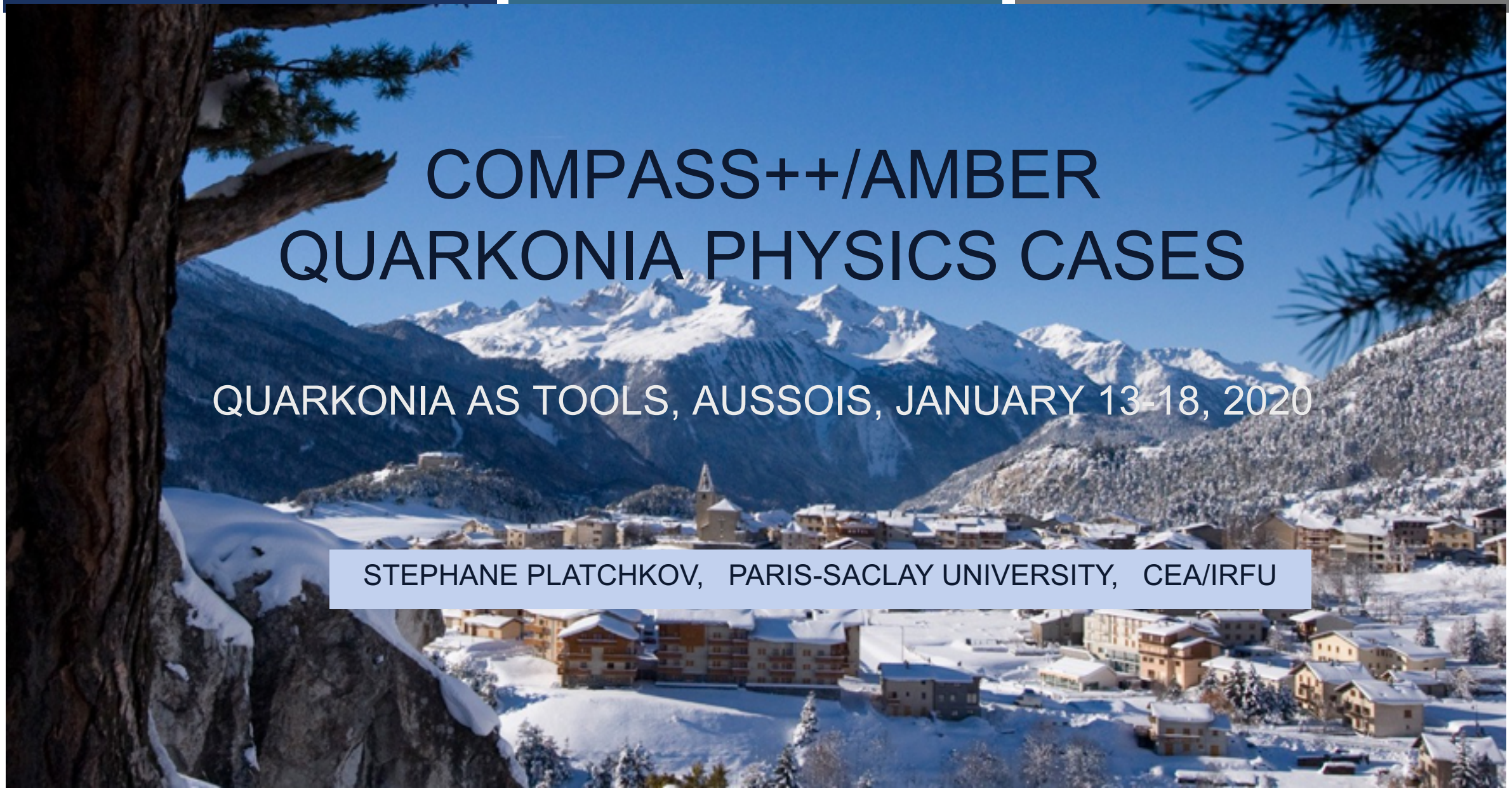


COMPASS++/AMBER QUARKONIA PHYSICS CASES

QUARKONIA AS TOOLS, AUSSOIS, JANUARY 13-18, 2020

STEPHANE PLATCHKOV, PARIS-SACLAY UNIVERSITY, CEA/IRFU

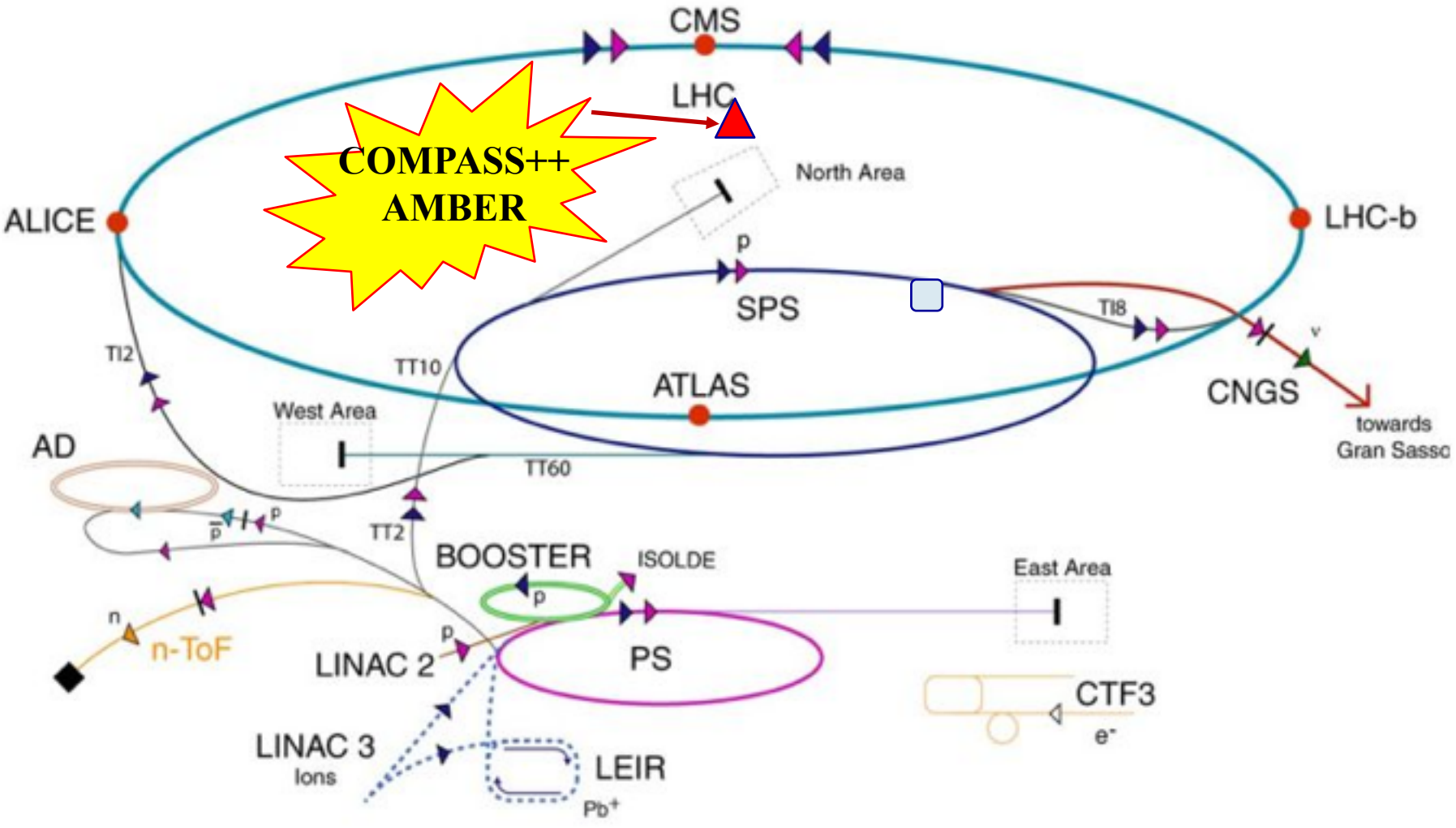
COMPASS++/AMBER COLLABORATION

- Experiments planned for CERN RUN3 (2022-2024) :
  proposal submitted to CERN SPSC
  - Drell-Yan and charmonium production with π^+ and π^- beams

- Experiments planned for CERN RUN4 (2026++) :
  described in a Letter of Intent (with a RF-separated beamline upgrade)
  - Drell-Yan and charmonium production with kaon and antiproton beams:

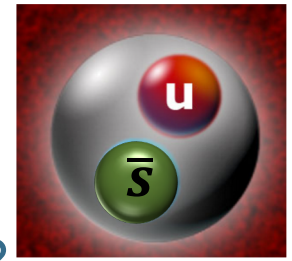
Dedicated web page: https://nqf-m2.web.cern.ch/

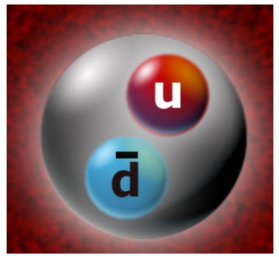
COMPASS++/AMBER@CERN ACCELERATOR COMPLEX



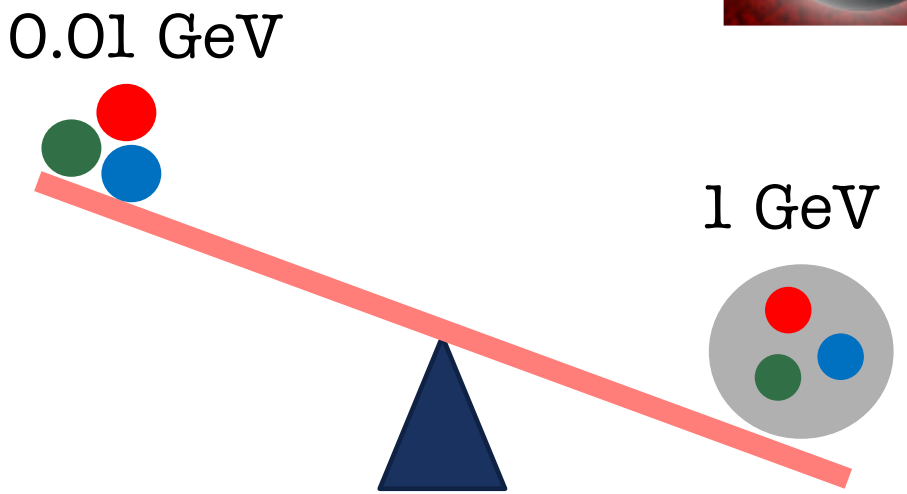
MAIN GOAL OF PROPOSED STUDIES – MESON STRUCTURE

Contrary to nucleon, the meson structure is nearly unknown



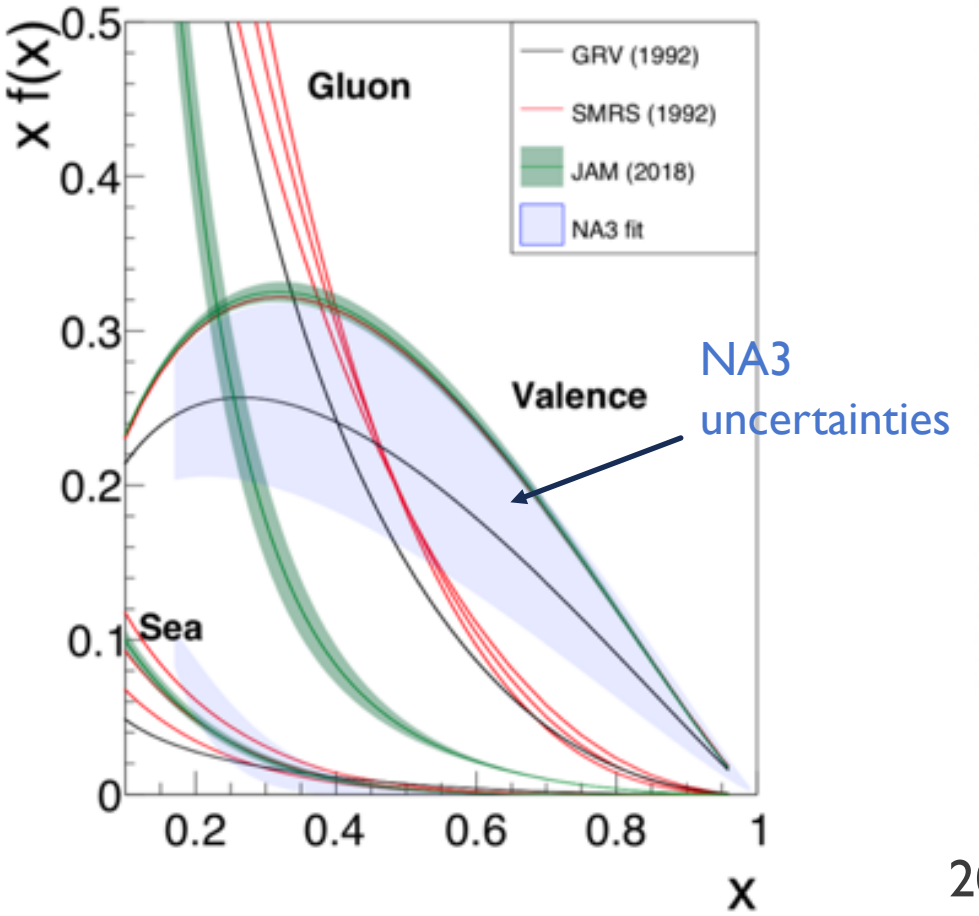


- Meson structure
  - What is the behavior of the kaon and pion PDFs vs the PDFs in the nucleon?
  - The s quark in the kaon is heavier: Are kaon and pion gluon PDFs identical?
- Double nature
  - The lightest quark-antiquark pairs
  - Massless Nambu-Goldstone bosons
- Understand the hadron mass budget
  - Higgs mechanism can't explain hadron masses
  - meson PDFs: Important input



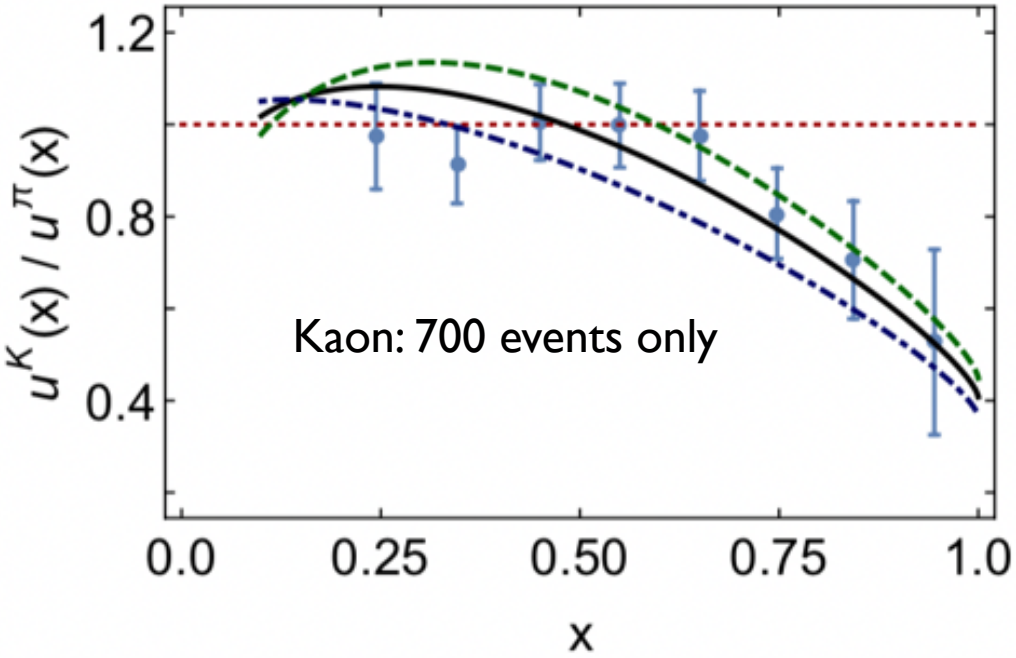
2020: STATUS OF THE LIGHT MESON PDFS

Pion PDF



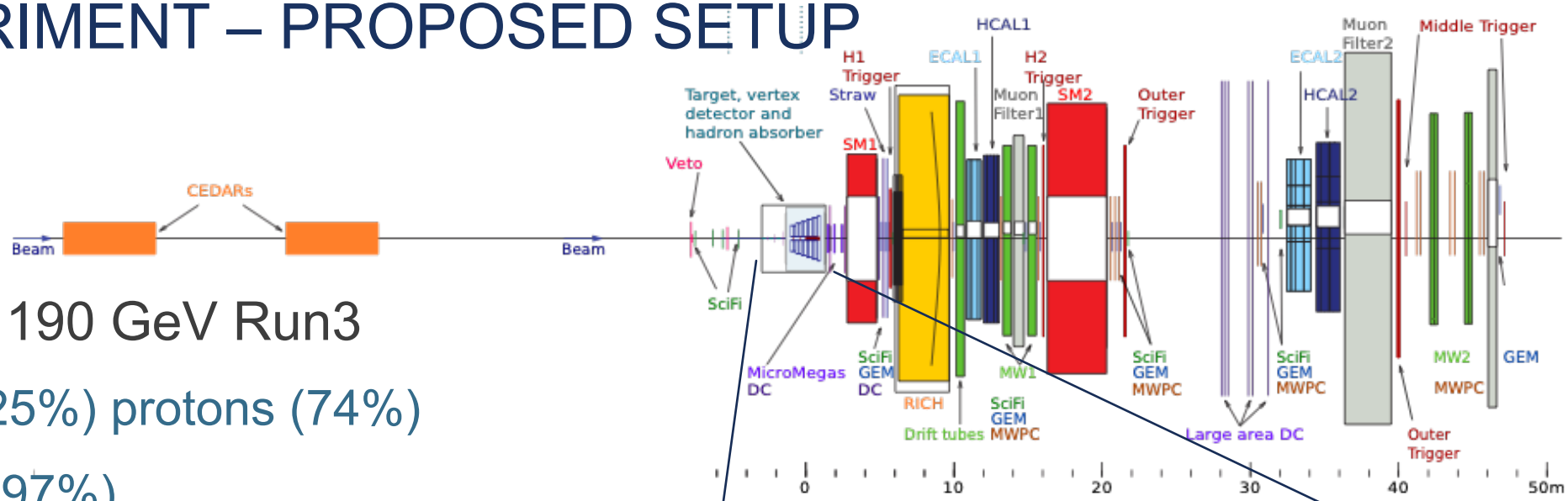
NA3 uncertainties

Ratio kaon/pion PDFs

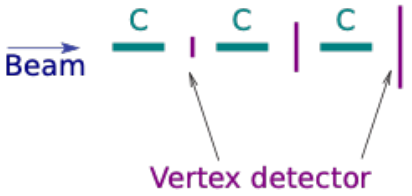


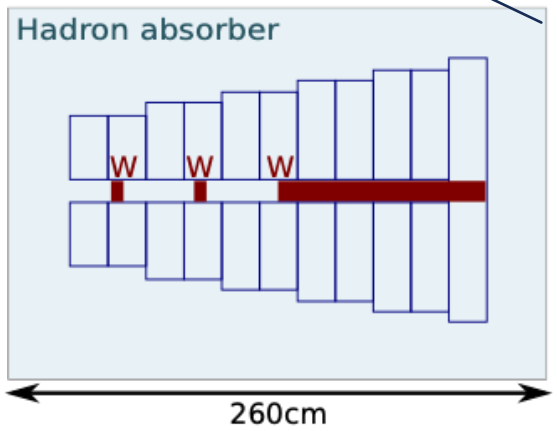
2019: a number of new calculations on meson PDFs: Lattice QCD, DSE, holographic QCD,

AMBER EXPERIMENT – PROPOSED SETUP



- Beams available 190 GeV Run3
  - positive pions (25%) protons (74%)
  - negative pions (97%)
- Beams available at ~100 GeV Run4 (with RF)
  - negative kaons (~50%), pions (~50%)
  - positive kaons
  - antiprotons





Only place in the world with pion and (kaon, antiproton) beams

CHARMONIUM STUDIES IN COMPASS++/AMBER

- Advantages of FT energies: 100 – 200 GeV
  - J/ψ has large cross sections – factor of 30-40 larger than Drell-Yan at 190 GeV
  - Fixed target energy: production is dominated by 2 -> 1 processes

    however: $p_T \leqslant M(J/\psi)$: complementary to LHC, where $p_T >> M(J/\psi)$;
  - Can measure x_F, p_T, λ distributions with unprecedented statistics (> 1 M events)
  - Study light (^{12}C) and heavy (^{184}W) targets
  - Simultaneous measurements with π^+ and p, and also π^-
  - New, high statistics measurements with K^+ and K^-

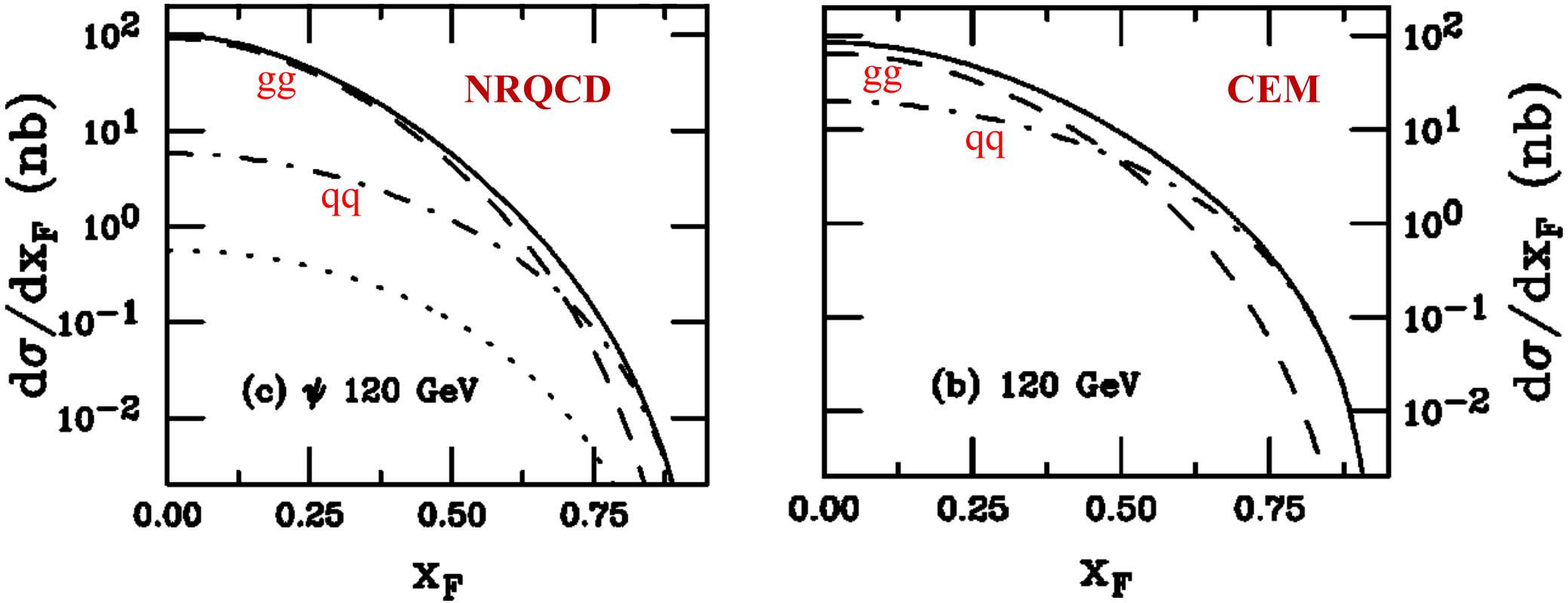
CHARMONIUM STUDIES IN COMPASS++/AMBER

- Difficulties – and impetus for deeper studies
  - Model dependence: the production mechanism is not well known. A long history…
  - Mainly two production models: CEM and NRQCD. At FT energies, both models have $q\bar{q}$ and gg as dominant contributions to the cross section
- Potential interest
  - Access quark/gluon PDFs of pion and kaon
  - Access gluon PDFs in nuclei

DO WE UNDERSTAND THE J/ψ PRODUCTION?

- Two models: CEM and NRQCD – quantitatively different results

(R. Vogt, 2000)



Model dependence!! prevents a reliable PDF extraction

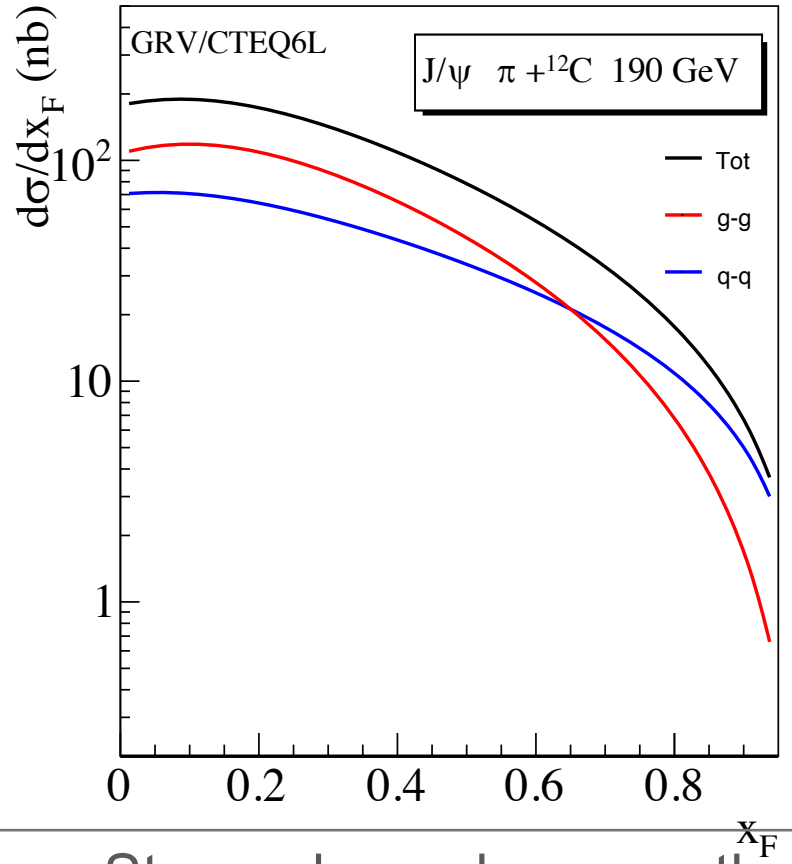
J/ψ PRODUCTION MECHANISMS

- Color Evaporation Model (CEM)
  - Simple cross section for producing $Q\bar{Q}$ pairs. Ignores quantum numbers.
  - Considerable phenomenological success
- Recent improvements ICEM (Cheung+Vogt, PRD98,2018 and priv. comm.)
  - includes p_T dependence, ICEM + k_T factorization => cross sections, x_F and p_T dependence, polarization, etc…
- NRQCD (Bodwin, Braaten, Lepage): rigorous consequence of QCD
  - Long-Distance Matrix Elements (LDME): probability of the *cc* pair to evolve into a quarkonium state. LDME: conjectured to be universal

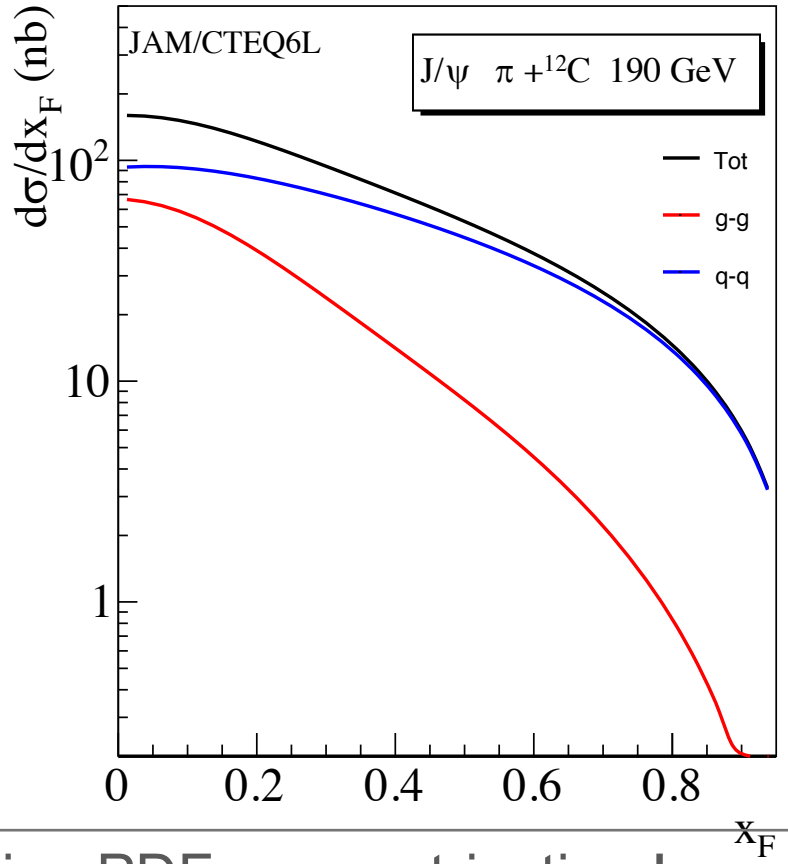
Could new FT data help improving our knowledge on J/ψ production?

π + ^{12}C CROSS SECTION FOR TWO PDF "GLOBAL" FITS (CEM AT LO)

π PDF: GRV (1992)

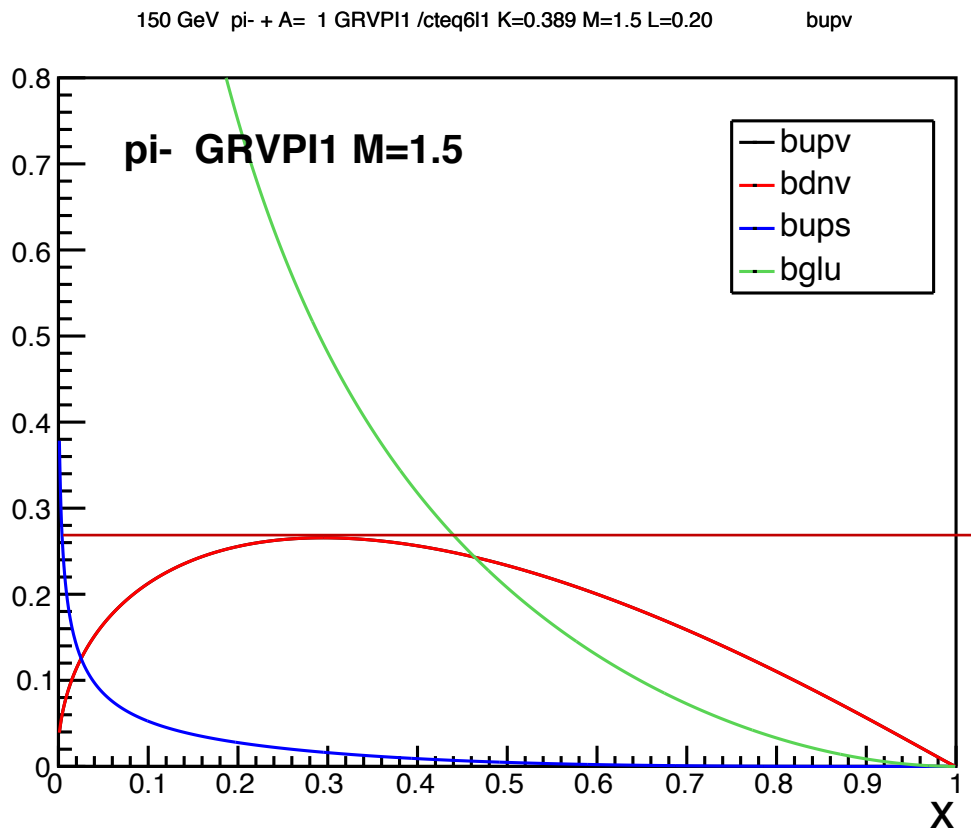


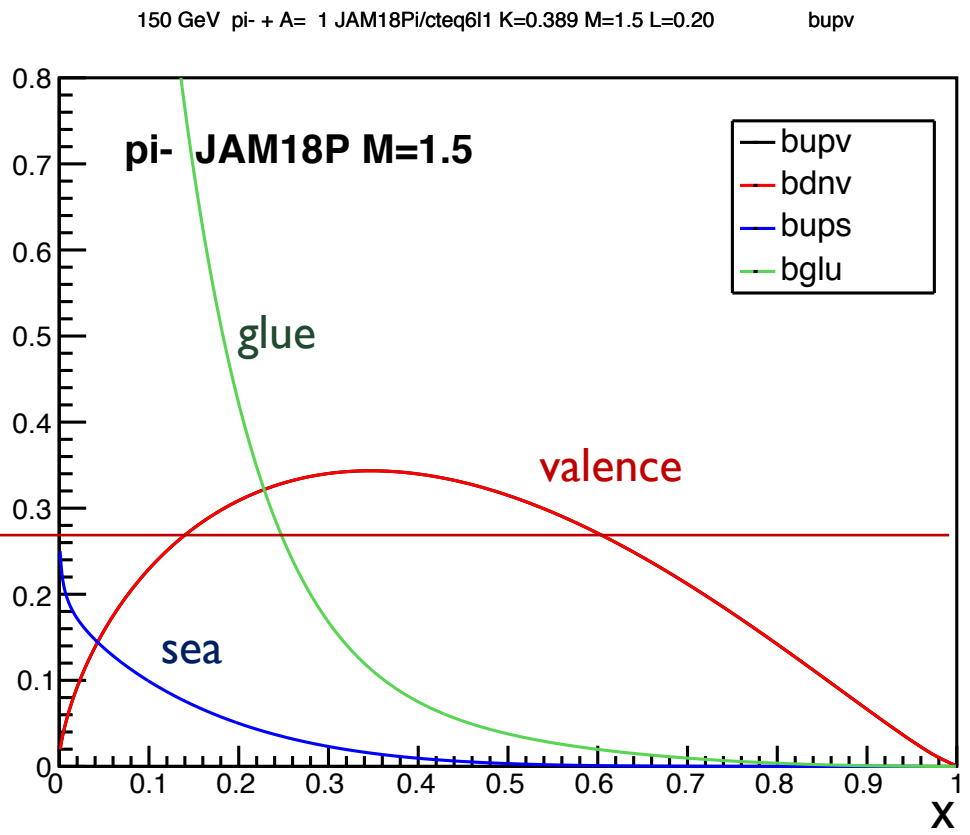
π PDF: JAM (2018)



Strong dependence on the pion PDF parametrization !

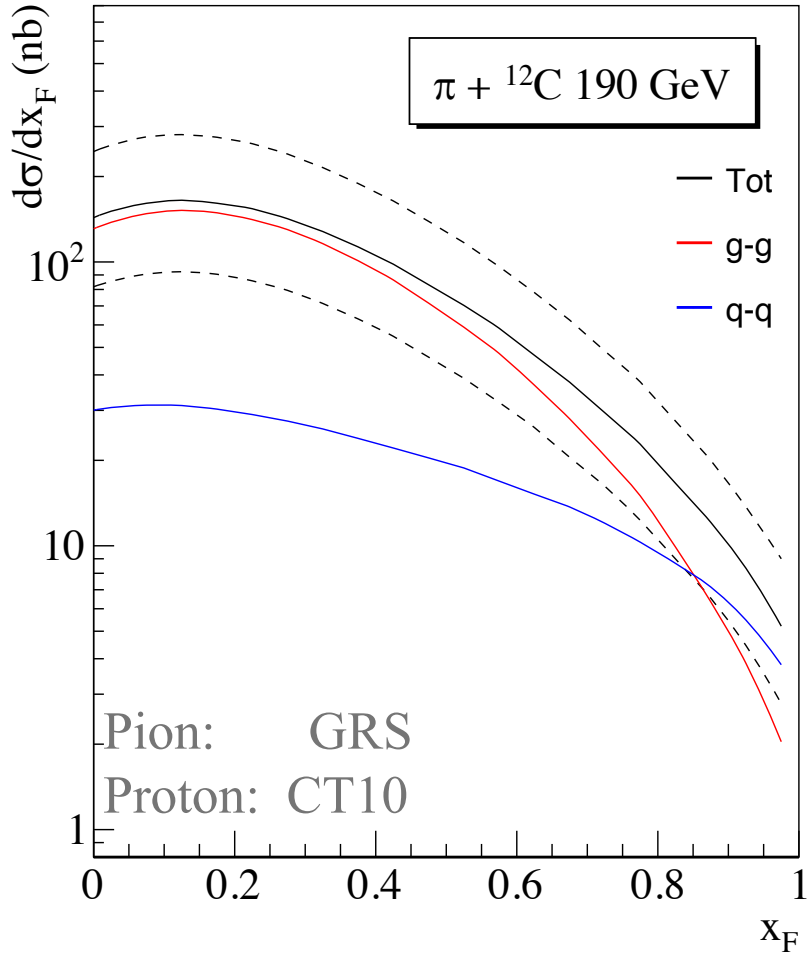
GRV(1992) VS JAM(2018) PION PDFS

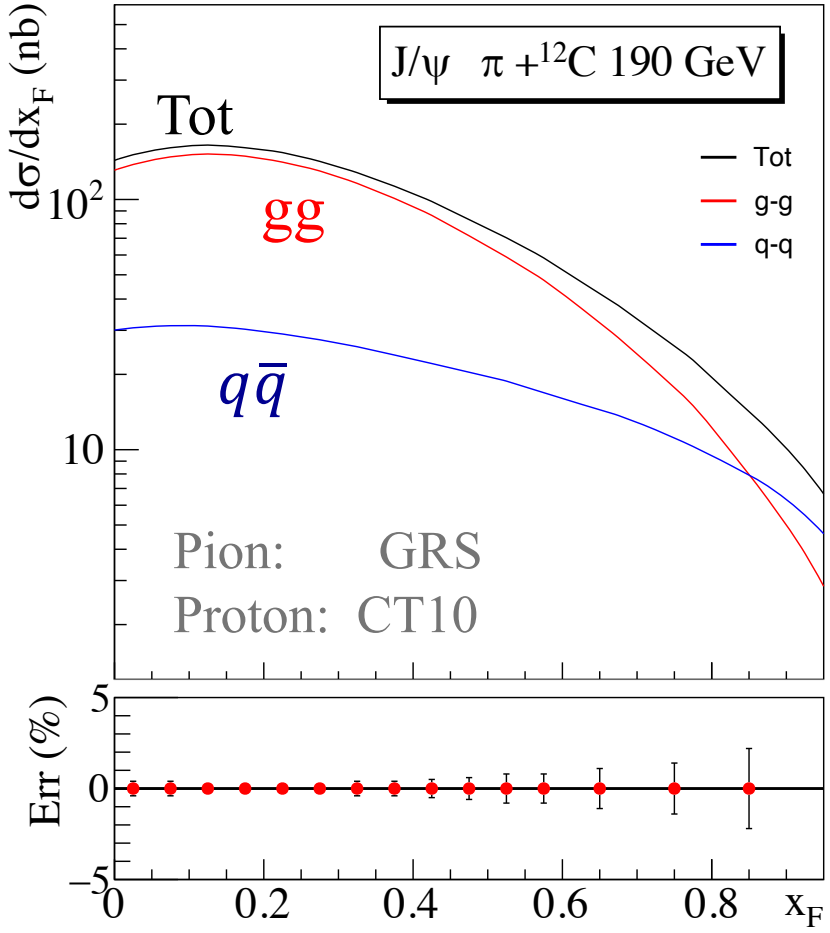




The two global fits provide different PDFs: valence, gluon, sea

ICEM PREDICTIONS – X_F DEPENDENCE (CHEUNG AND VOGT, 2019)





Relative statistical errors

POLARIZATION

- J/ψ is a 1^{--} particle; its third component is $J_z = 0, +1, -1$.

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

  - $\alpha = -1$ corresponds to 100% longitudinal polarization ($J_z = 0$)
  - $\alpha = +1$ corresponds to 100% transverse polarization ($J_z = \pm 1$)

- Polarization as a fundamental observable
  - angular momentum, chirality, parity conservations preserve the properties of the J/ψ: from production to the 2μ decay
  - Key variable for understanding the bound state formation

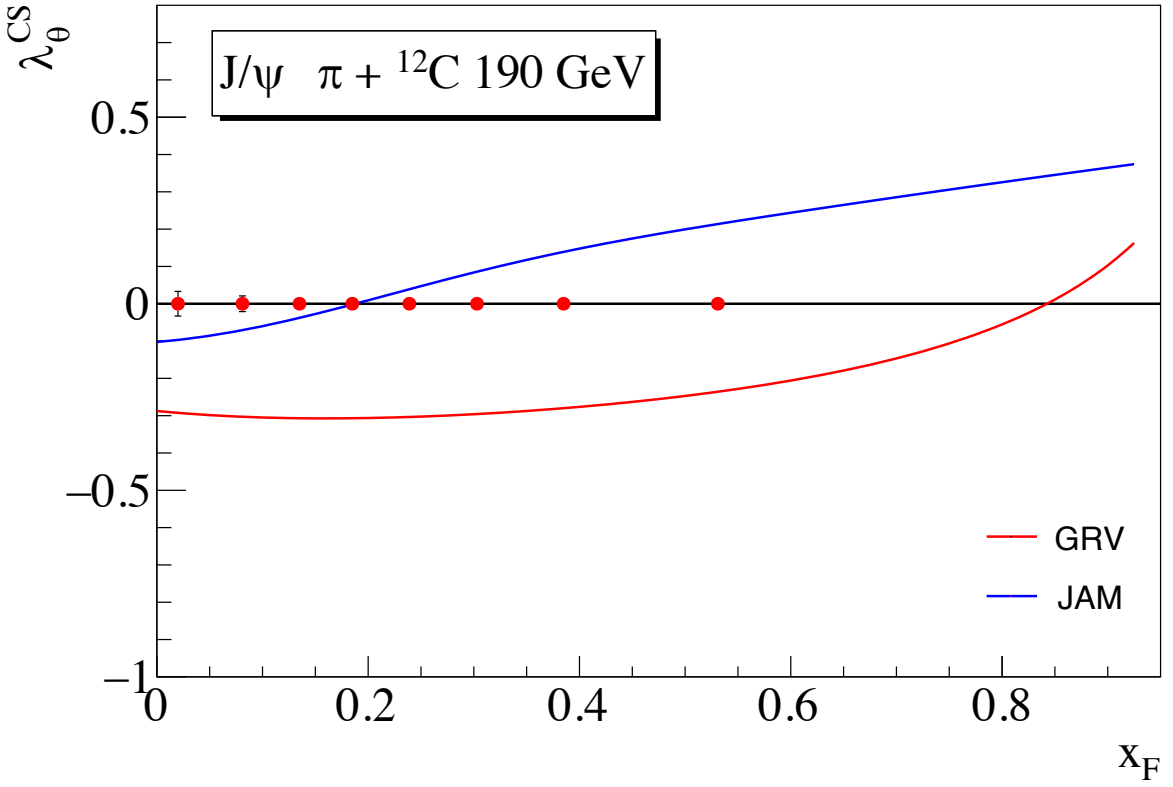
POLARISATION: EXPECTED RESULTS (CHEUNG AND VOGT, PRIV. COMM.)

- ICEM predictions for each term:
  - with minimal model-dependence

$$\lambda_\vartheta^{CS} \approx +0.4 \text{ for } q\bar{q}$$

$$\lambda_\vartheta^{CS} \approx -0.6 \text{ for } gg$$

  - The difference between the two predictions illustrates the different amount of $q\bar{q}$ and gg contributions as a function of x_F.



A second observable to disentangle between production models and pion PDF.

Errors estimated using 2015 Compass data

ESTIMATED J/ψ STATISTICS

Experiment	Target type	Beam energy (GeV)	Beam type	J/ψ events
NA3 [76]	Pt	150	π^-	601000
		280	π^-	511000
		200	π^+	131000
			π^-	105000
E789 [127, 128]	Cu	800	p	200000
	Au			110000
	Be			45000
E866 [129]	Be	800	p	3000000
	Fe			
	Cu			
NA50 [130]	Be	450	p	124700
	Al			100700
	Cu			130600
	Ag			132100
	W			78100
NA51 [131]	p	450	p	301000
	d			312000
HERA-B [132]	C	920	p	152000
This exp	75 cm C	190	π^+	1200000
			π^-	1800000
			p	1500000
	12 cm W	190	π^+	500000
			π^-	700000
			p	700000

Comments

Cross sections not published, only plots available

OK, x_F and p_T cross sections available

Only ratios of cross sections available

Only A-dependent studies of total cross sections

Only A-dependent studies of total cross sections

OK, x_F and p_T cross sections available

…

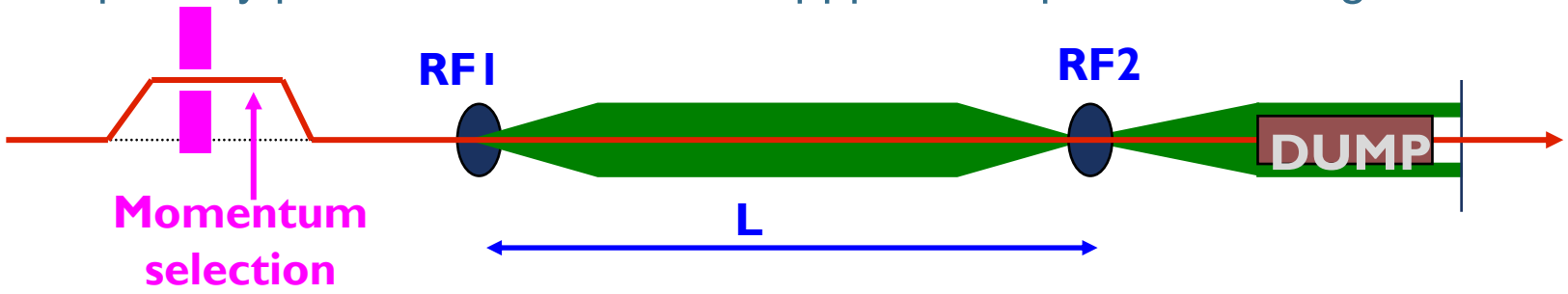
Estimations based on Compass preliminary numbers

ψ' PRODUCTION

- Advantages
  - No feed-down contributions. Consequences:
    - straightforward test of production models, no dilution.
    - $q\bar{q}$ and gg contributions could reach their maximum polarization values
  - x_F and p_T dependences could be measured altogether with the polarisation
  - AMBER could provide the largest ψ' data set ever.
- Requirements
  - Good mass resolution (≤ 100 MeV) to separate J/ψ and ψ' – vertex detectors
- Expected statistics
  - between 100 and 300 k events per target/beam

RUN4++ : RF SEPARATED BEAMS – HIGH-INTENSITY

- Studies underway at CERN for RUN4 (2026++)
- Some assumptions:
  - L = 450 m, f = 3.9 GHz, beam spot within 1.5 mm
  - Reasonable primary target efficiency, 80% wanted particles pass dump
  - Number of primary protons: 100 - 400x10^{11} ppp on the production target

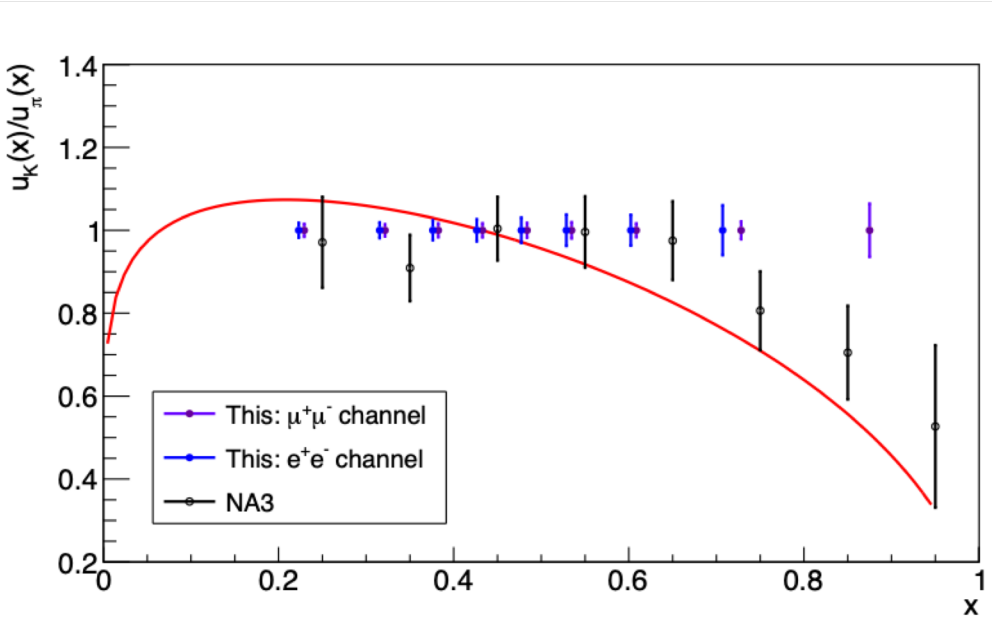


  - Energy limitation : 100 GeV

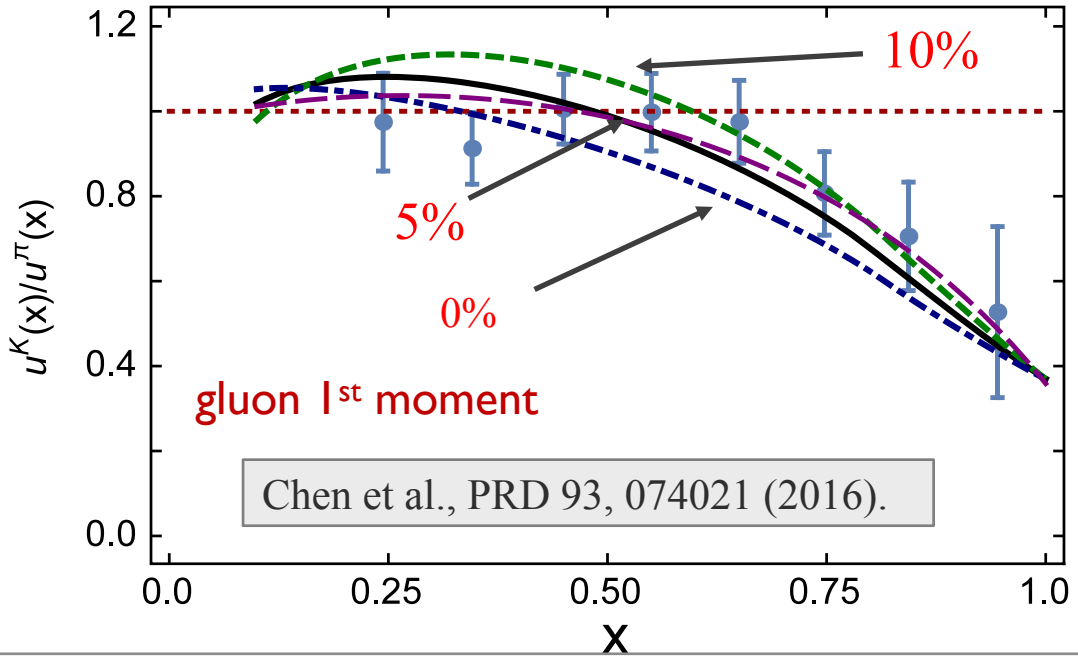
Large improvement in kaon and antiproton intensities (> x 20- 40 !)

KAON PDF: ESTIMATED STATISTICAL ERRORS

Kaon PDF: estimated DY data statistics



DSE calculation



DSE: at the hadronic scale gluons carry

5% of the momentum of the kaon BUT

30% of the momentum of the pion !

J/ψ – MODEL-INDEPENDENT ACCESS TO THE KAON VALENCE PDF!

- Production cross section for K^+ and K^-

$$K^-(\bar{u}s)+p(uud)\propto gg+\left[\bar{u}_v^K u_v^p\right]+\left[\bar{u}_v^K u_s^p+s_v^K s_s^p\right]+\left[\bar{u}_s^K u_v^p\right]+\left[\bar{u}_s^K u_s^p+u_s^K \bar{u}_s^p+s_s^K \bar{s}_s^p+\bar{s}_s^K s_s^p\right]$$

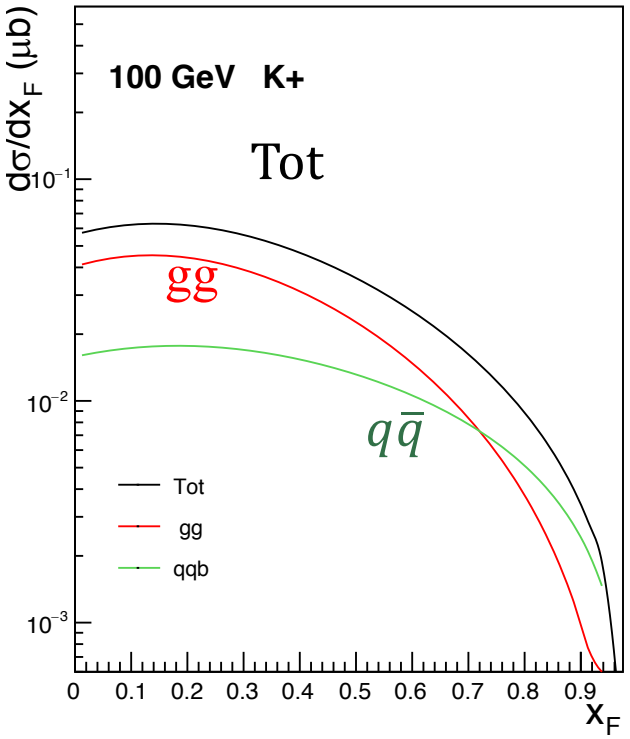
$$K^+(u\bar{s})+p(uud)\propto gg+\left[---\right]+\left[u_v^K \bar{u}_s^p+\bar{s}_v^K s_s^p\right]+\left[\bar{u}_s^K u_v^p\right]+\left[\bar{u}_s^K u_s^p+u_s^K \bar{u}_s^p+s_s^K \bar{s}_s^p+\bar{s}_s^K s_s^p\right]$$

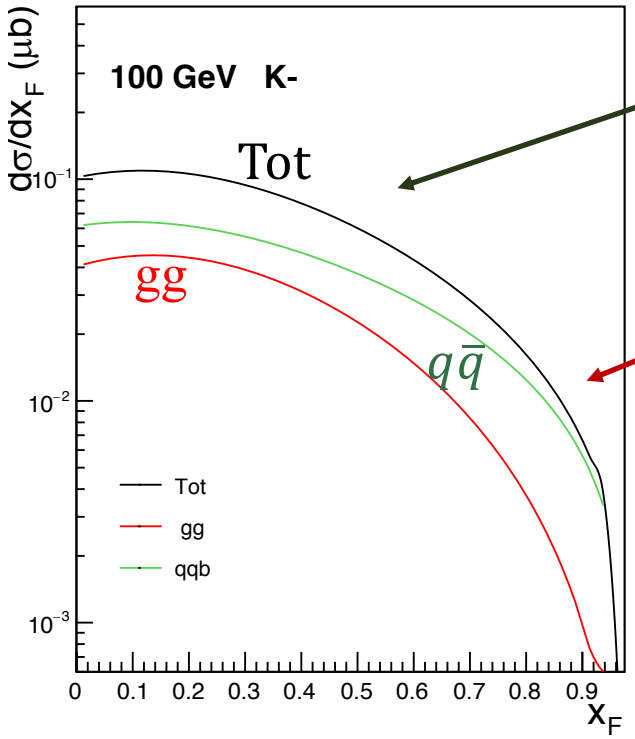
val-val val-sea sea-val sea-sea

  - The cross section difference isolates the val-val term: $\sigma(K^-)-\sigma(K^+)\propto \bar{u}_v^K u_v^p$

KAON-INDUCED J/ψ PRODUCTION

LO CEM calculations





identical val-sea and sea-sea contributions

identical gg contributions

Similar cancellations for $\bar{p}/p$:

$$p^-(\overline{uud}) + p(uud) \sim \bar{u}_p u_p + \bar{d}_p d_p + g_p g_p$$

$$p^+(uud) + p(uud) \sim + g_p g_p$$

SUMMARY

- DY and J/ψ data with π+ and π− beams (Run 3)
  - DY data: pion PDFs, flavor dependence of the nuclear men field
  - J/ψ and ψ' data: high-statistics FT data for production mechanism studies
  - Could charmonium data be used to infer the meson PDFs?
    - ✓ CERN + AMBER is unique for such measurement; no direct competition

- DY and J/ψ data with kaon beams (Run 4 – using RF separated beams)
  - DY data: kaon PDF measurements
  - J/ψ and ψ' data: comparison K^- and K^+ data – production mechanism, kaon structure
    - ✓ Particularly motivating extensions with kaon and antiproton beams