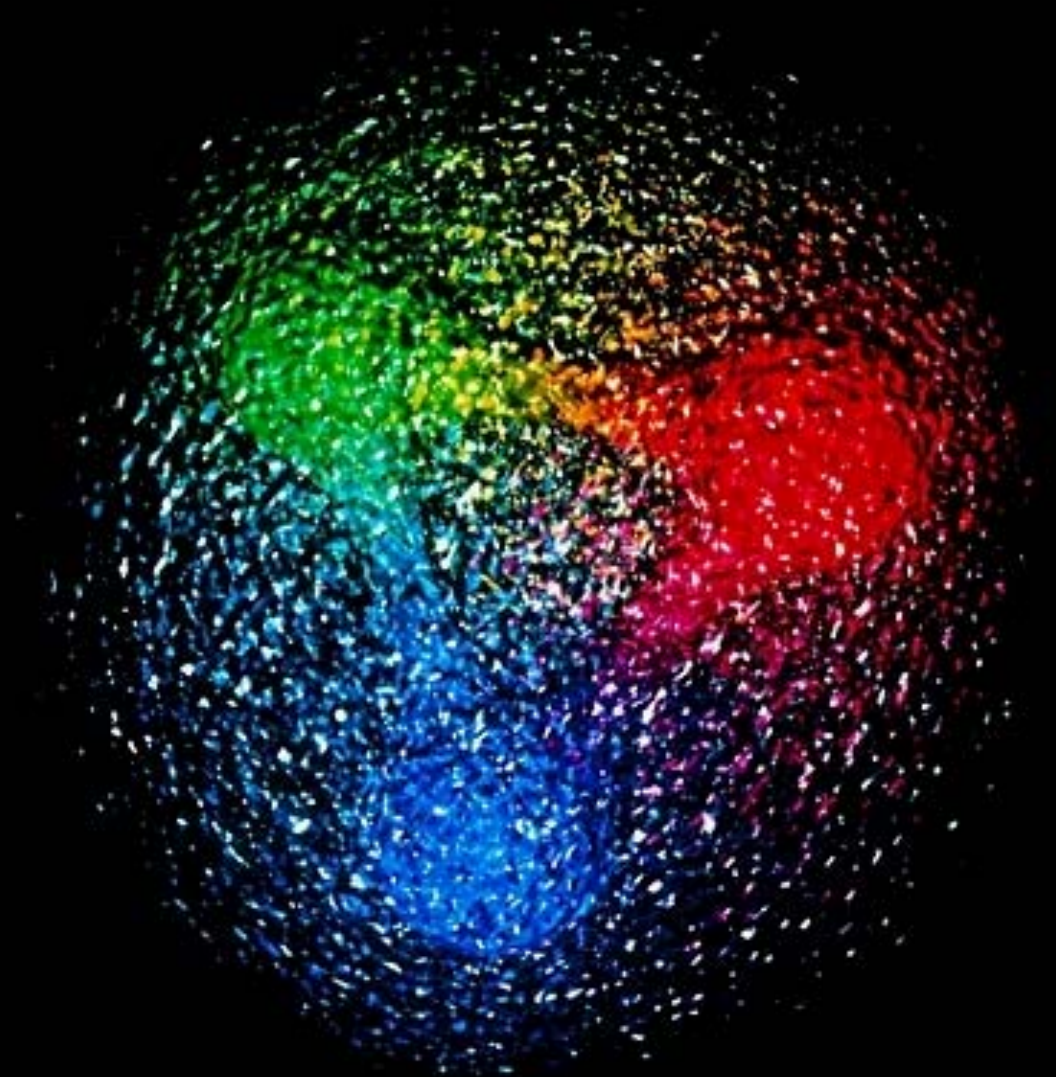


Verso una nuova era nella comprensione della struttura interna del protone

Alessandro Bacchetta
Università di Pavia e INFN

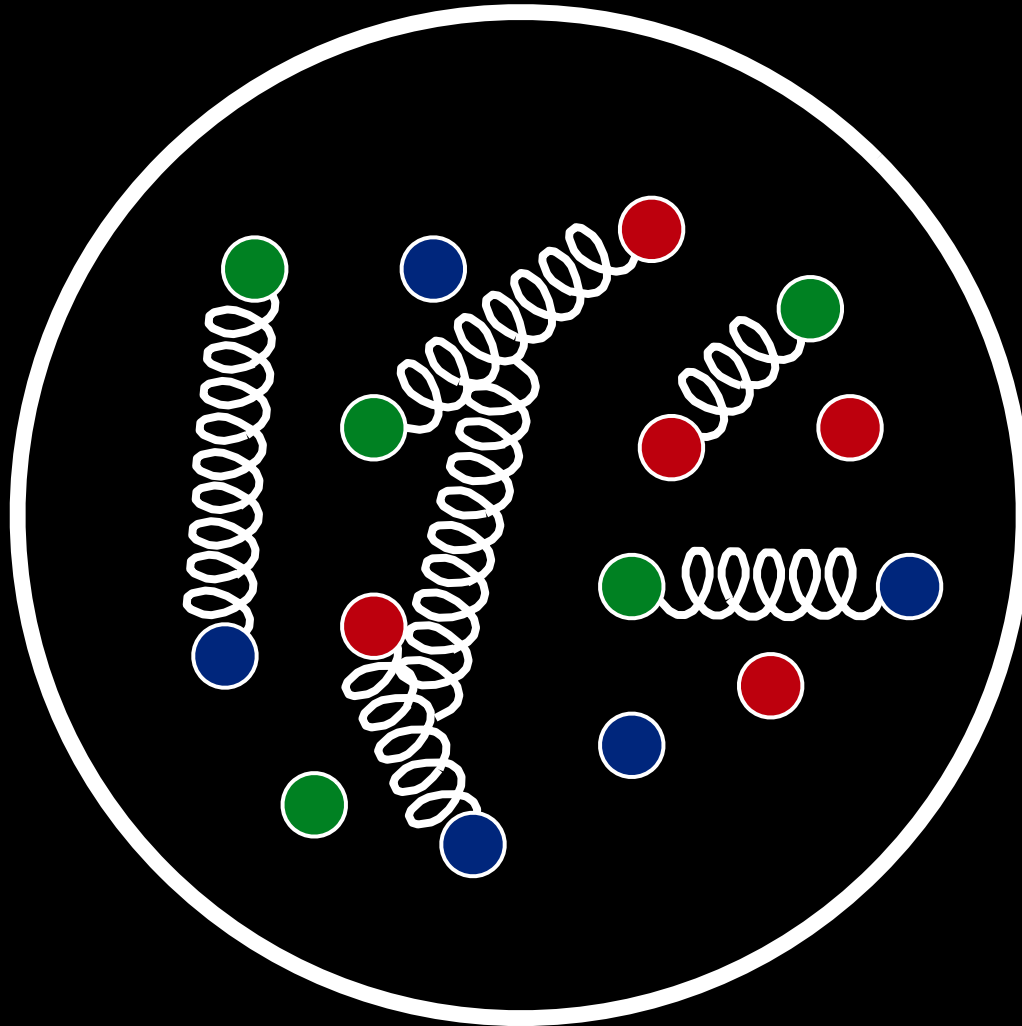


Come è fatto un nucleone?

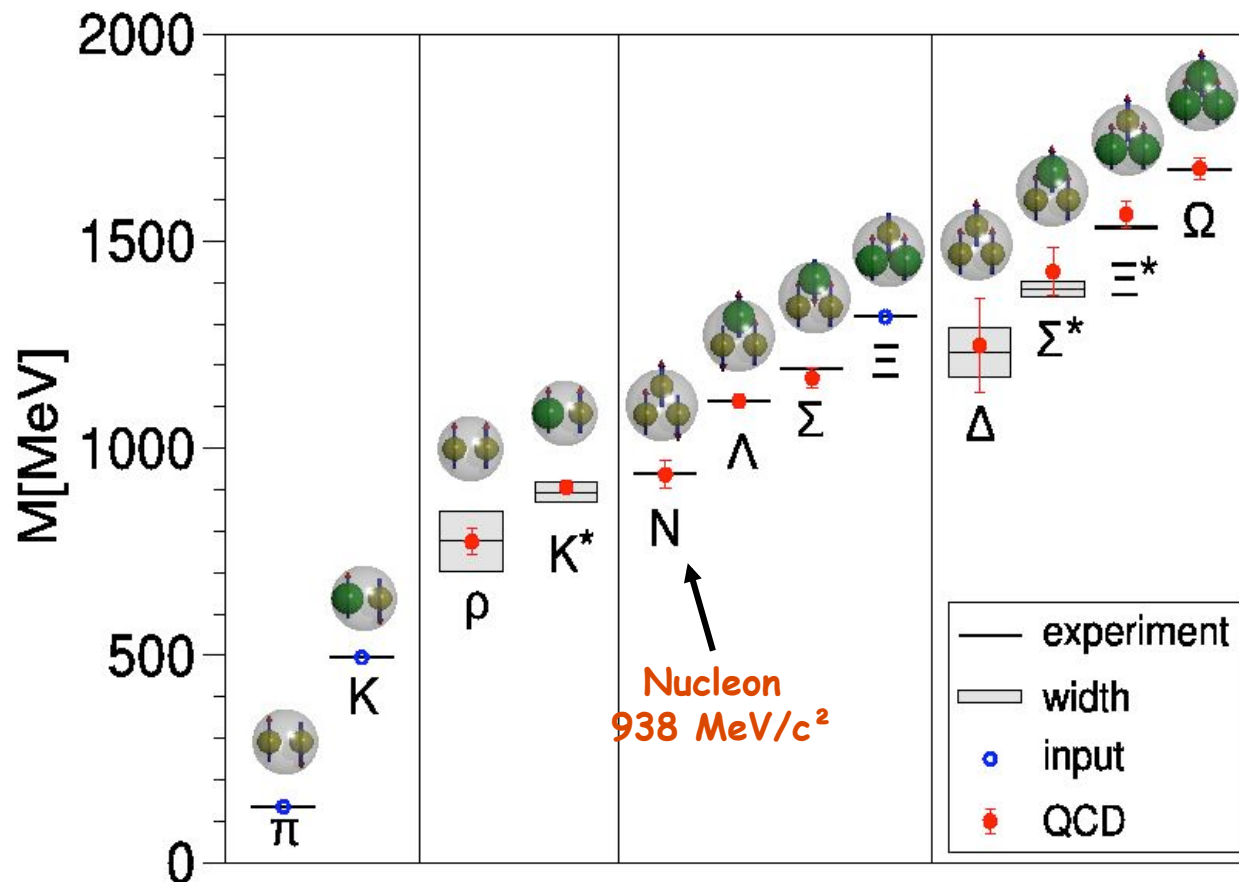


A. Bacchetta/INFN

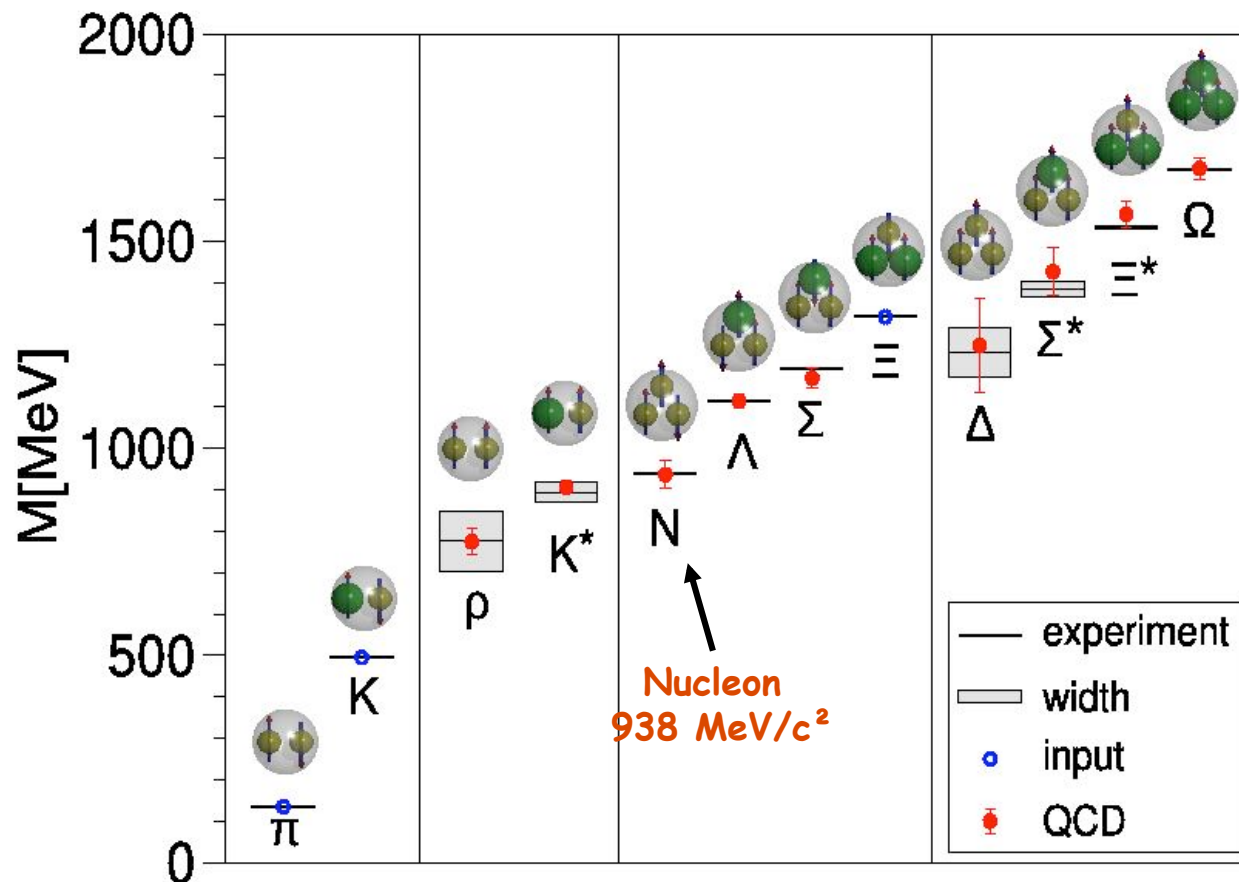
Obiettivo a lungo termine: Capire la QCD e il confinamento



Un primo modo di studiare gli adroni: Spettroscopia Adronica



Un primo modo di studiare gli adroni: Spettroscopia Adronica



Durr et al., Science 322 (08)

Il nostro approccio:

Il nostro approccio:



ottenere **immagini**
della struttura del nucleone

Messaggio promozionale:

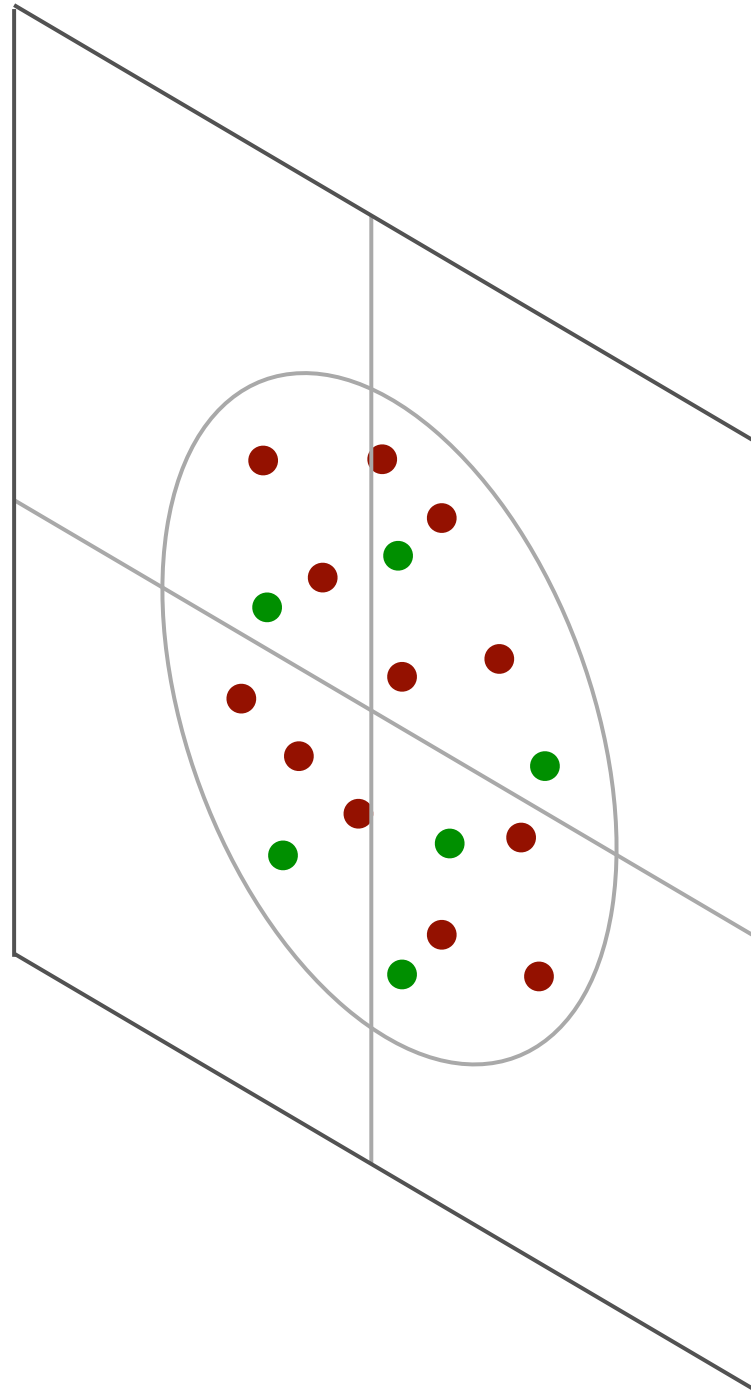
Messaggio promozionale: articolo su “Il Nuovo Saggiatore”

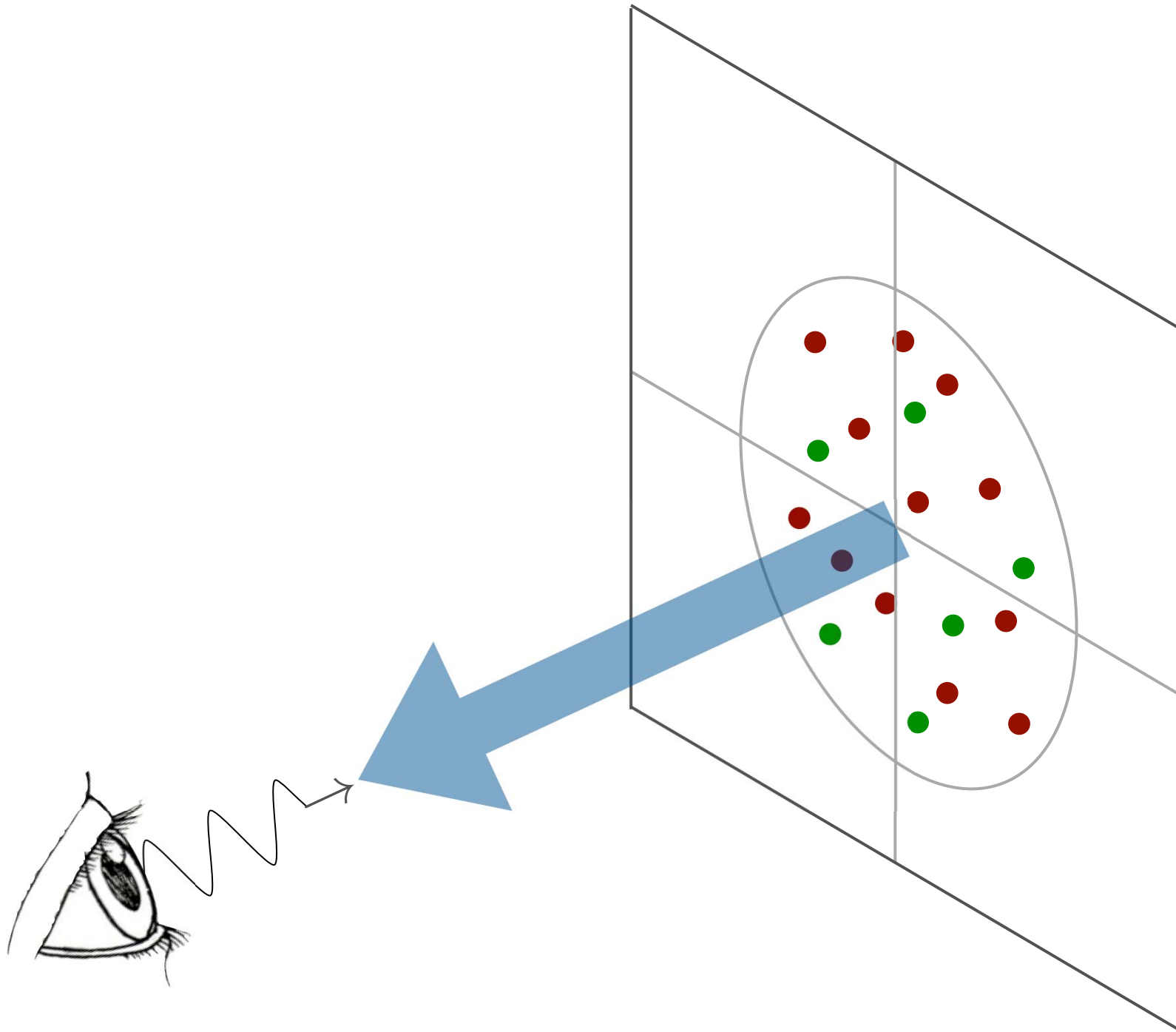
<http://www.sif.it/attivita/saggiatore/econtents>

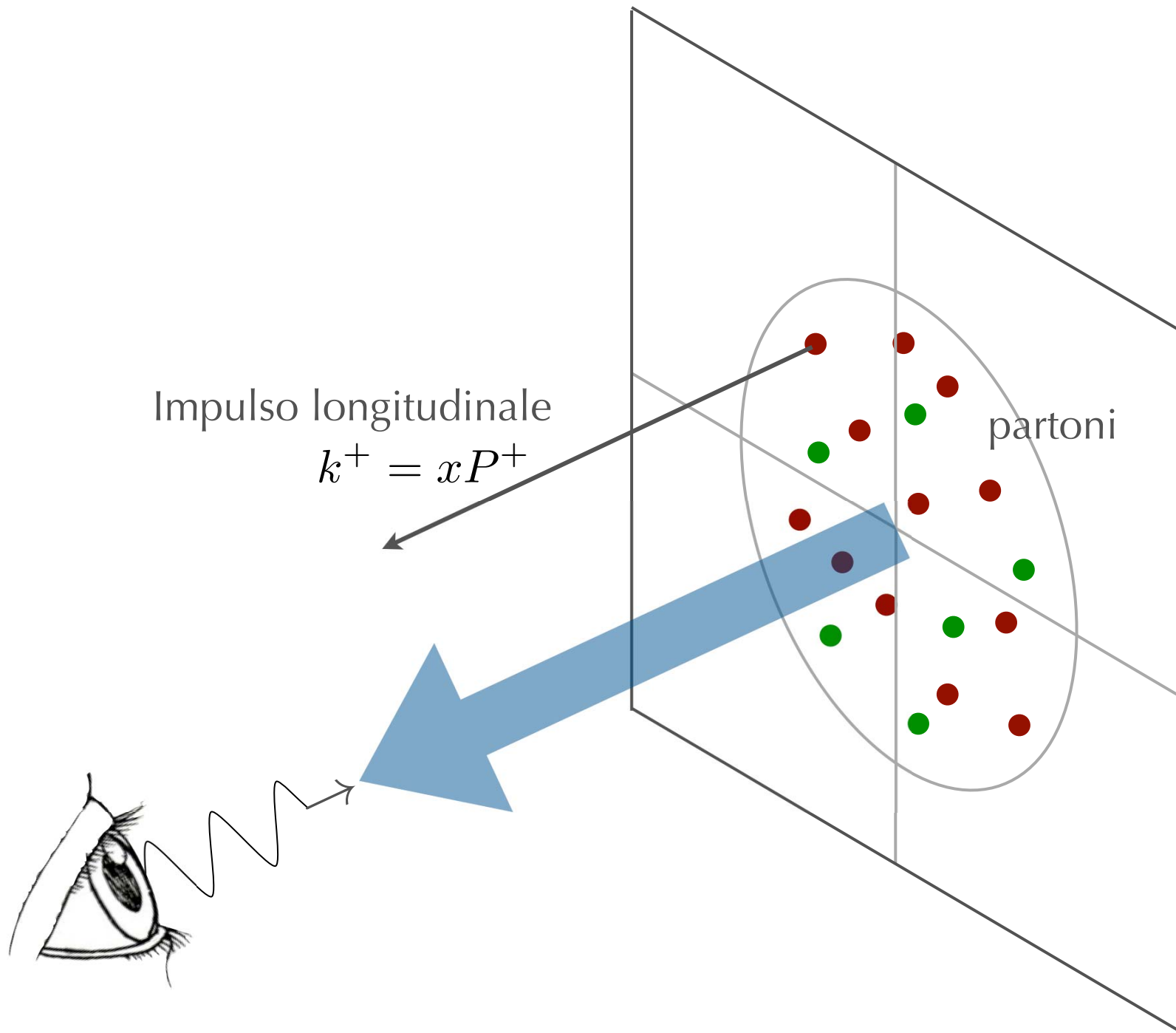


Altre review recenti:

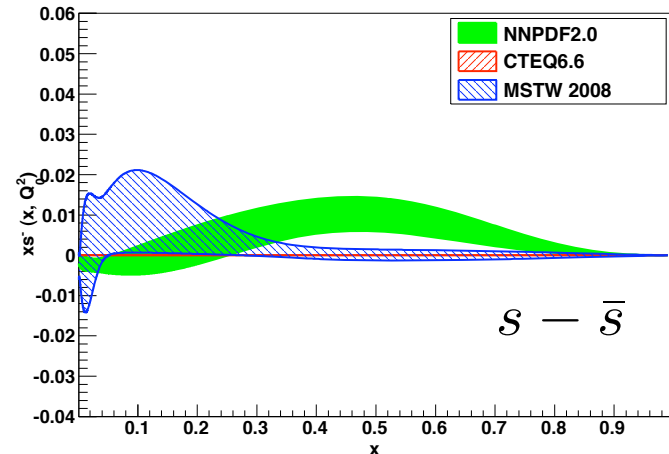
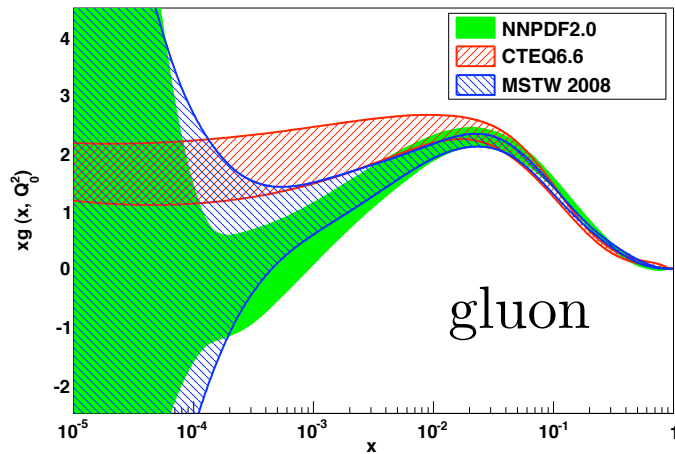
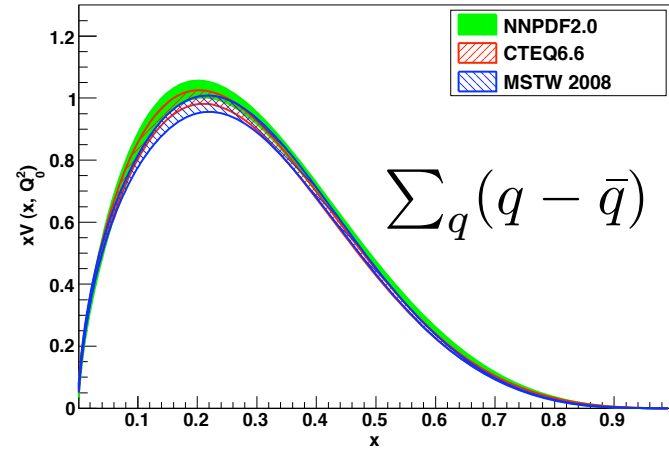
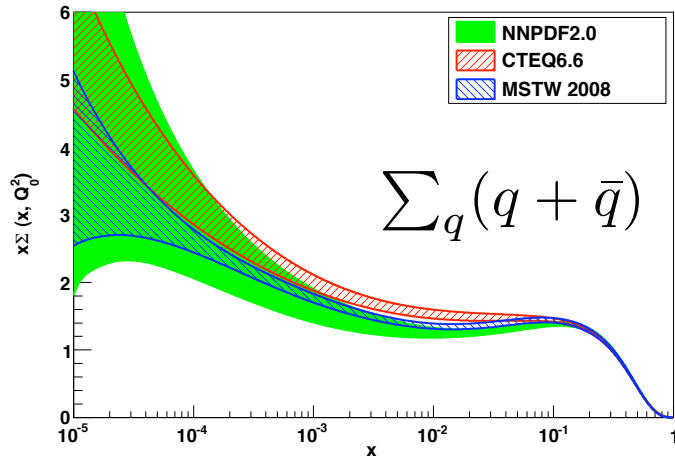
- Aidala, Bass, Hasch, Mallot: “The Spin Structure of the Nucleon,” arXiv:1209.2803 [hep-ph]
- Boer et al. “Gluons and the quark sea at high energies: Distributions, polarization, tomography,” arXiv:1108.1713 [nucl-th]
- Barone, Bradamante, Martin: “Transverse-spin and transverse-momentum effects in high-energy processes,” Prog. Part. Nucl. Phys. 65 (2010)
- Burkardt, Miller, Nowak: “Spin-polarized high-energy scattering of charged leptons on nucleons,” Rept. Prog. Phys. 73 (2010)







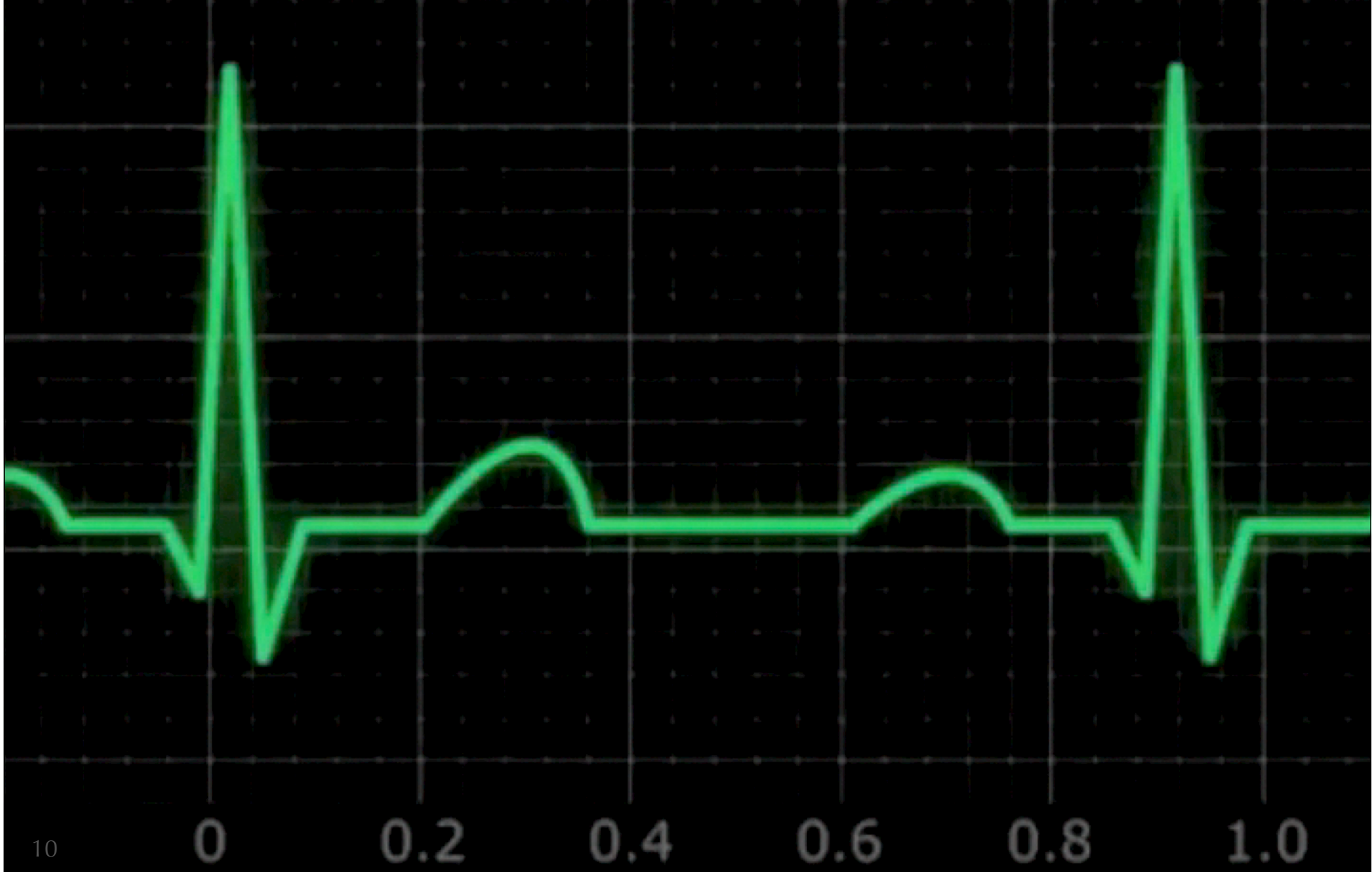
Parton Distribution Functions (PDFs): descrivono la struttura dei nucleoni in una dimensione (impulso longitudinale)





Tuesday, 13 November 12

ECG: informazione monodimensionale sull'attività del cuore



Il nostro obiettivo è
aprire nuove dimensioni



Risonanza magnetica funzionale: tomografia del cuore e della sua attività



Stiamo aprendo l'era della

Stiamo aprendo l'era della

STEREO FEMTOFISICA

©E. Barone



Stiamo aprendo l'era della

STEREO FEMTOFISICA

©E. Barone



studio di
immagini **multidimensionali**
del nucleone

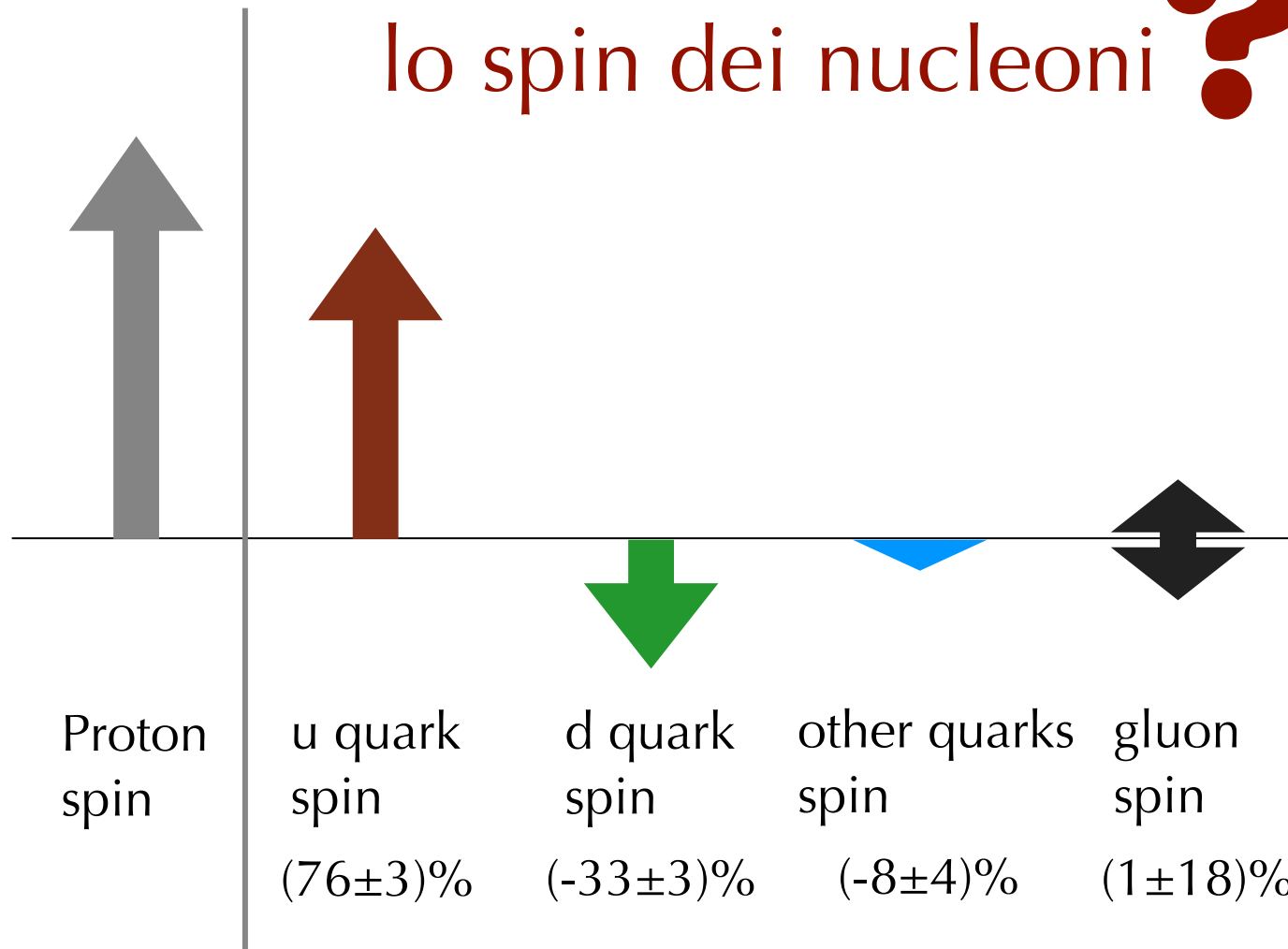
Una delle tante domande a cui vorremmo dare
una risposta

Una delle tante domande a cui vorremmo dare
una risposta

Da dove viene
lo spin dei nucleoni ?

Una delle tante domande a cui vorremmo dare una risposta

Da dove viene
lo spin dei nucleoni ?

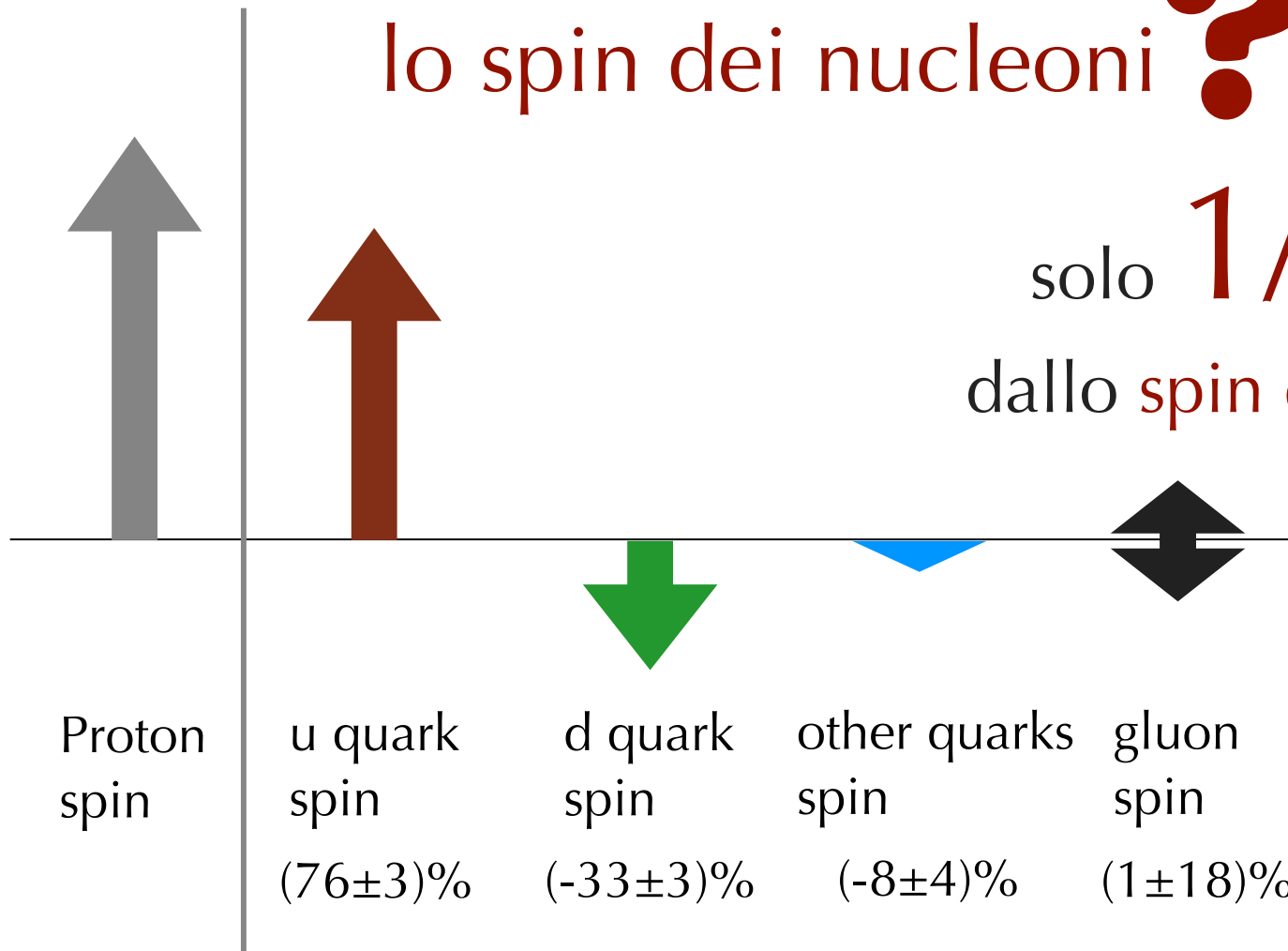


si veda, ed es., De Florian, Stratmann, Sassot, Vogelsang, Phys. Rev. D80 (2009)

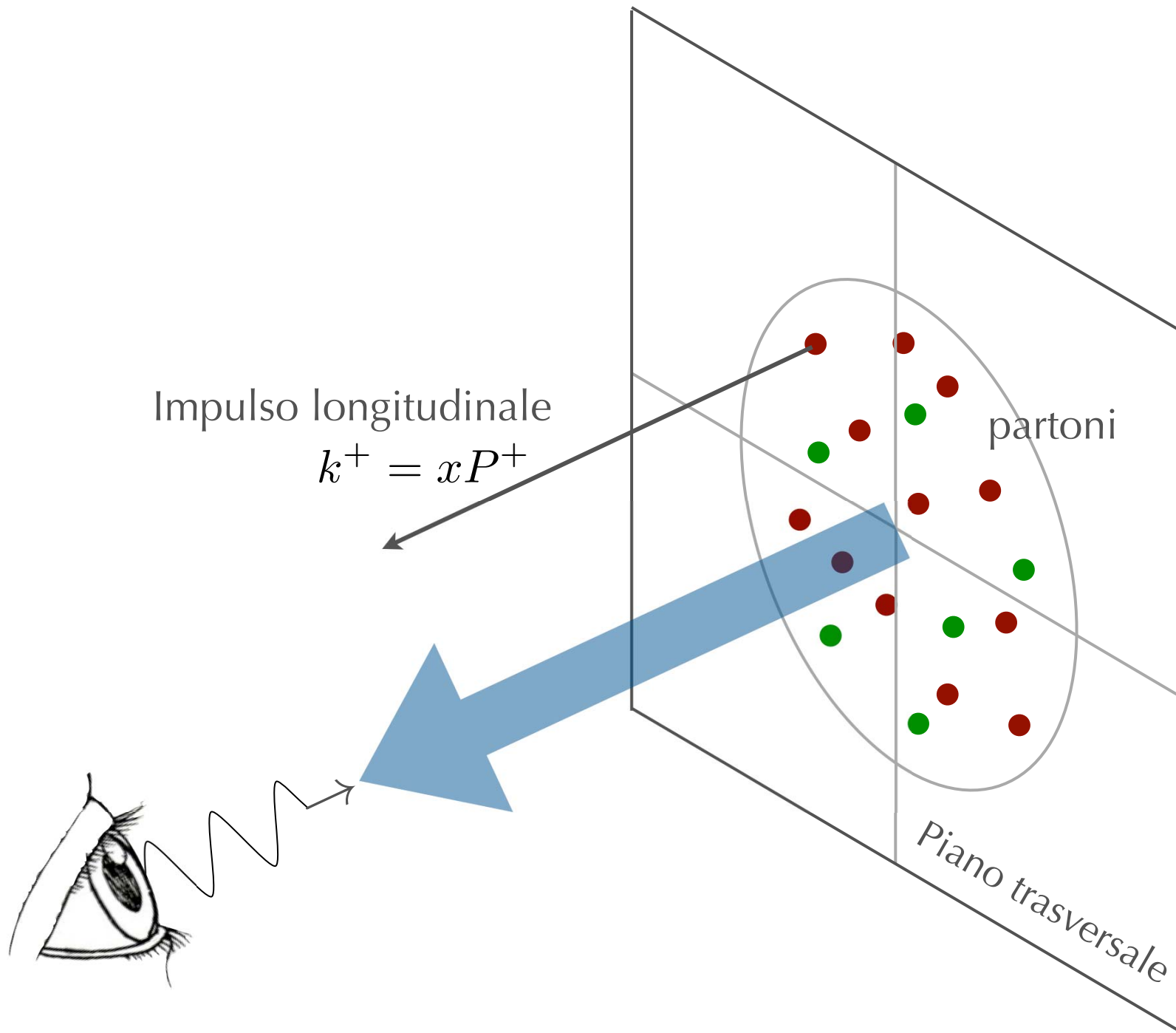
Una delle tante domande a cui vorremmo dare una risposta

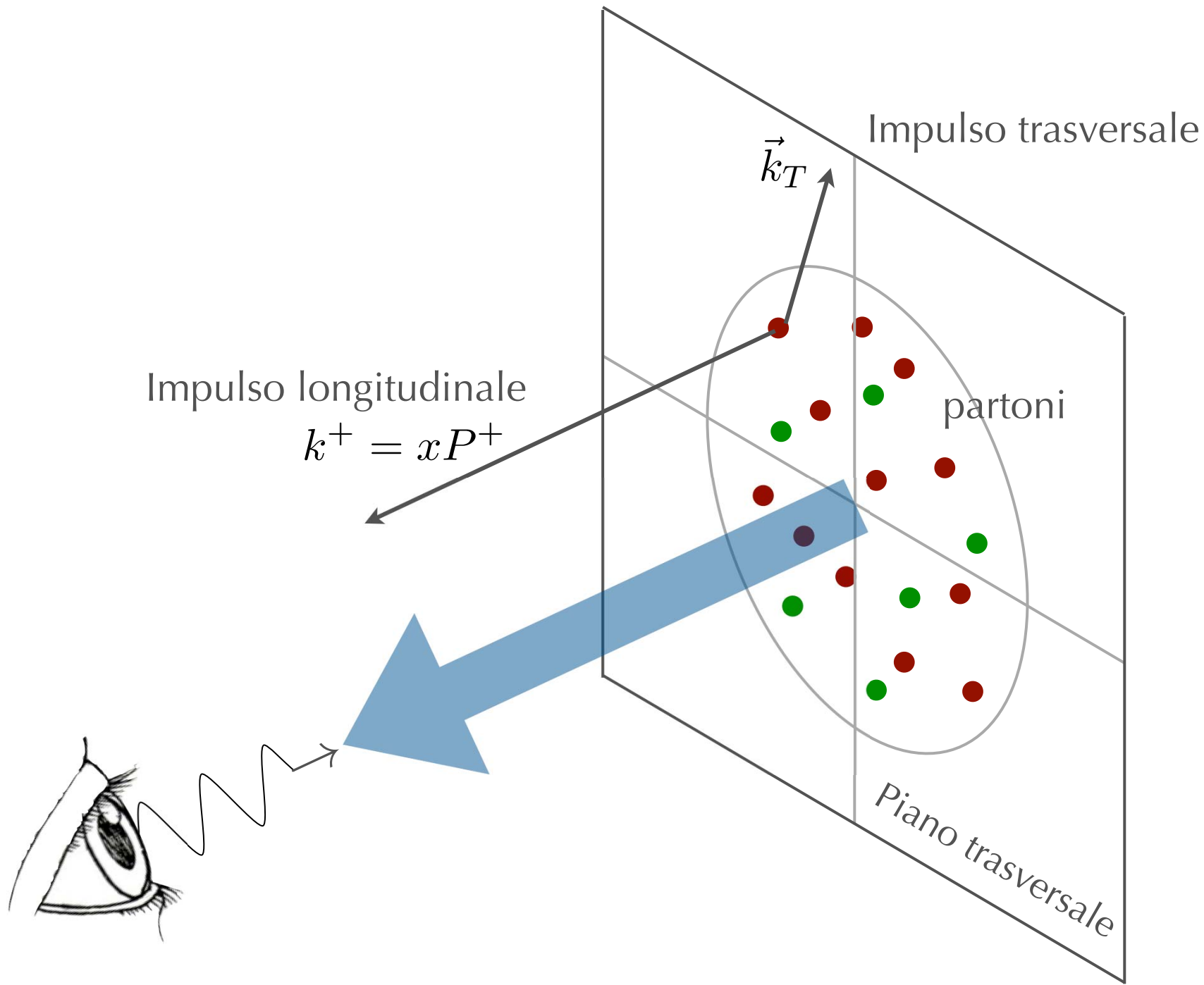
Da dove viene lo spin dei nucleoni ?

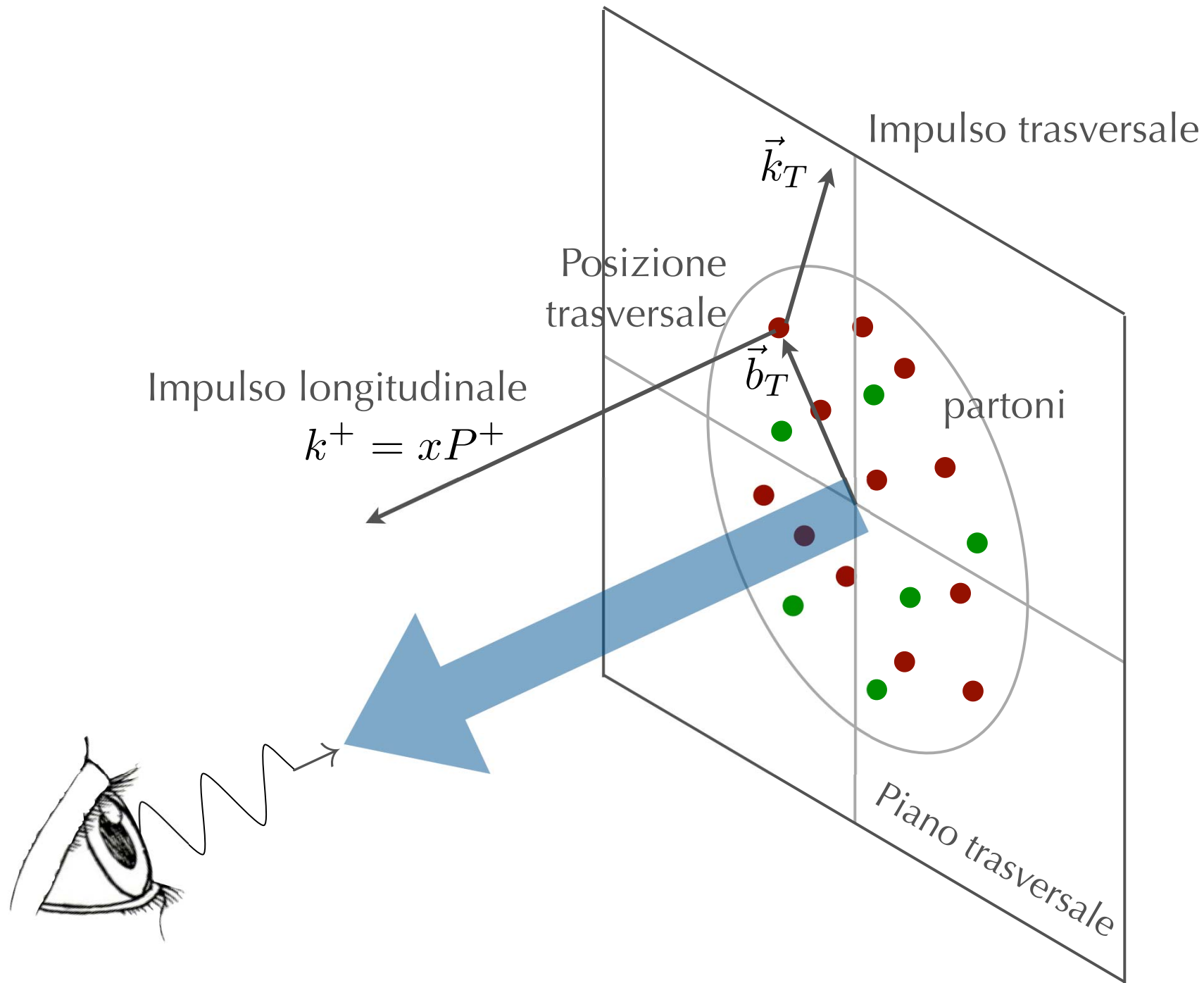
solo $1/3$ viene dallo spin dei partoni



si veda, ed es., De Florian, Stratmann, Sassot, Vogelsang, Phys. Rev. D80 (2009)

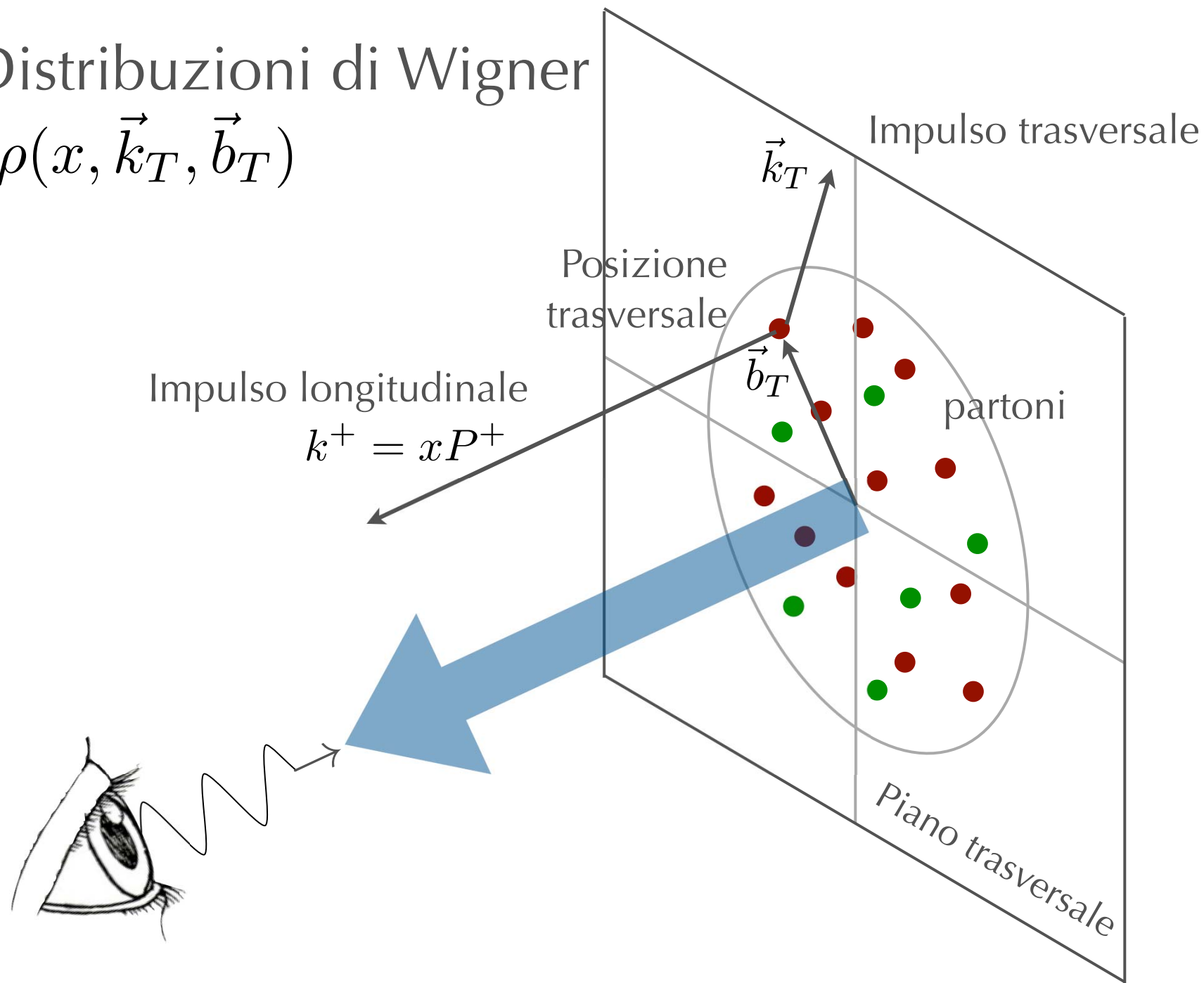






Distribuzioni di Wigner

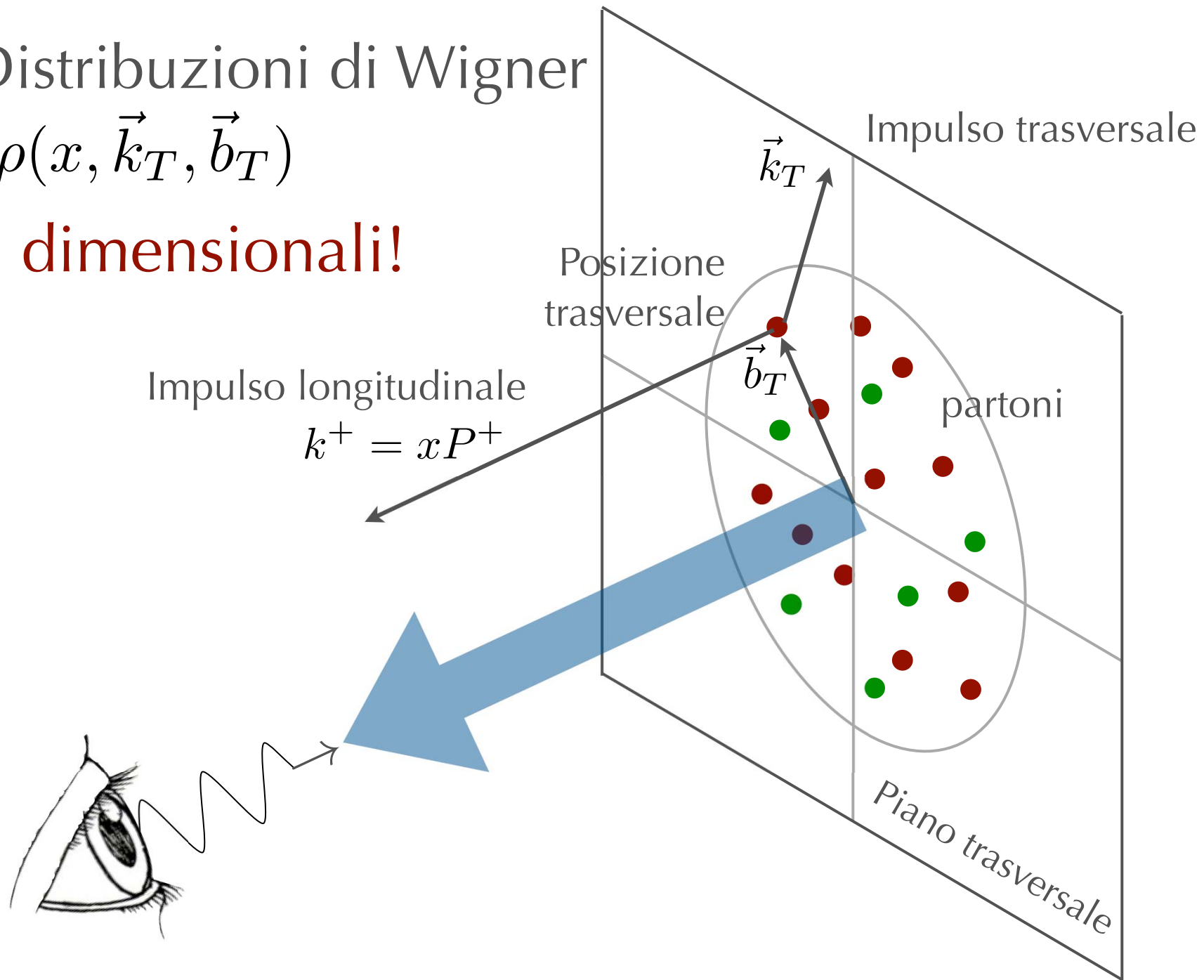
$$\rho(x, \vec{k}_T, \vec{b}_T)$$



Distribuzioni di Wigner

$$\rho(x, \vec{k}_T, \vec{b}_T)$$

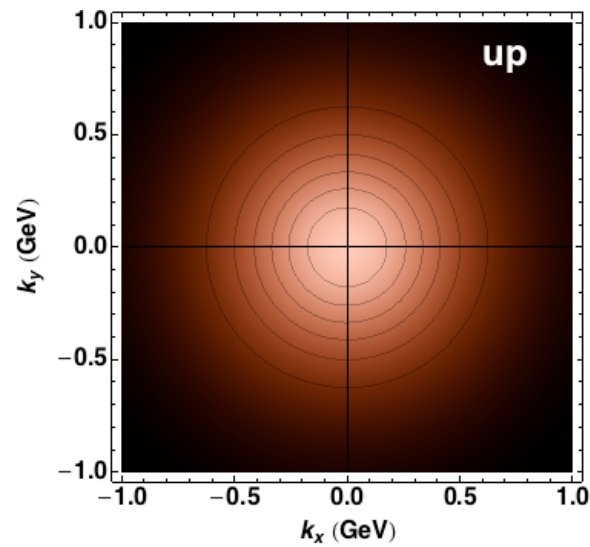
5 dimensionali!



Integrate su b_T
Transverse
momentum
distributions

(TMDs)

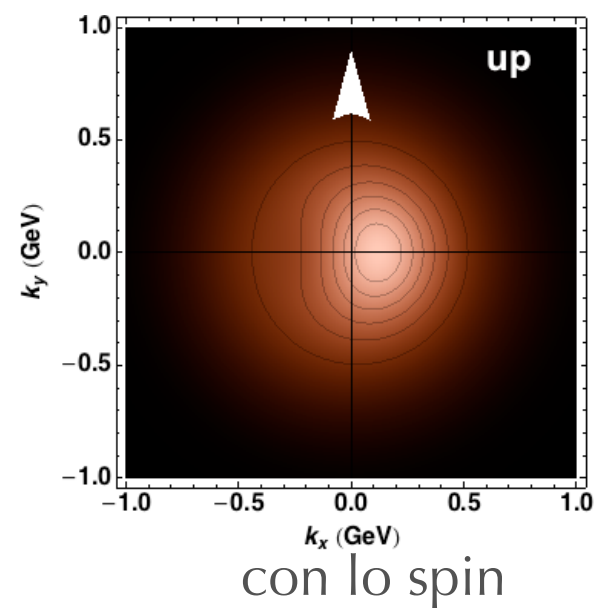
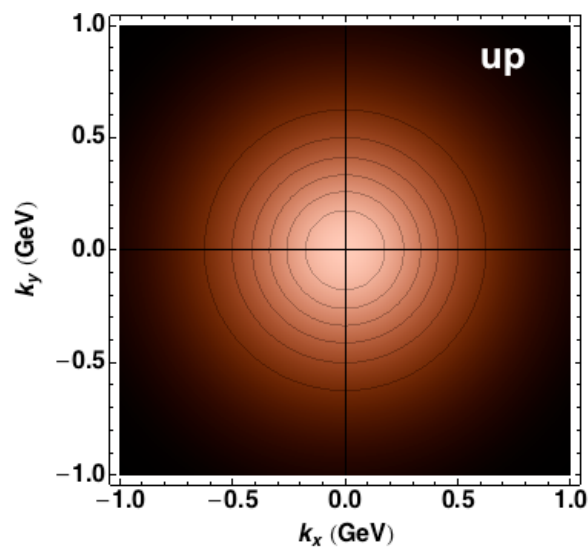
Tridimensionali



Integrate su b_T
Transverse
momentum
distributions

(TMDs)

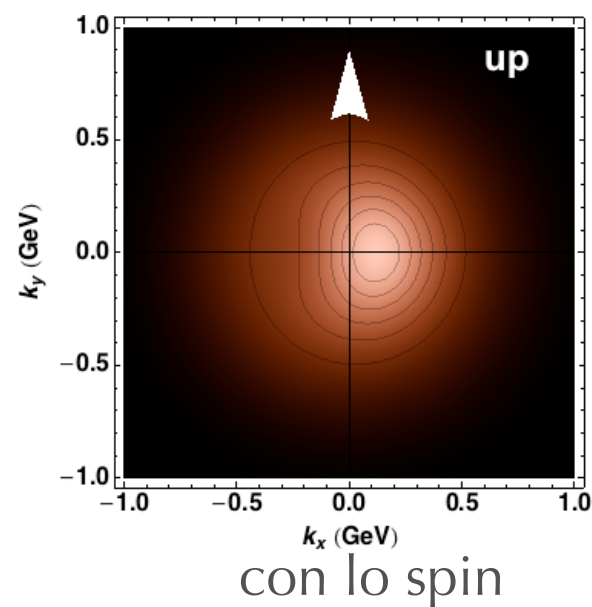
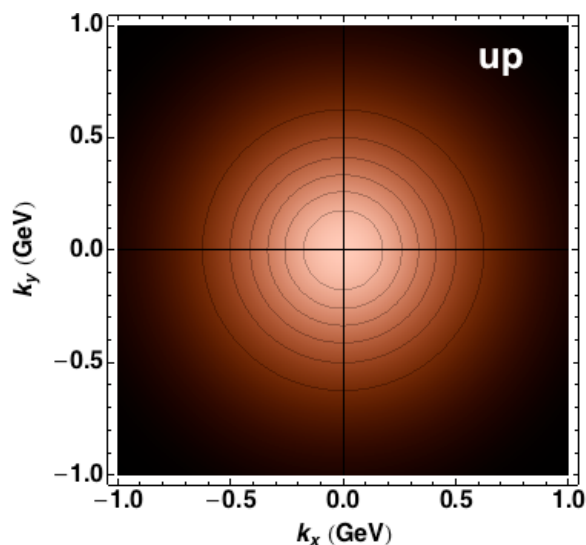
Tridimensionali



Integrate su b_T
Transverse
momentum
distributions

(TMDs)

Tridimensionali



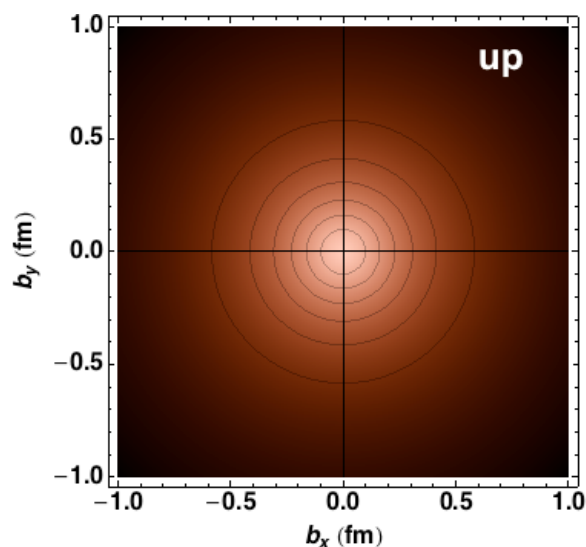
Integrate su k_T

Impact
parameter
distributions

(Fourier transf. delle

GPDs)

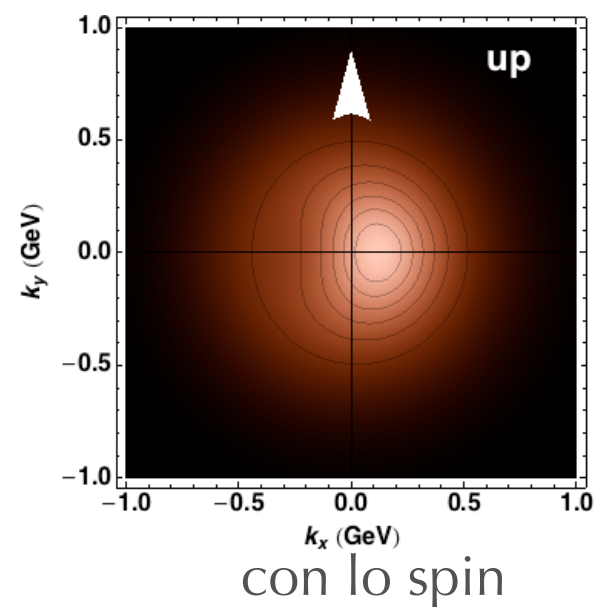
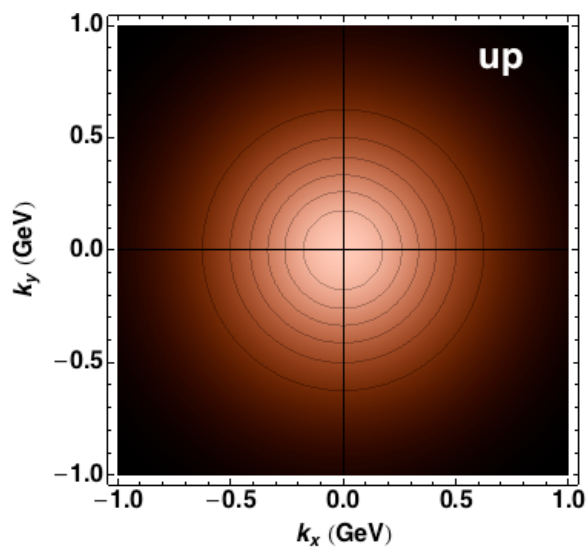
Tridimensionali



Integrate su b_T
Transverse
momentum
distributions

(TMDs)

Tridimensionali



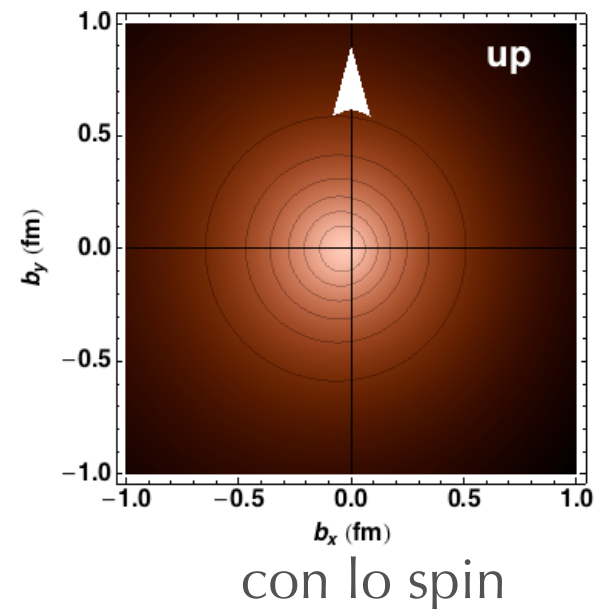
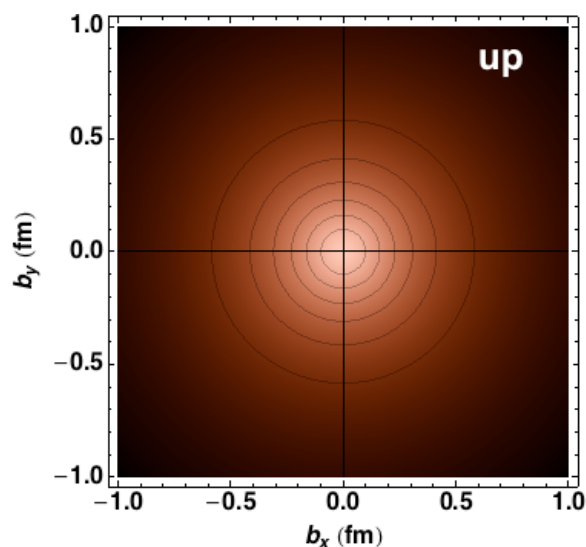
Integrate su k_T

Impact
parameter
distributions

(Fourier transf. delle

GPDs)

Tridimensionali



si veda, ad es., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

Parton distribution
functions (x)

si veda, ad es., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

→ \vec{b}_T dependence

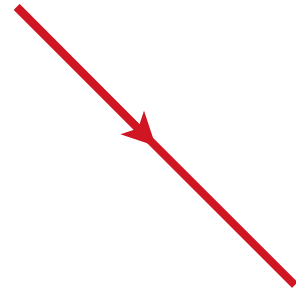
Parton distribution
functions (x)

Impact-parameter
distributions (x, \vec{b}_\perp)

si veda, ad es., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

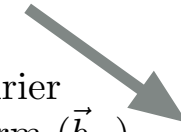
→ \vec{b}_T dependence

Parton distribution
functions (x)



Impact-parameter
distributions (x, \vec{b}_\perp)

2D Fourier
transform (\vec{b}_\perp)

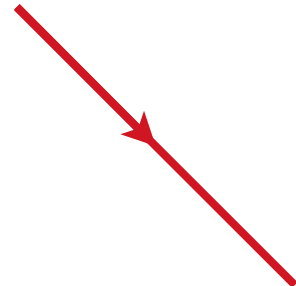


Generalized parton
distributions
($x, \xi = 0, \vec{\Delta}_T$)

si veda, ad es., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

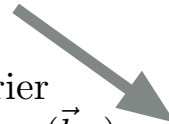
→ \vec{b}_T dependence

Parton distribution functions (x)



Impact-parameter distributions (x, \vec{b}_\perp)

2D Fourier transform (\vec{b}_\perp)





Generalized parton distributions ($x, \xi = 0, \vec{\Delta}_T$)

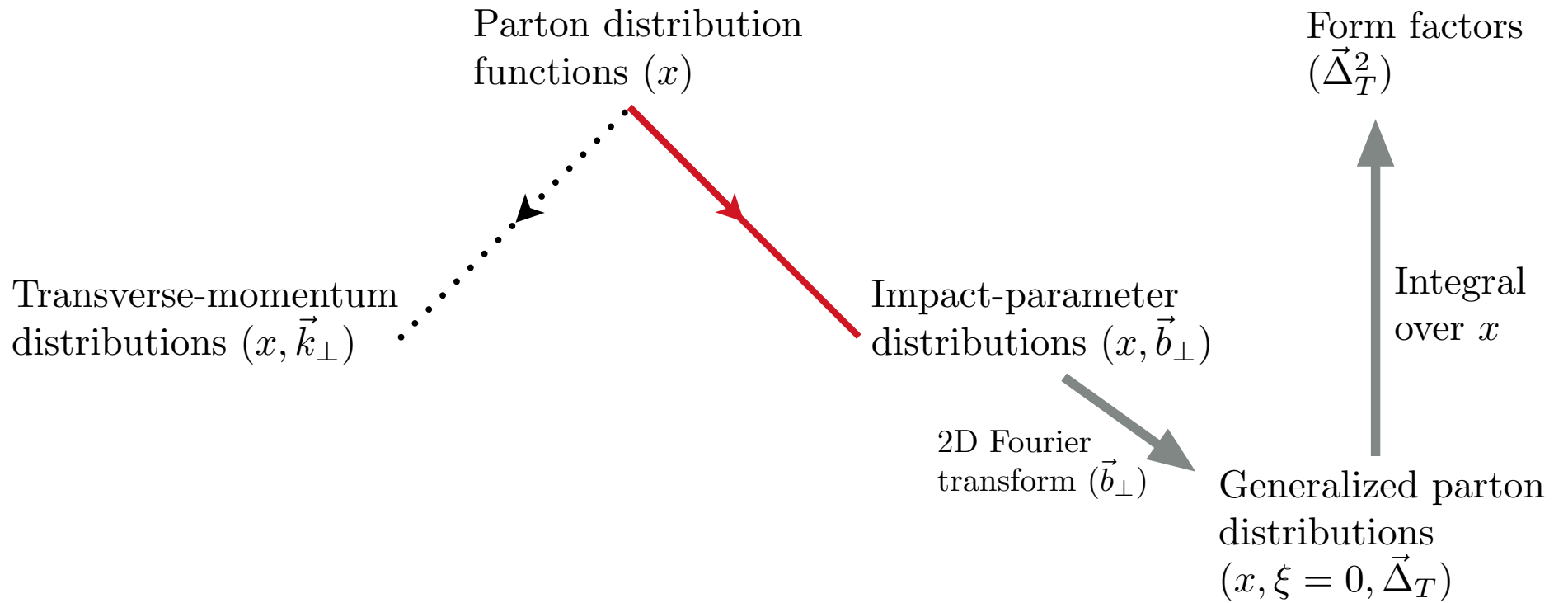
Form factors ($\vec{\Delta}_T^2$)





Integral over x

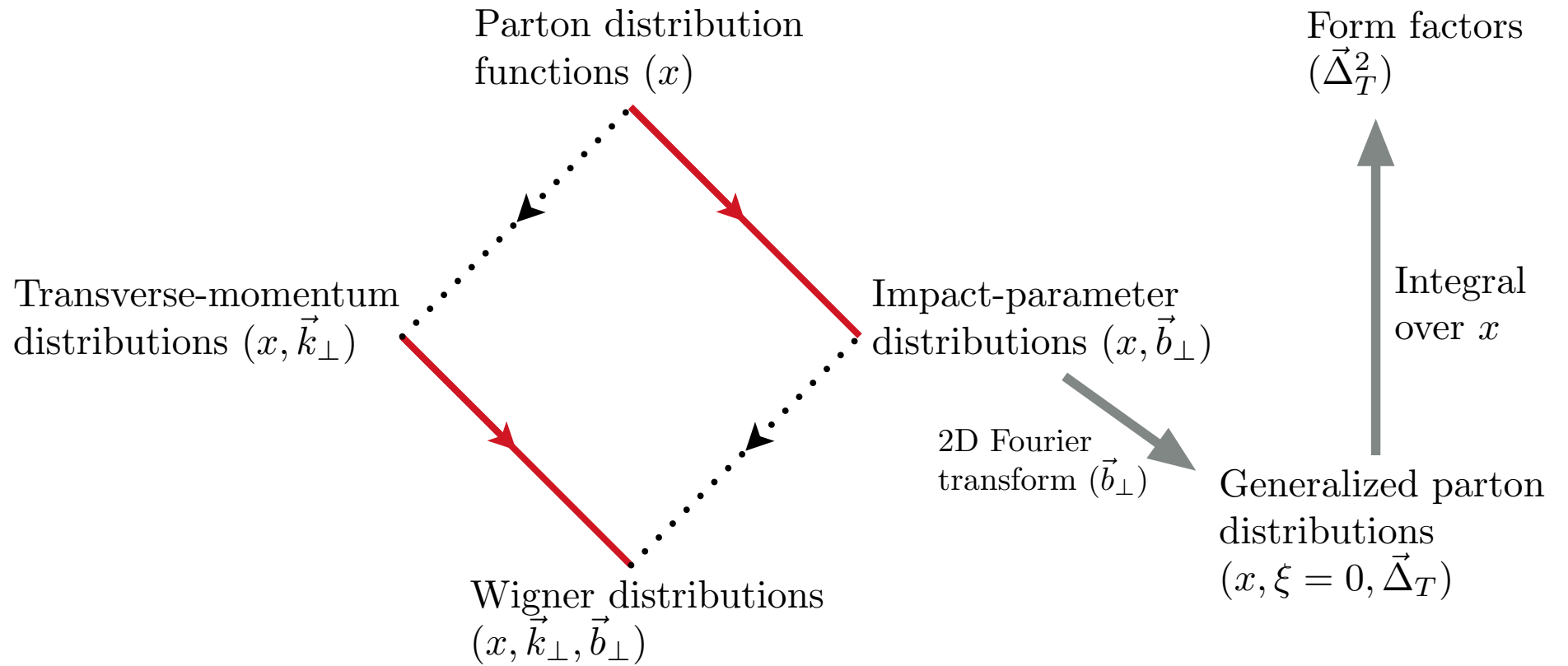
si veda, ad es., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

 \vec{b}_T dependence
 \vec{k}_T dependence





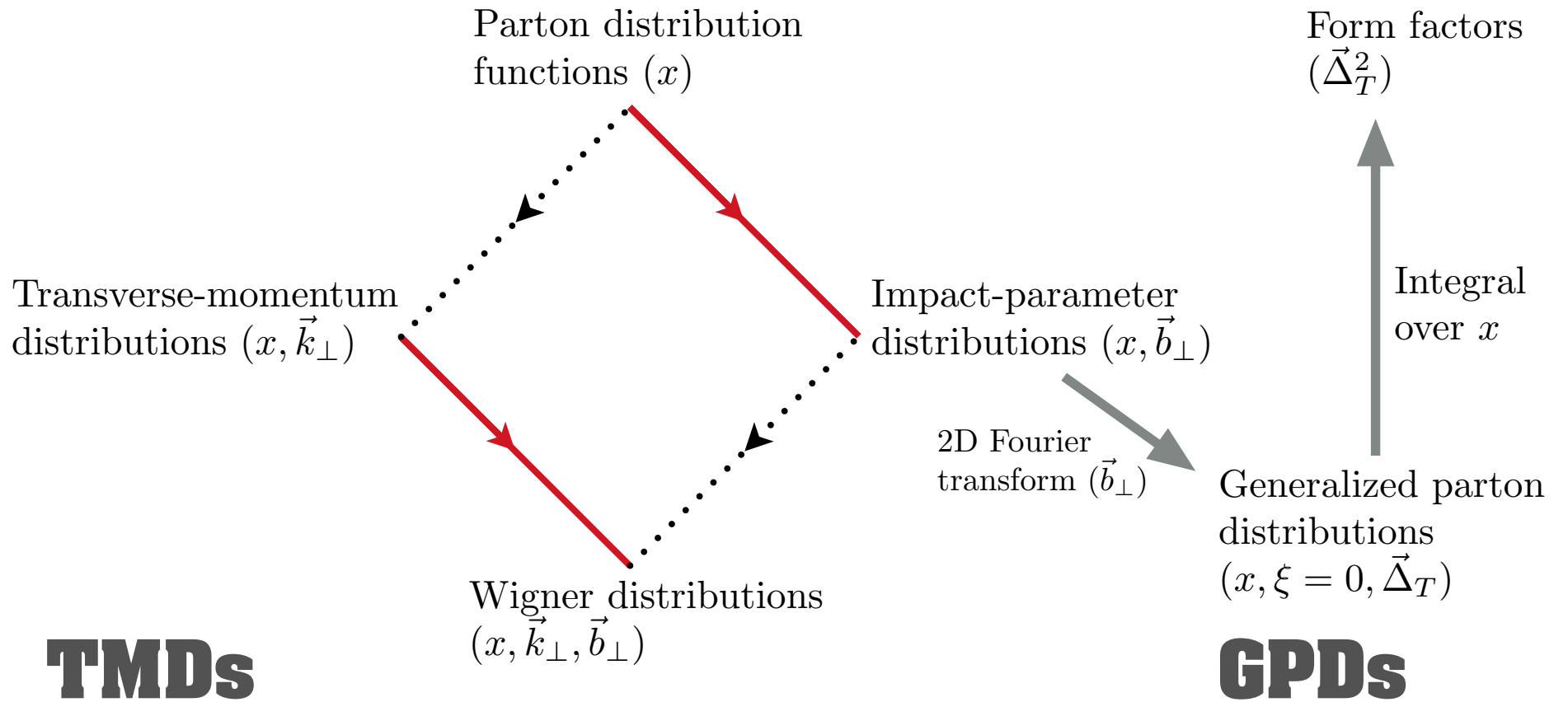
si veda, ad es., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

 \vec{b}_T dependence
 \vec{k}_T dependence



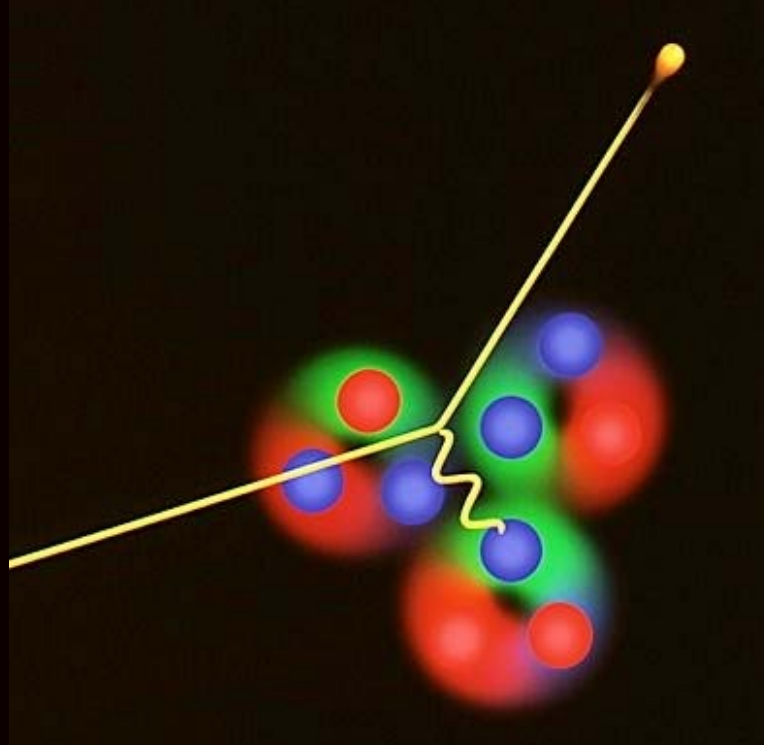
si veda, ad es., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

 \vec{b}_T dependence
 \vec{k}_T dependence



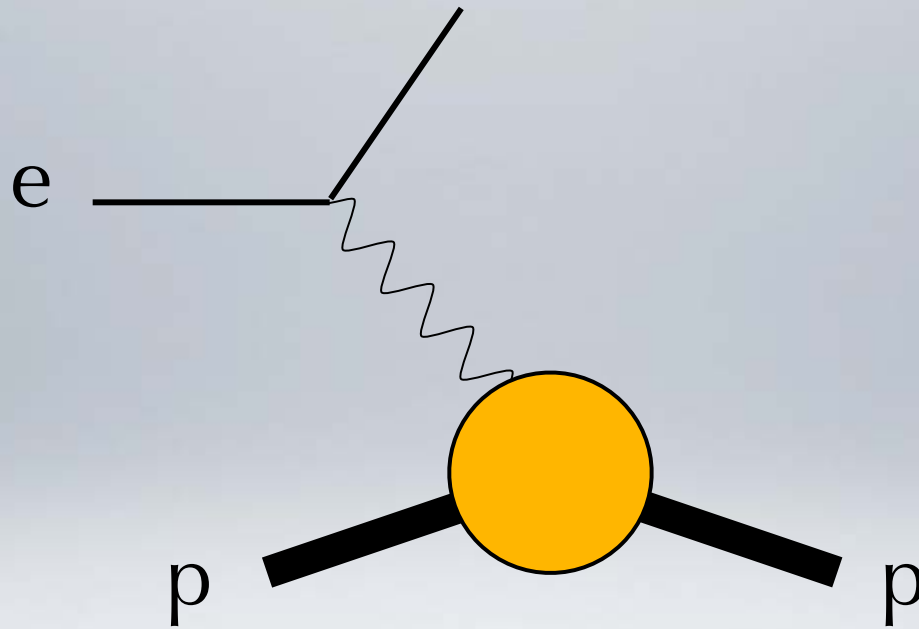
si veda, ad es., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

Come estrarre questi oggetti?

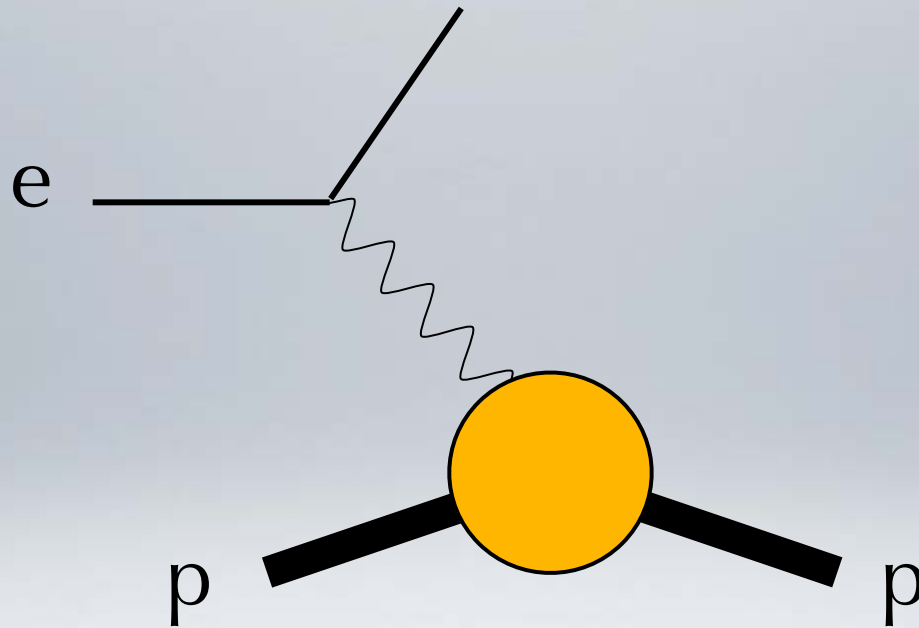


In numerosi processi di scattering.
Segue una lista di processi "tipici".

Scattering elastico

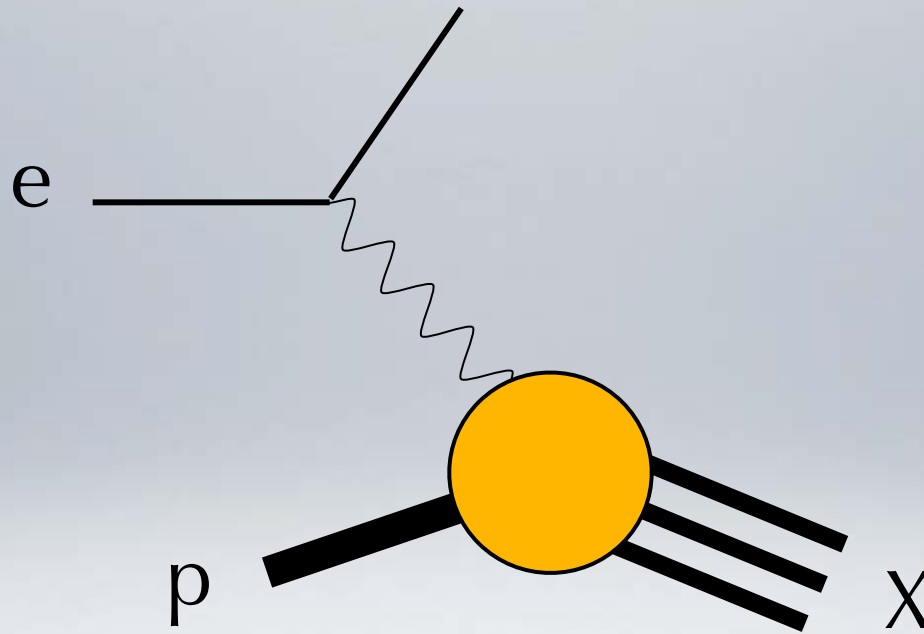


Scattering elastico

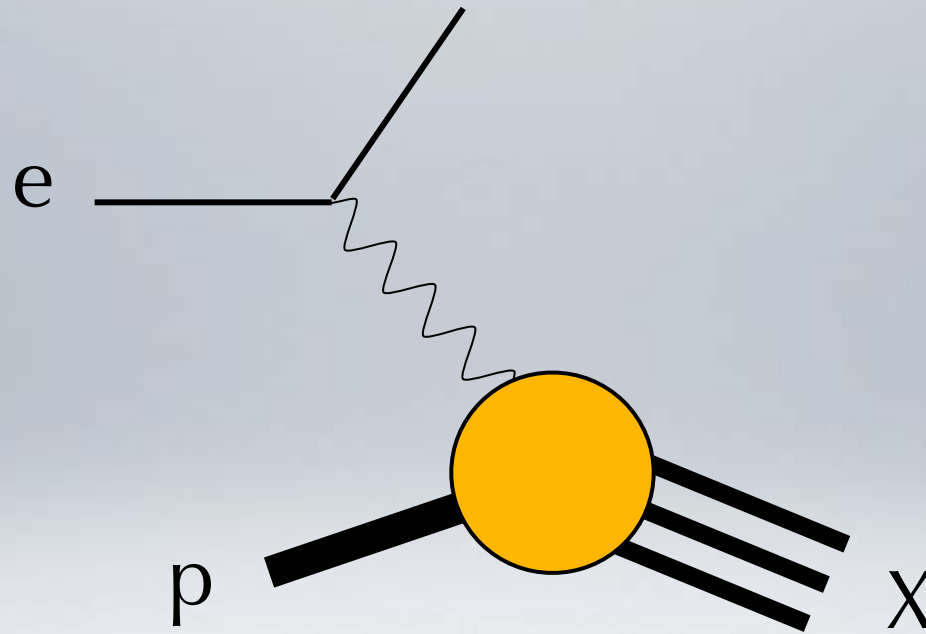


accesso a Form Factors

DIS inclusivo

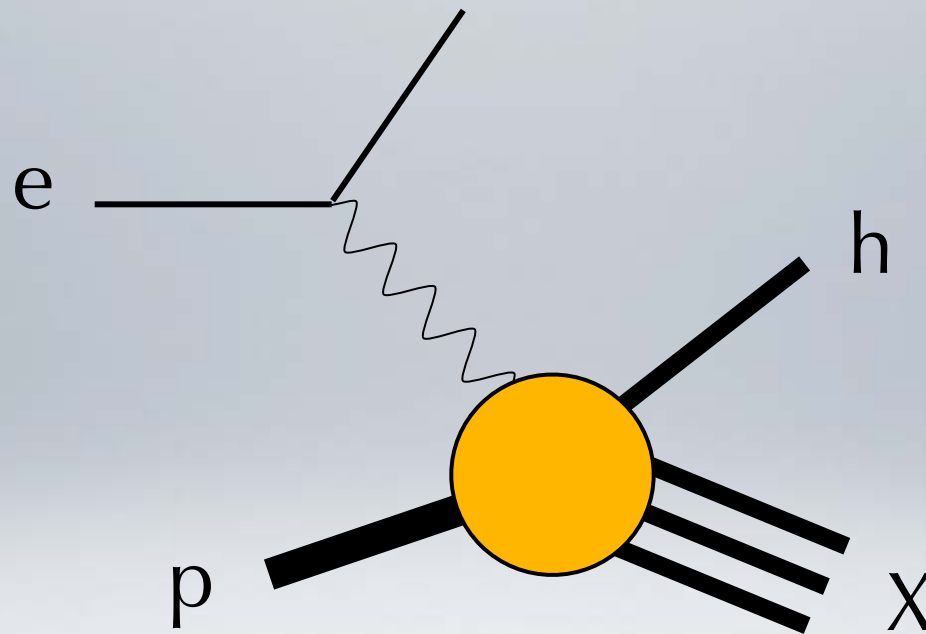


DIS inclusivo

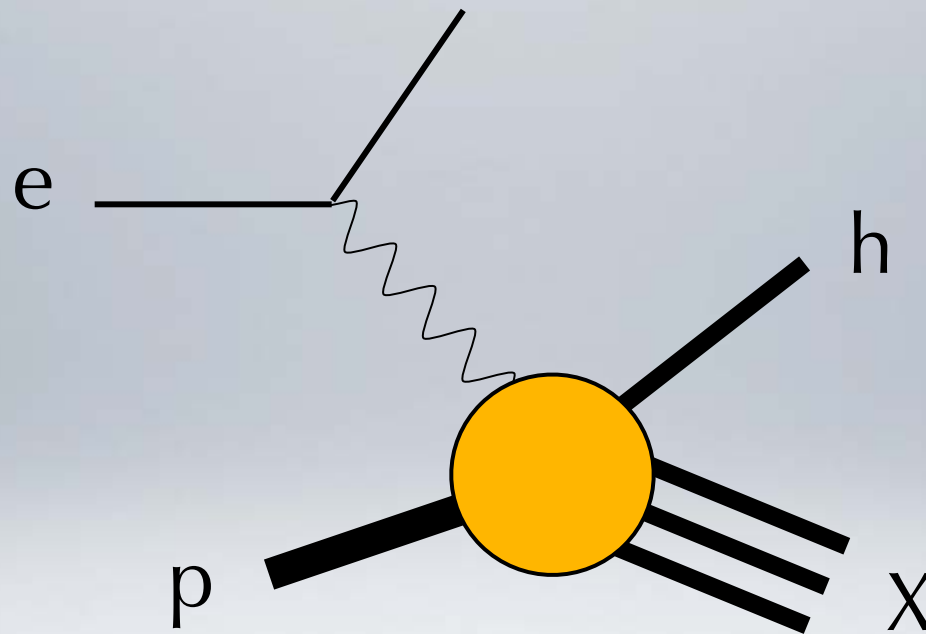


accesso a Parton Distribution Functions

DIS semi inclusivo

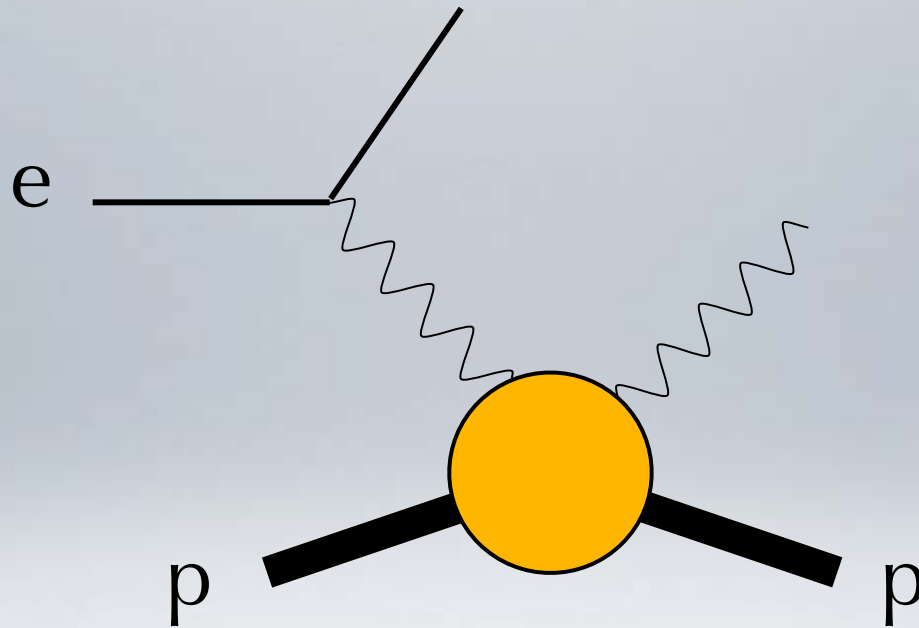


DIS semi inclusivo

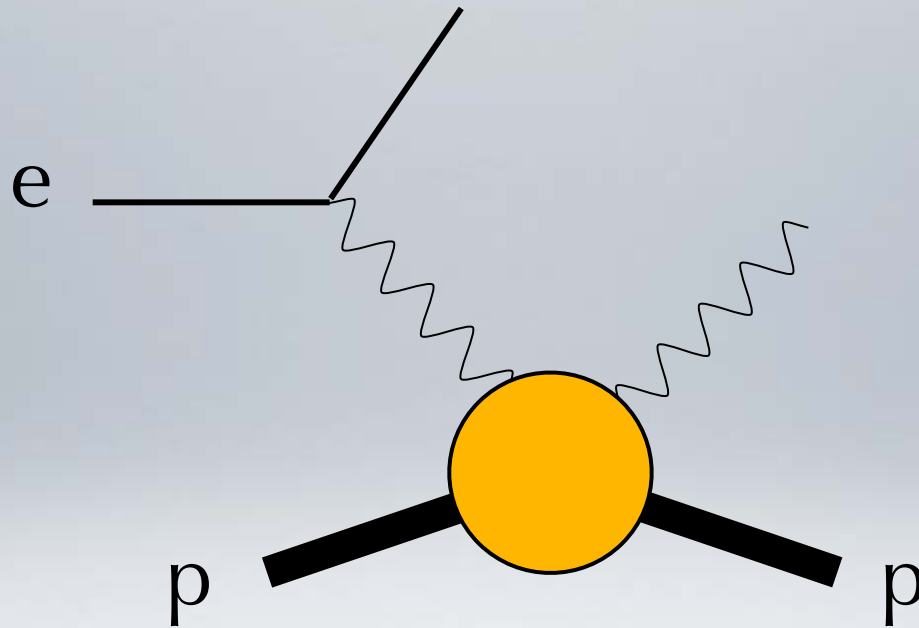


accesso a Transverse Momentum Distributions

Deeply-virtual Compton scattering

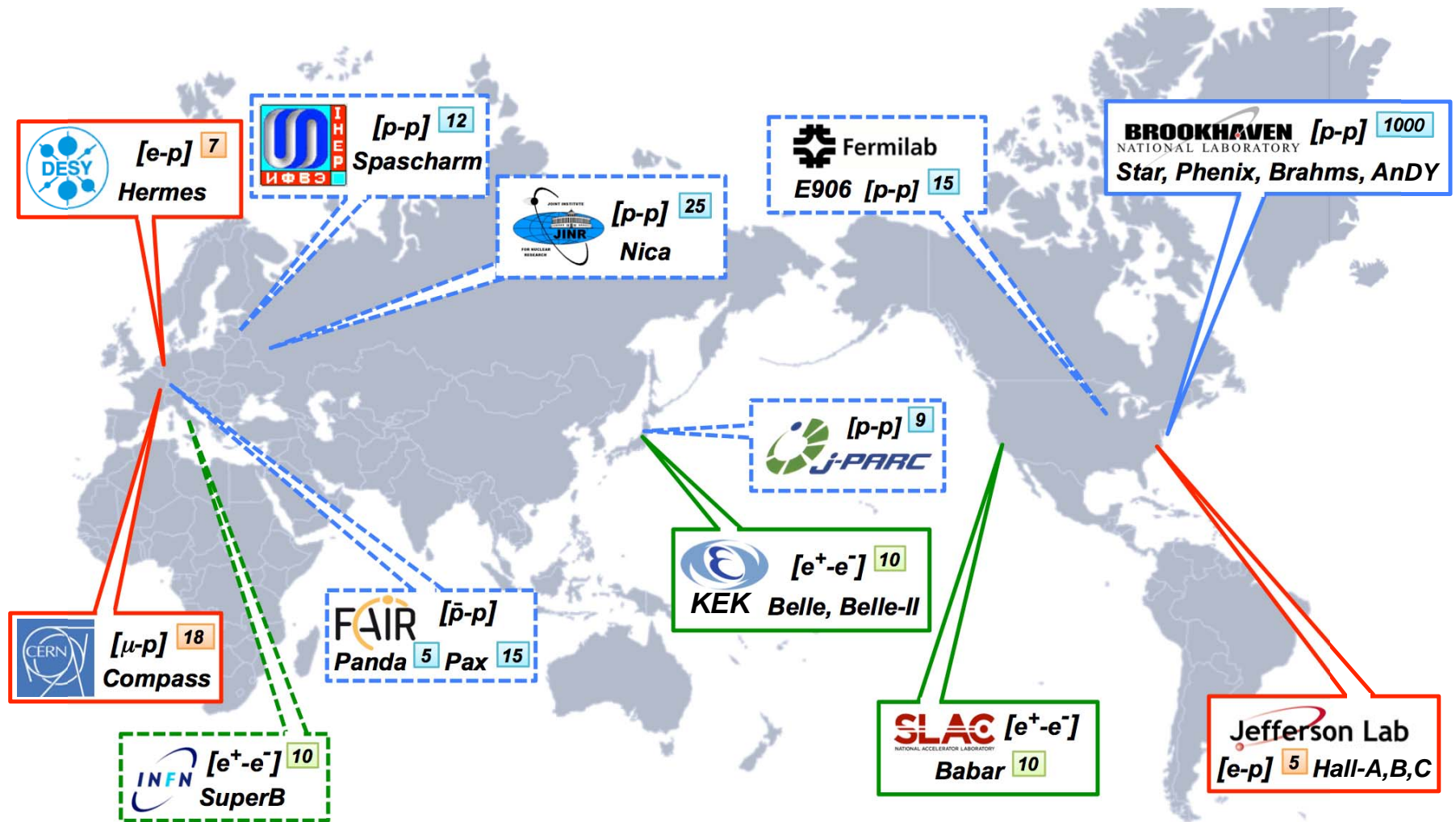


Deeply-virtual Compton scattering



accesso a Generalized Parton Distributions

Tanti esperimenti coinvolti

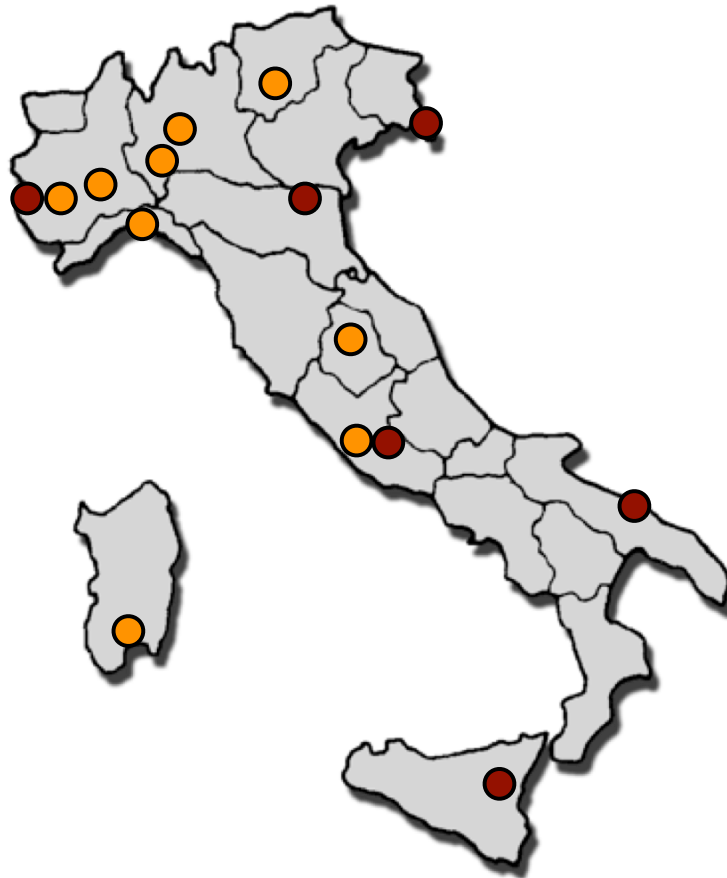


si veda il talk di Marco Mirazita

Chi lavora nel campo in Italia

Teoria (AD31 e TO31)

Alessandria
Cagliari
Genova
Milano Bic
Pavia
Perugia
Roma I e II
Torino
Trento



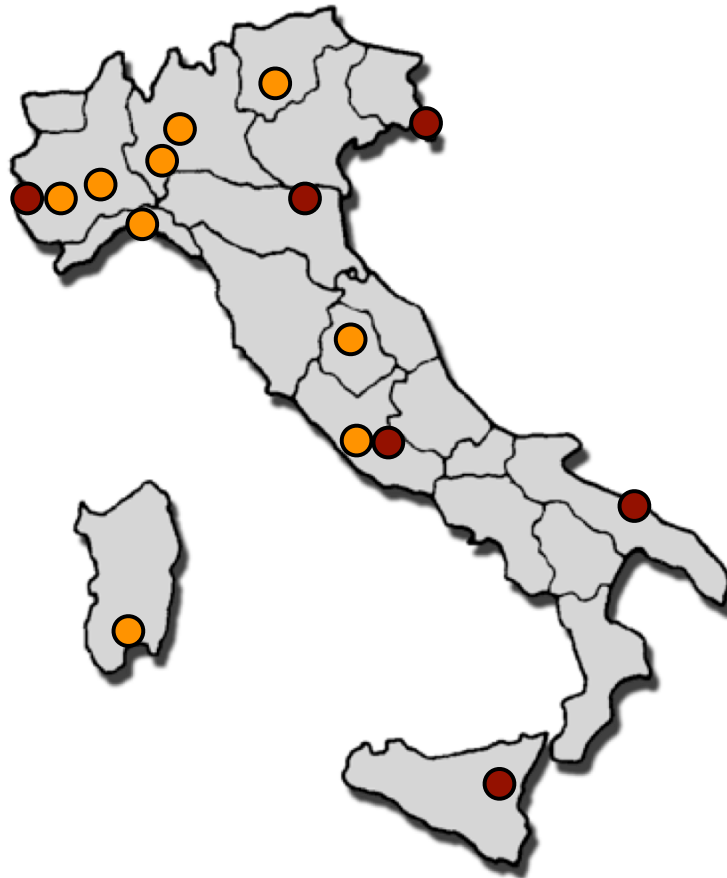
Esperimenti (Compass e JLab12)

Bari
Catania
Ferrara
Frascati
ISS
Roma I e II
Torino
Trieste

Chi lavora nel campo in Italia

Teoria (AD31 e TO31)

Alessandria
Cagliari
Genova
Milano Bic
Pavia
Perugia
Roma I e II
Torino
Trento



Esperimenti (Compass e JLab12)

Bari
Catania
Ferrara
Frascati
ISS
Roma I e II
Torino
Trieste

*si veda talk di
Marco Mirazita e
Guido Urciuoli*

Teorici coinvolti

Alessandria

Vincenzo Barone

Cagliari

Umberto D'Alesio
Cristian Pisano

Francesco Murgia

Genova

Mauro Giannini

Elena Santopinto

Milano Bic

Philip Ratcliffe

Pavia

Alessandro Bacchetta
Andrea Bianconi
Sigfrido Boffi

Marco Guagnelli
Barbara Pasquini
Marco Radici

Perugia

Claudio Ciofi degli Atti
Leonid Kaptar
Chiara Mezzetti

Sergio Scopetta
Matteo Rinaldi

Roma I e II

Emanuele Pace

Giovanni Salmè

Torino

Mauro Anselmino
Elena Boglione

Oswaldo Gonzalez
Stefano Melis

Trento

Pietro Faccioli
Marco Cristoforetti

Marco Traini

Contributi essenziali

Contributi essenziali

- Sviluppi formali riguardanti GPDs, TMDs, Wigner distributions (Pavia, Torino, Cagliari, Alessandria, Milano)

Contributi essenziali

- Sviluppi formali riguardanti GPDs, TMDs, Wigner distributions (Pavia, Torino, Cagliari, Alessandria, Milano)
- Modelli per le GPDs e TMDs (Perugia, Roma, Pavia, Trento)

Contributi essenziali

- Sviluppi formali riguardanti GPDs, TMDs, Wigner distributions (Pavia, Torino, Cagliari, Alessandria, Milano)
- Modelli per le GPDs e TMDs (Perugia, Roma, Pavia, Trento)
- Effetti nucleari sulle distribuzioni partoniche (Perugia, Roma)

Contributi essenziali

- Sviluppi formali riguardanti GPDs, TMDs, Wigner distributions (Pavia, Torino, Cagliari, Alessandria, Milano)
- Modelli per le GPDs e TMDs (Perugia, Roma, Pavia, Trento)
- Effetti nucleari sulle distribuzioni partoniche (Perugia, Roma)
- Time-like e space-like form factors (Roma, Genova, Pavia)

Contributi essenziali

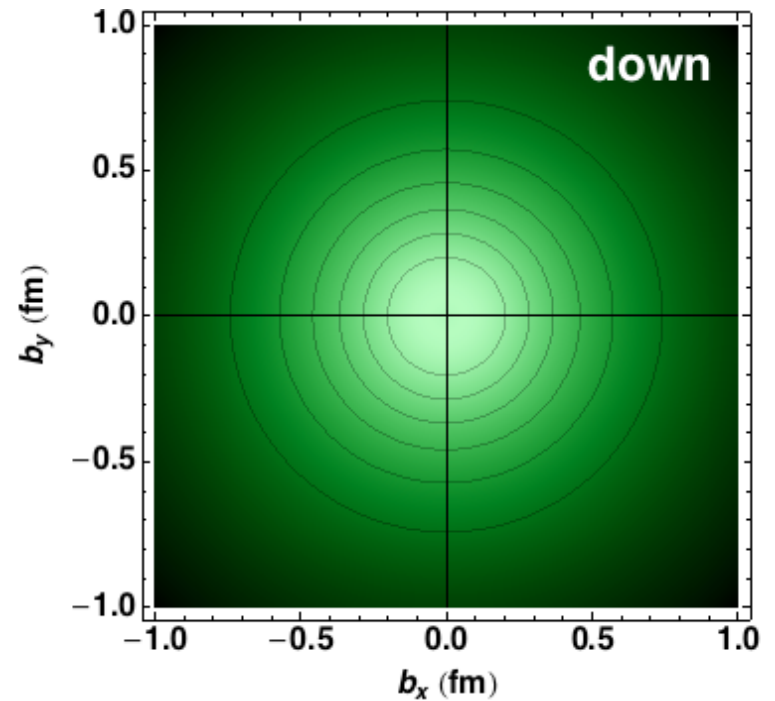
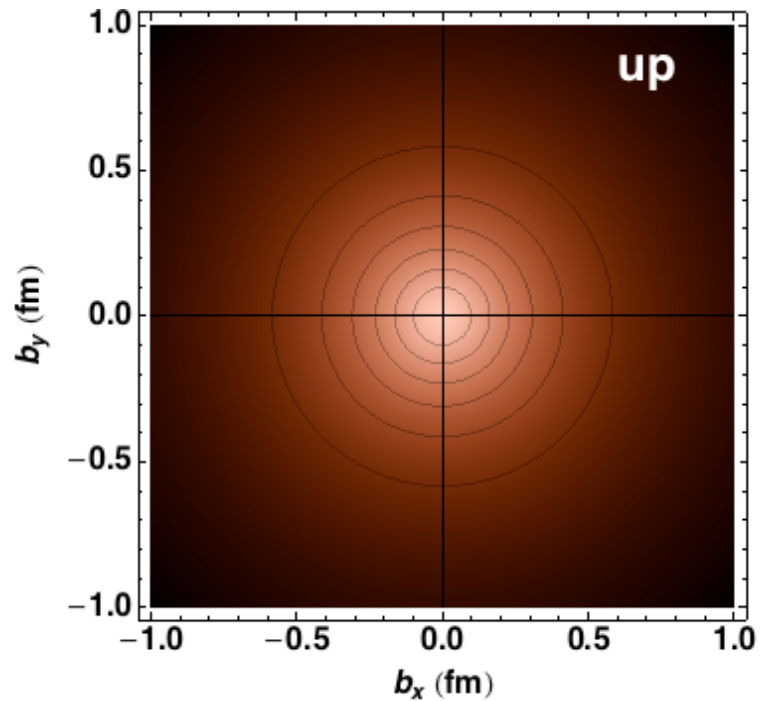
- Sviluppi formali riguardanti GPDs, TMDs, Wigner distributions (Pavia, Torino, Cagliari, Alessandria, Milano)
- Modelli per le GPDs e TMDs (Perugia, Roma, Pavia, Trento)
- Effetti nucleari sulle distribuzioni partoniche (Perugia, Roma)
- Time-like e space-like form factors (Roma, Genova, Pavia)
- Fenomenologia delle TMDs (Torino, Cagliari, Alessandria, Pavia)

Contributi essenziali

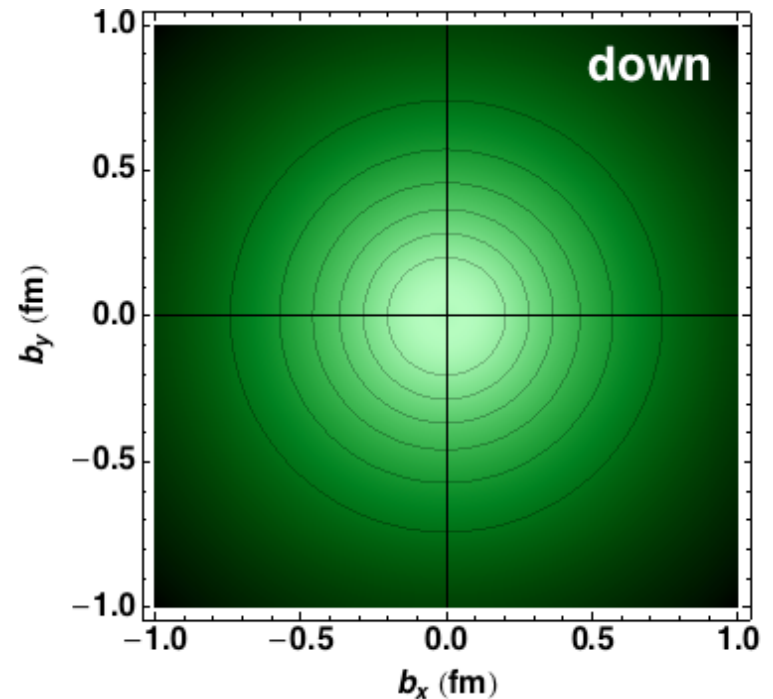
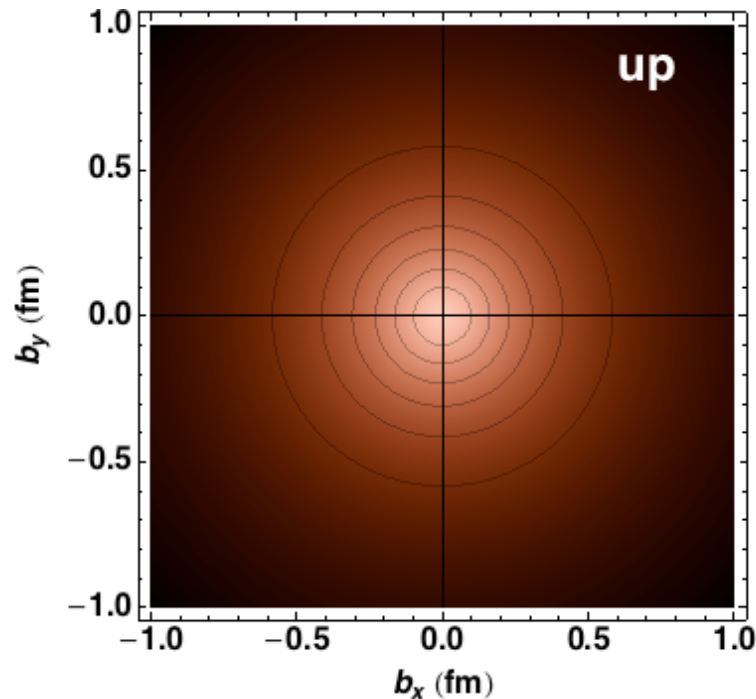
- Sviluppi formali riguardanti GPDs, TMDs, Wigner distributions (Pavia, Torino, Cagliari, Alessandria, Milano)
- Modelli per le GPDs e TMDs (Perugia, Roma, Pavia, Trento)
- Effetti nucleari sulle distribuzioni partoniche (Perugia, Roma)
- Time-like e space-like form factors (Roma, Genova, Pavia)
- Fenomenologia delle TMDs (Torino, Cagliari, Alessandria, Pavia)
- Applicazione di tecniche QCD a sistemi complessi (Trento)

Una selezione di risultati importanti

Impact-parameter distribution

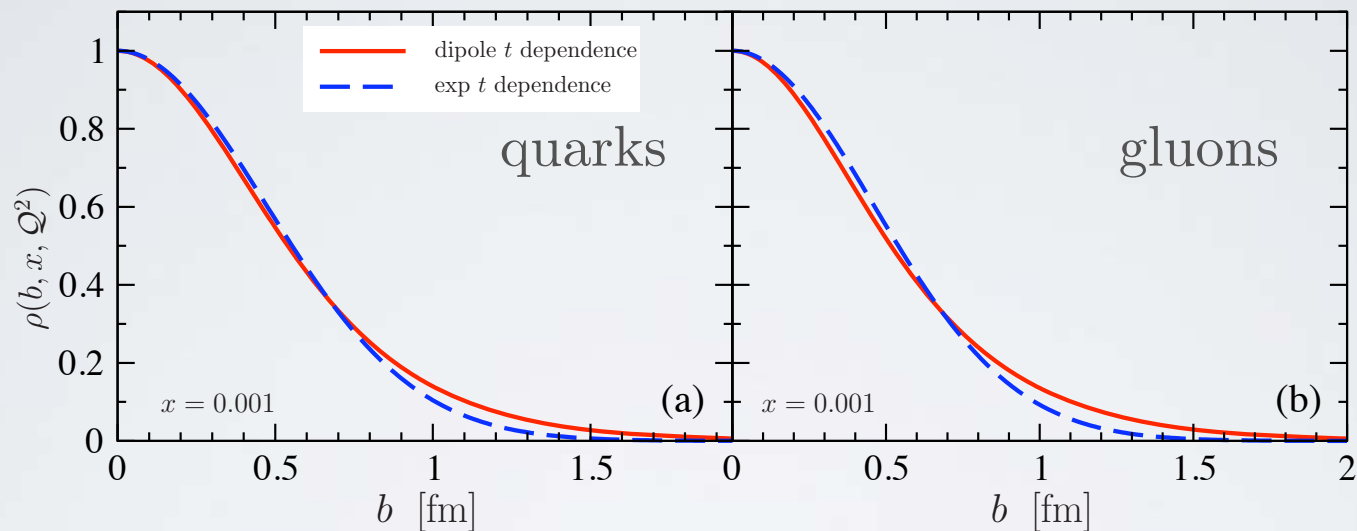


Impact-parameter distribution



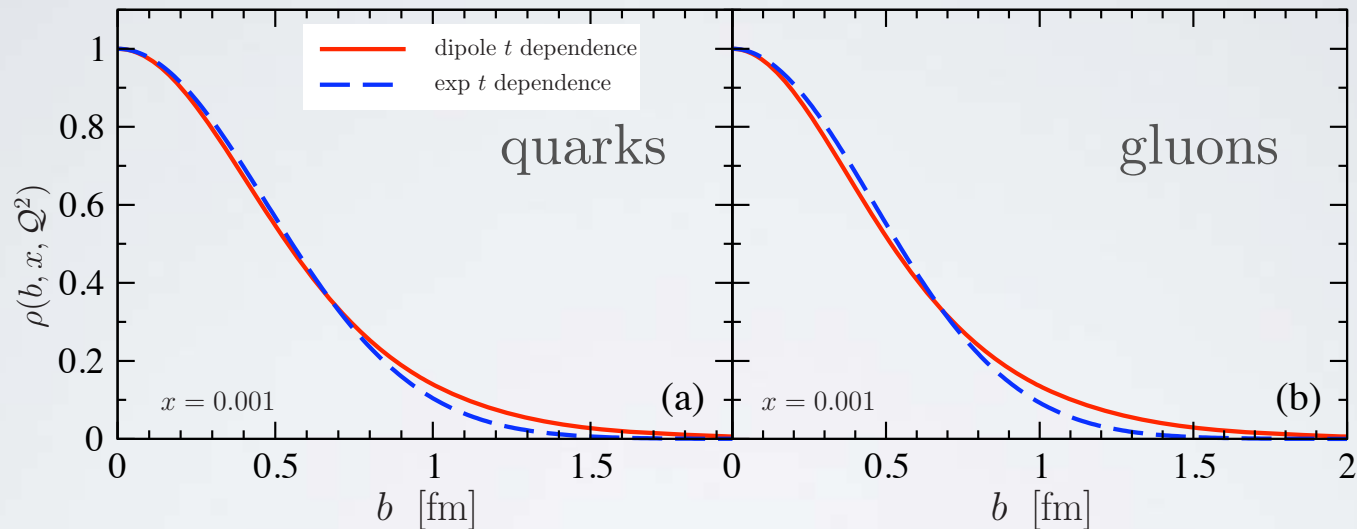
- Immagini ottenute dal fattore di forma di Dirac
- Descrivono solo la combinazione di valenza
- Sono integrate su x

Quark di mare e gluoni



Kumericki, Mueller, NPB841 (10)

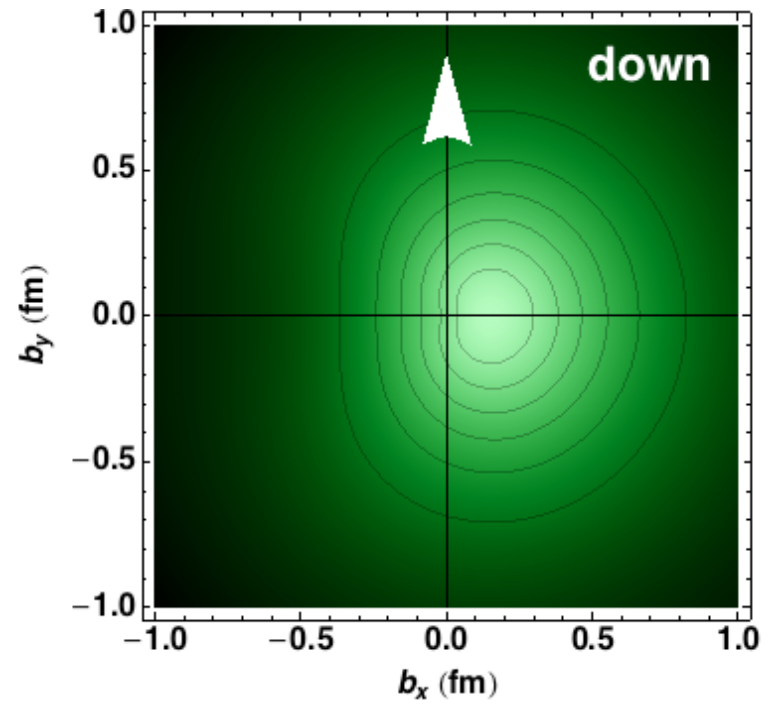
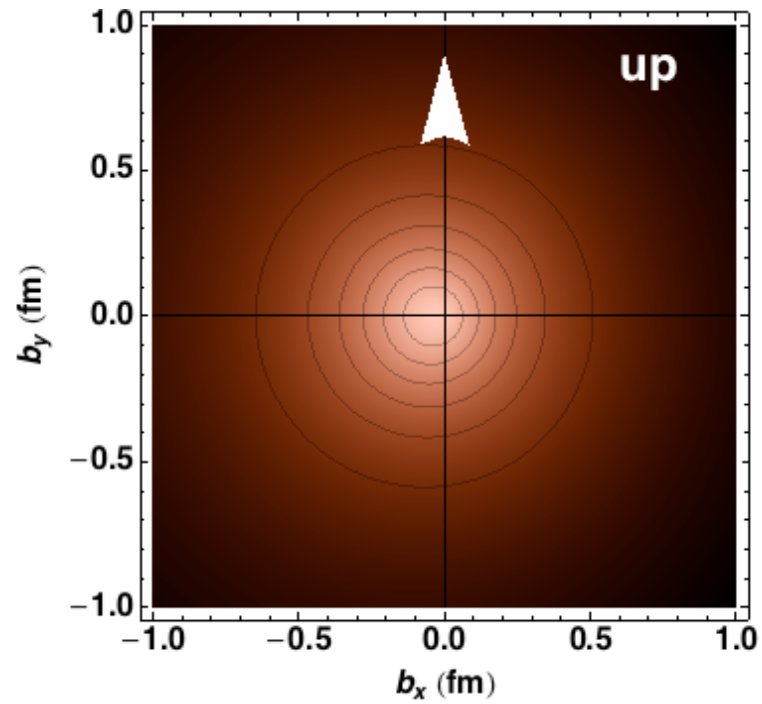
Quark di mare e gluoni



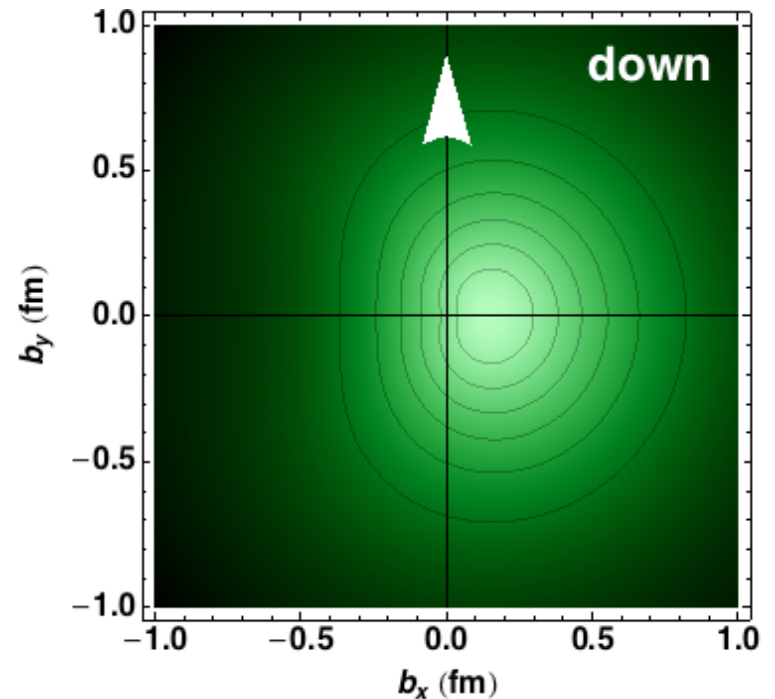
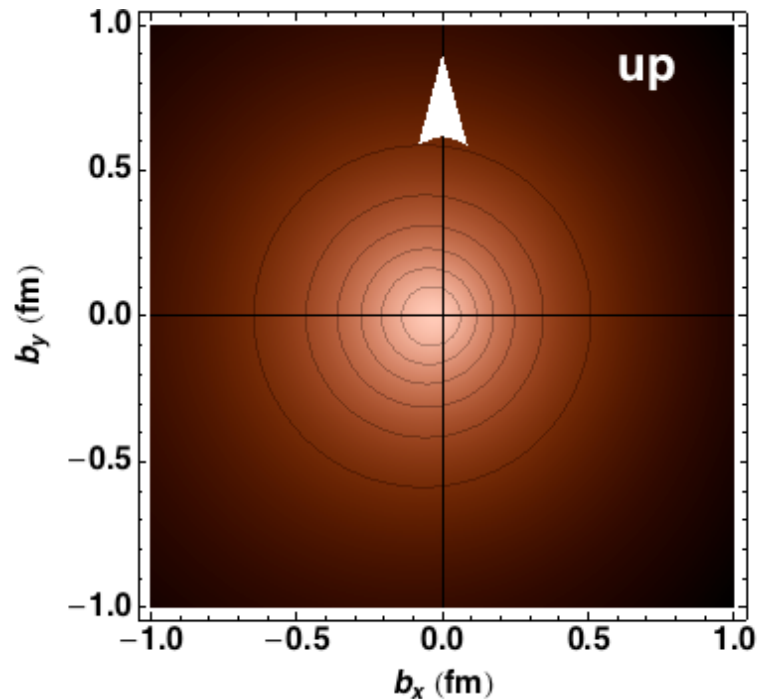
- Ottenute dalle GPD estratte da DVCS
- Quark di mare e gluoni sono simili

Kumericki, Mueller, NPB841 (10)

Inclusione dello spin

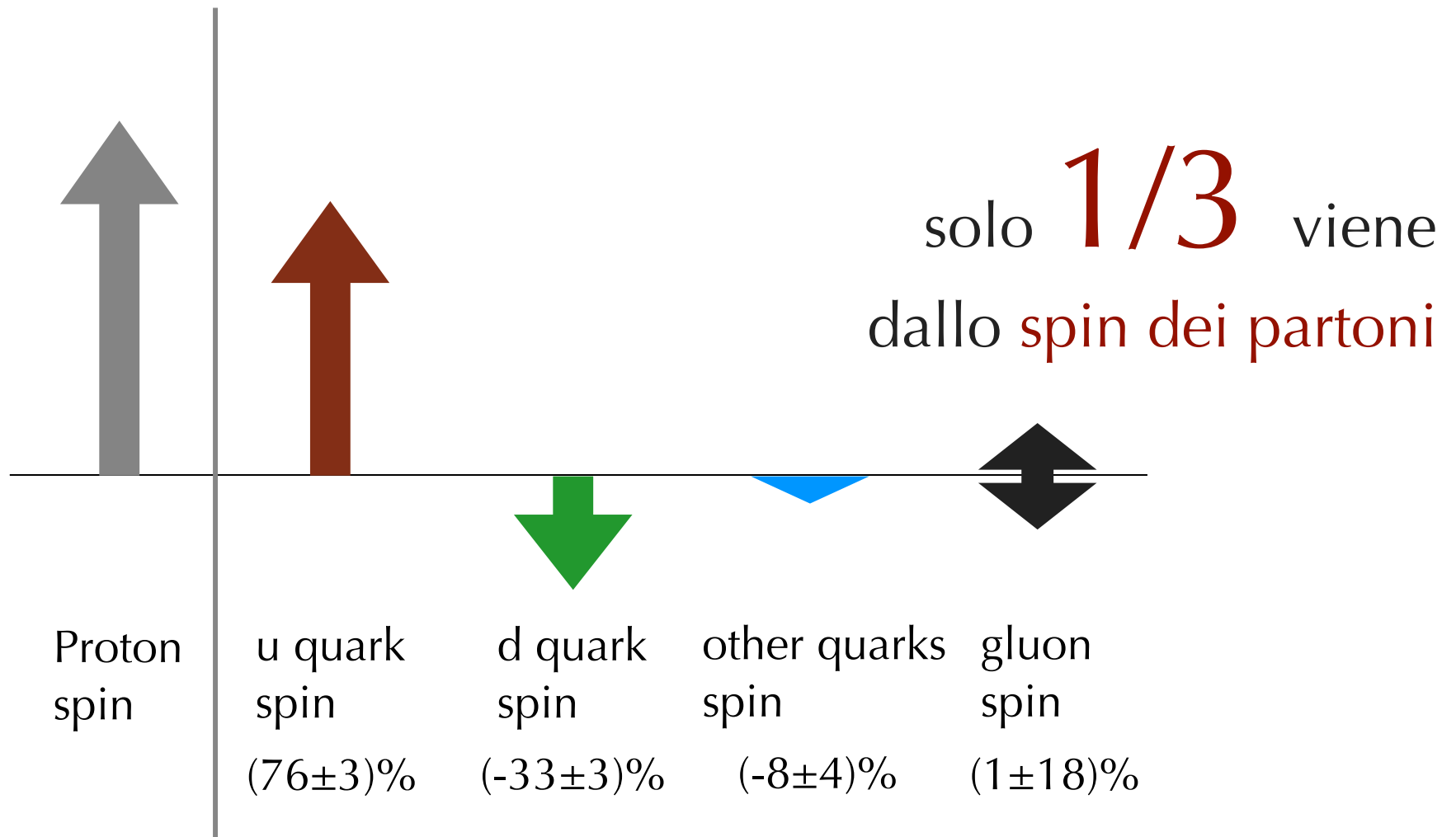


Inclusione dello spin



- Immagini ottenute dalla trasformata di Fourier del fattore di forma di Pauli (Kelly parametrization)
- Descrivono solo la combinazione di valenza
- Sono integrate su x

Da dove viene lo spin dei nucleoni ?



Momento angolare


X. Ji, PRL 78 (97)

$$J^q = \frac{1}{2} \int_0^1 dx x \left(H^q(x, 0, 0) + E^q(x, 0, 0) \right)$$

Momento angolare

X. Ji, PRL 78 (97)


Limiti “forward” delle GPDs


$$J^q = \frac{1}{2} \int_0^1 dx x \left(H^q(x, 0, 0) + E^q(x, 0, 0) \right)$$

Momento angolare

X. Ji, PRL 78 (97)

Limiti “forward” delle GPDs



$$J^q = \frac{1}{2} \int_0^1 dx x \left(H^q(x, 0, 0) + E^q(x, 0, 0) \right)$$

1038 citazioni

Momento angolare

X. Ji, PRL 78 (97)

Limiti “forward” delle GPDs


$$J^q = \frac{1}{2} \int_0^1 dx x \left(H^q(x, 0, 0) + E^q(x, 0, 0) \right)$$

Momento angolare

X. Ji, PRL 78 (97)

Limiti “forward” delle GPDs

$$J^q = \frac{1}{2} \int_0^1 dx x \left(H^q(x, 0, 0) + E^q(x, 0, 0) \right)$$

$q(x)$

PDF non polarizzata:
ben conosciuta

Momento angolare

X. Ji, PRL 78 (97)

Limiti “forward” delle GPDs

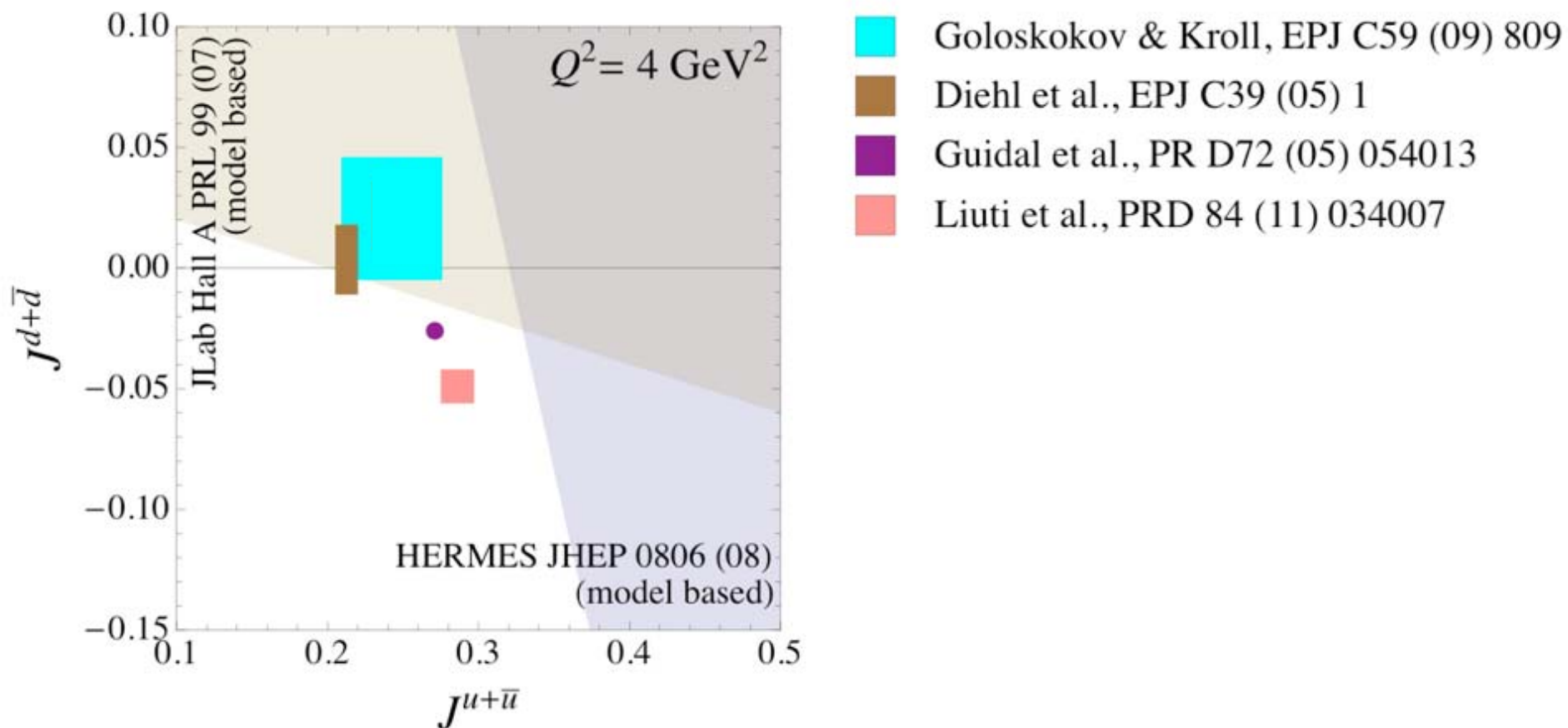
$$J^q = \frac{1}{2} \int_0^1 dx x \left(H^q(x, 0, 0) + E^q(x, 0, 0) \right)$$

$q(x)$

PDF non polarizzata:
ben conosciuta

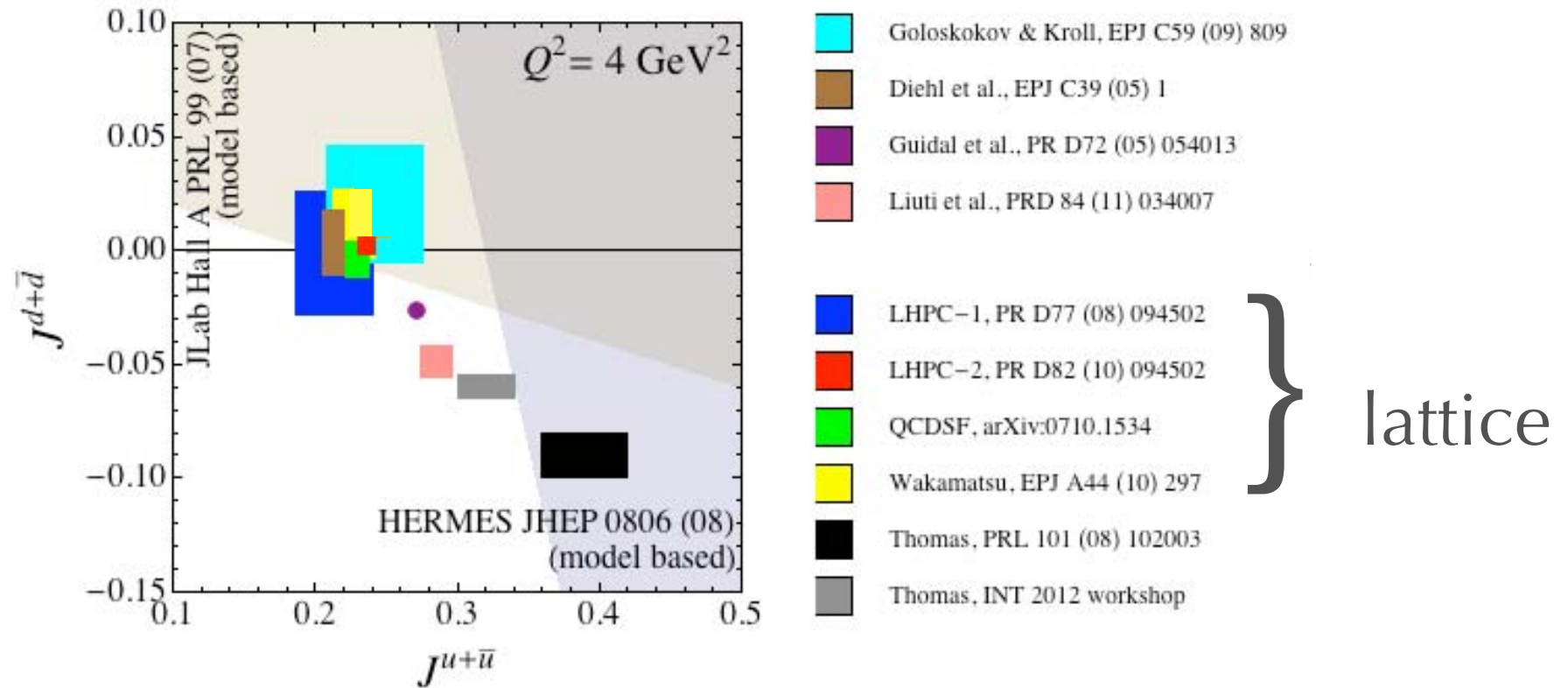
Estrapolazioni
dipendenti da
modelli...

Risultati dallo studio delle GPD



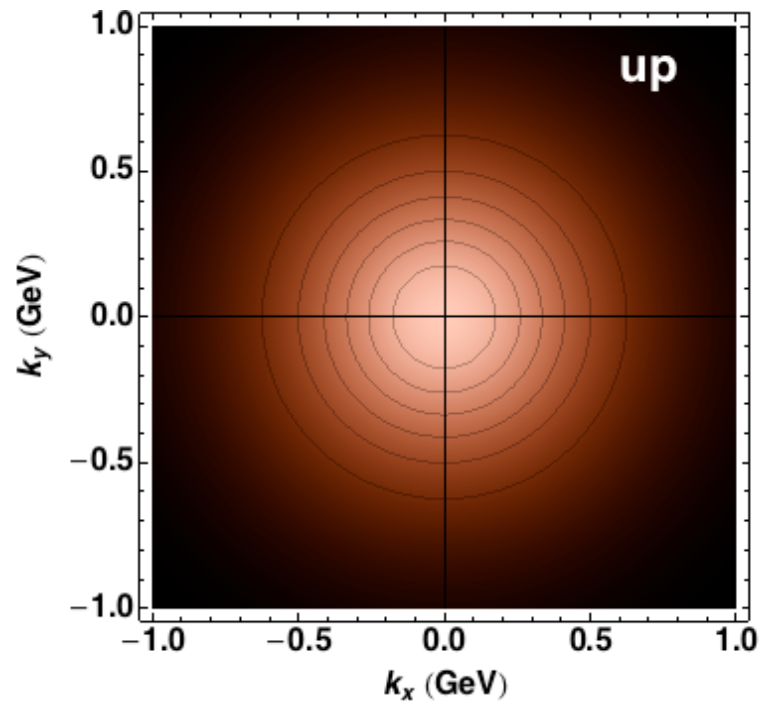
*si veda Bacchetta, Radici, arXiv:1206.2565 [hep-ph]
e "Physics Opportunities with the 12 GeV Upgrade at Jefferson Lab", arXiv:1208.1244 [hep-ex]*

Confronto con lattice QCD

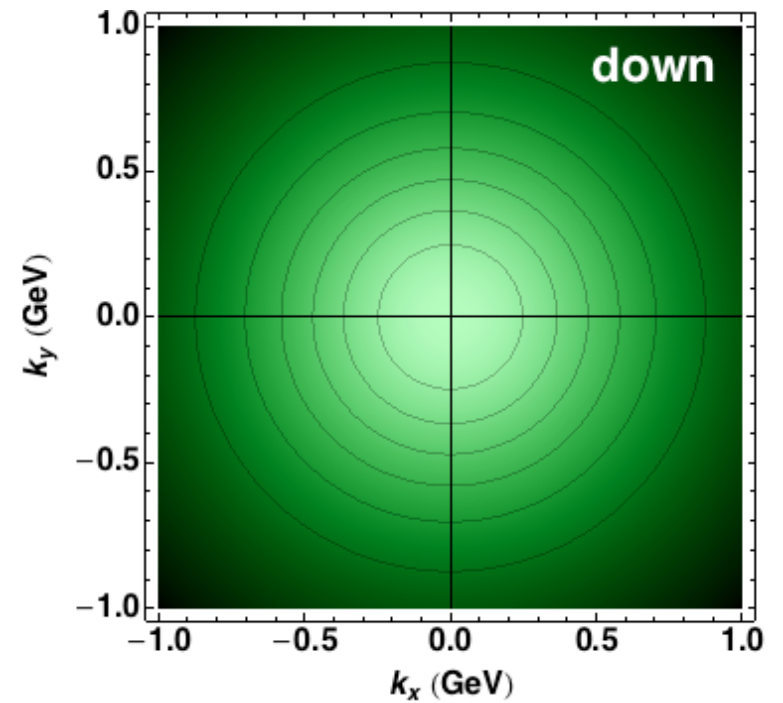
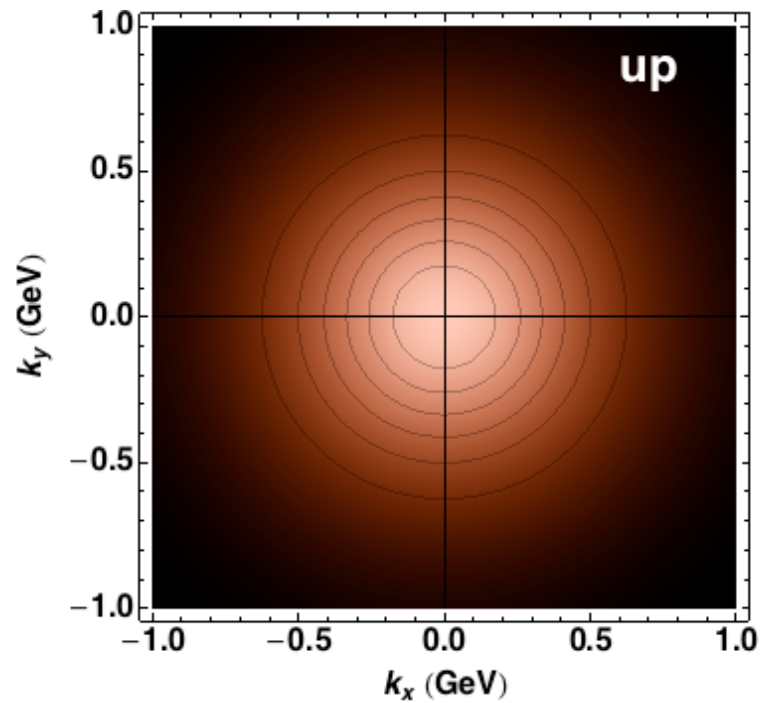


*si veda Bacchetta, Radici, arXiv:1206.2565 [hep-ph]
 e "Physics Opportunities with the 12 GeV Upgrade at Jefferson Lab", arXiv:1208.1244 [hep-ex]*

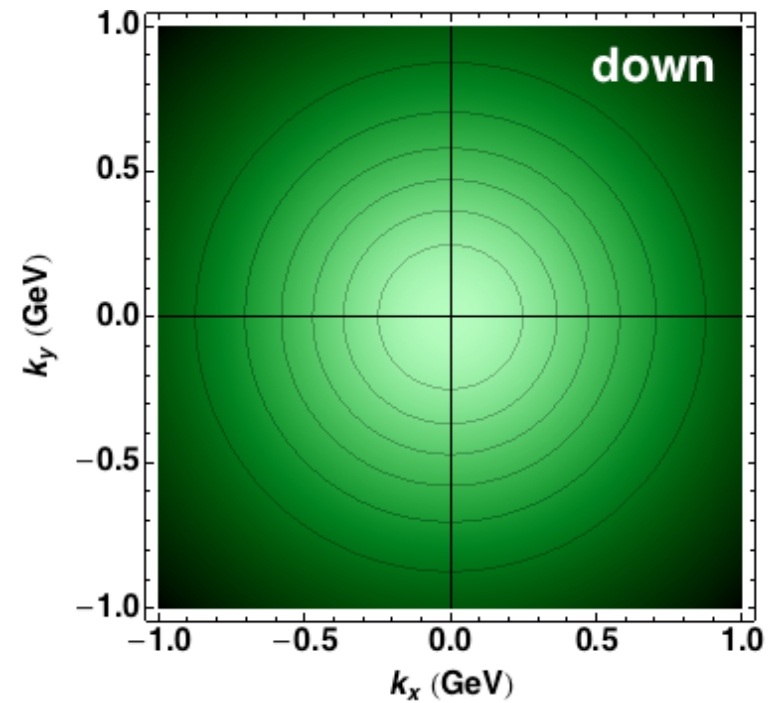
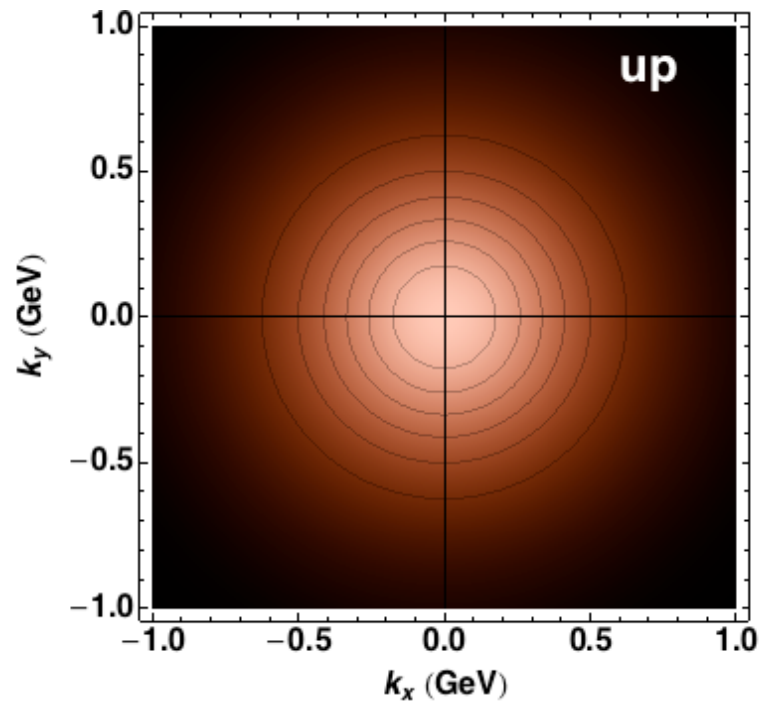
Transverse-momentum distributions



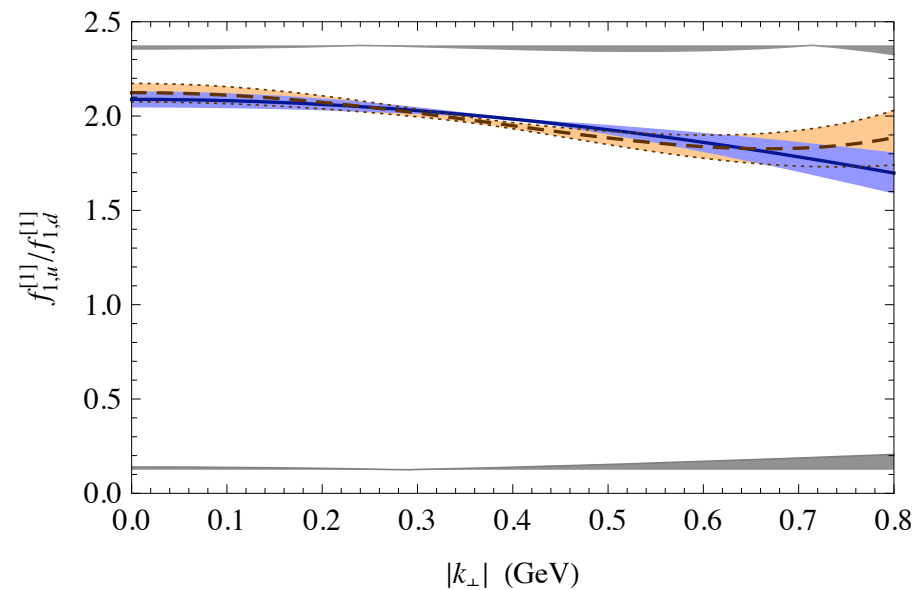
Transverse-momentum distributions



Transverse-momentum distributions



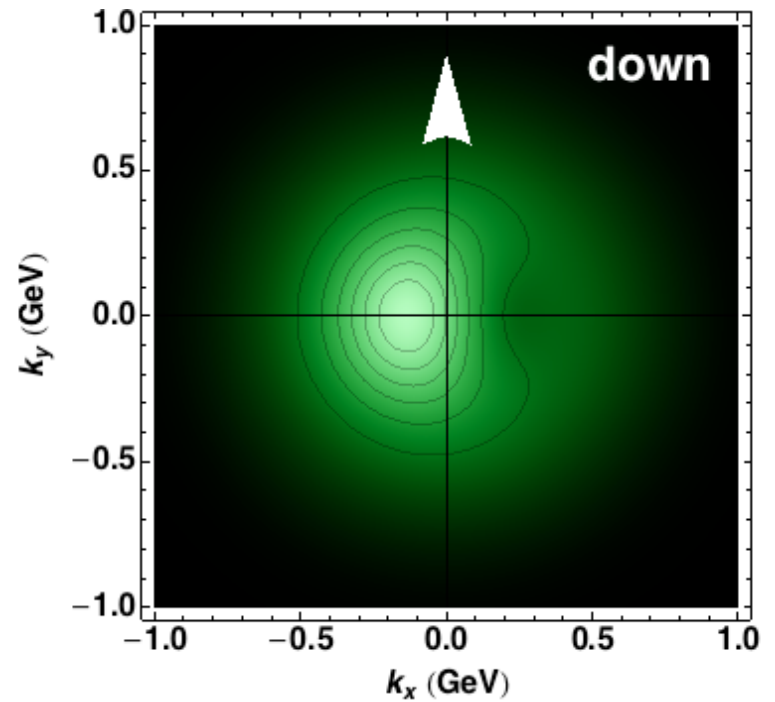
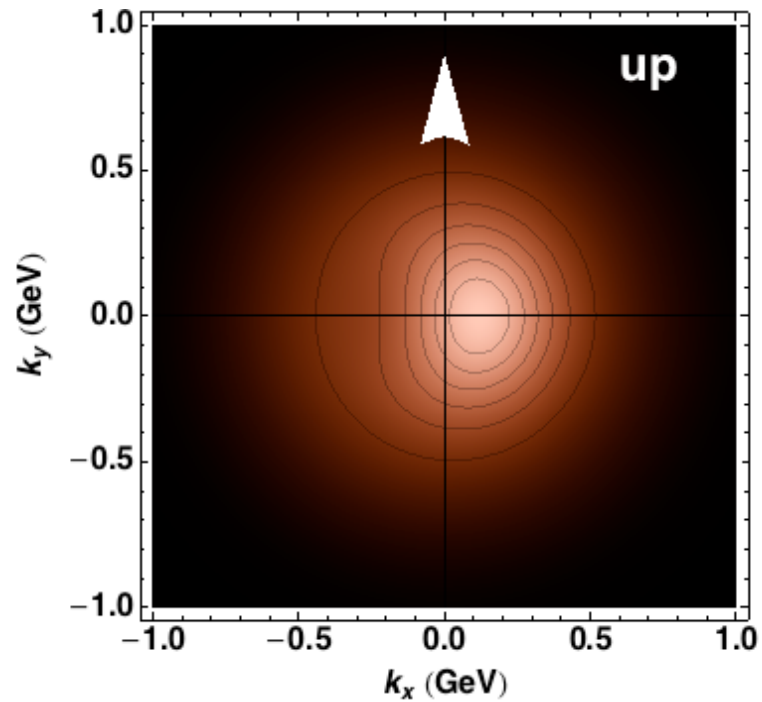
Indicazioni da QCD su reticolo



Studi pionieristici di lattice QCD indicano
che down è più largo di up

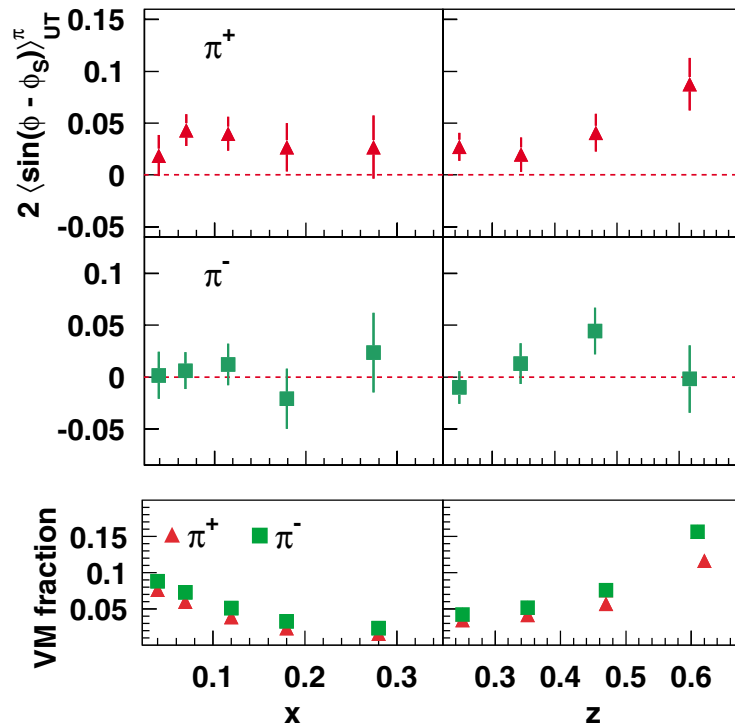
Musch, Hagler, Negele, Schafer, PRD 83 (11)

Inclusione dello spin



Distorsione legata alla TMD di Sivers

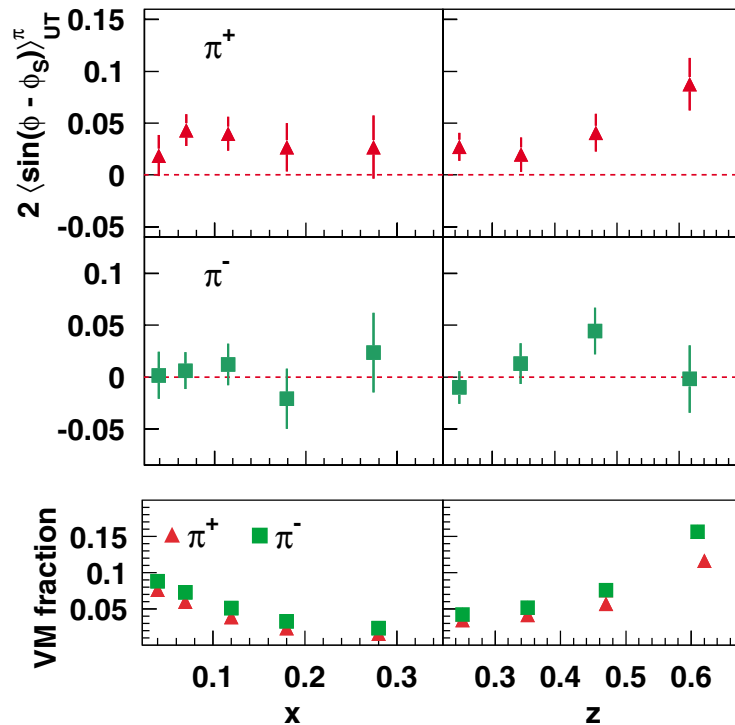
First experimental evidence



“Single-spin asymmetries in semi-inclusive deep-inelastic scattering on a transversely polarized hydrogen target”

HERMES, Phys. Rev. Lett. 94 (05)

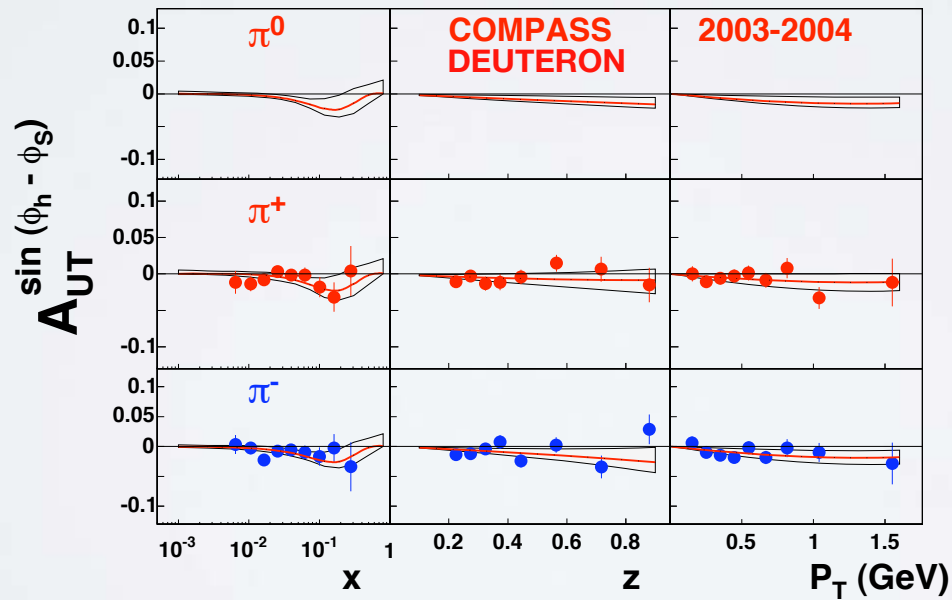
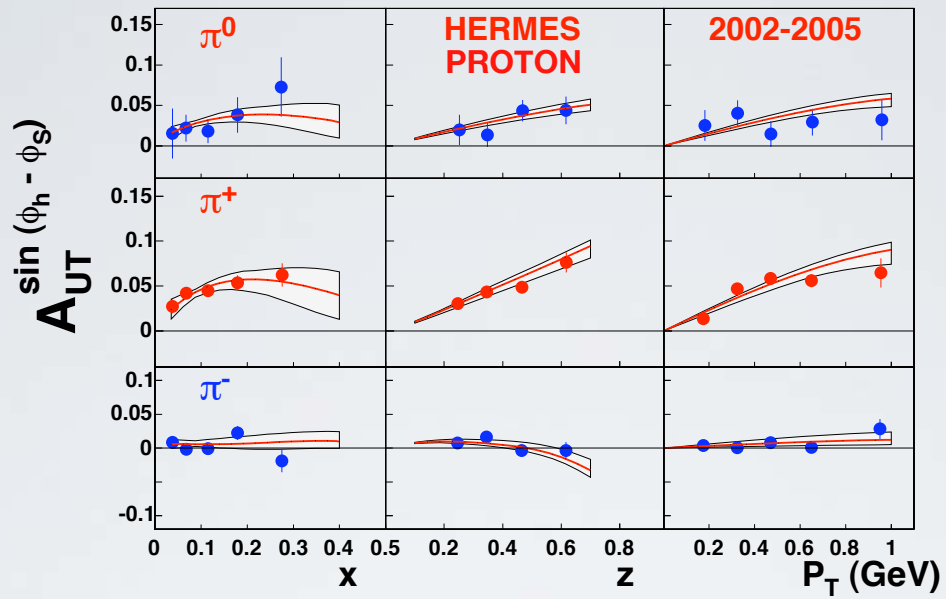
First experimental evidence



“Single-spin asymmetries in semi-inclusive deep-inelastic scattering on a transversely polarized hydrogen target”

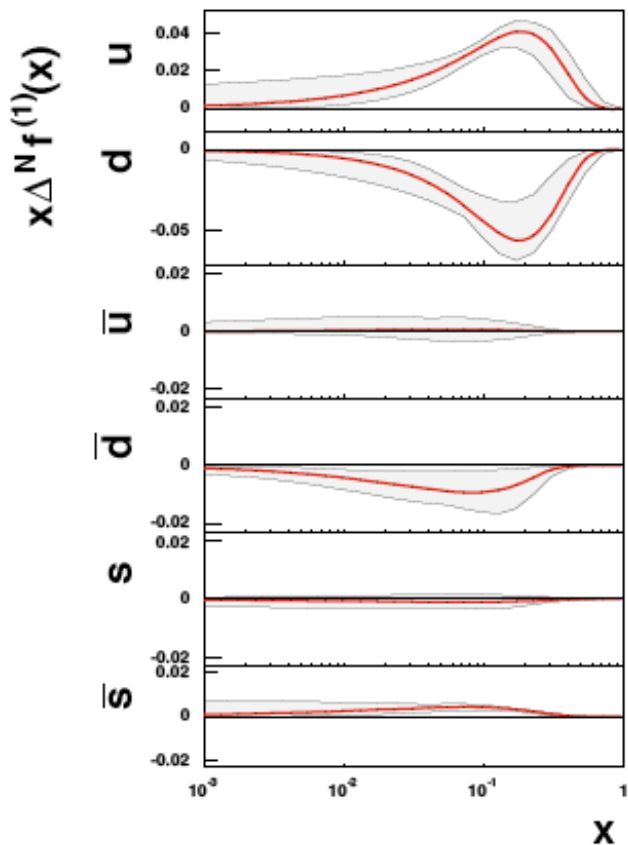
HERMES, Phys. Rev. Lett. 94 (05)

443 citazioni

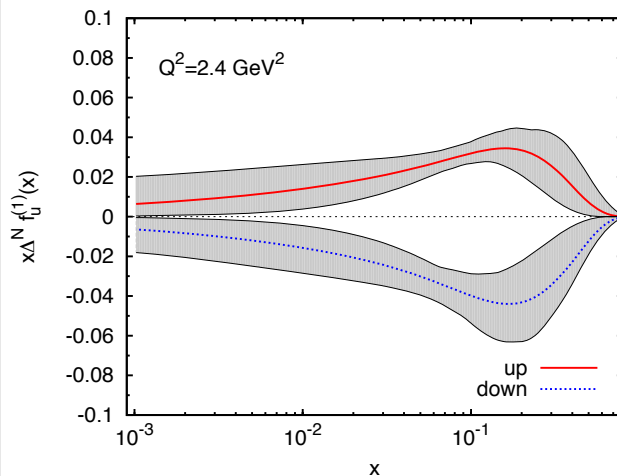


fit: Anselmino et al., EPJA39(09)

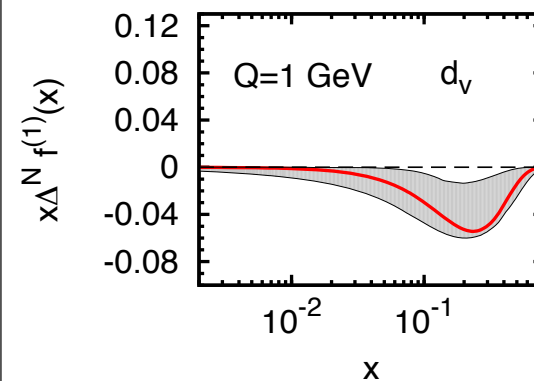
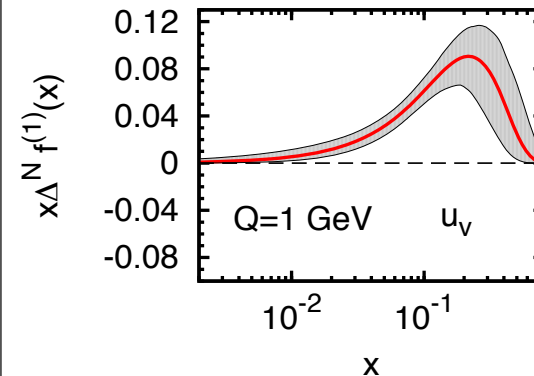
Torino-Cagliari extractions



Anselmino et al.
EPJA39(09)

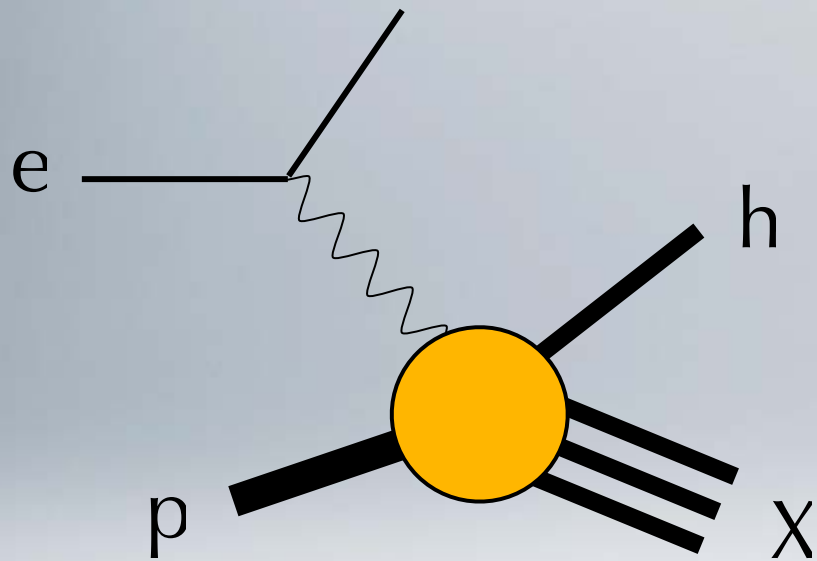


Anselmino et al.
arXiv:1107.4446



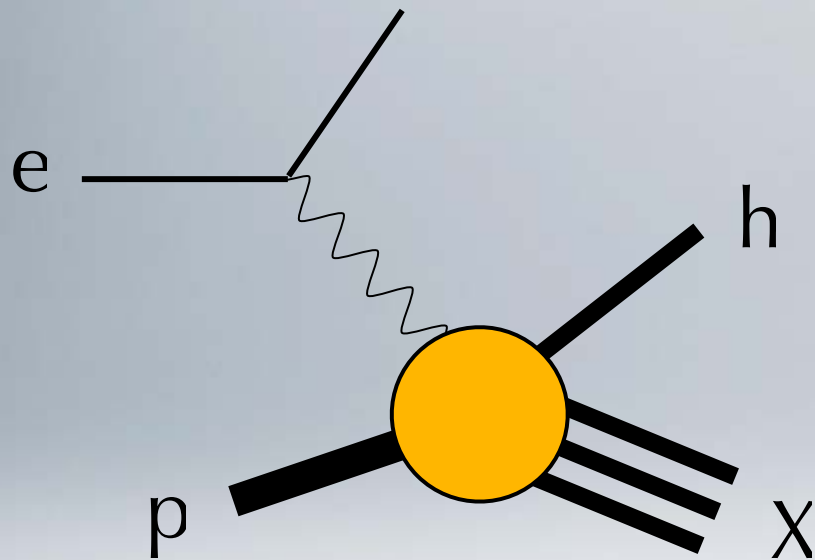
Anselmino et al.
arXiv:1204.1239

Cosa accade in processi diversi?

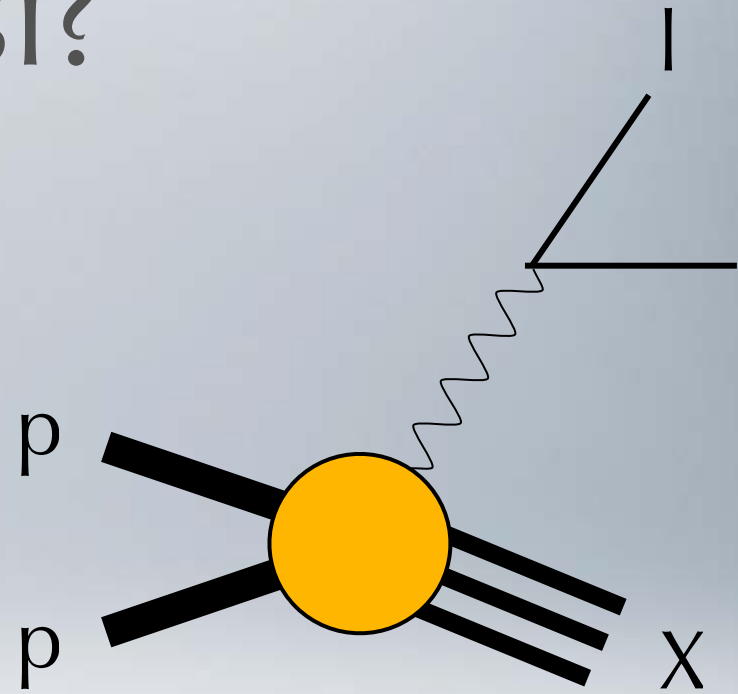


DIS semi-inclusivo

Cosa accade in processi diversi?

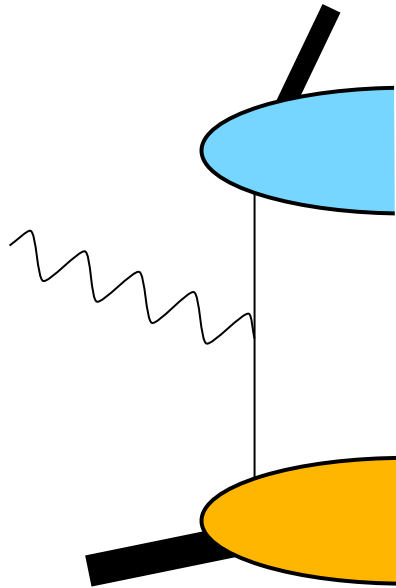


DIS semi-inclusivo

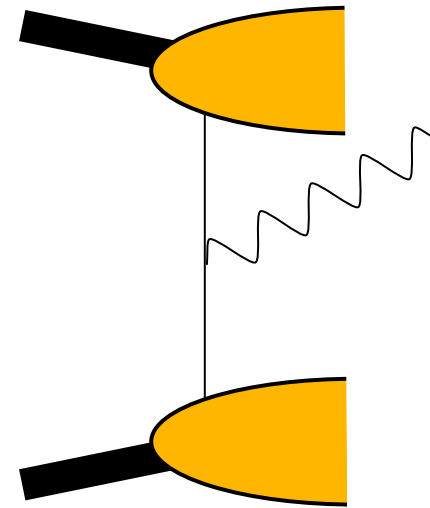


scattering Drell-Yan

Fattorizzazione e universalità

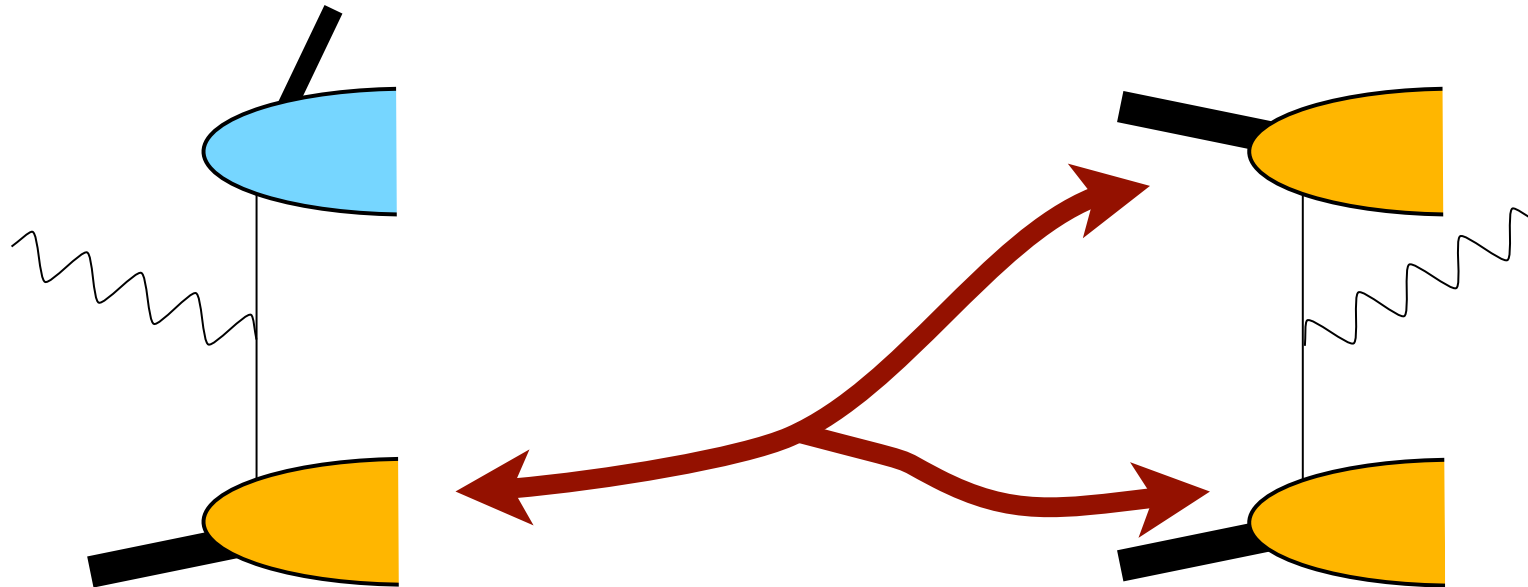


Semi-inclusive DIS



Drell-Yan scattering

Fattorizzazione e universalità



Semi-inclusive DIS

Drell-Yan scattering

Risultato chiave della QCD

Comportamento inaspettato

$$\text{Sivers} \Big|_{\text{SIDIS}} = -\text{Sivers} \Big|_{\text{D-Y}}$$

Collins, PLB 536 (02)

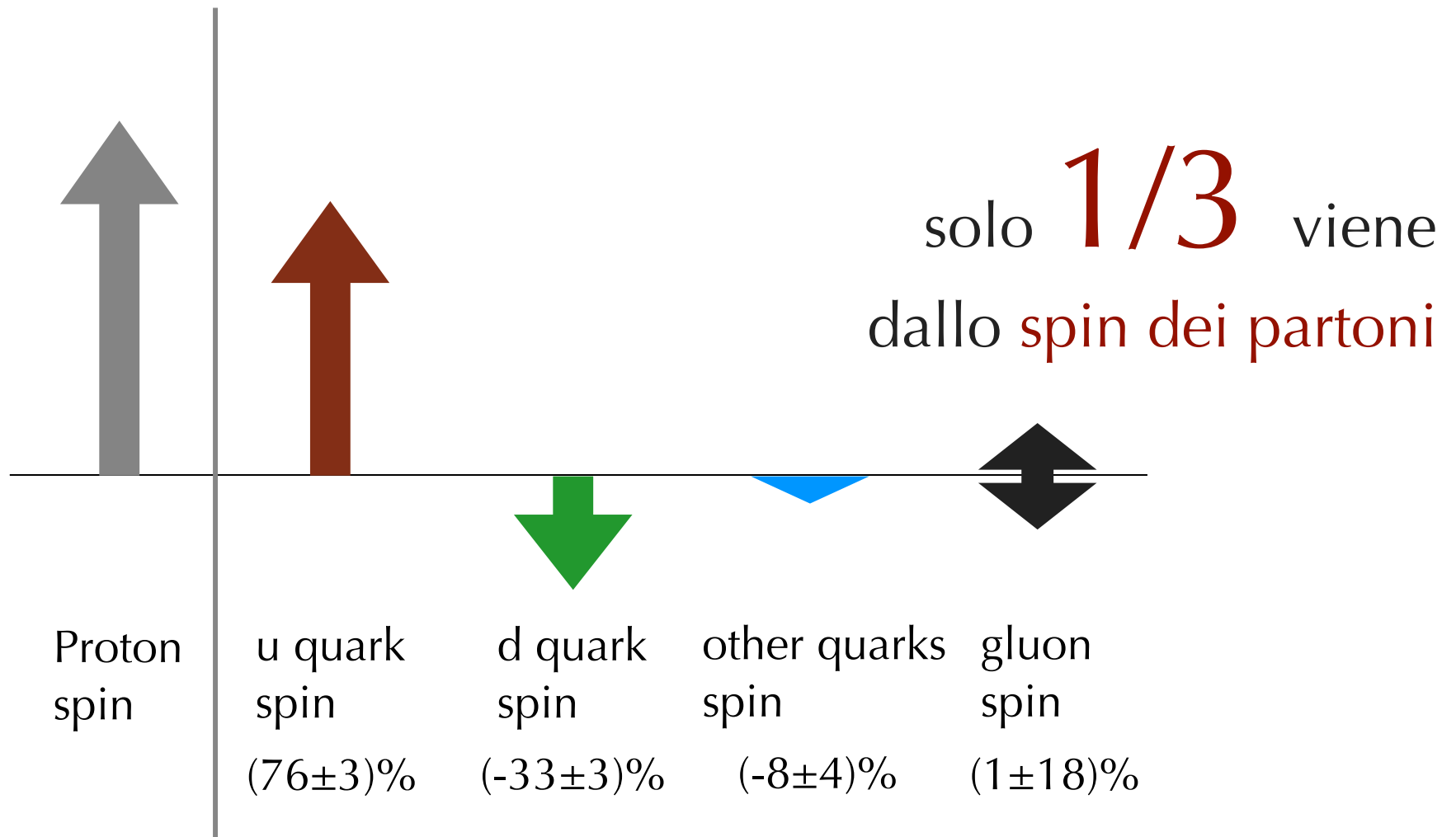
Comportamento inaspettato

$$\text{Sivers} \Big|_{\text{SIDIS}} = -\text{Sivers} \Big|_{\text{D-Y}}$$

Collins, PLB 536 (02)

La distorsione della distribuzione dei quark cambia segno se osservata nel SIDIS o nel Drell-Yan.
Questa predizione non è ancora stata verificata.

Da dove viene lo spin dei nucleoni ?



Model-inspired assumption

$$f_{1T}^{\perp(0)a}(x) = -L(x)E^a(x, 0, 0)$$

TMD di Sivers




Funzione di lensing
(final-state interactions)



Momento angolare

X. Ji, PRL 78 (97)

Limiti “forward” delle GPDs


$$J^q = \frac{1}{2} \int_0^1 dx x \left(H^q(x, 0, 0) + E^q(x, 0, 0) \right)$$

Momento angolare

X. Ji, PRL 78 (97)

Limiti “forward” delle GPDs

$$J^q = \frac{1}{2} \int_0^1 dx x \left(H^q(x, 0, 0) + E^q(x, 0, 0) \right)$$

$q(x)$

PDF non polarizzata:
ben conosciuta

Momento angolare

X. Ji, PRL 78 (97)

Limiti “forward” delle GPDs

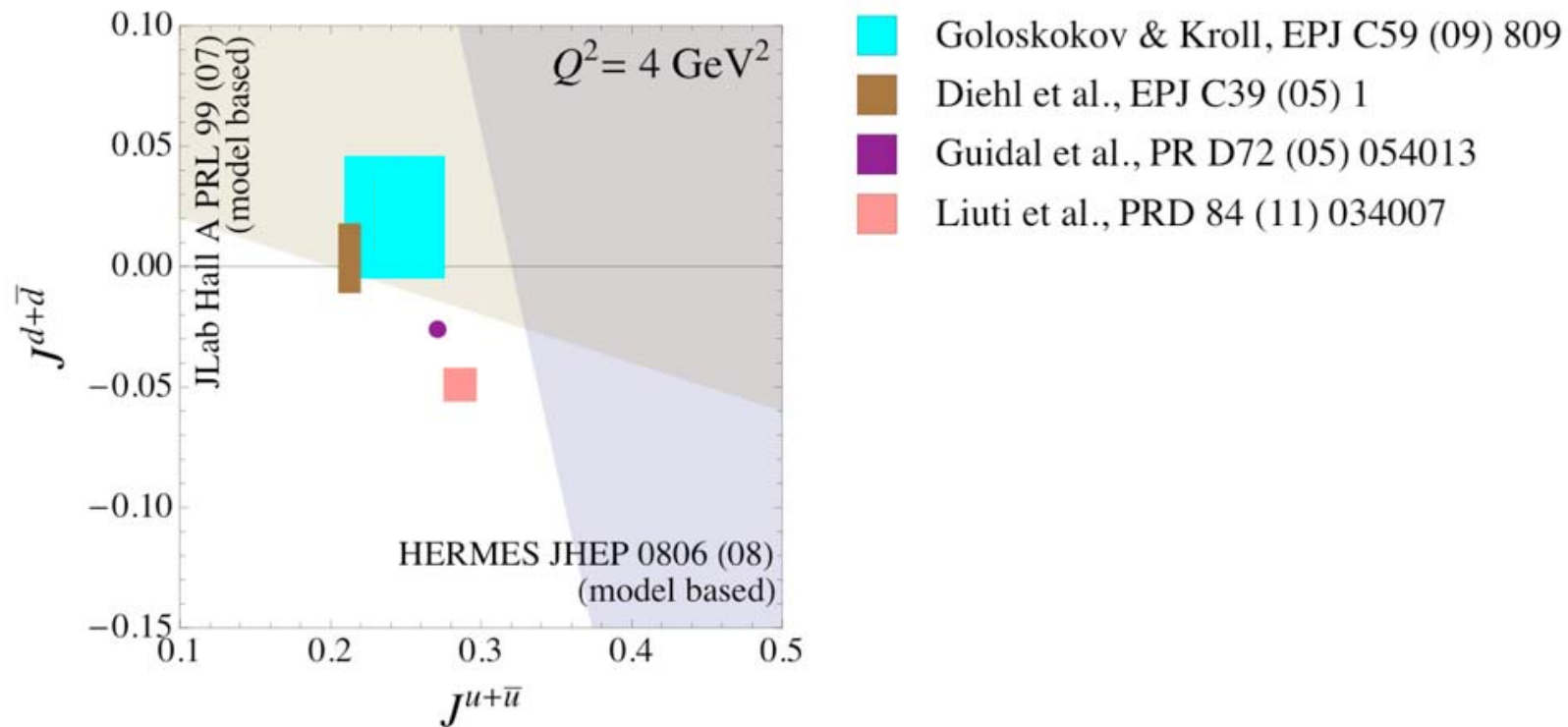
$$J^q = \frac{1}{2} \int_0^1 dx x \left(H^q(x, 0, 0) + E^q(x, 0, 0) \right)$$

$q(x)$

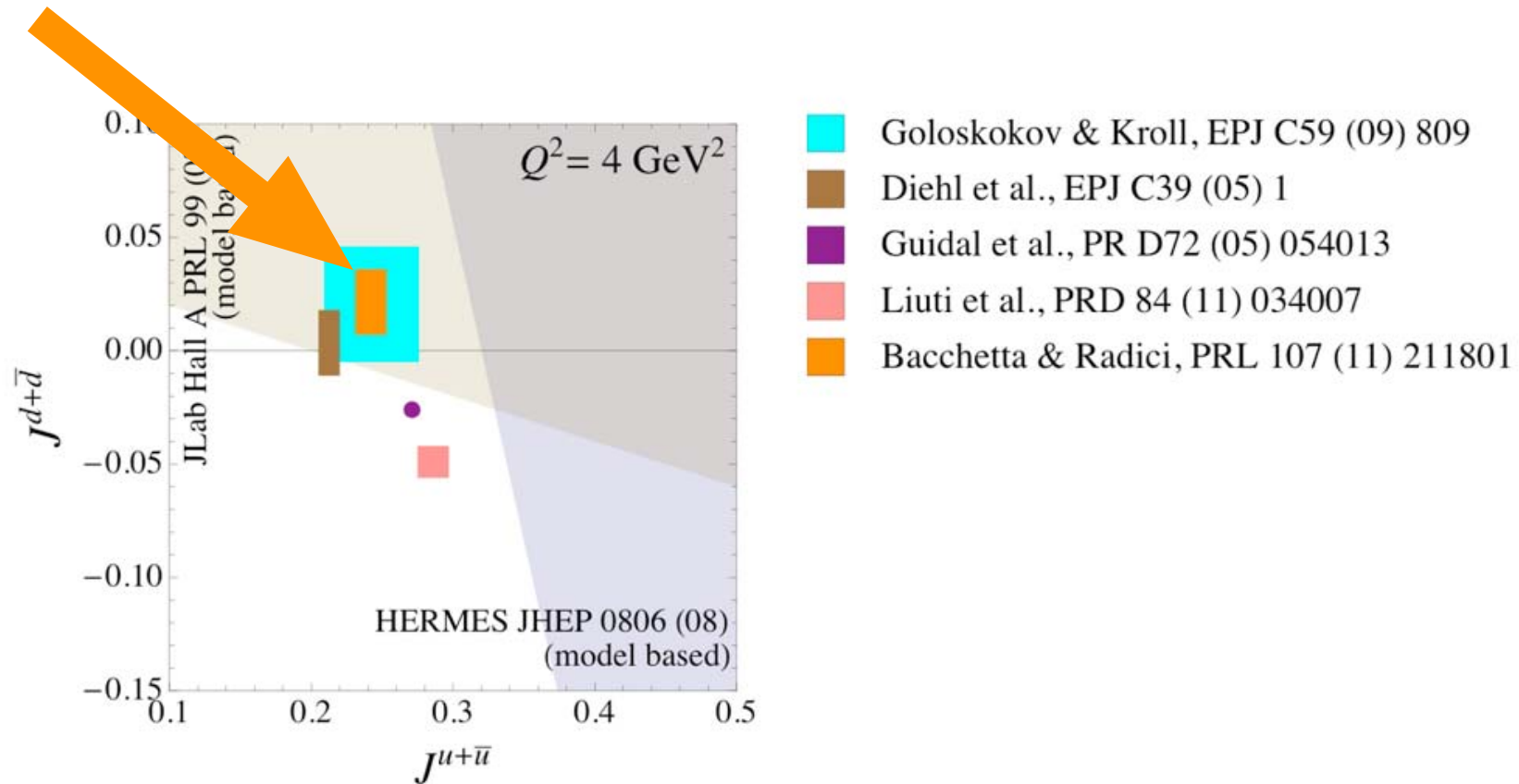
PDF non polarizzata:
ben conosciuta

Dal collegamento
con la funzione di
Sivers...

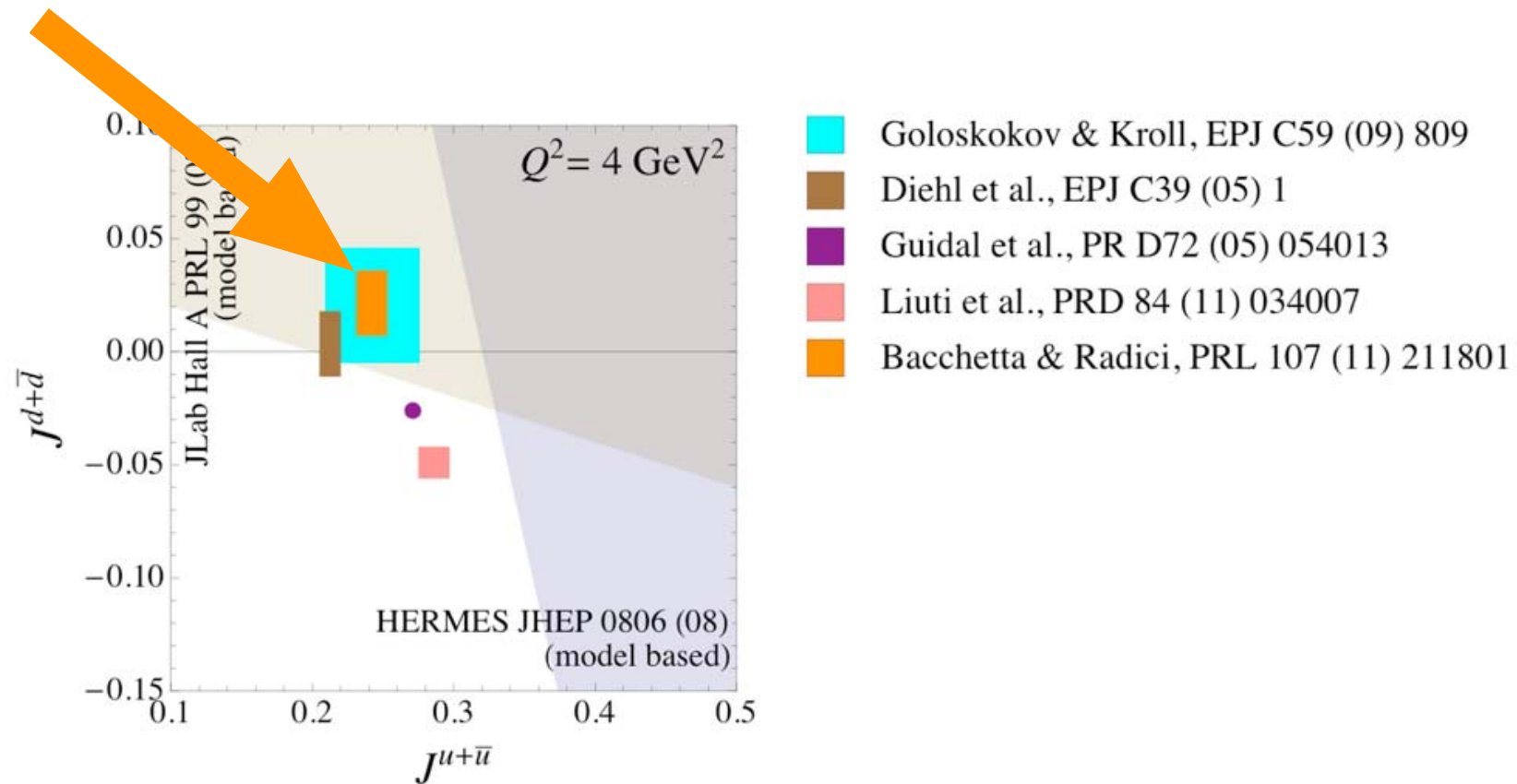
Momento angolare dalle TMD



Momento angolare dalle TMD



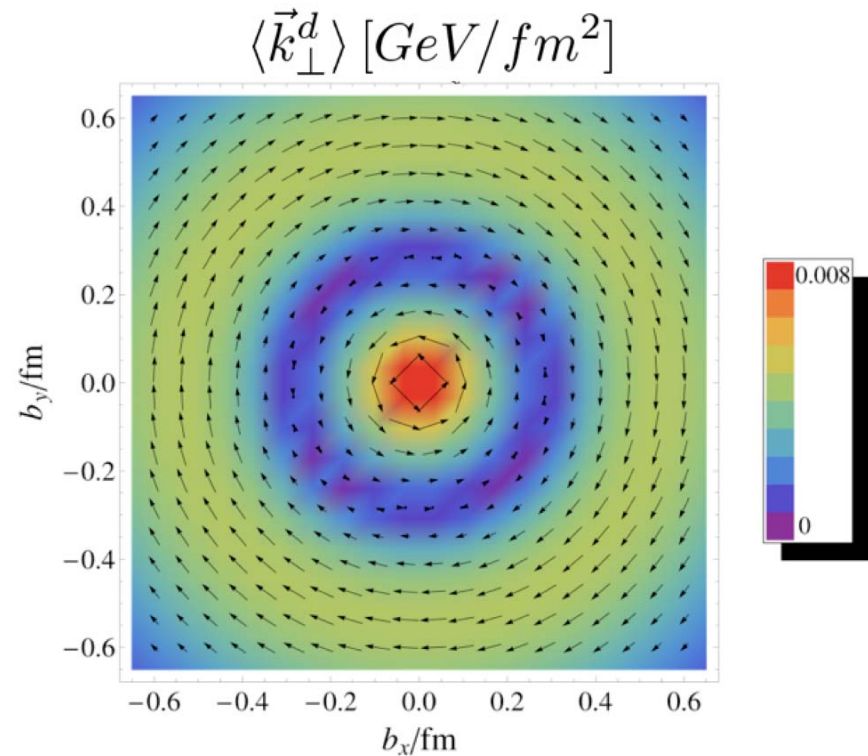
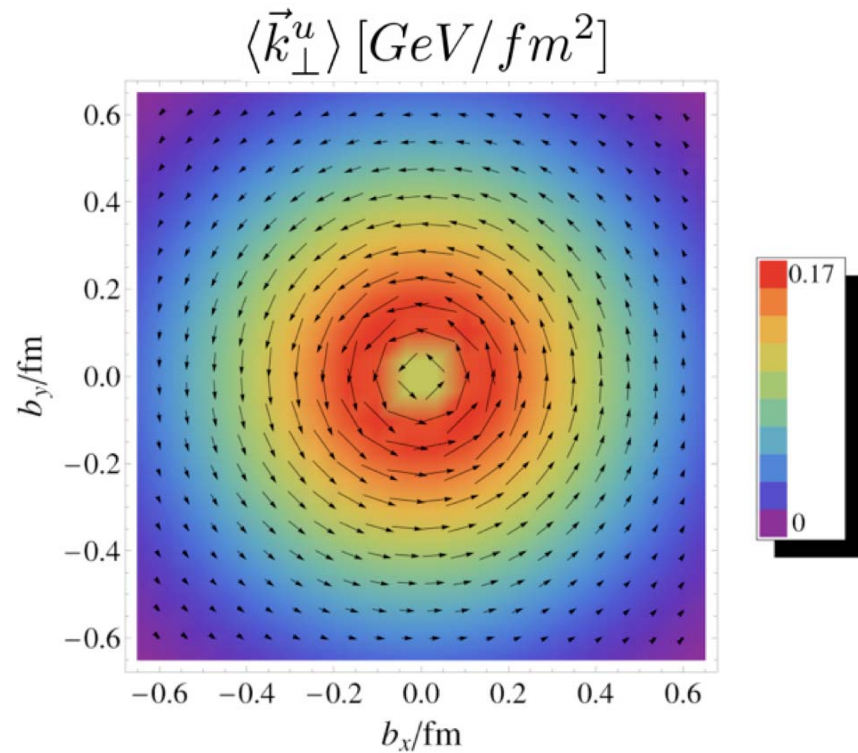
Momento angolare dalle TMD



Stima in accordo con i risultati delle GPDs

Momento orbitale e distribuzioni di Wigner

$$\mathcal{L}_z^q = \int dx d^2\vec{k}_\perp d^2\vec{b}_\perp (\vec{b}_\perp \times \vec{k}_\perp) \rho_{LU}^q(\vec{b}_\perp, \vec{k}_\perp, x)$$

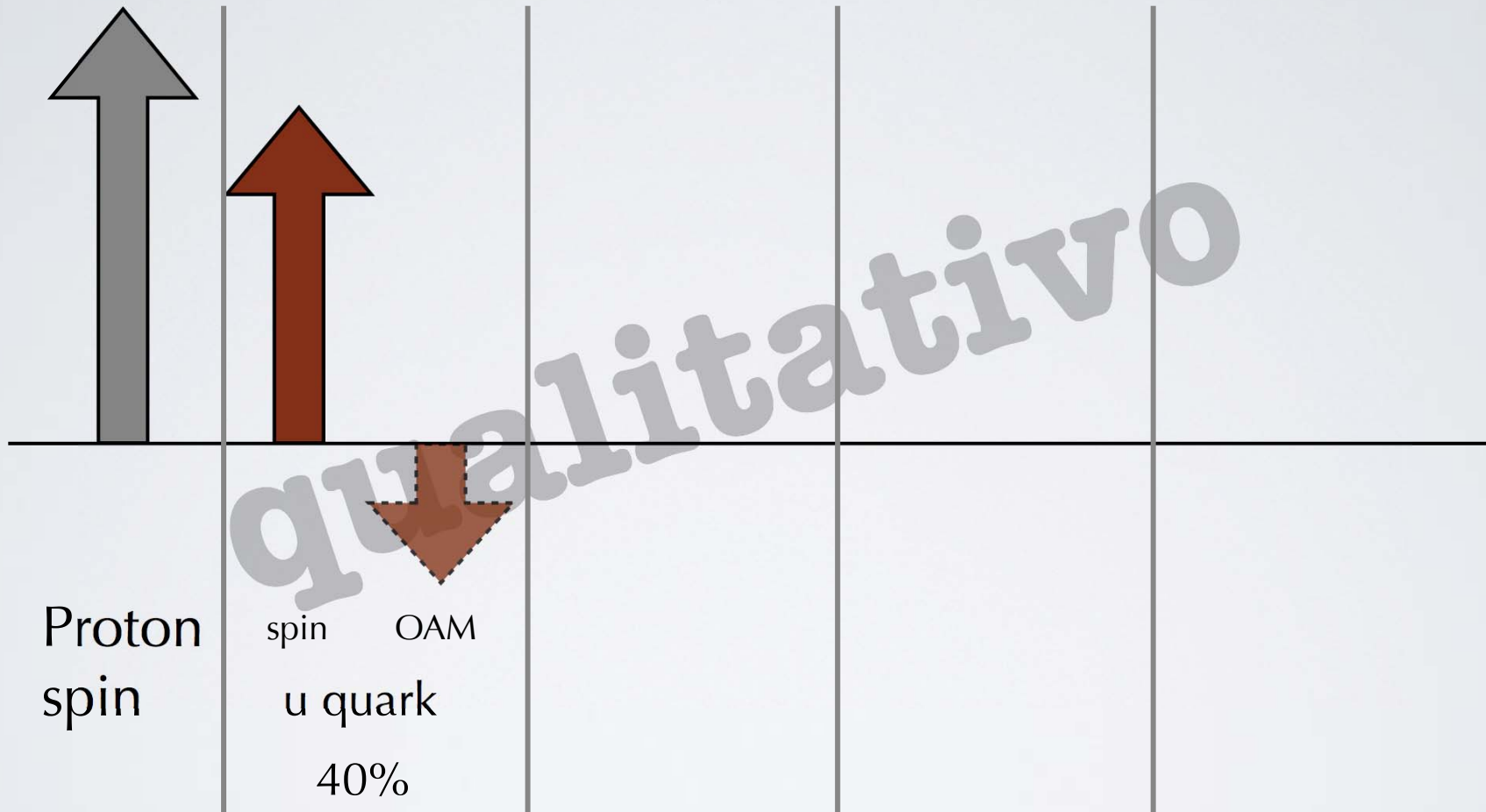


Scenario plausibile



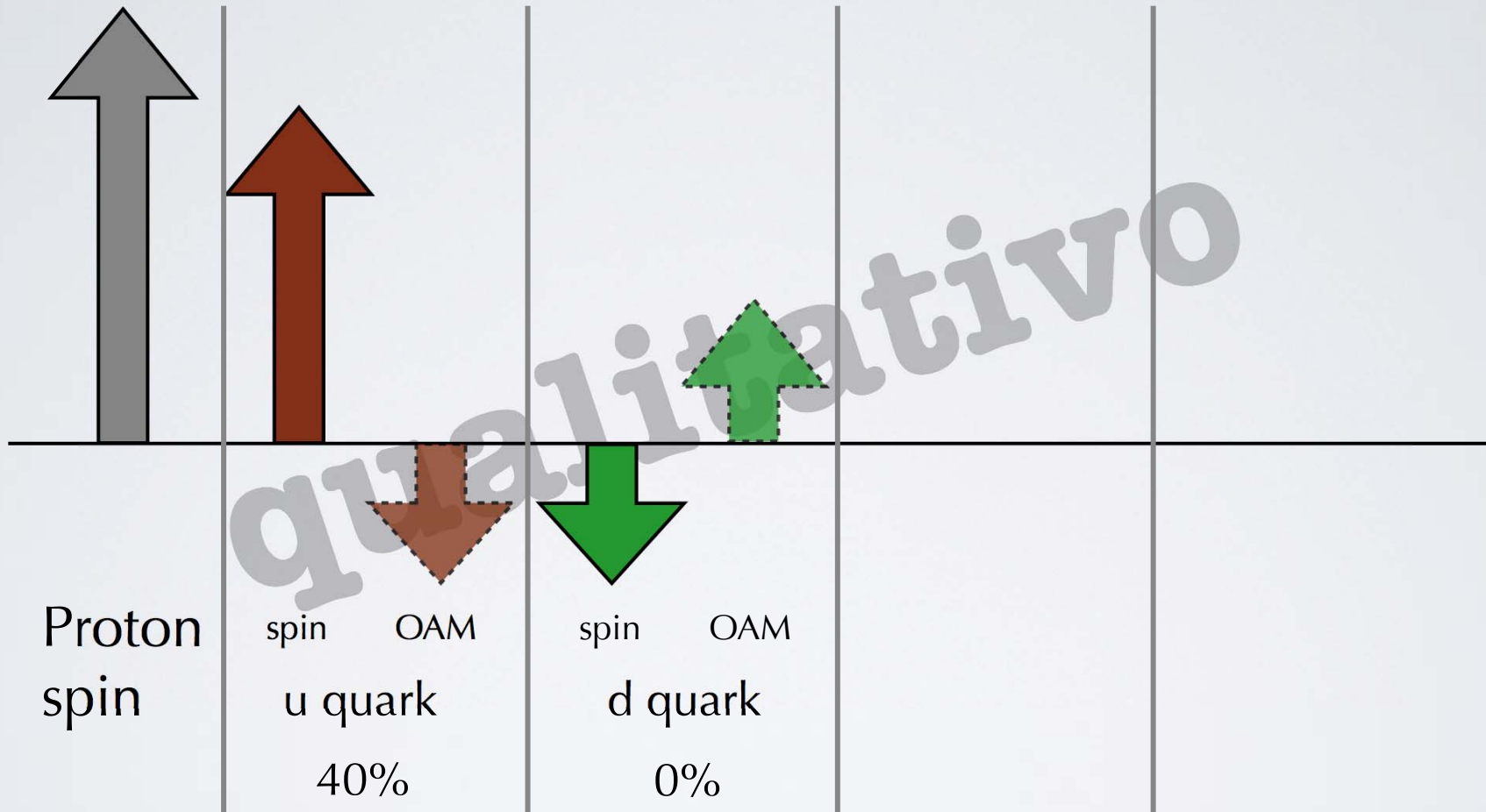
Con MOLTE incertezze,
specialmente su quark di mare e gluoni

Scenario plausibile



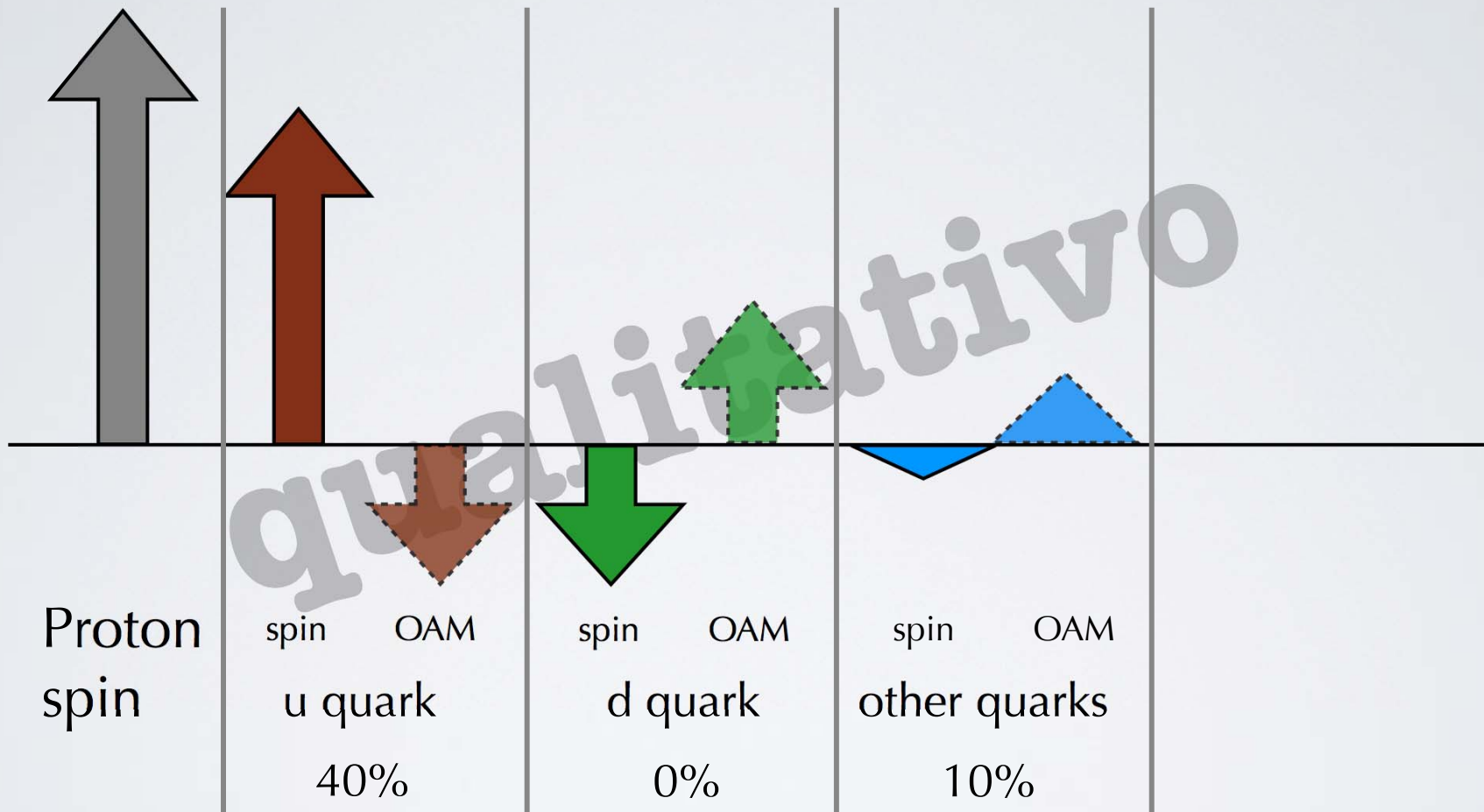
Con MOLTE incertezze,
specialmente su quark di mare e gluoni

Scenario plausibile



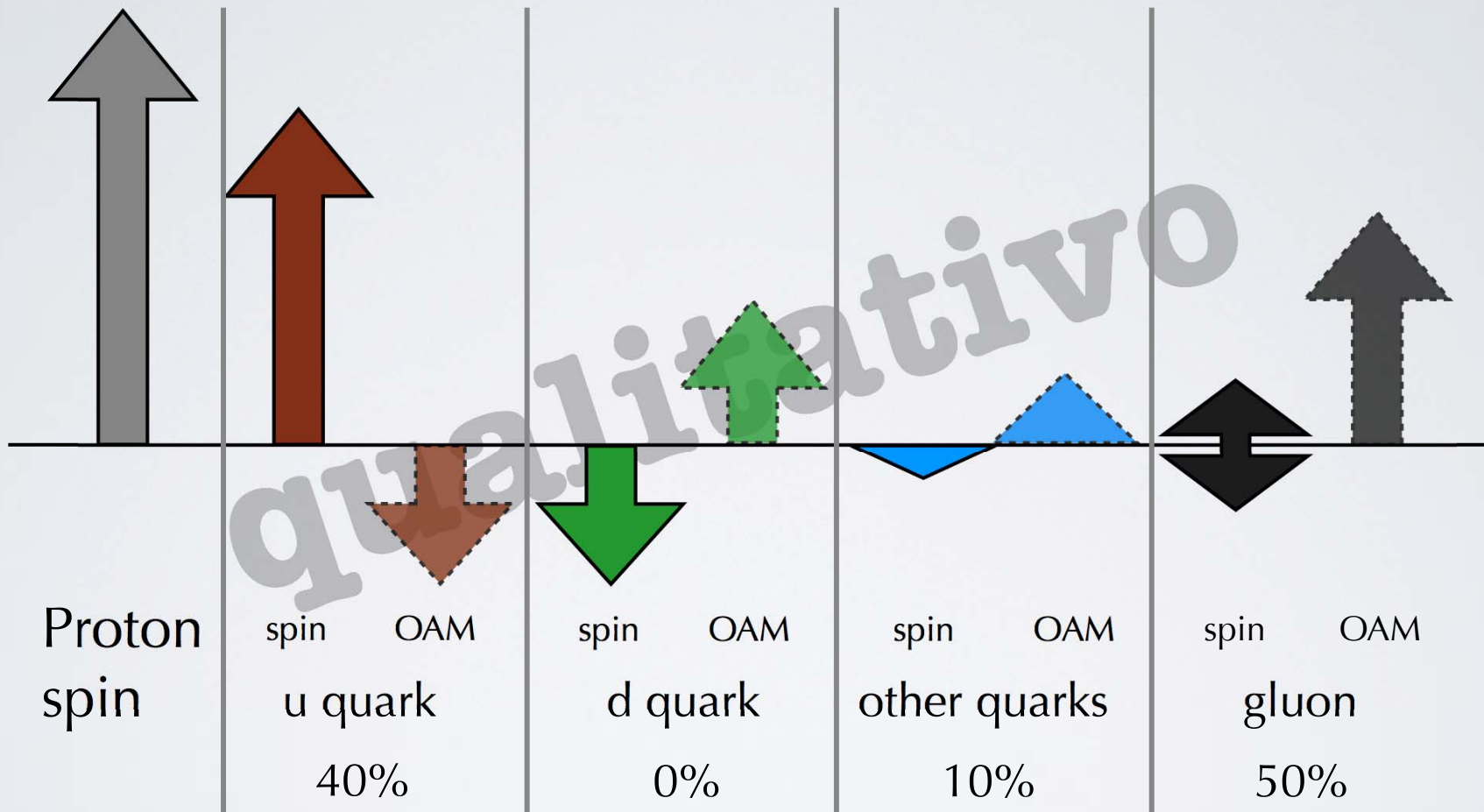
Con MOLTE incertezze,
specialmente su quark di mare e gluoni

Scenario plausibile



Con MOLTE incertezze,
specialmente su quark di mare e gluoni

Scenario plausibile



Con MOLTE incertezze,
specialmente su quark di mare e gluoni

“ With 3D projections, we will be entering a new age. Something which was never technically possible before: a stunning visual experience which ‘turbocharges’ the viewing. ”

James Cameron

