QCD Phenomenology using Effective Field Theory

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in collaboration with

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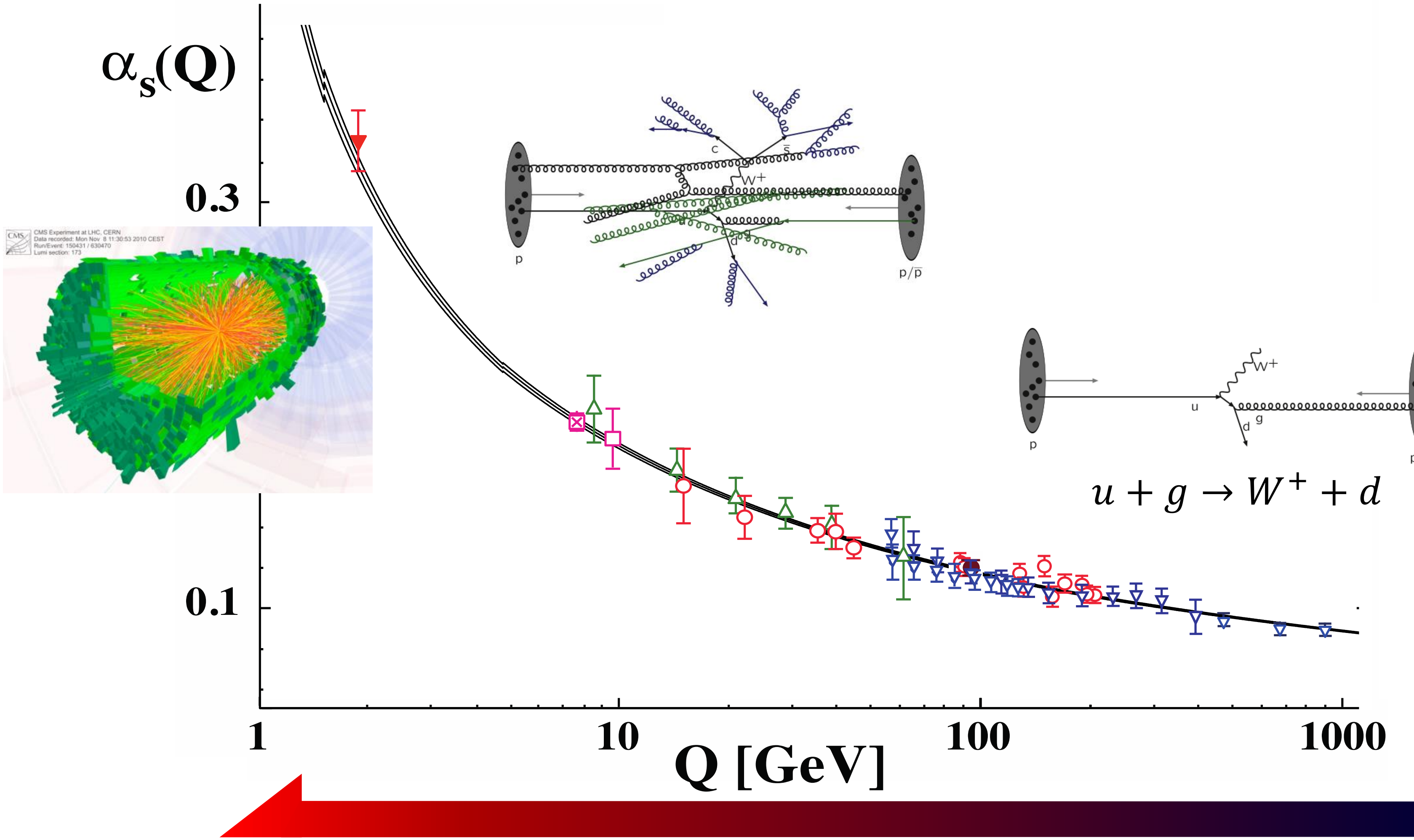
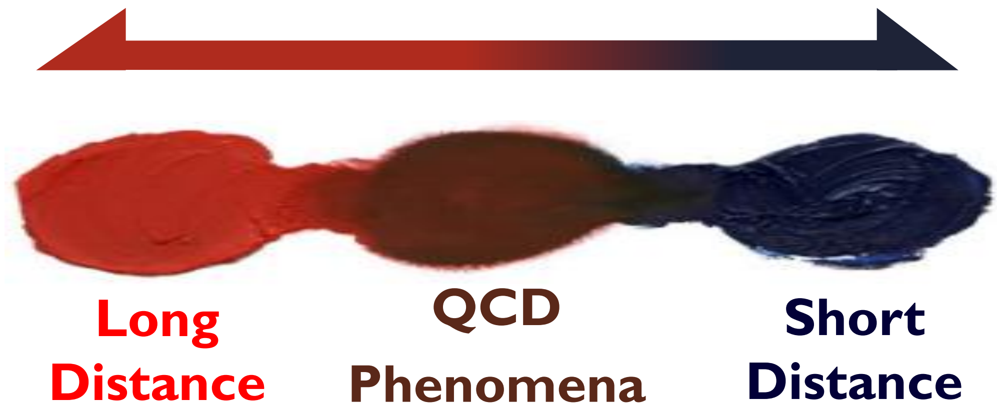
QCD at colliders

Asymptotic freedom at Short Distances (SD) and the confinement at Long Distances (LD)



Factorizing SD and LD

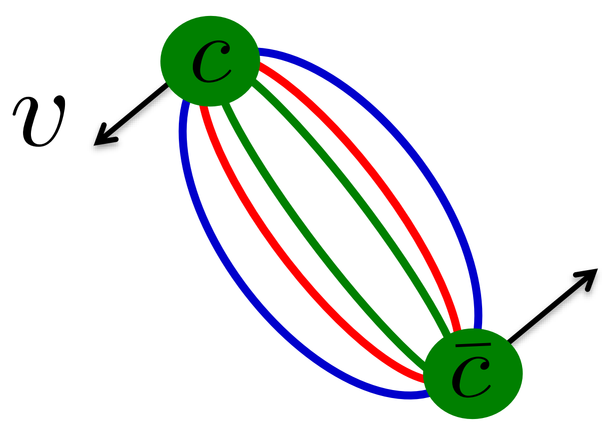


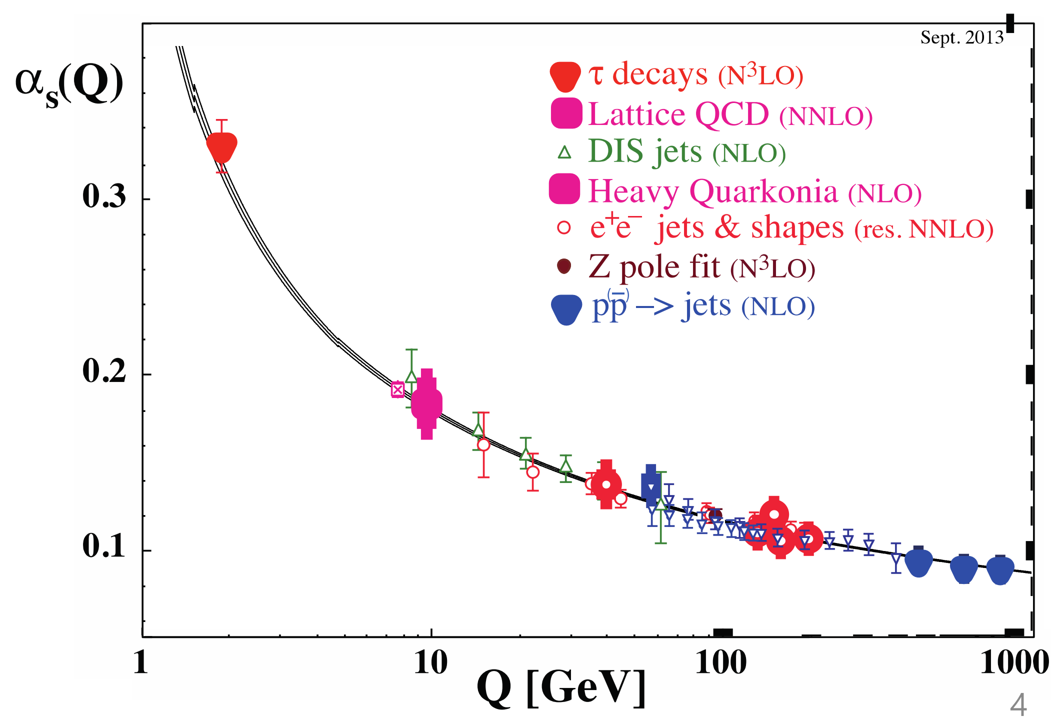
Once factorization is available,

- ✓ **SD** is calculable in perturbation theory, order by order in α_s
- ✓ Nonperturbative **LD** can be determined from experiments or lattice simulations, or modeled with a few parameters

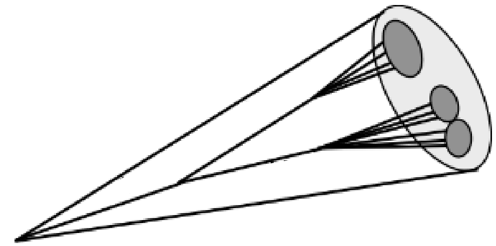
Quarkonium physics

- ✓ Bound state of heavy quark and anti-heavy quark pair
- ✓ Extensive studies on its production and polarization
- ✓ Higgs coupling to b or c quarks

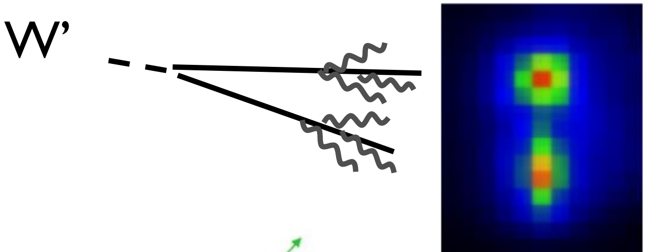


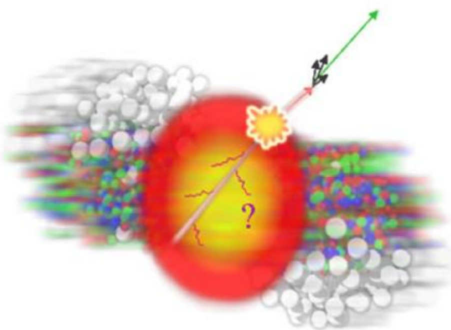


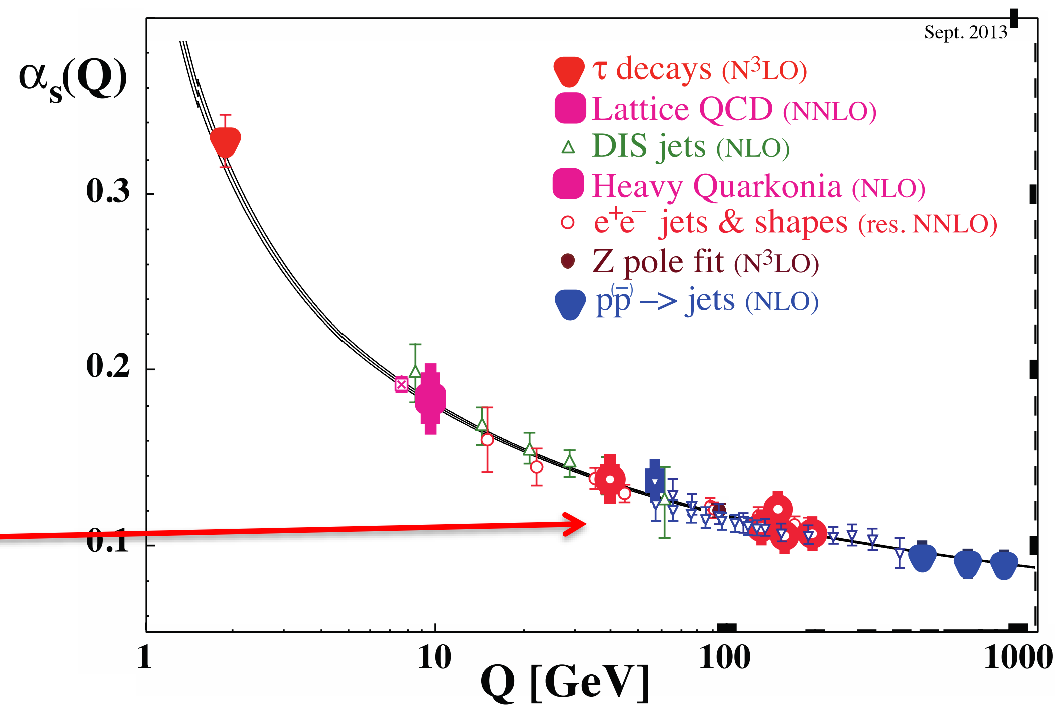
Jet physics



- ✓ A hadron group travelling along the same direction
- ✓ New physics search or probe of quark-gluon plasma







- ✓ Precision test (α_s determination)

Effective Field Theory

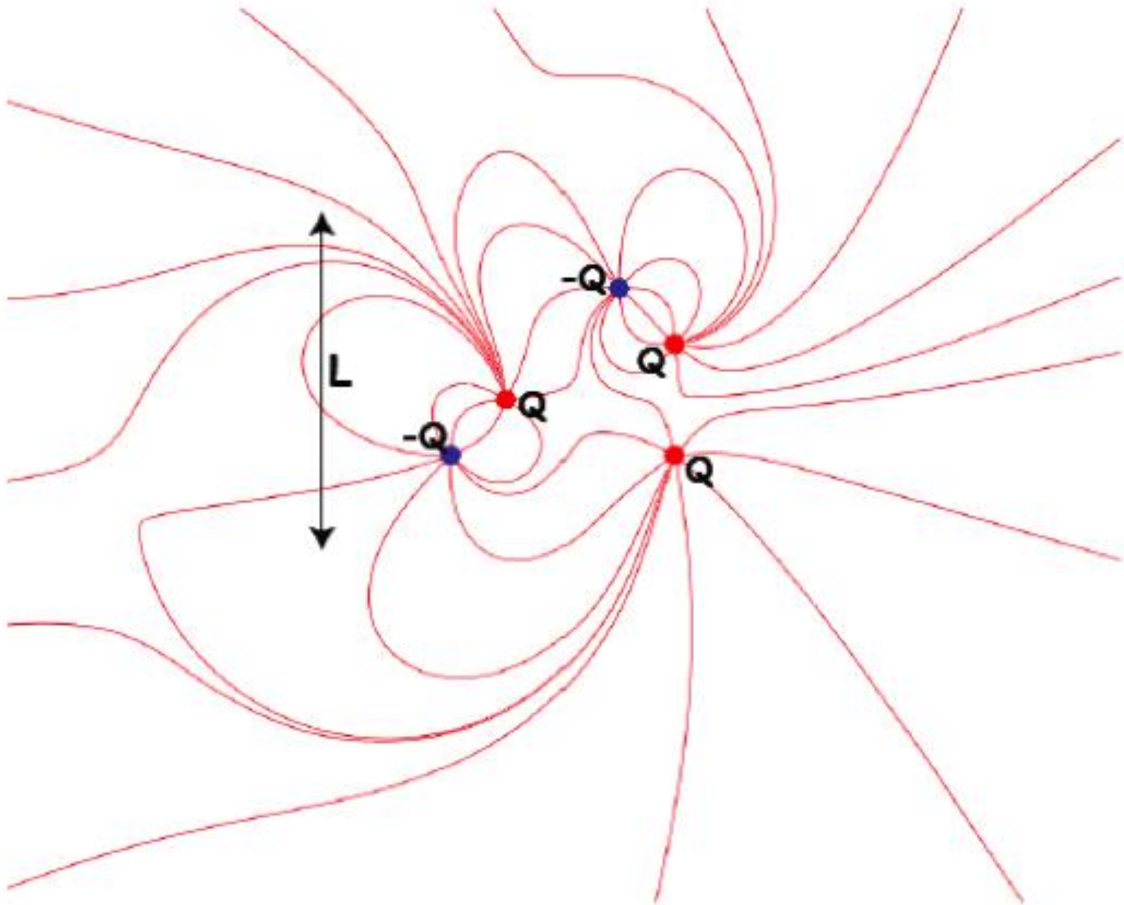
Effective field theory of QCD

- ✓ QCD in a specific phase space region

- ✓ What's good with EFT?
  - simple and handy
  - Factorization of non-pert. and pert. parts
  - Expansion with systematic power counting
  - can be improved to a desired accuracy

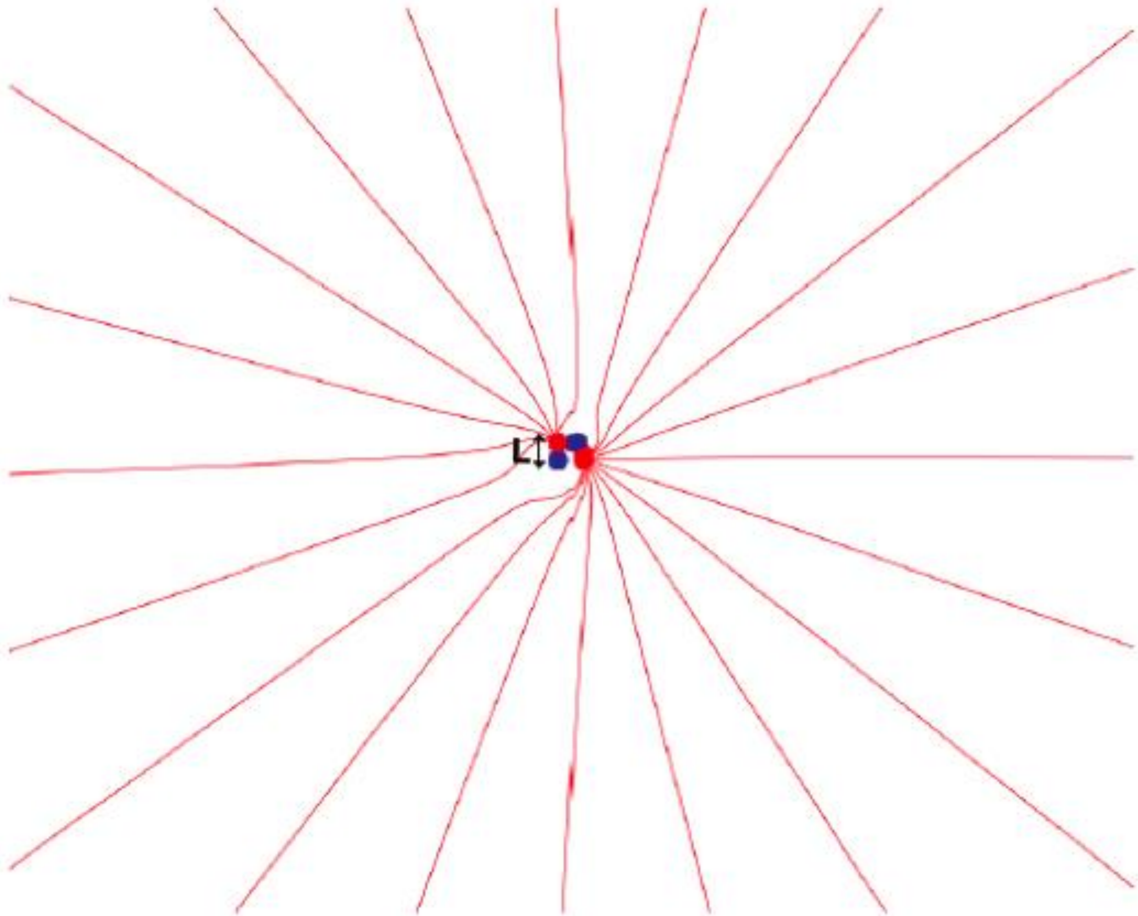
- ✓ Example of classical Effective ~~Field~~ Theory:
  Multipole expansion

Multipole expansion



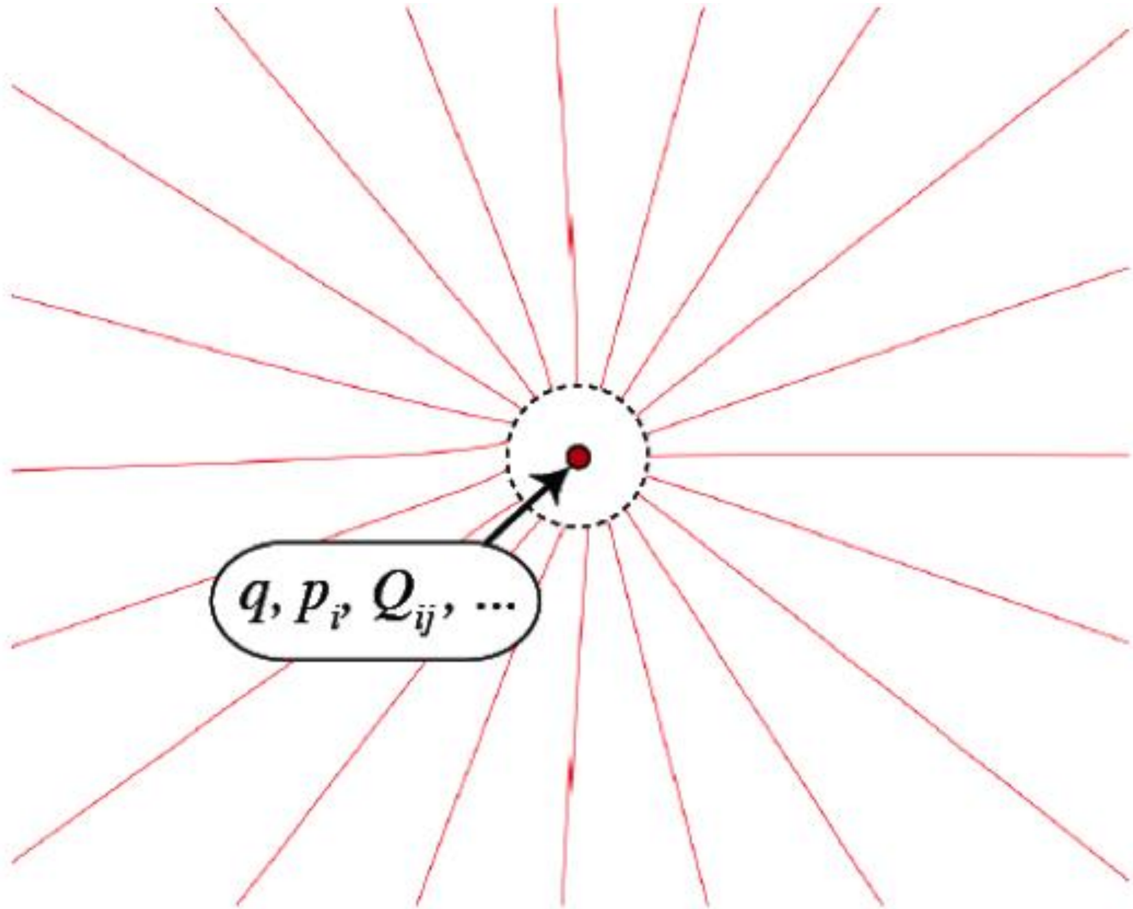
At distance R~L, physics depends
on all the details of charge distribution

Multipole expansion



At longer distance R>>L,
things look a lot simpler

Multipole expansion



Replace the charge distribution by
a point source + additional interactions

Multipole expansion

- ✓ Monopole, dipole, quadrupole, …

$$V(R) = \frac{q}{R} + p_i \frac{R_i}{R^3} + \frac{1}{2} Q_{ij} \frac{R_i R_j}{R^5} + \ldots$$

SD

- ✓ Power counting: *L/R<<1*
- ✓ Factorization: Short Distance x Long Distance

Multipole expansion

- ✓ Monopole, dipole, quadrupole, …

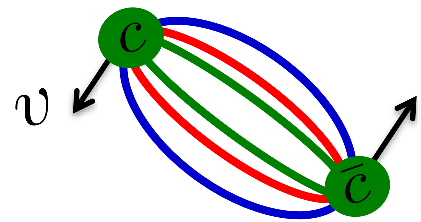
$$V(R) = \frac{q}{R} + p_i \frac{R_i}{R^3} + \frac{1}{2} Q_{ij} \frac{R_i R_j}{R^5} + \ldots$$

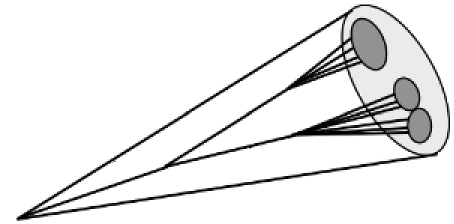
$\sim 1/R \qquad \sim L/R^2 \qquad \sim L^2/R^3$

- ✓ Power counting: *$L/R \ll 1$*

- ✓ Factorization: Short Distance x Long Distance

EFT's for quarkonium and for jet





Pheno	Electrostatics	quarkonium	jet
EFT	Multipole	NRQCD	Soft Collinear EFT
Small parameter	L/R	v (rel. velocity)	soft~ $(\lambda^2, \lambda^2, \lambda^2)$ coll.~ $(1, \lambda^2, \lambda)$ $(E+p_z, E-p_z, p_T)$
SD	q, p_i, Q_{ij}	$\sigma(cc[n])$	H
LD	$1/R^{1+n}$	$\langle O[n]\rangle \sim v^{3+2n}$ Non-perturvative	$J_1 \times J_2 \times S \sim \lambda^{4+2n}$ NP partially

Effective Field Theory for Quarkonium

NRQCD Factorization

Bodwin, Braaten, Lepage, PRD (1995)

NRQCD Lagrangian is given by

$$\mathcal{L}_{\mathrm{NRQCD}} = \mathcal{L}_{\mathrm{light}} + \mathcal{L}_{\mathrm{heavy}} + \delta\mathcal{L}$$

where

$$\delta\mathcal{L} = \delta\mathcal{L}_{\mathrm{bilinear}} + \delta\mathcal{L}_{\mathrm{four\text{-}fermion}}$$

$\delta\mathcal{L}_{\mathrm{bilinear}}$ is given by a standard nonrelativistic particle interacting with chromo-electromagnetic fields

Full QCD is reproduced at the scale of order Mv or less

NRQCD operators

Bodwin, Braaten, Lepage, PRD (1995)

$\delta\mathcal{L}_{\text{four-fermion}}$ is given by

$$\delta\mathcal{L}_{\text{four-fermion}} = \sum_n \frac{f_n(\Lambda)}{m_Q^{d_n-4}} \mathcal{O}_n(\Lambda)$$

where $f_n(\Lambda)$ is a SD coefficient,

$\mathcal{O}_n(\Lambda)$ is a higher dimensional operator (LD)

Dimension-6 operators

$$\begin{aligned}
\mathcal{O}(^1S_0^{[1]}) &= \psi^\dagger \chi \chi^\dagger \psi, \\
\mathcal{O}(^3S_1^{[1]}) &= \psi^\dagger \boldsymbol{\sigma} \chi \cdot \chi^\dagger \boldsymbol{\sigma} \psi, \\
\mathcal{O}(^1S_0^{[8]}) &= \psi^\dagger T^a \chi \chi^\dagger T^a \psi, \\
\mathcal{O}(^3S_1^{[8]}) &= \psi^\dagger \boldsymbol{\sigma} T^a \chi \cdot \chi^\dagger \boldsymbol{\sigma} T^a \psi.
\end{aligned}$$

Dimension-8 operators

$$\begin{aligned}
\mathcal{O}(^1P_1^{[1]}) &= \psi^\dagger \left(-\frac{i}{2}\overleftrightarrow{\boldsymbol{D}}\right) \chi \cdot \chi^\dagger \left(-\frac{i}{2}\overleftrightarrow{\boldsymbol{D}}\right) \psi, \\
\mathcal{O}(^3P_0^{[1]}) &= \psi^\dagger \left(-\frac{i}{2}\overleftrightarrow{\boldsymbol{D}} \cdot \boldsymbol{\sigma}\right) \chi \chi^\dagger \left(-\frac{i}{2}\overleftrightarrow{\boldsymbol{D}} \cdot \boldsymbol{\sigma}\right) \psi, \\
\mathcal{O}(^3P_1^{[1]}) &= \psi^\dagger \left(-\frac{i}{2}\overleftrightarrow{\boldsymbol{D}} \times \boldsymbol{\sigma}\right) \chi \cdot \chi^\dagger \left(-\frac{i}{2}\overleftrightarrow{\boldsymbol{D}} \times \boldsymbol{\sigma}\right) \psi, \\
\mathcal{O}(^3P_2^{[1]}) &= \psi^\dagger \left(-\frac{i}{2}\overleftrightarrow{D}^{(i}\sigma^{j)}\right) \chi \chi^\dagger \left(-\frac{i}{2}\overleftrightarrow{D}^{(i}\sigma^{j)}\right) \psi,
\end{aligned}$$

_v_ scaling, double expansion, efficient

...

NRQCD in hadroproduction

- ✓ According to NRQCD,
  the cross section $d\sigma$ of the production of quarknonium H can be factorized into

$$d\sigma_{ij\to H(q\bar{q})+X} = \sum_n \boxed{d\hat{\sigma}_{ij\to q\bar{q}(n)+X}}\,\boxed{\langle 0|O^H(n)|0\rangle}$$

short-distance coefficient

long-distance matrix elements

- ✓ SD are for $c\bar{c}$ or $b\bar{b}$ pair production in quantum state $n = {}^{2S+1}L_J^{[a]}$, where S =spin, L =orbital, J =total angular momentum, and a =color: 1 or 8

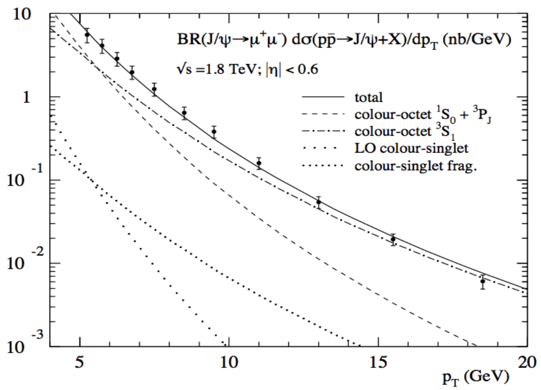
- ✓ LDMEs are determined by fitting to the experimental data

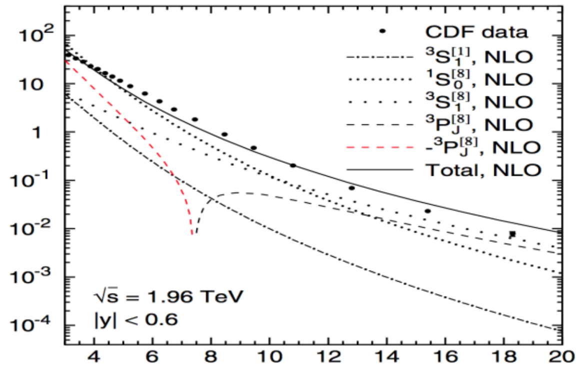
J/ψ polarization puzzle

LO+Frag.

Full NLO

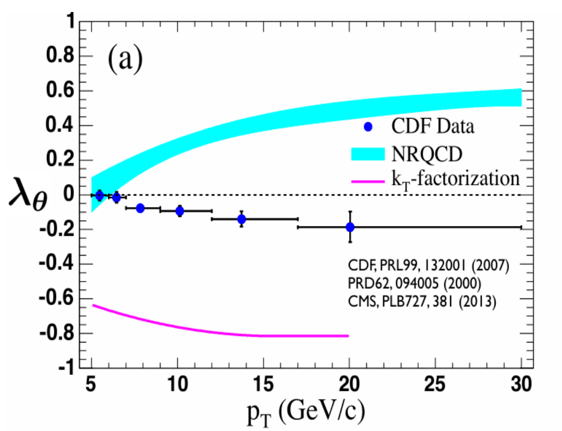
Cross section

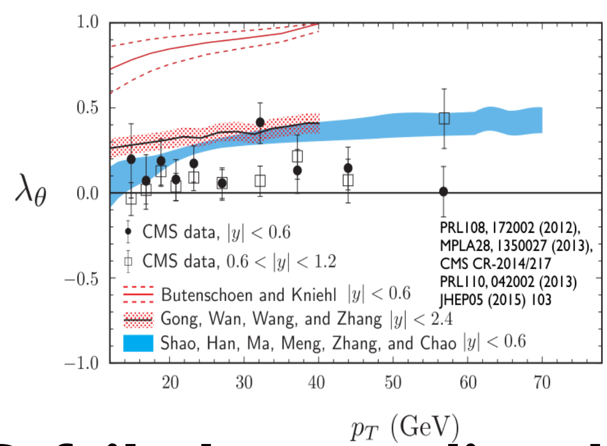




$^3S_1^{[8]}$ dominance

Polarization





large transverse polarization at high p_T
→ Disagreement with the measurement

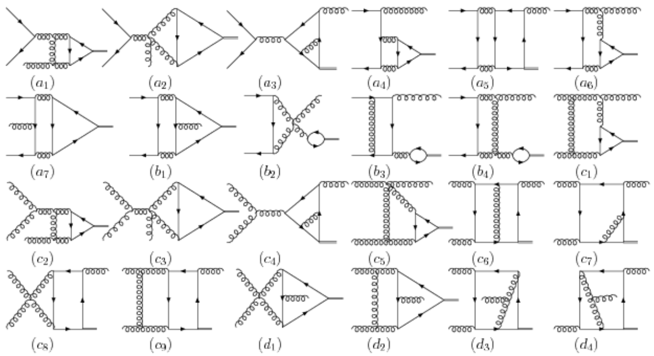
→ Even NLO NRQCD failed to predict the measured polarization

NNLO? or …

Leading-power (LP) approximation

Hee Sok Chung, Geoffrey T. Bodwin, U-Rae Kim, JL
PRD93, 034041(2016), PRL113, 022001 (2014)

J/ψ hadroproduction at NLO in α_s

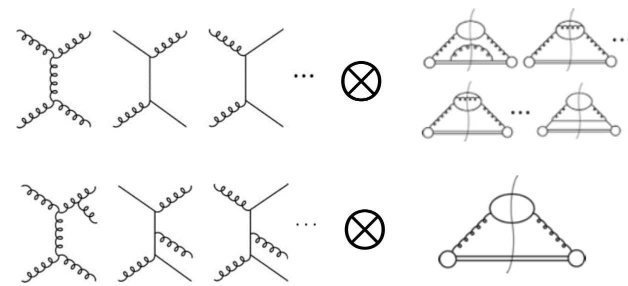


\+ …

[PRD83, 114021 (2011)]

$\sim$ at large $\mathrm{p_T}$

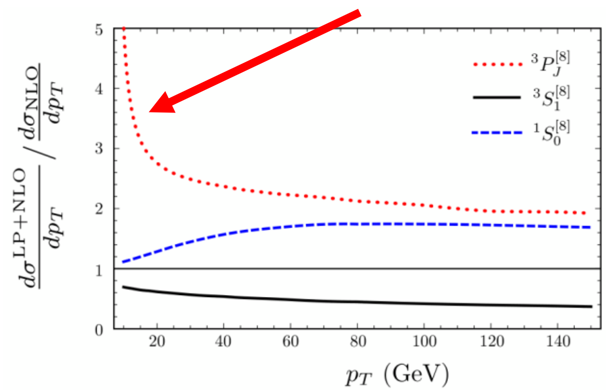
LP approximation in J/ψ hadroproduction at NLO in α_s



\+ …

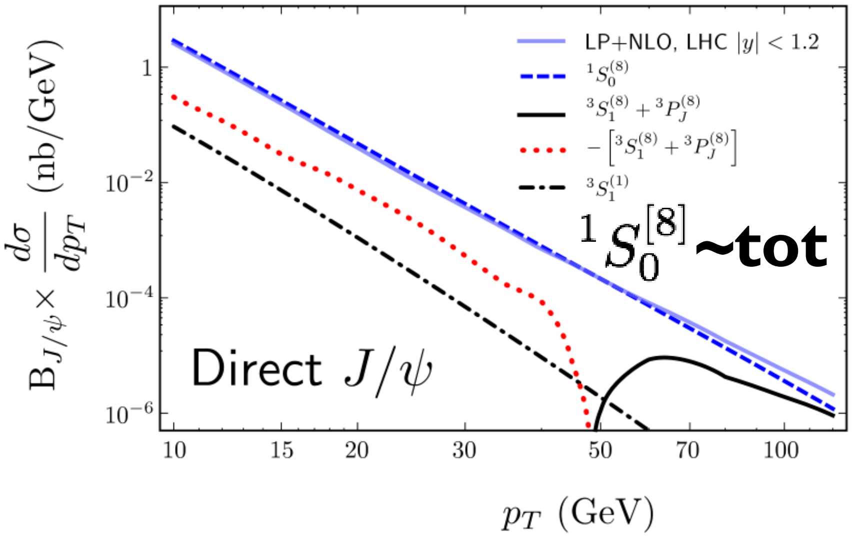
Dramatic modification of ${}^3P_J^{[8]}$

- ✓ **Leading power approximation ($\sim 1/p_T^3$) in high p_T limit up to NNLO in α_s**



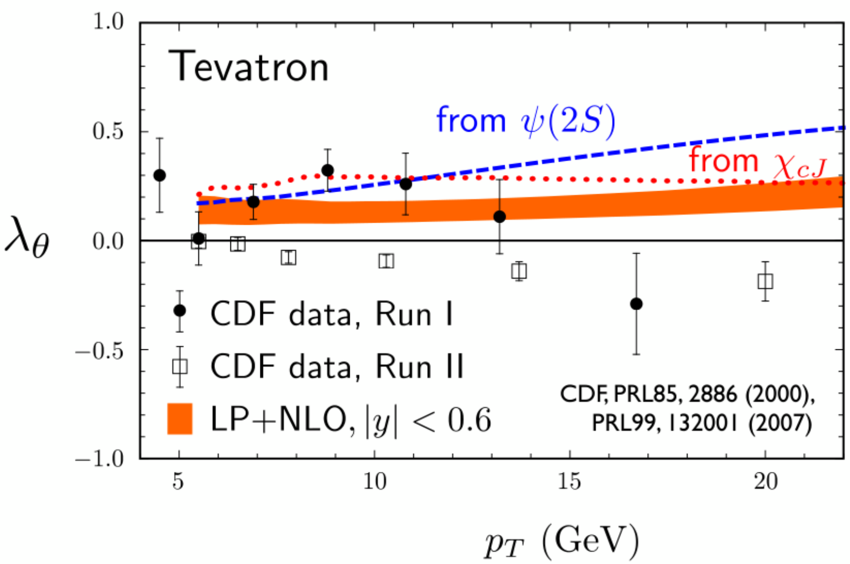
J/ψ polarization puzzle resolved?

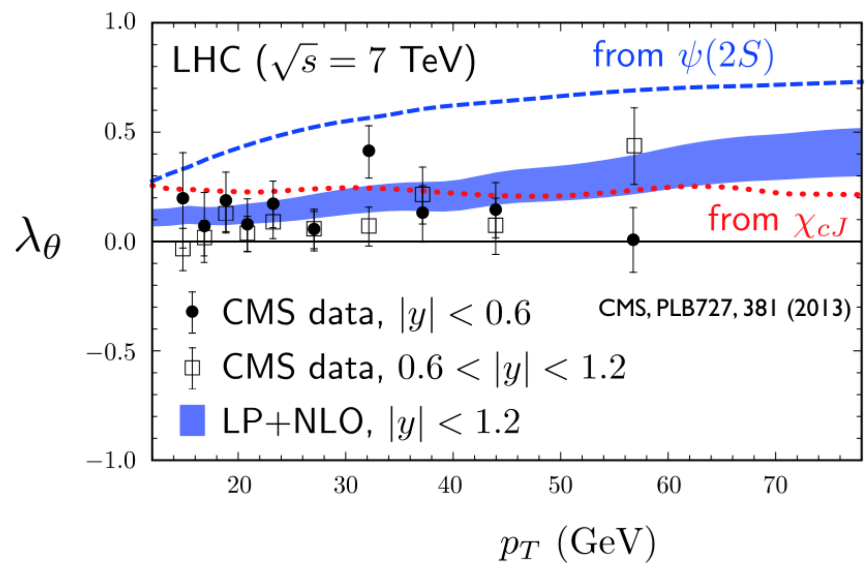
Large cancellation between ${}^3P_J^{[8]}$ and ${}^3S_1^{[8]}$



~~${}^3S_1^{[8]}$ is dominant (1995~)~~

${}^1S_0^{[8]}$ **is dominant (2014~)**



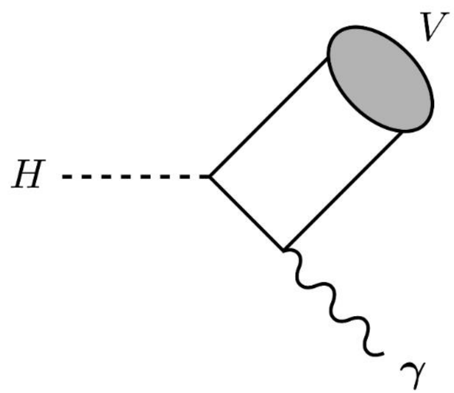


Measuring the $Hc\bar{c}$ coupling

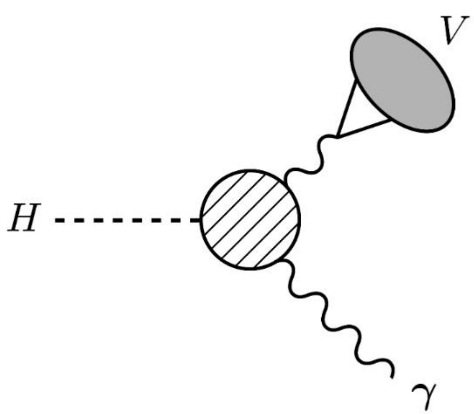
Geoffrey T. Bodwin, Hee Sok Chung, June-Haak EE, JL, Frank Petriello, [PRD90, 113010 (2014)]
Geoffrey T. Bodwin, Hee Sok Chung, June-Haak EE, JL, [PRD95, 054018 (2017)]

The couplings to 1st- and 2nd-generation quarks are unknown

One could hope to measure the $Hc\bar{c}$ coupling in direct decays $H \to J/\psi$+γ



- **Direct** process
- Proportional to $Hc\bar{c}$ coupling
- The corresponding decay width is far too small to be observed at LHC. (Keung, PRD 27, 2762 (1983))



- **Indirect** process
- A newly identified process for producing J/ψ and a photon.
- Dominated by t quarks and W bosons in the loop.
- **For J/ψ, $\mathcal{M}_{\text{indirect}} \approx 10 \times \mathcal{M}_{direct}$**

The interference between the direct and indirect amplitudes is large enough to be measured at the LHC.

Direct process

- Nonrelativistic QCD (NRQCD) is used to compute the direct amplitude with relativistic corrections of order v^2 ($v^2 \approx 0.25$ for J/ψ)

Bodwin, Braaten, Lepage, PRD 51, 1125 (1995)

- QCD 1-loop correction is known and included

Vysotsky, PLB 97, 159 (1980)

- Nonperturbative matrix elements are extracted from J/ψ leptonic decay rate

Bodwin, Chung, Kang, Lee, Yu, PRD 77, 094017 (2008)

- We use the light-cone method to compute leading logarithms of m_H^2/m_c^2

Lepage and Brodsky, PRD 22, 2157 (1980)

Indirect process

- Indirect process can be computed from $H \to \gamma\gamma^*$ followed by $\gamma^* \to J/\psi$.

- Because J/ψ is much lighter than H, $H \to \gamma\gamma^*$ can be approximated by $H \to \gamma\gamma$, which has been computed to high accuracy.

Dittmaier et al, arXiv:1101.0593

Dittmaier et al, arXiv:1201.3084

- $\gamma^* \to J/\psi$ can be extracted from the J/ψ leptonic decay rate, rather than using NRQCD.

- **This approach effectively includes QCD radiative and relativistic corrections to all orders, and lead to greatly reduced uncertainties.**

Observability of $H \to J/\psi+\gamma$ at LHC

- $\mathcal{B}_{\text{SM}} \times \mathcal{B}_{J/\psi\to\mu^+\mu^-} = 1.66^{+0.09}_{-0.09} \times 10^{-7}$ is comparable to the continuum background $\mathcal{B}_{H\to\mu^+\mu^-\gamma} = 2.3 \times 10^{-7}$.

$$(m_{J/\psi} - 0.05\ \text{GeV} < m_{\mu^+\mu^-} < m_{J/\psi} + 0.05\ \text{GeV})$$

Firan and Stroynowski, PRD 76, 057301 (2007)

- Combined number of events for ATLAS+CMS, electron+muon final state:
  - 0.3 events at 8 TeV LHC
  - **113 events at 14 TeV high-luminosity LHC (157 events from the background)**
- **Expected acceptance/efficiency is about 50%.**

Higgs-Stoponium mixing

Heavy higgs and stop-antistop bound state (stoponium)

- ✓ have same quantum numbers
- ✓ can mix in amplitudes
- ✓ decay into two photons

A naïve estimation in [PLB 765, 175 (2017)]

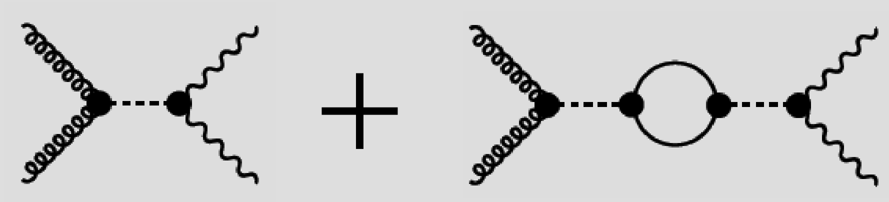
If the heavy higgs and stoponium have similar masses, then their mixing in the amplitude will lead to large enhancement of the diphoton cross section, ranging from factors of 2-8

EFT approach to Higgs-Stoponium mixing

We perform an analysis using nonrelativistic effective field theory methods to investigate how mixing effects actually impact two-photon cross sections at LHC.

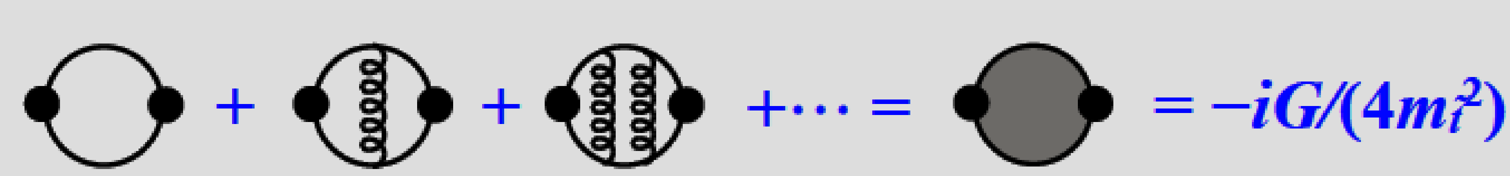
Coulomb-divergent corrections near stop-antistop threshold

- ✓ $gg \to H \to \gamma\gamma$ tree level + corrections from $\tilde{t}\tilde{t}$



- ✓ $\tilde{t}\tilde{t}$ near threshold has Coulomb divergent corrections of the form $\left(\frac{\alpha_s}{v}\right)^n$

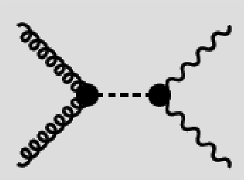
→ ***<u>Resummation</u>***



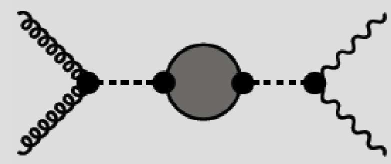
where ***G*** is a Coulomb Green's function

Resummation of stop-antistop corrections near stop-antistop threshold

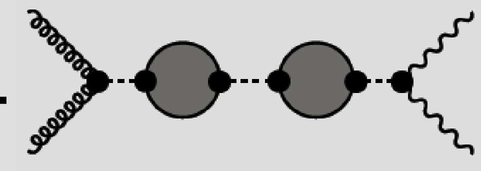
- ✓ $gg \to H \to \gamma\gamma$ tree level+corrections from $\tilde{t}\tilde{t}$



$+$



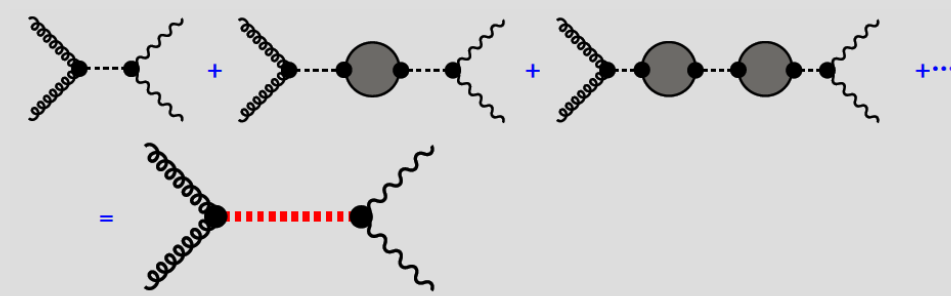
$+$



$+ \quad \cdots$

- ✓ Corrections from $\tilde{t}\tilde{t}$ are greatly enhanced near threshold

  → ***Resummation***

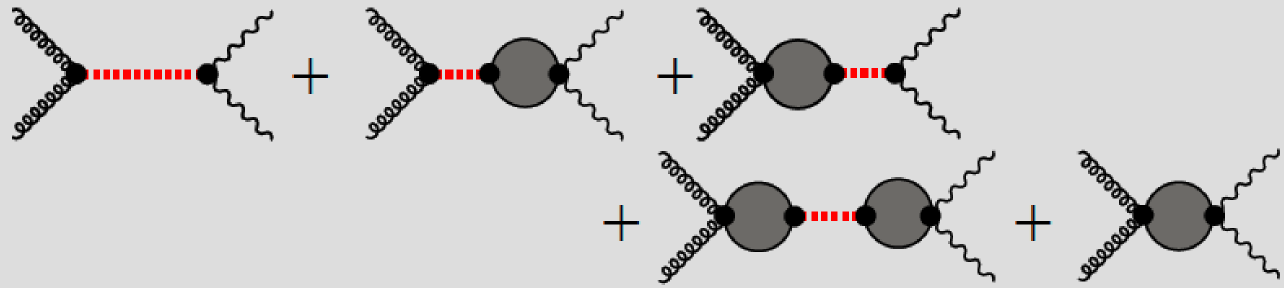


- ✓ Resummation dresses Higgs propagator

Amplitude $A(gg \to \gamma\gamma)$

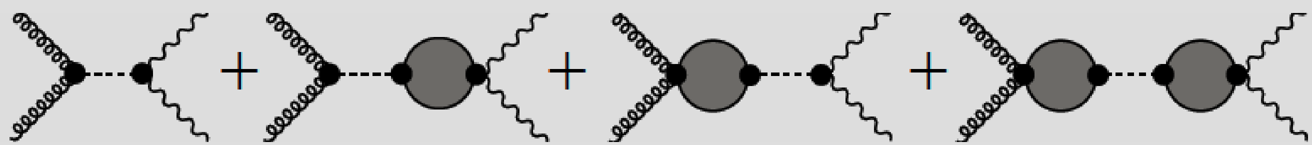
- ✓ Amplitude Including resumed corrections

$$A_{tot}(gg \to \gamma\gamma) =$$



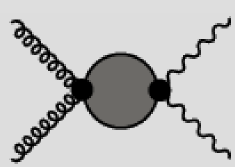
- ✓ Naïve prediction for Higgs contributions

$$A_{H}^{Bare}(gg \to \gamma\gamma) =$$



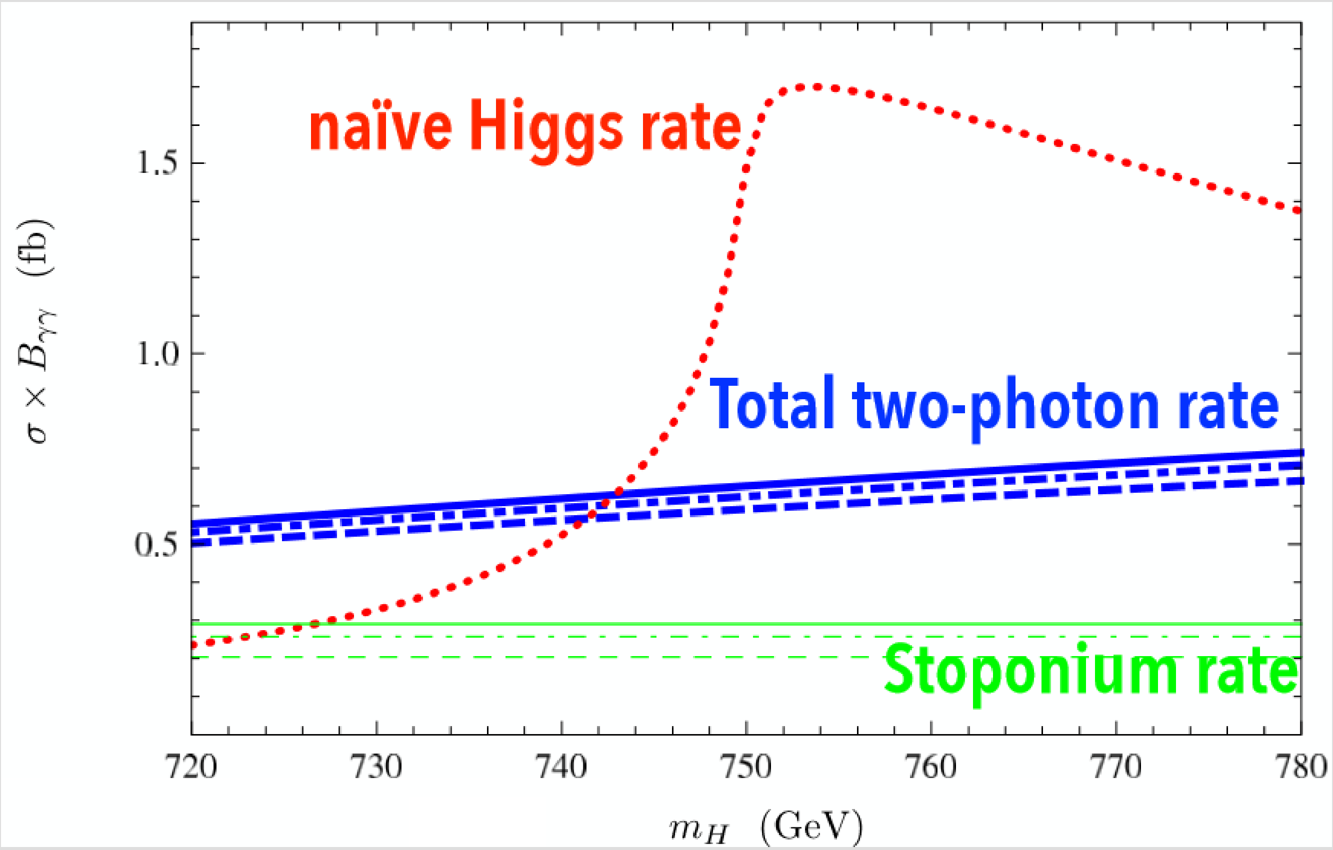
- ✓ Contribution from stoponium only

$$A_{\tilde{t}\tilde{t}}^{Bare}(gg \to \gamma\gamma) =$$



$\sigma \times B_{\gamma\gamma}$ VS m_H

Hee Sok Chung, Geoffrey T. Bodwin,
Carlos E. M. Wagner, [PRD95, 015013 (2017)]



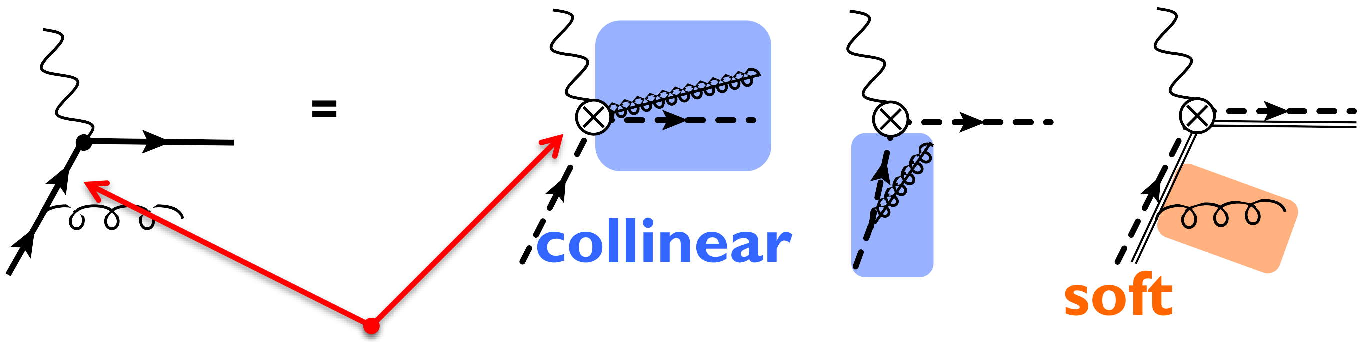
- ✓ More rigorous understanding of $H - \tilde{t}\tilde{t}$ mixing mechanism
- ✓ Good example where EFT methods developed for SM physics can prove useful for BSM phenomenology

Effective Field Theory for jet

SCET factorization

Bauer, Fleming, Luke, Pirjol, Stewart (2000, 2001)

QCD SCET



$+ O(\lambda^4)$

hard propagator shrinks into a point

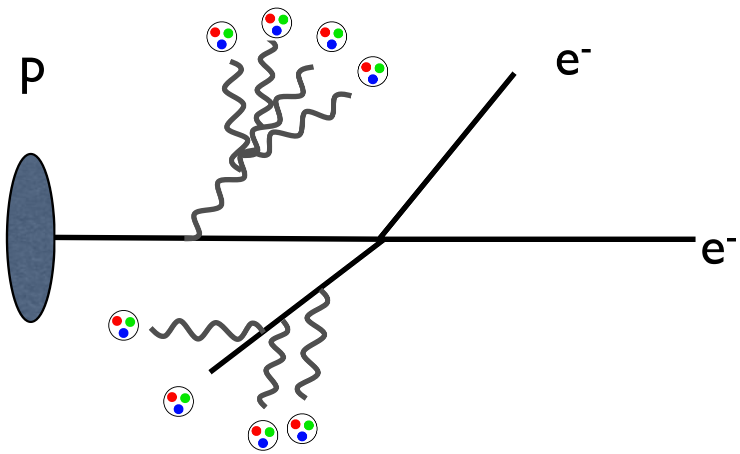
$$\bar\psi\gamma^\mu\psi = C(Q)\,\bar\chi_{\bar n,p}\,\gamma_\perp^\mu\, T[Y_{\bar n}^\dagger Y_n]\,\chi_{n,p} + O(\lambda^4)$$

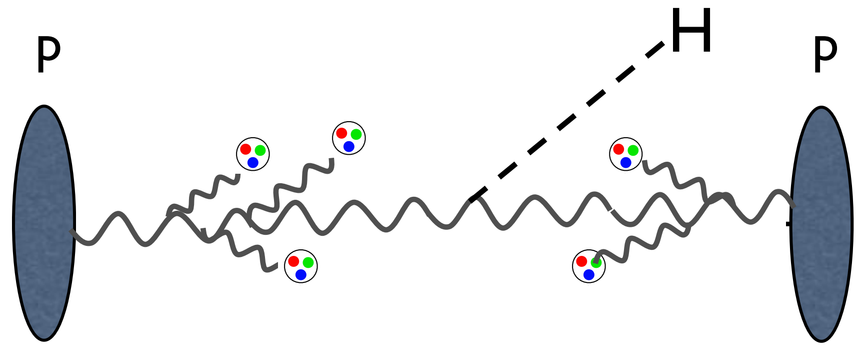
collinear jet field

soft Wilson line

hard coefficient

SCET factorization for *ep*, *pp*





$$H_{ep} \times J \otimes f \otimes S_{ep} \qquad H_{pp} \times f \otimes f \otimes S_{pp}$$

DK, Lee, Stewart, PRD '13

Also, similar fact. in ee to di-jet!

Universal fact. structure captured by EFT,
Not easy in QCD!

$p_H \sim (1,\ 1,\ 1)\,Q$

$p_c \sim (1,\ \lambda^2,\ \lambda)\,Q$

$p_s \sim (\lambda^n,\ \lambda^n,\ \lambda^n)\,Q$

$\lambda \sim pT/Q \ll 1$

H: q/g created at the short distance

f, J: coll. radiations from initial/final state

S: radiation of soft partons

Large Log under control

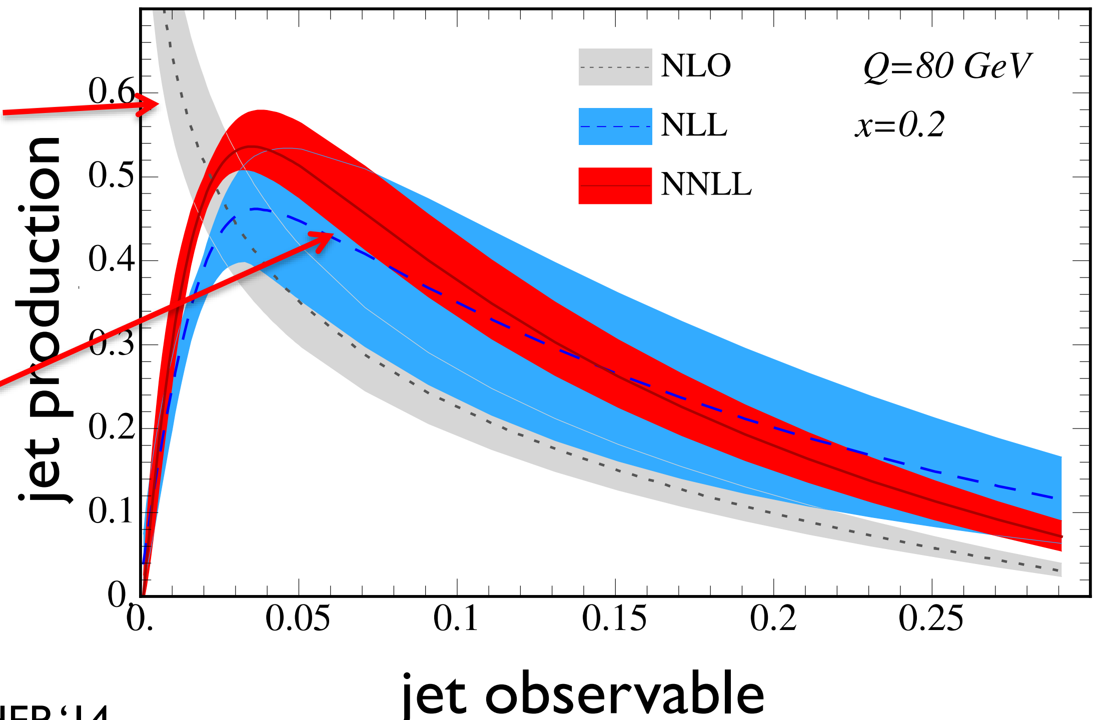
$$\sigma_{\text{jet}} \ni \alpha_s^n \log^{n+1}(\lambda)$$

$\lambda \ll 1$: ratio of typical jet observable to collision E

SCET easily captures the logs and resum by RG evolution.

Log singularity in NLO cured by resummation.

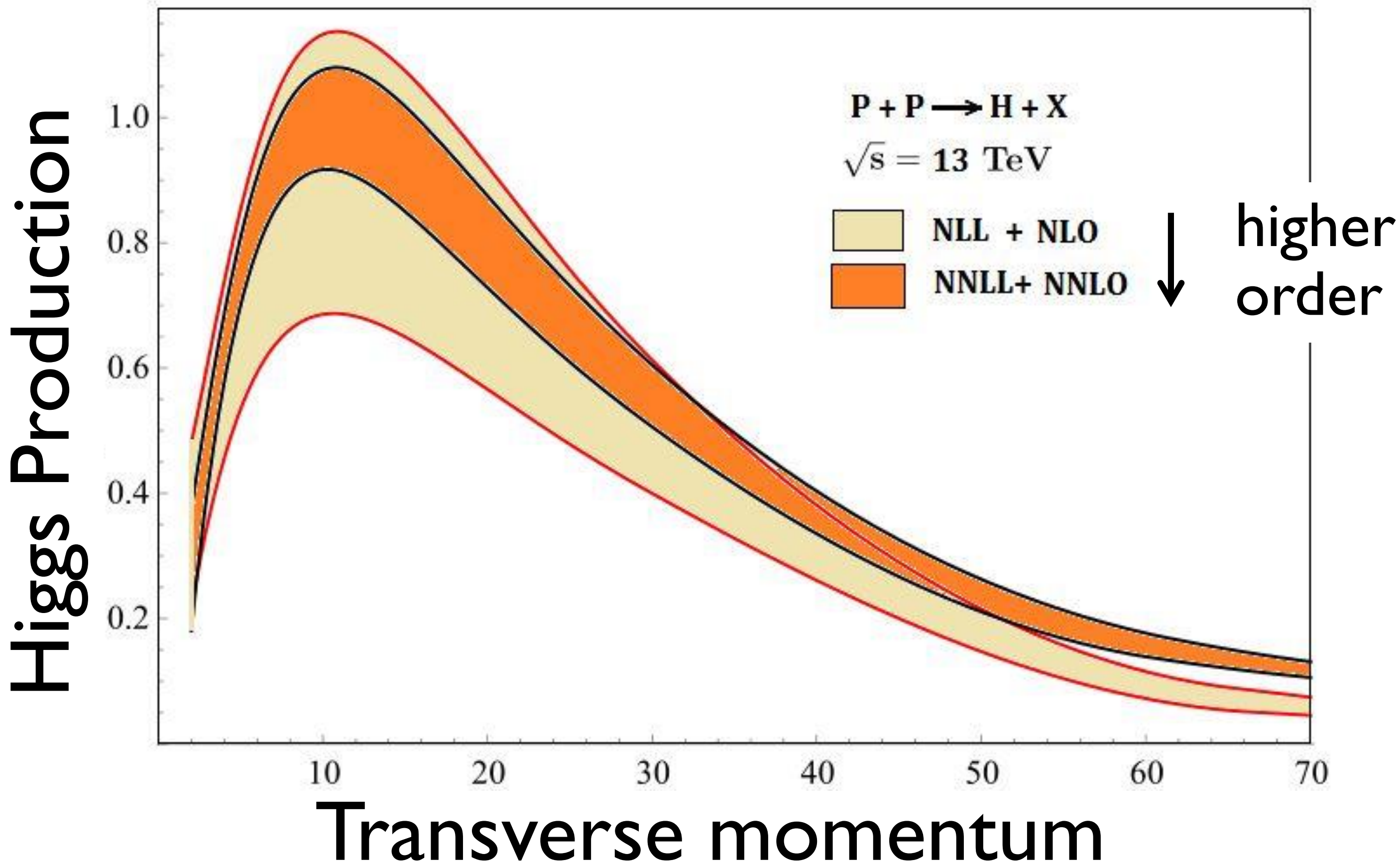
Good convergence w/ higher orders resum. (NLL, NNLL)



Daekyong Kang, Lee, Stewart, JHEP '14
Daekyong Kang, Laban, Lee, PLB '15

Higgs distribution at small pT

- ✓ Data dominated region but large Log(pT/M_{Higgs})
- ✓ Large pert. uncertainty induced by large color factor motivates the higher-order computation.

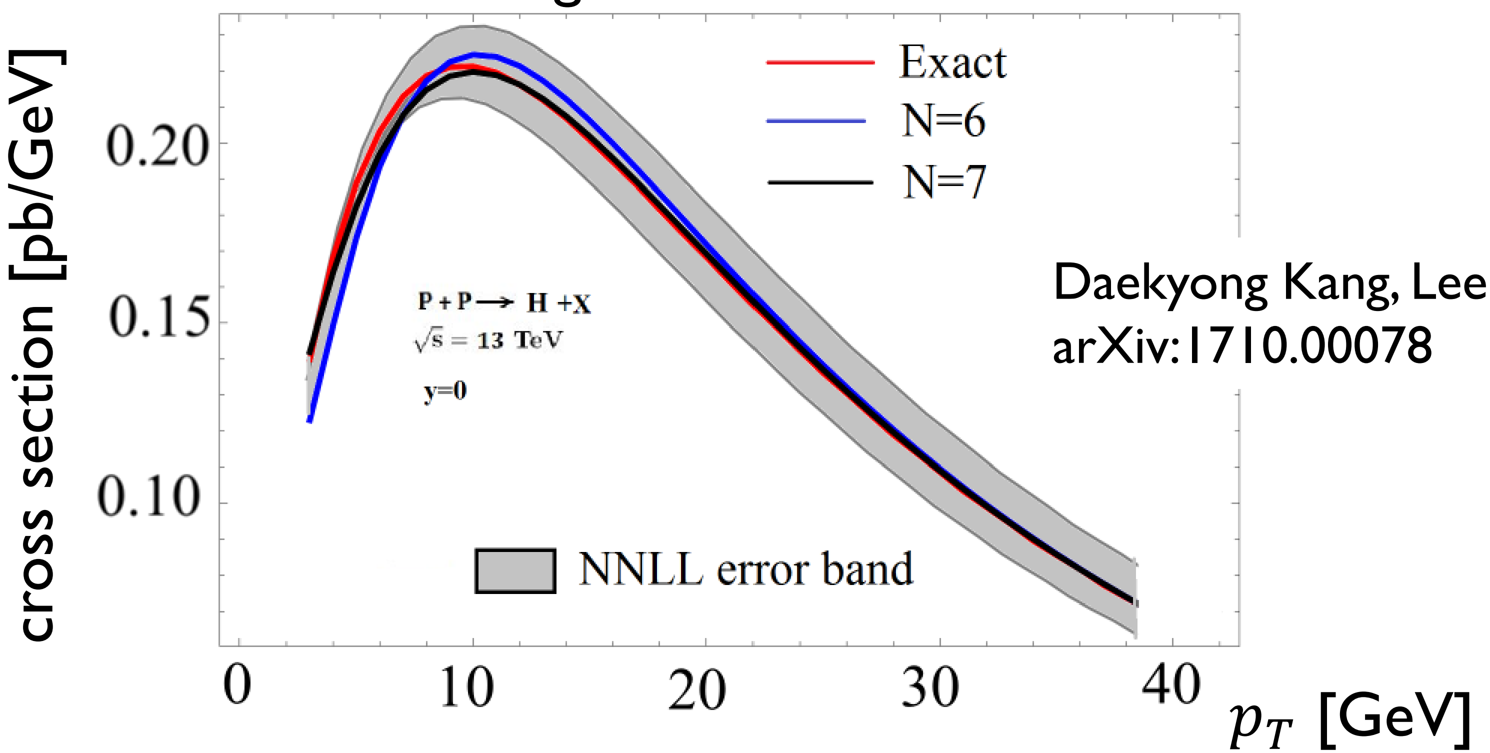


Progress in Higgs p_T

- ✓ To higher accuracy, available up to N^3LL
- ✓ To faster computation w/ series expansion

Li, Neill, Zhu, PRD 2016, PRL 2017, Bizon, Monni, Re, Rottoli, Torrielli arXiv:1705.09127

Good convergence at N=7



Daekyong Kang, Lee, Vaidya arXiv:1710.00078

Summary

Summary and Outlook

- Understanding strong interaction requires quantitative information on both perturbative and nonperturbative regimes
- QCD Effective field theory is a strong theoretical tool to investigate strong interaction systematically
- Quantitative analysis based on QCD EFT is quite powerful to explore unknown area like BSM because of its rigorousness

Thank you