

THEORY SUMMARY

Photon 2009

H. Spiesberger

THEORETICAL SUMMARY OF THEORY SUMMARIES

Photon 2009

H. Spiesberger

- Electroweak and new physics
 - Nazila Mahmoudi
 - Andreas von Manteuffel
 - Emilien Chapon
 - Klaus Moenig
 - Michael Spira
 - Rui Ribeiro Santos
 - Rohini Godbole
 - Maria Krawczyk
 - Ilya Ginzburg
- Vacuum polarisation and light-by-light scattering
 - Gabriel Lopez Castro
 - Joaquim Prades
- Small x, diffraction and total cross sections
 - Dieter Müller
 - Florian Schwennsen
 - Giovanni Chirilli
 - Edmond Iancu
- Exclusive channels and resonances
 - Samuel Wallon
 - Jean-Philippe Lansberg
 - Wojtek Broniowski
 - Valeriy Serbo
- Prompt photons
 - Francois Arleo
- Photon Structure
 - Ken Sasaki
 - Lech Szymanowski
- Jets and heavy flavours
 - Francesco Hautmann
 - Vladimir A. Saleev

24 Talks

PHOTON2009: THE LEITMOTIF

Conference on the Structure and the Interactions of the Photon
including
Photon-Photon Collisions and High Energy Photon Linear Colliders

- Photon: a Tool
 - in photon colliders: search for new physics supersymmetry, anomalous couplings, Higgs prompt photons to study QCD
- Photon: a Research Object
 - the photon structure: structure functions, generalized parton distribution functions, generalized distribution amplitudes; and its interaction: $g - 2$
- Photon: a Theory Laboratory
 - theory of exclusive processes, factorization
- Photon probes hadronic matter and interactions → QCD

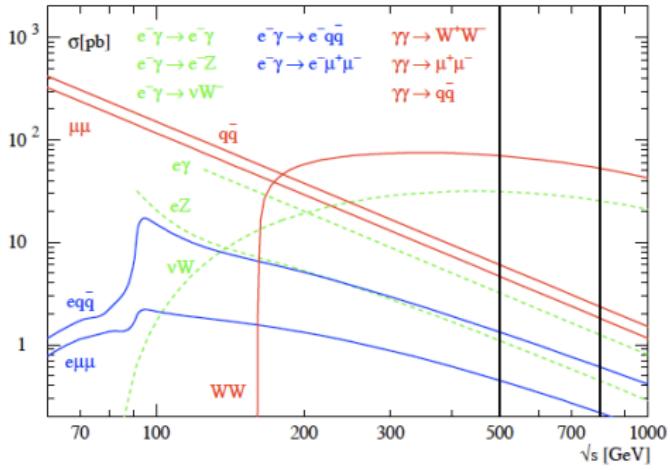
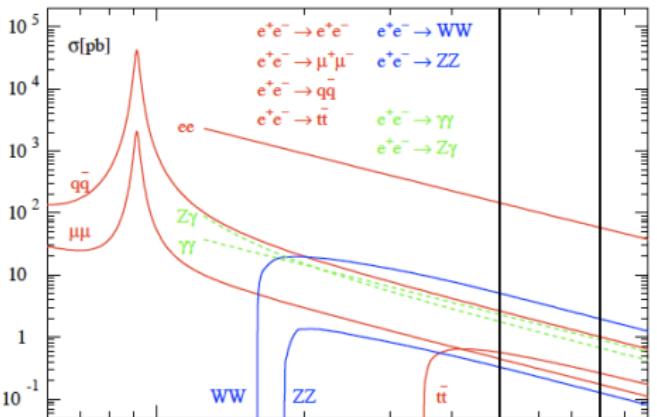
ELECTROWEAK AND NEW PHYSICS

- Klaus Moenig: Physics at a photon collider
- Michael Spira: Higgs physics at ee and photon collider
- Rohini Godbole: SUSY/New physics at $\gamma\gamma$ collider
- Maria Krawczyk: Study of CP violation in self interaction at PLC
- Rui Ribeiro Santos: Double Higgs production at a photon collider
- Nazila Mahmoudi: New constraints on supersymmetric models from $b \rightarrow s\gamma$
- Ilya Ginzburg: Selected problems for Photon Colliders
- Emilien Chapon: Anomalous gauge couplings in photon-photon interactions at the LHC
- Andreas von Manteuffel: Anomalous couplings in $\gamma\gamma \rightarrow WW$ at LHC and ILC

Physics at a photon collider

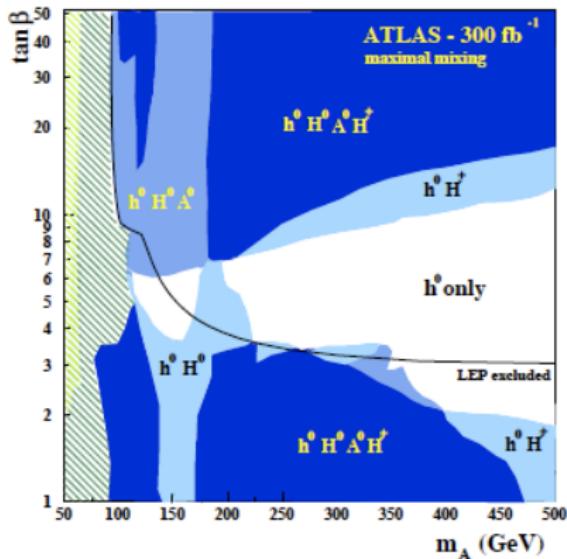
Cross sections typically larger than in e^+e^-

- Polarization
- Higgs physics
- SUSY
- Measurement of $\tan \beta$
- Anomalous couplings



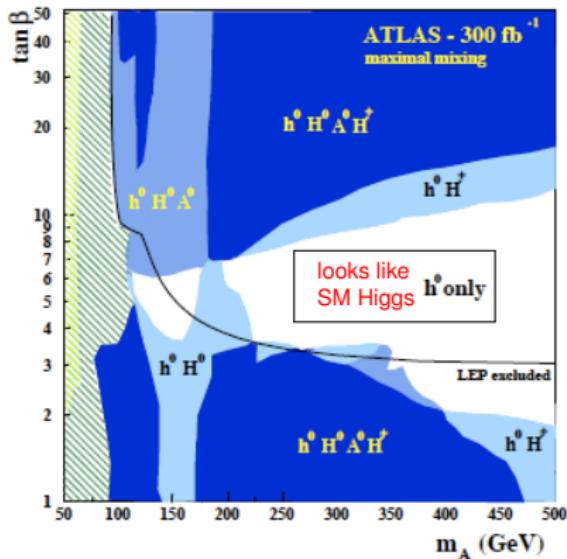
HIGGS PHYSICS AT e^+e^- AND PHOTON COLLIDERS

- SUSY Higgs bosons:
LHC: blind wedge



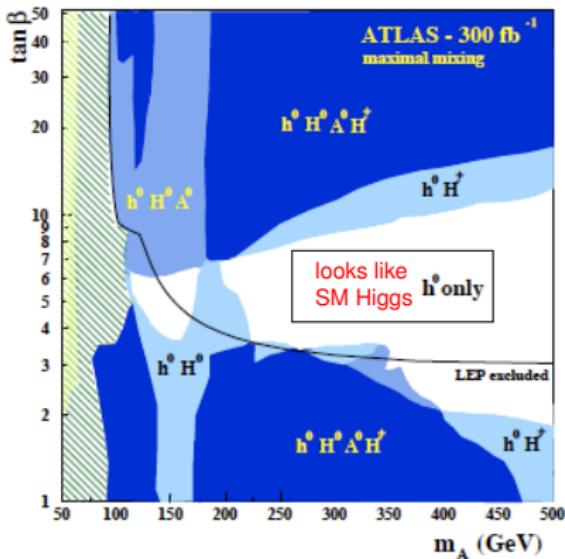
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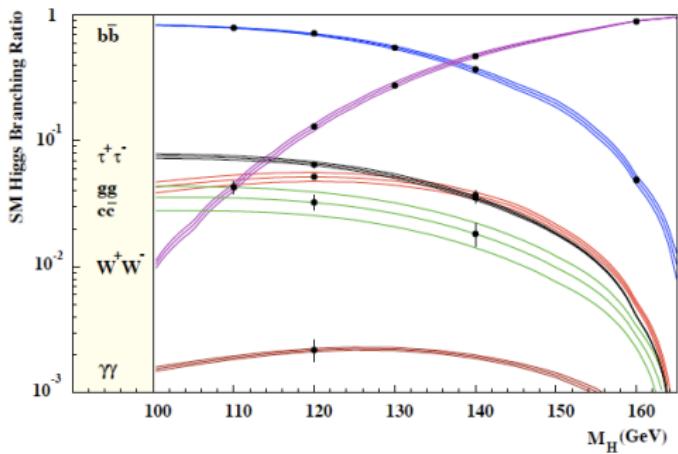


HIGGS PHYSICS AT e^+e^- AND PHOTON COLLIDERS

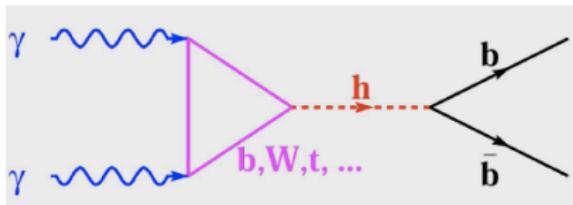
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LHC: blind wedge



measurements of SM Higgs
branching ratios at e^+e^- ILC
determine Higgs Yukawa couplings

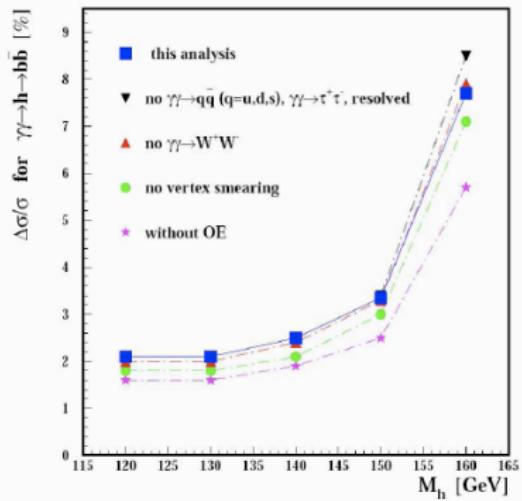
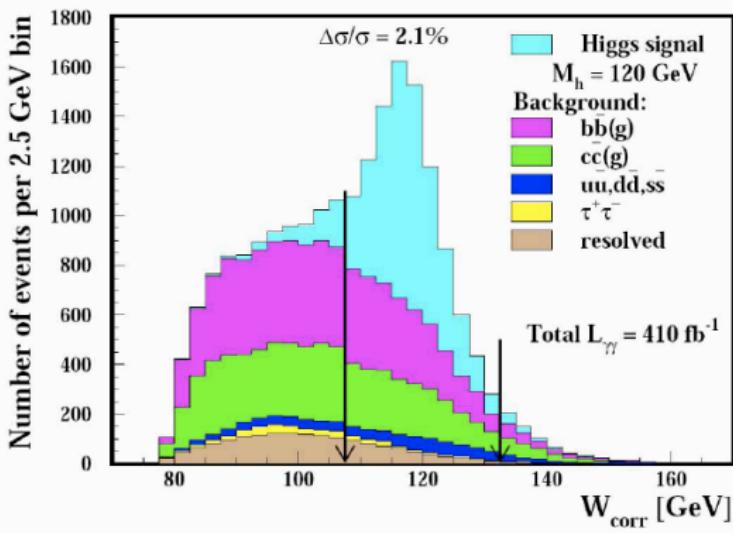


III HIGGS PHYSICS @ PLC



$$\Gamma(H \rightarrow \gamma\gamma) = \frac{G_F \alpha^2 M_H^3}{128\sqrt{2}\pi^3} |\mathcal{A}|^2$$

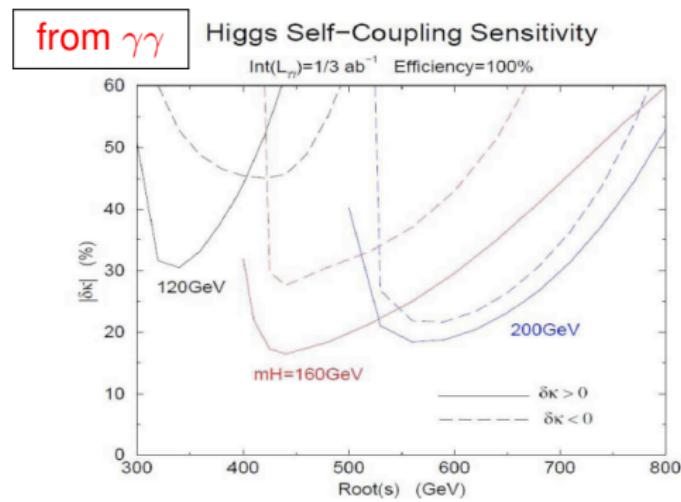
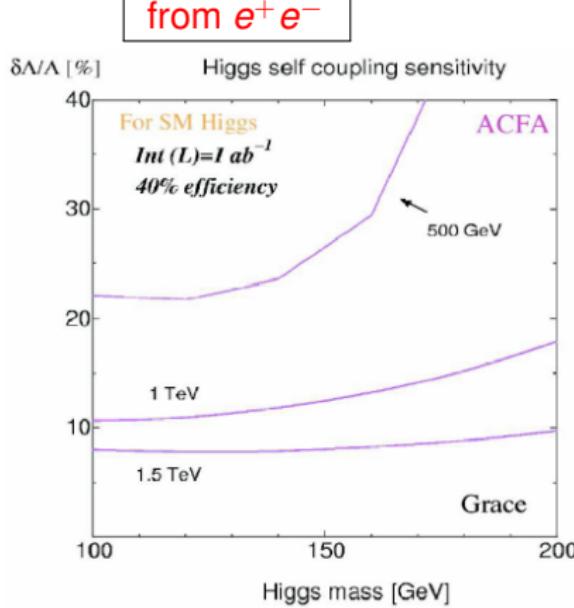
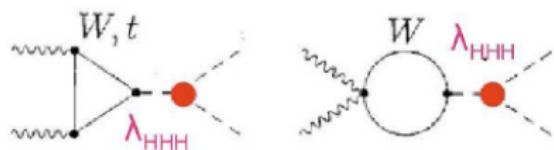
$$\mathcal{A} = |\mathcal{A}| e^{i\phi_{\gamma\gamma}}$$



Nieżurawski, Żarnecki, Krawczyk
Jikia, Söldner-Remboldt

compare: determination of
the Higgs boson self coupling

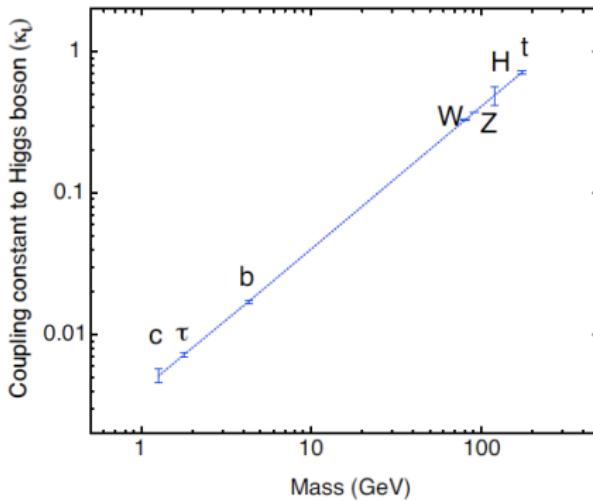
$$\lambda_{HHH} = \lambda_{HHH}^{SM}(1 + \delta\kappa)$$



⇒ model-independent measurements of Higgs couplings

→ test $g \propto \text{mass}$: $g_i = \sqrt{2\sqrt{2}G_F} m_i$

Coupling-Mass Relation

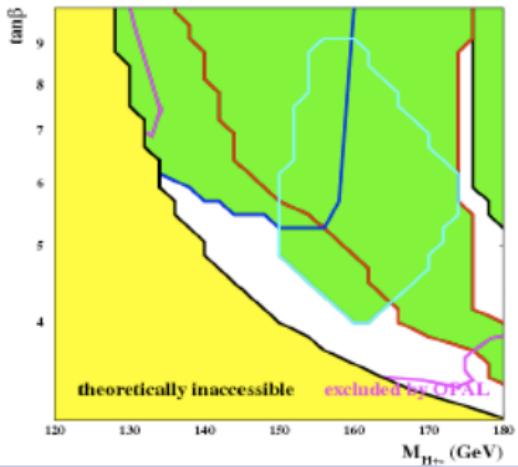
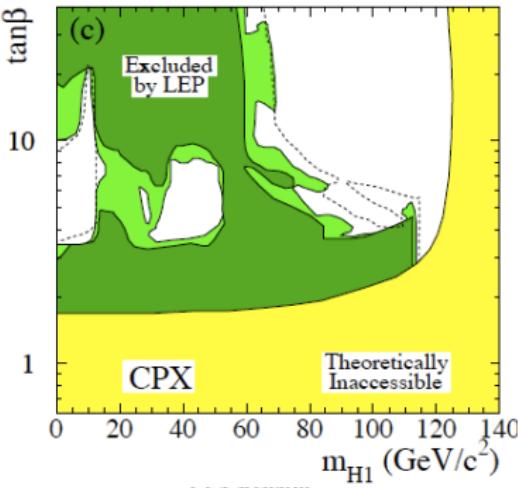


The ultimate test
of Higgs couplings

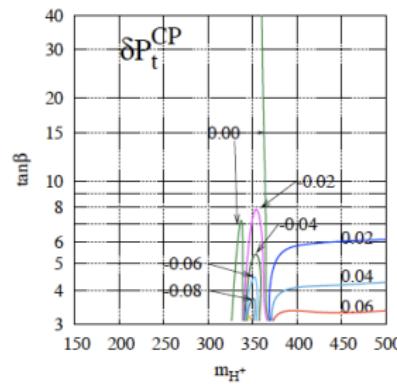
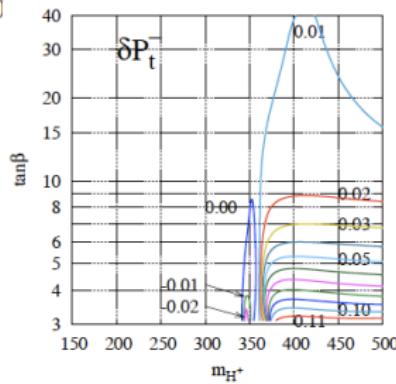
$$M_H = 120 \text{ GeV}$$

SUSY and New Physics at the Photon Collider.

- ◊ What special rôle can a photon collider play in the context?
 - a Searching for sparticles at $\gamma\gamma$ colliders *directly*
 - b Study of the Heavy Higgs H/A sector and CP-mixing if \not{P} in SUSY. WW/ZZ final states, t/τ polarisation.
 - c SUSY parameter determination: PLC can help probe the regions of the SUSY parameter space which are difficult and/or inaccessible for the LHC and/or in the e^+e^- mode.
 - d New physics via anomalous couplings, extra dimensions?



Scenarios with CP-violation
 → need $\gamma\gamma$ collider and use
 top (τ) polarization observables



Study of CP violation in the Higgs selfinteraction at the Photon Linear Collider

Maria Krawczyk

J-invariants

Mass matrix: $J_1 \sim \text{Im}(\Lambda_5^* \Lambda_6^2)$

Interactions: $J_2 \sim \text{Im}(\Lambda_5^* \Lambda_7^2)$, $J_3 \sim \text{Im}(\Lambda_7^* \Lambda_6)$

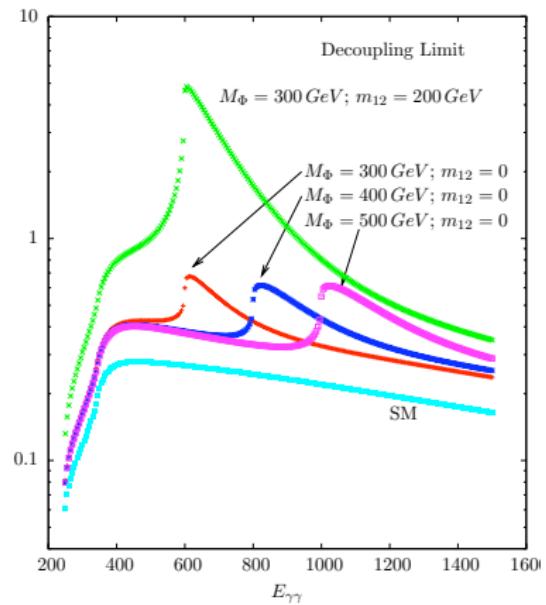
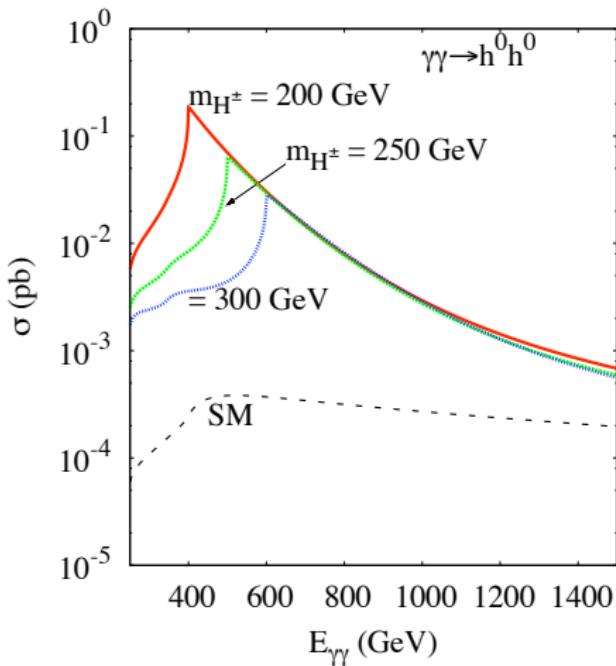
- CP conservation: all $J = 0$
- If J_1 not zero \rightarrow CP mixing in states, no definite CP-parity for $h1, h2, h3$
- If $J_1 = 0$ and $J_{2,3}$ not zero \rightarrow no CP mixing

CP violation in interaction at the tree level

A 2HDM in 7 steps

A Do-It-Yourself kit for the model builders
+ experimental bounds + theoretical constraints

- Cross sections for hh and AA production in $\gamma\gamma$ collisions may be much larger than in the SM
- Non-decoupling effects (due to the hH^+H^- -coupling and 2-loop effects) may be visible
- Many other production mechanisms "stand a chance"
- Study of possible final states to identify promising regions in parameter space (some need new analysis)



Very good chance to see it happen

Note again that the low mass region can only be probed at a $\gamma\gamma$ collider

B Physics

Farvah Nazila Mahmoudi

A good strategy to find the information on SUSY particles would be

- to look at where the SM contributions are vanishingly small,
- to study processes for which QCD corrections are known with high accuracy
- and branching ratios can be measured precisely.

⇒ Rare B decays are IDEAL CHOICES for that!

Download

http://superiso.in2p3.fr

SuperIso

By Farvah Nazila Mahmoudi

SuperIso

→ Description

→ Manual

SuperIso Relic

→ Description

→ Manual

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Calculation of flavor physics observables in supersymmetry

SuperIso is a program for calculation of flavor physics observables in the minimal supersymmetric extension of the Standard Model (MSSM). SuperIso, in addition to the Isospin asymmetry of $B \rightarrow K^* \gamma$, which was the main purpose of the first version, incorporates other flavor observables such as the branching ratio of $B \rightarrow X_S \gamma$ at NNLO, the branching ratio of $B_s \rightarrow \mu^+ \mu^-$, the branching ratio of $B \rightarrow \tau \bar{\nu}_\tau$, the branching ratio of $B \rightarrow D \tau \bar{\nu}_\tau$ and the branching ratio of $K \rightarrow \mu \bar{\nu}_\mu$. It also computes the muon anomalous magnetic moment ($g-2$).

For the Isospin asymmetry, the program calculates the NLO supersymmetric contributions using the effective Hamiltonian approach and within the QCD factorization method. Isospin asymmetry is a particularly useful observable to constrain supersymmetric parameter spaces.

SuperIso uses a SUSY Les Houches Accord file (SLHA1 or SUHA2) as input, which can be either generated automatically by the program via a call to SOFTSUSY or ISAJET, or provided by the user.

SuperIso is able to perform the calculations automatically in different supersymmetry breaking scenarios, such as mSUGRA, NUHM, AMSB and GMSB.

Manual

The latest version of the manual can be found [here](#) (05/03/2009).

For more information:

- F. Mahmoudi, arXiv:0710.3791 [hep-ph], JHEP12 (2007), 026
- M.R. Ahmady and F. Mahmoudi, hep-ph/0609212, Phys. Rev. D75 (2007), 015007
- A. Arbey and F. Mahmoudi, arXiv:0803.0741 [hep-ph], Phys. Lett. B 669 (2008), 46
- D. Eriksson, F. Mahmoudi and O. Stål, arXiv:0809.3551 [hep-ph], JHEP11 (2008), 035
- A.G. Akeroyd and F. Mahmoudi, arXiv:0902.2393 [hep-ph], JHEP04 (2009), 121

Conclusion

Farvah Nazila Mahmoudi

- Indirect constraints and in particular flavor physics are essential to restrict new physics parameters
- That will become even more interesting when combined with LHC data
- $b \rightarrow s\gamma$ transitions and in particular isospin asymmetry provide valuable information

Perspectives

New observables:

- forward-backward asymmetry in $B \rightarrow K^* \ell^+ \ell^-$
- $B_{(s,d)}^0 - \bar{B}_{(s,d)}^0$ mixings: $\Delta M_{B_{s,d}}$

New Models:

- Non Minimal Flavor violation
- CP violation

Selected problems for Photon Colliders

Ilya Ginzburg

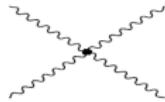
- Multiple production of SM gauge bosons

$$\begin{aligned}\gamma\gamma &\rightarrow WW \text{ at 2-loop} \\ \gamma\gamma &\rightarrow 3V \text{ and } \gamma\gamma \rightarrow 4V\end{aligned}$$

- Strong interaction in Higgs sector

strong interaction in $\gamma + \gamma^*(Z^*) \rightarrow WW$ or $\gamma^*(Z^*) \rightarrow WW$
different charge asymmetry

- High energy large angle photons to hunt for exotics



$$L \propto \frac{F^{\mu\nu} F^{\alpha\beta} F_{\rho\sigma} F_{\phi\tau}}{\Lambda^4},$$

extra dimensions, unparticles,
point-like monopoles

$$\sigma_{tot} = \frac{1}{32\pi s} \left(\frac{s}{4\Lambda^2} \right)^4, \quad \frac{d\sigma}{dp_\perp^2} = \sigma_{tot} \Phi \left(\frac{p_\perp^2}{s} \right) \frac{2dp_\perp^2}{\sqrt{s(s - 4p_\perp^2)}}$$

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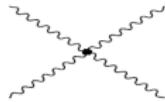
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All these models seem
hardly probable to ME

Anomalous gauge coupling in photon-photon interactions

Sensitivity in generic experiments at the LHC

Emilien Chapon

Lagrangian for anomalous quartic gauge couplings:

$$\mathcal{L}_6^0 = \frac{-e^2}{8} \frac{a_0^W}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} W^{+\alpha} W^{-}_{\alpha} - \frac{e^2}{16 \cos^2 \Theta_W} \frac{a_0^Z}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} Z^{\alpha} Z_{\alpha}$$

$$\mathcal{L}_6^C = \frac{-e^2}{16} \frac{a_C^W}{\Lambda^2} F_{\mu\alpha} F^{\mu\beta} (W^{+\alpha} W^{-}_{\beta} + W^{-\alpha} W^{+}_{\beta}) - \frac{e^2}{16 \cos^2 \Theta_W} \frac{a_C^Z}{\Lambda^2} F_{\mu\alpha} F^{\mu\beta} Z^{\alpha} Z_{\beta}$$

where $F_{\mu\nu}$ is the electromagnetic field tensor $F_{\mu\nu} = \partial_{\mu} A_{\nu} - \partial_{\nu} A_{\mu}$

Lagrangian for anomalous triple gauge couplings:

$$\begin{aligned} \mathcal{L}_{\text{TGC}} / ig_{WW\gamma} &= \left(W_{\mu\nu}^{\dagger} W^{\mu} A^{\nu} - W_{\mu\nu} W^{\dagger\mu} A^{\nu} \right) + (1 + \Delta\kappa^{\gamma}) W_{\mu}^{\dagger} W_{\nu} W^{\mu\nu} \\ &\quad + \frac{\lambda^{\gamma}}{M_W^2} W_{\rho\mu}^{\dagger} W_{\nu}^{\mu} A^{\nu\rho} \end{aligned}$$

consider independent variation of parameters

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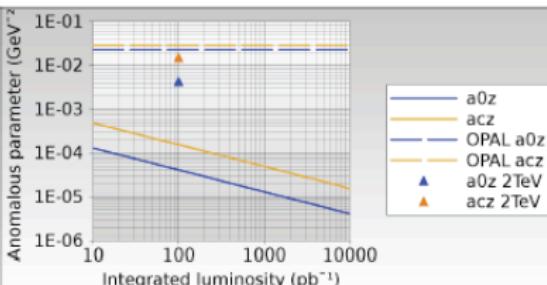
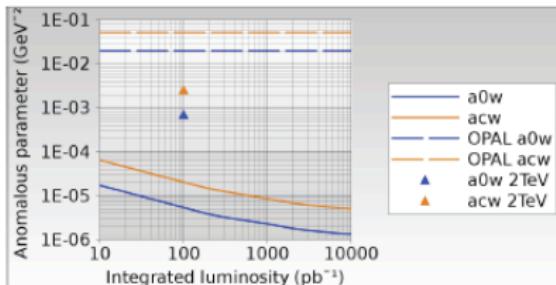
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consider independent variation of parameters

A parametrization of anomalous couplings suitable to parametrize deviations from the SM, but not a consistent theory

Results



Couplings	OPAL limits [GeV ⁻²]	Limits @ 10 TeV [GeV ⁻²] $\mathcal{L} = 10 \text{ pb}^{-1}$	Limits @ 10 TeV [GeV ⁻²] $\mathcal{L} = 100 \text{ pb}^{-1}$	Limit @ 2 TeV [GeV ⁻²] $\mathcal{L} = 100 \text{ pb}^{-1}$
a_0^W/Λ^2	$[-0.020, 0.020]$	1.72×10^{-5}	5.4×10^{-6}	7×10^{-4}
a_C^W/Λ^2	$[-0.052, 0.037]$	6.50×10^{-5}	2.05×10^{-5}	2.6×10^{-3}
a_0^Z/Λ^2	$[-0.007, 0.023]$	1.29×10^{-4}	4.10×10^{-5}	4.25×10^{-3}
a_C^Z/Λ^2	$[-0.029, 0.029]$	4.85×10^{-4}	1.55×10^{-4}	1.5×10^{-2}

Note: we present the expected 95% confidence level upper limits on the parameters.

Improvement of a factor up to 1000 with respect to the OPAL limits

Emilien Chapon

Anomalous couplings in $\gamma\gamma \rightarrow W^+W^-$ at LHC and ILC

Effective Lagrangian before EWSB

Gauge and gauge-Higgs anomalous couplings

- pure gauge and gauge-Higgs part: $\mathcal{L}_2 = \frac{1}{v^2} \sum h_i O_i$

$$O_W = \epsilon_{ijk} W_\mu^{i\nu} W_\nu^{j\lambda} W_\lambda^{k\mu},$$

$$O_{\tilde{W}} = \epsilon_{ijk} \tilde{W}_\mu^{i\nu} W_\nu^{j\lambda} W_\lambda^{k\mu},$$

$$O_{\varphi W} = \frac{1}{2} (\varphi^\dagger \varphi) W_\mu^{i\nu} W^{i\mu\nu},$$

$$O_{\varphi \tilde{W}} = (\varphi^\dagger \varphi) \tilde{W}_\mu^{i\nu} W^{i\mu\nu},$$

$$O_{\varphi B} = \frac{1}{2} (\varphi^\dagger \varphi) B_{\mu\nu} B^{\mu\nu},$$

$$O_{\varphi \tilde{B}} = (\varphi^\dagger \varphi) \tilde{B}_{\mu\nu} B^{\mu\nu},$$

$$O_{WB} = (\varphi^\dagger \tau^i \varphi) W_\mu^{i\nu} B^{\mu\nu},$$

$$O_{\tilde{W}B} = (\varphi^\dagger \tau^i \varphi) \tilde{W}_\mu^{i\nu} B^{\mu\nu},$$

$$O_\varphi^{(1)} = (\varphi^\dagger \varphi) (\mathcal{D}_\mu \varphi)^\dagger (\mathcal{D}^\mu \varphi),$$

$$O_\varphi^{(3)} = (\varphi^\dagger \mathcal{D}_\mu \varphi)^\dagger (\varphi^\dagger \mathcal{D}^\mu \varphi).$$

- 10 dimensionless anomalous couplings h_i , where 4 ops. CP odd

$$h_i \sim \mathcal{O}\left(v^2/\Lambda_{NP}^2\right),$$

Anomalous couplings in $\gamma\gamma \rightarrow W^+W^-$ at LHC and ILC

Effective Lagrangian before EWSB

Gauge and gauge-Higgs anomalous couplings

respects SU(2) symmetry

- pure gauge and gauge-Higgs part: $\mathcal{L}_2 = \frac{1}{v^2} \sum h_i O_i$

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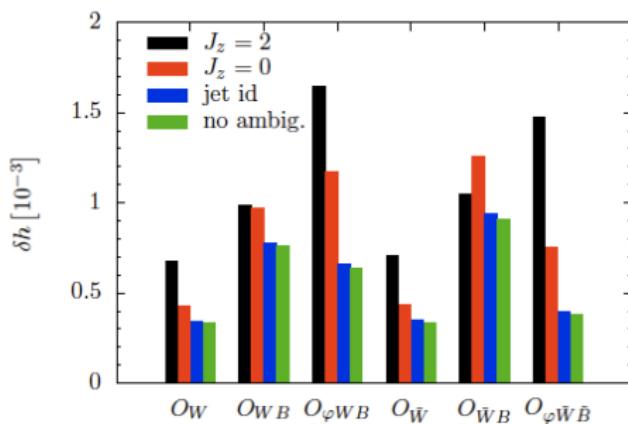
$$h_i \sim \mathcal{O}\left(v^2/\Lambda_{NP}^2\right),$$

$\gamma\gamma \rightarrow W^+W^-$
including decays

Results: Sensitivities at the ILC semi-leptonic channels

- semi-leptonic, no jet id
 \Rightarrow ambiguities (ν , jet)
- $\int L_{ee} = 500 \text{ fb}^{-1}$;
- $m_{Higgs} = 120 \text{ GeV}$
- cuts on observed fermions:
 - ▶ energy $\geq 10 \text{ GeV}$
 - ▶ angle wrt. beam $\geq 10^\circ$
 - ▶ angle betw. ferm. $\geq 25^\circ$

preliminary

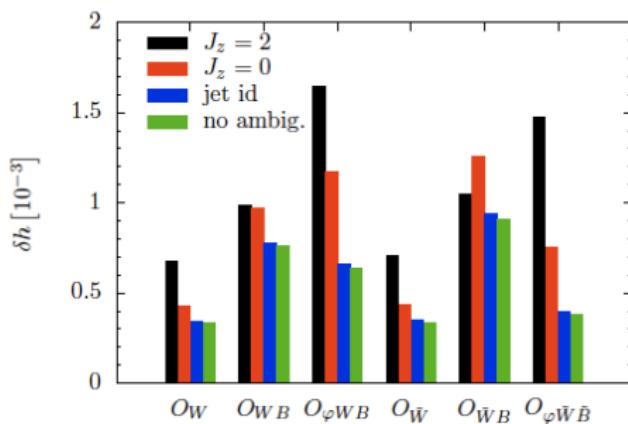


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preliminary



note: different couplings are correlated

PHOTON COLLIDER

... the far future.

(no recommendation for a $\gamma\gamma$ precursor to the ILC)

PHOTON COLLIDER

... the far future.

(no recommendation for a $\gamma\gamma$ precursor to the ILC)

Ongoing work on $\gamma\gamma$ colliders:

- anticipate the physics landscape after discoveries (?) at the LHC in 2025+
- $\gamma\gamma$ (and γp) at the LHC

PHOTON COLLIDER

... the far future.

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More on photons as a tool ...

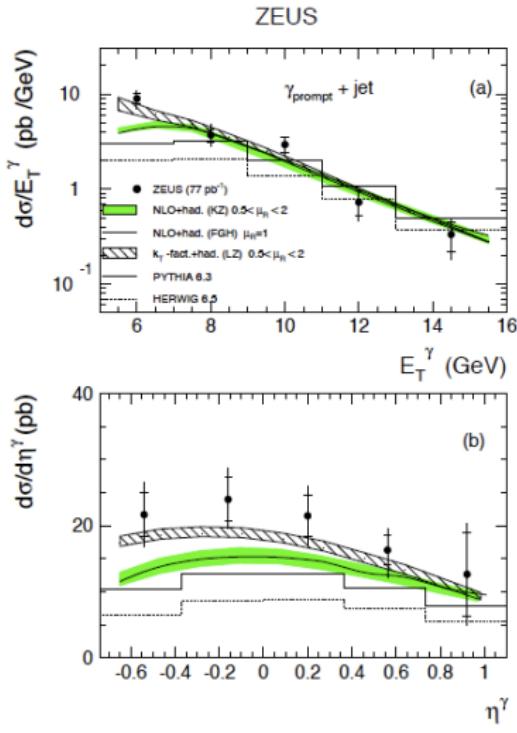
Prompt Photons

- Francois Arleo: Prompt photon production: theoretical overview
- Valeriy Serbo: Strong field effects for lepton and photon production in AA collisions at RHIC and LHC
- Vladimir Saleev: Quasi-Multi-Regge-Kinematics approach, quark-reggeization and applications

... QCD

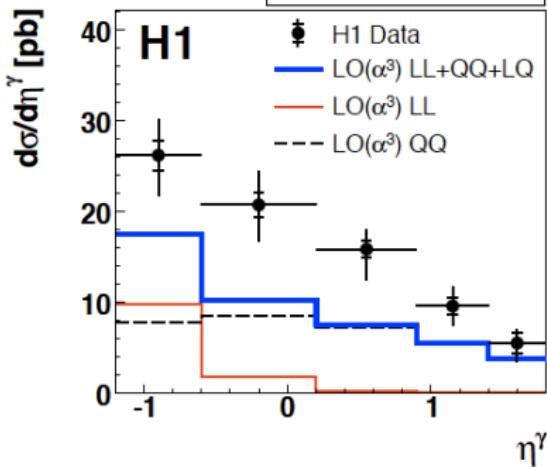
Prompt photon phenomenology from HERA to LHC

Francois Arleo



discrepancy at low p_T :
need larger p_T for
meaningful comparison
with fixed-order pQCD

comparison
with LO fails

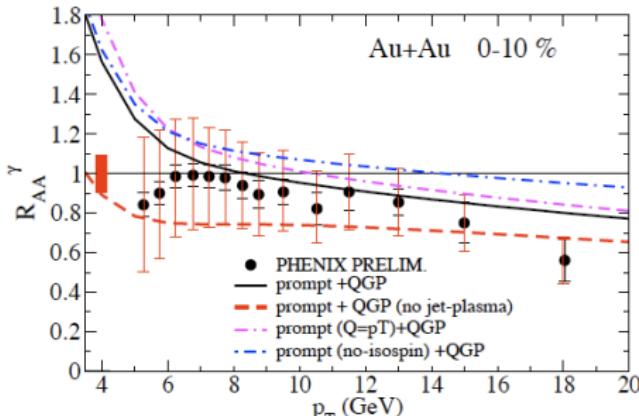
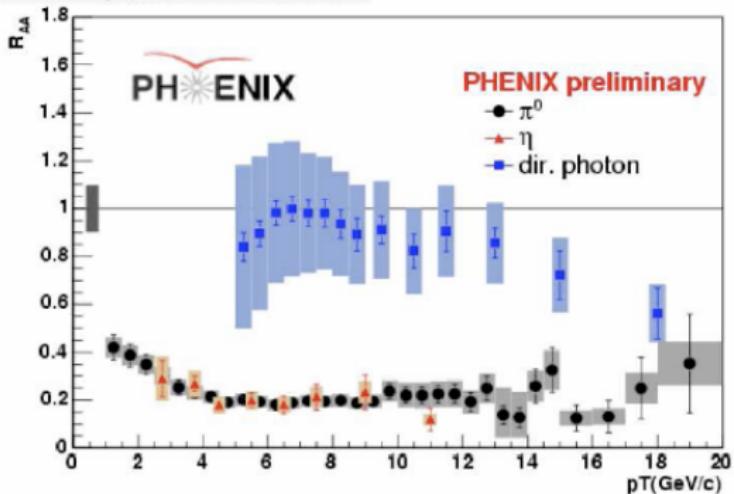


PROMPT PHOTONS

Expect more progress ...

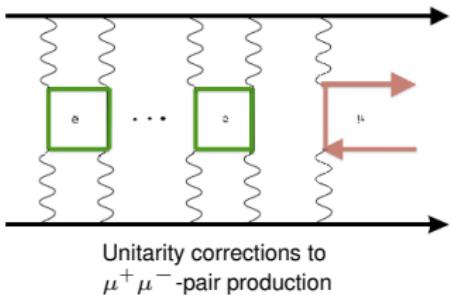
... both in theory and experiment

- NLO for inclusive prompt photon production in DIS
- prompt photon + c -/ b -tagged jet (\rightarrow D0)
- prompt photon + rapidity gap (\rightarrow H1)
- Photon versus jet quenching in collisions of heavy nuclei



Strong-field effects for lepton and photon production

Collisions of relativistic heavy nuclei:
 electric and magnetic field exceeds the
critical Schwinger field by several
 orders of magnitude
 → perturbative series in $Z\alpha \simeq 0.6$
 has to be resummed



Coulomb and unitarity corrections to the e^+e^- pair production

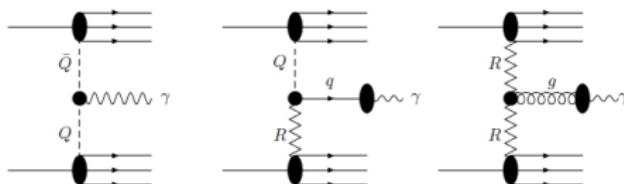
Collider	$\frac{\sigma_{\text{Coul}}}{\sigma_{\text{Born}}}$	$\frac{\sigma_{\text{unit}}}{\sigma_{\text{Born}}}$	$\frac{\sigma_{\text{Coul}}}{\sigma_{\text{Born}}} [\text{Baltz}]$
RHIC, Au-Au	-10%	-5.0%	-17%
LHC, Pb-Pb	-9.4%	-4.0%	-11%

In the last column is shown the result of A. Baltz. nucl-th/0409044 obtained by numerical calculations using its formula which allows to calculate the Coulomb correction in **the leading logarithmic approximation only**.

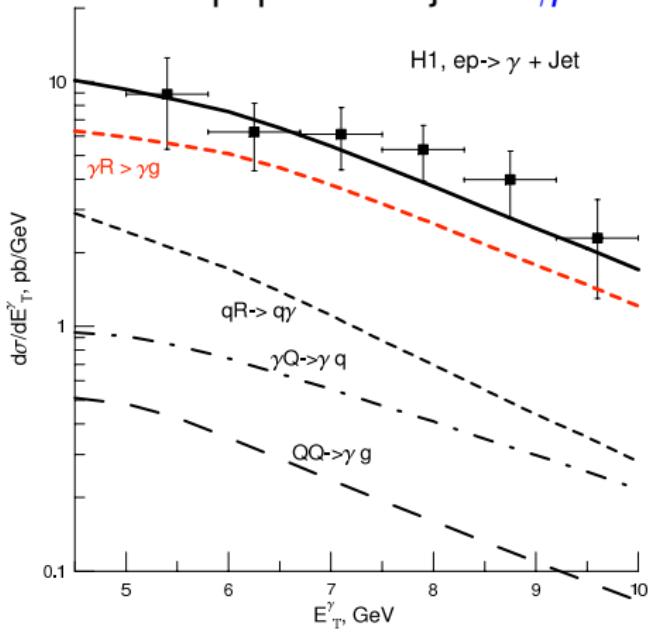
Only a few EM processes are related to Fundamental Physics, but some of EM processes are of great importance mainly for two reasons: they are **dangerous** or they are **useful**.

It means that various EM processes have to be estimated (their cross sections and distributions) **not to miss** something interesting or dangerous.

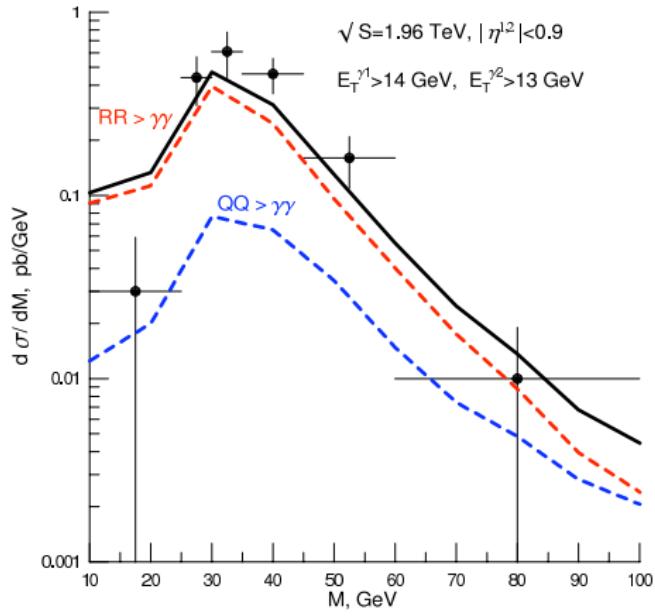
Quasi-multi-Regge kinematics approach, quark-reggeization and applications



Prompt photon + jet in $\gamma p \dots$



and diphotons in $p\bar{p}$

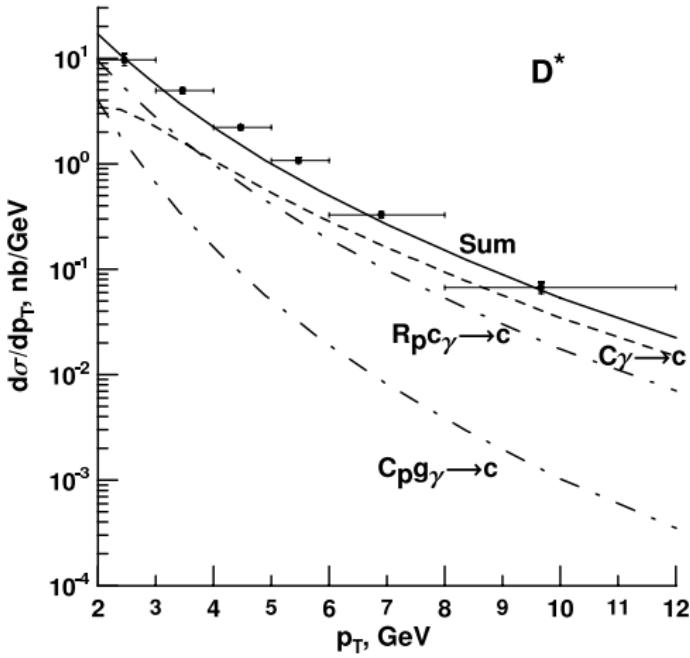


Heavy quark production in photoproduction at HERA

Vladimir Saleev

quark-gluon reggeization:
effective field theory in
the high-energy limit +
corrections beyond
collinear radiation

needs only tree diagrams



Heavy quark production in photoproduction at HERA

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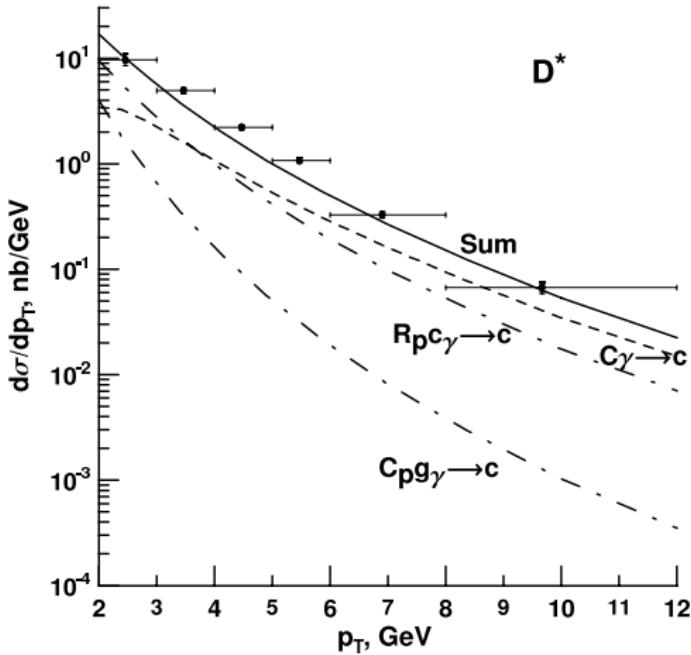
quark-gluon reggeization:
effective field theory in
the high-energy limit +
corrections beyond
collinear radiation

needs only tree diagrams

what about NLO ?

needed to

estimate theoretical uncer-
tainties and range of appli-
cability



PHOTON STRUCTURE EXCLUSIVE PROCESSES

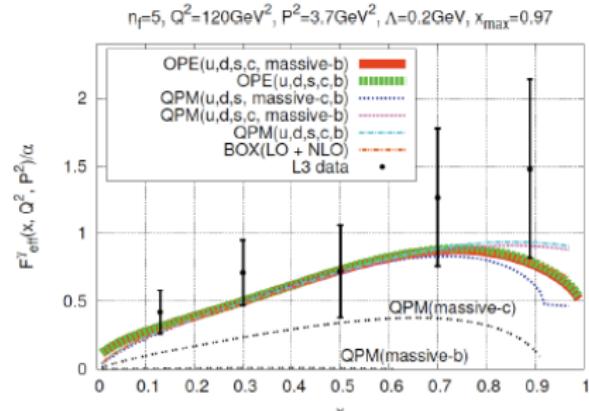
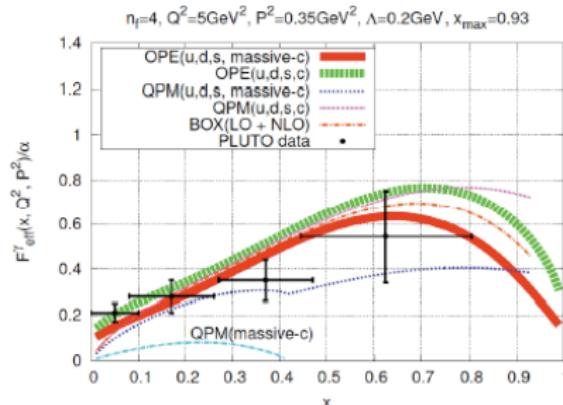
- Ken Sasaki: Virtual photon structure at NNLO QCD
- Dieter Müller: Theory of generalised parton densities and deeply virtual Compton scattering
- Jean-Philippe Lansberg: Backward DVCS and electroproduction of mesons
- Lech Szymanowski: Photon GPDs and diphoton GDAs
- Igor Anikin: Photon-photon collisions: Ambiguity and duality in QCD factorization theorem
- Florian Schwennsen: Looking for the Odderon in photon collisions
- Samuel Wallon: Theory of exclusive processes
- Wojtek Broniowski: Photon interactions and chiral dynamics

Heavy quark and target mass effects on the virtual photon in QCD

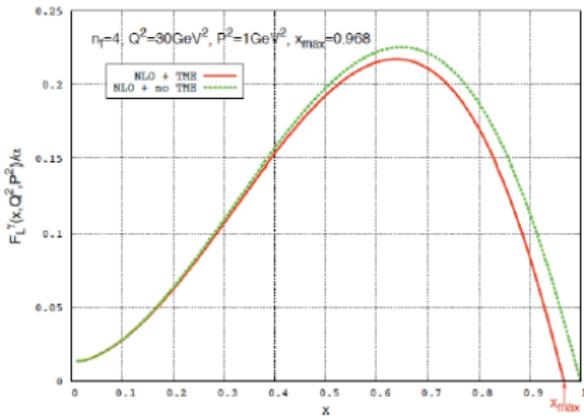
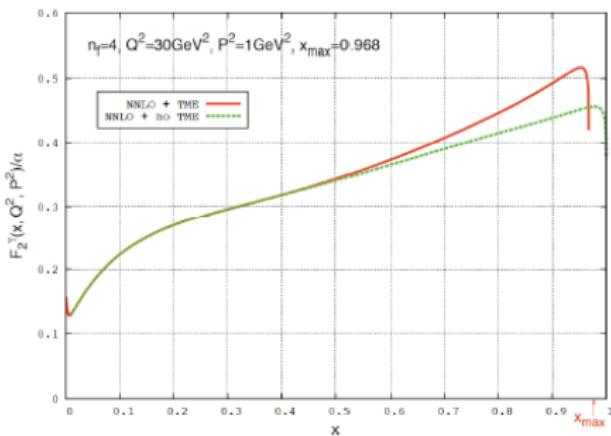
Ken Sasaki

- Heavy quark mass effects on the virtual photon structure functions were investigated in the framework of OPE and the mass-independent renormalization method up to NLO (α)
- Heavy quark mass effects appear in the photon matrix elements of the twist-2 quark & gluon operators and coefficient functions
- NLO QCD predictions for $F_{\text{eff}}^{\gamma}(x, Q^2, P^2)$ are compared with the exp. data of PLUTO & L3

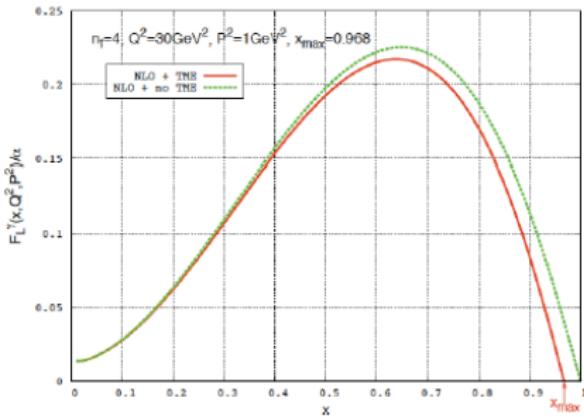
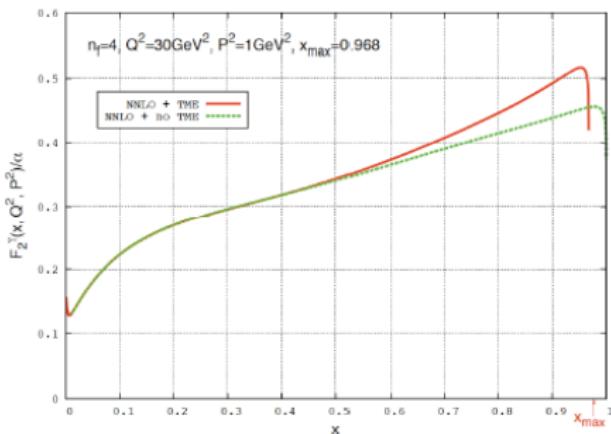
$$\Lambda^2 \ll P^2 \ll Q^2$$



- We also analyzed the target mass effects on the virtual photon structure functions up to NNLO ($\alpha\alpha_s$)



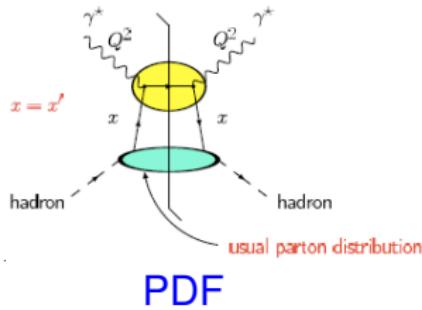
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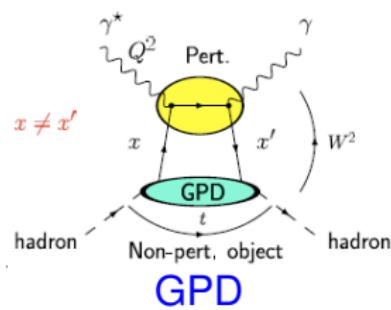
Factorization scheme →
fixed flavor number versus variable
flavor number: (S)ACOT χ ?

Hard exclusive processes: some basics about theory

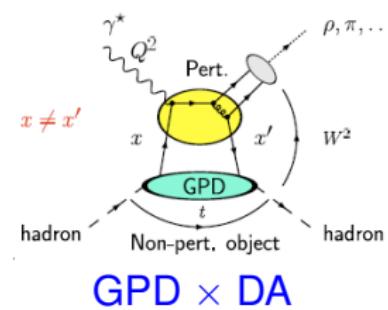
Samuel Wallon



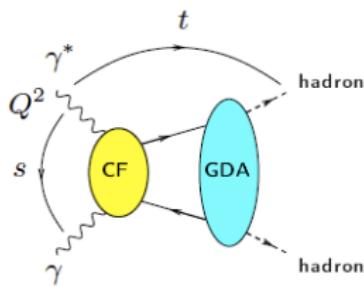
PDF



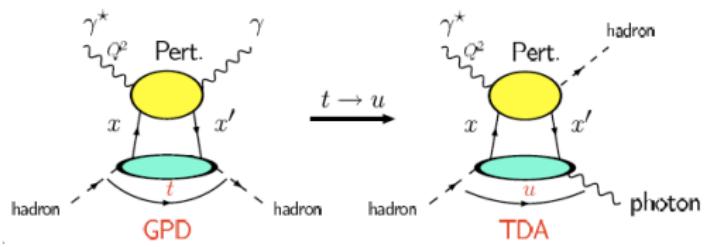
GPD



GPD \times DA



GDA



TDA

- since a decade, there have been much progress in the understanding of **hard** exclusive processes
 - at moderate energies, combined with GPD, **there is now a framework starting from first principle to describe a huge number of processes**
 - at high energy, **the impact representation** is a powerful tool for describing exclusive processes in diffractive experiments; they are and will be essential for studying QCD in the hard Regge limit (Pomeron, Odderon, saturation...)
- still, **some problems remains:**
 - proofs of factorization have been obtained only for a very few processes (ex.: $\gamma^* p \rightarrow \gamma p$, $\gamma_L^* p \rightarrow \rho_L p$, $\gamma^* p \rightarrow J/\Psi p$)
 - for some other processes factorization is highly plausible, but not fully demonstrated at any order (ex.: processes involving TDAs)
 - **some processes explicitly shows sign of breaking of factorization** (ex.: $\gamma_T^* p \rightarrow \rho_T p$ which has end-point singularities at Leading Order)
 - models and results from the lattice for the non-perturbative correlators entering GPDs, DAs, GDAs, TDAs are needed, even at a qualitative level!
 - the effect of QCD evolution and renormalization/factorization scale might be relevant with the increasing precision of data
- links between theoretical and experimental communities are very fruitful
- **message to experimentalists:** high luminosity e^+e^- machine like BaBar, BELLE, BEPC-II are gold places for exclusive processes studies in $\gamma^*\gamma^{(*)}$
⇒ it is time to realize this and to use the potential of these experiments!
We need your help!

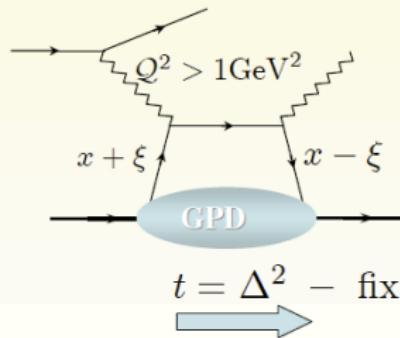
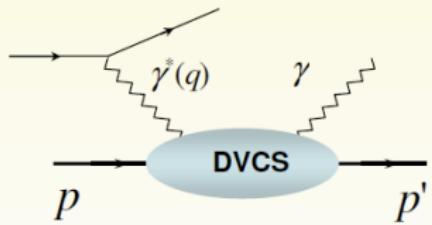
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Theory of generalized parton distributions and deeply virtual Compton scattering

Dieter Müller



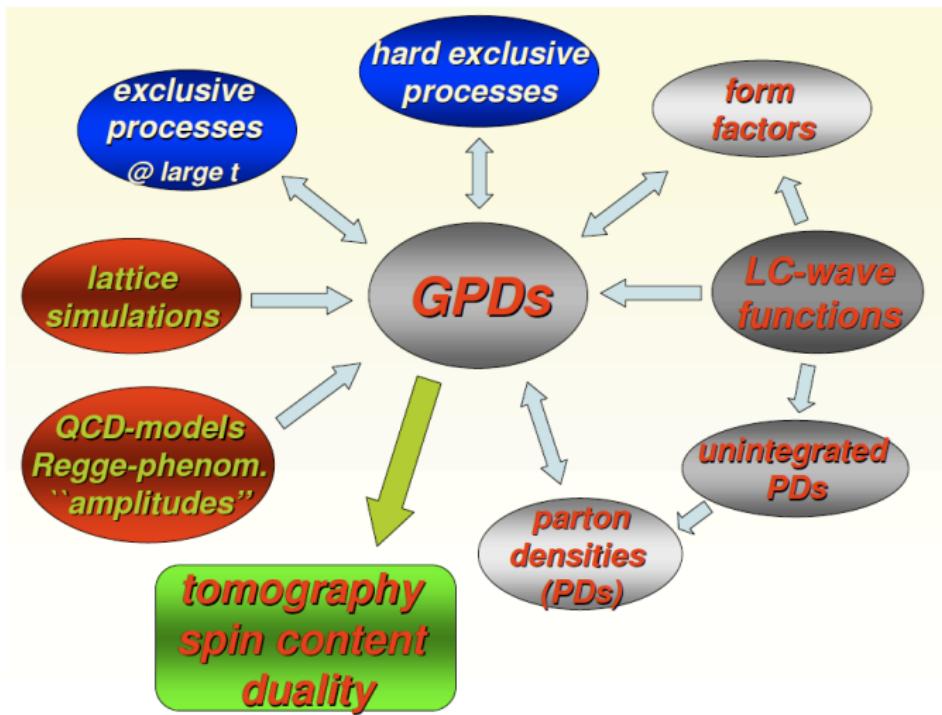
$$\mathcal{F}(\xi, Q^2, t) = \int_{-1}^1 dx C(x, \xi, \alpha_s(\mu), Q/\mu) F(x, \xi, t, \mu) + O(\frac{1}{Q^2})$$

CFF

hard scattering part

GPD

higher twist



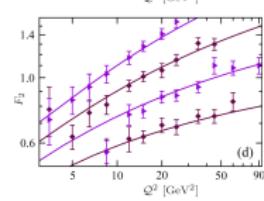
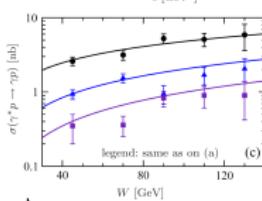
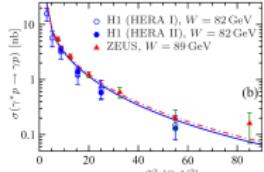
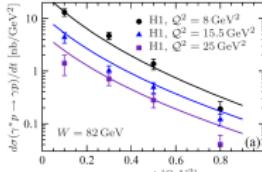
Strategies to analyze DVCS data

Dieter Müller

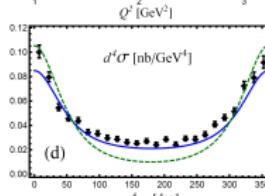
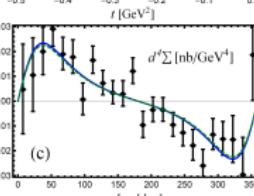
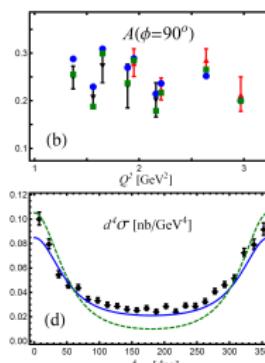
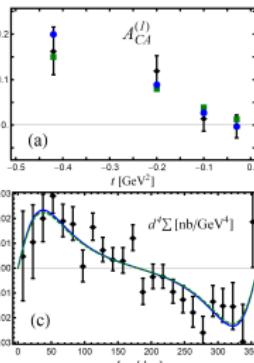
D. Mueller

K. Kumerički

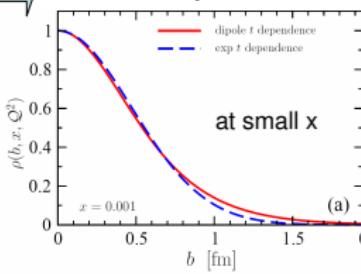
*fits to H1/ZEUS DVCS data
at LO, NLO, and NNLO*



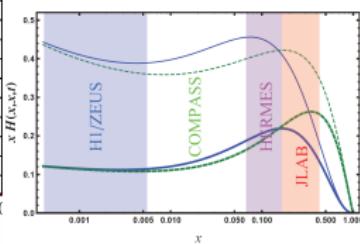
*dispersion relation fits to
HERMES and JLAB DVCS data*



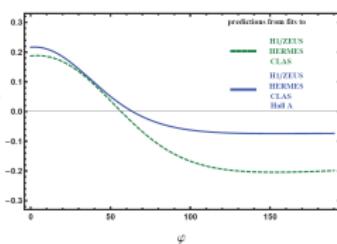
transverse parton distribution

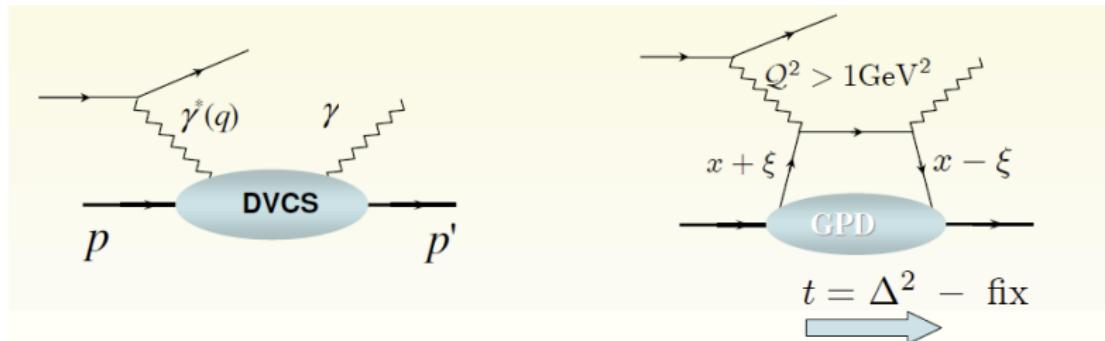


x-shape of GPD $H(x,x,t)$



prediction for COMPASS





$$\mathcal{F}(\xi, Q^2, t) = \int_{-1}^1 dx C(x, \xi, \alpha_s(\mu), Q/\mu) F(x, \xi, t, \mu) + O(\frac{1}{Q^2})$$

CFF

hard scattering part

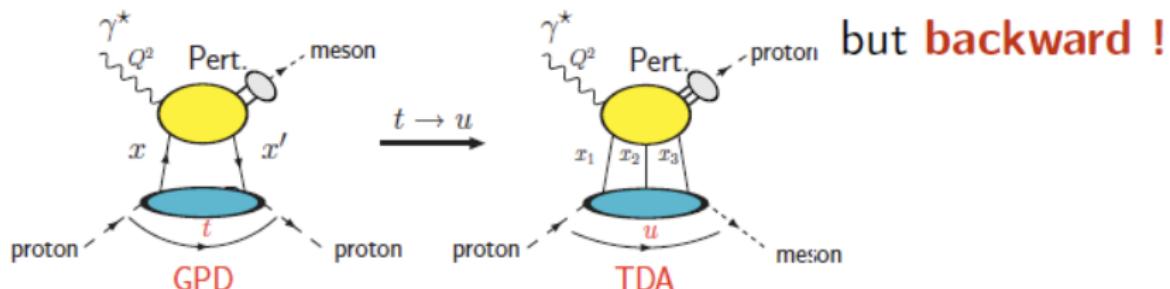
GPD

higher twist

→ exploit factorization scale dependence
to estimate theoretical uncertainties
and range of applicability

Backward Hard Exclusive Processes

Jean-Philippe Lansberg



Transition Distribution Amplitudes
→ 3-quark operator matrix element
→ relation to the proton wave function

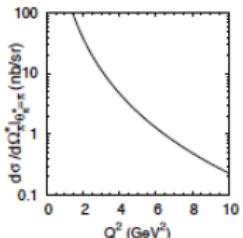
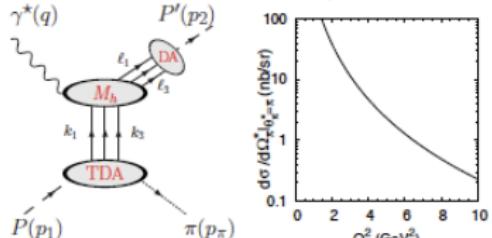
A Feynman diagram showing a proton p interacting with a meson system. The meson is represented by two black circles (quarks) and three horizontal lines (gluons). The outgoing meson is labeled p' . Below the diagram is an equation: $p \rightarrow \text{meson} = p \rightarrow \text{meson} \times \left[\begin{array}{c} \text{meson} \\ p' \end{array} \right]^*$.

Interpretation at the amplitude level

(for $x_i > 0$)

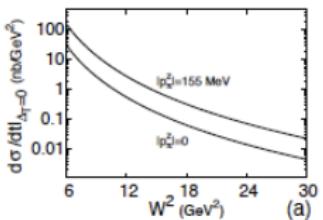
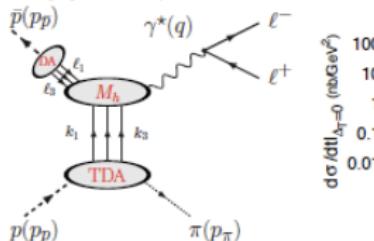
Amplitude of probability to find a meson within the proton !

→ Backward Electroproduction of π : Data from JLab exist: analysis on-going



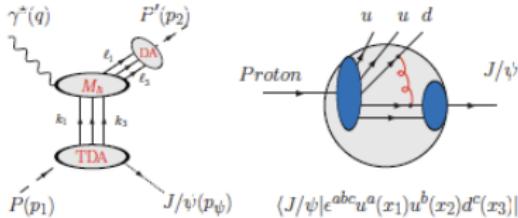
JPL, B. Pire, L. Szymanowski, PRD 75:074004, 2007

→ $\bar{p}p \rightarrow \gamma^*(Q^2)\pi^0 \rightarrow \ell^+\ell^-\pi^0$ at GSI/FAIR (Analysis planned by PANDA)



JPL, B. Pire, L. Szymanowski PRD76 :111502(R), 2007
Physics Perf. Rep. for PANDA, 0903.3905 [hep-ex]

→ Dedicated test of Intrinsic Charm: $\gamma^* p \rightarrow p J/\Psi$ (at COMPASS ?)



S.J. Brodsky, JPL, work in progress

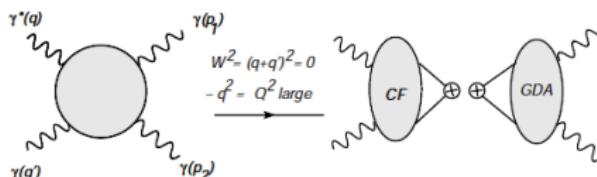
Revealing of the ANOMALOUS structure of γ in EXCLUSIVE processes

DIS study by Witten 77' extended for the exclusive case

Derivation of the **diphoton anomalous generalized distribution amplitudes (GDAs)**

$$\text{e.g. } \Phi_1^q(z, \zeta, 0) = \frac{N_C e_q^2}{2\pi^2} \log \frac{Q^2}{m^2}$$

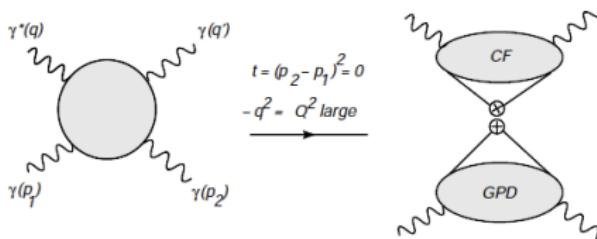
$$\left[\frac{\bar{z}(2z - \zeta)}{\bar{\zeta}} \theta(z - \zeta) + \frac{\bar{z}(2z - \bar{\zeta})}{\zeta} \theta(z - \bar{\zeta}) + \frac{z(2z - 1 - \zeta)}{\zeta} \theta(\zeta - z) + \frac{z(2z - 1 - \bar{\zeta})}{\bar{\zeta}} \theta(\bar{\zeta} - z) \right]$$



Derivation of the **anomalous generalized parton distributions (GPDs) in a photon**

$$\text{e.g. } H_1^q(x, \xi, 0) = \frac{N_C e_q^2}{4\pi^2} \ln \frac{Q^2}{m^2}$$

$$\left[\theta(x - \xi) \frac{x^2 + (1 - x)^2 - \xi^2}{1 - \xi^2} + \theta(\xi - x) \theta(\xi + x) \frac{x(1 - \xi)}{\xi(1 + \xi)} - \theta(-x - \xi) \frac{x^2 + (1 + x)^2 - \xi^2}{1 - \xi^2} \right]$$



Refs.: Phys.Lett.B645,153,2007 and Phys. Rev. D78, 034009 (2008)

Lech Szymanowski

Conclusions for φ_E^3 -model (I.V. Anikin et al arXiv:0806.4551[hep-ph])

Regime (a)[small "s"] and (b)[small "t"]:

NO Ambiguity in Factorization.

Regime (c)[small "s" and "t"]

Option 1: NO Factorization \Rightarrow

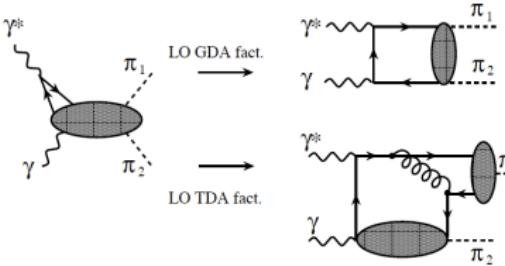
$$\tilde{\mathcal{A}} \approx (\beta_1 - \text{wing}) \oplus (\beta_2 - \text{wing}) \equiv \text{"ADDITIVITY"}$$

Option 2: Factorization \Rightarrow

$$\tilde{\mathcal{A}} \approx \text{either } \tilde{\mathcal{A}}_{GDA}^{as} \text{ or } \tilde{\mathcal{A}}_{TDA}^{as} \equiv \text{"DUALITY"}$$

Igor Anikin

QCD factorization in $\gamma^*\gamma$ collisions: duality between GDA and TDA
in the Euclidean



Igor Anikin

Thus, duality in QCD we observed means that

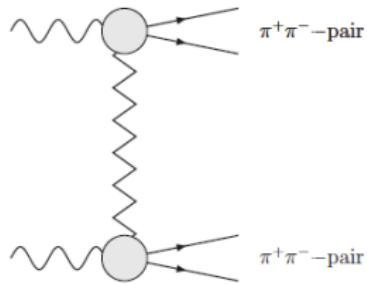
$$\mathcal{A}_{(0,+)}^{\text{TDA}} = \frac{\varepsilon'^{(+)} \cdot \Delta^T}{Q} [4\pi \alpha_s(Q^2)] \left(\text{tw}-2 \text{ DA} \right) \left(\text{tw}-2 \text{ TDA} \right),$$

and

$$\mathcal{A}_{(0,+)}^{\text{GDA}} = \frac{\varepsilon'^{(+)} \cdot \Delta^T}{Q} \left(\text{tw}-3 \text{ GDA} \right),$$

are equivalent each other.

The Process

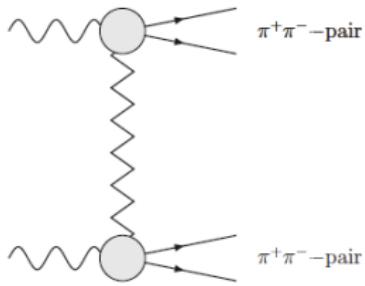


- exclusive production of two $\pi^+\pi^-$ pairs → colorless exchange between them
- C-parity of $\pi^+\pi^-$ pair not fixed
 - $\pi^+\pi^-$ pair C odd \Rightarrow Pomeron
 - $\pi^+\pi^-$ pair C even \Rightarrow Odderon
- 2π GDA depends on polar angle θ in rest frame of 2π

$$\frac{\int \cos \theta_1 \cos \theta_2 d\sigma(s, t, m_{2\pi,1}, m_{2\pi,1}, \theta_1, \theta_2)}{\int d\sigma(s, t, m_{2\pi,1}, m_{2\pi,1}, \theta_1, \theta_2)} \sim \frac{|\mathcal{M}_0 \mathcal{M}_P|}{|\mathcal{M}_P|^2 + |\mathcal{M}_0|^2}$$

Florian Schwennsen

The Process



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used three models
for 2π GDA

$$\frac{\int \cos \theta_1 \cos \theta_2 d\sigma(s, t, m_{2\pi,1}, m_{2\pi,1}, \theta_1, \theta_2)}{\int d\sigma(s, t, m_{2\pi,1}, m_{2\pi,1}, \theta_1, \theta_2)} \sim \frac{|\mathcal{M}_0 \mathcal{M}_P|}{|\mathcal{M}_P|^2 + |\mathcal{M}_0|^2}$$

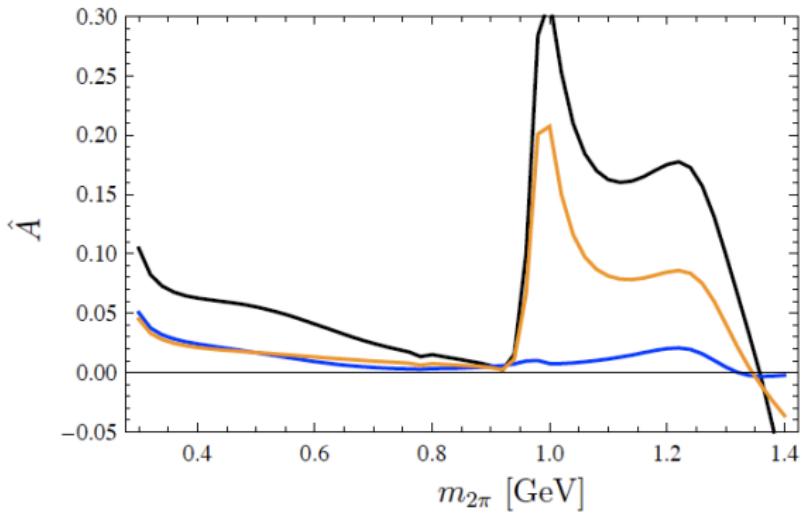
Florian Schwennsen

Single Differential at $t = -2\text{GeV}^2$

Integrate asymmetry for one $\pi^+\pi^-$ pair from .3GeV to
 $m_\rho=776\text{MeV}$

Florian Schwennsen

ansatz I, ansatz II, ansatz III for isoscalar GDA

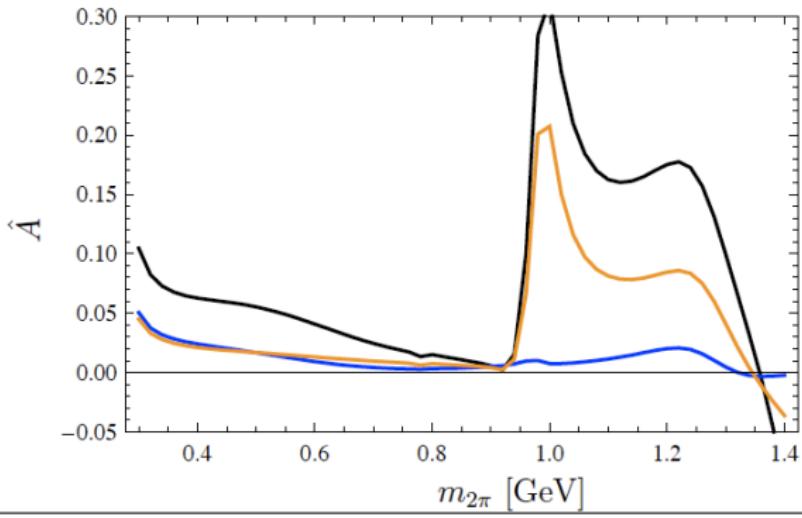


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Florian Schwennsen

ansatz I, ansatz II, ansatz III for isoscalar GDA



Asymmetry a promising candidate to find the perturbative Odderon

- ➊ Chiral quark models provide a link between high- and low-energy analyses
- ➋ Numerous predictions for soft matrix element involving the Goldstone bosons and photons
- ➌ They yield in a **fully dynamical** way the initial conditions for the QCD evolution, which is **essential** to bring the predictions to experimental/lattice scales
- ➍ Scale in chiral quark models is very low, 300-500 MeV, QCD evolution “fast”
- ➎ Simple analytic formulas – useful to understand general properties, (e.g., no factorization of the t -dependence)
- ➏ For the pion, with the LO QCD evolution the overall agreement with the available data and lattice simulations is **very reasonable** (PDF, DA, generalized form factors, GPD, TDA, . . .)
- ➐ Predictions can be further tested with future lattice simulations also for the photon/ ρ

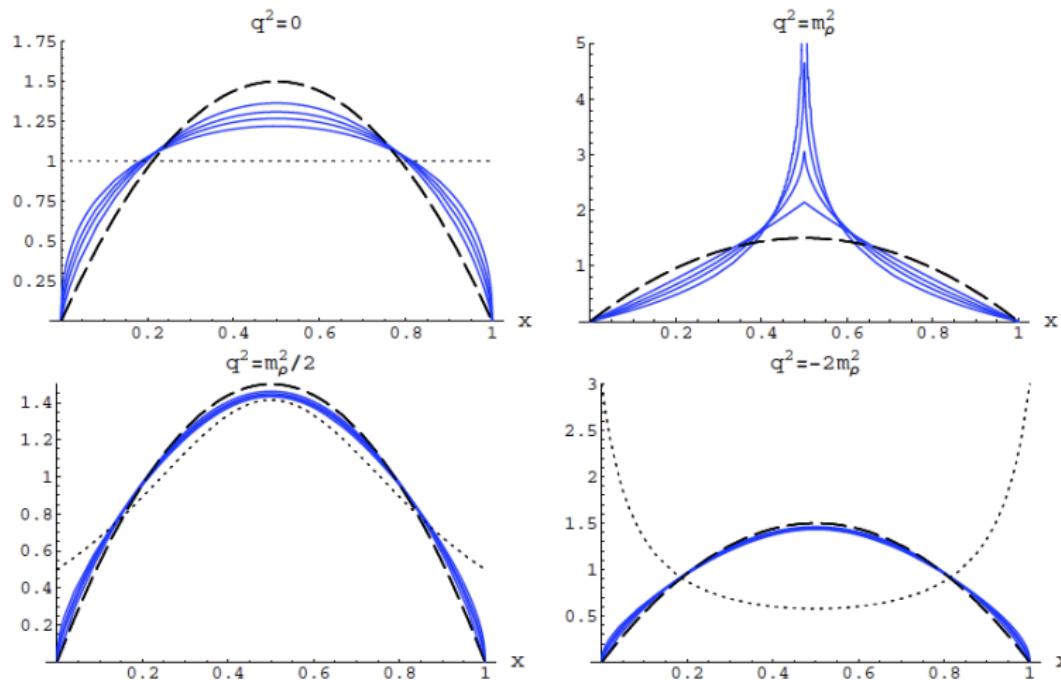
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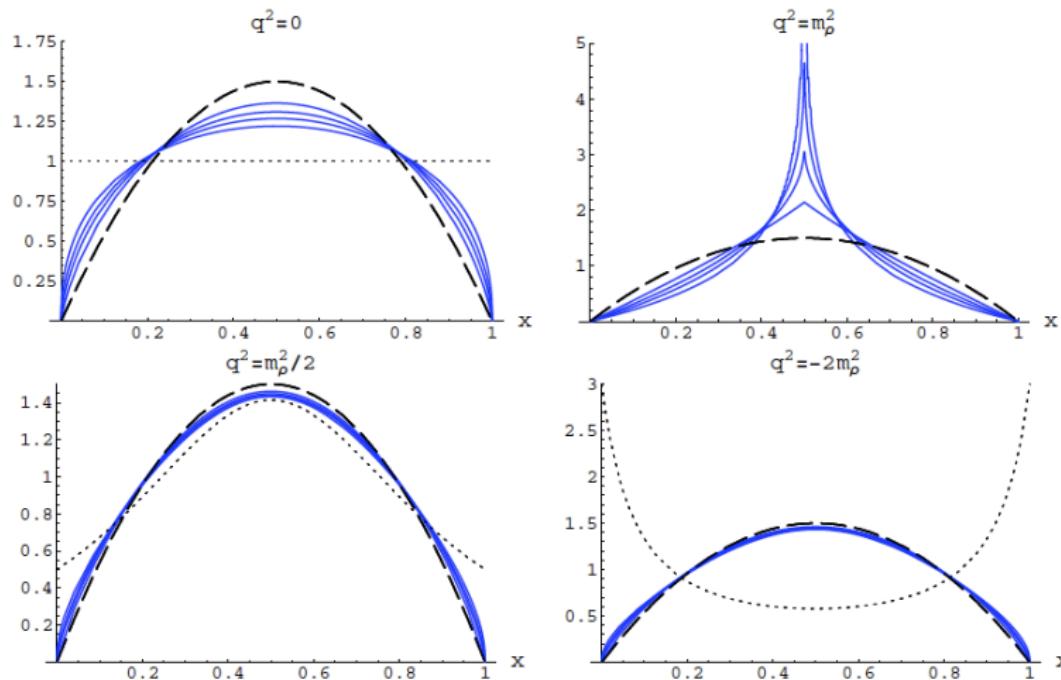
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LO ERBL for the tensor DA



Initial conditions (dots) from the Spectral Quark Model. Solid lines: LO QCD evolution to scales 1, 2.4, 10, and 1000 GeV, asymptotic form $6x(1-x)$:
dashed line

Wojciech Broniowski



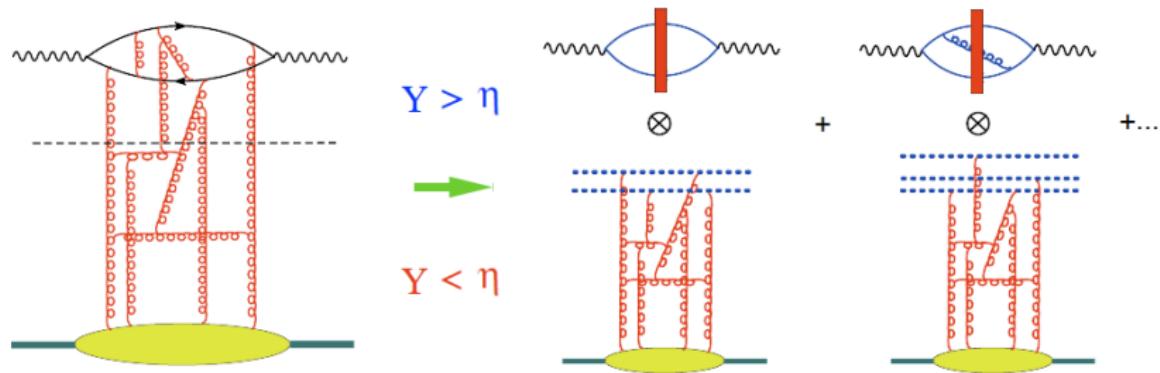
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... BACK TO INCLUSIVE CROSS SECTIONS

- [Giovanni Chirilli](#): Next-to-leading order evolution of color dipoles in QCD and in $N = 4$ Super Yang-Mills theory
- [Francesco Hautmann](#): Angular correlations in jet production and applications to jets in the forward region at the LHC
- [Edmond Iancu](#): Photon interactions from weak to strong coupling

Expansion of $F_2(x)$ in color dipoles in the next-to-leading order



$$F_2(x_B) \simeq \int d^2 z_1 d^2 z_2 I_0(z_1, z_2) \langle \text{tr}\{U_{z_1}^\eta U_{z_2}^{\dagger\eta}\} \rangle$$

$$\eta = \ln \frac{1}{x_B}$$

$$+ \frac{\alpha_s}{\pi} \int d^2 z_1 d^2 z_2 d^2 z_3 I_1(z_1, z_2, z_3) \langle \text{tr}\{U_{z_1}^\eta U_{z_3}^{\dagger\eta}\} \text{tr}\{U_{z_3} U_{z_2}^{\dagger\eta}\} \rangle$$

Evolution of the color dipole $\text{tr}\{U_{z_1}^\eta U_{z_2}^{\dagger\eta}\}$: I. Balitsky and G.A.C., 2006-09

$$\frac{d}{d\eta} \{U_{z_1}^\eta U_{z_2}^{\dagger\eta}\} = K_{\text{BK}} \{U_{z_1}^\eta U_{z_2}^{\dagger\eta}\} + K_{\text{NLO BK}} \{U_{z_1}^\eta U_{z_2}^{\dagger\eta}\}$$

NLO “Impact factor” I_1 - work in progress

Giovanni Chirilli

NLO evolution of color dipoles in QCD

$$\begin{aligned}
 \frac{d}{d\eta} \text{tr}\{U_{z_1} U_{z_2}^\dagger\}^{\text{conf}} &= \frac{\alpha_s}{2\pi^2} \int d^2 z_3 \left([\text{tr}\{U_{z_1} U_{z_3}^\dagger\} \text{tr}\{U_{z_3} U_{z_2}^\dagger\} - N_c \text{tr}\{U_{z_1} U_{z_2}^\dagger\}] \right. \\
 &\times \frac{z_{12}^2}{z_{13}^2 z_{23}^2} \left[1 + \frac{\alpha_s N_c}{4\pi} (b \ln z_{12}^2 \mu^2 + b \frac{z_{13}^2 - z_{23}^2}{z_{13}^2 z_{23}^2} \ln \frac{z_{13}^2}{z_{23}^2} + \frac{67}{9} - \frac{\pi^2}{3}) \right] \quad b = \frac{11}{3} N_c - \frac{2}{3} n_f \\
 &+ \frac{\alpha_s}{8\pi^2} \int \frac{d^2 z_4}{z_{34}^4} \left\{ \left[-2 + \frac{z_{14}^2 z_{23}^2 + z_{24}^2 z_{13}^2 - 4z_{12}^2 z_{34}^2}{2(z_{14}^2 z_{23}^2 - z_{24}^2 z_{13}^2)} \ln \frac{z_{14}^2 z_{23}^2}{z_{24}^2 z_{13}^2} \right] \right. \\
 &\times [\text{tr}\{U_{z_1} U_{z_3}^\dagger\} \text{tr}\{U_{z_3} U_{z_4}^\dagger\} \text{tr}\{U_{z_4} U_{z_2}^\dagger\} - \text{tr}\{U_{z_1} U_{z_3}^\dagger U_{z_4} U_{z_2}^\dagger U_{z_3} U_{z_4}^\dagger\} - (z_4 \rightarrow z_3)] \\
 &+ \frac{z_{12}^2 z_{34}^2}{z_{13}^2 z_{24}^2} \left[2 \ln \frac{z_{12}^2 z_{34}^2}{z_{14}^2 z_{23}^2} + \left(1 + \frac{z_{12}^2 z_{34}^2}{z_{13}^2 z_{24}^2 - z_{14}^2 z_{23}^2} \right) \ln \frac{z_{13}^2 z_{24}^2}{z_{14}^2 z_{23}^2} \right] \\
 &\times [\text{tr}\{U_{z_1} U_{z_3}^\dagger\} \text{tr}\{U_{z_3} U_{z_4}^\dagger\} \text{tr}\{U_{z_4} U_{z_2}^\dagger\} - \text{tr}\{U_{z_1} U_{z_4}^\dagger U_{z_3} U_{z_2}^\dagger U_{z_4} U_{z_3}^\dagger\} - (z_4 \rightarrow z_3)] \left. \right\}
 \end{aligned}$$

$\text{tr}\{U_{z_1} U_{z_2}^\dagger\}^{\text{conf}}$ \equiv conformal composite dipole operator

$$= \text{tr}\{U_{z_1} U_{z_2}^\dagger\} + \frac{\alpha_s}{4\pi^2} \int d^2 z_3 [\text{tr}\{U_{z_1} U_{z_3}^\dagger\} \text{tr}\{U_{z_3} U_{z_2}^\dagger\} - N_c \text{tr}\{U_{z_1} U_{z_2}^\dagger\}] \frac{z_{12}^2}{z_{13}^2 z_{23}^2} \ln \frac{az_{12}^2}{z_{13}^2 z_{23}^2}$$

$K_{\text{NLO BK}} = \text{Running coupling part} + \text{Conformal "non-analytic" (in } j \text{) part}$ $+ \text{Conformal analytic } (\mathcal{N} = 4 \text{ SYM) part}$
--

Linearized $K_{\text{NLO BK}}$ agrees with the forward NLO BFKL kernel.

Giovanni Chirilli

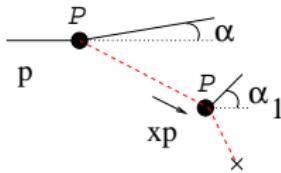
K_⊥-DEPENDENT PARTON BRANCHING

- implement all-order summation of $(\alpha_S \ln s/p_T^2) \oplus$ IR $x \rightarrow 1$ behavior

- branching eq. : $\mathcal{A}(x, k_T, \mu) = \mathcal{A}_0(x, k_T, \mu) + \int \frac{dz}{z} \int \frac{dq^2}{q^2} \Theta(\mu - zq)$

$\times \underbrace{\Delta(\mu, zq)}_{\text{Sudakov}} \underbrace{\mathcal{P}(z, q, k_T)}_{\text{uninteg. splitting}} \mathcal{A}\left(\frac{x}{z}, k_T + (1-z)q, q\right)$

include effects of coherent gluon radiation at small x

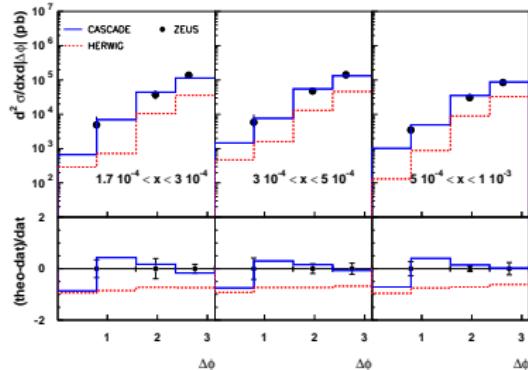
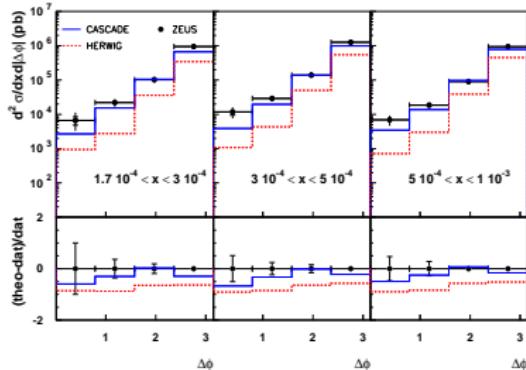


$$, \quad \frac{P}{\sqrt{x}} = \text{---} \swarrow \text{---} + \text{---} \nwarrow \text{---} + ..$$

(left) Coherent radiation in the space-like parton shower for $x \ll 1$;
 (right) the unintegrated splitting function \mathcal{P} , including small- x virtual corrections.

$$\alpha/x > \alpha_1 > \alpha \quad (\text{small } -x \text{ coherence region})$$

ANGULAR JET CORRELATIONS FROM K_⊥-SHOWER (CASCADE) AND COLLINEAR-SHOWER (HERWIG)



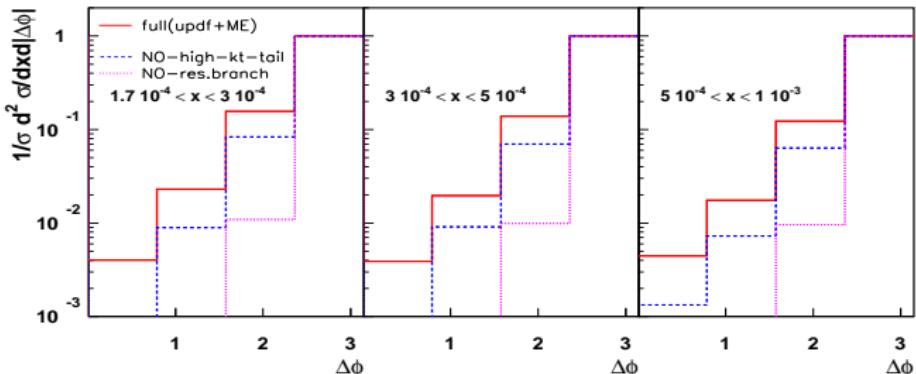
$\Delta\phi$ distribution
ZEUS data

(left) di-jet cross section; (right) three-jet cross section

Jung & H, arXiv:0805.1049 [hep-ph]

- largest differences at small $\Delta\phi$
- good description of measurement by k_{\perp} -shower
- collinear shower insufficient to describe shapes

Normalize to the back-to-back cross section:



collinear branchings only

— updf \oplus ME

- - - updf \oplus ME_{collin.} : $\mathcal{M} \rightarrow \mathcal{M}_{collin.}(k_T) = \mathcal{M}(0_\perp) \Theta(\mu - k_T)$

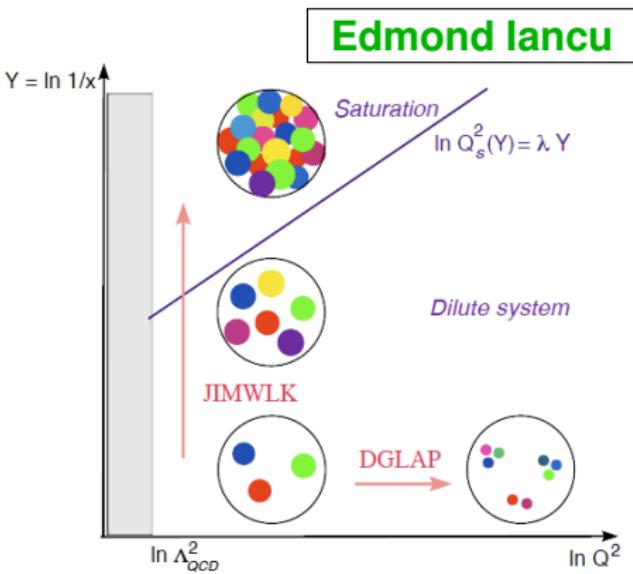
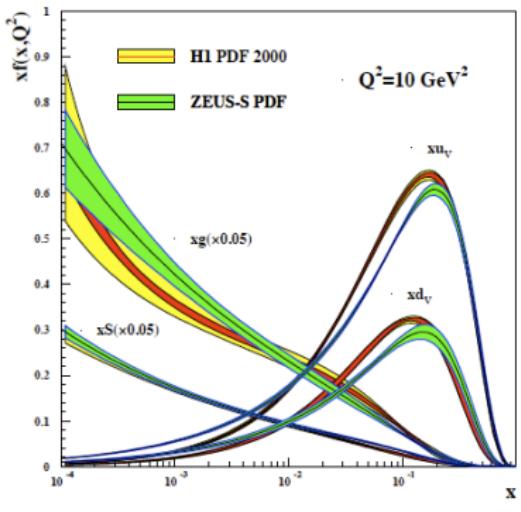
..... no resolved branching : $\mathcal{A} \rightarrow \mathcal{A}_{no-res.}(x, k_T, \mu) = \mathcal{A}_0(x, k_T, Q_0) \Delta(\mu, Q_0)$

i.e. intrinsic k_T only

▷ high- k_\perp , coherent effect essential for correlation at small $\Delta\phi$

(cfr., e.g., MC by Höche, Krauss & Teubner, arXiv:0705.4577:
u-pdf but no ME correction)

Gluon saturation at weak coupling

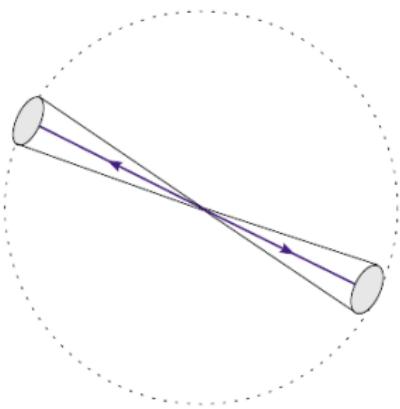


High-energy evolution \implies increasing gluon density

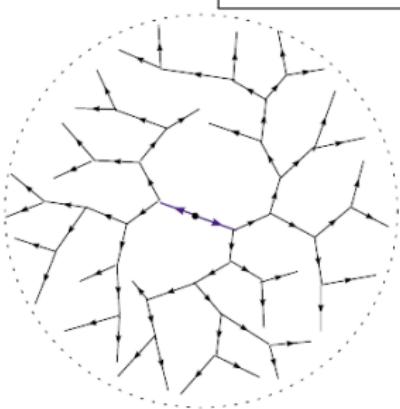
- Evolution equation in pQCD: **JIMWLK** (BFKL + saturation)
- Hard saturation scale: $Q_s^2(x) \propto 1/x^\lambda$ with $\lambda \simeq 0.25$

No jets at strong coupling !

Edmond Iancu



weak coupling



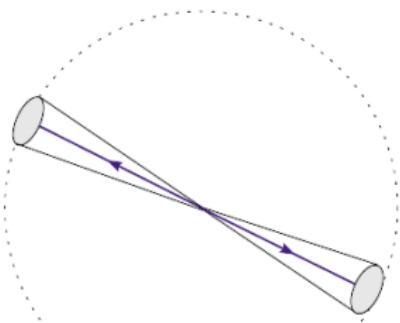
strong coupling

Gauge-string duality \Rightarrow rapid evolution via parton branching

- No jets in e^+e^- annihilation at strong coupling
- No large- x partons in the hadron wavefunction
- Saturation momentum increases much faster: $Q_s^2(x) \propto 1/x$

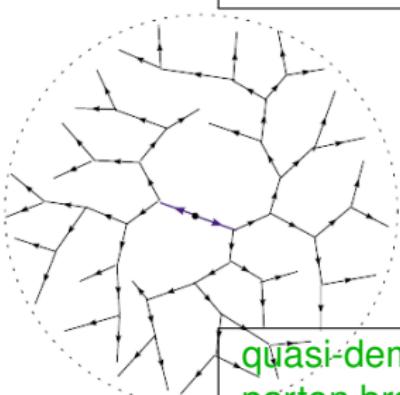
No jets at strong coupling !

Edmond Iancu



radiation suppressed
by g

weak coupling



quasi-democratic
parton branching

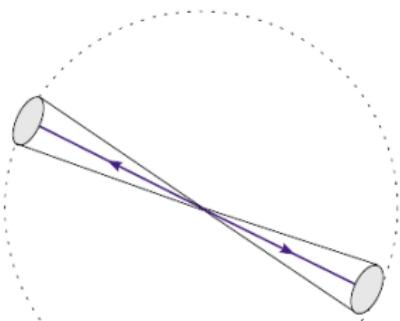
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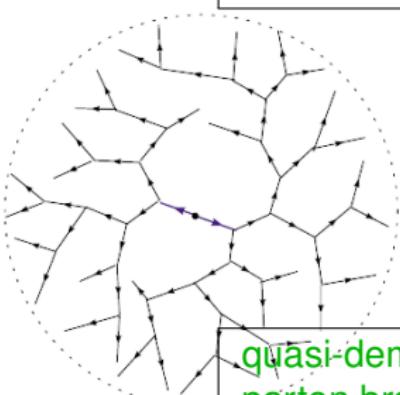
Edmond Iancu



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$\mathcal{N} = 4$ SYM

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VACUUM POLARISATION AND LIGHT-BY-LIGHT SCATTERING

- Gerco Onderwater: Measurement of g-2 including future projects
- Gabriel Lopez Castro: $g - 2$ predictions
- Joaquim Prades: Light-by-light scattering

Measurement of Muon Dipole Moments

Past and Future of $g-2$ Measurements

Storage ring results

Gerco Onderwater

	Year	a_μ	σa_μ	Ref.
QED	1961	0.001145	0.000022	Charpak
	1965	0.001162	0.000005	Charpak
	1966	0.001165	0.000003	Farley
QCD	1969	0.001060	0.000067	Henry
	1972	0.00116616	0.00000031	Bailey
	1975	0.001165895	0.000000027	Bailey
	1979	0.001165910	0.000000012	Bailey
	1979	0.001165936	0.000000012	Bailey
QFD	1999	0.001165925	0.000000015	Carey
	2000	0.0011659191	0.0000000059	Brown
	2001	0.0011659202	0.0000000015	Brown
	2002	0.0011659204	0.0000000009	Bennett
	2004	0.0011659214	0.0000000009	Bennett
new?		$a_\mu(\text{expt.}) - a_\mu(\text{th}) = (30 \pm 8) \times 10^{-10} (3.6\sigma)$		

CERN

BNL

Experiment: $\sigma_a/a = 0.54 \text{ ppm}$
Theory: $\sigma_a/a = 0.44 \text{ ppm}$

muon $g - 2$

Summary of SM contributions and experiment

Contrib.	$10^{11} \times a_\mu$
<i>QED</i>	$116584718.09 \pm 0.14 \pm 0.04$
<i>EW</i>	$154 \pm 2 \pm 1$
<i>had, HO</i>	-98 ± 1
<i>had, $l \times l$</i>	105 ± 26
$a_\mu^{\text{exp}} - a_\mu^{\text{previous}}$	$7564 \pm 26 \pm 63$
<i>BNL - E821</i>	116592080 ± 63

Recent evaluations of had. (LO & $l \times l$).

- Discrepancy $> 3\sigma$ confirmed,
- Theory uncertainty dominated by LO hadronic contribs.

Calcul.	$a_\mu^{\text{had,LO}}$	a_μ^{SM}	$a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$
<i>DEHZ - 03</i>	6963 ± 72	116591842 ± 77	$238 \pm 99 [3.4\sigma]$
<i>HMNT - 03</i>	6961 ± 62	116591840 ± 67	$240 \pm 92 [2.6\sigma]$
<i>DEHZ - 06</i>	6909 ± 44	116591788 ± 51	$292 \pm 81 [3.6\sigma]$
<i>HMNT - 06</i>	6894 ± 46	116591773 ± 53	$307 \pm 82 [3.7\sigma]$
<i>J - 08</i>	6923 ± 60	116591802 ± 65	$278 \pm 90 [3.1\sigma]$
<i>DH....YZ09</i>	6884 ± 45	116591763 ± 53	$317 \pm 82 [3.9\sigma]$

Lattice 6670 ± 200 (T. Blum, TAU08):

muon $g - 2$

Summary of SM contributions and experiment

many new data,
KLOE: 2π

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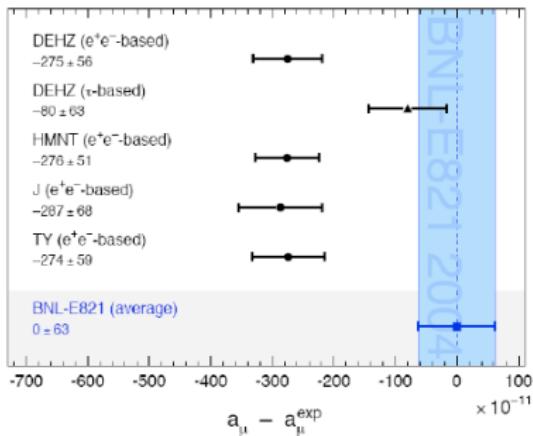
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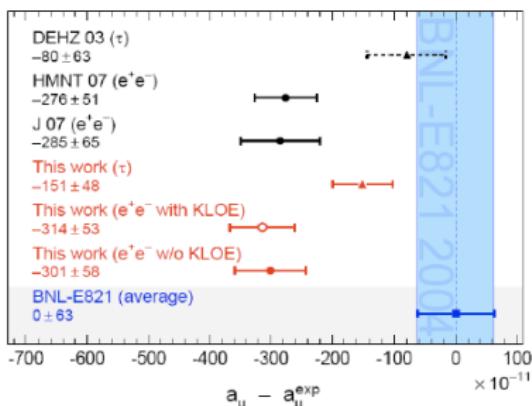
Comparison of SM predictions based on e^+e^- and τ lepton data

DHLMMTWYZ (09)

Previous to 2008



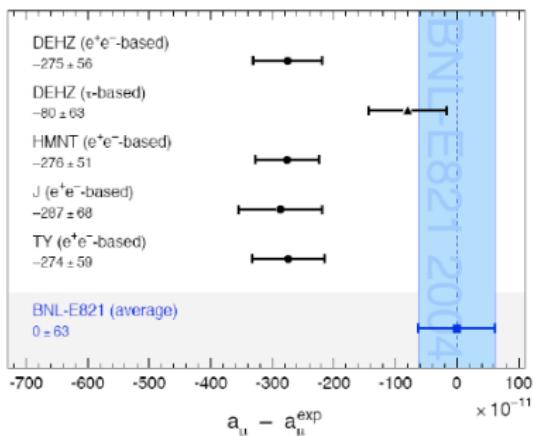
With Belle, KLOE & new IB corrections



- Discrepancy e^+e^- & τ reduced, but persists...
- For first time τ -based prediction does not overlap with E821

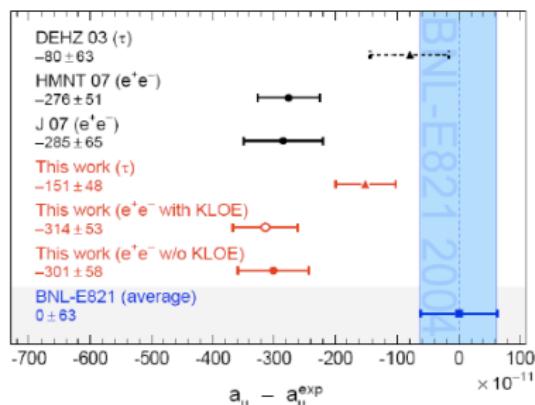
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Previous to 2008



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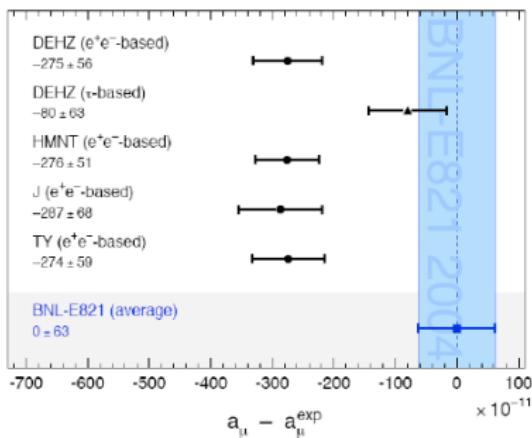
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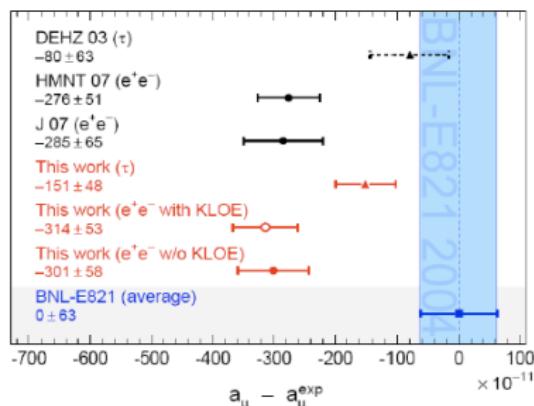
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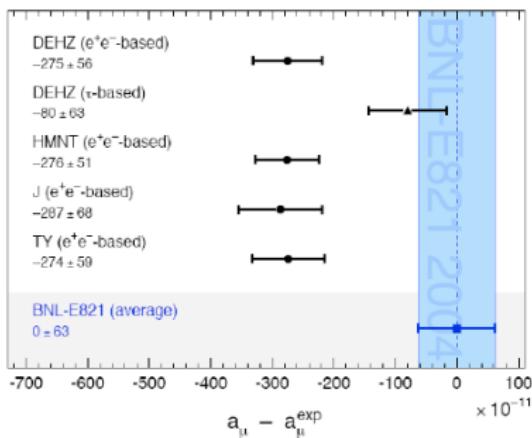
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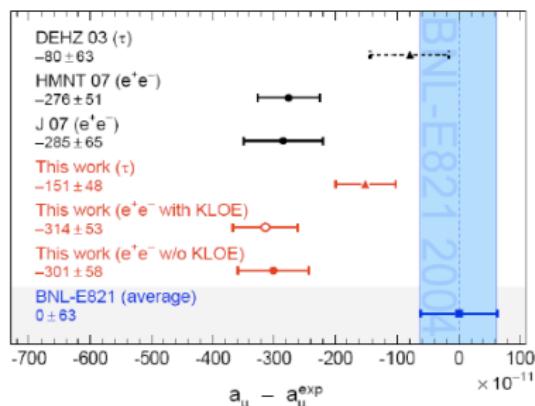
- Discrepancy e^+e^- & tau reduced, but persists...
- For first time τ -based prediction does not overlap with E821
- larger $a_\mu^{\text{had}, LO}$ would cause tension with Higgs mass limits

Comparison of SM predictions based on e^+e^- and τ lepton data

Previous to 2008



With Belle, KLOE & new IB corrections



- Discrepancy e^+e^- & τ reduced, but persists...
- For first time τ -based prediction does not overlap with E821

soon to come: more data from BaBar ISR

LIGHT-BY-LIGHT SCATTERING

Joaquim Prades

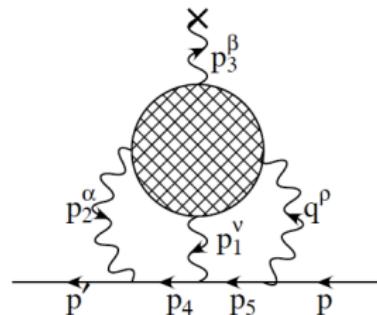
a dominating uncertainty in

$$a_\mu = (g - 2)_\mu$$

$$\Delta a_\mu^{had, LO} = \pm 53 \times 10^{-11},$$

$$a_\mu^{exp} - a_\mu^{th} = (290 \pm 90) \times 10^{-11}$$

exp. goal: 15×10^{-11}



$$\begin{aligned} \mathcal{M} = & |e|^7 A_\beta \int \frac{d^4 p_1}{(2\pi)^4} \int \frac{d^4 p_2}{(2\pi)^4} \frac{1}{q^2 p_1^2 p_2^2 (p_4^2 - m^2) (p_5^2 - m^2)} \\ & \times \underline{\Pi^{\rho\nu\alpha\beta}(p_1, p_2, p_3)} \bar{u}(p') \gamma_\alpha (\not{p}_4 + m) \gamma_\nu (\not{p}_5 + m) \gamma_\rho u(p) \end{aligned}$$

LIGHT-BY-LIGHT SCATTERING

Joaquim Prades

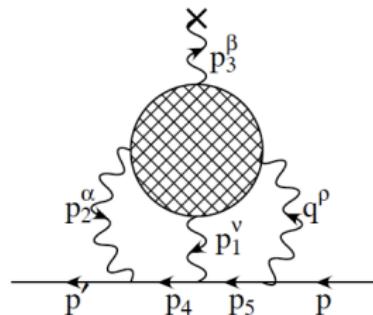
a dominating uncertainty in

$$a_\mu = (g - 2)_\mu$$

$$\Delta a_\mu^{had, LO} = \pm 53 \times 10^{-11},$$

$$a_\mu^{exp} - a_\mu^{th} = (290 \pm 90) \times 10^{-11}$$

exp. goal: 15×10^{-11}



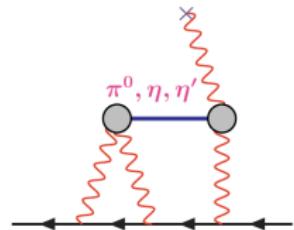
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need $\langle 0 | T V^\rho(0) V^\nu(x) V^\alpha(y) V^\beta(z) | 0 \rangle$

no full first-principle calculation available → lattice ?

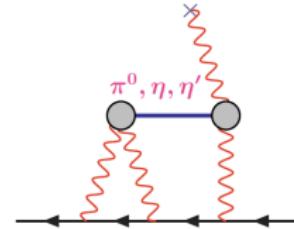
LIGHT-BY-LIGHT SCATTERING

- low-energy and OPE limits
- quark loops
- large- N_c
- chiral perturbation theory:
pseudo-scalar exchange (dominant) +
pseudo-vector + scalar



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Comparison

BPP vs MV:

Full	$10^{10} \times a_\mu$
BPP	8.3 ± 3.2
MV	13.6 ± 2.5

Several order $1.5 \cdot 10^{-10}$ differences,
in addition to new OPE effects •

$$\begin{aligned}& -1.5 \cdot 10^{-10} \text{ (Different pseudo-vector mass mixing)} \\& -0.7 \cdot 10^{-10} \text{ (No scalar exchange)} \\& -1.9 \cdot 10^{-10} \text{ (No pion+kaon loop)} \\& = \underline{-4.1 \cdot 10^{-10}} \bullet\end{aligned}$$

Final [BPP-MV] difference: $\underline{-5.3 \cdot 10^{-10}}$ •

Bijnens, Pallante, Prades
Melnikov, Vainshtein

other calculations by

Hayakawa, Kinoshita, Sanda
Knecht, Nyffeler; Perrottet, de Rafael
and more recent:

Prades, de Rafael, Vainshtein
Nyffeler

LIGHT-BY-LIGHT SCATTERING

Conclusions Prospects

Adding effects beyond leading order in $1/N_c$, in a conservative analysis, J.P. E. de Rafael and A. Vainshtein

π^0 , η and η' exchanges : $(11.4 \pm 1.3) \times 10^{-10}$

Scalar exchange : $-(0.7 \pm 0.7) \times 10^{-10}$

Axial-vector exchange : $(1.5 \pm 1.0) \times 10^{-10}$

Pion and kaon loops: $-(1.9 \pm 1.9) \times 10^{-10}$

Charm quark loop: 0.23×10^{-10}

$$\star a_\mu^{\text{lbl}} = (10.5 \pm 2.6) \times 10^{-10}$$

LIGHT-BY-LIGHT SCATTERING

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More work needed to have hadronic light-by-light contribution with a precision corresponding to the experimental goal

A new full calculation is desirable and possible

PHOTONS IN ASTROPARTICLE PHYSICS

- Christopher van Eldik: Very high energy (TeV) gamma rays: HESS, MAGIC, ...
- Jan Conrad: High energy gamma rays and cosmic rays: PAMELA, GLAST (FGST), AMS, ...
- Alejandro Ibarra: Implications of observations for astrophysics and particle physics

Apologies for not discussing this interesting topic

Thanks to all speakers
for their contributed summaries