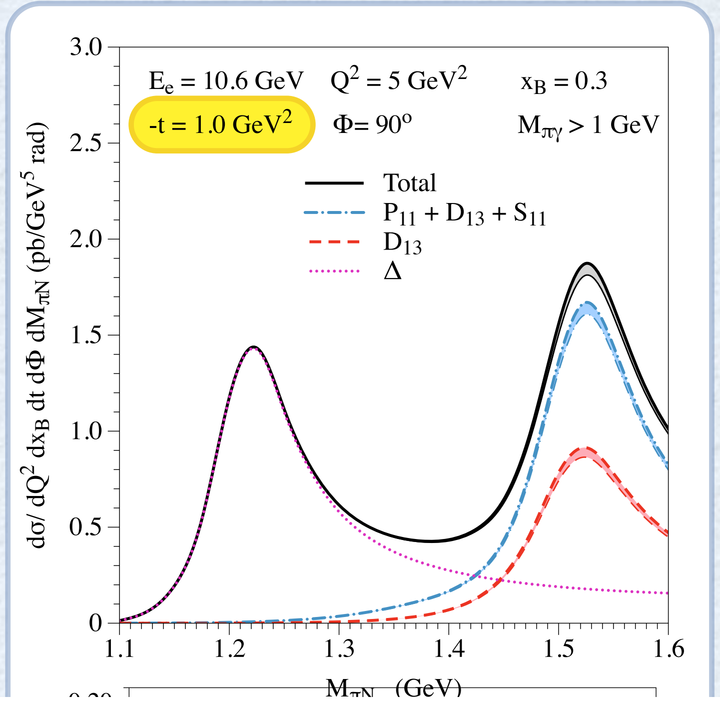
$e^- p \rightarrow e^- \gamma N^* \rightarrow e^- \gamma \pi^+ n$: cross section and BSA

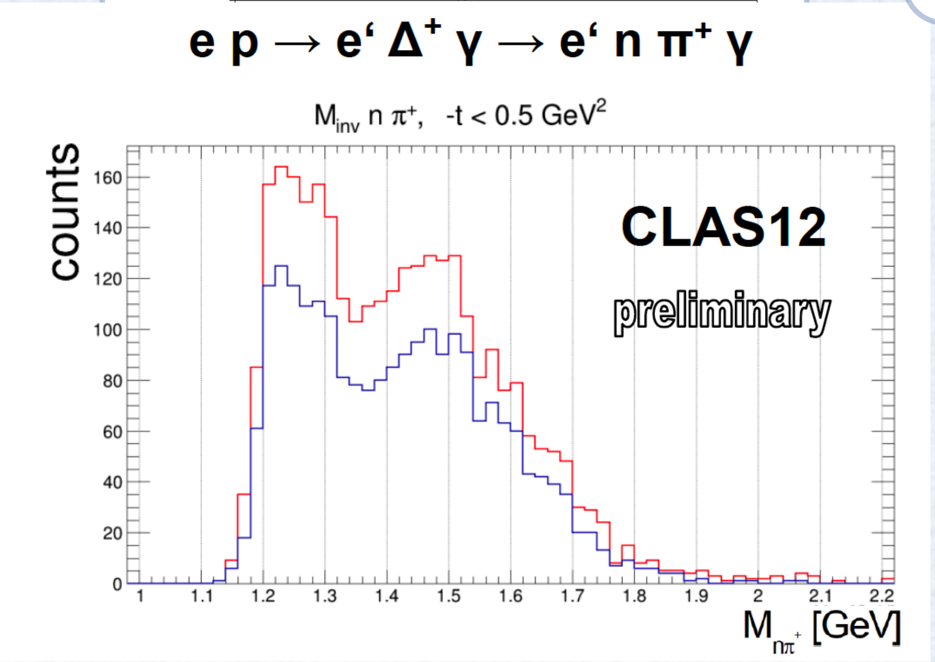


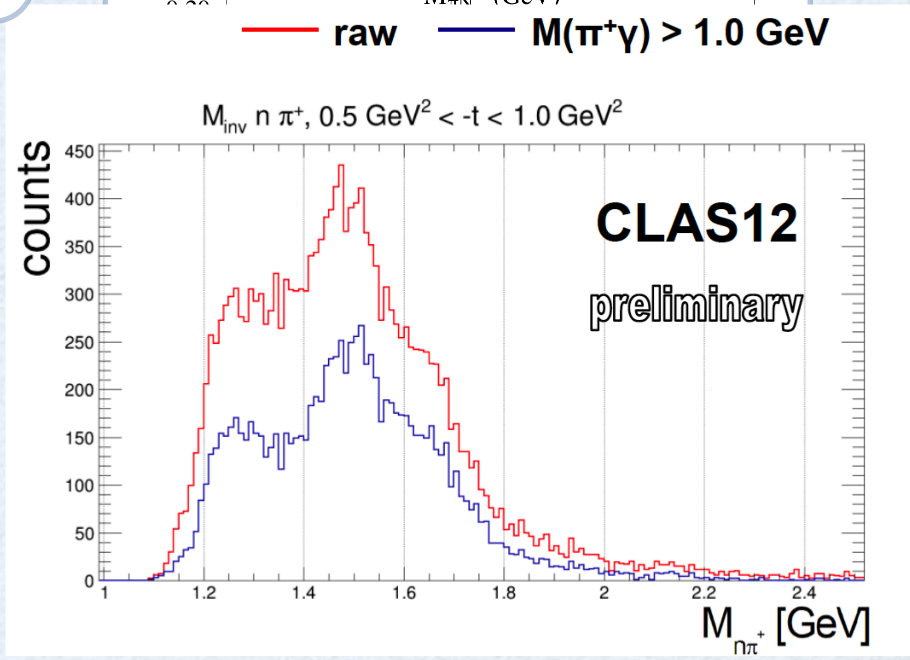


new opportunities for JLab luminosity and energy upgrade

`S.Diehl @ ECT* workshop(2023)`

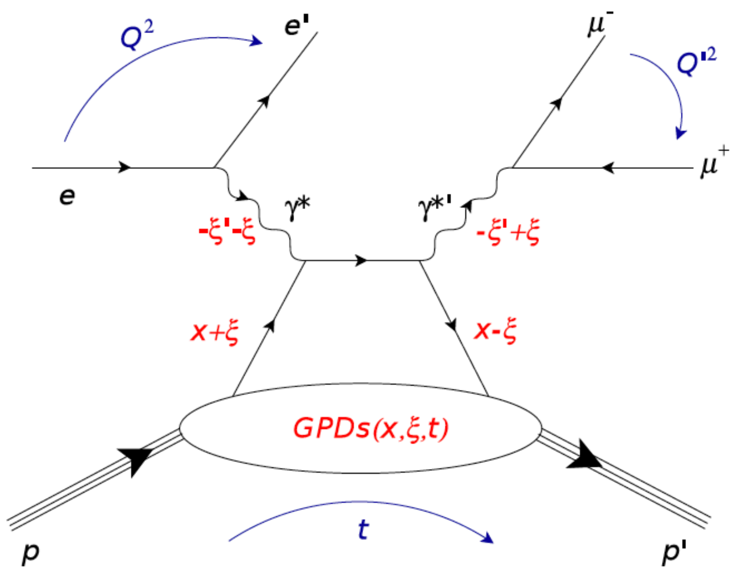






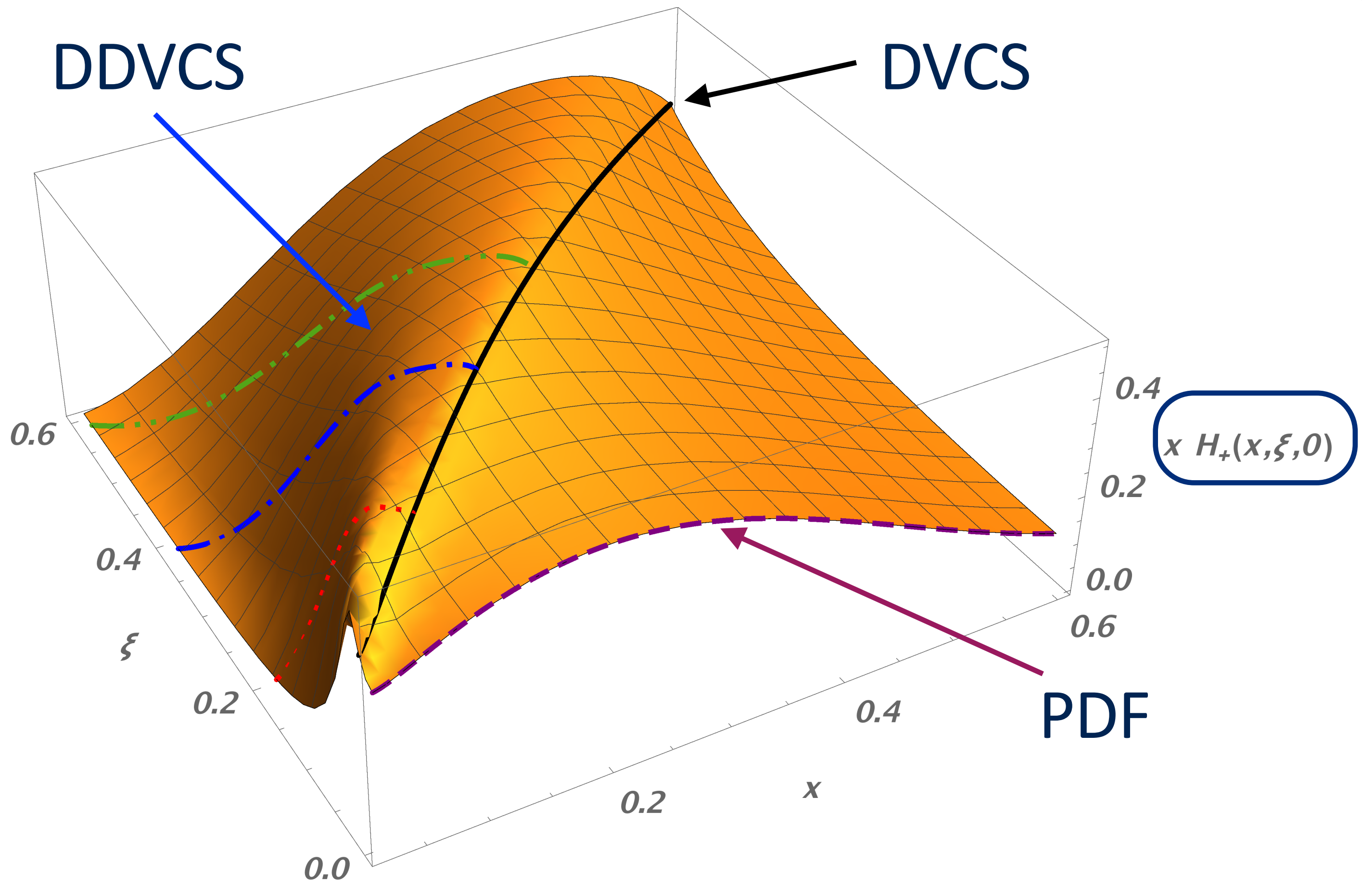
Double DVCS allows direct access to GPDs

Talks: Diehl, Voutier



$$\xi' = \frac{Q^2 - Q'^2 + t/2}{2Q^2/x_B - Q^2 - Q'^2 + t}$$

$$\xi = \frac{Q^2 + Q'^2}{2Q^2/x_B - Q^2 - Q'^2 + t}$$



$$\mathcal{F}(\xi',\xi,t) = \mathcal{P}\int_{-1}^{1} dx\, F_+(x,\xi,t)\left[\frac{1}{x-\xi'} \pm \frac{1}{x+\xi'}\right] - i\pi F_+(\xi',\xi,t)$$

CLAS12 lumi upgrade

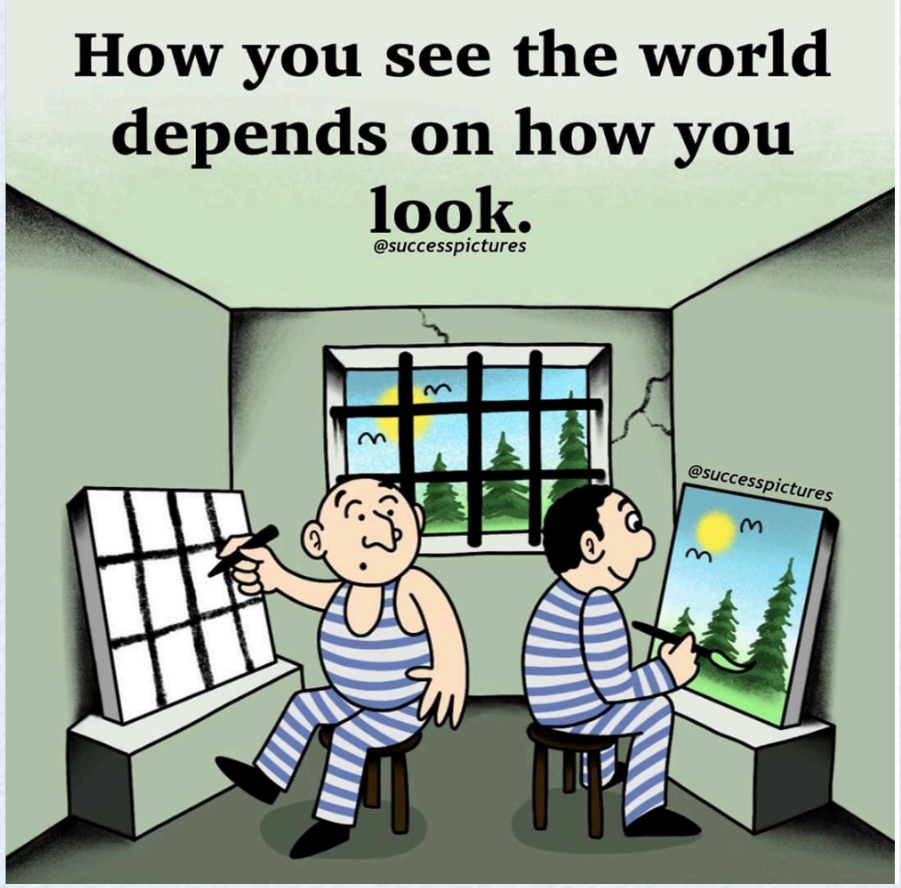
SoLID

Guidal, Vdh(2003); Belitsky, Mueller (2003)

new works: DDVCS: Deja et al.(2003)

$\gamma p \to \gamma\gamma p$ at large $M_{\gamma\gamma}$ Grocholski et al.(2021, 2022)

Proton gluonic radius



Nucleon Energy-Momentum Tensor (EMT)

- $\langle P|T^{\mu\nu}|P\rangle = 2P^\mu P^\nu$

$$\boxed{2M^2 = \langle P|\frac{\tilde{\beta}(g)}{2g}G^a_{\alpha\beta}G^{a\alpha\beta}|P\rangle + \langle P|\sum_{l=u,d,s} m_l(1+\gamma_{m_l})\bar{q}_l\bar{q}_l|P\rangle}$$

In chiral limit all of hadron mass is due to the trace anomaly

Quark contributions to hadron mass: sigma-terms

Gluonic contribution

~ 10% (u, d, s) Lattice QCD

- Matrix element of full nucleon EMT: parametrised by **3 form factors (FFs)**

$$\langle P+\frac{q}{2}\,|\,T^{\mu\nu}(0)\,|\,P-\frac{q}{2}\rangle = \bar{u}(P+\frac{q}{2})\Big\{A(Q^2)\,\gamma^{(\mu}P^{\nu)} + B(Q^2)\,P^{(\mu}i\sigma^{\nu)\alpha}\frac{q_\alpha}{2\,M}$$
$$+\,C(Q^2)\,\big(q^\mu q^\nu - q^2 g^{\mu\nu}\big)\,\frac{1}{M}\Big\}u(P-\frac{q}{2})$$

`Pagels`

`(1966)`

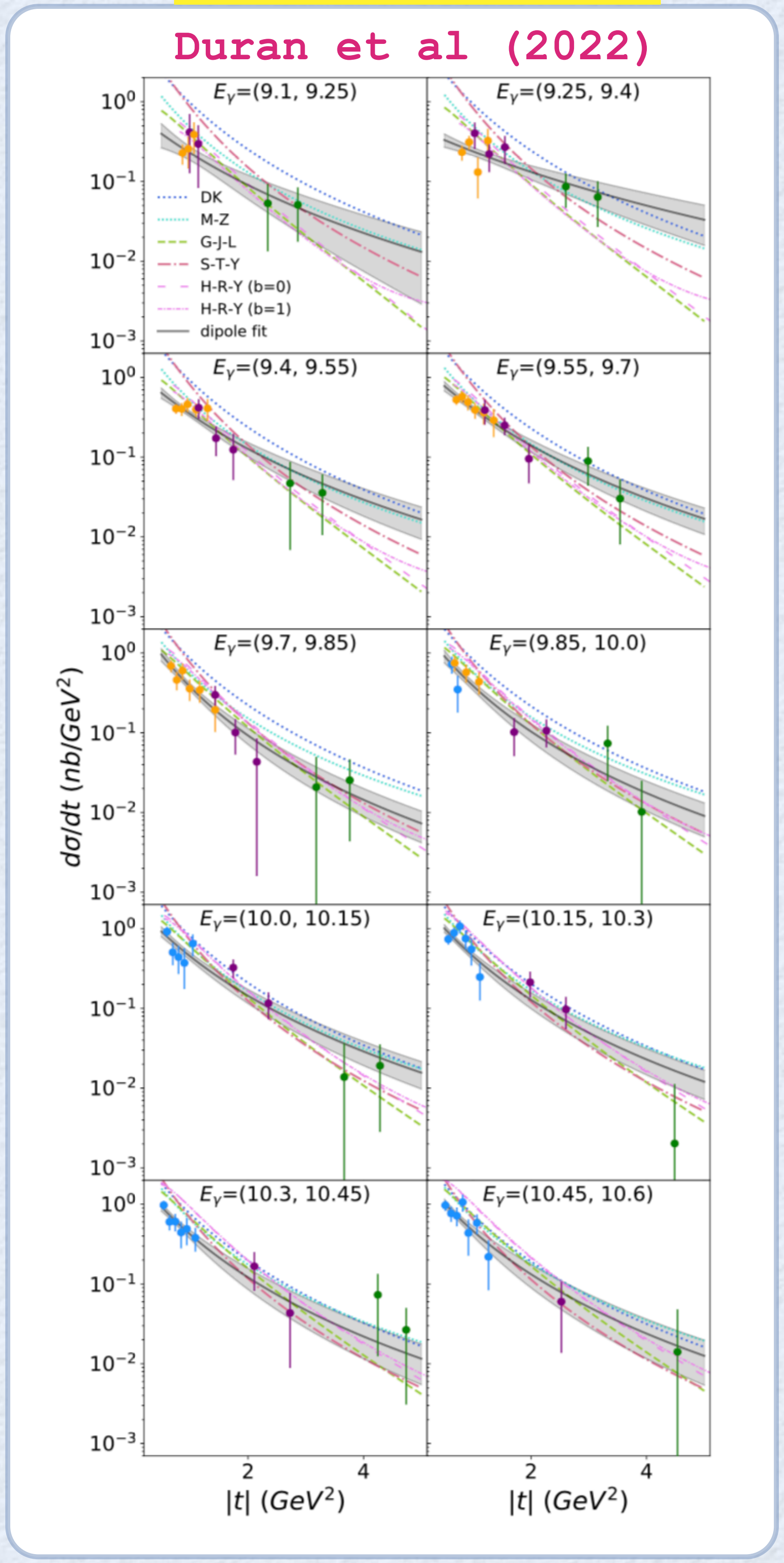
A -> momentum distribution

A + B -> angular momentum distribution

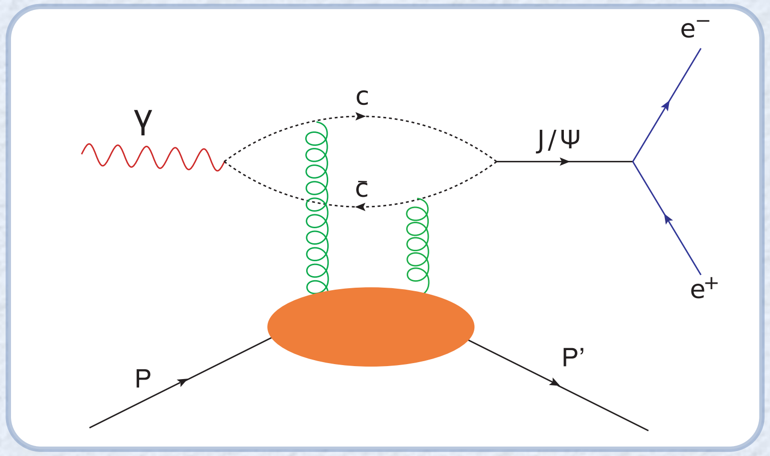
C -> pressure distribution

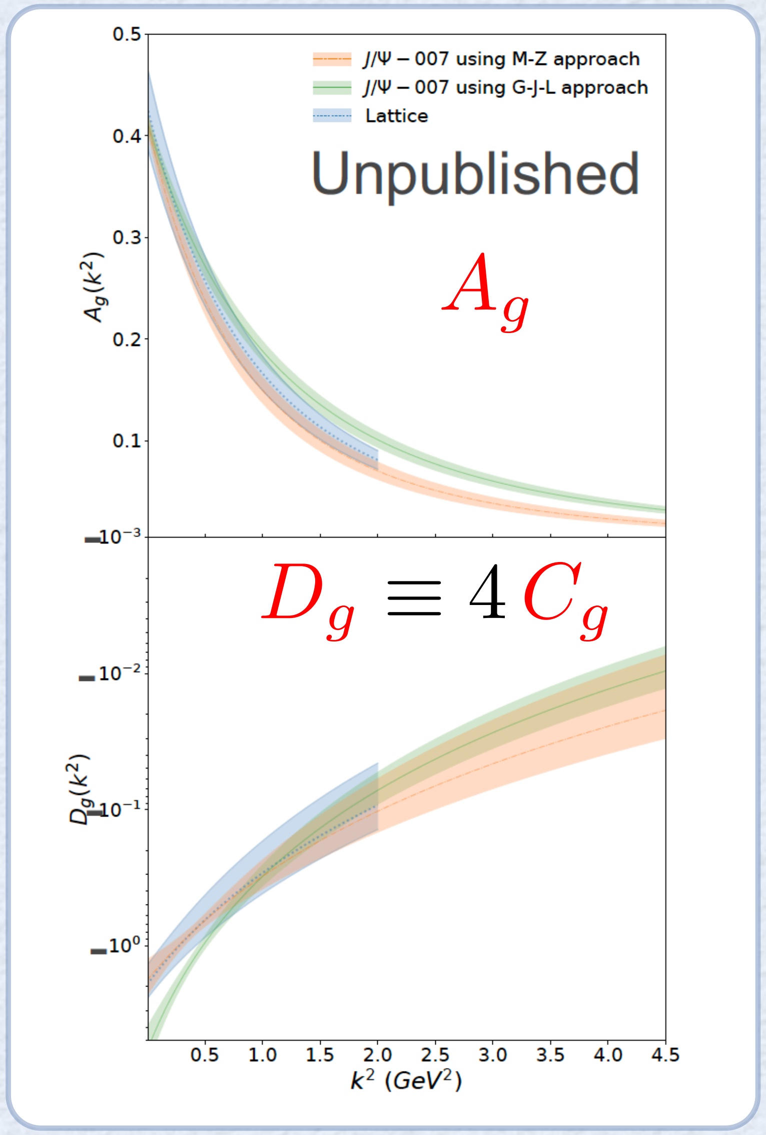
Threshold J/ψ photo-production

JLab/Hall C data



Duran et al (2022)





Unpublished

A_g

$D_g \equiv 4\,C_g$

Talks: Meziani, Joosten, Pefkou

Analyzed in different approaches

➡ Holographic QCD model **(M-Z)**

Mamo, Zahed (2021)

➡ GPD model **(G-J-L)**

Guo, Ji, Liu (2021)

➡ Lattice QCD

Pefkou, Hackett, Shanahan (2022)

- **to reliably interpret slope as a scalar gluonic radius: estimate of $\overline{C}_g$ (lattice)**
- **checks with heavier quarkonia: JLab energy upgrade -> ψ(2S) EIC -> Υ**
- **Electroproduction: new scale**

Outlook

- **QCD is 50 years, but hadron imaging at the femtoscale just started**
- **Interactions with precision and high-energy frontiers enrich field**
- **Close synergy theory <-> experiment will move field forward**

For deeper still, the story lies,
Where quarks unite, a grand surprise,
Their energies entwined in space,
A dance of colors, an embrace.

courtesy: Zein-Eddine Meziani