

Rohini Godbole : A Life in High Energy Physics

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Plan of this talk

- Rohini the physicist : Facts and Numbers - academic trajectory & some statistics
- Particle Physics & Collider Physics : In a nutshell
- Research Areas explored 1974-2024
- Journey into the world of HEP
- Scientific contributions
- My journey with Rohini

Rohini - The Physicist

“I work in the area of high energy physics phenomenology : the subject of fundamental constituents of nature and how they are put together”

- Rohini Godbole in “Lilavati’s Daughters” “

*“President Kovind presents Padma Shri to Prof. Rohini Madhusudan Godbole for Science and Engineering. She is a Professor at the Indian Institute of Science, Bangalore and **has contributed enormously to particle physics and collider physics in India.***

- President of India citation read at the Rashtrapati Bhavan investiture ceremony



Rohini's academic journey - the trajectory

- National Science Talent Scholar 1969
- B.Sc. - Pune University 1972
- M.Sc. - I.I.T., Bombay 1974
- Ph.d. - State University of Stony Brook, New York, USA 1974-79
- Visiting Fellow TIFR 1979 - 1982
- CSIR Research Associate, Institute of Science, Bombay 1982
- Department of Physics, University of Bombay 1982-1995
- Indian Institute of Science, Bangalore 1995 - 2024
- On Sabbatical
- University of Dortmund, Dortmund, West Germany 1986-1988

In addition, a number of visiting positions at CERN(Geneva), ICTP(Trieste), Utrecht University and University of Amsterdam(Amsterdam), DESY(Hamburg), Madison(Wisconsin), LNF-INFN(Frascati), Hawai(USA), LAPTH(Annecy), LPT(Orsay)

Research Output : Some statistics

In collaboration with ~75-80 collaborators (excluding the big reports like Les Houches/LHC working Group Report)



350 results | cite all | claim

Citation Summary

Most Recent

Citation Summary

☒ Exclude self-citations ?

	Citeable ?	Published ?
Papers	312	172
Citations	11,055	7,383
h-index ?	52	43
Citations/paper (avg)	35.4	42.9

Papers

CiteablePublished

Citations

Looking into the quantum entanglement in $H \rightarrow ZZ^*$ at LHC within SMEFT framework #1

Amir Subba (IISER, Kolkata, Mohanpur), Ritesh K. Singh (IISER, Kolkata, Mohanpur), Rohini M. Godbole (Bangalore, Indian Inst. Sci.) (Nov 28, 2024)

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Image Credit : HEP INSPIRE

Particle Physics and Collider Physics

In a nutshell

Particle Physics is the study of the most fundamental constituents of matter and the forces that describe their behaviour under different conditions

Standard Model of Particles Physics describes EM, Weak, Strong(nuclear) Forces between basic constituents

Fundamental constituents : **Quarks** and **Leptons**

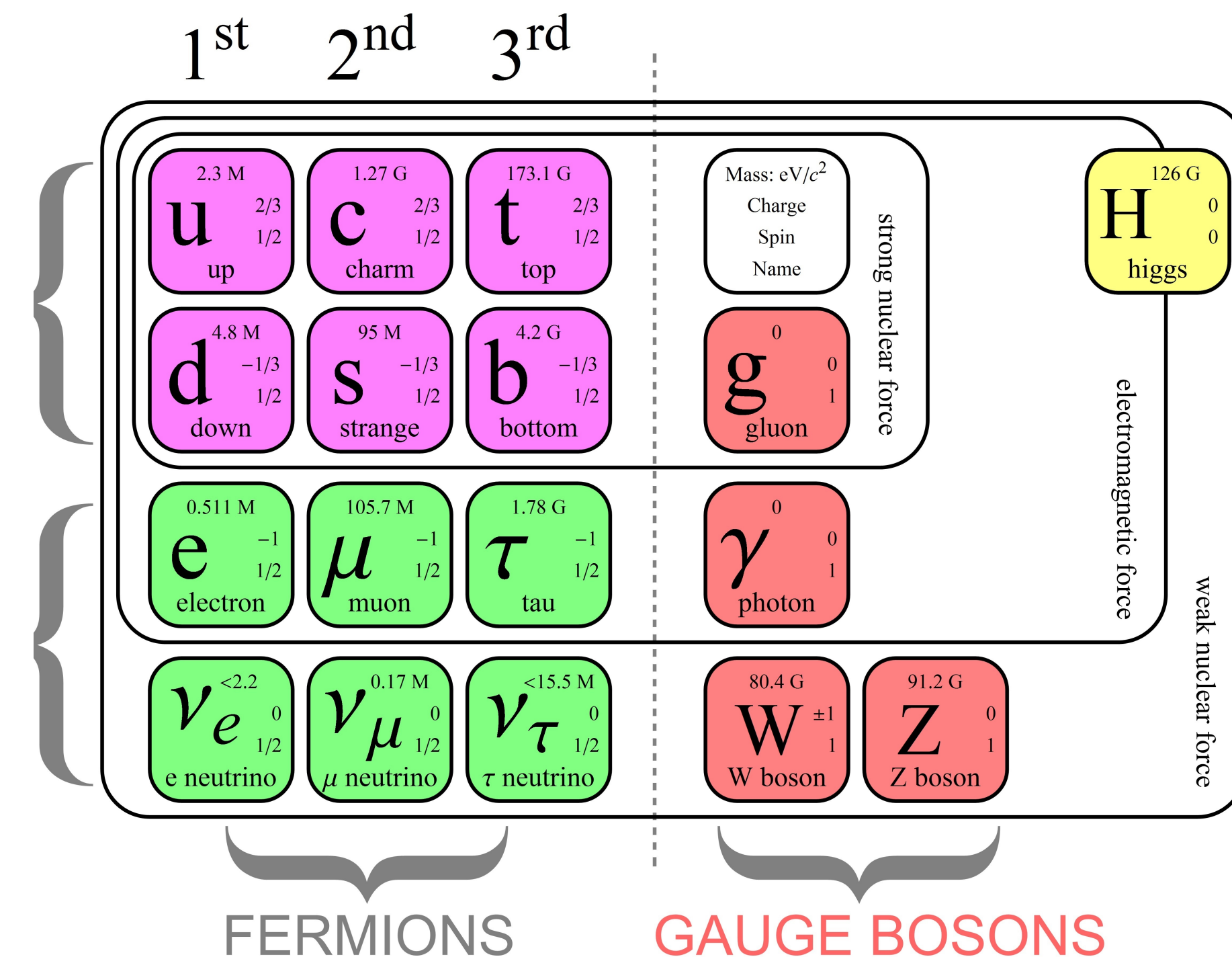
Fundamental Forces : **EM, Weak, Strong(nuclear)** mediated by **gauge bosons**

Photon : Mediator of electromagnetic force

$W^{\pm}, Z$: Mediators of Weak Force

Gluons : Mediators of strong force

Higgs boson : an essential component of SM proposed for the consistency of the theory and found in lab in 2012 at Large Hadron Collider at CERN.



Standard Model (Image Credit: Wikipedia)

Particle Phenomenology

Part of the theory that describes the strong interactions is **Quantum Chromodynamics (QCD)**

Electromagnetic and weak interactions are described by **Electroweak Theory**

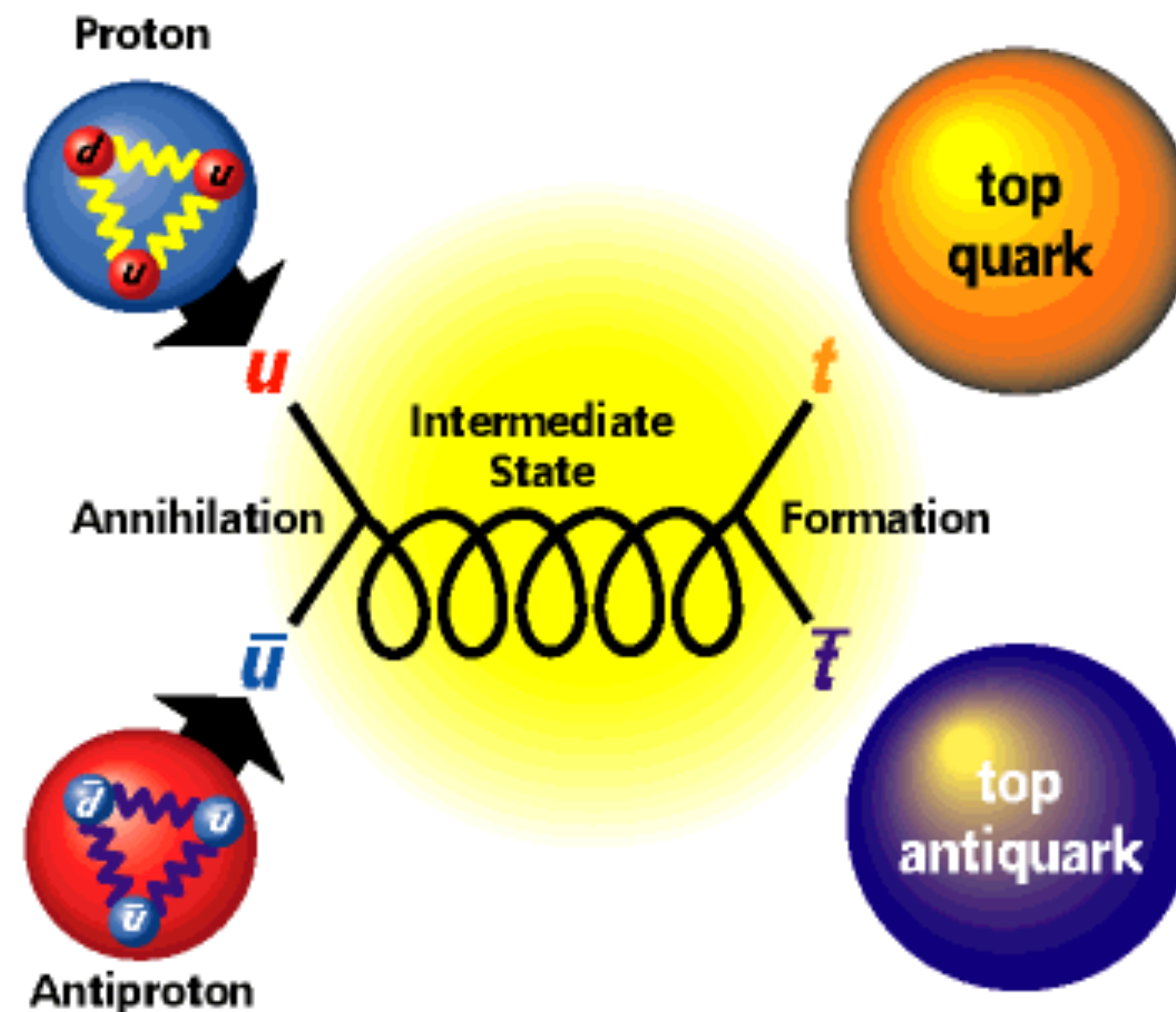
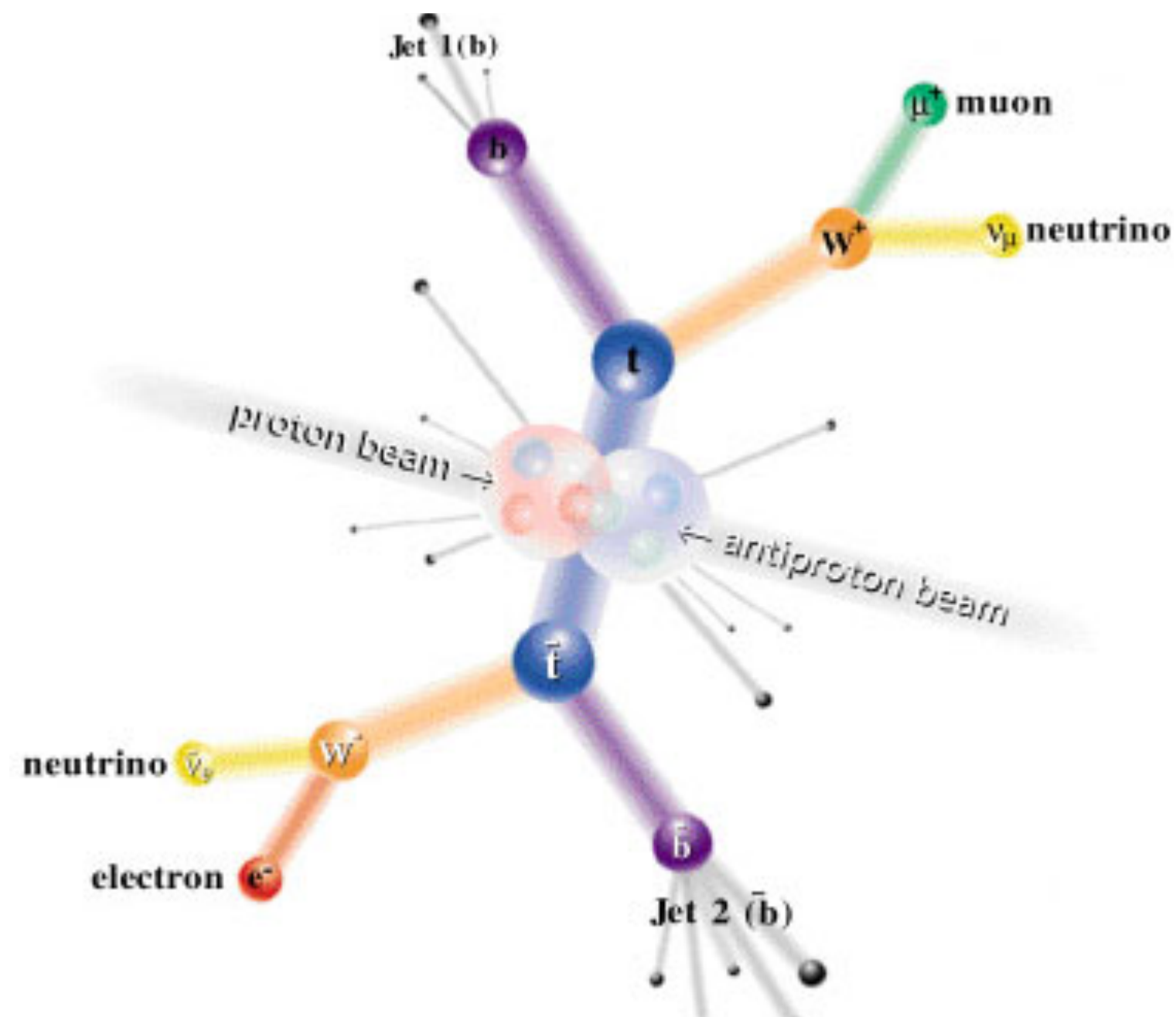
Both of these belong to a special class of quantum field theories (QFTs) called gauge theories

One uses rules of QFT to calculate physically observable quantities which can be compared with the experimental results to validate the theory and then to make predictions which the experimentalists can verify in the lab

Phenomenologists provide the link for communication between the theory and experiment

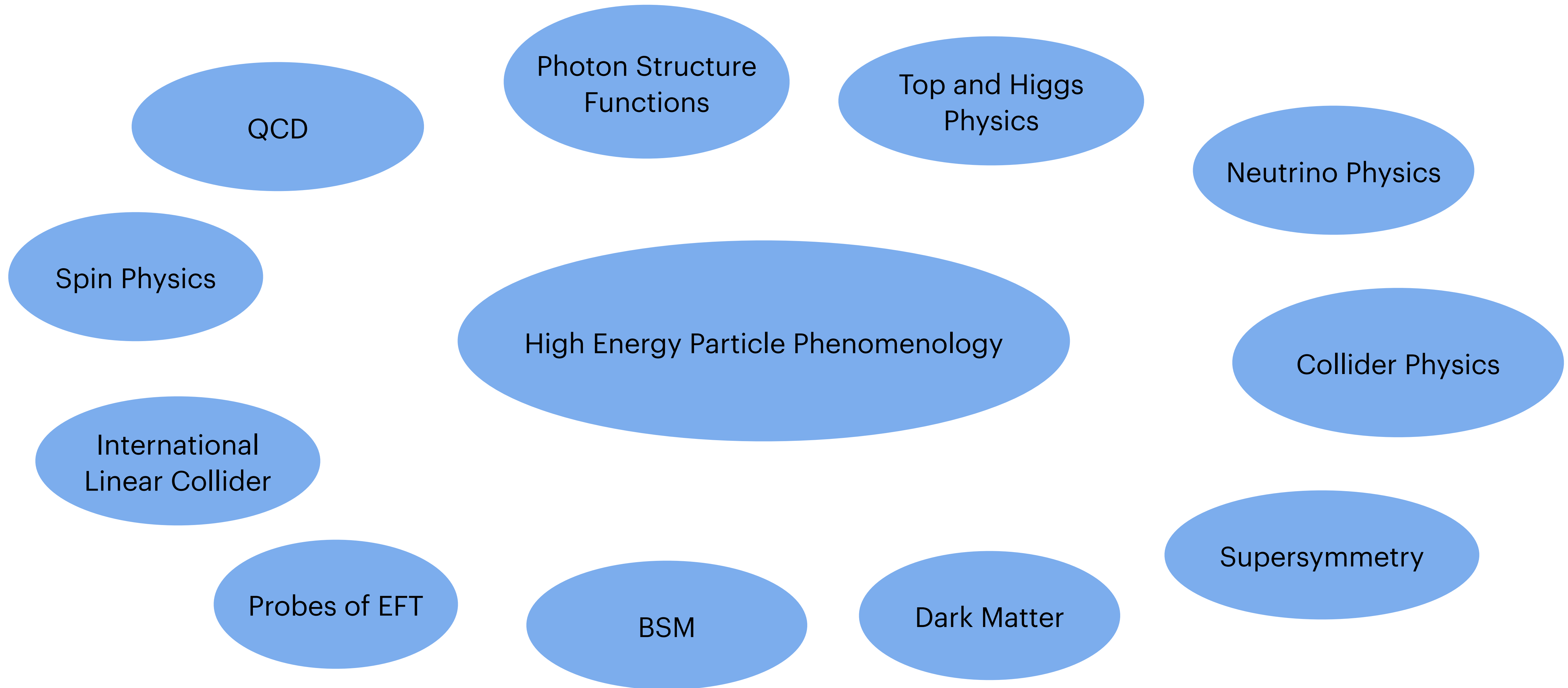
Prof. Rohini Godbole was the one of the leading experts on particle phenomenology

Standard Model has been verified at high energy colliders where high energy particle beams consisting of particles like electron, positron, proton, anti-proton, muon, pion etc are accelerated and made to collide to produce new particles and the distributions of these new particles are studied to infer information about the particle world



Beyond Standard Model(**BSM**) physics models address unanswered questions in SM.

Research areas explored by Rohini (1974-2024)



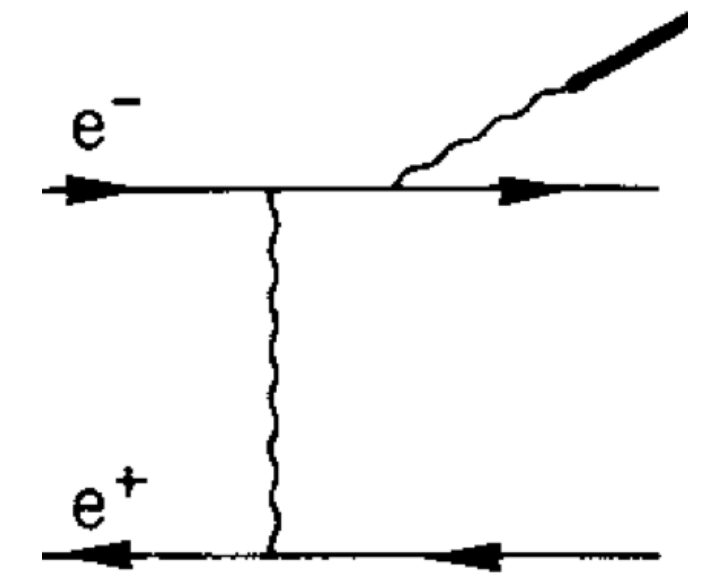
Journey into the world of HEP

SUNY Stony Brook (Ph.D) years (1974-1979)

Her very first publication discussed proton structure functions, an exercise in the then-newly minted theory of strong interactions, the quantum chromodynamics (QCD)

- S. Raychaudhuri and R. Ramaswamy in Current Science (2025)

Worked with her supervisor Prof. J. Smith on the production of neutral vector mesons by bremsstrahlung in electron-positron colliding beams ($e^+e^- \rightarrow e^+e^-V$) -involved a QED calculation with an added interaction term of the form $\mathcal{L}^{int} = eF_V \epsilon_\mu^V \epsilon_\gamma^\mu$



Published 5 papers including 2 single author papers on

- Weak corrections to muon magnetic moment
- Trimuon events due to neutrino and anti-neutrino induced production of vector mesons and Higgs bosons

TIFR & University of Bombay years (1979 -1995)

During her post doc years at TIFR and Institute of Science in Bombay, she collaborated with K.V.L.Sharma, D.P.Roy, Probir Roy among others on different aspects of strong and electroweak interactions.

The collaborations continued when she joined Bombay University. In 1983, she along with D.P.Roy and Sandip Pakvasa **predicted the top quark signal** at Tevatron which was the top discovery channel at Tevatron in 1994

During her sabbatical to Dortmund University in 1986-1988, Rohini started her collaboration with Manuel Drees on Photon Structure Functions. The idea known as **Drees–Godbole Effect** is going to play an important role at future colliders.

During this period, she calculated along with Gluck and Reya, parton density functions in the proton using next-to-leading order QCD corrections - famously known as the **GGR parton densities** after Gluck, Godbole and Reya

She also worked, during this period, on Higgs Physics, SUSY signals and QCD with various experts including, Van Neervan, Vemaseren, and Saurabh Rindani

During University of Mumbai period (1982-1995), she also worked on Charmonium production and polarization with R. Gai and K Sridhar

This period saw her publishing some of her most cited journal papers including the papers on R-parity violation with Probir Roy and Xerxes Tata.

“I remember the day her first publication from India reached us in Stony Brook. That she could continue to carry out high-quality research convinced many of us a career back home was a valid option, and we were inspired to eventually head back ourselves.”

*- Sunil Mukhi in *The Hindu* (2024)*

In fact, he mentions in the same article about Stony Brook that “it became quite enthusiastic about Indian students, largely due to the success of early recruits like Prof. Godbole”

IISc Years (1995 - 2024)

Worked on Higgs physics, SUSY, QCD, photon structure functions, total photonic and hadronic cross sections, BSM physics, Dark Matter, J/ψ production mechanism, spin physics and collider physics with a number of collaborators in India as well as around the globe including Giulia Pancheri, Saurabh Rindani, Agne Grau, Geneviève Bélanger, Fawzi Boudjema.

Apart from around 300 research papers, she also co-authored several reviews article including highly cited Physics Reports on Physics at e^+e^- linear colliders and the working group reports including Les Houches Report on SUSY

Became passionately engaged in promoting international collaboration in scientific research (Government of France awarded her the **Ordre National du Mérite** in 2021, mentioning her important role in furthering scientific collaboration between India and France)

Established herself as an authority on Collider Physics. She was a key international organizer in the efforts for envisioning the next generation of collider experiments

In this period she became passionately involved with the Women in Science cause also

Awards and Honours

Member of all the 3 National Academies of Science in India

Member of The World Academy of Sciences

Padmashree & Ordre National du Mérite by the French Govt

Honorary D.Sc IIT Kanpur and a couple of other universities

R.D.Birla award of IPA

Distinguished Alumnus Award of IIT Bombay

Member of various national and international committees, panels, boards and governing bodies

Keynote speaker at international conferences

Invited by CERN for a study on upgrading the LHC to include electron beam

Visiting professor at European universities

Chief Editor of *Pramana*

The list is long and would require a 45 minute lecture by itself !!!

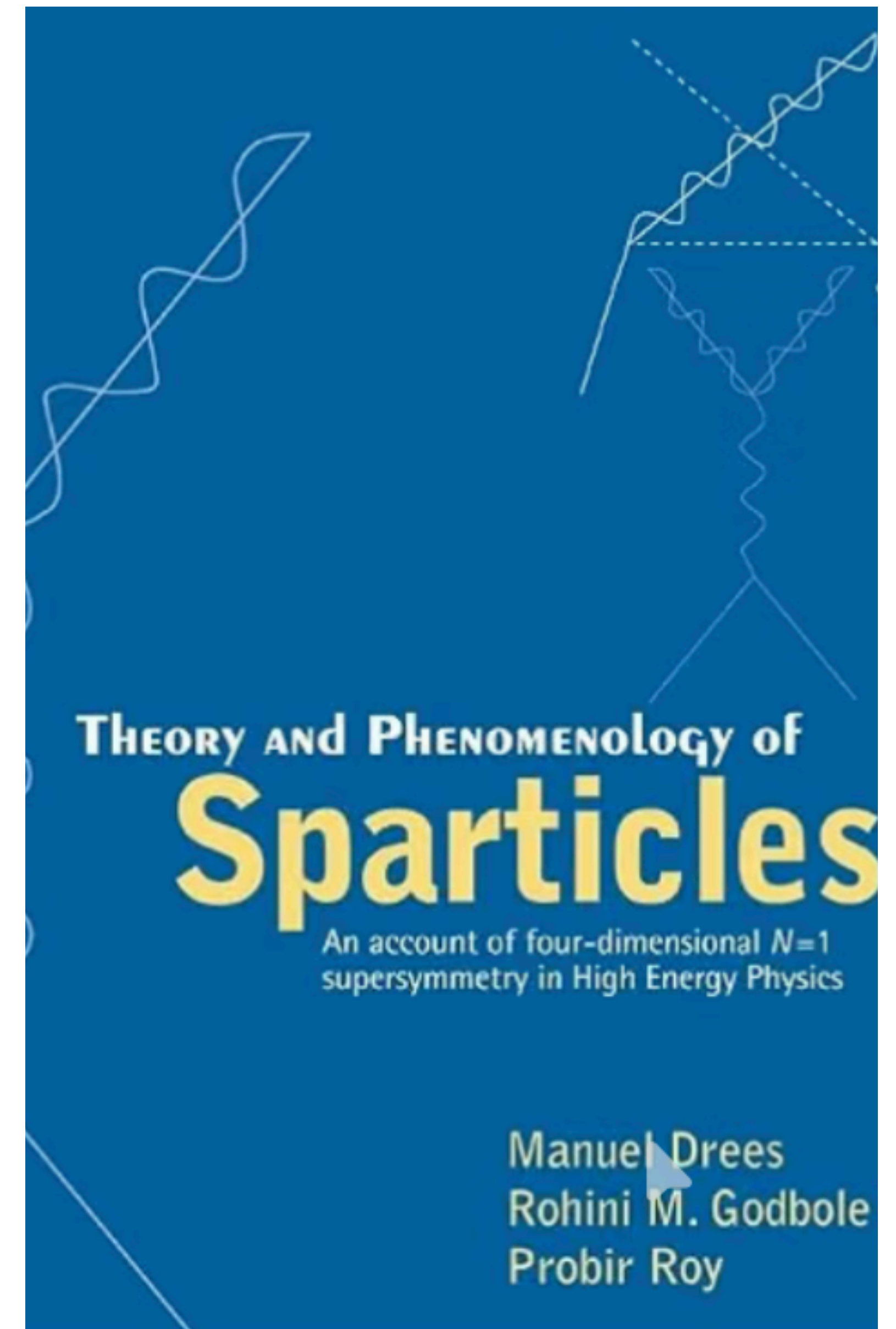
Rohini as teacher and mentor

In spite of a prolific research career, Rohini always took her teaching very seriously and was a much loved teacher - both at University of Mumbai and IISc Bangalore

Mentored around 10 - 12 Ph D students and a large number of post docs as well as masters students

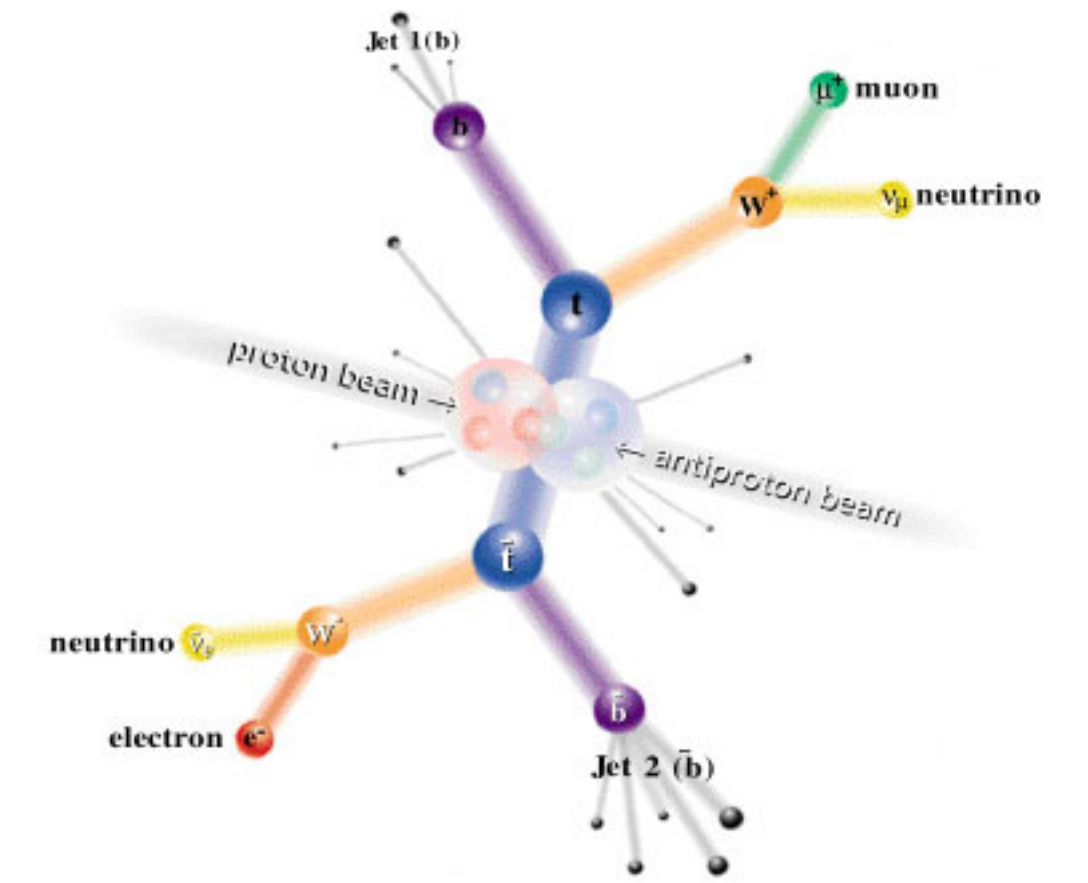
Taught and actively took part in the SERC schools in HEP

Co-authored a book on Supersymmetry with Manuel Drees and Probir Roy



QCD and Collider Physics

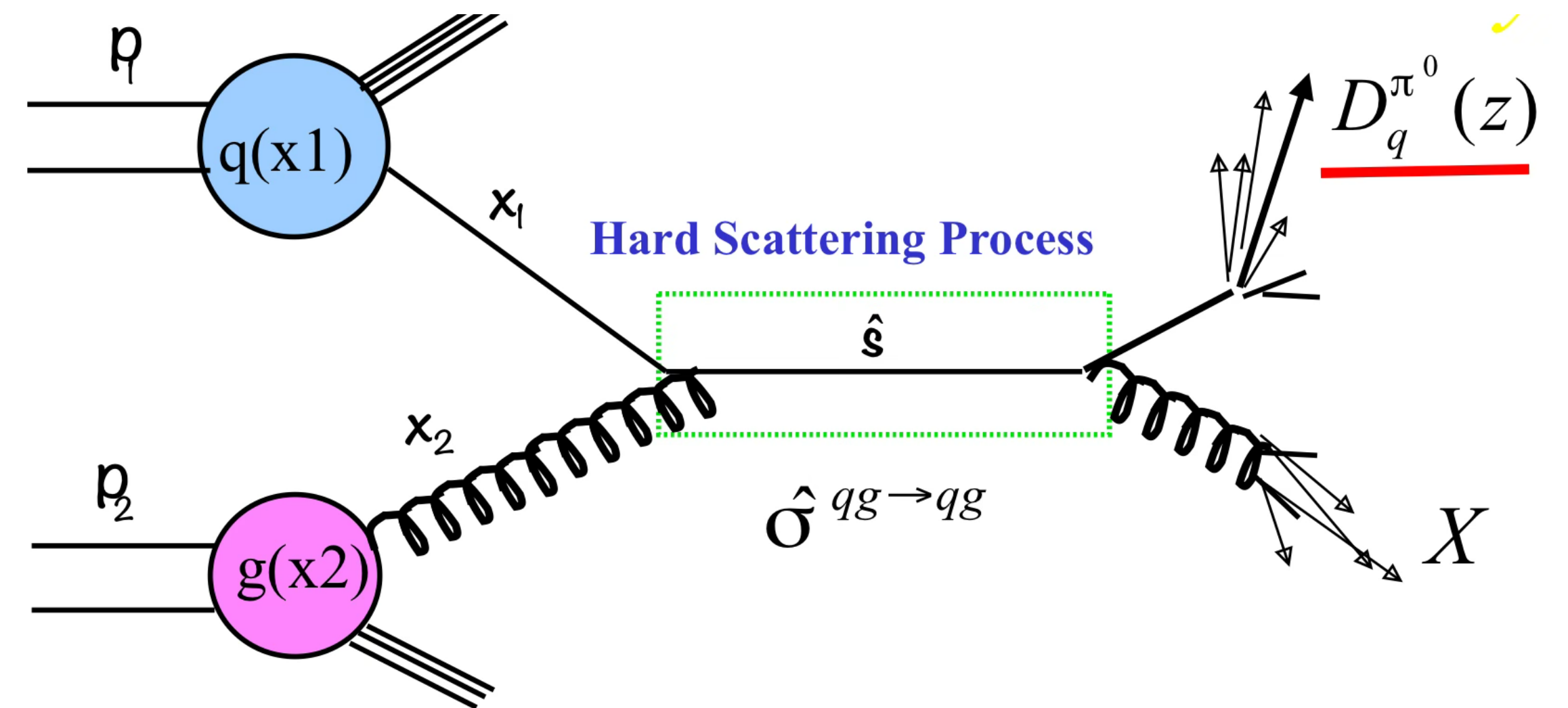
- QCD enables us to calculate theoretically quantities like scattering cross section for a partonic process like $q\bar{q} \rightarrow q\bar{q}$
- However, the physical observables measured in the lab involve hadrons which are composites of quarks and anti-quarks : $AB \rightarrow CD$
- Factorization theorems of QCD provide the bridge to connect the experimentally observed hadronic observables and theoretically calculated partonic quantities



Collinear Factorization

- $f_{q/p}(x)$: probability that the quark q in proton p is carrying a momentum fraction x of the proton's momentum
- $f(x, Q^2)$ cannot be calculated in QCD perturbation theory and needs to be fitted from experimental data
- Combining these with partonic cross section calculated using perturbative QCD, one can calculate hadronic cross sections

$$p + \bar{p} \rightarrow \pi^0 + X$$



$$\sigma(pp \rightarrow \pi^0 X) \sim q(x_1) \otimes g(x_2) \otimes \hat{\sigma}^{qg \rightarrow qg}(\hat{s}) \otimes D_q^{\pi^0}(z)$$

Drees Godbole Effect

Resolved photons

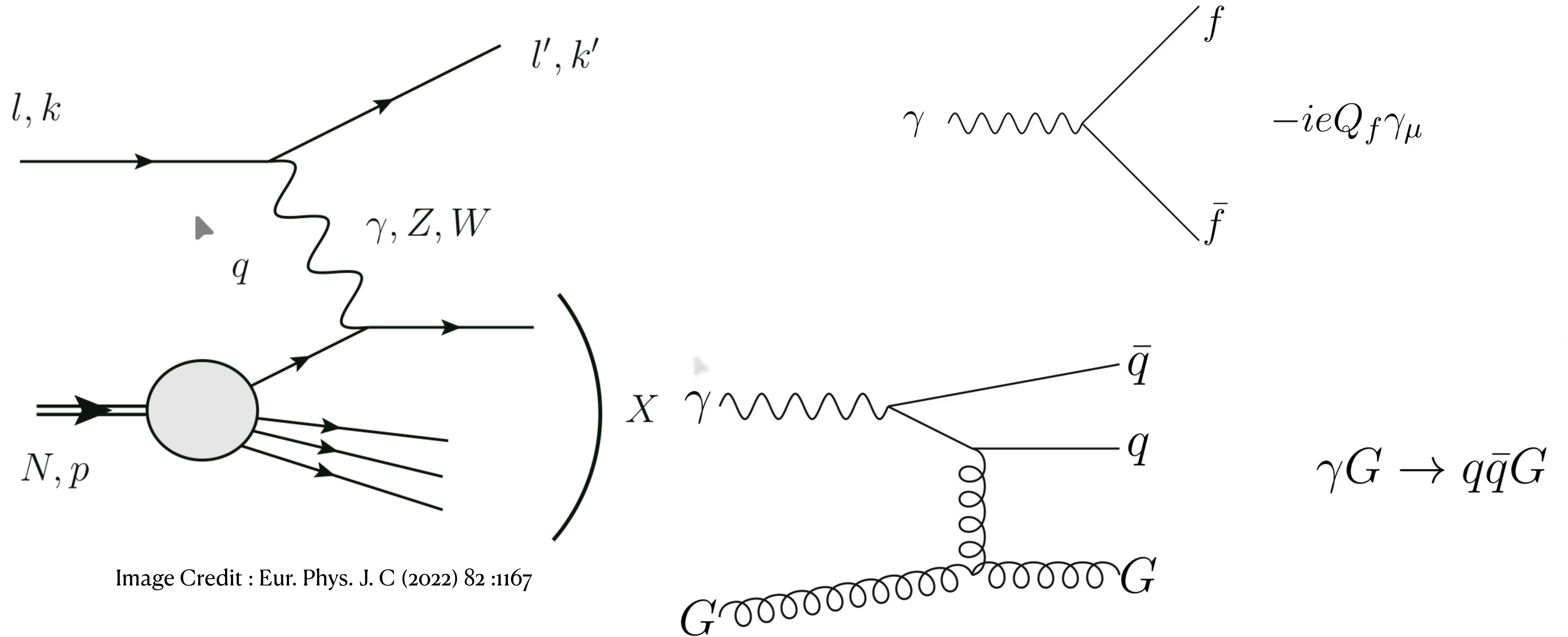
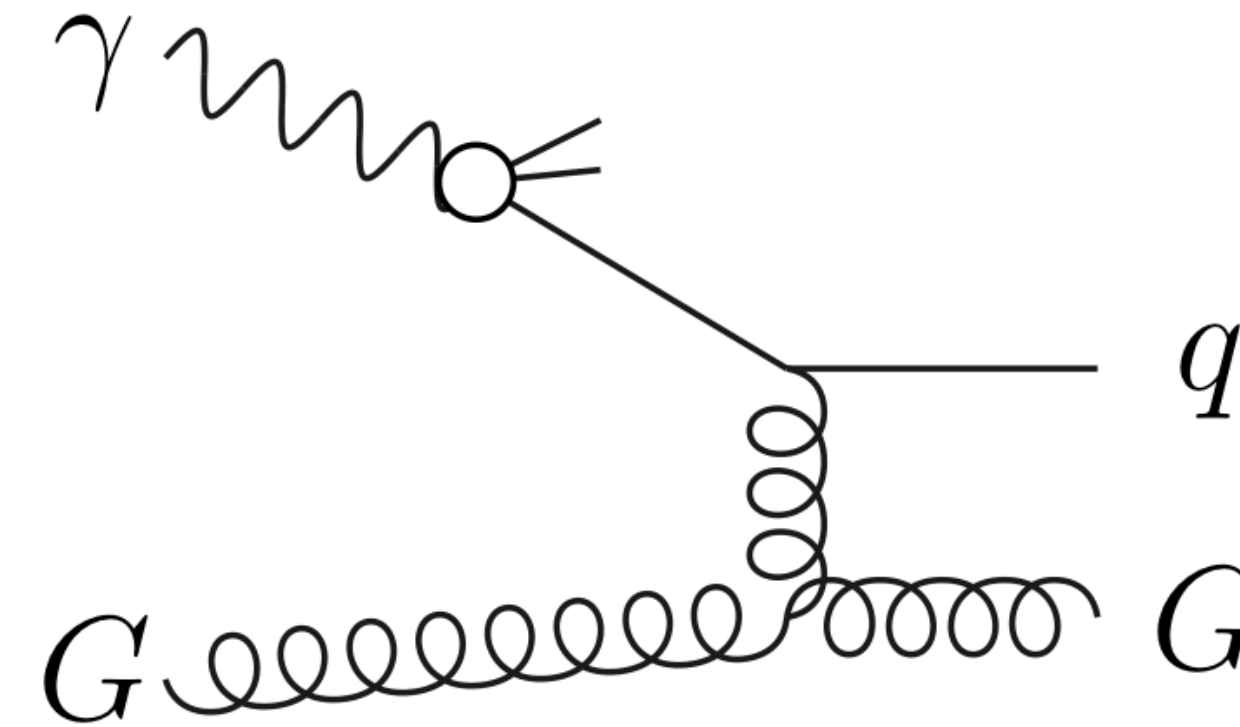
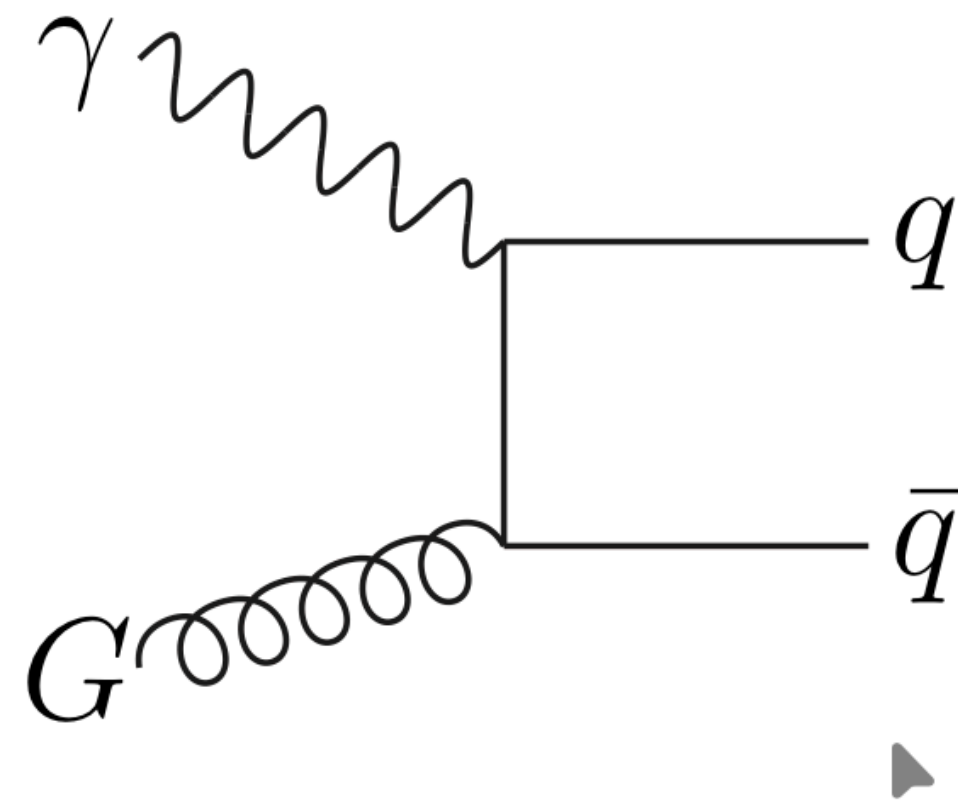


Image Credit : Eur. Phys. J. C (2022) 82 :1167

Deep Inelastic Scattering

Image credit: Manuel Drees, RGM C, IISc, Bangalore 2025



One can define photonic pdfs $f_{q/\gamma}(x)$ (distributions of partons inside the photon) just like pdfs in QCD and use them to calculate the contribution of resolved process also

$f_{q/\gamma}(x)$ grow logarithmically with Q which implies that photonic PDFs are $\mathcal{O}(\alpha_{em}/\alpha_s)$ (Witten 1977)

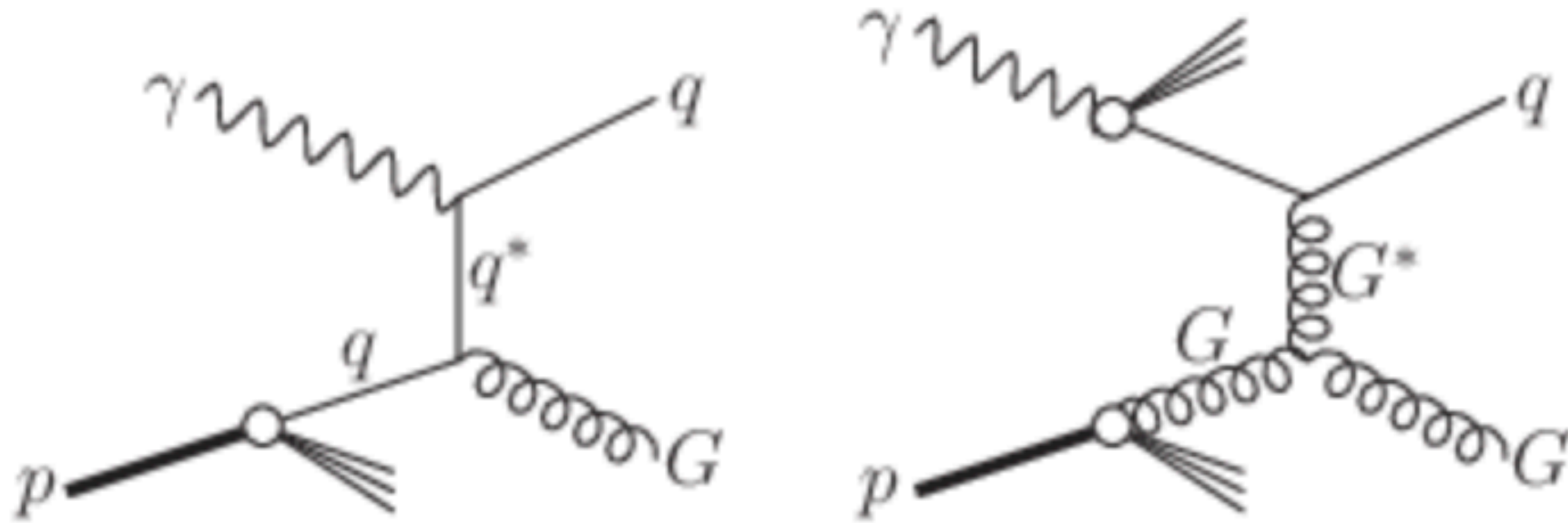
Since $f_{q/\gamma} \sim \mathcal{O}(\alpha_{em}/\alpha_s)$, direct and resolved contributions are of the same order - first pointed out by M. Drees and Rohini Godbole

Direct and Resolved contributions to dijet production in photon -proton scattering

events
M.Drees & R. Godbole, PRL 61, 682 (1988) , J.Phys. G21, 1559(1995):

Resolved component dominates for $p_T \leq 30$ GeV over direct component for e-p centre of mass energy of $\sqrt{s} = 314$ GeV at HERA collider at DESY which was later confirmed by the experiments

Resolved vs direct contribution in this process can be further confirmed at an upgrade of upcoming EIC at BNL



Resolved photons at e^+e^- collider

$$e^+e^- \rightarrow e^+e^- + \text{hadrons}$$

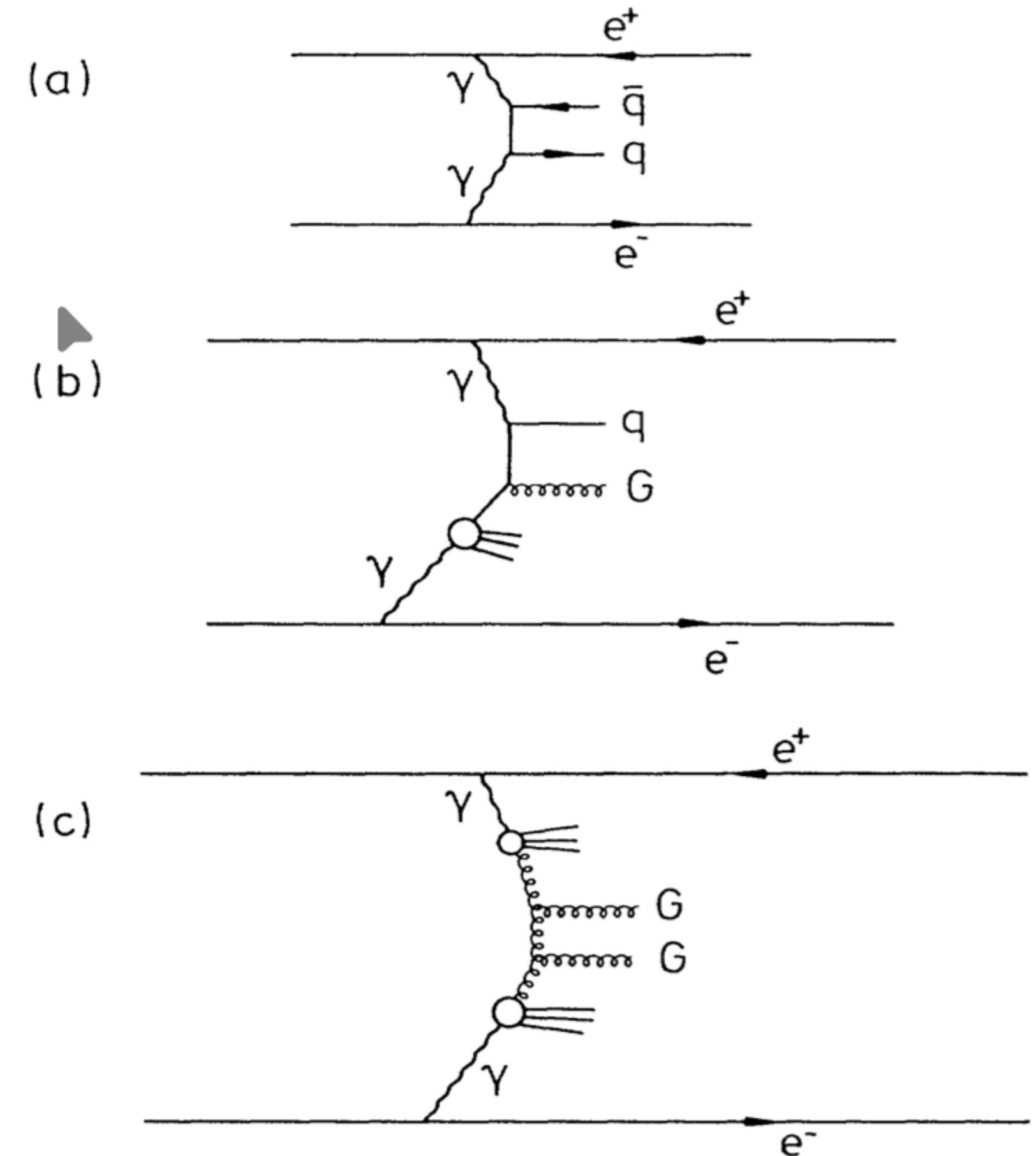
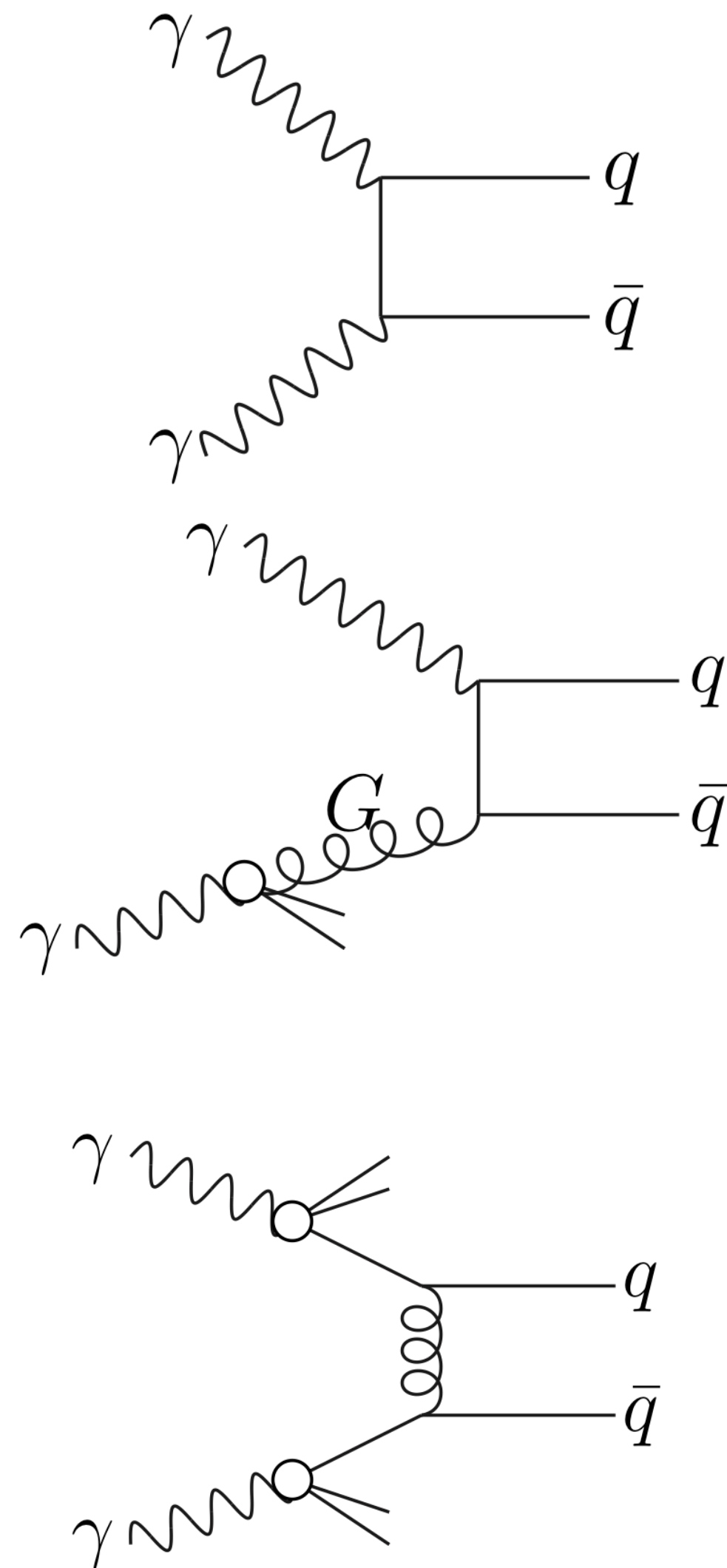


FIG. 1. Typical Feynman diagrams for the (a) direct, (b) once-resolved, and (c) twice-resolved contributions to the production of high- p_T jets in $\gamma\gamma$ collisions at e^+e^- colliders.

M. Drees and R. Godbole, Nucl. Phys. B339, 355(1990), Phy. Lett. B234, 375(1990) : made predictions for TRISTAN e^+e^- collider in Japan and showed that at TRISTAN energy $\sqrt{s} \approx 60$ GeV, resolved photon contributions should dominate the dijet production for $p_T \leq 3$ GeV.

Minijets that required inclusion of resolved contributions were indeed identified at TRISTAN confirming their quantitative predictions

M. Drees and R.M.Godbole, PRL 67, 1189(1991) : Predicted mini jet events due to the hadronic structure of the photon at e^+e^- supercolliders at $\sqrt{s} = 1TeV$ leading to a very large rate of $\gamma\gamma \rightarrow jets$

This work is going to be relevant at the future e^+e^- and $\mu^+\mu^-$ colliders as jet production from direct and resolved photons may contribute to hadronic backgrounds

“As usual in our field, we always used alphabetical ordering of authors. Everybody in the field knows this doesn’t mean I contributed more. In fact, we collaborated as equals”

– Manuel Drees on the Drees-Godbole Effect

My journey with Rohini



April 1985 IISc Bangalore



February 2024 IIT Bombay

My Research Journey with Rohini

Probing Gluon Sivers Function through TSSAs

- Sivers Effect and transverse single spin asymmetry in $e + p^\uparrow \rightarrow e + J/\psi + X$, **R.M. Godbole**, A. Mukherjee, AM and **Vaibhav Rawoot**, Phys. Rev. D85, 094013(2012)
- Transverse single spin asymmetry in $e + p^\uparrow \rightarrow e + J/\psi + X$ and Q^2 evolution of the Sivers function, **R.M. Godbole**, A. Mukherjee, AM and **Vaibhav Rawoot**, Phys. Rev. D88, 014029(2013)
- Transverse single spin asymmetry in $e + p^\uparrow \rightarrow e + J/\psi + X$ and transverse momentum dependent evolution of the Sivers function -II, **R.M. Godbole**, Abhiram Kaushik, AM and **Vaibhav Rawoot**, Phys. Rev. D91, 014005(2015)
- Transverse single spin asymmetry in $p + p^\uparrow \rightarrow D + X$, R.M. Godbole, Abhiram Kaushik and AM, Phys. Rev. D94, 114022(2016)
- Transverse single spin asymmetry in $p + p^\uparrow \rightarrow J/\psi + X$, **R.M. Godbole**, Abhiram Kaushik, AM and **Bipin Sonawane**, Phys. Rev. D96, 096025(2017)
- Transverse single spin asymmetry in low -virtuality leptonproduction of open charm as a probe of gluon Sivers function , R.M. Godbole, Abhiram Kaushik and AM, Phys. Rev. D97, 076001(2018)
- Single spin asymmetry in prompt photon production in mid-rapidity and backward region at RHIC, R.M. Godbole, Abhiram Kaushik, AM and Siddhesh Padval, Phys. Rev. D99, 014003(2019)
- Gluon Sivers function and transverse Single spin asymmetry in $e + p^\uparrow \rightarrow \gamma + X$, **Siddhesh Padval**, **R.M. Godbole**, Abhiram Kaushik and AM, Phys. Rev. D103, 036008(2021)

Spin Structure of the Proton

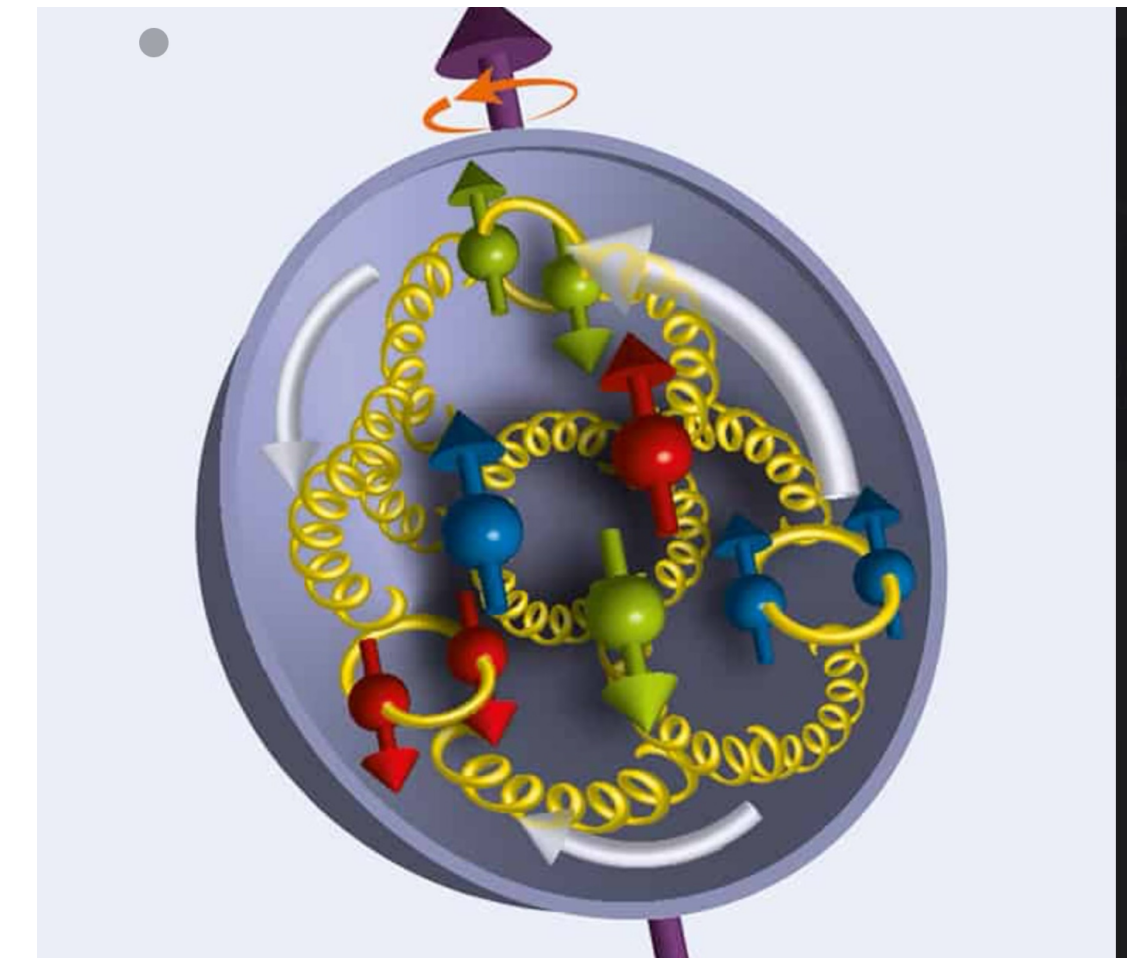
- Quark Model : spins of the quarks and anti-quarks add up to make spin -1/2 of the proton
- Polarized beam experiments(1988) at CERN : Quark spin contributes only 20-30% of the total spin of proton
- RHIC (2014) : Gluons could potentially account for up to 30 of the missing 70% of proton spin

$$\frac{1}{2} = \frac{1}{2} \Delta\Sigma + L_q + J_g^*$$

quark spin $\Delta\Sigma \approx \frac{1}{3}$

quark orbital angular momentum

gluon spin & orbital angular momentum



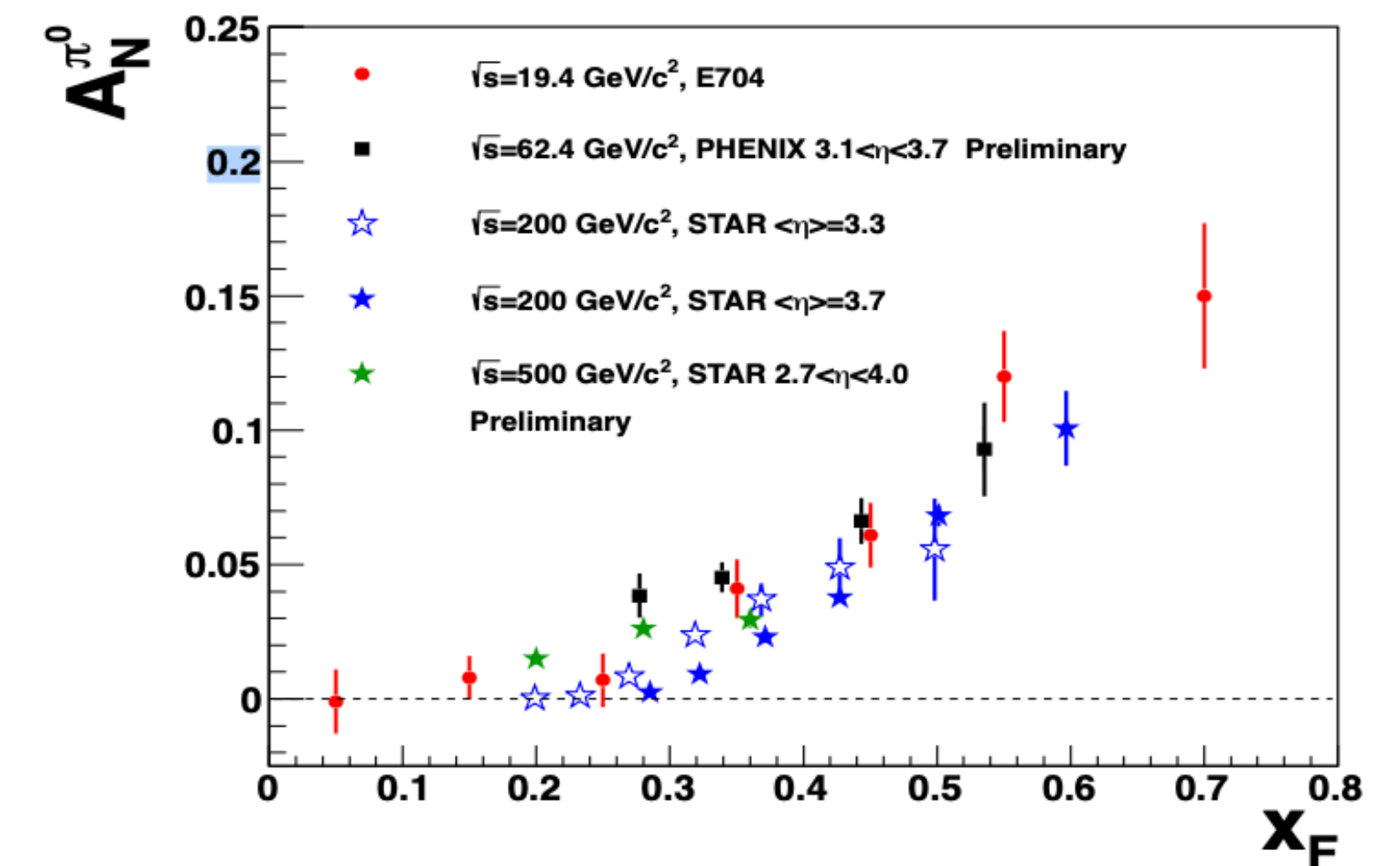
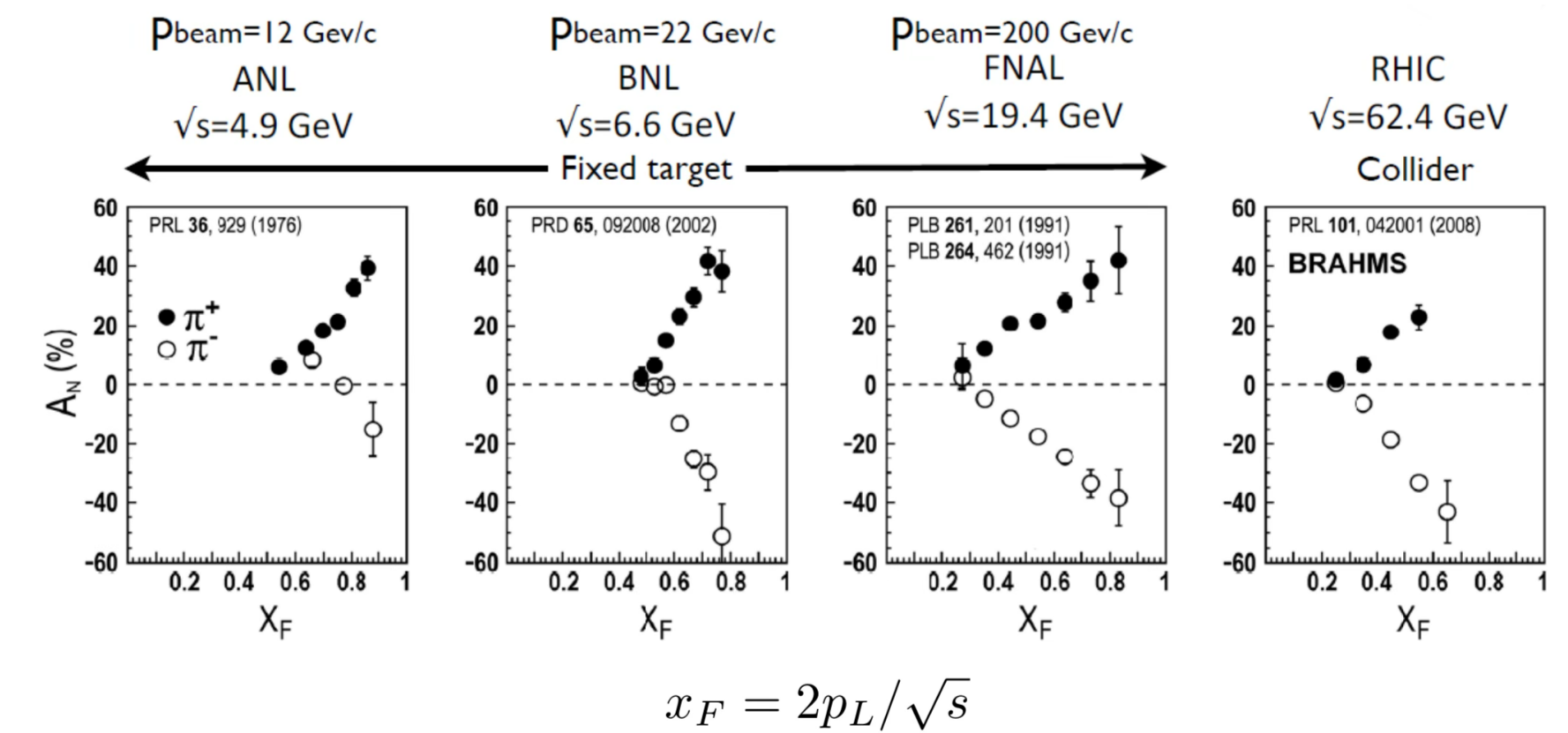
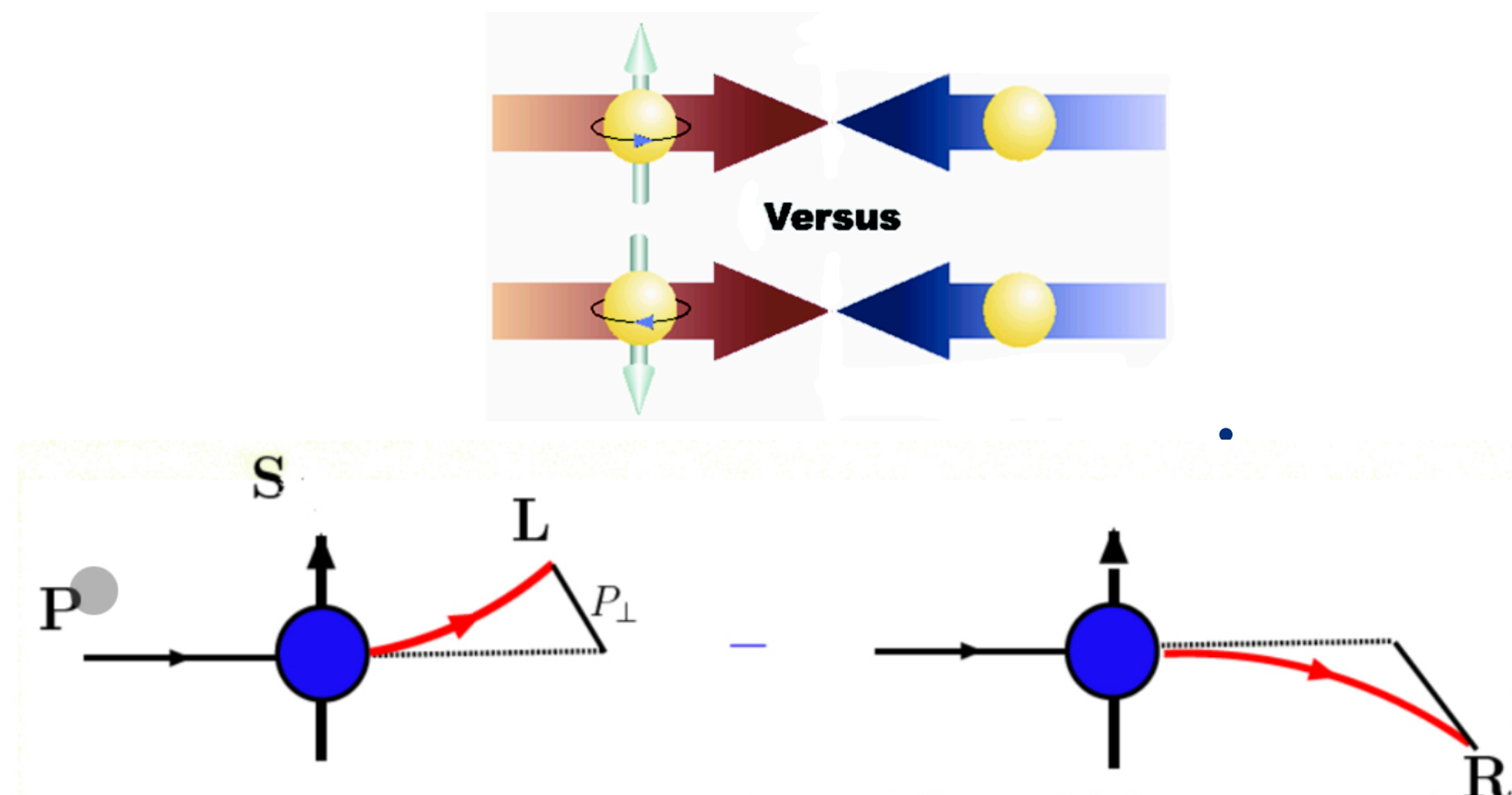
Missing amount of about 40% can be accounted for by the unmeasurable orbital angular momentum of (OAM) of both quarks and gluons

How can we get access to OAM of partons?

Perform experiments with polarized beams

Large transverse single spin asymmetries in fixed target $pp^\uparrow \rightarrow \pi X$ pion production have been observed experimentally late 1990s

$$A_N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$$



Transverse Single Spin Asymmetries

TSSAs in the scattering of a transversely polarized nucleon off an unpolarized target $A + B^\uparrow \rightarrow C + D$

$$A_N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$$

Appear as asymmetric distribution of observed hadrons in the plane transverse to the beam direction

Asymmetric distribution is due to orbital motion of quarks and gluons or due to recoil of gluons radiated off the active quarks

How do we explain these asymmetries?

TSSAs cannot be explained in a parton model approach without taking transverse momentum dependence of partons in the nucleon

TMD approach : include transverse momentum dependence in PDFs

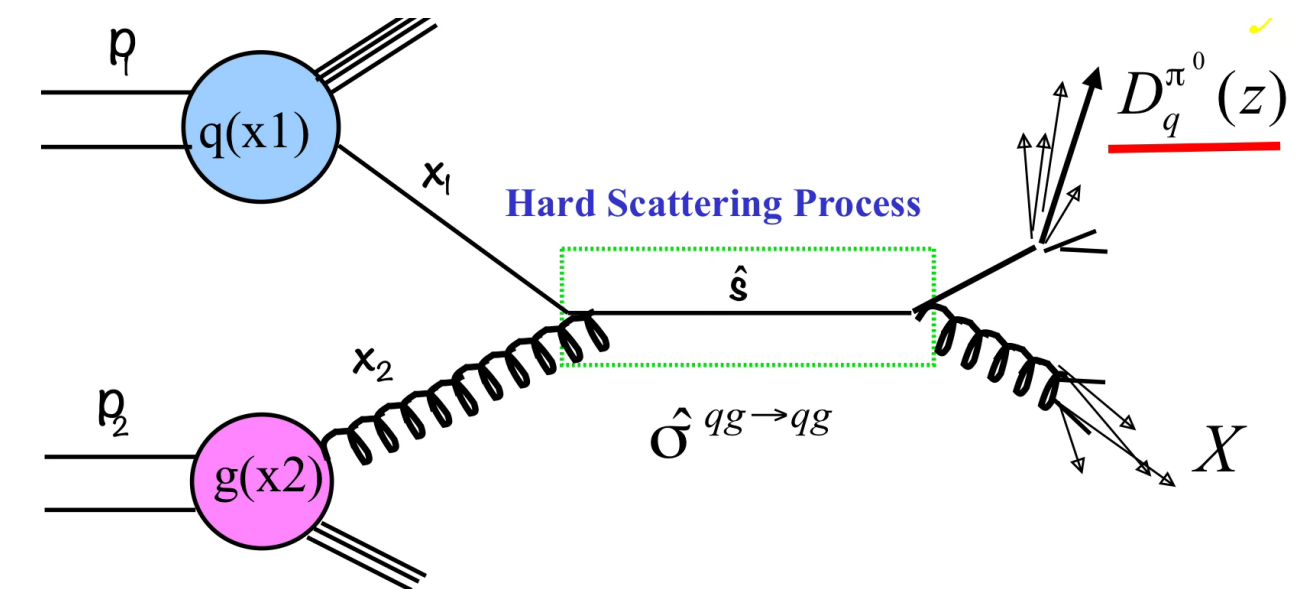
Generalise the collinear factorized expression

$$\sigma(pp \rightarrow \pi^0 X) \sim q(x_1) \otimes g(x_2) \otimes \hat{\sigma}^{qg \rightarrow qg}(\hat{s}) \otimes D_q^{\pi^0}(z) \text{ to}$$

include the effects of spin and transverse momentum

$$\text{dependent effects} \quad f_{a/p}(x) \rightarrow f_{a/p}(x, \mathbf{k}_\perp^2)$$

$$\sigma(pp \rightarrow \pi^0 X) \sim q(x_1, k_{1\perp}) \otimes g(x_2, k_{2\perp}) \otimes \hat{\sigma}^{qg \rightarrow qg}(\hat{s}) \otimes D_q^{\pi^0}(z, q_\perp)$$

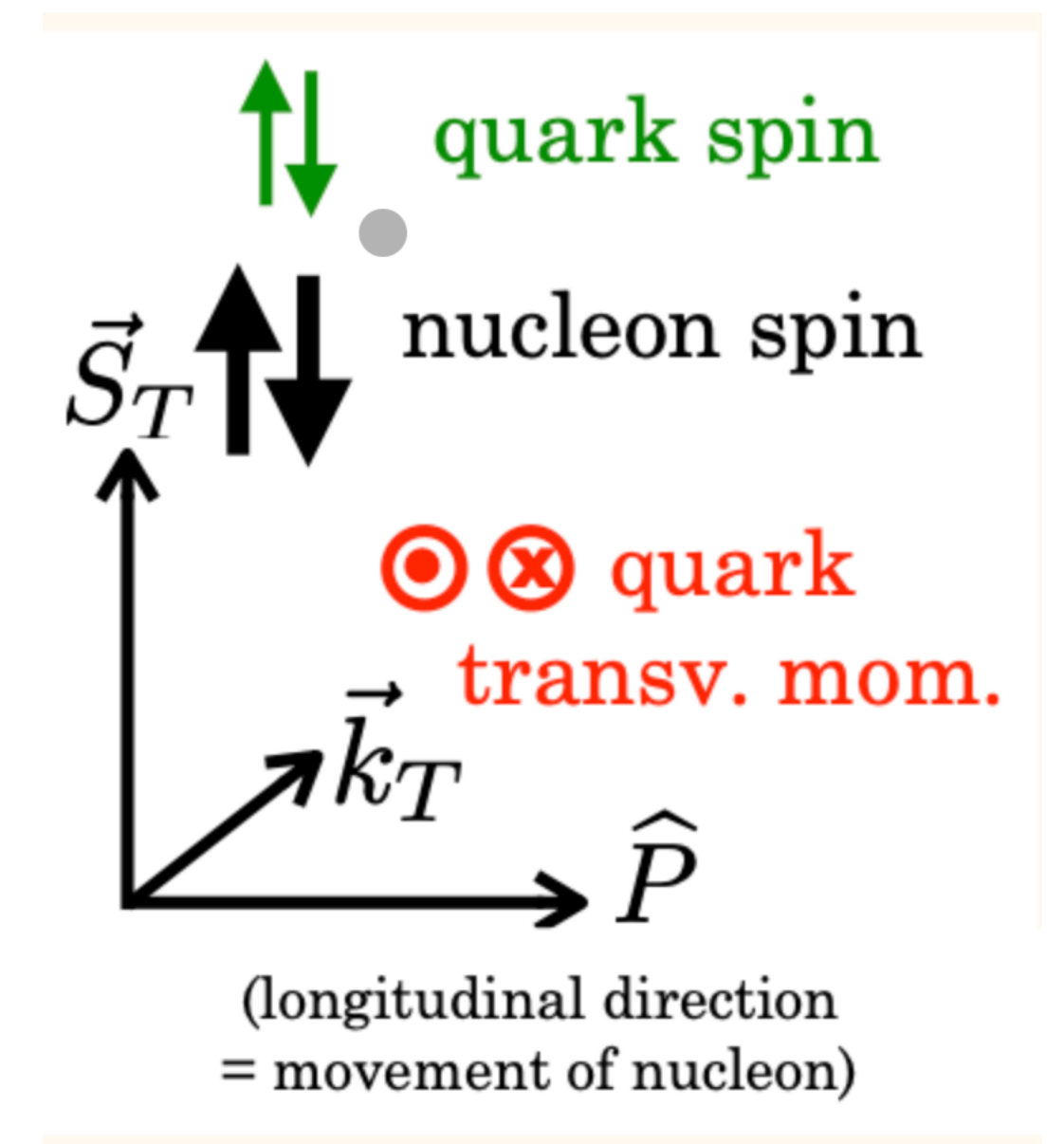


TMD Factorization

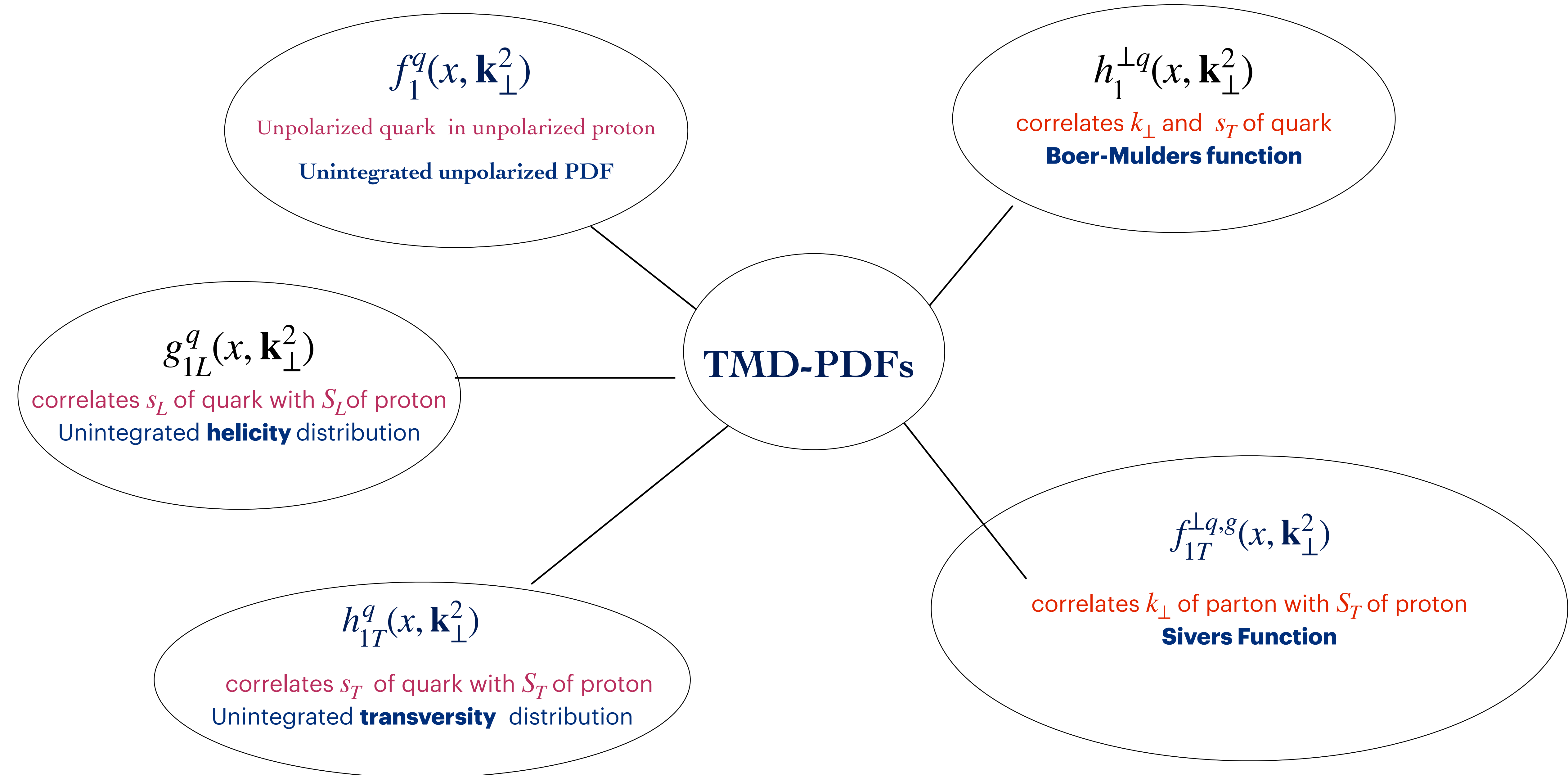
pQCD factorisation including spin and intrinsic transverse momentum effects in PDFs and FFs

TMDs : Spin and Transverse Momentum Dependent PDFs (TMD-PDFs) and Transverse Momentum Dependent Fragmentation functions (TMD-FFs)

General form : $\mathbf{S} \cdot (\mathbf{p}_1 \times \mathbf{p}_2)$, where $\mathbf{S}$ can be spin of proton or the struck parton and $\mathbf{p}_i$'s can be momenta of initial proton, final state particle or jet momentum, transverse momentum of parton or final state particle's transverse momentum



TMDs in Parton Model



Sivers Function

Sivers function : correlation between the nucleon transverse spin and parton transverse momentum in the polarized nucleon

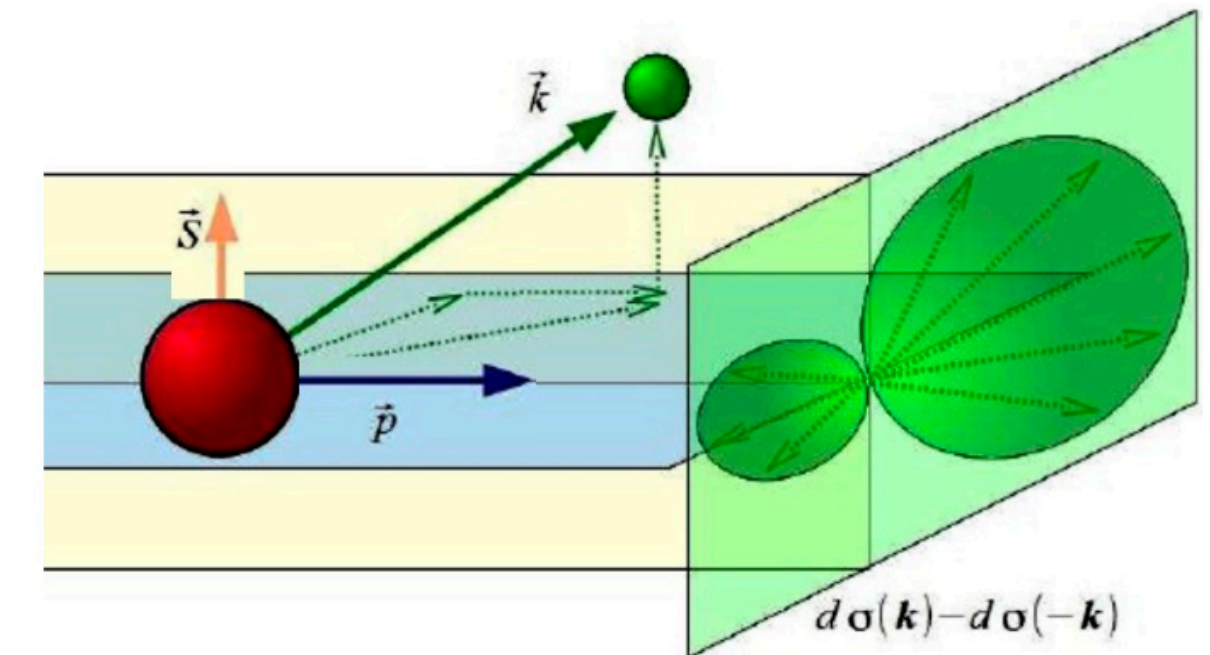
$$\mathbf{S}^T \cdot (\mathbf{P} \times \mathbf{k}_T)$$

Anisotropy due to spin-orbit coupling between the proton's spin and parton's $\mathbf{k}_\perp$

$$f_{a/p^\uparrow}(x, \mathbf{k}_\perp) = f_{a/p}(x, \mathbf{k}_\perp) + \Delta^N f_{a/p^\uparrow}(x, \mathbf{k}_\perp) \mathbf{S} \cdot (\mathbf{p} \times \mathbf{k}_\perp)$$

Anisotropy at parton level leads to TSSA (A_N) in the final state

To investigate TMDs, look at processes which relate physical observable to parton intrinsic motion



What do we know about **Sivers Function** ?

Quark Sivers Functions - widely studied, however not much information available on GSF

Question that we asked : **Can we have “direct” probes of GSF?**

Traditionally, open and closed heavy-flavour production as well as direct photon production have been used to get information on the gluon density in unpolarized and longitudinally polarized proton

M. Anselmino 2004 : D - meson production in $pp^\uparrow$ collisions could be used for exploring GSF

However, the process $pp^\uparrow \rightarrow DX$ receives contribution from QSF as well

What can be a **clean** probe for probing GSF ?

Rohini proposed

- 1. Look at low virtuality electroproduction of J/ψ : $e + p^\uparrow \rightarrow e + J/\psi + X$, at LO heavy quark production receives contribution only from gluons**

TMD factorization not established for this process

- 2. Resort to Generalised Parton Model which is a phenomenological approach**

Heavy quarks and gluons

To have direct probes of GSF, choose final states where gluon will contribute dominantly

Final states which dominated gluon determination contain heavy quarks - either charmonium or open charm production in DIS or in pp collisions

For γp or $\gamma^* p$ initial states (photo production and DIS) the sub process is

$$\gamma + g \rightarrow c + \bar{c} \quad \text{or} \quad \gamma^* + g \rightarrow c + \bar{c}$$

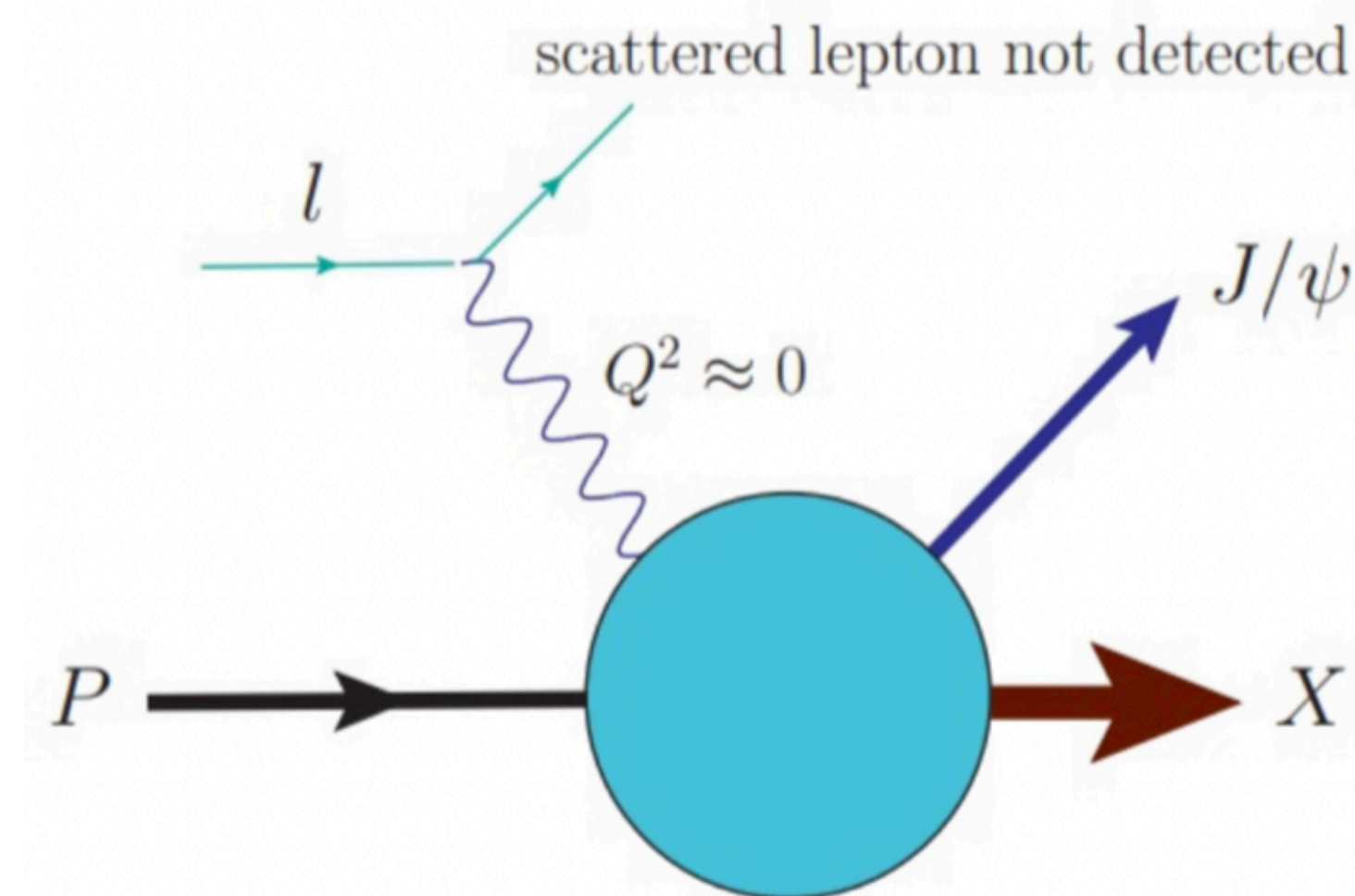
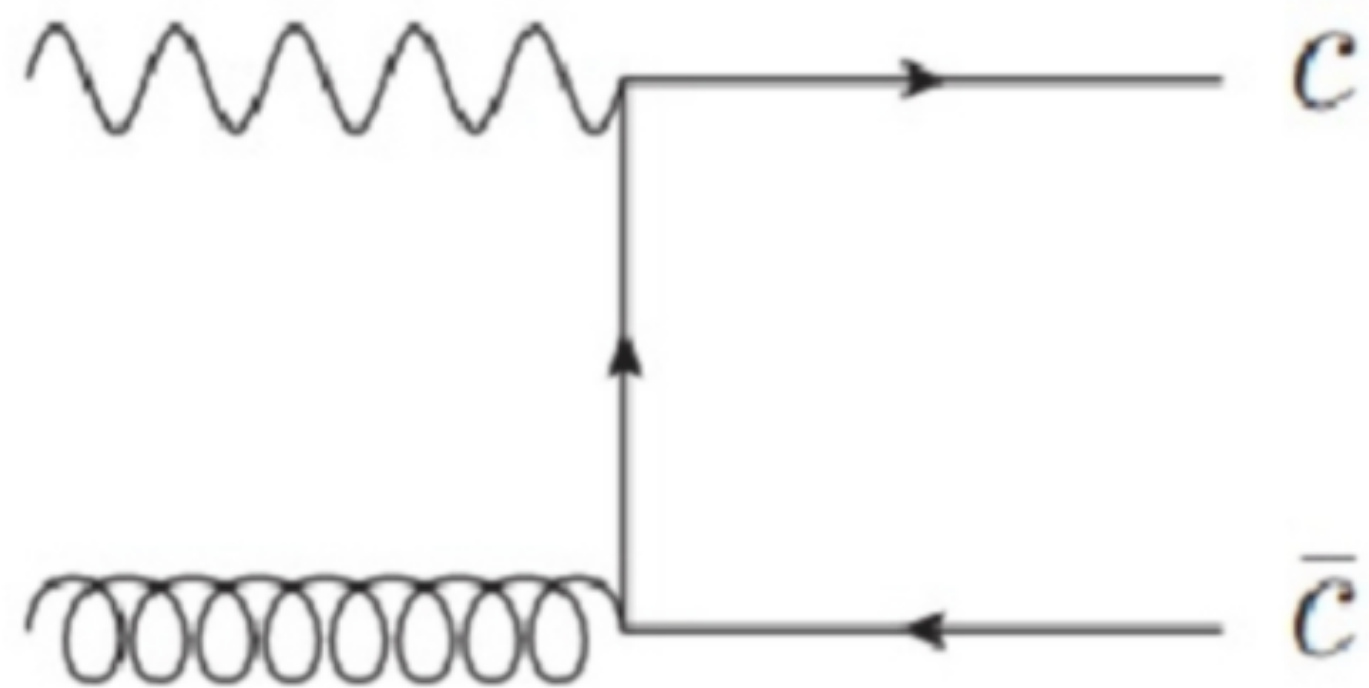
Thus at LO, for suitable chosen kinematic region, heavy quark production receives contribution **ONLY** from gluons in proton

What is a good probe to investigate GSF then?

Low virtuality leptonproduction of J/ψ : $e + p^\uparrow \rightarrow J/\psi + X$ with $Q^2 \approx 0$

J/ψ produced through photon-gluon fusion $\Rightarrow$ Direct probe of gluon

Inclusive production of J/ψ and D in $ep^\uparrow$: $e + p^\uparrow \rightarrow e + J/\psi + X$ and $e + p^\uparrow \rightarrow e + D + X$, where the γ is quasi-real



Generalized Parton Model

TMD Factorization - rigorously proved for some processes :

Semi-inclusive DIS : $l + N \rightarrow l' + H + X$

Drell-Yan Process : $H_1 + H_2 \rightarrow l^+ + l^- + X$

$e^+ - e^-$ annihilation : $e^+ + e^- \rightarrow H_1 + H_2 + X$

In many phenomenological studies, validity assumed - **GPM approach**

TSSA in heavy flavour production as a probe...

GPM formalism

GPM then to my thinking is a phenomenological approach to TMD . In fact the road from Parton Model to QCD improved Parton Model also went through such approaches. There we were helped by '**universality**' OR **Process independence** of the collinear parton densities. Things are different for TMD's. They may be process dependent.

Asymmetry in GPM approach

Asymmetry in $pp^\uparrow$ collisions is defined as $A_N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$

Numerator of asymmetry now involves

$$\Delta \hat{f}_{a/p^\uparrow}(x, \mathbf{k}_{\perp a}) = \hat{f}_{a/p^\uparrow}(x, \mathbf{k}_{\perp a}) - \hat{f}_{a/p^\downarrow}(x, \mathbf{k}_{\perp a}) = -2 \frac{k_{\perp a}}{M_p} f_{1T}^{\perp a}(x, \mathbf{k}_{\perp a}) \cos \phi_a$$

$\hat{f}_{a/p^\uparrow}(x, \mathbf{k}_{\perp a})$ is the number density of parton a with light cone momentum fraction x and transverse momentum $\mathbf{k}_{\perp a} = k_{\perp a}(\cos \phi_a, \sin \phi_a)$ inside the transversely polarized proton

TMD PDFs are parametrised by fitting the data of Semi-inclusive DIS (SIDIS) to simple parametrization assuming factorized $\mathbf{k}_\perp$ and $\mathbf{p}_\perp$ dependences

TSSA in Charmonium Production

Low virtuality leptonproduction of J/ψ as an example

Low virtuality leptonproduction of $J/\psi : e + p^\uparrow \rightarrow J/\psi + X$ with $Q^2 \approx 0$

Sivers Effect and transverse single spin asymmetry in $e + p^\uparrow \rightarrow e + J/\psi + X$, **RMG**, A. Mukherjee, **AM** and Vaibhav Rawoot, Phys. Rev. D85, 094013(2012)

Sizeable asymmetries predicted for HERMES, COMPASS, eRHIC and JLab energies using both DGLAP and TMD evolved PDFs

Asymmetries reduced substantially when TMD evolution effects were taken into account

R.M. Godbole, A. Mukherjee, **AM** and Vaibhav Rawoot, Phys. Rev. D88, 014029(2013)

R.M. Godbole, Abhiram Kaushik, **AM** and Vaibhav Rawoot, Phys. Rev. D91, 014005(2015)

Asymmetry in Color Evaporation Model of Charmonium Production :

$$A_N = \frac{\mathcal{N}}{\mathcal{D}}$$

$$\mathcal{N} = \frac{\mathcal{F}_{J/\psi}}{s} \int_{2m_c}^{2m_D} dM^2 d^2\mathbf{k}_{\perp\gamma} d^2\mathbf{k}_{\perp g} \Delta^N f_{g/p\uparrow}(x_g, \mathbf{k}_{\perp g}) f_{\gamma/e}(x_\gamma, \mathbf{k}_{\perp\gamma}) \delta^2(\mathbf{k}_{\perp g} + \mathbf{k}_{\perp\gamma} - \mathbf{q}_T) \hat{\sigma}^{\gamma g \rightarrow c\bar{c}}(M^2)$$

$$\mathcal{D} = 2 \frac{\mathcal{F}_{J/\psi}}{s} \int_{2m_c}^{2m_D} dM^2 d^2\mathbf{k}_{\perp\gamma} d^2\mathbf{k}_{\perp g} f_{g/p}(x_g, \mathbf{k}_{\perp g}) f_{\gamma/e}(x_\gamma, \mathbf{k}_{\perp\gamma}) \delta^2(\mathbf{k}_{\perp g} + \mathbf{k}_{\perp\gamma} - \mathbf{q}_T) \hat{\sigma}^{\gamma g \rightarrow c\bar{c}}(M^2)$$

$f_{\gamma/e}(x_\gamma, \mathbf{k}_{\perp\gamma})$: William Weizsacker function - distribution of a quasi-real photon in a lepton

Parametrization of Gluon Sivers Function

- We assume $\mathbf{k}_\perp$ dependence PDF and WW function to be Gaussian

$$f(x, \mathbf{k}_\perp) = f(x) \frac{1}{\pi \langle \mathbf{k}_\perp^2 \rangle} e^{-\mathbf{k}_\perp^2 / \langle \mathbf{k}_\perp^2 \rangle}, \quad f_{\gamma/e}(x_\gamma, \mathbf{k}_{\perp\gamma}) = f_{\gamma/e}(x_\gamma) \frac{1}{\pi \langle \mathbf{k}_{\perp\gamma}^2 \rangle} e^{-\mathbf{k}_{\perp\gamma}^2 / \langle \mathbf{k}_{\perp\gamma}^2 \rangle}$$

- Parammerization for Sivers function

$$\Delta^N f_{g/p^\uparrow}(x, \mathbf{k}_\perp) = 2 \mathcal{N}_g(x) h(\mathbf{k}_\perp) f_{g/p}(x) \frac{e^{-\mathbf{k}_\perp^2 / \langle \mathbf{k}_\perp^2 \rangle}}{\pi \langle \mathbf{k}_\perp^2 \rangle} \cos \phi_{k_\perp}$$

$$\text{with } \mathcal{N}_g(x) = N_g(x) x^{\alpha_i} (1-x)^{\beta_i} \frac{(\alpha_i + \beta_i)^{\alpha_i + \beta_i}}{\alpha_i^{\alpha_i} \beta_i^{\beta_i}}$$

The parameters used have been extracted from experimental data of the HERMES and COMPASS experiment (hep-ph/1107.4446)

Sizeable asymmetries predicted for HERMES, COMPASS, eRHIC and JLab energies using both DGLAP and TMD evolved PDFs

Asymmetries reduced substantially when TMD effects were taken into account

Other processes as probes of GSF -

Open and closed charm Inclusive production of D in $e + p^\uparrow \rightarrow e + D + X$

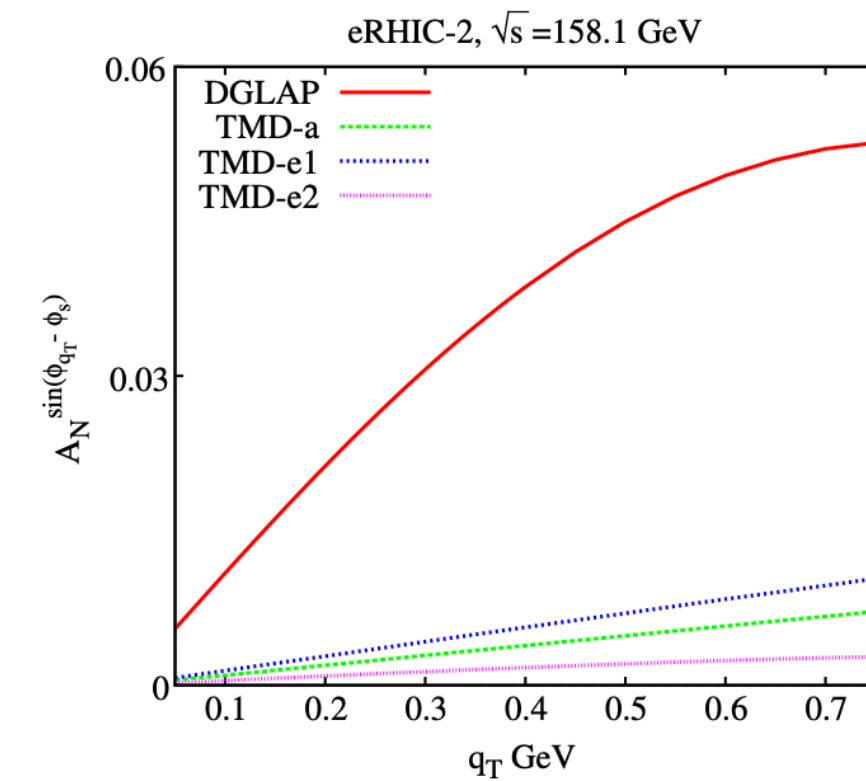
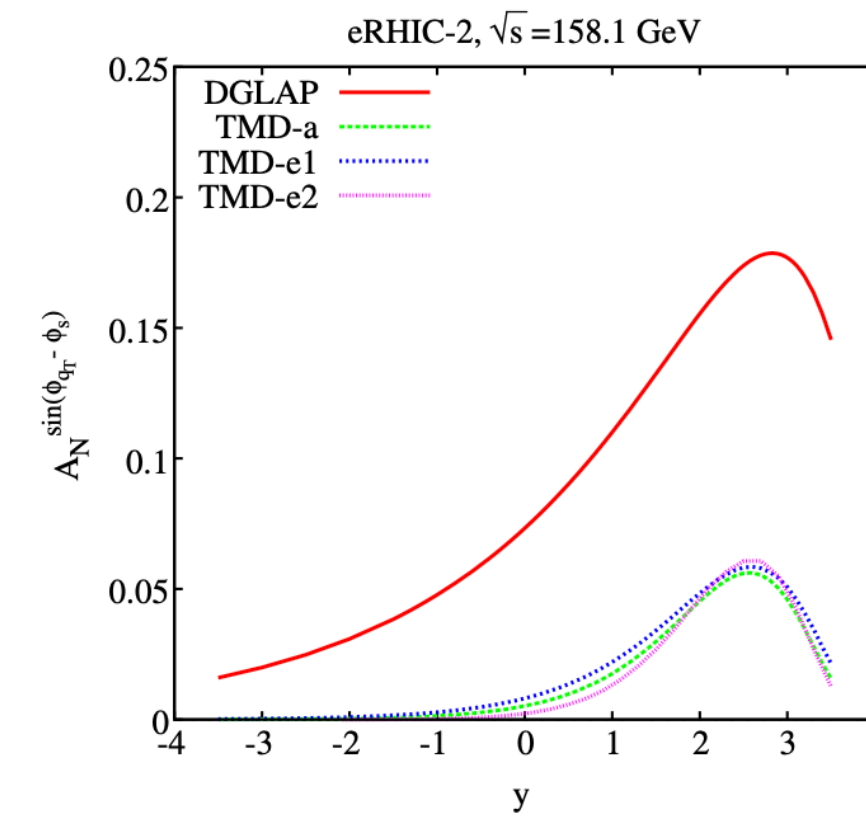
Inclusive production of D in $p + p^\uparrow \rightarrow D + X$

Inclusive production of J/ψ in $p + p^\uparrow \rightarrow J/\psi + X$

D. Direct photons as probe of GSF

(Phys. Rev. D99, 014003(2019), Phys. Rev. D103, 036008(2021))

These predictions shall be verified at the upcoming eRHIC and JLab experiments



Rohini's legacy ...@UoM

TSSAs in $ep^\uparrow \rightarrow J/\psi X$ an improved color evaporation model (Himanshu Mishra, Suraj Gupta, Vaibhav Rawoot and Siddhesh Padval 2025)(ongoing work with Himanshu Mishra, Suraj Gupta, Vaibhav Rawoot and Siddhesh Padval)

Exploring GSF in photon + jet production (Deepesh Bhamre, Aman Gupta, AM & Siddhesh Padval, Preliminary results presented at DAE symposium 2024 by Aman Gupta (a National Initiative for Undergraduate Science program mentee from NISER, Bhubaneswar))

Particle Physics continues to be the most sought after elective at University of Mumbai

Number of UoM students pursuing research in HEP at various national and international institutions, many of them working as graduate students at Spin Physics group at IIT Bombay

Lilavati's Daughters continue to inspire the next generation of aspiring Indian woman scientists

Rohini's legacy continues through

- her Ph.d, Masters, Academies' summer students, post docs and mentees
- next generation of very able HEP experts, many of them inspired by her lectures, courses taught at SERC and other schools or just through interaction with her during conferences, meetings
- “Lilavati's daughters” and the new generation of champions of Women in Science cause

Legacy beyond HEP & WiS initiative.....



THANK YOU !