MAX-PLANCK-INSTITUT FÜR PHYSIK

A look inside the proton

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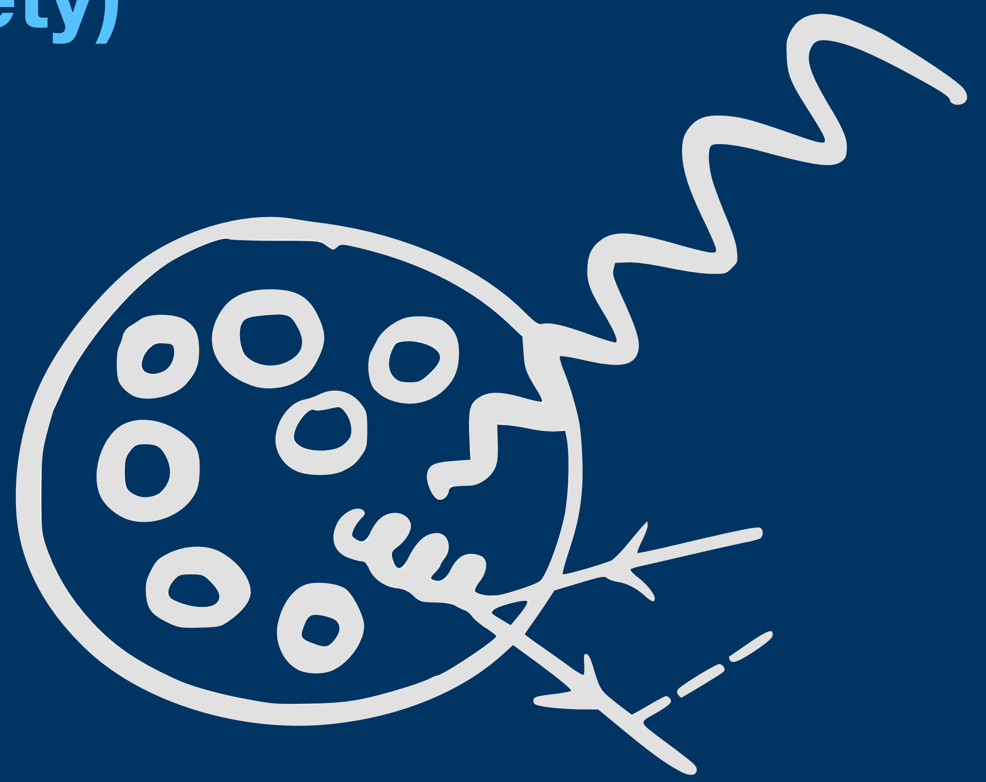
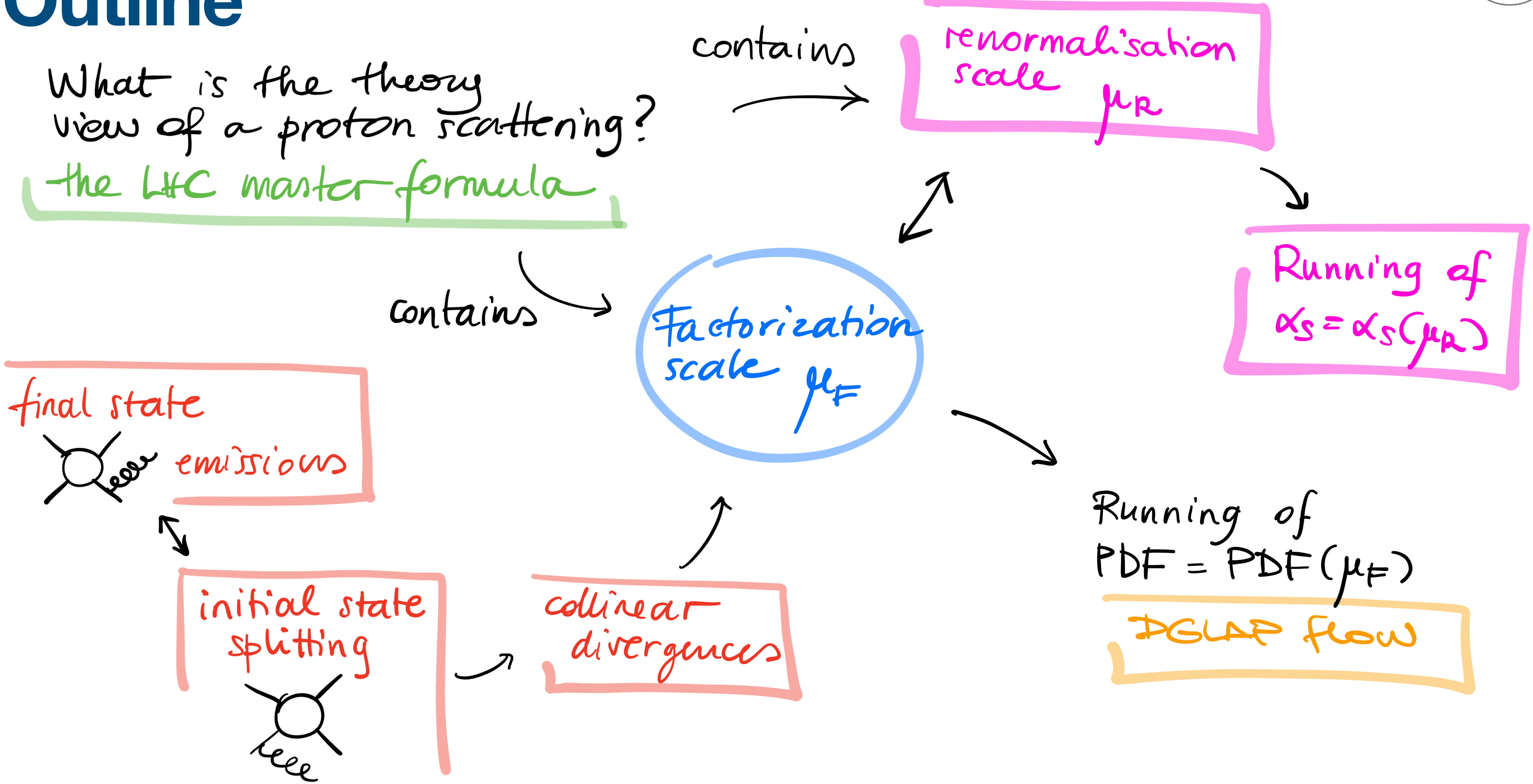
Max-Planck Institute for Physics

IMPRS Young Scientist Workshop
Ringberg Castle (Max-Planck Society)
November 23rd, 2023



Outline

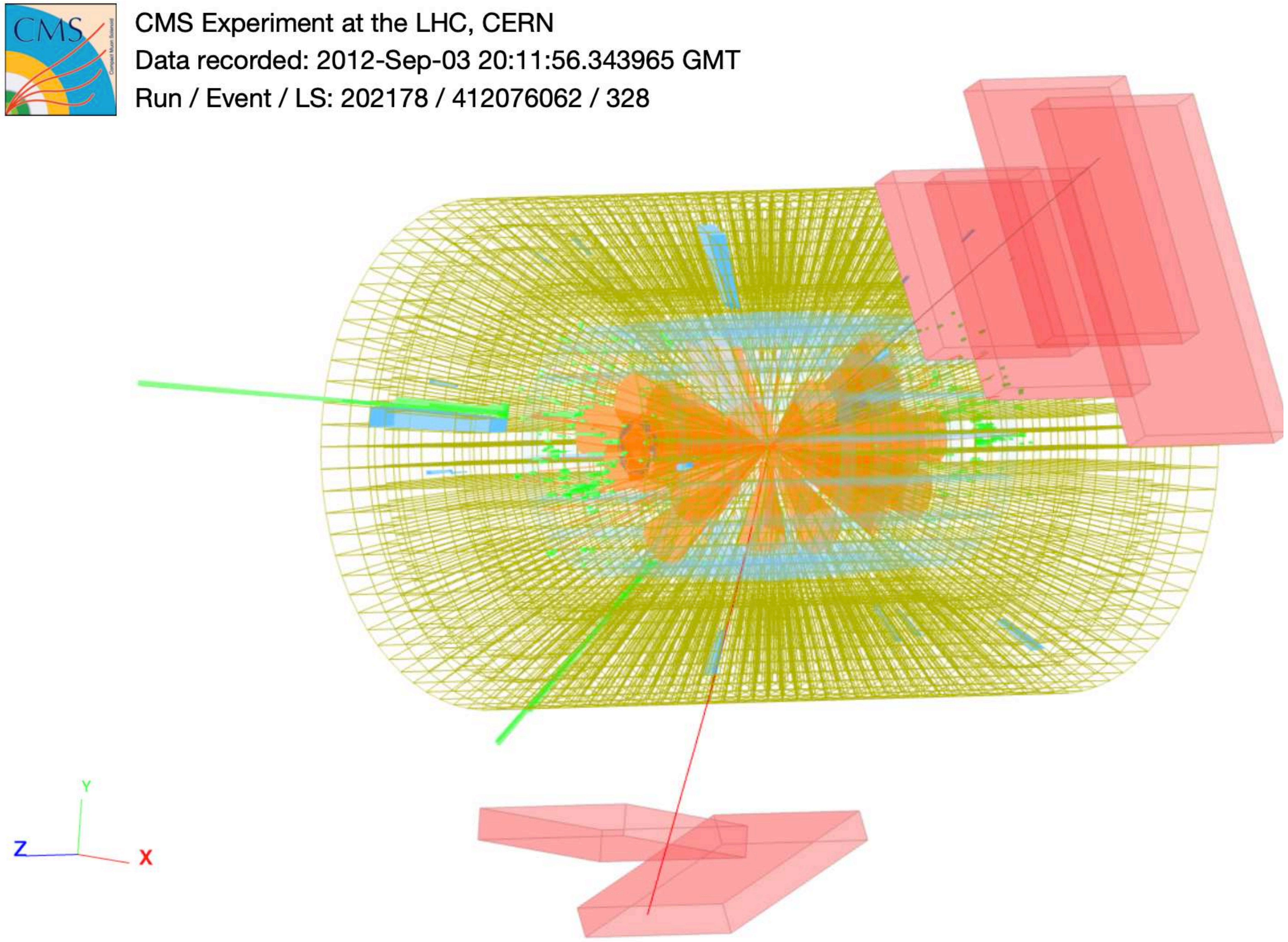

What is the theory view of a proton scattering?
the LHC master formula
contains
contains
renormalisation scale μ_R
Running of $\alpha_s = \alpha_s(\mu_R)$
Factorization scale μ_F
Running of PDF = PDF(μ_F)
DGLAP flow
final state emissions
initial state splitting
collinear divergences

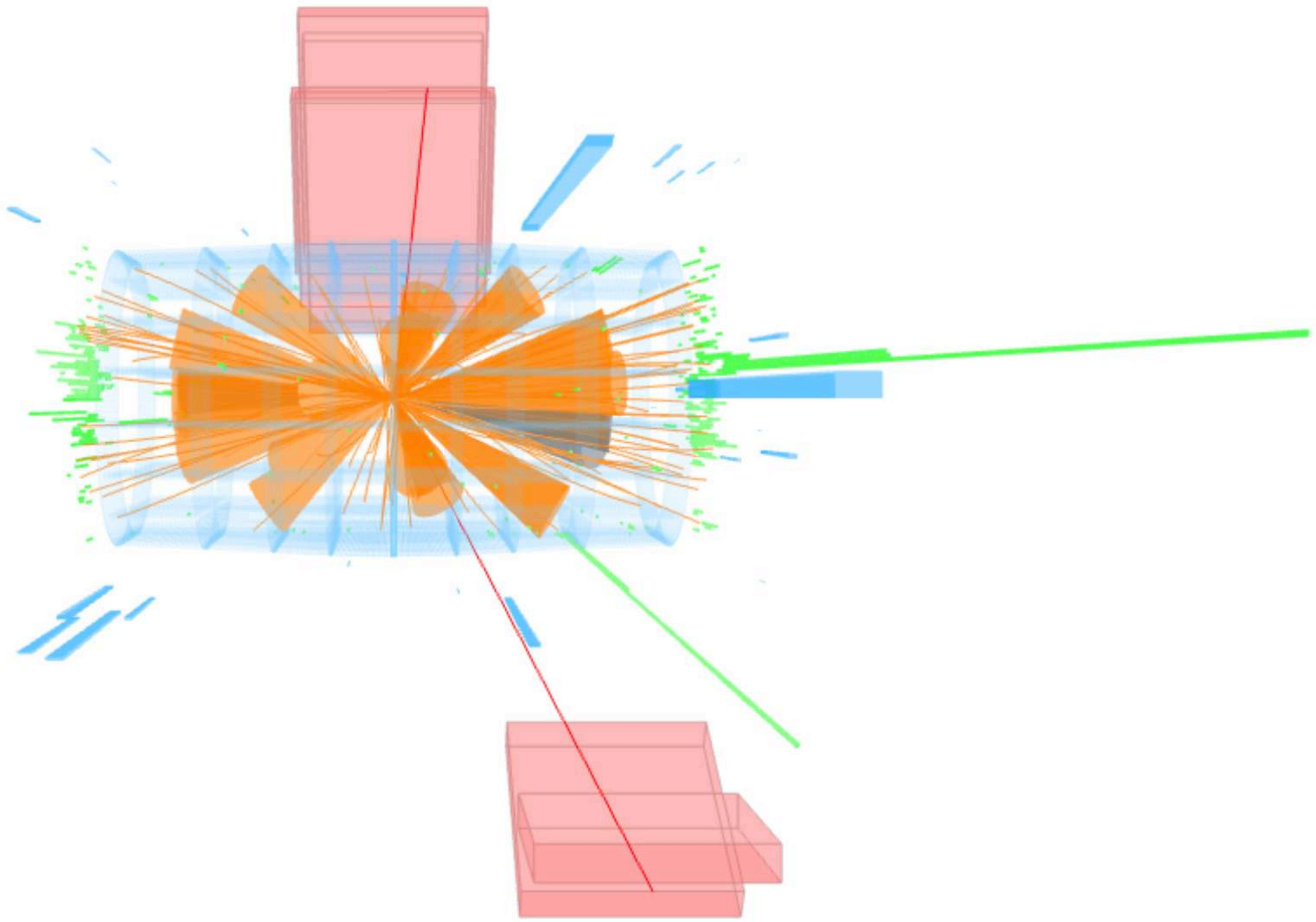
Divide et impera

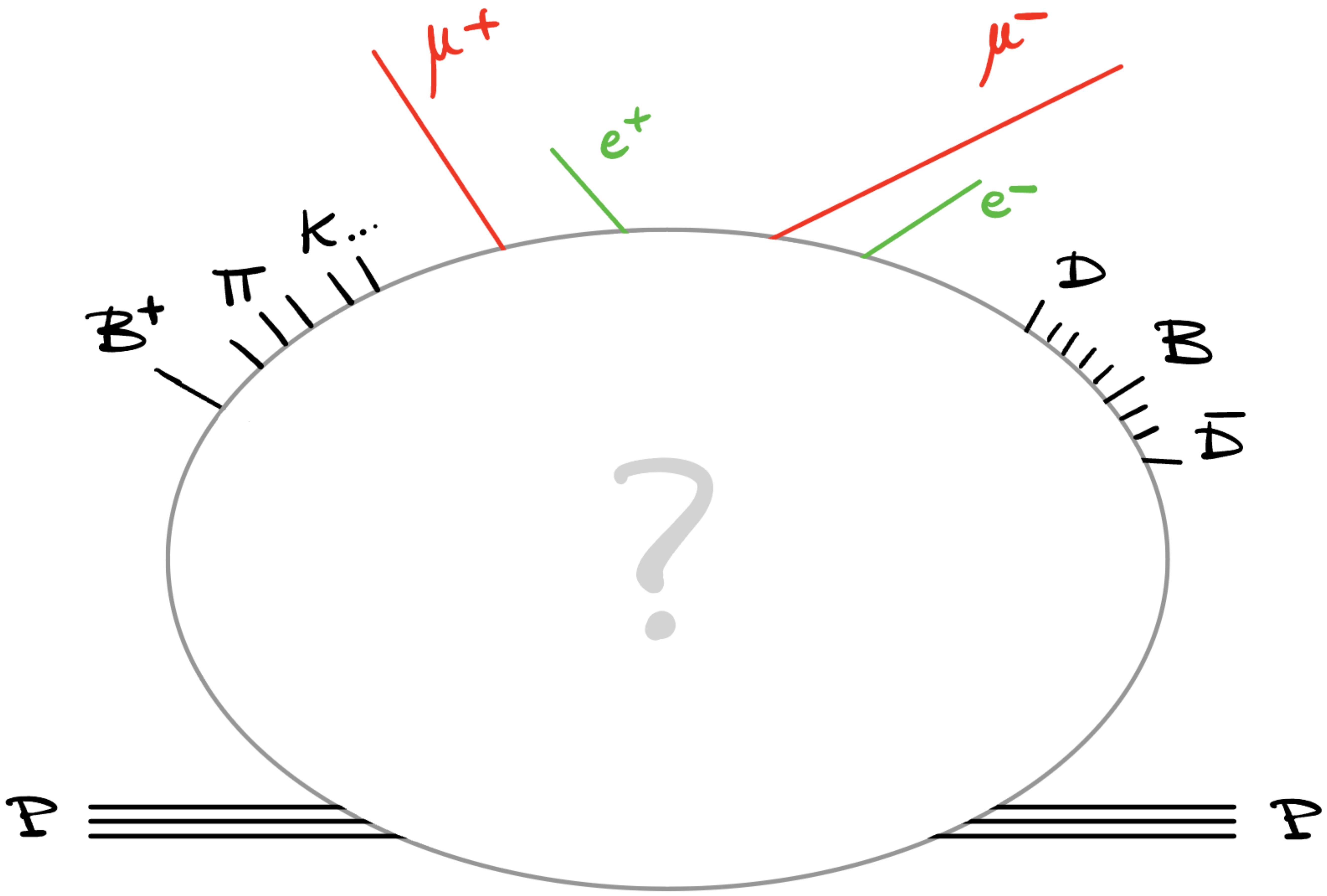
- **How can we describe an LHC event?**
  - QCD loves to split particles, how do we treat them?
  - How and where can we absorb the collinear divergence?
  - What is the role of PDFs in a phenomenological calculation?
  - “Shut up and calculate” a cross-section

An LHC event looks like…

[www.i2u2.org/elab/cms/ispy-webgl]

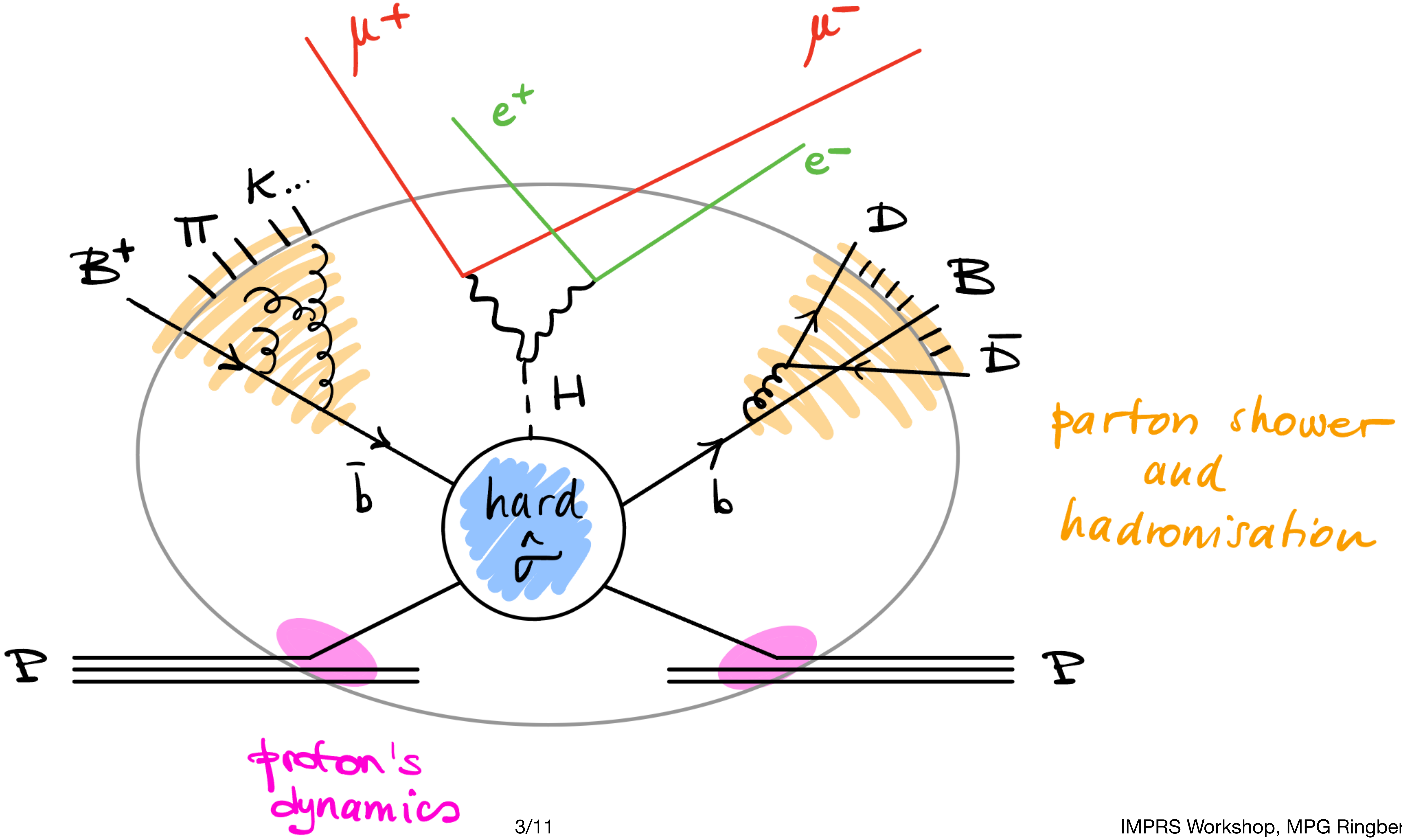




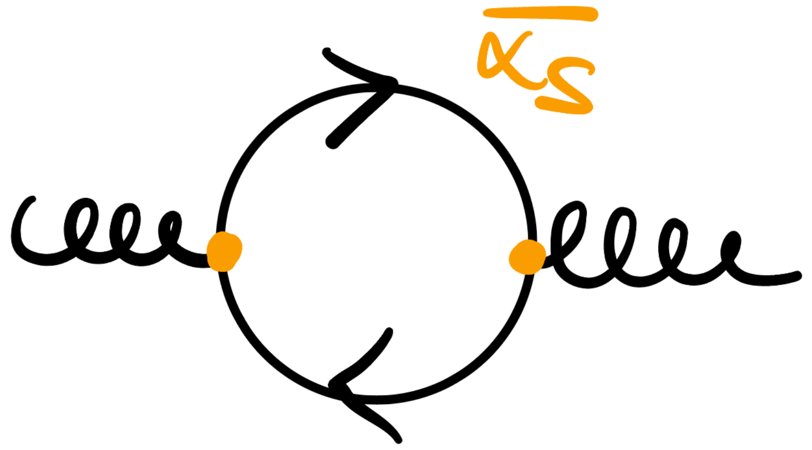

μ+
e+
μ−
e−
K...
π
B+
D
B
D̄
?
P
P

Proton's dynamics
Final hadrons' dynamics $\Big\} \mathcal{O}(1\,\text{fm}) \gg 0.002\,\text{fm} \sim \mathcal{O}\left(\frac{1}{m_H}\right)$ $\Big\{$ timescale hard process

We separate (*factorise*) hadronic dynamics and hard interactions!

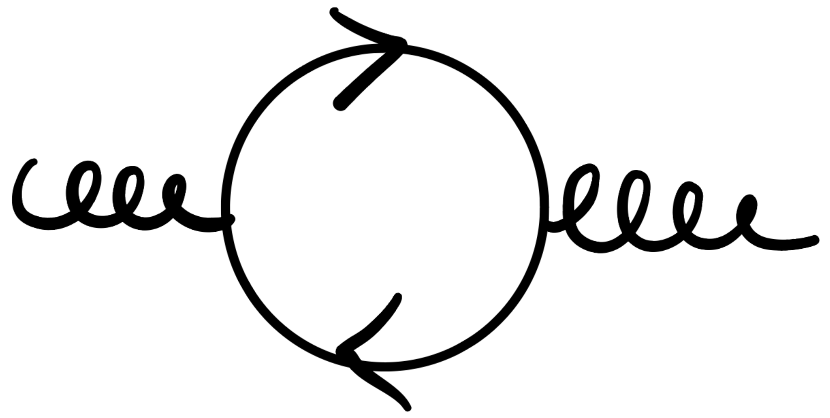


Short-scale interaction



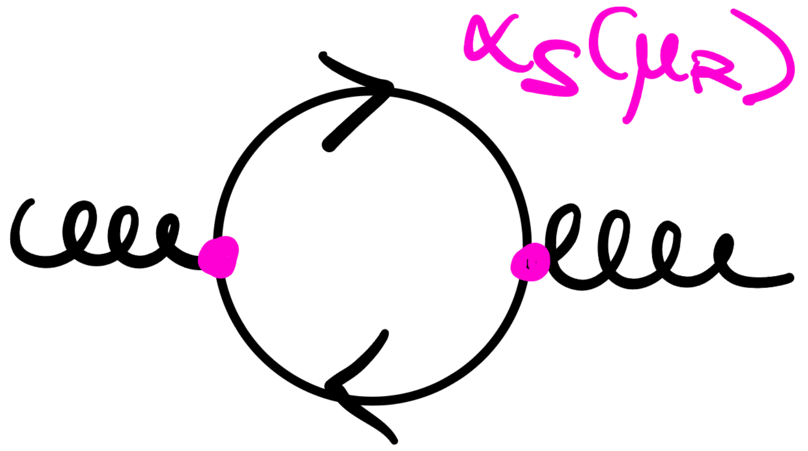
$$\overset{\text{UV}}{\sim} \bar{\alpha}_s \int \frac{d^4\ell}{\ell^4} \simeq \bar{\alpha}_s \int^{\infty} \frac{d\ell}{\ell} = \infty \quad !?$$

regularise



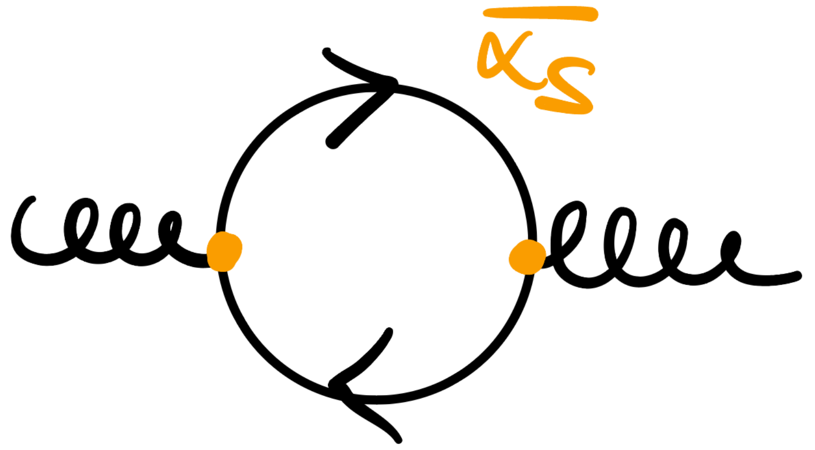
$$\sim \bar{\alpha}_s \int^{\mu_R} \frac{d\ell}{\ell} \ldots \sim \bar{\alpha}_s \left[\ln \mu_R + \text{finite}\right]$$

renormalise ⇝ $\alpha_s = \alpha_s(\mu_R)$



$$= \alpha_S(\mu_R) \cdot \text{finite}$$

Short-scale interaction



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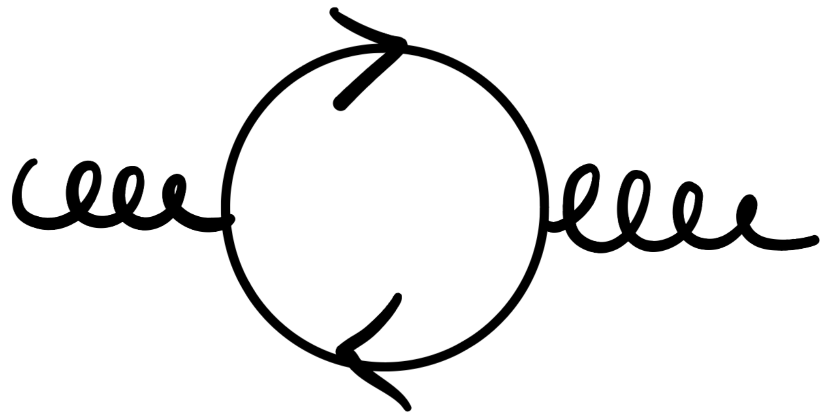

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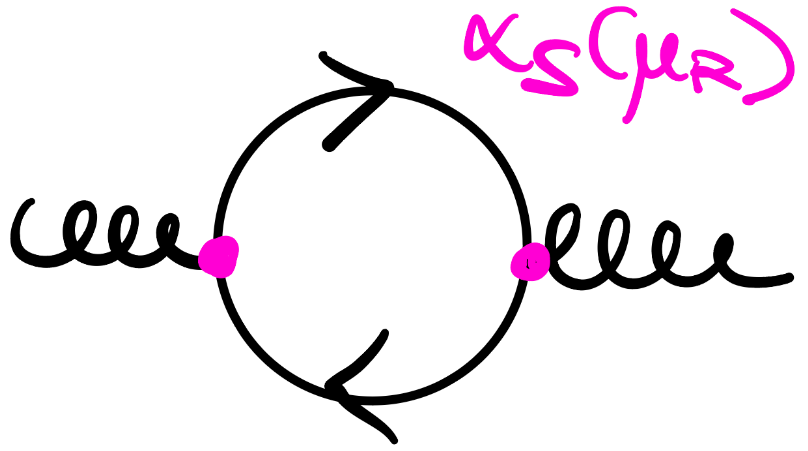

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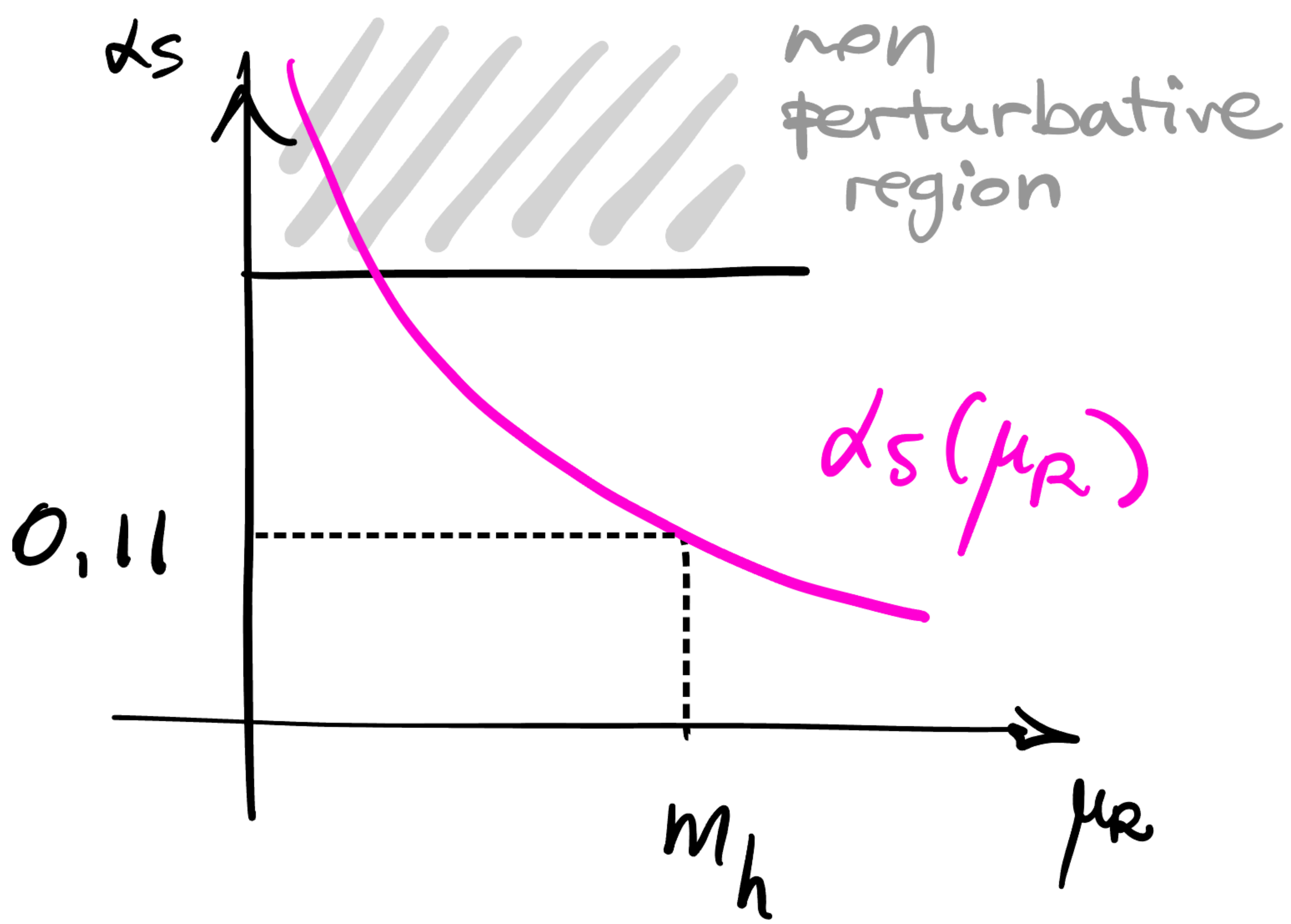
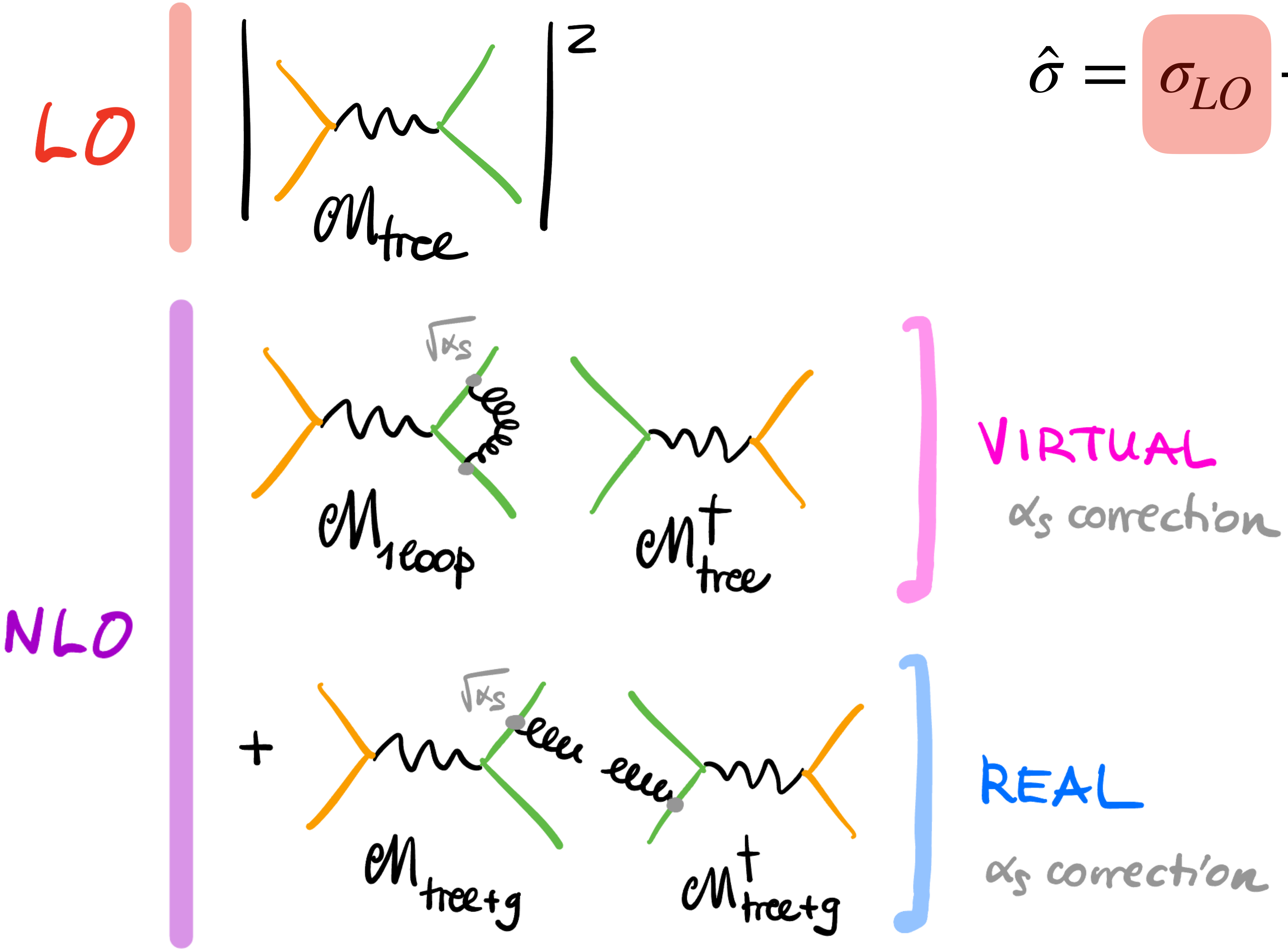


Thanks to the asymptotic freedom, we can use pQCD for the hard process:

$$\hat{\sigma} = \sigma_{LO} + \alpha_s \, \sigma_{NLO} + \alpha_s^2 \, \sigma_{NNLO} + \ldots$$

Hard interaction: perturbative expansion

$$\hat{\sigma} = \sigma_{LO} + \alpha_s\, \sigma_{NLO} + \alpha_s^2\, \sigma_{NNLO} + \ldots$$



IR divergences

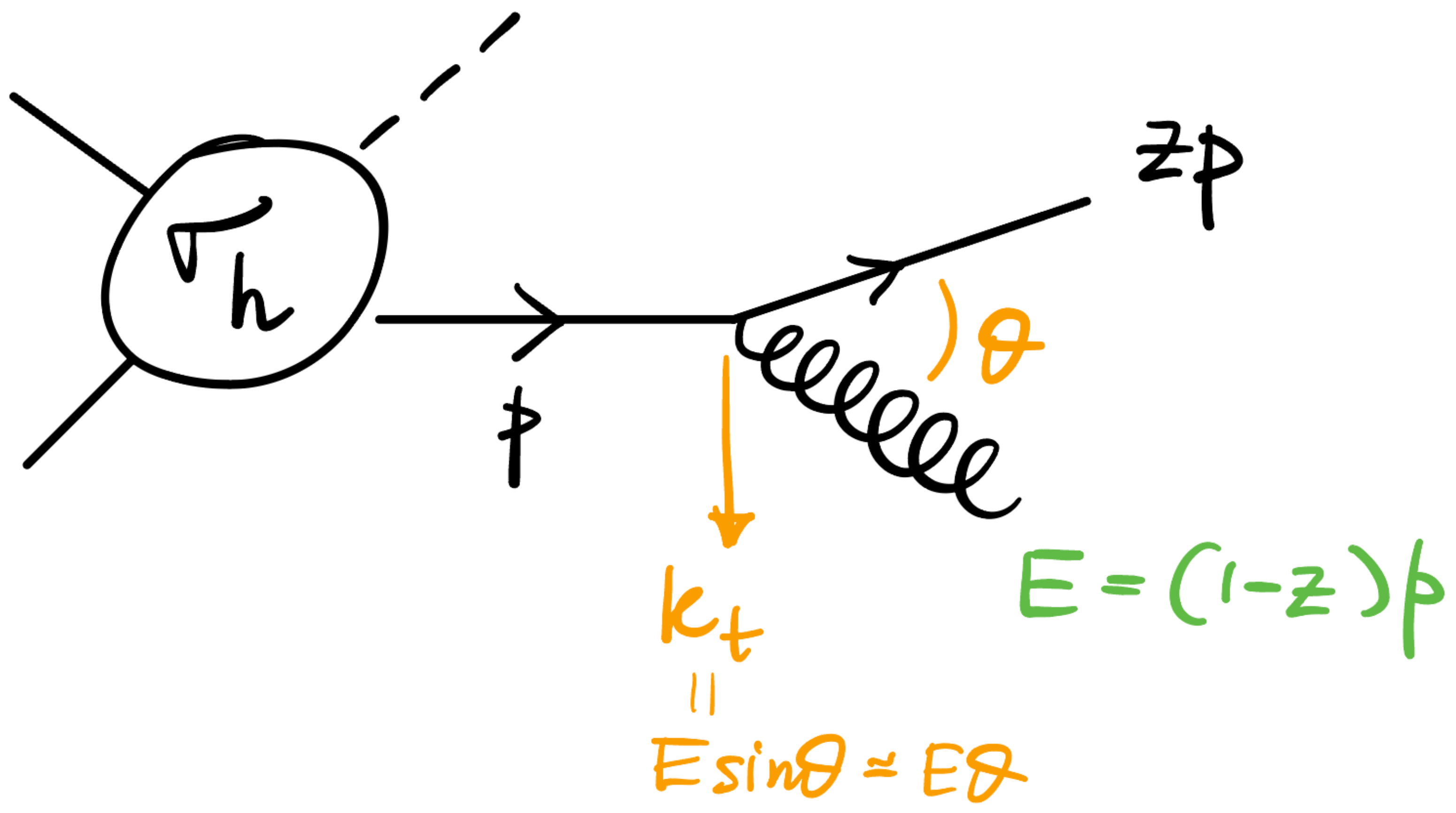
- How we can describe an LHC event?
- **QCD loves to split particles, how do we treat them?**
- How and where can we absorb the collinear divergence?
- What is the role of PDFs in a phenomenological calculation?
- “Shut up and calculate” a cross-section

Final-state splitting

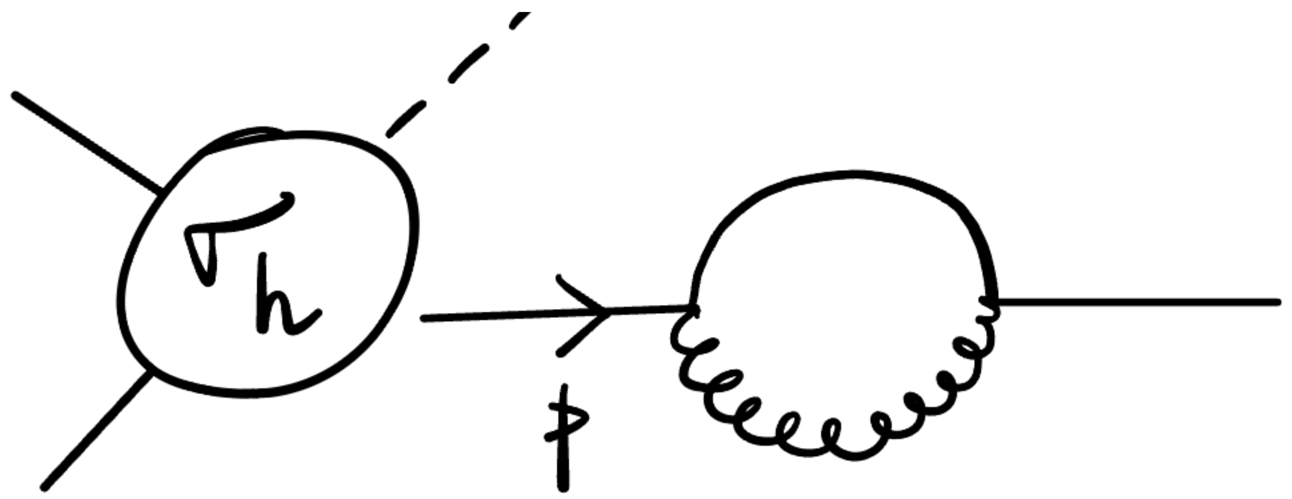
In the collinear ($\theta \ll 1$) and soft ($E \ll p$) limit

$z =$ energy fraction $\in [0,1]$

$k_t =$ transverse mom $\in [0, +\infty)$



$$d\sigma_{h+g} \sim \sigma_h\, \alpha_s \frac{dE}{E} \frac{d\theta^2}{\theta^2} = \sigma_h\, \alpha_s \frac{dz}{1-z} \frac{dk_t^2}{k_t^2}$$

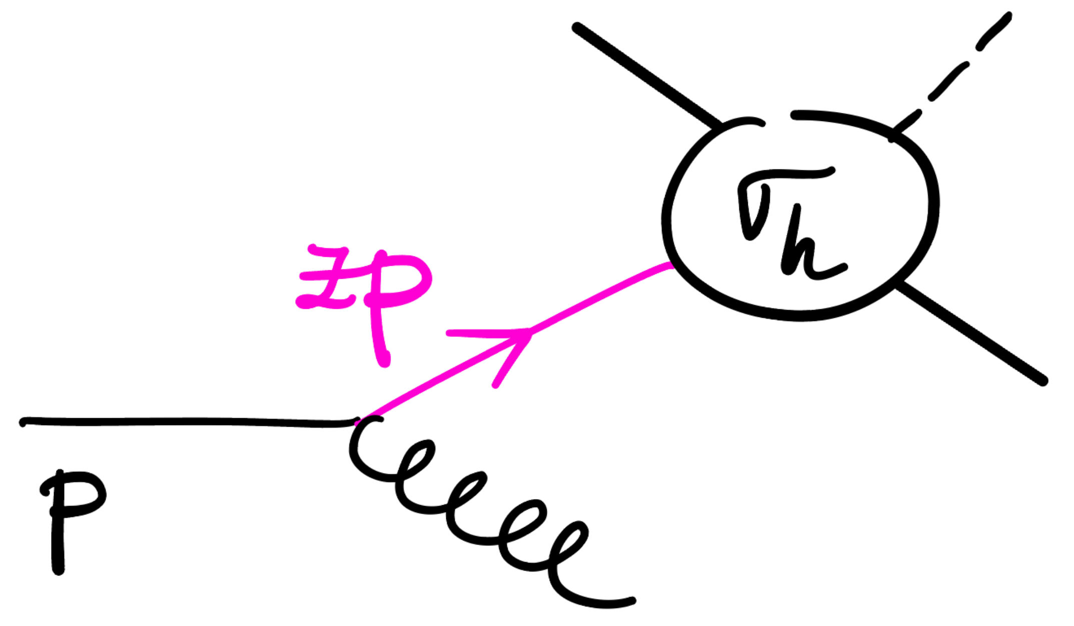


$$d\sigma_{h+V} \sim -\sigma_h\, \alpha_s \frac{dz}{1-z} \frac{dk_t^2}{k_t^2}$$

If we are inclusive, the divergent real and virtual corrections cancel out!

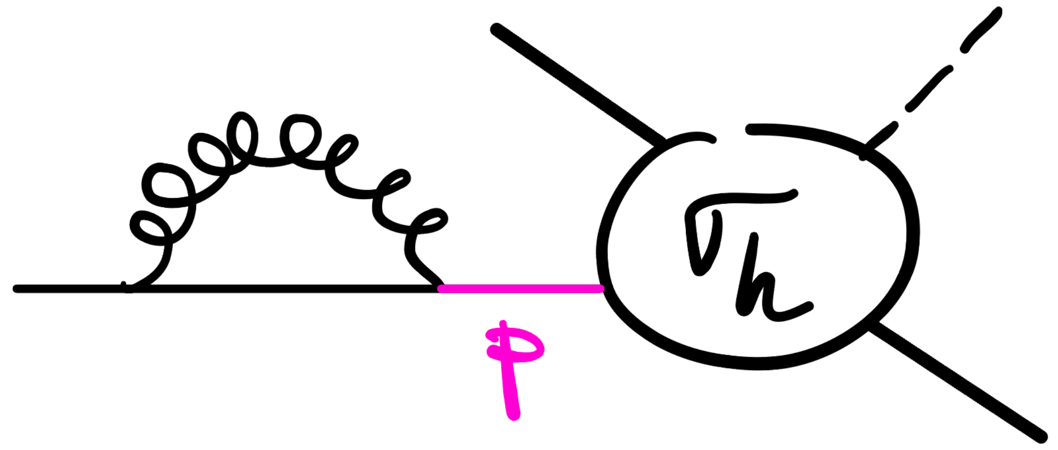
Initial-state splitting

The hard contributions have a different longitudinal momentum!



$$d\sigma_{h+g} \simeq \sigma_h(zp)\ \alpha_s \frac{dz}{1-z}\frac{dk_t^2}{k_t^2}$$

+



$$d\sigma_{h+V} \simeq -\sigma_h(p)\ \alpha_s \frac{dz}{1-z}\frac{dk_t^2}{k_t^2}$$

$$\sigma_{is} \sim \alpha_s \int_0^{Q^2} \frac{dk_t^2}{k_t^2} \int_0^1 \left[\sigma_h(zp) - \sigma(p)\right]\frac{dz}{1-z}$$

$\to \infty$ finite

Cross-sections with incoming partons are not collinear safe!

! $k_T \to 0$

Regularise PDFs

- How we can describe an LHC event?
- QCD loves to split particles, how do we treat them?
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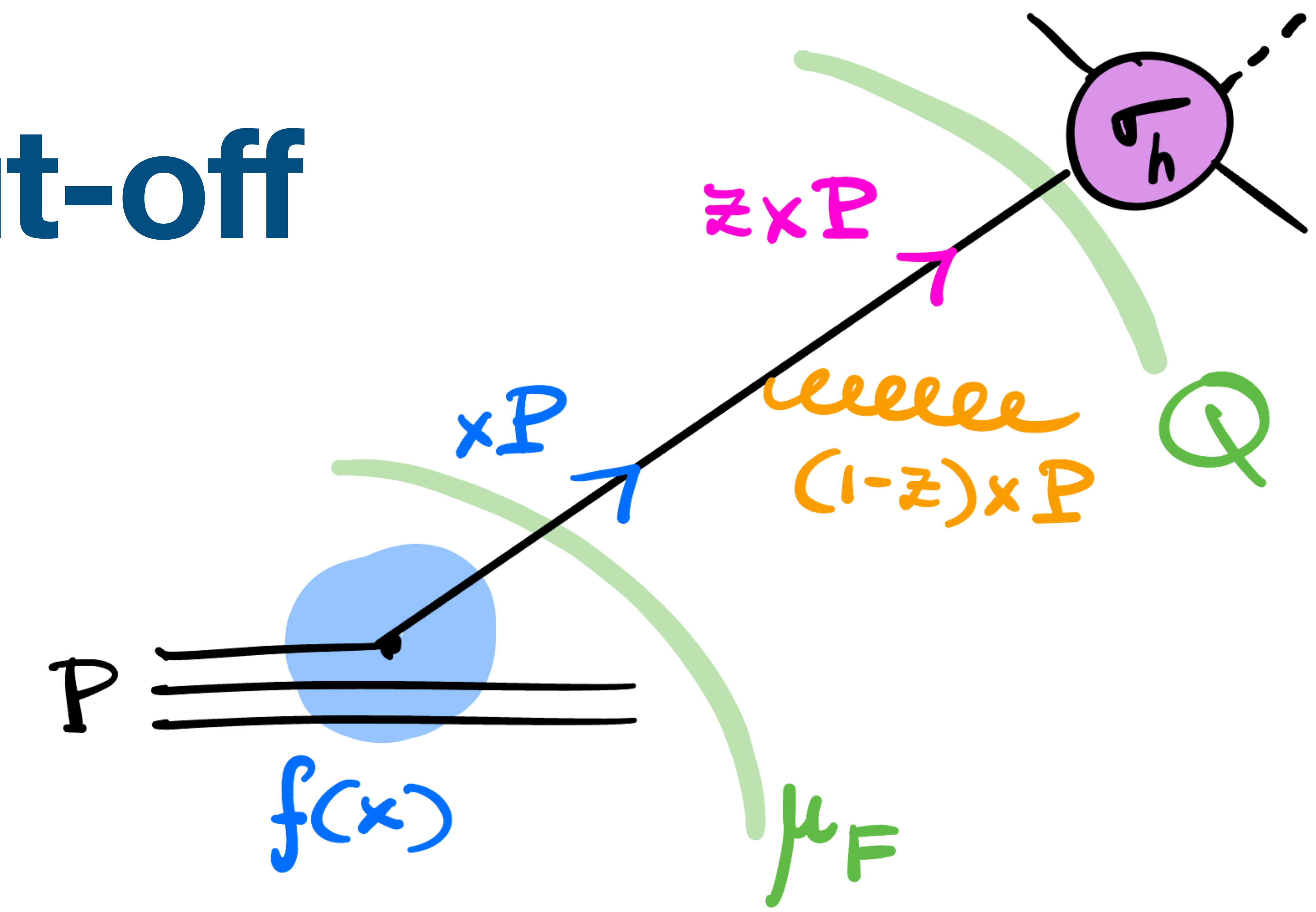
Introduce a factorisation cut-off



The divergence arises from a soft transverse scale treated in pQCD:

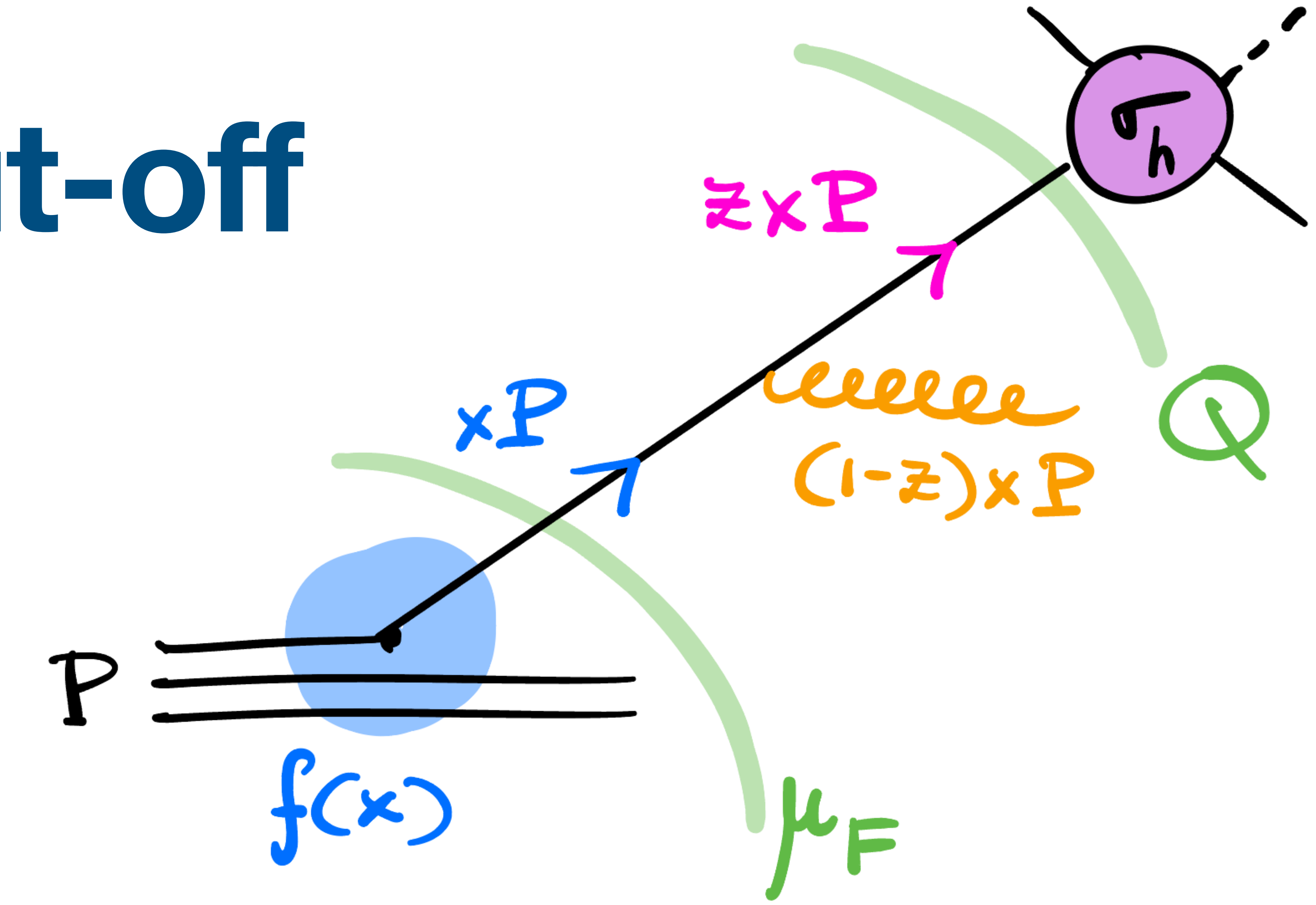
- Introduce a cut-off μ_F for the splitting
- Use a PDF for treating the non-perturbative region below $k_T < \mu_F$

now finite

$$\sigma_{is} = \int_0^1 \mathrm{d}x\, [\sigma_{is}]_{cutoff}\, f(x) \sim \alpha_s \int_{\mu_F^2}^{Q^2} \frac{\mathrm{d}k_T^2}{k_T^2} \int_0^1 \mathrm{d}x \int_0^1 \frac{\mathrm{d}z}{1-z} \left[\sigma_h(zxP) - \sigma_h(xP)\right] f(x)$$

μ_F is an arbitrary scale that factorises **proton non-perturbative dynamics** from the **perturbative hard process**

Introduce a factorisation cut-off



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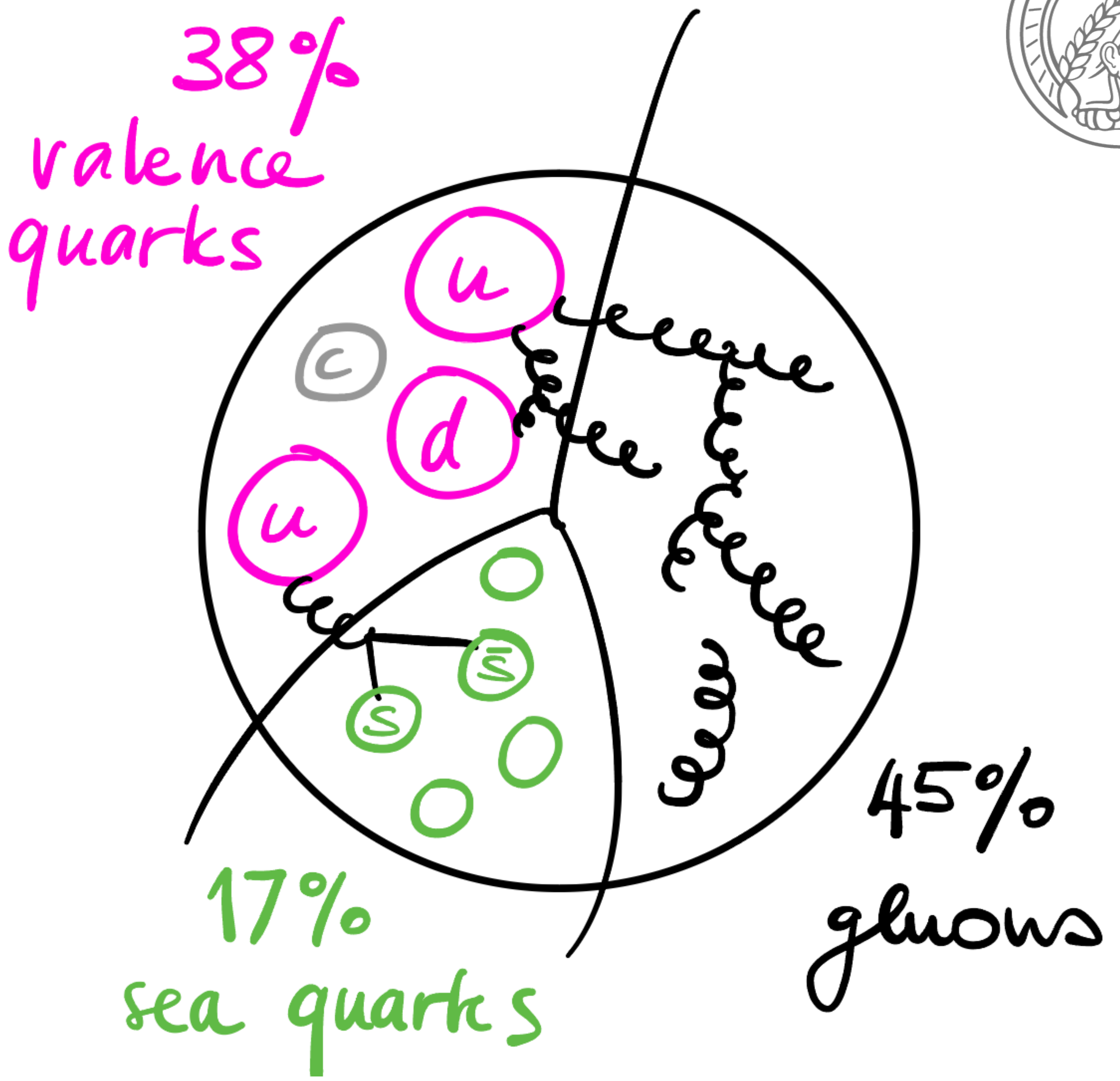
$f(x) \to f(x, \mu_F)$

μ_F is an arbitrary scale that factorises **proton non-perturbative dynamics** from the **perturbative hard process**

DGLAP flow

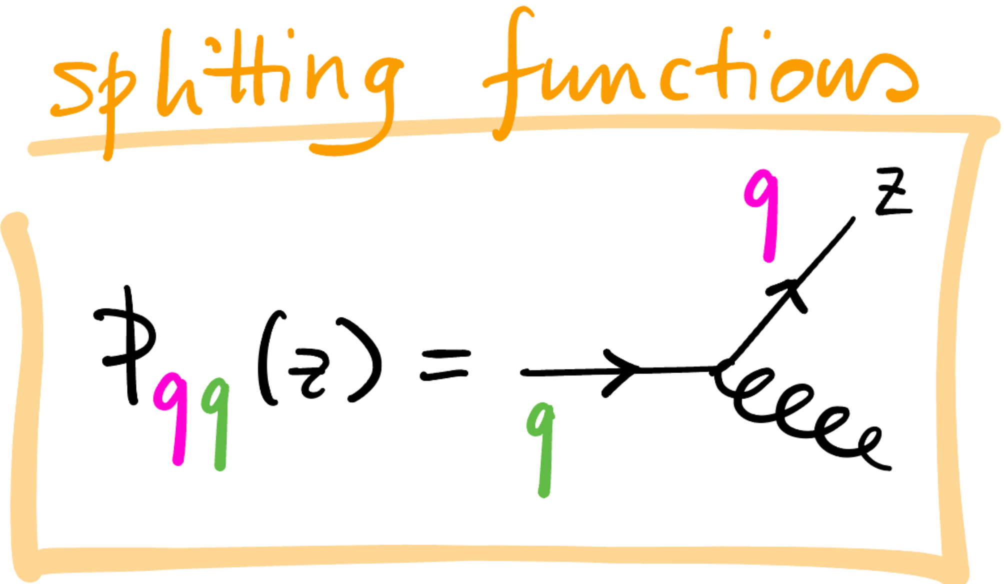
Similarly to the running of $\alpha_s(\mu_R)$, we can change μ_F and get a Renormalisation Group Flow for PDFs:

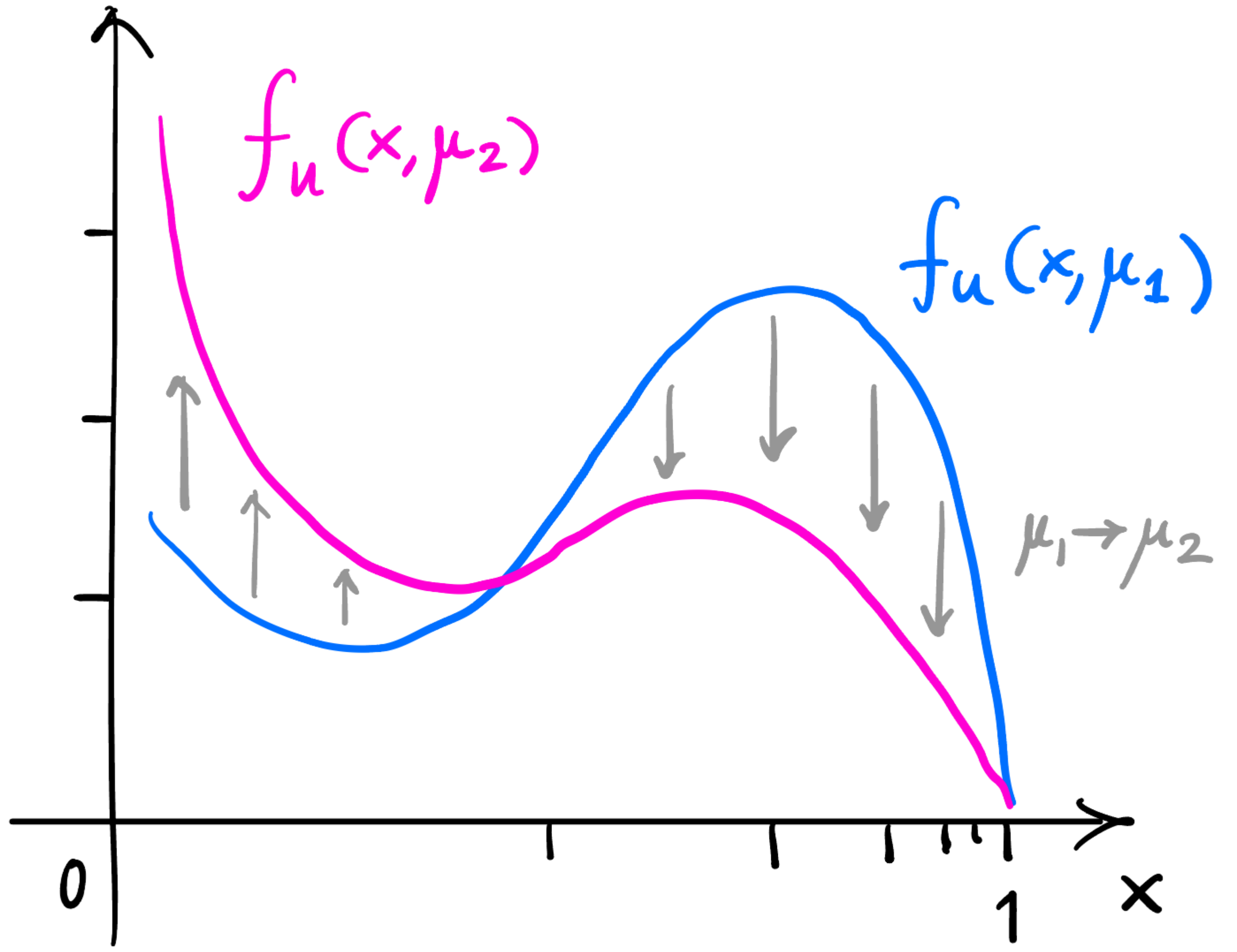
Dokshitzer–Gribov–Lipatov–
Altarelli–Parisi (DGLAP) equations



Also gluons represent a proton component! DGLAP is a matrix in flavour space

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu_F^2}\begin{pmatrix} f_q \\ f_{\bar{q}} \\ f_g \end{pmatrix} = \begin{pmatrix} P_{qq} & P_{q\bar{q}} & P_{qg} \\ P_{\bar{q}q} & P_{\bar{q}\bar{q}} & P_{\bar{q}g} \\ P_{gq} & P_{g\bar{q}} & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} f_q \\ f_{\bar{q}} \\ f_g \end{pmatrix}$$





From data to data

- How we can describe an LHC event?
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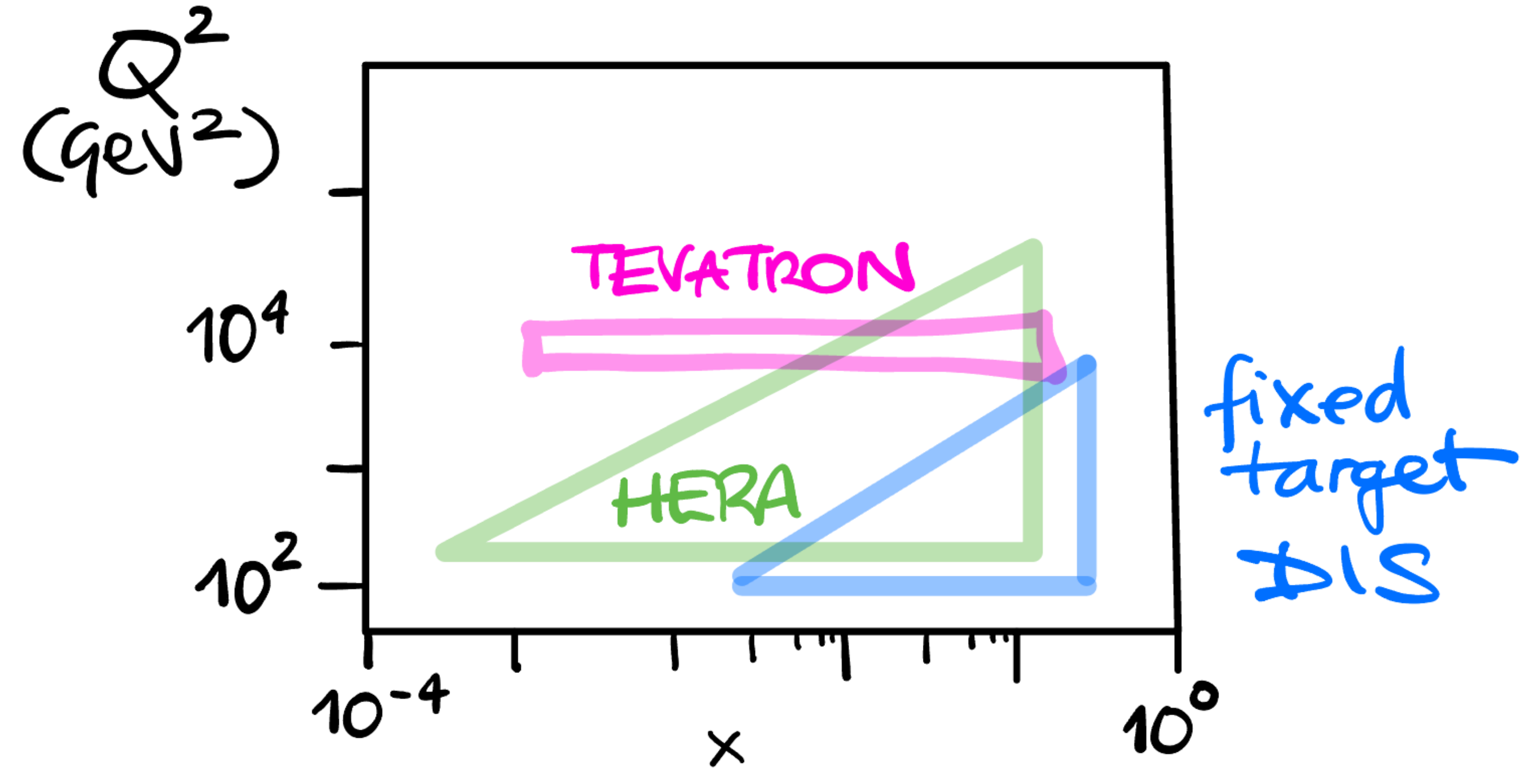
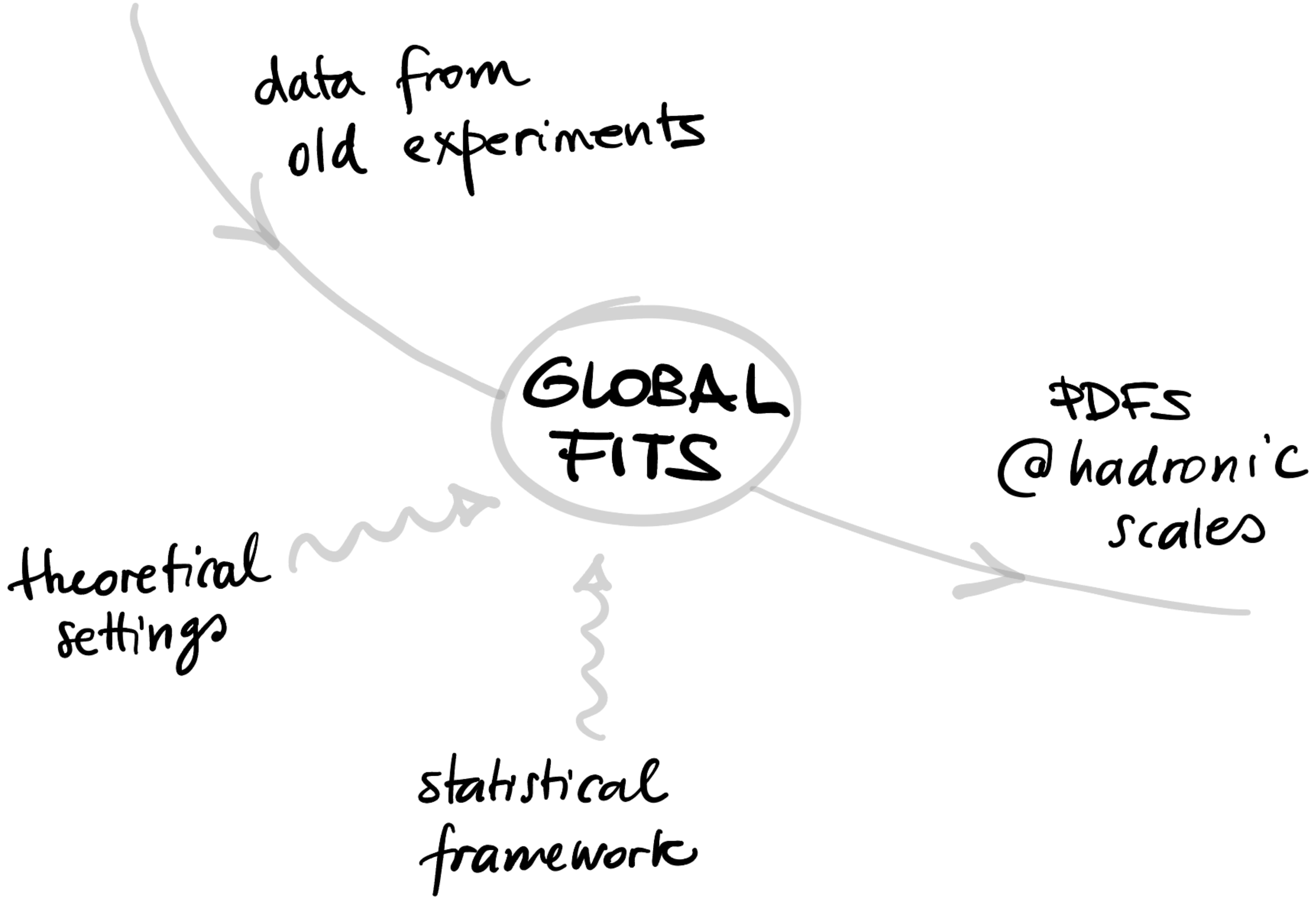
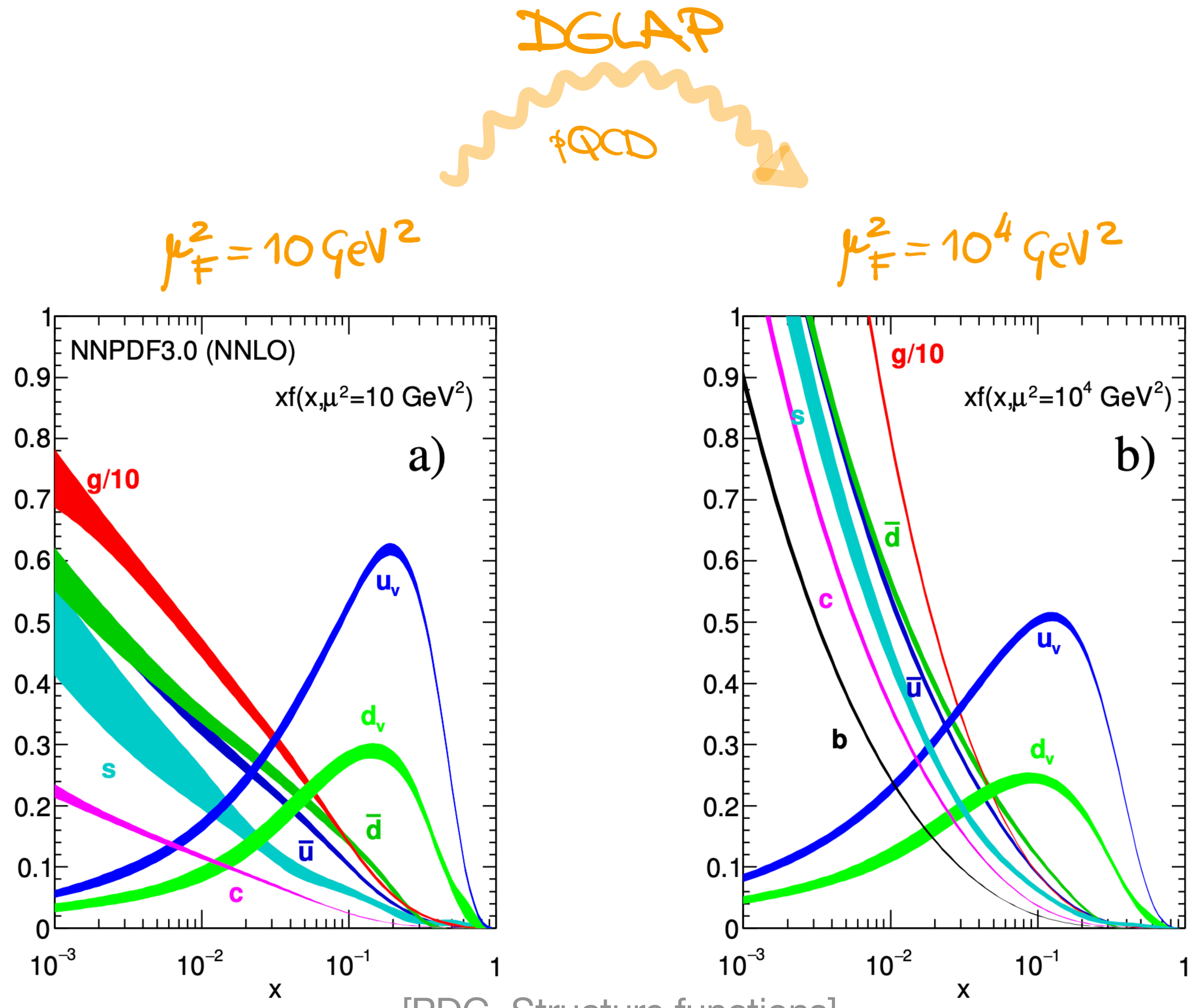
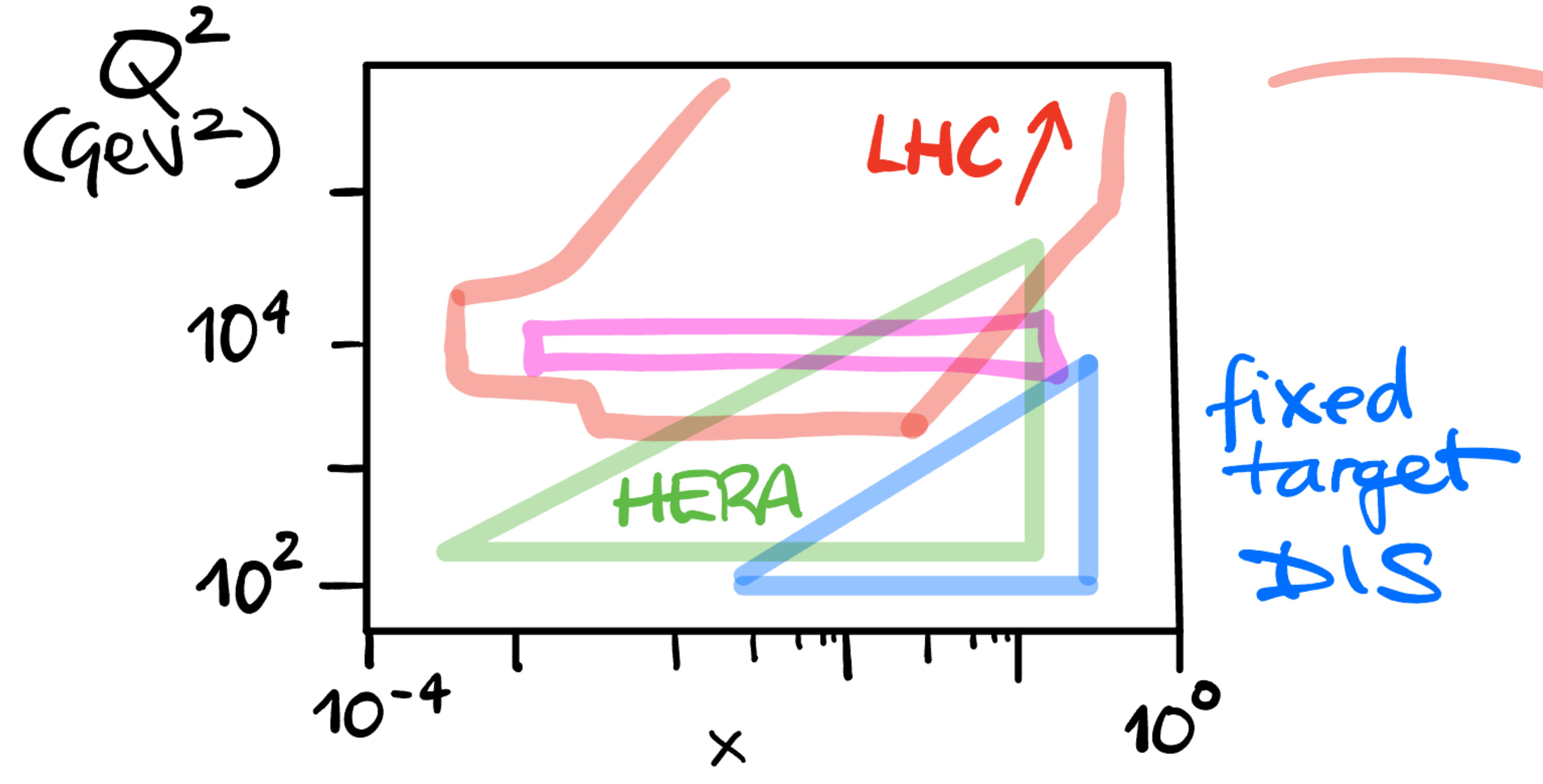
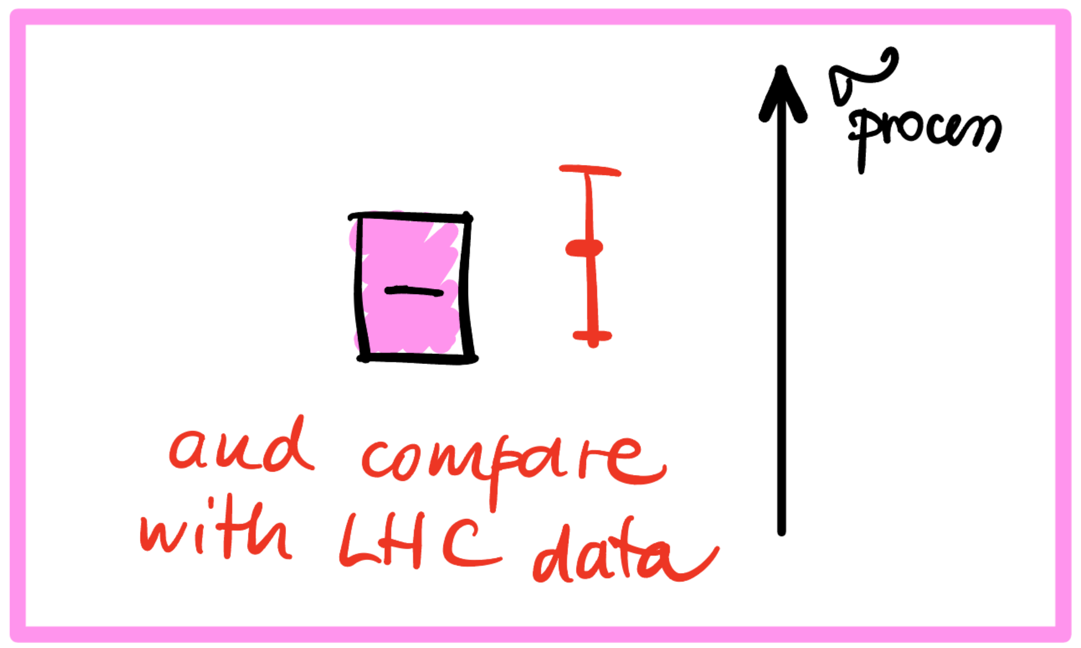


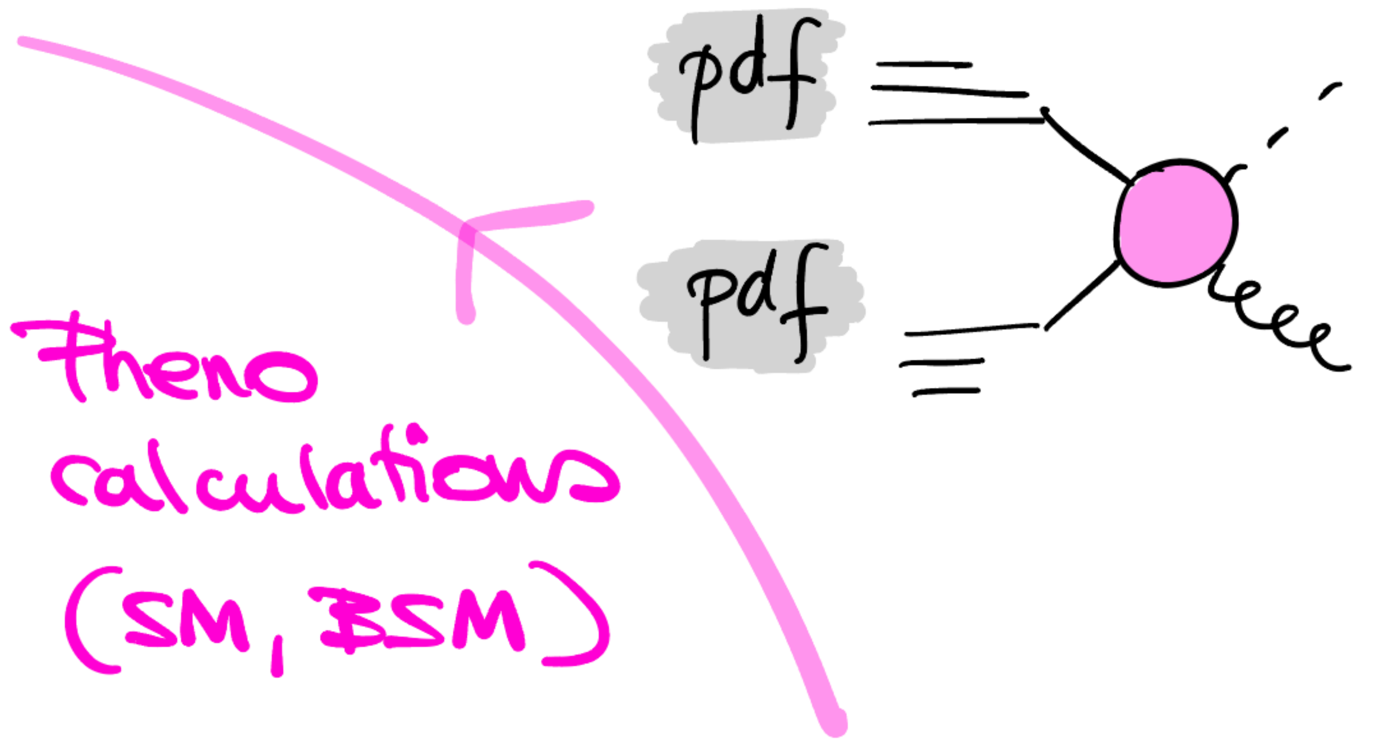


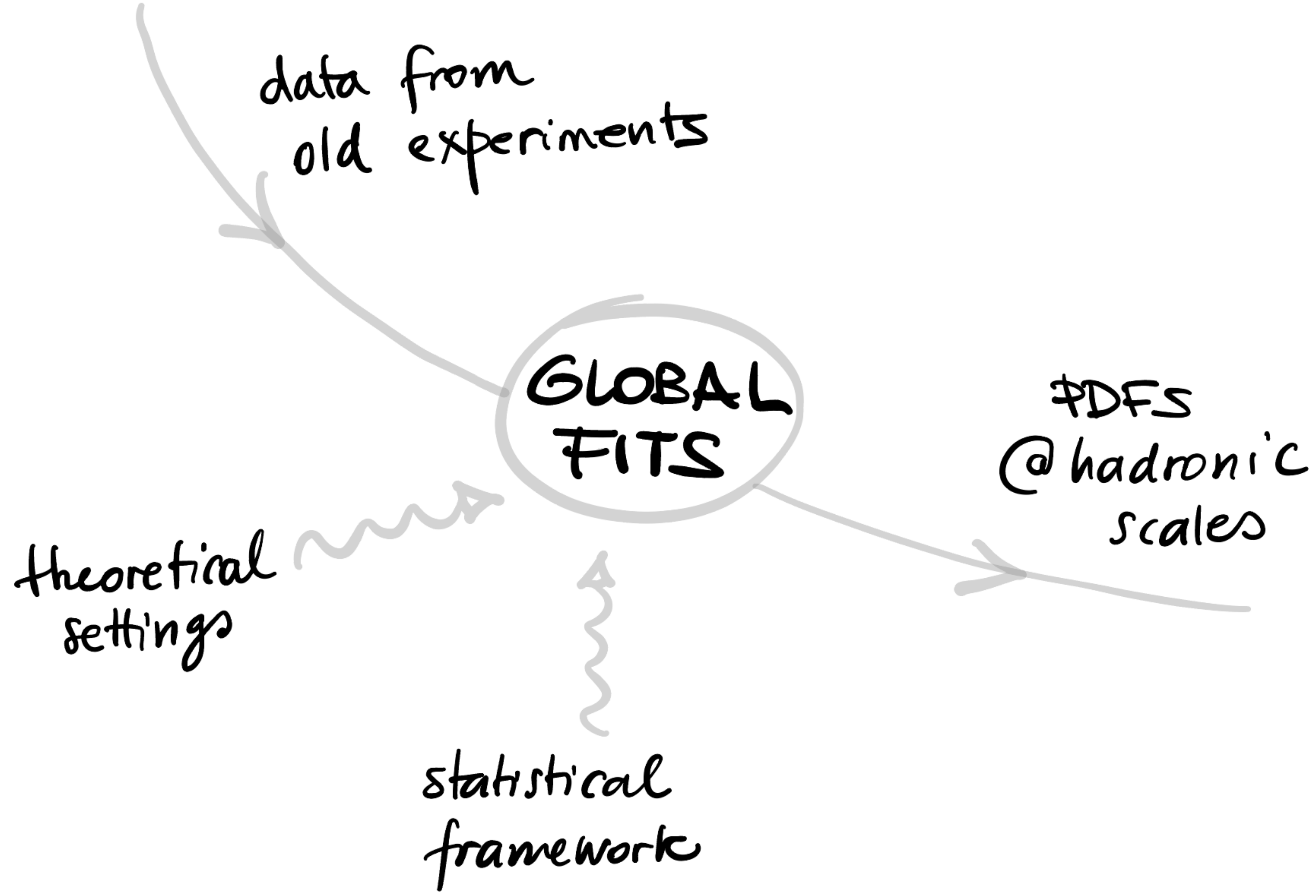


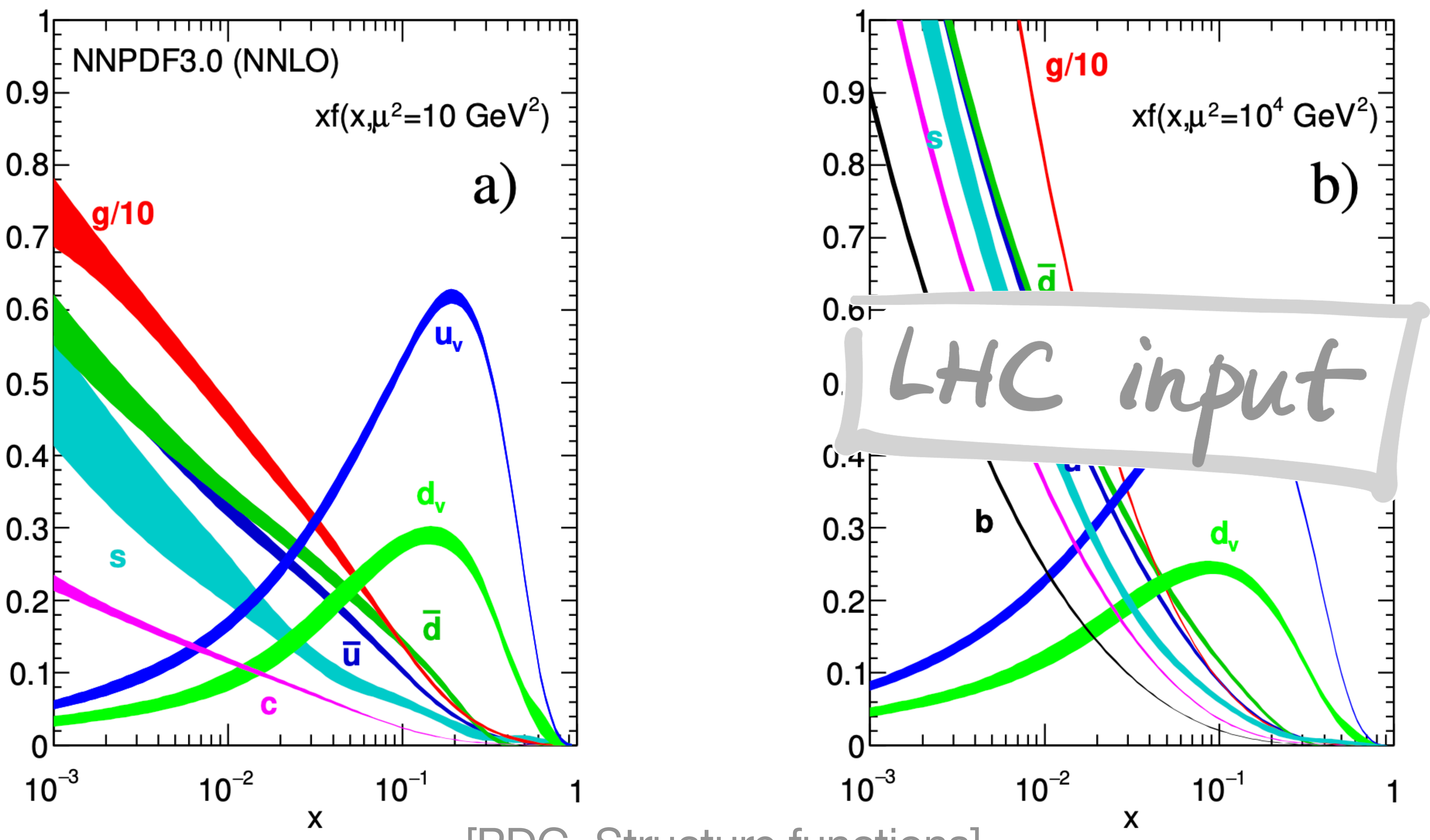
[PDG, Structure functions]











[PDG, Structure functions]

The LHC master formula

- How we can describe an LHC event?
- QCD loves to split particles, how do we treat them?
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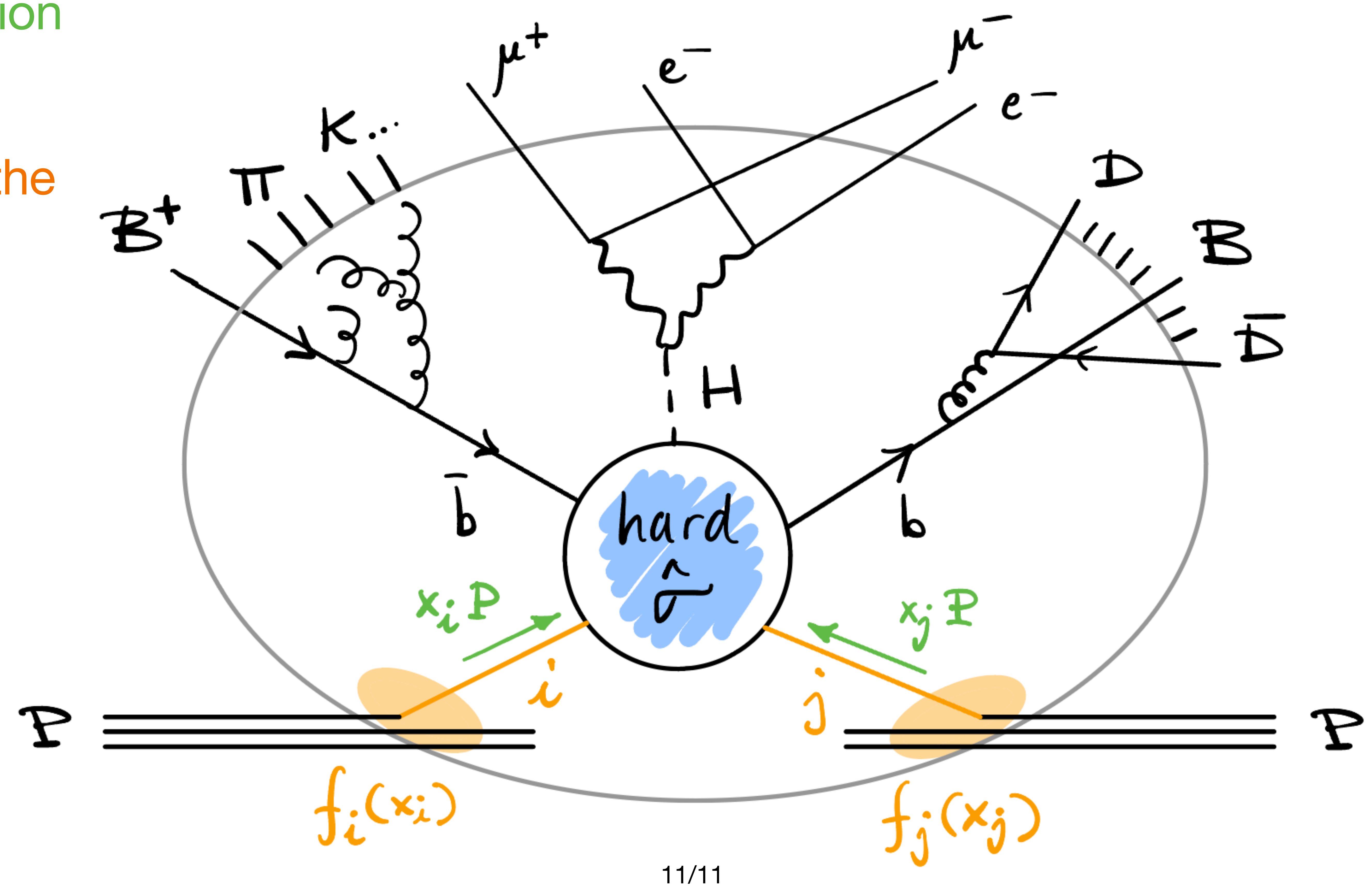
- **“Shut up and calculate” a cross-section**

The LHC master formula

$$\sigma(P_1P_2 \to b\bar{b}H + X) = \sum_{ij} \int \mathrm{d}x_1\, \mathrm{d}x_2\, f_i(x_1, \mu_F^2)\, f_j(x_2, \mu_F^2) \sum_n \alpha_s^n(\mu_R)\, \hat{\sigma}^{(n)}(x_1 x_2 E_{CM}^2, \mu_R^2, \mu_F^2)$$

x_1 = momentum fraction of the parton

f_i = probability to find the parton i in the proton



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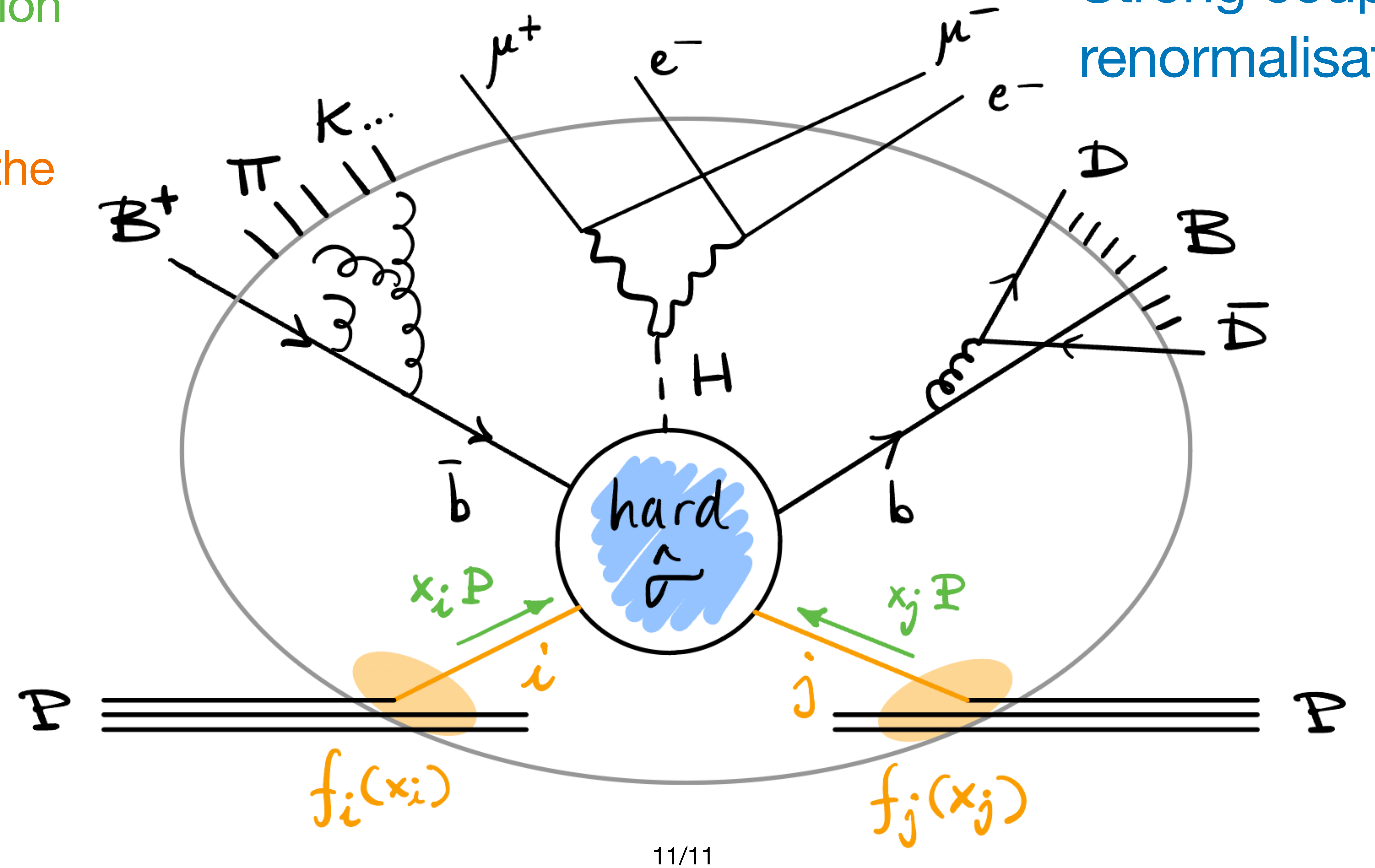
Strong coupling and renormalisation scale

x_1 = momentum fraction of the parton

f_i = probability to find the parton i in the proton



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Hard interactions in pQCD

x_1 = momentum fraction of the parton

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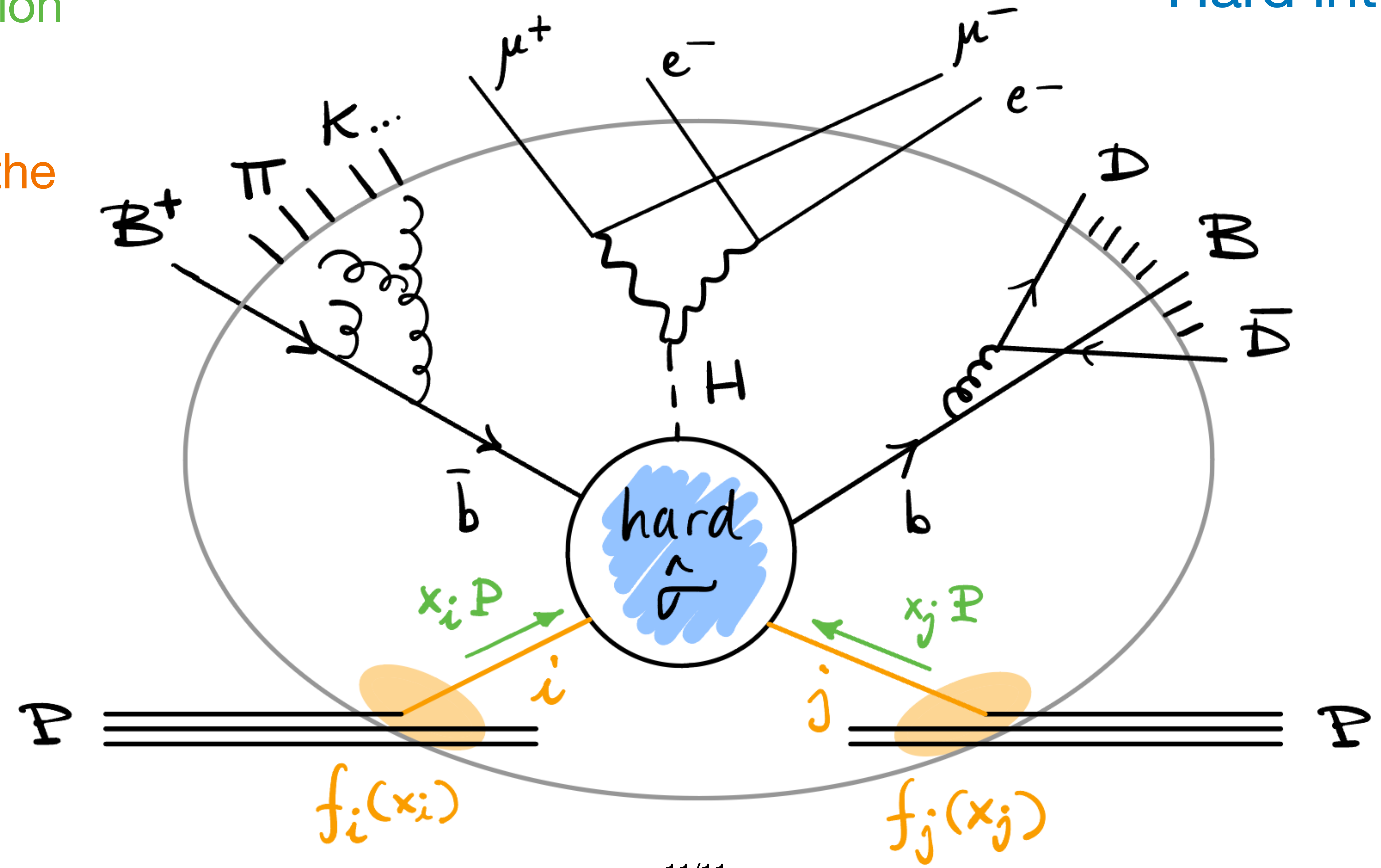

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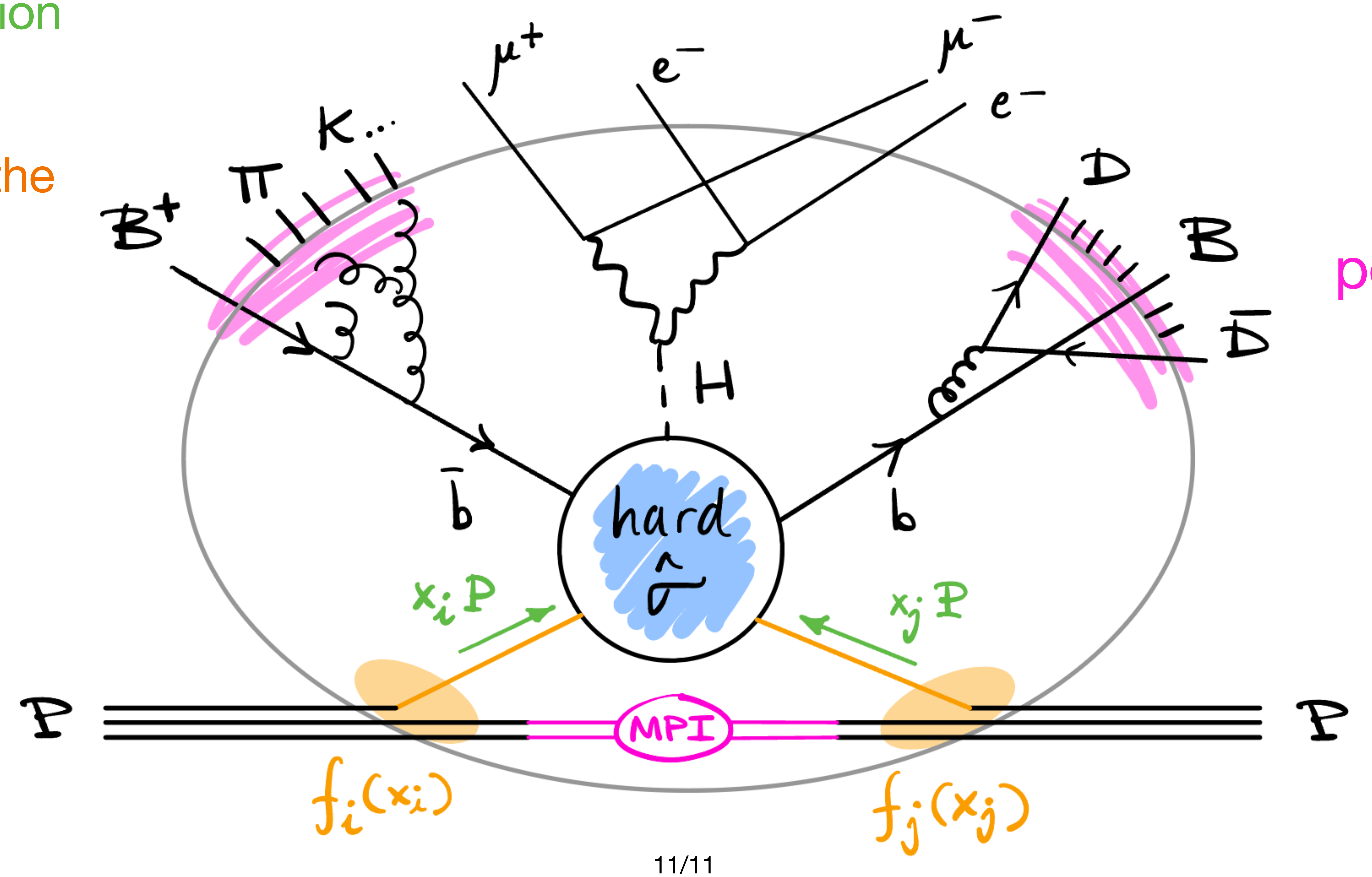
$$+\mathcal{O}\left(\frac{\Lambda_{QCD}}{m_h}\right)$$

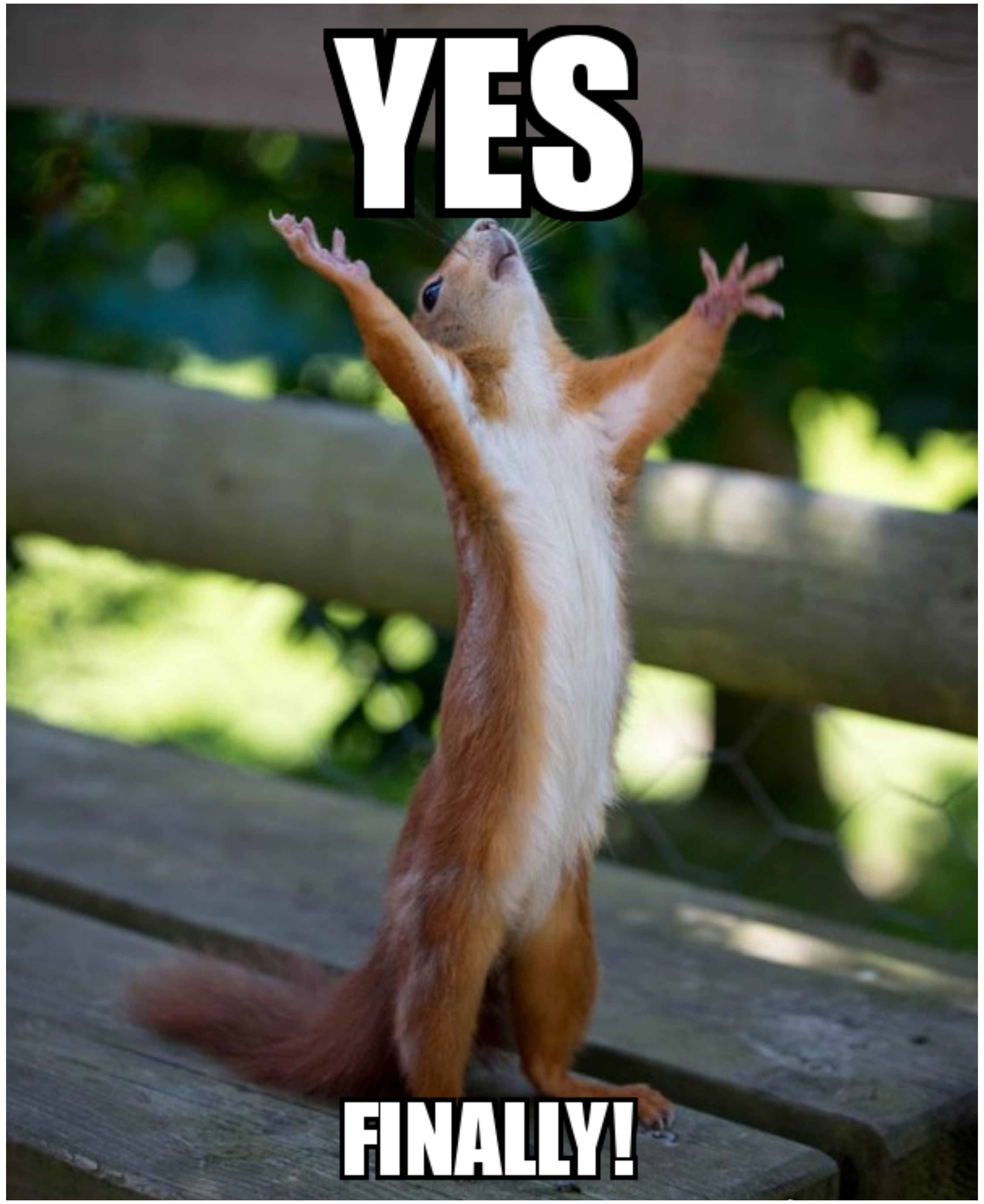
Additional non perturbative effects

x_1 = momentum fraction of the parton

f_i = probability to find the parton i in the proton



Thank you for your attention!

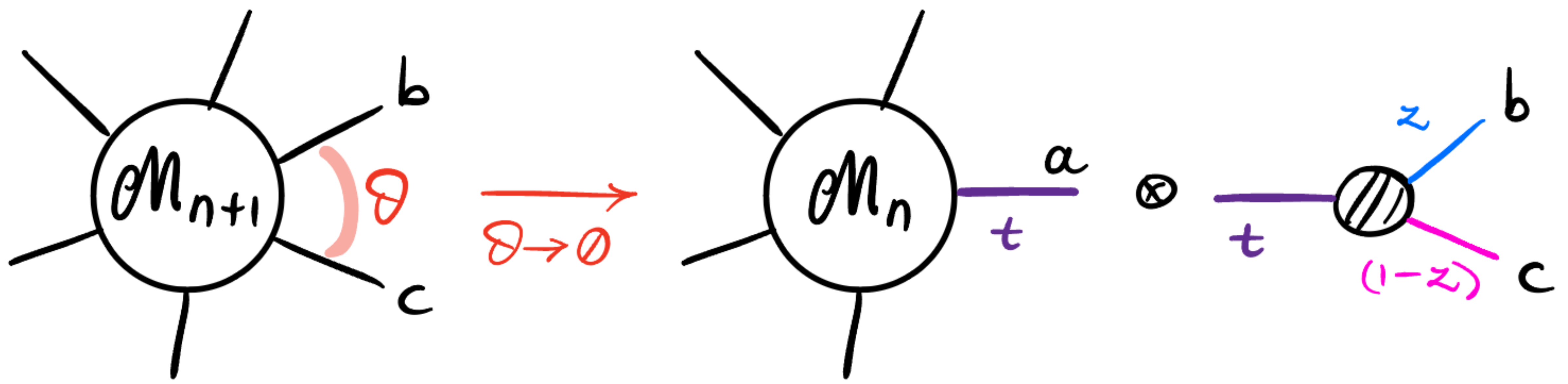


Backup slides (1)
PWG and MiNNLO

Shower Monte Carlo

Marchesini, Webber [NPB238(1984)1]
Sjostrand [PLB157(1985)321]
Altarelli, Parisi [NPB126(1977)298]

The Parton Shower formalism is based on **collinear factorisation** with a probabilistic description of the splitting process.



Similarly to a radioactive decay, the probability of evolving between two scales and emitting no gluons is

$$\Delta_t = \exp\left[-\int_t \frac{dt'}{t'} dz' d\varphi' \frac{\alpha_s}{2\pi} P(z')\right]$$

exp(−λt) = non-radiation probability

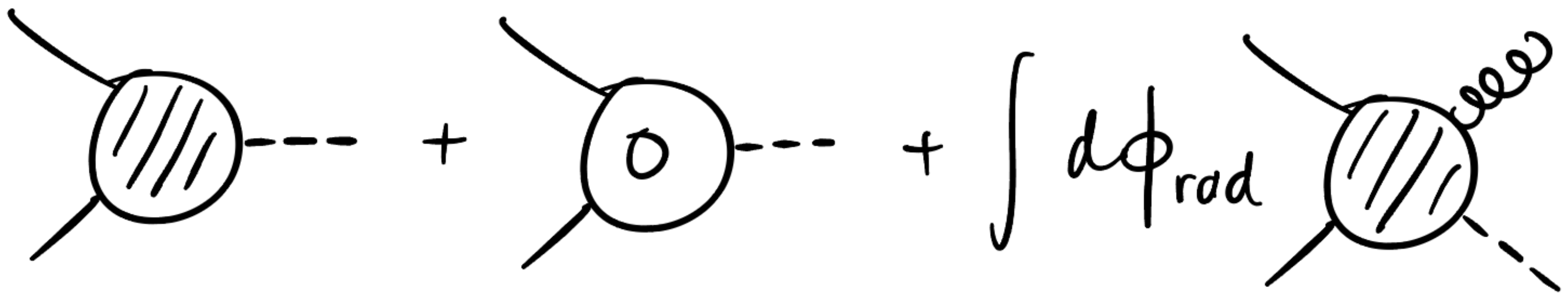
Using this form factor we can deduce the SMC prediction with the first emission

$$\langle \mathcal{O} \rangle = \int d\Phi_n B(\Phi_n) \left[\mathcal{O}(\Phi_n)\Delta_{t_0} + \int_{t_0} \frac{dt}{t} dz d\varphi \mathcal{O}(\Phi_n, \phi_r)\Delta_t \frac{\alpha}{2\pi} P(z)\right]$$

exp(−λt) λδt = probability of the 1st radiation

$$\simeq \int d\Phi_n B(\Phi_n) \left[\mathcal{O}(\Phi_n) + \int_{t_0} \frac{dt}{t} dz d\varphi \left(\mathcal{O}(\Phi_n, \phi_r) - \mathcal{O}(\Phi_n)\right) \frac{\alpha_s}{2\pi} P(z)\right]$$

NLO



✓ NLO accuracy for inclusive observables

✓ Reduced theoretical uncertainty

✓ Correct quantum interference

- Wrong shape for small-p_T region
- Description only at the parton level
- Computationally expensive

SMC (LOPS)

- Total normalisation accurate only at LO
- Poor description at high-p_T
- Partial interference through shower ordering

✓ Sudakov suppression of small-p_T emissions (LL resummation)

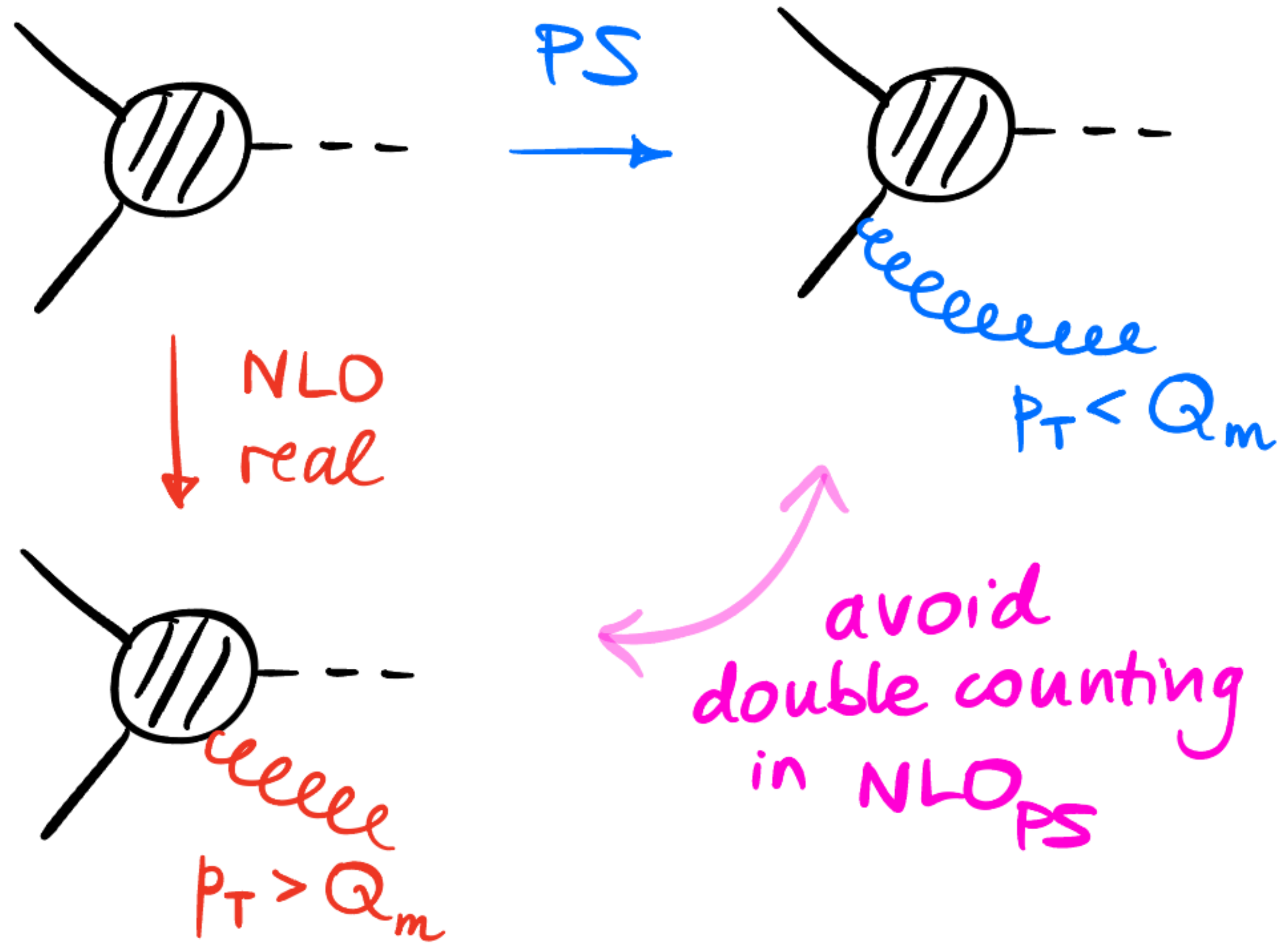
✓ Simulate high-multiplicity events at the hadron level

✓ Computationally cheap

HERWIG, SHERPA, PYTHIA, …

Approaches are complementary: combine them in a consistent way

Matching problem



Double counting can be easily solved by applying a cut in phase space:

- **Reject hard jets** produced by PS with $p_T > Q_m$

But how can we obtain smooth distributions without a critical dependence on the matching scale Q_m?

MC@NLO [Frixione, Webber, 2002] and POWHEG [Nason, 2004] are two fully tested solutions.

POWHEG Idea

Write a simplified Monte Carlo that generates just one emission (the hardest one) which alone gives the correct NLO result.

$$\Delta^{pwg} = \exp\left[-\int \text{exact real-radiation probability above } p_T\right]$$

POWHEG in a nutshell

$$\bar{B} = B + V + \int d\phi_{rad} R$$

The exact NLO prediction is

$$\langle \mathcal{O} \rangle = \int d\Phi_n \, \mathcal{O}(\Phi_n) \bar{B}(\Phi_n) + \int d\Phi_n \, d\phi_{rad} \big(\mathcal{O}(\Phi_n, \phi_{rad}) - \mathcal{O}(\Phi_n) \big) R(\Phi_n, \phi_{rad})$$

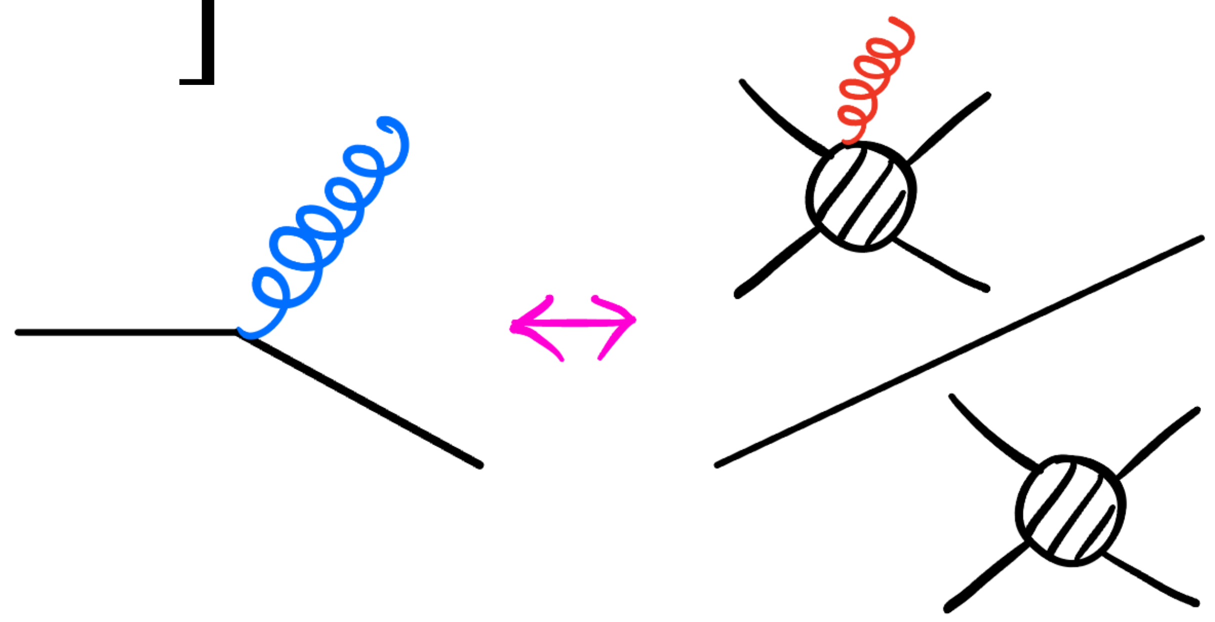
Comparing with the SMC

$$\langle \mathcal{O} \rangle_{SMC} \simeq \int d\Phi_n \left[\mathcal{O}(\Phi_n) B(\Phi_n) + B(\Phi_n) \int_{t_0} \frac{dt}{t} dz d\varphi \left(\mathcal{O}(\Phi_n, \phi_r) - \mathcal{O}(\Phi_n) \right) \frac{\alpha_s}{2\pi} P(z) \right],$$

we deduce the Sudakov form factor and the shower formula in POWHEG

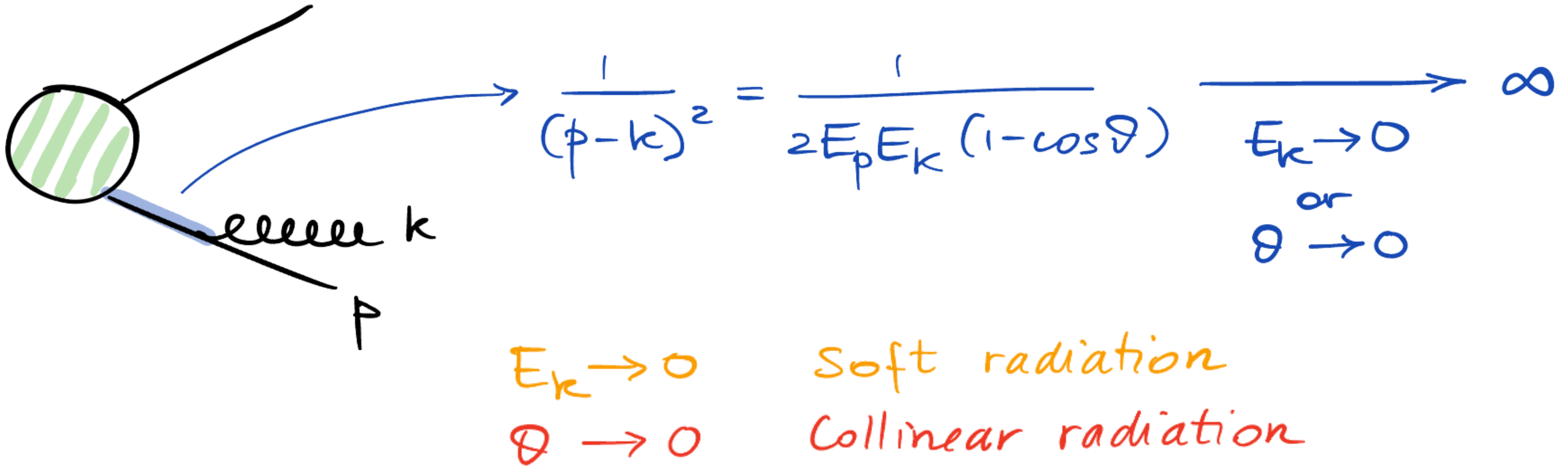
$$\langle \mathcal{O} \rangle = \int d\Phi_n \bar{B}(\Phi_n) \left[\mathcal{O}(\Phi_n) \, \Delta_{t_0}^{pwg} + \int d\phi_{rad} \, \mathcal{O}(\Phi_n, \phi_{rad}) \, \Delta_t^{pwg} \frac{R(\Phi_n, \phi_{rad})}{B(\Phi_n)}) \right]$$

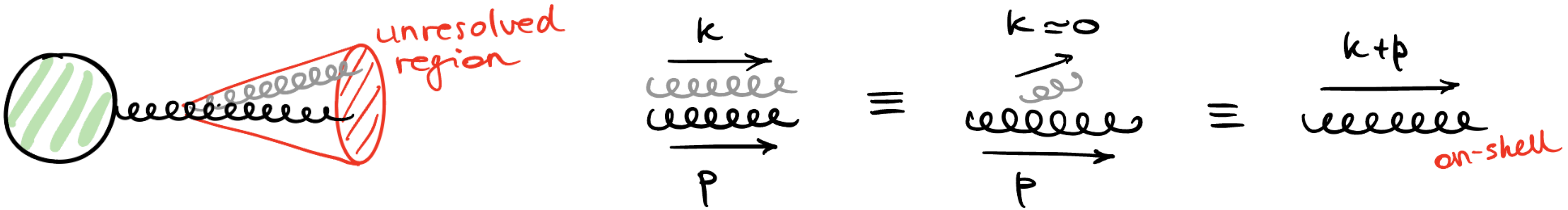
with $\Delta_t^{pwg} = \exp \left[- \int d\phi'_{rad} \frac{R(\Phi_n, \phi'_{rad})}{B(\Phi_n)} \Theta(t' - t) \right]$



IR divergences

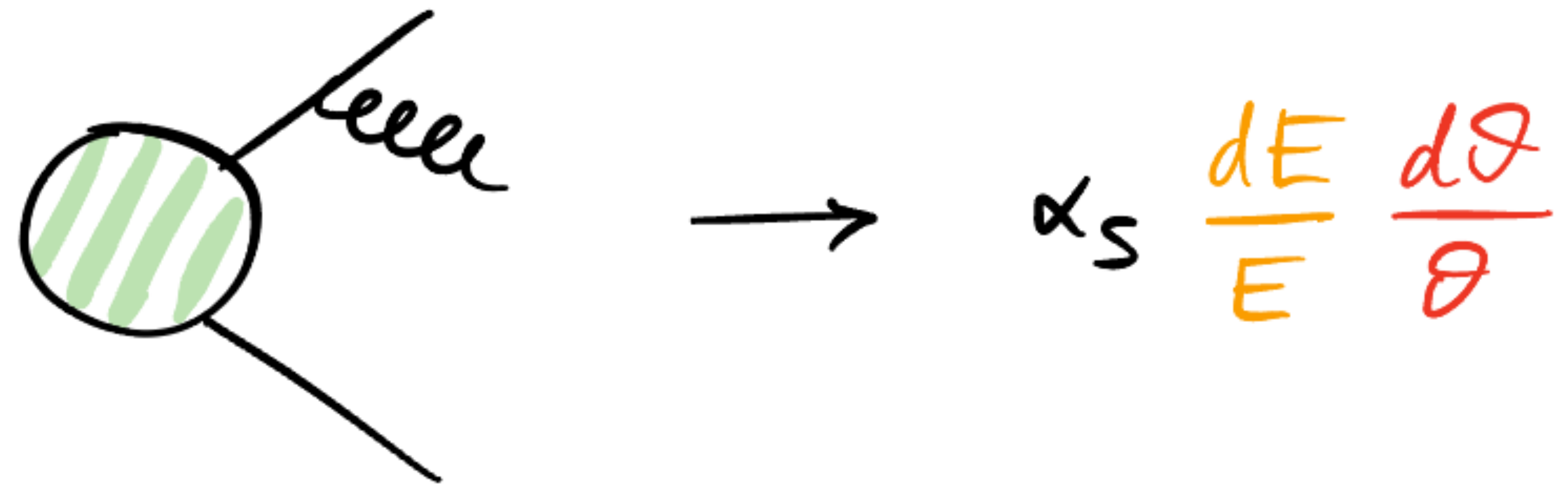
The radiation of a *massless* particle produces divergences: a manifestation of the degeneration of these states

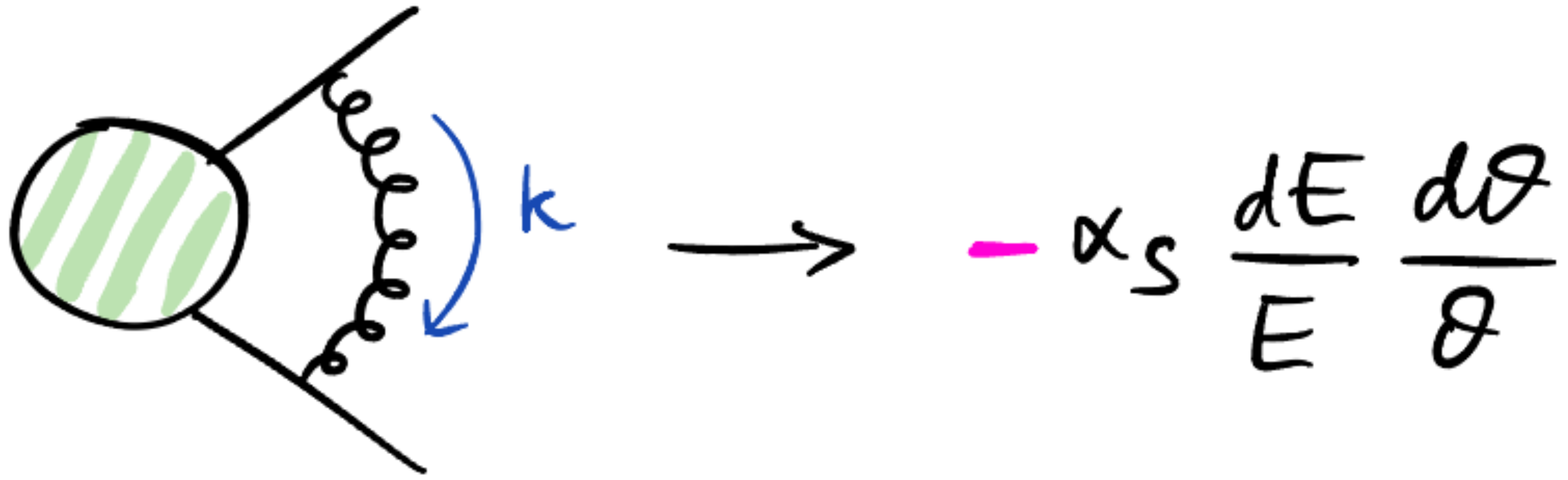




Logs as residues of IR divergences

A divergent structure is also present in the virtual contribution.
The **IR divergences cancel out** order by order in perturbation theory!

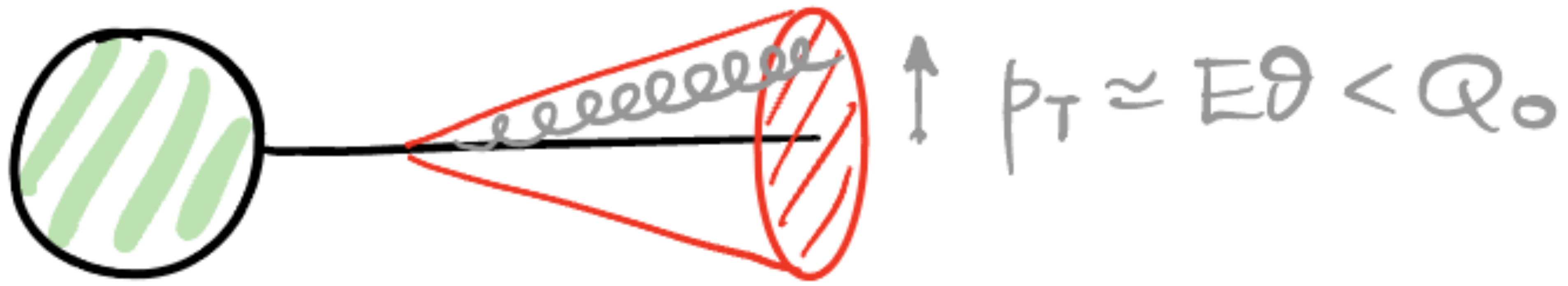




The IR divergences are cancelled, but if we are exclusive…

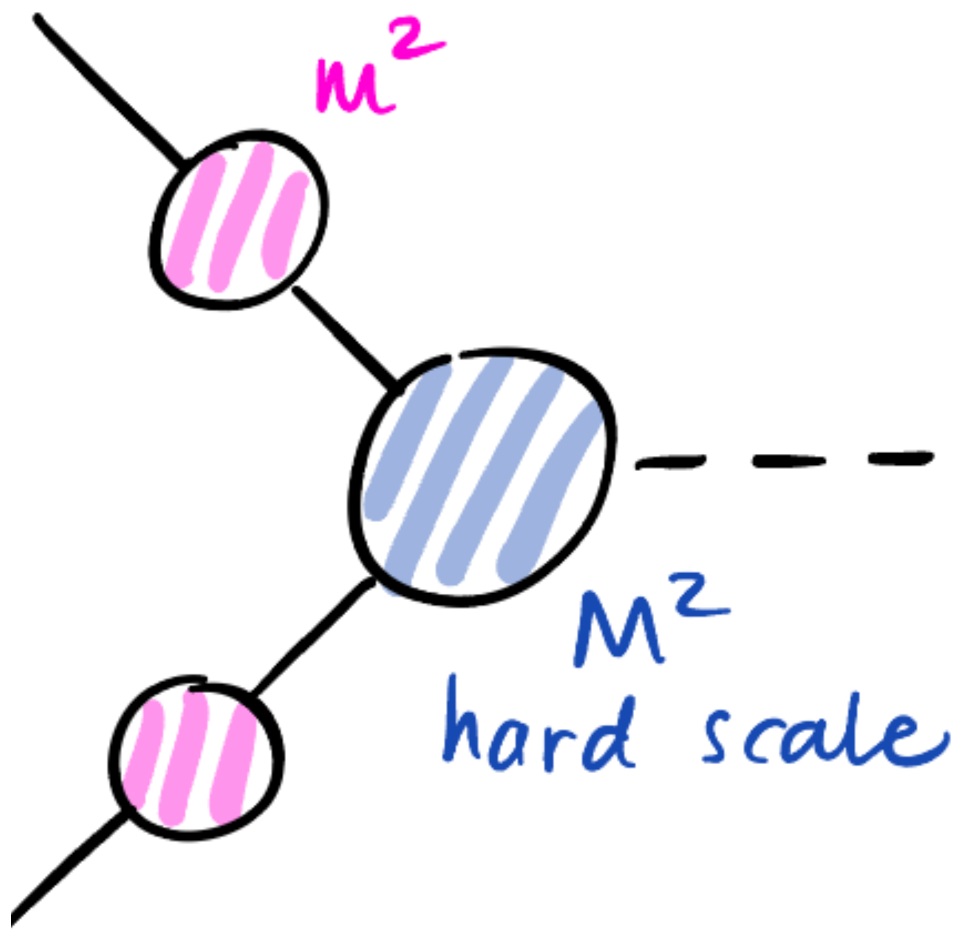
$$-\alpha_s \int_0^Q \frac{dE}{E}\frac{d\theta}{\theta}\,\Theta\left(E\theta < Q_0\right)\Big|_{\text{real}} + \alpha_s \int_0^Q \frac{dE}{E}\frac{d\theta}{\theta}\Big|_{\text{virt}} = \alpha_s \ln^2 \frac{Q}{Q_0}$$

Double Log



Resummation from factorisation

Consider a physical quantity $\mathcal{O}(M^2, m^2)$ in which m^2 measures the distance from the IR region.



Hard — Soft

$$\text{If } m^2 \ll M^2, \qquad \mathcal{O}(M^2, m^2) = H\left(\frac{M^2}{\mu^2}\right) S\left(\frac{m^2}{\mu^2}\right)$$

$$\mathcal{O} \text{ is } \mu - \text{independent} \quad \Rightarrow \frac{1}{H}\frac{d\ln H}{d\ln \mu^2} = -\frac{1}{S}\frac{d\ln S}{d\ln \mu^2} =: \gamma(\mu^2)$$

Solving the differential equation,

$$\mathcal{O}(M^2, m^2) = H(1)\, S(1)\, \exp\left[-\int_{m^2}^{M^2} \frac{dq^2}{q^2}\gamma(q^2)\right]$$

✓ for $m^2 \to 0$

Sudakov form factor:
it captures at *all order*
the log-enhanced terms

Transverse momentum resummation

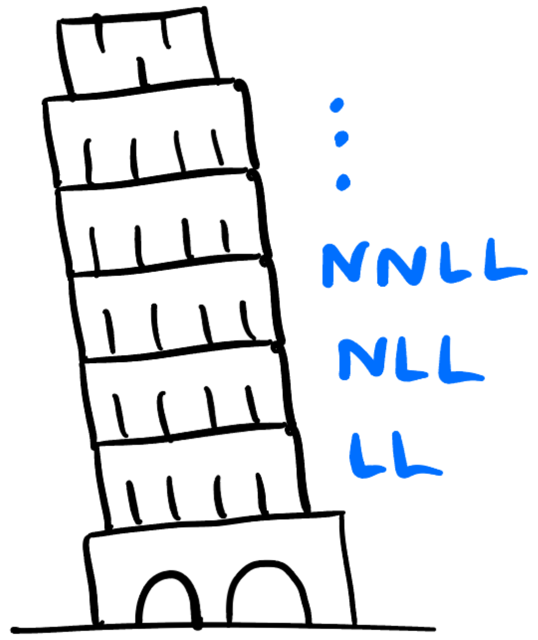
What is the probability that a boson is produced with transverse momentum $< p_T$?

$$\mathscr{P} \simeq -\#\alpha_s \ln^2 \frac{Q}{p_T} + \mathcal{O}(\alpha_s^2) \to \exp\left[-\#\alpha_s \ln^2 \frac{Q}{p_T}\right]$$

for small p_T we need to sum up the logs

In general we have a tower of logs

$$\exp\left[-\sum_{n,m} \alpha_s^n \ln^m \frac{Q}{p_T}\right]$$

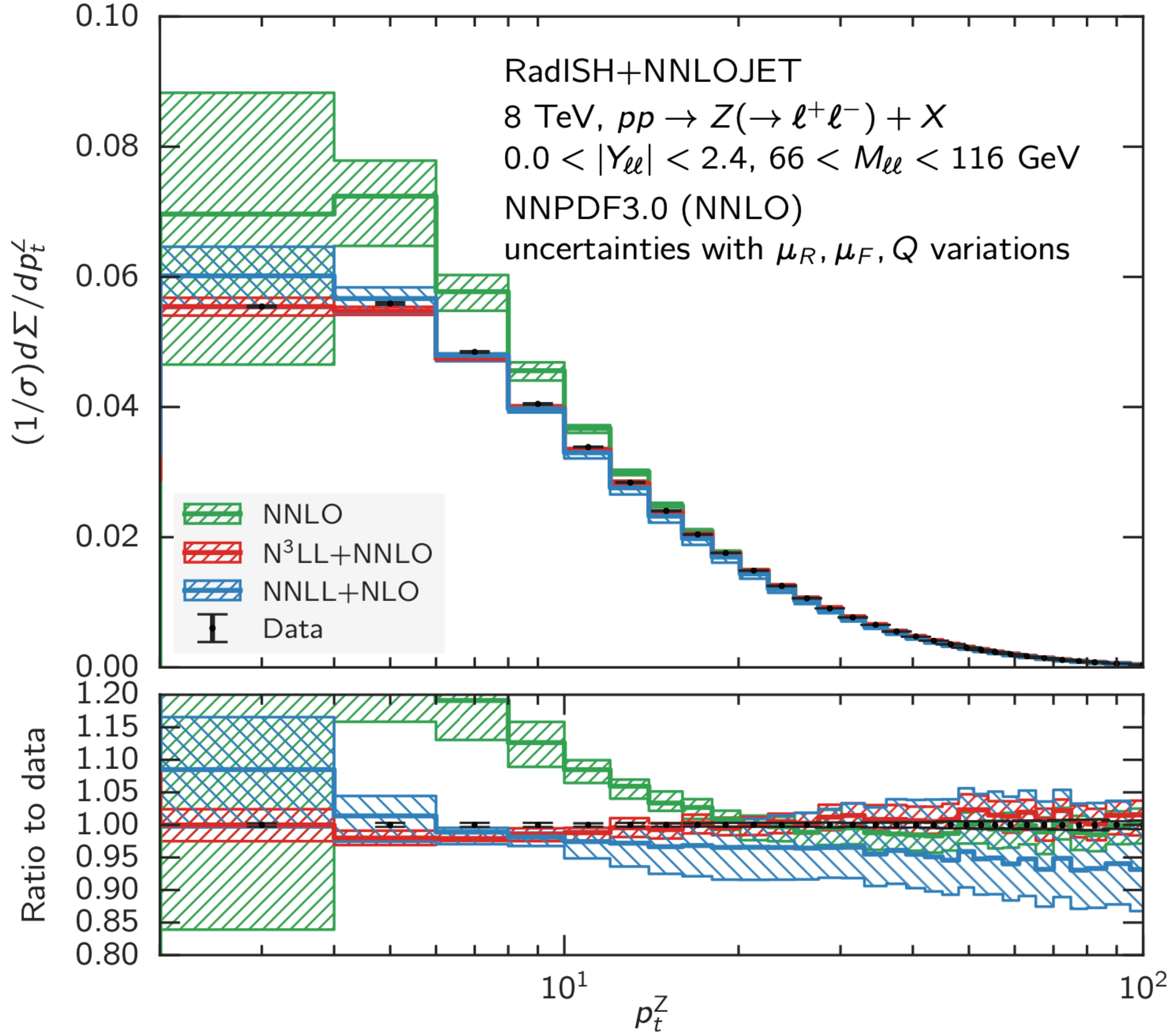


$m = n + 1$ → Leading Logs (LL)

$m = n$ → Next-To-LL (NLL)

$m = n - 1$ → Next-To-NLL (NNLL) . . .

Brizon et al. [1805.05916]



MiNLO

$$\sigma_{Xj}^{FO} = \sigma_1 + \alpha_s \sigma_2 + \dots$$ FO cross section

$$\mathcal{F} = 1 + \alpha_s S_1 + \alpha_s^2 S_2 + \dots$$ Sudakov form factor

We can introduce the Sudakov factor, but we don't have to spoil the accuracy:

$$\mathcal{F}\sigma_{Xj} = \sigma_1 + \alpha_s(\sigma_2 + S_1\sigma_1) \neq \sigma_{Xj}^{FO}\left(1 + \mathcal{O}(\alpha_s^2)\right)$$

We define the MiNLO cross section in order to recover the merging

$$\sigma_{MiNLO} = \mathcal{F}\left(\sigma_1(1 - \alpha_s S_1) + \alpha_s \sigma_2\right) = \sigma_{Xj}^{FO}\left(1 + \mathcal{O}(\alpha_s^2)\right)$$

We can keep track of logs fixing the scales and defining the MiNLO Sudakov

$$\mathcal{F}(p_T, Q) = \exp\left\{-\int_{p_T}^{Q} \frac{dq^2}{q^2}\left[A\left(\alpha_s(q)\right)\ln\frac{Q^2}{q^2} + B\left(\alpha_s(q)\right)\right]\right\}$$

NLO Xj ⟶ NLO X

Hamilton, Nason, Zanderighi [1206.3572]
Hamilton, Nason, Oleari, Zanderighi [1212.4504]

MiNNLO

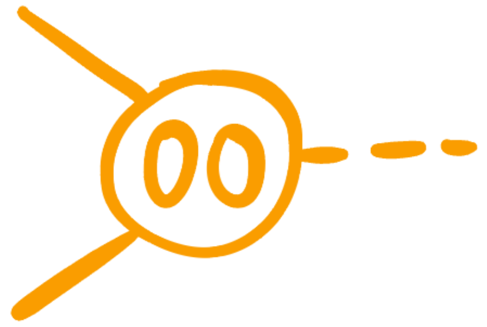
NLO Xj ⟶ NNLO X

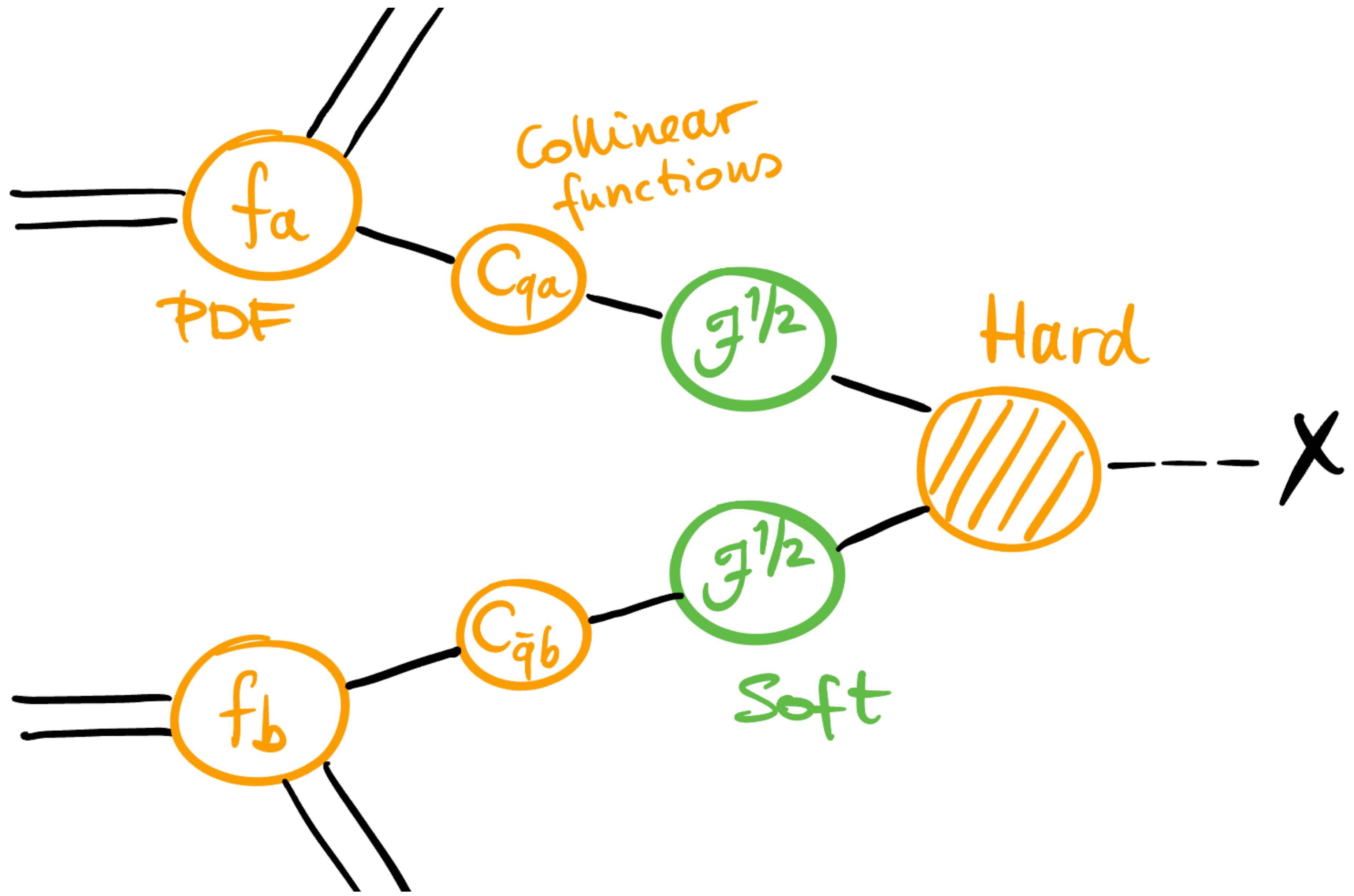
Monni, Nason, Re, Wiesemann, Zanderighi [1206.3572]

$$\frac{d\sigma^{sing}}{dp_T^2\, d\Phi_X} = \frac{d}{dp_T^2}\left\{\mathcal{F}(p_T, Q)\mathcal{L}(p_T)\right\} =: \mathcal{F}(p_T, Q)D(p_T)$$

Sudakov form factor

Luminosity: it also contains



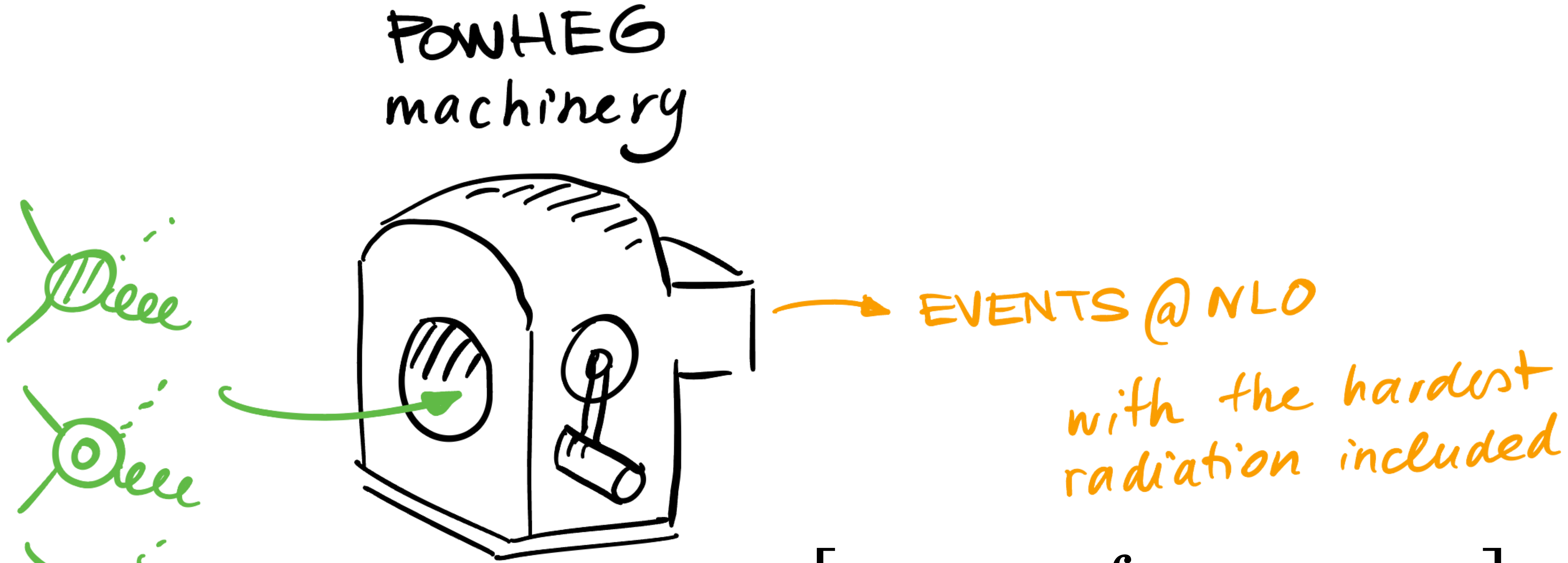


$$\frac{d\sigma}{dp_T^2\, d\Phi_X} = \mathcal{F}(p_T, Q)\left\{\frac{d\sigma_1}{dp_T^2\, d\Phi_X}\left(1 - \alpha_s S_1\right) + \alpha_s(p_T)\frac{d\sigma_2}{dp_T^2\, d\Phi_X} + [D_3\text{-term}]\right\}$$

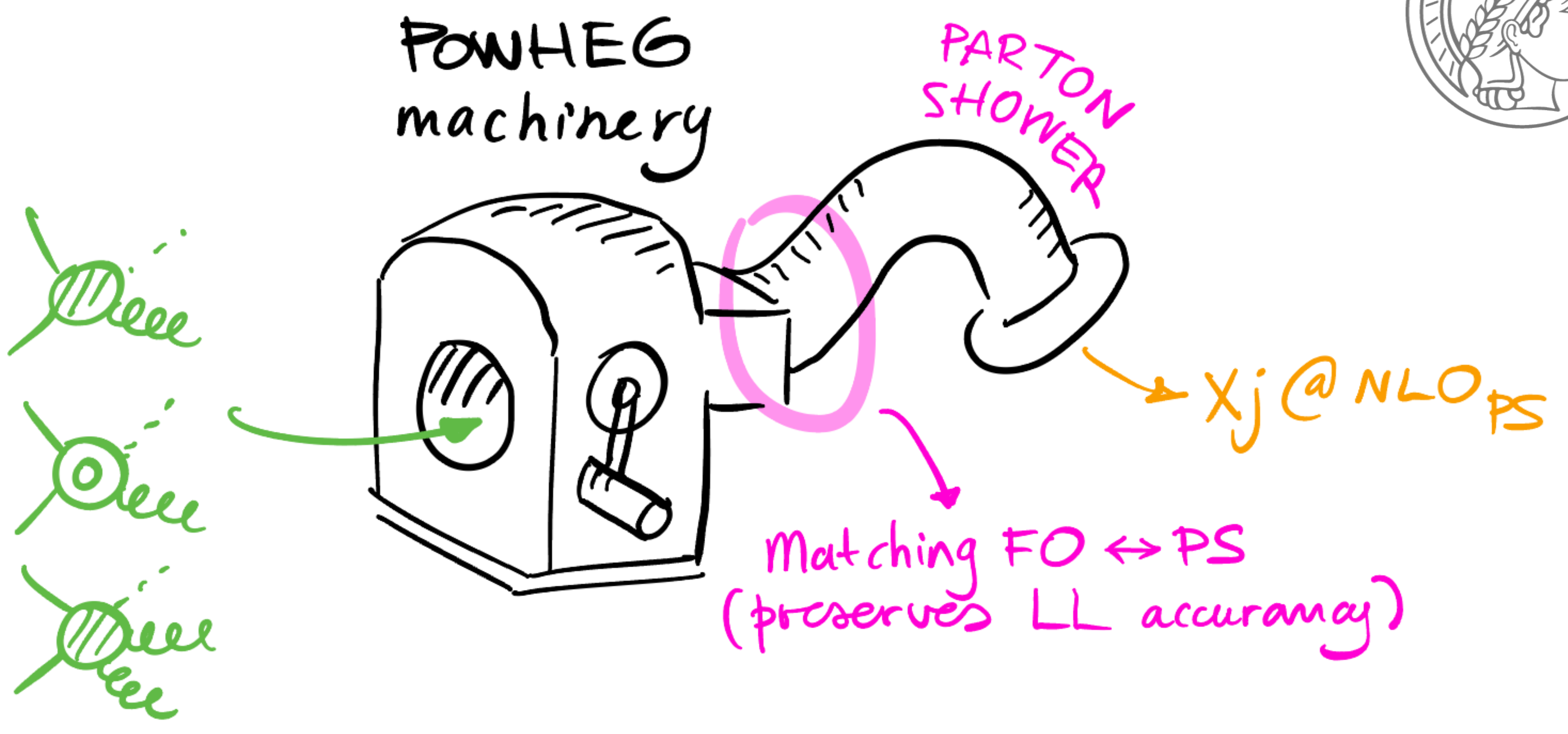
MiNLO structure

It ensures NNLO accuracy

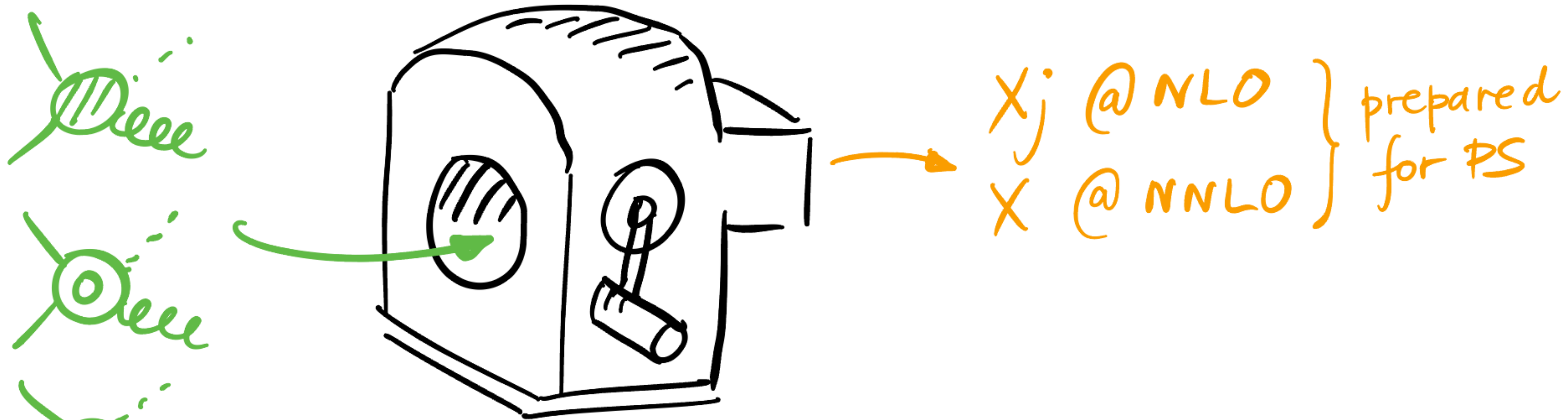
POWHEG



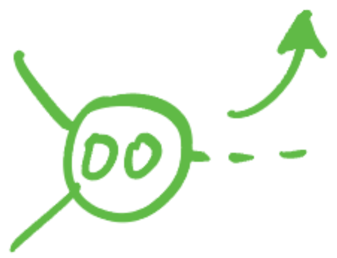
$$\bar{B}(\Phi_{Xj}) = B(\Phi_{Xj}) + \left[V(\Phi_{Xj}) + \int d\phi_{rad} R(\Phi_{Xjj})\right]$$

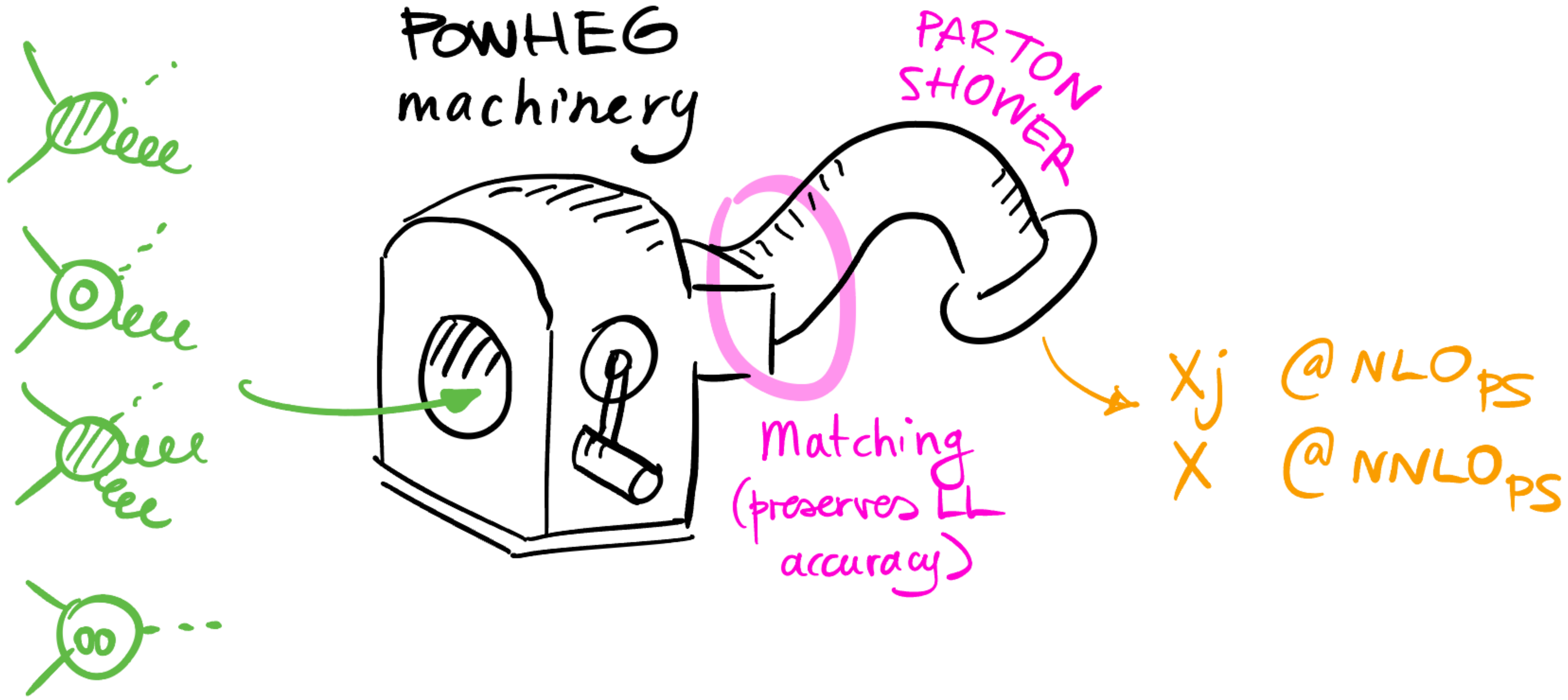


MiNNLO+POWHEG



$$\bar{B}(\Phi_{Xj}) = \mathcal{F}(p_T, Q)\Big\{B(\Phi_{Xj})\big(1 - \alpha_s S_1\big) + \left[V(\Phi_{Xj}) + \int d\phi_{rad} R(\Phi_{Xjj})\right] + [D_3\text{-term}]\, F(\Phi_{Xj})\Big\}$$



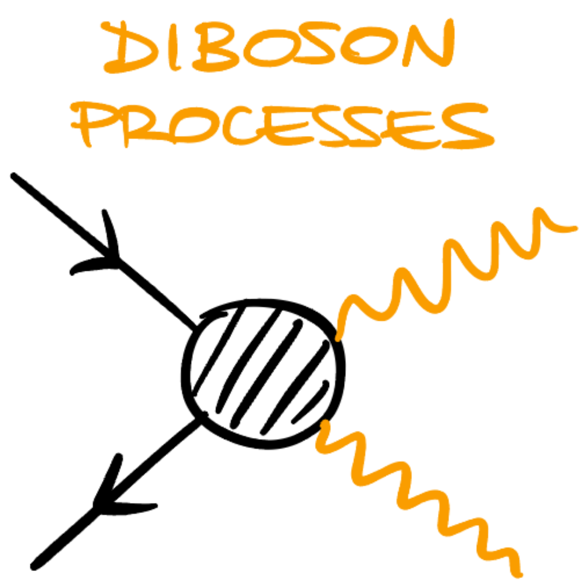


Monni, Nason, Re, Wiesemann, Zanderighi [1908.06987]

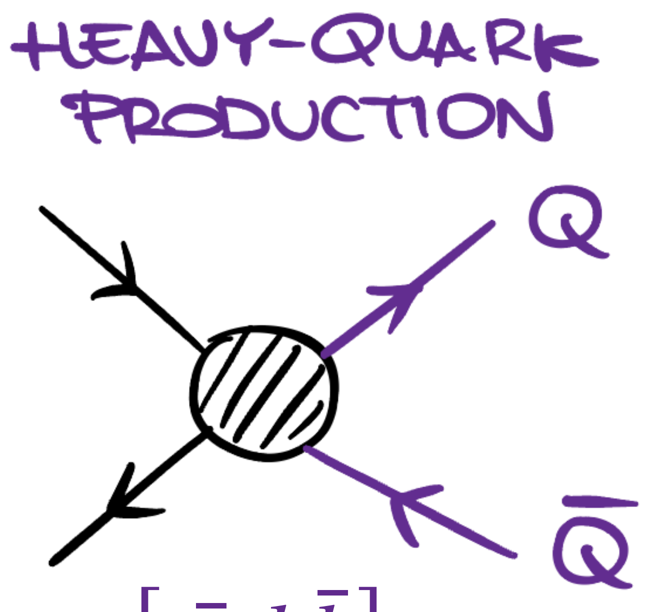
NNLO+PS timeline

Using the MiNNLO method, there was an increasing number of processes with predictions accurate at NNLO+PS.

MiNNLO was firstly implemented for a color singlet production. The method can be extended to more complex processes.

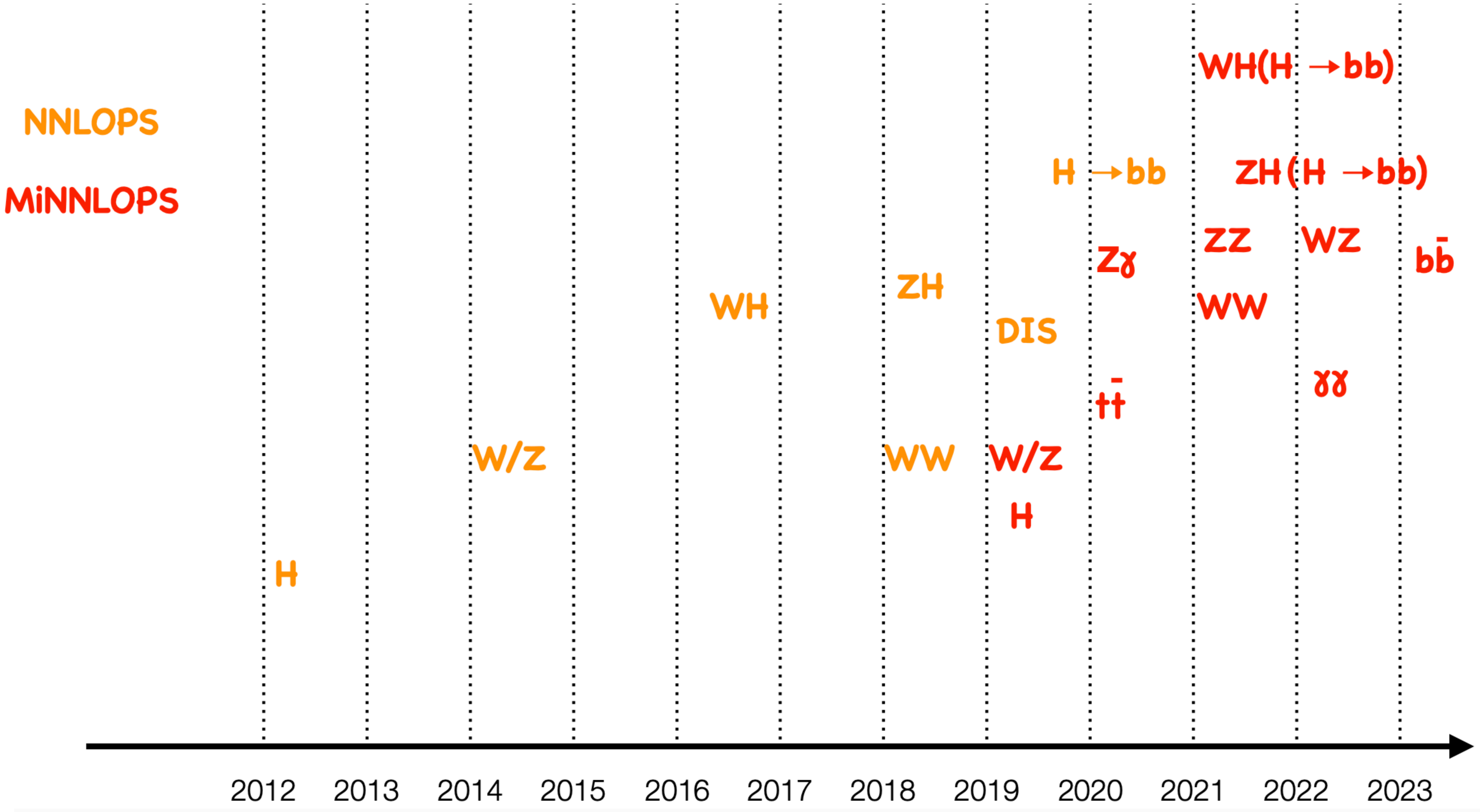


$[Z\gamma, WW, ZZ, \gamma\gamma, WZ]$

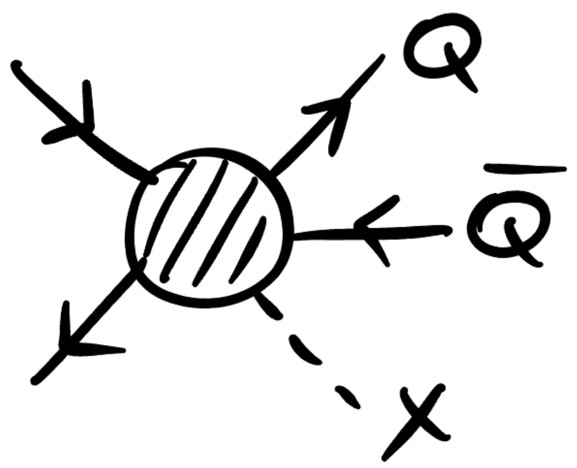


$[t\bar{t}, b\bar{b}]$

We are working on QQF extension.



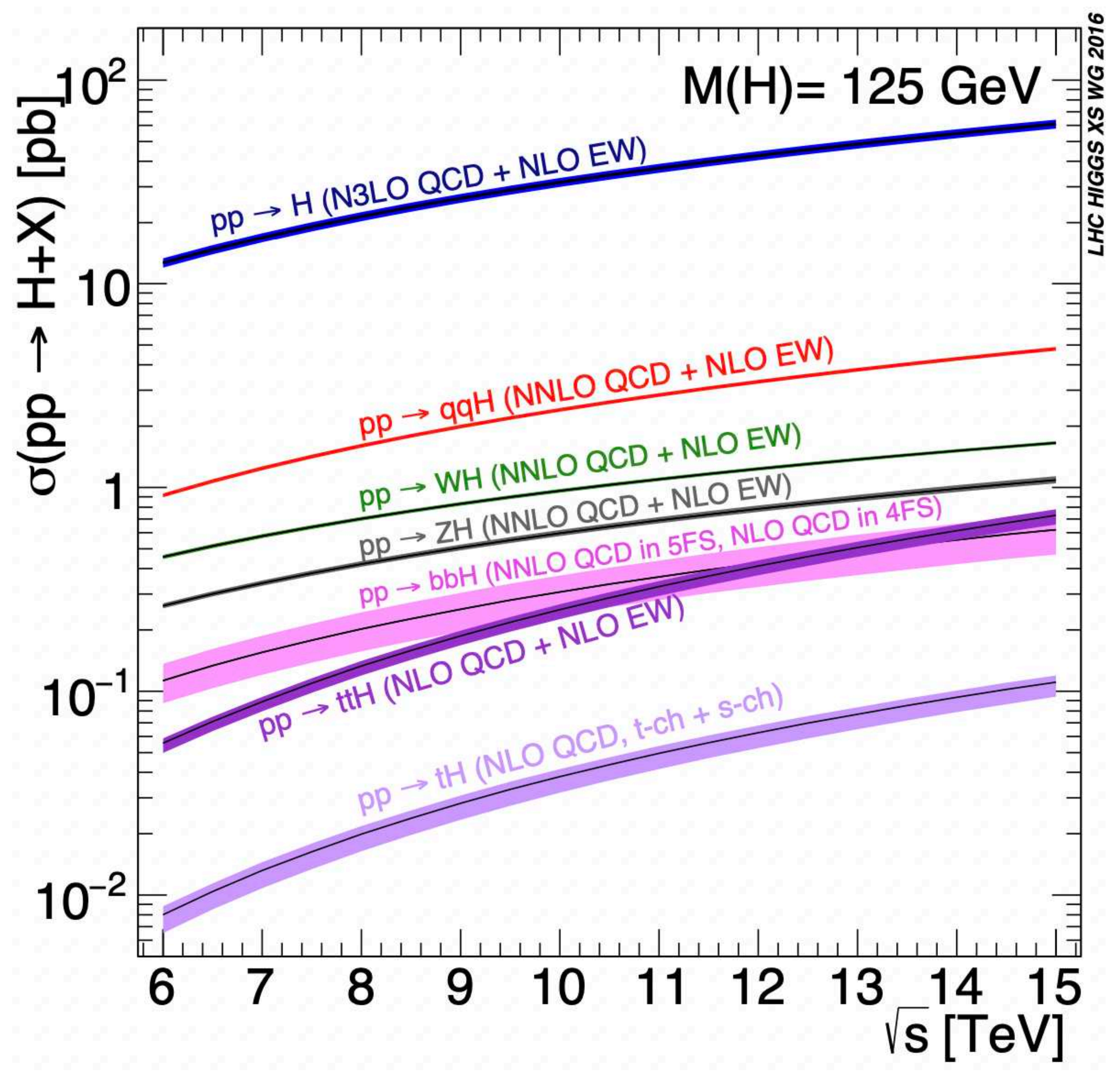
extracted from a Zanderighi's talk



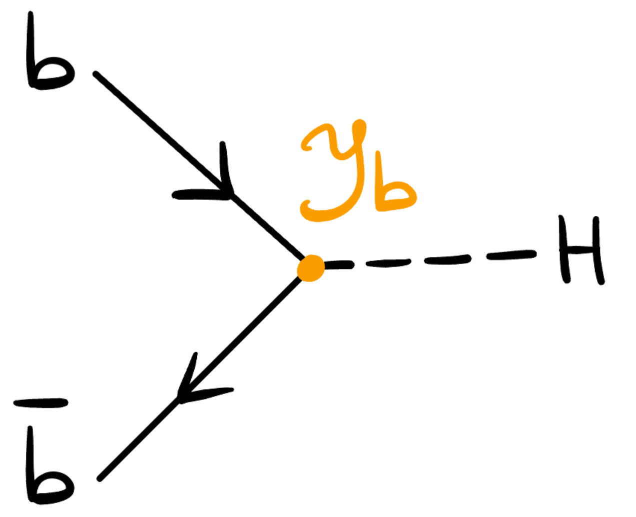
e.g. $b\bar{b}H$ production

Backup slides (2)
bbH production

Higgs production via bottom fusion



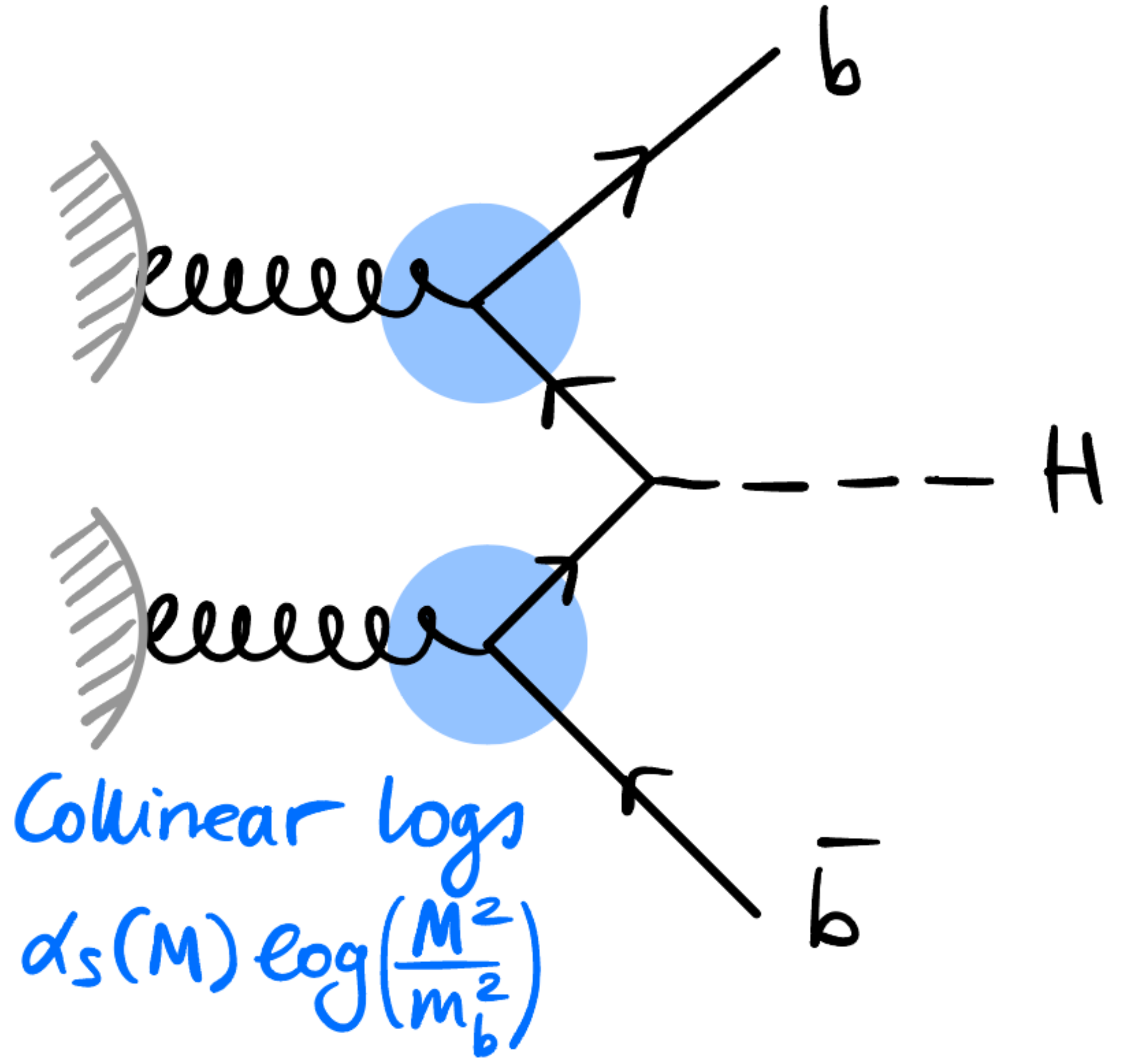
Although it is not the main production channel, the Higgs creation via bottom fusion



- allows a direct evaluation of the bottom Yukawa coupling
- is enhanced in SUSY theories with large $\tan\beta$ and it can become the dominant channel

For all processes that feature bottom quarks at the hard-process level there are two ways of performing computations:

4FS



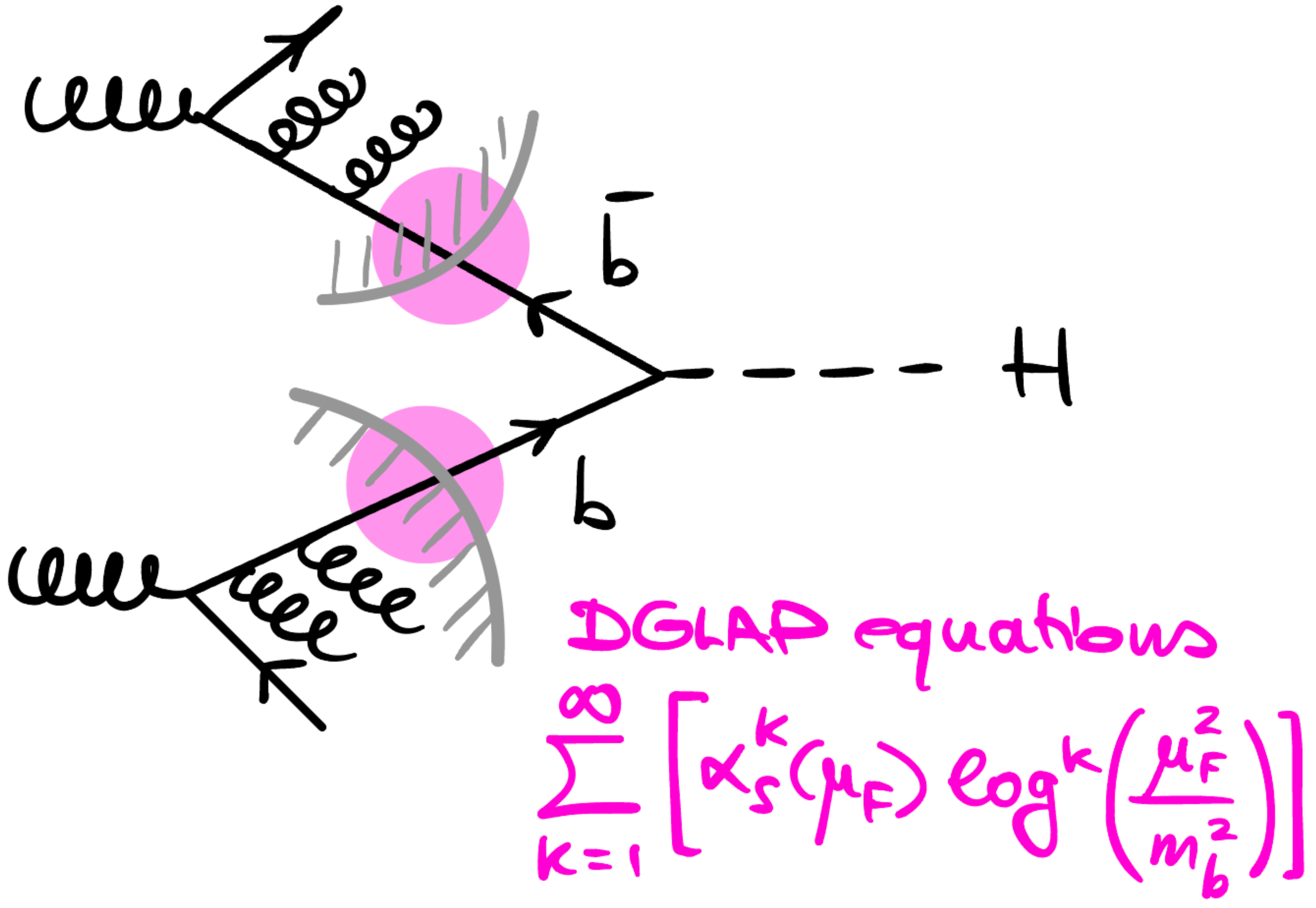
decoupling/massive scheme

- It does not resum possibly large collinear logs
- Computing higher orders is more difficult due to higher multiplicity

✓ Mass effects $O(m_b/m_H)$ are there at any order

✓ Straightforward implementation in MC event generators at LO and NLO

5FS



massless scheme

✓ DGLAP evolution resum initial state logs into f_b

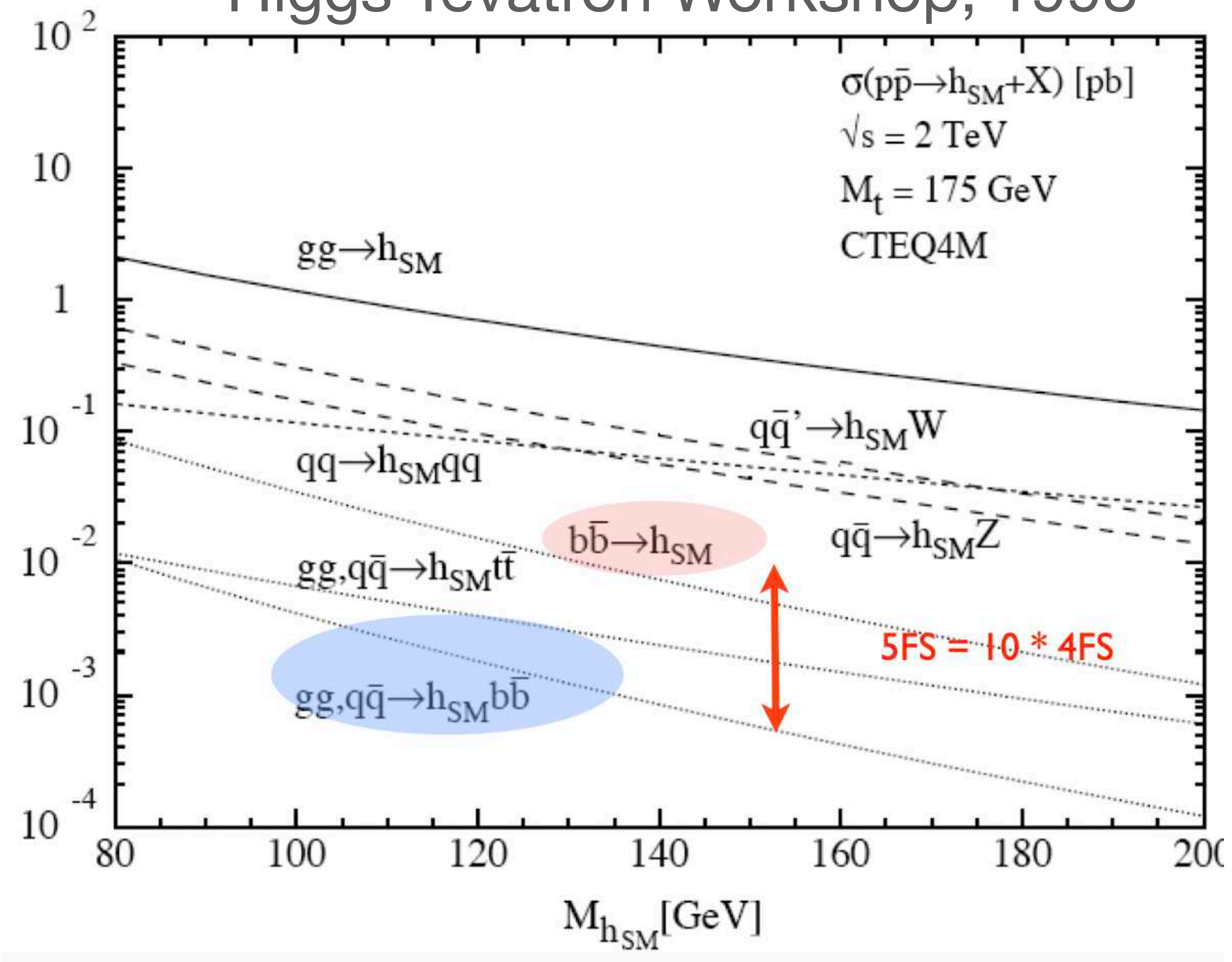
✓ Computing higher orders is easier

- Neglecting $O(m_b/m_H)$, it yields less accurate description of bottom kinematic distribution
- Implementation in MC depends on the gluon splitting model in the PS

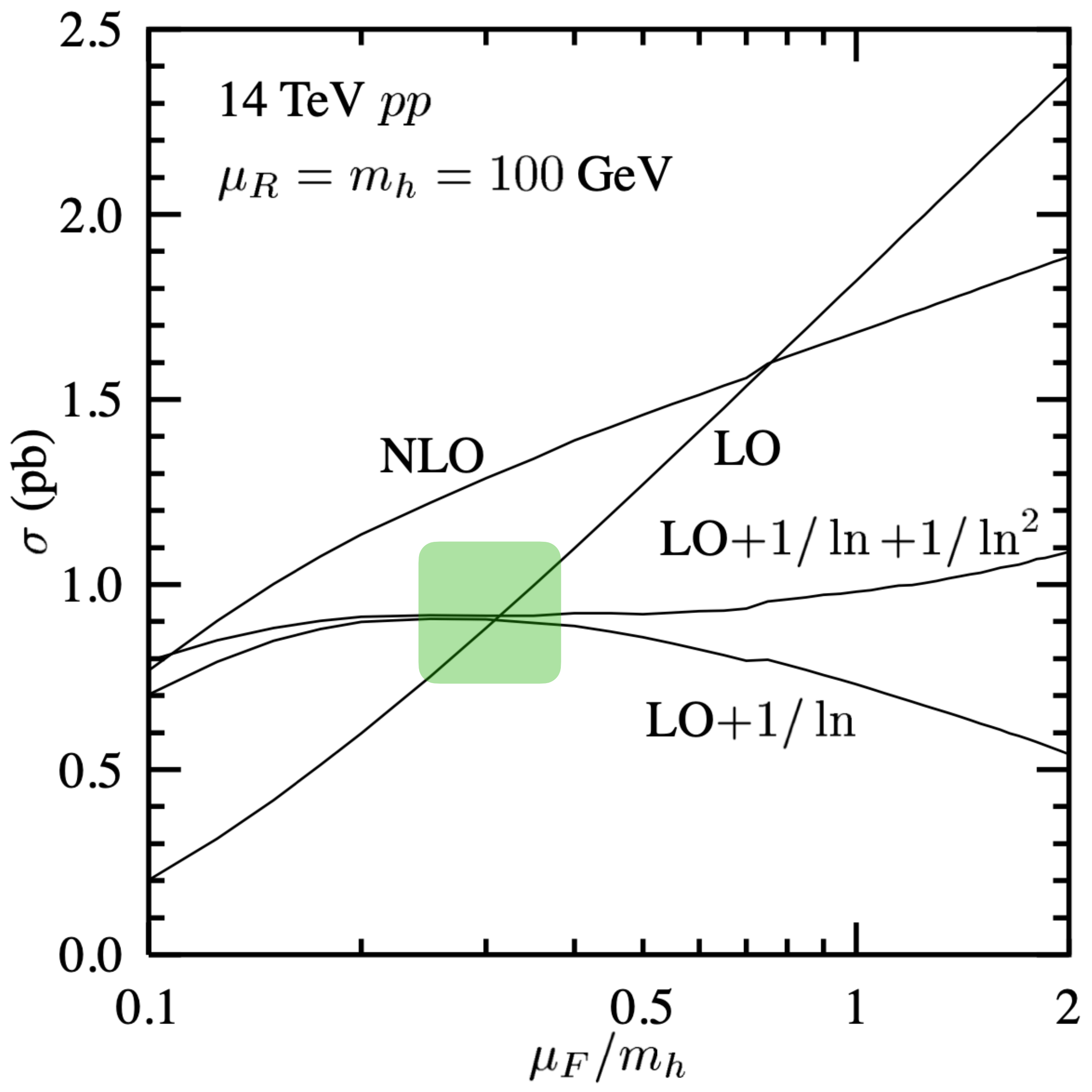
Historical LO comparisons

Large differences in the predictions were first observed at the leading order: the effect of collinear resummation is extremely large.

Higgs Tevatron Workshop, 1998



Maltoni, Sullivan, Willenbrock [hep-ph/0301033]



For $\mu_F = m_H/4$, FO computations in the different schemes become compatible, indeed the collinear logs have a small effect. This also improved the convergence of the perturbation series.

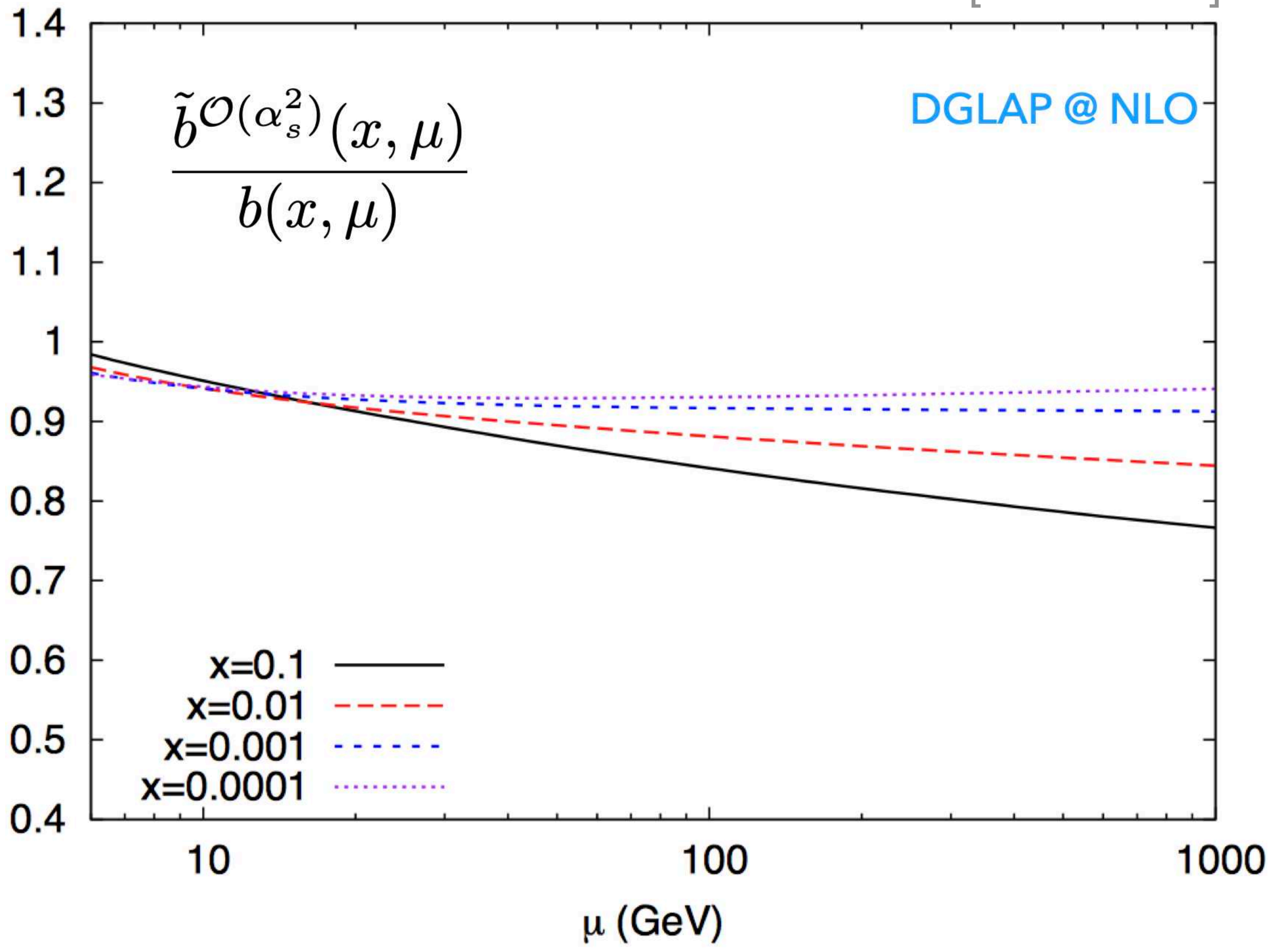
The improvement of the compatibility opens the possibility to match together the predictions at least at the inclusive level (Santander matching, FONLL…)

Differences between schemes

Maltoni, Ridolfi, Ubiali [1203.6393]
Thorne [1402.3536]
Olness, Schienbein [0812.3371]

Lot of progress in understanding the origin of the differences. The predictions can be merged into a consistent picture by taking into account two main results.

[1203.6393]



1. At NLO, the resummation effects of collinear logs are important only at high Bjorken-x
2. The possibly large ratios m_H^2/m_b^2 are always accompanied by universal phase space factors f

$$\ln^2 \frac{m_H^2 f}{m_b^2} = \ln^2 \frac{\tilde{\mu}^2}{m_b^2}, \quad \tilde{\mu} < m_H$$

FONLL

Forte, Napoletano, Ubiali [1508.01529]
Forte, Napoletano, Ubiali [1607.00389]

- FONLL matches the flavour schemes

  $\sigma^{FONNL} = \sigma^{4FS} + \sigma^{5FS}$ – double couting.

  For a consistent subtraction, we have to express the two cross-sections in terms of the same α_s and PDFs.

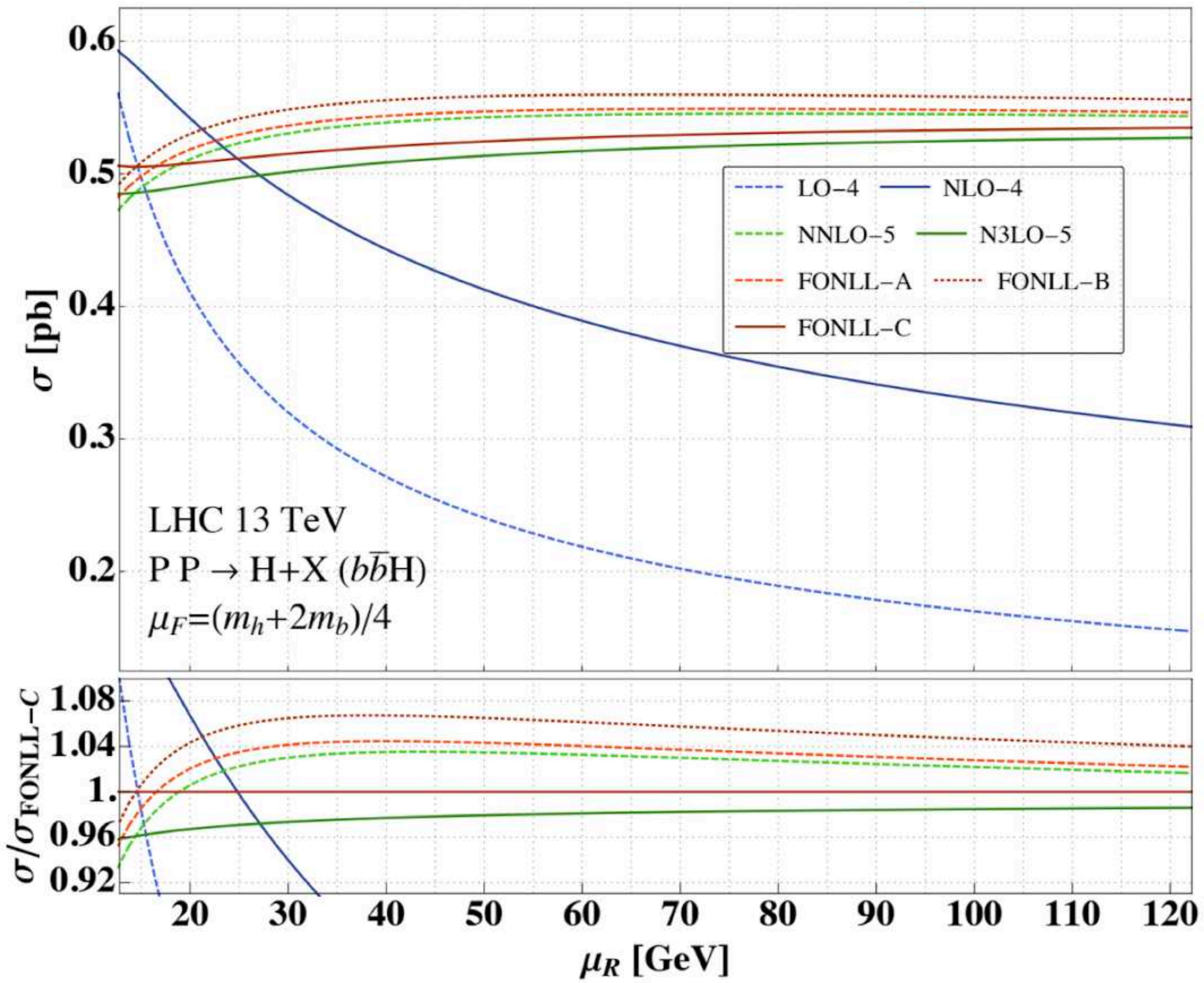
- Currently, the flavour matching for bbH is performed at

  $$\text{FONNL}_C := \text{N}^3\text{LO}_{5FS} \oplus \text{NLO}_{4FS}.$$

- Differential FONLL applied for Z+b-jet

$$d\sigma^{FONLL} = d\sigma^{5FS} + \left(d\sigma^{4FS}_{m_b} - d\sigma^{4FS}_{m_b \to 0}\right)$$

Duhr, Dulat, Hirschi, Mistlberger [2004.04752]



[Gauld, Gehrmann-De Ridder, Glover, Huss, Majer, 2005.03016]

Exclusive observables

Recent developments in fully differential calculations, for example:

1. Introduce an unphysical scale μ_b in order to switch from 4FS to 5FS in a region where mass effects and collinear logs are not crucial [Bertone, Glazov, Mitov, Papanastasiou, Ubiali, 1711.03355]
2. Massive 5FS at NLO [Krauss, Napoletano, 1712.06832]
3. Differential FONLL applied for Z+b-jet [Gauld, Gehrmann-De Ridder, Glover, Huss, Majer, 2005.03016]

$$d\sigma^{FONLL} = d\sigma^{5FS} + \left(d\sigma^{4FS}_{m_b} - d\sigma^{4FS}_{m_b \to 0} \right)$$

H(bb) production in 5FS

Using the Sudakov factor $\mathscr{F}(p_T, Q)$, we can resum the logs at low transverse momenta.

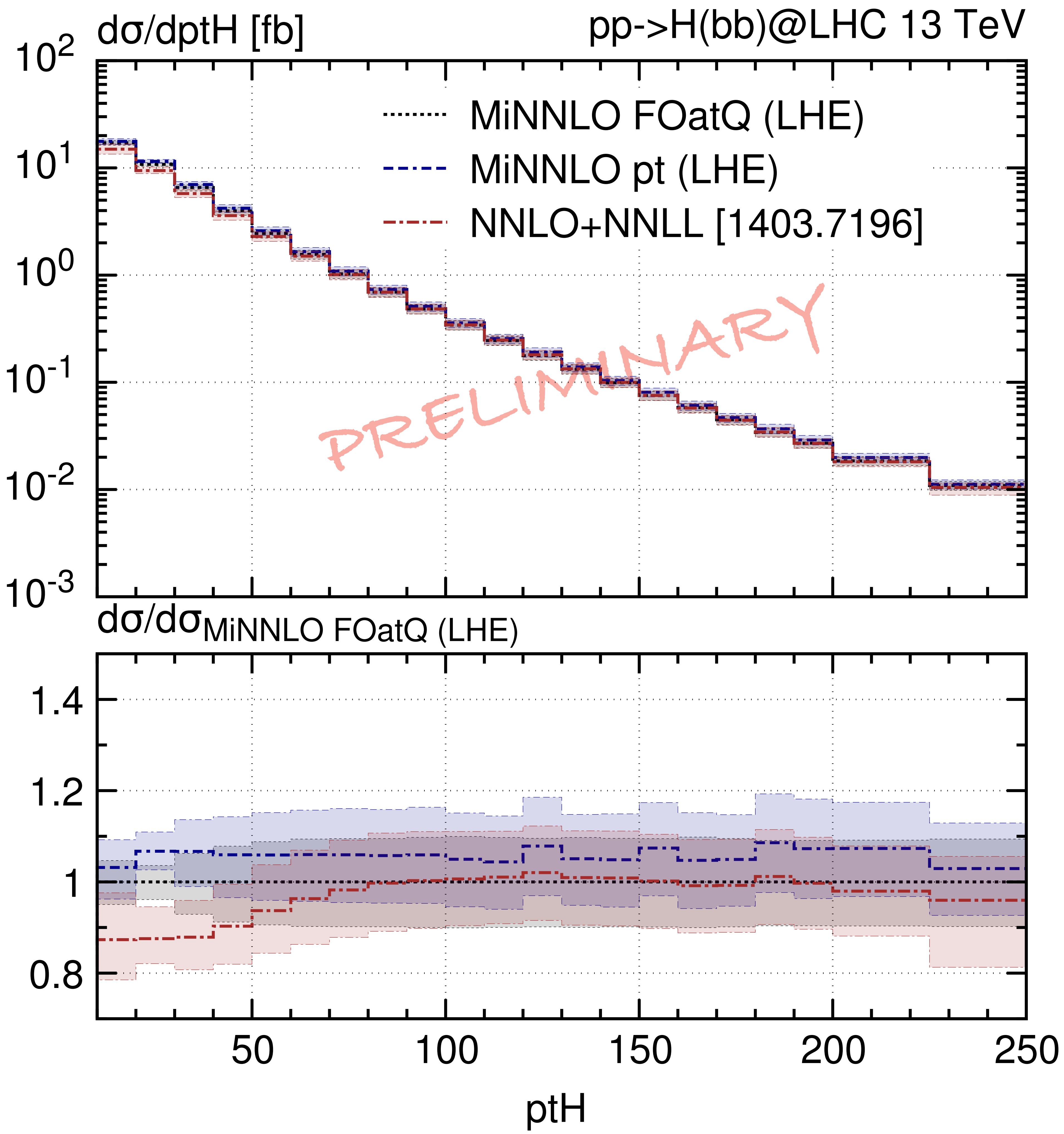
Including the 2-loop correction, we obtained inclusive predictions for Higgs accurate at NNLO.

The non-singular part of the cross-section was evaluated with two different scale choices as done for the diphoton production.

Gavardi, Oleari, Re [2204.12602]

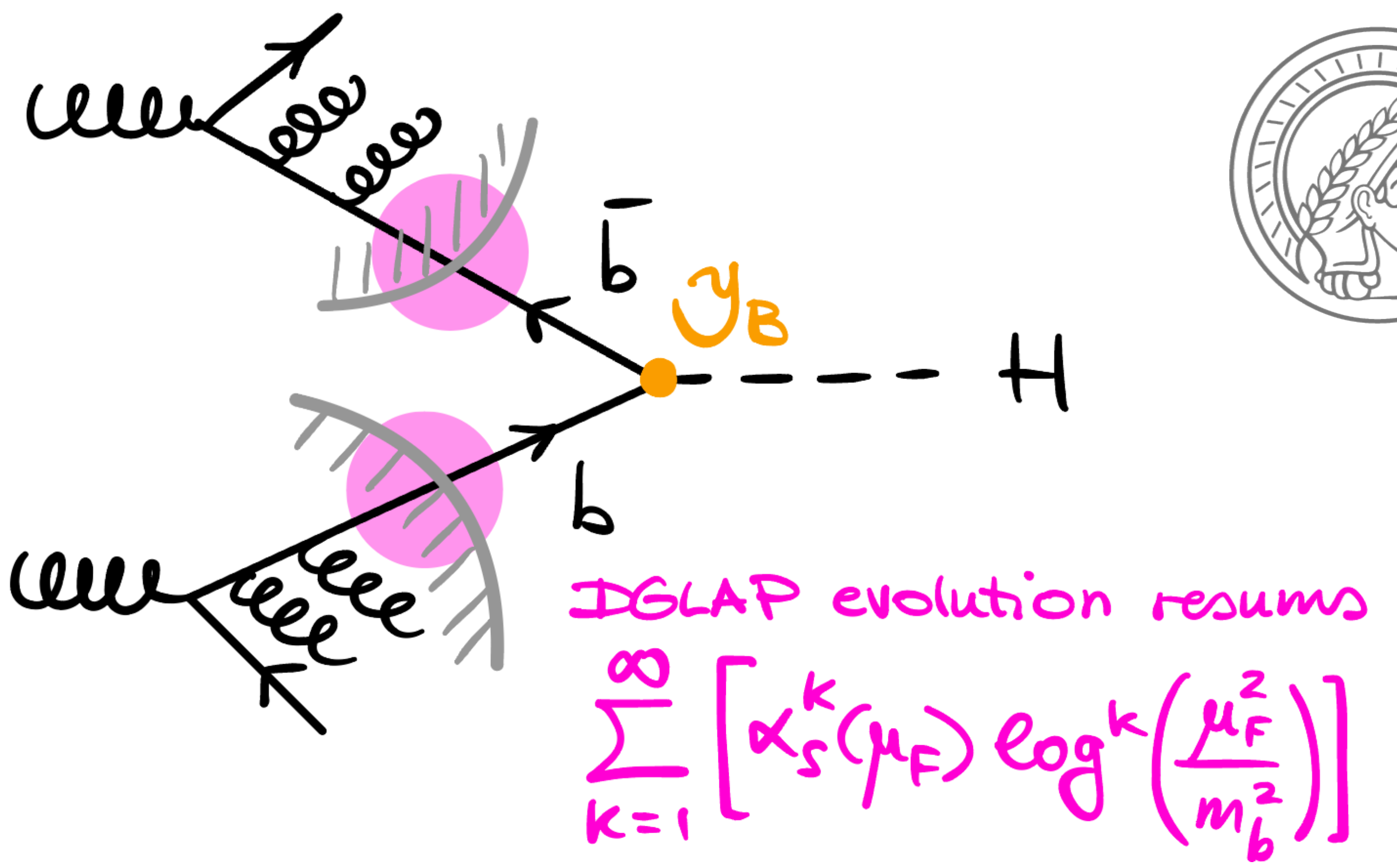
$$\bar{B}(\Phi_{Xj}) = \mathscr{F}(p_T, Q)\Big\{B(\Phi_{Xj})\big(1 - \alpha_s S_1\big) + \Big[V(\Phi_{Xj}) + \int d\phi_{rad} R(\Phi_{Xjj})\Big] + [D_3\text{-term}]\, F(\Phi_{Xj})\Big\}$$

Use p_T as reference for scales or evaluate them at the hard scale Q



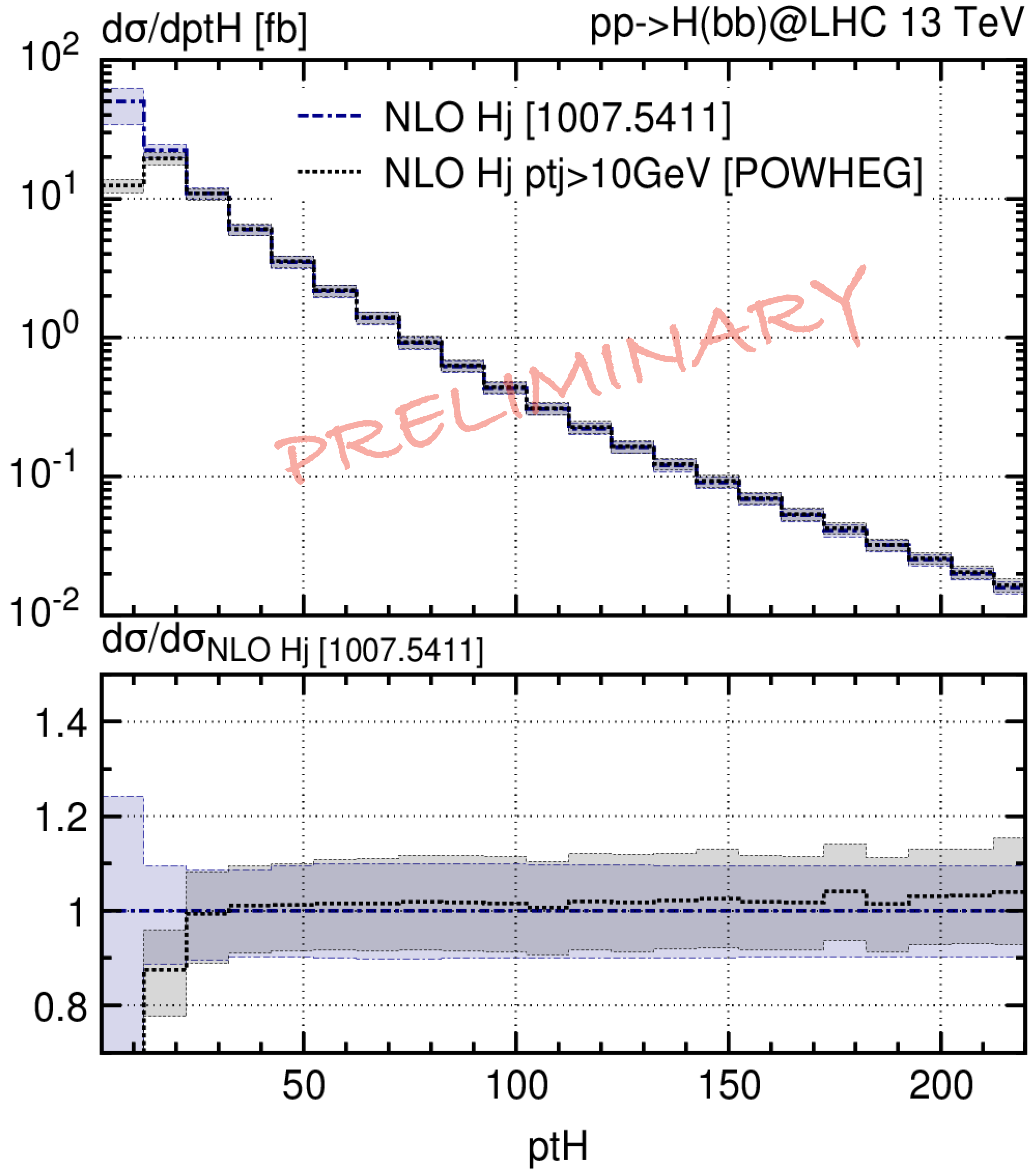
CB, Sankar, Wiesemann, Zanderighi in progress

H(bb) production in 5FS



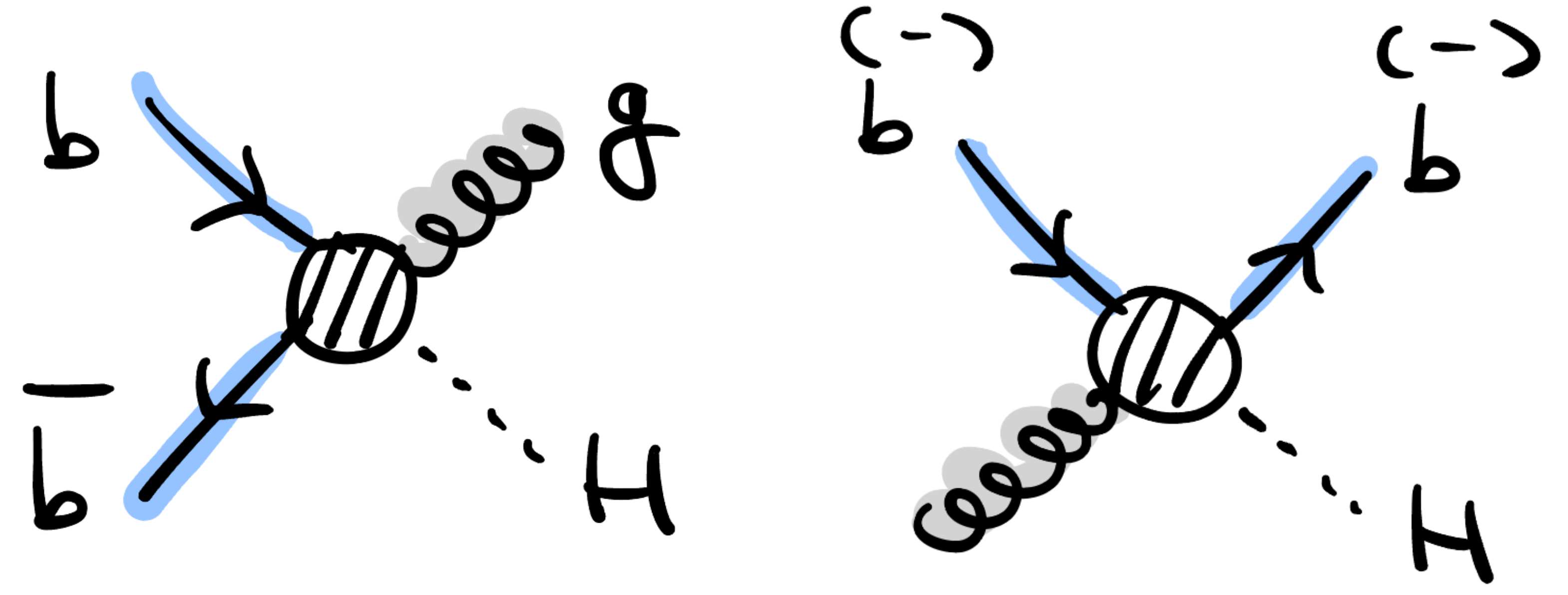
We implemented the MiNNLO method in 5 flavour-scheme for the Higgs production via bottom fusion in SM.

- Direct access to bottom Yukawa coupling
- Although it is a subdominant channel, it has effects on the shape of the transverse momentum spectrum
- In SUSY models, this channel can be enhanced



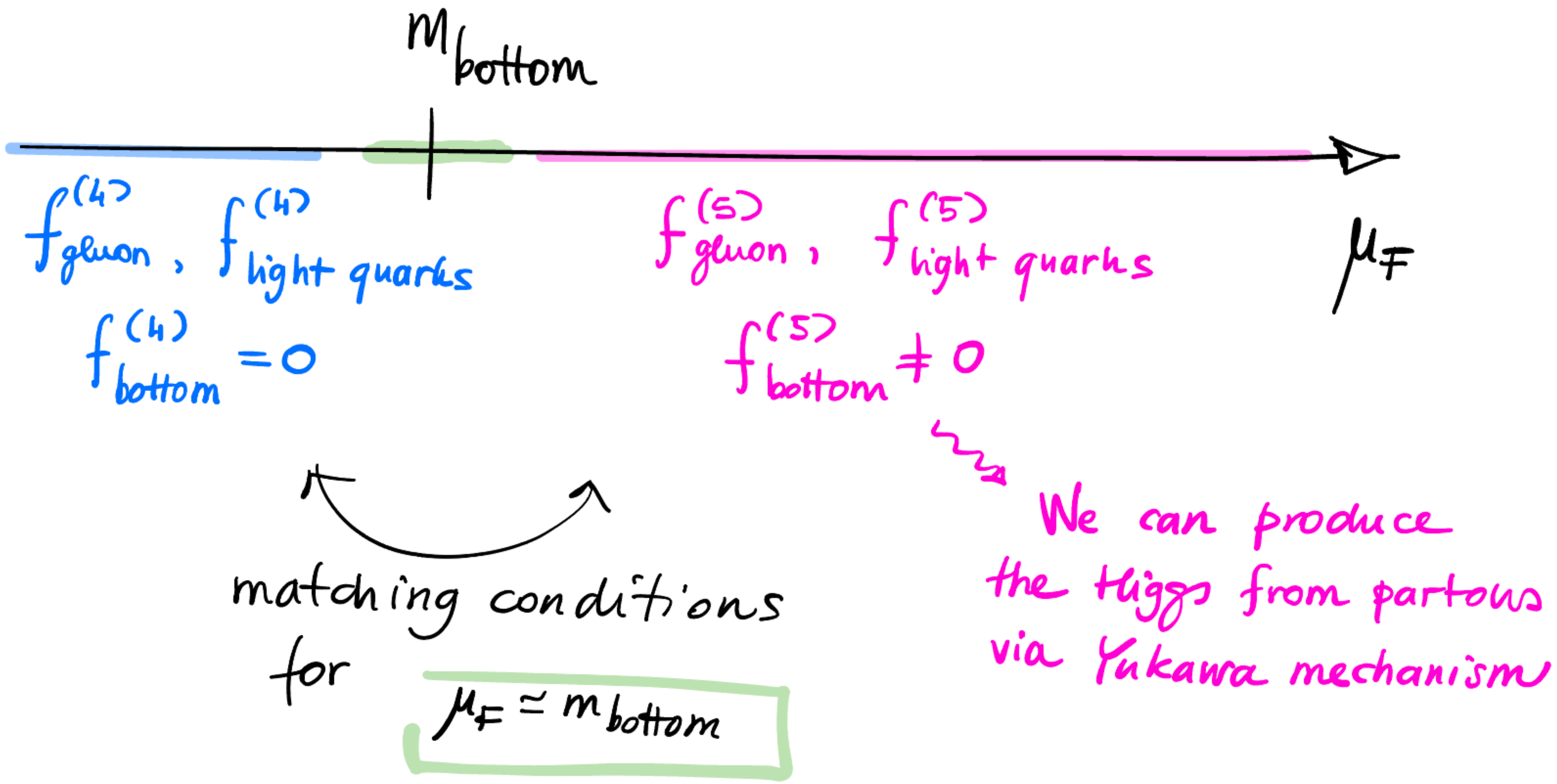
We started performing NLO$_{PS}$ predictions in POWHEG framework for the Hj production.

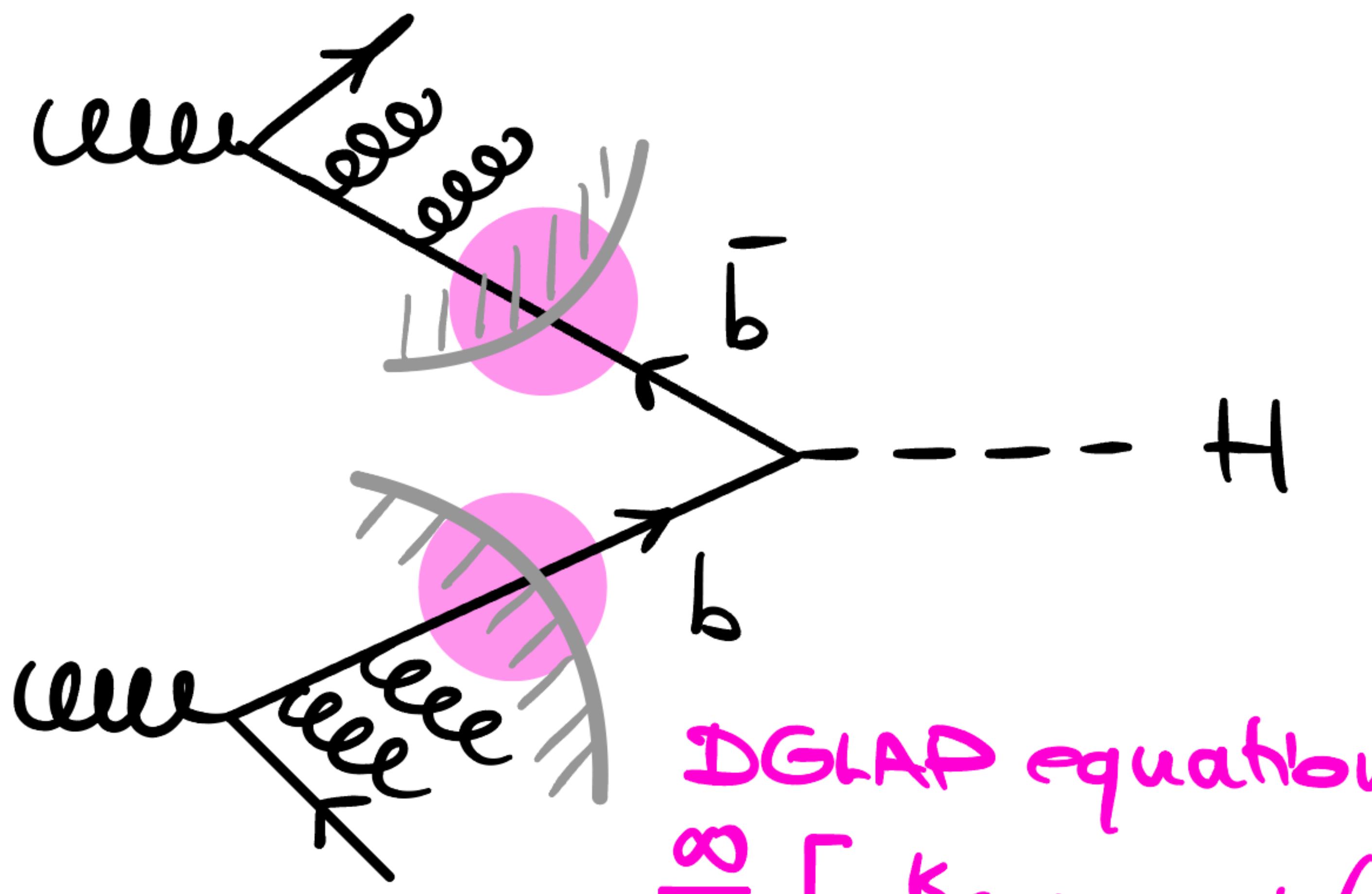
@LO



Heavy flavours inside the proton?

Thanks to the gluon splittings, we can have a DGLAP component of heavy flavours in the proton.



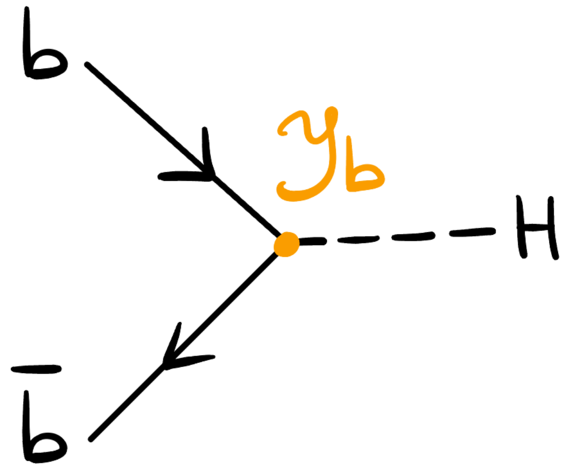


$$\sum_{k=1}^{\infty}\left[\alpha_s^k(\mu_F)\log^k\left(\frac{\mu_F^2}{m_b^2}\right)\right]$$

5FS

NNLO matching eqs [hep-ph/9612398]
Impact on PDF fits [1707.05343]

Higgs production via bottom fusion



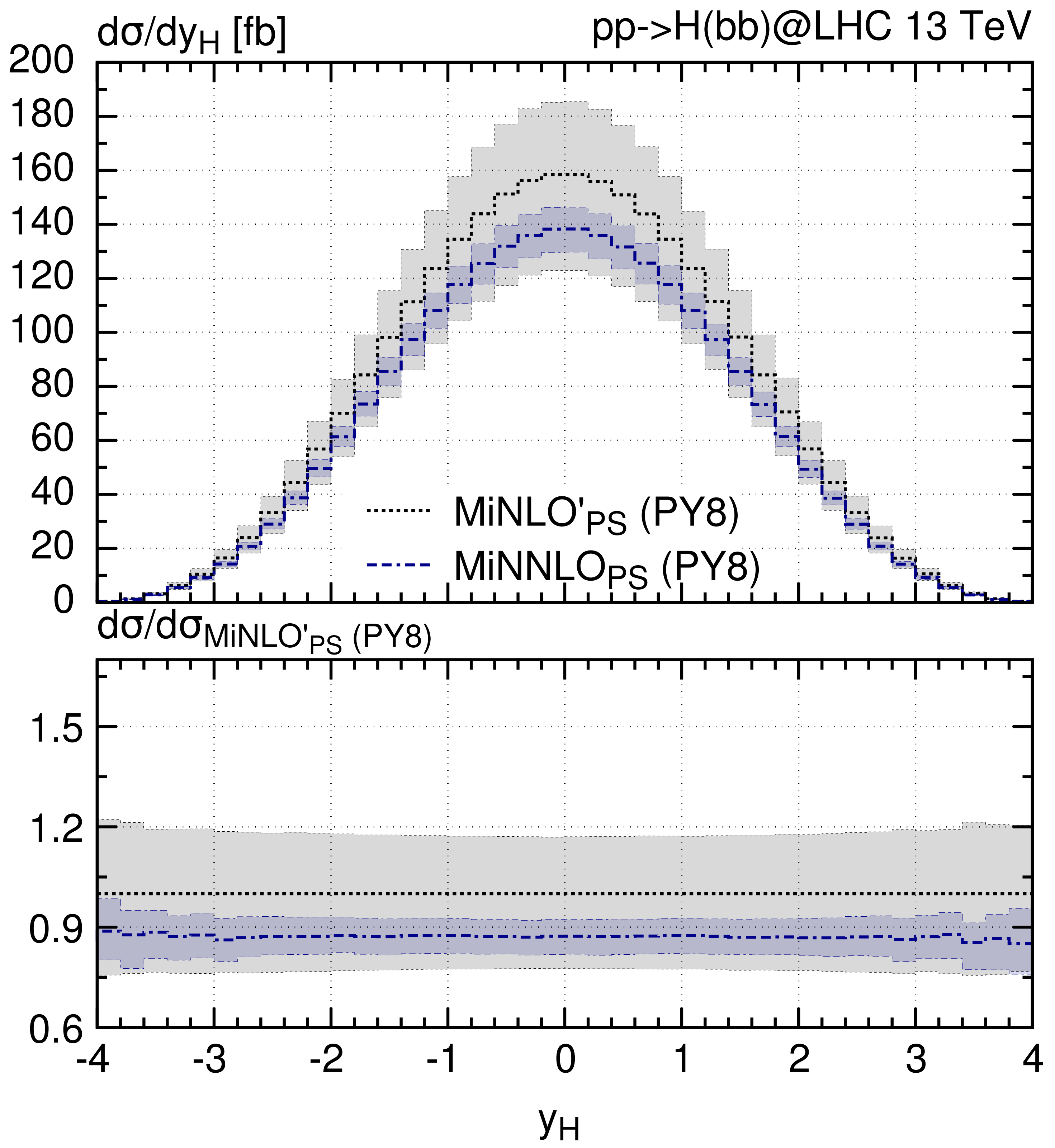
We implemented a MC code for the Higgs production via bottom fusion in SM.

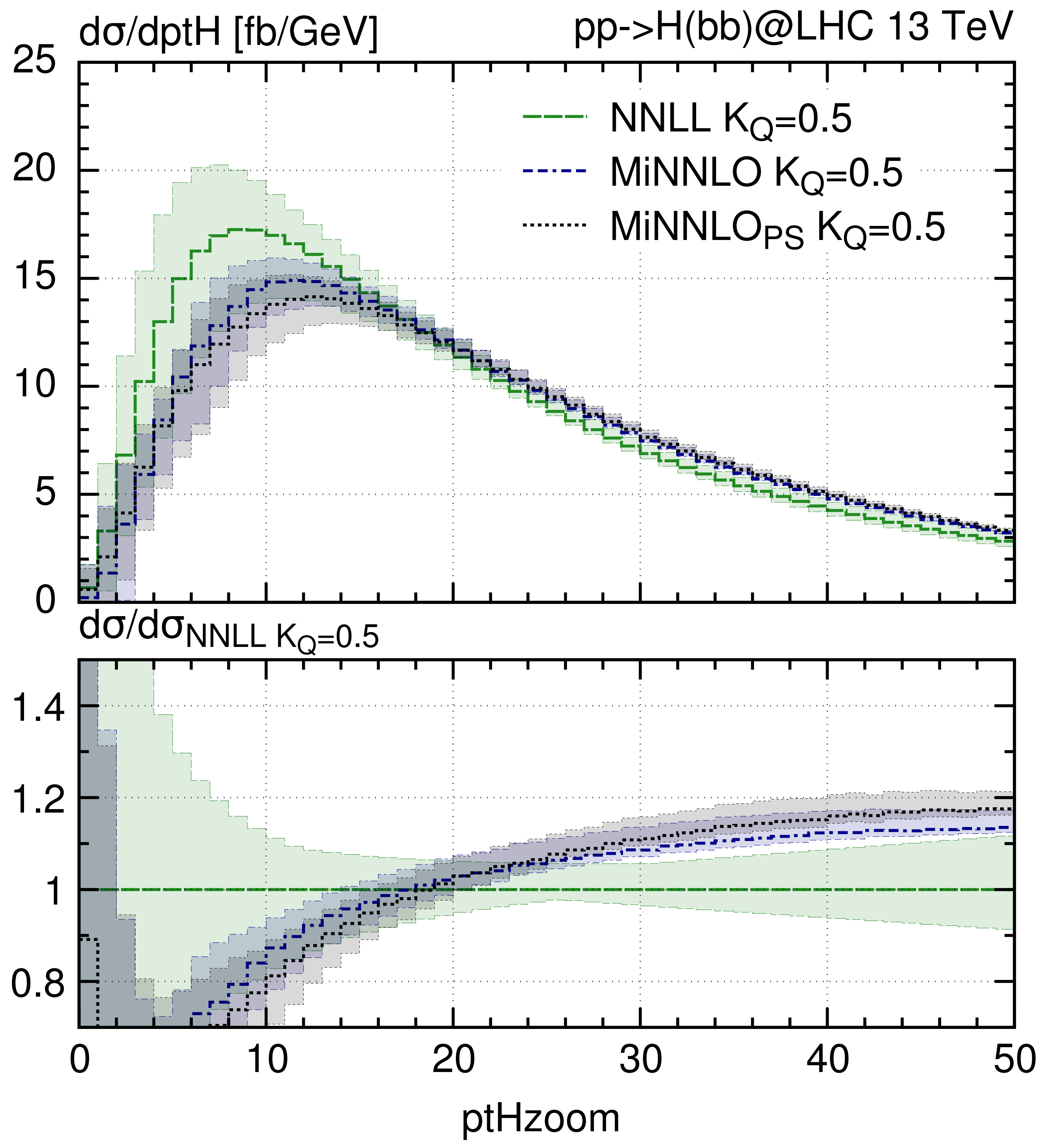
WHY?

- Direct access to bottom Yukawa coupling
- In SUSY models, this channel can be enhanced

HOW?

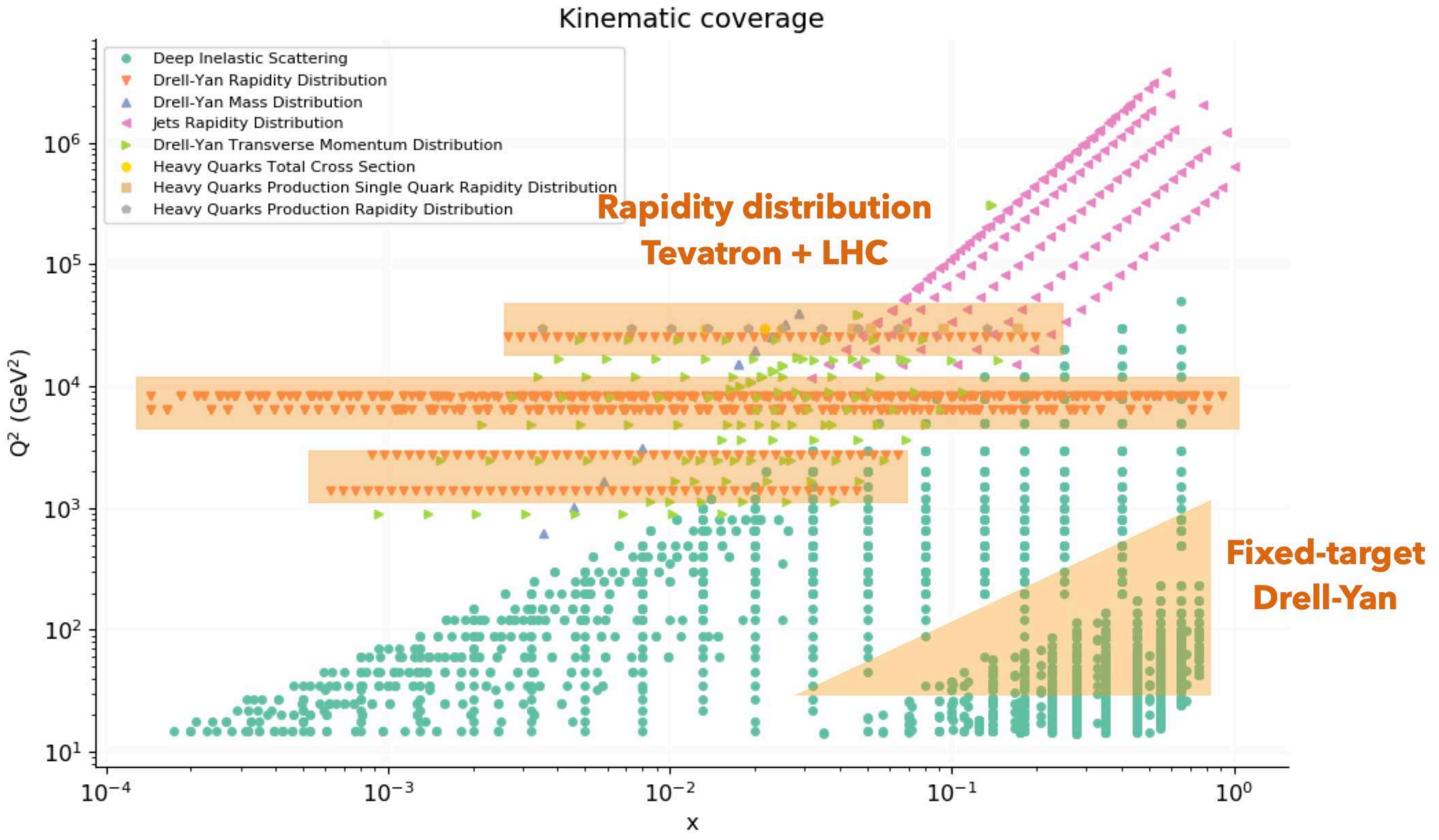
- We used NNPDF4.0 as PDFs sets in the **5FS** with bottom component included
- We used the MiNNLO method in POWHEG framework

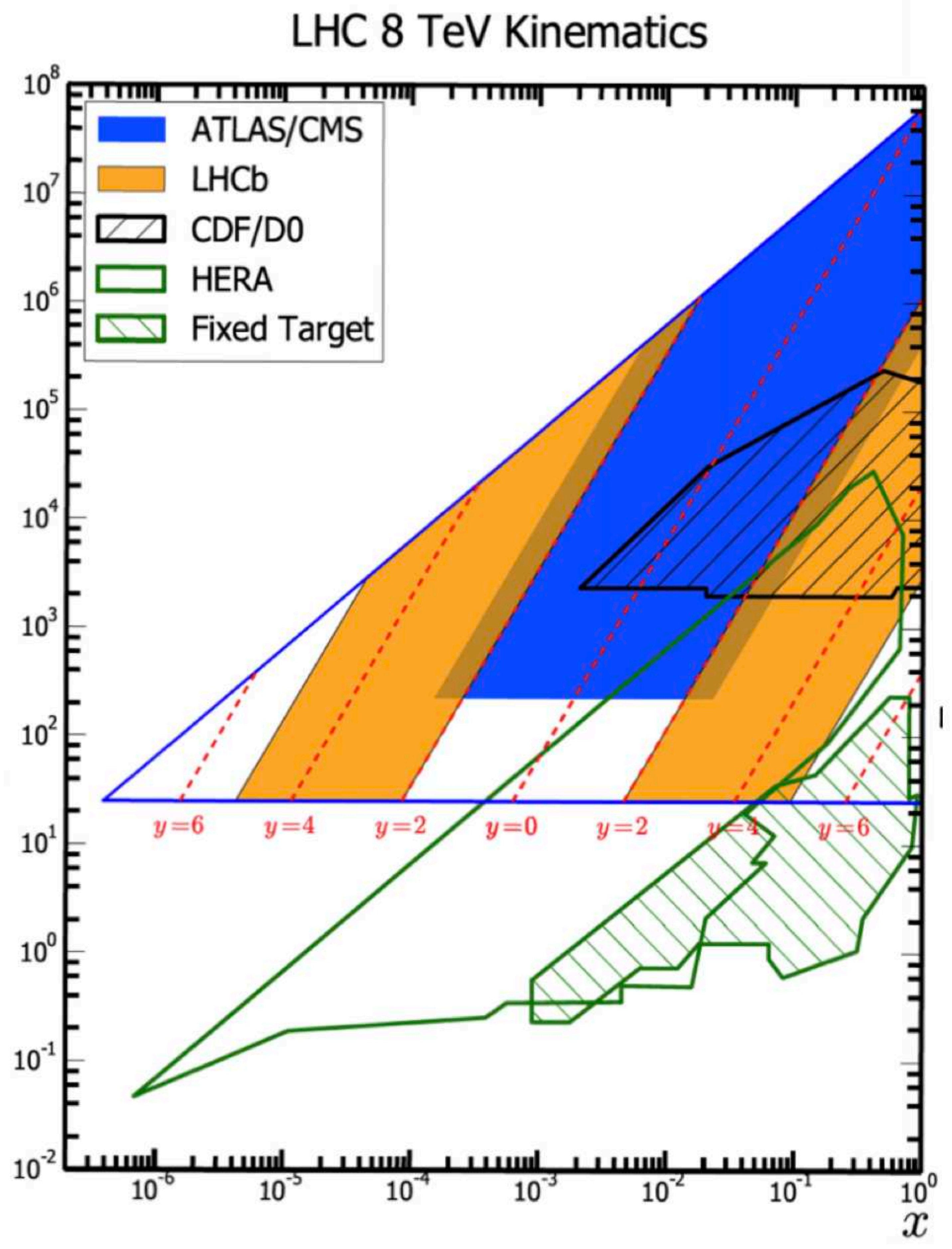




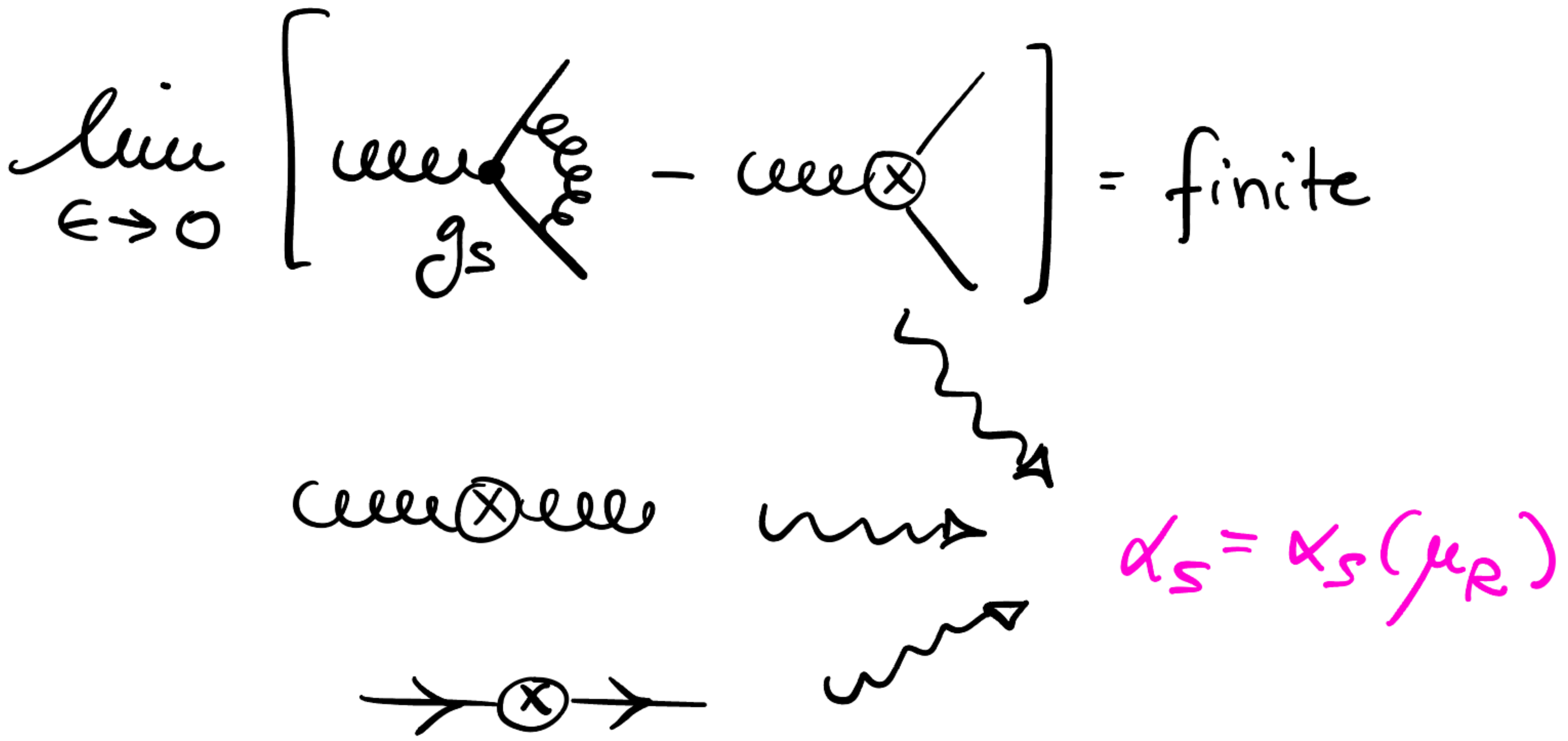
CB, Sankar, Wiesemann, Zanderighi [in preparation]

Data for PDF fits



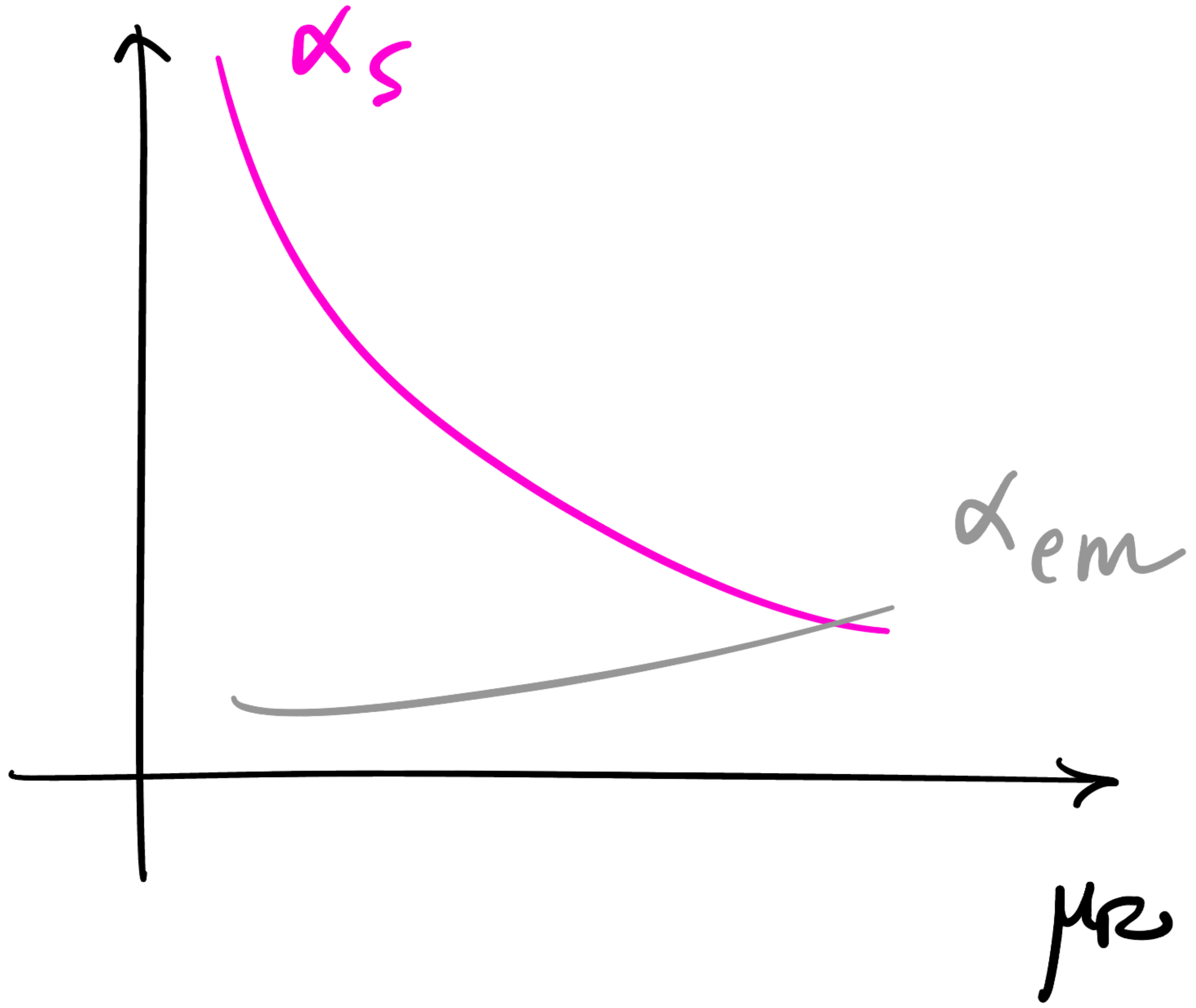


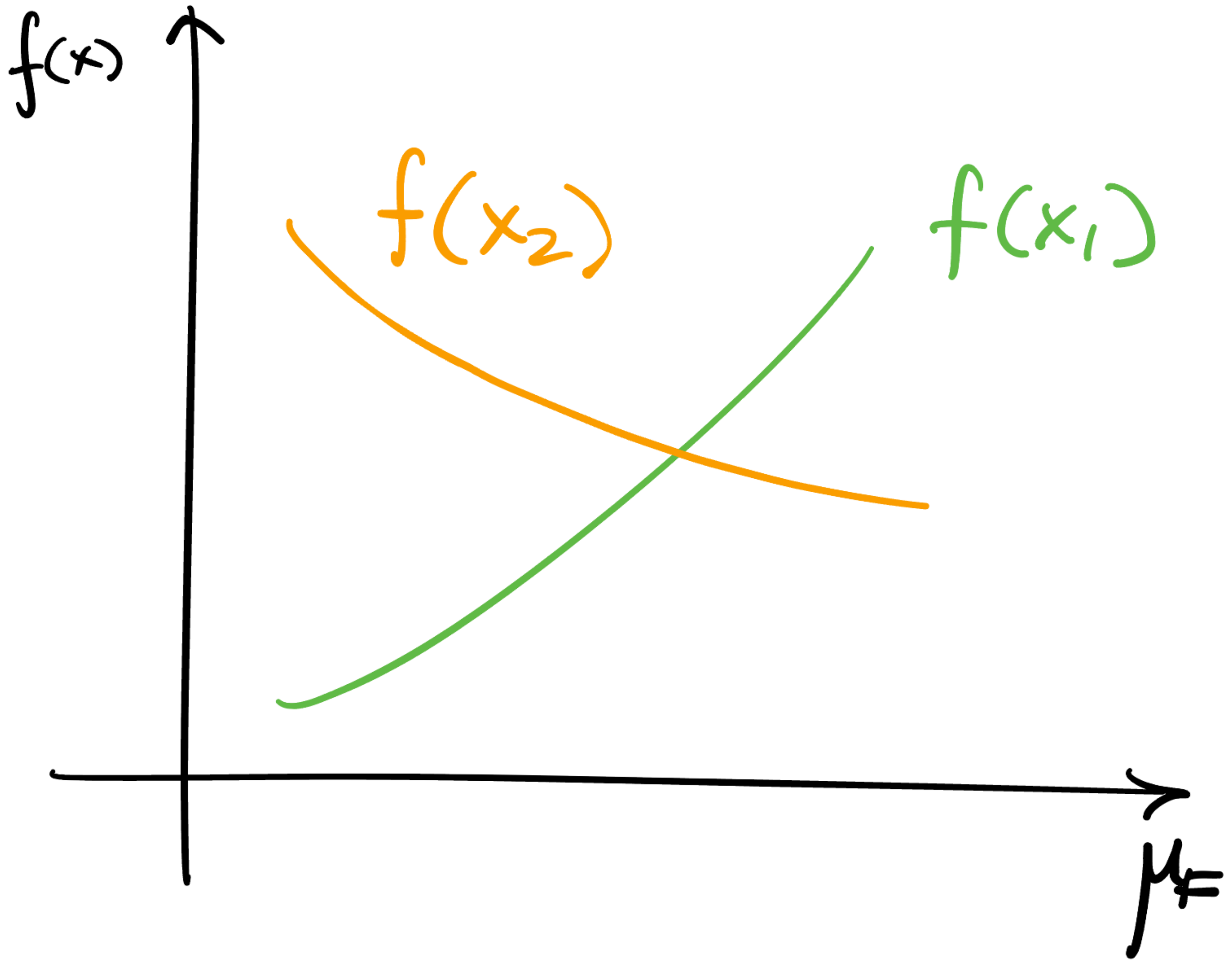
PDFs renormalisation flow: DGLAP



Similarly to the running of $\alpha_s(\mu_R)$, we can change μ_F and get a Renormalisation Group Equation for PDFs:

Dokshitzer–Gribov–Lipatov–Altarelli–Parisi (DGLAP) eqs

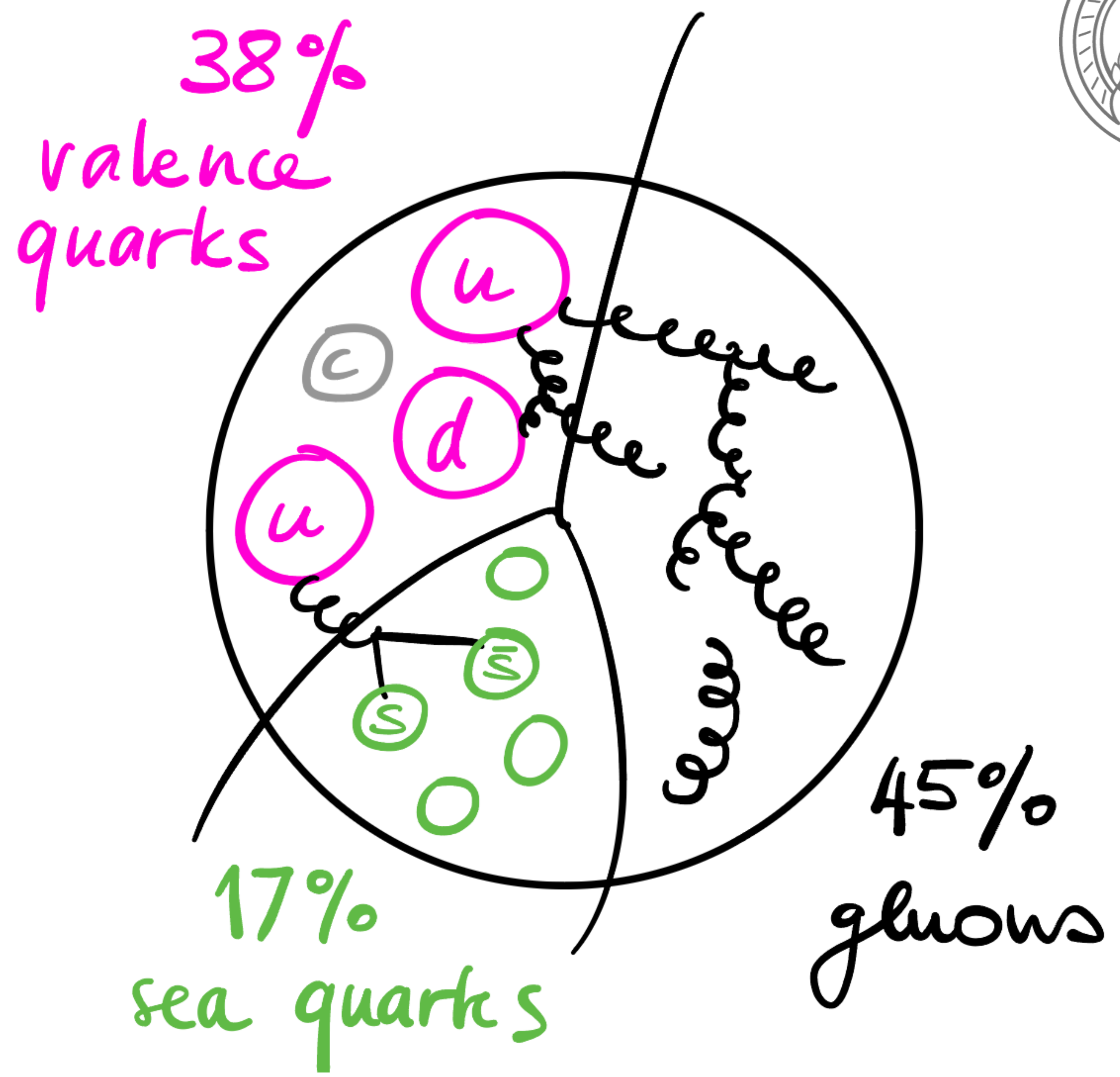




DGLAP flavour structure

Also gluons represent a proton component!

DGLAP is a matrix in flavour space

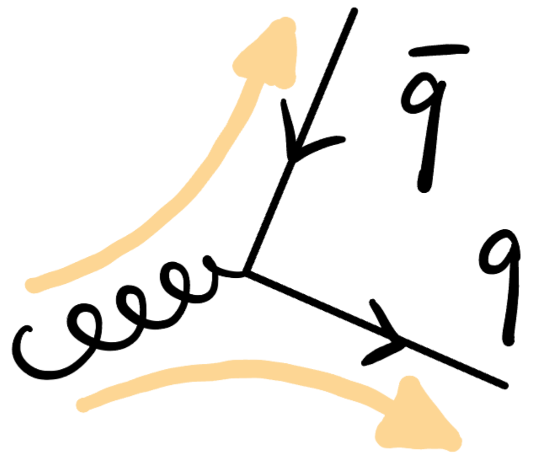


$$\frac{d}{d\ln\mu_F^2}\begin{pmatrix} q \\ q' \\ g \end{pmatrix} = \begin{pmatrix} P_{qq} & P_{qq'} & P_{qg} \\ P_{q'q} & P_{q'q'} & P_{q'g} \\ P_{gq} & P_{gq'} & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} q \\ q' \\ g \end{pmatrix}$$

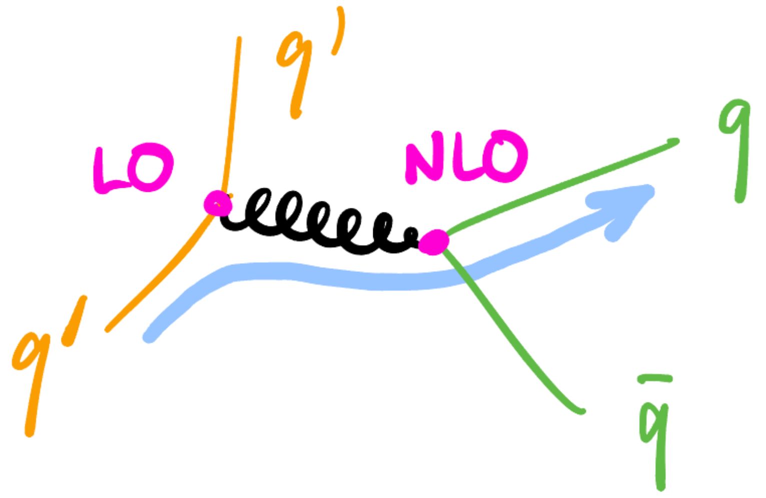
$$P_{qq}^{LO}(z) = C_F\left(\frac{1+z^2}{1-z}\right)_+$$

$$\to C_F\left(\frac{1}{1-z}\right)_+$$

$P_{\bar q g} = P_{qg}$



$P_{qq'} = 0$ @ LO



P_{ij}@LO	DGLAP, 1972-77
P_{ij}@NLO	Curci et al, 1980
P_{ij}@N^{2}LO	Moch at al, 2004
P_{ij}@N^{3}LO	Moch et al, 2020-