# Pion/kaon gluon PDF study in charmonia and prompt photon production

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**On behalf of the COMPASS++/AMBER Collaboration**

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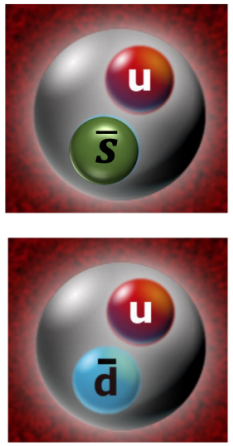
# Motivations: meson structure

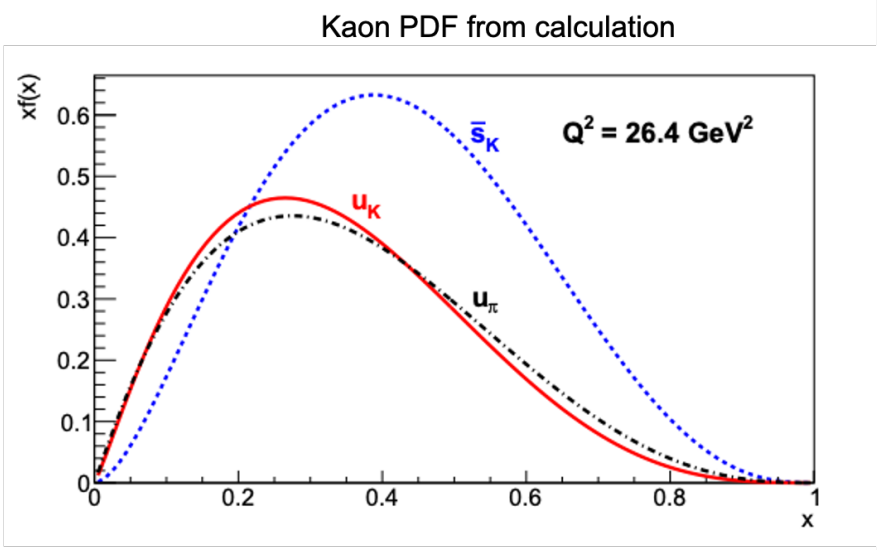
Unlike the proton, mesons structure remains largely unknown !

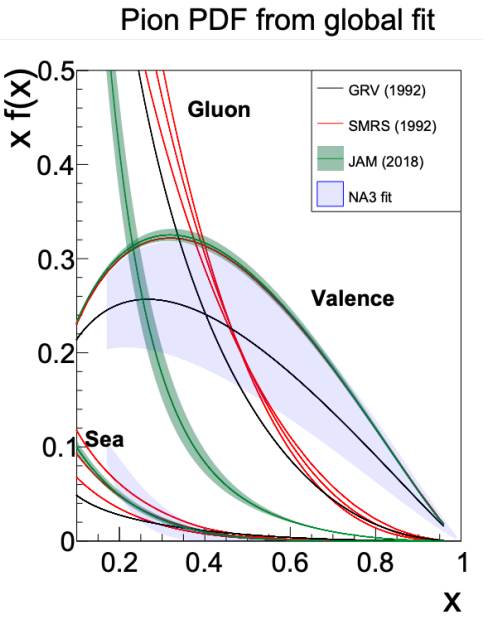
**Mesons information**

- 1 heavy/1 light valence quark: $M_K \sim 490$ MeV
- 2 light valence quarks: $M_\pi \sim 140$ MeV

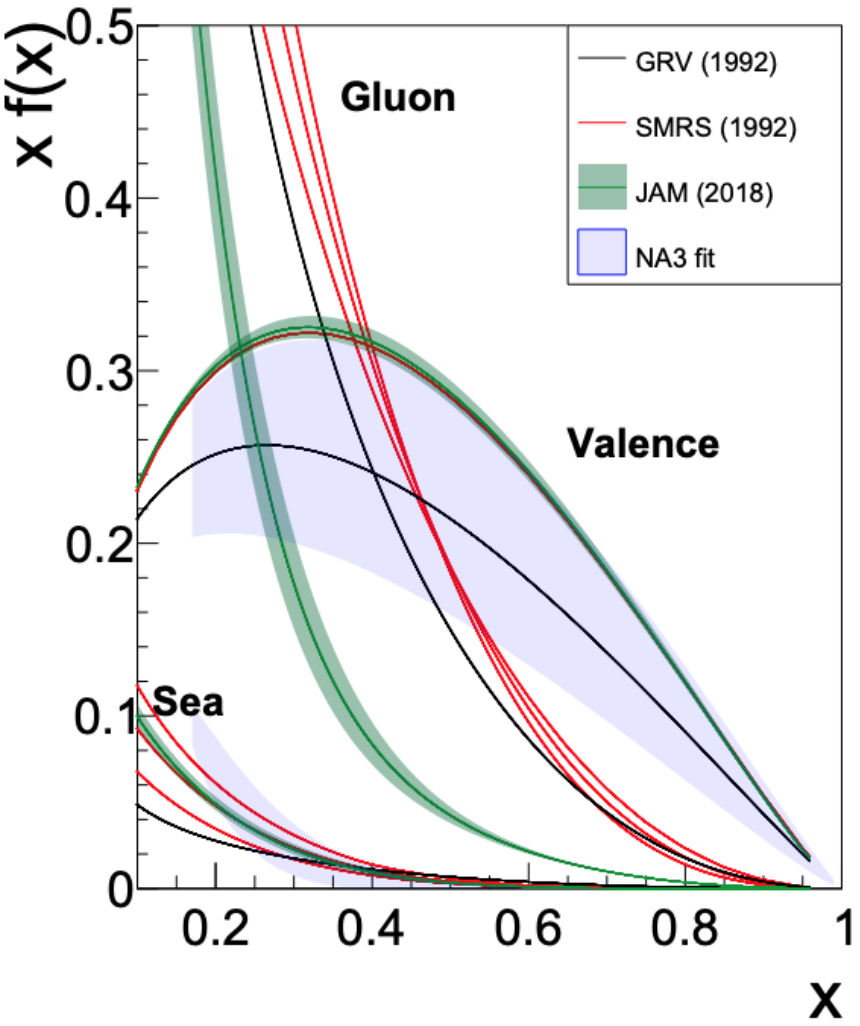



The $s$ quark in the kaon is heavier: what is the difference between $xG(x)^\pi$ and $xG(x)^K$ ?



# Status of the light mesons PDF: pion meson I

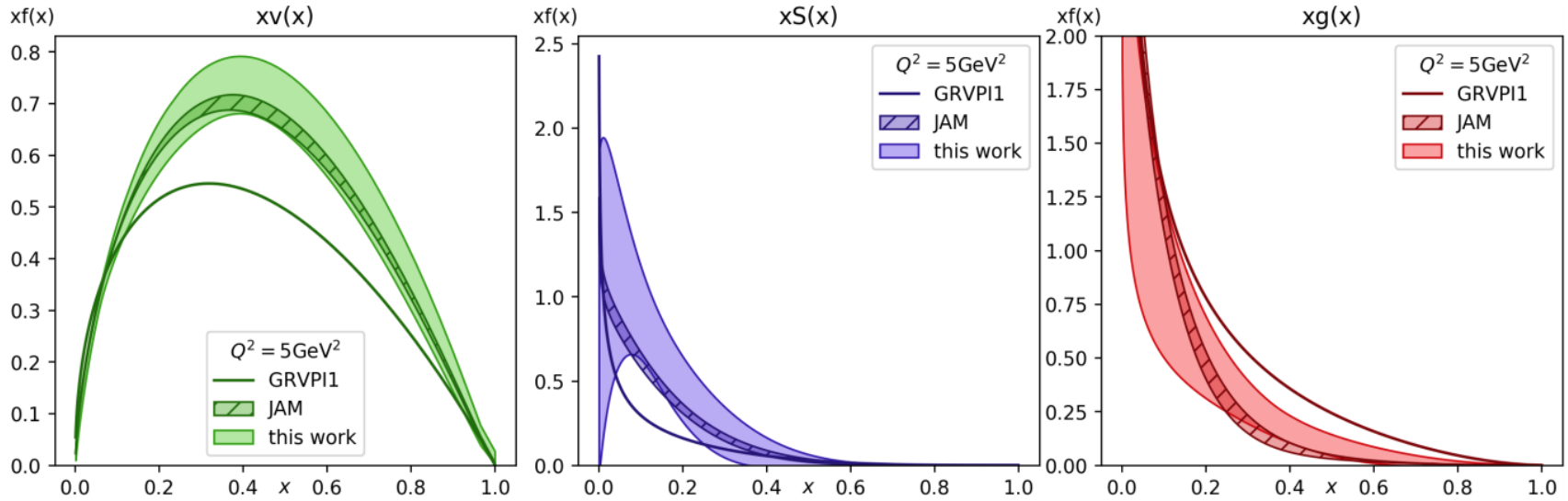



## Pion PDF at NLO

- GRV/SMRS: Drell-Yan (E615,NA10) and prompt photon measurements (WA70,NA24)
- JAM: Drell-Yan + leading neutron data in DIS (ZEUS,H1) constraining $x_\pi \sim 10^{-3}$

**Important differences between pion PDF → Need new precise data !**

# Status of the light mesons PDF: pion meson II

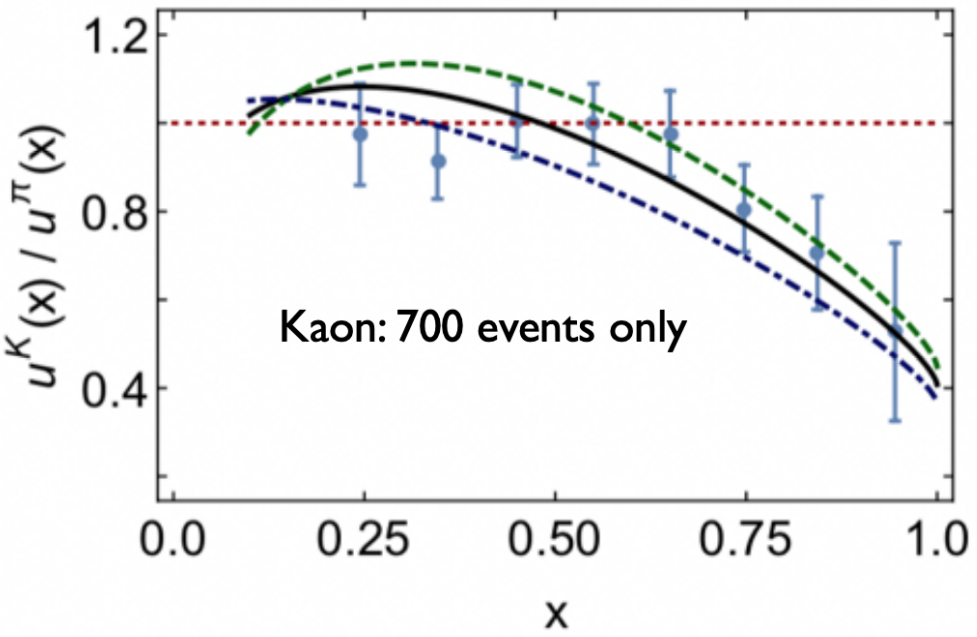



- Last pion PDF from xFitter Framework using Drell-Yan (E615,NA10) and prompt photon measurements (WA70,NA24) data
- Error bars larger compared GRV and JAM PDF
- Predicts $v(x) \sim (1-x)$ as $x \to 1$

**NLO extraction but need to take into account ressumation term at large $x$ (P. Barry and W. Vogelsang talks on Wednesday)**

# Status of the light mesons PDF: kaon meson

Chen et al, 1602.01502




## Kaon PDF

- Drell-Yan data (NA3) only 700 events !
- Information on valence $\bar{u}$ quark from kaon

$$\frac{\sigma(K^-)}{\sigma(\pi^-)} \propto \frac{\bar{u}_K}{\bar{u}_\pi} < 1$$

- $\bar{u}^K$ is steeper compared to $\bar{u}^\pi$
- Only few information about kaon gluon PDF

**Kaon PDF is very little known → Need data !**

# How can we probe the gluon structure ?

**Charmonia production:**

$gg \rightarrow Q\bar{Q} \rightarrow J/\psi + X$

- High cross section: nice signal !
- Strong production model dependence
- Important nuclear effects in hadron-nuclei collisions

**Prompt photon-production:**

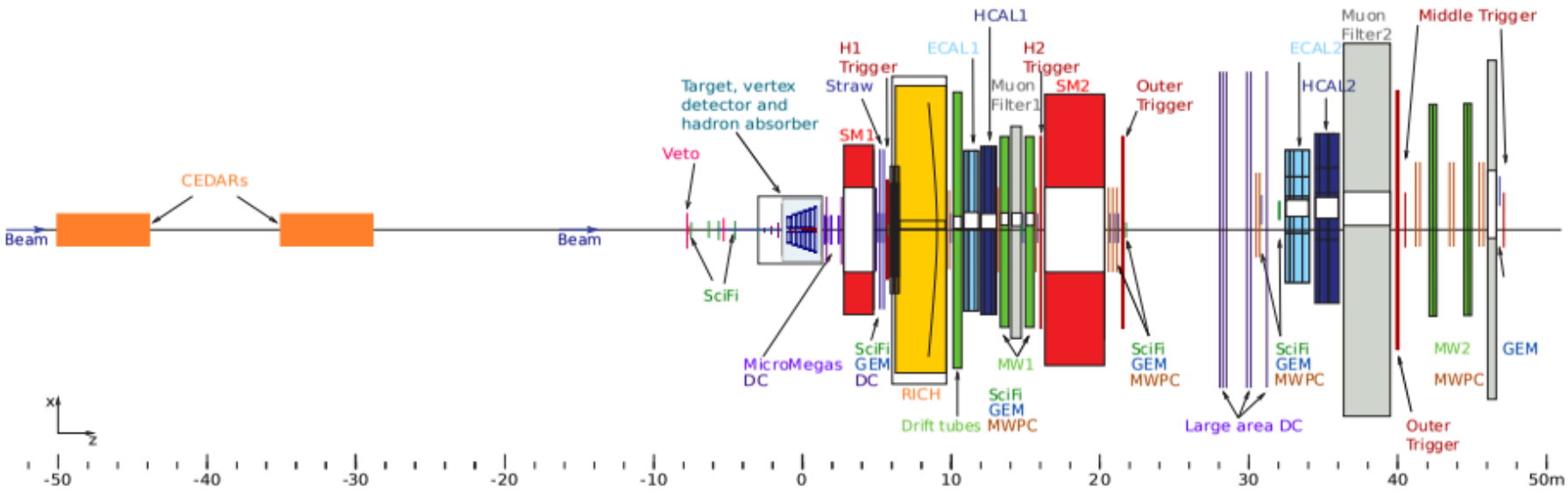
$gq \rightarrow \gamma q$

- An alternative way to access gluon PDF
- But other process $q\bar{q} \rightarrow g\gamma$
- Important photon-background from $\pi^0$ and $\eta$

**2 complementary processes to access to gluon structure**

# COMPASS++/AMBER collaboration

- Experiments planned for CERN in 2022-2024 (RUN 3) [Proposal]
  - Drell-Yan and charmonium production with $\pi^-/\pi^+$ beams
- Experiments planned for CERN in 2026++ (RUN 4) [Letter of Intent]
  - Drell-Yan, charmonium and prompt photons production with kaon/antiproton beams

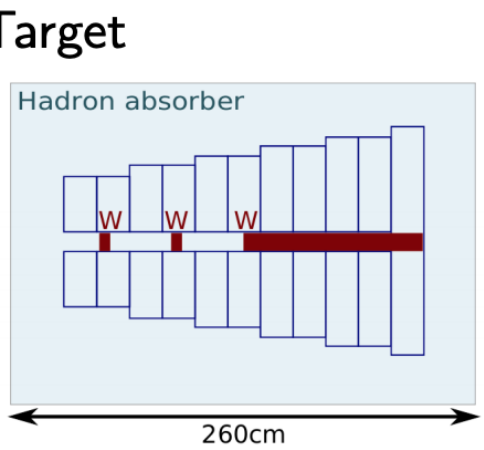



**Dedicated web page: https://nqf-m2.web.cern.ch/**

# Charmonia production possibilities

[COMPASS++/AMBER, SPSC-P-360]

- RUN 3: $E_{beam} = 190$ GeV
  1. $\pi^+$ (25%) and $p$ (74%)
  2. $\pi^-$ (97%)
- RUN 4: $E_{beam} \sim 100$ GeV
  1. $K^-$ ( 50%), $\pi$ ( 50%)
  2. $K^+$
  3. $\bar{p}$


- Fixed target configuration, access to large $x_F \to 1$ and $x_2 \sim 0.1$
- Probe small $p_\perp \lesssim M$ dominated by resummation contribution
- Light C and heavy W nuclear targets

Possible to study polarization, cross section and nuclear effects with different beams with high statistics !

**Unique place in the world!**

# Charmonia production possibilities Phase 1

**Phase-1**

| Experiment | Target type | Beam energy (GeV) | Beam type | J/$\psi$ events |
|---|---|---|---|---|
| NA3 [76] | Pt | 150 | $\pi^-$ | 601000 |
| | | 280 | $\pi^-$ | 511000 |
| | | 200 | $\pi^+$ | 131000 |
| | | | $\pi^-$ | 105000 |
| E789 [129, 130] | Cu | 800 | p | 200000 |
| | Au | | | 110000 |
| | Be | | | 45000 |
| E866 [131] | Be | 800 | p | |
| | Fe | | | 3000000 |
| | Cu | | | |
| NA50 [132] | Be | 450 | p | 124700 |
| | Al | | | 100700 |
| | Cu | | | 130600 |
| | Ag | | | 132100 |
| | W | | | 78100 |
| NA51 [133] | p | 450 | p | 301000 |
| | d | | | 312000 |
| HERA-B [134] | C | 920 | p | 152000 |
| COMPASS 2015 | 110 cm $NH_3$ | 190 | $\pi^-$ | 1000000 |
| COMPASS 2018 | | | | 1500000 |
| This exp | 75 cm C | 190 | $\pi^+$ | 1200000 |
| | | | $\pi^-$ | 1800000 |
| | | | p | 1500000 |
| | 12 cm W | 190 | $\pi^+$ | 500000 |
| | | | $\pi^-$ | 700000 |
| | | | p | 700000 |

- Large statistics in both C and W nuclear targets
- More than 1M events in C target for $\pi$ and $p$ beams
- 10K-30K $\psi'$ events per beam/target

Simultaneous measurements with different beams

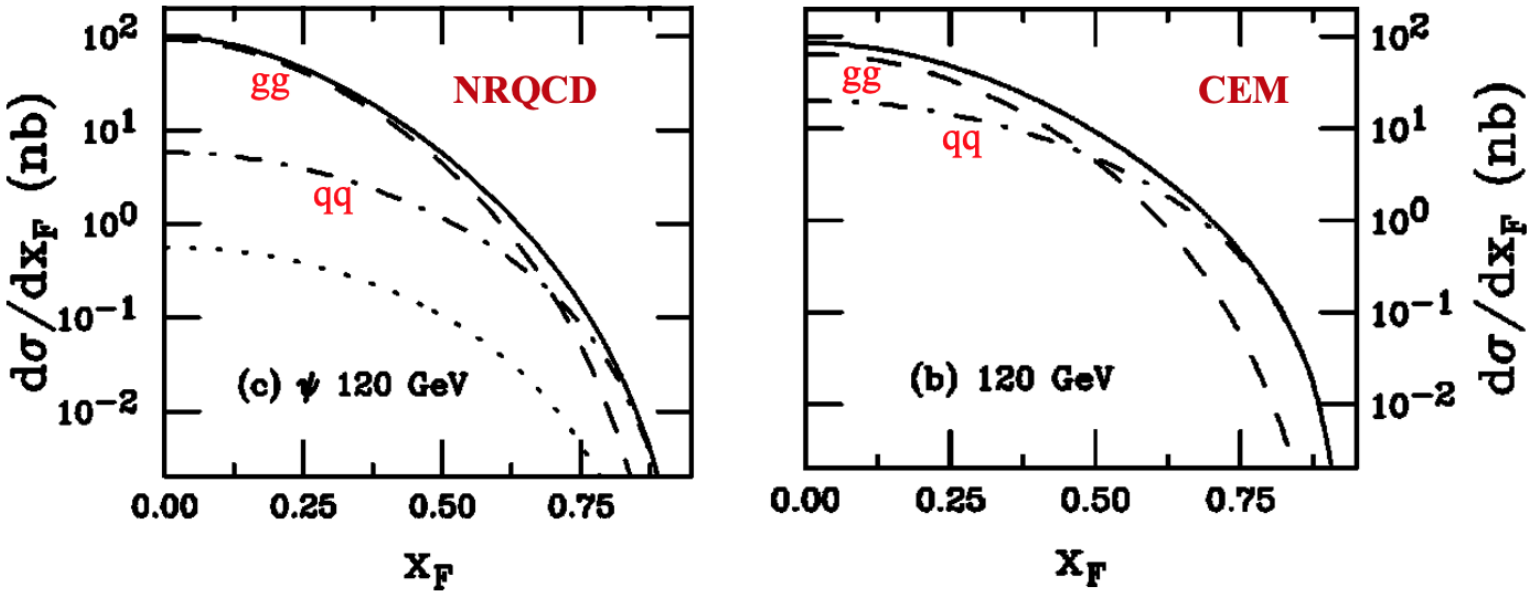
# $J/\psi$ production models: a puzzle

- **Color Evaporation Model (CEM)**
  - Simple cross section for producing $c\bar{c}$ pair with $t_{had} \gg t_{hard}$
  - Simple model dominated by color octet state
  - Important phenomenological success especially at SPS energies
- **Recent improvements ICEM**
  - By taking into account soft gluons between $c\bar{c}$ and various color sources between $c\bar{c}$ production and its hadronization into bound state
  - Can reproduce $p_\perp$ shape and polarisation at RHIC and LHC
- **Color Singlet and Non-Relativistic QCD models (color singlet and octet)**
  - Based on Long-Distance Matrix Elements (LDME) assumed to be universal : probability of the $c\bar{c}$ to evolve into a bound state
  - CSM reproduces at NNLO($\alpha_S^5$) LHC data
  - NRQCD reproduces at NLO LHC data

**Could new data help improving our knowledge on J/$\psi$ production?**

# Initial state production model dependence

$J/\psi$ production model at $E_{\text{beam}} = 120$ GeV in pp [Vogt, 9907317]

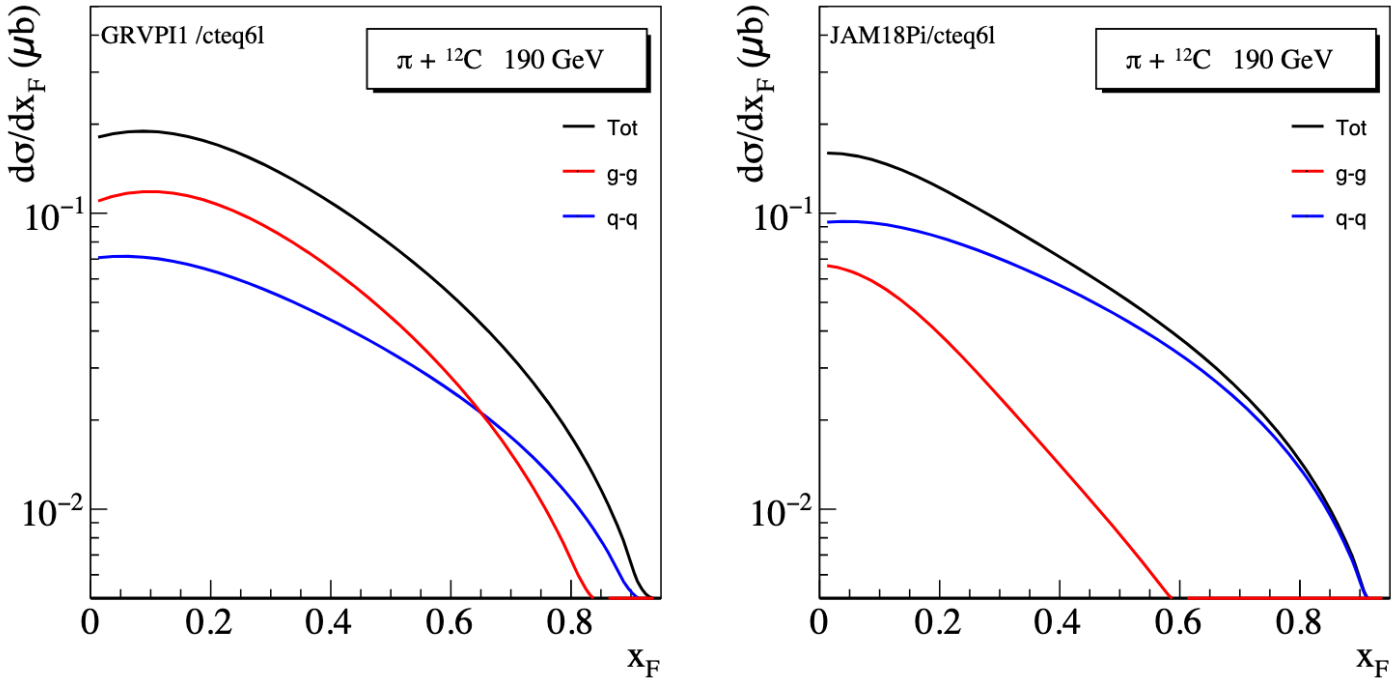



- The relative contribution $q\bar{q}/gg$ depends on the production model
- To extract the PDF correctly, we must identify which is the dominant channel $q\bar{q}$ or $gg$

**Model dependence: prevents a reliable PDF extraction**

# $J/\psi$ production in pion collisions in CEM model

## Color Evaporation Model (CEM) calculation at leading order




- GRV gives gg dominant at $0 \lesssim x_F \lesssim 0.8$
- JAM gives $q\bar{q}$ dominant at all $x_F$

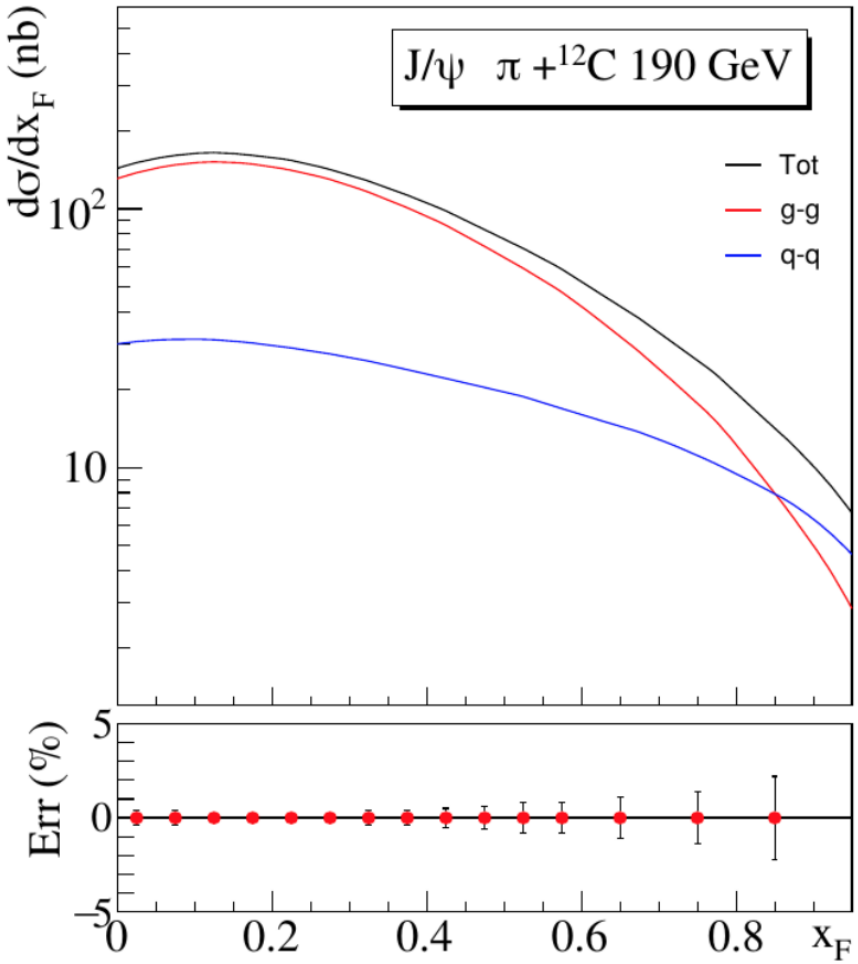
} Unknown initial state

**Strong dependence on the pion PDF parametrization !**

# ICEM predictions - $x_F$ dependence

- $J/\psi$ absolute cross section

ICEM prediction at AMBER [COMPASS++/AMBER, SPSC-P-360]




- Errors estimated using 2015 COMPASS data
- High statistics: strong constraint on the shape of cross sections directly related to the PDF shape

**New measurement can give a constraint on the production model and on the PDF**

# ICEM prediction - polarization

- $J/\psi$ polarisation

$\mathrm{J}/\psi$ is a $1^{--}$ particle; its third component is $\mathrm{J_z} = 0, +1, -1$:

$$\frac{d\sigma}{d(\cos\theta)} \propto 1 + \alpha \cos^2\theta$$

1. If $\alpha = -1$ corresponds to 100% longitudinal polarization ($\mathrm{J_z} = 0$)
2. If $\alpha = +1$ corresponds to 100% transverse polarization ($\mathrm{J_z} = \pm 1$)

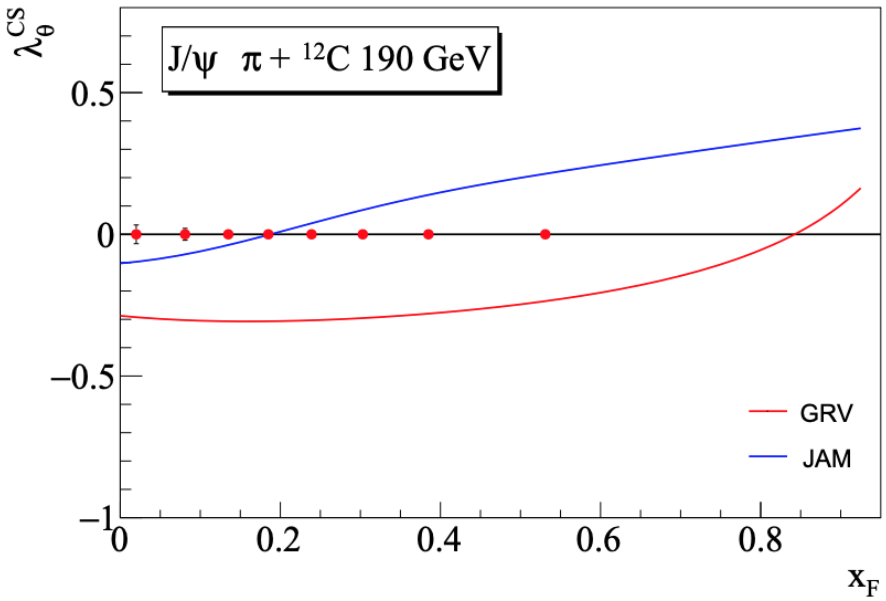
Angular momentum, chirality and parity conservations preserve the properties of the $J/\psi$

**Key variable for understanding the bound state formation**

# ICEM prediction - polarization

- $J/\psi$ polarisation

ICEM prediction at AMBER [COMPASS++/AMBER, SPSC-P-360]



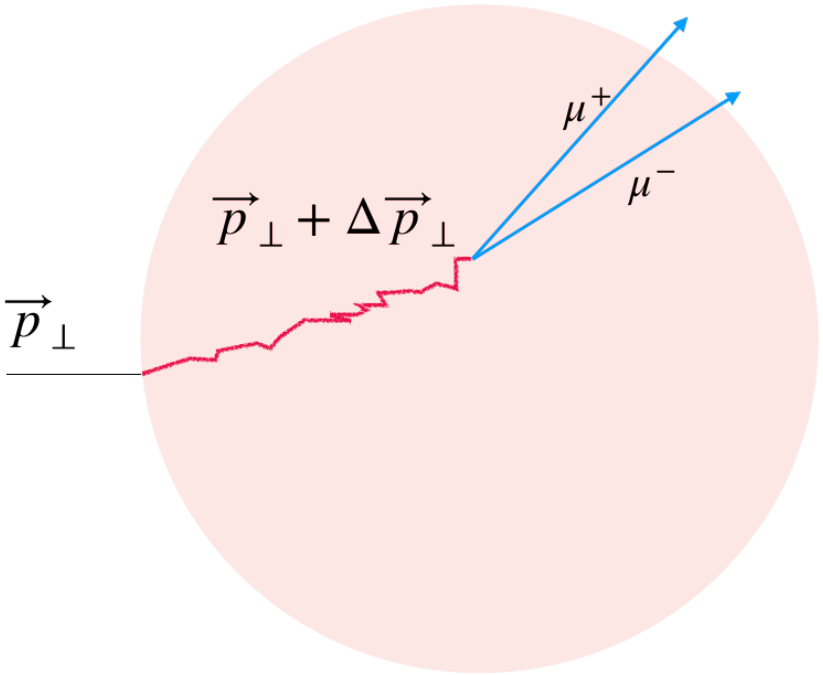

$\lambda_\vartheta^{CS} \approx +0.4$ for $q\bar{q}$
$\lambda_\vartheta^{CS} \approx -0.6$ for $gg$

Strong difference as a function of $x_F$ depending on pion PDF used

**It is possible to disentangle pion PDF !**

# Broadening effect

- Nuclear broadening in $\pi$A $\propto \mathcal{C}_F$ [Arleo Naïm, 2004.07188]




Due to multiple scattering in the nuclear matter, the $p_\perp$ shape is modified compared to hp collisions:

$$\Delta p_\perp^2 = \langle p_\perp^2 \rangle_{\pi A} - \langle p_\perp^2 \rangle_{\pi p}$$

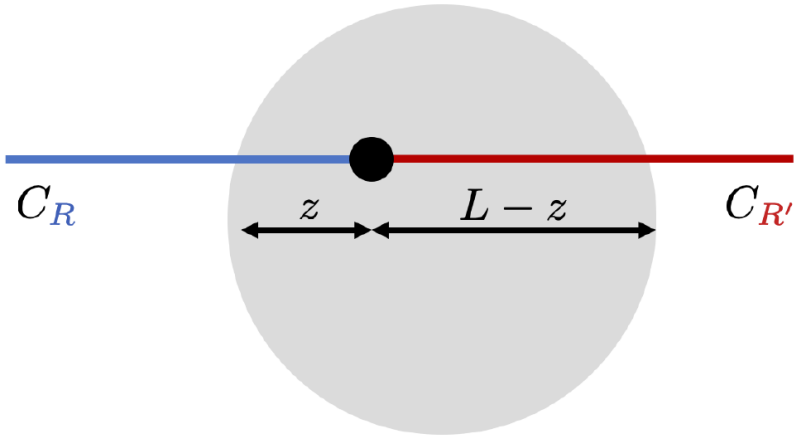
The broadening effect depends on the parton color charge $\mathcal{C}_F$

# Broadening effect

- Nuclear broadening in $\pi$A $\propto C_F$ [Arleo Naïm, 2004.07188]

$$\Delta p_\perp^2 \propto (C_R + C_{R'})\,(\hat{q}_\mathrm{A} L_\mathrm{A} - \hat{q}_\mathrm{p} L_\mathrm{p})$$

with $\hat{q}$ which encodes scattering properties of nuclear matter




**If gluon channel is dominant:**

Quarkonium (octet): $C_g + C_{[Q\bar{Q}]_8} = N_c + N_c$

**If quark channel is dominant:**

Quarkonium (octet): $C_{\bar{q}} + C_{[Q\bar{Q}]_8} = C_F + N_c$

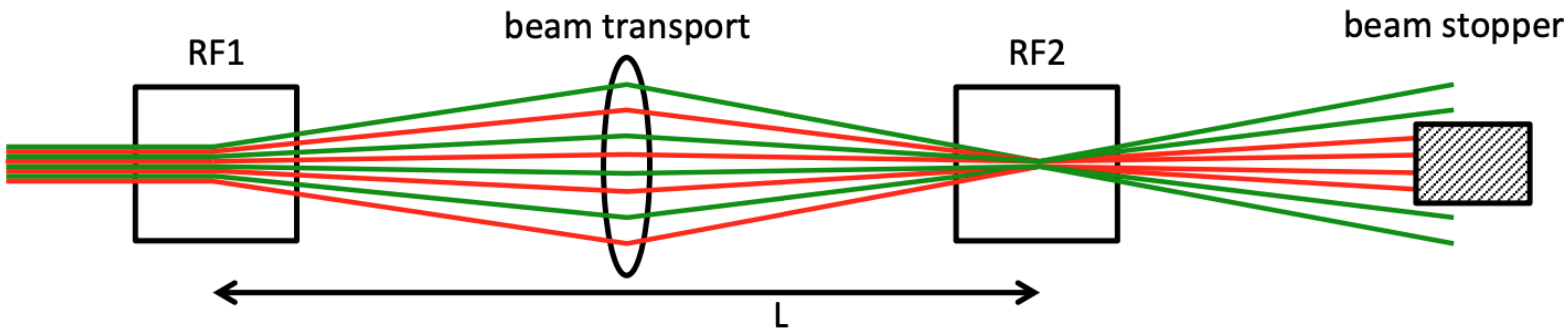
**Possible to probe the initial color state/the production model**

# Charmonia production possibilities: Phase 2

[COMPASS++/AMBER Letter of Intent, 1808.00848]

**Phase-2**

- Studies underway at CERN for RUN4 (2026++)
- Radio-Frequency (RF) separated beams allows to produce $K$ and $\bar{p}$ beams: unique in the world !
- High statistics measurements with $K^+$ and $K^-$
- $K^-$: more than 1 million $J/\psi$ events per year of data taking on a carbon target.



# $J/\psi$ production in kaon collisions in CEM model

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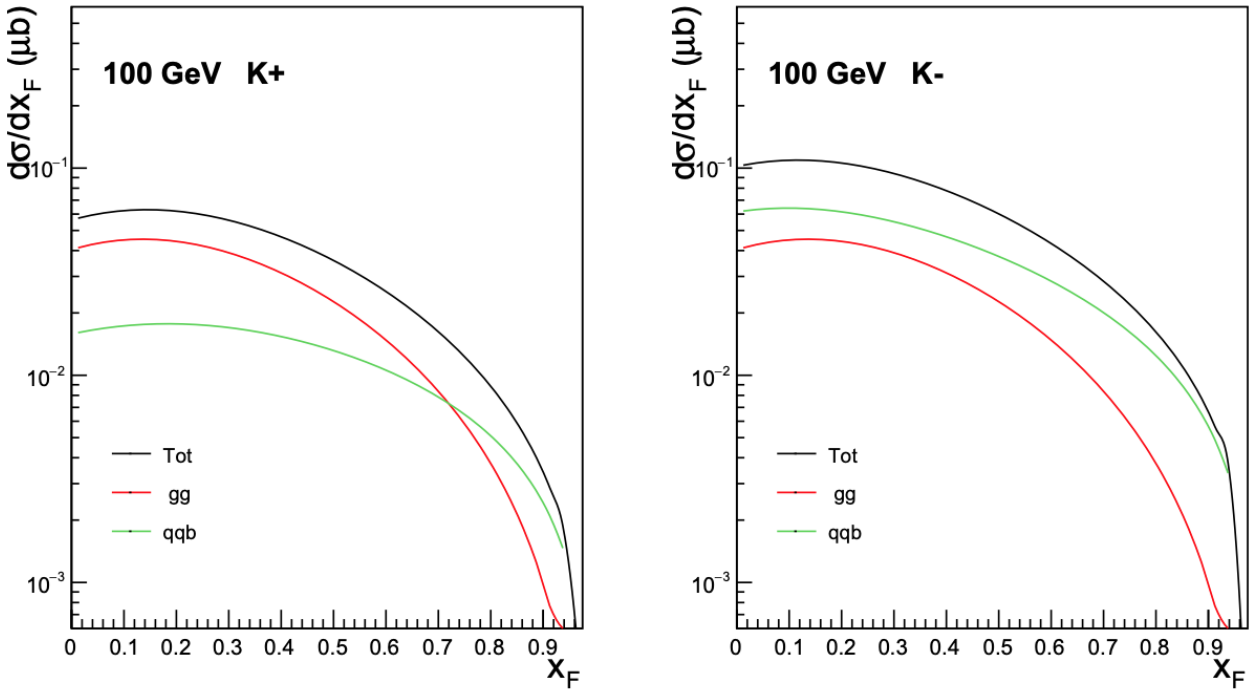
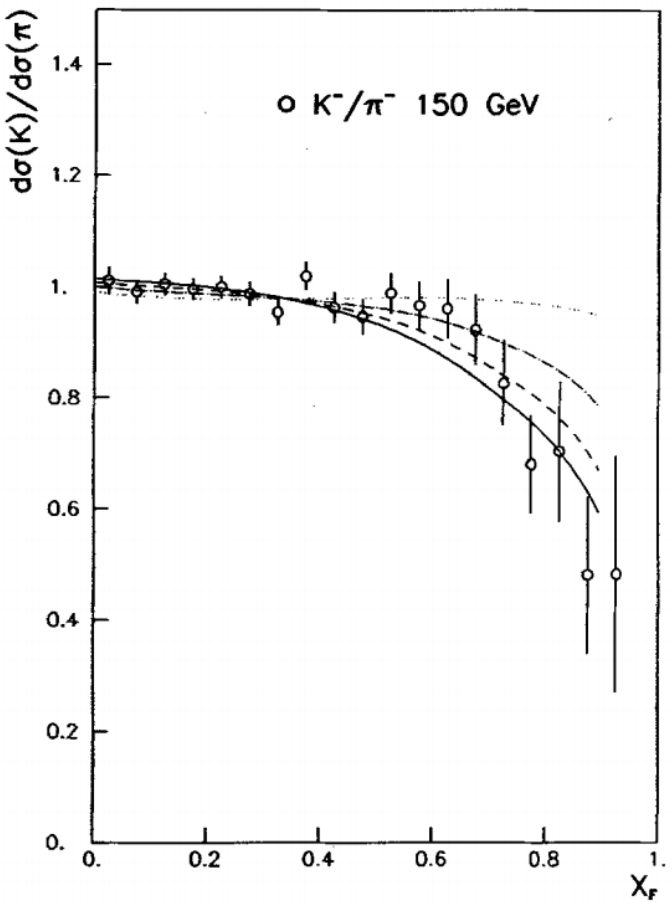



- Not the same dominant channel in $K^-$ and $K^+$ due to the $\bar{s}$ quark
- Same gluon contribution in both $K^-$ and $K^+$
- It possible to isolate valence quark PDF from the difference of cross section: $\sigma^{K^-}_{J/\psi} - \sigma^{K^+}_{J/\psi} \propto \bar{u}^{K^-} u^N$

# Comparison between pion and kaon collisions

$K$Pt and $\pi$Pt collisions [NA3 Collaboration, BF01573213]




- 150 GeV $\sim$ 20 000 $K^-$ events
- At large $x_F$, *i.e.* $x_1 \to 1$, we have

$$\frac{\sigma(K^-)}{\sigma(\pi^-)} \propto \frac{\bar{u}_K}{\bar{u}_\pi} < 1$$

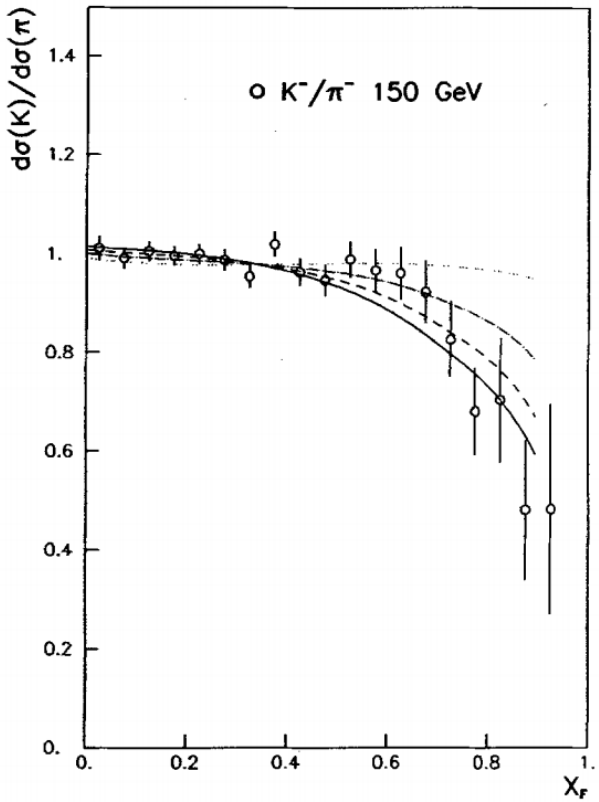
- $\bar{u}^K$ is steeper compared to $\bar{u}^\pi$
- At moderate $x_F \sim 0$, we have

$$\frac{\sigma(K^-)}{\sigma(\pi^-)} \sim 1$$

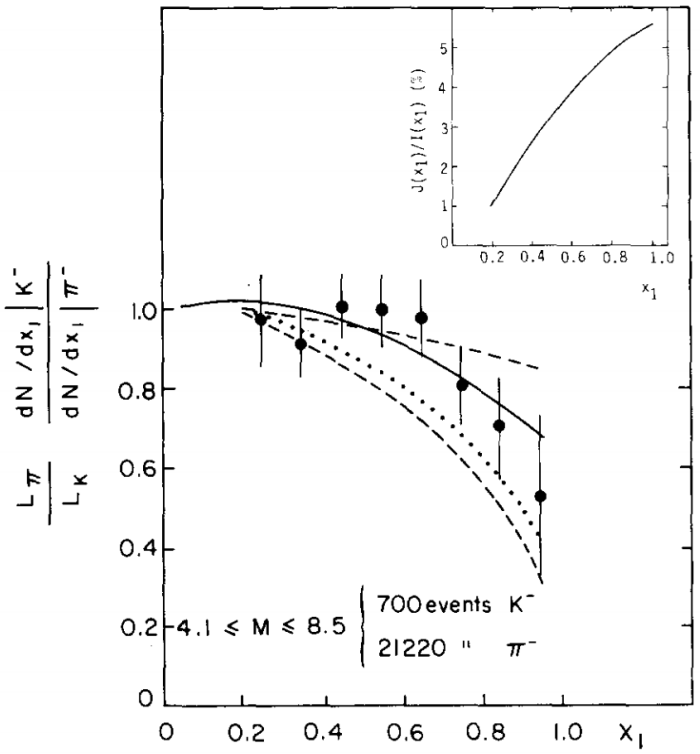
**Can we use this ratio to identify the dominant channel $q\bar{q}$ or $gg$ ?**

# Kaon/pion ratio: DY vs $J/\psi$

$J/\psi$




DY



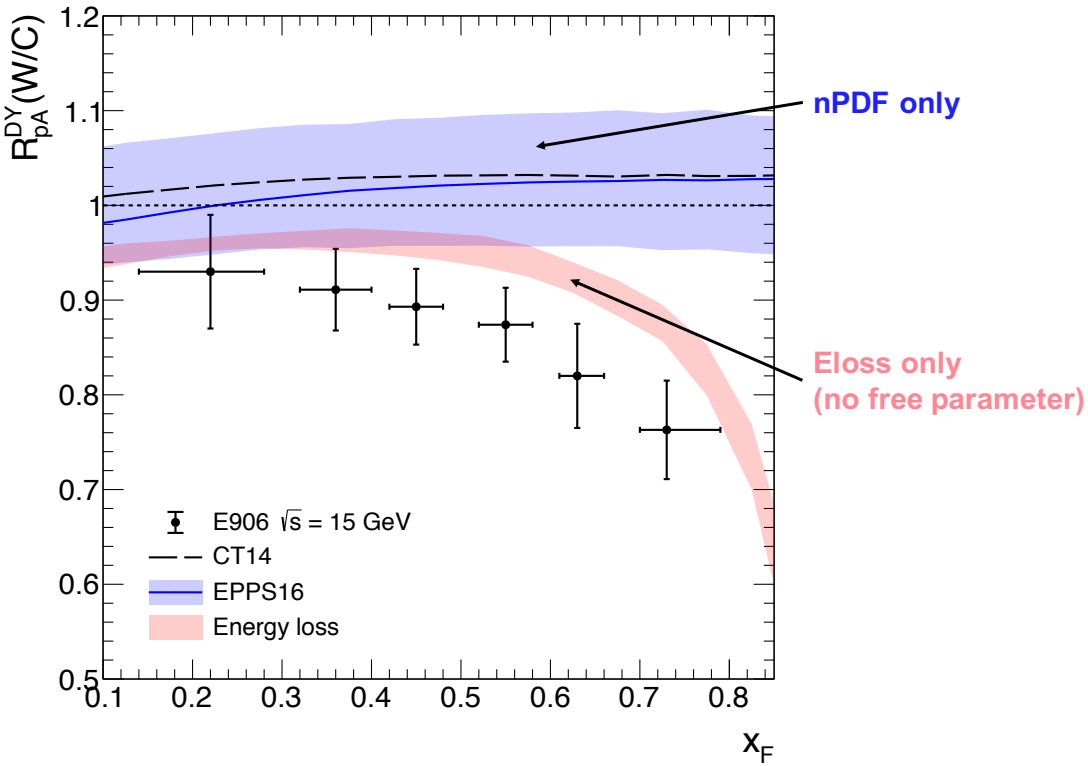

- We observe the same amplitude of suppression and the ratio is equal to 1 at moderate $x_F \sim 0$

**Same initial partonic state ?**

# Nuclear effect at large $x \to 1$

[Arleo, Naïm, Platchkov, 1810.05120]

- DY large statistics only on heavy nuclear targets
- $\bar{u}^K$ is steeper compared to $\bar{u}^\pi$
- Initial energy loss has an impact at large $x \to 1$ (V. Andrieux talk on Tuesday)
- Important effect at SPS energies $\Delta E_{\mathrm{LPM}}/E$

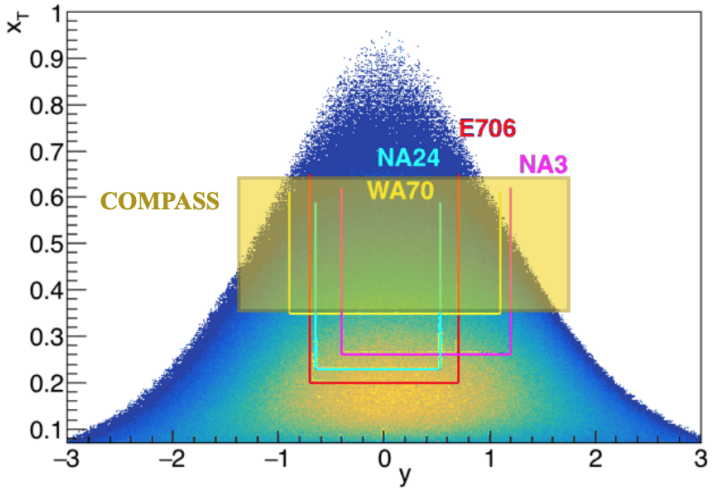


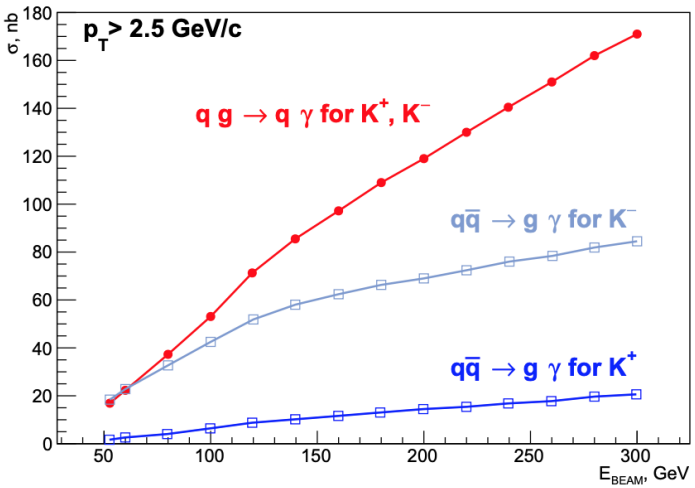
# Gluon PDF via prompt photon production

**Opportunities:**

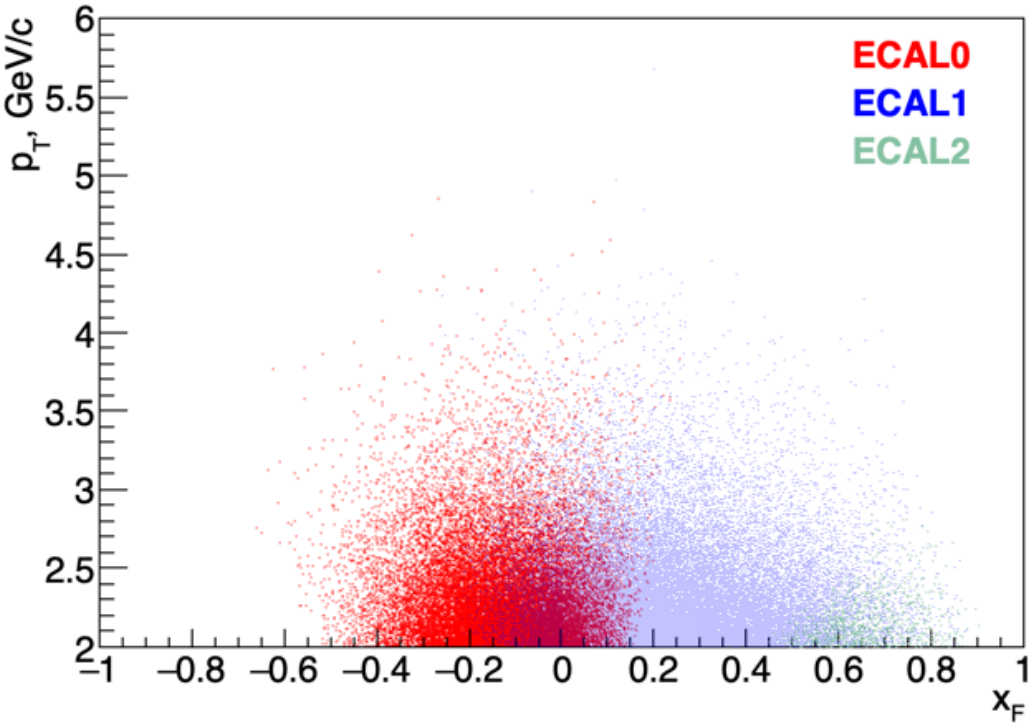
- Direct access to the gluon PDF via $gq \to q\gamma$
- Using a positive kaon beam at 100 GeV at I = 5 $\times 10^6$ $s^{-1}$ to minimise $q\bar{q} \to \gamma g$ annihilation process
- $\sim$ 10% of contamination from $q\bar{q}$ process
- Contribution of fragmentation photons $\sim$ 10%
- Large rapidity acceptance $-1.4 < y < 1.8$

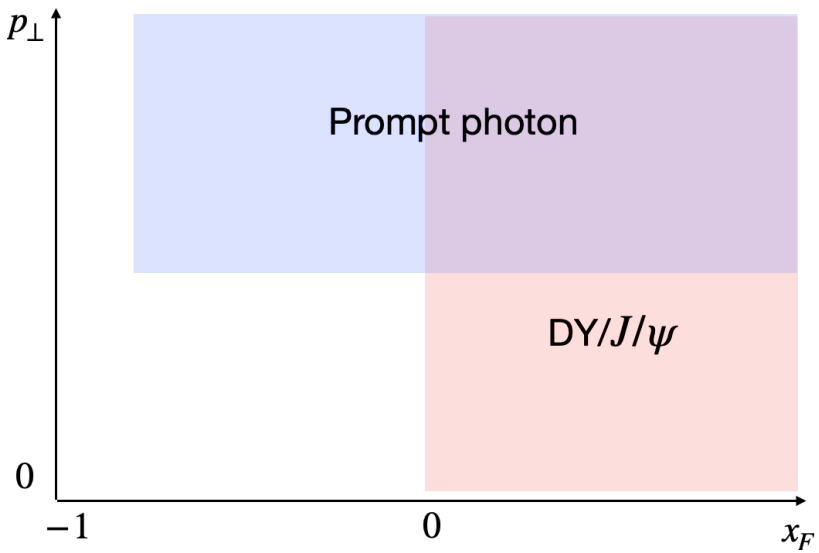
[COMPASS++/AMBER, 1808.00848]



# $x_F$ phase space



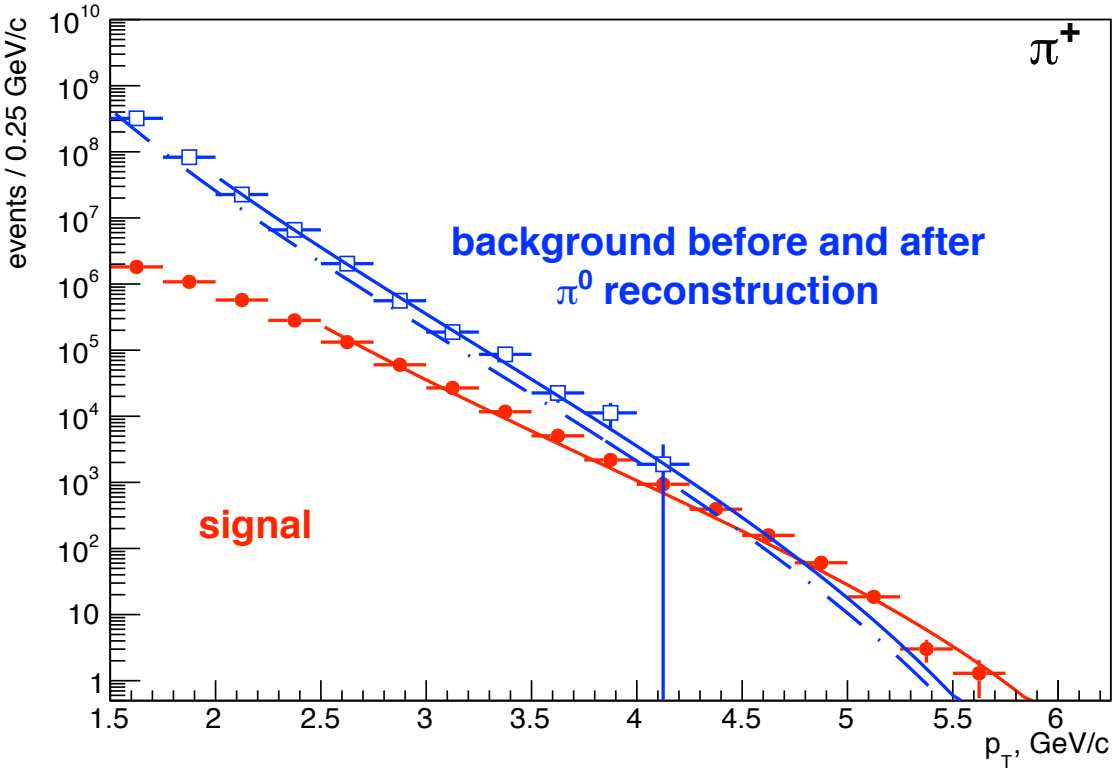




- Possible to access negative values of $x_F \sim -0.5$ (rapidiy)
- Possible to access small values of $x_\pi \sim 0.03$

**Complementary measurements with charmonia where $x_F \gtrsim 0$**

# Background from decays mesons

- Large background from $\pi^0 \to 2\gamma$ and $\eta \to 2\gamma$ at low $p_\perp$
- Access only $p_\perp \gtrsim 2$ GeV: need to take into account ressumation ?




- The most important systematic error will be due to the presence of this background especially at $p_\perp \lesssim 4$ GeV

# Conclusion

**Charmonia production**

- Fixed target configuration allows to probe large $x_F \gtrsim 0$ values
- Despite the ignorance of production model, COMPASS++/AMBER will allow to constrain the production model and mesons PDF with unprecedented statistics (more than 1M $J/\psi$ events in each target !)
- Many relevant observable: $p_\perp$ distribution, polarisation, cross section as a function of $x_F$ etc.

**Prompt photon production**

- It is a direct process to access to gluon PDF
- No important background at $p_\perp \gtrsim 2$ GeV
- Complementary measurements with charmonia: possible to access negative $x_F$ values !

**COMPASS++/AMBER experiment is a unique place in the world to study all these topics !**